Indirect Dark Matter Searches with the Whipple 10m Gamma Ray Telescope

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Outline

- Indirect detection of DM with VHE gamma-rays
- Annihilation Spectrum
- DM Density Profiles
- Data/Results
- Prospects for Future Work

Motivation: Indirect Detection of Supersymmetric DM

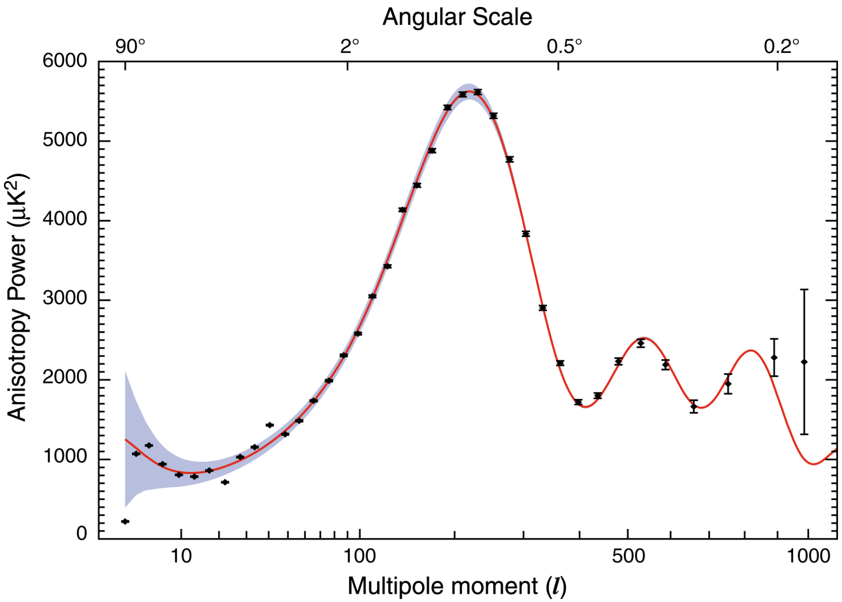
- A weakly-interacting massive particle (WIMP) can reproduce the astrophysically observed relic DM density

- SUSY provides a natural candidate for WIMPs in the form of the lightest supersymmetric particle (LSP) which is normally the neutralino

- Self-annihilation of neutralinos in high density astrophysical environments may result in a detectable flux of gamma-rays

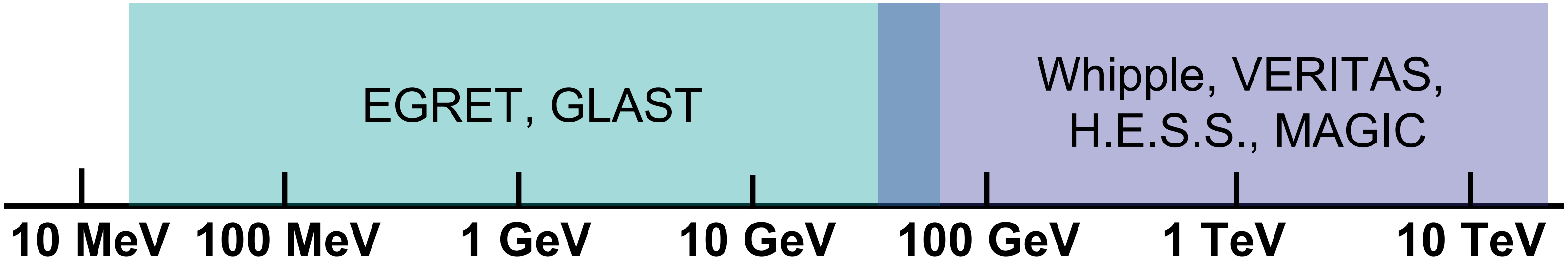
Goals of Indirect Detection

- Evidence for DM was first obtained through astrophysical observations
- Can astrophysical observations identify the nature of DM?
- Even if SUSY is discovered at the LHC, detection in an astrophysical context will be necessary to conclusively identify the LSP with DM



Indirect Detection with VHE Gamma-rays

- Pros
  - Unambiguous spectral signature
  - Potential to constrain branching ratios from spectral endpoint
  - Complementary to direct and accelerator searches
- Cons
  - Large theoretical uncertainties due to unknown DM distribution in the cores of DM halos
  - Potentially large conventional astrophysical backgrounds



EGRET, GLAST

Whipple, VERITAS, H.E.S.S., MAGIC

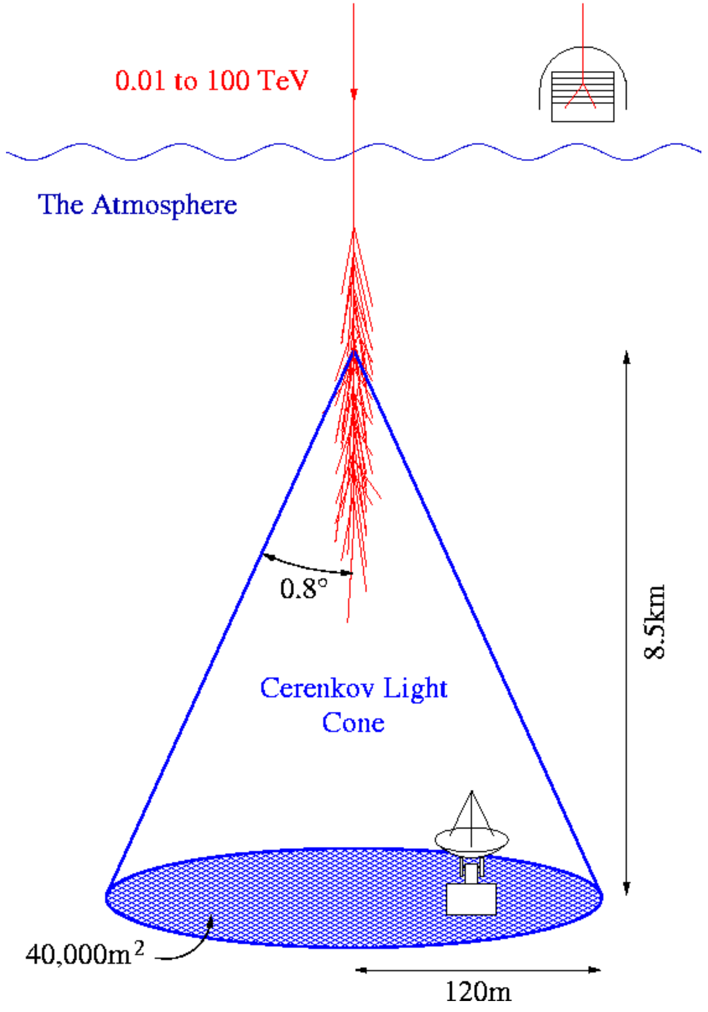
10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV 10 TeV

High Energy (HE)

Very High Energy (VHE)

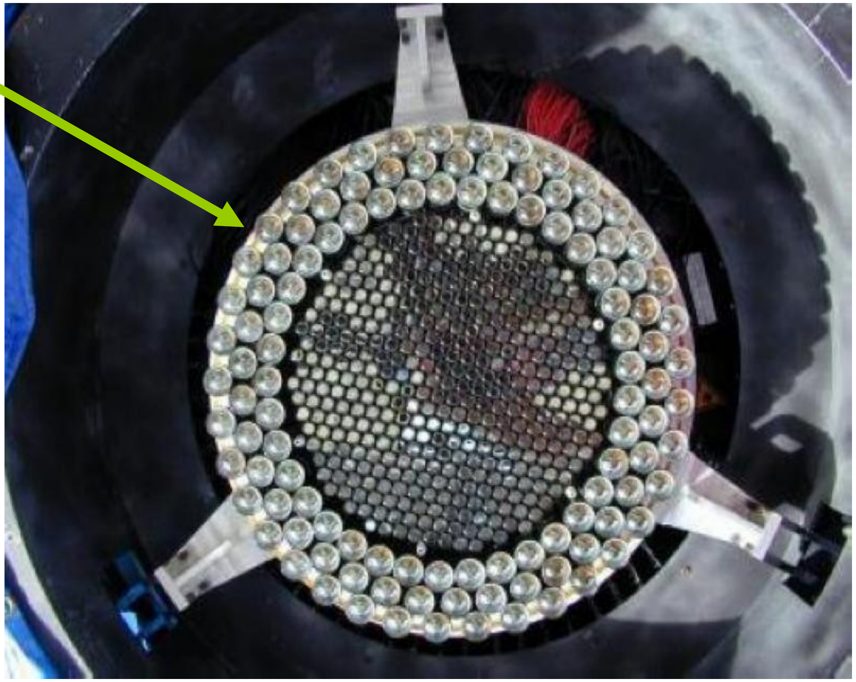
Air Cherenkov Telescopes (ACTs)

- Detect secondary Cherenkov light from EM shower initiated by gamma-ray primary
- Whipple 10m Telescope
  - First generation instrument
  - Detected the first VHE gamma-ray source (Crab Nebula) in 1989
  - Sensitivity: F ~ 3-5 % Crab @ E > 400 GeV



Whipple 10m Telescope

10m telescope

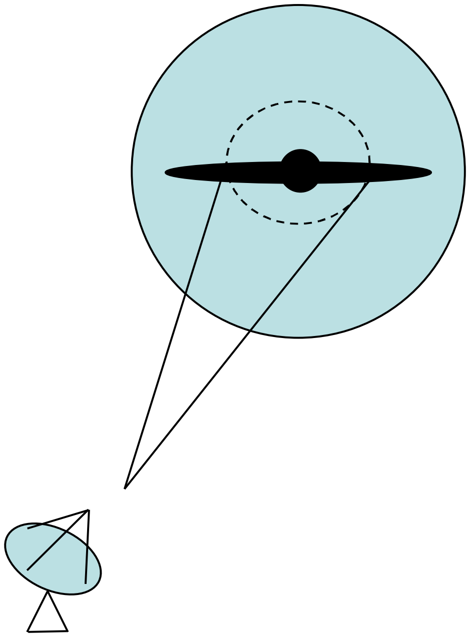


490 pixel camera

DM Annihilation Flux

Differential Flux

$$\frac{d\phi(\vec{\psi},\Delta\Omega)}{dE} = \underbrace{\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\left(\frac{dN_\gamma}{dE}\right)}_{\text{Cosmology/Particle Physics Component}} \underbrace{\left[\int_{\Delta\Omega} d\Omega \int \rho^2 ds(\vec{\psi})\right]}_{\text{Astrophysics Component}}$$



Astrophysical Enhancement Factor J

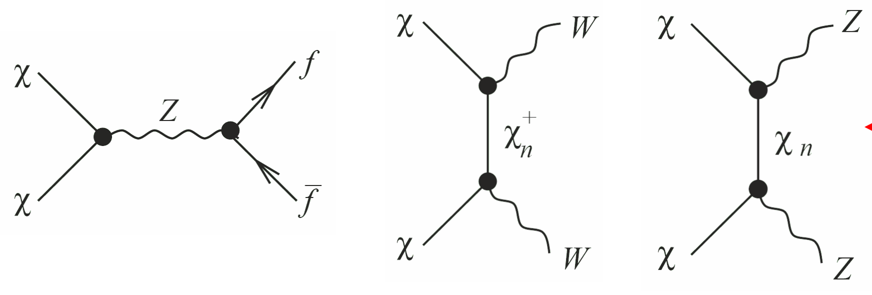
$$J(\vec{\psi},\Delta\Omega) = \left(\frac{1}{\rho_c^2 R_H}\right)\int_{\Delta\Omega} d\Omega \int \rho^2 ds(\vec{\psi})$$

$J/\Delta\Omega \sim 1$ → Cosmological Value

J $\sim 10^4$ → Detectable Flux for $<\sigma v> \sim 10^{-26}$ cm^3 s^{-1} and $m_\chi \sim 100$ GeV

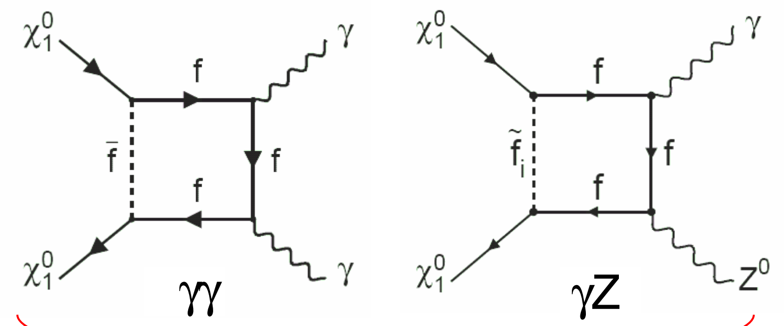
Neutralino Annihilation Channels

Annihilation to fermions and bosons (continuum component)



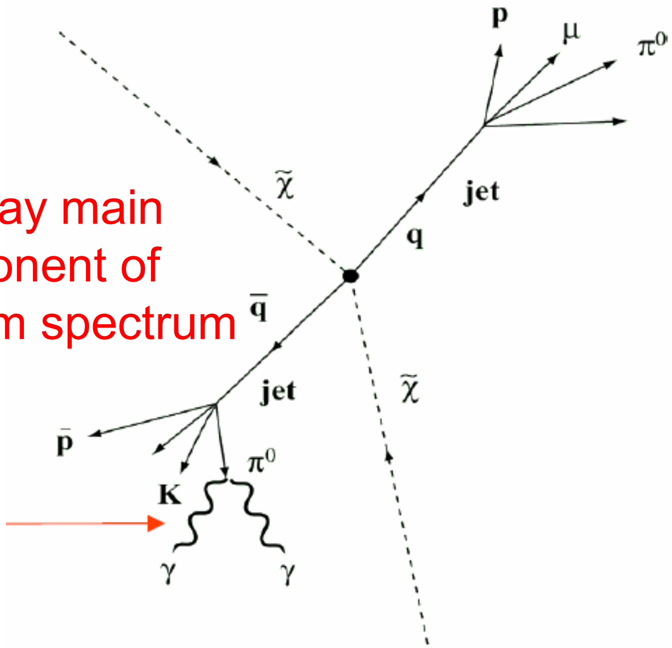
Heavy final states (bb,tt,WW,ZZ) kinematically favored

Annihilation channels with mono-energetic photons



Suppressed ($b_{\gamma\gamma}$ and $b_{\gamma Z}$ ~ 10^{-2}-10^{-3})

π^0 decay main component of continuum spectrum

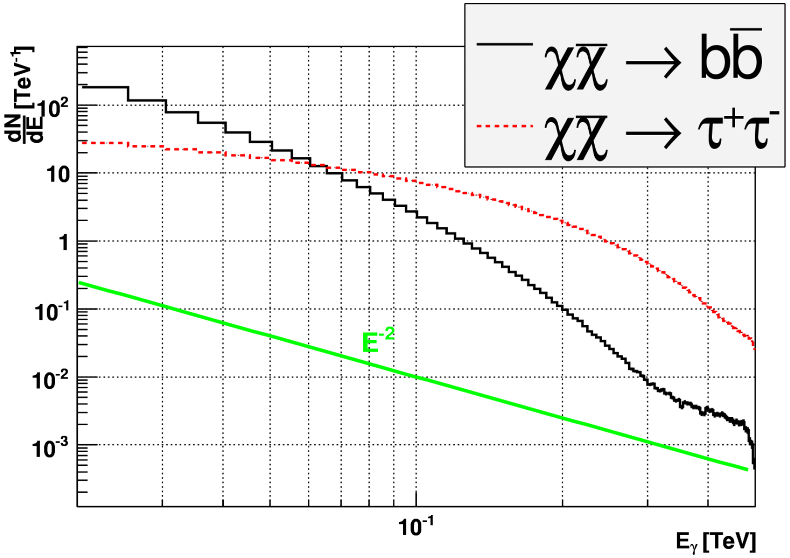


DM Annihilation Spectrum

- Distinguishable from astrophysical backgrounds
    - Not a power-law spectrum
    - Truncation and mono-energetic line at E = m_χ

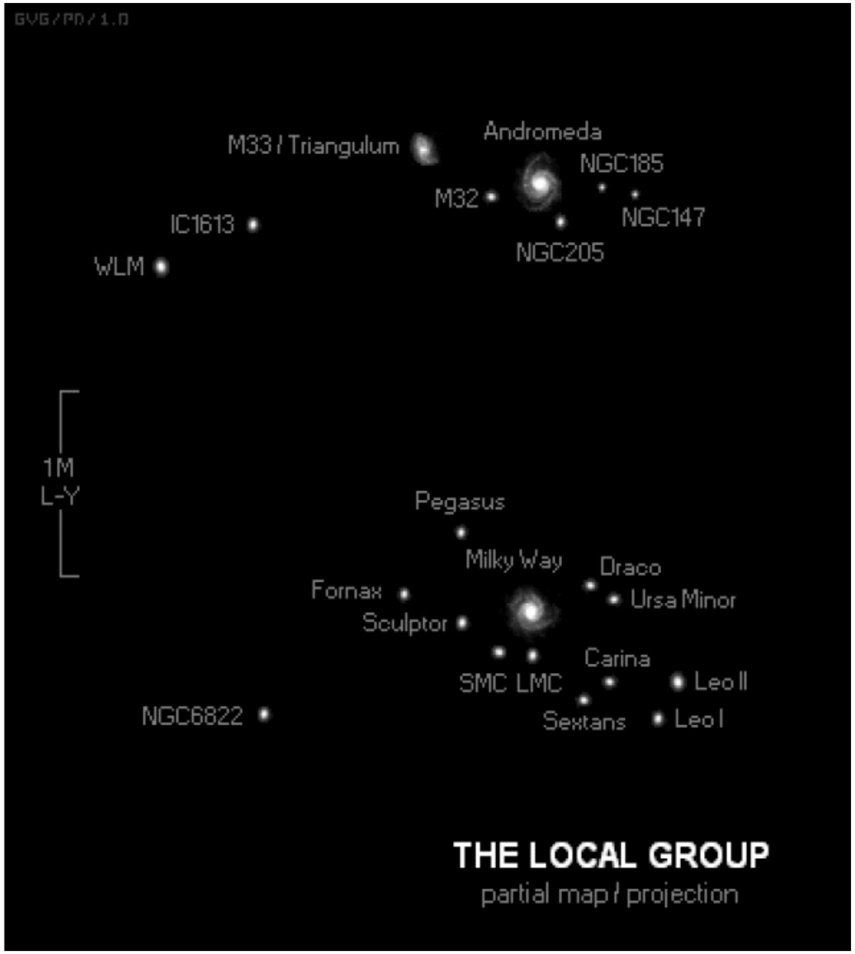
- Two scenarios investigated
    - Soft mode: $\chi\chi \rightarrow bb$
    - Hard mode: $\chi\chi \rightarrow \tau\tau$

Differential Photon Yield per Annihilation for m_χ = 500 GeV



Astrophysical Target Selection

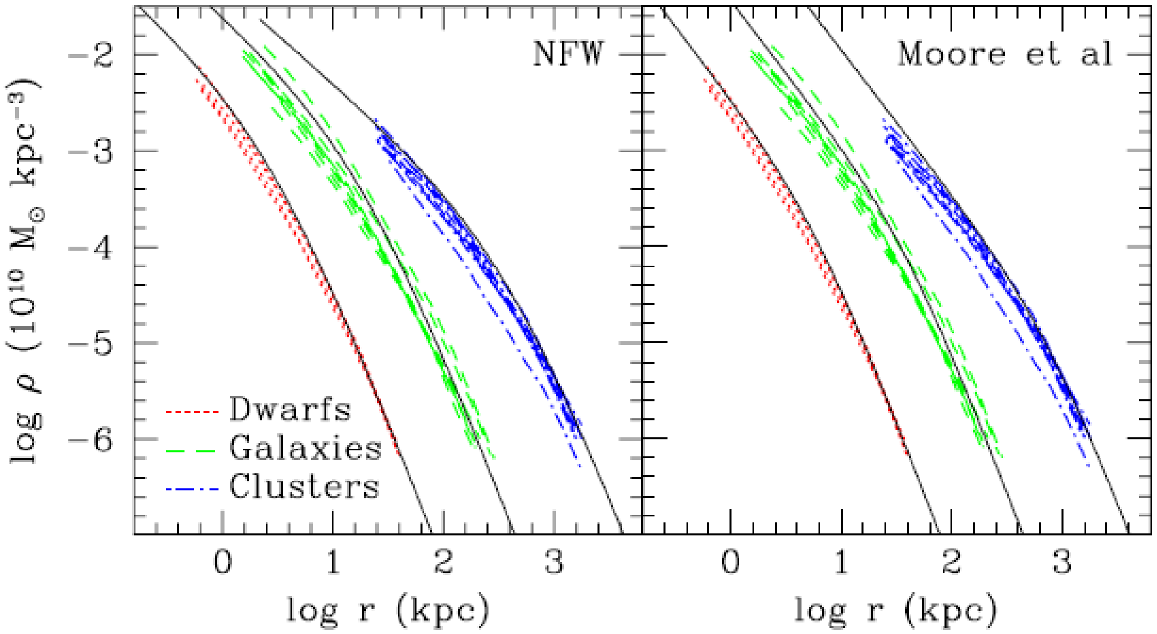
- Flux scales as $V\rho_{DM}^2/D^2$
- Criteria
  - Nearby
  - Large Density of DM
- Targets for Indirect DM Search
  - Galactic Center
  - Local Group Galaxies
  - Globular Clusters
  - Dwarf Galaxies
  - MW Satellite DM sub-structures



CDM Simulations

Universal DM density profile
for dwarf galaxies → clusters

$$\rho(r) = \rho_0 \left(\frac{r}{r_c}\right)^{-\gamma} \left(1 + \left(\frac{r}{r_c}\right)^{\alpha}\right)^{-\frac{\beta-\gamma}{\alpha}}$$



NFW Profile
(α,β,γ) = (1,3,1)

Moore Profile
(α,β,γ) = (1.5,3,1.5)

Navarro et al. 2004

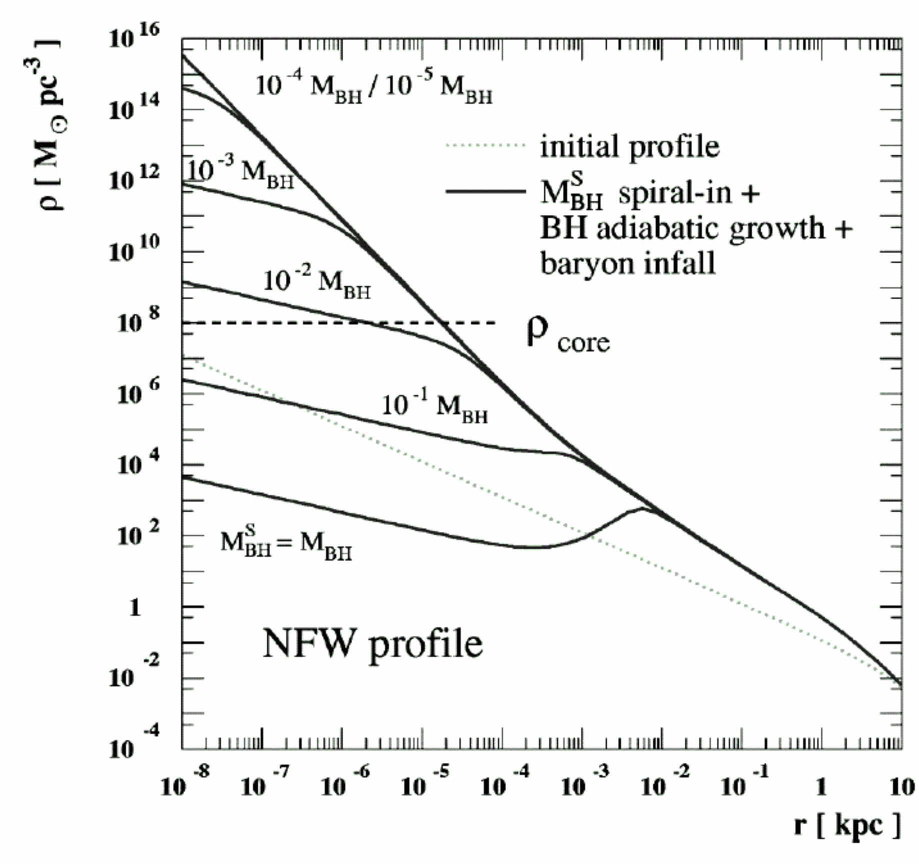
Physics on Small Scales

- Limitations of CDM simulations
  - Resolution of ~ 0.1 – 1 kpc
  - Effects of baryonic matter on small scale DM distribution is not simulated

- Additional considerations on small scales (< 10-100 pc)
  - Enhancement Factors
    - Condensation of stars/gas (e.g. core-collapse)
    - Growth of a central SMBH
  - Depletion Factors
    - Galactic merger events
    - Heat transfer to dark matter particles by stars and inspiraling SMBHs

Enhancement Factors: Adiabatic Compression

- Adiabatic compression can enhance a DM cusp (e.g. NFW) into a 'spike' with $\gamma \geq 1.5$
- Annihilation rate is divergent for $\gamma \geq 1.5 \rightarrow$ maximum density set by dynamical effects
- Adiabatic Compression Mechanisms
  - Growth of SMBH
  - Baryon infall (e.g. core collapse)

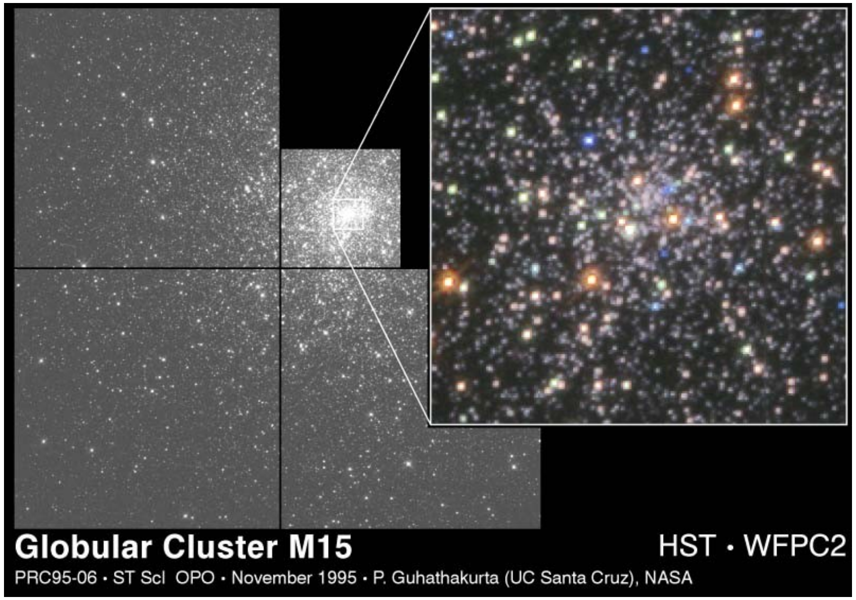


Ullio et al. 2001

Two-Body Relaxation

- In stellar environments with large ρ and small σ^2 two-body interactions can dominate if $t_r \leq 1/H_o$
- Predicted central stellar density distribution after relaxation
  - $\rho \sim r^{-1.75}$ w/ central BH (Bahcall and Wolf 1976)
  - $\rho \sim r^{-2.23}$ w/o central BH (Cohn 1980)
- However, heat transfer to DM by stars or inspiraling BH could cause DM depletion

Core-collapsed Globular Cluster M15

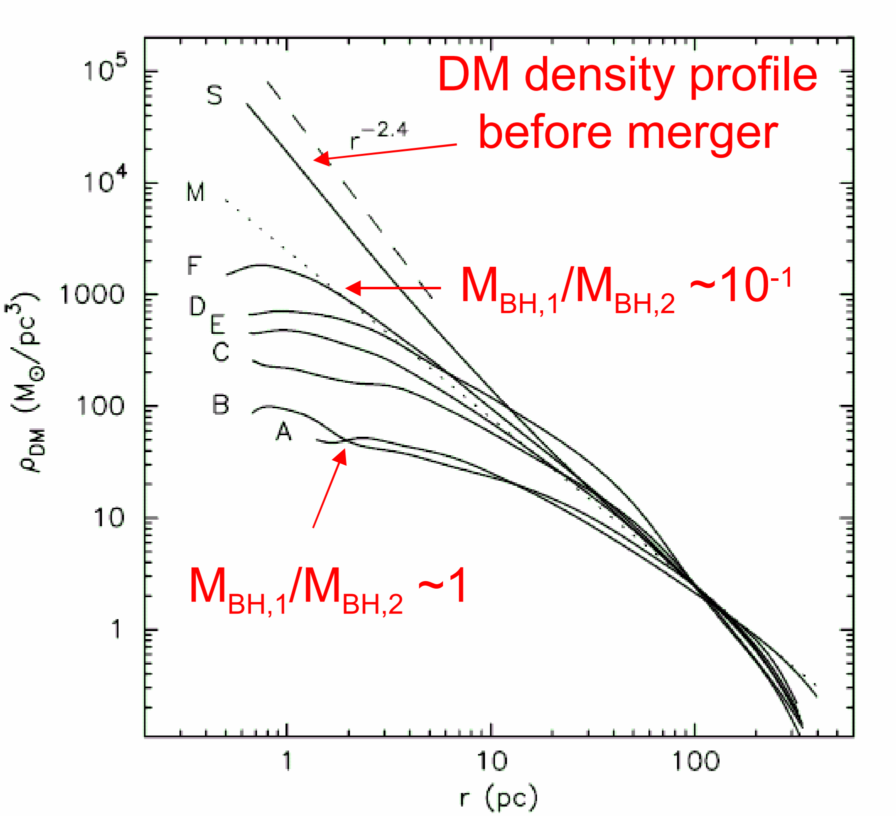


Depletion Factors: Galactic Mergers

- Hierarchical mergers
  - Disruption of central cusp for mergers of halos with SMBHs of comparable mass
  - Cusp preserved when BH mass ratio is $< 10^{-1}$

- History of DM halo is an important consideration

- Did the MW experience a recent merger event?



DM density profile before merger

$M_{BH,1}/M_{BH,2} \sim 10^{-1}$

$M_{BH,1}/M_{BH,2} \sim 1$

Merritt et al. 2002

Whipple 10m DM Sources

- Selection of Sources representing diverse astrophysical environments

Target List

Source	Distance (kpc)	Exposure (h)	Type
M32	784	6.9	Compact Elliptical
M33	840	17.0	Spiral
M15	10	3.1	Globular Cluster
Draco	80	14.3	Dwarf Galaxy
Ursa Minor	66	17.2	Dwarf Galaxy
M87	18000	40.6	Giant Elliptical

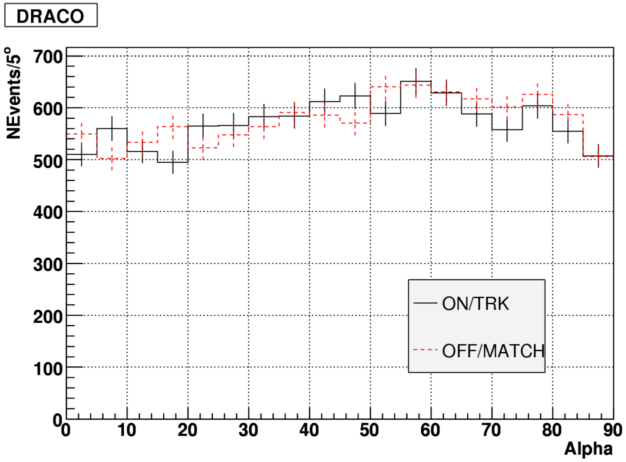
Point-source Analysis

Significances obtained with
standard point-source analysis

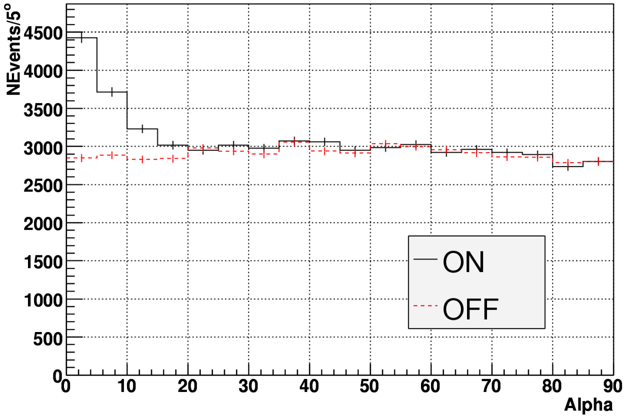
Source	σ
Draco	0.02
Ursa Minor	1.07
M32	-1.44
M33	-0.14
M87	0.28
M15	0.21

No Surprises…

14.3h Observation of Draco

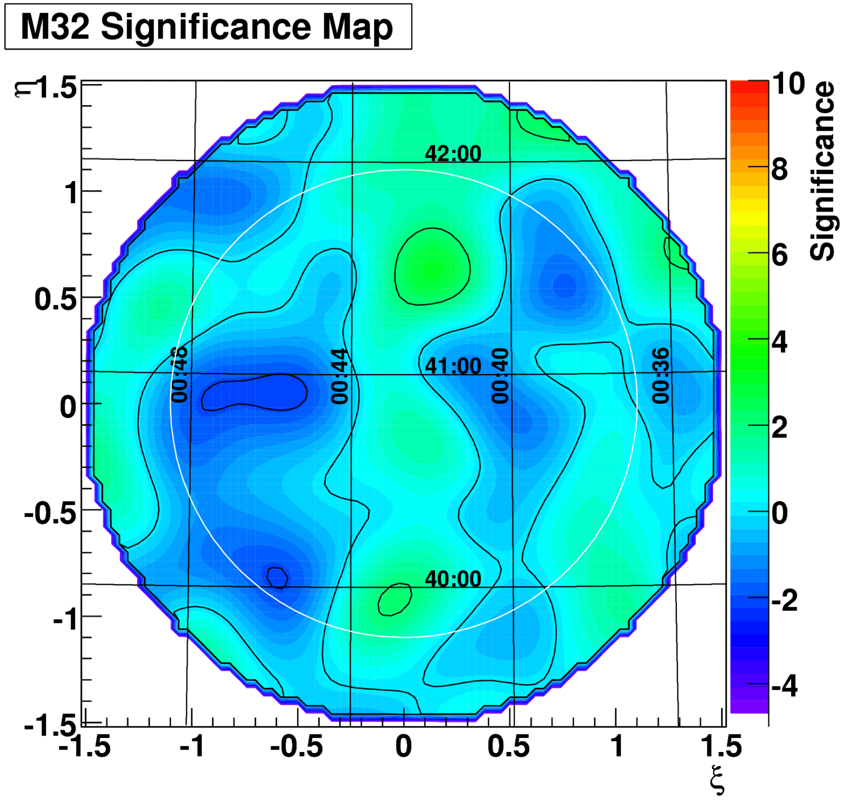


13.4h Observation of Crab Nebula



2D Analysis

- Dark Matter substructures in external regions of MW Halo
  - Predicted by CDM simulations to be isotropically distributed with M ≥ 10^{-6} M
  - Any field a potential source



5 fields explored
No surprises…

Deriving SUSY Limits

- Placing limits on the SUSY parameter space is difficult given the astrophysical uncertainties

- Approaches to deriving astrophysical enhancement factor J
  - Extrapolate direct measurement of DM distribution on large scales (~0.1-1 kpc) down to core (1-10 pc)
  - Assume that the DM distribution follows the baryonic distribution with some relative scaling λ

Estimates of J

Detectable flux threshold:
Whipple 10m → $J\sim10^6$
Current Generation ACT → $J\sim10^5$

M_{DM}/M_b

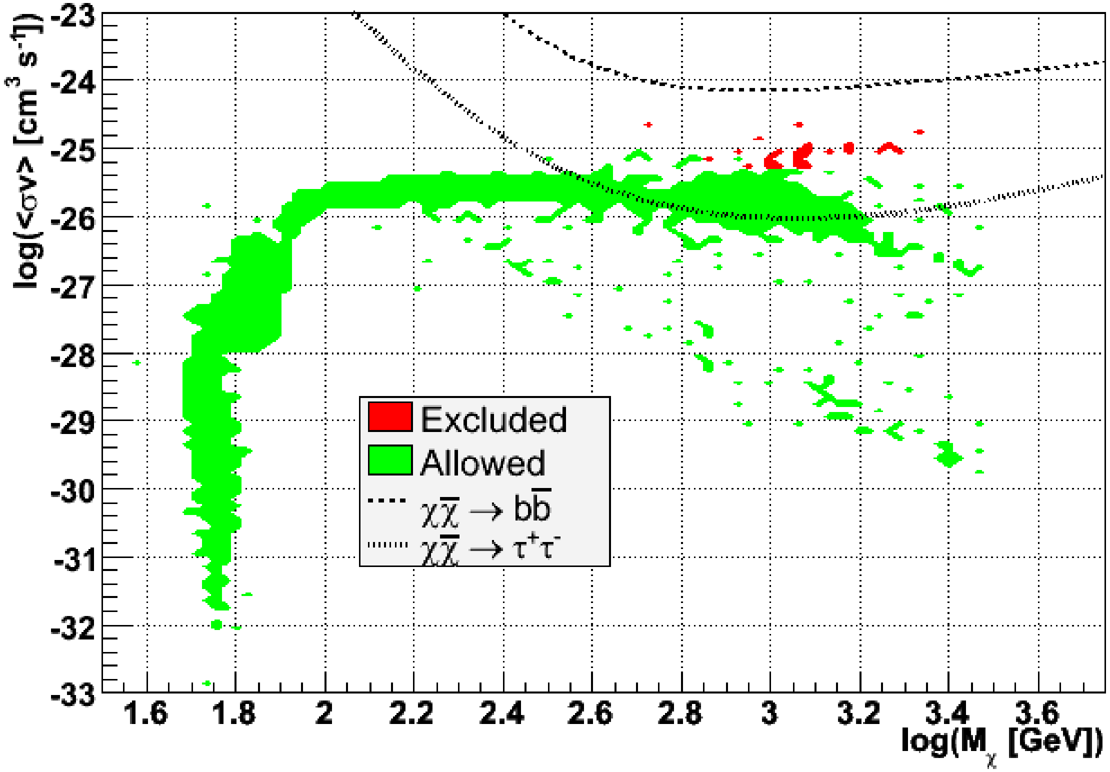
Robust Lower Limits on J from Direct DM Measurements

Extrapolations from Baryonic Matter Distribution (large uncertainty)

Source	λ	J	$\delta J/J$
Draco	---	11	0.1-1
Ursa Minor	---	19	0.1-1
M87	---	3.5	0.1-1
M32	1	1.1×10^5	$10\text{-}10^3$
M33	1	1.2×10^3	$10\text{-}10^3$
M15	10^{-2}	1.2×10^6	$10\text{-}10^3$

SUSY Limits

M15 Limits with J = 1.2 ×10^6



Range in uncertainty from J

Scan of 10^6 MSSM Models with DarkSUSY (Gondolo et al. 2004)

All models within 3σ of current WMAP Constraints on Ωh^2

Prospects and Future Work

- Future Improvements
  - Calculation of J using N-body simulations of baryons and dark matter in galactic nuclei
  - Observations with VERITAS (x10 sensitivity and E_{th} ~ 100 GeV)
- Search is complimentary to sensitivity range of GLAST
- Follow-up observations of GLAST detections
  - Fine spectroscopy
  - Search for MW halo substructures

Sensitivity Comparison of Whipple, VERITAS, and GLAST