Cosmology and Fundamental Physics with Gamma-Ray Astronomy

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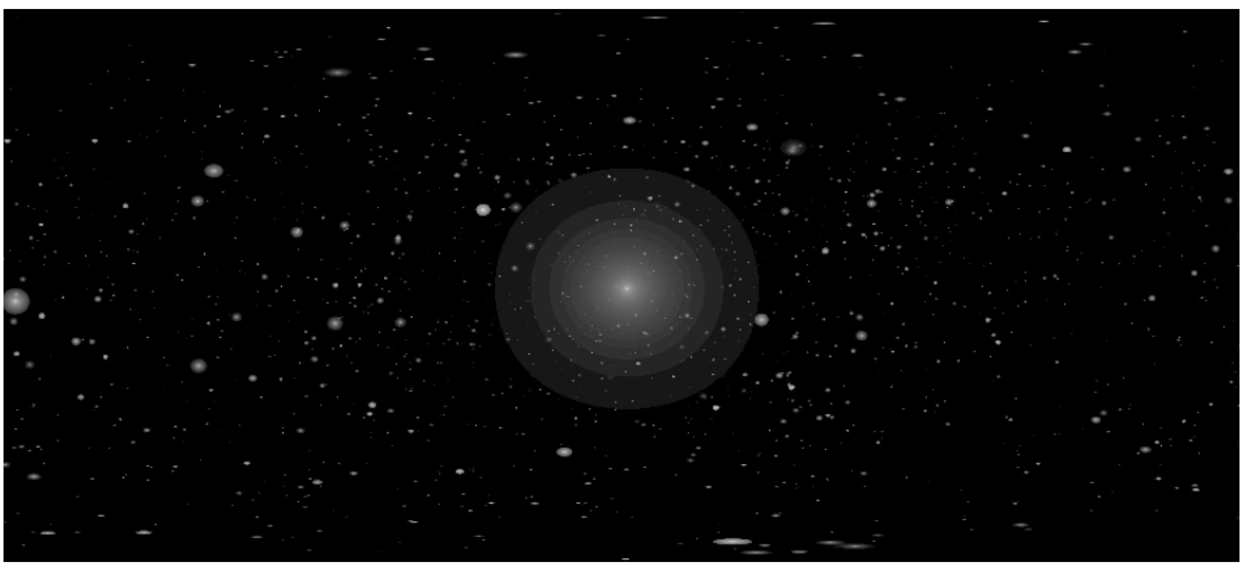

Simulated appearance of the gamma-ray sky from neutralino annihilation in the Galactic halo plotted as the intensity in Galactic coordinates. The Galactic center appears as the bright object at the center of the field of view. If the sensitivity of a future ACT experiment were high enough, a number of the other Galactic substructures visible in this figure could be detected with a ground-based gamma-ray experiment.

Abstract

This report draws on the findings of the dark matter science working group for the APS white paper on the status and future of TeV γ-ray astronomy (arXiv:0810.0444). We discuss some of the most important questions about the nature of dark matter and its role in structure formation and describe how γ-ray measurements complement other indirect, direct or accelerator-based searches. Ground-based γ-ray measurements can also provide probes of the diffuse extragalactic radiation fields, constrain scenarios for the formation of the first stars, and provide constraints on other aspects of $>$TeV-scale physics.

1. Introduction

Within the last decade, a standard cosmological picture (the ΛCDM cosmology) has emerged, including a detailed breakdown of the main constituents of the energy-density of the universe. This theoretical framework is now on a firm empirical footing, given the remarkable agreement of a diverse set of astrophysical data. In the ΛCDM paradigm, the universe is spatially flat and its energy budget is balanced with $\sim$4% baryonic matter, $\sim$26% cold dark matter (CDM) and roughly 70% dark energy. While the dark matter has not been directly detected in laboratory experiments, the gravitational effects of dark matter have been observed in the Universe on all spatial scales, ranging from the inner kiloparsecs of galaxies out to the Hubble radius.

Just as an unseen component of the Universe is required by astrophysical observations, compelling theoretical arguments promote the existence of new particle degrees of freedom in the TeV to Planck scale energy range. In particular, a possible solution to the hierarchy problem predicts the existence of new particle degrees of freedom in the 100 GeV to several TeV mass range. A weakly interacting particle in this mass range could constitute the dark matter, naturally producing the required cosmological density through its thermal decoupling. For example, R-parity conserving supersymmetry (SUSY) models have a stable lightest supersymmetric particle (LSP) that is typically a charge neutral Majorana particle, providing a natural dark matter candidate.

For a subset of SUSY parameter space, neutralinos could be produced at the Large Hadron Collider (LHC) or observed in direct detection experiments. But even if these efforts are successful, *γ-ray observations provide the only avenue for measuring the dark matter halo profiles and illuminating the role of dark matter in structure formation.*

Neutralinos could also be observed through other *indirect* searches that detect the by-products of the annihilation of the lightest supersymmetric particle such as positrons, low-energy antiprotons, and high-energy neutrinos. Since positrons and antiprotons are charged particles, their propagation in the galaxy suffers scattering off of the irregular inter-stellar magnetic field and hides their origin. Electrons with energy above $\sim$10 GeV suffer severe energy losses due to synchrotron and inverse-Compton radiation, limiting their range to much less than the distance between Earth and the Galactic center. Detection of electrons from dark matter annihilation thus depends critically on large uncertainties in the clumpiness of the local halo. *Compared with all other detection techniques (direct and indirect), γ-ray measurements of dark-matter are unique in going beyond a detection of the local halo to providing a measurement of the actual distribution of dark matter on the sky and to understand the role of dark matter in the formation of structure in the Universe.*

Several astrophysical signals have already been tentatively attributed to WIMP annihilations. For instance, the PAMELA collaboration has recently presented evidence for a larger than expected positron fraction in the 10-80 GeV range while ATIC has claimed a broad bump at 300 – 800

GeV in the spectrum of $e^+ + e^-$. The steep rise in the positron fraction observed at high energies deviates significantly from predictions of secondary production models, and requires a primary source of $e^\pm$ pairs. Although pulsars could account for the observed emission, DM annihilations or decays can provide a consistent explanation of both datasets, although matching the PAMELA results requires an injection strength orders of magnitude larger than that naturally suggested for thermal WIMPs.

However, the annihilation cross-section for the slowly moving DM particles in the present epoch can be enhanced with respect to the value at freeze-out by a factor as large as 10^3. This so-called Sommerfeld enhancement effect is due to the presence of light scalar or vector bosons in the spectrum giving rise to an attractive long range force between the DM particles at small distances. Models with DM annihilation into light particles of a hidden sector (which subsequently decay into SM particles) or that proceeds through long-lived *W*IMPonium bound states also give large cross section boost factors. Due to the $\sim 1/v$ behavior, larger enhancements may be seen in colder objects such as dwarf galaxies.

The cosmic-ray (CR) electron results are still preliminary, awaiting confirmation by other experiments. Fermi has good sensitivity to electrons up to ∼1 TeV and should soon be able to test these results. Imaging Atmoshperhic Cherenkov Telescope (IACT) arrays (such as HESS and VERITAS) also have the ability to detect strong features in the electron spectrum. In fact, for present IACT arrays, the γ-ray background is *dominated* by CR electrons below ∼100 GeV. Future large arrays with further improvements in background rejection will offer even more sensitive searches for features in the electron spectrum that might be attributed to exotic processes.

Other extensions of the standard model involving TeV-scale extra dimensions, include new particles in the form of Kaluza-Klein partners of ordinary standard-model particles. The lightest Kaluza-Klein particle (LKP) could be stable and hence provide a candidate for the dark matter. TeV-scale extra dimensions may also manifest themselves in a dispersion in the propagation velocity of light (Lorentz invariance violation) in extragalactic space. Observations of the shortest flares, at the highest energies from the most distant objects place the tightest constraints on theories with large extra dimensions. Such constraints have already been produced by TeV measurements but could be dramatically improved with a future high-sensitivity γ-ray instrument, capable of detecting shorter flares from more distant AGNs and GRBs. Recent observations by the Fermi Space Telescope show delayed emission of γ-rays of up to at least 10 GeV from high-z GRBs, underscoring the potential of future ground-based γ-ray arrays that combine lower energy thresholds ($\sim$ tens of GeV) with the ability to slew rapidly to a GRB; these measurements would provide an effective area ∼5 orders of magnitude larger than Fermi and allow unprecedented observations of the shortest variability timescales of these sources. *Thus, ground-based TeV γ-ray astronomy probes TeV-scale particle physics both by providing a possible avenue for detection of a Kaluza-Klein particle and by constraining the the TeV^{-1}-scale structure of space-time from γ-ray propagation effects.*

2. Dark Matter Annihilation into γ-rays

For any of the scenarios that have been considered, the dark-matter particle must be neutral and does not couple directly to photons, however most annihilation channels ultimately lead to the production of photons through a number of indirect processes. While the total cross section for γ-ray production is constrained by the measured relic abundance of dark matter, the shape of the γ-ray spectrum is sensitive to the details of the specific particle-physics scenario. Dark matter annihilation may yield photons in three ways: (1) by the direct annihilation into a two-photon final state (or a $Z^0\gamma$ or $H\gamma$ final state) giving a nearly monoenergetic line, (2) through the annihilation into an intermediate state (e.g. a quark-antiquark pair) that subsequently decays, hadronizes, and yields photons with a broad featureless continuum spectrum or (3) through internal-bremsstrahlung into a three-particle state, e.g. $\chi\chi \rightarrow W^+W^-\gamma$ yielding γ-rays with a very hard spectrum and sharp cutoff. The cross section for the direct annihilation into photons are loop-suppressed and can be at least 2 orders of magnitude less than the processes that lead to the continuum emission. However, for some cases of interest (e.g., a massive Higgsino) or the next-to-minimal supersymmetric standard model the annihilation line can be substantially enhanced. *A number of different particle physics and astrophysical scenarios can lead to the production of an observable γ-ray signal with a spectral form that contains distinct features that can be connected, with high accuracy, to the underlying particle physics.*

The flux of γ-rays from a high-density annihilating region can be written as the product of two terms, the line of sight integral of the square of the dark matter density profile and a *p*article physics function that includes the cross sections and spectral shapes for the different photon production mechanisms. While the total cross sections can have a large uncertainty if one covers the entire mass range, at high energies the neutralino is either almost purely a Higgsino (for mSUGRA) or a Wino (for anomaly-mediated SUSY breaking) and $\langle\sigma v\rangle$ takes a fairly constant value (within an order of magnitude of $\approx 2\times10^{-26}\,\mathrm{cm^3s^{-1}}$) for M_χ approximately between 100 GeV and 1 TeV. While there are also large uncertainties in halo profiles, dissipationless N-body simulations suggest power-law density profiles with an index of roughly $0.7 \leq \gamma \leq 1.2$ down to $\sim 0.1\%$ of the virial radius of the halo with a corresponding uncertainty in the flux of roughly a factor of ∼6.

3. Targets for Gamma-Ray Detection

The Galactic Center (GC) has been considered the most promising target for the detection of dark matter annihilation, with a flux more than an order of magnitude larger than any other potential source. The γ-ray emission from the GC detected by the Whipple and H.E.S.S. collaborations could, in principle, include a contribution from annihilating dark matter. Fits to the HESS data with a Kaluza-Klein (KK) $B^{(1)}$ DM particle, with WIMPs annihilating into W^+W^- followed by decay to final states $b\bar{b}$ (with 30% and 70% branching ratios, respectively) give reasonable agreement but require a very large astrophysical boost factor and very high WIMP mass (10-20 TeV at the ∼90% confidence level) well above the natural mass range. While the implied WIMP mass is quite large, some rather fine-tuned supersymmetric models (e.g., anomaly-mediated SUSY) can accommodate large enough pair annihilation cross sections and masses to both give a good fit to the HESS data and thermally produce the right DM abundance

The interpretation of the GC data is particularly complicated by the low mass-to-light ratio of the Milky Way core, and domination by baryonic matter in the form of a central massive black hole, young massive stars, supernova remnants and compact stellar remnants. An observational techniques to reduce background is to look instead at an annulus about the GC position. Even though the background grows in proportion to the solid angle of the annular region, for a sufficiently shallow halo profile the signal-to-noise ratio for detection continues to grow out to large angles. Moreover, any component of diffuse contaminating background falls off more steeply as a function of latitude than the annihilation of the smooth component of the dark matter halo. If the PAMELA/ATIC excess proves correct, one would also expect an observable γ-ray signal from

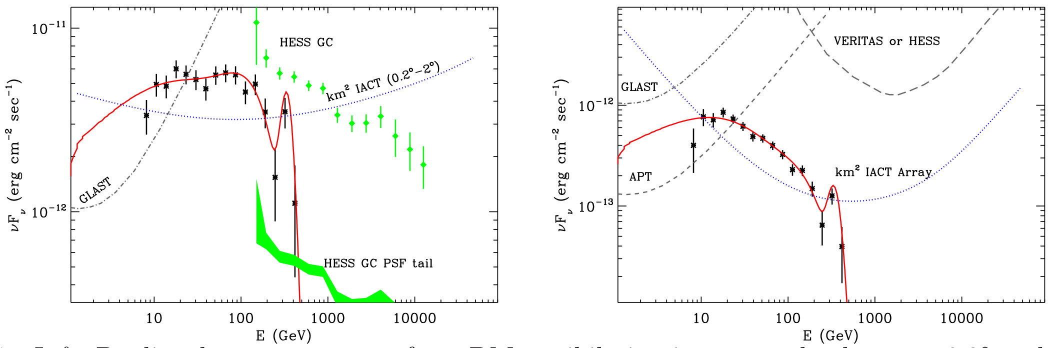

Figure 1: *Left:* Predicted γ-ray spectrum from DM annihilation in an annulus between $0.2°$ and $2°$ about the GC assuming an NFW halo with a central density of $\rho_s = 5.4 \times 10^6\, M_\odot/\mathrm{kpc}^3$ and a scale radius of $r_s = 21.7\,\mathrm{kpc}$ *Right:* Predicted γ-ray signal from the dSph Ursa Minor for neutralino mass of 330 GeV and mixed decay into $\tau^+\tau-$ and $b\bar{b}$ assuming a conservative boost factor and $\langle\sigma v\rangle = 2 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$.

inverse-Compton scattering by electrons throughout the galactic halo, but with the strongest signal near the GC region. Still, given the large backgrounds in the central part of our galaxy, the observation of a wider class of astrophysical targets is desirable.

3.1. Dwarf Spheroidals

Dwarf spheroidal (dSph) systems are ideal dark matter laboratories because astrophysical backgrounds and baryon-dark matter interactions are expected not to play a major role in the distribution of dark matter. These are also DM dominated systems with mass–to–light ratio up to a few hundred. A number of theoretical studies point to the potential for detecting γ-rays DM annihilation in dSph or local group galaxies based on measurements of the distribution of gravitating matter. With the advent of the Sloan Digital Sky Survey (SDSS), the number of known dSph satellites of the local group has roughly doubled during the last decade and the number of sources with high quality stellar data has grown substantially. Recent data on the radial velocity distribution of stars in dSphs has made it possible to constrain the shapes of potential dark matter profiles and improve quantitative estimates of the annihilation signal; γ-ray fluxes as large as 10^{-12} photons cm^{-2} s^{-1} have been predicted. Fig. 1 shows an example of one possible spectrum that might be measured for the Ursa Minor dSph given a density profile constrained by stellar velocity measurements and conservative assumptions about the cross section and boost factor. This example demonstrates that detection from dSph galaxies is most likely out of reach of the current generation of IACT experiments or proposed EAS experiments, but may be within reach of a future km^2 IACT instrument, if the point-source sensitivity is improved by an order of magnitude.

3.2. Milky Way Substructure

A generic prediction of the hierarchical structure formation scenario in CDM cosmologies is the presence of rich substructure; bound dark matter halos within larger host halos. Small dark matter halos form earlier, and therefore have higher characteristic densities. This makes some of these subhalos able to withstand tidal disruption as they sink in the potential well of their host halo due to dynamical friction. The most direct experimental way to probe the presence of otherwise dark substructure in the Milky Way is through γ-ray observations. Theoretical studies as well as numerical simulations of a Milky Way-size halo, predict that given the probability of an otherwise completely dark subhalo nearby, the expected flux in γ-rays can be as large as $\sim 10^{-13}$ cm^{-2} s^{-1}.

The smallest DM halos formed are set by the RMS dark matter particle velocities at kinetic decoupling, the energy scale at which momentum–changing interactions cease to be effective. For supersymmetric dark matter this cutoff scale spans a mass range for *m*icrohalos of around $10^{-13} \leq [M/M_{\odot}] \leq 10^{-2}$. While the survival of microhalos in the Solar neighborhood is still under debate, there are indications that some fraction ($\sim 20\%$) may still be present. Such objects are most likely to be detected by very wide-field space-based instruments like Fermi or a larger-area future space telescope. Follow-up measurements with IACT arrays would be required to determine the characteristics of the spectrum and angular extent of these sources at higher energies, and might even be used to look for proper motion in very nearby objects.

3.3. Halo Spikes

Other potential dark matter sources in our own Galaxy may be formed by a gravitational interplay of dark halos and baryonic matter. In particular, it is possible that a number of intermediate-mass black holes (IMBHs) with cuspy halos, might exist in our own galaxy. *Adiabatic* growth of a massive object at the center of a power-law distribution of DM, with index γ, induces a redistribution of matter into a new power-law (dubbed "spike") with index $\gamma_{sp} = (9-2\gamma)/(4-\gamma)$. The process of adiabatic growth may be valid for the SMBH at the GC, but may have been disrupted by dynamical processes such as mergers and gravitational scattering off of stars.

However, IMBHs with mass $10^2 < M/\mathrm{M}_{\odot} < 10^6$ are not affected by these destructive processes. Scenarios that seek to explain the observed population and evolutionary history of supermassive-black-holes actually result in the prediction of a large population of wandering IMBHs, with a number in our own Galaxy. They may form in rare, overdense regions at high redshift, $z \sim 20$, as remnants of Population III stars, and have a characteristic mass-scale of a few $10^2\,\mathrm{M}_{\odot}$. Alternatively, IMBHs may form directly out of cold gas in early-forming halos and are typified by a larger mass scale of order $10^5\,\mathrm{M}_{\odot}$. The spiky halos around galactic intermediate-mass black holes could provide a large enhancement in the γ-ray signal that could be effectively detected by all-sky low-threshold instruments such as Fermi then followed-up by ground-based measurements. Over most of the allowed parameter space, Fermi would detect the onset of the continuum spectrum but would lack the sensitivity to measure the detailed spectral shape above hundreds of GeV. In some scenarios, even present-day ground-based instruments (e.g, with VERITAS or HESS) have the point-source sensitivity and energy resolution (∼15%) required to measure the spectral cutoff and other features of the annihilation spectrum.

4. Complementarity

Fermi is now operational, and first science results are being released. Soon the LHC will be on-line and a number of new direct detection are near completion (e.g., Xenon-100 and LUX). What is the role of future γ-ray experiments in view of these developments? The ATLAS and CMS experiments at the Large Hadron Collider (LHC) are designed to directly discover new supersymmetric particles in the range of a few ~ 100 GeV/c^2 and will start collecting data in the very near future. The LHC alone will not, under even the most optimistic circumstances, provide all of the answers about the nature of dark matter. *In general, a combination of laboratory (LHC) detection and astrophysical observations or direct detection experiments will be required to pin down all of the supersymmetric parameters and to make the complete case that a new particle observed in the laboratory really constitutes the dark matter.*

Due to the fact that the continuum γ-ray signal depends directly on the total annihilation cross section, there are relatively tight constraints on the γ-ray production cross-section from the cosmological constraints on the relic abundance. For direct detection, on the other hand, the nuclear recoil cross section is only indirectly related to the total annihilation cross section and thus there are a number of perfectly viable model parameters that fall orders of magnitude below the threshold of currently planned direct detection experiments. While liquid-Noble detectors offer the potential for scaling to a volume sensitive to much of the high-mass parameter space, upper limits are much more straightforward than a detection. Even with the excellent progress on discrimination of nuclear recoils in multi-mode experiments and reduction of internal radioactive backgrounds, it will be difficult to conclusively prove that a few nuclear recoil events (in a single experiment) are the unambiguous signature of dark matter or to constrain the mass and other properties of the dark matter. For the LHC to see the lightest stable SUSY particle, it must first produce a gluino from which the neutralino is produced. This limits the reach of the LHC up to neutralino masses of $m_\chi \approx 300$GeV, well below the upper end of the natural mass range. Direct detection of WIMP-nucleon recoil is most sensitive in the 60 to 600 GeV regime. Indirect observations of self-annihilating neutralinos through $\gamma-$rays with energies lower than ~ 100 GeV will best be accomplished by Fermi, while VERITAS and the other ground-based γ-ray observatories will play a critical role in searches for neutralinos with mass larger than ~ 100 GeV. *In summary, there is a large region of parameter space for which γ-ray instruments could provide the only detection for cases where the nuclear recoil cross section falls below the threshold of any planned direct detection experiment, or the mass is out of range of the LHC or even the ILC.*

5. Key Questions and Recommendations

We identify four key questions for future experiments:

(1) What is the nature of the dark matter? How does it interact with ordinary matter?

(2) What is the role of dark matter in structure formation? Is the standard model of ΛCDM hierarchical structure formation matter correct? Do halo profiles match these predictions?

(3) What was the role of dark matter in determining the epoch of star formation, the mass function of the first stars, and the seeds of massive black holes?

(4) How do the laws of physics (e.g., Lorentz invariance) change at the shortest length scales and highest energies?

Below, we summarize the ways in which future γ-ray measurements can uniquely address the four questions:

• Compared with all other detection techniques (direct and indirect), γ-ray measurements of dark-matter are unique in going beyond a detection of the local halo to providing a measurement of the actual distribution of dark matter on the sky. Such measurements are needed to understand the nature of the dominant gravitational component of our own Galaxy, and the role of dark matter in the formation of structure in the Universe.

• Gamma-ray DM searches are unique in that the detection cross-section is closely related to the total annihilation cross section that determines the relic abundance. Different astrophysical sources could show different flux enhancements due to the details of the density profile, but the detailed spectral form of the γ-ray emission will be *universal*, and contains distinct features that can be connected, with high accuracy, to the underlying particle physics.

• The Galactic center is predicted to be the strongest source of γ-rays from dark matter annihilation but contains large astrophysical backgrounds. To search for γ-ray emission from dark-matter annihilation in the GC region, the requirements for the future instrument include: extremely good angular resolution to reject background from other point sources, a moderately large field of view ($\gtrsim 8^\circ$ diameter) and location at a southern hemisphere site.

• Observations of local-group dwarf galaxies may provide the cleanest laboratory for dark-matter searches, since these dark-matter dominated objects are expected to lack other astrophysical backgrounds. For these observations, a very large effective area and excellent point-source sensitivity are required.

• Observations of halo-substructure could provide important new constraints on CDM structure formation, providing information on the mass of the first building blocks of structure, and on the kinetic decoupling temperature. The most direct experimental way to probe the presence of otherwise dark halo substructure in the Milky Way is through γ-ray observations. Space-based low-threshold all-sky measurements will be most effective for identifying candidate objects, but ground-based measurements will be required to determine the detailed spectral shape (cutoff, line-to-continuum ratio) needed to identify the dark matter candidate.

• Gamma-ray astronomy has the unique potential to provide constraints on the history of structure formation in the universe through dark-matter observations of dark-matter halos on a range of mass scales in addition to probing the history of star formation through measurements of the diffuse infrared background radiation.

• A future IACT array could also provide cosmological constraints on exotic contributions to the diffuse infrared background, as well as constraints on Lorentz Invariance (through measurements of dispersion in rapid high energy flares from GRBs)

• In general, a combination of laboratory (LHC, ILC) detection and astrophysical observations or direct detection experiments will be required to pin down all of the supersymmetric parameters and to make the complete case that a new particle observed in the laboratory really constitutes the dark matter.

A future ground-based γ-ray instrument with an order-of-magnitude improvement in sensitivity over current instruments, lower energy threshold ($\lesssim 50$ GeV), wider field-of-view $\sim 8^\circ$, good energy resolution ($\lesssim 15\%$), a fast response to GRB triggers, and angular resolution ($\sim 0.05^\circ$) is strongly motivated the goal to identify the dark matter, to provide a means of probing intergalactic radiation fields and to test new theories of TeV to Planck-scale physics. A $\sim$km^2 IACT array consisting of 50 to 100 large IACTs is probably the best means of meeting these requirements. EGRET and Fermi results showing delayed emission up to $\sim$10 GeV from distant GRBs underscores the potential for triggered observations by instruments with the best sensitivity rather than instantaneous sky coverage.

We reiterate that *any comprehensive scientific roadmap that puts the discovery of dark matter as its priority must include support for a future, high-sensitivity ground-based γ-ray experiment in addition to accelerator and direct searches.* With an order-of-magnitude improvement in sensitivity and reduction in energy threshold, a future IACT array should have adequate sensitivity to probe much of the most generic parameter space for a number of DM sources including Galactic substructure, Dwarf galaxies and other extragalactic objects as well as addressing a variety of other questions in fundamental physics at the TeV-scale and beyond.

[1] The full author list, the APS whitepaper, and other supplemental information is available at http://physics.wustl.edu/buckley/astro2010/