

Search for Dark Matter Annihilation in M5

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Daniel Jackson, Jodi Christiansen

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Contents

I. Abstract	3
II. Introduction	3
III. Theory	4
A. The Globular Cluster M5	4
B. Dark Matter in Galaxies	5
C. Dark Matter in Clusters	8
D. The Nature of Dark Matter	10
IV. The Apparatus & Observations	12
A. VERITAS	12
VI. Analysis	16
A. VEGAS	16
B. Data	17
C. VEGAS configurations/cuts	19
V. Results	19
VII. Conclusion	24
VIII. References	25

I. Abstract

We analyzed the Messier 5 (M5) globular cluster for dark matter annihilation using data from VERITAS (Very Energetic Radiation Imaging Telescope Array System) to improve the flux upper limit previously done by Michael McCutcheon. We used updated software and lower energy thresholds. VERITAS consists of four ground-based gamma-ray telescopes located at the Fred Lawrence Whipple Observatory in southern Arizona. Thirty-five 20 minute observations of M5 from VERITAS are used in our analysis. The observations were collected from February to March in 2009, for a total exposure time of 10.63 hours. Gamma-rays from dark matter annihilation were not found, but better upper limits than were reported in a previous analysis. For the standard VERITAS analysis, a statistical upper limit of 9.96 photons was found. For the lower energy soft analysis, a statistical upper limit of 21.2 photons was found. Rolke 95% confidence interval bounded limits were found but are preliminary.

II. Introduction

Evidence for dark matter is very strong. Observations of gravitational lensing and the velocity profiles of spiral galaxies are impossible to understand without it. Dark matter does not absorb, emit, or scatter light of any wavelength, and has only been seen by its gravitational influence. Dark matter accounts for 23% of the universe, ordinary matter only takes up 4.6%, and the rest of the universe consists of dark energy. Because such a large percent of the universe is made of dark matter, it is essential for cosmology and the history of the universe. Since dark matter does not interact with normal matter in the classical sense, it has so far avoided direct detection. It is theorized that dark matter is a neutralino. A neutralino is a weakly interacting massive particle (WIMP), and is its own

anti-particle. When the neutralino self-annihilates, very high gamma rays may be emitted. VERITAS can detect very high energy gamma rays, and one of its goals is to detect dark matter. M5 is an ideal candidate for dark matter detection because it is close by, is believed to have a large amount of dark matter, and does not contain any other sources of gamma-rays.

Michael McCutcheon has already analyzed M5 for VERITAS, and found no dark matter. He established a flux limit above an energy threshold of 600 GeV and $2.92\text{E-}09 \text{ m}^{-2} \text{ s}^{-1}$ for a photon index of -2.5. Our goal was to reanalyze the data with updated software and lower the energy threshold, to either find dark matter or improve the limits.

III. Theory

A. The Globular Cluster M5

Messier 5 (M5) was discovered by the German astronomer Gottfried Kirch in 1702 while he was observing a comet on a clear night. Although faint, it can be seen with the naked eye. Globular clusters are collections of old stars bound together by gravity. M5 is a globular cluster located in the constellation Serpens. It is 13 billion years old, is 24.5 kly away from earth, with a visual brightness of 5.6 magnitude, a radius of 80 light years, and an apparent dimension of 23.0 arc minutes. There are 105 stars of variable brightness, and a dwarf nova has been observed in M5.

M5 is an excellent candidate for detecting dark matter. Orbital interactions of stars in globular clusters show evidence for relatively large densities of dark matter. There is also no black hole in the center of M5 that would cause gamma-ray emission

which could be confused with gamma-rays produced by dark matter annihilations. There are no pulsars in M5 and since M5 is 13 billion years old, there is also no current star formation to produce gamma-rays. Any gamma-rays detected can therefore be assumed to come from dark matter annihilation. The Figure 1 below shows a picture of M5.



Figure 1: Messier 5 by the Hubble Space Telescope.

B. Dark Matter in Galaxies

We call dark matter nonbaryonic matter because it does not absorb, emit, or scatter light of any wavelength. Large amounts of dark matter have been observed through galaxy rotation measurements, galaxy cluster dynamics, and gravitational lensing. All of these methods observe the gravitational influence on visible matter. One method is looking at the orbital speeds of stars in spiral galaxies. Spiral galaxies consist of a flat rotating disk containing stars, gas, and dust, and a central concentration of stars. The galaxy is surrounded by a fainter halo of stars. Examples of spiral galaxies are our

own Milky Way, Whirlpool, and Andromeda. Within the disk, the stars are on a nearly circular orbit around the center of the galaxy.

For a circular orbit, the velocity of an object in orbit like a star can be calculated by

$$v = \sqrt{\frac{Gm(r)}{r}}$$

where v is the velocity of the object, G is the gravitational constant ($6.67428 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$), r is the radius of the orbit, and m is the mass of the star as a function of the radius. For a spiral galaxy, once you are far from the center, the mass of the stars becomes essentially constant. Since G and $m(r)$ are constant, the velocity of the star becomes proportional to $1/\sqrt{r}$ for large radii.

In order to calculate the mass of a spiral galaxy we need its velocity relative to the galaxies own center of mass. When we observe a galaxy we see the velocity relative to earth, and we often see the galaxy at an inclination angle. Simple geometry can help us solve for the spiral galaxies true velocity. Redshift and blueshift spectral observations can determine the orbital speed of stars within spiral galaxies by observing edge on galaxies. Since we do not see the spiral galaxy perfectly edge on, but at an inclination, we will see elliptical projection of the galaxy with a ratio of the semimajor axis and semiminor axis of

$$\frac{b}{a} = \cos \theta_i$$

where b is the semiminor axis, a is the semimajor axis, and θ_i is the angle between our line of sight to the galaxy and the line perpendicular to the galaxy. By measuring the absorption or emission lines of the galaxy for $\theta_i \approx 90^\circ$, the radial velocity along the apparent long axis of the galaxy can be determined. The redshift will only contain stars in our line of sight, so the radial velocity measured will be

$$v_{radial}(r) = v_{galaxy} + v_{orbital}(r) \sin i$$

where v_{galaxy} is the velocity of the galaxy as a whole from the expansion of the universe, and $v_{orbital}(r)$ is the orbital speed of the galaxy. The above equation can be rearranged to get the orbital speed of the galaxy to be

$$v_{orbital}(r) = \frac{v_{radial} - v_{galaxy}}{\sin i} = \frac{v_{radial} - v_{galaxy}}{\sqrt{1 - \frac{b^2}{a^2}}}.$$

We now have an expression for the theoretical velocity of a spiral galaxy and a way to get the velocity from observation. A graph of the theoretical velocity versus the

observed velocity for NGC3198 can be seen below in Figure 2.

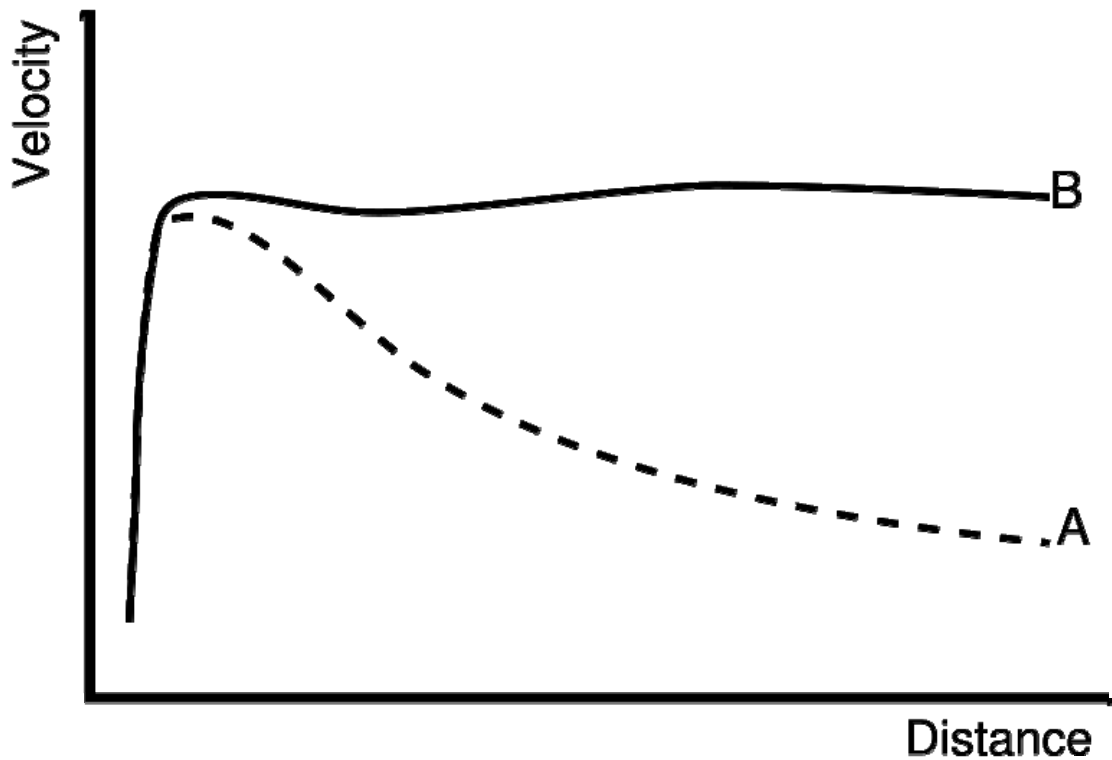


Figure 2: The theoretical velocity (A) and observed velocity (B) for spiral galaxies

As one can see from the graph, the velocity for large radii remains constant, and does not drop off as theory predicts. Since the speed of the stars is greater than it would be if only stars and galaxies were present, we conclude from this that there is a large amount of dark matter at larger radii than we can observe with star spectra. Thousands of spiral galaxies have had their velocities measured, and they all follow this pattern. From these observations it has been concluded that dark matter is five times denser than normal matter.

C. Dark Matter in Clusters

The steady state viral theorem states that

$$K = -\frac{PE}{2}$$

where K is the kinetic energy and PE is the potential energy. For a cluster of galaxies, the potential energy is

$$PE = -\alpha \frac{GM^2}{r_h}$$

where M is the mass of all the galaxies in the cluster, α is the order of unity and depends on the density, and r_h is the half-mass radius. The half mass radius is the radius from the center of mass that contains half the mass of the cluster. For most galaxy clusters, $\alpha \approx 0.4$. Plugging in this potential energy and the standard Newtonian definition of kinetic energy into the viral theorem, the mass of a cluster of galaxies can be expressed as

$$M = \frac{\langle v^2 \rangle r_h}{\alpha G}$$

where $\langle v^2 \rangle$ is the three-dimensional mean square velocity. Solving for the mass for the Coma cluster, it is found that only three percent of the cluster consist of stars and ten percent consists of hot intracluster gas that emits x-rays. The rest of the mass is dark matter. If there was no dark matter the intracluster gas would escape the cluster, but it is held inside by the gravitational pull of dark matter. Other clusters mass has also been estimated with the viral theorem and found to have large amounts of dark matter.

Gravitaitonal lensing was first observed in 1979 in the Twin QSO" SBS 0957+56. Gravitational lensing occurs when light from a distant source is bent around a massive

cluster; it is a prediction of Einstein's general theory of relativity. Evidence of dark matter is easily observed through gravitational lensing by clusters. The figure below shows the arcing of blue background galaxies when their light is bent around the massive cluster. The mass of the clusters can be estimated by how much the background galaxies are lensed. Only 1% of the mass needed for this gravitational lensing is visible matter. The rest is from dark matter.



Figure 3:In this picture from the Hubble Telescope, Abell 1689 cluster of yellow galaxies is so massive that the bluer galaxies which lie behind the cluster are distorted by gravitational lensing. Only 1% of the mass needed for this gravitational lensing is visible matter. The rest is from dark matter.

Photo courtesy of NASA/ESA/ACS Science Team

D. The Nature of Dark Matter

The matter that you and I are familiar with and interact with everyday is made of quarks and leptons and we refer to this as baryonic matter. Dark matter is a new kind of matter that is nonbaryonic and only interacts weakly, so that it doesn't form structures

like atoms, molecules, and solids. The density of dark matter is five times greater than regular baryonic matter. Dark matter accounts for 23% of the universe, and ordinary matter accounts for only 4.6% of the universe. The rest of the universe consists of dark energy.

The leading theory for dark matter proposes weakly interactive massive particle (WIMP). Candidates include neutralinos, neutrons, and kaluza-klein dark matter. Other dark matter theories involve T-odd particles in little Higgs theories and excited states in extra warped dimensions. WIMPs are thermal relics of the early universe, and have a cross section on the weak scale. WIMPs have the right density for dark matter and help explain a flat universe. The predicated WIMP candidates are neutralinos for super symmetry and Kaluza-Klein particles in theories with extra dimensions.

Neutralinos are their own anti-particle, and self annihilate. Their self annihilation produces gamma rays that are expected to be different from the standard power-law that most very high energy gamma ray sources exhibit. A neutralino self annihilation would have a unique spectral index. Neutralinos are predicted to have masses in the range of a few GeV/c^2 to a few TeV/c^2 .

Astrophysical objects with high dark matter densities are the natural choice for dark matter annihilation. Spherical dwarf galaxies in the Milky Way are ideal targets because they are nearby and their dark matter profiles have been derived from kinematics. The lack of star formation in spherical dwarf galaxies also makes them ideal candidates. Other sources like the cores of galaxies have unknown dark matter profiles with central black holes that could produce gamma-rays as they accrete matter.

IV. The Apparatus & Observations

A. VERITAS

VERITAS (Very Energetic Radiation Imaging Telescope Array System) is a ground-based gamma-ray telescope array located at the Fred Lawrence Whipple Observatory in southern Arizona. The array consists of four 12 meter optical reflectors used for gamma-ray astronomy in the GeV – TeV energy range. The VERITAS collaboration consists of several Universities and research groups. Funding for the project comes from the Department of Energy, The Smithsonian Astrophysical Observatory, the National Science Foundation, the Natural Sciences and Engineering Research Council, Science Foundation Ireland, and the Science & Technology Facilities Council. VERITAS complements the NASA Fermi mission. A picture of VERITAS is shown below in Figure 4.



Figure 4: VERITAS observatory in southern Arizona

Many astrophysical objects, such as active galactic nuclei, galactic supernova remnants, pulsars, globular clusters, galaxies, and gamma-ray bursts are known to produce high-energy gamma-ray photons. Leptonic or hadronic matter accelerated to

relativistic speeds produce gamma-rays through inverse Compton scattering or through the decay of neutral pions produced by hadronic interactions. Gamma-ray fluxes decrease drastically with increasing energy, so a much larger collection area is required to measure gamma rays above 30 GeV. Effective collective areas of 10^5 m^2 can be achieved by using Atmospheric Cherenkov detectors by using the Earth's atmosphere as a fundamental part of the detection technique.

A high energy gamma-ray incident upon the Earth's atmosphere produces a particle shower. The particles in the shower are charged with relativistic energies, and produce Cherenkov radiation (ultraviolet or blue) emitted along the shower direction. This creates a light pool on the ground with a radius of about 130 m. The largest emission occurs at about 10km where the cascade is the largest. Photons are scattered and absorbed by the atmosphere, and light at the telescope peaks at a wavelength of 300-350 nm. The photon density is about 100 photons/ m^2 and creates a nanosecond flash that can be detected from any point in the light pool using large reflective surfaces to focus the light onto photon detectors. A camera with a 499 photomultiplier tubes placed at the focus of the reflector record an image of each shower. The shape and orientation of these images are used to differentiate between gamma-ray photon events from the cosmic-ray background. The photon energy and directions on arrival are also determined. Within a telescope array, the source position is the intersection point of the images from each telescope. This detection process can be seen in the figure below.

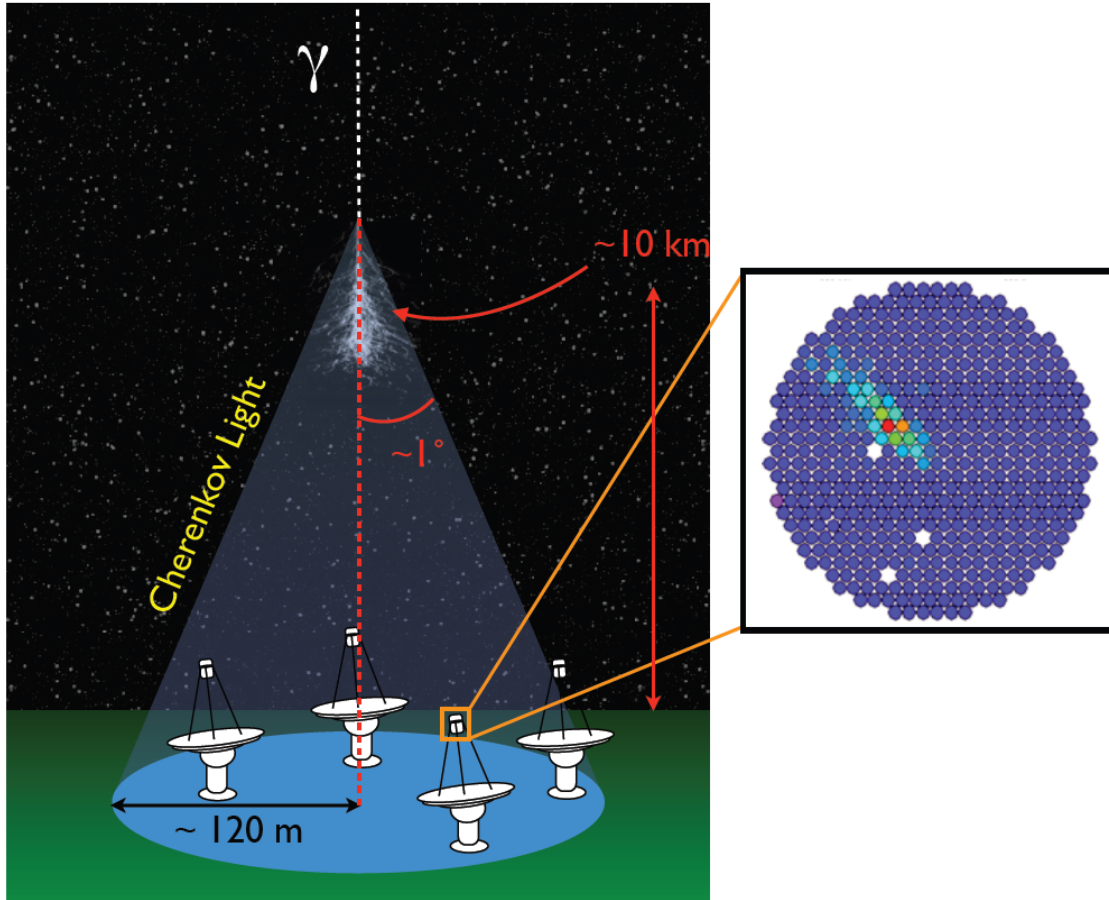


Figure 5: Gamma-ray Detection by VERITAS

VERITAS uses Cherenkov telescopes described above. The energy range of reconstructed showers in VERITAS is 100 GeV to 30 TeV. The energy resolution is 15% at 1 TeV, and the peak effective area is 100,000 m². The angular resolution is 0.1 degrees at 1 TeV, and 0.14 degrees at 200 GeV. The source location accuracy is 50 arcseconds, and the point source sensitivity is 10% of the Crab nebula in 45 minutes. These numbers are true for VERITAS before July 2009 when the first telescope was moved to improve the sensitivity of the telescope by about 20%.

VERITAS observes about 740 non-moonlight hours per year if weather permits, and 200 hours during moonlight. Typically 70-100 hours per month are observed over 10

months. VERITAS only observes during clear, dark skies. Observations are not possible under very cloudy or rainy conditions. Observations can be made when the moon is less than half full, but the observatory shuts down 6 days every month around full moon. During July and August observations are not made because of monsoon weather conditions. VERITAS is located near Tucson, Arizona at $+31^{\circ} 40' 30.21''$, $-110^{\circ} 57' 7.77''$ with an altitude of 4159 ft. The array works best for sources at high elevations because observations made below 60 degrees have increased atmospheric absorption that results in reduced sensitivity and a higher energy threshold. Thus VERITAS sources are mainly limited to declinations of 0 degrees to 40 degrees.

To record shower events, VERITAS employs three levels of triggers, A CFD, L2, and L3 triggers that deny signals through the hardware if the conditions are not met. The CFD trigger has an energy threshold of -48 to -70 mV depending on L2 multiplicity. The L2 trigger is the trigger for the individual telescopes. The main options for L2 are the trigger multiplicity and the pattern trigger level. The multiplicity is the minimum number of pixels needed for a trigger. The pattern trigger level sets an adjacency requirement for an event trigger. The pattern trigger level can be set for 2,3, or 4, and sets how many adjacent phototubes need to detect an event. The L3 trigger is the array trigger. It takes the output of all 4 telescopes to determine if there is a coincidence. The coincidence multiplicity, which ranges from 1-4, determines how many telescopes have to see a signal. If the multiplicity is 1, the system will trigger on any one L2 event. For example, if T1 L2 or T2 L2 or both are triggered, the system will trigger. There is also a coincidence window, which is the window in which one even seen by two different telescopes is considered the same event. The coincidence window can be set from 0-125

nanosecond in 1.25 nanosecond increments. The L3 trigger is also adjusted for the L2 delays. It takes different amounts of time for each trigger to make it to the L3 hardware, and this delay is accounted for.

VI. Analysis

A. VEGAS

The VERITAS collaboration has developed the VERITAS Gamma-ray Analysis Suite (VEGAS) to analyze sources from single and multiple telescopes. The software was written in C++ to be configurable by the user. VEGAS uses CERN's data-analysis framework ROOT and runs on UNIX based operating systems. The package consists of Stages 1 through Stage 6.

Stage 1 uses the laser run to calculate the hardware dependent calibration quantities. VERITAS VBF data, recorded by the online system and calculates the pixel, telescope, and array information. This stage then saves the information in the ROOT format for access by the other stages. The rest of the stages may then proceed without access to the database since stage 1 has collected all related array information from the database.

Stage 2 and stage 3 are one combined process that identifies shower images in each telescope and generates hardware independent parameterized events. It then computes the background level for all PMTs and subtracts this from islands of single pixels. The input is the ROOT file from stage 1. The output is written to the same ROOT file. Stage 3 treats each telescope individually and generates analysis parameters for each

camera. The input is the ROOT file from stage 2. This stage produces Hillas parameters for each telescope event image. This output file can be used as input to stage 4 or stage 6.

Stage 4 brings together the data from each telescope and puts them together to measure the gamma-ray energy location and angle. Measurements of right ascension, declination, azimuth, and elevation are determined. It then calculates the shower direction, and core location. It then gets the energies from the lookup tables. Lookup tables are provided at the UCLA repository. There is VERITAS code to produce your own lookup tables to determine the energy. It then calculates the theta square and the energy of the source. Stage 5 is no longer used in VERITAS analysis.

Stage 6 is the last stage in the VEGAS package. It uses ROOT files from stage 4 and performs final analysis of the data. It has the ability to produce a wide variety of graphs and figures.

B. Data

We are working with Bob Wagner at VERITAS to improve the current analysis done on M5. VEGAS has been improved and updated since M5 was first analyzed. Our goal was to analyze M5 using the same algorithms that are currently used to analyze dwarf galaxies by VERITAS. We are lowering the energy threshold from 600 GeV to 159 GeV to 244 GeV to determine stronger new limits. Table 1 lists the Thirty-five 20 minute observations of M5 by VERITAS that are used in our analysis. The observations were collected from February to March in 2009, for a total exposure time of 10.63 hours. The elevation ranged from 55 to 61 degrees and the azimuth ranged from 142 to 201 degrees.

Table 1: Summary of M5 Runs Used

Date	Run	Duration (min)	Sky	Elevation (Degrees)	Azimuth (Degrees)
20090226	44709	20	A	57	147
20090226	44711	20	A	60	166
20090226	44712	20	A	60	178
20090227	44738	20	B	55	142
20090227	44739	20	B	56	151
20090227	44741	20	B	60	171
20090227	44742	20	B+	61	182
20090227	44743	20	B	59	193
20090228	44769	20	B-	60	165
20090301	44798	20	A	58	152
20090301	44799	20	A	59	162
20090301	44800	20	A	60	171
20090301	44801	20	A	60	182
20090301	44802	20	A	60	195
20090302	44829	20	A	58	154
20090302	44830	20	A	60	162
20090302	44831	20	A	60	173
20090302	44832	20	A	60	183
20090302	44833	20	A	60	195
20090303	44850	20	A	59	157
20090303	44851	20	A	59	167
20090326	45158	20	A	59	158
20090326	45159	20	A	59	168
20090326	45160	20	A	60	178
20090326	45161	20	A	60	191
20090326	45162	20	A	59	201
20090327	45191	20	A-	61	180
20090327	45192	20	A-	59	192
20090328	45218	20	A	60	171
20090328	45219	20	A	60	184
20090328	45220	20	A	60	193
20090331	45286	20	A	59	164
20090331	45287	20	A	60	176
20090331	45288	20	A	61	187
20090331	45289	20	A	59	197

As many runs as were available were used for the analysis. The only omitted runs had bad weather or unreliable data based on observer comments. The weather is graded from a scale of A to F where A is the highest. Only runs with A or B weather were accepted.

C. VEGAS configurations/cuts

Background cosmic-ray events are reduced by requiring the width and length of the shower to be small, consistent with Monte Carlo simulations. A standard analysis was done as well as a "soft" analysis with a lower energy threshold. Standard analysis requires that all images have 400 (standard) or 200 (for soft) observed phototelectrons. Events were selected within 0.13 degrees of the location of M5 (ON) for standard analysis and 0.141421 for soft analysis. Remaining background events (OFF) were selected at other locations in the camera with the same detection efficiency as the signal. If only T1 and T4 triggered, this combination was denied, and did not count as an ON event.

V. Results

For this analysis, we ran four different sets of parameters on the 35 M5 data runs discussed previously. The flux is related to the energy by

$$FLUX = F_0 E^{Photon Index}$$

where F_0 is the flux constant, and E is the energy. After analyzing M5 in VEGAS, we got a flux upper limit and an energy threshold. These results are one point on the flux equation above. Dark matter is believed to have a photon index of -2.5 to -3.1. These photon indices were then used to calculate F_0 for each index. We now have an equation

of flux versus energy for each photon index. This equation was then plotted for a range of energies. Anything above our flux versus energy line can be dismissed and is not possible to exist. We ran soft and standard analyses, each for two theoretical gamma-ray energy indexes, -2.5 and -3.1. The OFF, ON, and signal for the standard and soft analysis can be seen below in Table 2.

Table 2: ON, OFF, and Signal for Standard and Soft Analysis

Analysis	ON events	OFF events	Signal
Standard	183	1880	-48 ± 15
Soft	199	1839	58 ± 18

Each signal is a 3σ negative fluctuation.

The 2D significance map distributions for each analysis are shown below in Figure 6. The maps for the standard and soft analyses are very similar. Each graph has a range of approximately -4σ to 4σ . They both have a few 4σ spikes which can be seen by the yellow in the graphs, and a similar numbers of -4σ which can be seen by the purple. The signal in the center of the graph is negative. This means that the background was greater than the signal for this area, so the excess is negative. There are other positive fluctuations to balance out this negative. Since the signal was negative, by looking at these graphs, it is very clear that there was no signal detected from M5.

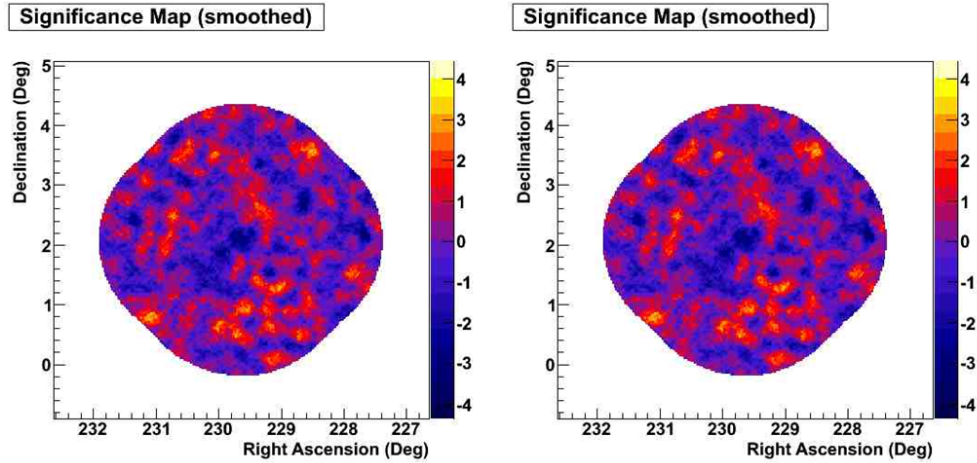


Figure 6: Standard Significance Map (LEFT) and Soft Significance Map (RIGHT). Each analyses shows a negative signal in the center where M5 is located.

The significance distributions for all for analyses are shown below in Figure 7. If there was a signal, there would be a bump at the end of the distribution, as seen in the 1ES1218 distribution of significance in Figure 8. It is very easy to see that the distribution follows a Gaussian distribution and that there is no signal because there is no bump. The probability is much higher (0.6137) for the soft cuts versus the standard cuts (0.01517). They all have approximately the same number of entries around 23,000.

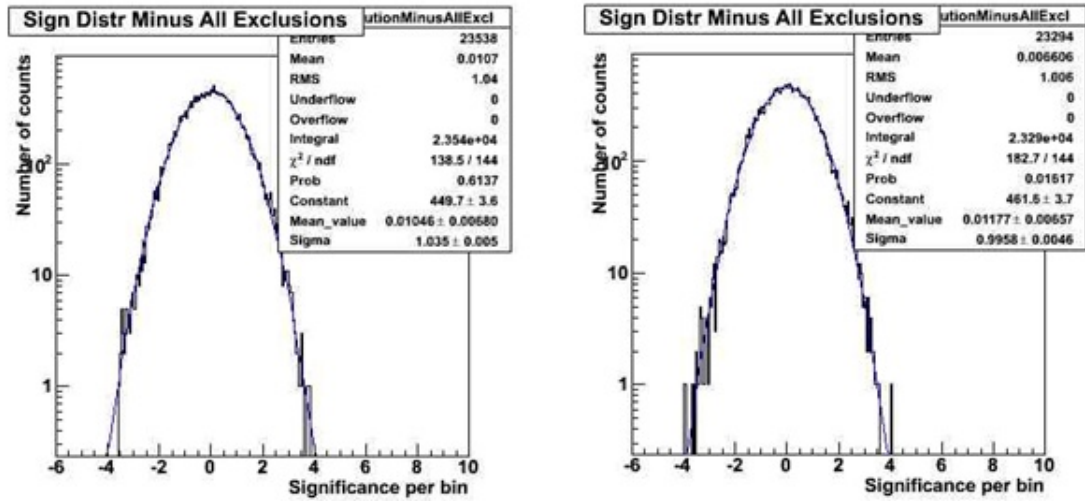


Figure 7: The Soft Analysis (LEFT) Significance Distribution and the Standard Analysis Significance Distribution (RIGHT) for M5. No signal was detected.

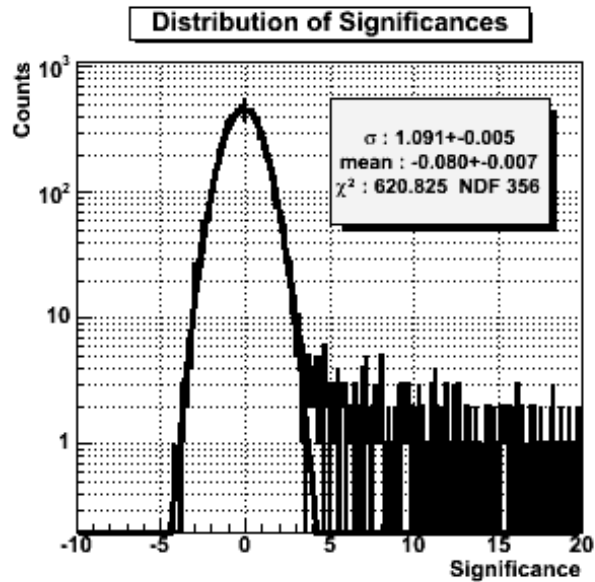


Figure 8: Distribution of Significances for 1ES1218.

The upper limits were calculated using the probability function of the number of source events, as outlined by Helene and a bounded Rolke method. The Helene and Rolke limits were calculated with a 95% confidence level. The bounded Rolke upper limits are generally similar to those produced by the Helene method since Helene is a Bayesian

method with a signal that is uniformly distributed from 0 to ∞ . Below in Table 4 is the energy and limit that came out of using the Helene and Rolke limit parameter in VEGAS and Michael McCutcheons analysis. The current Helene and Rolke limits are not reliable. We suspect an error in the way that the energy threshold is being calculated may be the main reason for the error. In table 4 the statistical upper limit for the standard and soft analysis is shown.

Table 3 : Statistical Upper Limit for M5

Analysis	Statistical Upper Limit
Standard	9.96
Soft	21.2

The statistical upper limit is the maximum amount of photons that can be detected for a given theory. If more are produced, we know that that theory is wrong. The energy and flux upper limit were used to calculate F_0 for each analysis. An equation was generated for each analysis the preliminary results and are graphed in Figure 9.

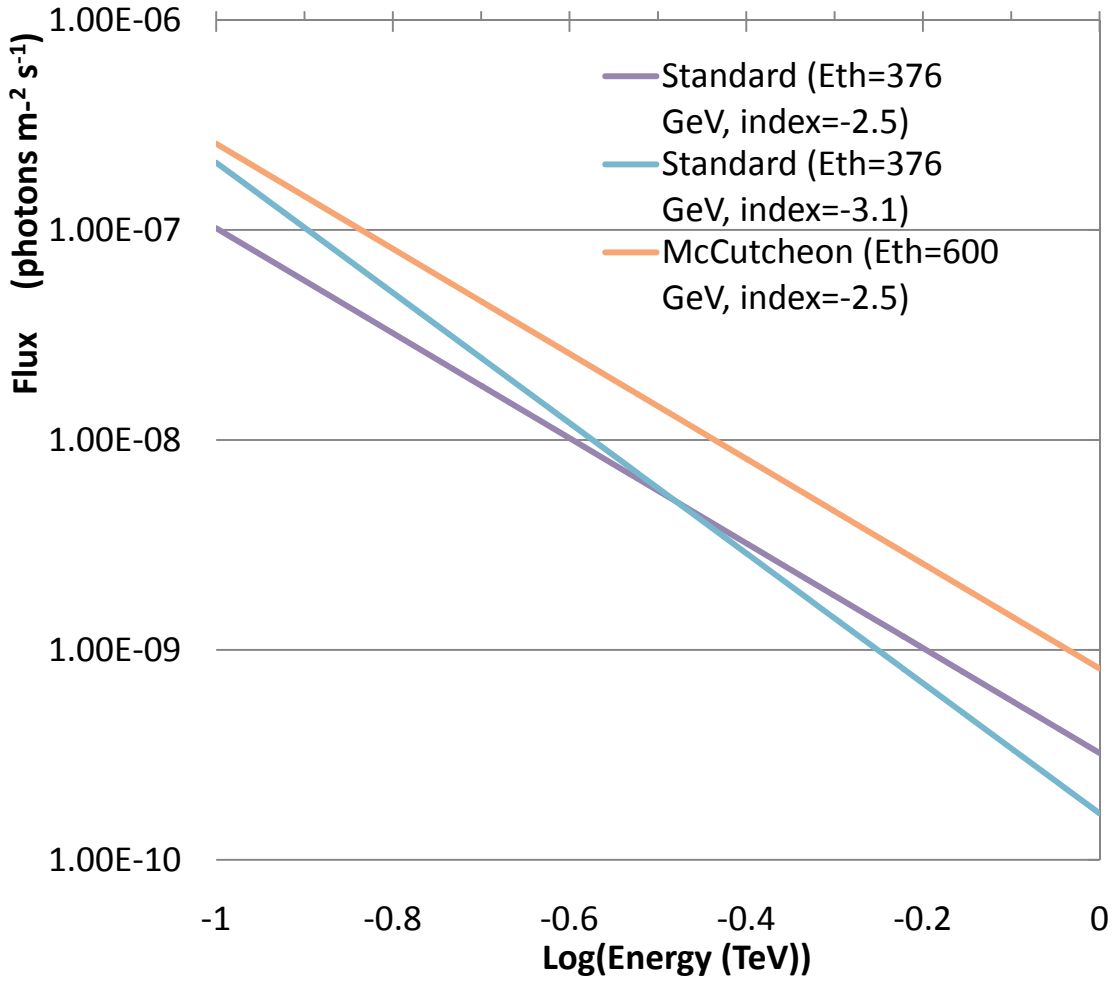


Figure 9: Flux versus Energy for M5

The 95% confidence interval Rolke bounded limits we calculated are much better than the previous limits that can be seen in Figure 9.

VII. Conclusion

From the significance distribution and the 2D significance map, we conclude that there was no signal. Gamma-rays from neutralino self-annihilation were not found, and we cannot conclude that dark matter exists in M5 from neutralino decay. Using the Rolke bounded limits with a 95% confidence interval we established a flux upper limit

and energy threshold and a statistical upper limit. Due to updated software and a lower energy threshold we established superior limits to the previous VERITAS analysis.

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