Indirect Dark Matter Detection

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- Overview
- Electron/Positron Experiments
- Neutrinos
- Gamma-Ray Searches
- Future Experiments
Gravitational effect of DM is visible in many astrophysical settings.

Bullet cluster image shows gravitational mass inferred from lensing (blue) and X-ray emission from baryonic matter (red).

Not modified gravity, not gas - dark matter behaves like stars, weakly interacting particles

From WMAP: $\Omega_{\text{DM}} h^2 = 0.1123 \pm 0.0035$

For a thermal relic of the big bang, the larger the annihilation cross section the longer the DM stays in equilibrium and the larger the Boltzmann suppression $\sim e^{-m_{\chi}/kT}$ before freeze-out.

$$\Omega_{\chi} \approx \frac{0.1}{h^2} \left( \frac{3 \times 10^{-26} \text{cm}^3 \text{sec}^{-1}}{\langle \sigma v \rangle} \right)$$
• Cold dark matter also required for structure formation. In regions of highest density, WIMPS (e.g., neutralinos) annihilate forming standard model particles and photons.

• Indirect detection can link a new particle created in a terrestrial accelerator to dark matter halos, for gamma-ray measurements providing a measurement of the halo profile and substructure.
Direct and Indirect Detection

- Scientific complementarity
- Technical complementarity


Proposed CTA SC camera module with 25 2” MAPMTs
Complementarity

Indirect measurements can probe parameter space above energy reach or LHC, help determine the mass and nature of the DM, and measure the halo distribution on the sky.
\[
E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \left( E_{\gamma,\text{TeV}} \frac{dN}{dE_{\gamma,\text{TeV}}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^{-3} \text{s}^{-1}} \right) \left( \frac{100 \text{ GeV}}{M_\chi} \right)^2 J(\theta) \ \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}
\]

Particle Physics Input

\[
J(\theta) = \frac{1}{8.5 \text{kpc}} \left( \frac{1}{0.3 \text{ GeV/cm}^3} \right)^2 \int_{\text{line of sight}} \rho^2(l) dl(\theta)
\]

Astrophysics/Cosmology Input
Gamma-rays from DM

\[ E_{\gamma} \Phi_{\gamma} (\theta) \approx 10^{-10} \left( \frac{dN}{dE_{\gamma}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^{-3} \text{s}^{-1}} \right) \left( \frac{100 \text{ GeV}}{M_\chi} \right)^2 \]

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Line-of-sight integral of \( \rho^2 \) for a Milky-Way-like halo in the VL Lactea II \( \Lambda \)CDM N-body simulations (Kuhlen et al.)
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Astrophysics/Cosmology Input

\[ J(\theta) = \text{VERITAS (50 hrs)} \]

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Gamma-rays from DM

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Line-of-sight integral of \( \rho^2 \) for a Milky-Way-like halo in the VL Lactea II \( \Lambda \)CDM N-body simulations (Kuhlen et al.)
Fig from 1998 - there were still large uncertainties in Halo model ranging from the unphysical Isothermal Halo, to very steep profiles.

Improvements in N-body simulations pointed to something close to NFW profile.

Dynamical measurements of stars in dwarf galaxies allowed constraints on Halo profile, J relatively insensitive to details.

But profile inside 1kpc is still quite uncertain with little detailed modeling of effects of baryonic matter - could be steepened by adiabatic compression, washed out by mergers - cored or cusped!
Annihilation Channels

<table>
<thead>
<tr>
<th>Annihilation Channel</th>
<th>Secondary Processes</th>
<th>Signals</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi\chi \rightarrow q\bar{q}, , gg$</td>
<td>$p, \bar{p}, \pi^\pm, \pi^0$</td>
<td>$p, e, \nu, \gamma$</td>
<td></td>
</tr>
<tr>
<td>$\chi\chi \rightarrow W^+W^-$</td>
<td>$W^\pm \rightarrow l^\pm \nu_l, , W^\pm \rightarrow u\bar{d} \rightarrow \pi^\pm, \pi^0$</td>
<td>$p, e, \nu, \gamma$</td>
<td></td>
</tr>
<tr>
<td>$\chi\chi \rightarrow Z^0Z^0$</td>
<td>$Z^0 \rightarrow l\bar{l}, \nu\bar{\nu}, , q\bar{q} \rightarrow \text{pions}$</td>
<td>$p, e, \gamma, \nu$</td>
<td></td>
</tr>
<tr>
<td>$\chi\chi \rightarrow \tau^\pm$</td>
<td>$\tau^\pm \rightarrow \nu_\tau e^{\pm} \nu_e, , \tau \rightarrow \nu_e W^\pm \rightarrow p, \bar{p}, \text{pions}$</td>
<td>$e, \gamma, \nu$</td>
<td>Rapid energy loss of $\mu$s in sun before decay results in sub-threshold $\nu$s</td>
</tr>
<tr>
<td>$\chi\chi \rightarrow \mu^+\mu^-$</td>
<td></td>
<td>$e, \gamma$</td>
<td></td>
</tr>
<tr>
<td>$\chi\chi \rightarrow \gamma\gamma$</td>
<td></td>
<td>$\gamma$</td>
<td>Loop suppressed</td>
</tr>
<tr>
<td>$\chi\chi \rightarrow Z^0\gamma$</td>
<td></td>
<td>$\gamma$</td>
<td>Loop suppressed</td>
</tr>
<tr>
<td>$\chi\chi \rightarrow e^+e^-$</td>
<td></td>
<td>$e, \gamma$</td>
<td>Helicity suppressed</td>
</tr>
<tr>
<td>$\chi\chi \rightarrow \nu\bar{\nu}$</td>
<td></td>
<td>$\nu$</td>
<td>Helicity suppressed (important for non-Majorana WIMPs?)</td>
</tr>
<tr>
<td>$\chi\chi \rightarrow \phi\phi$</td>
<td>$\phi \rightarrow e^+e^-$</td>
<td>$e^\pm$</td>
<td>New scalar field with $m_\chi &lt; m_\phi$ to explain large electron signal and avoid overproduction of $p, \gamma$</td>
</tr>
</tbody>
</table>
Detection Techniques

- Fermi
- VERITAS
- Super-K
- IceCube
- PAMELA
- AMS

Indirect Detection of DM

\[ \gamma, \nu, e^-, e^+, p, \bar{p} \]
Electron and Antiproton Experiments
• Electrons and Protons deflected by magnetic fields while propagating through the galaxy.

• > GeV electrons undergo rapid energy loss by synchrotron and inverse-Compton limiting their range to a few kpc - sources could be a nearby pulsar or subhalo.
Positron/Antiproton Detection

- Typical instruments include:
  - MS for measurement of momentum (rigidity)
  - EC for measurement of energy and for discrimination of hadronic showers
  - Redundant measurement of Lorentz factor (e.g., RICH or TRD) for particle discrimination against large background of protons.

**Schematic of HEAT**

![HEAT Schematic](image)

**Fig. 2.—HEAT instrument schematic cross section**

TIPP11 Indirect Detection of DM

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- **EC** for measurement of energy and for discrimination of hadronic showers
- Redundant measurement of Lorentz factor (e.g., RICH or TRD) for particle discrimination against large background of protons.

(BETS-Tori, et. al.)
## Electron Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detectors</th>
<th>$E$ Range (GeV)</th>
<th>Exposure ($m^2sr$)</th>
<th>Calorimeter Material</th>
<th>Calorimeter Depth</th>
<th>Calorimeter Layers</th>
<th>Magnet Spectrometer $B_{ave}$</th>
<th>Calorimeter $\sigma_x$</th>
<th>Calorimeter length</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPB-BETs</td>
<td>EC</td>
<td>10-800</td>
<td>$\sim 4 \times 10^4$</td>
<td>Pb/SF?</td>
<td>9 $X_0$</td>
<td>36</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATIC</td>
<td>EC</td>
<td>10-100,000</td>
<td>$\sim 3 \times 10^5$</td>
<td>BGO</td>
<td>18 $X_0$</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HESS</td>
<td>EC</td>
<td>6-8000 300-800</td>
<td>$\sim 8 \times 10^7$ \ $\sim 2 \times 10^7$</td>
<td>Air</td>
<td>27 $X_0$</td>
<td>$\infty$</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fermi LAT</td>
<td>EC</td>
<td>20-1000</td>
<td>$\sim 3 \times 10^7$ (181 days)</td>
<td>CsI(Tl)</td>
<td>8.6 $X_0$</td>
<td></td>
<td>Earth’s Field</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAMELA</td>
<td>EC, MS</td>
<td>50-300 (e$^+$)</td>
<td>$\sim 1.5 \times 10^5$ (850 days)</td>
<td>W/Si</td>
<td>16 $X_0$</td>
<td>22</td>
<td>0.4 T</td>
<td>$\sim 7 \mu$m</td>
<td>40.5 cm/ 6 layers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10-700 (e$^-$)</td>
<td>$\sim 2.1 \times 10^5$ (1200 days)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEAT</td>
<td>EC, MS, TRD</td>
<td>5-50</td>
<td>$\sim 1.3 \times 10^3$</td>
<td>Pb/PS</td>
<td>9 $X_0$</td>
<td>10</td>
<td>1 T</td>
<td>70 $\mu$m</td>
<td>61 cm/18 layers</td>
</tr>
</tbody>
</table>

### Future Experiments

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<th>Calorimeter $\sigma_x$</th>
<th>Calorimeter length</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMS</td>
<td>EC, MS, TRD, RICH</td>
<td>$\sim 4.5 \times 10^7$ (5 yr)</td>
<td>Pb/SF</td>
<td>18</td>
<td>0.125 T</td>
<td>10 $\mu$m</td>
<td>/8 layers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CALET</td>
<td>EC</td>
<td>10-10,000</td>
<td>$\sim 2 \times 10^7$ (5 yr)</td>
<td>PbWO$_4$</td>
<td>27 $X_0$</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VERITAS</td>
<td>EC, MS</td>
<td>100-10,000</td>
<td>$\sim 10^7$</td>
<td>Air</td>
<td>27 $X_0$</td>
<td>$\infty$</td>
<td>Moon Shadow</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Electron measurements with ATIC showed peak.

• Subsequent measurements with Fermi, now PAMELA show no strong excess.
• Positron excess but no antiprotons motivated leptophillic models to boost electron production, while suppressing hadronic channels.
Fermi Positron Fraction

• Muller and Tang proc. 19th ICRC, 2, 378 (1985) used Earth’s magnetic field as a natural magnet spectrometer for first balloon measurements of positron fraction from 10-20 GeV (showing an excess that was not apparent in the more sensitive HEAT measurements)

• Recent preliminary result from Fermi agree with PAMELA positron spectrum

Mitthumsiri, W. et al., Fermi Symposium, May 2011
Annihilation into light leptons is helicity suppressed with respect to annihilation into heavier fermions:

\[
R \sim \left( \frac{m_e}{m_f} \right)^2 \left( \frac{m_{\chi}^2 - m_e^2}{m_{\chi}^2 - m_f^2} \right)
\]

New scalar fields with appropriate mass can allow electron-production, but make hadronic production kinematically forbidden. Sommerfeld enhancement by exchange of \( \phi \) can result in a further boost in cross section.

Internal bremsstrahlung can circumvent helicity suppression, but electromagnetic IB gives gamma-rays near kinematic maximum and \( W^\pm, Z \) bremsstrahlung can overproduce antiprotons.
Boosting Electrons

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\[ R \sim \left( \frac{m_e}{m_f} \right) \left( \frac{m_\chi^2 - m_e^2}{m_\chi^2 - m_f^2} \right)^2 \]

\[ \text{spin flip penalty} \quad \text{phase space} \]

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Problems with Positrons

- Schubnell (2009; arXiv:0905.0444) points out that old measurements (pre 1990) showed rise in positron fraction - found to be a problem with instruments using small permanent magnets and limited particle ID.

- Intensity of CR protons exceeds that of positrons by a factor of $5 \times 10^4$ above 10 GeV.

- PAMELA, originally designed to include a TRD, suffers from lack of strong particle discrimination.

- EC power is limited by the irreducible background from single $\pi^0$ that mimic electromagnetic showers.
Neutrino Experiments
Neutrino Detection

Neutrinos from DM annihilation in the Sun or Galactic Halo travel through Earth, convert to upward going muons which produce Cherenkov light and relatively straight upward going tracks in the PMTs

(simulated neutrino event in ICECUBE)
Neutrino Capture by Sun

- As sun sweeps through dark matter halo, WIMPs can undergo collisions with nuclei and become gravitationally trapped. Eventually these thermalize, and the rate of capture is balanced by the rate of annihilation (and perhaps evaporation).

- Existing Amanda, SuperK and other limits

- DeepCore extension of ICECUBE, adding 6 additional strings and pushing the muon detection threshold down to 10 GeV
DM Neutrinos from the Sun

- Limits on the DM annihilation flux and Spin-Dependent wimp-nucleon cross-section from IceCube compared with Direct detection limits.

- In red, expected improvement in sensitivity with the addition of the six-string Deep Core detector.

de los Heros for the IceCube Collaboration, Dec 2010, arXiv:1012.0184

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Neutrinos from GC Region

\[ J(\psi) = \int_0^{l_{\text{max}}} \frac{\rho^2(\sqrt{R_{sc}^2 - 2lR_{sc}\cos\psi} + l^2)}{R_{sc}\rho_{sc}^2} \, dl, \]

\[ \frac{d\phi_{\nu}}{dE} = \frac{\langle \sigma_A v \rangle}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_{\chi}^2} \frac{dN_{\nu}}{dE}, \]

Abbasi et al. (for the ICECUBE collaboration) (Jan 17, 2011 arXiv: 1101.3359)
Gamma-Ray Experiments
• Both space-based and ground-based instruments use electromagnetic calorimeters, but for ground-based instruments the earth’s atmosphere is basically a continuous 27 rad. length total absorption calorimeter, viewed with an array of telescopes.
VERITAS Array

- First Light in April 2007
• First Light in April 2007

• 10 mCrab sensitivity - $5\sigma$ detection at 1% Crab ($2\times10^{-13}$ erg cm$^{-2}$ s$^{-1}$ @ 1 TeV) in 28 hrs.

• Effective area $10^5$ m$^2$ above 500 GeV

• Angular resolution <0.1 deg

• Energy range 150 GeV - 30 TeV, 15% resolution (for spectral measurements)
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Telescope (x 4)
12-m diameter Davies-Cotton
f 1.0, 110 m² area
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499 PMTs, 3.5° FOV
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Mirror Facets (x 350)
Reflectivity ~ 88%
(Recoated every 2 years)
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Electronics
500 Msp FADC, CFD trigger, 3-fold adjacent pixels and 2/4 telescope coincidence
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Stage et al. 2006
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VHE Gamma-Ray Status

VERITAS

MILAGRO

MAGIC

H.E.S.S.
VHE Gamma-Ray Status

γ-rays from Starburst Galaxy

MILAGRO

VERITAS

M82

MAGIC

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VERITAS

γ-rays from <50 Rc of Supermassive BH

M87

γ-rays from Starburst Galaxy

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M87

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MAGIC

H.E.S.S.
VHE Gamma-Ray Status

M82
- γ-rays from Starburst Galaxy

VERITAS
- γ-rays from <50 R<sub>s</sub> of Supermassive BH

MILAGRO
- Image of SNR molec cloud -π<sup>0</sup> γ-rays ?

H.E.S.S.
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M87
- γ-rays from Starburst Galaxy
VHE Gamma-Ray Status

- **M82**: γ-rays from Starburst Galaxy
- **VERITAS**
- **M87**: γ-rays from <50 R<sub>Ь</sub> of Supermassive BH
- **MILAGRO**
- **G106.3+2.7**: Image of SNR molec cloud -π<sup>0</sup> γ-rays?
- **H.E.S.S.**
- **MAGIC**
- Rapid variability of PKS 2155, LIV tests

**TIPP11**
**Indirect Detection of DM**
**James Buckley**
Where to Look?

Milky Way GC

Line of Sight Integral, $I(θ)$

- Minihalo
- Dwarf Gal.
- Gal. Center
- Andromeda
- Virgo

Detection Significance, $S/B$

Solid Angle, $Ω$ [str]
Where to Look?

Milky Way GC

Andromeda

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Detection Significance, $S/B$

Solid Angle, $\Omega$ [str]
Where to Look?

- Milky Way GC
- Andromeda
- Galaxy Cluster

![Graphs showing line of sight integral and detection significance vs. solid angle.](image-url)
Where to Look?

- Milky Way GC
- Andromeda
- Galaxy Cluster
- Draco Dwarf

Line of Sight Integral, $I(\theta)$

Detection Significance, $S/\sqrt{B}$

- Minihalo
- Dwarf Gal.
- Gal. Center
- Andromeda
- Virgo

Solid Angle, $\Omega$ [str]
Galactic Center

Beilicke, M. for VERITAS Collaboration, Fermi Symposium, May 2011
Galactic Center appears to have a strong Astrophysical source, but can still cut out a region around center.

For 12sigma VERITAS detection, optimum region is between 0.34 and edge of field.
GC DM Prospects

VERITAS sensitivity to GC region excluding point source for 3 TeV neutralinos with ~x10 boost (Sommerfeld or Astrophysical boost)
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CTA can detect ~>100-200 GeV neutralinos with no boost

Angular resolution + sensitivity + southern hemisphere
Dwarf Upper Limits

- Dwarf satellites of the Milky Way are the most promising DM targets outside of the Galactic Center
- Dark-Matter dominated objects with mass to light ratios of more than 100
- DM Distribution is tightly constrained by stellar velocity dispersion measurements the map out the DM gravitational potential
- Clean sources with limited uncertainties, but currently one to two orders of magnitude beyond the reach of Fermi, VERITAS or HESS

<table>
<thead>
<tr>
<th>dSph</th>
<th>Draco</th>
<th>Ursa Minor</th>
<th>Bootes I</th>
<th>Willman</th>
<th>Segue I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (kpc)</td>
<td>82</td>
<td>66</td>
<td>62</td>
<td>38</td>
<td>23</td>
</tr>
<tr>
<td>DM profile</td>
<td>NFW</td>
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<td>NFW</td>
<td>NFW</td>
<td>Einasto</td>
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<tr>
<td>$\log_{10}&lt;J&gt;$ (GeV$^2$/cm$^5$)</td>
<td>18.2</td>
<td>18.4</td>
<td>18.1</td>
<td>18.9</td>
<td>19</td>
</tr>
<tr>
<td>$T_{\text{obs}}$ (h)</td>
<td>18.4</td>
<td>18.9</td>
<td>14.3</td>
<td>13.7</td>
<td>25.0</td>
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<td>Ann. channel</td>
<td>$\tau^+\tau^-$, bbar</td>
<td>$\tau^+\tau^-$, bbar</td>
<td>$\tau^+\tau^-$, bbar</td>
<td>$\tau^+\tau^-$, bbar</td>
<td>$\tau^+\tau^-$, bbar</td>
</tr>
<tr>
<td>$&lt;\alpha\nu&gt;_{95%}$ (cm$^3$/s$^1$)</td>
<td>$5 \times 10^{-23}$</td>
<td>$2 \times 10^{-23}$</td>
<td>$5 \times 10^{-22}$</td>
<td>$10^{-23}$</td>
<td>$8 \times 10^{-24}$</td>
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</table>

<table>
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<tr>
<th>Sgr</th>
<th>Carina</th>
<th>Sculptor</th>
<th>Canis Major</th>
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<tr>
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<td>NFW</td>
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<tr>
<td>19.3/20.8</td>
<td>17.6</td>
<td>18.5</td>
<td>18.0</td>
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<tr>
<td>11.0</td>
<td>14.8</td>
<td>11.8</td>
<td>9.6</td>
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</table>

Veritas

- Dwarf Upper Limits

HESS

- Dwarf Upper Limits

Belokurov et al. (2007)
Dwarf Galaxy Limits

Fermi observations of Dwarf galaxies typically 1-2 orders of magnitude above natural cross-section. Stacking sources (actually joint maximum likelihood!) gives more exposure is bringing results closer to canonical cross section for < 100 GeV DM.
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VERITAS Dwarf Limits

Acciari, V.A. et al. (for the VERITAS collaboration)


Projected Sensitivity

VERITAS upgrade (new PMTs) and longer Exposure Time
At sufficiently high neutralino masses, the W and Z can act as carriers of a long-range (Yukawa-like) force, resulting in a velocity dependent enhancement in cross section (1/\(v\) or even \(1/v^2\) enhancement near resonance).

Lattanzi and Silk, PRD 79, 083523 (2009), Profumo (2005)
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- At high mass, expect Sommerfeld enhancement from W, Z exchange for standard neutralinos can give large enhancement in cross section, larger at small velocities in smaller halo substructure (e.g., Dwarfs)

- While HAWC will have a relatively high threshold, would be sensitive to some models at > several TeV where Sommerfeld enhancement is possibly quite large
Future Experiments
Future Space Experiment?
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- No serious proposals for a follow up to Fermi aimed at better DM sensitivity, but...
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JB, D. Hunter, et al. proposed APT concept using SF tracker, thin calorimeter and largest available shroud to get order of magnitude increase in exposure in 1-10 GeV regime.
Future Experiments

CTA

- CTA baseline design consists of
  - 4 x 24m Large Size Telescopes (LSTs) for the lowest energies
  - 23 x 12m Mid-Size Telescopes (MSTs) for medium energies (100 GeV - 10 TeV)
  - 50 x 6m Small-Size Telescopes (SSTs) for high energies (>10 TeV)
- CTA-US will supplement this with 36 more MST telescopes
- HAWC will consist of 300 water tanks at 4100m a.s.l to provide all-sky survey observations above TeV energies
- As MILAGRO guided HESS, MAGIC and VERITAS HAWC will guide CTA
• Add 36 telescopes to existing 24-scope mid-sized telescope array.
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• Collective effects in combining experiments - in large array, higher percentage of showers fall between scopes than beyond edge - lower energy threshold, better angular resolution, better sensitivity
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CTA-US Technology R&D

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Wider field of view, better sensitivity, better angular resolution for Astrophysics and DM searches.
CTA Prospects

Wider field of view, better sensitivity, better angular resolution for Astrophysics and DM searches

Simulated Sky Map with Improved Angular Resolution, FoV, Sensitivity

Dark Matter

\[ \nu_F (\text{erg cm}^{-2} \text{ sec}^{-1}) \]

\[ \nu [\text{cm}^3 \text{ s}^{-1}] \]

\( M_\chi [\text{GeV}] \)

Veritas/HESS (50 hr)

AGIS/CTA (200 hr)

Veritas/HeSS (50 hr)

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- Indirect detection is complementary to other approaches - lots of common detector technology including photomultiplier tubes and waveform digitizers.
Backup Slides
Indirect Detection of DM

James Buckley