Search for line signal candidates in the Fermi-LAT data

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In this work, we aim to search for the line-like signals in the Fermi-LAT data. We have searched over 49000 regions of interest (ROIs) that cover the whole sky. No ROI displays a line signal with a test statistic (TS) value above 25, while for 50 ROIs weak line-like excesses with TS > 16 are present. These tentative line signals are most likely due to the statistical fluctuation, though the dark matter annihilation origin of a few of them can not be ruled out. We also use the number of the line signal candidates to constrain the cross section of dark matter annihilating to gamma-ray lines, ⟨σv⟩γγ.

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I. INTRODUCTION

A gamma-ray line signal robustly detected is deemed as a smoking-gun signature of particle dark matter (DM) since no known astrophysical process can generate a signal like that. In the scenario of DM, this signal could come from DM particles annihilating to gamma-rays directly (i.e., χχ → γγ, γZ or γH). The gamma-ray line signals may be captured if the annihilation cross section is large enough that the line signal exceed the detection sensitivity of gamma-ray telescopes such as Fermi-LAT [1] and DAMPE [2]. Great efforts have been made in the previous literature to search for such kind of signal, but none is conclusively detected so far [3–20].

Some tentative evidence of line signals has been reported. By analyzing an optimized region around the Galactic center, a line-like excess at 130 GeV was found in the 4 years’ Fermi-LAT Pass 7 data [6, 7]. This signal was also reported with lower significance in the searches of galaxy clusters [13]. However, analysis by Fermi-LAT collaboration using 5.8 years of Pass 8 data resulted in very weak significance of this 130 GeV feature [15]. More recently, a tentative line-like excess at 42.7 GeV was found in the stacked spectrum of 16 nearby galaxy clusters, the global significance of this excess is ∼ 3.0 σ [17].

The most promising site one might observe a line signal is the region around the center of our Milky Way. Beside the Galactic center (GC), other regions that may produce considerable line signals include dwarf spheroidal galaxies (dSphs) [8, 19], DM subhalos [9, 20] and galaxy clusters [13, 16, 17]. In this work, we do not examine specific objects/regions, but perform blind searches for the line signals in the whole sky using the Fermi-LAT data. One possible origin of such signals is the DM annihilation in subhalos. Our search results may be taken as a list of candidates of DM line signals from subhalos. We also set limits on the DM properties utilizing the number of the candidates (see Sec. 4).

II. FERMI-LAT DATA AND LINE SIGNAL SEARCHING

In this work, we use the Fermi-LAT data to perform the searches1. We will search for the signals with line energies from 5 GeV to 300 GeV, thus we take into account the Fermi-LAT data in the energy range of 1 GeV to 500 GeV to address the energy dispersion of the instrument. The time period of the data we use is from Aug. 4th, 2008 to Aug. 4th, 2017 (corresponding to MET 239554717-523497605). We take the recommended zenith angle cut (θzenith < 90°) and data quality cut (DATA_QUAL=1 && LAT_CONFIG=1) to avoid the contamination from Earth limb emission and to guarantee the data is suitable for science use2. To reduce the contamination from residual cosmic rays in the LAT data, and also to be consistent with our previous works [17, 19, 20], we make use of the ULTRACLEAN data. For achieving better energy resolution, we exclude the EDISP0 data in our analysis (evtype = 896). We use the Fermi Science Tools of version v10r0p5 to do the data selection and the exposure calculation.

To search for the line signals in the whole sky, we select totally 49152 ROIs with a radius of 2 degree for each. The

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1 https://fermi.gsfc.nasa.gov/ssc/data/
2 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html
centers of the ROIs are corresponding to the HEALPix [21] coordinates list with \( n_{\text{side}} = 64 \). Such a strategy ensures that all the sky is covered by our ROI sample. Assuming a point-like spatial model for the line signal, the \( 2^\circ \) radius also ensures that most of the line signal photons are included by the ROI even the signal is located at the edge of a HEALPix pixel considering the point spread function (PSF) of Fermi-LAT is smaller than \( 1^\circ \) for \( > 5 \) GeV data [22] and the radius of the pixel is roughly 0.5 degree\(^3\).

In each ROI, the sliding window technique [3, 7, 17] is adopted to perform the search. For each putative line with energy \( E_\gamma \), we perform unbinned likelihood fittings in a narrow window of \((E_\gamma - 0.5E_\gamma, E_\gamma + 0.5E_\gamma)\). The test statistics (TS) is obtained by comparing the likelihoods of null model (no line signal model) and the signal model. We approximate the null model to a power law function. In consideration of that the background mixing all astrophysical components should be smooth and continuous in spectra, the power law approximation is guaranteed since we are using a very narrow energy window. For the signal model, we adopt the form of a line component \((\delta(E - E_\gamma))\) superposing on the power law background. For the line component, we have also convoluted it with the energy dispersion function of the data. The method of searching for line signal in the Fermi-LAT data have been extensively introduced in Ref.[7, 12, 15, 17]. We refer readers to these literatures for details.

### III. RESULTS

Adopting the aforementioned approach, we searched totally 49152 ROIs for the line signal. We summarize our search results in this section. Figure 1 presents the \( T S_{\text{max}} \) distribution over all the ROIs. The \( T S_{\text{max}} \) denotes the maximum TS value among a series of attempted line energies\(^4\) in each ROI. As expected, most of ROIs give relatively low TS value \((T S_{\text{max}} < 9\) for 94\% ROIs\). Theoretically, the \( T S_{\text{max}} \) for the background only data should follow a trial-corrected \( \chi^2 \) distribution [7, 17]. We find that this distribution can fit our searching results well with trials \( t = 29.1 \) and degree of freedom \( n = 0.88 \) (dashed line in figure 1).

In our all-sky searches, no signal is found to have a TS value greater than 25 \((T S = 25 \) corresponds to a local significance of 5\( \sigma \)). The most significant line-like excess appears in the ROI centered on \((l = 182.81, b = -15.09)\), with a TS value of 24.3. The corresponding line energy for this excess is 74.9 GeV. We plot the observed spectrum of this ROI in the first panel of Figure 2. Beside this signal, in total 50 ROIs result in \( T S_{\text{max}} > 16 \) and 2933 result in \( T S_{\text{max}} > 9 \). All the ROIs with \( T S_{\text{max}} > 16 \) is presented in Table I. Note that since the radius of our ROI \((2^\circ)\) is larger than the ROI center intervals, there is possibility that several ROIs cover a same signal. In such a case we only retain the ROI with the largest TS value. We also show the spectra of some selected ROIs in Figure 2. Evidence of excess is clearly seen for all these ROIs, indicating that our searching strategy can effectively identify such a kind of signal in the spectra. Note that the binned plots in Figure 2 are just for illustration, while in the above searching procedure an unbinned method is adopted.

We would emphasize that since we have searched a lot of ROIs and for each ROI a series of line energies, a very large trial-factor is introduced if we convert the TS value to the significance. Thus the tentative signals presented here have intrinsically low significance. These signals are most likely from statistical fluctuation. However, at this stage we can neither rule out the hypothesis that a few of them are originated from DM annihilation within nearby subhalos or unknown astrophysical processes. The regions listed in this work are therefore worth further attention. If other/future experiments can also observe same signals in the same regions, the statistical origin can then be excluded. Table I offers a list of line signal candidates for later study and their positions in the sky are shown in Figure 3.

### IV. SEARCHING FOR COUNTERPARTS OF THE LINE SIGNAL CANDIDATES

The dark matter particles that generate the gamma-ray lines may simultaneously annihilate to other Standard Model particles (e.g., \( b\bar{b}, \tau^+\tau^- \)) [23], which could yield continuum gamma-ray emission at lower energies. This model-independent gamma-ray emission provide us a way to identify the DM origin of the line signal candidates. Specifically, for a certain line signal, if we could detect another gamma-ray component in the ROI with its

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\(^3\) The shape of the HEALPix pixel is in fact not a circle, the radius here is an estimation derived using the solid angle of each pixel.

\(^4\) Explicitly, 110 \( E_\gamma \) in the range of \( 5-300 \) GeV.
TABLE I: Line signal candidates with TS > 16 identified in this work.

| #     | Energy [GeV] | TS Value | LON [°] | LAT [°] | RA [°] | Dec [°] |
|-------|--------------|----------|---------|---------|--------|---------|
| 25363 | 74.0         | 24.3     | 0.0     | 182.81  | -15.09 | 74.40   |
| 21714 | 17.5         | 22.4     | 0.1     | 114.61  | -5.98  | 357.97  |
| 9695  | 29.2         | 21.5     | 3.8     | 269.15  | 50.48  | 171.98  |
| 45226 | 16.2         | 21.0     | 0.0     | 272.81  | -78.28 | 20.20   |
| 15172 | 48.6         | 20.1     | 6.3(91.3)| 296.32  | 50.48  | 188.56  |
| 24414 | 9.4          | 20.0     | 1.2     | 97.73   | 31.39  | 256.35  |
| 34934 | 18.2         | 19.6     | 0.9     | 62.58   | -41.81 | 332.47  |
| 18272 | 38.4         | 19.6     | 5.8(68.7)| 25.31   | 7.78   | 272.45  |
| 37762 | 5.2          | 19.5     | 1.8     | 125.36  | -59.92 | 20.20   |
| 36744 | 5.6          | 19.1     | 3.2     | 37.97   | -12.64 | 255.31  |
| 45227 | 5.5          | 18.5     | 0.0     | 234.84  | 34.95  | 76.89   |
| 46981 | 8.0          | 18.3     | 0.0     | 333.98  | 32.80  | 302.38  |
| 20889 | 50.6         | 18.1     | 3.6     | 97.73   | 14.48  | 281.32  |
| 29481 | 38.4         | 18.0     | 0.8     | 20.39   | -32.80 | 308.78  |
| 14243 | 10.5         | 17.8     | 0.0     | 333.37  | 53.57  | 210.44  |
| 35888 | 26.0         | 17.6     | 9.5(60.4)| 45.00   | 34.95  | 319.13  |
| 7168  | 9.0          | 17.6     | 2.8     | 135.00  | 42.61  | 163.57  |
| 14313 | 66.6         | 17.3     | 1.3     | 345.37  | 60.43  | 212.36  |
| 29638 | 13.3         | 17.2     | 1.6     | 270.70  | -7.18  | 130.02  |
| 16786 | 11.8         | 17.2     | 0.2     | 7.73    | -20.74 | 291.84  |
| 7867  | 8.0          | 17.1     | 1.2     | 91.67   | 70.17  | 206.89  |
| 28138 | 31.6         | 17.1     | 4.1(64.1)| 186.33  | 24.62  | 115.70  |
| 1666  | 37.0         | 17.0     | 1.3     | 49.92   | 37.17  | 253.34  |
| 27865 | 5.4          | 17.0     | 0.0     | 182.11  | 14.48  | 102.60  |
| 42296 | 29.2         | 17.0     | 0.0     | 260.08  | -45.78 | 62.38   |
| 30431 | 10.5         | 16.9     | 2.3     | 284.06  | 6.58   | 161.66  |
| 30245 | 13.3         | 16.8     | 0.5     | 280.55  | -4.78  | 145.21  |
| 19922 | 31.6         | 16.8     | 0.9     | 13.36   | 23.32  | 253.21  |
| 46538 | 35.5         | 16.8     | 3.6     | 346.64  | -38.68 | 311.85  |
| 6201  | 35.5         | 16.8     | 1.8     | 111.80  | 27.28  | 279.44  |
| 29823 | 6.1          | 16.8     | 0.5     | 298.12  | -5.38  | 180.12  |
| 38012 | 29.2         | 16.7     | 0.5     | 168.96  | -50.48 | 40.14   |
| 24463 | 9.0          | 16.6     | 0.9     | 84.37   | 29.31  | 269.93  |
| 28712 | 12.3         | 16.5     | 1.1     | 265.78  | -36.42 | 76.96   |
| 22401 | 21.3         | 16.3     | 0.0     | 107.58  | 5.98   | 335.47  |
| 2458  | 10.5         | 16.2     | 0.3     | 28.83   | 41.81  | 243.14  |
| 1240  | 46.8         | 16.2     | 1.5     | 68.91   | 34.95  | 259.92  |
| 15976 | 45.0         | 16.1     | 2.4     | 295.91  | 65.70  | 189.97  |
| 26070 | 74.9         | 16.1     | 0.0     | 217.27  | 4.78   | 109.09  |
| 23595 | 12.3         | 16.1     | 0.4     | 85.78   | 5.38   | 307.71  |
| 20147 | 9.7          | 16.0     | 3.3     | 343.12  | 21.38  | 235.67  |
| 15410 | 9.7          | 16.0     | 0.2     | 314.17  | 49.70  | 200.28  |
| 27195 | 59.2         | 16.0     | 1.4     | 144.84  | -1.79  | 52.47   | 54.20  |

| #      | Energy [GeV] | TS Value | LON [°] | LAT [°] | RA [°] | Dec [°] |
|--------|--------------|----------|---------|---------|--------|---------|
| 61     | 61.8         | 61.8     | 61.8    | 61.8    | 61.8   | 61.8    |

*aThe HEALPix index in NESTED ordering.

*bThe largest TS values for the second line signals. Please see the main text for details. For the four ROIs with TS_{2nd} > 4, we also provide the corresponding energies of the second lines in the brackets (in units of GeV).

spectrum and spatial distribution compatible with DM continuum emission, it is a strong evidence that both the line and continuum emission are from DM annihilation within subhalo. For this reason, we analyze the unas-
associated point sources within the ROIs presented in Table I. Due to the complicated gamma-ray backgrounds in the Galactic plane, we ignore the ROIs with latitudes $|b| < 10^\circ$. Totally, 13 unassociated point sources in FL8Y\(^5\) are found within the selected ROIs. We apply the standard likelihood analysis of Fermi-LAT data\(^6\) to these unassociated sources in the energy range from 300 MeV to 300 GeV. The unassociated point sources are modeled with spectrum of DM annihilation\(^7\) and the spectral function adopted in FL8Y. For the DM model, we consider the annihilation channel of $b\bar{b}$ and $\tau^+\tau^-$, and the DM mass is fix to the $E_\gamma$ leading to the largest TS value in each ROI. The delta likelihood between these two models, $\Delta \ln \mathcal{L} = \ln \mathcal{L}_{\text{DM}} - \ln \mathcal{L}_{\text{FL8Y}}$, is used to determine whether a DM annihilation hypothesis is favored. The $\Delta \ln \mathcal{L}$ for the 13 unassociated sources are listed in Table II. Our results show that only 1 among 13 sources, FL8Y J1656.40410, marginally favor the DM spectrum than the spectral model used in FL8Y. The $\Delta \ln \mathcal{L} = 7.0$ corresponds to a local significance of $< 4\sigma$, not offering a strong evidence of DM signal from subhalo.

Besides, the line-like excesses in the Table I could be from any channel of $\chi\chi \rightarrow \gamma\gamma$ or $\gamma Z$ or $\gamma H$, then it is possible that the dark matter particles also annihilate through another channel among the three. For example, assuming the first line signal is from $\chi\chi \rightarrow \gamma\gamma$, the second line would be located at $E'_\gamma = m_\chi(1 - m_X^2/4m_\chi^2)$, where $X$ could be $Z$ or $H$. If the second line is found with high significance, it also offers an indication that the line-like excess in Table I is a real DM signal. Thus for the 50 ROIs, we calculate the TS values of the second line signals at the corresponding energies. The largest TS values for the second lines are listed in Table I as well. We find that only 4 ROIs result in $TS_{2\text{nd}} > 4$, and the highest

\(^5\) https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/
\(^6\) https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/binned_likelihood_tutorial.html
\(^7\) The DM spectra are implemented with DMFitFunction: https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source_models.html

FIG. 2: The observed spectra of 9 sample ROIs displaying line signals with $TS > 16$. For the energy bin with photon number less than 2, we plot $1\sigma$ confidence level upper limits for better visualization.
one appears in the ROI #35888. The combined TS of this ROI reaches 27.1 for the two gamma-ray lines, however considering additional degree of freedom and very large trial factors, the global significance is still very low.

V. CONSTRAINING THE LINE SIGNAL CROSS SECTION WITH THE CANDIDATE NUMBERS

In the cold dark matter paradigm, structure forms hierarchically, and it is predicted that there exist large amount of DM subhalos around the Milky Way. Such a prediction is supported by numerical N-body simulations [24–26]. The concentration of DM in the subhalos leads to a higher DM annihilation rate. If massive subhalos are close to the Earth sufficiently, they may generate gamma-ray signals detectable by Fermi-LAT. For some subhalos which are too small to capture enough baryonic matters (i.e., $M_{\text{sub}} < 10^8 M_\odot$), the gamma-ray annihilation signals would be the only channel to observe them. Thus, it is supposed that some unassociated Fermi-LAT sources are potentially DM subhalos [27–35], especially those spatially extended and with spectra compatible with DM signals [31, 34, 35].

There is possibility that the line signal candidates identified in this paper are coming from DM subhalos. According to the numbers of the candidates, we can place limits on the DM cross section of annihilating to gamma-rays, $\langle \sigma v \rangle_{\gamma\gamma}$. The basic idea is that, higher cross section may leads to brighter gamma-ray annihilation flux that more subhalos far from us can be detected [27–30, 32, 33]. The number of observable subhalos is therefore proportional to the cross section.

Here we use the expression derived in Ref. [32] (hereafter H16) to give the predicted numbers of the observable DM subhalos,

$$N_{\text{obs}} = \Omega \int \int \int D^2 \frac{dN}{DMdV} \frac{dP}{dR_b} \frac{dP}{dR_b} \frac{d\gamma}{d\gamma} \Theta[\Phi_\gamma(M, D, R_b, \gamma) - \Phi_0] dM dD dR_b d\gamma,$$

(1)

where $D$ and $M$ are the distance and mass of subhalo, respectively. The gamma-ray flux of the line signal generated in a given subhalo is

$$\Phi_\gamma = \frac{\langle \sigma v \rangle_{\gamma\gamma}}{4 \pi m_\chi^2 D^2} \int \rho^2(r) dV.$$

(2)
For the DM distribution in the subhalo $\rho(r)$, following H16, a density profile of power law with exponential cutoff (PLE) is adopted rather than the Navarro-Frenk-White [36] one,

$$\rho(r) = \frac{\rho_0}{r^\gamma} \exp\left(\frac{-r}{R_b}\right).$$  \hspace{1cm} (3)$$

It is found that a PLE density profile can better match the characteristics found in the VL-II and ELVIS simulations considering the effects of tidal stripping [32]. In Eq. 1, the $dN/dMdV$, $dP/d\gamma$ and $dP/dR_b$ are subhalo distribution and the functions of the values of $\gamma$ and $R_b$ near the Earth’s location. For these distributions we also utilize the formalism reported in H16, which are presented in Appendix A as well. When deriving the distributions, their dependences on both the subhalo mass and the location relative to the galactic center have been taken into account [32]. Please note that these distributions in the integrand of Eq. (1) are only valid in the local environment; especially, to simplify the calculation, a uniform subhalo number density ($dN/dV \propto \text{const}$) is assumed following H16. We thus consider only subhalos within the distance of 5 kpc $^8$. Subhalos at larger distances may also be detectable, our choice of $D_{\text{max}}$ will lead to relatively conservative results.

The $\Phi_0$ in Eq. 1 denotes the flux threshold above which the line signals will be significantly detected. Since no line signal is found with $TS > 25$, we make use of the Monte Carlo simulation to derive the $\Phi_0$. We use a PLE function to model the observation spectrum averaged over all the sky (excluding the Galactic plane and the regions around bright gamma-ray sources, see below).

Based on this PLE background spectrum, we generate pseudo photons in the $2^\circ$ ROI. Besides, a line-like component is superposed onto the background, the profile of which is the energy dispersion function of the Fermi-LAT data used in this work. We perform the same searching procedure as that in Sec. II on these pseudo data, and derive corresponding TS value of the line component. By varying the flux $\Phi$ of the input line component, for each $E_\gamma$ we determine the threshold $\Phi_0$ above which the line component with a TS value greater than 25. The resulting $\Phi_0$ curve is shown in the left panel of Figure 4.

The background gamma-ray emission in the Galactic plane region and near bright gamma-ray point sources are much stronger than in other regions, thus lower the detectability of a line signal from subhalo. In this section, for both calculating the observed solid angle $\Omega$ and deriving the flux threshold $\Phi_0$, the regions of $|b| < 20^\circ$ and those within $2^\circ$ around the 100 most bright point sources in 3FGL [37] are excluded.

From the elements described above, we can calculate the expected number of subhalos that can yield line signals significantly detectable by Fermi-LAT. The $N_{\text{obs}}$ as a function of cross section for 100 GeV DM is shown in the right panel of Figure 4. We then apply poisson statistics to the expected number to place a 95% upper limit on the annihilation cross section for a given value of the DM mass. The obtained constraints are shown in Figure 5. As a comparison, also plotted are the constraints derived based on the Fermi-LAT observation towards the regions around the Galactic center [15]. We find that our constraints here are not competitive with these Galactic ones (thin solid line for the isothermal density profile and dashed line for the NFW). We would like want to emphasize that in the calculation we have considered only the subhalos within 5 kpc. If including those subhalos farther away, the current constraints would be improved.

$^8$ The bounds of the integral in Eq. (1) for $M$, $R_b$ and $\gamma$ are $[10^8, 10^{10}] M_\odot$, [0, 5] kpc and [0, 1.45], respectively.
VI. SUMMARY

In this work, we have analyzed the Fermi-LAT data to blindly search for the potential line signals originated from anywhere of the sky. We make use of the sliding window technique to perform unbinned likelihood fittings in 49152 ROIs, which cover the whole sky. Our searches found no line signal with $TS > 25$. However, line-like excesses with $TS > 16$ are found in the spectra of 50 regions. These line signals are most likely originated from statistic fluctuation. However the possibility that a few come from DM annihilation can not be excluded. If the same regions are observed by other/future gamma-ray observatory, their real origin may be identified. We thus suggest that these regions are worth further attention. All these signal regions have been presented in Table I.

The DM particles that generate the line-like signals may simultaneously annihilate through other channels, thus leading to counterpart gamma-ray emission (either continuum emission at lower energies or a second gamma-ray line). If detected, these counterparts provide indications of DM origin of the line signals. In Section IV, we have attempted to search for the counterpart gamma-ray emission for the line signal candidates in Table I by analyzing the Fermi-LAT unassociated point sources within selected ROIs (for continuum emission) or by examining the significances of the second lines at specific energies. However, no strong evidence of the counterparts is found in the analyses.

Some previous works have pointed out that the number of DM subhalo candidates can be used to place constraints on the DM cross section. The reason is that higher cross section leads to brighter gamma-ray flux of the signals, thus we can observe more sub-halos far away from us. With such an idea, we derive the expected number of subhalos as a function of the cross section of DM annihilating to gamma-ray lines, and then set constraints on the latter. We found that the constraints obtained here are much weaker than those given according to the Fermi-LAT observations towards the Galactic central region. However our work offers a novel approach to support these previous constraints independently.

Finally, we would point out that some other on-orbit or proposed space borne gamma-ray telescopes, such as DAMPE [2], Gamma-400 [38] and HERD [39], all of which have significantly better energy resolution comparing to Fermi-LAT, will contribute significantly to the gamma-ray line search.

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Appendix A: Subhalo distribution and the distributions of $\gamma$ and $R_b$

The subhalo distribution and the distributions of $\gamma$ and $R_b$ adopted in our analysis are from Ref. [32]. When deriving the distributions, their dependences on both the subhalo mass and the location relative to the galactic center have been taken into account [32]. The subhalo distribution is

$$\frac{dN}{dMdV} = \frac{628}{M_\odot \text{kpc}^3} \left( \frac{M}{M_\odot} \right)^{-1.9}. \quad (A1)$$

The distributions of $R_b$ is

$$\frac{dP}{dR_b} = \frac{1}{\sigma \sqrt{2\pi}} \frac{1}{R_b} \exp \left( -\frac{(\ln R_b - \ln \langle R_b \rangle)^2}{2\sigma^2} \right). \quad (A2)$$

where $\sigma = 0.496$ and $\langle R_b \rangle = 10^{-3.945} \times (M/M_\odot)^{0.421}$. The distributions of $\gamma$ is found to be independent of subhalo mass and is expressed as

$$\frac{dP}{d\gamma} = \frac{1}{\sqrt{2\pi} \sigma} \frac{1}{\kappa(\gamma - \langle \gamma \rangle)} \times \exp \left( -\frac{\ln^2(1 - \kappa(\gamma - \langle \gamma \rangle)/\sigma)}{2\kappa^2} \right), \quad (A3)$$

with $\langle \gamma \rangle = 0.74$, $\sigma = 0.42$ and $\kappa = 0.10$. 
