The CALET Project for All-Sky Gamma-Ray and Electron Observations on JEM-EF of ISS

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Abstract

The CALorimetric Electron Telescope, CALET, is a new all-sky gamma-ray and electron observatory being developed for the Exposure Facility of Japanese Experiment Module on the International Space Station. The mission goal is to investigate high-energy universe by observing cosmic-ray electrons in 1 GeV – 10 TeV, gamma rays in 20 MeV – 10 TeV, and protons, heavier nuclei in several 10 GeV – 1 PeV. The main instrument consists of an imaging calorimeter of scintillating fibers, IMC, and a total absorption calorimeter of BGO, TASC. CALET has a unique capability to observe electrons and gamma rays over 1 TeV with a hadron rejection power larger than 10^5 and an energy resolution better than a few % above 100 GeV. This capability enables us to search for nearby cosmic-ray sources, dark matter and so on. With an auxiliary detector, CALET will also monitor gamma-ray bursts.

Key words: ISS:JEM-EF — cosmic rays:electrons — gamma rays

1. Introduction

We are developing CALorimetric Electron Telescope (CALET) for all-sky gamma ray and electron observations on the Japanese Experiment Module Exposure Facility (JEM-EF) of the International Space Station (ISS). The mission goal is to investigate the high-energy phenomena in the universe by observing electrons in 1 GeV – 20 TeV, gamma rays in 20 MeV – several TeV, and protons, heavier nuclei in several 10 GeV – 1 PeV.

Since 1993, we have developed an imaging calorimeter of the BETS (Balloon-borne Electron Telescope with Scintillating fibers) for balloon experiments, and successfully observed cosmic-ray electrons of 10 GeV – 100 GeV (Torii et al. 2001) and atmospheric gamma rays in a few GeV – several 10 GeV (Kasahara et al. 2002). In 2004, by using the Polar Patrol Balloon in Antarctica, we also carried out the observations of high-energy electrons in 100 GeV – 800 GeV for 13 days (Torii et al. 2008). The CALET is designed on the basis of the BETS instrument to observe higher energy electrons and gamma rays up to ∼10 TeV on the ISS.

In this paper, we will discuss the science, technique, observation and current status of the CALET project.

2. CALET instrument

2.1. Detector concept

The CALET detector consists of the IMaging Calorimeter (IMC), the Total AbSorption Calorimeter (TASC), the SIlicon pixel Array (SIA), and the Anti-Coincidence Detector (ACD). In addition, the Gamma-ray Burst Monitor (GBM) is put together. The total detector weight is $\sim 1.45\times 10^3$ kg. Figure 1 and 2 present an overview of the CALET at JEM-EF on the ISS and a

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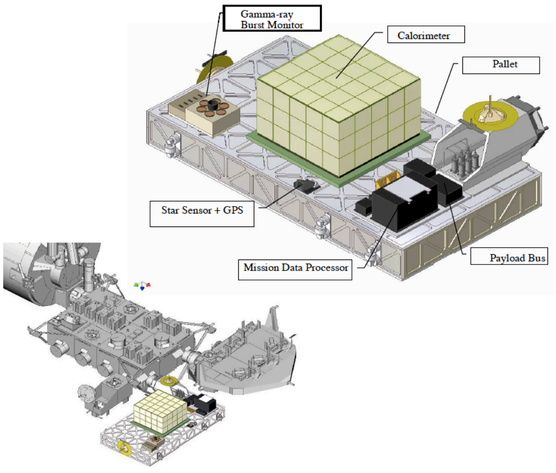

Fig. 1. Overview of the CALET at JEM-EF on the ISS.

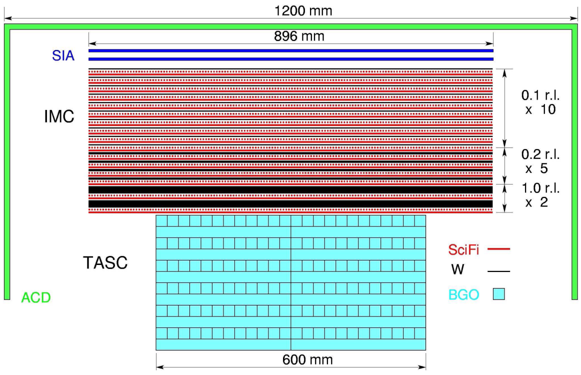

Fig. 2. Schematic side view of the CALET detector.

schematic structure of the CALET detector, respectively.

The IMC is a tracking-type calorimeter using scintillating fibers and tungsten plates. The scintillating fibers with a 1 mm cross section are used to observe particles in pre-shower stage. The IMC has 36 layers of scintillating fiber belts which are set in right angle alternately to observe the projected shower profile in x and y direction. The dimensions of IMC are 89.6 cm × 89.6 cm. While the total thickness of the tungsten plates is 4 radiation lengths (r.l.) and about 0.13 mean free paths (m.f.p.) for proton nuclear interactions, the first 10 tungsten plates are placed with 0.1 r.l. each, followed by 5 plates with 0.2 r.l. each and finally 2 plates with 1 r.l. each. This provides the precision necessary to separate the incident particle from backscattered particles, precisely determine the starting point for the electromagnetic shower, and identify the incident particle. The readout for the scintillating fiber layers is planned to consist of multi-anode photomultiplier tubes (MA-PMT), such as the Hamamatsu R5900. The front-end electronics for the IMC are based upon a high density ASIC such as the 32 channel Viking (VA32HDR2) chip (Tamura et al. 2007). Figure 3 shows an exploded view of the IMC.

The TASC measures the development of the electromagnetic shower to determine the total energy of the incident particle and separate electrons and gamma rays from hadrons. The TASC is composed of 12 layers of BGO logs where each log has dimensions of 2.5 cm × 2.5 cm × 30 cm and there are 48 such logs in each layer. Alternate layers are oriented 90° to each other to provide an x, y coordinate for tracking the shower core. The total area of TASC is 3.6×10^3 cm^2 and the vertical thickness is 32 r.l. and 1.6 m.f.p. Each BGO log is read by a photodiode for measuring in a high dynamic range (Katayose et al. 2007). Figure 4 shows an exploded view of the TASC.

At the top of IMC, the SIA is placed to improve the charge resolution of incident particles and eliminate effectively the back-scattered particles. The ACD also covers the whole detector to reject charged particles for low energy gamma-ray observations.

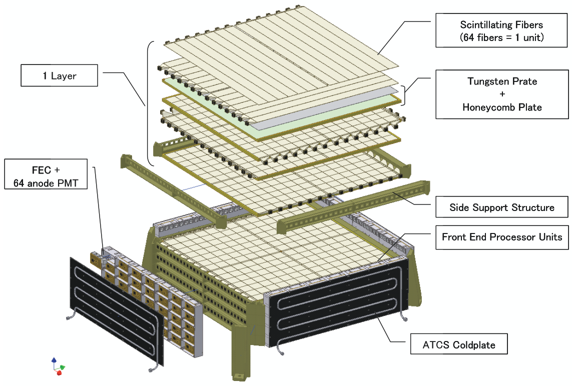

Fig. 3. Exploded view of the IMC.

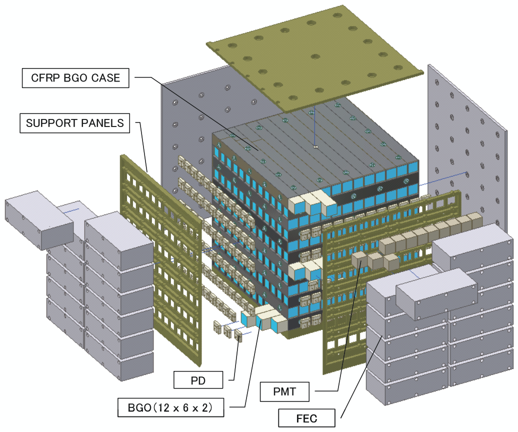

Fig. 4. Exploded view of the TASC.

2.2. Beam test and balloon experiment of the proto-type detectors

We have carried out a beam test in 2003 by use of CERN-SPS for the prototype detector, which consists of the IMC of 512 scintillating fibers with 4 r.l. lead plate and the TASC of 26 BGO logs with 23 r.l. in thickness (Katayose et al. 2005). The performance of the prototype detector has been studied on the rejection power against protons, the energy resolution, the angular resolution, and so on. These results were consistent with the Monte-Carlo simulations.

We have also carried out a balloon observation of cosmic rays with a 1/64 scale model of the CALET detector, so-called bCALET-1, at Sanriku Balloon Center of JAXA in 2006 (Shimizu et al. 2007). The bCALET-1 consists of 1024 scintillating fibers with tungsten plates for the IMC and 24 BGO scintillator logs for the TASC. The area of IMC is 12.8 cm × 12.8 cm. We used 8 MA-PMTs to read out the scintillation light of each scintillating fiber, and developed a front-end circuit with an analog ASIC chip, VA32HDR14, for the readout of the MA-PMTs. We optimized the VA32HDR14 to read out the MA-PMTs to obtain a higher dynamic range of a few thousands. As for the TASC, BGO logs were read out with photo-diodes. The observation was carried out at an altitude between 35 and 37 km for about 3.5 hours. We measured the energy spectrum of electrons from 600 MeV to 20 GeV, verifying the front-end circuits and the detector. We are planning a series of balloon experiments with larger-scale detectors and longer-duration flights, which includes one-month observation by a super-pressure balloon.

2.3. Performance of CALET

We have studied the detector performance by the balloon experiments, accelerator beam tests of the proto-type detector, and Monte-Carlo simulations.

As shown in Fig. 5, the CALET can observe electrons and gamma rays with the energy resolution of a few % at 100 GeV and better for higher energies due to the thick radiation lengths of the TASC. Figure 6 shows the angular resolution as a function of gamma-ray energy. The angular resolution for one photon is ~0.1 degree above several 10 GeV with the IMC. The angular resolution for one electron is ~0.06 degree above several 10 GeV, which is better than gamma rays (Akaike et al. 2008). The CALET also has an excellent capability of the proton rejection power larger than 10^5 with the TASC, which is necessary to select electrons and gamma rays in the TeV region. As for the separation of electrons and gamma rays, below 10 GeV, we separate by the anti-coincidence system. Over 10 GeV region, electrons and gamma rays are separated by the IMC, since gamma rays have no tracks at the incident position to the IMC except for back-scattered particles. Gamma-ray rejection power for the electron observation is larger than 5×10^2, and electron rejection power for the gamma-ray observation is larger than 10^5.

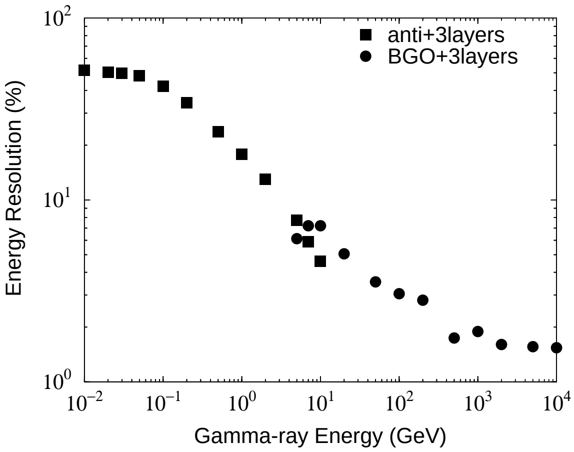

Fig. 5. The energy resolution as a function of gamma-ray energy.

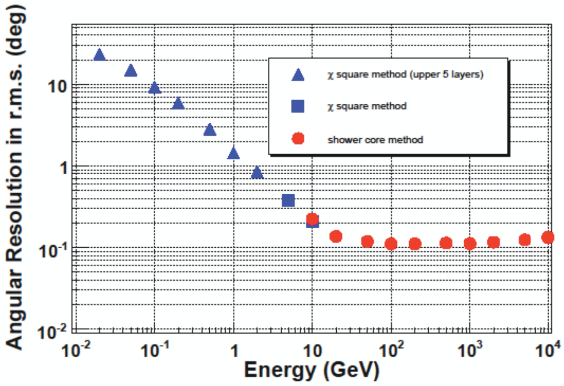

Fig. 6. The angular resolution as a function of gamma-ray energy.

The event trigger will be performed in the following three modes: gamma rays in 20 MeV - 10 GeV by anti-coincidence and tracking of shower particles in the IMC, electrons and gamma rays over 10 GeV by shower trigger in the IMC, and protons over 1 TeV by shower trigger in the TASC. The electrons in 1 GeV - 10 GeV are observed only for the limited term by reducing the threshold of the shower trigger in the IMC. The trigger rates estimated by simulations are ~51 Hz for 20 MeV - 10 GeV gamma rays (~37 Hz for albedo gamma rays), ~40 Hz for electrons and gamma rays over 10 GeV, in which almost triggered events are protons and heliums as background, and <0.1 Hz for protons over 1 TeV.

3. Expected scientific results

The JEM-EF on the ISS gives us an excellent opportunity to carry out the high-energy electron and gamma-ray observation for a long exposure. The CALET has a wide field of view of 0.5 – 1.8 sr, and a large area of $\sim$0.8 m^2. The CALET can perform all sky gamma-ray and electron survey without attitude control of the instrument by using the ISS orbit, observing gamma-ray point sources for $\sim$40 – 50 days.

3.1. Gamma-ray observations

The EGRET instrument performed the first complete sky survey with gamma rays in the energy range of 20 MeV to 30 GeV (Hunter et al. 1997). EGRET revealed that the high-energy gamma-ray sky is surprisingly dynamic and diverse, and found many unidentified sources. The GLAST, being a successor of EGRET, was launched in 2008 to study the high-energy universe by the observations of gamma rays in the 20 MeV – 300 GeV (The GLAST team 2008). CALET will continuously survey the gamma-ray sky up to higher energies and with better energy resolution than GLAST.

Figure 7 presents the expected point source sensitivity of CALET, compared to the other experiments. For air Cherenkov telescopes on the ground, the sensitivities are derived for a 50 hour exposure on a single source. For CALET, EGRET, AGILE, and GLAST, the sensitivities are shown for one year of all sky survey. As presented in Fig. 7, for individual point sources, air Cherenkov telescopes on the ground have a higher sensitivity over 100 GeV. However, since the ground based telescopes have limitations such as low duty cycles (10 %), a small field of view (< 5 deg), and incapability of rejection of the background electrons, CALET has a better sensitivity for observations of diffuse gamma-rays such as the Galactic and extra-galactic diffuse emission. Figure 8 presents the CALET detection limit of Galactic diffuse gamma rays for 4 years.

In addition, CALET can derive wide-band energy spectra of gamma-ray bursts (GRB) over an unprecedented 9 order of energy from a few keV to a few TeV by a combination of the CALET calorimeter and the GBM (Nakahira et al. 2008).

3.2. Electron observations

Evidences of non-thermal X-ray emission and TeV gamma-rays from supernova remnants (SNRs) reveal that high energy cosmic ray electrons and/or protons are accelerated in SNRs.

High-energy electrons lose energy via synchrotron and inverse Compton processes during propagation in the Galaxy. Since the energy loss rate by these processes is proportional to the square of energy, TeV electrons released from SNRs at distances larger than $\sim$ 1 kpc, or times older than $\sim$10^5 yr, cannot reach the solar system. Kobayashi et al. (2004) suggested that some nearby SNRs in space ant time, such as Vela, Cygnus Loop, or Monogem, could leave unique signatures in the form of identifiable structure in the energy spectrum of TeV electrons, and show increases of the flux towards the sources. Thus, the primary electron component of the Galactic cosmic rays is of fundamental importance to identify cosmic-ray sources, providing acceleration and propagation mechanisms.

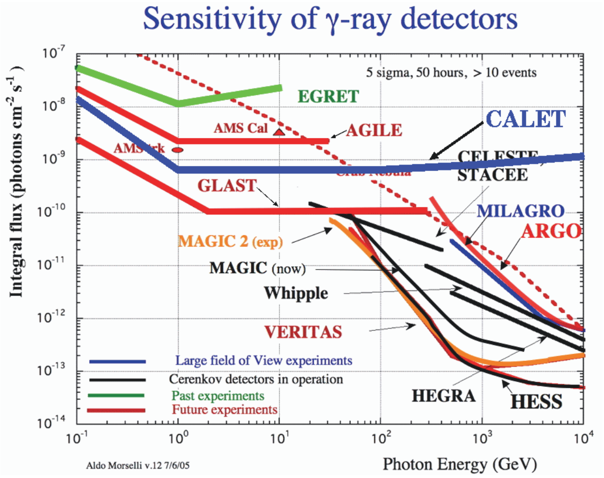

Fig. 7. Gamma-ray point source sensitivity of CALET, compared to the other instruments.

In the case of one of the calculations by Kobayashi et al. (2004), a diffusion coefficient of $D_0 = 2 \times 10^{29}$cm^2/s at 1 TeV, a cut-off energy of E_c=20 TeV for the electron source spectrum, and the burst-like release at $\tau = 5{\times}10^3$ yr after the supernova explosion, we simulated the energy spectrum observed with the CALET, as shown in Fig. 9. This figure presents that the CALET has a capability to identify the unique signature in the energy spectrum with high statistical precision, especially originated from the Vela SNR.

Because the rate of energy loss due to radiation is much higher for electrons than for nuclei, the degree of anisotropy of high-energy cosmic ray electrons is expected to be higher than that of the nuclear component (Shen et al. 1971). Figure 10 shows the electron intensity distribution along Galactic longitude in the case of a diffusion coefficient of $D_0 = 2{\times}10^{29}$cm^2/s at 1 TeV and a cut-off energy of E_c=20 TeV for the prompt release after the explosion ($\tau = 0$). The maximum intensity is in the direction of Vela at $(\ell, b) = (263^\circ.9, -3^\circ.3)$. As shown in this figure, CALET has a capability of the detection of anisotropy toward the nearby SNR.

3.3. Dark matter search

Although the nature and origin of the dark matter are one of the most important unresolved problem in astrophysics, we do not know what the dark matter is made of. The most predominant candidates of dark matter are some weekly interacting massive particles (WIMPs). WIMPs are, perhaps, the most plausible class of can-

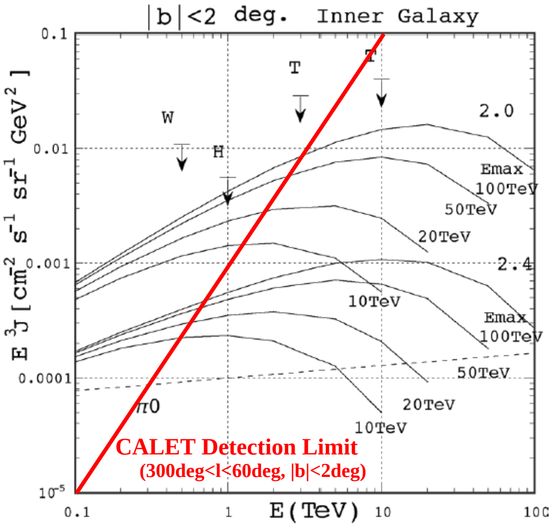

Fig. 8. The CALET detection limit of Galactic diffuse gamma rays above 0.1 TeV for 4 years, compared with the calculated energy spectra (Tateyama 2006).

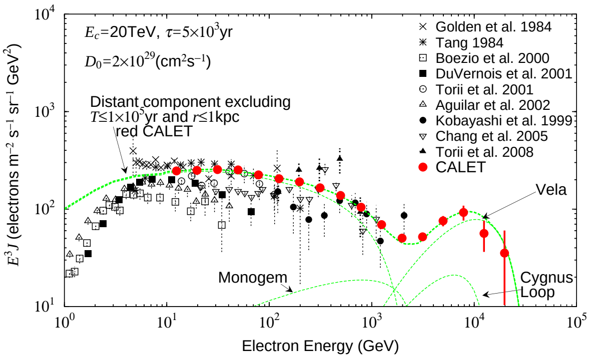

Fig. 9. Simulated electron energy spectrum of the CALET compared with previous data (Kobayashi et al. 2004 and references therein).

didates for dark matter. Among these, neutralino, χ, of the lightest stable supersymmetric (SUSY) particle is the most well motivated. Models with extra dimensions can also provide an alternative candidate for dark matter. In particular, the lightest Kaluza-Klein particle (LKP) in models of universal extra dimensions may be stable and can be a dark matter candidate. The most natural LKP is the first Kaluza-Klein excitation of the hypercharge gauge boson, $B^{(1)}$. This state is referred as Kaluza-Klein particle. These WIMPs are expected to annihilate and/or decay into gamma rays, e^+e^-, and so on. Hence, the indirect observations of dark matter is possible by the detection of these products.

There are many calculations of neutralino gamma-ray signals from accreting Galactic halo dark matter. By using the result of a calculation of Bergström et al. (2001), we estimated the possibility of detection of a neutralino annihilation. In the case of the annihilation rate σv of 7.5×10^{-29} cm^{3}s^{-1} with the gamma-ray energy of 690 GeV, the gamma-ray line flux is estimated to be 1.7×10^{-8} (cm^{-2} s^{-1} sr^{-1}) in a field of 44°×5° along the Galactic plane in the direction of Galactic center. Figure 11 shows the simulated energy spectrum of a gamma-ray line at 690 GeV from neutralino annihilation for the four years observations, including the background of the Galactic diffuse emission. As shown in Fig. 11, the CALET has the excellent energy resolution less than a few % above 100 GeV that is suitable to observe line features in the gamma-ray energy spectrum. Thus, the CALET has a possibility to detect a gamma-ray line in the GeV - TeV region from dark matter annihilations.

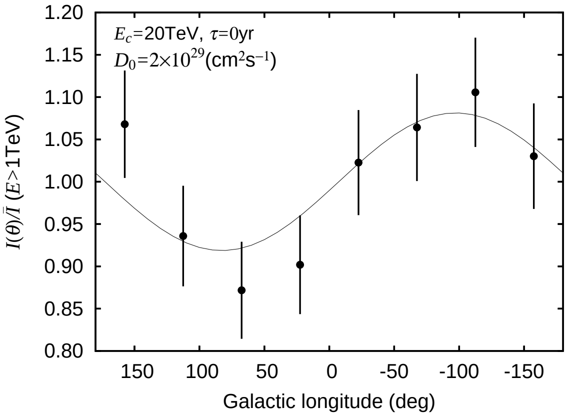

Fig. 10. Electron intensity distribution along the Galactic longitude with the simulated distribution of CALET.

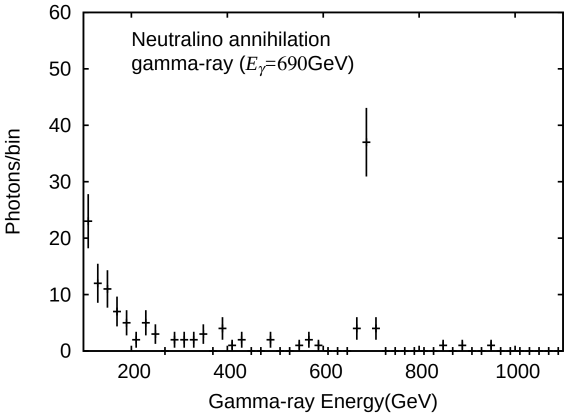

Fig. 11. Simulated energy spectrum of a gamma-ray line at 690 GeV from neutralino annihilation toward the Galactic center with CALET.

Although the direct annihilation to e^+e^- is suppressed for neutralino in the SUSY theory, Kaluza-Klein dark matter directly annihilates to e^+e^- with a large fraction of ∼20 %. Although the produced mono-energetic

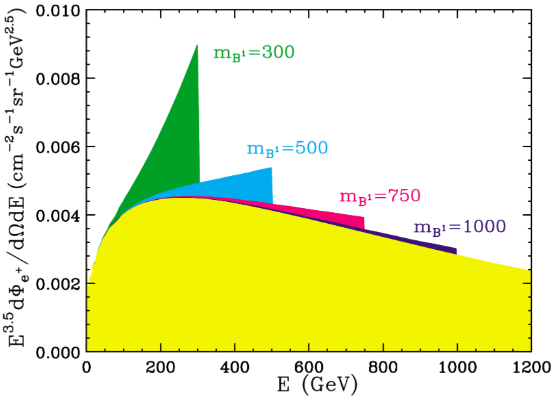

Fig. 12. Predicted positron signals from annihilation of Kaluza-Klein dark matter candidates from Cheng et al. (2002).

e^+e^- lose energy during the propagation in the Galaxy, the observed spectrum would still have a distinctive feature. Figure 12 shows the predicted positron signals for possible Kaluza-Klein particle masses with the estimated background flux of purely secondary positrons (Cheng et al. 2002).

In the case of Kaluza-Klein dark matter for the 300 GeV mass, we simulated the electron + positron spectrum observed with the CALET for the four years observations. The "background" continuum spectrum is the power-law with an index of −3.26 that well represents the observed cosmic-ray electron + positron spectra over a few 10 GeV (Kobayashi et al. 2002). Although the CALET cannot separate electrons and positrons, the high precise measurements of electrons + positrons enable us to detect the distinctive features from dark matter annihilation in the Galactic halo, as shown in Fig. 13.

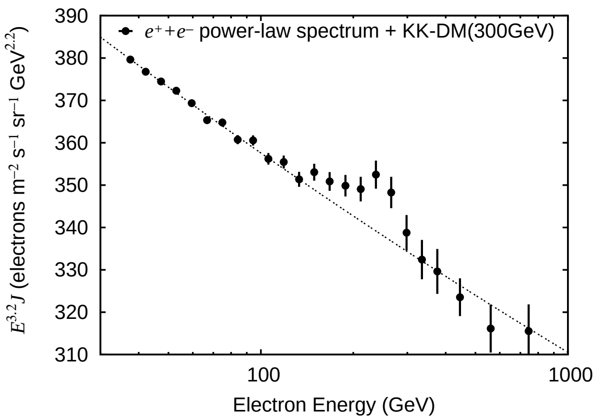

Fig. 13. Simulated energy spectrum of the electron, $e^+ + e^-$, power-law spectrum with Kaluza-Klein dark matter annihilation for 300 GeV mass.

4. Summary and future prospects

We have successfully been developing the CALET instrument for JEM-EF on ISS from the experience of balloon experiments. CALET would provide the first direct identification of cosmic-ray sources by the measurements of the TeV electrons. No other current of planned electron detector has the high-energy reach of CALET. This makes CALET a unique window into the high-energy universe. CALET will also continuously survey the gamma-ray sky up to higher energies with better energy resolution than GLAST. GRB measurements are complementary to those of GLAST and SWIFT but at substantially higher energies. In particular, CALET offers two separate channels by which dark matter candidates may be sought. Neutralinos could annihilate to produce a high-energy gamma ray emission line, or Kaluza-Klein particles could produce high-energy electrons that would show up above the background.

We have already completed a pre-phase A study within last 6 years by a support of JAXA (JSF) budget. International collaboration team (Japan, US, Italy, China) has successfully been established with an allocation of sub-component development. JAXA has selected CALET as one of three mission candidates in May, 2007 for concept study and definition of mission instrument (∼phase A). CALET will be launched around 2013 if it will be approved by the next selection expected within one year.

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