Detection of TeV photons from the active galaxy Markarian 421

M. PUNCH†, C. W. AKERLOF‡, M. F. CAWLEY§, M. CHANTELL†, D. J. FEGAN†, S. FENNELL†, J. A. GAIDOS†, J. HAGAN†, A. M. HILLAS‡, Y. JIANG†, A. D. KERRICK§, R. C. LAMB§, M. A. LAWRENCE†, D. A. LEWIS§, D. I. MEYER‡, G. MOHANTY§, K. S. O'FLAHERTY†, P. T. REYNOLDS§, A. C. ROVERO†, M. S. SCHUBNELL‡, G. SEMBROSKI‡, T. C. WEEKES†, T. WHITAKER† & C. WILSON§

Whipple Observatory, Harvard-Smithsonian CfA, Box 97, Amado, Arizona 85645 USA
‡Physics Department, University College Dublin, Belfield, Dublin 4, Ireland
§Physics Department, University of Michigan, Ann Arbor, Michigan 48109, USA
Physics Department, St. Patrick's College, Maynooth, County Kildare, Ireland
Physics Department, Purdue University, West Lafayette, Indiana 47907 USA
Physics Department, University of Leeds, Leeds LS2 9JT, UK
Physics and Astronomy Department, Iowa State University, Ames, Iowa 50011 USA

PHOTONS of TeV energy have been observed from a few sources in our Galaxy, notably the Crab Nebula. We report here the detection of such photons from an extragalactic source, the giant elliptical galaxy Markarian 421. Mk 421 has a nucleus of the BL Lacertae type, and emission from it has been observed at radio, optical, and X-ray frequencies, and most recently in the MeV-GeV bands, by the EGRET detector aboard the Compton observatory. In March–June 1992, we observed Mk 421 with the Whipple Observatory γ-ray telescope, a ground-based detector that images Čerenkov light from air showers, and found a signal with statistical significance of 6σ above background. The flux above 0.5 TeV is 0.3 of that from the Crab Nebula. The source location agrees with the position of Mk 421 within the angular uncertainty (6 arc minutes) of the Whipple instrument. The fact that we have observed this relatively nearby source (redshift $z = 0.031$), whereas active galaxies and quasars that are brighter at EGRET energies but more distant have not been detected in the TeV energy range, may be consistent with suggestions that TeV photons are strongly attenuated by interaction with extragalactic starlight.

- In 1992, while finishing my thesis, my friend Tim McKay (working on CASA-MIA) told me about a paper on the discovery of TeV gamma-rays from Mrk421. Combined with a wonderful talk I had heard by Trevor on the Crab discovery, I remember at that moment deciding I must work for Trevor at Whipple! (When I arrived the signal disappeared).
I remember, after a quick lunch at Trevor’s home in Green Valley, I took my first ride up the mountain as Trevor’s new postdoc - white knuckled but trying to act calm.

Trevor was very kind, and told me about all of the “head-to-heads” that occurred over the years and about the merits of having no guard rails, pointing all of the time to the steep drop-off - alternating between trying to put me at ease and to terrify me.

I soon learned from TCW the great sport of terrifying newcomers with stories about wild animals, scary roads and other dangers.
Working on the Ridge

- Many hazards working on the ridge -
  - Dismal coffee (also at Steward, made by Trevor out of residue of past pots and perhaps mouse droppings).
  - German drivers, Irish drivers, French drivers (and second-hand smoke.)
  - Cows and Javalinas in the road (Mark Chantel’s Saturn)
  - Rattle snakes.
  - Bears (Vampire Bears, in particular)
  - Mountain lions (especially fond of pouncing on new Irish students walking between dorm and 10m - according to TCW)
  - The ghost of Geronimo (fond of slamming doors at 3:00 AM)
  - The *so-called* 11m telescope.
  - Killer deer.
  - Bas van’t Sant (biggest risk to Christians or cleaning crew).
  - Arizona pack rats.
  - Trevor’s wrath if potential observing time was lost.
Since 1968 not much has changed - 10m DC telescopes still rule the gamma-ray sky!
Collaboration with Trevor

- Trevor gave me a lot of freedom to work on science. He also let me quit working on the 11m telescope - a task he specifically hired me to work on! (Would I let my own postdoc do that?).

- During my years in Tucson he and I worked closely on a number of topics:
  - Origin of Cosmic Rays (following up on the exciting suggestion of Drury, Aharonian and Volk, indulging my obsession with IC443)
  - Active Galaxies (we came up with the idea that it was time to turn away from EGRET sources to look at X-ray selected BL Lacs - some from an old Trevor source list)
  - Optical/multiwavelength astronomy with the 48inch and 60inch (encouraging me and Julie to work on this)
  - Coming from Chicago, I was somewhat obsessed with the idea of detecting dark matter from the GC - Trevor teased me ruthlessly, but must have really liked the idea. My fascination with null results (from my early years with Trevor) keeps me interested in dark matter.
I learned many lessons about hardware and data analysis from our failures as well as successes - importance of killing false signals, sometimes the importance of putting telescopes out of their misery (although divine intervention may be required).
VHE Gamma-Ray Status

VERITAS

MILAGRO

MAGIC

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

- MILAGRO
- VERITAS
- H.E.S.S.
- MAGIC

γ-rays from Starburst Galaxy

M82

γγ

γγ
VHE Gamma-Ray Status

γ-rays from Starburst Galaxy

M82

γ-rays from <50 R_c of Supermassive BH

M87

γ-rays from Starburst Galaxy

MILAGRO

VERITAS

H.E.S.S.

MAGIC

γ-rays from Starburst Galaxy

γ-rays from <50 R_c of Supermassive BH

γ-rays from Starburst Galaxy

γ-rays from <50 R_c of Supermassive BH

γ-rays from Starburst Galaxy

γ-rays from <50 R_c of Supermassive BH
VHE Gamma-Ray Status

- γ-rays from Starburst Galaxy (M82)
- Image of SNR molecular cloud (G106.3+2.7)
- γ-rays from <50 Rc of Supermassive BH (M87)

Accretion Disks, Gamma-rays and Jets

H.E.S.S., MAGIC, VERITAS, MILAGRO

γ-rays from Supermassive Black Holes

- HBL, IBL, FRI, FSRQ, LBL
- uQuasar Cat. Var. BIN, WR

TrevorFest
CTA and the Road Ahead
James Buckley
VHE Gamma-Ray Status

- **M82**: γ-rays from Starburst Galaxy
- **MILAGRO**
- **VERITAS**
- **H.E.S.S.**
- **M87**: γ-rays from <50 R<sub>c</sub> of Supermassive BH

- **G106.3+2.7**: Image of SNR molecule cloud -π<sup>0</sup> γ-rays?
- **Mrk421**: 4min bins

TrevorFest  CTA and the Road Ahead  James Buckley
The Future
Cherenkov Telescope Array CTA

**Low-energy section:**
4 x 23 m tel. (LST)  
(FOV: 4-5 degrees)
energy threshold of some 10 GeV

**Core-energy array:**
23 x 12 m tel. (MST)  
FOV: 7-8 degrees
best sensitivity in the 100 GeV–10 TeV domain

**High-energy section:**
30-70 x 4-6 m tel. (SST)
- FOV: ~10 degrees
10 km² area at multi-TeV energies

First Science: ~2016
Completion: ~2019

- CTA is being built by an international consortium of ~1000 scientists - *Many Body Physics*
Simulated Galactic-plane Sky Map with Improved Angular Resolution, FoV, Sensitivity

**Dark Matter**

\[ \nu F_\alpha \sim 10^{-13} \]

- Fermi (1 yr)
- Fermi (10 yr)
- VERITAS (50 hrs)
- CTA (100 hr)
- CTA (500 hr)

**Larger Redshifts and Rapid Transients**

- Fermi (1 min)
- HAWC (1 min)
- GRB (Z=1), ISM
- CTA (1 min)

Digel, Funk and Hinton

Buckley et al., APS whitepaper, 2008
Simulated Galactic-plane Sky Map with Improved Angular Resolution, FoV, Sensitivity

Digel, Funk and Hinton

Dark Matter

Larger Redshifts and Rapid Transients

(Buckley et al., APS whitepaper, 2008)
**NSF MRI and CTA-US timeline**

- 2012-2013  SCT prototype design
- 2013-2014  SCT prototype construction
- 2014-2015  SCT prototype commissioning & operation
- 2016      CTA-US “CTA Extension” construction proposal
Contained Events

From current arrays to CTA

Light pool radius
$R \approx 100-150 \text{ m}$
≈ typical telescope spacing

Sweet spot for best triggering and reconstruction:
Most shower cores miss it!

Large detection area
More images per shower
Lower trigger threshold
TrevorFest  
CTA-US  

SC-MST (Dual Mirror)  
DC-MST (Single Mirror)  

Hybrid-1 (50 hr)  
Prod-1 Array I (50 hr)  

~2-3x improvement in core energy range from US contribution  

CTA: Point-Source Sensitivity  

Fermi (3yr)  

CTA: Angular Resolution  

Hybrid-1 SC-MST  
Hybrid-1 DC-MST  

0.1°  

0.03°  

100 GeV  
1 TeV  

0.0  
1.0 2.0 3.0 4.0  
10^{-1} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14}  

Energy [log10(E/GeV)]  
Differential Flux Sensitivity [erg cm^{-2} s^{-1}]  

CTA and the Road Ahead  
James Buckley
Simulated Images

- **y-ray Shower**
  - Energy: 1 TeV
  - Impact Distance: 100m

- **Proton Shower**
  - Energy: 3.16 TeV
  - Impact Distance: 0m

**Dual Mirror Telescope**

**Single Mirror Telescope**
• We are in the second year of a 3-year MRI grant to construct an SCT telescope. The SCT Prototype will be constructed at the VERITAS site, using old T1 pad.
SCT Prototype

- 10m diameter, 2-mirror Schwarzshild-Couder optical design providing high angular resolution over an 8deg FOV

- Small plate-scale (f/0.58) new technology camera (with 11,000 0.06 degree pixels) cost of ~$70 per pixel.

- As SiPMs improve, could have the same light collection as a 12m DC telescope.
Electronics based on TARGET were developed by SLAC and U. Hawaii
Dark Matter
Evidence for Dark Matter

Beyond the stars, the enclosed mass $M$ should be roughly constant

$$\frac{mv^2}{r} = \frac{GmM}{r^2}$$

$$v \sim r^{-1/2}$$
Evidence for Dark Matter

Beyond the stars, the enclosed mass $M$ should be roughly constant

$$\frac{mv^2}{r} = \frac{GmM}{r^2}$$

$$v \sim r^{-1/2}$$

There appears to be a dark halo that extends beyond the distribution of stars, with a mass that exceeds that in stars by a factor of $>10$
Dark Matter Intro

Gravitational effect of DM is visible in many astrophysical settings (needed to hold galaxies and clusters together)

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 weakly interacting particles

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.

\[
\Omega_\chi \approx \frac{0.1}{h^2} \left( \frac{3 \times 10^{-26} \text{cm}^3\text{sec}^{-1}}{\langle \sigma v \rangle} \right)
\]
\[ E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \left( E_{\gamma,\text{TeV}} \frac{dN}{dE_{\gamma,\text{TeV}}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^{-3}\text{s}^{-1}} \right) \left( \frac{100 \text{ GeV}}{M_\chi} \right)^2 J(\theta) \text{ erg cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \]

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

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

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

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 \( \Lambda \)CDM N-body simulations (Kuhlen et al.)
Galactic Center and Dark Matter

- **EGRET:** 3EG J1746-2851 (Hartman et al. 1999)


**Dark Matter with CTA**

* A CTA like instrument with ~60 Mid-sized telescopes has the sensitivity to probe the natural cross section for WIMP annihilation from 100 GeV to 10 TeV.
• CTA would provide a powerful new tool for searching for WIMP dark matter. The angular distribution would determine the distribution of dark matter in halos, and the universal spectrum would be imprinted with information about the mass and annihilation channels needed to ID the WIMP.

• A $20M DOE contribution (< a G2 DM experiment) would build the cameras, 2 times that from NSF would build the telescopes.

\[ m(\tilde{\chi}_1^0) \text{ (GeV)} \]

\[
\begin{align*}
\text{XENON1T} & \quad \text{Survives DD, ID, and LHC} \\
\text{Excluded by DD and ID} & \quad \text{Excluded by ID but not DD or ID} \\
\text{Excluded by DD but not ID} & \quad \text{Not excluded by DD or ID}
\end{align*}
\]
US Contribution to CTA

- Total construction costs: ~$70M
  - Cost per telescope: 2.4M$
  - DOE: cameras: 18.5M$
  - NSF-Phys: 37M$
  - NSF-Astr: 10M$

- DOE groups led by SLAC & ANL

- Secondary optics:
  - Reduction in plate-scale
  - Use cheaper sensors and
  - Improve angular resolution
Conclusions

• In the field of gamma-ray astronomy, we are standing on the shoulders of giants...

• The view from the top is always much clearer, and the roads are much smoother after the pioneers have paved the way!

• The climb is still steep, and one has to be careful not to look too far ahead, and keep an eye on your footing.
Backup Slides
**Telescope (x 4)**

12-m diameter Davies-Cotton

f 1.0, 110 m² area
**Technical Details**

**Telescope (x 4)**
- 12-m diameter Davies-Cotton
- f 1.0, 110 m² area

**Camera (x 4)**
- 499 PMTs, 3.5° FOV
Technical Details

**Telescope (x 4)**
12-m diameter Davies-Cotton
f 1.0, 110 m² area

**Camera (x 4)**
499 PMTs, 3.5° FOV

**Mirror Facets (x 350)**
Reflectivity ~ 88%
(Recoated every 2 years)
Technical Details

Telescope (x 4)
12-m diameter Davies-Cotton
f 1.0, 110 m² area

Mirror Facets (x 350)
Reflectivity ~ 88%
(Recoated every 2 years)

Camera (x 4)
499 PMTs, 3.5° FOV

Electronics
500 Msp FADC, CFD trigger, 3-fold adjacent pixels and 2/4 telescope coincidence
Technical Details

Telescope (x 4)
12-m diameter Davies-Cotton
f 1.0, 110 m2 area

Camera (x 4)
499 PMTs, 3.5° FOV

Mirror Facets (x 350)
Reflectivity ~ 88%
(Recoated every 2 years)

Electronics
500 Msp FADC, CFD trigger, 3-fold adjacent pixels and 2/4 telescope coincidence
TARGET Design Overview
Radio Synchrotron and gamma-ray IC limits for Pamela scenario (Bertone, Cirelli, Strumia and Taoso, arXiv:0811.2744v3). Note: Radio bounds are sensitive to assumptions about B-fields and diffusion, may be optimistic.

- Pamela excess implies a large radio synchrotron and inverse Compton signal, and a boost in secondary gammas from the GC that are not observed.
Gamma-Ray Sensitivity

CTA covers the high-mass WIMP space

\[ \gamma \gamma \rightarrow b\bar{b} \]

LAT Galaxy cluster stacking
LAT Dwarf spheroidal stacking
LAT Isotropic Diffuse
LAT GC Halo
LAT 10 years, 3x more Dwarfs
CTA GC Halo (500 hrs)
Current IACTs 30 hrs Dwarf Spheroidal
Current IACTs 100 hrs GC Halo
A Typical Source

(Adapted from Buckley, Science, 1998)
A Typical Source

(Adapted from Buckley, Science, 1998)

Markarian 501 SED

\[ \nu = \frac{\delta \gamma^2 m_C^2}{\gamma^2 - 1} \]
• Stereoscopic reconstruction provides point of origin of gamma-rays from intersection of images (like convergence of lines of perspective)
• Stereoscopic reconstruction provides point of origin of gamma-rays from intersection of images (like convergence of lines of perspective)

• Images also converge on impact point on the ground, together with multiple samples of total light providing corrections for the Cherenkov light lateral distribution and good calorimetry
Performance enhancement

Angular resolution (deg)

- $R_{se} = 0.010$ deg
- $R_{se} = 0.040$ deg
- $R_{se} = 0.020$ deg
- $R_{se} = 0.080$ deg

Pixel Size [deg]

12m Single Mirror telescope

9.5m Dual Mirror telescope

40%
“Can dark matter be convincingly discovered by indirect searches given astrophysical and propagation model uncertainties? Do indirect searches only serve a corroborating role?”

• The primary astrophysical uncertainties come for gamma-ray production come from uncertainties in the halo model. But even with uncertainties, the limits still reach the natural decoupling cross section.

• An annihilation line in the gamma-ray spectrum would also provide a smoking gun signature (if detected at high significance!).

• Neutrinos from DM annihilation in the sun would be a smoking gun signature.

• Wouldn’t a hint of a signal of, say 20 TeV neutralinos provide important guidance for the Energy Frontier, and motivate a new 100 TeV accelerator?
Dwarf galaxies have almost no known astrophysical backgrounds, for backgrounds the GC is worst case.  HESS provides the best data on the GC (below, with point source at Sgr A* subtracted).  Better angular resolution can reduce the background from the tail of the PSF function, which dominates over other sources in the plane.
“Given large and unknown astrophysics uncertainties (for example, when observing the galactic center), what is the strategy to make progress in a project such as CTA which is in new territory as far as backgrounds go? How can we believe the limit projections until we have a better indication for backgrounds and how far does Fermi data go in terms of suggesting them? What would it take to convince ourselves we have a discovery of dark matter?”

Backgrounds get lower at higher energies, but even at 1-3 GeV with no background subtraction get a limit within $1^\circ \sim 1 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \Rightarrow \langle \sigma v \rangle = 1.6 \times 10^{-25} \text{cm}^{3}\text{s}^{-1}$

(Tim Linden, SLAC CF meeting)

Unlike other astrophysical sources, would see a universal hard spectrum (typically harder by $\sim E^{0.5}$) with a sharp cutoff. The spectral shape would be universal: the same throughout the GC halo, in halos of Dwarf galaxies, with no variability.
Particle Accelerators

Black hole extended horizon or accretion disk - conductor spinning in a magnetic field - $10^{20}$ V Generator! (Blandford, Lovelace)

Gamma-ray observations provide direct evidence for acceleration of charged particles up to $>\text{tens of TeV}$ in SNR
Targets?

Modern accelerators use colliding beams for higher cm energy
- dark matter halos are matter-antimatter colliding beams!

The sun or earth is sometimes the fixed target!

Molecular clouds can be the target

CMB photons and primordial starlight are also targets for high energy cosmic particles
Synchrotron Radiation

\[ e^- \]
Synchrotron Radiation

- Particles are deflected by magnetic fields, causing them to gyrate in circles.
Synchrotron Radiation

- Particles are deflected by magnetic fields, causing them to gyrate in circles.
- Circular motion implies acceleration giving radiation.
• Particles are deflected by magnetic fields, causing them to gyrate in circles.

• Circular motion implies acceleration giving radiation

• The emitted “synchrotron radiation” is very different than thermal radiation, having a very broad spectrum that can span radio to X-ray wavelengths
• Particles are deflected by magnetic fields, causing them to gyrate in circles.

• Circular motion implies acceleration giving radiation

• The emitted “synchrotron radiation” is very different than thermal radiation, having a very broad spectrum that can span radio to X-ray wavelengths.
• Particles are deflected by magnetic fields, causing them to gyrate in circles.

• Circular motion implies acceleration giving radiation

• The emitted “synchrotron radiation” is very different than thermal radiation, having a very broad spectrum that can span radio to X-ray wavelengths
Protons and other nuclei like bags of quarks, interact by radiating and exchanging gluons. Neutral or charged pions can be formed in interactions.
Pion Production

- Protons and other nuclei like bags of quarks, interact by radiating and exchanging gluons. Neutral or charged pions can be formed in interactions.
• Protons and other nuclei like bags of quarks, interact by radiating and exchanging gluons. Neutral or charged pions can be formed in interactions.
### 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>$W^\pm \rightarrow l^\pm \nu_l, \ W^\pm \rightarrow ud \rightarrow \pi^\pm, \pi^0$</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>$\tau^\pm \rightarrow \nu_\tau e^\pm \nu_\tau, \tau \rightarrow \nu_\tau W^\pm \rightarrow p, \bar{p}, \text{pions}$</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></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>$\chi \chi \rightarrow \phi\bar{\phi}$</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>
### Annihilation Channels

<table>
<thead>
<tr>
<th>Annihilation Channel</th>
<th>Secondary Processes</th>
<th>Signals</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi\chi \rightarrow qq, gg$</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>$\tau^\pm \rightarrow \nu_\tau e^\pm\nu_e, \tau \rightarrow \nu, W^\pm \rightarrow p, \bar{p}, \text{pions}$</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 $m_\phi &lt; m_q$ to explain large electron signal and avoid overproduction of $p, \gamma$</td>
</tr>
</tbody>
</table>

*internal/final state brems, inverse Compton $\gamma$'s*
### 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>$W^\pm \rightarrow l^\pm \nu_l, W^\pm \rightarrow ud \rightarrow \pi^\pm, \pi^0$</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>$\chi\chi \rightarrow \gamma\gamma$</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>$e, \gamma$</td>
<td>Helicity suppressed</td>
<td></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>

**Notes:**
- Helicity suppressed
- Loop suppressed
- Rapid energy loss of $\mu$s in sun before decay results in sub-threshold $\nu$s
- Helicity suppressed (important for non-Majorana WIMPs?)

---

**Diagram:**
- Annihilation Channels for SUSY particles, including annihilations to $q\bar{q}$, $gg$, $W^+W^-$, $Z^0Z^0$, and other channels.

---

**Text:**
- Internal/final state bremsstrahlung and inverse Compton effects for $\gamma$ production.
- Helicity suppression noted for certain channels.
Halo Uncertainties

bb Channel

Cored Isothermal
NFW
Einasto
Einasto (CU10)

tau Channel

Cored Isothermal
NFW
Einasto
Einasto (CU10)

500 hour exposure and 3 sigma detection threshold
## Specifications

<table>
<thead>
<tr>
<th>Parameter \ OS Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwarzschild aplanat q</td>
<td>2/3</td>
</tr>
<tr>
<td>Schwarzschild aplanat a</td>
<td>2/3</td>
</tr>
<tr>
<td>Focal Length (F) [m]</td>
<td>5.5863</td>
</tr>
<tr>
<td>Aperture [m]</td>
<td>9.6638</td>
</tr>
<tr>
<td>f/# [1]</td>
<td>f/0.5781</td>
</tr>
<tr>
<td>Primary Radius max [m]</td>
<td>4.8319</td>
</tr>
<tr>
<td>Primary Radius min [m]</td>
<td>2.1935</td>
</tr>
<tr>
<td>Secondary Radius max [m]</td>
<td>2.7081</td>
</tr>
<tr>
<td>Secondary Radius min [m]</td>
<td>0.3950</td>
</tr>
<tr>
<td>Effective light collecting area /unvignetted [m(^2)]</td>
<td>50.31</td>
</tr>
<tr>
<td>Unvignetted Size [deg]</td>
<td>3.50</td>
</tr>
<tr>
<td>Effective light collecting area at FOV edge [m(^2)]</td>
<td>47.73</td>
</tr>
<tr>
<td>Vignetting at the FOV edge [%]</td>
<td>-5.17</td>
</tr>
<tr>
<td>Primary projected area [m(^2)]</td>
<td>58.23</td>
</tr>
<tr>
<td>Secondary projected area [m(^2)]</td>
<td>22.55</td>
</tr>
<tr>
<td>Design FOV [deg]</td>
<td>8.00</td>
</tr>
<tr>
<td>Design FOV solid angle [deg(^2)]</td>
<td>50.35</td>
</tr>
<tr>
<td>Ideal PSF at the FOV edge (2MAX {RMS}) [arcmin]</td>
<td>3.81</td>
</tr>
<tr>
<td>M1 to M2 separation [m]</td>
<td>3/2 * F</td>
</tr>
<tr>
<td>M2 to camera separation [m]</td>
<td>1/3 * F</td>
</tr>
<tr>
<td>Shadowing by the OSS</td>
<td>Less than 12%</td>
</tr>
<tr>
<td>Vignetting by the OSS</td>
<td>TBD</td>
</tr>
</tbody>
</table>

Table 1. Main parameters of the SCT OS designed to provide 8 degree FoV.

<table>
<thead>
<tr>
<th>Parameter \ OS Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOV [deg]</td>
<td>8.00</td>
</tr>
<tr>
<td>FOV solid angle [deg(^2)]</td>
<td>50.35</td>
</tr>
<tr>
<td>Camera FP diameter [m]</td>
<td>0.78</td>
</tr>
<tr>
<td>FP plate scale [mm/arcmin]</td>
<td>1.625</td>
</tr>
<tr>
<td>FP plate scale [microns/arcsec]</td>
<td>27.083</td>
</tr>
<tr>
<td>FP figure</td>
<td>Parabolic</td>
</tr>
<tr>
<td>FP sag at the FoV edge [mm]</td>
<td>-22.00</td>
</tr>
<tr>
<td>Characteristic photon incidence angle [deg]</td>
<td>51.25</td>
</tr>
<tr>
<td>FP figure constants</td>
<td>See [4]</td>
</tr>
<tr>
<td>FP distortion constants</td>
<td>See [4]</td>
</tr>
</tbody>
</table>

Table 2. Main parameters of the SCT OS focal plane