The Search For Dark Matter with ACTs

James Buckley
Washington University, St. Louis
Dark Matter Complementarity

Complementarity - SUSY scan (pMSSM)

M. Cahill-Rowley et al. - Snowmass white paper

Dark Matter Direct Detection

Direct Detection DM

Indirect Detection DM

Particle Colliders SM

Astrophysical Probes DM

XENON1T Survives DD, ID, and LHC
Excluded by LHC but not DD or ID
Excluded by DD and ID
Excluded by DD but not ID

LUX

LZ

VERITAS

CTA

Dark Matter Direct Detection in Context

Direct detection is only one method to search for dark matter. Because dark matter can potentially interact with any of the known particles or, as in the case of hidden sector dark matter, another currently unknown particle, it is important to place direct detection in the larger context of dark matter research. The Snowmass Cosmic Frontier Working Group CF4 has prepared a report exploring the Community Planning Study: Snowmass 2013.
VERITAS Array
VERITAS Array

- **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)
• 10 mCrab sensitivity - $5\sigma$ detection at 1%
  Crab ($2 \times 10^{-13}$ 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)
VERITAS Array

• 10 mCrab sensitivity - 5σ detection at 1%
  Crab (2x10^{-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)
VERITAS Array

- 10 mCrab sensitivity - 5σ detection at 1% Crab (2x10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} @ 1 \text{ TeV}) in 28 hrs.
- Effective area $10^5 \text{ m}^2$ above 500 GeV
- Angular resolution <0.1 deg
- Energy range 150 GeV - 30 TeV, 15% resolution (for spectral measurements)
VERITAS Array

- 10 mCrab sensitivity - 5σ detection at 1% Crab (2×10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} @ 1 \text{ TeV}) in 28 hrs.
- Effective area $10^5 \text{ m}^2$ above 500 GeV
- Angular resolution $<0.1 \text{ deg}$
- Energy range 150 GeV - 30 TeV, 15% resolution (for spectral measurements)
VERITAS Array

- **10 mCrab sensitivity** - $5\sigma$ detection at 1% Crab ($2 \times 10^{-13}$ 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)
VERITAS Array

- **10 mCrab sensitivity** - $5\sigma$ detection at 1% Crab (2x10$^{-13}$ 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)
ACTs have now detected so many sources, we can make a constellation (the TeraBird Constellation of TeV sources!)
ACTs and Ground Arrays
ACTs and Ground Arrays

- ACTs like VERITAS detect Cherenkov light from air showers with a narrow FoV on dark/moonless nights.
ACTs and Ground Arrays

• ACTs like VERITAS detect Cherenkov light from air showers with a narrow FoV on dark/moonless nights.

• Ground arrays like HAWC detect shower particles reaching the ground (albeit at high altitudes). These have higher energy threshold, and lower angular resolution, but are wide field, high duty cycle.
The WIMP Miracle

- In the beginning the universe was very hot, DM particles and SM particles were in thermal equilibrium.

- Particles in equilibrium were Boltzmann suppressed $\sim e^{-mc^2/kT}$

- Annihilation and recombination rates $\Gamma \sim n^2 \langle \sigma v \rangle$

- As the number density $n$ dropped due to expansion, particles with the smallest $\langle \sigma v \rangle$ fell out of equilibrium first

- *the weak survive* with a relic density
The WIMP Miracle

- In the beginning the universe was very hot, DM particles and SM particles were in thermal equilibrium.

- Particles in equilibrium were Boltzmann suppressed $\sim e^{-mc^2/kT}$

- Annihilation and recombination rates $\Gamma \sim n^2 \langle \sigma v \rangle$

- As the number density $n$ dropped due to expansion, particles with the smallest $\langle \sigma v \rangle$ fell out of equilibrium first

- *the weak survive* with a relic density

$$\Omega_{DM} \approx 0.30 \left( \frac{2 \times 10^{-26} \text{cm}^3 \text{sec}^{-1}}{\langle \sigma v \rangle} \right)$$
In the beginning the universe was very hot, DM particles and SM particles were in thermal equilibrium.

Particles in equilibrium were Boltzmann suppressed \( \sim e^{-mc^2/kT} \)

annihilation and recombination rates \( \Gamma \sim n^2 \langle \sigma v \rangle \)

As the number density \( n \) dropped due to expansion, particles with the smallest \( \langle \sigma v \rangle \) fell out of equilibrium first

*the weak survive* with a relic density

\[
\Omega_{\text{DM}} \approx 0.30 \left( \frac{2 \times 10^{-26}\text{cm}^3\text{sec}^{-1}}{\langle \sigma v \rangle} \right)
\]

Any theory with a new stable weakly interacting particle will work. Theorists (used to) really like SUSY - for every fermion loop there is a boson loop to cancel contributions to amplitudes, getting rid of embarrassing divergences in Higgs mass, gauge coupling unification, etc.
\[ E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \left( \frac{E_{\gamma,\text{TeV}}}{dE_{\gamma,\text{TeV}}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^{-3} \text{s}^{-1}} \right) \left( \frac{100 \text{GeV}}{M_\chi} \right)^2 J(\theta) \text{ erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

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

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.)
Gamma-rays from DM

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

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

Line-of-sight integral of \( \rho^2 \) for a Milky-Way-like halo in the VL Lactea II \( \Lambda \text{CDM} \) N-body simulations (Kuhlen et al.)
Gamma-rays from DM

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

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

Line-of-sight integral of \( \rho^2 \) for a Milky-Way-like halo in the VL Lactea II \( \Lambda \text{CDM} \) N-body simulations (Kuhlen et al.)
$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \left( \frac{E_{\gamma,\text{TeV}}}{dE_{\gamma,\text{TeV}}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^{-3} \text{s}^{-1}} \right) \left( \frac{100 \text{GeV}}{M_X} \right)^2 J(\theta) \text{ erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$

### 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

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.)
\[ E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \left( \frac{E_{\gamma, \text{TeV}}}{dE_{\gamma, \text{TeV}}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^{-3} \text{s}^{-1}} \right) \left( \frac{100 \text{ GeV}}{M_X} \right)^2 J(\theta) \text{ erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

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

Line-of-sight integral of \( \rho^2 \) for a Milky-Way-like halo in the VL Lactea II \( \Lambda \text{CDM} \) N-body simulations (Kuhlen et al.)
Gamma-rays from DM

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

Particle Physics Input

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

Astrophysics/Cosmology Input

Line-of-sight integral of \( \rho^2 \) for a Milky-Way-like halo in the VL Lactea II ΛCDM N-body simulations (Kuhlen et al.)
## DM and Gamma-Rays

<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>$W^\pm \rightarrow \ell^\pm \nu\ell, \ W^\pm \rightarrow u\bar{d}$</td>
<td>$p, e, \nu, \gamma$</td>
<td></td>
</tr>
<tr>
<td>$\chi\chi \rightarrow Z^0Z^0$</td>
<td>$Z^0 \rightarrow ll, \nu\bar{\nu}, q\bar{q} \rightarrow \text{pions}$</td>
<td>$p, e, \gamma, \nu$</td>
<td></td>
</tr>
<tr>
<td>$\chi\chi \rightarrow \tau^\pm$</td>
<td>$\tau^\pm \rightarrow \nu_{\tau} e^\pm \nu_{e}, \tau \rightarrow \nu_{\tau} W^\pm \rightarrow p, \bar{p}, \text{pions}$</td>
<td>$p, e, \gamma, \nu$</td>
<td></td>
</tr>
<tr>
<td>$\chi\chi \rightarrow \mu^+\mu^-$</td>
<td></td>
<td>$e, \gamma$</td>
<td>Rapid energy loss of $\mu$s in sun before decay results in sub-threshold $\nu$s</td>
</tr>
<tr>
<td>$\chi\chi \rightarrow \gamma\gamma$</td>
<td></td>
<td>$\gamma$</td>
<td>Loop suppressed</td>
</tr>
<tr>
<td>$\chi\chi \rightarrow Z^0\gamma$</td>
<td>$Z^0$ decay</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 $m_\chi &lt; m_q$ to explain large electron signal and avoid overproduction of $p, \gamma$</td>
</tr>
</tbody>
</table>
## DM and Gamma-Rays

<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>$W^\pm \rightarrow l^\pm \nu_l, W^\pm \rightarrow ud \rightarrow \pi^\pm, \pi^0$</td>
<td>$p, e, \nu, \gamma$</td>
<td></td>
</tr>
<tr>
<td>$\chi \chi \rightarrow Z^0Z^0$</td>
<td>$Z^0 \rightarrow ll, \nu\bar{\nu}, q\bar{q} \rightarrow \text{pions}$</td>
<td>$p, e, \gamma, \nu$</td>
<td></td>
</tr>
<tr>
<td>$\chi \chi \rightarrow \tau^\pm$</td>
<td>$\tau^\pm \rightarrow \nu_\tau e^\pm \nu_e, \tau \rightarrow \nu_\tau W^\pm \rightarrow p, \bar{p}, \text{pions}$</td>
<td>$p, e, \gamma, \nu$</td>
<td></td>
</tr>
<tr>
<td>$\chi \chi \rightarrow \mu^+\mu^-$</td>
<td></td>
<td>$e, \gamma$</td>
<td>Rapid energy loss of $\mu$s in sun before decay results in sub-threshold $\nu$s</td>
</tr>
<tr>
<td>$\chi \chi \rightarrow \gamma\gamma, \chi \chi \rightarrow Z^0\gamma$</td>
<td>$Z^0 \text{ decay}$</td>
<td>$\gamma, \gamma$</td>
<td>Loop suppressed, 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 $m_\chi &lt; m_q$ to explain large electron signal and avoid overproduction of $p, \gamma$</td>
</tr>
</tbody>
</table>

*internal/initial state brems inverse Compton $\gamma$’s*
## DM and Gamma-Rays

<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>$W^\pm \rightarrow l^\pm \nu_l, W^\pm \rightarrow ud \rightarrow \pi^\pm, \pi^0$</td>
<td>$p, e, \nu, \gamma$</td>
<td></td>
</tr>
<tr>
<td>$\chi \chi \rightarrow Z^0Z^0$</td>
<td>$Z^0 \rightarrow ll, \nu\bar{\nu}, q\bar{q} \rightarrow$ pions</td>
<td>$p, e, \gamma, \nu$</td>
<td></td>
</tr>
<tr>
<td>$\chi \chi \rightarrow \tau^\pm$</td>
<td>$\tau^\pm \rightarrow \nu_e e^\mp \nu_e, \tau \rightarrow \nu_e W^\pm \rightarrow p, \bar{p},$ pions</td>
<td>$p, e, \gamma, \nu$</td>
<td></td>
</tr>
<tr>
<td>$\chi \chi \rightarrow \mu^+\mu^-$</td>
<td></td>
<td>$e, \gamma$</td>
<td>Rapid energy loss of $\mu$s in sun before decay results in sub-threshold $\nu$s</td>
</tr>
<tr>
<td>$\chi \chi \rightarrow \gamma\gamma$</td>
<td></td>
<td>$\gamma$</td>
<td>Loop suppressed</td>
</tr>
<tr>
<td>$\chi \chi \rightarrow Z^0\gamma$</td>
<td>$Z^0$ decay</td>
<td></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 $m_\chi &lt; m_q$ to explain large electron signal and avoid overproduction of $p, \gamma$</td>
</tr>
</tbody>
</table>

All channels lead to $\gamma$-rays. Cross section for $\gamma$-ray production is closely tied to total annihilation cross section in the early universe.
• EGRET detected GC source 3EG J1746-2851 (Hartman et al. 1999). Whipple 10m observed GC for ~ ten years (1995-2003) resulting in ~4 sigma evidence for emission from GC. HESS definitively detected the GC, followed by Fermi, VERITAS and MAGIC
• EGRET detected GC source 3EG J1746-2851 (Hartman et al. 1999). Whipple 10m observed GC for ~ ten years (1995-2003) resulting in ~4 sigma evidence for emission from GC. HESS definitively detected the GC, followed by Fermi, VERITAS and MAGIC
EGRET detected GC source 3EG J1746-2851 (Hartman et al. 1999). Whipple 10m observed GC for ~ ten years (1995-2003) resulting in ~4 sigma evidence for emission from GC. HESS definitively detected the GC, followed by Fermi, VERITAS and MAGIC.
While it is more sensible to build a telescope in the southern hemisphere to look for DM from the Galactic Center, LZA observations provide an enormous effective area at high energies - especially important for annihilation channels that result in gamma-ray emission near the kinematic maximum.
Including in this work, the ring background model (light from incident gamma rays having to traverse a much greater path) observations detailed in this work. Due to the Cherenkov effect, we estimate an energy resolution of 1%.

For the imaging analysis and significance calculations, VERITAS took by IACTs at small elevation angles. Through the use of the Displacement method, the VERITAS observables at multi-TeV energies. By providing a joint fit to the VERITAS and H.E.S.S. points along with the model fits described in the text.

Table 1 lists the fluxes of the detected sources. While the H.E.S.S. observations allow for very rich statistics at lower energies, the large error bars make component extraction of the di-ray region problematic. As such, we take the approach of using component from the Sgr A* region never transits above 30 degrees. The VERITAS GC Data provides an important mechanism to study particle accelerators in the Galactic Center Ridge (significance skymap shown in Figure 1). The HERA J1745-290 (SGA A*) was detected at a statistical significance of 18 sigma.

The composite supernova remnant G0.9+0.1 consists of four 12-meter IACTs. Since the commissioning of the VERITAS array in 2007, VERITAS has provided excellent angular resolution and sensitivity to TeV gamma-ray sources. The VERITAS position of VER J1745-290 (SGA A*) was centered on VER J1745-290 (SGA A*) with coordinates l = 359.94 ± 0.05 and b = -29.0 ± 0.3.

The position of VER J1745-290 (SGA A*) is shown, along with the PSF for the Sgr A* region. The black dashed circle represents the total error on the VERITAS fit. On the right is shown the differential energy spectrum using both VERITAS and H.E.S.S. points along with the model fits described in the text.

Aharonian et al. (2008) have investigated spectra following the shape of 1.) a pure power law, 2.) a power law with an exponential cutoff, and 3.) a smoothly broken power law. These functions were fit to the observed data.

The resulting fits are shown in Figure 2. The VERITAS data are well described by a power law with an exponential cutoff (dashed line). The H.E.S.S. points are also consistent with this model.

Aharonian et al. (2008) note that the measured spectrum includes contributions from Sgr A*, G0.9+0.1, and a distant source coincident with Sgr A*.

The refined values of Sgr A* provide a significant improvement in statistics. As such, we take the approach of using the displacement method to study particle accelerators in the Galactic Center Ridge.
**VERITAS GC Data**


- 85 hours of Large Zenith Angle (~30deg elevation at transit) from 2010-2014.
VERITAS GC Data


- 85 hours of Large Zenith Angle (~30deg elevation at transit) from 2010-2014.

- GC seen at 25 sigma using LZA analysis method. Spectrum in good agreement with HESS.
VERITAS GC Data


- 85 hours of Large Zenith Angle (~30deg elevation at transit) from 2010-2014.

- GC seen at 25 sigma using LZA analysis method. Spectrum in good agreement with HESS.

- Lots of other sources in GC region!
VERITAS GC Data


- 85 hours of Large Zenith Angle (~30deg elevation at transit) from 2010-2014.

- GC seen at 25 sigma using LZA analysis method. Spectrum in good agreement with HESS.

- Lots of other sources in GC region!
Where to Look for DM

Milky Way GC

Graphs showing line of sight integral and detection significance for different regions.

JB 2002
Where to Look for DM

- Milky Way GC
- Andromeda

Graphs showing line of sight integral and detection significance as functions of solid angle. Legends include Dwarf Gal., Gal. Center, Andromeda, Virgo.
Where to Look for DM

- Milky Way GC
- Andromeda
- Galaxy Cluster

Graphs showing line of sight integral and detection significance for different regions and clusters.
Where to Look for DM

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

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

Detection Significance, $S/B$

JB 2002
Ten Years of Dwarf Galaxy Observations

Stellar velocity dispersion of stars in Dwarf galaxies giving density profiles, and J-factors (the figure of merit for detectibility). VERITAS conducted a 10 year program of Dwarf observing.

<table>
<thead>
<tr>
<th>Dwarf</th>
<th>$\log_{10} J_1(0.5^\circ)$ [GeV cm$^{-2}$]</th>
<th>$\log_{10} J_2(0.5^\circ)$ [GeV cm$^{-2}$]</th>
<th>$\log_{10} D_1(0.5^\circ)$ [GeV cm$^{-2}$]</th>
<th>Exposure v4 [min]</th>
<th>Exposure v5 [min]</th>
<th>Exposure v6 [min]</th>
<th>Total Expos [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segue 1</td>
<td>$19.4^{+0.3}_{-0.4}$</td>
<td>$17.0^{+0.2}_{-0.3}$</td>
<td>$18.0^{+0.2}_{-0.3}$</td>
<td>0</td>
<td>6121</td>
<td>4921</td>
<td>11042</td>
</tr>
<tr>
<td>Ursa Major II</td>
<td>$19.4^{+0.4}_{-0.4}$</td>
<td>$19.9^{+0.7}_{-0.5}$</td>
<td>$18.4^{+0.3}_{-0.3}$</td>
<td>0</td>
<td>0</td>
<td>10869</td>
<td>10869</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>$18.9^{+0.3}_{-0.2}$</td>
<td>$19.0^{+0.1}_{-0.1}$</td>
<td>$18.0^{+0.2}_{-0.1}$</td>
<td>711</td>
<td>2209</td>
<td>6844</td>
<td>9724</td>
</tr>
<tr>
<td>Draco</td>
<td>$18.8^{+0.1}_{-0.1}$</td>
<td>$19.1^{+0.4}_{-0.2}$</td>
<td>$18.5^{+0.1}_{-0.1}$</td>
<td>1169</td>
<td>2170</td>
<td>3435</td>
<td>6813</td>
</tr>
<tr>
<td>Coma Berenices</td>
<td>$19.0^{+0.4}_{-0.4}$</td>
<td>$19.6^{+0.8}_{-0.7}$</td>
<td>$18.0^{+0.3}_{-0.3}$</td>
<td>0</td>
<td>0</td>
<td>2204</td>
<td>2204</td>
</tr>
<tr>
<td>Segue II</td>
<td>$16.2^{+1.1}_{-1.0}$</td>
<td>$18.9^{+1.1}_{-1.1}$</td>
<td>$15.9^{+0.4}_{-0.4}$</td>
<td>0</td>
<td>0</td>
<td>1128</td>
<td>1128</td>
</tr>
<tr>
<td>Boötes I</td>
<td>$18.2^{+0.4}_{-0.4}$</td>
<td>$18.5^{+0.6}_{-0.5}$</td>
<td>$17.9^{+0.3}_{-0.3}$</td>
<td>960</td>
<td>0</td>
<td>0</td>
<td>960</td>
</tr>
<tr>
<td>Leo II</td>
<td>$18.0^{+0.2}_{-0.2}$</td>
<td>$17.8^{+0.2}_{-0.2}$</td>
<td>$17.2^{+0.4}_{-0.5}$</td>
<td>0</td>
<td>0</td>
<td>946</td>
<td>946</td>
</tr>
<tr>
<td>Willman 1</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>931</td>
<td>0</td>
<td>0</td>
<td>931</td>
</tr>
<tr>
<td>Triangulum II</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0</td>
<td>0</td>
<td>909</td>
<td>909</td>
</tr>
<tr>
<td>Canes Ver. II</td>
<td>$17.7^{+0.5}_{-0.4}$</td>
<td>$18.5^{+1.2}_{-0.9}$</td>
<td>$17.0^{+0.2}_{-0.2}$</td>
<td>0</td>
<td>0</td>
<td>864</td>
<td>864</td>
</tr>
<tr>
<td>Canes Ver. I</td>
<td>$17.4^{+0.4}_{-0.3}$</td>
<td>$17.5^{+0.4}_{-0.3}$</td>
<td>$17.6^{+0.7}_{-0.7}$</td>
<td>0</td>
<td>0</td>
<td>850</td>
<td>850</td>
</tr>
<tr>
<td>Hercules I</td>
<td>$16.9^{+0.7}_{-0.7}$</td>
<td>$17.5^{+0.7}_{-0.7}$</td>
<td>$16.7^{+0.4}_{-0.4}$</td>
<td>0</td>
<td>0</td>
<td>794</td>
<td>794</td>
</tr>
<tr>
<td>Sextans I</td>
<td>$18.0^{+0.2}_{-0.2}$</td>
<td>$17.6^{+0.2}_{-0.2}$</td>
<td>$17.9^{+0.2}_{-0.2}$</td>
<td>0</td>
<td>0</td>
<td>783</td>
<td>783</td>
</tr>
<tr>
<td>Draco II</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0</td>
<td>0</td>
<td>598</td>
<td>598</td>
</tr>
<tr>
<td>Ursa Major I</td>
<td>$17.9^{+0.6}_{-0.3}$</td>
<td>$18.7^{+0.6}_{-0.5}$</td>
<td>$17.6^{+0.2}_{-0.4}$</td>
<td>0</td>
<td>0</td>
<td>482</td>
<td>482</td>
</tr>
<tr>
<td>Leo I</td>
<td>$17.8^{+0.2}_{-0.2}$</td>
<td>$17.8^{+0.5}_{-0.2}$</td>
<td>$17.9^{+0.2}_{-0.2}$</td>
<td>0</td>
<td>0</td>
<td>409</td>
<td>409</td>
</tr>
<tr>
<td>Leo V</td>
<td>$16.4^{+0.9}_{-0.9}$</td>
<td>$16.1^{+1.2}_{-1.0}$</td>
<td>$15.9^{+0.5}_{-0.5}$</td>
<td>0</td>
<td>0</td>
<td>167</td>
<td>167</td>
</tr>
<tr>
<td>Leo IV</td>
<td>$16.3^{+1.1}_{-1.7}$</td>
<td>$16.2^{+1.5}_{-1.6}$</td>
<td>$16.1^{+0.7}_{-1.1}$</td>
<td>0</td>
<td>0</td>
<td>151</td>
<td>151</td>
</tr>
</tbody>
</table>
VERITAS Combined Dwarf Limits

Mass [GeV]

$\langle \sigma v \rangle$ [cm$^3$s$^{-1}$]

$W^+W^-$ $gg, c \bar{c}$ $u \bar{u}, d \bar{d}, s \bar{s}$
$ZZ$ $hh$ $\tau^+\tau^-$
$\bar{b}b$ $\gamma\gamma$ $t \bar{t}$
e$^+e^-$ $\mu^+\mu^-$

“Dark matter constraints from a joint analysis of dwarf Spheroidal galaxy observations with VERITAS”, Archambaldt et al. (for VERITAS), PRD, 95, 082001 (2017)
VERITAS Combined Dwarf Limits

- VERITAS 95% CL velocity-averaged cross section as a function of DM mass for stacked dwarf galaxy observations for different Annihilation channels.

“Dark matter constraints from a joint analysis of dwarf Spheroidal galaxy observations with VERITAS”, Archambaldt et al. (for VERITAS), PRD, 95, 082001 (2017)
VERITAS Combined Dwarf Limits

- VERITAS 95% CL velocity-averaged cross section as a function of DM mass for stacked dwarf galaxy observations for different Annihilation channels.

- Results depend on Dwarf galaxies with the highest J-factor. New measurements (e.g., DES) are revealing more, and perhaps better Dwarfs.

“Dark matter constraints from a joint analysis of dwarf Spheroidal galaxy observations with VERITAS”, Archambaldt et al. (for VERITAS), PRD, 95, 082001 (2017)
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.

\[ \chi \rightarrow W^+W^- \]

\[ W, Z \]

\[ \ell^- \]

\[ \ell^+ \]

\[ \chi^0 \]

\[ \chi^- \]

\[ \chi^+ \]

Lattanzi and Silk, PRD 79, 083523 (2009), Profumo (2005)

(Matthieu Vivier et al. for the VERITAS Collaboration)
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.

- At high mass, we generically expect Sommerfeld enhancement from W, Z exchange for standard neutralinos can give large enhancement in cross section,
HAWC Dwarf Limits

Figure 3. 95% confidence level upper limits on the dark matter annihilation cross-section for 15 dwarf spheroidal galaxies within the HAWC field of view for the $b\bar{b}$, $t\bar{t}$, $\chi\chi$, $\mu^+\mu^-$ and $W^+W^-$ annihilation channels. The solid black line shows the combined limit using all dSphs resulting from a joint likelihood analysis. The dashed black line shows the combined limit using 14 dSphs, excluding Triangulum II. The gray band shows the systematic uncertainty on the combined limits due to HAWC systematics and dark orange band shows the systematic uncertainty due to J-factor uncertainty.

Figure 4. 95% confidence level upper limits on the dark matter annihilation cross-section for the five dark matter annihilation channels considered in this analysis and their comparison of the dark matter annihilation cross-section limits of HAWC to other experimental results for the $b\bar{b}$, $t\bar{t}$, $\chi\chi$, $\mu^+\mu^-$ and $W^+W^-$ annihilation channels. The HAWC 507 days limits from data are shown by the black solid line. The dashed black line shows the combined limit using 14 dSphs, excluding Triangulum II. Fermi-LAT combined dSph limits (Ackermann et al. 2014), Veritas Segue 1 limits (Archambault et al. 2017), HESS combined dSph limits (Abramowski et al. 2014) and MAGIC limits (Ahnen et al. 2016) are shown for comparison. The same color scheme is used for all the experiment comparison plots.

GC Upper Limits

```
Search for dark matter annihilations towards the inner Galactic halo from 10 years of observations with H.E.S.S.”, Abdallah et al. (for the HESS collaboration), 2016, PRL, 117, 1301
```
FIG. 1: Constraints on the velocity-weighted annihilation cross section \( h v_i \) for the \( W^+ W^- \) (left panel) and \( \tau^+ \tau^- \) (right panel) channels derived from observations taken over 10 years of the inner 300 pc of the GC region with H.E.S.S. The constraints for the \( b \bar{b} \), \( t \bar{t} \) and \( \mu^+ \mu^- \) channels are given in Fig. 4 in Supplemental Material [16]. The constraints are expressed as 95% C. L. upper limits as a function of the DM mass \( m_{DM} \). The observed limit is shown as black solid line. The expectations are obtained from 1000 Poisson realizations of the background measured in blank-field observations at high Galactic latitudes. The mean expected limit (black dotted line) together with the 68% (green band) and 95% (yellow band) C. L. containment bands are shown. The blue solid line corresponds to the limits derived in a previous analysis of 4 years (112 h of live time) of GC observations by H.E.S.S. [10]. The horizontal black long-dashed line corresponds to the thermal relic velocity-weighted annihilation cross section (natural scale).

FIG. 2: Left: Impact of the DM density distribution on the constraints on the velocity-weighted annihilation cross section \( h v_i \). The constraints expressed in terms of 95% C. L. upper limits are shown as a function of the DM mass \( m_{DM} \) in the \( W^+ W^- \) channels for the Einasto profile (solid black line), another parametrization of the Einasto profile (dotted black line), and the NFW profile (long dashed-dotted black line), respectively. Right: Comparison of constraints on the \( W^+ W^- \) channels with the previous published H.E.S.S. limits from 112 hours of observations of the GC [10] (blue line), the limits from the observations of 15 dwarf galaxy satellites of the Milky Way by the Fermi satellite [23] (green line), the limits from 157 hours of observations of the dwarf galaxy Segue 1 [24] (red line), and the combined analysis of observations of 4 dwarf galaxies by H.E.S.S. [25] (brown line). The increase of the sensitivity of the analysis presented here.

``Search for dark matter annihilations towards the inner Galactic halo from 10 years of observations with H.E.S.S.”, Abdallah et al. (for the HESS collaboration), 2016, PRL, 117, 1301
CTA

**Low energies**
Energy threshold 20-30 GeV
23 m diameter
4 telescopes
*(LST’s)*

**Medium energies**
100 GeV – 10 TeV
9.5 to 12 m diameter
25 telescopes
*(MST’s/SCTs)*

**High energies**
10 km² area at few TeV
3 to 4m diameter
70 telescopes
*(SST’s)*
Flux Sensitivity

Major sensitivity improvement & wider energy range

→ Factor of >10 increase in source population

(caption: Rene Ong)
Figure 1. Left: Sensitivity for $\sigma v$ from observation on the Galactic Halo with Einsasto dark matter profile and for different annihilation modes as indicated. Right: for cuspy (NFW, Einasto) and cored (Burkert) dark matter halo profiles. For both plots only statistical errors are taken into account. The dashed horizontal lines indicate the level of the thermal cross-section of $3 \times 10^{-26}$ cm$^3$ s$^{-1}$.

`Prospects for Indirect Dark Matter Searches with the Cherenkov Telescope Array (CTA)` , J. Carr et al. (for the CTA Consortium), 2015 in Proc. of the 34th ICRC conference,
If the US Funded CTA...

- If NSF and DOE had the budget to follow through on the advice of the NWNH decadal survey, Snowmass and P5 this is what we could have achieved...
II. Gamma-Ray Searches for Axion-Like-Particles
Axions and ALPs

One expects CP violating term in QCD Lagrangian:

\[ \mathcal{L}_{\text{QCD}} = \frac{1}{4} G_{\mu \nu}^{a} G_{a \mu \nu} + g \phi G_{\mu \nu}^{a} \tilde{G}_{a \mu \nu} + \text{interactions.} \]

Note: \( F_{\mu \nu} \tilde{F}^{\mu \nu} = \tilde{B} \cdot \tilde{E} \leftrightarrow G_{\mu \nu} \tilde{G}^{\mu \nu} = \tilde{B}_{a} \cdot \tilde{E}_{a} \) which is odd under \( T \Rightarrow \text{odd under } CP \)

**Peccei-Quinn** solution: introduce new field (with MH potential). At \( T < f_{a} \) symmetry broken, and axial mode of field settles at some angle \( \theta = a \).
Axions and ALPs

One expects CP violating term in QCD Lagrangian:

$$\mathcal{L}_{\text{QCD}} = \frac{1}{4} G^{\mu\nu}_a G_{a\mu\nu} + g \phi G^{\mu\nu}_a \bar{G}_{a\mu\nu} + \text{interactions}.$$  

*Note:* $F_{\mu\nu} \tilde{F}^{\mu\nu} = \tilde{B} \cdot \tilde{E} \leftrightarrow G_{\mu\nu} \bar{G}^{\mu\nu} = \tilde{B}_a \cdot \tilde{E}_a$ which is odd under $T \Rightarrow$ odd under $CP$

**Peccei-Quinn** solution: introduce new field (with MH potential). At $T < f_a$ symmetry broken, and axial mode of field settles at some angle $\theta = a$.

When $T \sim \Lambda_{\text{QCD}}$ tilting of hat gives axion field a VEV $\langle a \rangle = 0$ that cancels the CP violating term. The $a$ field oscillates about its VEV with a mass given by the curvature of the potential.
Axions and ALPs

One expects CP violating term in QCD Lagrangian:

$$\mathcal{L}_{\text{QCD}} = \frac{1}{4} G^\mu_\nu G^a_\mu\nu + g\phi G^\mu_\nu \tilde{G}^a_\mu\nu + \text{interactions}.$$ 

**Note:** $F^\mu_\nu \tilde{F}^\nu_\mu = \tilde{B} \cdot \tilde{E} \leftrightarrow G^\mu_\nu \tilde{G}^\nu_\mu = \tilde{B}^a \cdot \tilde{E}^a$ which is odd under $T \Rightarrow$ odd under $CP$

**Peccei-Quinn** solution: introduce new field (with MH potential). At $T < f_a$ symmetry broken, and axial mode of field settles at some angle $\theta = a$.

When $T \sim \Lambda_{\text{QCD}}$ tilting of hat gives axion field a VEV $\langle a \rangle = 0$ that cancels the CP violating term. The $a$ field oscillates about its VEV with a mass given by the curvature of the potential.
Axions and ALPs

One expects CP violating term in QCD Lagrangian:

$$\mathcal{L}_{\text{QCD}} = \frac{1}{4} G^a_{\mu \nu} G_a^{\mu \nu} + g \phi G^a_{\mu \nu} \tilde{G}_a^{\mu \nu} + \text{interactions.}$$

Note: $F_{\mu \nu} \tilde{F}^{\mu \nu} = \vec{B} \cdot \vec{E} \leftrightarrow G_{\mu \nu} \tilde{G}^{\mu \nu} = \vec{B}_a \cdot \vec{E}_a$ which is odd under $T \Rightarrow$ odd under $CP$

**Peccei-Quinn** solution: introduce new field (with MH potential). At $T < f_a$ symmetry broken, and axial mode of field settles at some angle $\theta = a$.

When $T \sim \Lambda_{\text{QCD}}$ tilting of hat gives axion field a VEV $\langle a \rangle = 0$ that cancels the CP violating term. The $a$ field oscillates about its VEV with a mass given by the curvature of the potential.

$$\mathcal{L}_{\text{EM}} + g_{a \gamma \gamma} a F_{\mu \nu} \tilde{F}^{\mu \nu} = g_{a \gamma \gamma} a \vec{E} \cdot \vec{B}$$
One expects CP violating term in QCD Lagrangian:
\[
    \mathcal{L}_{\text{QCD}} = \frac{1}{4} G_{a\mu\nu} G_{a\mu\nu} + g \phi G_{a\mu\nu} \bar{G}_{a\mu\nu} + \text{interactions}.
\]

Note: \( F_{\mu\nu} \tilde{F}^{\mu\nu} = \vec{B} \cdot \vec{E} \leftrightarrow G_{\mu\nu} \tilde{G}^{\mu\nu} = \vec{B}_a \cdot \vec{E}_a \) which is odd under \( T \Rightarrow \text{odd under } CP \)

**Peccei-Quinn** solution: introduce new field (with MH potential). At \( T < f_a \) symmetry broken, and axial mode of field settles at some angle \( \theta = a \).

When \( T \sim \Lambda_{\text{QCD}} \) tilting of hat gives axion field a VEV \( \langle a \rangle = 0 \) that cancels the CP violating term. The \( a \) field oscillates about its VEV with a mass given by the curvature of the potential.

The single parameter \( f_a \) determines axion mass, coupling constant and relic density. Axion-Like Particles (ALPs) are pseudoscalars with similar coupling to photons, but are less constrained/motivated. Axions and ALPs can be detected with Haloscopes like ADMX (via the Primakoff process), cooling curves of stars and compact objects, or light-through-wall experiments.
Axion-Photon Mixing

From the total Lagrangian $\mathcal{L}_{\text{EM}} + g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$ one can find the equations of motion for the two components of the vector potential $A_x$ and $A_y$ and for the axion field $a$. Grouping these into a single 3 component wave function, one obtains the Schrödinger like equation:

$\left(i \frac{d}{dz} + E + \mathcal{M}\right) \Psi(z) = 0$

$\Psi(z) = \begin{pmatrix} A_y \\ A_x \\ a \end{pmatrix}$

$\mathcal{M} = \begin{pmatrix} \Delta_{pl} & 0 & \Delta_{a\gamma} \sin \psi \\ 0 & \Delta_{pl} & \Delta_{a\gamma} \cos \psi \\ \Delta_{a\gamma} \sin \psi & \Delta_{a\gamma} \cos \psi & \Delta_a \end{pmatrix}$
Axion-Photon Mixing

From the total Lagrangian \( \mathcal{L}_{\text{EM}} + g_{\alpha\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu} \) one can find the equations of motion for the two components of the vector potential \( A_x \) and \( A_y \) and for the axion field \( a \). Grouping these into a single 3 component wave function, one obtains the Schrödinger like equation:

\[
\left( i \frac{d}{dz} + E + \mathcal{M} \right) \Psi(z) = 0 \quad \Psi(z) = \begin{pmatrix} A_y \\ A_x \\ a \end{pmatrix}
\]

\[
\mathcal{M} = \begin{pmatrix}
\Delta_{pl} & 0 & \Delta_{a\gamma} \sin \psi \\
0 & \Delta_{pl} & \Delta_{a\gamma} \cos \psi \\
\Delta_{a\gamma} \sin \psi & \Delta_{a\gamma} \cos \psi & \Delta_a
\end{pmatrix}
\]

\[
\Delta_{pl} = -\omega_{pl}^2/(2E_\gamma) \quad \Delta_a = -m_a^2/(2E_\gamma) \quad \Delta_{a\gamma} = B g_{a\gamma\gamma}/2
\]
Axion-Photon Mixing

From the total Lagrangian $\mathcal{L}_{\text{EM}} + g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$ one can find the equations of motion for the two components of the vector potential $A_x$ and $A_y$ and for the axion field $a$. Grouping these into a single 3 component wave function, one obtains the Schrödinger like equation:

$$\left( i \frac{d}{dz} + E + \mathcal{M} \right) \Psi(z) = 0$$

$$\Psi(z) = \begin{pmatrix} A_y \\ A_x \\ a \end{pmatrix}$$

$$\mathcal{M} = \begin{pmatrix} \Delta_{pl} & 0 & \Delta_{a\gamma} \sin \psi \\ 0 & \Delta_{pl} & \Delta_{a\gamma} \cos \psi \\ \Delta_{a\gamma} \sin \psi & \Delta_{a\gamma} \cos \psi & \Delta_a \end{pmatrix}$$

$$\Delta_{pl} = -\omega_{pl}^2/(2E_\gamma) \quad \Delta_a = -m_a^2/(2E_\gamma) \quad \Delta_{a\gamma} = B g_{a\gamma}/2$$

$$\Delta_{\text{osc}} \equiv \sqrt{(\Delta_{pl} - \Delta_a)^2 + 4\Delta_{a\gamma}^2}$$
Axion-Photon Mixing

From the total Lagrangian $\mathcal{L}_{\text{EM}} + g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$ one can find the equations of motion for the two components of the vector potential $A_x$ and $A_y$ and for the axion field $a$. Grouping these into a single 3 component wave function, one obtains the Schrödinger like equation:

$$\left( i \frac{d}{dz} + E + \mathcal{M} \right) \Psi(z) = 0 \quad \Psi(z) = \begin{pmatrix} A_y \\ A_x \\ a \end{pmatrix}$$

$$\mathcal{M} = \begin{pmatrix} \Delta_{pl} & 0 & \Delta_a \sin \psi \\ 0 & \Delta_{pl} & \Delta_a \cos \psi \\ \Delta_{a\gamma} \sin \psi & \Delta_{a\gamma} \cos \psi & \Delta_a \end{pmatrix}$$

$$\Delta_{pl} = -\omega_{pl}^2/(2E_\gamma) \quad \Delta_a = -m_a^2/(2E_\gamma) \quad \Delta_{a\gamma} = B g_{a\gamma\gamma}/2$$

$$\Delta_{osc} \equiv \sqrt{ (\Delta_{pl} - \Delta_a)^2 + 4\Delta_{a\gamma}^2 }$$

$$P_{a\gamma}(z = \ell) = \sin^2 2\theta \sin^2 \left( \frac{\Delta_{osc} \ell}{2} \right) \quad \text{where} \quad \tan 2\theta = 2\Delta_{a\gamma}/(\Delta_{pl} - \Delta_a)$$

Looks like neutrino oscillation where $\Delta m^2 = |\omega_{pl}^2 - m_a^2|$. But unlike neutrino oscillations, $\theta$ depends on $E_\gamma$ and there can be absorption due to $\gamma\gamma \rightarrow e^+e^-$
\[ P_{\alpha\gamma}(\ell) = \frac{1}{1 + \left(\frac{E_{\text{crit}}}{E_{\gamma}}\right)^2} \sin^2 \left[ \frac{B \ell g_{\alpha\gamma\gamma}}{2} \sqrt{1 + \left(\frac{E_{\text{crit}}}{E_{\gamma}}\right)^2} \right] \]

\[ E_{\text{crit}}(\text{GeV}) \equiv \frac{5}{2} \frac{\Delta m_{\mu\text{eV}}^2}{B_G} \left( \frac{g_{\alpha\gamma\gamma}}{10^{-11}\text{GeV}^{-1}} \right) \]

from Manuel Meyer (for CTA collaboration)

[e.g., De Angelis et al., 2007, 2011; Minizzi et al., 2007; Simet et al., 2008; Sanchez-Condé et al., 2009; Horns et al. 2012; Tavecchio et al. 2012; Mena & Razzaque 2013]
Anomalous Transparency?

Spectral hardening at high optical depths?

\[ E \frac{dN}{dE} \text{ [erg cm}^{-2} \text{s}^{-1}] \]

- Observed
- EBL corrected (Franceschini et al. 2008)
- EBL corrected (Inoue et al. 2013)
- Broken PL model

Tanaka et al. (2013)
Figure 3.2: Summary of current constraints, future prospects and hints in axion/ALP parameter space. The classical QCD axion parameter space is shown by a yellow band. Axionic dark matter parameter space is shown by orange bands. In the region labeled “WIMP-axion CDM” axions would only comprise a fraction of the dark matter energy density. Prospects for IAXO and ADMX are shown by hatched regions. Figure taken from Carosi et al. (2013).
Looking Under the Lamp Post
I’ve heard some theorists accuse experimentalists of lacking imagination by only looking for WIMP/SUSY DM is like “only looking for your lost keys under the lamp post”.
I’ve heard some theorists accuse experimentalists of lacking imagination by only looking for WIMP/SUSY DM is like “only looking for your lost keys under the lamp post”.

Theorem: If you don’t look under the lamp post where there is light, it is really hard to see anything!
Looking Under the Lamp Post

- I’ve heard some theorists accuse experimentalists of lacking imagination by only looking for WIMP/SUSY DM is like “only looking for your lost keys under the lamp post”.

- Theorem: If you don’t look under the lamp post where there is light, it is really hard to see anything!
  - Corollary: “Outside of a dog a book is a man’s best friend. Inside a dog it is too dark to read” (G. Marx).
• Observations of the GC region by current generation of ACTs reveal bright GeV - TeV emission from a number of sources, including steady emission from the GC. Even with these astrophysical backgrounds, ACTs can provide powerful constraints on DM up to tens of TeV reaching within an order of magnitude of the natural cross section.
Conclusions

• Observations of the GC region by current generation of ACTs reveal bright GeV - TeV emission from a number of sources, including steady emission from the GC. Even with these astrophysical backgrounds, ACTs can provide powerful constraints on DM up to tens of TeV reaching within an order of magnitude of the natural cross section.

• CTA observations of the GC could exclude much of the remaining parameter space for high mass WIMPs.
• Observations of the GC region by current generation of ACTs reveal bright GeV - TeV emission from a number of sources, including steady emission from the GC. Even with these astrophysical backgrounds, ACTs can provide powerful constraints on DM up to tens of TeV reaching within an order of magnitude of the natural cross section.

• CTA observations of the GC could exclude much of the remaining parameter space for high mass WIMPs.

• Even if VERITAS, HESS, MAGIC and even CTA fail to detect dark matter, they will reveal new information about phenomena ranging from relativistic jets from supermassive black holes, a census of supernovae across the galaxy, the origin of cosmic rays, the nature of pulsar magnetospheres, the history of star formation imprinted on the primordial starlight, constraints on the primordial magnetic field, and multimessenger science through searches for electromagnetic counterparts of gravitational wave and neutrino sources - not a bad consolation prize.
III. Backup Slides
The WIMP miracle is the only reason we are looking, or know where to look. Only way to design an instrument is by starting with a hypothesis.
The WIMP miracle is the only reason we are looking, or know where to look. Only way to design an instrument is by starting with a hypothesis.
The WIMP miracle is the only reason we are looking, or know where to look. Only way to design an instrument is by starting with a hypothesis.
The WIMP miracle is the only reason we are looking, or know where to look. Only way to design an instrument is by starting with a hypothesis.

Masses above the natural range motivated by hierarchy problem - reason for SUSY, or exceed unitarity bound

Masses below this are already constrained by Fermi

The Future

Thermal Relic Cross Section

(Steigman et al. 2012)
The WIMP miracle is the only reason we are looking, or know where to look. Only way to design an instrument is by starting with a hypothesis.

Masses above the natural range motivated by hierarchy problem - reason for SUSY, or exceed unitarity bound

Ground-based observations (CTA) of GC are better in this regime
Advanced Particle-astrophysics Telescope (APT)
APT Instrument

- Scintillating fiber tracker
- Imaging CsI calorimeter
**Gamma-Ray Transients with APT**

- Large area, almost all-sky coverage for MeV gamma-rays threshold could provide the best instrument for localizing astrophysical transients out to the edge of the visible universe.
  - Short gamma-ray bursts
  - NS merger gravitational wave sources
Gamma-Ray Transients with APT

- Large area, almost all-sky coverage for MeV gamma-rays threshold could provide the best instrument for localizing astrophysical transients out to the edge of the visible universe.
  - Short gamma-ray bursts
  - NS merger gravitational wave sources
Pair Telescope Mode

- TRD Radiator
- WLS Fiber
- CsI:Na Tiles
- WLS Fiber
- Tracker layer
Pair Telescope Mode

- TRD Radiator
- WLS Fiber
- CsI:Na Tiles
- WLS Fiber
- Tracker layer
Pair Telescope Mode

TRD Radiator
WLS Fiber
CsI:Na Tiles
WLS Fiber
Tracker layer

Pair
Pair Telescope Mode

TRD Radiator
WLS Fiber
CsI:Na Tiles
WLS Fiber
Tracker layer

Pair
Brems. (beginning of shower)
Compton Telescope
Compton Telescope
Compton Telescope
Compton Telescope
Compton Telescope
Compton Telescope

Diagram of the Compton Telescope with gamma rays and energy levels indicated.
Compton Telescope
• Slow signals from CsI+WLS can be distinguished from fast signals from ionizing particles passing through fibers. *Bow-tie* illumination pattern allows centroiding of x-y coordinates, some information of depth of interaction.
APT Performance

Angular resolution

Energy resolution

Effective Area (m²)

APT Performance

APT (normal-incident)
APT (omnidirectional-incident)
Fermi (acceptance weighted)
AMEGO (normal-incident)
e-ASTROGAM (normal-incident)

ΔE/E (68% containment)

68% containment angle (°)

APT (normal-incident)
APT (omnidirectional-incident)
Fermi (acceptance weighted)
AMEGO (normal-incident)
e-ASTROGAM (normal-incident)
Cosmic Ray Measurements

- APT with multiple dE/dx measurements can measure rare, ultra-heavy r-process elemental abundances
Pair Energy Reconstruction

Reconstructed energy as a function of the incoming $\gamma$-ray energy. Colors correspond to different reconstruction methods.

- **Mode I**: Most precise at low energies, energy bias is small.
- **Mode II**: Less precise than Mode I at lower energies, but energy bias increases with higher energy.
- **Mode III**: Not as precise as Mode I at lower energies, but its energy bias is small at GeV energy. Mode II is not as precise as Mode I at lower energies, while its energy bias is small at GeV energy.

The reconstructed energy bias is given by $E_{\text{recon}}/E$, where $E_{\text{recon}}$ is the reconstructed event energy and $E$ is the incident energy.
Source Localization

![Graph showing fluence versus offset angle and x, y coordinates](graph.png)
• Electromagnetic counterpart found for recent LIGO event, n-star merger
APT n-star Merger Sensitivity

Light Curve

Spectrum

Image
Evidence of beaming in some GRBs and the distribution of spatial offsets from host-galaxy centers suggests that short GRBs might be related to neutron star mergers. Over a wide range of delay times, as predicted theoretically, these observations provided strong hints that sGRBs might be supernovae.

Uncertainties in the progenitors of GRBs have been one of the key challenges in high-energy astrophysics. The advance of gravitational-wave detections has led to more discoveries of electromagnetic counterparts to those events.

Starting with GW150914, Partners have followed up binary black hole detections, and more and more candidates were discovered. Here, we report on the global effort to uncover the progenitor of GW170817.

Observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC4993. The source was detected across the electromagnetic spectrum — from X-ray to optical and infrared emission, a so-called kilonova.

The late-time infrared excess associated with GRB 130603B was followed by an sGRB and a kilonova powered by the radioactive decay of $^{56}$Ni which was synthesized in the ejecta. The kilonova; Li & Paczyński (1974) produced by the merger of two neutron stars in NGC4993, was the first optimally observable event of its type.

The source of GW170817 was discovered by the LIGO-Virgo collaboration on August 17, 2017, at 16:07:12 UTC. The first electromagnetic counterpart of gravitational-wave event GW170817 was reported 13 seconds after the gravitational-wave trigger by the Fermi-LAT collaboration.

The source was later confirmed as AT 2017gfo, a distance of 150 Mpc, in the galaxy NGC 4993. The source was detected across the electromagnetic spectrum — from X-ray to optical and infrared emission, a so-called kilonova.

The late-time infrared excess associated with GRB 130603B was followed by an sGRB and a kilonova powered by the radioactive decay of $^{56}$Ni which was synthesized in the ejecta. The kilonova, synthesized in the ejecta, produced by the merger of two neutron stars in NGC4993, was the first optimally observable event of its type.
APT simulations show $\sim 1^\circ$ error circle for an event with the measured GW spectrum and fluence
CTA Phases & Timeline

1 Design

2 Pre-Construction

SPRR  PDR  CDR

International Convention / ERIC

Construction Phase

3 Pre-Production

NOW

Advance Deployment

PPRRs & MoU

4 Production

5 Operations

- 2016: Hosting agreement, site preparations start (N)
- 2017: Hosting agreement, site preparations start (S)
- Funding level at ~65% of required for baseline implementation → start with threshold implementation → additional funding, telescopes needed to complete CTA
- Construction period of 5-6 years
- Initial science with partial arrays possible before construction end

(credit R. Ong)