A search for pair halos around active galactic nuclei through a temporal analysis of Fermi-LAT data

D. A. Prokhorov1 * and A. Moraghan2,3 †

1 Department of Physics and Electrical Engineering, Linnaeus University, 351 95 Växjö, Sweden
2 Academia Sinica Institute of Astronomy and Astrophysics, P. O. Box 23-141, Taipei 106, Taiwan
3 Center for Galaxy Evolution Research and Department of Astronomy, Yonsei University, Seoul 120-749, Republic of Korea

Accepted ..... Received ..... ; in original form ..... 

ABSTRACT
We develop a method to search for pair halos around active galactic nuclei (AGN) through a temporal analysis of γ-ray data. The basis of our method is an analysis of the spatial distributions of photons coming from AGN flares and from AGN quiescent states and a further comparison of these two spatial distributions. This method can also be used for a reconstruction of a point spread function (PSF). We found no evidence for a pair halo component through this method by applying it to the Fermi-LAT data in the energy bands of 4.5-6, 6-10, and >10 GeV and set upper limits on the fraction of photons attributable to a pair halo component. An illustration of how to reconstruct the PSF of Fermi-LAT is given.

Key words: gamma-rays: general, galaxies: active, methods: data analysis, intergalactic medium

1 INTRODUCTION
The existence of possible extended, diffuse, γ-ray sources (so-called pair halos) around active galactic nuclei (AGNs) was predicted by Aharonian et al. (1994). γ rays with energies above ~1 TeV emitted by distant AGNs cannot propagate over cosmological distances because of electron-positron pair production (γ + γ → e− + e+) on the optical/infrared extragalactic background light (EBL, see, e.g., Kneiske et al. 2002; Franceschini et al. 2008; Finke et al. 2011). The electron-positron pairs created in the γ-γ interactions travel in the intragalactic magnetic field and emit secondary cascade γ rays with energies ~1 GeV owing to inverse Compton (IC) scattering by cosmic microwave background (CMB) photons. Thus, a γ-ray image of an AGN is expected to exhibit a halo of secondary photons around a central point-like source. A potential detection of pair halos around AGNs will provide us with a measurement of the strength of the intergalactic magnetic field (for a review, see Neronov & Semikoz 2009). The existence of this weak “seed” magnetic field itself is unavoidable because this is required for the production of magnetic fields in galaxies and in clusters of galaxies which are about 10−6 gauss via field amplification mechanisms (for a review, see Ryu et al. 2012).

The Fermi Large Area Telescope (LAT) is a pair conversion telescope designed to cover the broad energy range from 20 MeV to greater than 300 GeV (Atwood et al. 2009). The broad energy range of Fermi-LAT, therefore, covers typical energies of secondary IC photons if the energies of primary γ rays are between ~1 and ~20 TeV. The Fermi-LAT normally operates in sky-survey mode where the whole sky is observed every 3 hr and Fermi-LAT sensitivity allows us to monitor AGNs on a daily basis. This quality of Fermi-LAT data is particularly important to search for γ-ray flares of AGNs. The second catalog of high-energy γ-ray sources (the 2FGL catalog, Nolan et al. 2012) detected by Fermi-LAT and derived from data taken during the first 2 years of the Fermi mission was released by the Fermi-LAT collaboration. The 2FGL catalog contains 1873 sources detected and characterised in the 100 MeV to 100 GeV range of which 127 are firmly identified and 1171 are reliably associated with counterparts of known or likely γ-ray producing source classes. Note that the 2FGL catalog contains 1047 γ-ray sources associated with AGNs, mostly blazars, and, therefore, this

*Neronov & Vovk 2010† Tavecchio et al. 2010 † Dolag et al. 2011. Note that the value of intergalactic magnetic field strength has not been measured by any approach (see Neronov & Semikoz 2009). The existence of this weak “seed” magnetic field itself is unavoidable because this is required for the production of magnetic fields in galaxies and in clusters of galaxies which are about 10−6 gauss via field amplification mechanisms (for a review, see Ryu et al. 2012).

* E-mail: phdmityr@gmail.com
† E-mail: ajm@asiaa.sinica.edu.tw
source class is dominant in the catalog. Since AGNs are extragalactic sources, AGNs are uniformly distributed on the γ-ray sky. This property will allow us to select a sample of AGNs which are not projected on the Galactic plane and, therefore, this sample will be less contaminated by Galactic γ-ray emission.

The importance of a careful point spread function (PSF) reconstruction from the on-orbit Fermi-LAT data was emphasized by [Ando & Kusenok (2010); Neronov et al. (2011)]. Neronov et al. (2013) compared the stacked AGN signal to the signal of the Crab pulsar and nebula, which is a bright galactic gamma-ray source, and found that the shapes of the two signals coincide. This means that the entire stacked AGN signal is well described by a point-source signal. A detailed analysis by Ackermann et al. (2013) showed that the PSF determined from two years of on-orbit data above 3 GeV is found to be broader than the pre-launch PSF determined through extensive Monte Carlo simulations and beam tests (this agrees well with the results by Neronov et al. (2011)). To calibrate the PSF, they adopted a technique of stacking sources, where the angular offsets of γ rays from their presumed sources are analyzed as if they came from a single source. Pulsars would be ideal for calibrating the PSF. However, the γ rays from pulsars above 10 GeV are limited. They selected a subset of 65 AGNs to calibrate the PSF. Out of the 65 sources, 35 were associated with BL Lac-type blazars, 27 with Flat Spectrum Radio Quasars (FSRQ), 1 with a non-blazar active galaxy, and 2 with an active galaxy of uncertain type. Ackermann et al. (2013) estimated the 68% containment radii for front and back events from the Geminga and Vela pulsars below 31.6 GeV and the AGN calibration data set above 3.16 GeV. Using the pulsed γ-ray emission between 1 GeV to 31.6 GeV from pulsars, which appears as a true point source to the Fermi-LAT, they placed limits on the angular extension of AGN emission relative to pulsar emission and derived the upper limits for the fraction of γ rays from the stacked AGN sample attributable to a pair halo component.

In this paper, we develop a method to reconstruct the Fermi-LAT PSF using AGN flares and to perform a search for a pair halo component which might contribute to a quiescent AGN emission.

2 OBSERVATIONS WITH FERMI-LAT AND DATA REDUCTION

The Fermi satellite was launched on 2008 June 11 into a nearly circular Earth orbit with an altitude of 565 km, an inclination of 25.6°, and an orbital period of 96 minutes. The principal instrument on Fermi is the LAT (Atwood et al. 2009), a pair-production telescope with a large effective area (~8000 cm² at 1 GeV) and field of view (2.4 sr). The energy range of LAT sensitivity spans from 20 MeV to >300 GeV with an angular resolution per single event of approximately ≈ 5° at 100 MeV and narrowing to ≈ 0°.15 at 10 GeV. After the commissioning phase, the Fermi-LAT began routine science operations on 2008 August 4. The Fermi-LAT normally operates in sky-survey mode which provides a full-sky coverage every 3 hours (i.e., 2 orbits).

We downloaded the Pass 7 Reprocessed Fermi-LAT data from the Fermi Science Support Center. Note that the Pass 7 Reprocessed Fermi dataset uses updated calibration constants (Bregen et al. 2013). The primary differences with respect to the Pass 7 data are the correction of a slight (1% per year) expected degradation in the Calorimeter light yield and significant improvement of the Calorimeter position reconstruction, which in turn significantly improves the LAT point-spread function at high energies (>5 GeV). For the data analysis, we use the Fermi Science Tools v9r32p5 package and P7REP instrument response functions (IRFs).

We used the Fermi LAT 2-year point source catalog [Nolan et al. 2012], gll_psc_v08.fit, to select the sample of AGNs for our analysis. Firstly, we recorded the source type of all 2FGL sources and selected sources associated with AGNs. To reduce the contamination by the Galactic diffuse foreground emission to the regions of interest, we excluded AGNs with Galactic longitude from between -30° and 30°. To reduce the contamination the regions of interest by 2FGL γ-ray sources, we excluded AGNs which have neighboring (2FGL) sources within 2°. At this stage, our sample contains 394 γ-ray AGNs. We began by selecting all gamma rays of energy above 1 GeV within a 4° radius around the direction of each AGN (the positions of AGNs taken from the 2FGL catalog [Nolan et al. 2012]), and satisfying the SOURCE event class. For this analysis, we have accumulated events obtained from 2008 August 4 to 2013 November 7 (i.e., 5.2 years of the Fermi-LAT data), corresponding to 239557417 and 405478386 in units of the Mission Elapsed Time. To reduce the contamination by the γ-ray emission coming from cosmic-ray interactions in the Earth’s upper atmosphere (so-called albedo γ rays) our selection is

1 http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/
2 http://heasarc.gsfc.nasa.gov/FTP/fermi/data/lat/weekly/photon/
3 http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
4 http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/v9r32p5.html
refined by choosing events with zenith angles <100°. We removed events that occur during satellite maneuvers when the LAT rocking angle was larger than 52°. Time intervals when some event has negatively affected the quality of the LAT data are also excluded. Both the front-converting and back-converting events are selected. Note that the statistics are higher when we consider both the front-converting and back-converting events together.

3 TEMPORAL ANALYSIS FOR A SEARCH FOR PAIR HALOS AROUND AGNS

To disentangle AGN flares from quiescent AGN emission states, we perform a temporal analysis of the Fermi-LAT data. Below, we will compare the spatial distribution of photons coming during AGN flare episodes with that of photons coming during quiescent AGN states. This will allow us to set the 95% upper limits on the fraction of γ rays attributable to a pair halo component. To perform this analysis, we will determine γ-ray flares for each AGN from our sample of 394 AGNs and calculate the distribution of photons into annular bins for AGN flares and for quiescent AGN states.

To disentangle AGN flares from quiescent AGN emission states, we define an AGN flare in a statistical way. We determine flares in the Poisson regime. The Poisson distribution expresses the probability of a given number of events occurring in a fixed interval of exposure assuming these events occur with the same average rate. During AGN flare episodes, the flux from AGN increases compared with its quiescent state. To improve the strength of the selection of flares, we calculate the total number of photons coming within the circle with a radius of 1° above 1 GeV. For maximum flare-detection sensitivity, we select only events within a relatively small spatial region of 1°, this is consistent with the selection choice of events for a pulse-detection sensitivity maximization.[5] Note that the 68% containment angle for events of 1 GeV is about 0.8° for the Reprocessed Fermi-LAT data, while the 95% containment angle is about 2°. Note that the selection of AGNs which have no neighboring 2FGL sources within 2° for the study allows us to significantly suppress the effect of neighboring sources on the detection of AGN flares, since less than 5% of photons above 1 GeV from a neighboring source at a distance of 2° can contribute to the region with a radius of 1° around a source from our sample.

To perform a search for AGN flares, we began by binning events in equal exposure intervals which contain an average number of 5 photons. Note that the equal exposure intervals do not directly correspond to equal time intervals and, therefore, we computed equal exposure intervals. Our choice of the equal exposure intervals containing 5 photons on average allows us to study AGN flares in the Poisson regime. To define an AGN flare in a statistical way, we calculate the probability of an observed number of photons in each equal exposure interval from the Poisson distribution with the mean number of photons. Furthermore, we multiply each of these probabilities by a total number of equal exposure intervals and then by 22, and compare the computed values with 1. If the computed value is less than 1, we record a flare occurrence in the corresponding exposure interval. Note that the multiplications performed here guarantee that only ≈5% of identical sources with the same average number of photons contain such an excess of photons within one of the exposure intervals. Note that the threshold value of ≈5% is chosen to guarantee that most of the computed flaring intervals corresponds to the rate of photons that rarely occurs in the Poisson regime and to make our selection of flaring intervals sufficiently clean. When an AGN flare is detected, we remove this exposure interval from the data set, re-calculate the average number of photons, and repeat the procedure described above to search for the next AGN flare. Finally, we record the start and end times for all the detected flares for each AGN from our sample. The total number of the computed flaring intervals is 965, only ≈2% of which are expected to be due to statistical deviations in the Poisson process.

For the analysis of spatial distributions of photons for flares and for quiescent states, we bin photons in three energy bands, namely, 4.5-6 GeV, 6-10 GeV, and >10 GeV. The selection of the highest energy band, E > 10 GeV, is motivated by the fact that multiple scattering is unimportant above 10 GeV and the accuracy of the directional reconstruction of photon events detected by Fermi-LAT is limited by the ratio of the silicon-strip pitch to silicon-layer spacing, whereas the first two energy bands are selected as tight as possible to reduce the systematic error caused by differences in the spectra of AGNs, yet still have enough photons for a meaningful statistical analysis. For each energy band, we bin photons in annular bins with radii of 0° < r < 0°.21, 0°.21 < r < 0°.3, 0°.3 < r < 0°.42, 0°.42 < r < 0°.52, 0°.52 < r < 0°.6, and 1°.0 < r < 1°.3. Note the first two annular bins have a surface area twice smaller than those of the 3rd, 4th, and 5th bins. This selection is motivated by the fact that the statistics for the first two bins is sufficient to perform the analysis. We do not divide the 1st annular bin into tighter annular bins in order to eliminate the effect caused by the uncertainties in the determination of AGN positions on the γ-ray sky in the 2FGL catalog. The outer annular bin is selected for an estimation of the rate of background photons and has a surface area which is ≈7.66 times larger than that of the 3rd, 4th, and 5th bins.

Below we demonstrate an application of the temporal analysis based on the separation of photon events recorded during AGN flares from those during quiescent states for a search for pair halos. Pair halos around AGNs are expected to possibly reveal themselves as an extended emission component in addition to a point source emission from AGNs. Note that the size of the extended component should be redshift-dependent. This dependence on a source redshift is caused 1) by a redshift-dependent deflection angle of secondary electrons and positrons in extragalactic magnetic fields (see Eqs. 30 and 31 from [Neronov & Semikoz, 2009]), and 2) by geometry of propagation of cascade γ rays from the source to the observer (see Eq. 33 from [Neronov & Semikoz, 2009]). Note that the motion of the secondary electron-positron pairs is determined by the value of the correlation length of extragalactic magnetic field. Thus, if the correla-

5 http://fermi.gsfc.nasa.gov/ssc/data/analysis/sci tools/pulsar_analysis_tutorial.html#extract data
6 http://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats_temporal.html
tion length, $\lambda_B$, is much less than electron cooling distance $D_e$, within which secondary electrons/positrons lose their energy via IC scattering of the CMB photons, deflections of secondary electrons/positrons are described as diffusion in angle. In the opposite case, motion of secondary electrons and positrons at the length scale of $D_e$ can be approximated by the motion in a homogeneous magnetic field. The redshift dependencies are different for both these cases of motion. Apart from the redshift dependence due to motion of secondary electrons and positrons, geometry of $\gamma$-ray propagation introduces another redshift dependent factor which is determined by the ratio of a mean free path of primary TeV $\gamma$ rays propagating through the EBL to a distance to the source. We perform two different analyses to search for a pair halo component to compromise between the number of detected photon events and the tightness of redshift bins. In Sect. 3.1, we start with a study of the spatial distributions of photons recorded during AGN flare and quiescent states. In Sect. 3.2, we will bin the AGNs from our sample in several redshift bands to search for pair halos in each of these selected redshift-dependent samples. Finally, in Sect. 4, we will perform a search for pair halos for individual strong AGNs included in our sample.

### 3.1 AGN flare and quiescent states

To extract the approximate PSF on the basis of photons recorded during AGN flares, we remove non-flaring AGNs from our sample. Our final sample then contains 158 AGNs including 56 BL Lac type blazars, of which 5 are definite identifications, 92 flat spectrum radio quasars of which 6 are definite identifications, 7 active galaxies of uncertain type, and 3 non-blazar AGNs, of which 1 is a definite identification.

The ten brightest AGNs from our final sample, corresponding to the 2FGL catalog, are PKS 1510-089, PKS 0537-441, 4C +21.35, Markarian 421, 3C 279, AO 0235+164, B2 1520+31, 3C 273, PKS 1424+240, and PKS 0447-439. Fermi-LAT observations revealed the flaring activity of PKS 1510-089 (Abdo et al. 2010a), 4C +21.35 (Ackermann et al. 2014), 3C 279 (Ciprini & Chaty 2008), B2 1520+31 (Cutini & Hays 2009, Sanchez 2010), 3C 273 (Abdo et al. 2010c), and PKS 1424+240 (Donat 2011; Szostek 2011).

We stacked the photon events separately for flares and for quiescent states for each selected energy band and each selected annular bin, using our sample of the selected AGNs and the computed flaring and quiescent states. The distribution of photons coming from AGN flaring states is computed for our sample of 158 AGNs showing flaring activity, while the distribution of photons coming from AGN quiescent states is computed for the sample of the 394 selected AGNs (see Sect.3). The stacked distributions of photons in annular bins for flares and for quiescent states are presented in Table A1.

We used the stacked distributions of photons in annular bins for flares and for quiescent states to derive the ratio of the number of photons coming from AGNs and detected during quiescent states to the number of photons coming from AGNs and detected during flares, $R_{Q/F}$. We performed this procedure for each annular bin and each selected energy band separately. The statistical error taken was the square root of the count number. To subtract background photons, we used the number of photons within the outer annular bin. The errors in the determination of background photon numbers were taken into account. The calculated numbers of photons in annular bins for flares and for quiescent states for each selected energy band after subtraction of a background are shown in Table A2. Note that the calculated number of photons for AGN flares provides us with similar statistics as provided by the Crab pulsar and accumulated by Fermi-LAT during 3.5 years (see Sect. 5.1). The calculated ratios, $R_{Q/F}$, and statistical errors are shown in Table A3. The calculated ratios are within the error bars for each energy bin. We also calculated the weighted mean of these ratios in the annular bin of $0.21 < r < 0.6$ for each energy band and the variance of the mean. The weighted mean of the ratios agrees with the ratio computed for the first annular bin. Note that the ratio of the number of photons from AGNs to that from a background is much higher for flares than for quiescent states and that the ratio of the number of photons from AGNs to that from a pair halo component is much higher for flares than for quiescent states. The fact that it is more promising to search for a pair halo during quiescent states than to search for a pair halo during flares was emphasized by Aharonian et al. 1994.

We also noted that the ratio of the number of photons coming from AGNs and detected during quiescent states to that detected during flares is higher for the energy band of $E > 10$ GeV compared with those for the energy bands of 4.5 GeV $< E < 6$ GeV and 6 GeV $< E < 10$ GeV. A probable explanation is the presence of the selection bias because the sample of 394 sources contains 185 BL Lac type blazars and 146 FSRQs, while the sample of 158 sources contains 56 BL Lac type blazars and 92 FSRQs.

We also repeated our analysis and computed the ratio of the number of photons coming from AGNs and detected during quiescent states to the number of photons coming from AGNs and detected during flares by using only the sample of the 158 AGNs showing flaring activity. This is useful to suppress a possible selection effect due to considering different AGN samples for flaring and quiescent states. These ratios are shown in Table A4. The calculated ratios are also within the error bars for each energy bin. The ratios shown for the first annular bin are statistically significantly different between the energy band, $> 10$ GeV, and the other two energy bands. However, a detailed study of this question is beyond the scope of our paper.

| Annular bin | Energy bands |
|-------------|--------------|
| $0^\circ < r < 0^\circ.5$ | $4.5 - 6$ GeV | $6 - 10$ GeV | $> 10$ GeV |
| $0^\circ.21 < r < 0^\circ.3$ | $3.2 \pm 0.2$ | $3.38 \pm 0.15$ | $4.7 \pm 0.7$ |
| $0^\circ.3 < r < 0^\circ.42$ | $2.9 \pm 0.3$ | $2.9 \pm 0.3$ | $5.2 \pm 0.8$ |
| $0^\circ.42 < r < 0^\circ.52$ | $2.8 \pm 0.3$ | $3.7 \pm 0.5$ | $4.9 \pm 0.9$ |
| $0^\circ.52 < r < 0^\circ.6$ | $4.3 \pm 0.9$ | $3.1 \pm 0.7$ | $4.7 \pm 1.1$ |

### Table 1. The ratio of the number of photons coming from 158 AGNs and detected during quiescent states to the number of photons coming from AGNs and detected during flares
3.2 Search for pair halos around AGNs within several redshift intervals

The sizes of pair halos depend on the source redshifts and, therefore, to search for pair halos around AGNs the redshifts should be taken into account. Below, we present the temporal analysis for samples of AGNs with known redshifts belonging to several redshift intervals. Using the second catalog of AGNs detected by Fermi-LAT (Ackermann et al. 2014), we select only the AGNs with known redshifts from our sample of 394 AGNs. Since the number of photon events coming during AGN flares is much smaller (∼5 times) than that coming during quiescent states (see Table A2), we will use all 158 AGNs showing γ-ray flaring activity to approximate the PSF using flares of AGNs. To have a higher number of photons during AGN quiescent states, we select all AGNs with known redshifts from our sample of 394 AGNs. We sort AGNs in redshift intervals only for quiescent states.

To perform the analysis within several redshift intervals, the redshift intervals should be as tight as possible to expect a similar angular extension of pair-halos within each redshift interval and should be as broad as possible to increase the number of photon events from AGNs within similar redshifts. In this paper, we sort the AGNs with known redshifts belonging to our sample into four redshift intervals, z < 0.2, 0.2 < z < 0.6, 0.6 < z < 1.3, and 1.3 < z. The numbers of AGNs in these redshift intervals are 34, 60, 83, and 57, respectively. Note that these redshift intervals are tighter than those chosen by Ando & Kusenko (2010) which were z < 0.5 and 0.5 < z. We introduce two redshift intervals to gather nearby AGNs (z < 0.2) in one of these two intervals and very distant AGNs (z > 1.3) in the other interval. Since the sizes of extended emission from pair halos steeply decrease with a distance and is proportional to the strength of extragalactic magnetic field (see, e.g., Neronov & Semikoz 2009), the introduction of these two redshift intervals allows us to cover the cases of a lower and a higher strength of extragalactic magnetic field. We estimated the strength of extragalactic magnetic field which can be tested by using the present analysis by assuming that the angular extension of pair halos within each redshift interval is 0.30 and that the correlation length, Λ, is much less than the electron cooling distance Dc. Putting the values of the redshift and angular extension in Eq. 35 of Neronov & Semikoz (2009), we found that the values of strength of extragalactic magnetic field which can be tested by using this analysis, B × (λ0/1kpc)1/2, are about 10−15, 10−14, 5 × 10−14, and 10−13 gauss for the redshift intervals of z < 0.2, 0.2 < z < 0.6, 0.6 < z < 1.3, and 1.3 < z, respectively. The stacked distributions of photons in annular bins for quiescent states of AGNs within the four redshift intervals are presented in Table A3.

To compare the spatial distributions of photons detected during quiescent states of AGNs within the given redshift interval with that of photons detected during the flares of AGNs from our final sample of 158 AGNs, we divide these numbers by each other. The ratios of these numbers of photons for each annular bin and each energy band are shown in Table A2. Note that background rates and statistical errors were estimated in the same way as the analysis of photons from AGNs belonging to our final sample presented above. If the relative error on the ratio is high, we do not list such a value in this Table. The calculated ratios are in general within the error bars for each energy bin and each redshift interval. Therefore, no evidence for a pair halo component is found in any of the selected redshift intervals.

3.2.1 Upper limits for the fraction of γ rays attributable to a pair halo component

To set the upper limits for the fraction of γ rays attributable to a pair halo component, we should make an assumption about the spatial profile of a pair halo (e.g., see Ackermann et al. 2013). Note that if the pair halo profile is narrow compared with the PSF, it would be difficult to disentangle a point-like component from a pair halo. Therefore, in this analysis we assume that a pair halo is an extended component to Fermi-LAT with an angular size of ≥ 0.30 (which exceeds the radius of the second annular bin). Since the signal-to-noise ratios of the γ-ray signal from the stacked source centered on AGNs are highest for the first and second annular bins, we will use these two annular bins to set the upper limits for the fraction of γ rays attributable to a pair halo component. Note that the fluxes from AGNs during episodes of γ-ray flares are much higher than those during quiescent states due to the definition of flares (see the beginning of Section 3) and, therefore, the contribution of a pair halo component to flare fluxes is negligible compared to that of quiescent state fluxes. Thus, we assume that the contribution to the first and second annular bins from a pair halo component are the same for quiescent AGN states and that the contribution from a pair halo component to AGN flares is negligible. First we divided the number of photons after the substraction of a background in the first bin by that in the second bin for AGN flares and for quiescent AGN states. Second we subtracted the equal number of photons, x, from the first and second annular bins for quiescent AGN states (these photons come from a possible pair halo component). After this procedure, the ratios of the number of photons must be the same. Thus, this procedure leads to the equation for the ratios of the numbers of photons in the first and second annular bins for the energy band of 4.5-6 GeV and for the redshift interval, z < 0.2,

\[
\frac{504 - 19 \pm 22 - x}{165 - 19 \pm 13 - x} = \frac{570 \pm 24}{178 \pm 14},
\]

where the left-hand side of this equation is for quiescent states (see Table A3) and the right-hand side is for flares (see Table A2). The equations for the energy band of 6-10 GeV and >10 GeV were obtained using the same procedure. Taking the error bars into account, we computed the 95% upper limit for the fractions of γ rays from the stacked AGN sample attributable to a pair halo component in the first annular bin (r < 0.210) for each selected redshift interval. For the redshift interval of z < 0.2, we found that these fractions equals 12% for the energy band of 4.5-6 GeV, 7% for the energy band of 6-10 GeV, and 6% for the energy band of >10 GeV. For the redshift interval of 0.2 < z < 0.6, we found that these fractions equal 11% for the energy band of 4.5-6 GeV, 7% for the energy band of 6-10 GeV, and 10%
Table 2. The ratio of the number of photons detected during quiescent states of AGNs within the given redshift interval with that of photons detected during the flares of AGNs from our entire sample.

| Redshift | Annular bin | 4.5 - 6 GeV | 6 - 10 GeV | > 10 GeV |
|----------|-------------|-------------|------------|----------|
| z < 0.2  | 0° ≤ r < 5°.21 | 0.85 ± 0.05 | 1.07 ± 0.06 | 2.15 ± 0.11 |
| z < 0.2  | 0°.21 ≤ r < 5°.3 | 0.82 ± 0.09 | 0.89 ± 0.11 | 2.28 ± 0.35 |
| z < 0.2  | 0°.3 ≤ r < 5°.42 | 0.66 ± 0.10 | 0.94 ± 0.15 | 2.35 ± 0.43 |
| z < 0.2  | 0°.42 ≤ r < 5°.52 | 0.99 ± 0.27 | 1.03 ± 0.28 | 2.03 ± 0.53 |
| z < 0.2  | 0°.52 ≤ r < 6°.6 | – | – | 1.02 ± 0.65 |
| 0.2 ≤ z < 0.6 | 0° ≤ r < 0°.21 | 0.90 ± 0.06 | 0.93 ± 0.05 | 1.36 ± 0.07 |
| 0.2 ≤ z < 0.6 | 0°.21 ≤ r < 0°.3 | 0.81 ± 0.13 | 0.74 ± 0.09 | 1.44 ± 0.22 |
| 0.2 ≤ z < 0.6 | 0°.3 ≤ r < 0°.42 | 0.75 ± 0.10 | 1.16 ± 0.16 | 1.29 ± 0.24 |
| 0.2 ≤ z < 0.6 | 0°.42 ≤ r < 0°.52 | 1.51 ± 0.30 | 1.23 ± 0.25 | 1.53 ± 0.36 |
| 0.2 ≤ z < 0.6 | 0°.52 ≤ r < 6°.6 | 0.83 ± 0.25 | 2.10 ± 0.57 | 2.14 ± 0.70 |
| 0.6 ≤ z < 1.3 | 0° ≤ r < 0°.21 | 1.04 ± 0.06 | 1.07 ± 0.06 | 1.17 ± 0.07 |
| 0.6 ≤ z < 1.3 | 0°.21 ≤ r < 0°.3 | 0.95 ± 0.11 | 1.11 ± 0.13 | 1.30 ± 0.23 |
| 0.6 ≤ z < 1.3 | 0°.3 ≤ r < 0°.42 | 0.90 ± 0.15 | 1.02 ± 0.20 | 1.26 ± 0.31 |
| 0.6 ≤ z < 1.3 | 0°.42 ≤ r < 0°.52 | 1.30 ± 0.40 | 0.83 ± 0.31 | 1.08 ± 0.43 |
| 0.6 ≤ z < 1.3 | 0°.52 ≤ r < 6°.6 | – | 1.50 ± 0.72 | – |
| 1.3 ≤ z | 0° ≤ r < 0°.21 | 0.58 ± 0.04 | 0.41 ± 0.03 | 0.43 ± 0.03 |
| 1.3 ≤ z | 0°.21 ≤ r < 0°.3 | 0.51 ± 0.07 | 0.37 ± 0.07 | 0.31 ± 0.11 |
| 1.3 ≤ z | 0°.3 ≤ r < 0°.42 | 0.48 ± 0.10 | 0.58 ± 0.13 | 0.60 ± 0.21 |
| 1.3 ≤ z | 0°.42 ≤ r < 0°.52 | 0.90 ± 0.29 | 0.77 ± 0.26 | – |
| 1.3 ≤ z | 0°.52 ≤ r < 6°.6 | 0.63 ± 0.40 | 0.97 ± 0.29 | – |

Note that the obtained constraints on the fraction of γ rays attributable to a pair halo component were derived under the assumption that a pair halo component does not contribute to the region of 1°.0 ≤ r < 1°.3. This region was used to estimate a background. Using the number of photons in the outer annular bin (see Table A1), we found that the fraction of γ rays from the stacked AGN sample attributable to a background in the first annular bin (r < 0°.21) is 2.4% for the three energy bands and for the redshift interval of z < 0.2, 4.6% for the three energy bands and for the redshift interval of 0.2 < z < 0.6, 6.7% for the three energy bands and for the redshift interval of 0.6 < z < 1.3, and 9.11% for the three energy bands and for the redshift interval of z > 1.3. The assumption that a pair halo component does not contribute to the region of 1°.0 ≤ r < 1°.3 can be weakened. For this purpose, we modified the procedure described above. First we divided the number of photons without the subtraction of a background (see Table A2) in the first bin by that in the second bin for AGN flares and for quiescent AGN states. Second we subtracted the equal number of photons, x, from the first and second annular bins for quiescent AGN states (these photons come from a possible pair halo component + a background). Note that a background contributes the same number of photons in the first and second annular bins, because their surface areas are the same. Thus, this procedure leads to the equation for the ratios of the numbers of photons in the first and second annular bins for the energy band of 4.5-6 GeV and for the redshift interval, z < 0.2, z < 0.6, 0.6 < z < 1.3, and z > 1.3.

\[
\begin{align*}
504 \pm 22 - x & = 574 \pm 24 \\
165 \pm 13 - x & = 182 \pm 14
\end{align*}
\] (2)

where the left-hand side of this equation is for quiescent states (see Table A4) and the right-hand side is for flares (see Table A1). We compute the 95% upper limits for the fraction of γ rays from the stacked AGN sample attributable to a pair halo component + a background in the first annular bin (r < 0°.21). For the redshift interval of z < 0.2, we found that these fractions equal 13% for the energy band of 4.5-6 GeV, 7% for the energy band of 6-10 GeV, and 6% for the energy band of >10 GeV. For the redshift interval of 0.2 < z < 0.6, we found that these fractions equal 11% for the energy band of 4.5-6 GeV, 8% for the energy band of 6-10 GeV, and 10% for the energy band of >10 GeV. For the redshift interval of 0.6 < z < 1.3, we found that these fractions equal 14% for the energy band of 4.5-6 GeV, 15% for the energy band of 6-10 GeV, and 12% for the energy band of >10 GeV. Finally, for the redshift interval of 1.3 < z, we found that these fractions equal 20% for the energy band of 4.5-6 GeV, 17% for the energy band of 6-10 GeV, and 15% for the energy band of >10 GeV.

4 METHOD TO RECONSTRUCT THE FERMI-LAT PSF

In this Section, we perform a temporal analysis of each of the five brightest γ-ray AGNs from our sample in order to search for pair halos around each of these sources. Further we reconstruct the Fermi-LAT PSF which is not affected by a pair halo component.

As was mentioned above, the contribution of a pair halo component to the total AGN γ-ray emission is much smaller for flares than that for quiescent states. Therefore, the spatial distribution of photons coming during AGN flares can be used as a proxy of the PSF.
The spatial distribution of photons coming during quiescent AGN states, \(D_Q(x)\), for each energy band and each source can be written as

\[
D_Q(x) = \alpha_Q \text{PSF}(x) + H_Q(x) + B_Q(x),
\]
where the first, second, and third terms are the contributions of a point source, a pair halo, and a background, respectively, and \(x\) is the label for annular bins, \(\alpha_Q\) is the normalisation of a point source flux. Note that the PSF component is not affected by a pair halo component. Similarly the spatial distribution of photons coming during AGN flares, \(D_F(x)\), can be written as

\[
D_F(x) = \alpha_F \text{PSF}(x) + H_F(x) + B_F(x).
\]
The pair halo and background fluxes are time-invariant and, therefore,

\[
\frac{H_F(x) + B_F(x)}{H_Q(x) + B_Q(x)} = \frac{N_F}{N_Q},
\]
where \(N_Q\) and \(N_F\) are the total number of equal exposure intervals for quiescent states and for flares, respectively, for the given AGN. Multiplying Eqs. 3 and 4 by \(N_Q\) and \(N_F\), respectively, and subtracting one equation from the other, we find

\[
\text{PSF}(x) = \frac{D_F(x)N_Q - D_Q(x)N_F}{\alpha_Q N_F - \alpha_F N_Q}.
\]
Note that the ratio of the values of the point spread function for two annular bins depends only on the values of \(D_F(x)N_Q - D_Q(x)N_F\) for these annular bins. This fact can be used to reconstruct the PSF by computing the ratios of the PSF values for different annular bins.

### 4.1 Analysis of individual sources
To outline the method of the PSF reconstruction, below we calculate the ratio, \(R\), of the values of the point spread function for the two annular bins of \(0 < r < 0.021\) and \(0.21 < r < 0.42\). Note that the later annular bin corresponds to the sum of the second and third annular bins from Table A2. For this study, we selected the five brightest sources from our final sample, namely 4C +21.35, 3C 279, PKS 1510-08, PKS 0537-441, and Mkn 421. We calculate the ratio, \(R\), for each of these sources and the weighted mean of these ratios. For an illustration, we selected photons in the energy band of 4.5-6 GeV and photons in the energy band of 6-10 GeV. The observed numbers of photons in the two annular bins of \(0 < r < 0.21\) and \(0.21 < r < 0.42\) for flares and for quiescent states for the five brightest sources are shown in Table A3. Using Eq. 5 and Table A3 we calculated the ratios of the values of the point spread function for these two annular bins, \(R\), for the five brightest sources. The calculated ratios are shown in Table 3. The weighted mean of the ratios for these five sources is \(R = 1.7 \pm 0.3\) for the energy band of 4.5-6 GeV and is \(R = 2.7 \pm 0.4\) for the energy band of 6-10 GeV. We compared the calculated weighted mean of the ratios for these five sources for the energy band of 4.5-6 GeV, \(R = 1.7 \pm 0.3\), with the ratio of the numbers of photons in these two annular bins for flares and for quiescent states (see Table A2). The ratios of the numbers of photons in these two annular bins coming during flares and quiescent states are \(R_F = 1.9 \pm 0.1\) and \(R_Q = 2.2 \pm 0.1\), respectively. All these three ratios (\(R, R_F\), and \(R_Q\)) agree within the error-bars. Note that the value of \(R\) is close to that of \(R_F\) as was expected. We also compared the calculated weighted mean of the ratios for these five sources for the energy band of 6-10 GeV, \(R = 2.7 \pm 0.2\) and \(R_Q = 2.8 \pm 0.1\), respectively. These three values (\(R, R_F\), and \(R_Q\)) agree within the error-bars for the energy band of 6-10 GeV. Therefore, no evidence for a pair halo is found by means of these comparisons.

We also obtained the constraints on the fraction of \(\gamma\) rays attributable to a pair halo component for each of the five brightest AGNs. We divided the number of photons without the subtraction of a background (see Table A3) in the first bin by that in the second bin for quiescent AGN states and for AGN flares. Then we subtracted the number of photons, \(x\), from the first annular bin and subtracted the number of photons, \(3x\), from the second annular bin for quiescent AGN states (these photons come from a possible pair halo component + a background). To improve the constraints we used our final sample of 158 AGNs to compute the number of photons during AGN flares. We found that the 95% upper limit for the fraction of \(\gamma\) rays from the stacked AGN sample attributable to a pair halo component + a background in the first annular bin (\(r < 0.21\)) equals 20% for the energy band of 4.5-6 GeV and 7% for the energy band of 6-10 GeV for 4C +21.35. For the other four selected AGNs these ratios for the energy bands of 4.5-6 GeV and 6-10 GeV are 10% and 19% for 3C 279, 13% and 7% for PKS 1510-08, 7% and 5% for PKS 0537-441, and 12% and 4% for Mkn 421. Note that as a proxy of the PSF for the computation of the upper limits on the fraction of \(\gamma\) rays attributable to a pair halo component, we used the spatial distribution of photons coming from AGNs during their flares.

### 4.2 Reconstruction of the Fermi-LAT PSF
We take each of the 158 flaring sources of our sample and derive the angular distribution of \(\gamma\) rays for each source for both flaring and quiescent states. Then we compute the value of \(D_F(x)N_Q - D_Q(x)N_F\) for each source and for each annular bin. This give the “pure” PSF profile, free of the possible extended pair-halo signal. Then we stack the PSF
Table 4. The PSF profiles derived from the analysis of 158 flaring sources by using the method developed in Sect. 4 and from the Crab pulsar data

| Annular bin       | Energy bands |
|-------------------|--------------|
|                   | 4.5 – 6 GeV  | 6 – 10 GeV | > 10 GeV |
| Method from Sect. 4 | -           | -         | -        |
| $0^\circ < r < 0^\circ.21$ | 61.8 ± 3.8   | 69.8 ± 3.9 | 79.4 ± 4.8 |
| $0^\circ.21 < r < 0^\circ.3$ | 19.6 ± 2.1   | 14.6 ± 1.7 | 9.9 ± 1.7  |
| $0^\circ.3 < r < 0^\circ.42$ | 11.8 ± 1.6   | 9.1 ± 1.1  | 6.5 ± 1.4  |
| $0^\circ.42 < r < 0^\circ.52$ | 3.7 ± 1.0    | 5.0 ± 0.6  | 3.4 ± 0.9  |
| $0^\circ.52 < r < 0^\circ.6$ | 3.0 ± 0.8    | 1.6 ± 0.6  | 0.8 ± 0.5  |
| From the Crab pulsar data | -           | -         | -        |
| $0^\circ < r < 0^\circ.21$ | 57.2 ± 2.1   | 67.0 ± 2.2 | 81.2 ± 2.4 |
| $0^\circ.21 < r < 0^\circ.3$ | 17.9 ± 1.1   | 15.4 ± 1.1 | 9.2 ± 0.8  |
| $0^\circ.3 < r < 0^\circ.42$ | 14.8 ± 1.1   | 11.4 ± 0.9 | 5.8 ± 0.7  |
| $0^\circ.42 < r < 0^\circ.52$ | 6.7 ± 0.7    | 3.4 ± 0.5  | 2.3 ± 0.4  |
| $0^\circ.52 < r < 0^\circ.6$ | 3.4 ± 0.5    | 2.7 ± 0.5  | 1.4 ± 0.4  |

5 COMPARISON OF METHODS TO RECONSTRUCT THE FERMI-LAT PSF

In this Section, first we compare the PSF computed by using the method developed in Sect. 4 with the PSF provided by the Fermi-LAT collaboration for an analysis of Pass 7 Reprocessed Fermi dataset. Furthermore, we compare the PSF computed above with that obtained by using the Crab pulsar and nebula.

5.1 Released P7REP_SOURCE IRF PSF

In the P7REP_SOURCE_V15 instrument response functions (IRFs) the PSF is derived from flight data and are provided by the Fermi-LAT team. The updated instrument calibrations used to produce the P7REP data release improve the LAT PSF above 3 GeV, resulting in a better overall agreement between the Monte Carlo (MC) PSF model and the angular distributions of gamma-ray point sources. However the MC PSF was still found to slightly underestimate the PSF width above 3 GeV. The LAT team has derived a new on-orbit PSF for P7REP data (included in the P7REP_V15 IRFs) by rescaling the MC PSF model to match the angular distribution of Vela below 10 GeV and the stacked distribution of bright, high-latitude blazars above 10 GeV. In order to provide an independent validation of the P7REP_SOURCE PSF for an analysis of point sources with the Fermi Science Tool (FST), we perform a comparison of the PSF derived in Sect. 4.2 with the P7REP_SOURCE PSF released by the LAT team.

Using the routine, gtmodel, we model a point source using the P7REP_SOURCE_V15 IRFs for three energy bands, 4.5 – 6, 6 – 10, and > 10 GeV. To compare the PSF derived in Sect. 4.2 with that modelled for a point source, we compute a normalisation factor for a modelled point source by minimising the $\chi^2$ value. Note that we use the 5 annular bins described in Sect. 3. In Fig. we show the best-fit values of fractions (the sum of the fractions over the five annular bins equals 100) obtained by modelling (triangles) and the observed values with error bars computed by using AGN flares (the upper panel is for the energy band of 4.5–6 GeV, the middle panel is for the energy band of 6 – 10 GeV, and the bottom panel is for > 10 GeV).

Figure 1. The best-fit values of fractions (the sum of the fractions over the five annular bins equals 100) obtained by modelling (triangles) and the observed values with error bars computed by using AGN flares (the upper panel is for the energy band of 4.5–6 GeV, the middle panel is for the energy band of 6 – 10 GeV, and the bottom panel is for > 10 GeV).
annular bins equals 100) obtained by modelling (triangles) and the observed values with error bars computed by using the method developed in Sect. 4. The observed and modelled distributions look very similar in Fig[1] To quantitatively access the quality of the best fits, we computed the $\chi^2$ values and found the $\chi^2$ values equal 7.4, 3.9, and 2.6 at 4 d.o.f. for the three energy bands, 4.5 – 6, 6 – 10, and $> 10$ GeV, respectively. Therefore, no significant deviations of the modelled spatial distribution from the spatial distribution computed by using the procedure developed in Sect. 4 are found. We conclude that the method of the PSF reconstruction developed in Sect. 4 independently validates the usage of the P7REP SOURCE PSF.

5.2 PSF from the Crab pulsar data

The $\gamma$-ray signal from the bright galactic gamma-ray source at the location of the Crab pulsar in the Fermi energy band consists of two contributions: emission from the pulsar and from the associated pulsar wind nebula (PWN). Neronov et al. (2011) noticed that the size of the associated PWN is below the angular resolution of the LAT telescope onboard Fermi and proposed the Crab pulsar for the Fermi-LAT PSF calibration.

We applied the same data reduction procedures to the data for the region of the Crab pulsar and accumulated events for the same time interval described in Sect. 2. The distribution of photons in annular bins for three energy bands are presented in Table A2 Note that the Crab pulsar provides us with a higher number of photons than that provided by AGN flares. $\gamma$-ray flares computed above for our sample of AGNs and accumulated during 5.2 years provide us with the number of photons which corresponds to $\lesssim 3.5$ years of the Crab pulsar observation with Fermi-LAT. In Table[3] we show the PSF profiles derived from the Crab pulsar data (the sum of the fractions over the five annular bins for each energy band equals 100). We checked and found that the PSF profiles derived from the Crab pulsar data agree well with those that are derived by using the method developed in Sect. 4. The future observations with Fermi-LAT are important for a further comparison of the PSFs which are reconstructed with these two different methods. Note that 10 years of Fermi-LAT observations and better event reconstruction algorithms (resulting in a higher effective area) are expected to make error-bars tighter by a factor of $\approx 2$.

6 CONCLUSION

We developed a method to search for pair halos through a temporal analysis of AGN emission. Our method is based on an analysis of the spatial distributions of photons coming from AGN flares and from AGN quiescent states, and a further comparison of these two spatial distributions.

To apply the method to the Fermi-LAT data, we selected 394 AGNs for our study. We found flaring activity in 158 AGNs of our sample. Performing the stacking of the selected AGNs, we found that the ratios of the number of photons coming from AGNs with known redshifts (sorted in the four redshift intervals) and detected during quiescent states to the number of photons coming from AGNs and detected during flares in annular bins are within the error bars for each of the three energy bands (4.5 – 6 GeV, 6 – 10 GeV, and $> 10$ GeV) and, therefore, no evidence for a pair halo component is found in this search. We also set the 95% upper limit for the fraction of $\gamma$ rays from the stacked AGN quiescent states for each redshift interval attributable to a pair halo component in the annular bin of $r < 0.21^\circ$.

We presented our method for the reconstruction of the Fermi-LAT PSF by using the observations of AGN flares and quiescent states (see Sect. 4). We compare the computed PSF with that obtained by using the Fermi-LAT dataset for the Crab pulsar. We found that both the PSFs are in good agreement. Furthermore, we applied the method of the PSF reconstruction developed in this paper to independently validate the usage of the P7REP SOURCE IRF PSF released by the Fermi-LAT team.

ACKNOWLEDGEMENTS

Computations were performed using a high performance computing cluster in the Korea Astronomy and Space Science Institute (KASI).

We are grateful to the referee for the constructive suggestions that helped us to improve this manuscript.

APPENDIX A:

The stacked distributions of photons in annular bins for flares and for quiescent states for each selected energy band are shown in Table A1

The calculated numbers of photons in annular bins for flares and for quiescent states for each selected energy band after subtraction of a background are shown in Table A2

The ratios of the number of photons coming from 394 AGNs and detected during quiescent states to the number of photons coming from AGNs and detected during flares are shown in Table A3

The stacked distributions of photons in annular bins for quiescent states for each selected energy band and for each selected redshift interval are shown in Table A4

The observed numbers of photons with energies between 4.5 GeV and 6 GeV in the first two annular bins for flares and for quiescent states for the five brightest sources from our final sample are shown in Table A5

The distributions of photons in annular bins for three energy bands for the Crab pulsar are shown in Table A6

| Table A3. | The ratios of the number of photons coming from 394 AGNs and detected during quiescent states to the number of photons coming from AGNs and detected during flares |
|-----------|--------------------------------------------------|
| Anular bin | Energy bands                                      |
| $0^\circ < r < 0.21^\circ$ | $4.5 - 6$ GeV | $6 - 10$ GeV | $> 10$ GeV |
| $0.21^\circ < r < 0.3^\circ$ | $5.0 \pm 0.2$ | $4.5 \pm 0.4$ | $4.8 \pm 0.4$ | $8.4 \pm 1.1$ |
| $0.3^\circ < r < 0.42^\circ$ | $4.1 \pm 0.5$ | $5.8 \pm 0.7$ | $8.9 \pm 1.5$ |
| $0.42^\circ < r < 0.52^\circ$ | $5.9 \pm 1.3$ | $5.0 \pm 1.0$ | $7.3 \pm 1.7$ |
| $0.52^\circ < r < 0.6^\circ$ | $4.2 \pm 1.4$ | $5.6 \pm 2.0$ | $7.2 \pm 3.0$ |
| $0.21^\circ < r < 0.6^\circ$ | $4.5 \pm 0.3$ | $5.0 \pm 0.3$ | $8.2 \pm 0.8$ |
Table A1. The stacked distributions of photons in annular bins for flares and for quiescent states for each selected energy band.

| Annomal bin | State   | Energy bands       |
|-------------|---------|--------------------|
|             |         | 4.5 – 6 GeV | 6 – 10 GeV | > 10 GeV |
| $0^\circ < r < 0^\circ.21$ | flare    | 574    | 686     | 620  |
| $0^\circ.21 < r < 0^\circ.3$ | flare    | 182    | 162     | 73   |
| $0^\circ.3 < r < 0^\circ.42$ | flare    | 130    | 101     | 58   |
| $0^\circ.42 < r < 0^\circ.52$ | flare    | 49     | 51      | 36   |
| $0^\circ.52 < r < 0^\circ.6$ | flare    | 32     | 28      | 20   |
| $1^\circ.0 < r < 1^\circ.3$ | flare    | 58     | 61      | 49   |
| $0 < r < 0^\circ.21$ | quiescent | 3040   | 3881    | 5019 |
| $0^\circ.21 < r < 0^\circ.3$ | quiescent | 1012   | 992     | 802  |
| $0^\circ.3 < r < 0^\circ.42$ | quiescent | 920    | 1001    | 889  |
| $0^\circ.42 < r < 0^\circ.52$ | quiescent | 702    | 675     | 644  |
| $0^\circ.52 < r < 0^\circ.6$ | quiescent | 521    | 573     | 527  |
| $1^\circ.0 < r < 1^\circ.3$ | quiescent | 3220   | 3538    | 3287 |

Table A2. The calculated numbers of photons in annular bins for flares and for quiescent states for each selected energy band after subtraction of a background.

| Annomal bin | State   | Energy bands       |
|-------------|---------|--------------------|
|             |         | 4.5 – 6 GeV | 6 – 10 GeV | > 10 GeV |
| $0^\circ < r < 0^\circ.21$ | flare    | 570±24  | 682±26    | 617±25 |
| $0^\circ.21 < r < 0^\circ.3$ | flare    | 178±14  | 158±13    | 70±9   |
| $0^\circ.3 < r < 0^\circ.42$ | flare    | 122±11  | 93±10     | 52±8   |
| $0^\circ.42 < r < 0^\circ.52$ | flare    | 41±7    | 43±7      | 30±6   |
| $0^\circ.52 < r < 0^\circ.6$ | flare    | 24±6    | 20±5      | 14±5   |
| $0 < r < 0^\circ.21$ | quiescent | 283±55  | 3650±62   | 4805±71 |
| $0^\circ.21 < r < 0^\circ.3$ | quiescent | 802±32  | 761±32    | 588±29 |
| $0^\circ.3 < r < 0^\circ.42$ | quiescent | 500±30  | 540±32    | 460±31 |
| $0^\circ.42 < r < 0^\circ.52$ | quiescent | 282±26  | 214±27    | 216±26 |
| $0^\circ.52 < r < 0^\circ.6$ | quiescent | 101±23  | 112±25    | 98±24  |

Table A4. The stacked distributions of photons in annular bins for quiescent states for each selected energy band and for each selected redshift interval.

| Redshift | Annomal bin | Energy bands       |
|----------|-------------|--------------------|
|          |             | 4.5 – 6 GeV | 6 – 10 GeV | > 10 GeV |
| $z < 0.2$ | $0^\circ < r < 0^\circ.21$ | 504    | 752     | 1346 |
| $z < 0.2$ | $0^\circ.21 < r < 0^\circ.3$ | 165    | 163     | 181 |
| $z < 0.2$ | $0^\circ.3 < r < 0^\circ.42$ | 118    | 132     | 165 |
| $z < 0.2$ | $0^\circ.42 < r < 0^\circ.52$ | 79     | 89      | 104 |
| $z < 0.2$ | $0^\circ.52 < r < 0^\circ.6$ | 47     | 50      | 57  |
| $z < 0.2$ | $1^\circ.0 < r < 1^\circ.3$ | 294    | 339     | 327 |
| $0.2 < z < 0.6$ | $0^\circ < r < 0^\circ.21$ | 546    | 666     | 836 |
| $0.2 < z < 0.6$ | $0^\circ.21 < r < 0^\circ.3$ | 173    | 147     | 133 |
| $0.2 < z < 0.6$ | $0^\circ.3 < r < 0^\circ.42$ | 150    | 168     | 131 |
| $0.2 < z < 0.6$ | $0^\circ.42 < r < 0^\circ.52$ | 120    | 113     | 110 |
| $0.2 < z < 0.6$ | $0^\circ.52 < r < 0^\circ.6$ | 78     | 102     | 94  |
| $0.2 < z < 0.6$ | $1^\circ.0 < r < 1^\circ.3$ | 461    | 472     | 497 |
| $0.6 < z < 1.3$ | $0^\circ < r < 0^\circ.21$ | 639    | 784     | 765 |
| $0.6 < z < 1.3$ | $0^\circ.21 < r < 0^\circ.3$ | 216    | 227     | 135 |
| $0.6 < z < 1.3$ | $0^\circ.3 < r < 0^\circ.42$ | 202    | 197     | 154 |
| $0.6 < z < 1.3$ | $0^\circ.42 < r < 0^\circ.52$ | 149    | 138     | 121 |
| $0.6 < z < 1.3$ | $0^\circ.52 < r < 0^\circ.6$ | 107    | 132     | 104 |
| $0.6 < z < 1.3$ | $1^\circ.0 < r < 1^\circ.3$ | 703    | 741     | 681 |
| $1 < z$ | $0^\circ < r < 0^\circ.21$ | 333    | 311     | 271 |
| $1 < z$ | $0^\circ.21 < r < 0^\circ.3$ | 121    | 89      | 51  |
| $1 < z$ | $0^\circ.3 < r < 0^\circ.42$ | 120    | 116     | 88  |
| $1 < z$ | $0^\circ.42 < r < 0^\circ.52$ | 98     | 95      | 68  |
| $1 < z$ | $0^\circ.52 < r < 0^\circ.6$ | 76     | 74      | 58  |
| $1 < z$ | $1^\circ.0 < r < 1^\circ.3$ | 464    | 476     | 438 |
Table A5. The observed numbers of photons with energies between 4.5 GeV and 6 GeV in the first two annular bins for flares and for quiescent states for the five brightest sources from our final sample.

| Source name | State          | Energy band | Annular bins | Number of intervals |
|-------------|----------------|-------------|--------------|---------------------|
| 4C +21.35   | flare          | 4.5-6 GeV   | 0° < r < 0°.21 | 51 34 60            |
| 3C 279      | flare          | 4.5-6 GeV   | 0°.21 < r < 0°.42 | 21 13 40          |
| PKS 1510-08 | flare          | 4.5-6 GeV   |              | 56 22 80           |
| PKS 0537-441| flare          | 4.5-6 GeV   |              | 34 16 51           |
| Mkn 421     | flare          | 4.5-6 GeV   |              | 17 7 20            |
| 4C +21.35   | quiescent      | 4.5-6 GeV   | 0° < r < 0°.21 | 32 21 633          |
| 3C 279      | quiescent      | 4.5-6 GeV   | 0°.21 < r < 0°.42 | 49 21 497         |
| PKS 1510-08 | quiescent      | 4.5-6 GeV   |              | 73 44 1052         |
| PKS 0537-441| quiescent      | 4.5-6 GeV   |              | 106 48 858         |
| Mkn 421     | quiescent      | 4.5-6 GeV   |              | 228 110 1206       |

Table A6. The distributions of photons in annular bins for three energy bands for the Crab pulsar.

| Quantity | Annular bin          | Energy bands |
|----------|----------------------|--------------|
|          | 4.5 – 6 GeV          | 6 – 10 GeV   | > 10 GeV     |
| Photons  | 0° < r < 0°.21       | 782 948 1118 |
| Photons  | 0°.21 < r < 0°.3     | 247 220 129  |
| Photons  | 0°.3 < r < 0°.42     | 208 164 85  |
| Photons  | 0°.42 < r < 0°.52    | 98 51 37    |
| Photons  | 0°.52 < r < 0°.6     | 54 41 24    |
| Photons  | 1°.0 < r < 1°.3      | 56 35 37    |

REFERENCES

Abdo A. A. et al., 2010a, ApJ, 721, 1425
Abdo A. A. et al., 2010b, ApJ, 722, 520
Abdo A. A. et al., 2010c, ApJ, 714, L73
Ackermann M. et al., 2011, ApJ, 743, 171
Ackermann M. et al., 2014, ApJ, 786, 157
Ackermann M. et al., 2013, ApJ, 765, 54
Ackermann M. et al., 2010, ApJ, 721, 1383
Aharonian F. A., Coppi P. S., Voelk H. J., 1994, ApJ, 423, L5
Ando S., Kusenko A., 2010, ApJ, 722, L39
Atwood W. B. et al., 2009, ApJ, 697, 1071
Bregeon J., Charles E., Wood for the Fermi-LAT collaboration, 2013, ArXiv e-prints: 1304.5456
Ciprini S., Chaty S., 2008, The Astronomer’s Telegram, 1864, 1
Cutini S., Hays E., 2009, The Astronomer’s Telegram, 2026, 1
Dolag K., Kachelriess M., Ostapchenko S., Tom"us R., 2011, ApJ, 727, L4
Donato D., 2010, The Astronomer’s Telegram, 2583, 1
Finke J. D., Razzano S., Dermer C. D., 2010, ApJ, 712, 238
Franceschini A., Rodighiero G., Vaccari M., 2008, A&A, 487, 837
Kneiske T. M., Mannheim K., Hartmann D. H., 2002, A&A, 386, 1
Neronov A., Semikoz D. V., 2009, Phys. Rev. D., 80, 123012
Neronov A., Semikoz D. V., Tinyakov P. G., Tkachev I. I., 2011, A&A, 526, A90
Neronov A., Vovk I., 2010, Science, 328, 73
Nolan P. L. et al., 2012, ApJS, 199, 31
Ryu D., Schleicher D. R. G., Treumann R. A., Tsagas C. G., Widrow L. M., 2012, Space Science Reviews, 166, 1
Sanchez D., 2010, The Astronomer’s Telegram, 3050, 1
Szostek A., 2011, The Astronomer’s Telegram, 3329, 1
Tavecchio F., Ghisellini G., Foschini L., Bonnoli G., Ghirlanda G., Coppi P., 2010, MNRAS, 406, L70