

Search for TeV decaying dark matter from the Virgo cluster of galaxies

The HAWC Collaboration

(a complete list of authors can be found at the end of the proceedings)

E-mail: nisamehr@msu.edu, jpharding@lanl.gov

Galaxy clusters' dynamics constitute a major piece of evidence for the existence of dark matter in astrophysical structures. The decay or annihilation of dark matter particles is hypothesized to produce a steady flux of very-high-energy gamma rays correlated with the direction of a cluster of galaxies. The Virgo cluster, being only 16 Mpc away and spanning several degrees across the sky is an excellent target to search for signatures of particle dark matter interactions. The High Altitude Water Cherenkov (HAWC) observatory, due to its wide field of view and sensitivity to gamma rays at an energy-scale of 300 GeV—100 TeV is well-suited to perform the aforementioned search. We perform a search from the Virgo cluster for gamma-ray emission, assuming various dark matter sub-structure models using 1523 days of HAWC data. Our results provide the strongest constraints on the decay life-time of dark matter for masses above 20 TeV.

Corresponding authors: Mehr Un Nisa^{1*}, Pat Harding²

¹ *Michigan State University*

² *Los Alamos National Labs*

* Presenter

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1. Introduction

Over 80% of all the mass in the universe is known to consist of invisible non-baryonic matter known as dark matter (DM) [1–3]. However, despite decades of experimental searches, the particle composition of DM remains a puzzle. Astrophysical observations can complement direct detection and collider searches for DM by looking for signatures of DM annihilation or decay from regions of high DM density in the universe. Galaxy clusters with their large masses ($10^{12} - 10^{15} M_{\odot}$) are amongst the most suitable candidates to search for signals of decaying DM. In this work, we consider the nearby Virgo cluster of galaxies as a possible site of DM decay. We search for gamma rays produced as a result of DM decaying via different quark and bosonic channels from an extended region of the sky spanning 8° centered at the Virgo cluster, and place constraints on the decay lifetime of TeV DM.

2. Detector and Data-set

The HAWC observatory is a 22,000 m² array of water tanks instrumented with four photomultiplier tubes (PMTs) each. It is located at an altitude of 4100 m above sea-level and continuously monitors two-thirds of the sky every 24 hours. The detector is sensitive to air-showers produced by gamma rays with energies above 300 GeV and up to 100 TeV. The data used in this work uses the same methodologies and cuts described in Refs. [4, 5].

3. Analysis

The Virgo Cluster spans about 8° on the sky and consists of multiple galaxies. The Virgo Cluster itself contains three sub-clusters. Two of these sub-clusters, Virgo-A and Virgo-B, are centered at M87 and M49. The other sub-cluster is centered around M86, an elliptical galaxy which is a galaxy merging with M87 [6]. M87, with a total mass of $2.1 \times 10^{14} M_{\odot}$, assuming a radius of 1.5 Mpc for the center of the subcluster A, is a super-massive elliptical galaxy that is close to the center of the Virgo Cluster. The Active Galactic Nucleus (AGN) at the center of M87 is a source of TeV gamma rays and has been observed to go through active periods called flares [7]. M49 is the brightest elliptical galaxy in the Virgo Cluster and its total mass is about $8.7 \times 10^{13} M_{\odot}$, assuming a radius of 0.75 Mpc for the center of the sub-cluster [6]. These two objects constitute a large fraction of the the Virgo Cluster by mass. The large apparent size and the structure of the cluster make it difficult to search for DM decay and annihilation signals via Imaging Air Cherenkov telescopes (IACTs). In addition, possible astrophysical gamma rays from the galaxies within the cluster may contaminate the analysis.

The HAWC observatory's wide FOV is well-suited to search for gamma-ray emission from extended regions in the sky. For the Virgo Cluster region, we don't detect any statistically significant gamma-ray excess due to DM with the HAWC data (Fig. 1). Therefore, we calculate lower limits on the decay lifetime of DM.

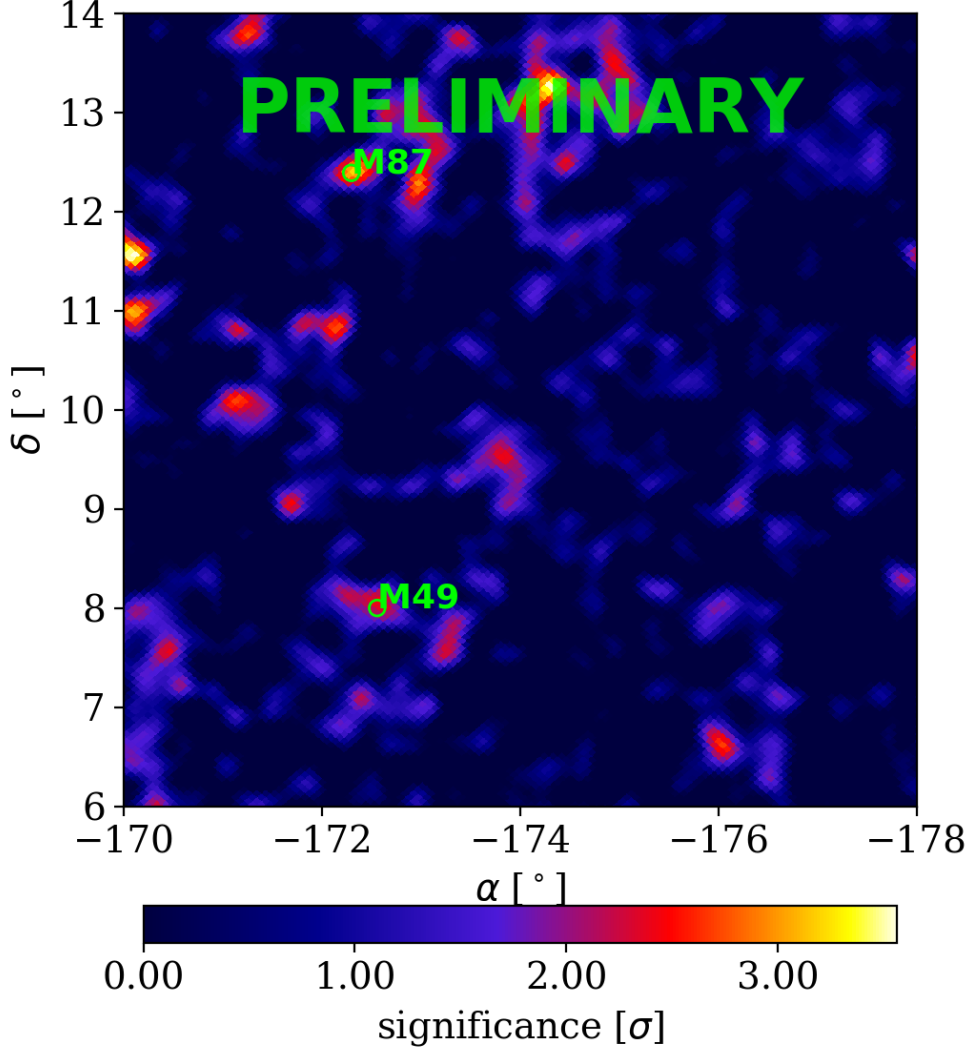


Figure 1: The point-source significance map around the Virgo cluster region using 1523 days of HAWC data with pass 4 reconstruction and the methods used in Ref. [5]. The positions of the two main sub-clusters used in this analysis M87 and M49 are labelled.

3.1 Spectral and Spatial Models

The expected gamma ray flux from decaying DM is given by,

$$\frac{d\phi}{dE} = \frac{1}{4\pi\tau M_\chi} \frac{dN}{dE} D, \quad (1)$$

where τ is the decay lifetime of DM, M_χ is the DM mass, dN/dE is the gamma-ray spectrum

per DM decay, and D is known as the D-factor encoding the spatial distribution of DM in the target of interest. It is defined as the integral of the DM density ρ_{DM} along the line-of-sight (l.o.s.) and over the solid angle $\Delta\Omega$,

$$D = \int_{\Delta\Omega} \int_{\text{l.o.s.}} d\Omega ds \rho_{\text{DM}}[r(s, \Omega)]. \quad (2)$$

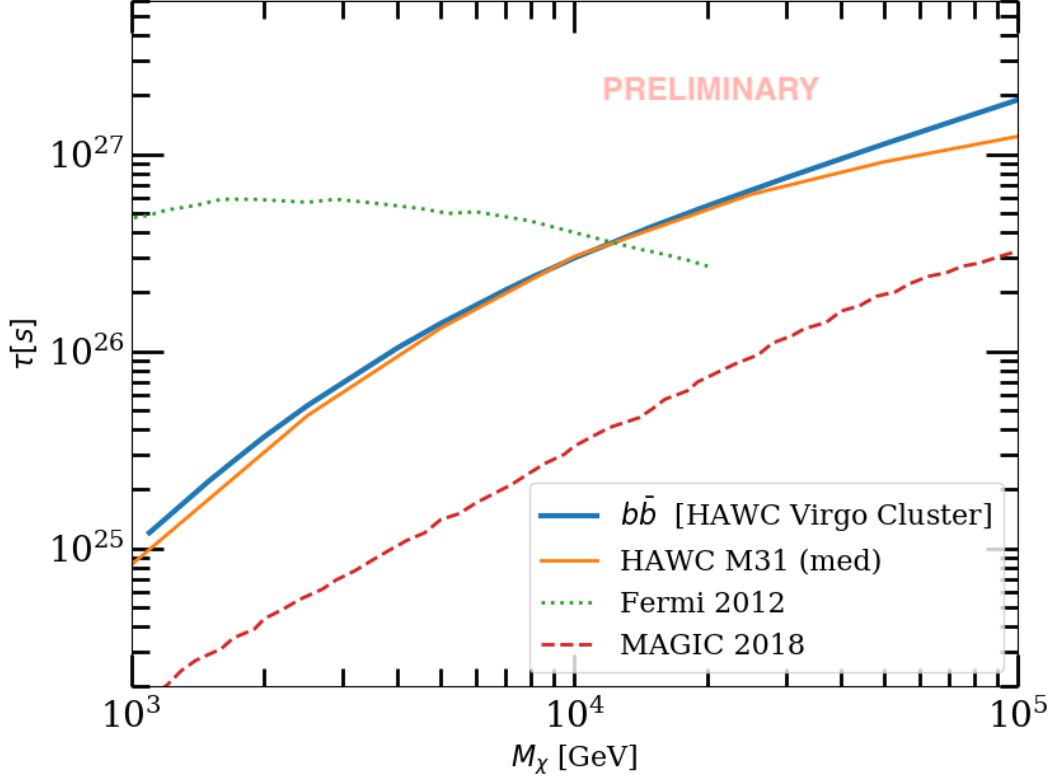


Figure 2: HAWC 95% CL limits on the decay lifetime of dark matter decaying to $b\bar{b}$, assuming the spatial template parameters described in the text. Also shown are limits obtained using the M31 galaxy as a target with HAWC [8], Fermi-LAT [9] and MAGIC [10].

We consider DM decay to three different channels: $b\bar{b}$, $\tau\bar{\tau}$ and W^+W^- . The expected photon spectrum each channel is obtained using the publicly available “Particle Physicist Cookbook” PPPC [12] for DM masses between 1 TeV and 100 TeV.

The DM halo for galaxies consist of a main halo, that has a smooth distribution within the galaxy, and substructure, that is attributed to the gravitationally clumped over-densities in the main halo. We construct a spatial template for the Virgo cluster as a combination of the DM templates for M87 and M49 using the software package CLUMPY [13].

Each generated template encompasses a region of interest with radius 7° and the combined M87-M49 template covers 10° in right ascension and 12° in declination. To generate these templates, we define the parameters for the underlying DM distribution by referring to the main halo and substructure properties inferred by the velocity profiles of the stars in the galaxies and N-body

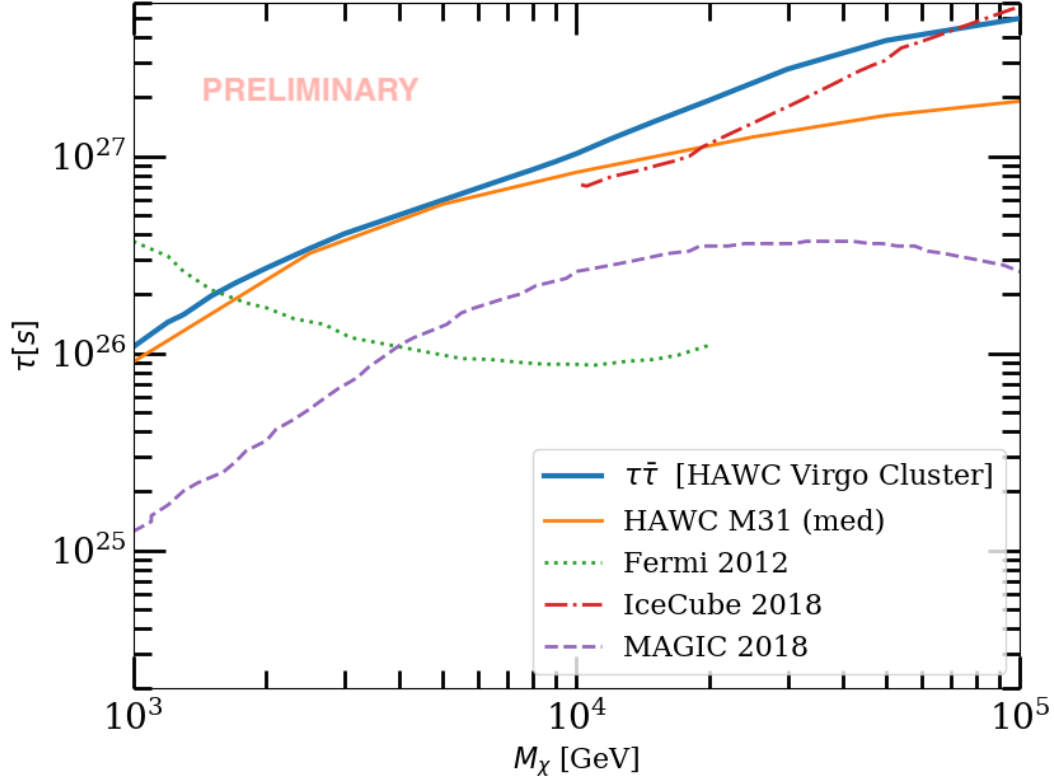


Figure 3: HAWC 95% CL limits on the decay lifetime of dark matter decaying to $\tau\bar{\tau}$, assuming the spatial template parameters described in the text. Also shown are limits obtained using the M31 galaxy as a target with HAWC [8], Fermi-LAT [9], MAGIC [10] and IceCube [11]

Object	Distance [Mpc]	z	R_{vir} [kpc]	ρ_s [$M_\odot/\text{kpc}^3$]	r_s [kpc]
M87	17.2	0.00428	1700	6.96×10^5	403.8
M49	17.1	0.00327	880	1.41×10^6	157.7

Table 1: The various properties of M87 and M49 used in the construction of D factors. Columns 2–6 list the distance, redshift, virial radius, scale density and scale radius respectively.

simulations [14]. For the distribution of DM in the main halo and sub-haloes we use the generalized Navarro-Frenk-White (NFW) profile [15], with the values of free parameters fixed following Refs. [16]. The mass concentration within the sub-haloes, we adopt the model in Ref.[17, 18]. Other characteristic properties of M87 and M49 used in the simulations are listed in table 1.

3.2 Likelihood Fitting

We perform a likelihood maximization to place lower limits on the decay lifetime of DM corresponding to every decay channel and DM masses sampled between 1 TeV and 100 TeV. The

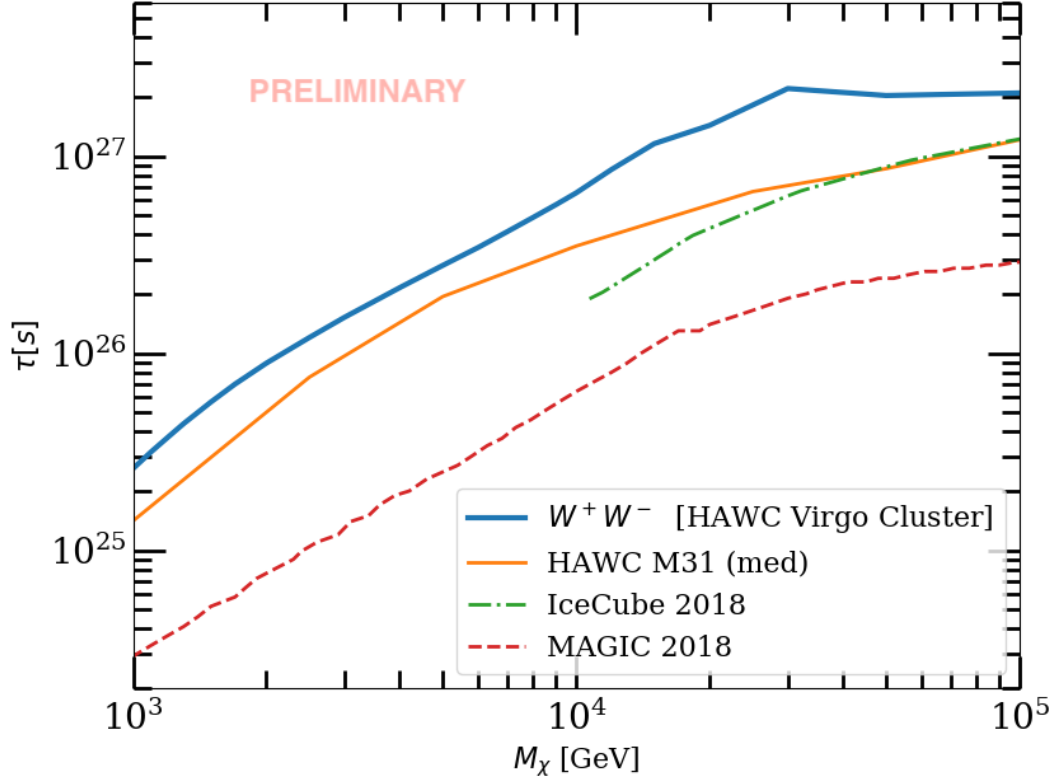


Figure 4: HAWC 95% CL limits on the decay lifetime of dark matter decaying to W^+W^- , assuming the spatial template parameters described in the text. Also shown are limits obtained using the M31 galaxy as a target with HAWC [8], MAGIC [10] and IceCube [11].

source hypothesis consists of the DM template with the expected flux calculated according to equation 1, in addition to a point source centered at the AGN M87. The point source at M87 is best-fit by a cut-off power-law spectrum, $\frac{dN}{dE} \sim \left(\frac{E}{E_c}\right)^{-i}$ with a spectral index i of -1.8 and a cutoff energy E_c of 6 TeV. The likelihood fits and limit calculation are performed using a generalized maximum likelihood Python package called Multi-Mission Maximum Likelihood (3ML) [19].

4. Results

Figures 2, 3 and 4 show the 95% lower limits on the decay lifetime of DM. For comparison, we also show limits obtained in a similar work by HAWC using the M31 galaxy [8]. Also shown are the limits obtained by IceCube [11], Fermi-LAT [9] and the MAGIC collaboration using the Perseus cluster of galaxies [10]. As seen in the figures, HAWC limits are the strongest for the W^+W^- channel across all masses. For $b\bar{b}$ and $\tau\bar{\tau}$, HAWC constraints are the strongest above ~ 20 TeV.

5. Conclusions

We search for gamma-ray emission from decaying DM correlated with the direction of galaxies in the Virgo cluster. Finding no significant excess, we set limits on the decay lifetime of the DM for three different channels. For 100 TeV, HAWC results constrain τ upto a few time 10^{27} s which are amongst the strongest constraints in the world for these masses.

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Full Author List: HAWC Collaboration

A.U. Abeysekara⁴⁸, A. Albert²¹, R. Alfaro¹⁴, C. Alvarez⁴¹, J.D. Álvarez⁴⁰, J.R. Angeles Camacho¹⁴, J.C. Arteaga-Velázquez⁴⁰, K. P. Arunbabu¹⁷, D. Avila Rojas¹⁴, H.A. Ayala Solares²⁸, R. Babu²⁵, V. Baghmanyanyan¹⁵, A.S. Barber⁴⁸, J. Becerra Gonzalez¹¹, E. Belmont-Moreno¹⁴, S.Y. BenZvi²⁹, D. Berley³⁹, C. Brisbois³⁹, K.S. Caballero-Mora⁴¹, T. Capistrán¹², A. Carramiñana¹⁸, S. Casanova¹⁵, O. Chaparro-Amaro³, U. Cotti⁴⁰, J. Cotzomi⁸, S. Coutiño de León¹⁸, E. De la Fuente⁴⁶, C. de León⁴⁰, L. Diaz-Cruz⁸, R. Diaz Hernandez¹⁸, J.C. Díaz-Vélez⁴⁶, B.L. Dingus²¹, M. Durocher²¹, M.A. DuVernois⁴⁵, R.W. Ellsworth³⁹, K. Engel³⁹, C. Espinoza¹⁴, K.L. Fan³⁹, K. Fang⁴⁵, M. Fernández Alonso²⁸, B. Fick²⁵, H. Fleischhack^{51,11,52}, J.L. Flores⁴⁶, N.I. Fraija¹², D. Garcia¹⁴, J.A. García-González²⁰, J. L. García-Luna⁴⁶, G. García-Torales⁴⁶, F. Garfias¹², G. Giacinti²², H. Goksu²², M.M. González¹², J.A. Goodman³⁹, J.P. Harding²¹, S. Hernandez¹⁴, I. Herzog²⁵, J. Hinton²², B. Hona⁴⁸, D. Huang²⁵, F. Hueyotl-Zahuantitla⁴¹, C.M. Hui²³, B. Humensky³⁹, P. Hütemeyer²⁵, A. Iriarte¹², A. Jardin-Blicq^{22,49,50}, H. Jhee⁴³, V. Joshi⁷, D. Kieda⁴⁸, G. J. Kunde²¹, S. Kunwar²², A. Lara¹⁷, J. Lee⁴³, W.H. Lee¹², D. Lennarz⁹, H. León Vargas¹⁴, J. Linnemann²⁴, A.L. Longinotti¹², R. López-Coto¹⁹, G. Luis-Raya⁴⁴, J. Lundeen²⁴, K. Malone²¹, V. Marandon²², O. Martinez⁸, I. Martinez-Castellanos³⁹, H. Martínez-Huerta³⁸, J. Martínez-Castro³, J.A.J. Matthews⁴², J. McEnery¹¹, P. Miranda-Romagnoli³⁴, J.A. Morales-Soto⁴⁰, E. Moreno⁸, M. Mostafá²⁸, A. Nayerhoda¹⁵, L. Nellen¹³, M. Newbold⁴⁸, M.U. Nisa²⁴, R. Noriega-Papaqui³⁴, L. Olivera-Nieto²², N. Omodei³², A. Peisker²⁴, Y. Pérez Araujo¹², E.G. Pérez-Pérez⁴⁴, C.D. Rho⁴³, C. Riviére³⁹, D. Rosa-Gonzalez¹⁸, E. Ruiz-Velasco²², J. Ryan²⁶, H. Salazar⁸, F. Salesa Greus^{15,53}, A. Sandoval¹⁴, M. Schneider³⁹, H. Schoorlemmer²², J. Serna-Franco¹⁴, G. Sinnis²¹, A.J. Smith³⁹, R.W. Springer⁴⁸, P. Surajbali²², I. Taboada⁹, M. Tanner²⁸, K. Tollefson²⁴, I. Torres¹⁸, R. Torres-Escobedo³⁰, R. Turner²⁵, F. Ureña-Mena¹⁸, L. Villaseñor⁸, X. Wang²⁵, I.J. Watson⁴³, T. Weisgarber⁴⁵, F. Werner²², E. Willox³⁹, J. Wood²³, G.B. Yodh³⁵, A. Zepeda⁴, H. Zhou³⁰

¹Barnard College, New York, NY, USA, ²Department of Chemistry and Physics, California University of Pennsylvania, California, PA, USA, ³Centro de Investigación en Computación, Instituto Politécnico Nacional, Ciudad de México, México, ⁴Physics Department, Centro de Investigación y de Estudios Avanzados del IPN, Ciudad de México, México, ⁵Colorado State University, Physics Dept., Fort Collins, CO, USA, ⁶DCI-UDG, Leon, Gto, México, ⁷Erlangen Centre for Astroparticle Physics, Friedrich Alexander Universität, Erlangen, BY, Germany, ⁸Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Puebla, México, ⁹School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA, USA, ¹⁰School of Physics Astronomy and Computational Sciences, George Mason University, Fairfax, VA, USA, ¹¹NASA Goddard Space Flight Center, Greenbelt, MD, USA, ¹²Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, México, ¹³Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México, México, ¹⁴Instituto de Física, Universidad Nacional Autónoma de México, Ciudad de México, México, ¹⁵Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland, ¹⁶Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brasil, ¹⁷Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad de México, México, ¹⁸Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla, México, ¹⁹INFN Padova, Padova, Italy, ²⁰Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, Monterrey, N.L., 64849,

México, ²¹Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA, ²²Max-Planck Institute for Nuclear Physics, Heidelberg, Germany, ²³NASA Marshall Space Flight Center, Astrophysics Office, Huntsville, AL, USA, ²⁴Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA, ²⁵Department of Physics, Michigan Technological University, Houghton, MI, USA, ²⁶Space Science Center, University of New Hampshire, Durham, NH, USA, ²⁷The Ohio State University at Lima, Lima, OH, USA, ²⁸Department of Physics, Pennsylvania State University, University Park, PA, USA, ²⁹Department of Physics and Astronomy, University of Rochester, Rochester, NY, USA, ³⁰Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China, ³¹Sungkyunkwan University, Gyeonggi, Rep. of Korea, ³²Stanford University, Stanford, CA, USA, ³³Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, USA, ³⁴Universidad Autónoma del Estado de Hidalgo, Pachuca, Hgo., México, ³⁵Department of Physics and Astronomy, University of California, Irvine, Irvine, CA, USA, ³⁶Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, Santa Cruz, CA, USA, ³⁷Universidad de Costa Rica, San José, Costa Rica, ³⁸Department of Physics and Mathematics, Universidad de Monterrey, San Pedro Garza García, N.L., México, ³⁹Department of Physics, University of Maryland, College Park, MD, USA, ⁴⁰Instituto de Física y Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México, ⁴¹FCFM-MCTP, Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México, ⁴²Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA, ⁴³University of Seoul, Seoul, Rep. of Korea, ⁴⁴Universidad Politécnica de Pachuca, Pachuca, Hgo, México, ⁴⁵Department of Physics, University of Wisconsin-Madison, Madison, WI, USA, ⁴⁶CUCEI, CUCEA, Universidad de Guadalajara, Guadalajara, Jalisco, México, ⁴⁷Universität Würzburg, Institute for Theoretical Physics and Astrophysics, Würzburg, Germany, ⁴⁸Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA, ⁴⁹Department of Physics, Faculty of Science, Chulalongkorn University, Pathumwan, Bangkok 10330, Thailand, ⁵⁰National Astronomical Research Institute of Thailand (Public Organization), Don Kaeo, MaeRim, Chiang Mai 50180, Thailand, ⁵¹Department of Physics, Catholic University of America, Washington, DC, USA, ⁵²Center for Research and Exploration in Space Science and Technology, NASA/GSFC, Greenbelt, MD, USA, ⁵³Instituto de Física Corpuscular, CSIC, Universitat de València, Paterna, Valencia, Spain

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