Perspective of monochromatic gamma-ray line detection with the High Energy cosmic-Radiation Detection (HERD) facility onboard China’s Space Station

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HERD is the High Energy cosmic-Radiation Detection instrument proposed to operate onboard China’s space station in the 2020s. It is designed to detect energetic cosmic ray nuclei, leptons and photons with a high energy resolution (≈ 1% for electrons and photons and 20% for nuclei) and a large geometry factor (≈ 3 m² sr for electrons and diffuse photons and ≈ 2 m² sr for nuclei). In this work we discuss the capability of HERD to detect monochromatic γ-ray lines, based on simulations of the detector performance. It is shown that HERD will be one of the most sensitive instruments for monochromatic γ-ray searches at energies between ≈ 10 to a few hundred GeV. Above hundreds of GeV, Cherenkov telescopes will be more sensitive due to their large effective area. As a specific example, we show that a good portion of the parameter space of a supersymmetric dark matter model can be probed with HERD.

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I. INTRODUCTION

Cosmological observations have well established that dark matter (DM) constitutes ≈ 25% of the Universe’s energy content and dominates the ordinary, baryonic matter [1−5]. The search for the DM particle becomes one of the most important tasks in the modern physics. The high energy monochromatic γ-ray emission would be a “smoking gun” signature of particle DM [3]. With the remarkable improvement of the sensitivity and energy resolution of the γ-ray detection by space and ground-based γ-ray instruments, great efforts have been undertaken to search for monochromatic γ-rays or sharp spectral features in the past few years [4−13]. There is no compelling evidence for the existence of line-like γ-rays yet.

Increasing the energy resolution is very crucial for the monochromatic γ-ray detection. The energy resolution of the current γ-ray detectors, such as the Fermi Large Area Telescope (Fermi-LAT) in space and the Imaging Atmospheric Cherenkov Telescope (IACT) arrays on the ground, is of the order of 10%−15% for O(100) GeV photons. Such a resolution is not enough to firmly identify a γ-ray line, when the photon statistics is not very high [8,9]. The Alpha Magnetic Spectrometer (AMS-02) onboard the International Space Station has an energy resolution of ≈ 2% at O(100) GeV, but the effective area of AMS-02 is too small to search for the weak signals [14]. The next generation of space-borne high energy cosmic ray (CR) and γ-ray detectors, including the CALori-

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4 Particle Explorer (DAMPE), the DAＲark Matter Particle Explorer (DAMPE) and GAMMA-400 are designed to perform very high energy resolution (≈ 1%−2%) detection of photons with large effective areas. On the other hand, at TeV energies the ground-based Cherenkov Telescope Array (CTA, [18]) will improve the capability of line-like γ-ray searches. See Refs. [19−23] for the expected performance of these future experiments.

The High Energy cosmic-Radiation Detection (HERD) facility onboard China’s space station has been proposed recently [24]. HERD is basically a five-side active calorimeter designed to perform high energy resolution and high statistics measurements of the CR nuclei, electrons and positrons, and γ-ray photons in space. The scientific objectives of HERD include the high sensitivity search for particle DM, direct measurements of the CR nuclei spectra and composition up to knee energies, and high energy γ-ray sky surveys. Based on the detailed simulations of the HERD detector [25], we investigate the expected performance of HERD on the monochromatic γ-ray line detection and the potential on the constraints of DM model parameters in this work.

This paper is organized as follows. In Sec. II we briefly introduce the design and performance of the HERD detector. The sensitivity of line searches is presented in Sec. III. Taking the Minimal Supersymmetric Standard Model (MSSM) as an example, we show the capability of HERD to explore the corresponding DM parameter space in Sec. IV. Finally we
conclude in Sec. V.

II. HERD DESIGN AND PERFORMANCE

HERD is composed of a 3-D cubic calorimeter (CALO) surrounded by microstrip silicon trackers (STKs) from five sides, while the bottom is left for mechanical support. Fig. 1 shows a schematic plot of the basic design and the major functions of each part of the detector. The CALO is made of $21 \times 21 \times 21$ cubic LYSO crystals with each cell $3 \times 3 \times 3$ cm$^3$ which is coupled with the wavelength shifter fibers and read out by ICCD. This design corresponds to about 55 radiation lengths and 3 nuclear interaction lengths, respectively. The CALO detects the total energy deposited by the electromagnetic (EM) shower from CR leptons/photons and the hadronic shower from CR nuclei, and provides lepton/hadron separation through the differences of the shower shape. The five sides of identical STKs, each consists of seven layers laid perpendicularly one by one, are sandwiched with tungsten converters (2 radiation lengths), to ensure the maximum field of view (FOV) and provide charge identification, trajectory measurements, back scattering rejection, as well as some early shower information of photons and electrons. The detector is surrounded by plastic scintillators from five sides, which are used to reject the low energy charged particles to maximize the efficiency for photons and high energy CRs including electrons.

Extensive simulations have been carried out with GEANT4 [26] and FLUKA [27] to get the scientific performance of HERD [25]. We generate events, including photons, electrons and protons, at energy grids of 0.5, 1, 5, 10, 50, 100, 200, 300, 500, 700, and 1000 GeV, with an isotropic event generator. The shower development in the detector of each event is simulated using the Quark-Gluon String Precompound (QGSP) interaction model for photons/electrons and DPMJET-III model for protons. The size, orientation, and shape of the shower is used to reconstruct the energy, direction, and type of the incident particle. To ensure the best determination of the energies for photons and electrons, we select those events whose shower maximum is fully sampled in CALO, which results in a decreasing fiducial area with increasing energy. The lepton-hadron discrimination is primarily based on the shower shape in CALO. The charge measurement by STKs can be used to identify neutral particles from charged ones. A machine learning, multivariate analysis with boosted decision trees is adopted to identify the particle type. The background (electrons and protons) rejection efficiency is obtained when keeping 90% signal (photons). We assume infinite shield of the bottom side of the detector from the space station. The shield of the other five sides is negligible. This assumption will effectively exclude the earth limb’s photons due to the fact that the space station will point away from the earth surface for almost all of the time. The secondary events due to interactions between incident CRs and the space station, which would travel upwards in the detector, will also be excluded.

The ideal energy resolution of the EM shower is about 0.1% at 200 GeV. Considering the stochastic fluctuation of the number of photoelectrons and the error of energy calibration, the energy resolution for the EM component can be $\sim 1 \%$. Due to the large nuclear interaction length of the CALO, the energy resolution of the hadronic component is around 20%, almost constant from hundreds of GeV up to PeV. The CALO can be also used for the lepton/hadron separation due to the fact that the EM and hadronic showers differ in their spatial and energy distributions in the high granulated crystals. The hadron efficiency is about $5 \times 10^{-6}$ when keeping 90% of the EM events. The key performance of HERD, in comparison with previous and other proposed missions, is its extremely large effective geometry factor for all types of high energy particles, primarily due to its thick 3-D CALO and five-sided STKs. With homogeneous design for detecting particles from every un-blocked direction, the effective geometry factor is $> 3$ m$^2$sr for electron and diffuse $\gamma$-rays, and $> 2$ m$^2$sr for CR nuclei.

The energy resolution of CALO can be parameterized as the quadratic addition of the statistical fluctuation term ($\propto E^{-1/2}$) and the electronic noise term ($\propto E^{-1}$)

$$\frac{\sigma_E}{E} = \left( \frac{49 \text{ GeV}}{E} + \frac{12 \text{ GeV}^2}{E^2} \right)^{1/2} \%.$$  

The minimum energy resolution is taken to be 1%, due to the systematic effect of the calibration and the non-uniformity. The effective exposure depends on the orbit of the space station. Employing the orbit of Tiangong-1 in 2012-2013, we simulate the all-sky exposure map of HERD, taking the shield of the space station into account. The Galactic center region is of particular interest for the DM searches. An average exposure of $\sim 0.65$ yr is achieved for this direction and one year of operation. The photon detection efficiency is the product of the $e^+e^-$ pair conversion efficiency ($\sim 80\%$), the reconstruction efficiency ($\sim 90\%$), the efficiency for electron rejection (90% for $10^{-3}$ residual electrons), and the efficiency for hadron rejection (90% for $10^{-5}$ residual hadrons), which is in total $\sim 60\%$. The geometry area of HERD/CALO is $63 \times 63$ cm$^2$ on each side. If the energy of the incident $\gamma$-ray photon is high enough, there will be leakage of the shower for the events.
hitting the edge of the detector. The fiducial area for good
events can be approximated as $$(3660 \sim 717 \times \log(E/\text{GeV}))$$
cm$^2$, for the energies from $\sim 10$ GeV to $\sim$TeV. Considering
the correction of the shower leakage, the effective area can be
larger. Here we adopt this result as a somehow conservative
estimate.

### III. SENSITIVITY OF THE LINE SEARCH

#### A. Backgrounds

The backgrounds for monochromatic $\gamma$-ray searches in-
clude misidentified charged particles (nuclei and leptons)
and the continuous $\gamma$-ray events. The misclassified CRs are
isotropic, due to the loss of the direction information during
the diffusive propagation. For the proton flux, we adopt a fit-
ting formula based on the recent AMS-02 data
$$
\phi_p(E_k) = 7.8 \times 10^{-2}(E_k/\text{GeV})^{-0.9} \\
\times \left[1 + (E_k/4.9\text{ GeV})^{1.87}\right]^{-1}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}.
$$

(2)

The nucleon flux from Helium, is lower by a factor of $\sim 3 - 5$
in the energy range of $10 - 1000$ GeV/nucleon
$\text{[29]}$. Heavier nuclei play an even less important role compared to pro-
tons. Since the hadron rejection power of HERD is very high,
the nucleon background is always subdominant in the current
study. The total $e^- + e^+$ spectra observed by AMS-02
$\text{[30]}$ and HESS $\text{[31]}$ can be fitted by
$$
\phi_{e^\pm}(E_k) = 1.85 \times 10^{-4}(E_k/\text{GeV})^{-0.71} \\
\times \left[1 + (E_k/3.5\text{ GeV})^{2.63 - 0.05\log_{10}(E_k/\text{GeV})}\right]^{-1} \\
\times \left[1 + (E_k/1300\text{ GeV})^{3.03}\right]^{-1}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}.
$$

(3)

The efficiencies of protons as well as $e^+$ and $e^-$, $\eta_p = 10^{-8}$
and $\eta_e = 10^{-3}$, are multiplied with the CR fluxes in order to get
the backgrounds of the misclassified CRs. With such a high
rejection power of the CR hadrons, the hadronic background
can be safely neglected for HERD. This is different from the
IACTs, for which the hadronic background is comparable to
other backgrounds $\text{[32]}$.

The $\gamma$-ray sky is composed of diffuse emission and point or
extended sources. Since the bright point-like sources can be
effectively removed in the data analysis, and the residual weak
sources are expected to contribute $\lesssim 10\%$ to the diffuse events
$\text{[3]}$, we disregard the point sources in this analysis. Only the
Galactic and extragalactic diffuse $\gamma$-rays are taken into account
as the continuous background.

The Galactic diffuse $\gamma$-ray emission can be modeled with
three components that can be distinguished according to their
radiation mechanisms: (a) the decay of neutral pions produced
by inelastic collisions of CR protons with the interstellar gas,
(b) inverse Compton scattering of the interstellar soft photons
by CR electrons and positrons, and (c) bremsstrahlung radiation
produced by CR electrons and positrons
with the interstellar gas. There are also a few identified large
scale structures such as the Fermi bubbles $\text{[33] [34]}$. Loop I
$\text{[35]}$, and the Magellanic stream. The majority of the Fermi
diffuse $\gamma$-ray emission can be relatively well modelled with
the CR interactions, the large scale structures, the residual
CR events and point sources, except for some excesses in the
Galactic plane $\text{[36]}$. Based on the physical modeling of
the Galactic diffuse $\gamma$-ray emission and a likelihood fitting of
the all-sky data, the Fermi Collaboration built diffuse $\gamma$-ray
templates for the point source analyses. Those templates are
suitable to simulate the $\gamma$-ray background in order to forecast
the sensitivity of line searches with future experiments. Since
the Fermi data are limited to a few hundred GeV, we need to
extrapolate the templates to higher energies. We focus on
the inner Galaxy region, where the uncertainties of the spec-
tra of the Fermi bubbles will affect the extrapolations
$\text{[37]}$. Thus we adopt two different templates, to take such uncer-
tainties into account. The first template is the one used for the
“p6v11” data analysis $\text{[3]}$ without the Fermi bubbles. The sec-
done is built with the Fermi bubbles and is used for the Pass
7 Reprocessed Data$^5$. These templates are transformed into
HEALPix$^6$ projections with $N_{\text{side}} = 64$. Then the spectrum of
each pixel is extrapolated to 2 TeV. Due to the suppression of the
Klein-Nishina cross section, the simple extrapolation will
tend to over-estimate the inverse Compton scattering emission
at high energies, which makes the line limits more conserva-
tive.

For the extragalactic diffuse emission, we adopt the fitting
formula of the latest Fermi data, which extends up to 820 GeV
$\text{[38]}$
$$
\phi_{\text{EG}} = I_{01} \left(\frac{E}{0.1 \text{ GeV}}\right)^\gamma \exp\left(-\frac{E}{E_{\text{cut}}}\right).
$$

(4)

The parameters depend on the assumptions of the foreground
model $\text{[38]}$. In this work we adopt $I_{01} = 0.95 \times 10^{-4}$
GeV$^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, $\gamma = 2.32$ and $E_{\text{cut}} = 279$ GeV, corre-
sponding to model A in Ref. $\text{[38]}$. Different choices of the
parameters will not affect our results significantly because the
extragalactic background is only a sub-dominant contribution to
the total background.

Fig. 2 shows the contributions of different components to the
background. Since the Galactic diffuse emission is anisotropic,
the spectra are given for different directions in the sky, concretely
for the Galactic Center, as well as for low and high latitude regions. We can see that at low latitudes, the
contribution from the Galactic diffuse component dominates
over the other components. When approaching the high lat-
titude regions, the misclassified $e^+$ and $e^-$ become more and
more important, especially at low energies. The fluxes of mis-
classified protons and the extragalactic $\gamma$-ray background are
always lower than the $e^+$ and $e^-$ backgrounds.

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4 http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/aux/gll_iem_v02_P6_V11_DIFFUSE.fit
5 http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/aux/gll_iem_v05_1.fit
6 http://healpix.jpl.nasa.gov
B. DM profile and region of interest

The density profile of the DM distribution in the Milky Way halo comprises large uncertainties in the innermost region. As generally adopted in the literature, we consider several typical DM density profiles to take such uncertainties into account. The first one is the commonly adopted cuspy Navarro-Frenk-White (NFW) profile \[\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}\] (5) with \(r_s = 20\) kpc. The second one is the Einasto profile \[\rho(r) = \rho_s \exp\left\{-(2/\alpha)\left[(r/r_s)^\alpha - 1\right]\right\}\] (6) where \(r_s = 20\) kpc and \(\alpha = 0.17\), which is favored by more recent simulations. The third one is the cored isothermal profile \[\rho(r) = \frac{\rho_s}{1 + (r/r_s)^2}\] (7) with \(r_s = 5\) kpc. All the profiles are normalized to local density of \(\rho_0 = 0.4\) GeV cm\(^{-3}\).

Optimized regions of interest (ROI) are very important in the search for the weak DM signal. Since the expected signal depends on the DM density profile, we adopt different ROIs for different assumed profiles. Following Ref. [6], we choose a circular region with radius of 16° (R16) for the Einasto profile, 41° (R41) for the NFW profile, and 90° (R90) for the isothermal profile, in the case of DM annihilation. We also discuss the decaying DM scenario, for which the optimized search region (R180) corresponds to the whole sky for all these profiles. In fact, the integrals of the DM density over the Milky Way are very similar among these profiles (see Table I). For definiteness, we adopt the NFW profile for decaying DM. In all these ROIs the Galactic plane with \(|l| > 6^\circ\), \(|b| < 5^\circ\) is removed. Fig. 3 shows the ROIs adopted to search for monochromatic gamma-rays in this work. Table I summarizes the optimized ROI for each DM halo profile and the corresponding J-factors (integral of \(\rho^2\) or \(\rho\) over the line-of-sight and ROI). The results differ slightly from that of Ref. [6], due to the mask of point sources in Fermi’s paper.

| Profile   | ROI (deg) | \(J_{\text{ann}}\) (\(10^{-22}\) GeV\(^2\) sr cm\(^{-5}\)) | \(J_{\text{dec}}\) (\(10^{-23}\) GeV sr cm\(^{-2}\)) |
|-----------|-----------|---------------------------------------------|---------------------------------------------|
| Einasto   | R16 16°   | 9.39                                        | 2.55                                        |
| NFW       | R41 41°   | 9.17                                        | 2.52                                        |
| Isothermal| R90 90°   | 6.95                                        | 2.56                                        |

TABLE I: Summary of the optimized ROIs and J-factors.

![FIG. 3: Illustration of the different ROIs for different assumptions of the DM density distribution. From inside to outside, the regions are R16, R41, R90, and R180, respectively.](image-url)
C. Mock Data and statistical treatment

Given the expected γ-ray fluxes including the CR backgrounds and the performance of the instrument, we can generate mock data for HERD. We set 400 energy bins per decade in the energy range 5 GeV – 2 TeV, and calculate the expected number of counts \( n_{\text{exp}}^{i} \) in each energy bin \( i \) with width \( \Delta E_i \) is

\[
n_{\text{exp}}^{i} = \Delta t \int \int dE \int dE'R(E, E') A_{\text{eff}}(E') \Phi_{\text{DM}}^{\text{roi}}(E'),
\]

where \( \Delta t \) is the exposure time, \( R(E, E') \) is the energy response function of the instrument, \( A_{\text{eff}}(E') \) is the effective area, and \( \Phi_{\text{DM}}^{\text{roi}} \) is the total γ-ray and CR background in the ROI. In this work we adopt 5 years of survey time, which corresponds to an average \( \sim 3.25 \) year effective exposure. The energy response function is assumed to be Gaussian, and its width is given in Eq. \( \text{Eq} \). Assuming background only, we generate the mock observational counts \( n_{\text{obs}}^{i} \) in each energy bin, by generating random numbers that are drawn from a Poisson distribution with expectation \( n_{\text{exp}}^{i} \). Here we neglect the effect of the point spread function (PSF), which is expected to be small since we integrate the γ-ray fluxes in large enough sky regions compared to the resolution angle.

Then we calculate the expected number of counts of the theoretical model with the DM contribution. The monochromatic flux from DM annihilations or decays reads

\[
\Phi_{\text{DM}}^{\text{roi}}(E) = N_{\gamma} \left\{ \begin{array}{ll}
\left( \langle \sigma v \rangle \frac{J_{\text{ann}}}{8 \pi m_{\chi}} \times R(m_{\chi}, E) \right), & \text{annihilation} \\
\left( \frac{J_{\text{dec}}}{4 \pi m_{\chi}^2} \times R(m_{\chi}, E) \right), & \text{decay}
\end{array} \right.
\]

in which \( \langle \sigma v \rangle \) or \( \tau \) is the annihilation cross section or decay lifetime of the DM particle, \( m_{\chi} \) is the DM mass, and \( N_{\gamma} \) is the multiplicity of one annihilation or decay. On the other hand, the theoretical background is parameterized as a single power-law function \( \Phi_{\text{bkg}} = CE^{-\gamma} \), which is good enough to approximate the background spectrum in a narrow energy window (see below the definition of the energy window). Our model for the γ-ray flux contains thus three parameters, the two background parameters \( C \) and \( \gamma \), as well as the flux from DM annihilation or decay (proportional to \( \langle \sigma v \rangle \) or \( 1/\tau \)). The expected number \( n_{\text{exp}}^{i} \) of counts are calculated by substituting the background with our three parameter flux model, \( \Phi_{\text{bkg}}^{\text{roi}} + \Phi_{\text{DM}}^{\text{roi}} \), in Eq. \( \text{Eq} \). The likelihood function is given by

\[
\mathcal{L} \propto \prod_i \left( \frac{n_{\text{exp}}^{i}}{n_{\text{obs}}^{i}} \frac{\exp(-n_{\text{exp}}^{i})}{n_{\text{obs}}^{i}!} \right).
\]

We adopt the profile likelihood analysis \( \text{Eq} \) and implement the sliding window technique \( \text{Ref} \), in order to derive the upper limits of the DM flux. We follow Ref. \( \text{Ref} \) to define the energy windows. For a specified central energy \( E \), which is the energy of the γ-ray line to be searched, the energy window is defined to be \([E-\epsilon \sqrt{E}, E+\epsilon \sqrt{E}]\). The parameter \( \epsilon \) is determined to ensure that the astrophysical background is well described by a power law. Specifically, we employ \( \chi^2 \) fittings to the 300 mock data sets with a power-law model, for each ROIs and for different window sizes (from \( \epsilon = 1.2 \) to \( \epsilon = 8 \)). The resulting distribution of the 300 \( \chi^2 \) values for each ROI is then tested against a \( \chi^2 \) distribution with the number of degrees of freedom given by the number of energy bins in the energy window minus 2 (number of fitting parameters). An energy window is rejected if the corresponding p-value is smaller than 0.01. And our chosen energy window corresponds to the largest window that fulfills that criterion for all ROIs under consideration. This procedure gives \( \epsilon \sim 1.6 \) at 20 GeV and \( \sim 4 \) at 1 TeV. We have tested that adopting the parameter \( \epsilon \) twice as large as the above derived values, the limits improve by only 7% above 40 GeV. A possible optimization is to choose different \( \epsilon \) for different ROIs. However, the results will not change significantly.

Maximizing the logarithm of Eq. \( \text{Eq} \) with respect to the two background free parameters \( C, \gamma \) and one DM parameter \( \Phi_{\text{DM}}^{\text{roi}} \), we find the best-fit log-likelihood \( \log \mathcal{L}_{\text{bf}} \). The one-sided 95% confidence level (CL) upper limit on the DM flux is found by increasing the signal starting from the best fit value until \( -2 \log \mathcal{L}(\Phi_{\text{DM}}^{\text{roi}}) = -2 \log \mathcal{L}_{\text{bf}} + 2.71 \) \( \text{Ref} \).

D. Results

We perform a scan of the photon energies from 10 GeV to 1 TeV, and calculate the profile likelihood with respect to the monochromatic line flux for each photon energy. The 95% CL upper limits of the line fluxes for different ROIs are shown in Fig. \( \text{Fig} \). Here we adopt the “p7v6” Galactic background model. The results are the geometric mean of the limits obtained from 300 mock data realizations. It is shown that at low energies the differences among various ROIs are larger than at high energies. This reflects the effect of the relative weights between the electron background and the Galactic diffuse emission. At low energies the electron background plays an important role in the total background. Thus the backgrounds in different ROIs scale with the solid angles of the sky regions, and hence differ significantly. At high energies, however, the anisotropic Galactic diffuse background, which is dominated by low latitude emissions, becomes more and more important, and the differences among these ROIs become smaller.

The upper limits of the line fluxes can be easily translated into the upper limits of the DM annihilation cross section or decay lifetime. The left panel of Fig. \( \text{Fig} \) shows the 95% upper limits on the cross section of DM annihilation into a pair of photons \( \langle \sigma v \rangle_{\gamma\gamma} \). We find very stringent limits, reaching cross sections of \( 6 \cdot 10^{-30} \sim 5 \cdot 10^{-29} \text{cm}^3\text{s}^{-1} \) at 10 GeV, and \( 4 \cdot 10^{-27} \sim 9 \cdot 10^{-27} \text{cm}^3\text{s}^{-1} \) at 1 TeV. For the two Galactic background templates we find very similar results in all three regions. The largest difference amounts to about 30%, due to the contribution of the Fermi bubbles to the background (see Fig. \( \text{Fig} \). We expect that below \( \sim 100 \) GeV the “p7v6” background should describe the actual background better, while above \( \sim 100 \) GeV where the energy spectra of the Fermi bubbles show a cutoff \( \text{Ref} \), the extrapolation of the “p7v6” template will over-estimate the background. The limits for R16 and R90 differ by a factor of about 5 at 10 GeV and 2 at 1 TeV, even though the J-factors of these regions are very similar.
Such differences come from the different background levels of these ROIs. In analogy to the flux limits, larger differences at low energies arise due to the electron background.

In the right panel of Fig. 3 we compare the HERD limits with the results from other current or upcoming γ-ray facilities. All the limits shown are for the Einasto profile. For the HERD limits we adopt the “p7v6” background model. The Fermi results are adopted from Ref. [7], with the same ROI (R16) and the newest analysis of the Pass 8 data. The prediction of GAMMA-400 is from a 20° region around the Galactic center, excluding the Galactic disc (|l| > 5° and |b| < 5°), for 5 years of full sky survey [21]. It is shown that HERD can improve the Fermi limits [7] from 5.8 years of observation by up to a factor of a few. The limits expected from GAMMA-400 and HERD are comparable. However, the effective area of GAMMA-400 used in Ref. [21], as well as the γ-ray efficiency, seems to be too ideal [17]. The IACTs are expected to be more effective to probe the γ-ray lines at high energies. We also show the limits from 112 h of Galactic center observation with the HESS telescopes [12] in a circular 1° region around the GC, excluding |b| < 0.3°, as well as the expected limits for CTA [23]. The CTA limits are derived for the same region and observation time as that of HESS [23] and are properly rescaled to γ-ray lines. We can see that below ∼ 300 GeV HERD is more sensitive than CTA, whereas at higher energies CTA is expected to be more sensitive.

The constraints on the lifetime of DM decay into γν are shown in Fig. 4. Here we adopt the NFW profile and the R180 region. For the sake of comparison with Fermi, we show the limits on τγν, for χ → γν channel. A classical example of this kind of DM is the gravitino in the supersymmetric model [43]. Similarly, we find that the HERD limits can improve the current Fermi-LAT constraints [7] by a factor of ∼ 2 − 3.

IV. CONSTRAINTS ON MSSM PARAMETERS

In this section we show the HERD potential on the constraints of the specific MSSM DM model parameter space. Since we are only interested in the γ-ray line features, we focus on the lightest neutralino in the MSSM, the DM candidate, that can monochromatically annihilate to γγ and Z via loop processes. Because of the loop suppression, the cross section is usually rather small compared to the total annihilation cross section. On the other hand, we want to demonstrate the power of HERD in the higher cross section region. Therefore we ignore the sfermion-DM coannihilation region that exhibits low annihilation cross sections. The mass splitting between a sfermion and DM is small enough to release the Boltzmann suppression so that the correct relic density can be reached by accounting for neutralino-sfermion coannihilation processes.

In this analysis we consider the DM sector of the MSSM, where we take into account the bino M1, wino M2, and higgsino µ mass parameters. The µ-term is assumed to be positive. Furthermore, the LHC multijet plus missing energy search [46] can put a very stringent mass limit on the gluino mass M3 and the squark masses. To avoid this limit, we take the gluino mass to be the same as the universal sfermion masses mF that are heavier than max[M1, M2, µ, mA, 800 GeV]. The pseudo-scalar Higgs mass mA and the value of tan β control the higgsino mixing and the A-resonance region which can have higher annihilation cross sections into monochromatic γ-rays. We unify all the trilinear couplings to be A0. Finally, we show the ranges of the MSSM7 parameters used in our scan:

$$\begin{align*}
3 &< \tan \beta < 62, \\
10 &< (M_1, M_2, \mu) / \text{GeV} < 4000, \\
200 &< m_A / \text{GeV} < 8000, \\
\max[M_1, M_2, \mu, m_A, 800.0 \text{GeV}] &< m_J < 8000 \text{GeV}, \\
M_3 &< m_J, \\
-5 &< A_0 / \text{TeV} < 5.
\end{align*}$$  \hspace{1cm} (11)

We assume a non-thermal relic scenario in which the neutralino can be reproduced by late decays from other particles. The advantage of this scenario is to allow for a smaller relic density during the thermal freeze-out stage, and hence a larger interaction cross section of DM. The late time production of DM can be responsible to the measured relic density today. The upper limit of relic density is taken from the PLANCK measurement [1]. Besides the relic density, we also consider some other common constraints. We only allow chargino masses greater than 103.5 GeV [47]. The Higgs mass is constrained using the most recent combined analysis from ATLAS and CMS [48] taking into account 2 GeV theoretical uncertainties in the Higgs likelihood function. In the neutralino mass region close to the Z/h mass, we consider the Z and Higgs invisible decays [49]. Moreover, one can use the measurement of B_s → μ⁺μ⁻ and B → sγ to further constrain the Higgs sector. Here we use the updated data BR (b → sγ) × 10^4 = 3.43 ± 0.22 ± 0.21 [50] and BR (B_s → μ⁺μ⁻) × 10^9 = 2.9 ± 0.7 [51]. In the B_s → μ⁺μ⁻

FIG. 4: 95% upper limits on the monochromatic photon fluxes for different ROIs, where the Galactic background template “p7v6” is adopted.
and the sampling effciency is 0.8. To obtain a good coverage of the parameter space, we combine six separate scans, three of which have log priors of the mass parameters and the other three have flat priors. The SUSY mass spectrum is computed by using SOFTSUSY [56] and then passed to DarkSUSY [57] for DM observables, SuperIso [58] for $B_i \rightarrow \mu^+\mu^-$ and $b \rightarrow s\gamma$ computation, and SUSY-HIT [59] for Higgs decay width. In addition, we have checked all our collected points under the package HiggsBounds [60] to ensure that we do not violate any existing Higgs constraints.

It is easier to identify the neutralino features by considering bino-like, wino-like, higgsino-like and mixed neutralinos. The neutralino $\chi^0_1$ is decomposed into bino, wino, and higgsinos as

$$\chi^0_1 = Z_{\text{bino}} \tilde{B} + Z_{\text{wino}} \tilde{W} + Z_{\text{higgsino}} \tilde{Z}_{\tilde{W}} + Z_{\tilde{H}} \tilde{H}.$$ 

The fraction of each component, $g_i$ where $i$ denotes bino, wino, or higgsino, is defined as $g_{\text{bino}} = Z_{\text{bino}}^2$, $g_{\text{wino}} = Z_{\text{wino}}^2$, and $g_{\text{higgsino}} = Z_{\tilde{H}}^2 + Z_{\tilde{W}}^2$. We, therefore, identify the neutralino composition as bino-, wino- or higgsino-like when the corresponding fraction $g_i > 0.95$. The other linear combinations are denoted mixed neutralinos.

In Fig. 7 we show the $2\sigma$ allowed scattering points for all the constraints described above, where for the relic density the $2\sigma$ upper limit is applied. The red, green, and purple lines are the HERD sensitivity for the R16, R41, and R90 regions (see Fig. 3). Note that the $Z$-boson and SM Higgs boson resonance do not appear in both plots since they have very low $\gamma\gamma$ and $\gamma Z$ annihilation cross sections in the MSSM [61]. In the neutralino mass region between the Higgs resonance region ($m_\chi \approx m_H/2$) and the chargino-neutralino coannihilation region $m_\chi \approx m_{\tilde{\chi}} > 100.0$ GeV, the DM relic density is over produced due to the absence of reduction mechanisms for the annihilation cross section at freeze out. Although we do not include the Sommerfeld enhancement (SE) in our cross section computation, we show the SE for pure wino ($g_{\text{wino}} = 1$) with the black line as a reference. Note that our wino-like (or-
FIG. 7: The symbols denote the scattering points in the $m_\chi$-⟨σv⟩ parameter space that satisfy the 2σ ranges (limits) of all the constraints described in the text. The bino- (red squares), wino- (orange cycles), and higgsino- (green stars) like neutralinos are defined by the neutralino composition fraction, $g_\\iota > 0.95$. In contrast, the mixed neutralino ($g_\\iota < 0.95$) is shown in gray diamonds. The Sommerfeld enhancement for pure wino ($g_\\text{wino} = 1$) is presented here as the black line for reference. The HERD 5-yr sensitivities as shown in Fig. 5 are over-plotted. The left panel is for $\gamma\gamma$ channel, and the right panel is for $\gamma Z$ channel, respectively. We would like to emphasize that in our analysis we assumed a non-thermal relic scenario, where the neutralino can be reproduced by late decays from other particles. However, we require that dark matter is not thermally overproduced in the early Universe.

V. CONCLUSION

In this work, we discuss the capability of γ-ray line searches of HERD onboard China’s space station. Based on the detailed simulations of the detector performance, including the energy resolution, effective area and exposure, and the background rejection power, the sensitivity of monochromatic photon detection of HERD is investigated with the maximum likelihood analysis. Different DM density profiles, and hence different optimal ROIs, are discussed. We find that the electrons (dominant at low energies) and Galactic diffuse γ-rays (dominant at high energies) constitute the main contributions to the background. Accordingly the results are more uncertain at low energies ($\lesssim 100$ GeV) due to the different ROIs for the different DM density profiles. Compared with the current Fermi results, HERD would improve the limits by a factor of a few, for similar observation time. This is mainly due to the largely improved energy resolution of HERD ($\sim 1\%$). Compared to ground based IACTs such as CTA, HERD will play a complementary role in γ-ray line searches. For energies below a few hundred GeV HERD will be more sensitive than the IACTs.

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