First Limits on the Dark Matter Cross-Section with the High Altitude Water Cherenkov (HAWC) Observatory

TAUP 2015

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The High Altitude Water Cherenkov Observatory

Altitude: 4100 m (13000 ft)  Latitude: 19° N
Water Cherenkov Detectors

- 300 WCD tanks
- 5 m x 7.3 m tanks
- 200,000L of water each
- 4 PMTs
  - 3 8” R5912
  - 1 10” R7081 HQE
- Inauguration of the completed array in March 2015
HAWC Sensitivity

- Average Angular Resolution: 0.5° (68% containment)
- Field-of-view: 2 sr (2/3 sky each day)
- Effective Area: 22500 m²
- Sensitivity: Observe Crab nebula each day

Abeysekara et al., Astropart. Phys. 50-52, 26 (2013)

Wide field-of-view, continuous operation
Dark Matter Annihilation and Decay

\[ \text{Flux}_{\text{ann}} \propto \langle \sigma v \rangle \frac{dN_\gamma}{dE} \int_{\text{l.o.s.}} dx \rho^2(r) \]

\[ \text{Flux}_{\text{decay}} \propto \frac{1}{\tau} \frac{1}{M_\chi} \frac{dN_\gamma}{dE} \int_{\text{l.o.s.}} dx \rho(r) \]
HAWC Sensitivity to Annihilating DM in the M31 Galaxy

- HAWC 5-year sensitivity to the dark matter annihilation cross-section (95% C.L. upper limits) for the M31 (Andromeda) galaxy
- HAWC limits assuming a conservative model of DM substructure (boosted) and without (smooth) are considered
- Limits from the H.E.S.S. observations of the Fornax galaxy cluster (14.5h) shown for comparison
- HAWC is sensitive to extended objects, like galaxies and galaxy clusters
HAWC Sensitivity to Annihilating DM in the Virgo Cluster

- HAWC 5-year sensitivity to the dark matter annihilation cross-section (95% C.L. upper limits) for the Virgo cluster
- HAWC limits assuming a conservative model of DM substructure (boosted) and without (smooth) are considered
- Limits from the H.E.S.S. observations of the Fornax galaxy cluster (14.5h) shown for comparison
- HAWC is most sensitive to high masses, which produce multi-TeV photons
HAWC Sensitivity to Decaying DM in the M31 Galaxy

- HAWC 5-year sensitivity to the dark matter decay lifetime (95% C.L. lower limits) for the M31 (Andromeda) galaxy
- Limits from the H.E.S.S. observations of the Fornax cluster (14.5h), MAGIC observations of the Perseus cluster (12h), and MAGIC sensitivity to the Perseus cluster (250h) shown for comparison
- HAWC is particularly sensitive to DM decay, which produces very extended emission (1.5° for M31, 3.3° for Virgo cluster)
HAWC Sensitivity to Decaying DM in the Virgo Cluster

- HAWC 5-year sensitivity to the dark matter decay lifetime (95% C.L. lower limits) for the Virgo cluster
- Limits from the H.E.S.S. observations of the Fornax cluster (14.5h), MAGIC observations of the Perseus cluster (12h), and MAGIC sensitivity to the Perseus cluster (250h) shown for comparison
- As the most massive object HAWC can observe, the Virgo cluster should give the best decay limits
HAWC DM Limits

- Data used in this analysis collected from August 2013 - March 2014
  - detector grew from 362 PMTs in 108 WCDs to 491 PMTs in 134 WCDs
- Limits calculated for WIMP masses annihilating with 100% branching ratios into:
  \[ b\bar{b}, \tau^{+}\tau^{-}, \mu^{+}\mu^{-}, \tau\tau, W^{+}W^{-} \]
- \( M_{\chi} \) ranging from 0.5 TeV - 1000 TeV
- Individual limits done for 14 dwarf spheroidal galaxies, and were treated as point sources

Stacked analysis done with all 14 dwarf spheroidal galaxies to produce a combined limit for each DM annihilation channel

Two dark matter density profiles were used in this analysis: 1) Einasto (Segue 1 with \( \alpha = 0.303 \)) and 2) NFW (all other sources)
Sources Considered: 14 Dwarf Galaxies

<table>
<thead>
<tr>
<th>Source</th>
<th>RA</th>
<th>Dec</th>
<th>$\rho_s$ GeV/cm$^3$</th>
<th>$r_s$ kpc</th>
<th>$R$ kpc</th>
<th>$J$ GeV$^2$cm$^{-5}$sr</th>
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<tbody>
<tr>
<td>Bootes 1</td>
<td>210.05</td>
<td>14.49</td>
<td>8.12</td>
<td>0.27</td>
<td>66</td>
<td>$3.8 \times 10^{18}$</td>
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<td>Canes Venatici I</td>
<td>202.04</td>
<td>33.57</td>
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<td>218</td>
<td>$2.9 \times 10^{16}$</td>
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<td>Canes Venatici II</td>
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<tr>
<td>Coma Berenices</td>
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<td>Leo I</td>
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<td>16.20</td>
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<tr>
<td>Ursa Major II</td>
<td>132.77</td>
<td>63.11</td>
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<td>Ursa Minor</td>
<td>227.24</td>
<td>67.24</td>
<td>3.89</td>
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<td>76</td>
<td>$9.6 \times 10^{18}$</td>
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</table>
First Limits with HAWC Data

- Individual limits for 14 dwarf spheroidal galaxies within the HAWC field-of-view
- Combined limit for each annihilation channel from stacked analysis with all 14 sources (solid black line)
HAWC Combined Limits from the Dwarf Galaxies

- Individual limits for the 5 dwarf spheroidal galaxies HAWC is most sensitive to are shown to the left
- Segue 1, Draco, BootesI, Sextans and Coma Berenices
- 14 source combined limit is shown (solid black line)
- HAWC expected 14 source combined limit is also shown with the associated systematic error on the expected number of counts from simulation (hatched gray area)
Combined Limits

- HAWC 14 source combined limits for five annihilation channels in this analysis
- Limits are spectrally dependent
Comparison to Other Experiments

- Individual Segue1 limit for HAWC-111 180-day
- HAWC Segue 1 5-year predicted limit (dashed magenta line)
- Compared to Segue 1 limits from MAGIC and Fermi-LAT
HAWC is Now!

- HAWC is sensitive to gamma rays from DM annihilation and decay
- Dark matter limits with \(~1/3\) of the detector have been made
  - Final observations should be an order of magnitude more sensitive
- HAWC is complete and taking data with the full detector
  - Further analysis coming soon
Extras
**Gamma/Hadron Separation**

- Hadron-induced showers produce subshowers with a lot of transverse momentum and muons, so their distributions tend to clump in several regions on the array.
- Gamma-ray showers produce a smoother, more peaked distribution on the array.
- Looking for the sub-showers on the array and the larger spread of the hadronic showers, we can distinguish gammas from hadrons.
TeV-Mass Dark Matter

- High-mass high-flux DM proposed to explain several astrophysical observations
  - PAMELA/Fermi/AMS positron excess
  - H.E.S.S. Galactic center gamma-ray excess
  - IceCube PeV neutrinos
- Lack of observed DM at LHC implies DM mass > TeV
- Can be consistent with production of DM
  - DM production by decay of heavy particles
  - Sommerfeld enhancement give larger cross-section today than in the early universe
Comparison of HAWC Sources and Channels

- HAWC 5-year sensitivity to the dark matter annihilation cross-section for the $b\bar{b}$ and $\tau^+\tau^-$ annihilation channels
- At lower masses, the substructure in the M31 galaxy gives the best limits
- At higher masses, the large DM density at the Galactic center gives the best limits
- The harder leptonic channel is better constrained at low masses, though similarly constrained at high masses
Annihilation to Gauge Bosons

- HAWC 5-year sensitivity to the dark matter annihilation cross-section for the $W^+W^-$ annihilation channel is similar to the $b\bar{b}$ channel.
- However, the exchange of the (relatively) light gauge bosons create a velocity-dependent resonance in the cross-section, increasing it by orders of magnitude. This is known as “Sommerfeld Enhancement”.
- For these channels, HAWC can probe thermal cross-sections.
Data for One Study

<table>
<thead>
<tr>
<th>Bin #</th>
<th>Obs. Sig</th>
<th>Bkg</th>
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<tr>
<td>8</td>
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<td>4</td>
<td>15.88</td>
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</table>

Data is for Segue 1 with a 10 TeV DM mass and \(\langle \sigma v \rangle = 10^{-22} \text{ cm}^3/\text{s}\)