Upper bounds on matter-antimatter admixture from gamma-ray observations of colliding clusters of galaxies with the Fermi Large Area Telescope

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We examined whether significant constraints on matter-antimatter admixture can be derived from gamma-ray observations of colliding clusters of galaxies with Fermi-LAT. We selected ten known systems of colliding clusters of galaxies for the analysis and computed the upper bounds on matter-antimatter admixture in these systems, which range from 7×10^{-9} to 2×10^{-6}. This allowed us to exclude a symmetric universe on scales of order ~20 Mpc at the confidence level of 99.9%. Adopting the number of systems of colliding galaxy clusters from the Marenostrum Universe cosmological simulation, we checked if the Fermi-LAT second source catalog contains a sufficient number of gamma-ray sources to provide us with the required number of sources possibly associated with $p\bar{p}$ annihilation from cluster-anticluster collisions. We found that a matter-antimatter-symmetric universe is strongly ruled out on scales of order ~20 Mpc if a matter-antimatter admixture in these bullet-like systems is of $f \gtrsim 10^{-5}$, and on scales of order ~400 Mpc if $f \gtrsim 10^{-4}$.

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I. INTRODUCTION

The observational discovery of the cosmic expansion and cosmic microwave background, and the success of big bang nucleosynthesis, established that the Universe was hot during the early stages of its history. In the very early Universe, matter and antimatter were created with equal abundances out of high-energy radiation, and antimatter was present while creation of matter and antimatter particles and their annihilation reactions were in thermal equilibrium (for a review, see Ref. [1]). Experiments demonstrated that a proton is an extremely stable particle and its lifetime exceeds the Hubble time ($\simeq$ the age of the Universe) by more than 15 orders of magnitude [2]. The CPT theorem provides that a particle and its antiparticle have exactly the same mass and lifetime, and exactly opposite charge [3,4]. When energies of particles in the cooling Universe became too small for pair creation, almost all particles and antiparticles were very likely annihilated with a tiny amount of matter surviving. The smallness of the number of survived baryons is strongly suggested by the ratio of baryons to photons, which is $\simeq 6 \times 10^{-10}$ at the epoch of big bang nucleosynthesis and at recombination [5].

Searches for the possible existence of antimatter deposits in objects ranging in size from planets to galactic clusters excluded significant matter-antimatter admixtures in such objects [6]. The process of creation of the observable matter-antimatter-asymmetric Universe from a matter-antimatter-symmetric initial state is known as baryogenesis. Three necessary conditions for successful baryogenesis were formulated by Sakharov [7], including baryon number violation, charge and charge-parity (CP) violation, and a deviation of thermal equilibrium. The Standard Model (SM) of particles and cosmology satisfies all of the conditions for baryogenesis [8], but alone is ineffective to produce the required baryon number [9].

Recent Planck and Large Hadron Collider (LHC) results put strong constraints on several baryogenesis scenarios. The Planck mission provides strong support for the inflationary theory of the Universe by demonstrating that the CMB temperature variations follow a Gaussian distribution, $f_{\rm NL} = 2.7 \pm 5.8$ [10], and that the scalar spectral index, $n_s = 0.9603 \pm 0.0073$ [11], is slightly less than 1. Most models of inflation predict a nearly flat spatial geometry of the Universe with small deviations from perfect spatial flatness of order $\sim 10^{-5}$, and the flatness of the Universe is also strongly confirmed by the Planck data supplemented by the WMAP large-scale polarization and baryon acoustic oscillation data, which provide $\Omega_{\rm K} = -0.0004 \pm 0.00036$ [12]. The success of inflationary theory suggests that if the baryon number was produced before the inflation era (e.g., by Planck-scale baryogenesis or by baryogenesis in Grand Unified Theories), it was completely diluted in the period of inflation. Therefore, a candidate explanation for baryogenesis must allow the Sakharov conditions to be satisfied at some time after the end of cosmological inflation. Baryogenesis during the electroweak (EW) phase transition [8] is, therefore, an intriguing scenario for the origin of the matter-antimatter-asymmetric Universe and has an advantage that one might hope to see new CP-violating effects in terrestrial experiments. However, departure from thermal equilibrium can occur at the EW epoch only if there is a sufficiently strong first-order phase transition, which requires a light Higgs boson. The lower bound on a Higgs boson mass, >114.4 GeV [13], excludes the possibility of a strong first-order EW phase transition in the SM (this transition does not occur in the SM with a Higgs boson of mass ≈ 125 GeV tentatively discovered at CERN [14,15]). Models of particle physics beyond the SM containing new processes of *CP* and B violation are of great interest. Supersymmetric extensions of the SM (for a review, see Ref. [16]) contain new sources of *CP* violation and an enlarged set of parameters which allow a greater possibility of a first-order transition. Supersymmetry is widely regarded as a prime candidate for such new physics, and the upcoming LHC experiments will put this hypothesis to a definite test.

While LHC experiments test supersymmetric extensions of the SM, all available astrophysical observations for the search of antimatter in the Universe should be performed. There are some baryogenesis scenarios which predict regions of antimatter in the Universe (for a review, see Ref. [17] and references therein). Note that it has been demonstrated in Ref. [18] that a matter-antimatter-symmetric universe is empirically excluded because the cosmic diffuse gamma-ray signal measured by Compton telescopes [19] is lower than that expected due to annihilation between the epochs of recombination and of the onset of structure formation. In this paper, we use the alternative method proposed in Ref. [20] to set bounds on the presence of antimatter. We perform an analysis of gamma-ray observations of ten systems of colliding galaxy clusters to search for an annihilation signal produced in proton-antiproton ($p\bar{p}$) interactions. For each $p\bar{p}$ annihilation, two gamma rays form with a mean energy of $\simeq 200$ MeV. The Fermi Large Area Telescope (LAT) [21] provides us with the all-sky gamma-ray map in this energy band allowing us to search for a $p\bar{p}$ annihilation signal. The importance of this test was stressed by Steigman [20], who set an upper bound on matter-antimatter admixture in the "Bullet" cluster of galaxies. This test is important in order to bring the maximum number of astrophysical and cosmological phenomena into harmony and provides support for a baryogenesis hypothesis by an independent method. We also check if the Fermi-LAT second source catalog [22] provides us with a sufficient number of gamma-ray sources which could possibly be associated with the simulated systems of colliding galaxy clusters [23].

II. METHODS TO SEARCH FOR ANTIMATTER IN THE COSMOS

The methods of cosmic antimatter searching can be divided into two categories: direct and indirect methods. This section briefly describes direct and indirect methods, summarizes the previously obtained results, and emphasizes the importance of the additional indirect method [20] based on the search of a gamma-ray $p\bar{p}$ annihilation signal from colliding clusters of galaxies.

The direct method of an antimatter search beyond the Solar System is based on observations of antihelium nuclei in cosmic rays. An antihelium nucleus has very low probability of being produced in the collisions between high-energy particles [24], and therefore, antihelium detection in the cosmic rays would be a clear indication of the existence of an antimatter area in the Universe. No antihelium nuclei were detected with the AMS-01, PAMELA, and BESS-Polar missions, and the tight upper limits on the flux ratio of antihelium to helium of 1.0×10^{-7} in the rigidity range from 1.6 to 14 GV [25] and of 4.7×10^{-7} at rigidities above 14 GV [26] were derived. AMS-02 will have the possibility to detect an antihelium nucleus or, at least, to lower the limit on the flux ratio of antihelium to helium by a factor of ~ 100 compared with that obtained by PAMELA.[1] Note that the detection of antinuclei with $Z > 2$ would imply the existence of antistars [6], because the ratio of secondary heavy nuclei (e.g., anticarbons) to secondary antiprotons is expected to be extremely small [27]. No antinucleus with $|Z| \geq 3$ was detected with AMS-01, and the upper limits on the flux ratio of anticarbon to carbon and of antinuclei to nuclei with $3 \leq |Z| \leq 8$ were derived in Ref. [28].

The indirect method for searching the existence of cosmologically distributed objects with significant matter-antimatter admixtures in which matter-antimatter annihilation takes place is provided by gamma-ray astronomy [6,29]. Upper bounds on the presence of antimatter in nearby and distant parts of the Universe were imposed by indirect detection methods [6]. Gamma-ray production from cosmic $p\bar{p}$ interactions was estimated in Ref. [29]. $p\bar{p}$ annihilation at rest into charged and neutral π-mesons ($p+\bar{p}\to\pi^{+}+\pi^{-}+\pi^{0}$) produces gamma rays with energies between 5 and 919 MeV coming from the decay of produced neutral π-mesons. The maximal energy of a photon generated in this process is about $E_{\max}\approx m_{\rm p}-m_{\pi}^{2}/m_{\rm p}$. The maximum of a gamma-ray spectrum produced by $p\bar{p}$ annihilation is about 100 MeV in the rest frame. Since the $p\bar{p}$ annihilation is a very efficient process, gamma-ray observations of Galactic and extragalactic sources lead to very tight upper bounds on the possible matter-antimatter admixtures in objects up to the size of galactic clusters. On the scale of individual x-ray-emitting clusters of galaxies, the upper bounds on the fraction of mixed matter and antimatter derived from EGRET gamma-ray observations [30] for the 55 clusters from the flux-limited x-ray survey [31] range from 5×10^{-9} to 1×10^{-6}. This strongly suggests that these individual clusters of galaxies are made entirely of matter or of antimatter (Ref. [20]; see also Ref. [32], where the upper limits on gamma-ray fluxes from galaxy clusters derived from the

[1] http://ams.nasa.gov/about.html.

Fermi-LAT data [33] were applied to revise the upper bounds on matter-antimatter admixture from those galaxy clusters).

Observations of photons produced by $p\bar{p}$ annihilation at cosmological distances and redshifted to current energies [29] provide an important method to exclude a symmetric universe consisting of large islands of matter and antimatter [18]. Demonstrating that particle-antiparticle annihilation is unavoidable from the time of recombination to the onset of structure formation, Cohen *et al.* [18] concluded that a matter-antimatter-symmetric universe is empirically excluded because the cosmic diffuse gamma-ray signal measured by Compton telescopes (Ref. [19]; see also Ref. [34]) is lower than the signal expected due to $p\bar{p}$ annihilation between these two epochs, $20 < z < 1100$. This result strongly suggests that the local dominance of matter over antimatter persists throughout the entire visible Universe and, therefore, supports the baryogenesis hypothesis [7].

As emphasized by de Rujula [35], measurements of photon fluxes and spectra of individual astrophysical objects do not allow us to determine whether or not an object is made of matter or of antimatter, but observations of encounters involving an object and an antiobject would be spectacular. Galaxy clusters are megaparsec-scale structures that consist of hundreds of galaxies and high-temperature ($T_{\rm plasma} \simeq 10^7$–$10^8$ K) sparse highly ionized plasmas filling the space between galaxies [36]. Galaxies and plasmas in a galaxy cluster are gravitationally bound to its dark matter halo. X-ray radiation via bremsstrahlung and via ionic emission lines from intracluster plasmas has permitted the study of thermal components of the intra-cluster medium (ICM). If a fraction, f, of the ICM were to consist of antiprotons mixed with the dominant protons (or vice versa), then the two-body collisions responsible for creating the x rays via bremsstrahlung emission would ensure the production of high-energy gamma rays from matter-antimatter annihilation [20]. A typical mass of the intergalactic gas in a rich galaxy cluster is about $10^{14} M_{\odot}$, and the number of baryons is $\sim 10^{71}$. If the plasma in a merging galaxy cluster consisted of $N \sim 10^{71}$ protons and the same number of antiprotons, the energy which could be produced in annihilation of these protons with antiprotons would be $N \times 2m_{\rm p}c^2 \sim 10^{68}$ erg. This would establish a collision of a matter cluster and an antimatter cluster as the most energetic event in the Universe since the big bang. A promising way to probe the possibility of separated clusters and anticlusters is to search for correlated x rays and gamma rays from colliding clusters of galaxies [20]. Observations of the "Bullet" cluster [37], which consists of two merging galaxy clusters, provides such an opportunity. Using the observed x-ray and the annihilation-predicted gamma-ray fluxes and the EGRET gamma-ray flux upper limit, the upper bound on matter-antimatter admixture, f, in the "Bullet" cluster of $f < 3 \times 10^{-6}$ was derived [20]. If this result can be generalized to other colliding galaxy clusters, cosmologically significant amounts of antimatter will be excluded on scales of order of $\sim$20 Mpc [20]. The search for a possible $p\bar{p}$ annihilation signal from ten systems of colliding galaxy clusters by using the Fermi-LAT data is presented in the next section.

III. FERMI-LAT OBSERVATIONS OF COLLIDING GALAXY CLUSTERS

Fermi was launched on 11 June 2008 into 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 [21], a pair-production telescope with a large effective area ($\sim$6000 cm^2 at 500 MeV) and field of view (2.4 sr) sensitive to gamma rays between 20 and > 300 GeV. The Fermi-LAT began science operations on 2008 August 4 and normally operates in sky-survey mode, where the whole sky is observed every 3 hr (i.e., two orbits).

Searches for a possible $p\bar{p}$ annihilation signal from colliding galaxy clusters slightly differ from most searches for gamma-ray sources with Fermi-LAT. This is because gamma rays produced as the result of $p\bar{p}$ annihilation at rest have energies between 5 and 919 MeV and because most of the discovered colliding clusters of galaxies are at redshifts of $z \approx 0.2$–0.7. Thus, the maximal energy of observed gamma rays produced in this process is redshifted to 612 MeV for $z = 0.5$, and the maximum of the gamma-ray spectrum is redshifted from $\approx$100 to $\approx$70 MeV. Note that the point-spread function (PSF) of the LAT instrument at energies between $\approx$60 and $\approx$900 MeV is determined primarily by the $\propto 1/E$ dependence of multiple scattering [21]. The effective area of the LAT instrument increases monotonically with energy in this band from $\sim$2000 cm^2 at 60 MeV to $\sim$8000 cm^2 at 900 MeV. Fermi-LAT sources for which an analysis in this energy band is required are the Moon [38] and supernova remnants [39], and these studies strongly validated the procedure of an analysis of the Fermi-LAT data in the energy band 60 MeV < E < 1000 MeV, by means of the Fermi Science Tools.[2] The Moon is a very soft gamma-ray source and is detected up to 2 GeV during the first 24 months of Fermi-LAT observations [38], while the analysis of supernova remnants at low energies, $E < 200$ MeV, allowed us to detect a characteristic pion-decay feature in the gamma-ray spectra of IC443 and W44 [39].

Clusters of galaxies, which are bright x-ray sources, are promising targets for gamma-ray telescopes [40], but an observational evidence for diffuse gamma-ray emission from galaxy clusters is still lacking [41–43]. IC emission of primary electrons or emission via neutral pion decay produced in cosmic ray (CR)-proton–ICM-proton

[2] http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/.

TABLE I. The list of the selected colliding clusters of galaxies.

Cluster	l, deg	b, deg	Redshift	T_X, keV	Abundance	X-ray flux, erg cm^{-2} s^{-1}
1E 0657 − 558	266.025	−21.247	0.296	13.9 [49]	0.25 [49]	5.6×10^{-12} (0.1–2.4 keV) [55]
MACS J0025.4 − 1222	99.264	−74.044	0.584	6.3 [51]	0.37 [51]	8.1×10^{-13} (0.1–2.4 keV) [56]
Abell 1914	67.203	67.457	0.171	10.9 [49]	0.24 [49]	1.5×10^{-11} (0.1–2.4 keV) [57]
DLSCL J0916.2 + 2951	196.323	43.048	0.534	2.7 [52]	0.3	4.5×10^{-14} (0.5–2.0 keV) [52]
ACT-CL J0102 − 4915	297.992	−67.763	0.87	14.5 [48]	0.19 [48]	9.25×10^{-13} (0.1–2.4 keV) [48]
Abell 2744	8.897	−81.238	0.308	9.5[a] [53]	0.27 [53]	5.23×10^{-12} (0.1–2.4 keV) [58]
Abell 520	195.802	−24.284	0.199	7.1 [49]	0.24 [49]	8.40×10^{-12} (0.1–2.4 keV) [57]
MACS J0717.5 + 3745	180.244	21.045	0.546	10.5 [59]	0.28 [59]	1.44×10^{-12} (0.1–2.4 keV) [56]
Abell 754	239.327	24.799	0.054	10.0 [49]	0.3 [49]	5.49×10^{-11} (0.5–2.0 keV) [60]
Abell 2146	100.141	41.671	0.234	6.7 [61]	0.37 [61]	4.2×10^{-12} (0.1–2.4 keV) [62]

[a]Central tidal debris.

interactions are the two most natural mechanisms that could establish a galaxy cluster as a diffuse source of gamma rays in the GeV regime. The analyses of the first 18 months of Fermi-LAT data [33] have allowed us to derive the flux upper limits on gamma-ray emission in the energy range 0.2–100 GeV from 33 clusters of galaxies assuming a power-law spectrum of high-energy cluster emission with photon index of 2. Note that integral flux upper limits over a broad energy range depend upon the assumed spectrum of radiation because the LAT effective area increases between 0.2 and 1 GeV and that the peak effective area is near 3 GeV. Gamma-ray emission produced via $p\bar{p}$ annihilation does not produce photons with energies higher than 1 GeV (see above) and the maximum of the gamma-ray spectrum produced by $p\bar{p}$ annihilation is about 100 MeV at which energy photons have not been included in the previous analysis [33]. The recent studies of Fermi-LAT observations of galaxy clusters [41–43] were focused on nearby galaxy clusters, $z < 0.2$, and on the gamma-ray emission at least higher than 500 MeV, because the PSF is tighter and the effective area is larger at these energies. In this paper, we focus on low-energy gamma-ray emission from colliding clusters of galaxies located at intermediate redshifts.

A. Cluster selection

We select ten systems of colliding clusters of galaxies in order to search for a signature of $p\bar{p}$ annihilation in the gamma-ray observations of these systems. Our sample of colliding galaxy clusters includes 1E 0657 − 558 (dubbed the "Bullet" cluster), MACS J0025.4 − 1222 (the "Baby Bullet" cluster), Abell 1914, DLSCL J0916.2 + 2951 (the "Musket Ball" cluster), ACT-CL J0102 − 4915 (the "El Gordo" cluster), Abell 2744 (the "Pandora's Cluster"), Abell 520 (the "Train Wreck" cluster), MACS J0717.5 + 3745, Abell 754, and Abell 2146. X-ray observations revealed the inhomogeneous distributions of gas in these systems, such as the spectacular bullet-shaped cloud, cold front and bow shock in the front boundary of the gas "bullet" in 1E 0657 − 558 [37]; the shock wave fronts propagating in Abell 520 [44], Abell 754 [45,46] and Abell 2146 [47]; the "cometary"-like shape of ACT-CL J0102 − 4915 [48] which originated in the collision of two clusters of galaxies; and the arch-like hot region in Abell 1914 [49]. A collision between two galaxy clusters causes a separation of dark matter and baryonic matter in several of these systems (1E 0657 − 558 [50], MACS J0025.4 − 1222 [51], DLSCL J0916.2 + 2951 [52], and Abell 2744 [53]). MACS J0717.5 + 3745 consists of four distinct subclusters, and measurements of the kinetic Sunyaev-Zel'dovich (SZ) effect revealed a large-scale peculiar velocity along the line of sight toward one of these subclusters and no evidence for a kinetic SZ signal toward another subcluster [54]. These systems of galaxy clusters represent one of the first cosmic bowling games in which gravity began to play more than five billion years ago. The characteristics of these systems of colliding galaxy clusters selected for our study are provided in Table I: the first column lists the names of the colliding galaxy clusters, column 2 the galactic longitudes, column 3 the galactic latitudes, column 4 the redshifts, column 5 the gas temperatures, column 6 the metal abundance relative to solar, and column 7 the x-ray fluxes. Note that the metal abundance of the DLSCL J0916.2 + 2951 is not included in Ref. [52]. A reasonable assumption is that the metal abundance relative to solar in DLSCL J0916.2 + 2951 is close to those in other galaxy clusters from our sample, i.e. $Z \approx 0.3$.

B. Observation and likelihood analysis

For the data analysis, we use the Fermi Science Tools v9r27p1 package and P7V6 instrument response functions. Events 60 MeV–60 GeV satisfying the P7SOURCE event selection are selected. Note that the P7SOURCE event class is one of the event classes for gamma rays which is optimized for astrophysical source analyses of Pass 7 gamma-ray data[3] of the Fermi-LAT and is intended for the analysis of point sources. Events included in the

[3]http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass7_usage.html.

P7SOURCE class passed tight cuts on energy and direction reconstruction qualities, on gamma-ray probabilities from the charged particle background analysis and from the tracker (TKR) and calorimeter (CAL) topology analyses, and on the combined estimator that the event is a gamma ray (for a review, see Ref. [63]). To reduce the contamination by the gamma-ray emission from the Earth limb, we select events with zenith angles $< 100°$. Note that the choice of the lower energy bound is motivated by the analysis of the Fermi-LAT data from SNRs [39] by the Fermi-LAT Collaboration. The regions of interest (ROI) centered on the selected galaxy clusters are of 20° for 1E 0657 − 558, Abell 520, Abell 754, and Abell 2146 and of 30° for MACS J0025.4 − 1222, Abell 1914, DLSCL J0916.2 + 2951, ACT-CL J0102 − 4915, Abell 2744, and MACS J0717.5 + 3745. The choice of the radius of the ROI depends mainly on a projected distance from each galaxy cluster to the Galactic plane.

We downloaded the P7V6 Fermi-LAT data from the Fermi Science Support Center.[4] We then searched for high background flares around the ten selected clusters and found that the strong solar flare on 7 March 2012 [64] was in the ROI centered on MACS J0025.4 − 1222. To remove photons coming from the solar flare within this ROI, we decided to use the Fermi-LAT data from 4 August 2008 until 2 February 2012 for the analysis of all the selected clusters of galaxies. Note that the upper bounds on matter-antimatter admixture for individual clusters presented in Sec. C will be very tight, and therefore, the inclusion of more data in the analysis will not affect our conclusion.

We adopt a background model for each ROI centered on the selected clusters that includes components describing the diffuse Galactic and isotropic gamma-ray emission, gal_2yearp7v6_v0.fits and iso_p7v6source.txt,[5] respectively. Note that for time intervals greater than a few months, residual particle background events (which also passed tight cuts used for the P7SOURCE event class) become approximately isotropically distributed in sky coordinates, and therefore, the residual particle background was combined with extragalactic diffuse background in one spectral template, iso_p7v6source.txt. To derive an isotropic template for the P7SOURCE event selection, a likelihood analysis of the high-latitude ($|b| > 30°$) sky has been performed, including all resolved individual sources and a model of the Galactic interstellar emission and fitting the spectrum of the isotropic component (for details, see Ref. [63]). This means that the derived isotropic template depends on the assumed model for the Galactic interstellar emission, notably on the inverse Compton component, which is smooth and far from negligible even at high Galactic latitude. On short timescales, especially less than the ≃53.4 day precession period of the Fermi orbit, changes in the distribution of geomagnetic latitudes through which the Fermi-LAT passes cause the residual background rates to be strongly dependent on the exact orbital history of the spacecraft and on the CR spectra at different geomagnetic locations. Given uncertainties in the Galactic interstellar emission and in the residual particle background, the normalizations of the Galactic diffuse component and isotropic component were allowed to vary. We include the 2FGL sources (from the Fermi Large Area Telescope second source catalog [22]) within the ROIs in the analysis. The spectral shapes of the sources are taken from the 2FGL catalogue [22], while the normalizations and spectral parameters of strong point sources are derived from the likelihood analysis (the list of the sources with a free normalization is shown in Table II). The normalizations of fainter point sources are held fixed at the 2FGL catalogue values. In the spectral-spatial model of each system of these colliding clusters of galaxies, we fixed its position at the localization determined by x-ray observations. To make the spectral model for each system of galaxy clusters using a FileFunction template, we take the gamma-ray spectrum resulting from $p\bar{p}$ annihilation at rest from the paper by Backenstoss *et al.* [65] and compute the redshifted spectrum which might be measured by the LAT instrument. At energies where most of the photons from $p\bar{p}$ annihilation are expected, if matter-antimatter admixture is significant in these systems of colliding clusters, a pointlike source approximation is expected to be adequate (see Refs. [38,66]) (for the nearest system, Abell 754 at $z = 0.054$, a size of 1 Mpc corresponds to 0.3).

Likelihood is the joint probability of the observed data given the hypothesis and is used to quantify the relative extent to which the data supports a statistical hypothesis. A likelihood function (often the likelihood) is a function of the parameters of a statistical model. The likelihood ratio test is used for hypothesis testing. The likelihood ratio is the likelihood of the null hypothesis for the data divided by the likelihood of the alternative hypothesis for the same data. The test statistic (TS, see Ref. [67] and references therein) value is used to assess the goodness of fit, and it is defined as twice the difference between the log-likelihood function maximized by adjusting all parameters of the model, with and without the source, and under the assumption of a precise knowledge of the Galactic and extragalactic diffuse emission. The TS is employed to evaluate the significance of the gamma-ray fluxes coming from the colliding galaxy clusters. Binned likelihood analysis is applied on the data, using the Fermi Science tool (*gtlike*) released by the Fermi-LAT Collaboration. The binned likelihood uses events selected in a square inscribed inside the circular ROI, aligned with celestial coordinates. We set the energy binning to 30 logarithmic bins between 60 MeV and 60 GeV. Using the binned likelihood analysis, we found

[4] http://heasarc.gsfc.nasa.gov/FTP/fermi/data/lat/weekly/p7v6/.
[5] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Background Models.html.

TABLE II. The list of strong point sources with fluxes computed from the likelihood analysis.

Cluster	2FGL sources
1E 0657 − 558	2FGLJ0516.8 − 6207, 2FGLJ0543.9 − 5532, 2FGLJ0644.2 − 6713, 2FGLJ0700.3 − 6611, 2FGLJ0718.7 − 4320
MACS J0025.4 − 1222	2FGLJ0050.6 − 0929, 2FGLJ0034.4 − 0534, 2FGLJ2345.0 − 1553, 2FGLJ2347.9 − 1629, 2FGLJ0030.4 + 0450, 2FGLJ0108.6 + 0135, 2FGLJ0118.8 − 2142, 2FGLJ2323.6 − 0316, 2FGLJ0145.1 − 2732, 2FGLJ2258.0 − 2759
Abell 1914	2FGLJ1419.4 + 3820, 2FGLJ1425.1 + 3615, 2FGLJ1426.1 + 3406, 2FGLJ1428.6 + 4240, 2FGLJ1433.8 + 4205, 2FGLJ1438.7 + 3712, 2FGLJ1439.2 + 3932, 2FGLJ1448.0 + 3608, 2FGLJ1345.4 + 4453, 2FGLJ1522.1 + 3144, 2FGLJ1310.6 + 3222, 2FGLJ1312.8 + 4828, 2FGLJ1427.0 + 2347, 2FGLJ1253.1 + 5302
DLSCL J0916.2 + 2951	2FGLJ0910.6 + 3329, 2FGLJ0912.5 + 2758, 2FGLJ0915.8 + 2932[a],2FGLJ0924.0 + 2819, 2FGLJ0819.3 + 2750, 2FGLJ0854.8 + 2005, 2FGLJ1012.6 + 2440, 2FGLJ0818.2 + 4223, 2FGLJ0840.7 + 1310, 2FGLJ0849.8 + 4852, 2FGLJ0920.9 + 4441, 2FGLJ0946.5 + 1015, 2FGLJ1032.6 + 3733
ACT-CL J0102 − 4915	2FGLJ0030.2 − 4223, 2FGLJ0210.7 − 5102, 2FGLJ0101.2 − 6425, 2FGLJ0245.9 − 4652, 2FGLJ2327.9 − 4037, 2FGLJ2327.9 − 4037, 2FGLJ2329.2 − 4956
Abell 2744	2FGLJ0009.9 − 3206, 2FGLJ0030.2 − 4223, 2FGLJ0033.5 − 1921, 2FGLJ0044.7 − 3702, 2FGLJ2325.3 − 3557, 2FGLJ2327.9 − 4037, 2FGLJ2330.9 − 2144, 2FGLJ0118.8 − 2142, 2FGLJ0120.4 − 2700, 2FGLJ2250.8 − 2808, 2FGLJ2258.0 − 2759, 2FGLJ2345.0 − 1553, 2FGLJ0132.8 − 1654, 2FGLJ2329.2 − 4956
Abell 520	2FGLJ0423.2 − 0120, 2FGLJ0442.7 − 0017, 2FGLJ0501.2 − 0155, 2FGLJ0339.4 − 0144, 2FGLJ0505.4 + 0419
MACS J0717.5 + 3745	2FGLJ0719.3 + 3306, 2FGLJ0622.9 + 3326, 2FGLJ0654.2 + 4514, 2FGLJ0818.2 + 4223, IC443, 2FGLJ0714.0 + 1933, 2FGLJ0742.6 + 5442, 2FGLJ0751.1 + 1809, 2FGLJ0533.0 + 4823, 2FGLJ0633.9 + 1746
Abell 754	2FGLJ0856.6 − 1105, 2FGLJ0906.2 − 0906, 2FGLJ0850.2 − 1212, 2FGLJ0814.0 − 1006, 2FGLJ0816.4 − 1311, 2FGLJ0818.2 − 0935, 2FGLJ0858.1 − 1952, 2FGLJ0908.7 − 2119, 2FGLJ0909.1 + 0121, 2FGLJ0927.9 − 2041, 2FGLJ0939.1 − 1734, 2FGLJ0948.8 + 0020, 2FGLJ0953.6 − 1504, 2FGLJ0957.6 − 1350
Abell 2146	2FGLJ1518.0 + 6526, 2FGLJ1542.9 + 6129, 2FGLJ1604.6 + 5710, 2FGLJ1700.2 + 6831, 2FGLJ1437.1 + 5640, 2FGLJ1748.8 + 7006, 2FGLJ1800.5 + 7829, 2FGLJ1806.7 + 6948, 2FGLJ1454.4 + 5123

[a]2FGLJ0915.8 + 2932 is a gamma-ray source in the 2FGL catalog and is projected onto the "Musket Ball" cluster. This 2FGL source is associated with the blazar B2 0912 + 29, and its gamma-ray spectrum is well described by a power law with hard photon index. The 2FGL catalogue reports the detection of this source in 0.3–1 GeV, 1–3 GeV, 3–10 GeV, and 10–100 GeV energy bands. The spectral properties of this source allow us to disentangle the signal from this source from a possible $p\bar{p}$ annihilation signal.

that the TS values for the sources with the $p\bar{p}$ annihilation photon spectrum at the positions of the systems of colliding galaxy clusters are less than 9, which correspond to the source significance of $< 3\sigma$. Thus, none of these ten systems of colliding clusters are detected as a source with the $p\bar{p}$ annihilation photon spectrum.

C. Upper bounds on matter-antimatter admixture

We evaluate the flux upper limits by applying the binned likelihood analysis and using the spectral-spatial models described above. We derived 95% flux upper limits by fitting a point source as the positions of the systems of colliding galaxy clusters, for which we increase the flux until the maximum likelihood decreases by $2.71/2$ in logarithm. The computed flux upper limits are shown in Table III. In Fig. 1, we illustrate a behavior of the likelihood with respect to changing the hypothesis, i.e. the increase of the $p\bar{p}$ annihilation flux, for one of the selected colliding systems, Abell 520. Note that the derived upper flux limit for this colliding system is one of the highest upper limits for our selected colliding clusters. This is because the likelihood slightly (but statistically insignificantly) increases, when a faint $p\bar{p}$ annihilation source is included at the location of this system, compared with that of the "null" hypothesis. i.e., no $p\bar{p}$ annihilation source. However, the derived upper flux limit for Abell 520 is sufficiently tight to permit us to set a tight upper limit on the matter-antimatter admixture in this system.

The absence of detected gamma rays coming from the systems of colliding galaxy clusters bounds the fraction of mixed matter and antimatter in these systems. The constraints are provided by a comparison of the upper flux limit on the cluster gamma-ray flux, $F_\gamma(> 100\ \mathrm{MeV})$ ph cm^{-2} s^{-1}, to the observed cluster x-ray flux. For a galaxy cluster at a distance R, whose intracluster gas

TABLE III. Upper flux limits and upper bounds on matter-antimatter admixture derived from the August 2008–March 2012 data set.

Cluster	Upper flux limit (E > 100 MeV), ph cm^{-2} s^{-1}	Upper bounds on matter-antimatter admixture
1E 0657 − 558	1.85×10^{-9}	4×10^{-8}
MACS J0025.4 − 1222	2.14×10^{-9}	2×10^{-7}
Abell 1914	2.25×10^{-9}	2×10^{-8}
DLSCL J0916.2 + 2951	2.64×10^{-9}	2×10^{-6}
ACT-CL J0102 − 4915	7.90×10^{-9}	1×10^{-6}
Abell 2744	3.17×10^{-9}	6×10^{-8}
Abell 520	7.76×10^{-9}	8×10^{-8}
MACS J0717.5 + 3745	5.44×10^{-9}	4×10^{-7}
Abell 754	5.97×10^{-9}	7×10^{-9}
Abell 2146	4.75×10^{-9}	1×10^{-7}

fills a volume V and is at a temperature T, the x-ray and the annihilation-predicted gamma-ray fluxes are functions of the gas emission measure of $\int n_{\mathrm{B}}^2\, \mathrm{d}V$ if matter and antimatter are mixed [6,20]. The annihilation-predicted gamma-ray flux is [20]

$$F_\gamma = 5.4 \times 10^{-14} \frac{f}{\sqrt{T_8}} \frac{\int n_{\mathrm{B}}^2 dV}{4\pi R^2}, \tag{1}$$

where $T_8 = T/10^8$ K and f is the fraction of mixed matter and antimatter. The predicted bolometric x-ray flux, F_{X} erg $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, emitted via bremsstrahlung is [68]

$$F_{\mathrm{X}} = 1.4 \times 10^{-23} \sqrt{T_8} \frac{\int n_{\mathrm{B}}^2 dV}{4\pi R^2}. \tag{2}$$

To compute the predicted x-ray fluxes from the colliding galaxy clusters in the photon energy bands shown in Table I, we use the Astrophysical Plasma Emission Code (APEC) [69]. We found that the radiation via emission lines does not contribute strongly in the x-ray flux for the metal abundance values from Table I and that the equation for a bolometric x-ray flux due to bremsstrahlung that was used in Ref. [20] gives the flux value within a factor of 3. The computed upper bounds on matter-antimatter admixture in the ten systems of colliding galaxy clusters are shown in Table III. Amongst the ten systems of colliding clusters, the tightest bound on matter-antimatter admixture of 7×10^{-9} is for Abell 754, and the weakest bound of 2×10^{-6} is for DLSCL J0916.2 + 2951 (the "Musket Ball" cluster). These derived upper bounds are very tight, strongly suggesting that each of these ten systems of colliding galaxy clusters is made entirely of matter or of antimatter. If the Universe is symmetric with an equal number of large matter and antimatter islands of order ∼20 Mpc, the chance of no detection of a gamma-ray annihilation flux from the ten systems of colliding clusters is only $2^{-10} \simeq 0.001$. This is because the chance of observation of a cluster-anticluster system in a matter-antimatter-symmetric universe is 1/2. Therefore, the performed analysis allows us to exclude a symmetric universe consisting of large islands of matter and antimatter on scales of order ∼20 Mpc at the confidence level of 99.9%.

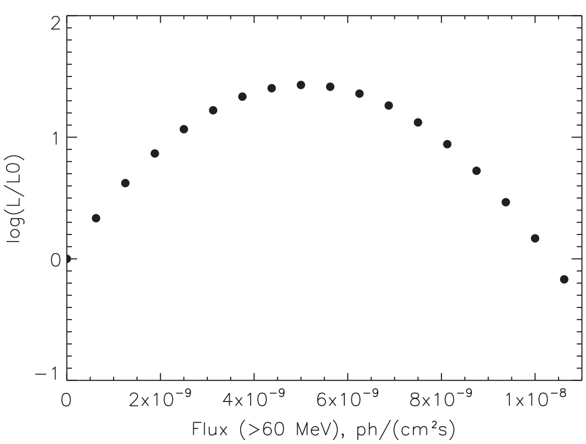

FIG. 1. Illustration of the behavior of the likelihood with respect to changing the hypothesis, i.e. the increase of the $p\bar{p}$ annihilation flux, for one of the selected colliding systems, Abell 520. $L0$ is the maximized likelihood for the "null" hypothesis.

D. Likelihood analysis of another dataset using P7REP IRFs

The result of the analysis presented above shows that the computed upper bounds on the matter-antimatter admixture in the ten systems of colliding galaxy clusters are very tight, $7 \times 10^{-9} < f < 2 \times 10^{-6}$. The presence of systematic errors can be tested with analysis of the procedure by comparing the results to other results obtained independently, using different techniques. To test the computed upper bounds on the presence of systematic uncertainties, we used the LAT data processed using Pass 7 along with updated calibration constants known as the Pass 7 reprocessed data (for details, see Ref. [70]). The corresponding P7REP_SOURCE_V15 IRFs were used to accurately

TABLE IV. Upper flux limits and upper bounds on matter-antimatter admixture derived from the July 2012–January 2015 data set.

Cluster	Upper flux limit (E > 100 MeV), ph cm^{-2} s^{-1}	Upper bounds on matter-antimatter admixture
1E 0657 − 558	4.25×10^{-9}	9×10^{-8}
MACS J0025.4 − 1222	5.49×10^{-9}	5×10^{-7}
Abell 1914	4.87×10^{-9}	4×10^{-8}
DLSCL J0916.2 + 2951	4.22×10^{-9}	3×10^{-6}
ACT-CL J0102 − 4915	7.90×10^{-9}	2×10^{-7}
Abell 2744	1.29×10^{-8}	2×10^{-7}
Abell 520	7.02×10^{-9}	7×10^{-8}
MACS J0717.5 + 3745	2.28×10^{-9}	2×10^{-7}
Abell 754	2.26×10^{-9}	3×10^{-9}
Abell 2146	3.57×10^{-9}	8×10^{-8}

represent those photons. For this data analysis, we used the Fermi Science Tools v9r33p0 package. To model the galactic diffuse foreground and extragalactic background emission, we used the templates gll_iem_v05_rev1.fit and iso_source_v05.txt provided by the Fermi-LAT team for analyses of Pass 7 reprocessed data. For this analysis, we selected the Fermi-LAT data set from 1 July 2012 to 1 January 2015. Note that this data set has not been included in the analysis presented above. To carefully treat point sources in ROIs, we additionally included the detected gamma-ray sources from the third Fermi-LAT (3FGL) catalog [71], which are not present in the 2FGL catalog, in the spectral-spatial model. We selected SOURCE events, applied data cuts, performed likelihood analyses, and derived flux upper limits by using the tools described above. The computed upper flux limits and upper bounds on matter-antimatter admixture are shown in Table IV.

The upper bounds on matter-antimatter admixture shown in Table IV are in the range of $(3 \times 10^{-9}, 3 \times 10^{-6})$ and agree with those that are derived in the previous section. Therefore, this supports the conclusion that each of the ten systems of colliding galaxy clusters is made entirely of matter or of antimatter.

IV. ARE COLLIDING GALAXY CLUSTERS IN THE FERMI-LAT SECOND SOURCE CATALOG?

A matter-antimatter-symmetric universe can potentially be excluded at a higher confidence level than that done in the previous section if the number of observed colliding cluster systems will increase. The sample of the ten systems of colliding galaxy clusters allowed us to exclude a matter-antimatter-symmetric universe consisting of large islands of matter and antimatter on scales of order ~20 Mpc at the confidence level of 99.9%. Note that the derived upper bounds on matter-antimatter admixture shown in Table III are very tight. Using the Fermi Large Area Telescope second source catalog [22] and the results of the Marenostrum Universe cosmological simulation [72], we check if a matter-antimatter-symmetric universe can be excluded at a higher confidence level.

The second source catalog [22] (the 2FGL catalog) was released by the Fermi-LAT Collaboration and contains the observed characteristics of 1873 gamma-ray sources detected during the first 24 months of the Fermi mission. The 2FGL catalog reports flux measurements in five energy bands (100–300 MeV, 300–1000 MeV, 1–3 GeV, 3–10 GeV, and 10–100 GeV). An annihilation signal produced in $p\bar{p}$ interactions can only contribute to the first two energy bands, i.e. 100–300 MeV and 300–1000 MeV. The brightest sources in the gamma-ray sky in these energy bands are Vela, Geminga, and Crab, which are young pulsars located in the Galactic plane.

Galaxy clusters are extragalactic x-ray sources, and therefore, they are uniformly distributed over the sky. Thus, if the number of systems of colliding galaxy clusters is about 50, the chance that more than 30 of them are located in 10% of the sky is only $\approx 2.4 \times 10^{-14}$. Therefore, we remove the 2FGL sources projected to the Galactic plane, $-6° < b < 6°$, from our analysis. Note that most of these removed sources are Galactic sources. The six brightest 2FGL sources after removing the 2FGL sources projected to the Galactic plane are blazars: PKS 1510 − 08, 3C 273, 4C +21.35, 3C 279, PKS 1502 + 106, and B2 1520 + 31. These sources are strongly variable in time, and their high averaged fluxes are due to flaring activity. To be conservative, we remove the regions of 10° centered on these sources from our analysis. The total surface area of these regions is about 5% of the sky. If the number of systems of colliding galaxy clusters is about 50, the chance that more than 30 of them are located in 15% of the sky (i.e. the Galactic plane + the regions of 10° around these six blazars) is only $\approx 3.7 \times 10^{-10}$. The seventh brightest source in the 2FGL catalog after subtraction of the Galactic plane is LAT PSR J1836 + 5935, which is a persistent gamma-ray source in time. Sitting 25° off the Galactic plane, PSR J1836 + 5925 is a 173 ms pulsar with a characteristic age of 1.8 million years [73]. The flux above $E > 100$ MeV from PSR J1836 + 5925 between the first and second peaks of its emission is $\approx 4.5 \times 10^{-7}$ ph cm^{-2} s^{-1}. Therefore, this flux is the highest which could possibly be associated with a system of colliding galaxy clusters in the reduced 2FGL catalog.

We use the results of a search for Bullet-like galaxy clusters in the Marenostrum Universe cosmological simulation [23] to constrain the number of systems of colliding galaxy clusters. The Marenostrum Universe cosmological simulation follows the evolution of gas and dark matter from $z = 40$ to $z = 0$ in a comoving cube of $500h^{-1}$ Mpc on a side. The Hubble parameter $h = 0.7$. The number of galaxy clusters with $M > 10^{14}h^{-1}M_{\odot}$ at redshift $z = 0.3$ is $N = 2662$ (see Table 1 in Ref. [23]). Using Eq. 1 from Ref. [23], we compute the number of Bullet-like systems with an 2D displacement between gas and dark matter peaks of > 180 kpc as $P_{2D} \times N \approx 80$, where $P_{2D} \approx 3\%$ is a cumulative distribution of 2D displacement of gas and dark matter peaks. The displacement of 180 kpc corresponds to that in MACS J0025.4 − 1222 (the "baby Bullet" cluster). Note that 80 systems of Bullet-like clusters is a very conservative estimate, because the comoving volume available from $z = 0$ to $z = 0.3$ over the full sky is about 20 times larger than the simulated box. Using the luminosity-mass relation [74] for galaxy clusters, we took the x-ray luminosity for a galaxy cluster with a mass of $10^{14}M_{\odot}$. Applying this x-ray luminosity value and noting that there are no systems with an annihilation flux exceeding that of PSR J1836 + 5925, we found no system of colliding clusters with a matter-antimatter admixture of $f \gtrsim 10^{-4}$. The chance of observation of a cluster-anticluster system in a matter-antimatter-symmetric universe is 1/2, and therefore, no observation of a $p\bar{p}$ annihilation signal from $\simeq 80$ systems of colliding galaxy clusters has a negligible probability of $2^{-80} \sim 10^{-24}$. Therefore, we conclude that a matter-antimatter-symmetric universe is ruled out on scales of order ∼20 Mpc based on the absence of possible gamma-ray $p\bar{p}$ annihilation source candidates associated with systems of colliding clusters if a matter-antimatter admixture in these systems exceeds $f \gtrsim 10^{-4}$.

More stringent constraints on a matter-antimatter-symmetric universe can be obtained if we extrapolate the number of Bullet-like systems of galaxy clusters from the simulated box to the comoving volume available from $z = 0$ to $z = 0.3$, which is about 20 times larger. Thus, the extrapolated number of Bullet-like systems is about 1600. If the Universe is matter-antimatter-symmetric, the number of systems consisting of colliding matter and antimatter clusters would be about $N_{tot} \approx 800$. Using the 2FGL catalog and excluding the 2FGL sources projected to the Galactic plane, $-6° < b < 6°$, we found that the summed fluxes in the first two energy bands for the ≈300 brightest sources in the reduced catalog exceed 4×10^{-8} ph cm^{-2} s^{-1}. However the fluxes for other sources are lower. Therefore, gamma-ray fluxes from at least 500 systems of colliding matter and antimatter clusters must not exceed this flux limit. Performing the computation similarly to that in the previous paragraph, we found that a matter-antimatter-symmetric universe is ruled out on scales of order ∼20 Mpc if a matter-antimatter admixture in these Bullet-like systems is of $f \gtrsim 10^{-5}$.

The extrapolation of the number of Bullet-like systems to the larger volume can also be used to rule out a matter-antimatter-symmetric universe on larger scales than 20 Mpc. Assuming that colliding clusters of galaxies are uniformly distributed in a matter-antimatter-symmetric universe and that a characteristic size of matter and antimatter islands in this universe is L, the number of colliding matter and antimatter galaxy clusters at borders between matter and antimatter islands is $\simeq N_{tot}d/L$, where $2N_{tot} \approx 1600$ is the total number of the systems of colliding (anti)clusters in this Universe and $d \simeq 10$ Mpc is the distance at which matter and antimatter galaxy clusters begin to attract each other via the gravitational force. The number of Bullet-like systems of matter and antimatter galaxy clusters at island borders is, therefore, about $800 \times 10/400 \simeq 20$ if the characteristic size of matter and antimatter islands is $L = 400$ Mpc. Noting that there are no systems with an annihilation flux exceeding that of PSR J1836 + 5925 in the reduced 2FGL catalog, a matter-antimatter-symmetric universe is ruled out on scales of order ∼400 Mpc if a matter-antimatter admixture in the Bullet-like systems is of $f \gtrsim 10^{-4}$.

The upcoming extended Roentgen Survey with an Imaging Telescope Array (eROSITA) will be very important to reveal numerous systems of colliding galaxy clusters, and therefore, to verify the simulated number of Bullet-like systems in the Universe. By detecting numerous systems of colliding galaxy clusters, eROSITA will provide us with a firm proof that a matter-antimatter-symmetric universe is observationally ruled out on scales of 10–500 Mpc by means of the method initially proposed by Steigman [20] and developed in this paper.

V. CONCLUSIONS

In this paper, we examined whether significant constraints on matter-antimatter admixture can be placed from gamma-ray observations of colliding clusters of galaxies with Fermi-LAT. We selected ten known systems of colliding clusters of galaxies for the analysis. We included a source with the $p\bar{p}$ annihilation photon spectrum at the positions of the systems of colliding galaxy clusters in the spectral-spatial models and performed the binned likelihood analysis. The performed likelihood analysis showed no detection of a $p\bar{p}$ annihilation signal from these systems of colliding clusters. Therefore, we derived the upper flux limit for each of these systems. Using the derived upper flux limits, we set the upper bounds on matter-antimatter admixture, which range from 7×10^{-9} to 2×10^{-6}. This allowed us to exclude a symmetric universe consisting of large islands of matter and antimatter on scales of order ~20 Mpc at the confidence level of 99.9%.

Our derived upper bounds on matter-antimatter admixture for the ten selected systems are very tight. Therefore, if the number of observed colliding cluster systems increases, it will allow us to exclude a matter-antimatter-symmetric universe at a higher confidence level. The Marenostrum Universe cosmological simulation [72] results in a significant number of systems of colliding galaxy clusters [23]. Adopting the number of simulated systems of colliding galaxy clusters, we checked if the Fermi Large Area Telescope second source catalog [22] contains the sufficient number of gamma-ray sources to provide us with the required number of sources possibly associated with $p\bar{p}$ annihilation from cluster-anticluster collisions. We checked and found that a matter-antimatter-symmetric universe is strongly ruled out on scales of order ~20 Mpc if a matter-antimatter admixture in these Bullet-like systems is of $f \gtrsim 10^{-5}$ and on scales of order ~400 Mpc if a matter-antimatter admixture in the Bullet-like systems is of $f \gtrsim 10^{-4}$. If the upcoming extended Roentgen Survey with an Imaging Telescope Array reveals numerous systems of colliding galaxy clusters predicted by the Marenostrum Universe cosmological simulation, a matter-antimatter-symmetric universe will observationally be ruled out on scales of 10–500 Mpc by the method initially proposed by Steigman [20] and developed in this paper.

[1] E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley, Reading, MA, 1990).
[2] Particle Data Group, Phys. Lett. B **667**, 1 (2008).
[3] G. Lüders and B. Zumino, Phys. Rev. **106**, 385 (1957).
[4] T. D. Lee, R. Oehme, and C. N. Yang, Phys. Rev. **106**, 340 (1957).
[5] V. Barger, J. P. Kneller, H.-S. Lee, D. Marfatia, and G. Steigman, Phys. Lett. B **566**, 8 (2003).
[6] G. Steigman, Annu. Rev. Astron. Astrophys. **14**, 339 (1976).
[7] A. D. Sakharov, JETP Lett. **5**, 24 (1967).
[8] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, Phys. Lett. **155B**, 36 (1985).
[9] M. Dine and A. Kusenko, Rev. Mod. Phys. **76**, 1 (2003).
[10] P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday *et al.* (Planck Collaboration), Astron. Astrophys. **571**, A24 (2014).
[11] P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday *et al.* (Planck Collaboration), Astron. Astrophys. **571**, A16 (2014).
[12] P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday *et al.* (Planck Collaboration), Astron. Astrophys. **571**, A22 (2014).
[13] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, and LEP Working Group For Higgs Boson Searches, Phys. Lett. B **565**, 61 (2003).
[14] G. Aad, T. Abajyan, B. Abbott, J. Abdallah, S. Abdel Khalek, A. A. Abdelalim, O. Abdinov, R. Aben, B. Abi, M. Abolins *et al.*, Phys. Lett. B **716**, 1 (2012).
[15] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan *et al.*, Phys. Lett. B **716**, 30 (2012).
[16] M. Dine, arXiv:hep-ph/9612389.
[17] A. D. Dolgov, arXiv:hep-ph/9605280.
[18] A. G. Cohen, A. De Rújula, and S. L. Glashow, Astrophys. J. **495**, 539 (1998).
[19] S. C. Kappadath, Ph.D. thesis, University of New Hampshire, 1998.
[20] G. Steigman, J. Cosmol. Astropart. Phys. 10 (2008) 001.
[21] W. B. Atwood, A. A. Abdo, M. Ackermann, W. Althouse, B. Anderson, M. Axelsson, L. Baldini, J. Ballet, D. L. Band, G. Barbiellini *et al.*, Astrophys. J. **697**, 1071 (2009).
[22] P. L. Nolan, A. A. Abdo, M. Ackermann, M. Ajello, A. Allafort, E. Antolini, W. B. Atwood, M. Axelsson, L. Baldini, J. Ballet *et al.*, Astrophys. J. Suppl. Ser. **199**, 31 (2012).
[23] J. E. Forero-Romero, S. Gottlöber, and G. Yepes, Astrophys. J. **725**, 598 (2010).
[24] R. Duperray, B. Baret, D. Maurin, G. Boudoul, A. Barrau, L. Derome, K. Protasov, and M. Buénerd, Phys. Rev. D **71**, 083013 (2005).
[25] K. Abe, H. Fuke, S. Haino, T. Hams, M. Hasegawa, A. Horikoshi, A. Itazaki, K. C. Kim, T. Kumazawa, A. Kusumoto *et al.*, Phys. Rev. Lett. **108**, 131301 (2012).
[26] A. G. Mayorov, A. M. Galper, O. Adriani, G. A. Bazilevskaya, G. Barbarino, R. Bellotti, M. Boezio, E. A. Bogomolov, V. Bonvicini, M. Bongi *et al.*, JETP Lett. **93**, 628 (2011).
[27] R. Hagedorn, Cargese Lectures in Physics **6**, 643 (1973).
[28] M. Cristinziani, Nucl. Phys. B, Proc. Suppl. **114**, 275 (2003).
[29] F. W. Stecker, Cosmic Gamma Rays, NASA Publication No. SP 249 (1971).
[30] O. Reimer, M. Pohl, P. Sreekumar, and J. R. Mattox, Astrophys. J. **588**, 155 (2003).
[31] A. C. Edge, G. C. Stewart, A. C. Fabian, and K. A. Arnaud, Mon. Not. R. Astron. Soc. **245**, 559 (1990).
[32] P. von Ballmoos, Hyperfine Interact. **228**, 91 (2014).
[33] M. Ackermann, M. Ajello, A. Allafort, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini, R. D. Blandford *et al.*, Astrophys. J. Lett. **717**, L71 (2010).

[34] V. Schoenfelder, F. Graml, and F.-P. Penningsfeld, Astrophys. J. **240**, 350 (1980).
[35] A. de Rujula, in *Very High Energy Phenomena in the Universe: Proceedings of the 22nd Moriond Workshop*, edited by Y. Giraud-Heraud and J. Tran Thanh Van (Les Arcs, France, 1997), p. 363.
[36] C. L. Sarazin, Rev. Mod. Phys. **58**, 1 (1986).
[37] M. Markevitch, A. H. Gonzalez, L. David, A. Vikhlinin, S. Murray, W. Forman, C. Jones, and W. Tucker, Astrophys. J. Lett. **567**, L27 (2002).
[38] A. A. Abdo, M. Ackermann, M. Ajello, W. B. Atwoo, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini *et al.*, Astrophys. J. **758**, 140 (2012).
[39] M. Ackermann, M. Ajello, A. Allafort, L. Baldini, J. Ballet, G. Barbiellini, M. G. Baring, D. Bastieri, K. Bechtol, R. Bellazzini *et al.*, Science **339**, 807 (2013).
[40] P. F. Michelson, W. B. Atwood, and S. Ritz, Rep. Prog. Phys. **73**, 074901 (2010).
[41] M. Ackermann, M. Ajello, A. Albert, A. Allafort, W. B. Atwood, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, K. Bechtol *et al.*, Astrophys. J. **787**, 18 (2014).
[42] B. Huber, C. Tchernin, D. Eckert, C. Farnier, A. Manalaysay, U. Straumann, and R. Walter, Astron. Astrophys. **560**, A64 (2013).
[43] D. A. Prokhorov and E. M. Churazov, Astron. Astrophys. **567**, A93 (2014).
[44] M. Markevitch, F. Govoni, G. Brunetti, and D. Jerius, Astrophys. J. **627**, 733 (2005).
[45] R. A. Krivonos, A. A. Vikhlinin, M. L. Markevitch, and M. N. Pavlinsky, Astron. Lett. **29**, 425 (2003).
[46] G. Macario, M. Markevitch, S. Giacintucci, G. Brunetti, T. Venturi, and S. S. Murray, Astrophys. J. **728**, 82 (2011).
[47] H. R. Russell, B. R. McNamara, J. S. Sanders, A. C. Fabian, P. E. J. Nulsen, R. E. A. Canning, S. A. Baum, M. Donahue, A. C. Edge, L. J. King *et al.*, Mon. Not. R. Astron. Soc. **423**, 236 (2012).
[48] F. Menanteau, J. P. Hughes, C. Sifón, M. Hilton, J. González, L. Infante, L. F. Barrientos, A. J. Baker, J. R. Bond, S. Das *et al.*, Astrophys. J. **748**, 7 (2012).
[49] F. Govoni, M. Markevitch, A. Vikhlinin, L. van Speybroeck, L. Feretti, and G. Giovannini, Astrophys. J. **605**, 695 (2004).
[50] D. Clowe, M. Bradač, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, and D. Zaritsky, Astrophys. J. Lett. **648**, L109 (2006).
[51] M. Bradač, S. W. Allen, T. Treu, H. Ebeling, R. Massey, R. G. Morris, A. von der Linden, and D. Applegate, Astrophys. J. **687**, 959 (2008).
[52] W. A. Dawson, D. Wittman, M. J. Jee, P. Gee, J. P. Hughes, J. A. Tyson, S. Schmidt, P. Thorman, M. Bradač, S. Miyazaki *et al.*, Astrophys. J. Lett. **747**, L42 (2012).
[53] J. Merten, D. Coe, R. Dupke, R. Massey, A. Zitrin, E. S. Cypriano, N. Okabe, B. Frye, F. G. Braglia, Y. Jiménez-Teja *et al.*, Mon. Not. R. Astron. Soc. **417**, 333 (2011).
[54] J. Sayers, T. Mroczkowski, M. Zemcov, P. M. Korngut, J. Bock, E. Bulbul, N. G. Czakon, E. Egami, S. R. Golwala, P. M. Koch *et al.*, Astrophys. J. **778**, 52 (2013).
[55] W. Tucker, P. Blanco, S. Rappoport, L. David, D. Fabricant, E. E. Falco, W. Forman, A. Dressler, and M. Ramella, Astrophys. J. Lett. **496**, L5 (1998).
[56] H. Ebeling, E. Barrett, D. Donovan, C.-J. Ma, A. C. Edge, and L. van Speybroeck, Astrophys. J. Lett. **661**, L33 (2007).
[57] H. Ebeling, A. C. Edge, H. Bohringer, S. W. Allen, C. S. Crawford, A. C. Fabian, W. Voges, and J. P. Huchra, Mon. Not. R. Astron. Soc. **301**, 881 (1998).
[58] H. Ebeling, A. C. Edge, A. Mantz, E. Barrett, J. P. Henry, C. J. Ma, and L. van Speybroeck, Mon. Not. R. Astron. Soc. **407**, 83 (2010).
[59] B. J. Maughan, C. Jones, W. Forman, and L. Van Speybroeck, Astrophys. J. Suppl. Ser. **174**, 117 (2008).
[60] D. Eckert, S. Molendi, and S. Paltani, Astron. Astrophys. **526**, A79 (2011).
[61] H. R. Russell, J. S. Sanders, A. C. Fabian, S. A. Baum, M. Donahue, A. C. Edge, B. R. McNamara, and C. P. O'Dea, Mon. Not. R. Astron. Soc. **406**, 1721 (2010).
[62] H. R. Russell, R. J. van Weeren, A. C. Edge, B. R. McNamara, J. S. Sanders, A. C. Fabian, S. A. Baum, R. E. A. Canning, M. Donahue, and C. P. O'Dea, Mon. Not. R. Astron. Soc. **417**, L1 (2011).
[63] M. Ackermann, M. Ajello, A. Albert, A. Allafort, W. B. Atwood, M. Axelsson, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri *et al.*, Astrophys. J. Suppl. Ser. **203**, 4 (2012).
[64] M. Ajello, A. Albert, A. Allafort, L. Baldini, G. Barbiellini, D. Bastieri, R. Bellazzini, E. Bissaldi, E. Bonamente, T. J. Brandt *et al.*, Astrophys. J. **789**, 20 (2014).
[65] G. Backenstoss, M. Hasinoff, P. Pavlopoulos, J. Repond, L. Tauscher, D. Tröster, P. Blüm, R. Guigas, H. Koch, M. Meyer *et al.*, Nucl. Phys. **B228**, 424 (1983).
[66] G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini, R. D. Blandford, A. W. Borgland, J. Bregeon, P. Bruel, R. Buehler, S. Buson *et al.*, Astrophys. J. **784**, 118 (2014).
[67] J. R. Mattox, D. L. Bertsch, J. Chiang, B. L. Dingus, S. W. Digel, J. A. Esposito, J. M. Fierro, R. C. Hartman, S. D. Hunter, G. Kanbach *et al.*, Astrophys. J. **461**, 396 (1996).
[68] G. B. Rybicki and A. P. Lightman, *Radiative Processes in Astrophysics* (John Wiley & Sons, New York, 1979).
[69] R. K. Smith, N. S. Brickhouse, D. A. Liedahl, and J. C. Raymond, Astrophys. J. Lett. **556**, L91 (2001).
[70] J. Bregeon, E. Charles, and M. Wood (Fermi-LAT Collaboration), arXiv:1304.5456.
[71] M. Ackermann, M. Ajello, W. Atwood, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, J. Gonzalez, R. Bellazzini, E. Bissaldi *et al.*, arXiv:1501.06054.
[72] S. Gottlöber and G. Yepes, Astrophys. J. **664**, 117 (2007).
[73] A. A. Abdo, M. Ackermann, M. Ajello, W. B. Atwood, L. Baldini, J. Ballet, G. Barbiellini, M. G. Baring, D. Bastieri, K. Bechtol *et al.*, Astrophys. J. **712**, 1209 (2010).
[74] A. Mantz, S. W. Allen, H. Ebeling, D. Rapetti, and A. Drlica-Wagner, Mon. Not. R. Astron. Soc. **406**, 1773 (2010).