Indirect Dark Matter Searches with VERITAS

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The VERITAS Collaboration

86 Scientists

22 Institutions in 4 countries

Support from:

U.S. DOE
U.S. NSF
Smithsonian
STFC (U.K.)
NSERC (Canada)
SFI (Ireland)

U.S.

Adler Planetarium
Argonne Natl. Lab.
Barnard College
DePauw Univ.
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Iowa State Univ.
Purdue Univ.
SAO
UCLA
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Univ. of Chicago
Univ. of Delaware
Univ. of Iowa
Univ. of Minnesota
Univ. of Utah
Washington Univ.

Canada

McGill Univ.

U.K.

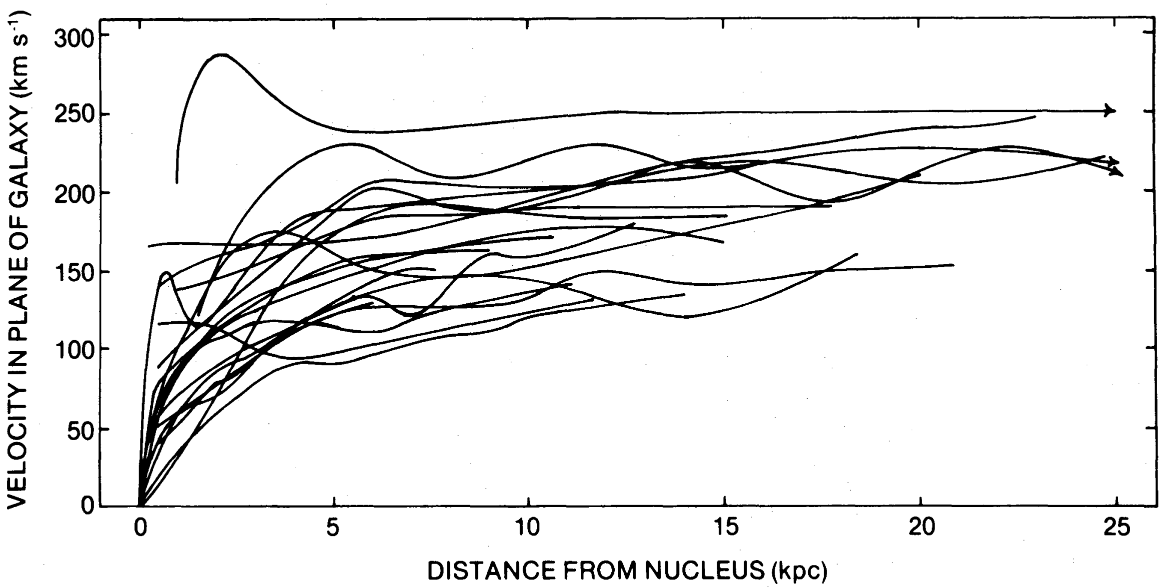
Leeds Univ.

Ireland

Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
Univ. College Dublin

+35 Associate Members including theorists, MWL partners, IceCube, Fermi, Swift, etc.

Evidence for Dark Matter



Rubin, Ford, & Thonnard, ApJ **238**, 471 (1980)

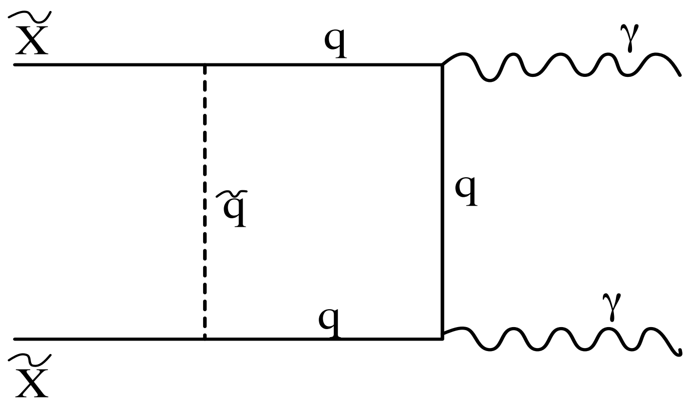
X-ray: Markevitch *et al.* Optical: Clowe *et al.* Lensing Map: Clowe *et al.*

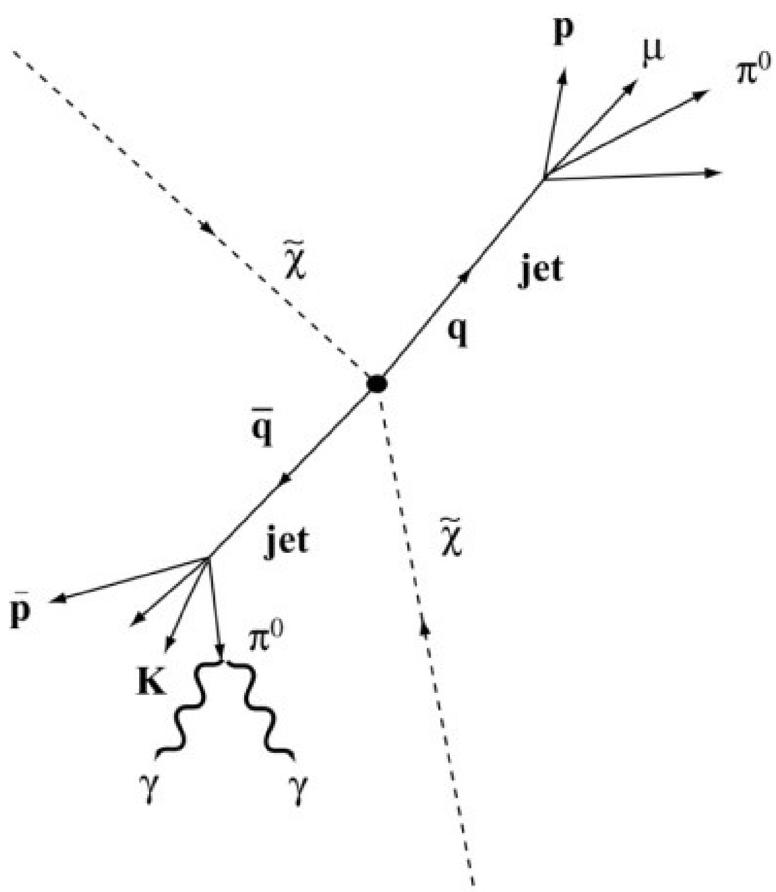
Existence of non-baryonic dark matter established through variety of phenomena:

- Galaxy Rotation Measurements
- Velocity dispersions of stars in galaxies and galaxies in clusters
- CMB multipole + SNIa + BAO fits
- Big bang nucleosynthesis
- Gravitational lensing

Existence of dark matter solely inferred from gravitational influence

WIMP Dark Matter & γ-Ray Production





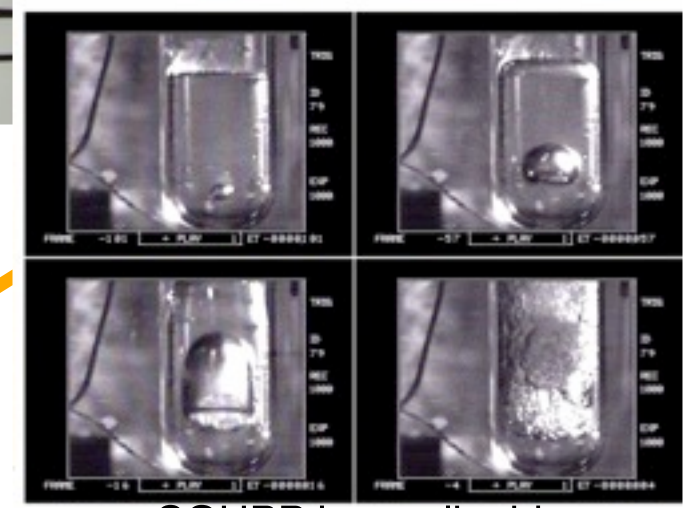
- Thermal relic of early universe with weak scale cross section & mass produces present DM density (Lee & Weinberg, 1977)
  $\Omega_{DM}h^2 = 0.113$ (WMAP+BAO+SNIa)
  $\Rightarrow \Omega_{DM} \approx 23\%$
- $\sim 50\ \mathrm{GeV}/c^2 < M_{WIMP} < \sim 10\ \mathrm{TeV}/c^2$
- WIMP annihilation producing γ-rays:
  - γ-ray line from direct annihilation (higher order process)
  - γ-ray continuum from hadronization
  - enhanced near M_{WIMP} from internal brem

The Dark Matter Search Triangle

Laboratory production of neutralinos Tevatron Collider, LHC

Required to demonstrate that terrestrial WIMPs we create or detect and astrophysical DM particles inferred via indirect detection are the same.

Direct WIMP detection in specialty (underground) detectors



COUPP heavy liquid bubble chamber

Three complementary approaches

Indirect detection of gamma-rays/ electrons/positrons from DM self-annhilation

Particle Physics — Astrophysics

$$\frac{d\phi(E,\vec{\psi},\Delta\Omega)}{dE} = \left[\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN(E,m_\chi)}{dE}\right] J(\vec{\psi},\Delta\Omega)$$

Line of Sight Integral over Source Region

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

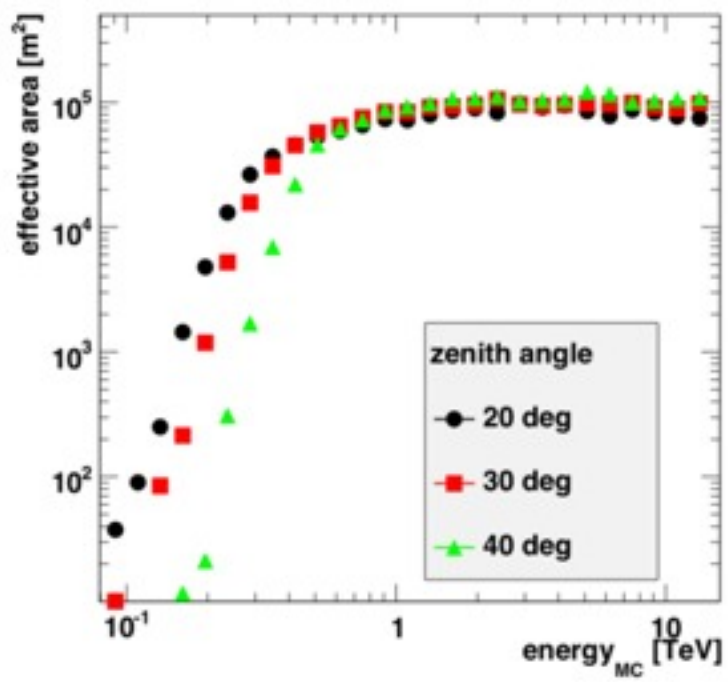
VERITAS Performance

Canonical Performance Values:

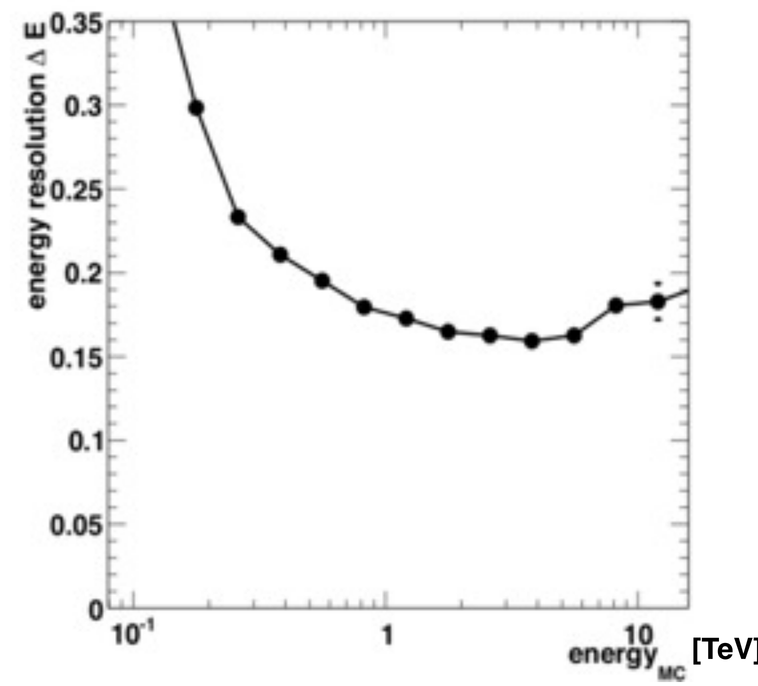
- Energy Range: 100 GeV – 30 TeV
- Energy Resolution: 15% – 25%

- Crab Rate ~ 50/min (trigger)
- Sensitivity: 5% Crab in < 2h
  1% Crab in < 30h

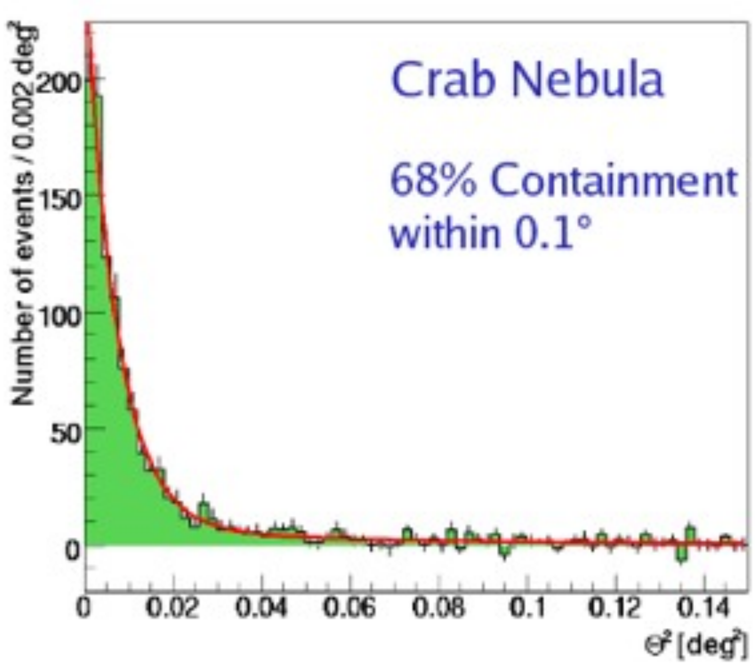
- Angular Resolution: r68 < 0.1°
- Pointing Accuracy: 50"

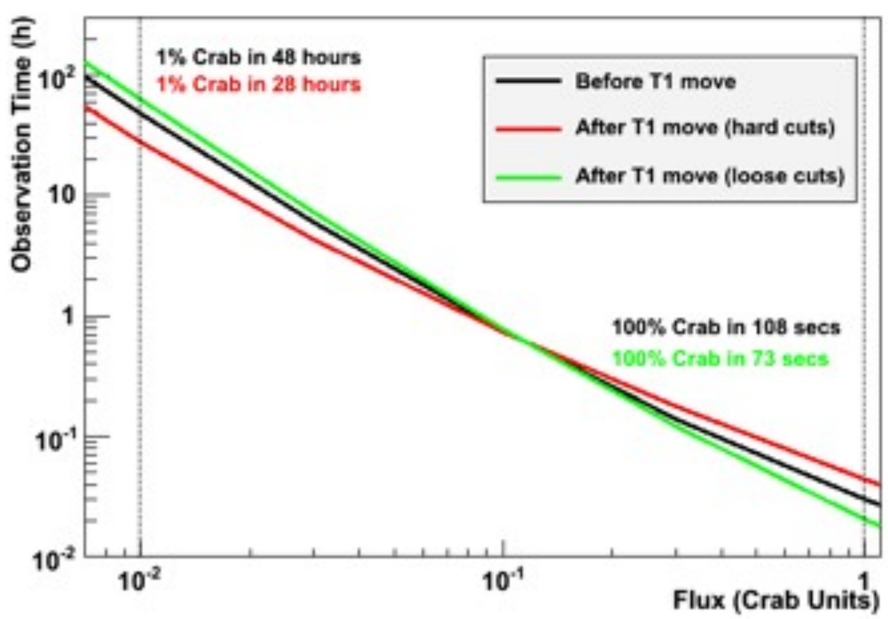


Effective Area (std. cuts)



Energy Resolution





2009/2010 Season:

- **1138 hours observed**
  - **99.8% ≥3 telescopes**
  - **~150 hrs "moonlight" observations**
- **105 "fields" observed**

Significant improvement in sensitivity due to:
1) Relocation of T1 (summer, 2009)
2) Better alignment

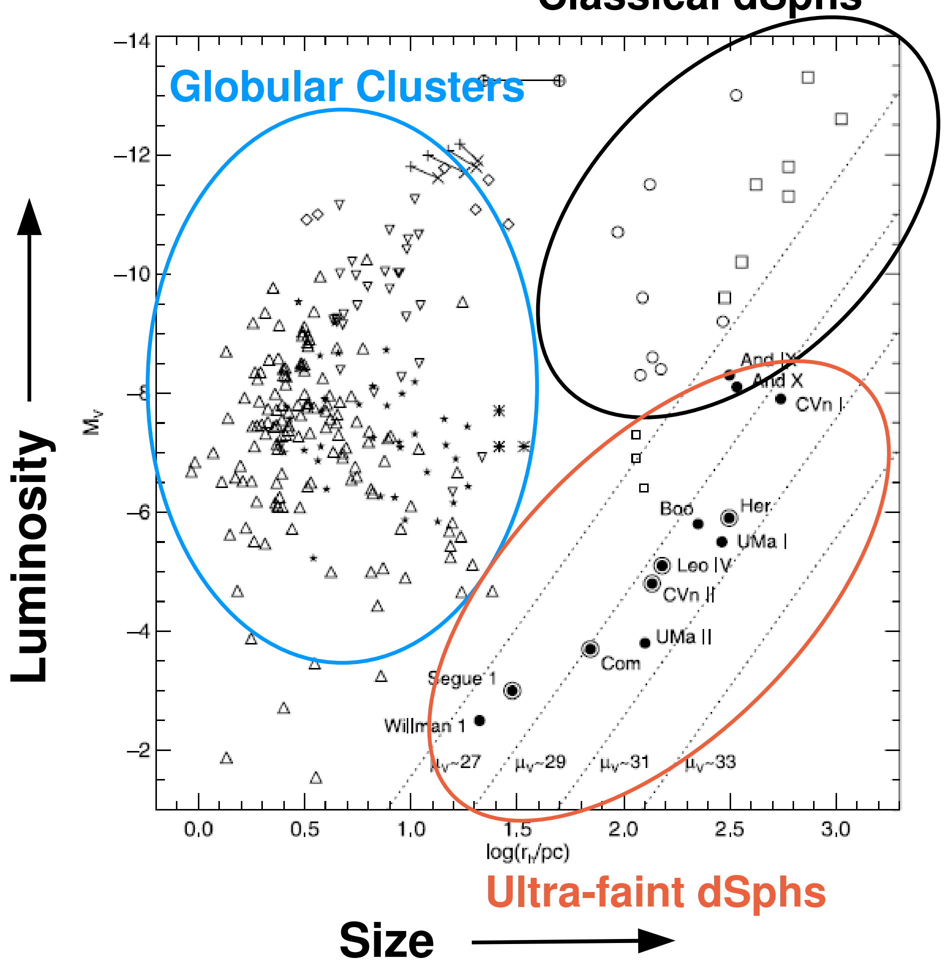
Crab detected in ~70 s (~90 hrs in 1989 !)

VERITAS Dark Matter Search Program

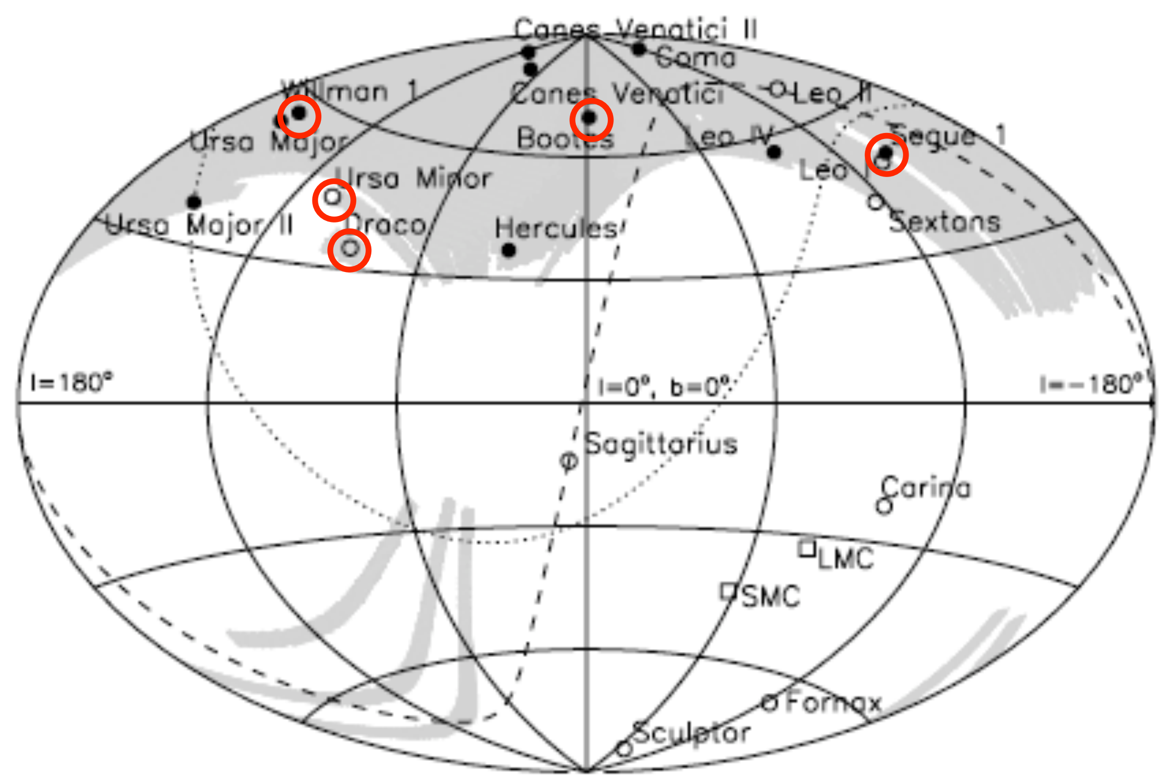
- Concentrate on WIMP scenario: SUSY or Kaluza-Klein particle with mass in GeV-TeV range
- Assume pair annihilation giving rise to flux of gamma-rays with cutoff at WIMP mass
- Uncertainty of mechanism, WIMP mass, cross section, astrophysical flux motivates survey of variety of targets:
  - *Local large galaxies: M32, M33*
  - *Globular clusters: M5, M15*
  - *Galaxy Clusters: Coma*
  - This talk → *Dwarf Spheroidal Galaxies (dSph): Ursa Minor, Draco, Willman 1, Boötes 1, SEGUE 1*

Motivation for dSph Observation

- Dark Matter dominated (stellar kinematics) M/L ~ 200-1000
- Absence of known VHE backgrounds (no recent star formation)
- Proximity: 10s of kiloparsecs
- Recent discovery of many dSphs by SDSS; likely more discoveries in future
- Possible substructure boosting flux



Belokurov et al. (2007)



Belokurov et al. (2007)

Disadvantages:

- Small expected flux for standard flux modeling (smooth NFW, no boost, no velocity-dependent σ)
- Tidal disruption common; complicates estimation of DM content and astrophysical flux calculations
- Sometimes ambiguous morphology: dSph vs Globular Cluster

dSph Observation and Analysis

- All data acquired in “Wobble” mode with camera center offset 0.5° from source Provides simultaneous background estimation using reflected regions bkgd estimation
- γ-ray event selection performed with cuts on both second moment analysis (Hillas parameters) & 3-d stereo reconstruction (mean scaled length/width, angular separation of γ candidate from dSph location)

dSph	Period	Exposure (hrs)	Zenith Angle(°)
Ursa Minor	2007 Feb-May	18.9	35-46
Draco	2007 Apr-May	18.4	26-51
Willman 1	2007 Dec-2008 Feb	13.7	19-28
Boötes 1	2009 Apr-May	14.3	17-29
SEGUE 1	2009 Dec-2010 Mar	27.6	16-32

Dwarf Galaxy Flux Limits

- Significance calculated using Li & Ma method (ApJ 272, 317 eqn. 17)
- 95% CL upper limits using Rolke, Lopez, & Conrad (arXiv:0403059v4) bounded profile likelihood method

SEGUE 1 Results
PRELIMINARY

No Significant Excess from any dSph

Quantity/dSph	Ursa Minor	Draco	Willman 1	Boötes 1	SEGUE 1
Excess (counts)	−30.4	−28.4	−1.45	28.5	−17.5
Significance (σ)	−1.77	−1.51	−0.08	1.35	−1.1
95% CL upper limit (counts)	15.6	18.8	36.7	72.0	13.4
Energy threshold (GeV)	380	340	320	300	300
95% CL flux upper limit ($cm^{-2}s^{-1}$)	0.40×10^{-12}	0.49×10^{-12}	1.17×10^{-12}	2.19×10^{-12}	0.28×10^{-12}

Similar limits for MAGIC on Draco & Willman 1
Improvement of ×40 for Whipple 10m on Ursa Minor & Draco

Neutralino Mass Limits -- Astrophysical Flux (J)

- $\langle\sigma v\rangle$ vs M_χ based on Navarro, Frenk, White (NFW) mass models
  NFW ref: ApJ **490**, 493 (1997)

- Astrophysical flux, J, based on scale density & radius, ρ_s, r_s:
  Ursa Minor, Draco --- Strigari *et al.* (2008)
  Willman 1 --- Bringmann *et al.* (2009)
  SEGUE 1 --- Martinez *et al.* (2009) Einasto profile
  Boötes 1 --- Elongation gives rise to large uncertainty in ρ_s, r_s
  Modeled by Martinez & Bullock (private comm.). J is peak of probability distribution function from model

Particle Physics | Astrophysics

$$\frac{d\phi(E,\vec{\psi},\Delta\Omega)}{dE} = \left[\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN(E,m_\chi)}{dE}\right] J(\vec{\psi},\Delta\Omega)$$

Line of Sight Integral over Source Region

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

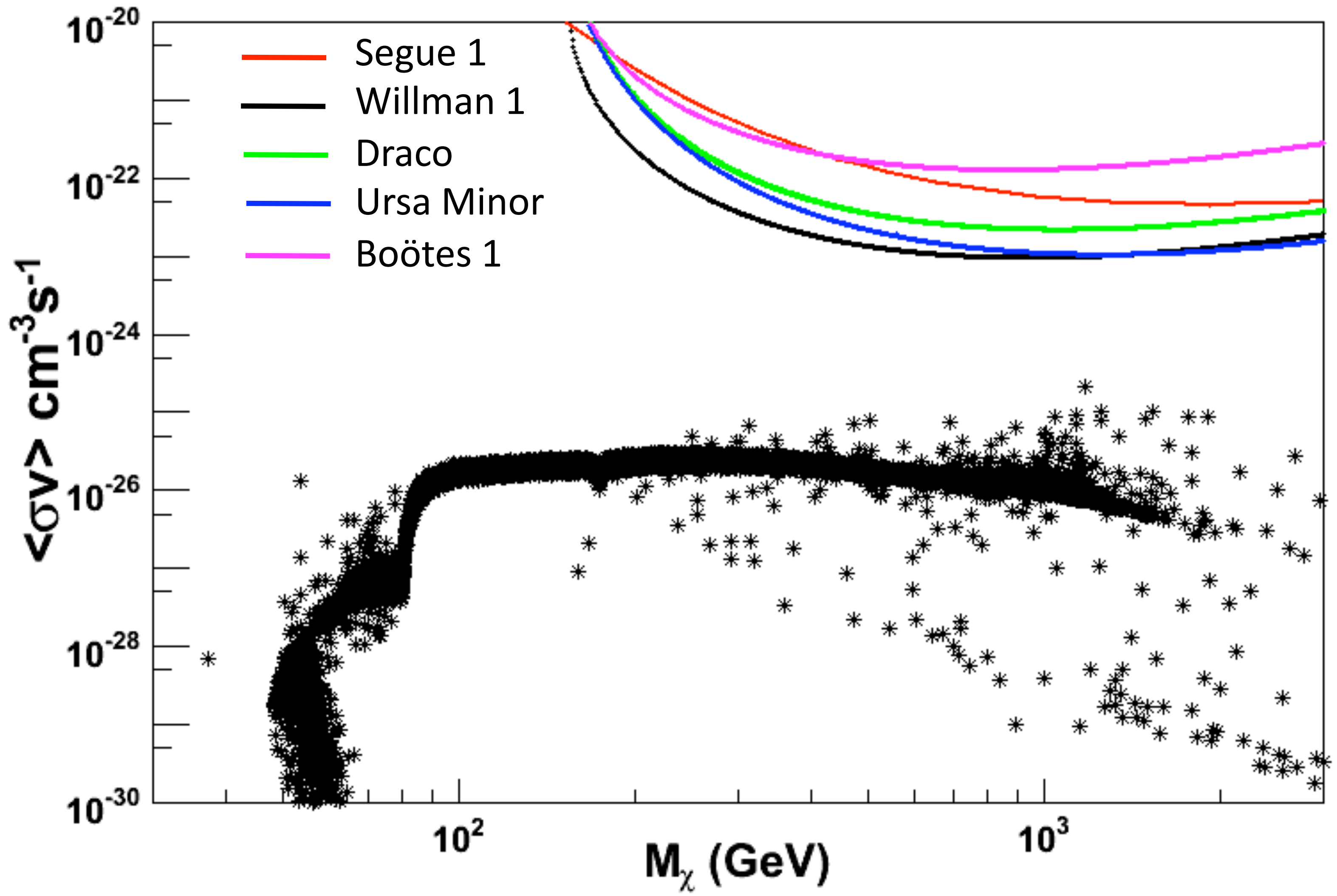
$$\rho(r) = \rho_s\left(\frac{r}{r_s}\right)^{-1}\left(1+\frac{r}{r_s}\right)^{-2}$$

Quantity/dSph	Ursa Minor	Draco	Willman 1	Boötes 1	SEGUE 1
Distance (kpc)	66	80	38	62	23
ρ_s ($M_\odot$/kpc^3)	4.5×10^7	4.5×10^7	4×10^8	---	1×10^8
r_s (kpc)	0.79	0.79	0.18	---	0.07
J ($\rho_c^2 R_H$)	7	4	22	3	3
J (GeV^2 cm^{-5})	2.68×10^{18}	1.53×10^{18}	8.43×10^{18}	1.15×10^{18}	1.15×10^{18}

nb: J in units of $\rho_c^2 \times R_H = 3.83 \times 10^{17}$ GeV^2 cm^{-5}

Neutralino Mass Limits --- <σv> vs M_χ

$$\frac{R_\gamma(95\%\ \mathrm{C.L.})}{\mathrm{hr}^{-1}} > \frac{J}{1.09\times10^4}\left(\frac{\langle\sigma v\rangle}{3\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times\int_0^\infty \frac{A(E)}{5\times10^8\mathrm{cm}^2}\left(\frac{300\ \mathrm{GeV/c}^2}{m_\chi}\right)^2\frac{EdN/dE(E,m_\chi)}{10^{-2}}\frac{dE}{E}$$



- MSSM models from DarkSUSY within ±3 standard deviations of WMAP measured relic density
- 95% CL upper limits from Reflected Region Background Model analysis and Rolke zero-bounded profile likelihood
- Boost factor from substructure, internal bremsstrahlung could give ×10-100 smaller <σv>

SEGUE 1 Results PRELIMINARY!

Older Large Galaxy and Globular Cluster Limits

95% C.L. Upper Limits based on Reflected Region Background Model Analysis

Quantity	M5*	M32	M33
Exposure (s)	5.40×10^4	4.07×10^4	4.25×10^4
Signal Region (events)	25	262	147
Total Background (events)	251	2156	992
Number Background Regions	9	7	7
Significance	-0.3	0.59	0.41
95% C.L. Upper Limit (counts)**	9.2	12.9	31.8
Rate Limit (photons s^{-1})	**1.7×10^{-4}**	**3.2×10^{-4}**	**7.4×10^{-4}**

*M5 Energy threshold = 600 GeV

**Rolke bounded profile likelihood method

Summary

- VERITAS Indirect Dark Matter Search program has observed variety of targets: local large galaxies, globular clusters, dwarf spheroidal galaxies
- Emphasis on dSphs
  - Close proximity typically with M/L > 100(1000?)
  - 5 observed with exposures of 14-27 hours
  - No significant signal detected from any of the observations
  - Limits on $\langle\sigma v\rangle \sim< 10^{-23}$ cm^3 s^{-1} set
    MSSM expectations 2+ orders of magnitude lower
  - Limits assume smooth NFW profile; substructure may boost by ×10-100
- Results from Ursa Minor, Draco, Willman 1, Boötes 1 reported in arXiv:1006.5955 (accepted for publication in ApJ)

- VERITAS Dark Matter Search is an ongoing program that will continue to emphasize dwarf spheroidal galaxy observations
- We are alert for possible targets of opportunity from Fermi GST
- VERITAS upgrade for trigger & PMTs will provide better discrimination for γ vs hadron and lower energy threshold
- Future large arrays such as CTA expected to significantly constrain neutralino limits and offer opportunity for a possible signal

Backup Slides

VERITAS Upgrade Plan (2010-2012)

- We plan to replace the PMT cameras and L2 trigger system to significant improve the sensitivity and energy threshold.

CAMERA Upgrade

PMT replacement with high efficiency PMTs.

Increase photon collection by ~35%.

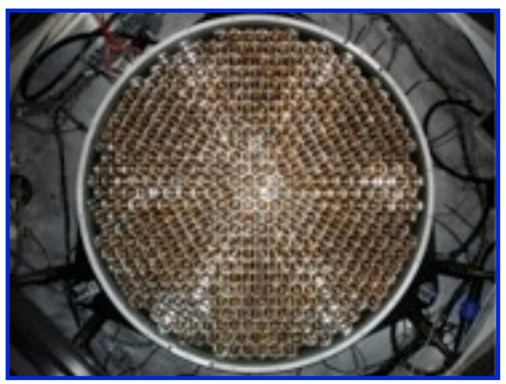
Improves background rejection, E_{th}, sensitivity.

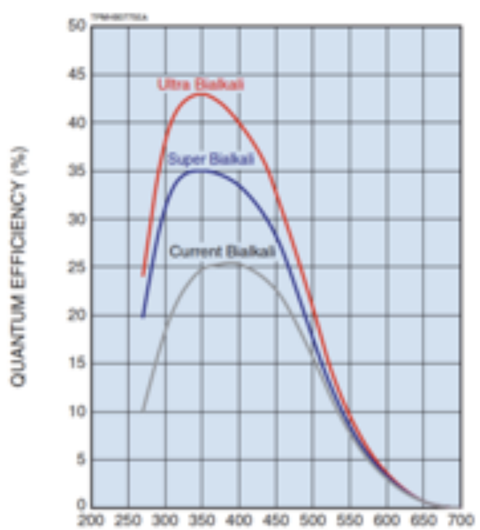
TRIGGER Upgrade

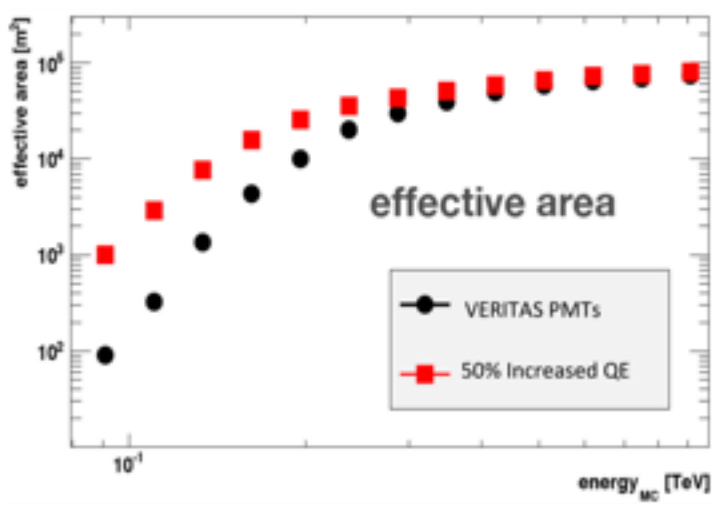
Smaller coincidence window

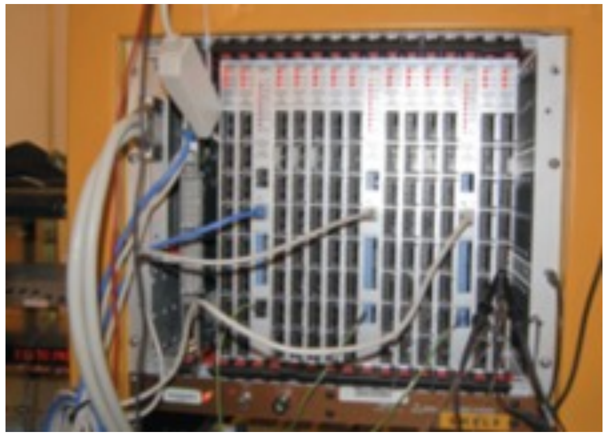
Topological Trigger

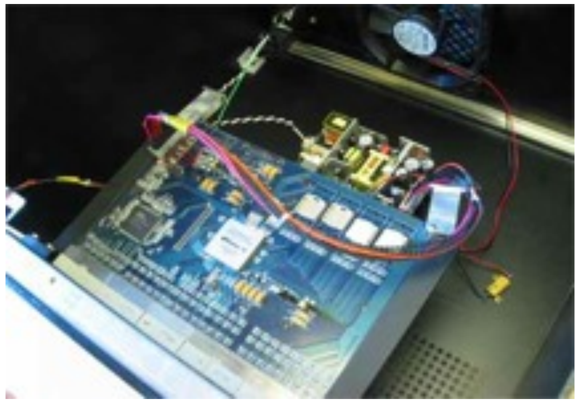
Improves E_{th} and CR event rejection.











Prototype Trigger Systems

Upgrade funded, will be completed by Summer 2012.