Prospects for Detecting Dark Matter with VERITAS and Future Gamma-ray Instruments

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(Special thanks to Ryan Dickherber, WU
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Bob Wagner, Argonne
Matthew Wood, UCLA)

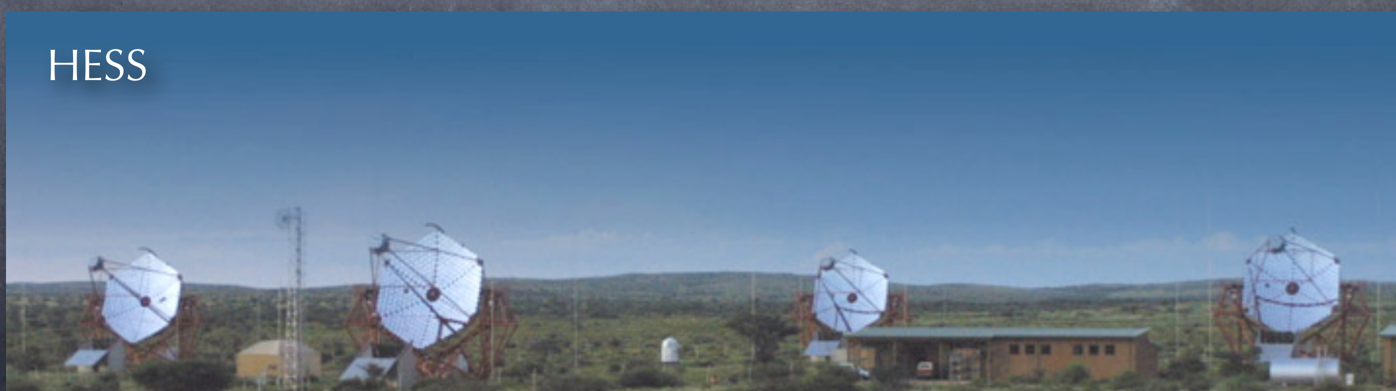
Impact of High Energy Astrophysics Experiments on Comological Physics, KICP, Chicago, Oct. 27, 2008

Status of VHE Astro

4x12m IACTs, Crab sensitivity ~36 σ/√hr, 1% Crab in 35 hours

1x17m IACTs ~ 19 σ/√hr, 2.2% of Crab in 50 hours

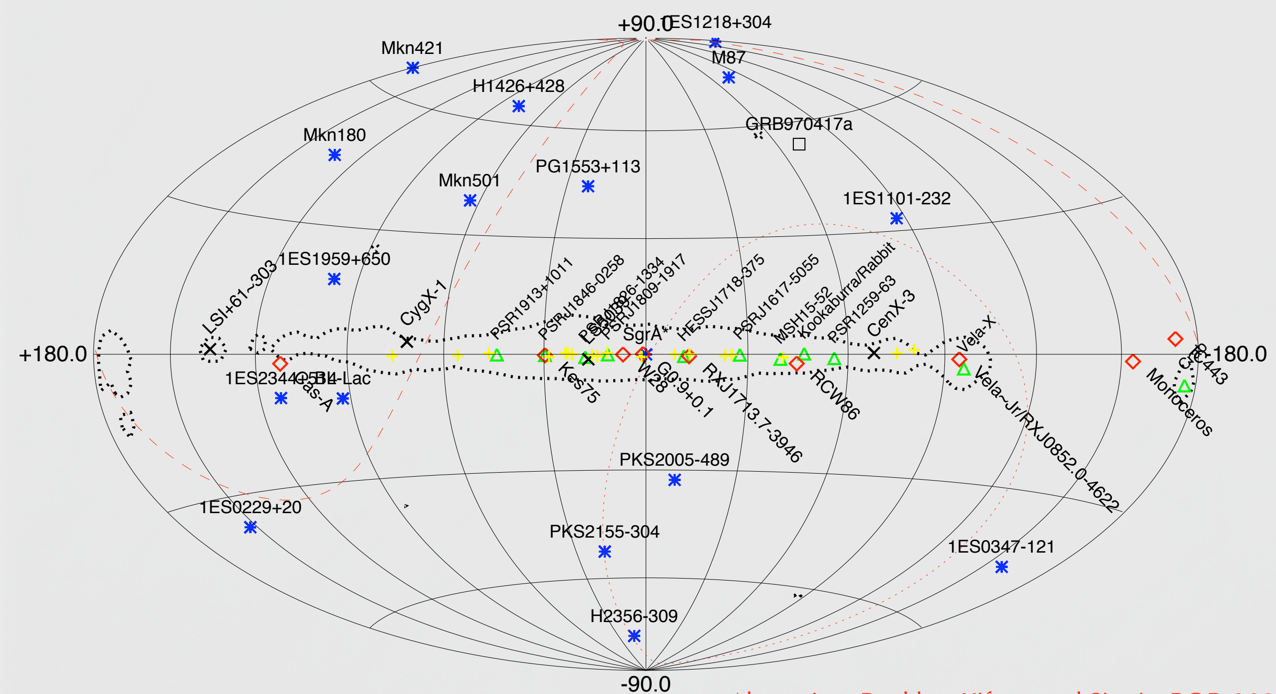
4x12m IACTs, Crab sensitivity ~43 σ/√hr (est)



All instruments have similar light collection area and have a "peak energy" of around 80-120 GeV (trigger level) but ~300 GeV after typical tight analysis cuts

Status of VHE Astronomy

TeV All Sky Map



Aharonian, Buckley, Kifune and Sinnis, ROP, 2008

- ~70 sources with source classes including: AGN, radio galaxies, shell-type SNR, PWNae, molecular clouds, X-ray binaries, dark sources, the Galactic Center

Why Gamma Rays?

- Why any comprehensive program for searching for dark matter must include gamma-ray measurements:
  - Strong evidence for weakly interacting particle dark matter, only thermal relics yield readily falsifiable predictions.
  - Generic predictions for GC or ``spikes'' are within reach of current experiments, for Dwarf galaxies and halo substructure for the next generation gamma-ray instrument.
  - Detection cross-section (annihilation to continuum γ-rays) is closely tied to the cross-section maintaining thermal equilibrium in early universe.
  - Gamma-rays provide the only means of mapping out the structure of dark matter in halos, and provide the link between new particles discovered in the lab and the cosmological dark matter.
  - The gamma-ray spectrum (both continuum and line emission) is imprinted with the detailed annihilation channels and can identify the dark matter particle.

Complementarity

- For energies < 200 GeV, GLAST most sensitive to continuum emission from γ-ray sources; >200 GeV instruments such as VERITAS and HESS provide the best sensitivity. However, for detection of an annihilation line or cutoff feature, ground-based instruments are probably the only means of detecting enough photons.

- If a neutralino has a mass <500 GeV, the LHC could directly observe it. Above 500 GeV, direct detection experiments and indirect astrophysical experiments are needed.

- While dark matter may be detected at the LHC or direct detection experiments, gamma-ray measurements provide the only possible means of observing the halo distribution and of verifying the role of such particles in structure formation of the universe.

- Liquid noble direct detection experiments are reaching the sensitivity required to probe a large fraction of parameter space, but following a detection, other measurements (such as gamma-ray measurements or measurements with the ILC) are required to identify the particle and measure its mass.

Complementarity

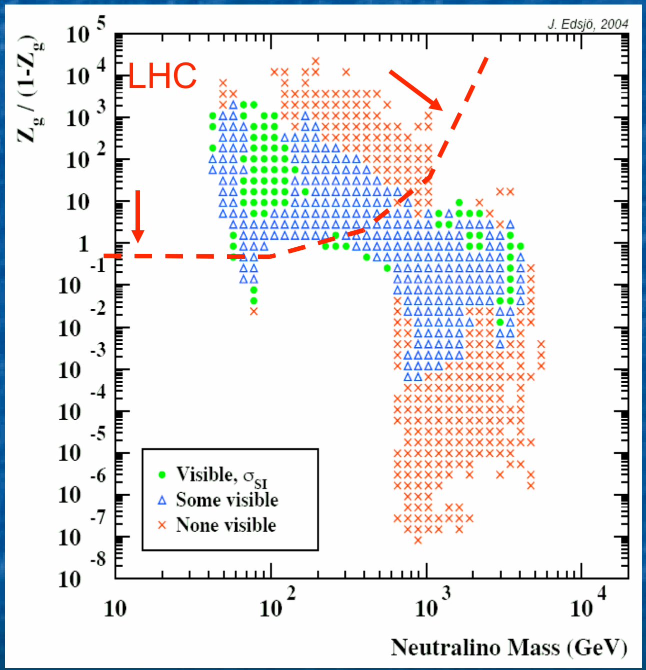
Direct Detection (Si)

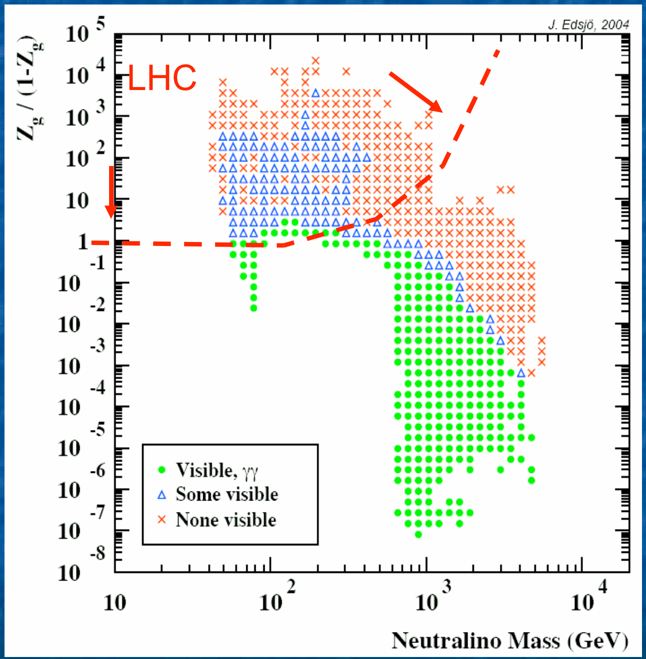
Indirect Detection
with $\gamma\gamma$ line

Gaugino

Mixed

Higgsino

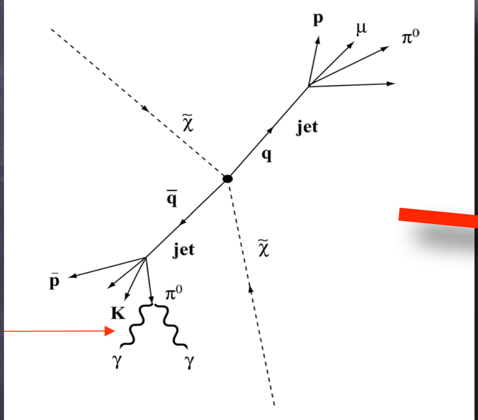




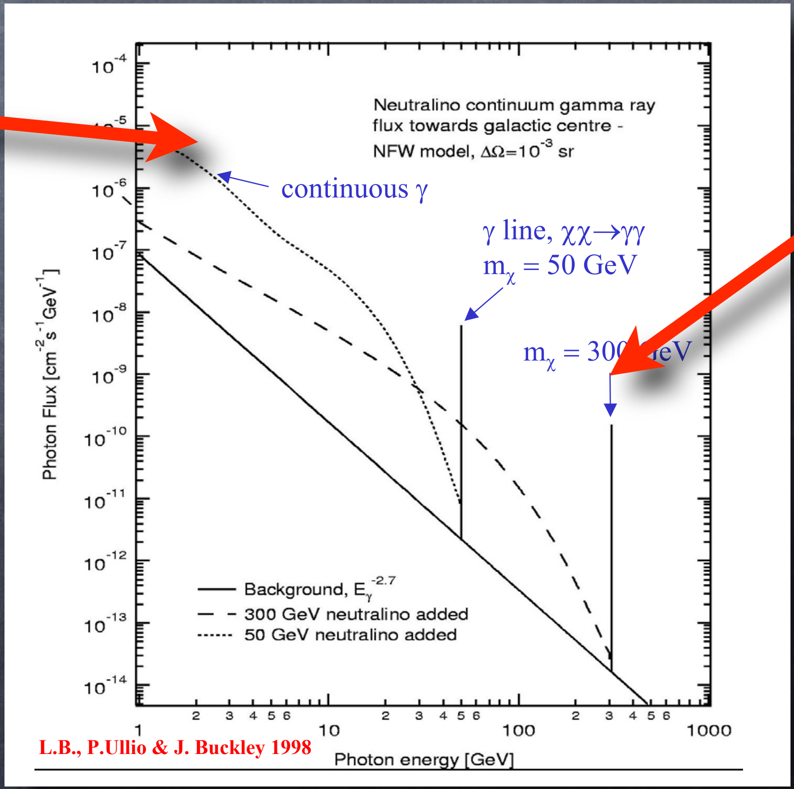
Edsjo 2004

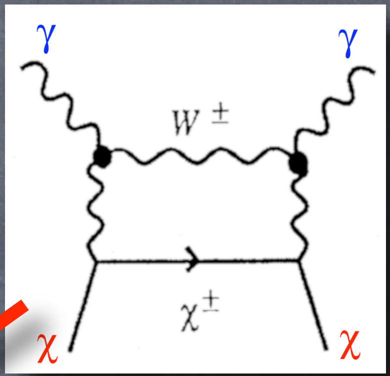
Background

- In regions of the highest dark matter density, dark matter particles and their antiparticles are expected to annihilate into gamma-rays, either directly into a gamma-ray line (with energy equal to the mass of the dark matter particle times the speed of light squared $E_\gamma = m_\chi c^2$) or a broad spectrum of gamma-rays.



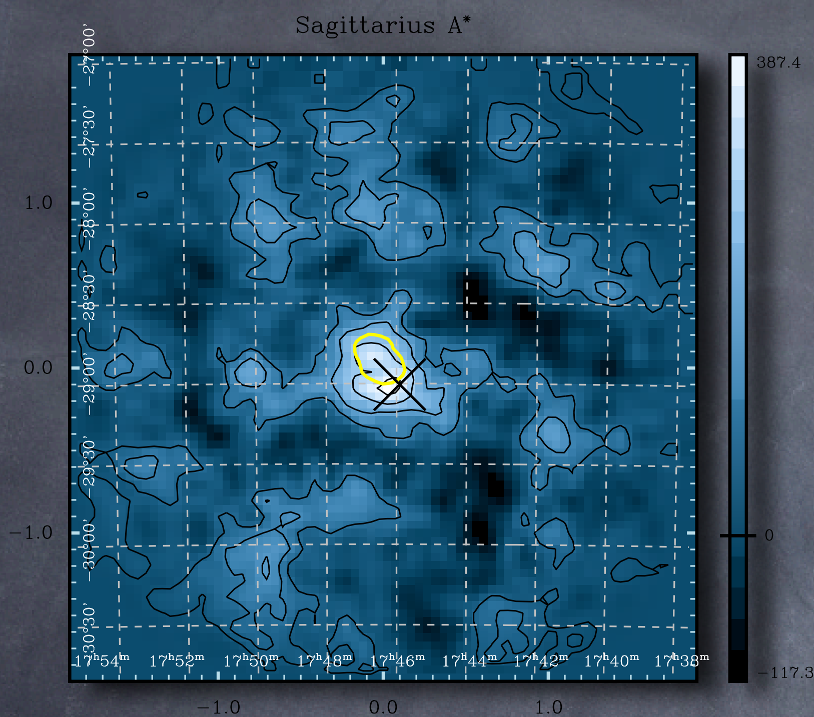
(Bergstrom 2006)

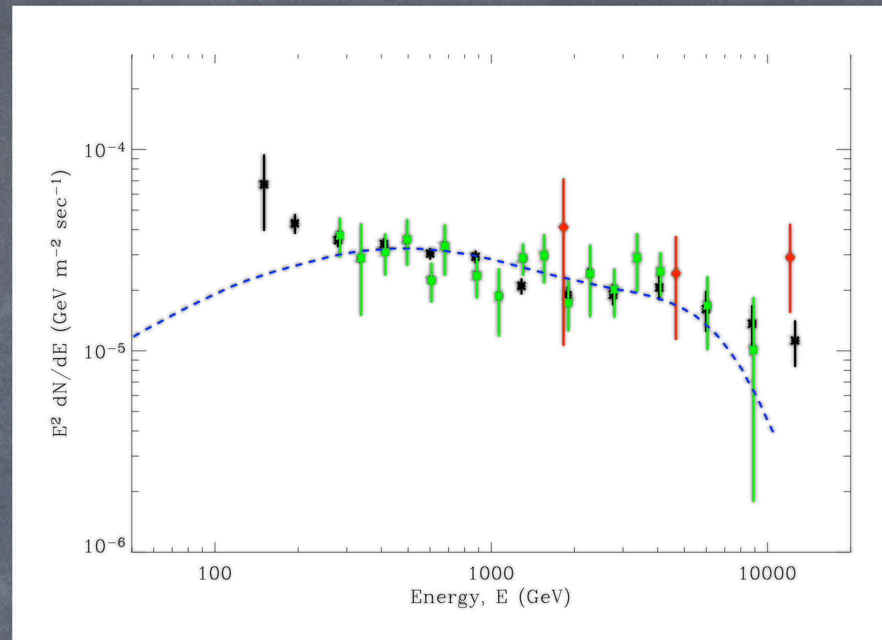




(Jungman and Kamionkowski, 1994)

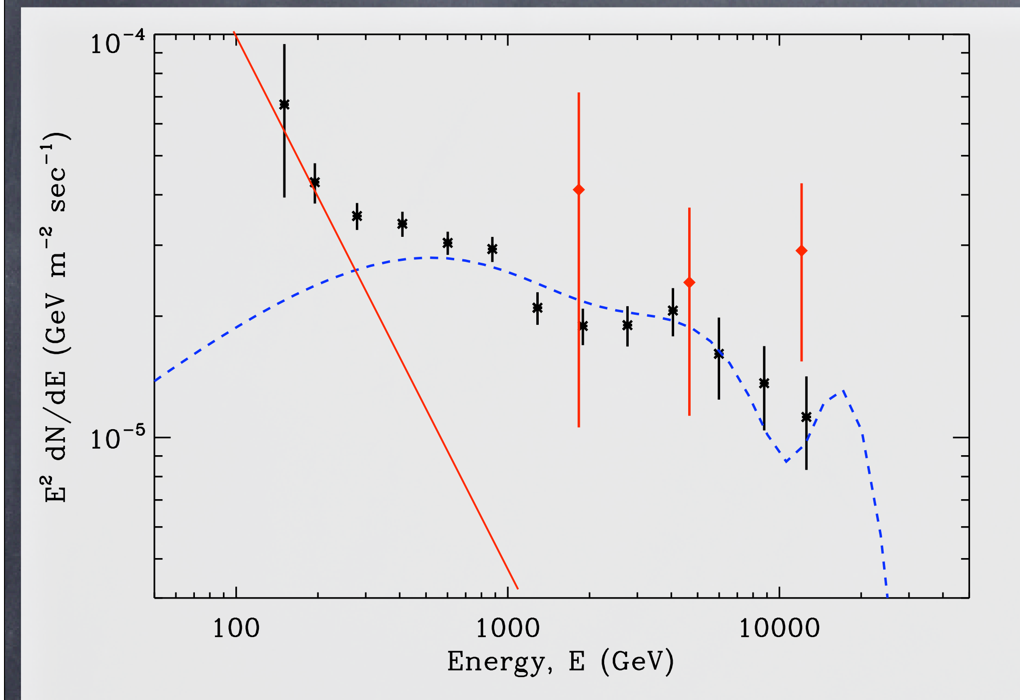
Galactic Center





- Kosack et al. found ~4σ evidence for emission above 2.8TeV based on 10 years of Whipple data (astro-ph 0403422; 2004, ApJ, 608, L97)
- HESS subsequently definitively detected the source with much higher significance. Whipple and HESS spectral analysis were consistent, but incompatible with CANGAROO results (Kosack, Ph. D. thesis, 2005)
- Spectrum is a good power law up to very high energies, *hard to explain as DM*

Hope for the GC?



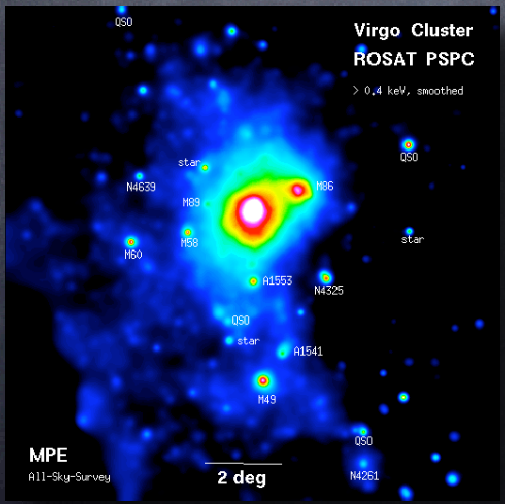
(Annihilation spectrum plotted over GC data points assuming 15 TeV mass, decay through t and τ-channels, 25% energy resolution assuming line/continuum ratio of 5×10^{-3} with continuum from Fornengo, Pieri and Scopel, PRD, 70, 103529, 2004; see also results of Profumo et al. for LKP and neutralino fits to GC data)

- New HESS data (not shown) now shows evidence for a cutoff.
- No evidence for strong variability between 1995 and 2004 in Whipple data, still no variability in HESS data
- Compatible with a point source but a cusp can not be ruled out
- Angular resolution worse at low energies - is source confusion or systematic error contaminating the 100-300 GeV data points?

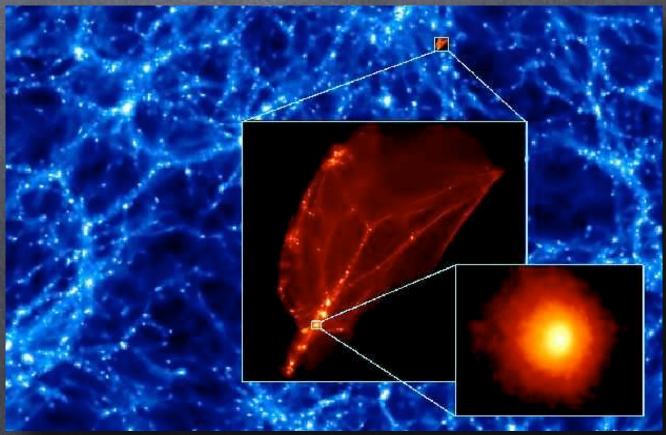
Dark Matter - Where Next?

Andromeda Galaxy

Dwarf Galaxies

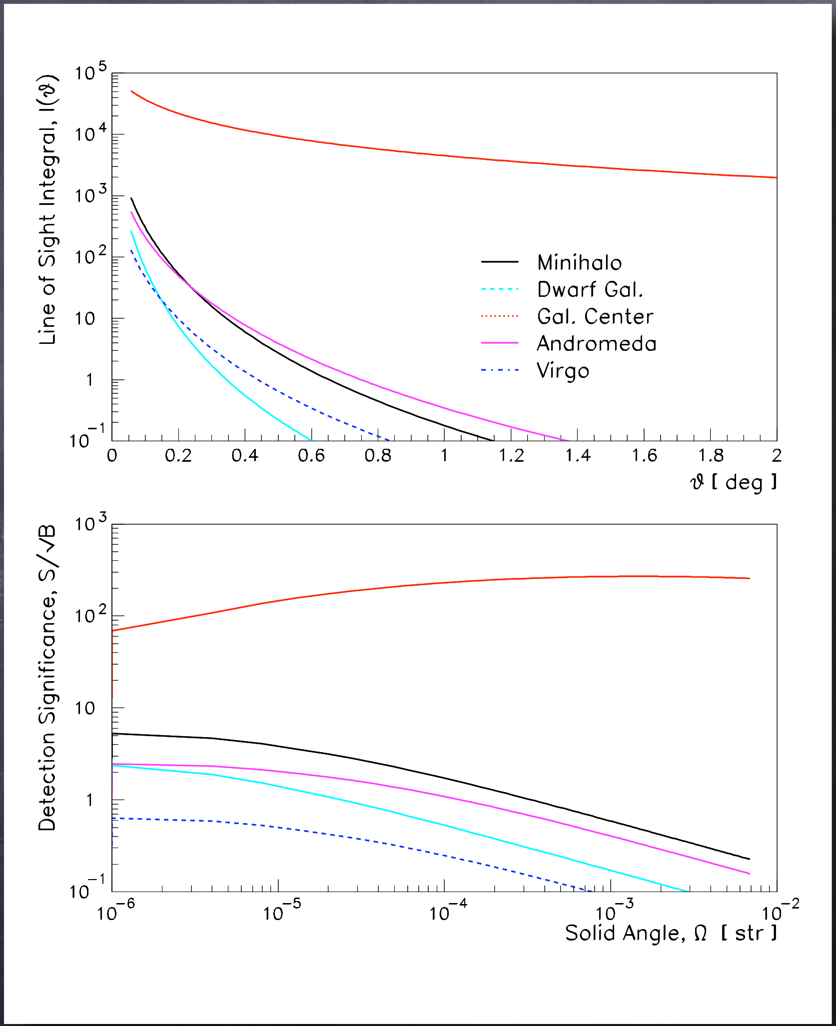


Virgo Galaxy Cluster (X-ray)



Galactic Minihalos

Flux calculation Method



- Surface brightness depends on “J” factor, or the line of sight integral of the density squared
- Calculate expected line or continuum angular distribution assuming a universal NFW halo distribution. (Note: the solid angle which optimizes the SNR depends on the halo profile.)
- For shallow power laws, halos are resolved and have relatively constant surface brightness independent of distance.
- The smart money was on the GC, next comes everything else.

Dwarfs: Halo Modeling

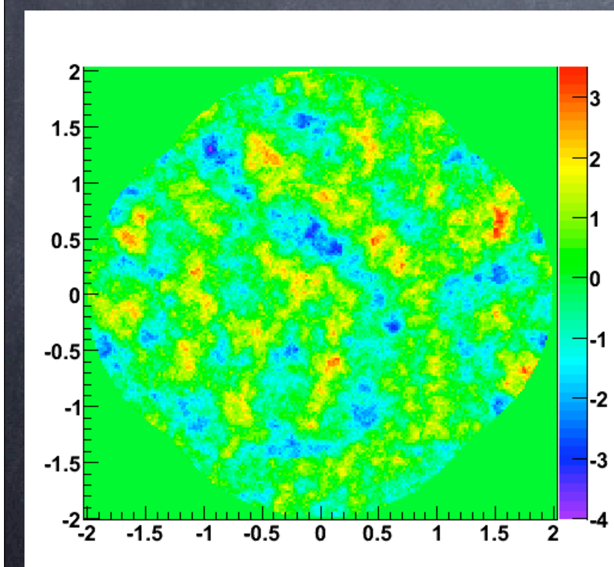
- Strigari et al. 2007 (arXiv:0709.1510) using velocity dispersion data and range of cusp profiles derived likelihood distributions for line-of-sight integrals for various Dwarf galaxies

	Line of sight integral, J
Ursa Minor	12
Draco	8
Wilman I	100
Coma Berenices	30
GC	1000

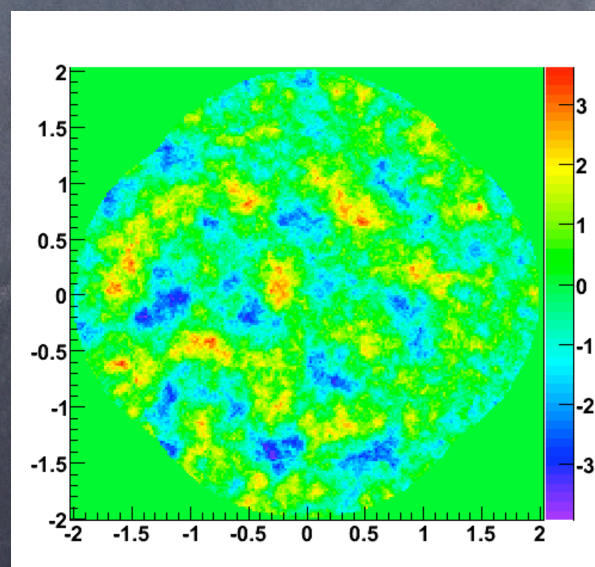
Preliminary VERITAS Results

	Exposure	Significance	95% C.L. Upper Limit (% Crab)
Draco	17.9hr	1.12	1.07
Ursa Minor	18.9hr	-0.46	0.74
Wilman I	13.7hr	0.50	1.06

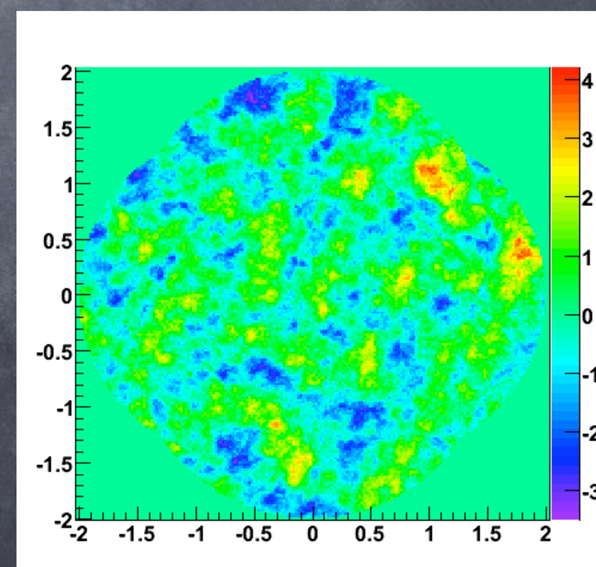
Draco



Ursa Minor

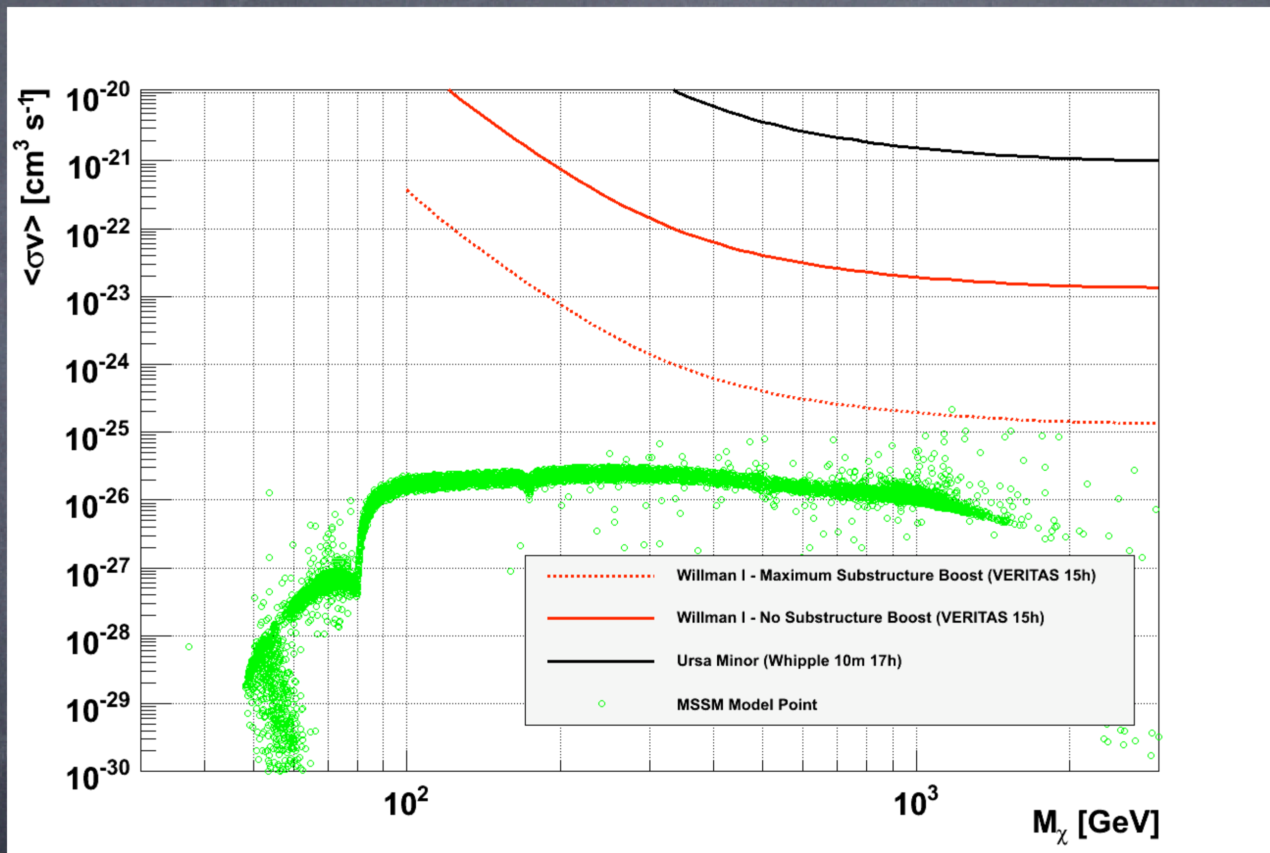


Willman I



Neutralino Constraints

Willman I constraints derived from Strigari et al. 2007 - converted to estimate of J factor



(Matthew Wood and Vladimir Vassiliev)

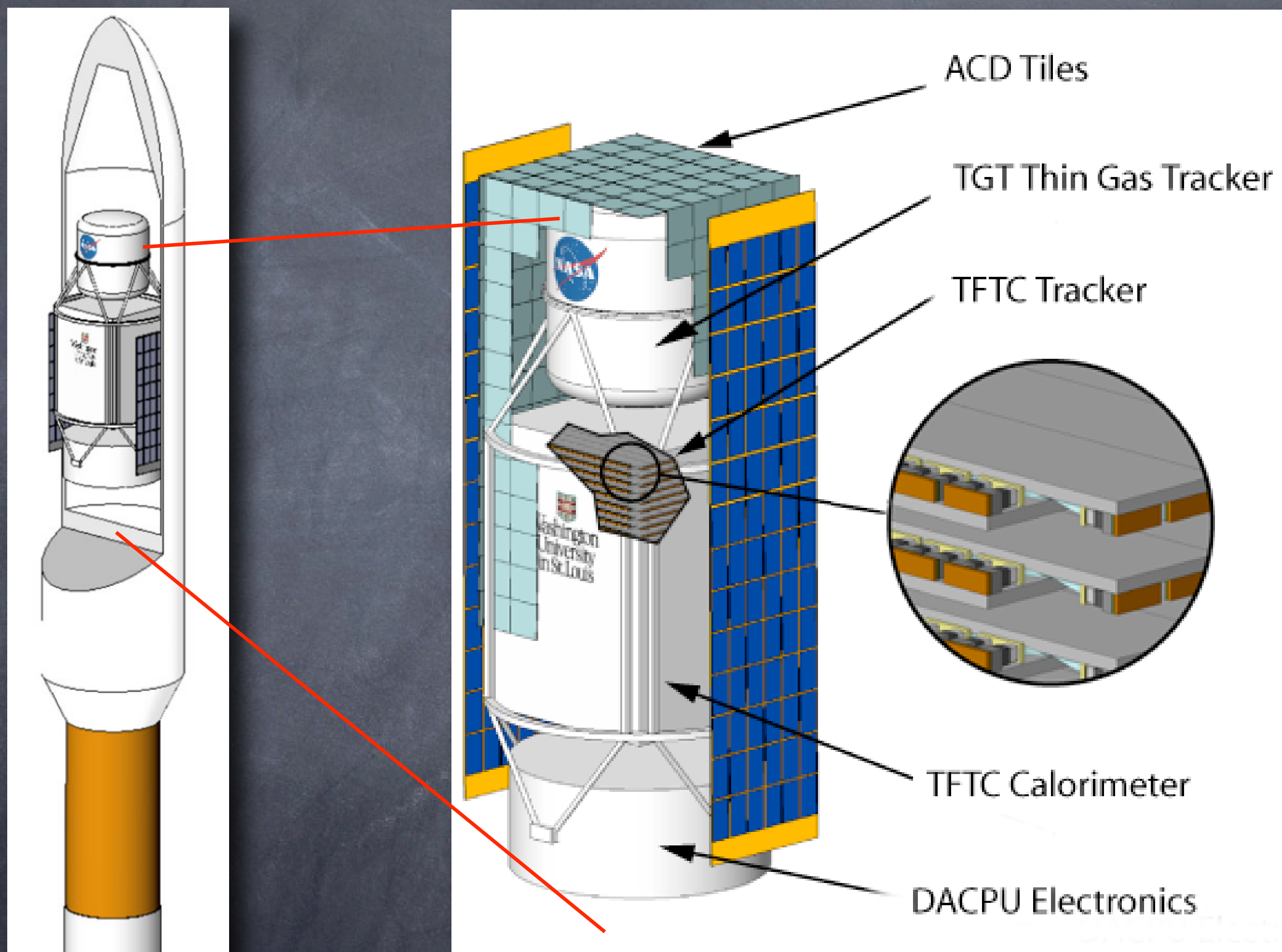
Future Plans

- Observe newly discovered Dwarfs Segue I, and others.
- Observe nearby galaxies.
- A long shot, but possibly the best strategy: Respond to GLAST targets of opportunity (steady, hard-spectrum, unidentified sources). These may be IMBHs with spikey halos, or may result from substructure with a very large boost factor.
- VERITAS and HESS had the sensitivity to see DM from the GC. A new generation of instruments are required to detect other sources...

AGIS Concept

- Concept is to build an array of ~50 ~12m wide-field IACTs covering an area of ~1 km² at a moderately high elevation (~2.5 km a.s.l)

Advanced Pair Telescope (APT)



- Future space-based follow-up to GLAST with 10x exposure, >3 times better angular resolution (WU and GSFC proposal)

AGIS Collaboration

AGIS Steering/Executive Committee

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Jim Buckley
Stefan Funk
Henric Krawczynski
Vladimir Vassiliev

AGIS Collaboration

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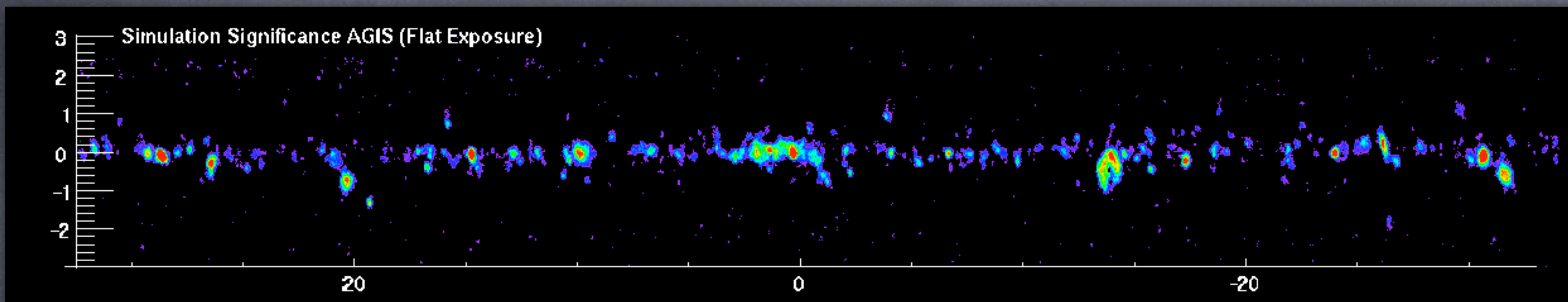
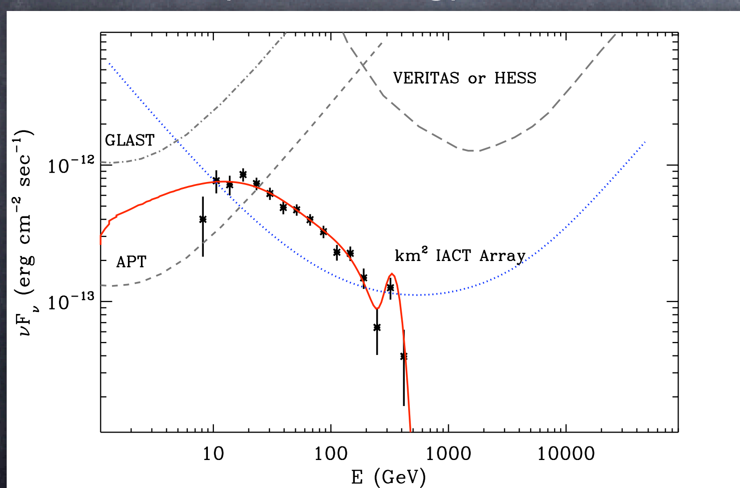
AGIS Science Drivers

Angular Resolution, FoV, Southern hemisphere



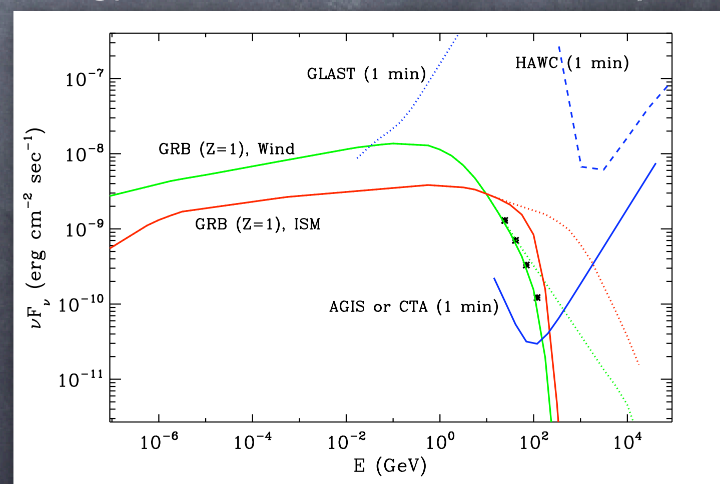
(Digel, Funk and Hinton, 2008)

Sensitivity and Energy Resolution



(Aharonian, Buckley, Kifune & Sinnis, Rep. Prog. Phys, 71, 096901, 2008)

Energy threshold, FoV and slew speed



Buckley et al, arXiv:0810.04442008)

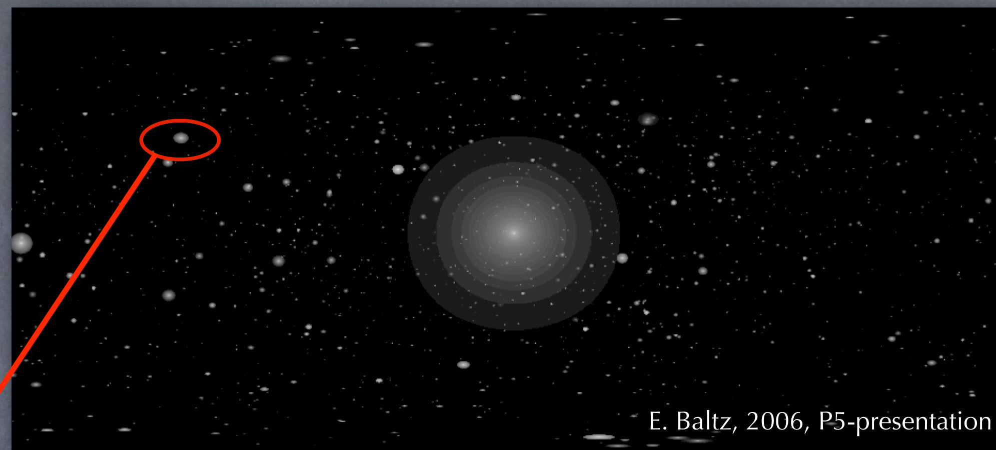
Dark Matter with AGIS

Ursa Minor Dwarf : $d = 66\,\mathrm{kpc}$

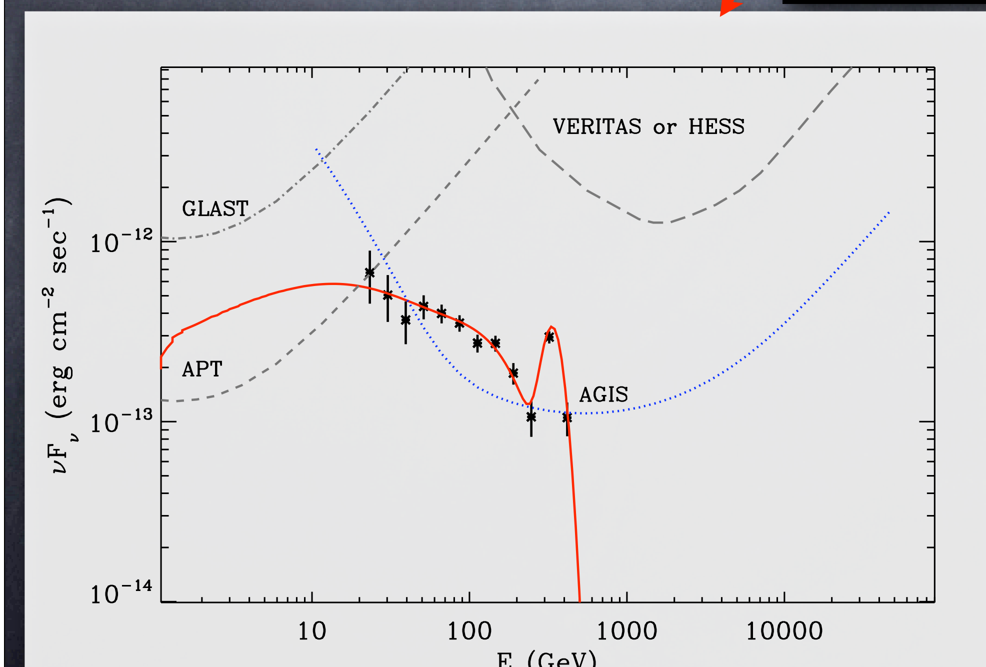
$\langle \sigma_{\chi\chi \to \mathrm{gammas}} \cdot v \rangle = 2 \times 10^{-26}\,\mathrm{cm^3 s^{-1}}$

e.g. $\chi\chi \to \tau^+\tau^-$ (30%) and $\chi\chi \to b\,\bar{b}$ (70%)

Halo : NFW profile, 1 pc core bias factor = 1



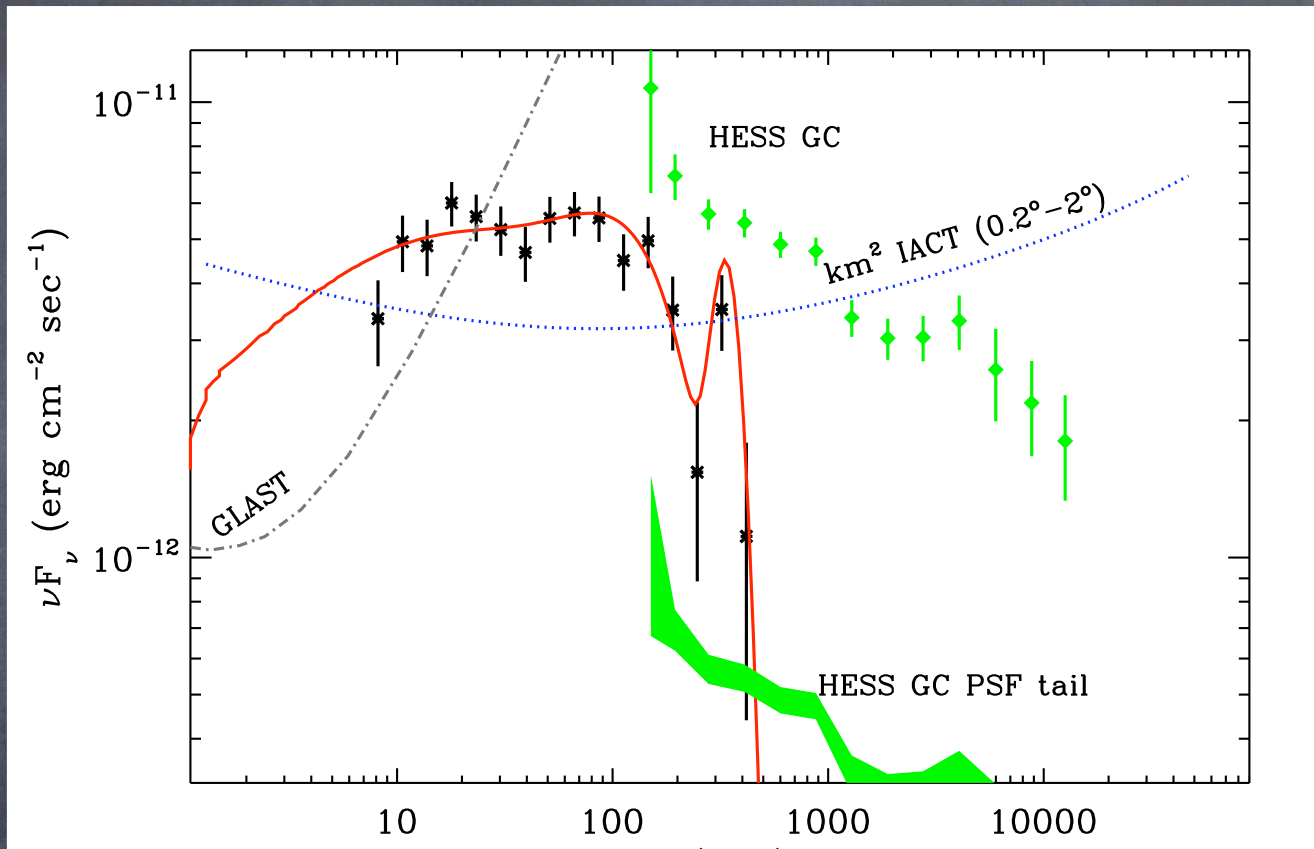
E. Baltz, 2006, P5-presentation



Aharonian, Buckley, Kifune and Sinnis, ROP, 2008

- AGIS would have the required sensitivity to see a more coservative flux from Dwarf galaxies without requiring a large boost factor.
- Energy resolution would be sufficient to resolve a line in some scenarios, and to resolve features in the continuum

Galactic Center



Aharonian, Buckley, Kifune and Sinnis, ROP, 2008

- Look at an annulus 0.2deg to 2deg around GC, with conservative assumptions about GC halo (NFW with 10pc core, no bias factor)

Conclusions

- Any comprehensive program for searching for dark matter must include gamma-ray measurements.
- Generic predictions for GC or ``spikes'' are within reach of current experiments. Dwarf galaxies and halo substructure are in reach for the next generation gamma-ray instruments.
- VERITAS has seen nothing yet, but will continue to take data on Dwarf galaxies and will begin to follow up observations of steady, hard-spectrum unidentified GLAST sources.
- Gamma-rays provide the only means of mapping out the structure of dark matter in halos, and provide the link between new particles discovered in the lab and the cosmological dark matter.
- The gamma-ray spectrum (both continuum and line emission) would be imprinted with the detailed annihilation channels and can identify the dark matter particle.
- Future km^2 gamma-ray observatories (CTA and AGIS) are in the serious planning stages, and could offer a dramatic step forward in providing the required sensitivity for gamma-ray measurements of dark matter.