Figure 1: The VERITAS Telescope Array

The VERITAS Science Plan: Introduction and Overview

Introduction

The scientific goals of the VERITAS collaboration are broad and ambitious, covering the mechanisms of particle acceleration in astrophysical sources, the physics of black holes and astrophysical jets, the use of gamma-rays as cosmological probes, and the study of fundamental physical laws and particle physics. In 2010-2011, the collaboration developed a scientific plan for operations until 2017, which was presented to the External Science Advisory Committee (ESAC) and to the funding agencies. This plan has provided a useful guide for our observations but, half-way through the original program, a re-evaluation and update is timely.

Over the past year, the collaboration has been engaged in a new planning exercise, the results of which are presented in this document. The motivation for this effort was primarily to establish the most effective means by which to achieve our scientific goals, within the lifetime of the observatory. The new plan includes major changes to our time allocation procedures, the most important aspect of which has been to move from an open competition, to a scheme in which 70% of our average annual observing time is pre-allocated in a "long-term plan" (LTP) for observations. It assumes that VERITAS will continue operating until at least 2019.

VERITAS Overview

VERITAS consists of four atmospheric Cherenkov telescopes sited at the Fred Lawrence Whipple Observatory in Arizona [1, 2]. Figure 1 shows the array in its completed configuration, with all four telescopes fully operational. Each telescope in the array consists of a 12 m diameter tessellated mirror which reflects the Cherenkov light from gamma-ray induced particle cascades onto a camera. The camera is made up of 499 photomultiplier tubes, which record an image of the Cherenkov light distribution in the sky. By combining the Cherenkov images of each particle shower from multiple telescopes, it is possible to reconstruct the parameters of incident gamma rays - their energy, arrival direction and shower core location on the ground - as well as to discriminate the gamma-ray images from the otherwise overwhelming background of particle cascades due to incident cosmic rays.

VERITAS has been operating with all four telescopes since 2007. The array has undergone a number of upgrades: relocation of the original prototype telescope to a more favorable position

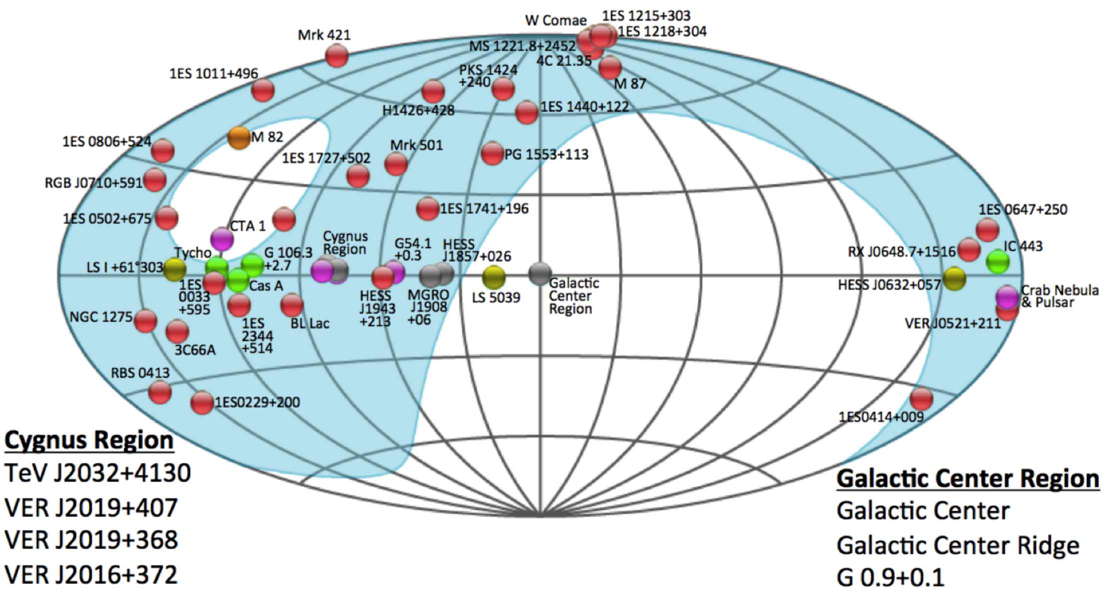

Figure 2: The VERITAS source catalogue as of September 2014 (in Galactic coordinates). The shaded area shows the region of the sky visible to VERITAS at elevations greater than 55°.

within the array in 2009 [3], an upgrade to the telescope-level trigger systems in 2011 [4], and the replacement of all of the camera photo-detectors with more sensitive devices in 2012 [5]. The current sensitivity of the array is such that a source with 1% of the steady flux from the Crab Nebula can be detected with a statistical significance of 5σ in ~ 25 hours. The angular resolution of the array is measured to be typically $\sim 0.1°$ for each gamma-ray photon, and the energy resolution is $\sim 15\%$.

VERITAS operates at night when the sky is clear. The average annual good quality data yield is 970 hours. This is supplemented by ~ 280 hours of less sensitive observations taken under bright moonlight conditions, and ~ 140 hours of data taken under poor sky conditions (which can still be useful for monitoring bright or transient sources). Prior to VERITAS, only a handful of northern hemisphere gamma-ray sources were known. 50 gamma-ray sources have now been detected by VERITAS, around half of which are new discoveries. Figure 2 shows this source catalog, in Galactic coordinates.

The collaboration consists of around 100 members, from ~ 25 institutions in the USA, Ireland, Germany and Canada, together with ~ 35 Associate members. The scientific activities of the collaboration are organized by science working groups, whose operations are overseen by a science board comprised of senior members from all of the collaborating institutions. The observing schedule is managed by a Time Allocation Committee (TAC). External scientists are encouraged to collaborate with VERITAS members to apply for time, and up to 15% of VERITAS observing time has been made available to the wider community, through the Fermi Guest Investigator (GI) program [6]. Operations support for the VERITAS Observatory is managed by the Smithsonian Astrophysical Observatory, and is funded through a combination of grants from the DOE and the NSF, as well as in-kind and financial support from the Smithsonian Institution. The DOE and NSF grants were recently renewed and observatory operations are currently fully funded through 2016.

VERITAS Long-term Plan Observations

The long-term plan observations for each of the three major science working groups (Galactic, Blazar, and Dark Matter/Astroparticle/Extragalactic) are included in this document, together with a shorter description of our ongoing search for gamma-ray bursts. The long-term plan provides a mechanism for VERITAS to achieve its scientific goals. In the case of Galactic sources and Dark Matter targets, a large component of the plan focusses on deep, multi-year exposures which allow us to measure source spectra and morphology, or to set the most constraining limits to the gamma-ray emission. In the case of the blazar group, the focus is on the detection of elevated flux states, which allow us to extract the most meaningful results for most of our scientific goals. Both long exposures and consistent monitoring benefit from the move to a long-term plan, which does not require yearly competition and approval by the Time Allocation Committee.

Each of the science working groups have taken their own approach to organising their observations, but they all follow a set of common guidelines, as follows:

- The LTP observations make up 70% of the average annual yield, and typically 70% of the available observations at any time of year (i.e. at any given right ascension).
- LTP targets are pre-approved by the science working groups, and have highest observing priority. The TAC implements a schedule using the LTP target rankings provided to them by the SWG leaders.
- During the first year of implementation, the SWG leaders, spokesperson and TAC chair will hold calls to review the program. Significant external events can also trigger a review; for example, input from the VERITAS ESAC, or a major data release (e.g. HAWC, Fermi-LAT pass 8).

The LTP constitutes a working document - while the science goals are reasonably well-established, the details of the long-term plan observations will be revised and updated in response to new results and information.

VERITAS Science outside of the Long-term Plan

The pre-allocated observing time in the long-term plan does not encompass all of the science goals of VERITAS. An important consideration in developing the plan has been to retain the ability to respond rapidly to new information, and to allow for creative and/or high risk opportunities. With this in mind, we have continued our annual time allocation competition, in order to schedule the remaining 30% of our observing time. Some notable projects from the current season include:

- Follow-up observations of IceCube neutrino events with well-measured arrival directions.
- A program to detect gamma-ray emission from gravitationally lensed blazars.
- Observations of unassociated Fermi sources, which may be linked with Dark Matter sub-halos. This project is supported by the VERITAS-Fermi GI program.
- An additional exposure on IC 443, beyond the long-term plan allocation, to follow-up on preliminary evidence for emission from the SNR shell.

The combination of the long-term plan and a reduced time allocation competition provides the stability required to complete major projects, whilst allowing room for creative and exciting new science. We have been operating under these procedures since summer 2014, and the initial feedback from the TAC and the science working groups has been positive. The progress of the LTP observations will be reviewed by the whole collaboration at the summer collaboration meeting in 2015.

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VERITAS ESAC Meeting 2014:
The Blazar Science Working Group Long Term Plan

Amy Furniss and Matteo Cerruti for the BSWG

Abstract

The Blazar Science Working Group (BSWG) Long Term Plan (LTP) includes observation of the 42 known northern VHE blazars, with a focus on the detection of elevated flux states. In addition to monitoring of the known VHE blazars via "snapshot" observations during visibility windows each season, the plan incorporates deep observations of distant and/or hard-spectrum blazars, notably variable blazars and the iconic blazars Mrk 421 and Mrk 501. The pre-planned BSWG LTP sums to 198 hours. In addition, the LTP incorporates 80 hours for pre-approved Target of Opportunity (ToO) observations. The BSWG references a detailed multiwavelength (MWL) trigger criteria spreadsheets in order to enable minimal delay in ToO response. For both the pre-planned and the ToO observations, the source-specific exposures have been systematically determined so as to address a wide range of specific scientific drivers. A noteworthy aspect of the VERITAS Blazar LTP is the strong MWL component, where contemporaneous MWL observations, including *Swift* X-ray, UV and Fred Lawrence Whipple Observatory optical exposures (B, V, r, and i) are organized to occur in tandem with the VERITAS blazar observations. The coverage of the MeV-GeV part of the spectrum is provided by the Fermi satellite, thanks to its all-sky observing strategy.

1 The BSWG LTP Science Drivers

1.1 Understand blazar gamma-ray emission mechanisms

The spectral energy distributions (SEDs) of blazars are characterized by broad non-thermal continua from radio to γ-rays, with two distinct components peaking in IR-to-X-rays and MeV-to-TeV, respectively. Although the origin of the low-energy peak is understood to result from the synchrotron radiation of relativistic leptons ($e^{\pm}$) in the presence of a tangled magnetic field, the emission mechanism responsible for the high energy peak has yet to be conclusively determined. This peak, occurring at γ-ray energies, can be attributed to inverse-Compton up-scattering by the relativistic leptons within the jet of either the synchrotron photons themselves, namely synchrotron self-Compton (SSC) emission, or a photon field external to the jet, namely external Compton (EC) emission [e.g. 1, 2]. The external photon field can be the thermal emission from the super-massive-black-hole accretion disk, from the dust torus or the reprocessed photons produced in the broad-line region (BLR). Models which attribute the higher-energy peak of blazar emission to hadronic processes, namely synchrotron emission by protons and pion production (from $p - \gamma$ interactions) and the resulting cascade emission, naturally leading to lower variability timescales of the gamma-ray emission, are also still viable [3, 4], although they can be already disfavored for powerful flat-spectrum-radio-quasars (FSRQs) and for rapid flaring events.

An effective means to differentiate between time-averaged emission model degeneracies is through contemporaneous observation and the subsequent modeling of broadband spectral variability [5]. For example, correlated variability between the lower and higher-energy SED peaks, can be well described by SSC emission, whereas non-correlated variability patterns require more complex emission models.

FSRQs represents the most powerful blazar sub-class, and are characterized by broad emission lines in their optical spectrum and a low-frequency-peaked SED. For these sources an EC model is preferred over a simple SSC scenario. However, given their low-frequency peak, and the fact that they are, on average, located at a higher distance compared to BL Lac objects, they are rather elusive VHE emitters. So far, only three FSRQs have been detected at VHE, and only during flaring activity; VERITAS has reported during the 2013/14 observing season the emission from PKS 1222+216.

Not only is it possible, but it is expected that emission mechanisms vary for different blazar subclasses, being potentially related to the mass and spin of the black hole powering the system and the AGN environment. However, the physical reason(s) behind these differences has yet to be determined. One possible paradigm (known as the blazar sequence, [6]) suggests that low-frequency peaked BL Lacs (LBLs, with a SED peak at infrared/optical wavelengths) are generally more powerful, more luminous, and have a richer jet environment compared to high-frequency-peaked BL Lacs (HBLs, with a SED peak above the ultraviolet). Evidence for this evolutionary paradigm has been found through VERITAS observations of the intermediate-peaked BL Lacs, 3C 66A and W Comae. The SED modeling of these sources during flaring periods suggest that SSC models with an external-Compton component are possibly more effective at describing the data than pure SSC models [7, 8, see Fig. 1, top]. The question of whether the emission mechanism(s) at work in the jets of 3C 66A and W Comae are flare-specific still remains. These are important results that, with the collection of additional contemporaneous broadband data to supplement the VERITAS VHE observations, can directly address blazar phenomenology and the possibility for BL Lac evolution.

For HBLs, which represent the majority of VHE blazars, a one-zone SSC model represents often a good description of the broad-band SED. The absence of an external-Compton contribution is supported by the non-detection of thermal emission from the accretion disk or the BLR, suggesting that in this case the γ-ray emission region is located in a clean environment. For these sources, it has been shown [see e.g. 9, 10] that, when the peaks of the SED are well sampled, it is possible to remove the degeneracy in the model and fully constrain the parameter space. As an example, in Figure 1, bottom, we show the SED and modeling of the HBL 1ES 0229+200, as published by VERITAS [11]: for the first time we proved that the emitting region moves towards the observer with a Doppler factor $\delta \geq 53$, and that the electron population has a cut-off at low-energies, with E_{min}/mc^2 of the order of 10^4; the other model parameters are relatively well estimated, with an uncertainty of less than one order of magnitude. This kind of modeling will be implemented for all VERITAS HBLs, and will provide insights on how SSC model parameters are related to observables such as the blazar luminosity or its peak frequency.

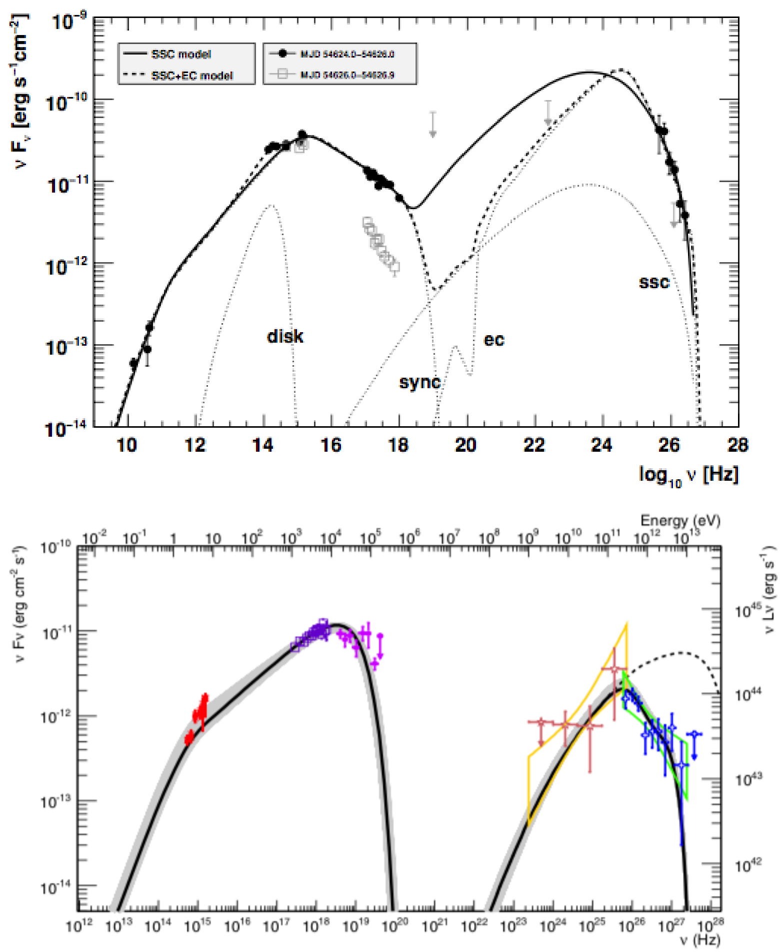

Figure 1: *Top:*:The SED of the LBL W Comae, as stated in the VERITAS publication [8]: "The SED can be modeled by a simple leptonic SSC model, but the wide separation of the peaks in the SED requires a rather low ratio of the magnetic field to electron energy density of $\epsilon_B = 2.3 \times 10^{-3}$. The SSC+EC model returns magnetic field parameters closer to equipartition, providing a satisfactory description of the broadband SED." *Bottom*: The SED of the HBL 1ES 0229+200, as stated in the VERITAS publication [11]. The gray band indicates the range of SSC models which correctly describe the data, while the black line represents the best-fit solution.

1.2 Locate the VHE emission region(s)

Locating the high-energy emission zone(s) of a blazar is challenging due to the beamed, point-like nature of the emission. Basic questions regarding the non-thermal emission region remain: *Is there one, or multiple VHE emission zones? Does the VHE emission emerge from the base of the jet, near the vicinity of the black hole, or does it emerge from beyond the broad-line region?* VHE-coordinated MWL observations, such as those outlined in the BSWG LTP, are necessary to address these questions.

Inconclusive experimental evidence exists for both a VHE-emission region near the base of the jet as well as farther out in the jet. VHE/radio observations of M87[1] show correlated flux increase of a region near the radio galaxy core, suggesting that the VHE emission might originate from a region near the base of the blazar jet [12]. Alternatively, high-resolution radio images, optical polarization and gamma-ray measurements of the blazar BL Lac suggest the blazar emission zone is located further out from the base of the jet [13]. The observation of repetitious MWL variability patterns would provide more conclusive interpretation on the location of the VHE emission zone, necessitating continued broadband observations of radio galaxies such as M87 and nearby, bright gamma-ray blazars like BL Lac. With nearby sources, the angular resolution of radio observations are able to better probe the base of the blazar jet.

An additional means of probing the location of the blazar emission region is through the detection of an emission zone interacting with an external photon field in the vicinity of the emission region. A spectral signature of interaction, such as photon-photon absorption, would provide evidence that the emission region lies within a source of external photons (e.g. a dusty torus [14] or a broad line region [15]). For example, for both W Comae and 3C 66A, emission models utilizing external radiation fields for Compton up-scattering were preferred. If the external radiation fields are in the vicinity of the VHE emission region of BL Lacs, they may have an observable effect due to gamma-gamma absorption of VHE gamma-rays by the same external radiation field that serves as target for inverse-Compton scattering. This feature would appear as an absorption trough at tens to hundreds of GeV and requires deep VHE observations as outlined in the LTP. Depending on the magnetic field near the blazar zone, secondaries may either be efficiently isotropized, in which case one would not expect to see evidence for the cascade emission in the blazar direction, or they continue to propagate down the jet direction and show up as a bump in the *Fermi* range (see [7, 8] for details). To convincingly perform this study, high-quality GeV-TeV spectra of non-HBL sources in both low and high states need to be combined with those of *Fermi* LAT to look for these signatures.

1.3 Understand the origin of differences in the gamma-ray flux states and spectral variability of blazars

It can be reasoned that flaring states of VHE blazars are composed of a constant (quiescent) component convolved with a temporary (elevated) component [see 16]. Deep observations of the quiescent emission from a source can enable the disentanglement of transient flaring emission from the steady flux through the comparison of the broadband characteristics of VHE blazars in quiescent and flaring states. Through modeling and the comparison of the emission characteristics in these different states, we can address some fundamental questions regarding VHE blazars: *Why are some VHE blazars continually bright gamma-ray emitters while others are dim? Why are some blazars widely variable while others are relatively steady? Why do some blazars exhibit soft intrinsic gamma-ray spectra while others display hard gamma-ray emission? Is the wide range of blazar spectral characteristics driven by fundamental differences in the populations of relativistic particles, or by the surrounding environment? What is the duty cycle of VHE blazars and does it depend on the blazar subclass? Are the emission mechanisms different for the flaring and the quiescent states? What triggers blazar flares?* In order to adequately address this question, baseline broadband SEDs should be compared for the population of VHE blazars. Additionally, the quiescent SED of a blazar needs to be compared to the flaring SED(s) of that blazar. As an example, the VERITAS monitoring of BL Lacertae revealed, during June 2011, a rapid VHE flare, with an exponential decay-time of only 13 minutes. The γ-ray part of the SED is shown in Fig.

[1]The “mis-alignment” of the radio-galaxy M87 has categorized the VERITAS efforts to better understand the source as an Astroparticle and Extragalactic Non-blazar (AsPEN) Science Group investigation. The science working group has organized a LTP which include monitoring observations of radio galaxies such as M87 to search for elevated states and trigger coordinated MWL campaigns.

2, and indicates that the γ-ray flare was associated to a significant hardening of the GeV emission, while the TeV spectral index was consistent with the low-flux state.

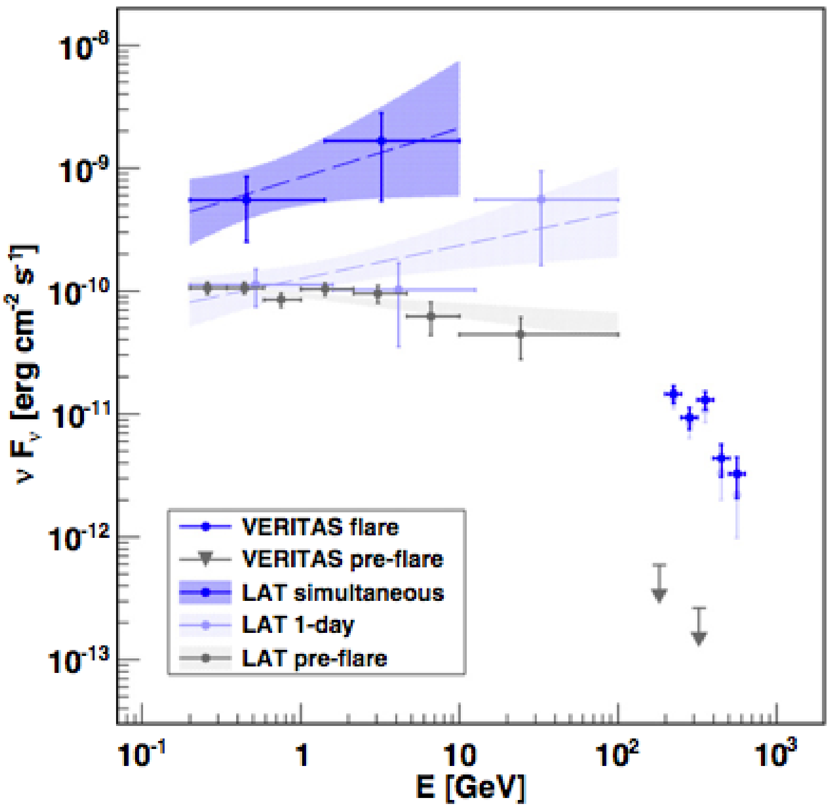

Figure 2: The γ-ray SED of the LBL BL Lacertae, from [16], showing the spectral variability of the γ-ray component during the rapid VHE flare observed by VERITAS in June 2011.

1.4 Indirectly probe the optical and IR photon density of the extragalactic background light (EBL)

In observational cosmology the diffuse background radiation fields that surround us provide invaluable insight into the history and structure of our Universe. From the ultraviolet to the far-infrared, the extragalactic radiation field consists of the accumulated and reprocessed radiation of all starlight produced thus far. This extragalactic background light (EBL) encodes the integrated history of structure formation and the evolution of stars in the Universe. The EBL density, therefore, contains integrated insight on all of the processes that contribute, e.g. structure formation and galactic evolution [23, 24].

VHE gamma rays that propagate through the intergalactic medium are absorbed by low energy EBL photons via pair production, $\gamma_{VHE} + \gamma_{EBL} \rightarrow e^+ + e^-$ [25]. There are various means to extract information about the EBL photon density. One common method investigates the absorption-corrected spectrum in the context of standard acceleration mechanisms [26, 27]. The absorption of VHE gamma rays can be estimated using the model-specific gamma-ray opacity, $\tau(E, z)$, where the intrinsically emitted flux, F_{int}, is estimated from the observed flux, F_{obs}, using the relation $F_{int} = F_{obs} \times e^{\tau(E,z)}$. The redshift and energy dependent opacities for the [24] model are shown in Figure 3.

The VERITAS observations of blazars benefit from contemporaneous *Fermi* LAT spectral measurements, where the EBL attenuation of gamma rays is negligible for sources at $z < 1$. These *Fermi* LAT observations allow the estimation of the intrinsic blazar spectrum in the VHE regime. By attributing the differences between the intrinsic VHE spectra and the observed VHE spectra to the imprint of the optical-IR EBL, its density can be estimated. Due to the distance and energy dependent manner in which the EBL and VHE photons interact, deep VHE observations of both hard and distant VHE blazars are valuable in constraining the EBL photon density.

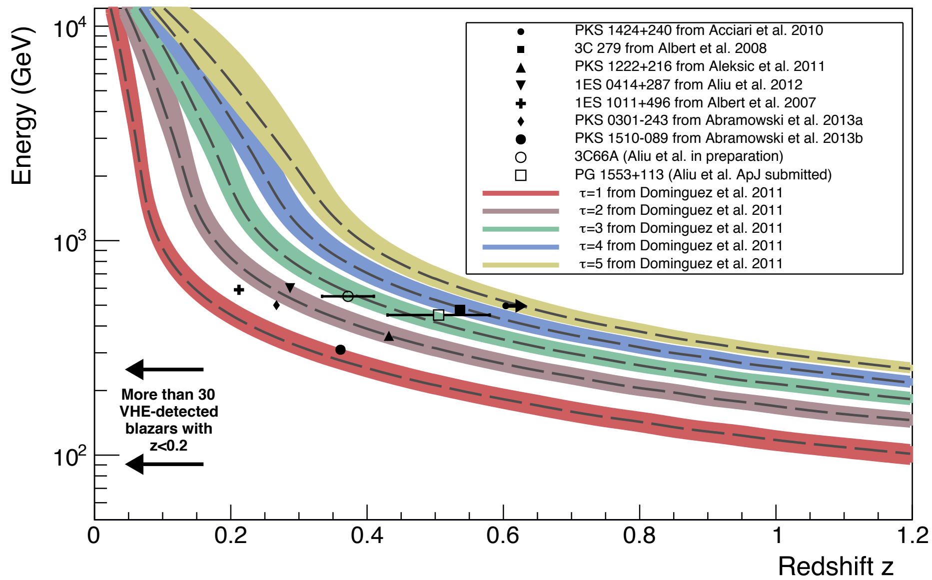

Figure 3: The $\tau = 1 - 5$ opacities due to photon-photon pair production of VHE gamma rays with EBL photons, according to [24]. These opacities are shown along with a number of the sources for which the VHE observations probe significant gamma-ray opacities. As part of the BSWG LTP, VERITAS is collecting deep observations on all northern VHE blazars determined to probe an opacity of greater than τ=2.

UCD student Yerbol Khassen's PhD thesis project is to use VERITAS observations of 7 hard-spectrum blazars to constrain the EBL. These blazars are 1ES0229+200, 1ES1218+304, 1ES1959+650, 1ES2344+514, H1426+428, PG1553+133 and RGBJ0710+591. The redshift of PG1553+113 is conservatively chosen to be the lowest limit of 0.395. The approach taken is to construct a grid of possible EBL intensities -vs- wavelength given by a set of knots, connected with splines. The splines interpolate the knots in log-log space which produces 6912 possible shapes for the EBL SED (see Fig. 4, left plot). EBL evolution is accounted for up to z=0.7, according to [28]. The optical depth for each EBL SED is calculated by triple integration over TeV γ-ray energy range, EBL SED energy range, and distance, using the pair production cross section for low- and high-energy photon interactions. Using this numerical method, an intrinsic spectrum for each source is recovered. Constraining of the EBL is based on the assumption that the intrinsic high-energy bump of a blazar SED (most commonly assumed to be due to inverse-Compton scattering) is concave in nature. Those intrinsic spectra which show un-physical hardening at high energies are rejected. SED shapes are eliminated if intrinsic spectra are not well-fit by one of the following models: power law, broken power law with transition region or double broken power law with exponential pile up. Generally a fit with the least number of parameters is preferred, however more complex function is chosen if it resulted in a significantly better fit. The 1FHL [2] catalogue provides the indices for 6 blazars as a proxy for the intrinsic spectrum and they are used as constraints. For 1ES0229+200 the 1.5 hardness limit derived from the shock acceleration concepts is used for the spectral index. In other words, the derived spectra of blazars must not exceed the experimental or theoretical limits within their uncertainty ranges. VHE light-curves are obtained for all sources in each observing season with VERITAS to ensure that there is no significant variability of their spectral indices. Based on this stacked analysis of eliminating the EBL shapes, the combined limit is derived from the upper envelope of allowed EBL SEDs. Fig. 4, right plot, shows the preliminary results of EBL maximal spectrum. Work is currently underway to extend this analysis to more sources detected by VERITAS and constrain the EBL SED in mid- and far-IR region.

To improve the current indirect constraints on the EBL by VHE blazar observations, VERITAS is working to collect deep exposures of blazars with well reconstructed VHE spectra up to high opacity at different distances are necessary. Notably, observation of these sources in VHE flaring states will allow a more efficient collection of the highest energy spectral statistics necessary to constrain the full

[2]http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1FHL/

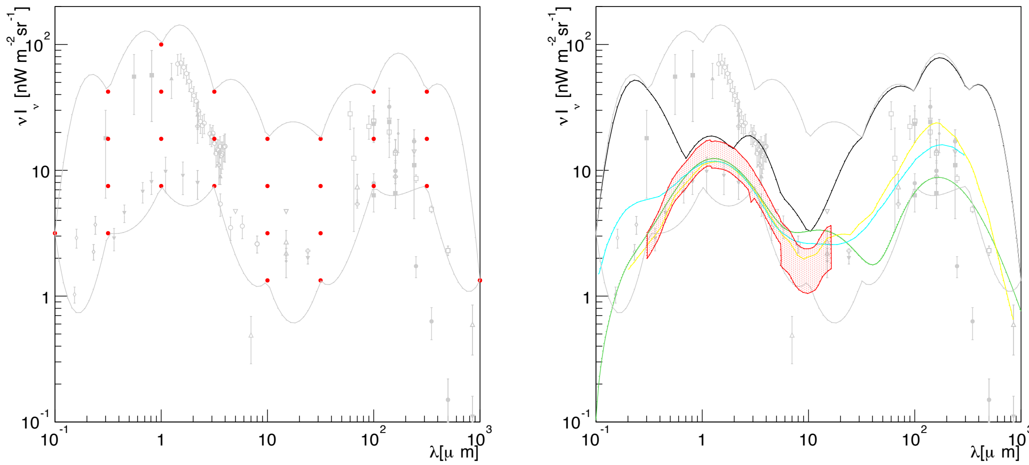

Figure 4: *Left*: knots are given as red points which are selected by dividing the 2D intensity-wavelength space into 9 by 9 grid. Knots which are located significantly above and below the direct EBL measurements are excluded. Therefore the interpolated splines cover most of the measurements and there are 6912 possible combinations left. *Right*: the combined UL derived from 7 blazars given as a black line compared to other measurements, limits and EBL models; red region is from [29], green line is from [30], blue line is the upper limit from [28], yellow line is the EBL model from [31]. Grey points represent direct EBL measurements and lower limits from galaxy counts.

range of the EBL UV to mid-IR SED peak.

The VERITAS BSWG LTP can also constrain the far-IR portion of the EBL SED peak. Deep VHE observations of Mrk 421 and Mrk 501, although relatively nearby at redshifts of z=0.03, have the potential to provide unprecedented constraints on the EBL density. Precise VHE spectral measurements of these nearby blazars above 15 TeV will allow us to probe the EBL photon density at energies above 10 microns. Spectral measurement of Mrk 421 and Mrk 501 photon spectra beyond 15 TeV are so far unprecedented and can be used to make the first indirect measurements on the IR photon density of the EBL, an energy range where significant difference between EBL models remain. The measurement of photon spectra at >15 TeV from Mrk 421 and Mrk 501 are possible through deep observation of the sources while in low states, as well as with shorter exposures during flaring states. Both of these measurements are enabled by the deep monitoring campaigns organized for these two sources.

1.5 Disentangle Possible VHE Flux Contributions from Cosmic Ray Line of Sight Interactions

A possible mechanism for VHE photon production is cascade emission from the propagation of ultra high energy cosmic rays (UHECRs) across extragalactic distances. If VHE blazars eject sufficiently accelerated protons/neutrons, photo-pion production with EBL and CMB can initiate cascades, producing secondary gamma rays along the source line of sight [32, 34]. An example of how this secondary emission can harden observed VHE blazar spectra is provided in Figure 5 for PKS 1424+240, taken from [33]. PKS 1424+240 is a distant source which probes a gamma-ray opacity of $\tau > 5$. The contribution of extragalactic cascade emission is difficult to quantify due to key unknowns such as the EBL density, the magnitude of the intergalactic magnetic field and the total power of the cosmic rays produced by the AGN.

Disentangling intrinsic VHE emission and line of sight VHE emission can be difficult, however, gamma-ray emission can be definitively associated with these secondary emission processes using the spectral shape and variability characteristics that are observed in the VHE band. For distant sources, it is expected that the secondary component could contribute a significant portion of the observed gamma-ray signal, particularly at the highest energies, where intrinsic gamma rays are attenuated by the EBL over the long path length. The cascade process, if present, would contribute a hard component to spectra of VHE blazars and occur at similar opacity values for all VHE blazars. Additionally, the hard component displayed by these sources would lack variability due to intrinsic variations in flux being washed out over a variety of path lengths.

A critical requirement in searching for signatures of line-of-sight interactions is a complete view of the intrinsic gamma-ray peak from the blazar, naturally provided contemporaneously by the *Fermi* LAT observations. Spectral hardening in the absorption-corrected emission can then be investigated as a possible signature of secondary emission from cosmic ray line-of-sight interactions.

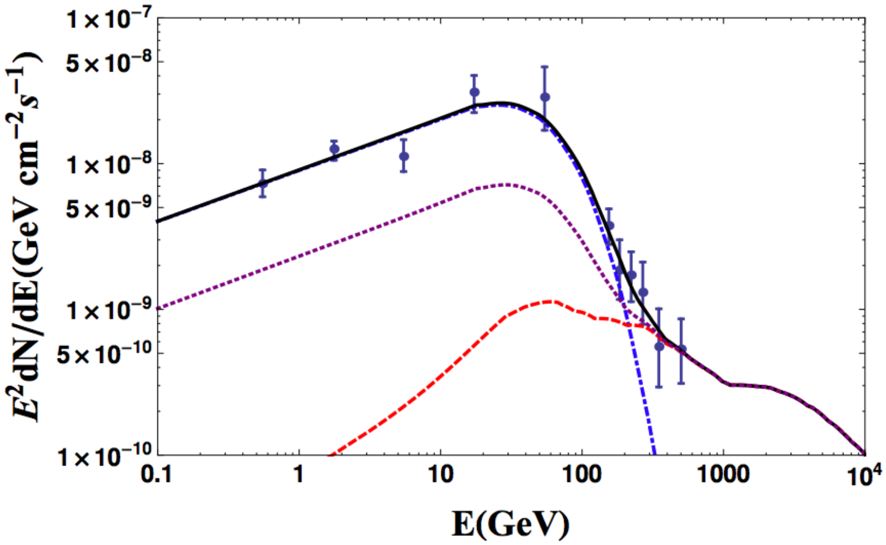

Figure 5: The observed spectrum of PKS 1424+240 (solid black line), assuming the source lies at $z = 0.6$. The blue dot-dashed line is primary emission from the source, produced with a spectral index of $\Gamma = 1.65$; the red dashed line is secondary secondary gamma rays, assuming an intergalactic magnetic field strength of $\mathrm{B} = 10^{-15}$ G. Also shown are the VERITAS and *Fermi* LAT contemporaneous observations. For reference to a possible low flux state, the purple line represents the total spectrum with primary signal suppressed by a factor of four. Figure taken from [33].

1.6 Constrain Magnitude of the Intergalactic Magnetic Field

The strength of the intergalactic magnetic field (IGMF) is of fundamental physical importance, and may provide clues into its generation in the early Universe [35]. The strength of the IGMF is only weakly constrained, with an upper limit 10^{-9} G and a lower limit of 10^{-17} G. Several methods probe the magnetic field strength, each of them sensitive to a different range of strengths. The search for gamma-ray pair halos around AGN probes magnetic field strengths between 10^{-12} G and 10^{-7} G [36].

The presence of a non-zero magnetic field will affect the development of electromagnetic cascades resulting both from VHE-EBL photon interactions and any possible UHECR interactions, as the electron-positron pairs will be deflected by the IGMF before inverse-Compton scattering. For weak fields (B$< 10^{-14}$ G), a magnetically broadened cascade is produced, as the secondary emission travels roughly concurrently with the beamed emission, but over a slightly longer path length. Stronger fields ($10^{-12} - 10^{-7}$ G) isotropize the electron-position pairs, which will collect in the vicinity of the AGN. The secondary gamma-ray emission can produce a symmetric GeV "halo" around the AGN. If it is sufficiently bright in comparison to the beamed emission, the halo will be detectable with VERITAS from the sources observed angular profile.

For deep VHE observations of blazars, the θ^2 distribution will be sharply peaked at zero, with a width dependent on the telescope arrays point spread function (PSF). A flat background from cosmic ray-induced showers with no specified arrival direction will appear under the signal peak. It is expected that extended emission could be observed as a broadening in the angular profile. The expected distribution in this case would be the sum of a point-like distribution from the beamed emission and a broader angular profile from the halo.

The spectral characteristic and distance to a source strongly affects the projected sensitivity to extended emission. The angular size of the halo is inversely proportional to the source redshift. Ideal candidates are between z=0.1 and 0.25, at distances where the extended emission is neither so compact that it is indistinguishable from the beamed emission, nor so broad that it is indistinguishable from the cosmic-ray background. Moreover, hard-spectrum sources with spectral reconstruction to high opacities are favored due to the high fraction of intrinsic VHE photons which will undergo interaction with the EBL and produce pair-cascades. This type of halo emission has been searched for in some VERITAS blazar observations, as shown in Figure 6. The current observations are consistent with no extended emission, however more stringent constraints on this possible emission are possible with deeper observations.

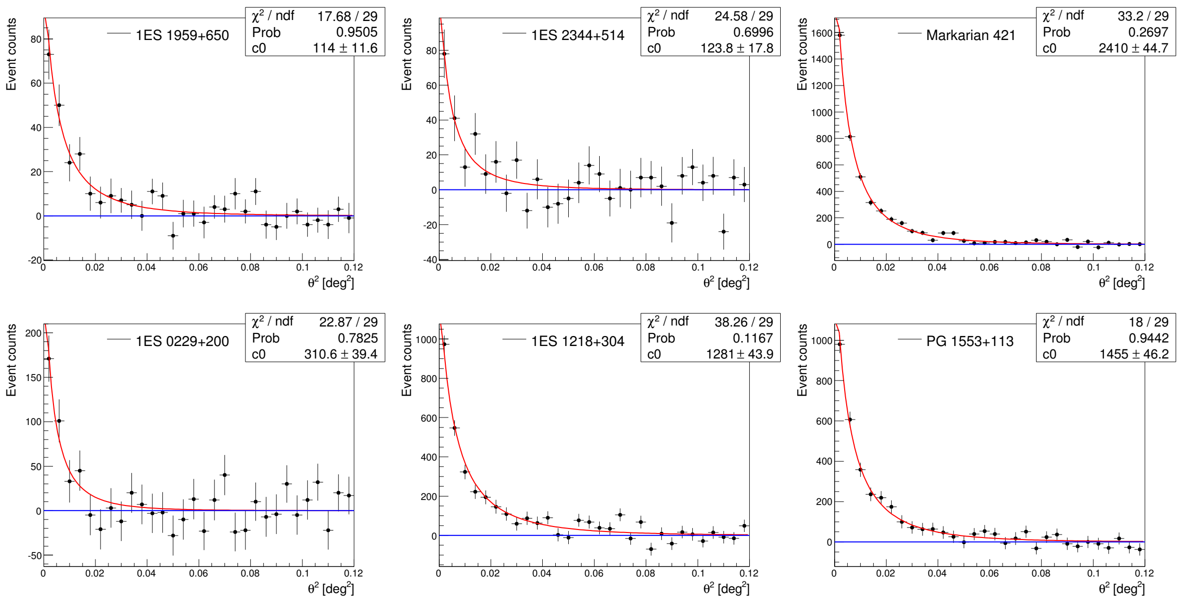

Figure 6: Angular profiles of VHE events as observed by VERITAS for the six AGN. The data are fit with a *sech* function with the width fixed to the value derived from simulation, with the exception of Mrk 421, whose expected width is derived from flare data from April 2013. No evidence for extended halo emission beyond the VERITAS PSF is observed. More stringent constraints on halo emission will be possible with deeper observations.

1.7 Search for Evidence for Axion-like Particles

There is an exotic mechanism which can potentially affect gamma-ray propagation over extragalactic distances. A hard high-energy gamma-ray tail similar to that produced from cosmic-ray interactions with extragalactic photon fields could result if VHE photons oscillate into axion-like particles (ALPs) in the presence of a magnetic field. This conversion would allow VHE photons (while in the form of an ALP) to propagate through the EBL without interaction and pair-production. Evidence for an effect of just this sort has recently been claimed [37]. Detailed MWL characterization of blazars at moderate optical depth is critical for understanding the viability of the existence of ALPs. An example of how the observed VHE spectrum of a distant blazar may be affected by the existence of ALPS is shown in Figure 7.

1.8 Search for potential violations of Lorentz invariance

It has been proposed that the speed of light is not constant, but instead energy dependent. This theoretical energy-dependent speed of light is referred to as Lorentz invariance violation (LIV; [18]). This energy-dependent speed of light is predicted in the framework of quantum gravity models and effective field theory, and is expected to appear at energies of the order the Planck energy (1.22×10^{19} GeV). At lower energies, the correction to the speed of light is predicted to be small. However, the slight modification of the speed of light can add up to measurable time delays for photons from sources at cosmological distances (see Figure 8, from [19]). In such a scenario, simultaneously emitted photons with different energies will arrive at a distant observer with a measurable time-lag. Gamma-ray blazars,

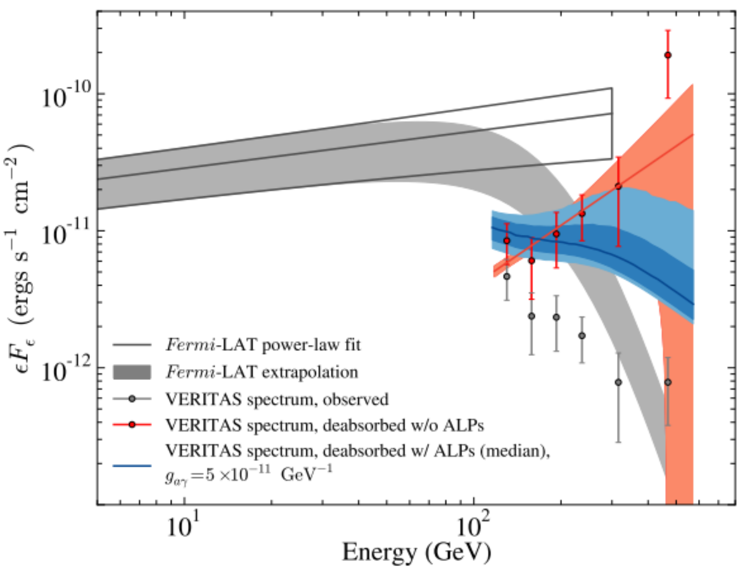

Figure 7: Spectral energy distribution for PKS 1424+240. The gray-shaded area shows the extrapolation of the Fermi-LAT spectrum under the assumption of a relatively low level EBL model. Figure taken from [38].

which have been observed to display fast, bright variable emission down to minute timescales, provide a natural laboratory for testing Lorentz invariance [20].

Quantifying possible time lags, or the lack thereof, through observation of rapid ($\sim$ 1-minute) VHE flaring by blazars can be used as a measure, or strong constraint, on the energy scale of the LIV speed of light modifications. The VHE emission from blazars is especially ideal for these tests since the fastest variability to date has been observed in this band, e. g. PKS 2155-304 [21] and Mrk 421 [22]. VERITAS observations of Mrk 421 in February of 2010 show the source to have displayed a huge flare, allowing VERITAS detection of significant variability on timescales as small as 2 minutes (see Figure 9). Regular monitoring observations of sources such as Mrk 421 and Mrk 501, which VERITAS does in collaboration with MAGIC, provide good temporal coverage of bright VHE emitters and improves the probability of observing these sources during exceptional flaring events.
It is important to note that since both Mrk 421 and Mrk 501 have much harder VHE spectra ($\Gamma \sim 2.3 - 2.7$) than PKS 2155-304 ($\Gamma \sim 3.5$), they can be more effectively leveraged for these studies by virtue of the better high-energy statistics.

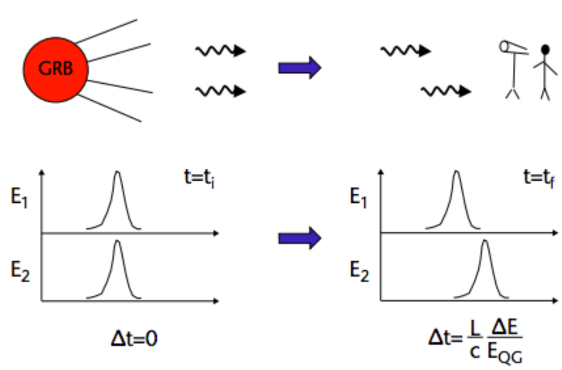

Figure 8: In quantifying LIV, measurements of photon time-of-flight are necessary for relatively distant sources which display a specific epoch of flux variability, such as a GRB (in the above scenario) or a flare from a VHE blazar. Quantifiable measurement or constraint are only possible with the assumption that the energy dispersion at the source is negligible. The measurement of any significant dispersion can therefore be attributed to the dispersive properties of the vacuum. Figure from [19].

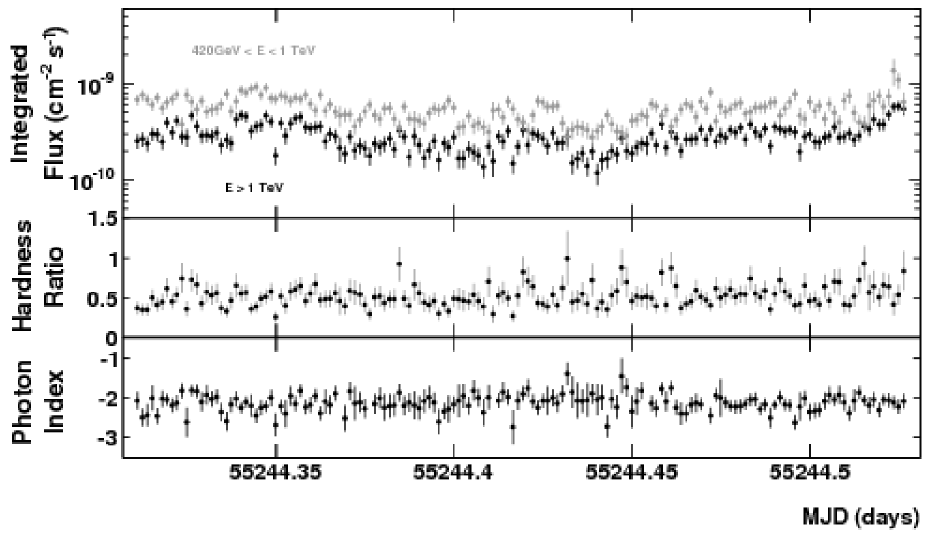

Figure 9: Light-curve of Mrk 421 during a flare in 2010, as measured by VERITAS. From top to bottom: integrated light-curve between 420 GeV and 1 TeV (grey) and above 1 TeV); hardness ratio ($F_{>1TeV}/F_{420GeV-1TeV}$); spectral index.

2 An Overview of the BSWG LTP

The LTP for VERITAS blazar observations covers all the known VHE blazars in the Northern Hemisphere, with different exposures chosen to maximize the overall scientific outcome. For all the VERITAS observations, we will organize simultaneous X-ray and ultra-violet coverage with the Swift satellite, as well as optical monitoring with the 48" telescope at the Fred Lawrence Whipple Observatory. This ensures the construction of unprecedented simultaneous broad-band SEDs for all the blazars. The MeV-GeV part of the SED is systematically covered by the Fermi satellite, thanks to its all-sky observing strategy. In order to maximize the possibility of catching flaring activities, the VERITAS observation will be taken with a monitoring strategy, spread along the entire source visibility window.

The total planned exposure is 198 hours of VERITAS observations. Among them, the deep monitoring of five blazars for EBL studies represents the biggest part, with 80 hours (see next Section for details). The main objectives are, to extend our spectral reconstruction above a γ-ray opacity (τ) of 2, and to obtain long-term simultaneous light-curves, to better study the properties of the source emission. By 2019, we expect to reach an exposure at least between 144 and 244 hours for these five different sources, which will be enough to achieve the goal of a spectral reconstruction at $\tau > 2$.

Three IBL/LBL detected by VERITAS will be monitored for ten hours per year for each source. The goal in this case is to reach a significant detection of the low-flux state (in order to compare it with the flaring activity), as well as to catch additional flares which, given the simultaneous Swift coverage, will all have a MWL coverage. By 2019, the cumulative exposure for these three objects is expected to be at least between 95 and 125 hours.

Particular attention is reserved to the two nearest and well known HBLs Mrk 421 and Mrk 501, which are the two brightest extra-galactic sources at VHE. For these objects, coordinated MWL campaigns involve as well the MAGIC telescope array, in order to better sample the VHE light-curves. A total of ten hours per year are reserved to Mrk 421 observations, and eight hours per year to Mrk 501. The cumulative exposure by 2019 is expected to be at least 228 and 121 hours, respectively: these data will be used as well to put constraints on the pair halo emission.

The remaining part (70 hours) of the LTP is focused on a snapshot program: we will take brief observations on a regular basis on all the remaining VHE blazars of the Northern Hemisphere, in order to catch flaring activity. The blazar snapshot program started during the 2013/2014 observing season, and it already proved to be an efficient tool: five flares from five different VHE blazars were detected, and each of them was the brightest γ-ray flare observed so far for that source.

An important goal of our project is to detect blazar flares. Given this, we do want to continue observations during flares evolution, as this rapidly increases overall spectral statistics, enables stronger studies of exotic phenomenas, as well as studies involving SED evolution. To do so, we have pre-approved a total of 80 hours of ToO observations. Although the majority of our ToOs are self-triggered (i.e. the detection of a high-state during monitoring observations automatically triggers additional follow-up), we have as well set up external triggers from MWL observations: we have automatic pipe-lines for both Fermi-LAT and the 48" telescope, and all the simultaneous Swift observations are automatically reduced by the Swift team and publicly accessible. The 80 hours per year have been estimated as the average of the ToO observations triggered by VERITAS during the past seasons.

Another product of this overall program is that we will, at minimum, ensure that another 10 hours of data are taken by VERITAS on every known VHE blazar in the Northern Hemisphere. As can be seen in Figure 10, for some ($\sim$ 10) objects this will be the first significant VERITAS exposure. For all other known Northern VHE blazars, the minimal exposure will be considered deep ($\geq$ 25 hours). As such, by 2019 VERITAS will have systematically studied the Northern VHE blazar sky and done everything possible to observe a VHE blazar flare during this time.

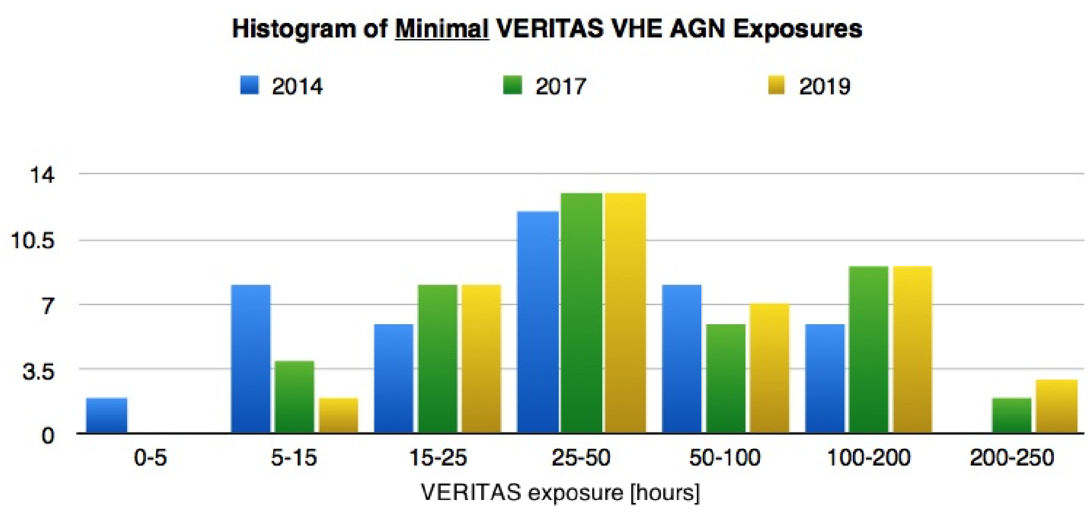

Figure 10: Histogram showing the number of VHE blazars with a given VERITAS exposure (in hours). In blue is shown the current status (at 2014), while in green and yellow we show the expected (minimal) exposure that will be obtained thanks to the blazar LTP in 2017 and 2019, respectively.

3 Details of the BSWG LTP

Scientific Drivers:

A: Understand blazar gamma-ray emission mechanisms (see Section 1.1)
B: Locate the VHE emission regions(s) (see Section 1.2)
C: Understand the origin of differences in the gamma-ray flux states and spectral variability of blazars (see Section 1.3)
D: Indirectly probe the optical and IR photon density of the extragalactic background light (see Section 1.4)
E: Disentangle Possible VHE Flux Contributions from Cosmic Ray Line of Sight Interactions (see Section 1.5)
F: Constrain Magnitude of the Intergalactic Magnetic Field (see Section 1.6)
G: Search for Evidence of Axion-like Particles (see Section 1.7)
H: Search for potential violations of Lorentz invariance (see Section 1.8)

3.1 Deep Monitoring of Blazars (110 hours)

3.1.1 EBL Blazars (80 hours)

Gamma-ray opacity of 2 is denoted as τ=2. For these 5 sources, dates are arranged with the Swift team prior to the shift. These dates drive when the VERITAS data should be taken. Dates are ideally simultaneous, but can be made up close to the date.

- **1ES 0229+200** (2% Crab, $\Gamma\sim2.5$, z=0.14, current spectral reconstruction < 4 TeV)
  - Request: 16 hrs (2-hr exposures 2X per month for four months)
  - Expected outcome: > 176 hrs by 2019, spectral reconstruction > 4 TeV
  - Required measurement(s) for impact on science drivers:
    * A: good contemporaneous multiwavelength (MWL) coverage for VERITAS observation epochs
    * D: significant spectral points above τ=2 (2.5 TeV)
    * E: well-measured spectral points above and below τ=2 (2.5 TeV)
    * F: significant source detection above τ=2 (2.5 TeV)
    * G: well-measured spectra extending across a wide range of gamma-ray opacities

- **RGB J0710+591** (3% Crab, $\Gamma\sim2.7$, z=0.125, current spectral reconstruction < 4.6 TeV)
  - Request: 16 hrs (2-hr exposures 2X per month for four months)
  - Expected outcome: > 179 hrs by 2019, spectral reconstruction > 4.6 TeV
  - Required measurement(s) for scientific impact:
    * A: good contemporaneous MWL coverage for VERITAS observation epochs
    * D: significant spectral points above τ=2 (3.4 TeV)
    * E: well-measured spectral points above and below τ=2 (3.4 TeV)
    * F: significant source detection above τ=2 (3.4 TeV)
    * G: well-measured spectra extending across a wide range of gamma-ray opacities

- **1ES 1218+304** (2-25% Crab, $\Gamma\sim3.1$, z=0.182, current spectral reconstruction < 1.8 TeV)
  - Request: 16 hrs (1-hr exposures 4X per month for four months)
  - Expected outcome: > 207 hrs by 2019, spectral reconstruction > 1.8 TeV
  - Required measurement(s) for scientific impact:
    * A: good contemporaneous MWL coverage for VERITAS observation epochs
    * C: observation on the source in elevated state (similar to 2009) with full MWL coverage of elevated state
    * D: significant spectral points above τ=2 (1.1 TeV)
    * E: well-measured spectral points above and below τ=2 (1.1 TeV)
    * F: significant source detection above τ=2 (1.1 TeV)
    * G: well-measured spectra extending across a wide range of gamma-ray opacities

- **PKS 1424+240** (1-3% Crab, $\Gamma\sim4.0$, z>0.6, current spectral reconstruction < 600 GeV with ∼2 spectral points > 300 GeV)
  - Request: 16 hrs (2-hr exposures twice per month for four months)
  - Expected outcome: > 244 hrs by 2019, spectral reconstruction > 600 GeV
  - Required measurement(s) for scientific impact:
    * A: good contemporaneous MWL coverage for VERITAS observation epochs
    * C: observation on the source in elevated state (similar to discovery in 2009) with full MWL coverage of elevated state
    * D: well-measured spectral points above τ=2 (300 GeV)
    * E: well-measured spectral points above and below τ=2 (300 GeV)

        * G: well-measured spectra extending across a wide range of gamma-ray opacities

- **H 1426+428** (1% Crab, $\Gamma\sim2$, z=0.129, current spectral reconstruction < 5.5 TeV)
    - Request: 16 hrs (2-hr exposures twice per month for four months)
    - Expected outcome: > 144 hrs by 2019, spectral reconstruction > 5.5 TeV
    - Required measurement(s) for scientific impact:
        * A: good contemporaneous MWL coverage for VERITAS observation epochs
        * D: significant spectral points above τ=2 (2.8 TeV)
        * E: well-measured spectral points above and below τ=2 (2.8 TeV)
        * F: significant source detection above τ=2 (2.8 TeV)
        * G: well-measured spectra extending across a wide range of gamma-ray opacities

3.1.2 Notably Variable Blazars (30 hours)

For these sources, Swift dates will be pre-arranged, but no make-up dates will happen regardless.

- **3C 66A** (3-10% Crab, $\Gamma\sim4.0$, 0.341<z<0.41, current spectral reconstruction < 550 GeV)
    - Request: 10 hrs (1-hr exposures 4X per month for four months, no bad weather makeup)
    - Expected outcome: > 118 hrs by 2019, significant detection of low state, copious MWL data, observation scheme to increase likelihood of catching a flare
    - Required measurement(s) for scientific impact:
        * A: good contemporaneous MWL coverage for VERITAS observation epochs
        * B: well-measured gamma-ray spectra which might show gamma-gamma absorption feature
        * C: good MWL coverage of low and any high state triggers
        * E: well-measured spectral points above and below τ=2 (500 GeV for z=0.341)
        * G: well-measured spectra extending across a wide range of gamma-ray opacities
- **W Comae** (2-8% Crab, $\Gamma\sim3.5$, z=0.102)
    - Request: 10 hrs (1-hr exposures 4X per month for four months, no bad weather makeup)
    - Expected outcome: > 155 hrs by 2019, significant detection of low state, copious MWL data, observation scheme to increase likelihood of catching a flare
    - Required measurement(s) for scientific impact:
        * A: good contemporaneous MWL coverage for VERITAS observation epochs
        * B: well-measured gamma-ray spectra which might show gamma-gamma absorption feature
        * C: good MWL coverage of low and any high state triggers
- **BL Lac** (variable flux, $\Gamma\sim3.0$, z=0.069)
    - Request: 10 hrs (1-hr exposures 4X per month for four months, no bad weather makeup)
    - Expected outcome: > 95 hrs by 2019, significant detection of low state, copious MWL data, observation scheme to increase likelihood of catching a flare
    - Required measurement(s) for scientific impact:
        * A: good contemporaneous MWL coverage for VERITAS observation epochs
        * B: well-measured gamma-ray spectra which might show gamma-gamma absorption feature and coordinated radio imaging data
        * C: good MWL coverage of low and any high state triggers

3.2 Iconic Objects (18 hours)

For these sources, Swift dates will be pre-arranged, but no make-up dates will happen regardless.

- **Mrk 421** (widely variable flux, $\Gamma \sim$2.0-3.0, z=0.03, current spectral reconstruction $<$ 20 TeV)
  - Request: 10 hrs (fixed date monitoring observations over 6 months coordinated with MAGIC, no bad weather makeup)
  - Expected outcome: $>$ 228 hrs by 2019, significant detection of low state, copious MWL data, observation scheme to increase likelihood of catching a flare
  - Required measurement(s) for scientific impact:
    - A: good contemporaneous MWL coverage for VERITAS observation epochs
    - B: high resolution radio imaging
    - C: good MWL coverage of all states
    - D: Spectral reconstruction beyond τ=2 (18 TeV) - most likely during flare
    - E: Challenged by measurement of significant variability above τ=2 (18 TeV)
    - F: Deep observations allows search for halo emission beyond VERITAS PSF
    - H: Observation of rapid variability, found to occur during elevated VHE emission
- **Mrk 501** (widely variable flux, $\Gamma \sim$2.0-3.0, z=0.03, current spectral reconstruction $<\tau$ 10 TeV)
  - Request: 8 hrs (fixed date monitoring observations over 4 months coordinated with MAGIC, no bad weather makeup)
  - Expected outcome: $>$ 121 hrs by 2019, significant detection of low state, copious MWL data, observation scheme to increase likelihood of catching a flare
  - Required measurement(s) for scientific impact:
    - A: good contemporaneous MWL coverage for VERITAS observation epochs
    - B: high resolution radio imaging
    - C: good MWL coverage of all states
    - D: Spectral reconstruction beyond τ=2 (18 TeV) - most likely during flare
    - E: Challenged by measurement of significant variability above τ=2 (18 TeV)
    - F: Deep observations allows search for halo emission beyond VERITAS PSF
    - H: Observation of rapid variability, found to occur during elevated VHE emission

3.3 Snapshot Program (70 hours)

3.3.1 Deeper MWL-coverage snapshots (22 hours)

For these sources, the snapshot dates should be lined up to be simultaneous with Swift if possible.

- **1ES 0414+009** (2% Crab, $\Gamma \sim$4.0, z=0.287, current spectral reconstruction $<$ 850 GeV)
  - Request: 8 hrs (1-hr exposures twice per month for four months)
  - Expected outcome: $>$ 132 hrs by 2019, spectral reconstruction $>$ 850 GeV
- **VER J0521+211** (variable flux, $\Gamma \sim$3.5, z=0.108, current spectral reconstruction $<$ 2 TeV)
  - Request: 4 hrs (30-min exposures twice per month for four months)
  - Expected outcome: $>$ 51 hrs by 2019, observation of source in multiple states, spectral points reconstruction $>$ 2 TeV
- **1ES 0502+675** (6% Crab, $\Gamma \sim$3.9, z=0.341(?), current spectral reconstruction $<$ 1 TeV)
  - Request: 2 hrs (15-min exposures twice per month for four months)
  - Expected outcome: $>$ 42 hrs by 2019, observation of source in multiple states, spectral points reconstruction $>$ 1 TeV
- **S5 0716+714** (variable flux, $\Gamma \sim$3.45, z=0.31, current spectral reconstruction : none)
  - Request: 2 hrs (15-min exposures twice per month for four months)

  - Expected outcome: $>$ 47 hrs by 2019, observation of source in multiple states, first VERITAS detection

- **PG 1553+113** (variable flux, $\Gamma\sim4.3$, z=0.43-0.58, current spectral reconstruction $<$ 500 GeV)
  - Request: 2 hrs (15-min exposures twice per month for four months)
  - Expected outcome: $>$ 124 hrs by 2019, observation of source in multiple states, spectral points reconstruction $>$ 500 GeV
- **1ES 1959+650** (variable flux, $\Gamma\sim2.5$-3.0, z=0.048, current spectral reconstruction $<$ 10 TeV)
  - Request: 2 hrs (15-min exposures twice per month for four months)
  - Expected outcome: $>$ 33 hrs by 2019, observation of source in multiple states, spectral points reconstruction $>$ 10 TeV
- **1ES 2344+514** (variable flux, $\Gamma\sim2.4$-2.9, z=0.044, current spectral reconstruction $<$ 8 TeV)
  - Request: 2 hrs (15-min exposures twice per month for four months)
  - Expected outcome: $>$ 52 hrs by 2019, observation of source in multiple states, spectral points reconstruction $>$ 8 TeV

- For all of them:
  - Required measurement(s) for scientific impact:
    * A: good MWL coverage of all observations
    * C: observation on the source in elevated state with full MWL coverage of elevated state
    * D: significant spectral points above τ=2
    * E: well-measured spectral points above and below τ=2
    * F: significant source detection above τ=2
    * G: well-measured spectra extending across a wide range of gamma-ray opacities

3.3.2 General snapshots (48 hours)

- Every northern VHE-detected blazar not explicitly summarized above
  - Requests: 2 hrs on each of the 24 remaining VHE-detected blazars (15-min exposures twice per month for four months)
  - Expected outcome: At least 10 hrs exposure on every VHE-detected blazar by 2019, enable likelihood of catching flares, measuring flux and spectral variability, and collection of copious MWL datasets
  - Required measurement(s) for scientific impacts in case of flare detection:
    * A: good contemporaneous MWL coverage for VERITAS observation epochs
    * B: well-measured gamma-ray spectra which might show gamma-gamma absorption feature as well as high resolution radio imaging
    * C: good MWL coverage of all states
    * D: Spectral reconstruction beyond τ=2
    * E: Challenged by measurement of significant variability above τ=2
    * F: Deep observations allows search for halo emission beyond VERITAS PSF
    * G: well-measured spectra extending across a wide range of gamma-ray
    * H: Observation of rapid variability, found to occur during elevated VHE emission opacities

3.4 Pre-approved ToO Observations (80 hours)

See spreadsheet with outline of sources, triggers and expected ToO responses. The spreadsheet does not cover everything, but the large majority of the expected triggers based on the previous knowledge of blazar variability at lower wavelengths.

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The VERITAS Galactic long-term observing plan 2014-2019

The Galactic Science Working Group

November 7, 2014

1 Introduction

VHE observations of Galactic particle accelerators provide a unique window into their workings. Free of thermal emission, this energy band reveals the spatial distribution and energy content of electrons and ions with energies from 100's of GeV up to many 10's or even 100's of TeV. This document summarizes the long-term observing plan of Galactic TeV sources with VERITAS. The long-term plan (LTP) outlines the multi-season exposures required by the top-priority Galactic programs to ensure they achieve their highest possible impact and meet their scientific goals within the anticipated lifetime of VERITAS. The outcome of the long-term plan together with the hitherto published observations of Galactic gamma-ray sources will constitute an important part of the legacy of VERITAS. This plan is the result of extensive discussions within the Galactic Science Working Group and the VERITAS collaboration and has been presented to a wider scientific community at a workshop on Galactic Science in New York in Spring 2014.

The major questions addressed in the Galactic long-term plan are:

- How do galactic particle accelerators work and what is their acceleration efficiency? What role does their environment play?
- What determines the yield of accelerated electrons, as opposed to that of ions, in Supernova Remnants (SNRs), Pulsar Wind Nebulae (PWNs), and X-ray Binaries?
- Can SNRs (and/or other sources) explain the bulk of Galactic cosmic rays?
- How do pulsar magnetospheres work?

Achievements of the VERITAS Galactic program. The observations and publications of the VERITAS Galactic program from 2007-2014 form the base of this long-term plan. They include (among others): discovery of very-high energy (VHE) emission from the young SNR Tycho, one of the strongest pieces of evidence for hadronic acceleration in SNRs; discovery of >100 GeV pulsed emission from the Crab pulsar, which strongly constrains the emission site of the pulsed gamma rays to greater than 10 stellar radii from the neutron star; high-resolution imaging of Milagro-detected sources in the Cygnus region and around MGRO J1908+06; expansion of the catalog of TeV pulsar wind nebula with the detection of gamma-rays from CTA 1, CTB 87, and others; deep investigation of TeV J2032+4130, the first unidentified TeV source, assisting in its identification as a PWN; and long-term monitoring of the bright gamma-ray binaries LS I +61 303 and HESS J0632+057, with our understanding of the binary nature of HESS J0632+057 being driven by a combination of VERITAS and Swift observations.

Galactic high-energy astrophysics 2014-2019. The impact of the long-term plan outlined in this document will be amplified by coordinated observations with instruments operating at gamma-ray (e.g. HAWC or Fermi LAT) and lower energies (e.g. Swift in X-rays). Coordination meetings with HAWC (multi-TeV energies) and Fermi-LAT (MeV-GeV) are currently taking place, and a closer collaboration with the TeV instruments MAGIC and HESS, especially important for the binary program, is planned. Additionally, in each right ascension band 30% of all VERITAS observing time is reserved for TAC-allocated observations, about ∼30% of which we expect to be Galactic targets. These observations will complement the long-term plan by adding discovery targets and deeper observations of promising targets.

Instrument performance for the observation of Galactic gamma-ray sources. VERITAS is sensitive to gamma rays in the energy range of 85 GeV (>200 GeV for moonlight observations) to 35 TeV. It can detect a point-like source with a flux of 1% of the Crab Nebula in less than 25 h at high elevation (2% / 10% Crab Nebula flux in 7 h / 30 min). The angular resolution (68% containment radius) is better than 0.15 deg at 200 GeV and better than 0.08 deg at 1 TeV; the field of view of VERITAS is 3.5 deg. The energy resolution is 10-15%; the systematic error on the flux is typically less than 20% for Galactic sources. Large-zenith observations increase the sensitivity at energies above 7 TeV by a factor of about 2 and the effective area by a factor of 3-5, without significantly degrading the angular resolution. Observations of Galactic objects are constrained by yearly monsoon weather in Arizona, which does not allow any operation in July and August. The total available observing time per year is around 1000 h (including moderate moonlight time).

2 The VERITAS Galactic long-term observing plan

The broad science goals of the long-term Galactic plan and the observations needed to address these goals are described below in detail. This long-term plan requests a total of 1125 h of observations of these targets in the period 2014-2019 (225 h per year). To avoid oversubscription of observing time due to LTP targets, the selection of targets has been coordinated within the Galactic plan and with objects chosen by the Blazar and the DM-Aspen science working groups. A yearly review of the progress of the plan is foreseen, allowing us to adapt the plan if necessary and react to new developments in the field from, for example, our own observing program, or those of Fermi-LAT, MAGIC, HESS, or HAWC.

2.1 The origin of cosmic rays - gamma rays from supernova remnants

Object	RA	Dec	Planned LTP exposure	Existing exposure[1]	Comments
Tycho	00 25	+64 08	100 h	138 h	
Tycho LZA	00 25	+64 08	100 h	-	30-40 deg elevation
IC 443	06 18	+22 39	85.0 h	85	

LZA=large zenith angle observations

[1] Existing VERITAS exposure may have been collected with an instrument configuration which was far less sensitive than VERITAS today.

Evidence that supernova remnants accelerate hadronic cosmic rays continues to grow, with the recent striking (but long-anticipated) results from the Fermi LAT observations of a 200-MeV spectral break characteristic of pion decay in IC 443 and W44 (Ackermann et al., 2013). In the VHE ($>$ 100 GeV) band, the evidence is less clear, though sophisticated modeling of broad-band emission from Tycho's SNR implies predominantly hadronic emission (Morlino & Caprioli, 2011). Modeling of RX J1713.7-3946 may require nonlinear diffusive shock acceleration (DSA), which also implies efficient acceleration of cosmic-ray hadrons (Ellison et al., 2012). VERITAS can contribute to answering open questions in this field with the following observations.

A deep observation of Tycho's SNR will allow us to refine and extend the measurement (Acciari et al., 2011) of the spectrum of this well studied historical SNR. Multiple broad-band models agree that the VHE emission from Tycho arises predominantly from hadronic interactions (Morlino & Caprioli, 2012; Berezhko et al., 2012; Zhang et al., 2013; Slane et al., 2014). These models are well constrained at radio through X-ray wavelengths, and the statistics in the GeV band continue to improve as Fermi-LAT continues to operate (and will benefit from the release of Pass 8 data products in mid 2015). However, only by better measurement of Tycho's spectrum at the highest energies can we provide a real test for a variety of theoretical models and very likely another case with strong experimental evidence for hadronic acceleration in SNRs and possibly find spectral structure in the GeV-to-TeV band that would be indicative of a change in the dominant emission process or location. Secondary goals include localizing the centroid of the VHE emission and searching for extended emission. Most of the existing models assume that the shell is the source of the VHE emissions. But, whether the VHE emission is coming from the shell or a nearby molecular cloud is ambiguous due to the limited statistics of the present measurement. Our prediction suggests that a deeper exposure of about 200 hours is required to determine the source of the emission, and this will constrain the existing theoretical models.

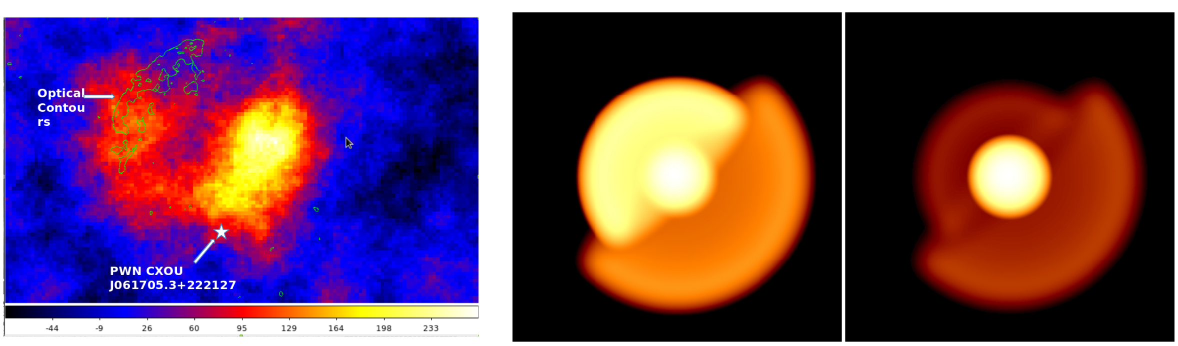

Figure 1: (left) Significance map of IC 443 based on data taken between 2009 and 2013, showing emergence of emission from the northeast shell of the remnant. In green are overlaid optical contours from DSS showing the region where the northeast shell is interacting with a neighboring HI cloud. (middle) GeV gamma-ray emission map for IC 443 for a typical model. (right) TeV gamma-ray emission map for the same model.

A deep observation of IC 443. This system is a classic case of an SNR shock interacting with a surrounding molecular cloud, which acts as a target medium for previously accelerated CRs. The clear detection of the "pion bump" spectral feature below 300 MeV by Fermi-LAT confirms that IC 443 is a cosmic-ray accelerator (Ackermann et al., 2013). We have 85 hours of data on IC 443, taken between 2007 and 2014; together, these data show strong evidence for emission extended across most of the northeastern lobe of the SNR (and not confined to the region where the MC crosses the line of sight, as suggested by shallower observations), as shown on the left in Figure 1. The center panel of Figure 1 shows the GeV emission expected in a typical model for IC 443, while the right panel shows the TeV emission for the same model (Telezhinsky; private communication). The very different morphology shows the opportunity to constrain models of CR diffusion, given sufficiently high-quality maps in both energy bands. A doubling of the exposure (implying more than doubling of the exposure at low energy, due to the upgrade) will allow a high-significance detection of this plateau emission, along with measurements of spectra from a number of sub-regions of the SNR (and, conversely, mapping of the emission in several energy bands). These measurements, when combined with an updated Fermi Pass-8 data analysis, will enable a detailed study of the CR escape and diffusion processes in the vicinity of an SNR.

2.2 Pulsar Wind Nebulae and the electron/positron content of the Galaxy

Object	RA	Dec	Planned LTP exposure	Existing exposure[1]	Comments
PSR B0355+54	03 58	+54 13	39.5 h	0.5 h	>60 deg el., dark, 3/4 tel
CTB 80	19 53	+32 52	30.0 h	-	>60 deg el., d+m, 3/4 tel
PSR J2022+3842	20 22	+38 42	25.0 h	5 h	>60 deg el., d+m, 3/4 tel
Boomerang PWN	22 29	+61 14	67.0 h	83 h	>55 deg el., dark, 3/4 tel

Requested observing conditions: see comments field (el.=elevation, d+m = dark and moderate moonlight observations), 3/4 tel = 3- and 4-telescope data

The Pulsar Wind Nebulae long-term plan has three areas of interest, addressing the most important periods of PWN evolution:

Survey of high-power systems. Young pulsars ($\tau_C \lesssim 10^5$ yr) of high spin-down power ($\dot{E} \gtrsim 10^{37}$ erg s^{-1}) frequently develop TeV PWNe - but not in all cases. TeV observations of these objects, both singularly and as a population, and especially when combined with multiwavelength data, allow us to test models of pulsar wind transport, magnetic field strength, and interactions with parent SNR material, revealing the conditions that lead to efficient particle acceleration. Within the LTP, we plan to focus on two high-$\dot{E}$ pulsars which lie in competitive RA bands: PSR J2022+3842 (G76.9+1.0; $\dot{E} = 3.0 \times 10^{37}$ erg s^{-1}) and PSR J1952+3252 (CTB 80; $\dot{E} = 3.7 \times 10^{36}$ erg s^{-1}). Of the top 10 most powerful Northern pulsars (Hobbs et al., 2004), these are the last two that lack a deep TeV observation by a current-generation instrument. Seven of the other eight have TeV associations, while the eighth was discovered only recently (2013) and does not yet have evidence for a PWN in radio or X-ray data, but was observed already as part of the HESS Galactic Plane Survey. We aim for 30 hr of exposure on each object, including good-quality archival data, to reach $\lesssim$ 1% Crab flux. A nondetection at this flux level would be a surprise; detections would allow us to better study the population of young, high-power pulsar nebula systems, to understand the underlying physical reasons for the varying TeV efficiency, and to provide new tests for models of

PWN physics.

Deep observation of a known extended source. Modeling efforts for PWNe are commonly one-zone models, focusing on volume-averaged properties of the nebula (i.e. they assume efficient mixing of material within the nebulae), and thus offer no detailed information on the internal structure and particle transport and cooling mechanisms. To better understand these phenomena, we require detailed imaging of the nebula morphology, including any energy-dependent changes. This requires a deep exposure of a significantly extended TeV PWN. The SNR G106.3+2.7, which contains the Boomerang nebula, has been selected as the most favorable such target. The previous VERITAS study of this SNR and nebula is shown in Figure 2. We estimate that a total exposure of ~ 150 hours is required to reach sufficient statistics for studying the morphology in multiple (> 2) energy bands, and extracting spatially resolved spectra. This estimate includes ~ 83 hours of archival data, less than 40 hours of which have been previously published.

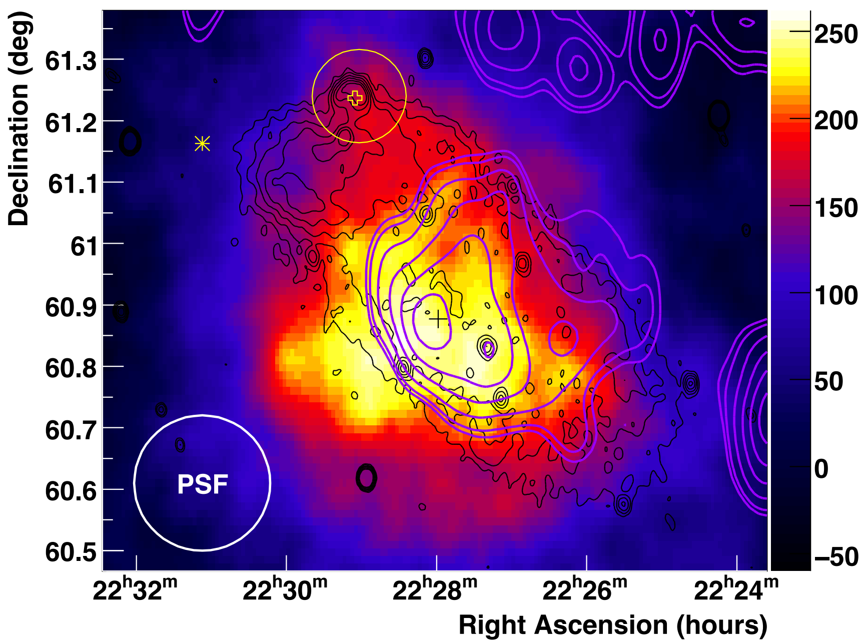

Figure 2: Excess counts map for the SNR G106.3+2.7 field (Acciari et al., 2009). Sky map of TeV gamma-ray emission from G106.3+2.7, as measured by VERITAS, using a squared integration radius of 0.08 deg^2. Black cross: centroid of the TeV emission. Thin black lines: 1420 MHz radio contours (Landecker et al., 2000). Magenta lines: ^{12}CO emission ($J = 1 - 0$) from Heyer et al. (1998). Open yellow cross: PSR J2229+6114. Yellow star: 1AGL J2231+6109. Yellow circle: 95% localization contour for 0FGL J2229.0+6114.

PWNe in a simpler environment (pulsar tails). The PWNe currently detected at TeV energies are typically in complex environments of SNR interiors. These are environments that evolve with time, depend on the initial conditions of the parent supernova and its surrounding medium, and may eventually lead to complicated interactions with the SNR reverse shock. In addition, any TeV emission detected may be confused with that from the SNR (e.g. interaction with nearby molecular clouds).

In contrast to this scenario are pulsar tails, formed by fast-moving pulsars which have escaped the parent SNR and are driving a bow shock through the ISM, a simpler medium. They exhibit a linear structure, so that the long-term history of particle injection is correlated to distance from the pulsar. Detection of such an object would offer an opportunity to test and calibrate simpler models of PWNe (where the only important radiation process in TeV is IC scattering on CMB) prior to approaching PWNe in more complex environments where additional radiative processes may be important.

Only ~ 12 pulsar tails are known (Kargaltsev et al., 2013). The tail associated with PSR B0355+54 is the most optimal for observation by VERITAS. For the seven tails visible to the HESS Galactic Plane survey (Carrigan et al., 2013), we estimate upper limits of 0.4-3% Crab flux (TeV luminosity of $(3\text{-}74)\times10^{32}$ erg/s). However, the larger distances to these objects (2.5-11 kpc) compared to PSR B0355+54 (1.0 kpc) means that we can achieve a superior constraint on the PWN luminosity ($\lesssim 9 \times 10^{31}$ erg/s) within only ~ 30 hours.

2.3 Pulsars

Object	RA	Dec	Planned LTP exposure	Existing exposure[1]	$\dot{E}$ [erg/s]	$\dot{E}/d^2$ [erg/s/cm^2]
Crab Pulsar	05 34	-22 00	140 h	160 h	$4.6 \cdot 10^{38}$	$1.2 \cdot 10^{38}$
PSR J0308+74	03 08	+74 42	20 h	0 h	$2.2 \cdot 10^{34}$	$1.9 \cdot 10^{35}$
PSR J1959+2048	19 59	+20 48	20 h	0 h	$1.6 \cdot 10^{35}$	$6.8 \cdot 10^{34}$
PSR J0751+1807	07 51	+18 07	20 h	0 h	$7.3 \cdot 10^{33}$	$4.6 \cdot 10^{34}$
PSR J0030+0451	00 30	+04 51	20 h	0 h	$3.5 \cdot 10^{33}$	$4.4 \cdot 10^{34}$
PSR J1024-0719	10 24	-07 19	20 h	0 h	$5.3 \cdot 10^{33}$	$2.2 \cdot 10^{34}$
PSR J2215+5135	22 15	+51 35	20 h	0 h	$5.2 \cdot 10^{34}$	$5.8 \cdot 10^{33}$
PSR J1816+4510	18 16	+45 10	20 h	0 h	$4.9 \cdot 10^{34}$	$2.8 \cdot 10^{33}$

Requested observing conditions: >55 deg elevation, dark conditions (no moonlight observations), 3- and 4-telescope data

Pulsars are rapidly spinning neutron stars surrounded by a co-rotating magnetosphere. The observation of pulsed electromagnetic emission up to gamma-ray energies tells us that pulsar magnetospheres are efficient particle accelerators. According to our present understanding, the acceleration takes place in vacuum gaps where an electric field, induced by the rotating magnetosphere, is not shorted by an electron-positron plasma. Where these gaps are, and how they form, is not well known. Gamma-ray observations provide indispensable clues to answer these questions and, furthermore, probe the dynamics of the particle acceleration process.

Detecting VHE gamma-ray emission above 100 GeV from a pulsar had been a long-standing quest in astroparticle physics. Only recently, the VERITAS Collaboration succeeded in detecting pulsed emission above 100 GeV from the Crab pulsar (Aliu et al., 2011). The result was surprising for the gamma-ray pulsar community, as theory did not predict strong gamma-ray emission at such energies. The origin of pulsed VHE emission is still not understood, but several ideas have been put forward that need to be tested (e.g., Aharonian et al., 2012; Lyutikov, 2013). The models differ in their predictions of the VHE flux above a few hundred GeV, which cannot be resolved with the existing VERITAS data. It could also be shown that pulsed VHE emission sensitively constraints Lorentz invariance violation (LIV) (Otte et al. (2013), Zitzer et al. (2013).) LIV limits, currently at E_{LIV} of 3×10^{17} GeV on the energy scale of LIV (Otte, 2011), can be improved in the future with deeper observations of the Crab pulsar and VHE detections of millisecond pulsars.

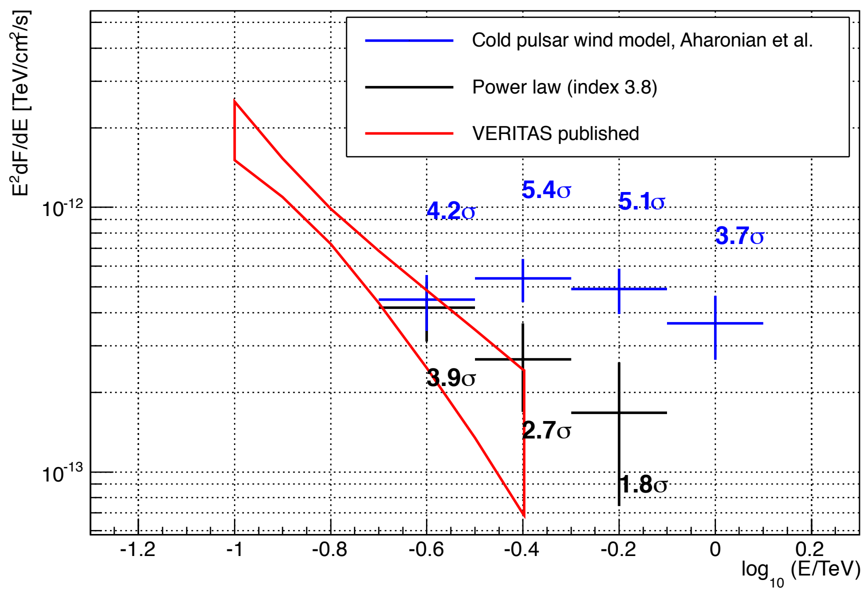

Figure 3: Simulations of the outcome of a 300 hour long observation of the Crab pulsar with VERITAS. The red butterfly shows the best-fit power law to the 110 hours VERITAS observation published in Aliu et al. (2011). The data points in black are predictions for a 300 hour long observation. They simulate the extension of the spectrum in the form of a power law, as predicted in Lyutikov (2013). The data points in blue show the outcome for an equally long observation, but simulate a separate spectral component as predicted by Aharonian et al. (2012). The numbers give the simulated statistical significance for each data point.

In order to become more sensitive to LIV effects and to better understand the pulsed VHE emission, the existing Crab observations will be extended by 140 hours to a total of 300 hours. The final data set will be sensitive enough to distinguish between a hard VHE component predicted by Aharonian et al. (2012) and a power-law extension with cut-off expected by Lyutikov (2013). Figure 3 shows simulation results for both scenarios. The MAGIC Collaboration has just announced a spectral measurement of the Crab pulsar at 1 TeV in a 300 hour long exposure. However, the measurement is only marginal significant above 800 GeV. A 300 hour long exposure with VERITAS will result in a substantially better resolved spectral measurement.

Another problem in understanding the VERITAS Crab pulsar detection is that it is the only pulsar detected above 100 GeV. The H.E.S.S. team announced the detection of the Vela pulsar above 20 GeV, but no emission was seen above 100 GeV (Stegmann, 2014). Whether other pulsars are VHE emitters remains unknown, as few observations have been made of other objects. The VERITAS LTP pulsar program aims at changing this for the northern hemisphere.

The limited time available per year and the long observations necessary to achieve sufficient sensitivity require a biased selection of targets. Some commonly used methods to rank pulsars is by spin-down luminosity and spin-down luminosity divided by distance squared. Without any further selection criteria, the tops of the two lists are dominated by young isolated pulsars, most of which have been serendipitously observed with VERITAS in the past. These data are being analyzed while new pulsar observations are carried out under the umbrella of the LTP.

Because the young pulsars are reasonably well covered with archival data, only millisecond pulsars (MSPs) were selected as LTP targets. The seven selected MSPs all show optical or X-ray emission from within their magnetosphere, or from within the direct vicinity of the magnetosphere. Each pulsar will be observed for 20 hours. The resulting sensitivity for each observation is close to 1% of the Crab-Nebula flux.

MSPs have a much more compact magnetosphere due to their higher spin frequencies than young pulsars. Therefore, the absolute number of electrons and low-energy photons can be much less than in the Crab, and still a detectable VHE flux could be produced via the inverse-Compton mechanism. This assumes that other factors are similar, *e.g.*, the energy of the electrons. That MSPs are more efficient in producing gamma rays than young pulsars was shown with the Fermi-LAT. Because the parameters of MSPs are different from those of young pulsars, MSPs are ideal complements to young pulsars when it comes to testing pulsar models.

The planned VERITAS observations over the next three to five years will provide the first comprehensive VHE MSP survey between 100 GeV and several TeV and give crucial input to constrain models of VHE emission from pulsars.

2.4 Gamma-ray binaries

Object	RA	Dec	Planned LTP exposure	Existing exposure[1]	Orbital period [d]
LS I +61 303	02 40	+61 13	12 h / y monitoring	7 y monitoring	26.5
HESS J0632+056	06 32	+05 48	15 h / y monitoring	7 y monitoring	315
IGR J00370+6122	00 37	+61 21	4.0	8.0	15.67
V662 Cas	01 18	+65 17	12.0	0.0	11.6
IGR J01363+6610	01 36	+66 11	12.0	0.0	?
IGR J01583+6713	01 58	+67 13	12.0	0.0	?
VES 737	02 20	+63 01	5.0	7.0	?
XTE J0421+560	04 19	+55 59	8.0	4.0	19.41
LS V +44 17	04 40	+44 31	9.0	3.0	155?
IGR J06074+2205	06 07	+22 05	11.0	1.0	?
LS IV -01 1	17 07	-01 05	7.0	5.0	?
4U 1907+09	19 09	+09 49	8.0	4.0	8.37
IGR J19140+0951	19 14	+09 52	10.0	2.0	13.56
LS III +49 13	20 56	+49 40	12.0	0.0	?
EXO 2030+375	20 32	+37 38	6.0	6.0	46.2
SAX J2103.5+4545	21 03	+45 45	10.0	2.0	12.68
4U 2206+543	22 07	+54 31	10.0	2.0	9.57

Requested observing conditions: >50 deg elevation, dark and moderate moonlight conditions, 3- and 4-telescope data

Modulated gamma-ray emission has been detected from five binary systems: PSR 1259-63, LS 5039, LS I +61 303, HESS J0632+057 and 1FGL J1018.65856 (see Dubus (2013) for a recent review). All of them are high-mass X-ray binaries consisting of an O or Be star orbiting a compact object with orbital periods between a few days and several years. The dominant physical mechanisms responsible for the acceleration of particles in these system are not well understood and depend on the nature of the compact object, the massive star, and on the geometry of the orbit. Two major scenarios can be found among the wealth of theoretical work: in the microquasar model, charged particles are accelerated in an accretion-driven relativistic jet, similar to the processes observed in active galactic nuclei. Gamma-ray emission observed from microquasars provides a window into the connection between accretion-ejection and acceleration. Alternatively, the high-energy emission is driven by shock interaction between a rotation-powered pulsar and the strong clumpy wind of the massive star.

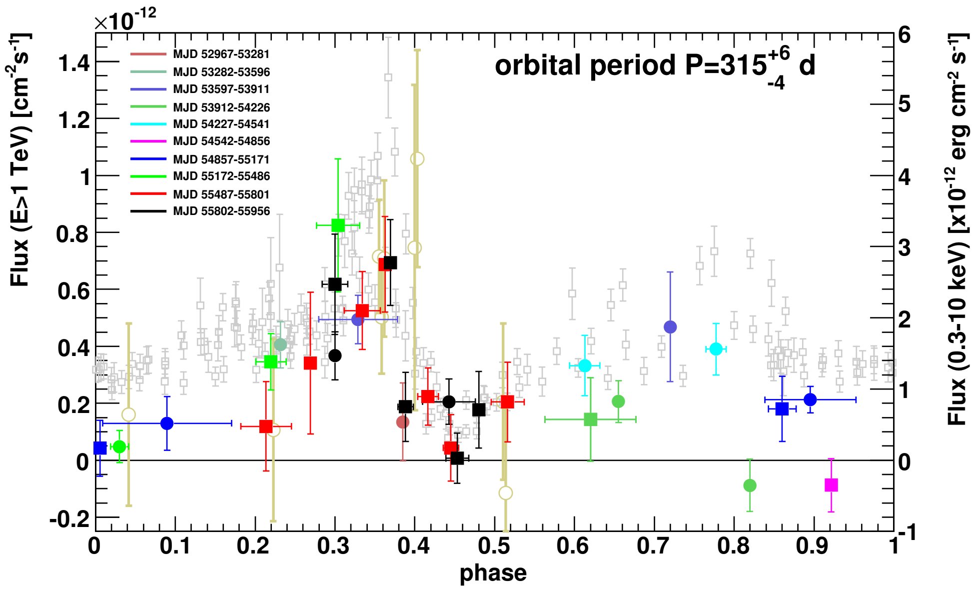

Figure 4: Long-term (8 years) light-curve of the gamma-ray binary HESS J0632+057 (Aliu et al., 2014). Integral γ-ray fluxes above 1 TeV (vertical scale on the left) from H.E.S.S. (filled round markers), MAGIC (brown round open markers, scaled to 1 TeV assuming a power law with index −2.6) and VERITAS (filled squared markers). X-ray fluxes (0.3–10 keV) are shown as measured by *Swift*-XRT (open square grey marker; vertical scale on the right). All measurements are folded with the orbital period of 315 days; the colors indicate different orbits.

Long-term monitoring of the binaries LS I +61 303 and HESS J0632+057. Long-term monitoring at gamma-ray and lower energies is needed to address the questions outlined above. This will allow to find the relation of the emission pattern to the orbital period, the state of the Be disk, or long-term modulation observed at other wavelengths (e.g., the observed four year modulation of the radio emission in LS I +61 303). VERITAS has been observing the binaries LS I +61 303 and HESS J0632+057 regularly for more than seven years (Fig 4). The observations outlined in this long-term plan will continue this successful program over the coming years, providing a data set which will be unique for years to come (even under consideration of the upcoming CTA observatory). It will allow detailed tests on orbital, intra- and super-orbital variability, that would be indicative of the emission site and the location of efficient particle acceleration. It is planned to apply for simultaneous observations at other wavelengths (especially in X-rays) and to coordinate these observations with the MAGIC collaboration.

A systematic search for new gamma-ray binaries. As it is not well understood what is special about the five detected binary systems, any new discovery could provide significant progress in the understanding of the underlying physical processes. The discovery program aims to perform a systematic search for new gamma-ray binaries. 14 candidates have been selected, according to the following criteria: a massive companion star (O/Be) and a relatively small distance (<5 kpc). The known VHE binaries tend to reach relatively high fluxes of 5-10% of the Crab Nebula flux at some point in their orbit. Therefore short observations on the order of a few hours might be enough to detect new sources. The cadence of observations will be of particular importance for this program: the observations for binaries with known orbital solutions shall be taken around apastron, if possible during 1-3 different orbits.

2.5 The Galactic Centre Region

Object	RA	Dec	Planned LTP exposure	Existing exposure[1]	Comments
Galactic Centre	17 45	-29 00	10 h	80 h	+10 h taken in the DM program

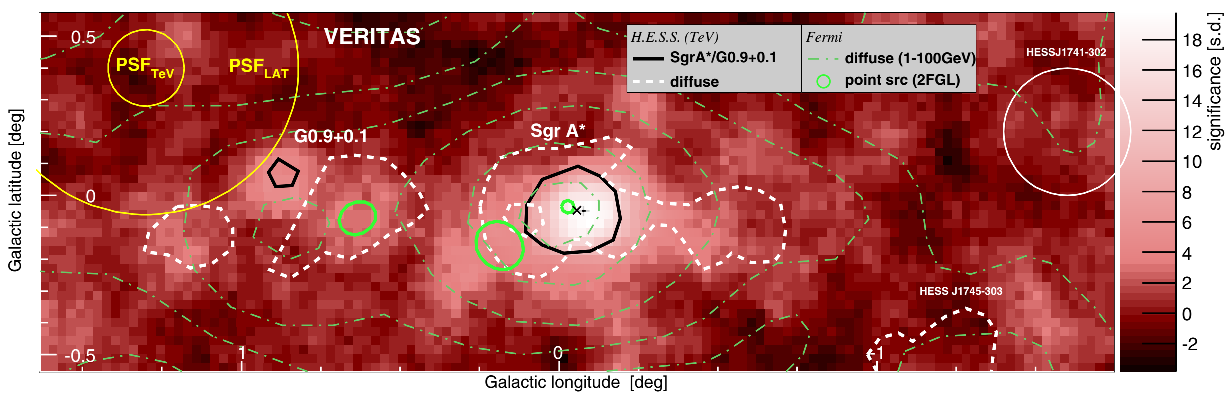

Figure 5: VERITAS sky map of the Galactic center region (Archer et al., 2014). The VERITAS centroid position is indicated by the cross (statistical and systematic errors) and the Sgr A* radio position is indicated by the x. The solid black contour lines indicate the Galactic center and the supernova remnant G 0.9+0.1 as seen by H.E.S.S.. The white dashed contour lines indicate the H.E.S.S. diffuse emission along the Galactic plane and from HESS J1745-303.

In the period 2014-2019, under a reasonable allocation of observing time (split between the Galactic and Dark Matter Working Groups), an additional 100 hours of live time can be taken on SgrA* and surrounding regions. The existing data on the region have revealed emission structures that are both consistent with previous HESS results, as well as possibly indicative of new acceleration regions. Our goal for taking additional time on the area around the Galactic centre is two-fold:

1. Investigate the > 2 TeV morphology of the region. Further observations will augment the existing data set, possibly resolving new regions of multi-TeV emission. This morphology study will provide key overlap with new and upcoming observations at other wavebands such as hard X-rays with NuStar or beyond 10 TeV with HAWC.

2. Constrain the high-energy cutoff in the energy spectrum of SgrA*. One of the unresolved questions about the non-thermal emission coming from the Galactic Center is the mechanism by which SgrA* is producing gamma rays at energies up to 35 TeV. While the current VERITAS spectrum is in good agreement with HESS measurements. Further observations by VERITAS can actually better constrain the cutoff energy of the spectral energy distribution. Note that this is also true for any possible future HESS results, since VERITAS has superior sensitivity in the cutoff region (> 10 TeV). Therefore, accurately constraining the cutoff energy of the SgrA* spectrum is a novel measurement that VERITAS alone is situated to provide.

The significant overlap with the Dark Matter Working Group should be pointed out. The Galactic center region is one of the most attractive target for dark-matter searches (see LTP Document of the Dark Matter Working Groups). A proper characterization of the astrophysical background from point, extended, and diffuse sources, as it is part of this program, is vital for any dark-matter studies.

2.6 Cygnus Deep Survey: the brightest region in gamma rays in the northern sky

Object	RA	Dec	Planned LTP exposure	Existing exposure[1]	Comments
CDS N1	20 17 30.15	42 34 17.6	6.5 h	0.33 h	
CDS N2	20 21 13.34	43 16 17.6	6.5 h	0.33 h	
CDS N3	20 28 39.71	43 58 17.6	6.5 h	1.0 h	
CDS N4	20 39 49.26	43 16 17.6	6.5 h	0.67 h	
CDS W1	20 17 30.15	41 10 17.6	12.5 h	22.55 h	
CDS W2	20 17 30.15	39 46 17.6	12.5 h	12.51 h	

Requested observing conditions: >55 deg elevation, dark conditions (no moonlight observations), 3- and 4-telescope data

The Cygnus region of the Galaxy is distinguished by both its proximity to us (∼1.4 - 3 kpc) and the density and variety of potential cosmic ray accelerators it contains. VERITAS observations of the Cygnus region promise a unique window on the life cycle of cosmic rays, from their production to the period shortly following their escape from their accelerators.

The Cygnus cocoon covers four square degrees and is coincident with a cavity carved in the ISM by winds from a nearby grouping of OB stars. Observations with Fermi-LAT (Ackermann et al., 2011, 2013) have revealed gamma-ray emission between 3 GeV and 500 GeV with a hard spectrum consistent with a power-law index of $\Gamma = 2.1 \pm 0.12$. The emission likely arises from freshly accelerated cosmic rays within the cavity. It is not known if the cocoon spectrum extends to higher energies, although it is co-located with an extended source of > 20 TeV gamma-rays seen by Milagro (Abdo et al., 2012) and ARGO (Bartoli et al., 2014). The type and source of accelerated particles in the cocoon is likewise unknown, although current interpretation favors proton acceleration due to shocks from both supernovae and high-velocity stellar winds within the Cygnus superbubble. The proximity of two other potential accelerators–the Cyg OB2 association and the radio and X-ray SNR gamma-Cygni (G78.2+2.1) (Aliu et al., 2013; Lande et al., 2012)–complicates the picture further. Fermi-LAT sees a disk of hard (power-law index of $\Gamma = 2.39 \pm 0.14$) emission between 10 – 500 GeV covering all of gamma-Cygni (Ackermann et al., 2011, 2013). VERITAS currently sees two more slightly extended gamma-ray sources: the likely pulsar wind nebula (PWN) TeV J2032+4127, and VER J2019+407 (Aliu et al., 2013), overlapping the northwestern shell of gamma-Cygni (Aliu et al., 2013; Leahy et al., 2013).

The energy-dependent morphology of the cocoon from a GeV to tens of TeV must be known to identify the type and origin of the energetic particles trapped within the cavity. VERITAS data cover a critical energy range with superior angular resolution and are the linchpin that connect Fermi-LAT data with those from Milagro, ARGO, and future data from HAWC. A new analysis method sensitive to large-scale gamma-ray emission permits VERITAS to exploit the considerable sample of archival data covering the Cygnus Cocoon and its environment. The goal of the Cygnus Deep Survey is to supplement that existing data at critical locations broken up between northern and western pointings. The northern pointings focus on the region north of TeV J2032+4127 and VER J2019+407 and bring the exposure up to at least 10 hours across the cocoon. This improves our sensitivity and allows more accurate characterization of the cocoon's energy-dependent morphology in the event of a detection. The western pointings improve exposure around the gamma-Cygni SNR. A VERITAS detection of (or upper limit on) emission from the entire gamma-Cygni SNR will help clarify the relationship between the gamma-Cygni SNR, VER J2019+407, and the cocoon and will have dramatic implications for our interpretation of this source and our understanding of Galactic cosmic-ray acceleration.

3 Anticipated impact from HAWC

HAWC has begun science operations with a partial array, and to date, has surveyed the northern sky to a depth of approximately 10% Crab above 2 TeV (Hüntemeyer, 2014). For the current VERITAS season (2014/2015), several HAWC-driven proposals have been submitted to the TAC. We anticipate being able to handle follow up of interesting warm spots with relatively brief exposures, primarily under moonlight. For future seasons, with HAWC at its full sensitivity and reaching a depth of a few % Crab or better, we can anticipate that HAWC will begin to provide a series of interesting targets for VERITAS follow up that will require a significant investment of time, as was the case for previous MILAGRO sources, including the Cisne region (~ 75 h) and MGRO J1908+06 (~ 62 h). Given these examples, we anticipate that high-priority HAWC follow-up may be included in the Galactic LTP at the level of 50 h/yr in future years, which would require a comparable adjustment to the rest of the observing program. Such an adjustment is difficult to make until the targets, their science opportunities, and their RA bands are known.

In a similar vein, one of the legacy sources from MILAGRO that remains undetected by VER-

ITAS is the Geminga PWN: this uniquely close and old PWN provides an opportunity to probe PWN evolution to late stages and may contribute to our understanding of the local cosmic-ray electron population, which is important to understanding the origin of the PAMELA positron excess. It is potentially very extended for VERITAS and dedicated analysis techniques are currently developed. Once these techniques are established and the existing exposure is analyzed, the Geminga PWN may also be addressed in future iterations of the LTP.

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The VERITAS Dark Matter and Astroparticle Long-Term Plan (LTP)

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1 Dark Matter

1.1 Introduction

In the cosmological paradigm, cold dark matter (DM) dominates the mass content of the Universe and is present at every scale. One of the best motivated candidates for DM is known as the weakly interacting massive particle (WIMP). One example of a WIMP is the neutralino, which appears in many supersymmetric extensions of the standard model as a with a mass in the range of ∼10 GeV to greater than 10 TeV. The self-annihilation of the WIMP in astrophysical regions of high DM density can produce secondary particles, including very-high-energy (VHE) gamma rays, with energies up to the DM particle mass. Therefore, observations with VERITAS of regions with a high inferred DM content allows for constraints to be made on the particle phenomenology of the WIMP.

While VERITAS has had a historical commitment to dark matter science, the 2011-2012 observing season was the first season in which DM observations were included in the 'Five Year Plan'. The first year of this program was a tremendous success in terms of hours of observation with approximately 130 hours of dark time observations taken. That trend has continued in the 2012-2013 and 2013-2014 observing seasons (the 2013-2014 accumulated over 150 hours); if executed consistently over the expected lifetime of VERITAS, these observations will form the basis of an important and unique contribution to the field of indirect DM detection.

This plan focuses on what we believe to be the most attractive targets for potential WIMP self-annihilation signatures: dwarf spheroidal galaxies (dSphs), the Galactic center, and Fermi unassociated objects (UFOs). We allocate a total of 156 hours of dark time (additional ToO time not included) to DM targets. Of this time, 146 hours are allocated to dSphs (divided between 14 different targets, 9 of which will be a survey) and 10 hours to the Galactic center (plus an additional 10 hours from the Galactic SWG Long-Term Plan). No LTP time is allocated for Fermi UFOs; these are promising candidates for DM detection, but extrapolation of their spectra to TeV energies show that very few can be detected by VERITAS without requiring very deep exposures. The two best candidates, 2FGL J1115.0-0701 and 2FGL J0545.6+6018, have been approved as part of a Fermi GI proposal, so additional time will not be required unless a strong hint of a signal is present in the analysis. If future Fermi-LAT data show UFOs with better detectibility prospects, we can revisit the possibility that they are included in the long-term plan.

Galaxy clusters are theorized to have larger amounts of DM than dSphs; however, most are very extended for IACTs, which makes the analysis difficult. VERITAS will continue to monitor the radio galaxy M 87 for 20 hours per year which is the center of the Perseus galaxy cluster. The prospects for additional clusters will be reevaluated at a later time if extended source analysis methods reach a more mature state and a better understanding of extended systematics is gained.

1.2 Spheroidal Galaxies - Deep Exposures

Dwarf spheroidal galaxies (dSphs) best meet the criteria for a clear and unambiguous detection of dark matter. They are gravitationally- bound objects and contain up to $\mathcal{O}(10^3)$ times more mass in DM than in visible matter [1]. As opposed to the Galactic center, globular clusters and clusters of galaxies, dSphs present the clear advantage of being free of any significant astrophysical emission. Their high Galactic latitude and relative proximity to Earth make them very good targets for high signal-to-noise detection.

Since early 2007, VERITAS has observed seven objects identified as dSphs with potentially the highest gamma-ray self-annihilation flux, namely Draco, Ursa Minor, Boötes 1, Willman 1, Segue 1, Segue 2, and Ursa Major II (see Table 1). Recent observations indicate that Willman 1 has strong evidence of tidal disruption and/or non-equilibrium kinetmatics [13]. Since dynamic equilibrium is a requirement for mass interference [12], Willman 1 is currently not being considered an observation target. Upper limits on the annihilation cross-section derived from these observations lie in the range $10^{-22} - 10^{-24}\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$, around two orders of magnitude away from the thermal WIMP prediction [2, 3], but already providing important constraints on the leptophillic models invoked to explain the PAMELA positron excess. The two VERITAS publications from these observations have been well received by the DM research community.

Given the relatively low gamma-ray fluxes predicted by generic DM models, the best prospects for setting important limits or possibly for discovery require ongoing long-term (multi-year) observations of a small set of the most promising sources and using a combined or 'stacking' analysis. The best dSphs in the northern hemisphere available for this study are Draco, Ursa Minor, Segue I, Coma Berencies and Ursa Major II (UMaII); these targets represent the best prospects to set limits as well as offering the chance for signal discovery. Draco and Ursa Minor (see [2] and references therein) are nearby classical dSphs with a very well measured stellar population, and hence a well measured DM distribution. Segue 1 is an ultra-faint dSph recently discovered in the Sloan Digital Sky Survey (SDSS) [9], and is often cited as the most DM-dominated dSph currently known [31, 22], despite having a relatively large uncertainty in its density profile (as compared to the classical dSphs). Additionally, despite some evidence that Segue I might be an interaction between two tidal streams, more recent stellar velocity dispersion measurements using a larger set of stars lend greater weight to the argument that Segue I is, in fact, a dSph. UMaII was discovered by SDSS and followed up by Subaru imaging. It is the second- closest known dSph (after Segue I) and at the time of its discovery it was the faintest known dSph [10]. Coma Berencies is also an ultra-faint, nearby dSph discovered by SDSS imaging data [11].

We propose a total of 110 hours per year devoted to deeper observations of dSphs over the three next years, split between Draco, Ursa Minor, Segue 1, Coma Berencies, and UMaII. The exact breakdown of these 110 hours is shown in Table 1. It was decided that ∼70% of the deep exposure time be committed to ultra-faint dSphs while ∼30% be committed to the well-known classical dSphs with the highest average J factors (Draco and Ursa Minor) as protection against changing J factors. By splitting observing time over several sources, we spread our observing request over a larger RA band; minimizing possible systematic for very deep exposures over a single star field. Such a spread also minimizes the risk that a dSph observational program would fail due to a single target falling out of favor as a good DM target or a single dSph reaching

[1] North and South wobble directions only.
[2] East and West wobble directions only.

DSph target (rank)	RA (hr)	$\log_{10}\bar{J}$ ($GeV^2 cm^{-5}$)	$\log_{10}\bar{J}_{decay}$ ($GeV^2\ cm^{-5}$)	Now (hrs)	Yearly (hrs)	Goal (hrs)
Ursa Major II (1)	8	$18.99^{+0.32}_{-0.34}$	$17.66^{+0.17}_{-0.23}$	28	50	180
Draco (5)	17	$18.33^{+0.14}_{-0.12}$	$17.76^{+0.06}_{-0.06}$	67	15	105
Ursa Minor[1] (3)	15	$18.88^{+0.31}_{-0.32}$	$17.67^{+0.04}_{-0.04}$	79	15	125
Coma Berencies (4)	12	$18.79^{+0.33}_{-0.35}$	$17.65^{+0.18}_{-0.21}$	0	15	45
Segue 1[2] (2)	10	$19.16^{+0.32}_{-0.34}$	$17.66^{+0.17}_{-0.23}$	159	15	205
Leo I (7)	10	$17.63^{+0.10}_{-0.09}$	$17.45^{+0.10}_{-0.09}$	0	4	12
Leo II (6)	11	$17.94^{+0.19}_{-0.17}$	$17.19^{+0.30}_{-0.44}$	0	4	12
Sextans (11)	10	$16.96^{+0.59}_{-0.33}$	$17.14^{+0.11}_{-0.09}$	0	4	12
CVn I (10)	12	$17.14^{+0.48}_{-0.26}$	$17.07^{+0.18}_{-0.29}$	0	4	12
CVn II (8)	13	$17.65^{+0.45}_{-0.43}$	$16.97^{+0.24}_{-0.23}$	0	4	12
Hercules (11)	16	$16.79^{+0.76}_{-0.73}$	$16.51^{+0.36}_{-0.31}$	0	4	12
Leo IV (13)	11	$16.32^{+1.06}_{-1.70}$	$16.12^{+0.71}_{-1.14}$	0	4	12
Leo V (12)	11	$16.37^{+0.94}_{-0.87}$	$15.86^{+0.46}_{-0.47}$	0	4	12
Ursa Major I (9)	10	$17.60^{+0.75}_{-0.44}$	$17.16^{+0.17}_{-0.15}$	0	4	12
Segue II (N/A)	12	$16.20^{+1.06}_{-0.98}$	$15.87^{+0.56}_{-0.37}$	19	0	19
Boötes I (N/A)	14	$17.86^{+0.31}_{-0.37}$	$17.32^{+0.18}_{-0.19}$	14	0	14
Willman I (N/A)	10	N/A	N/A	14	0	12

Table 1: A summary of the dSph properties and observations carried out by VERITAS since early 2007 and the proposed observation plan. $\bar{J}$ is the astrophysical factor and determines the level of the expected gamma-ray flux from DM annihilation within a target. $\bar{J}_{decay}$ is the astrophysical factor for DM decay as opposed to self-annihilation. Both J factors are from Geringer-Sameth et al [] with an integration region of 0.17 degree from the center of the dSph. In parenthesis is indicated the rank of the dSph according to its annihilation astrophysical factor. The amount of data A/B weather data accumulated with no other data quality issues taken into account is shown in the 'Now' column. The 'Yearly' column has the LTP time committed to that particular dSph and the 'Goal' column has the approximate exposure time after three years of executing the LTP.

the systematics limit.

The two best candidates for deep exposures are UMaII and Segue I. UMaII has been observed previously in the 2013-2014 observing season with only 28 hours of exposure as of the summer 2014 shutdown; of the two best ultra-faint candidates, it is the furthest away from the systematics limit. UMaII is in a historically under-subscribed RA band, so the fifty hours per year on UMaII is a large commitment but a reasonable one. It is a major LTP goal to have UMaII and Segue 1 have roughly the same exposure after three years. If VERITAS continues beyond three years, then yearly exposure to UMaII should be reduced in favor of more Segue 1 time to slow the approach of either reaching the systematics limit. **After three years, we plan to have roughly two hundred hours for Segue 1 and UMaII and over one hundred hours each on Draco and Ursa Minor to be used for a combined DM analysis.**

To reduce additional systematics due to bright stars, we request that only north and south wobble pointings (0.5° offset) for the Segue 1 observations and only east and west wobble pointings for the Ursa Minor.

To show the effect of the upper limit improvement over time, we show estimates in Figure 1 for the expected annihilation limits after a thousand hour exposure on a Segue 1-like dSph using a combined DM analysis. As can be seen, the limits are approximately an order of magnitude more sensitive than the current measurements with VERITAS. We consider this to be an 'ultimate' goal if the lifetime of the experiment is beyond 2017. We point out that the understanding of these objects is constantly evolving: the predicted upper limit for five years of data could become much more sensitive than the current estimate due to further understanding and improved measurements of the DM structure of the dSphs and advanced analysis techniques that would improve the sensitivity of VERITAS.

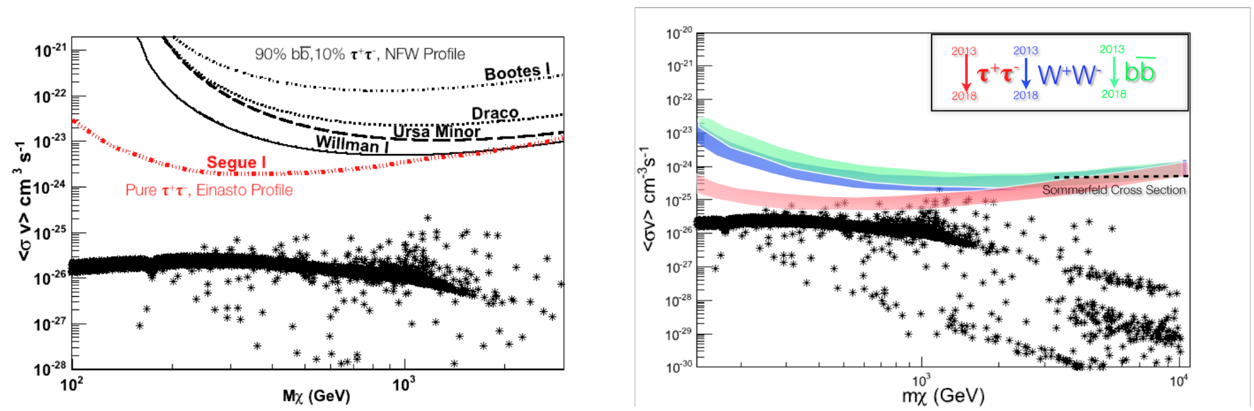

Figure 1: **Left** : Previously published 95% CL limits on the $\langle\sigma v\rangle$ as a function of DM mass for five different dSphs using the classical methodology. **Right** : Conservative estimate of the 95% CL limits on $\langle\sigma v\rangle$ as a function of the DM particle mass for a combined DM analysis for a thousand hours exposure on a hypothetical Segue 1-like dSph. While this may be overly optimistic, the uncertainty in the possible J factors associated with this analysis are a much more dominant effect.

While the results of the three-year observation plan may still be an order of magnitude away from constraining standard WIMP models, this exposure will severely constrain kinematically enhanced models of DM annihilation (models with a velocity-dependent annihilation cross-section). Additionally, these limits can be improved further through the approach of 'stacking' (or combining) the data set by combining all the dSph observations. Such an analysis can improve the sensitivity of the limits by a factor of 1.5-3 as well. Advanced analysis techniques (3D model, etc.) that would boost VERITAS sensitivity would improve the DM limits as well.

1.3 Dwarf Spheroidal Galaxies - Survey

In addition to the 110 hours dedicated to deeper exposure of dSphs with the largest J factors, a survey of most of the other known dSphs is requested for 36 hours per year, divided between nine dSphs, four hours devoted to each. Those dSphs for the survey are also listed in Table 1. Rankings for the survey dSphs and the deep exposure dSphs are based on mean J factors by Geringer-Sameth et al. [12]. Due to the smaller mean J factors, the survey targets are ranked below the deep exposure targets. These dSphs, like the deep exposure dSphs, could also contribute to a combined dSph limit, but would have, on average, a smaller contribution due to smaller J factors. Note that due to the smaller average J factors, higher ranking is given to the deep exposure dSphs for each RA band.

The reasoning behind the survey is that the uncertainties in the average J factors (shown in Table 1) could be large so it is therefore possible that a few of them potentially have a large enough J factor to make a significant impact on limits or possibly a dark matter detection. Advanced stellar

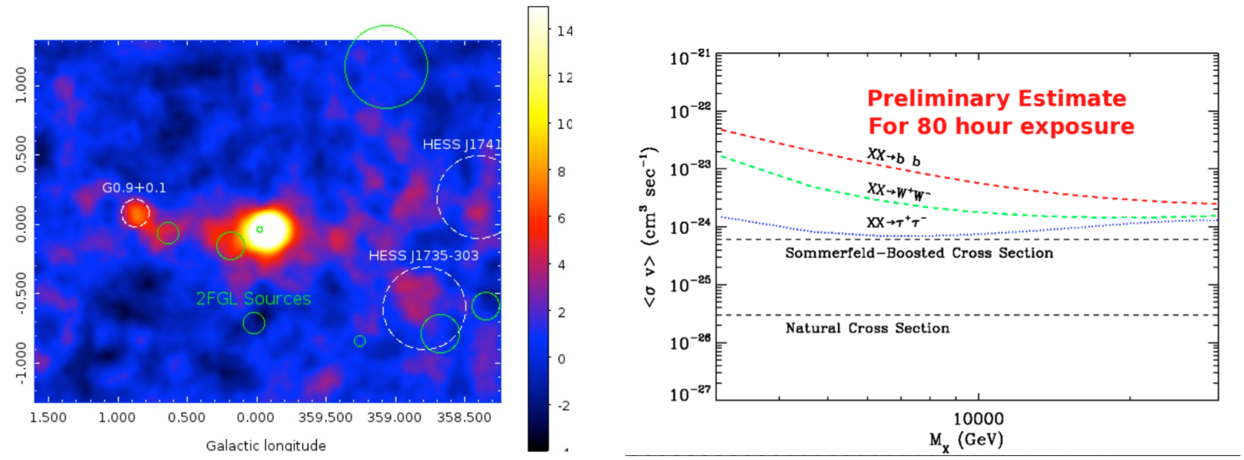

Figure 2: **Left:** Significance map of SgrA* region for 81.2 hours with VERITAS. **Right:** A preliminary estimate for an eighty hour exposure of the annihilation limits of $\langle \sigma \nu \rangle$ from a region offset from SgrA*.

velocity modeling or deeper optical observations will also add to our knowledge of the J factors and this could change the mean values of the J factors and reduce errorbars. Additionally, VERITAS can also make a legacy statement for each known northern hemisphere dSph that could potentially last for a decade or longer.

1.4 Observations of the Galactic Center Region

The center of our galaxy harbors a $4 \times 10^6\, M_\odot$ black hole (BH), coincident with the radio source Sgr A*. X-ray transients and MeV/GeV transients are observed regularly. Supernova remnants such as Sgr A East or a plerion [34] located in the close vicinity of the Galactic center are also capable of accelerating particles to multi- TeV energies. EGRET detected a MeV/GeV source, 3EG J1746-2851, coincident with the Galactic center position [23] and recently Fermi-LAT resolved several sources in the region [1]. At GeV/TeV energies an excess was seen by CANGAROO II [33], the Whipple 10 m [26], H.E.S.S. [4], and MAGIC [6]. A diffuse GeV/TeV γ-ray emission along the galactic plane was identified by H.E.S.S. with the intensity profile following the structure of molecular clouds [5]. The diffuse component (Figure 2, left) is explained by an interaction of local cosmic rays with the matter in the molecular clouds – indicating a harder cosmic ray spectrum and a higher cosmic ray flux in the Galactic center region.

The Galactic center was observed by VERITAS in 2010-2014 for ~ 80 hrs (good quality data) at zenith angles of $z = 60 - 66$ deg (average threshold of $E_{\rm thr} \simeq 2.5$ TeV). The shower directions were reconstructed with the *geo/disp* method as described in Elog AaC/1466. A highly significant excess is found in the data (Figure 2, left) at the Sgr A* position. The energy spectrum is compatible with the spectra measured by Whipple, H.E.S.S., and MAGIC. Given the ∼6 times higher LZA effective area (compared to H.E.S.S.) the VERITAS observations are now already the most sensitive VHE Galcatic center measurement above 2 TeV.

WIMPs are discussed as potential dark matter particles accumulating around the Galactic center. The WIMP would annihilate and produce a γ-ray line at the WIMP mass and a γ-ray continuum at lower energies [24] which could be detected at MeV/GeV/TeV energies. Assuming a certain density profile of the dark matter, the expected γ-ray flux along the line-of-sight can be calculated as a function of the WIMP mass and the annihilation cross section [14].

The VERITAS observations were accompanied by OFF-source observations of a field located in the vicinity of the Galactic center region (similar zenith angles and sky brightness) without a known TeV γ-ray source. These observations are used to study the background acceptance throughout the field of view and will support the estimate of a diffuse γ-ray component surrounding the position of the Galactic center. A preliminary upper limit spectrum of the extended region surrounding the Galactic center[3] is compared with line-of-sight integrals along the density profile $\int \rho^2 \mathrm{dl}$, in order to constrain the annihilation cross section for a particular dark matter model, dark matter particle mass and density profile $\rho(r)$ (work in progress). With future observations VERITAS will be able to derive the most constraining DM annihilation limit above 2 TeV addressing an important earlier recommendation of the External Science Advisory Committee. **Ten hours of the DM-AspEN LTP is requested for observations of the Galactic center, in addition to ten hours from the Galactic LTP, for a total of twenty hours per year.** With this twenty hour per year commitment, VERITAS can obtain annihilation limits that are competitive with HESS at energies above ~2 TeV.

1.5 Fermi Unassociated Objects

Recent cosmological N-body high-resolution simulations [32] indicate that DM halos are populated with a wealth of substructures [21]. Because of tidal disruption near the Galactic disk, most of the subhalos are thought to survive at high Galactic latitude. The lack of gas material in these regions prevents such over-densities to attract enough baryonic matter and trigger star formation. DM clumps would therefore be invisible to most astronomical observations from radio to X-rays. DM substructures are expected to reside in the MW halo, which can be nearby the Sun and therefore have a bright gamma-ray annihilation signal [29]. These clumps would likely be only visible at gamma-ray energies and therefore may not have shown up in astronomical catalogs yet. Since gamma-ray emission from DM annihilation is expected to be constant, DM clumps could then appear in all-sky monitoring programs [25] done at gamma-ray energies. This can be best provided by the Fermi-LAT instrument. Very likely, the distinct spectral cut-off at the DM particle mass is located at energies too high to be measurable by Fermi within a reasonable timescale (see, e.g. the WIMP mass lower limits in [28]) and can only be detected by ground-based telescopes, such as VERITAS. Furthermore, detection of this spectral cut-off at the same energy in multiple objects would stand as a visible signature of DM.

The Second Fermi-LAT Catalog (2FGL) contains 1873 high energy gamma-ray sources detected by the LAT instrument after the first 24 months of observations. For each source, positional and spectral information are provided as well as identification or possible associations with cataloged sources at other wavelengths. Although Fermi-LAT has a good angular resolution, a firm identification based on positional coincidence alone is not always feasible. Thus, 576 sources in the 2FGL lack any clear association. These are the so-called unassociated Fermi objects (UFOs), a population among which DM clumps might be represented [18].

In order to extract possible DM clump candidates out of the 2FGL UFOs we adapt the selection criteria from [37], filtering out sources, by requesting them:

- to lie outside the Galactic Plane,
- to be non-variable,
- to exhibit a power law spectra, and
- to not have possible counterparts.

[3] Due to its likely astrophysical origin the Galactic center and the region along the plane were excluded from this analysis.

The original list obtained from the 2FGL catalog is then filtered to select only sources observable with VERITAS with a maximum culmination zenith angle of 40°, in order to pursue the lowest energy threshold. Additionally, an estimate of required observation time for a 5σ detection, dubbed *detectability*, is computed based on a 2FGL Catalog flux extrapolation to the VERITAS energy range and the effective areas and background rates for two different sets of cuts: soft cuts and medium cuts (VEGAS 2.4). Sources with a *detectability* above 100 hours in the *medium cuts* scenario are discarded. All candidates surviving the previous selection are considered further in light of the Swift data publicly available; candidates with Swift X-ray sources in the Fermi error circle are also removed. In addition, the collection of Fermi high energy (E> 10 GeV) photons for each source is studied: this population of high energy photons helps to confirm the Fermi flux extrapolation and to sort out the final list of candidates. Sources showing high energy photons clustered in time (indicating variability at GeV energies) are removed. Table 2 shows the eight remaining candidates. Shown are 2FGL name, *detectability* for soft and medium cuts, test statistic and integral flux in the 1-100 GeV range, and the number of high-energy Fermi photons. The sources are ordered according to their *detectability* in the *medium cuts* scenario.

2FGL Name	Detectability		TS	$F_{1-100GeV}$ 10^{-10} [cm^{2}s^{-1}]	$\#\gamma$ $E_\gamma > E_0$ (10,50,100) GeV
	Med. Cuts [h]	Soft Cuts [h]			
J1115.0-0701	**2**	**7**	**4.8**	**1.61**	**5,1,0**
J0545.6+6018	**13**	**44**	**2.0**	**0.89**	**5,1,1**
J1741.0+1347	29	102	2.3	1.27	3, 0, 0
J1816.5+4511	31	98	3.3	1.34	4, 0, 0
J1659.2-0142	32	104	3.1	1.51	6, 2, 0
J1805.8+0612	37	117	0.8	0.79	2, 0, 0
J0418.9+6636	91	278	2.1	1.04	6, 1, 0
J1824.5+1013	99	328	1.4	0.91	3, 0, 0

Table 2: Summary of the eight best Fermi Unassociated Objects for DM searches, ordered by detectability prospects. We highlight our final selections in boldface.

At this time, we do not ask for any specific observations of Fermi subhalos as a part of the LTP. **The two most promising candidates for reasons described above, 2FGL J1115.0-0701 and 2FGL J0545.6+6018 have already been approved as part of a Fermi GI program, so we expect them to be approved at high priority by the TAC during the 2014-2015 observing season.** If a future Fermi-LAT catalog or independent analysis of Fermi data reveal new UFOs with high detectibility with VERITAS, the feasibility of those targets being included in the LTP or as a stand-alone TAC proposal will be reevaluated at that time.

1.6 Dark Matter Conclusions

Our observation plan offers the ability to not only improve our current DM upper limits by at least a factor of five, but also offers the possibility of making one of the highest impact scientific discoveries possible with VERITAS: detection of the first hints of DM. This comprehensive observation strategy offers the best case scenario for indirect dark matter studies by focusing on the best targets available for northern hemisphere observations.

The DM publication strategy is as follows: the data from the UFOs study will function as a standalone dataset and a publication based on it can proceed as soon as data taking is complete. A publication detailing the DM constraints from the existing observations of the Galactic center is already in an advanced state and will be completed soon by Beilicke and Buckley. The long term observations of both the Galactic center and dSphs can be published periodically as the upper limits only improve with time. The analysis of the dSphs for the combining analysis is underway by Zitzer, Tucci, Kelley-Hoskins and Finley, while Geringer-Sameth will use the photon list, effective areas and PSFs provided by Zitzer to compute a single dSph limit. A complimentary Bayesian approach is under development by Buckley and Bugayov. Future work in this area could include combining different types of DM targets (galaxy clusters, the Galactic center, M31) and/or instruments (Fermi-LAT, other IACTs, HAWC) into a single DM limit. In fact, this might be the best way to reach the natural thermally-averaged cross- section at $\sim 3\times10^{-26}\text{cm}^3\text{s}^{-1}$.

We believe that the program put forth in this proposal directly addresses the stated needs of the relevant funding agencies for an increased DM observation program and is clearly relevant to the VERITAS long term science plan goal of studying the fundamental particle physics properties of dark matter and its associated distribution within the Universe.

2 Astro-Particle and Extra-galactic Non-blazar Topics

VERITAS is engaged in a very active and diverse astro-particle program which includes, but not limited to, topics such as:

- Starburst galaxies
- Radio galaxies
- Cosmic ray electron ppectrum
- Electron/positron fraction via Moon shadow observations
- γ-ray halos around AGN
- Search for Lorentz invariance violations (LIV)
- High-Z Cosmic ray spectrum via direct Cherenkov (DC)
- Search for evaporating primordial black holes (PBHs)
- Search for Axion-like particles (ALPs)
- Search for VHE correlations with neutrino events from Icecube

2.1 Starburst Galaxies

Starburst galaxies are characterized by a central region of enhanced star formation, leading to a high density of gas and strongly increased rate of supernovae. Therefore, starburst galaxies were predicted to produce a detectable VHE gamma-ray signal ([44], [43])and in 2009 the detection of M82 by VERITAS [41] and NGC 253 by HESS [42] established starburst galaxies as a new class of gamma-ray emitters. Fermi LAT also detected M 82 and NGC 253 [39], and weaker GeV emission from the starbursting Seyfert 2 galaxies NGC 1068 and NGC 4945 [40].

Since the VERITAS publication of M 82, which constituted 140 hours of observations, an additional 100 hours of quality-selected VERITAS data has been taken on M 82. This exceptionally large dataset is needed because of the very weak flux (<0.9% Crab Nebula flux level) and low elevation culmination, which requires 100's of hours of VERITAS data to substantially increase the photon statistics. Analysis of the total dataset on M 82 is on-going, focusing on advanced methods to achieve a higher sensitivity and a better understanding of the systematic uncertainties of very large datasets. No further M 82 observations are requested in the long-term plan due to this existing large dataset. A new publication on M 82 is planned using the improved analysis methods, combined with the much deeper Fermi LAT observations.

In the long-term plan, no other starburst galaxy observations are requested, since based on the Fermi LAT results [40] all other northern starburst galaxies are expected to have a VHE flux more than a factor of two lower than M 82.

2.2 Radio Galaxies

Due to its super-massive black hole and its close proximity (structures of the jet can be resolved from radio to X-ray energies, M 87 is the only AGN which potentially allows us to spatially constrain the location of the VHE emission region, on the level of < 100 Schwarzschild radii. This would be of extremely high importance for the understanding of AGN (unification) and plasma jet physics in the jet formation zone. The questions of interest are: (i) Which is the site of the TeV emission? How close (e^+e^- pair absorption) to the black hole can it be constrained (VHE/radio)? Are different sites within the jet involved (VHE/X-ray/radio)? (ii) Can intra-night VHE flux variability further constrain the size of the emission region? (iii) Is the VHE emission the result of leptonic [50, 51] or hadronic [53] beam particles? So far, the M 87 observations resulted in a high scientific output, including five refereed VERITAS papers [45, 56, 46, 47, 48] with 250 citations to them.

M 87 shows TeV γ-ray flux variations on time scales of days [38, 49, 56]. VHE observations of past years were organized in joint campaigns between VERITAS and MAGIC. Three major VHE flares were recorded so far: in 2005 [38], in 2008 [38, 49, 56], and in 2010 [47, 48]. The recent flares were accompanied by intense MWL observations at radio to X-ray energies which maximized the scientific outcome (Fig. 3). The time of the 2008 VHE flare marked the onset of a strong rise of the 43 GHz radio flux from the nucleus of M 87 observed with the VLBA (Fig. 3, left). The radio observations resolve the formation region of the M 87 plasma jet on scales of $30 \times 60\,R_\mathrm{s}$. Combining the radio and VHE data gave first experimental evidence, that the VHE emission originates from the direct vicinity of the black hole [56] – favoring VHE models involving the nucleus [52] or the inner jet [50, 53, 54]. During the 2010 VHE flare, VLBA observations were triggered. The radio nucleus showed a marginal (lower than in 2008) increase of emission the weeks following the VHE flare [60]. A new radio feature was identified in the knot HST-1 following the 2010 flare [58]. Also, the times of both VHE flares, 2008 and 2010, correspond to the two maximum Chandra X-ray flux measurements from the nucleus (see Fig. 3). The 2010 flare is the best sampled VHE light curved taken so far. Although not reaching day-scale flaring levels, an increased TeV γ-ray flux was measured in March/April 2012. Surprisingly, the EVN/VERA 22/43 GHz monitoring campaign revealed a significant increase of the radio flux of the M 87 nucleus [59] following the increased 2012 VHE activity (Fig. 3, right). This indicates a repetition of the pattern observed in 2008 (VERITAS/VLBA) and further strengthens the need for continued monitoring of M 87. At this point, the location of the VHE emission region is not yet established; more observations are needed in order to identify common MWL patterns which have the potential to pin-down one (or more) sites of VHE γ-ray emission in the jet structure of AGN.

Following the successful 2008-2014 campaigns, the 2014/2015 VHE observations would again be closely coordinated with MAGIC to allow optimal coverage and quick reactions in the case of high flux states. **We propose to perform 20 hrs of regular monitoring per year of M87. In the case of a flare we ask for another 20 hrs of ToO observations.** One hour per night is sufficient to detect a flaring state (M 87 fluxes so far never substantially exceeded $\sim 10\%$ of the Crab Nebula flux). The condition to trigger the Chandra ToO and the 43 GHz VLBA ToO is a $> 4\,\sigma$ (or $7\,\%$ Crab) detection within one hour. A 7×5 ks Chandra ToO proposal is approved (cycle AO 15, PI: D. Harris), plus two 5 ks baseline measurements. A 43 GHz VLBA radio proposal renewed on a

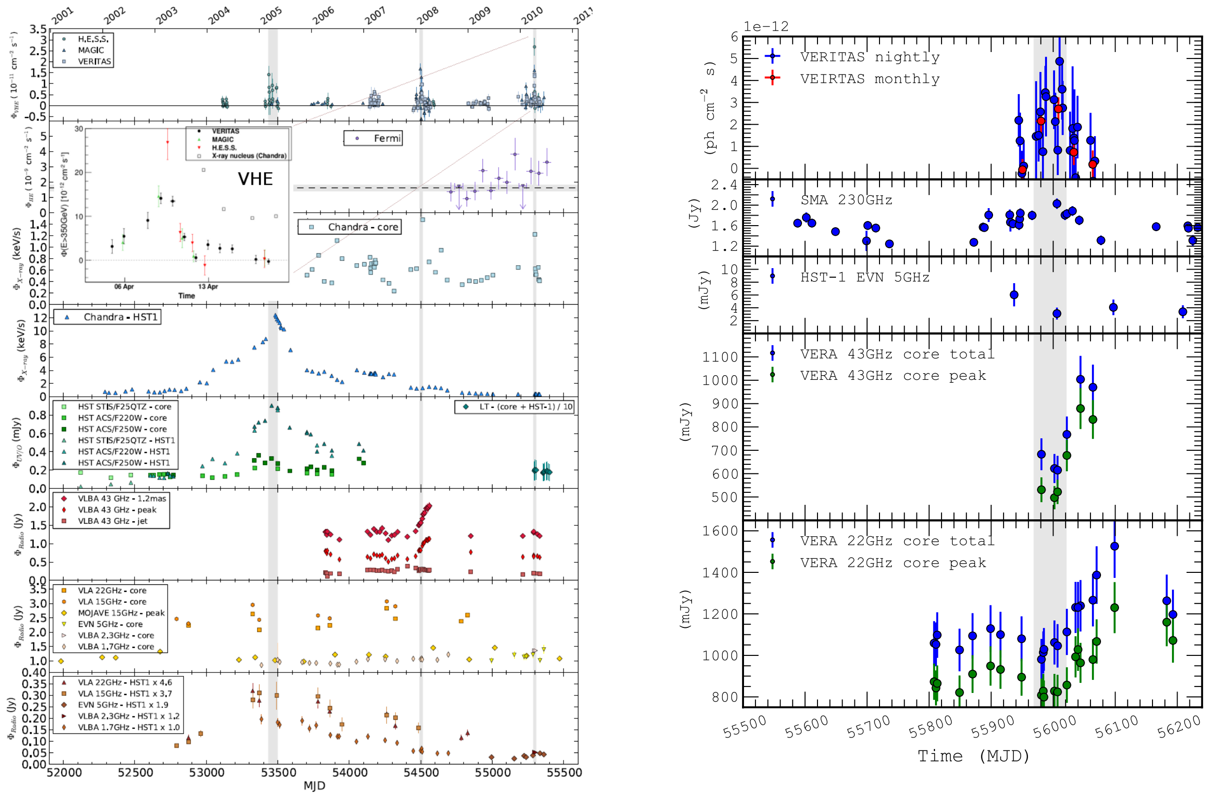

Figure 3: **Left:** M 87 2001-2010 MWL light curves [48], from top: VHE (VERITAS/MAGIC/HESS), MeV/GeV (Fermi), $2-10$ keV X-ray (Chandra; nucleus & HST-1) [55], optical (HST), and radio (VLBA/VLA). VLBA 43 GHz flux densities are shown for (i) the nucleus ($160\,R_{\rm s}$), (ii) the peak flux, and (iii) integrated along the jet ($r = 1.2 - 5.3$ mas). The times of the 3 VHE flaring episodes are indicated by gray vertical bands. The inlay shows the 2010 VHE flare – including the Chandra X-ray light curve (arbitrary units) [57]. **Right:** 2012 VERITAS light curve of M 87 together with radio data obtained from the EVN/VERA 22/43GHz monitoring project on M 87 [59].

yearly basis (PI: C. Walker). Both proposals can be triggered by a VHE flare.

Another radio galaxy, NGC 1275 (3C 84, Per A) is a radio galaxy (FR-I) located in the Perseus Cluster. It is one of the brightest and hardest extragalactic sources in the Fermi-LAT catalog. VERITAS observed it in 2009 and published an upper limit in [61]. It has been discovered as VHE emitter by MAGIC [62]. **We propose a ToO for 10 hours if NGC 1275 is in a high state (Flux above $6 \times 10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ above 100 MeV) in Fermi-LAT data.**

2.3 Search for Correlations with Neutrinos from Icecube

VERITAS can search for sources of cosmic rays using a multi-messenger approach. If the astrophysical neutrino flux reported by IceCube [63] is due to hadronic interactions in cosmic ray accelerators, VERITAS may be able to detect the gamma-ray emission associated with the decay of neutral pions produced in such interactions.

To achieve this, we use a two-part program: IceCube-triggered ToO observations of neutrino events with directions compatible with a list of monitored TeV sources [64], and regular observations of high-energy muon neutrinos that are likely astrophysical in origin. The expected rate of neutrino-triggered ToO observations is about 1– 2 per year (1 hour per ToO observation) for the entired monitored list, while the time allocated for regular observations of high-energy neutrinos depends on the targeted astrophysical purity of the sample but should be close to 3 – 4 targets per year (2 hours per target). We expect to convert the regular observations into a ToO program once IceCube implements an online filter capable of selecting these events in real time, which would greatly increase the sensitivity of the search were the sources transient.

The program represents a modest time investment (on the order of 7 – 10 hours per year) with the potential of providing a very high impact result. Even in the case of a null detection, the upper limits set by VERITAS can effectively constrain the population of sources responsible for the astrophysical flux of high-energy neutrinos [65, 66].

Given the short observation time required and varying locations, we do not allocate any LTP time to these observations. However, we strongly encourage the TAC to proceed with approving these ToOs which will be submitted as a separate standard TAC proposal.

2.4 Other Astro-Particle Topics

Most of the astro-particle topics that VERITAS undertakes do not require additional observations, triggering schemes or observing modes. The primoridal black hole search, and the direct Cherenkov and cosmic ray electron spectrum measurements make use of nearly all quality VERITAS data. LIV searches using time-of-flight differences require a highly variable VHE source, such as flaring AGN, pulsar or gamma-ray burst (GRB). The best candidates for each of these VHE targets is covered by their respective SWGs, with LIV as part of their science motivation. The data required for the search for secondary γ-rays from AGN halos and ALPs is covered by the Blazar SWG, however the data analysis falls under the category of the DM-AspEN SWG.

It should be noted that while very little additional data is needed for many of the astro-particle topics, they do require advanced analysis techniques and a very good understanding of systematics. It is therefore a major goal within the DM-AspEN group to develop these methods and have a better working understanding of these systematics (working with the analysis and calibration working group) which in turn benefits all science analysis carried out by the VERITAS collaboration.

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VERITAS Observations of Gamma-Ray Bursts

The Gamma-Ray Burst Science Working Group

November 6, 2014

1 Scientific Justification

The detection of VHE emission from a GRB, either in the prompt or in the afterglow stage, would be an extremely exciting and important result. No conclusive evidence for such emission yet exists. Even good upper limits on a well localized, relatively nearby (z<2) bursts are valuable for constraining emission models. A number of gamma-ray burst models have been proposed that predict VHE photon production which, in some cases, can last for more than 10,000 s (e.g. [1]). *Fermi*-LAT has now detected >100 MeV emission continuing up to ∼70,000 s for GRB 130427A [2]. At later times ($t > 100$ s), the dominant source of VHE photons in many GRB models is inverse Compton scattering of soft photons by relativistic electrons in the external forward shock which is set up when outflowing material from the GRB interacts with the external environment (e.g. [3, 4, 5]). It has been explicitly suggested that detection of VHE photons from these processes should be possible with current generation IACTs [6].

Additionally, the delayed X-ray flares discovered by *Swift* [7, 8] in somewhat fewer than half of bursts are particularly intriguing in terms of the prospects for VHE detection with follow-up observations. Simultaneous X-ray and VHE observations may yield clues about the burst medium and even constrain the microphysics in the shocks that give rise to the VHE emission [9]. The *Fermi*-LAT detected GeV photons associated with X-ray flaring during the afterglow of GRB 100728A [10]. The high-energy photons detected by the LAT arrived several hundred seconds after the beginning of the burst and the spectral index of this component was extremely hard ($\Gamma = 1.7$). Thus GRB X-ray flares are an extremely interesting target for VHE observatories such as VERITAS.

Results from VERITAS observations of GRBs can potentially address three of the four themes of scientific exploration endorsed previously by the ESAC: Particle Physics and Fundamental Laws, Cosmology, and Black Holes. Due to the large distances involved (the average redshift of *Swift*-detected GRBs is ~ 2), GRBs can be used as a probe of Lorentz invariance violation (LIV). Currently the most sensitive test to date comes from LAT observations of the short GRB 090510 [11] and with the much higher sensitivity of VERITAS at high energies, it is conceivable that the VERITAS detection of a GRB would result in a more constraining limit. Also as a result of their extreme distances, coupled with their extreme luminosities, GRBs can be used to characterize the extragalactic background light (EBL) at earlier times in the universe than is possible with active galactic nuclei (AGN). A better knowledge of the EBL at these times would enhance our understanding of early star and structure formation in the universe. Finally GRBs are thought to be associated with the supernovae of very massive stars and/or the mergers of compact objects. A better understanding of GRBs would lead to a better understanding of black holes, which may be the product of and in some cases the progenitors of GRBs (in the case of neutron star-black hole or black hole-black hole mergers).

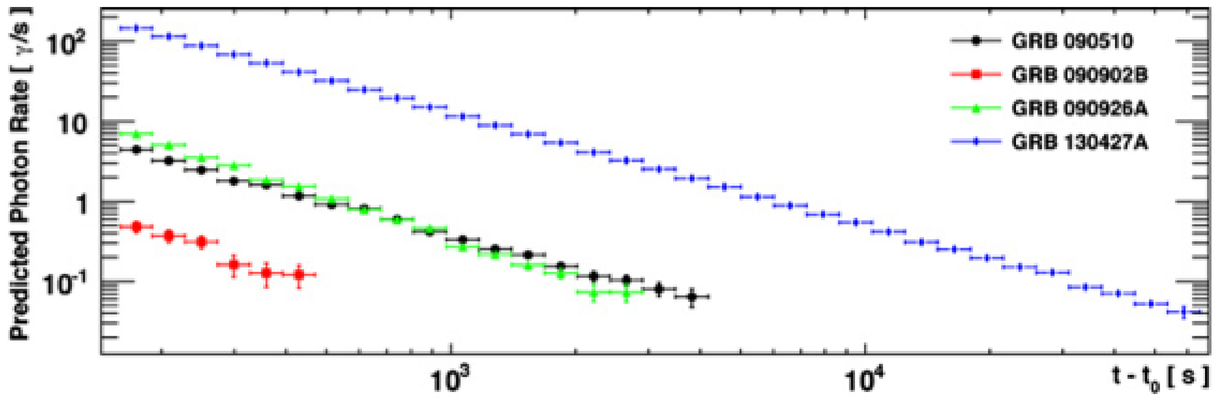

Figure 1: Predicted light curves for several fluent, LAT-detected GRBs: GRB 090510 [16], GRB 090902B [12], GRB090926A [17], and GRB130427A [18], as they would be seen by VERITAS at energies greater than 100 GeV assuming an elevation of 70°. The energy spectrum and temporal decay measured by LAT have been extrapolated into the VERITAS energy band, and the expected gamma-ray rates seen by VERITAS, after including the effect of absorption by the EBL, have been calculated. Each point shown corresponds to a rate at least 3 standard deviations above background. Figure from Ref. [15].

2 Observing Strategy

We conduct follow-up observations of all GRBs with an error circle less than 10° in radius, which are above 20° elevation, and which are less than an hour old,[1] continuing for up to three hours if the location is precisely determined. Since we receive only one or two observable GRB notifications per month, *we consider these observations to be the absolute highest priority for VERITAS.* When attempting to catch the fading afterglow of a gamma-ray burst, time is of the essence, particularly in light of the *Fermi*-LAT measurements of the high-energy afterglow. VERITAS observations proceed in any weather or moonlight conditions when observing is possible, regardless of the number of telescopes available in the array. We take observations even using reduced HV or the moonlight filters, since only several hours later do we know that a burst is a particularly close or bright one where a detection or constraining limit might be possible even with higher thresholds. Once a burst is more than an hour old and at least 30 minutes of data have been taken, we consider it acceptable under rare and particularly compelling circumstances to forego continued observations in order to pursue an alternative ToO or multiwavelength program.

Swift has been fully operational since April 2005 and is localizing gamma-ray bursts at a rate of approximately 100 per year. Positions with arcmin accuracy are relayed to VERITAS over a GCN socket connection in seconds. The *Fermi* Gamma-ray Burst Monitor (GBM) detects bursts at a rate of ∼250 per year and also distributes real-time (5–10 seconds after the burst trigger) GCN notices. *Fermi* distributes a few notices of LAT-detected bursts as well, which are of particular interest to VERITAS since the detection by the LAT points to the existence of higher energy photons. Indeed, in several LAT-detected bursts, e.g. [2, 12, 13], photons of 50–130 GeV (in the GRB frame, i.e. before cosmological redshift) have been seen. The 100 MeV–30 GeV emission detected by the LAT has been observed to decay following a power law with a temporal index around −1 and can persist for thousands of seconds; detectable emission from the bright, nearby GRB 130427A continued for nearly a day. Extrapolating the spectral and temporal characteristics of these bright LAT-detected

[1] As discussed in the following, very bright bursts less than a day old are also observed.

bursts and including the attenuation of the gamma-ray signal from interaction with the EBL, it is estimated that VERITAS could detect many of these bursts, often by a substantial margin [14, 15], as shown in Figure 1.

Based on the *Fermi*-LAT results for the extraordinary, nearby ($z = 0.34$) burst GRB 130427A, we also take *observations of the brightest ∼10% of bursts any time during the first 24 hours after the burst.* The duration of these observations is again three hours, but the observations start, e.g. at the beginning of the night after the burst. These bursts will be flagged to observe for 27 hours by the tracking software or are communicated manually to the TAC and the czar by a member of the GRB group. These ToO's are classified by the TAC as automatically approved and do not require TAC approval on a case by case basis. There were two such requests in the 2013–2014 observing season.

Historically, the observing program as described here requires about twenty hours of dark time per season. Two hours per season in each of the twelve RA bands have been factored into the Long Term Plan for GRB observations. Increased operating time under moonlight with reduced high voltage and filters has expanded our exposure to GRBs and increased the number for which we have data, at no additional cost in dark time.

The *Fermi* GBM is identifying bursts at 2–3 times the rate of *Swift*, but only the strongest of these are well localized. We slew to the center of the error circle for those *Fermi* GBM bursts that are localized within a 10° error radius. This procedure positions the telescopes to slew quickly to a more precise follow-up position, for example in the case of an on-board detection by the *Fermi* LAT. The total amount of time spent following up these bursts with less-than-ideal localizations is extremely modest, whereas the potential payoff is great: the GRBs with high-energy LAT detections will be especially important for VERITAS. Note that the LAT-detected bursts are among the brighter ones, which will also have more accurate positions from the *Fermi* GBM and therefore be more likely to be within the VERITAS field of view after the initial slew. We currently limit the observations to one hour for these poorly localized bursts if no improved position is reported.

Recently, progress has been made within the VERITAS collaboration towards adding an "orbit" observing mode in which the source is placed some distance from the center of the FOV (as in standard wobble observations) and the telescope pointing is continuously rotated about the source [19]. We are working this season to implement orbit-mode observations to rapidly cover *Fermi*-GBM error circles during GRB follow-up observations. We have investigated optimal covering strategies using several orbits of different radius. An alternative that we are also considering is to adapt orbit mode further to a spiral pattern around the target position.

3 Expected Outcomes

The *Fermi*-LAT results indicate that high-energy emission from GRBs is both delayed and longer-lived than lower-energy emission (e.g. [2, 20, 21]). The *Fermi*-LAT has detected photons with energy as much as ∼130 GeV in the GRB rest frame and the late-time (post-T_{90}) spectral characteristics indicate an extension of the canonical Band function extending to tens of GeV without a cutoff in nearly all LAT-detected GRBs. In several cases an underlying power-law component with index $\Gamma < 2$ is required in addition to the Band function, which results in spectral hardening at the highest energies [12]. The high-energy characteristics of LAT-observed GRBs make them extremely interesting targets for VHE observation. GRB observations using VERITAS have been ongoing since the end of the 2005–06 observing season and >50 GRBs have been observed during this time. The lower energy threshold from the VERITAS upgrade substantially improves the prospects for a GRB detection (and the value of VERITAS upper limits). All GRBs observed since 2006 have been analyzed, and results have been presented at conferences [22, 23], in papers [14, 15], and in a thesis

[24].

GRB follow-up observations with VERITAS are intrinsically high-risk, high-return ventures. We expect to follow up approximately twenty GRBs per year of which a third to a half will be well-localized. In the case of a GRB detection with VERITAS, the most sensitive measurements of the EBL and LIV can be obtained due to the presumably high redshift of the GRB (as compared to standard extragalactic VHE sources). VERITAS limits on VHE emission are typically unique and, particularly in association with a *Fermi*-LAT detection (as for GRB 130427A), help to characterize the acceleration physics in the GRB itself as well as the strength of the EBL.

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