Indirect Dark Matter Searches with the Whipple 10m Gamma Ray Telescope

Matthew Wood
Vladimir Vassiliev
Stephen Fegan

UCLA
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Outline

• Indirect detection of DM with VHE gamma-rays

• Annihilation Spectrum

• DM Density Profiles

• Data/Results

• Prospects for Future Work
Motivation: Indirect Detection of Supersymmetric DM

• A weakly-interacting massive particle (WIMP) can reproduce the astrophysically observed relic DM density

• SUSY provides a natural candidate for WIMPs in the form of the lightest supersymmetric particle (LSP) which is normally the neutralino

• Self-annihilation of neutralinos in high density astrophysical environments may result in a detectable flux of gamma-rays
Goals of Indirect Detection

• Evidence for DM was first obtained through astrophysical observations

• Can astrophysical observations identify the nature of DM?

• Even if SUSY is discovered at the LHC, detection in an astrophysical context will be necessary to conclusively identify the LSP with DM
Indirect Detection with VHE Gamma-rays

• Pros
  – Unambiguous spectral signature
  – Potential to constrain branching ratios from spectral endpoint
  – Complementary to direct and accelerator searches

• Cons
  – Large theoretical uncertainties due to unknown DM distribution in the cores of DM halos
  – Potentially large conventional astrophysical backgrounds

![Energy Spectrum Diagram](chart.png)

- EGRET, GLAST
- Whipple, VERITAS, H.E.S.S., MAGIC

**Energy Levels:**
- 10 MeV
- 100 MeV
- 1 GeV
- 10 GeV
- 100 GeV
- 1 TeV
- 10 TeV

**Energy Domains:**
- High Energy (HE)
- Very High Energy (VHE)
Air Cherenkov Telescopes (ACTs)

- Detect secondary Cherenkov light from EM shower initiated by gamma-ray primary

- Whipple 10m Telescope
  - First generation instrument
  - Detected the first VHE gamma-ray source (Crab Nebula) in 1989
  - Sensitivity: $F \sim 3\text{-}5\% \text{ Crab } @ E > 400 \text{ GeV}$
Whipple 10m Telescope

10m telescope

490 pixel camera
DM Annihilation Flux

Differential Flux

\[
\frac{d\phi(\vec{\psi}, \Delta \Omega)}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_{\chi}^2} \left( \frac{dN_\gamma}{dE} \right) \left[ \int_{\Delta \Omega} d\Omega \int \rho^2 dS(\vec{\psi}) \right]
\]

Astrophysical Enhancement Factor \( J \)

\[
J(\vec{\psi}, \Delta \Omega) = \left( \frac{1}{\rho_c^2 R_H} \right) \int_{\Delta \Omega} d\Omega \int \rho^2 dS(\vec{\psi})
\]

\( \frac{J}{\Delta \Omega} \sim 1 \rightarrow \text{Cosmological Value} \)

\( J \sim 10^4 \rightarrow \text{Detectable Flux for} \ \langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3 \text{ s}^{-1} \text{ and} \ m_{\chi} \sim 100 \text{ GeV} \)
Neutralino Annihilation Channels

Annihilation to fermions and bosons (continuum component)

Annihilation channels with mono-energetic photons

Heavy final states (bb, tt, WW, ZZ) kinematically favored

Suppressed ($b_{\gamma \gamma}$ and $b_{\gamma Z} \sim 10^{-2}$-$10^{-3}$)

$\pi^0$ decay main component of continuum spectrum
DM Annihilation Spectrum

- Distinguishable from astrophysical backgrounds
  - Not a power-law spectrum
  - Truncation and mono-energetic line at $E = m_\chi$

- Two scenarios investigated
  - Soft mode: $\chi\chi \rightarrow b\bar{b}$
  - Hard mode: $\chi\chi \rightarrow \tau^+\tau^-$

Differential Photon Yield per Annihilation for $m_\chi = 500$ GeV

\[
\frac{dN}{dE} \propto \begin{cases} 
E^2 & \text{for soft mode} \\
\text{constant} & \text{for hard mode}
\end{cases}
\]
Astrophysical Target Selection

- Flux scales as $V \rho_{DM}^2 / D^2$
- Criteria
  - Nearby
  - Large Density of DM
- Targets for Indirect DM Search
  - Galactic Center
  - Local Group Galaxies
  - Globular Clusters
  - Dwarf Galaxies
  - MW Satellite DM sub-structures
CDM Simulations

Universal DM density profile for dwarf galaxies → clusters

\[ \rho(r) = \rho_0 \left( \frac{r}{r_c} \right)^{-\gamma} \left( 1 + \left( \frac{r}{r_c} \right)^\alpha \right)^{-\frac{\beta-\gamma}{\alpha}} \]

NFW Profile
\( (\alpha, \beta, \gamma) = (1, 3, 1) \)

Moore Profile
\( (\alpha, \beta, \gamma) = (1.5, 3, 1.5) \)

Navarro et al. 2004
Physics on Small Scales

- Limitations of CDM simulations
  - Resolution of ~ 0.1 – 1 kpc
  - Effects of baryonic matter on small scale DM distribution is not simulated

- Additional considerations on small scales (< 10-100 pc)
  - Enhancement Factors
    - Condensation of stars/gas (e.g. core-collapse)
    - Growth of a central SMBH
  - Depletion Factors
    - Galactic merger events
    - Heat transfer to dark matter particles by stars and inspiraling SMBHs
Enhancement Factors: Adiabatic Compression

- Adiabatic compression can enhance a DM cusp (e.g. NFW) into a ‘spike’ with $\gamma \geq 1.5$

- Annihilation rate is divergent for $\gamma \geq 1.5 \rightarrow$ maximum density set by dynamical effects

- Adiabatic Compression Mechanisms
  - Growth of SMBH
  - Baryon infall (e.g. core collapse)

Ullio et al. 2001
Two-Body Relaxation

• In stellar environments with large $\rho$ and small $\sigma^2$ two-body interactions can dominate if $t_r \leq 1/H_0$

• Predicted central stellar density distribution after relaxation
  - $\rho \sim r^{-1.75}$ w/ central BH
    (Bahcall and Wolf 1976)
  - $\rho \sim r^{-2.23}$ w/o central BH
    (Cohn 1980)

• However, heat transfer to DM by stars or inspiraling BH could cause DM depletion

Core-collapsed Globular Cluster M15

Globular Cluster M15

PRC95-06 • ST ScI • OPO • November 1995 • P. Guhathakurta (UC Santa Cruz), NASA
Depletion Factors: Galactic Mergers

- **Hierarchical mergers**
  - Disruption of central cusp for mergers of halos with SMBHs of comparable mass
  - Cusp preserved when BH mass ratio is $< 10^{-1}$

- **History of DM halo is an important consideration**

- **Did the MW experience a recent merger event?**

Merritt et al. 2002

**DM density profile before merger**

$M_{BH,1}/M_{BH,2} \sim 10^{-1}$

$M_{BH,1}/M_{BH,2} \sim 1$
Whipple 10m DM Sources

Selection of Sources representing diverse astrophysical environments

Target List

<table>
<thead>
<tr>
<th>Source</th>
<th>Distance (kpc)</th>
<th>Exposure (h)</th>
<th>Type</th>
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<tbody>
<tr>
<td>M32</td>
<td>784</td>
<td>6.9</td>
<td>Compact Elliptical</td>
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<tr>
<td>M33</td>
<td>840</td>
<td>17.0</td>
<td>Spiral</td>
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<td>M15</td>
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<td>Globular Cluster</td>
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<td>80</td>
<td>14.3</td>
<td>Dwarf Galaxy</td>
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<tr>
<td>Ursa Minor</td>
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<td>Dwarf Galaxy</td>
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<tr>
<td>M87</td>
<td>18000</td>
<td>40.6</td>
<td>Giant Elliptical</td>
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Point-source Analysis

Significances obtained with standard point-source analysis

<table>
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<tr>
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<th>$\sigma$</th>
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<td>M15</td>
<td>0.21</td>
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No Surprises…
2D Analysis

- Dark Matter substructures in external regions of MW Halo
  - Predicted by CDM simulations to be isotropically distributed with $M \geq 10^{-6}$ M
  - Any field a potential source

5 fields explored
No surprises…
Deriving SUSY Limits

• Placing limits on the SUSY parameter space is difficult given the astrophysical uncertainties

• Approaches to deriving astrophysical enhancement factor $J$
  – Extrapolate direct measurement of DM distribution on large scales (~0.1-1 kpc) down to core (1-10 pc)
  – Assume that the DM distribution follows the baryonic distribution with some relative scaling $\lambda$
Estimates of $J$

Detectable flux threshold:
Whipple 10m $\rightarrow J \sim 10^6$
Current Generation ACT $\rightarrow J \sim 10^5$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\lambda$</th>
<th>$J$</th>
<th>$\delta J/J$</th>
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<tbody>
<tr>
<td>Draco</td>
<td>---</td>
<td>11</td>
<td>0.1-1</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>---</td>
<td>19</td>
<td>0.1-1</td>
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<td>---</td>
<td>3.5</td>
<td>0.1-1</td>
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<tr>
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<td>1</td>
<td>$1.1 \times 10^5$</td>
<td>10-10$^3$</td>
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<td>$1.2 \times 10^3$</td>
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<tr>
<td>M15</td>
<td>$10^{-2}$</td>
<td>$1.2 \times 10^6$</td>
<td>10-10$^3$</td>
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</table>
SUSY Limits

M15 Limits with $J = 1.2 \times 10^6$

Scan of $10^6$ MSSM Models with DarkSUSY (Gondolo et al. 2004)

All models within $3\sigma$ of current WMAP Constraints on $\Omega h^2$
Prospects and Future Work

• Future Improvements
  – Calculation of J using N-body simulations of baryons and dark matter in galactic nuclei
  – Observations with VERITAS (x10 sensitivity and $E_{\text{th}} \sim 100$ GeV)

• Search is complimentary to sensitivity range of GLAST

• Follow-up observations of GLAST detections
  – Fine spectroscopy
  – Search for MW halo substructures