Observations of Dwarf Galaxies With VERITAS

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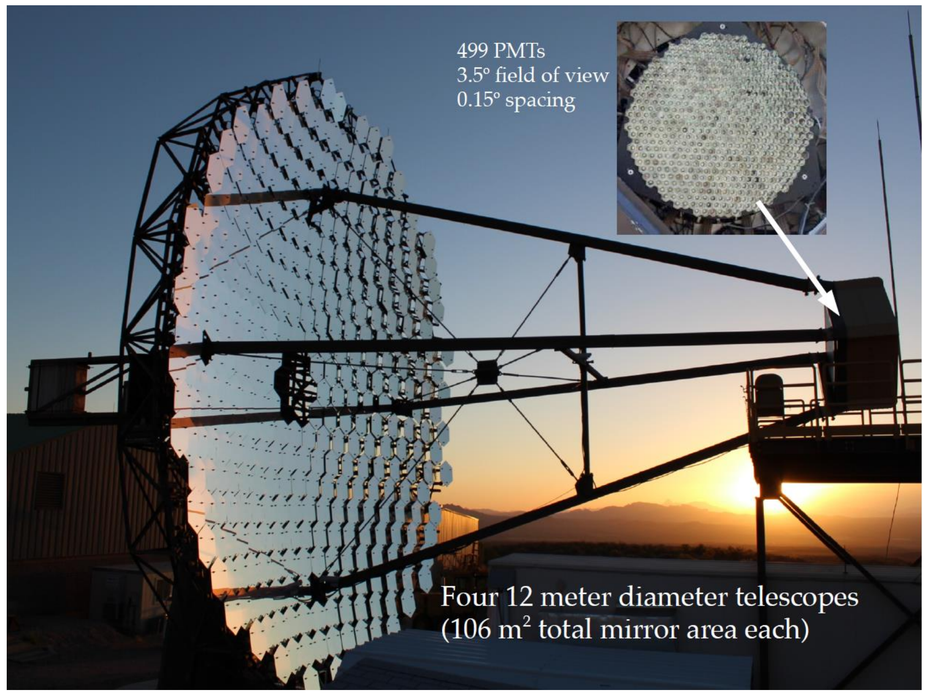
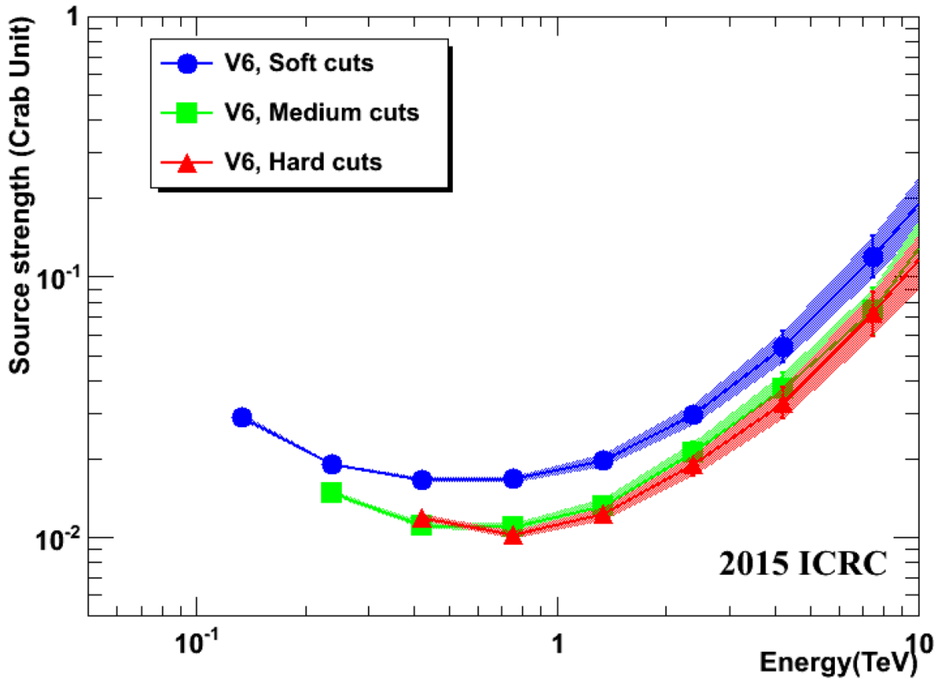
Introduction to VERITAS

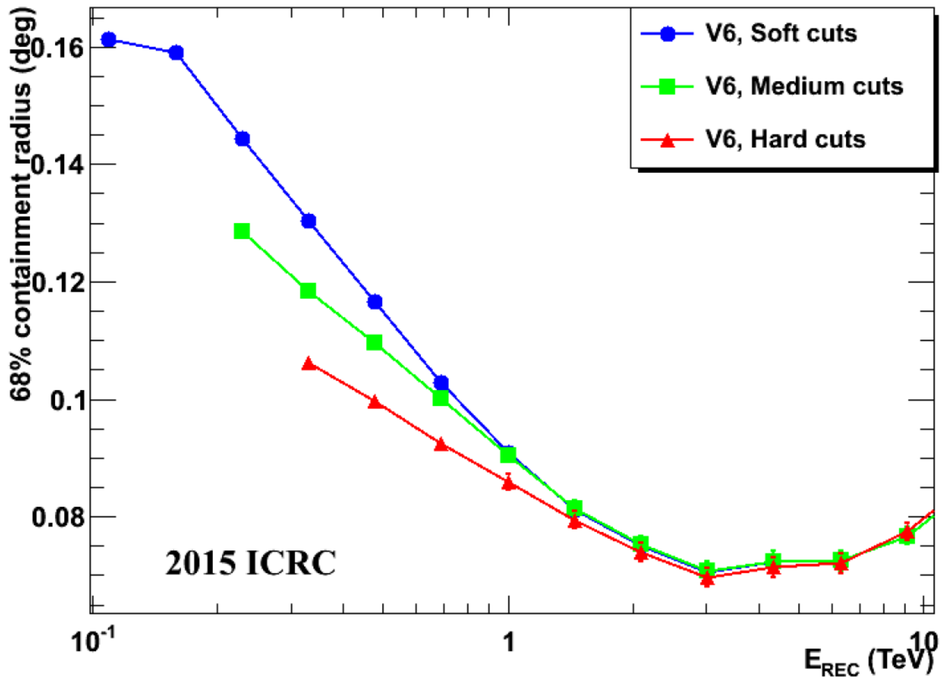


- Array of four IACTs in Southern AZ, USA
- Employs ~100 Scientists in five countries
- Full Array Operations in Fall 2007
- Upgrades:
  - Move of T1 in Summer 2009
  - Level-2 Trigger upgrade in Fall 2011
  - Camera Upgrade with High-QE PMTs in Summer 2012

- Support From:
  - NSF (USA)
  - DOE (USA)
  - Smithsonian Institution
  - NSERC (Canada)

VERITAS Performance

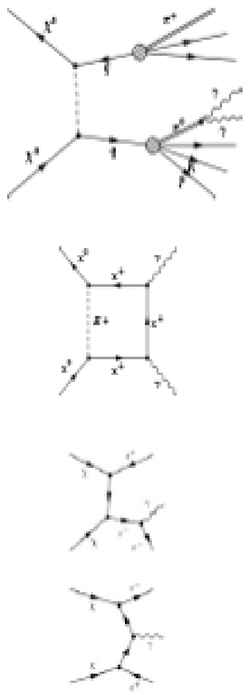




- V6: Mid – 2012 to Present
- Energy Range: 85 GeV to > 30 TeV
- Energy Resolution: 15-25%

- Sensitivity: 1% Crab in ~25 hrs
- Angular Resolution: <0.1 at 1 TeV (68%)
- Pointing Accuracy: Error < 50 arcsec

γ-rays from Dark Matter Annihilation



Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^{\pm} \to l^{\pm}\nu_l,\ W^{\pm} \to u\bar{d} \to \pi^{\pm},\ \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0Z^0$	$Z^0 \to ll,\ \nu\bar{\nu},\ q\bar{q} \to$ pions	p, e, γ, ν	
$\chi\chi \to \tau^+\tau^-$	$\tau^{\pm} \to \nu_\tau e^{\pm}\nu_e,\ \tau \to \nu_\tau W^{\pm} \to p, \bar{p},$ pions	p, e, γ, ν	
$\chi\chi \to \mu^+\mu^-$		e, γ	Rapid energy loss of μs in sun before decay results in sub-threshold νs
$\chi\chi \to \gamma\gamma$ $\chi\chi \to Z^0\gamma$	Z^0 decay	γ γ	Loop suppressed Loop suppressed
$\chi\chi \to e^+e^-$		e, γ	Helicity suppressed
$\chi\chi \to \nu\bar{\nu}$		ν	Helicity suppressed (important for non-Majorana WIMPs?)
$\chi\chi \to \phi\bar{\phi}$	$\phi \to e^+e^-$ internal/final state bremms inverse Compton γ's	$e^{\pm}$	New scalar field with $m_\chi < m_q$ to explain large electron signal and avoid overproduction of p, γ

All roads (almost) lead to gamma rays!

- Well-motivated theoretically by extensions of the SM of particle physics (SUSY, Kaluza-Klein) by a weakly -interacting massive particle (WIMP)
- WIMP annihilation production of gamma-rays
  - Gamma-ray line from direct annihilation
  - Gamma-ray continuum from hadronization
  - Enhanced near M from internal brem.
  - DM gamma-ray flux:

$$\frac{dF(E,\hat{\mathbf{n}})}{dEd\Omega} = \int d\ell\, \ell^2\, r(\ell\hat{\mathbf{n}}) \frac{dN_\gamma(E)}{dE} \frac{1}{4\pi\ell^2}$$

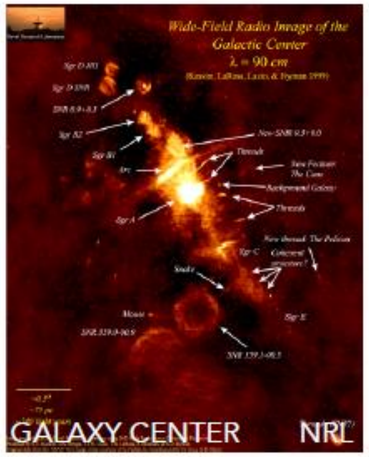
$$= \frac{\langle\sigma v\rangle}{8\pi M^2} \frac{dN_\gamma(E)}{dE} \int d\ell\, \rho^2(\ell\hat{\mathbf{n}})$$

Particle Physics

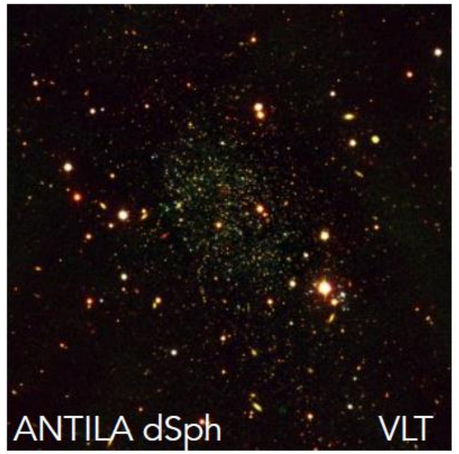
Astrophysics (J factor)

VERITAS Dark Matter Targets

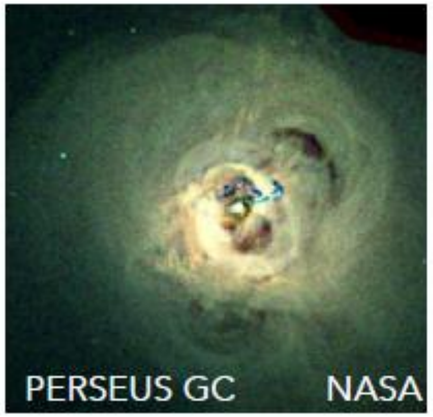
Galactic Center (GC)
- Close By
- Large DM Content
- Astrophysical Backgrounds
- Talk by A. Weinstein



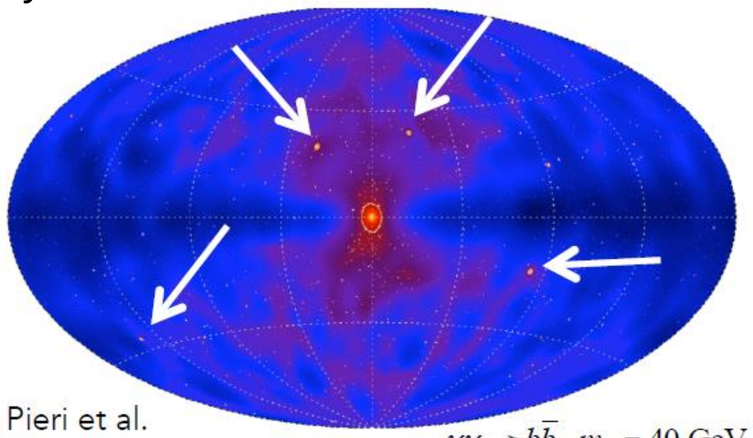
Dwarf Galaxies (DSphs)
- No Astrophysical Backgrounds
- Close By (~10's kpc)
- High M/L



Galaxy Clusters
- Distant
- Large DM Content
- Many are extended
- Astrophysical Background (?)



Fermi Unidentified Objects
- Potentially DM Subhalos?

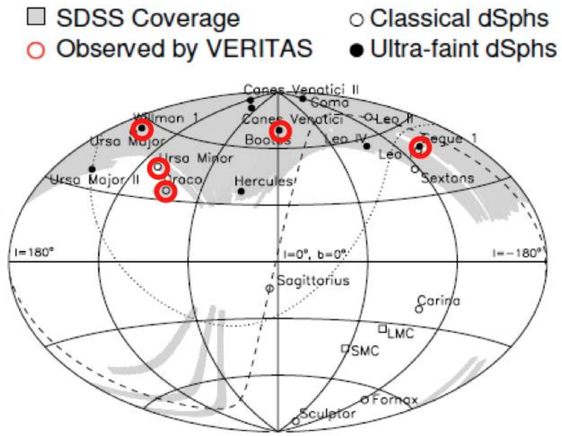


Pieri et al.
PRD 83:0235, 2008

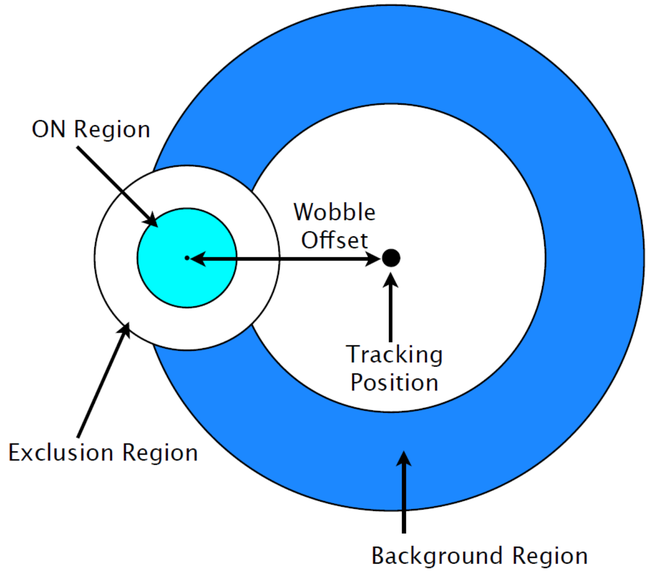
$\chi\chi \rightarrow b\bar{b},\ m_\chi = 40$ GeV

VERITAS Dwarf Galaxy Observations

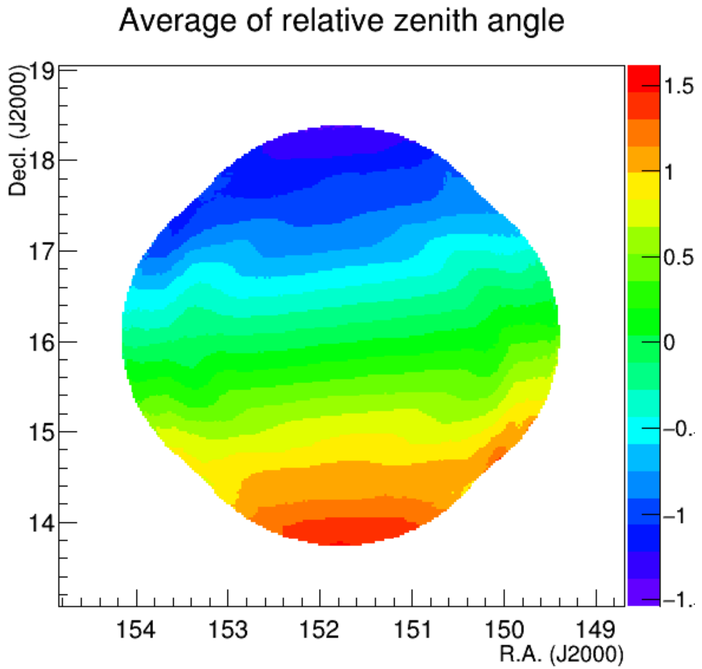
Dwarf	Live time [hrs]	$\log_{10} J$ [GeV^{2}cm^{-5}]	Significance [σ]	$F^{95\%}_{-12}$ [10^{-12}cm^{-2}s^{-1}]
Segue 1	92.0	$19.4^{+0.3}_{-0.4}$	0.7	0.34
Ursa Minor	60.4	$18.9^{+0.3}_{-0.2}$	-0.1	0.37
Draco	49.8	18.8 ± 0.1	-1.0	0.15
Boötes	14.0	18.2 ± 0.4	-1.0	0.40
Willman 1	13.7	N/A	-0.6	0.39



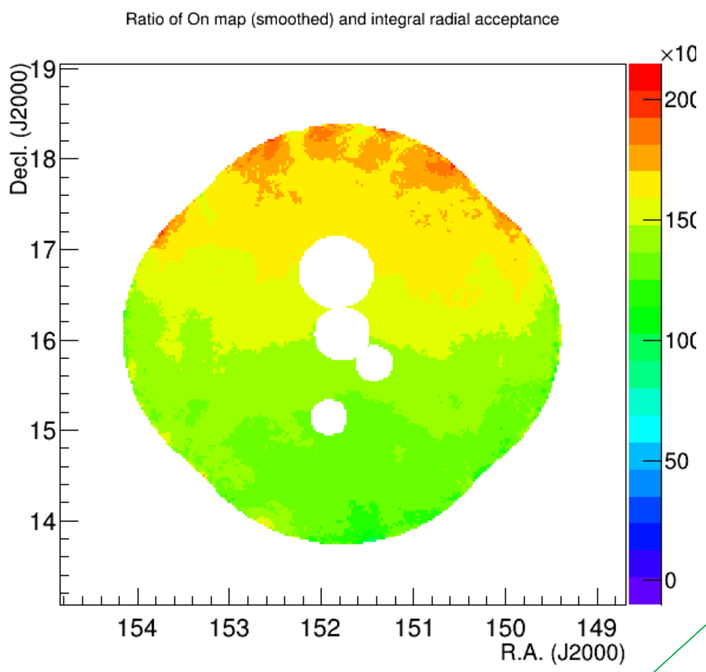
- Five dSphs observed by VERITAS between 2007 and 2013
  - Total of 230 hours
  - Deepest exposure on Segue 1: 92 hours
- Crescent-shaped region used for Bg subtraction
- No gamma-ray detection
- Flux upper limits above 300 GeV for each dSph
- J Factors from Geringer-Sameth et al. ApJ, Vol. 801, Issue 2 (2015)



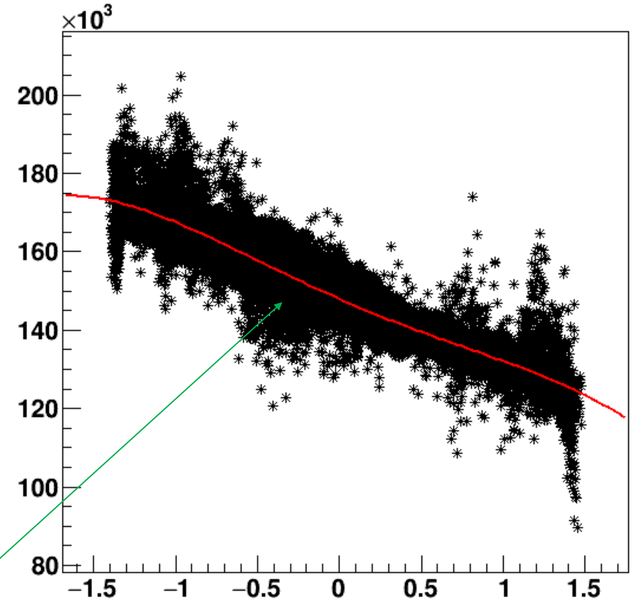
Background Systematics



Avg. Zn_rec – Zn_tracking angle



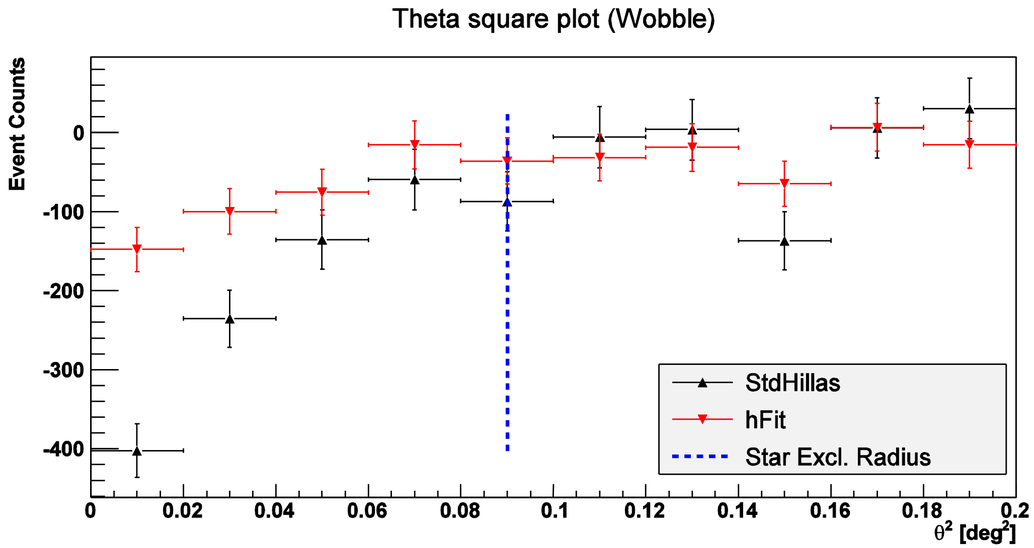
Ratio of ON counts to Acceptance

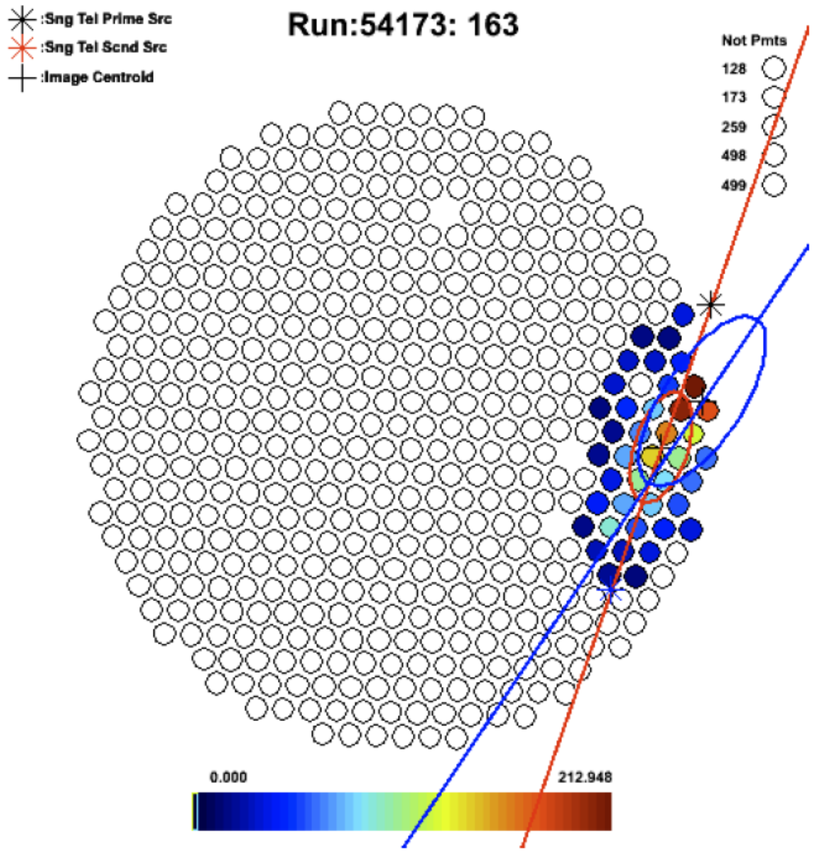


Use fit to re-weight acceptance, then recalculate alpha & significance

Bright Star Systematics

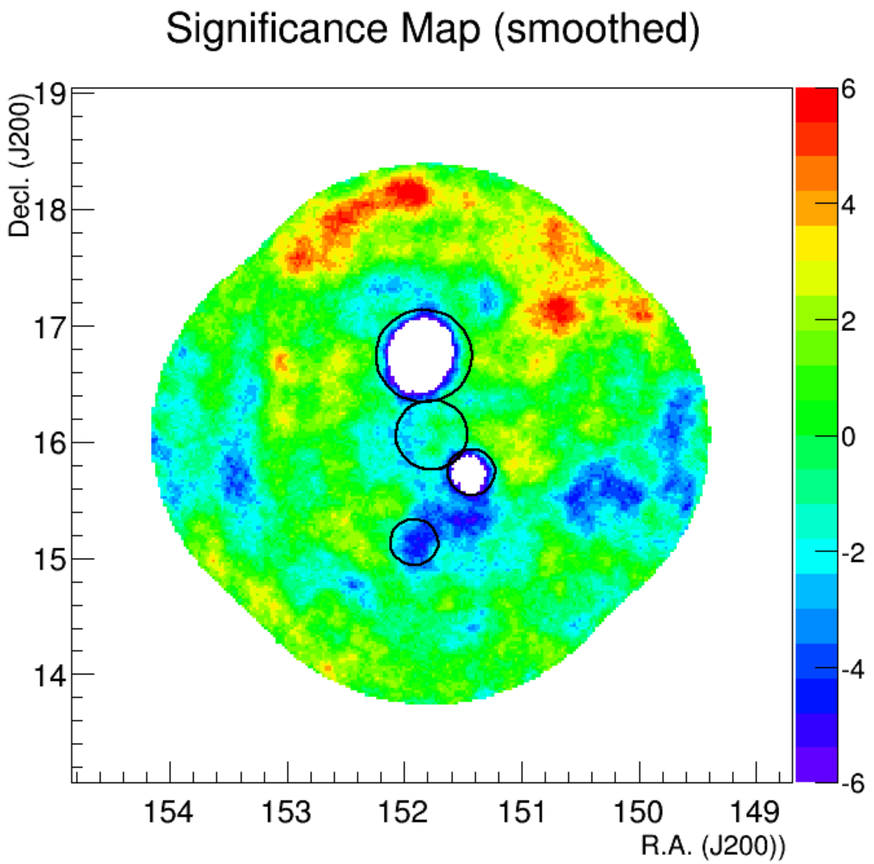
- Cherenkov shower images are elliptical in IACT cameras
- Optically bright stars have been problematic for IACTs
  - ‘Holes’ of negative excess in sky maps
  - Eta Leonis in the field of Segue 1, 0.6 deg away
- Standard shower reconstruction uses image moments
- This work uses 2D Elliptical Gaussian LL fit to showers (HFit)
  - Interpolates missing pixels or camera edge – uses all pixels
  - Greatly reduces width and depth of holes
  - improved PSF



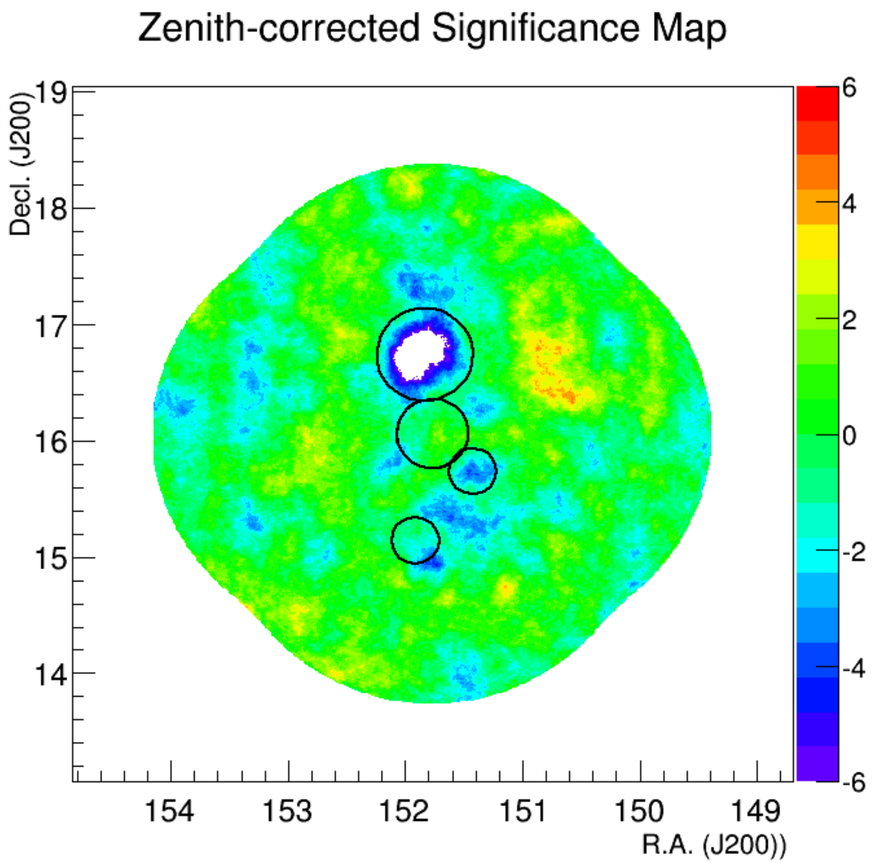


Red Ellipse: Standard Reconstruction
Blue Ellipse: HFit Reconstruction

Bright Star Systematics



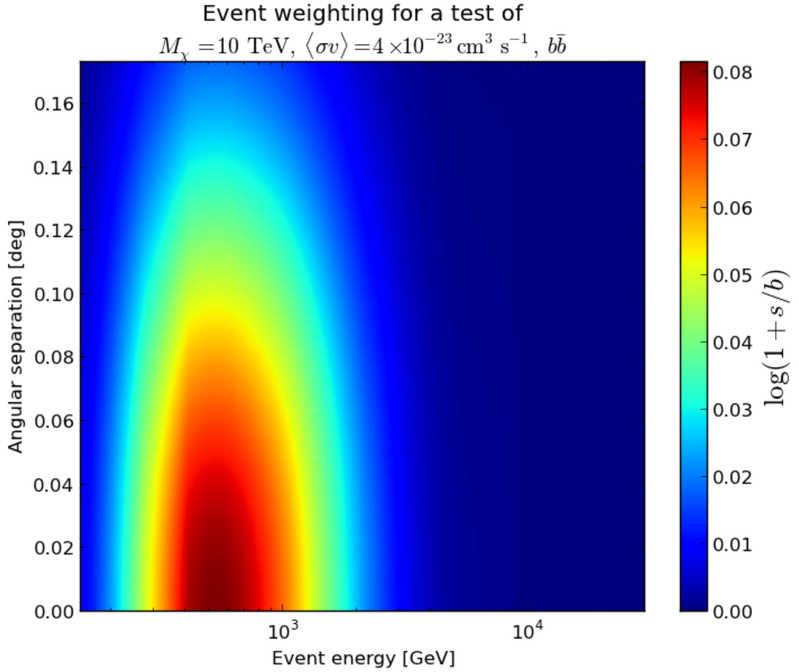
No Corrections



Zenith Correction + HFit

Dark Matter Search/ Limits from Dwarf Galaxies

- Applied to Fermi-LAT data - Phys. Rev. D 91, 083535 (2015)
- Each event in each ON region gets a weight based on the energy, theta and dwarf field
  - proportional to probability of event being produced by DM
- Test statistic for detection of DM at a given mass is the sum of weights from all dwarfs
- PDF generated from background from compound Poisson distributions
- PPP4 DM model used for single annihilation spectra
- Limits produced by repeating over several test mass and <σv> values
  - Limits on plots where DM hypothesis is rejected at 95% confidence for a given mass



Weight

$$w = \log\left[1 + \frac{s}{b}\right] \longrightarrow s(\nu, E, \theta) = \frac{dN(\nu, E, \theta)}{dE d\Omega} dE\, 2\pi \sin(\theta) d\theta$$

Particle Physics

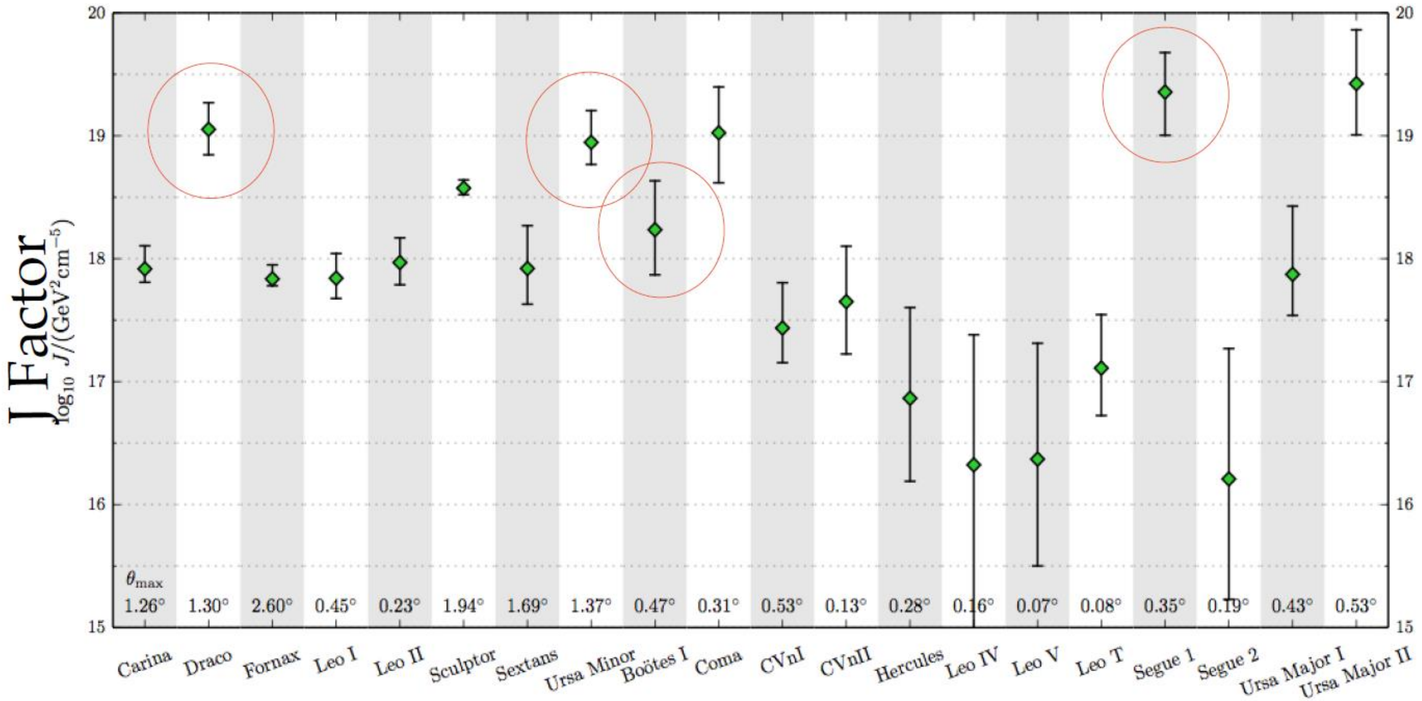
$$\frac{dF(E, \hat{\mathbf{n}})}{dE d\Omega} = \frac{\langle\sigma v\rangle}{8\pi M^2} \frac{dN_\gamma(E)}{dE} \frac{dJ(\hat{\mathbf{n}})}{d\Omega}$$

$$\frac{dN(E, \hat{\mathbf{n}})}{dE d\Omega} = \int_{E_t} \int_{\Omega_t} dE_t d\Omega_t \frac{dF(E_t, \hat{\mathbf{n}}_t)}{dE_t d\Omega_t} R(E, \hat{\mathbf{n}} | E_t, \hat{\mathbf{n}}_t)$$

Detector Response

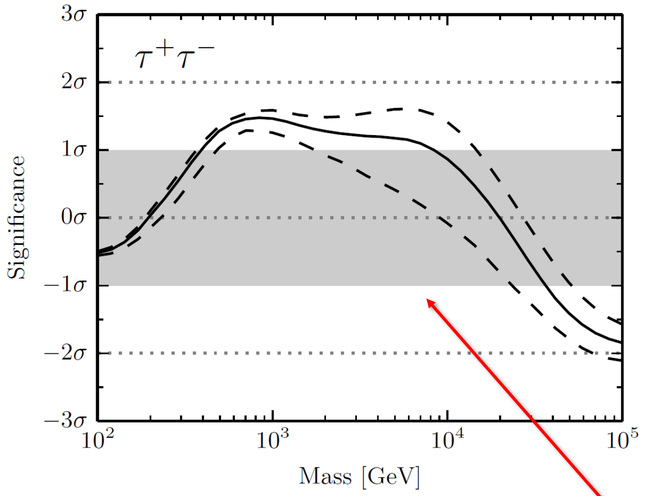
$$R(E, \hat{\mathbf{n}} | E_t, \hat{\mathbf{n}}_t) = \sum_{\text{runs}} \tau A_{\text{eff}}(E_t) \text{PSF}(\hat{\mathbf{n}} | E_t, \hat{\mathbf{n}}_t) D(E | E_t)$$

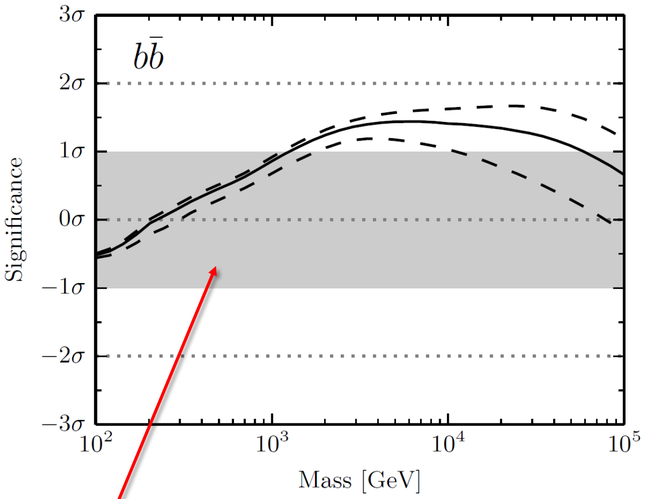
Dark Matter Annihilation Profiles

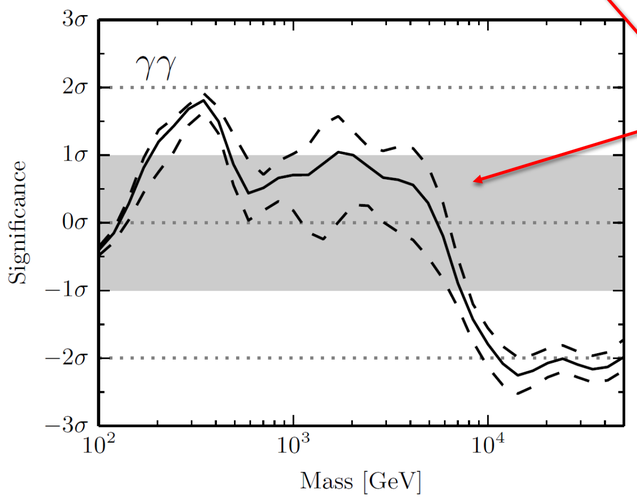


- J Factors from Geringer-Sameth et al. ApJ, Vol. 801, Issue 2 (2015)
- Up-to-date optical data
- Used Generalized NFW profile to fit 20 dwarfs in a united framework
- Segue 1 is brightest in this work, followed by Ursa Minor, Draco and Bootes
- Evidence of tidal disruption and/or non-equilibrium kinematics in Willman 1

Dark Matter Search from Dwarf Galaxies

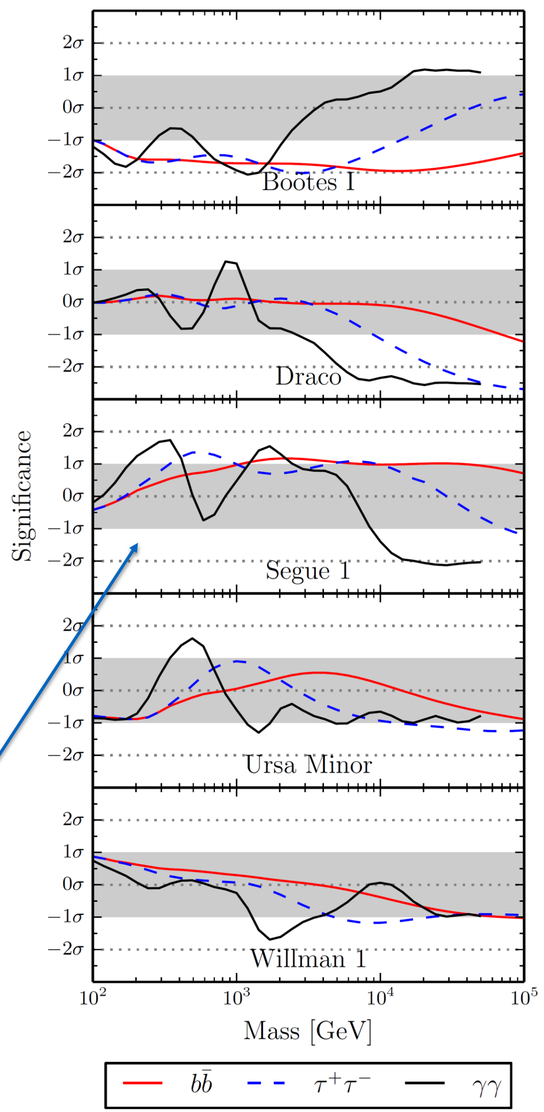




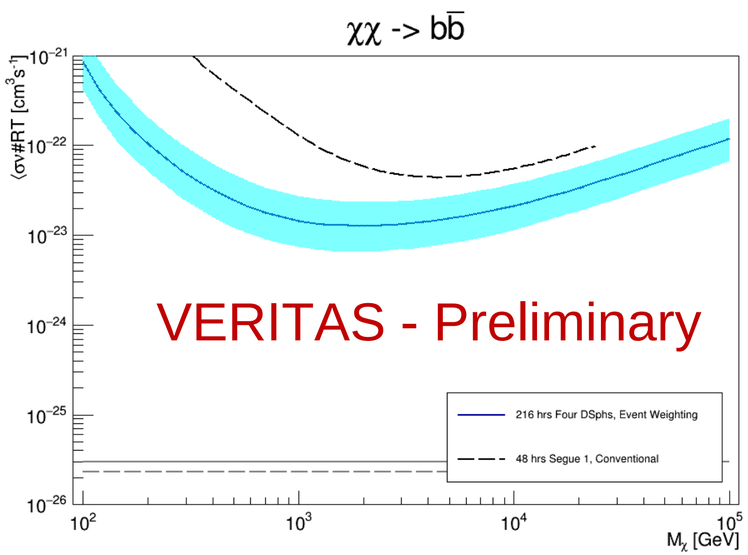


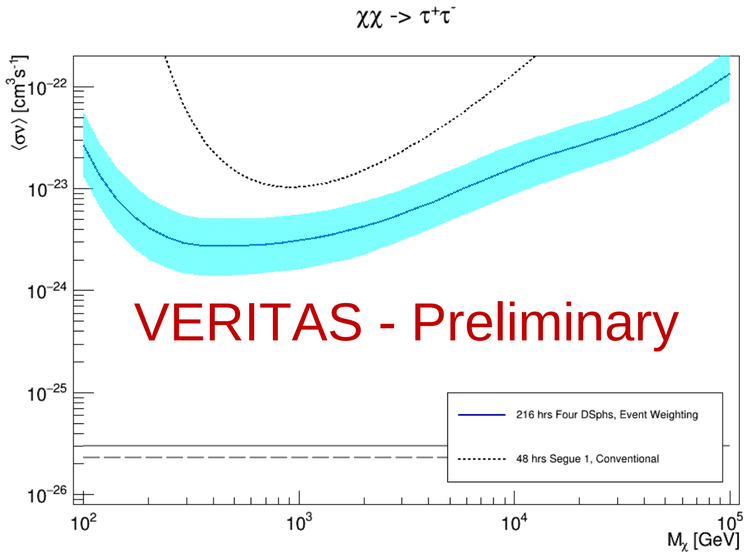
Combined Search

Individual Dwarf Search

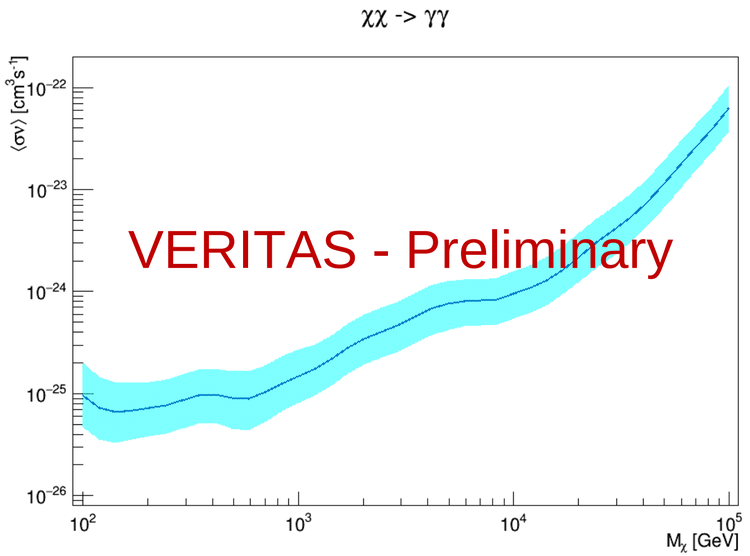


Dark Matter Limits

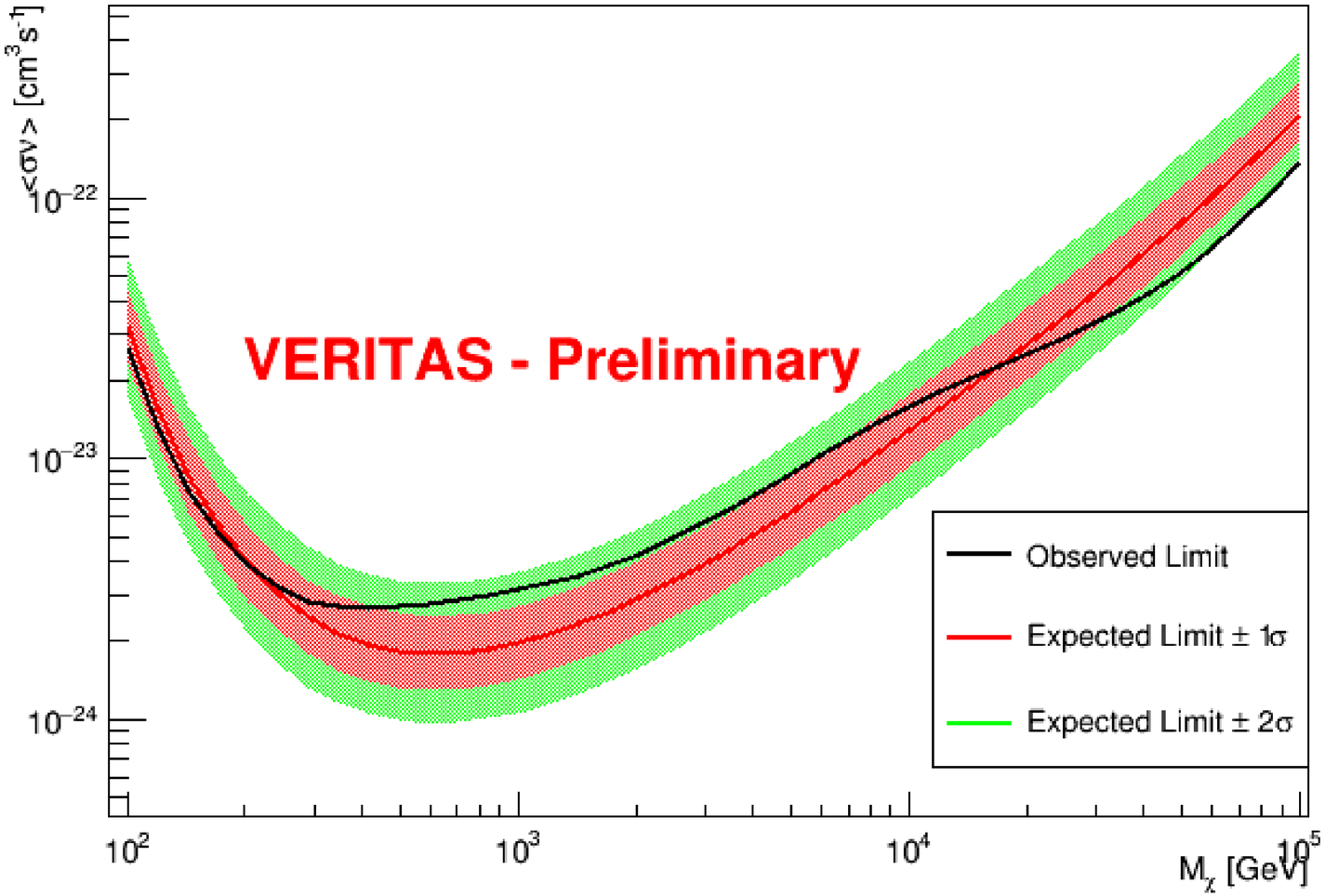




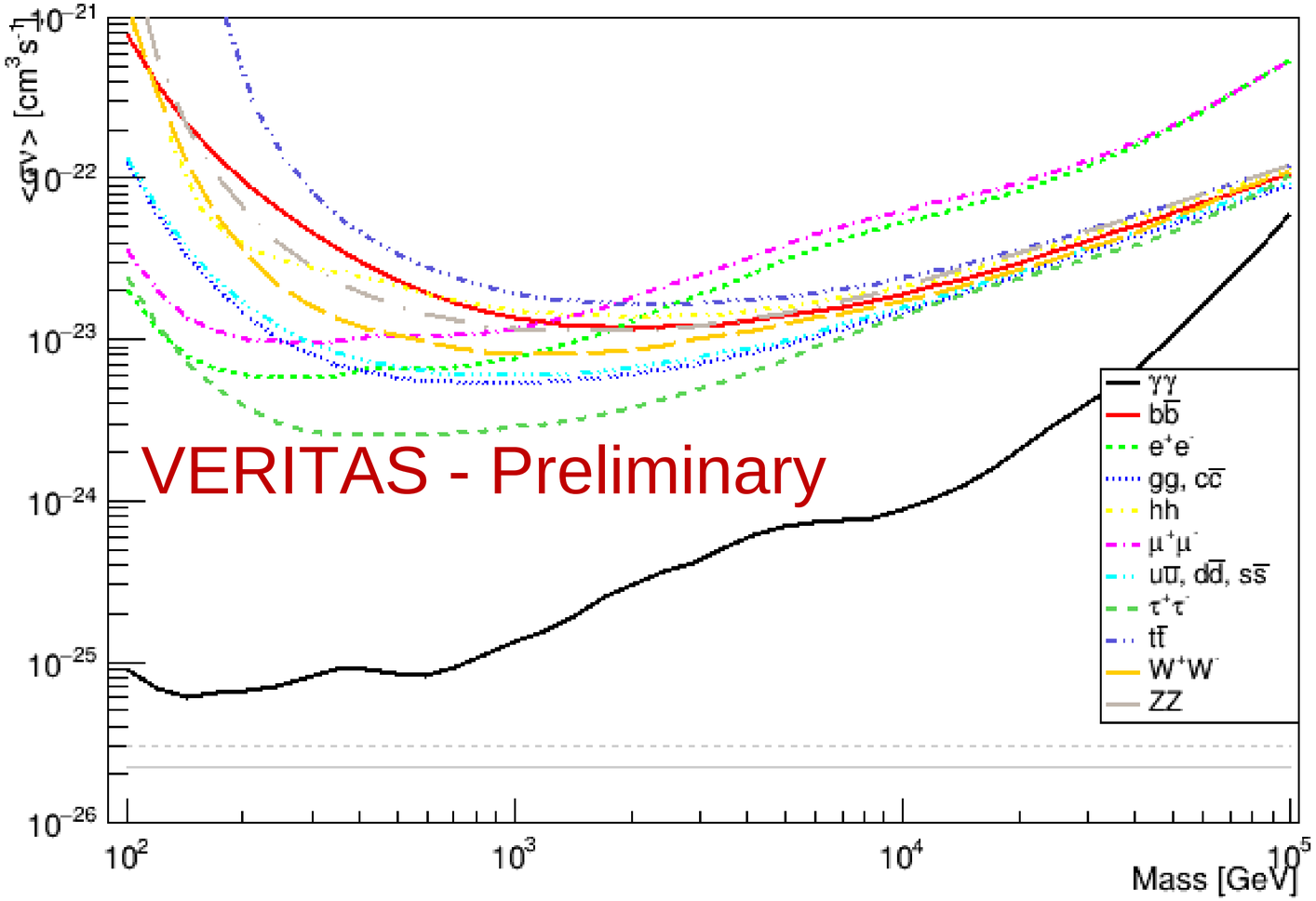
- 216 hours combined limit
  - Willman 1 not used
  - Band represents uncertainty in J factor
  - Substantial improvement over 48 hour Segue 1 result



Dark Matter Expected Limits



Dark Matter Limits – All Channels



Conclusions

- VERITAS Observations of 230 hours of dwarf galaxies
- Combined search and limits using 216 hours from 100 GeV to 100 TeV
- Method utilizing individual event energies and directions
- Paper currently undergoing internal collaboration review and final checks
- Future work:
  - VERITAS has a larger data set with data taken after 2013
  - Improvements from advanced analysis methods - boosted decision trees
  - Fermi – VERITAS – HAWC working group for standardization and combination of DM searches

Backup – Comparison with other Experiments