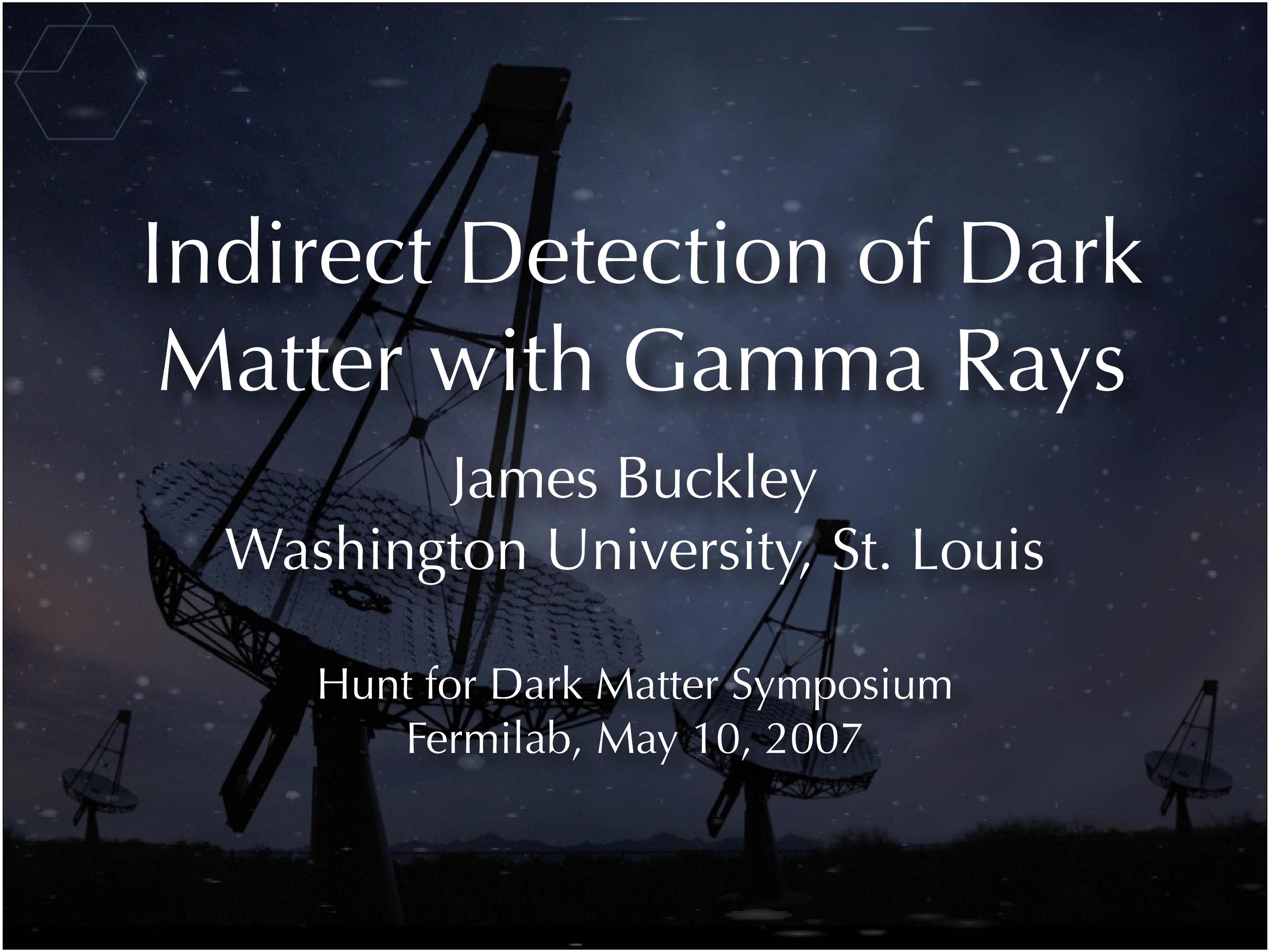


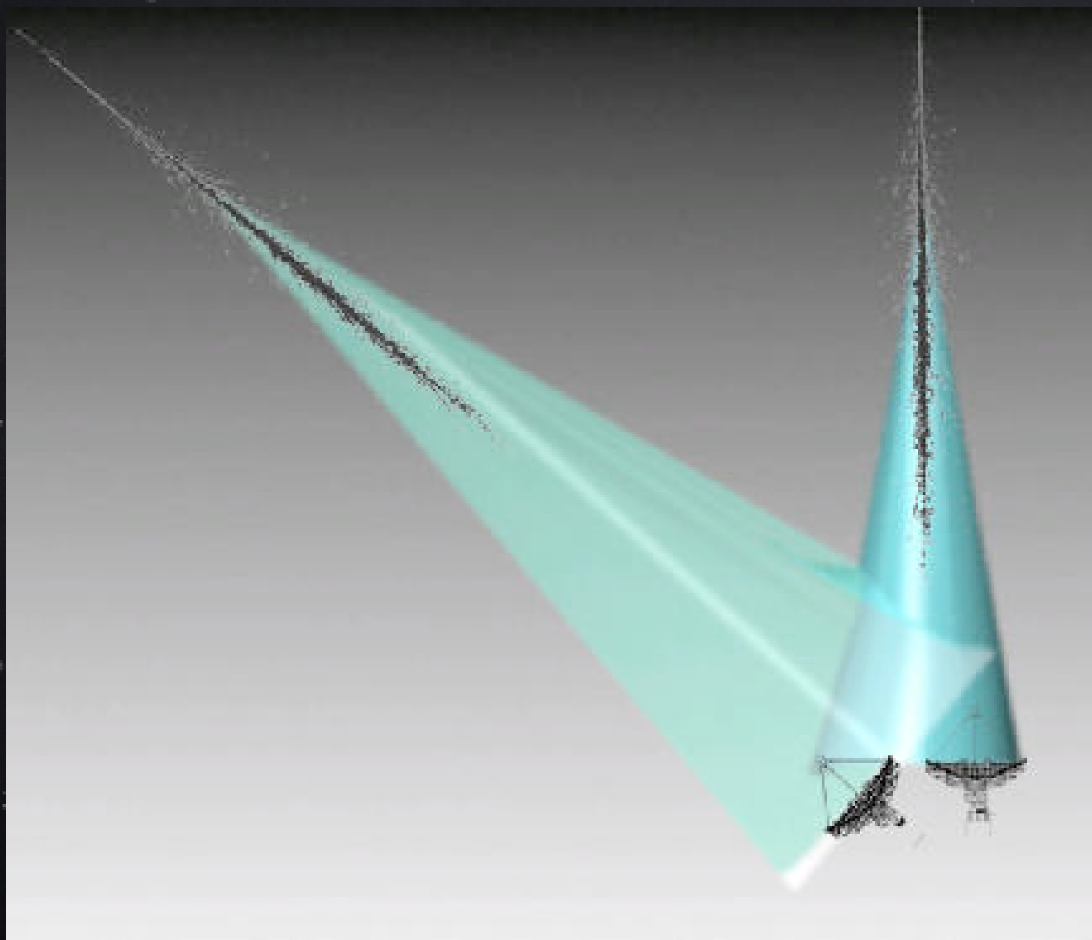
Indirect Detection of Dark Matter with Gamma Rays

James Buckley
Washington University, St. Louis

Hunt for Dark Matter Symposium
Fermilab, May 10, 2007

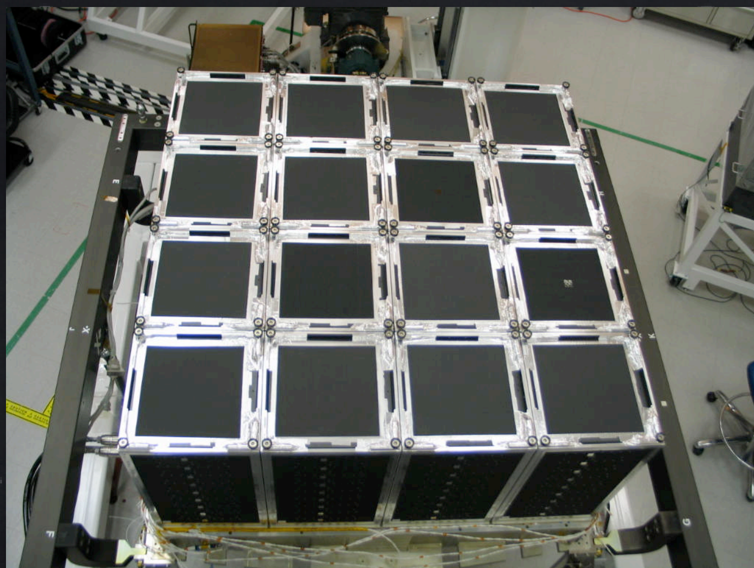
Gamma-Ray Observatories

Atm. Cherenkov Technique



- Image Cherenkov light from atmospheric e/m showers - gives direction and energy
- 10^5 m² effective area
- Stereoscopic imaging gives the direction to several arcminute resolution

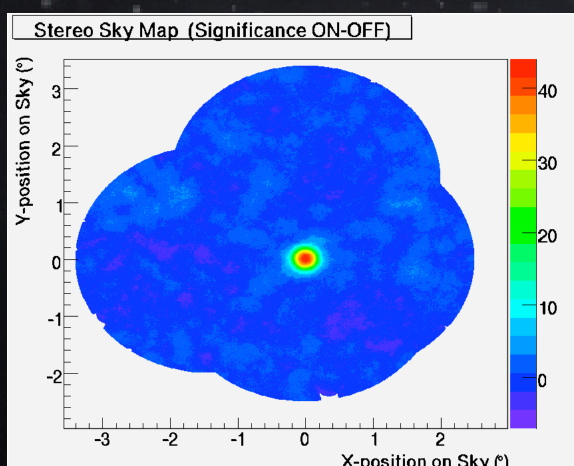
GLAST



In December, 2007 the Gamma Ray Large Area Space Telescope (GLAST) will be launched to map the Gamma Ray sky.

Gamma-Ray Observatories

Newly commissioned 4-telescope VERITAS array (first light April 28, 2007)



(Crab detected at 30 σ/√hr)

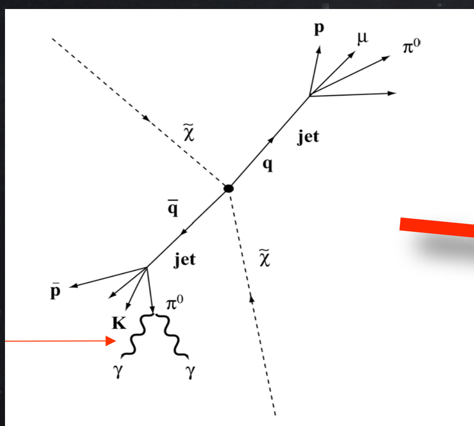
Sources already detected/discovered:

- Markarian 421, Markarian 501, Crab
- LSI+61 303 (pulsar in binary system)
- Blazar 1ES1218+304 (highest redshift)
- M87 (non BL Lac blazar)

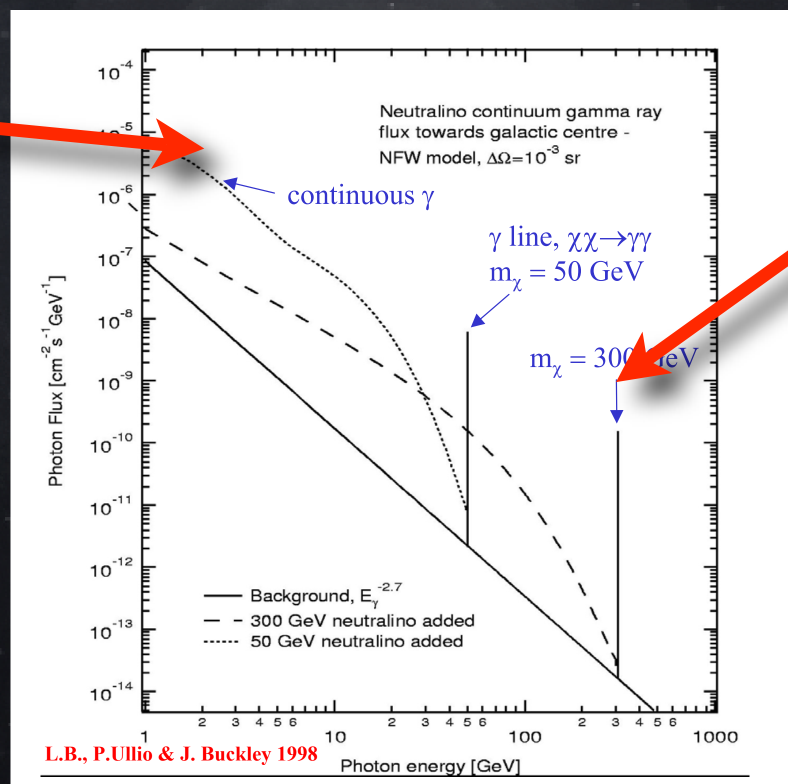
VERITAS Collaboration

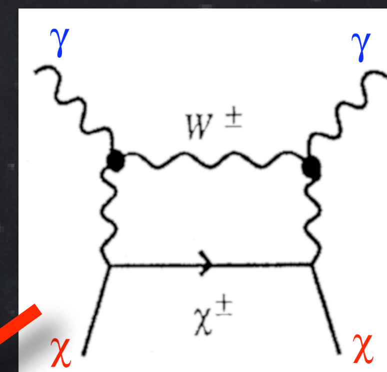
Background

- 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)

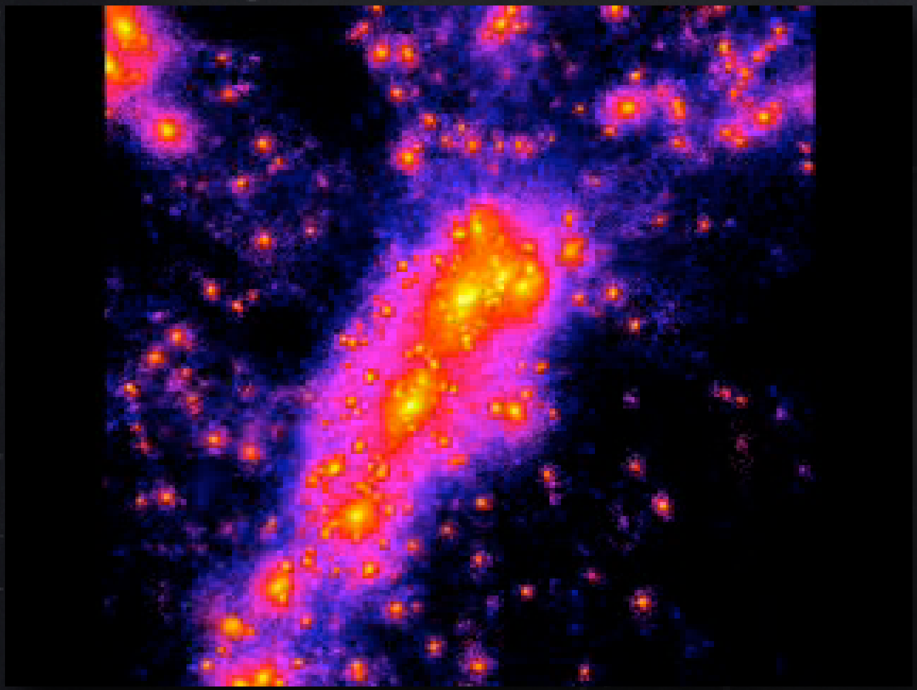


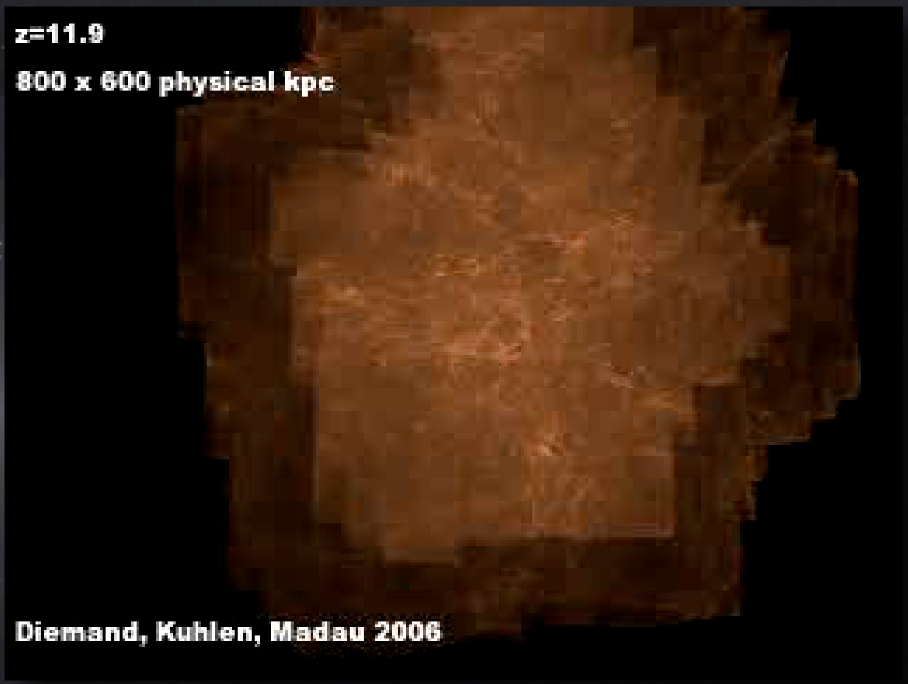


(Jungman and Kamionkowski, 1994)

Where should we look?

N-body simulations of ΛCDM structure formation

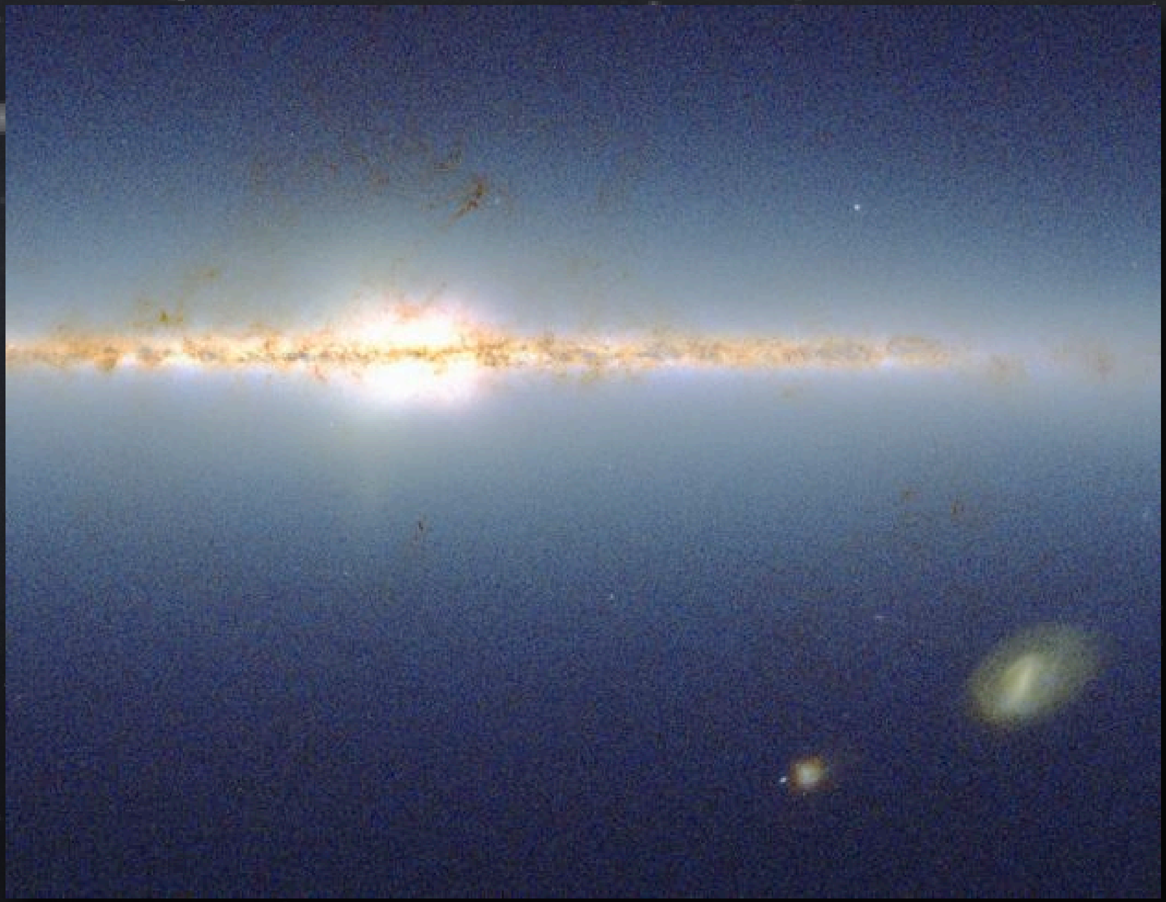




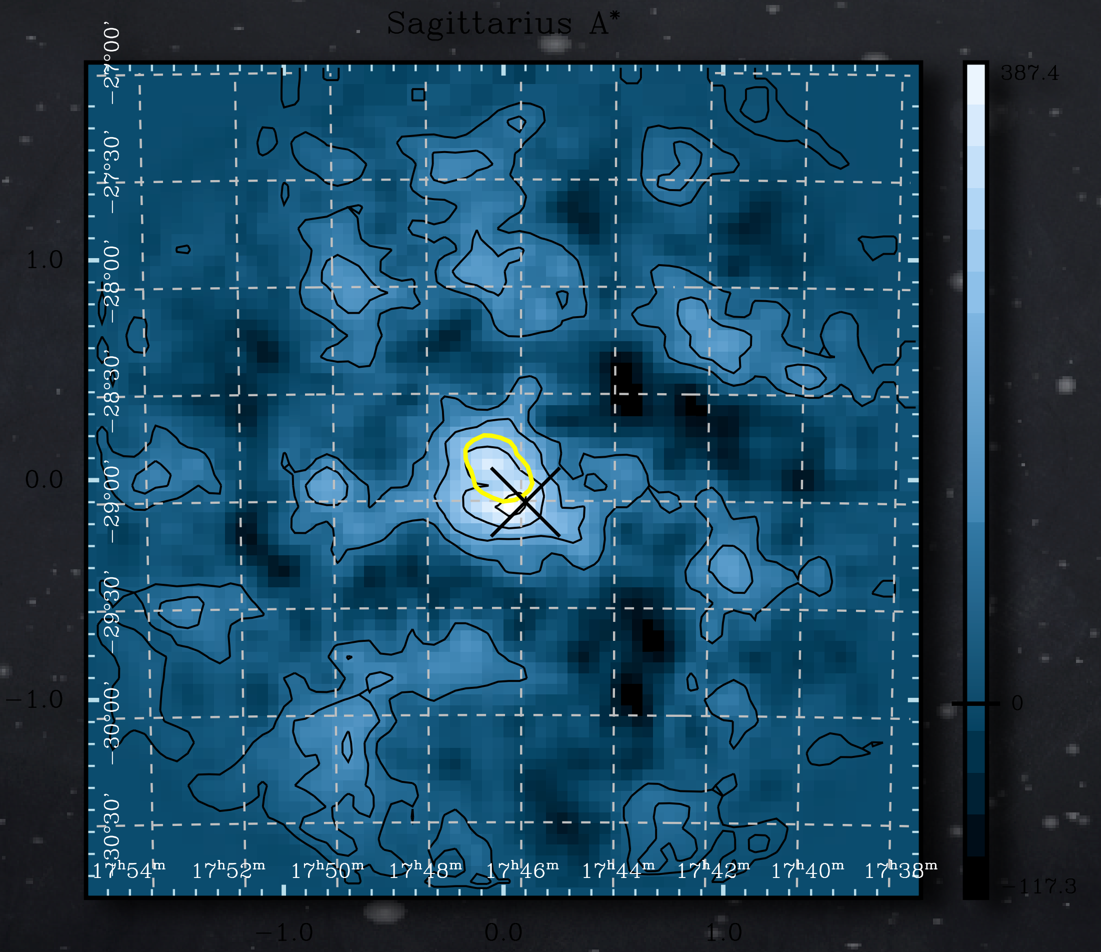
- Primordial fluctuations in dark matter density led to gravitational collapse.
- Structure formed in a hierarchy, from smallest to largest dark matter halos.
- When ordinary matter fell into these dark matter halos, it dissipated heat and collapsed to form stars and galaxies - cusps in density may persist in some galaxies, if not washed out by dynamics

Galactic Center

View towards the center of our galaxy as seen in the infrared waveband - Simulations of structure formations predict cusps in the dark matter profile near the center.

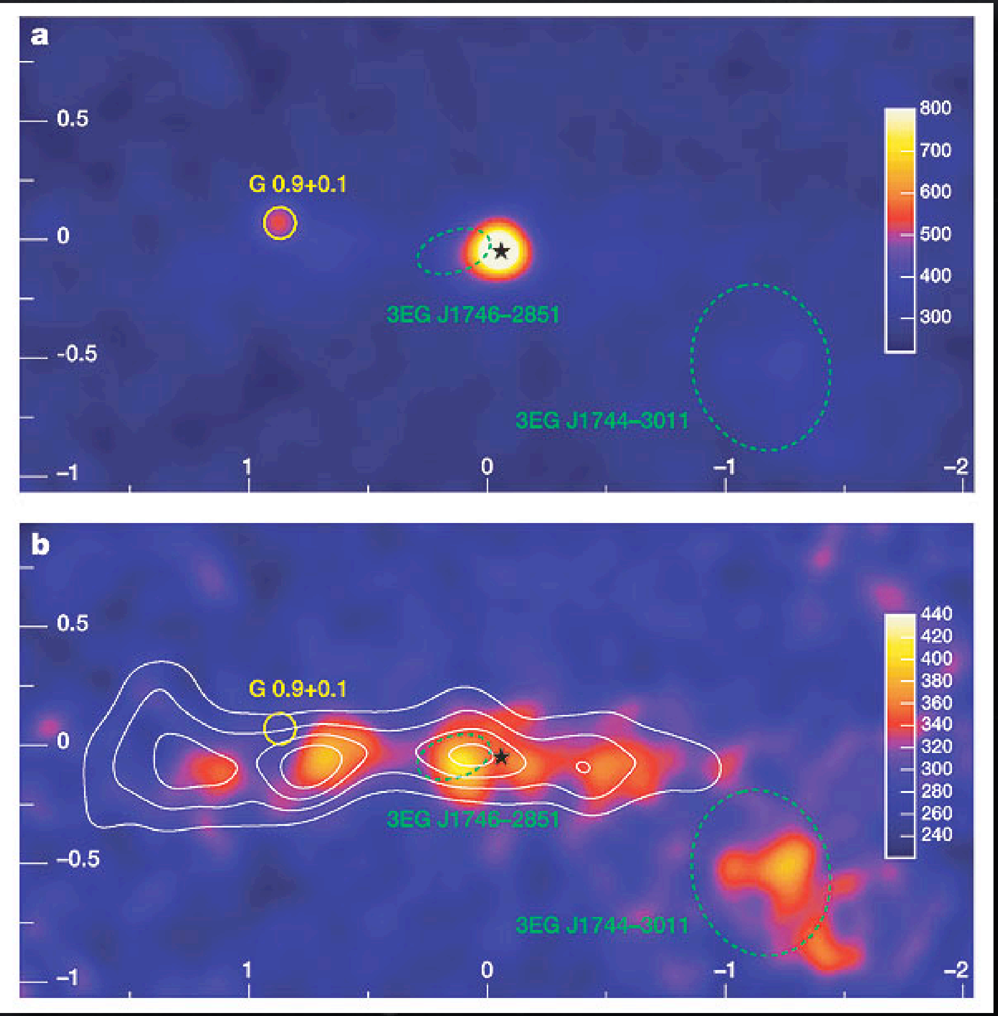


Whipple GC Detection



- Kosack et al. (astro-ph 0403422; 2004, ApJ, 608, L97)
- 26 hr data taken over 10 years at LZA, 3.7 sigma, 2.8 TeV

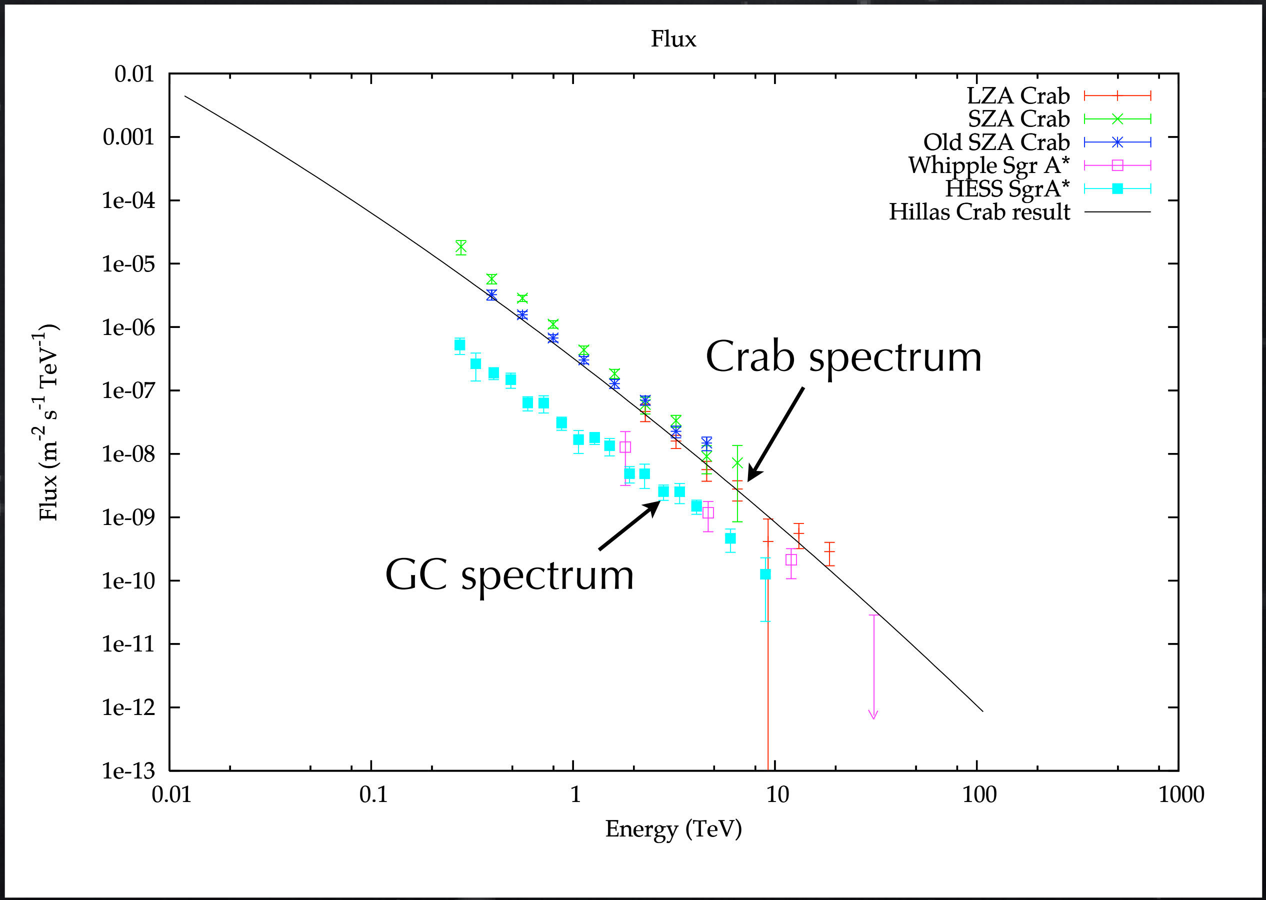
HESS GC Detection



- HESS has obtained beautiful measurements of the GC region, revealing rich astrophsyics.
- While the Galactic Center provides one of the best potential sources for gamma-ray emission from dark-matter annihilation, substantial astrophysical backgrounds from other sources make it very difficult to extract the dark matter signal.

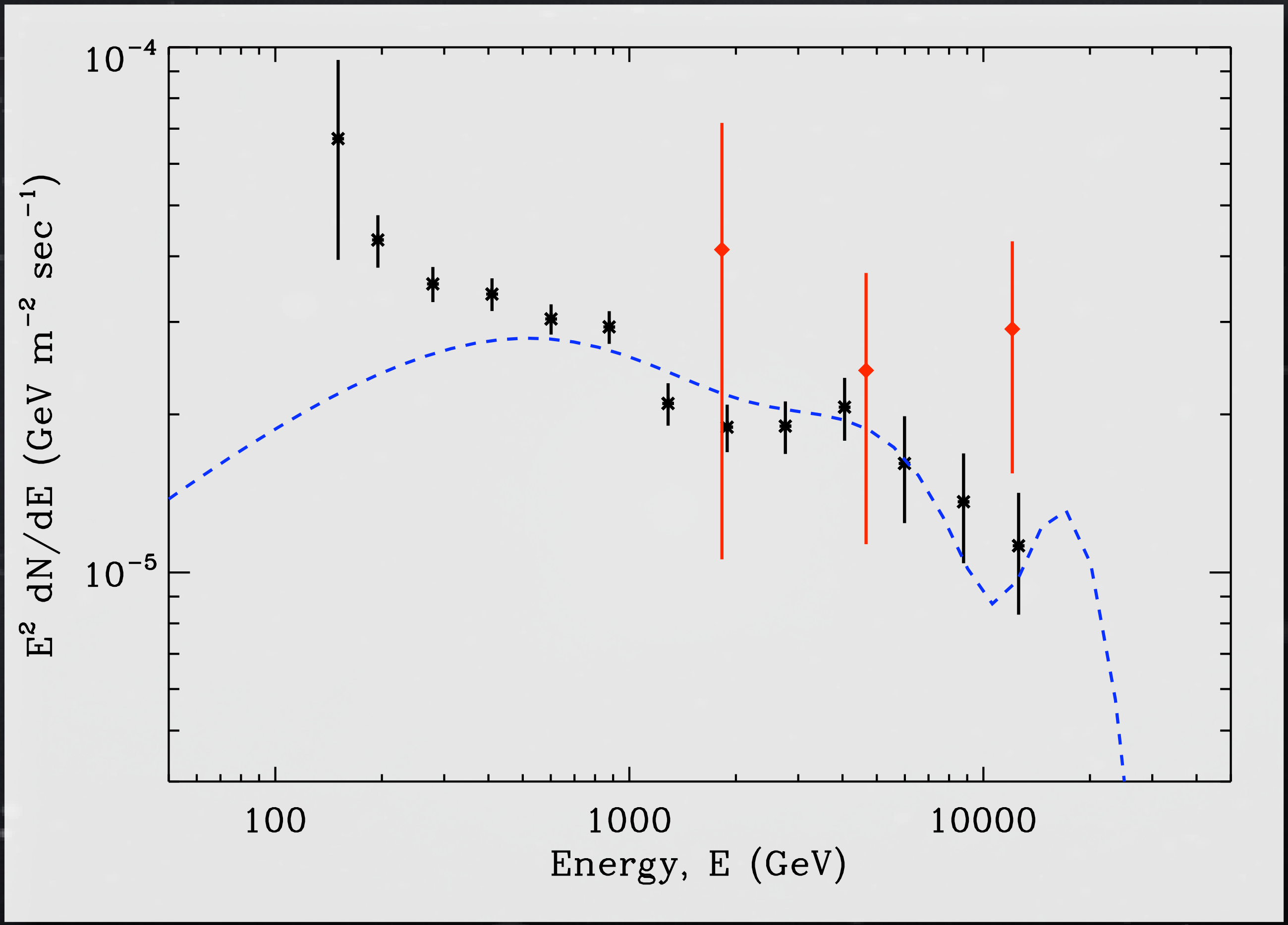
HESS image of GC region (Aharonian et al., 2006, Nature 439, 695) $E^{-2.3}$ spectrum, correlation with molecular clouds - first indication of CR near source?

GC Spectrum



- Whipple GC spectrum (Kosack et al. Ph.D. thesis, 2004) agrees well with newer HESS result.

GC Spectrum

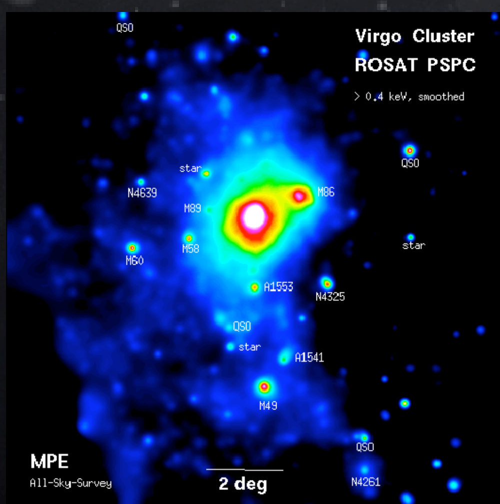


(Annihilation spectrum plotted over GC data points assuming 15 TeV mass, decay through t and τ channels, 25% energy resolution assuming line/continuum ratio of 5×10^{-4} following Fornengo, Pieri and Scopel, PRD, 70, 103529, 2004)

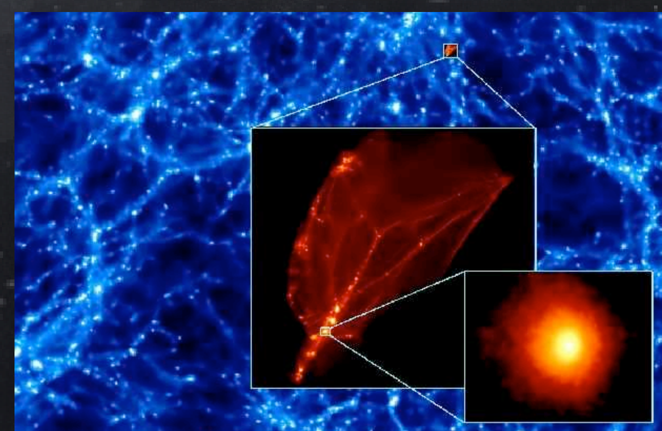
Dark Matter - Where Next?

Andromeda Galaxy

Dwarf Galaxies

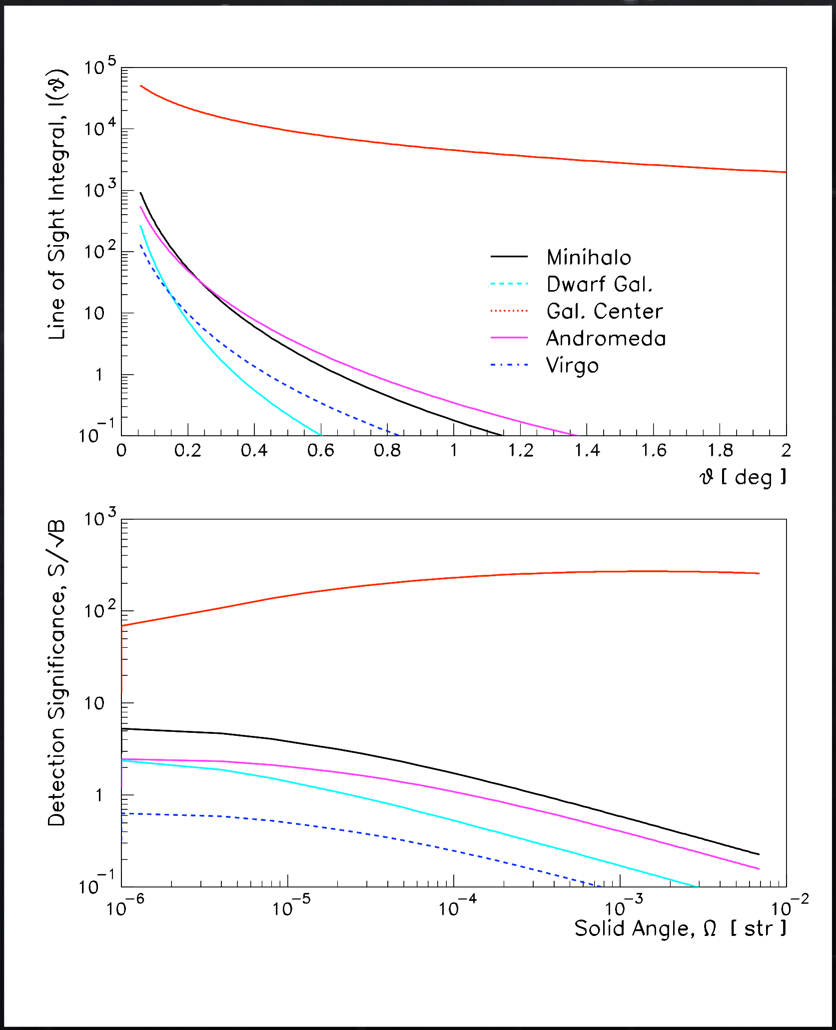


Virgo Galaxy Cluster (X-ray)



Galactic Minihalos

Flux calculation Method



$$J(\theta) \sim \int_{\text{line of sight}} \rho^2 dl$$

- Surface brightness depends on line of sight integral of the density squared
- Calculate expected line or continuum angular distribution for N-body (NFW) halo distributions.
- The solid angle which optimizes the SNR depends on the halo profile. ☠ Note that the sensitivity curves for ACTs are appropriate for *point sources*, for extended sources the curves move up by $\sqrt{\Omega_{source}/\Omega_{psf}}$
- For steep halo profiles, one observes something like a point source with $J \propto 1/d^2$
- For shallow power laws, halos are resolved and have relatively constant surface brightness independent of distance

Halo Gamma Signal

Maximal/GC compatible signal + universal NFW halo profile

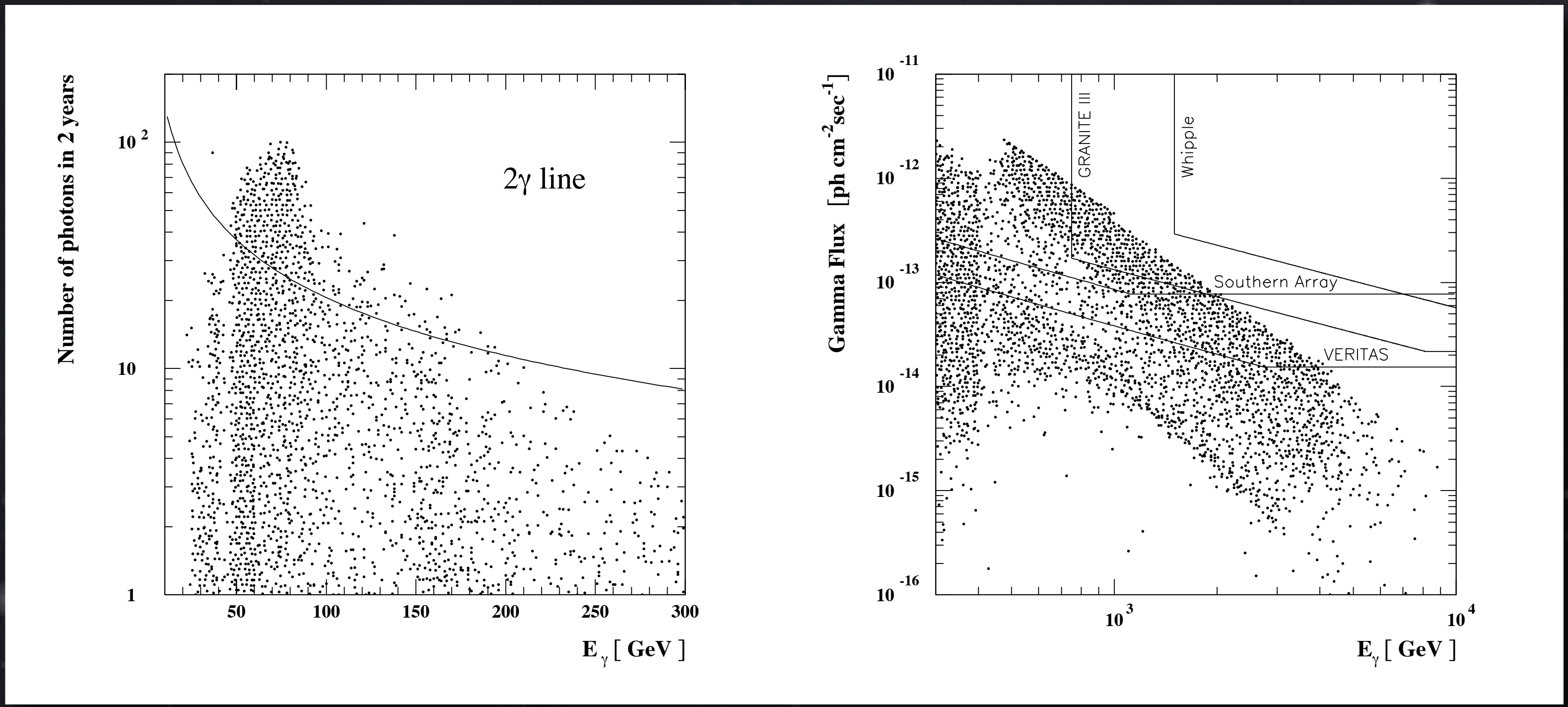
$$\rho(r) \propto \left[(r/r_s)(1 + r/r_s)^2\right]^{-1}$$

Object	Mass (M_{sun})	Distance	Ang. Size (vir rad/dist) (deg)	Optimum SNR (arb. units)	Optimum Aperture (deg)	Signal relative to GC (pt src)	Sensitivity requirement (erg $cm^{-2}s^{-1}$)
Minihalo	10^{-4}	0.5 pc	0.29	12	0.027	4×10^{-2}	2.3×10^{-13}
Dwarf Galaxy	10^{8}	75 kpc	0.15	5.8	0.020	1.1×10^{-2}	6.6×10^{-14}
GC	1.8×10^{11}	8.5 kpc	47	620	1.2	1.0	6.0×10^{-12}
Andromeda	1.8×10^{11}	730 kpc	0.48	5.6	0.034	2.7×10^{-2}	1.6×10^{-13}
Virgo Cluster	10^{14}	17 Mpc	0.39	1.5	0.034	0.6×10^{-2}	3.6×10^{-14}

Apples and Oranges...

- Often when one compares predictions for different types of objects, parameters like the density profile are optimistically tweaked to achieve a large signal - this makes it difficult to compare model predictions.
- Often constraint plots for instruments suppress the see of points stretching many orders of magnitude below the suppressed zero - this is especially bad for cases where the detection cross section is only loosely related to the decoupling cross section, or for gamma-rays, when the astrophysical uncertainties are large.
- In comparing GLAST and ACTs, it is possible to produce results that show the superiority of one instrument over the other by choosing the appropriate fiducial neutralino mass, or by comparing point source sensitivities for known sources (favorable for ACTs) or all-sky survey sensitivity (favorable for GLAST)

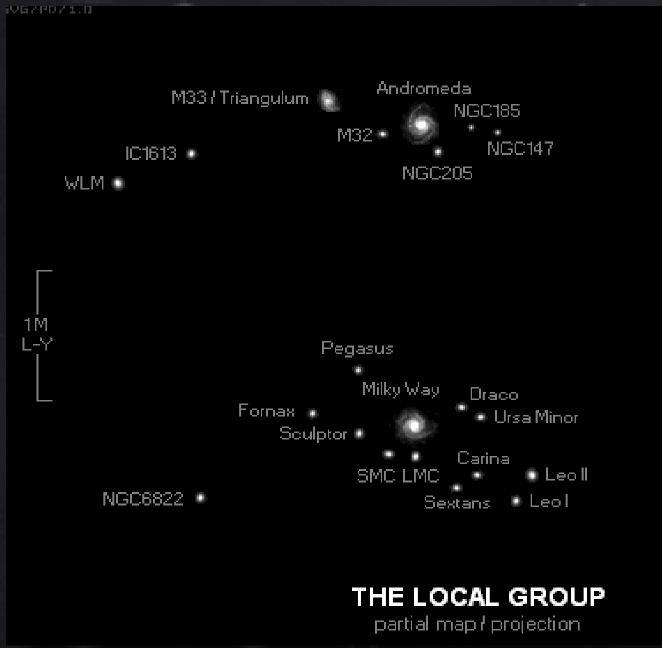
GLAST and ACTs

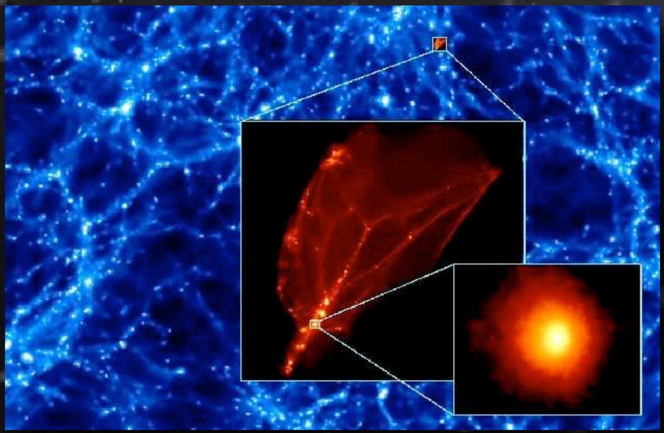


- Bergstrom, Ullio, Buckley (Astropart. Phys1998) found that for the GC, an ACT could potentially probe more parameter space with better sensitivity for detecting a gamma-ray line

- For the continuum emission, integrating down to the instrument threshold, GLAST can do better than VERITAS for masses up to a couple hundred GeV (e.g., Koushiappas 2006, Baltz 2006)

Promising Targets





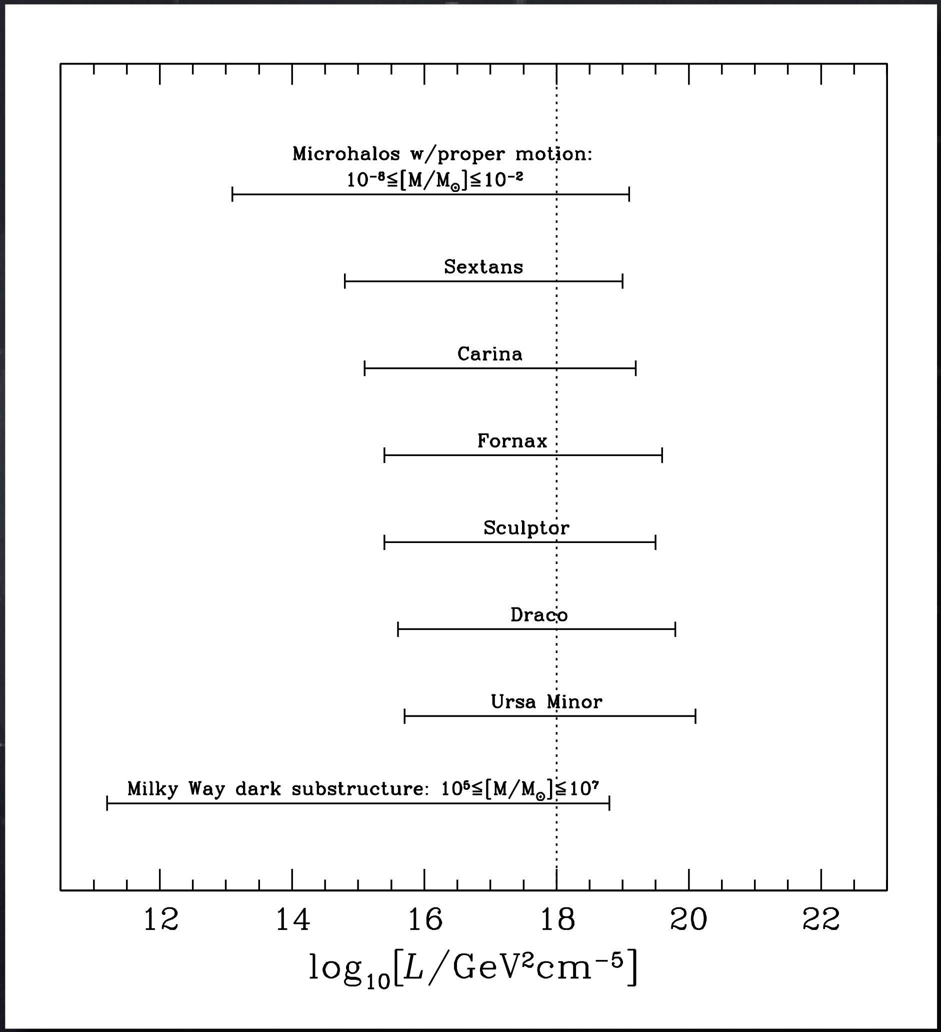
High resolution simulation of structure formation showing earth-sized microhalos which might pervade local space, and give an observable signal (Diemand et al., Koushiappas)

- The most promising new targets for DM searches may be the local-group Dwarf galaxies. Such sources are dominated by dark matter with mass-to-light ratios as high as 1000, and are relatively free of astrophysical backgrounds.
- Galactic substructure could be detected at about the same level as Dwarf galaxies. An exciting possibility is to detect the first CDM structures in the form of very nearby microhalos. These objects could exhibit proper motion and parallax. Guidance from GLAST is needed to locate the sources, or ground-based instruments with very wide field of view are needed to survey the whole sky.

Sensitivity Estimates

Comparison of signals from Dwarf Galaxies, microhalos and substructure of the galactic halo.

Uncertainties in halo structure (due to influence of baryons, e.g.) means a large sample variance ⇒ need to survey a number of different objects



(Koushiappas, 2007)

Complementarity

- For energies < 200 GeV, GLAST provides the most sensitive means of searching for continuum emission from gamma-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 over most of the allowed parameter space.

- If the mass lightest SUSY particle has a mass <500 GeV, the LHC could directly observe a neutralino. Above 500 GeV, direct detection experiments and indirect astrophysical experiments provide the only avenue for detection.

- While dark matter may be detected at the LHC or in direct detection experiments, and neutrino experiments may provide a detection of the dark matter in the local halo, 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.

Complementarity

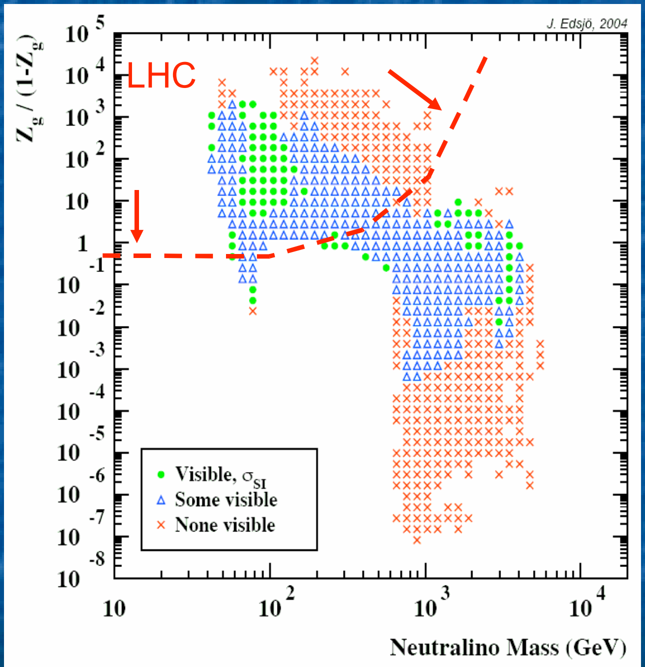
Direct Detection (Si)

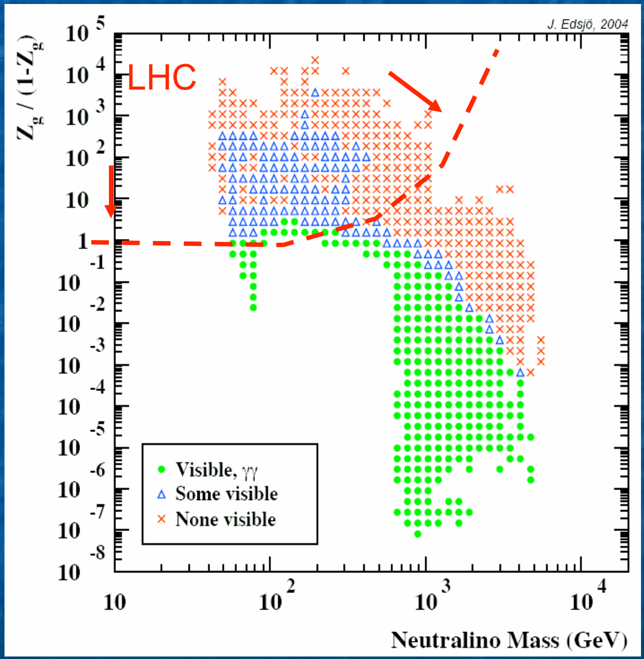
Indirect Detection
with $\gamma\gamma$ line

Gaugino

Mixed

Higgsino





Edsjo 2004

The Future

- U.S. (AGIS) and European groups (CTA) are currently in the planning stages for a next generation gamma-ray experiment with km^2 effective area, 10% energy resolution, arcmin angular resolution, and energy thresholds as low as 40 GeV. Such instruments could achieve sensitivities of 10^{-13} down to 10^{-14} erg cm^{-2} sec^{-1} at 200 GeV.

Artist's concept for a km^2 array of wide-field ACTs (J.Buckley, D. Braun)

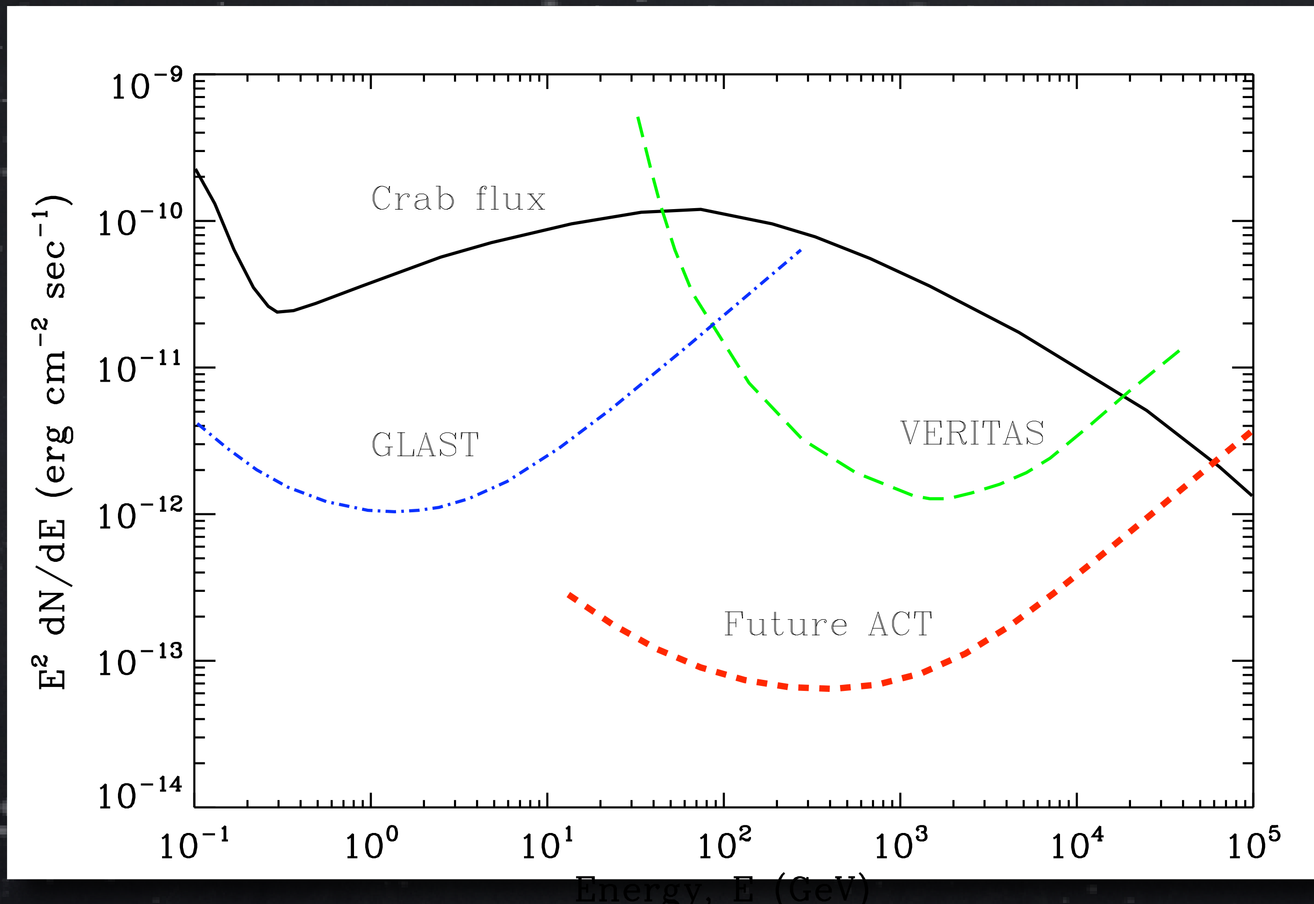
Please attend our meeting:

"The Future of Very High Energy Gamma-Ray Astronomy"

http://future-tev.uchicago.edu/

May 13&14, Chicago, IL
Wyndham Hotel

Sensitivity of km^2 Array



(Differential sensitivity plot for points sources/50hr)

- For a wide-field (8-10deg) km2 array, this sensitivity could be obtained for every point in a 90 degree swath of the galactic plane every 2 years

APS Whitepaper

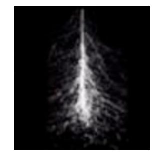
- Initial editorial board was formed Sept. 27, 2006 and expanded in Dec, 2006 to include external advisors
  - B. Dingus (MILAGRO)
  - H. Krawczynski (VERITAS, EXIST)
  - M. Pohl (Theory, GLAST)
  - V. Vassiliev (VERITAS)
  - W. Hofmann (HESS)
  - S. Ritz (GLAST)
  - F. Halzen (Ice Cube)
  - T. Weekes (VERITAS)

The charge from APS   Editorial board   Organizational meetings
Meeting at the GLAST Symposium

The future of ground-based gamma-ray astronomy

APS White Paper

The Status and Future of Ground Based Gamma-Ray Astronomy



In the last two years ground-based gamma-ray observatories have made a number of stunning astrophysical discoveries which have attracted the attention of the wider scientific community. The high discovery rate is expected to increase during the forthcoming years, as the VERITAS observatory and the upgraded MAGIC and HESS observatories commence scientific observations and the space-based gamma-ray telescope, GLAST, is launched. The continuation of these achievements into the next decade will require a new generation of ground-based observatories. In view of the long lead time for developing and installing new instruments, the Division of Astrophysics of the American Physical Society has requested the preparation of a White Paper on the status and future of ground-based gamma-ray astronomy. Scientists from the entire spectrum of astrophysics are invited to contribute to the concepts and ideas presented in the White Paper. We wish to stress that international participation is encouraged.

PAGE NAVIGATION
The charge from APS
Editorial board
Organizational meetings
Meeting at the GLAST Symposium

WORKING GROUPS
Extragalactic Astrophysics
Galactic compact objects
SNR and cosmic rays
Dark matter
Gamma-ray bursts
Technology

http://cherenkov.physics.iastate.edu/wp/

Working Groups

- Extragalactic Science - Henric Krawczynski (Washington U.)
- Dark Matter Science - Jim Buckley (WU)
- Gamma-ray Bursts - David Williams/Abe Falcone (Santa Cruz)
- Galactic Diffuse Emission, SNR and Origin of Cosmic Rays - Martin Pohl (Iowa State U.)
- Galactic Compact Objects - Phil Kaaret (U. Iowa)
- Technology - Karen Byrum (ANL)

APS Whitepaper

Dark Matter Working Group

Ted Baltz (SLAC)	Savvas Koushiappas (LANL)
Jim Buckley (Wash U)	Henric Krawczynski (Wash U)
Karen Byrum (ANL)	Stephan LeBohec (U. Utah)
Brenda Dingus (LANL)	Martin Pohl (ISU)
Stephen Fegan (UCLA)	Stefano Profumo (Caltech)
Paolo Gondolo (U. Utah)	Joe Silk (Oxford)
Geonfranco Bertone (INFN)	Vladimir Vassiliev (UCLA)
Dan Hooper (FNAL)	Scott Wakely (U. Chicago)
Deirdre Horan (ANL)	Matthew Wood (UCLA)

Theorist → Experimentalist/Theorist → Experimentalist

Conclusions

- Planning of next generation gamma-ray observatory will be driven, in part, by dark matter science.
- Even if other experiments detect dark matter in the lab or local halo, gamma-ray measurements provide a unique means to measure the halo structure
- Gamma-ray measurements are complementary to GLAST, Direct, Neutrino, LHC, ILC measurements
- Gamma-ray continuum signal is closely tied to total annihilation cross-section and relic abundance - primary uncertainty comes from halo model
- Much work remains to be done, more collaborators are welcome in planning the next generation experiment!

Dwarf Galaxies

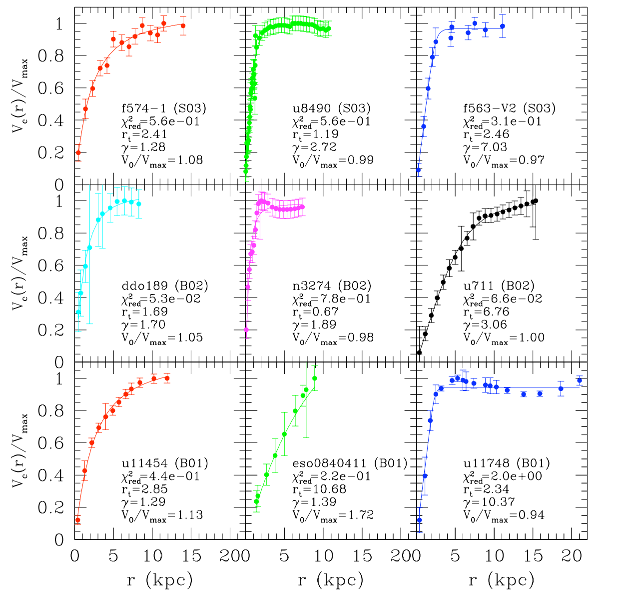
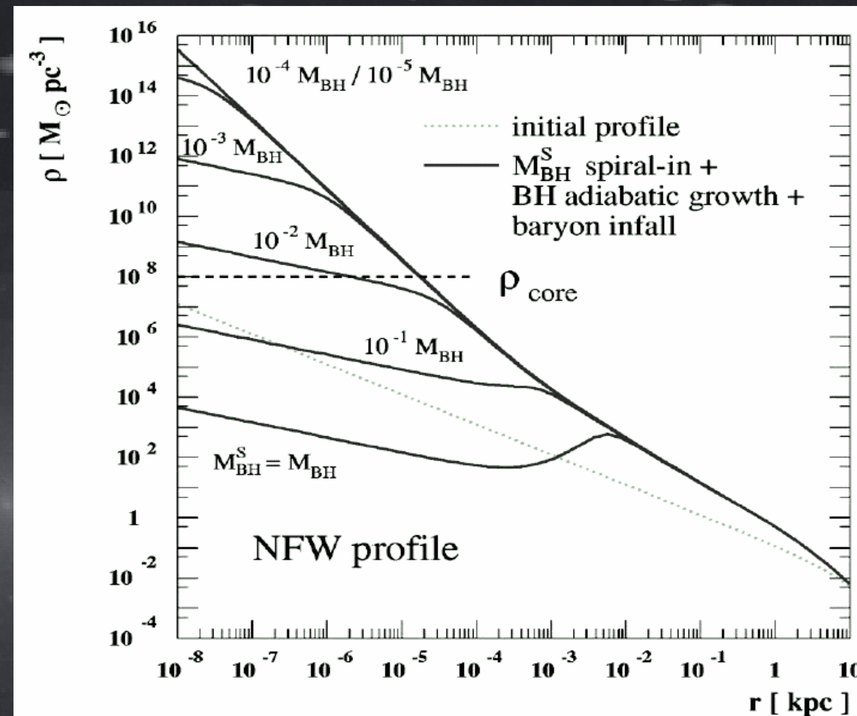


Fig. 6.— LSB rotation curves from the datasets of de Blok et al. (2001b) (B01), de Blok and Bosma (2002) (B02) and Swaters et al. (2003) (S03). Solid curves show best fits using the Courteau (1997) fitting formula given by eq. 7. Best fits with $\gamma \sim 1$ correspond to rotation curves that rise and turn over gently as a function of radius. Curves with $\gamma > 2$ feature a much sharper transition from the rising to the flat part of the curve. See text for full discussion.



(Woods and Vassiliev, 2006)

- Dwarf spheroidal galaxies in the local group have ~10^7-10^9 solar masses, but very low surface brightness with high mass-light rations of 100-1000
- From rotation curves, it appears that many have a flat core (M/L~1), but a few LSB galaxies may show evidence for cusps
- Formation of a steep stellar cusp or slow growth of a BH may create a DM spike