Recent Observations of the Draco Dwarf Spheroidal Galaxy with the Solar Tower Atmospheric Cerenkov Effect Experiment

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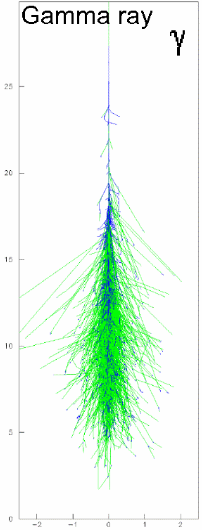
Outline

Indirect Detection of Dark Matter

- If dark matter particles can self-annihilate, they can decay into gamma-rays.
- The method is complementary to both direct detection and accelerator experiments, which probe elastic cross-section.
- Indirect detection is very sensitive to astrophysics!
- While we might not measure the absolute fluxes well, we can measure the WIMP mass by the shape of the spectrum.
- The Draco dwarf spheroidal galaxy is a strong candidate for dark-matter induced gamma-rays, and there is a possible detection by the CACTUS experiment.

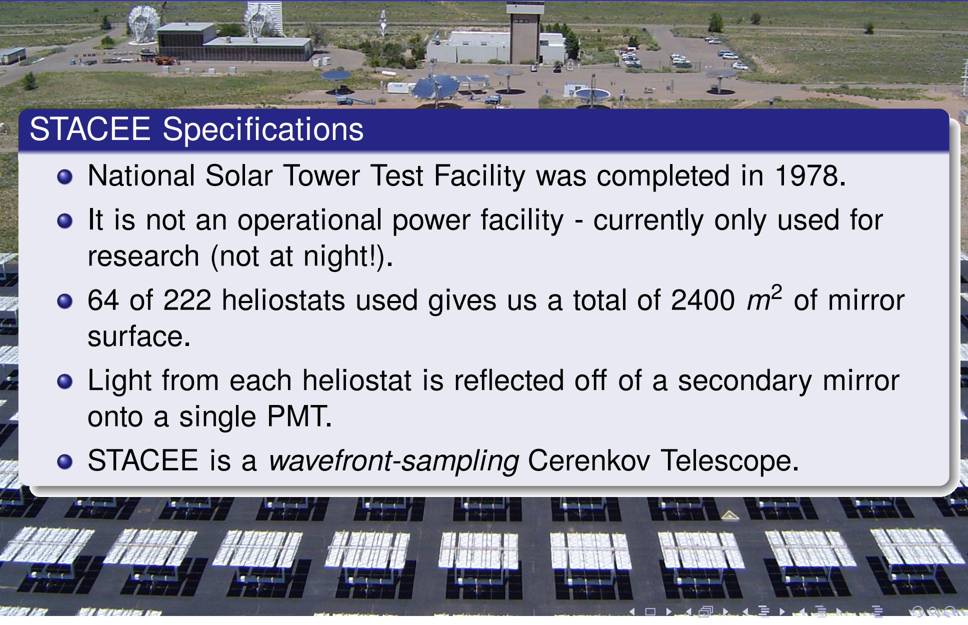
The Atmospheric Cerenkov Effect



- Gamma-rays strike the atmosphere at typical height of about 12 km above sea level.
- The resulting cascade of electromagnetic particles travels through the atmosphere near the speed of light *in vacuo*.
- The speed of the emitted light (in air) is lower than the speed of the particles, so a conical wavefront forms simliar to a "sonic boom,"
- The roughly spherical wavefront of bluish light forms a circle with an appproximate diameter of 250 meters when it strikes the ground.

STACEE at the NSTTF

STACEE at the NSTTF

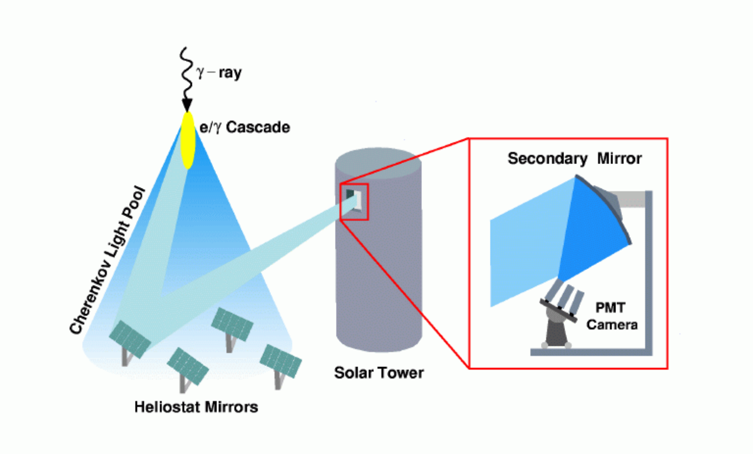


STACEE Specifications

- National Solar Tower Test Facility was completed in 1978.
- It is not an operational power facility - currently only used for research (not at night!).
- 64 of 222 heliostats used gives us a total of 2400 m^2 of mirror surface.
- Light from each heliostat is reflected off of a secondary mirror onto a single PMT.
- STACEE is a *wavefront-sampling* Cerenkov Telescope.

STACEE at the NSTTF

STACEE Optical Schematic



The Crab

The Crab is the brightest steady source of gamma-rays in the northern sky, making it the “Standard Candle” for gamma-ray astronomy.

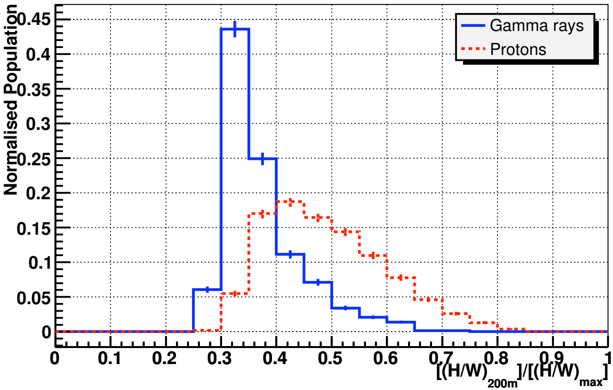
- Well-established source for STACEE:
    - First Detection: $\mathbf{6.8}\sigma$ (STACEE-32: Oser et al., 2001, ApJ, 547:949)
    - 2002-2003 Season (7.2 hrs.) - $\mathbf{5.1}\sigma$ (Kildea, ICRC 2005)
    - 2003-2004 Season (14.0 hrs.) - $\mathbf{5.5}\sigma$ (Kildea, ICRC 2005)
- Significance (Li & Ma, 1983, ApJ, 272:317):

$$\sigma = \frac{ON - OFF}{\sqrt{ON + OFF}} = \frac{(S+B)-B}{\sqrt{(S+B)+B}} \approx \frac{S}{\sqrt{2B}}$$

Grid Ratio Discrimination

- Compares H/W of summed pulse between timing aligned at maximum and 200 meters off-target.
- Showers from cosmic-rays are less sensitive to pointing offsets than showers from gamma-rays.
- Grid ratio cut gives almost a factor of 2 increase in significance!

"Grid Ratio" cut pioneered by CELESTE
(Bruel,P., et al., Proc. of Frontier Science 2004, Physics & Astrophysics in Space)



J. Kildea, "Observations of the Crab Nebula and Pulsar with STACEE," ICRC 2005

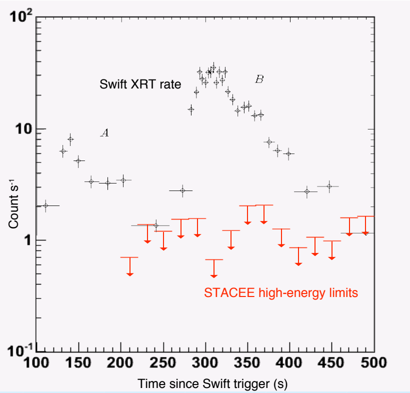
Active Galactic Nuclei

STACEE has observed many sources near 100 GeV.

Source	Type	Year (Livetime)	Notes
3C 66A	LBL	2003 (23 hrs) 2005 (18 hrs)	Bramel, Ap.J. 629 (2005)
OJ 287	LBL	2004 (6 hrs)	
Mrk 421	HBL	2003 (16 hrs) 2004 (12 hrs)	Carson, Forthcoming (2006) (5.8σ detection, energy spectrum)
1ES 1218+304	HBL	2005 (11 hrs)	
W Comae	LBL	2003 (10.5 hrs) 2004 (4.6 hrs) 2005 (5.1 hrs)	Scalzo, Ap.J. 607 (2004) Mukherjee, ICRC 2005 Mukherjee, ICRC 2005
1ES 1426+428	HBL	2003 (10 hrs) 2004 (20 hrs)	Mukherjee, ICRC 2005
Mrk 501	HBL	2005 (7 hrs)	
1ES 1741+196	HBL	2004 (3 hrs)	
BL Lac	LBL	2005 (2 hrs)	

R.Mukherjee, “STACEE observations of Active Galactic Nuclei,” HEAD 2006

Gamma-Ray Bursts



A.Jarvis, “GRB Observations around 100 GeV with STACEE,”

HEAD 2006

- STACEE actively monitors the GRB Coordinates Network.
- Response times of less than 1 minute are now possible.
- Since the fall of 2002, STACEE has made follow-up observations of 18 bursts, but no excess has been seen.
- Past observing season (2005-2006) has been unlucky (no bursts under 5 hours).
- GRB 050607 (left) was our fastest response time (191 seconds).

Dark Matter Annihilation

See Tyler, “Particle Dark Matter Constrains from the Draco Dwarf Galaxy” (Phys.Rev.D **66**, 023509, 2002)

- $\chi\bar{\chi} \Rightarrow \pi^0$ decays to gamma-rays.
- Models and experiments currently favor WIMP with $M_\chi \sim 50\ GeV - 10\ TeV$.
- A candidate target needs to be nearby and have a high concentration of dark matter.
  - Draco has one of the highest known Mass-to-Light ratios ($M/L \sim 450\ M_\odot/L_\odot$)
  - It is a satellite of our own Milky Way (79 kpc).
  - Stellar velocities indicate that Draco has relaxed to an isothermal sphere ($\rho \sim r^{-2}$) which has a high central density.

SDSS Image of Draco

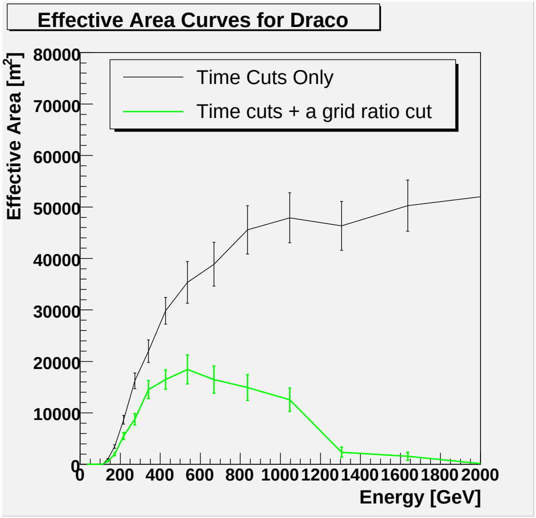
Robert Lupton and the Sloan Digital Sky Survey Consortium

Draco Data Summary

- 35 “pairs” of data were taken in May-June 2006 with $\sim$ 10 hours of livetime after cuts.
- Raw triggers (time cuts only): 177,498 - 177,273 = 225 (4.8 Hz)
- After grid ratio cut: 1576 - 1587 = -11 (-0.19σ)
- Gamma Rate: $-0.02 \pm 0.09\ \gamma/min$
- These results are model-independent, but any interpretation needs both:
  1. A measure of the the detector response.
  2. The source spectrum of the object being studied!

Effective Area

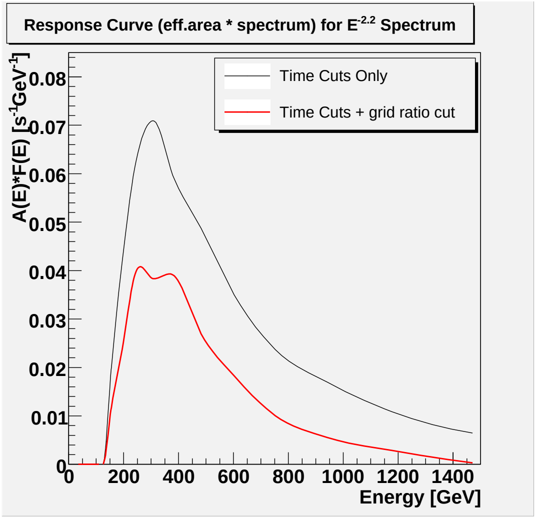
- Measures the probability that a shower will trigger given the projection on the ground.
- Grid ratio cut trades sensitivity at high energies for gamma-hadron separation.



(curves based on CORSIKA simulations)

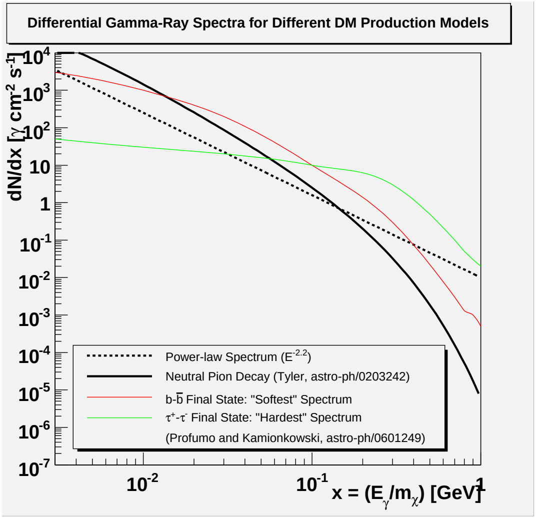
Detector Response

- Power-law spectra are "standard" for gamma-ray astronomy.
- "Energy threshold" is defined as peak of detector response.
- Time cuts + grid ratio cut (green) used to maximize response at lower energies.



Modelled Flux Spectra

- Power-law spectrum based on emission from galactic center.
- Self-annihilation spectra will have a sharp cutoff at M_χ.
- Magnitude depends on DM distribution, distance.



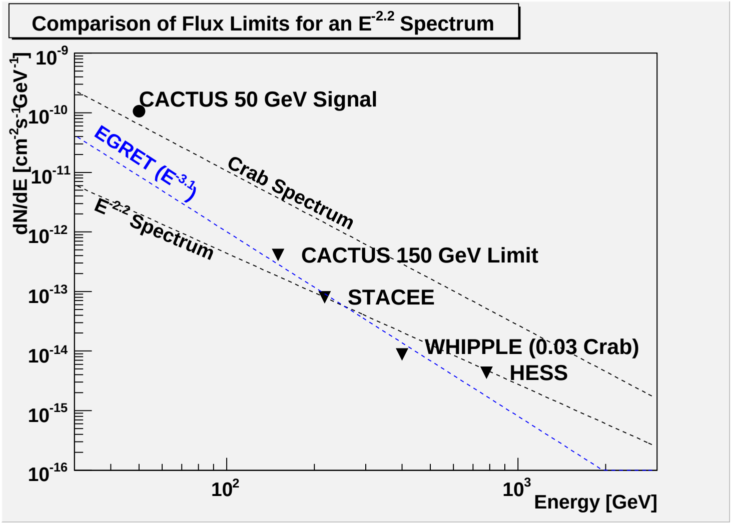
Comparison with Other Experiments

- EGRET [PK]: $\frac{d\Phi}{dE} \sim 1.6x10^{-6}\left(\frac{E}{GeV}\right)^{-3.1} cm^{-2}s^{-1}GeV^{-1}$
- CACTUS [BH]: an ACT like STACEE
  - Preliminary results hinted at in conference talks.
  - "Results" found in theory papers from non-CACTUS authors.
  - $\sim 60\sigma$ excess (30,000 events in 7 hours with $E > 50\ GeV$)
  - $\sim 20\sigma$ excess (7,000 events with $E > 100\ GeV$)
  - No signal seen above 150 GeV.
- WHIPPLE [H]: $\Phi(E > 400\ GeV) < 0.03\ Crab$
- HESS [PK]:

  $\frac{d\Phi}{dE}(E > 780\ GeV) < 1.0x10^{-8}\left(\frac{E}{GeV}\right)^{-2.2} cm^{-2}s^{-1}GeV^{-1}$

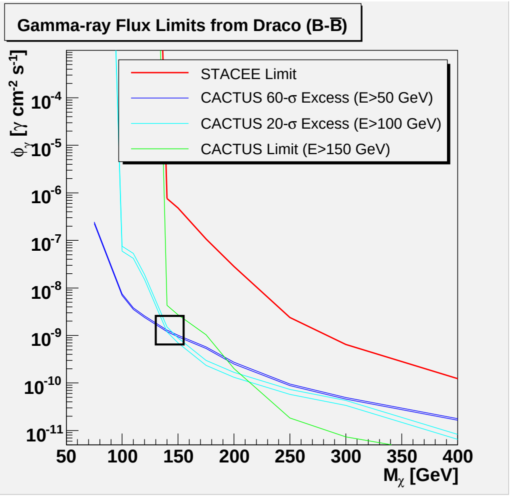
Profumo & Kamionkowski, astro-ph/0601249
Bergström & Hooper, astro-ph/0512317
Hall, ICRC 05, astro-ph/0507448

Flux Comparison



Dark Matter Limits

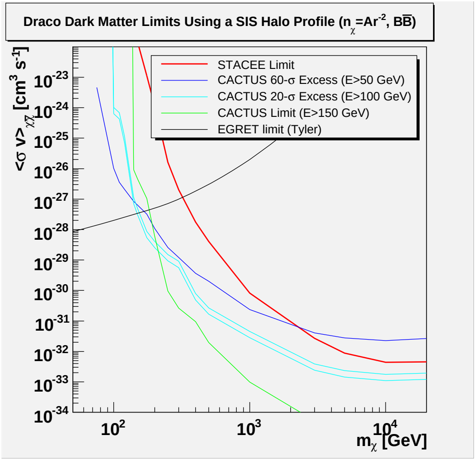
- Flux normalized to detector response from *shape* of spectrum.
- 50 GeV and 100 GeV CACTUS excesses have both upper and lower limits.
- Black box indicates where the two excess curves cross.



Our measurements favor a lower-mass WIMP.

Dark Matter Limits

- Normalized to distance and single isothermal sphere core model (Tyler).
- Also dependent on accuracy of mass, halo density, and central density.
- EGRET limits based on absence of Draco from 1 GeV catalog.



CACTUS excess "crossing point" excluded by EGRET limit

Summary

- STACEE does not see Draco with a sensitivity of about 0.07 times the Crab.
- The STACEE observations of Draco are competetive with other experiments for a power-law spectrum.
- The unofficial (?!) CACTUS result would only be possible (self-consistent) for a low-mass ($M_\chi \sim 50 - 200\ GeV$) WIMP.

Outlook

- 2006-2007 is the last STACEE observing season.
- VERITAS is now online and GLAST is soon to follow
- Further Draco observations are planned.
- Improved analysis techniques could find “hidden treasures” in past data!