The VERITAS Dark Matter Program

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VERITAS Introduction

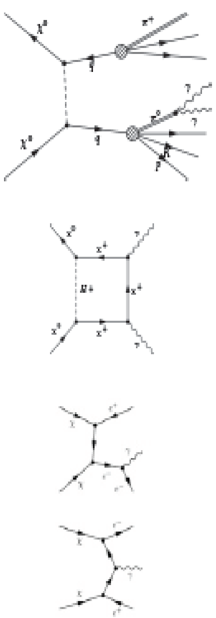
- Very Energetic Radiation Imaging Telescope Array System
- Consists of ~100 scientists in five countries
- Full Array Operations since fall 2007
- Four 12m Davies-Cotton Telescopes in Southern AZ
- Upgrades:
  - Move of T1 in Summer 2009
  - Trigger Upgrade in November 2011
  - Camera Upgrade in Summer 2012

Support From:
- US DOE
- US NSF
- SmithsonianInst.
- STFC (UK)
- SFI (Ireland)
- NSERC (Canada)

Performance:
- Energy Range: 0.85 – 30 TeV (Post-Upgrade)
- Energy Res: $\Delta E/E \sim 0.2$
- Angular Res: ~0.1 deg (68%)
- Angular Accuracy: 50 arcsec
- FOV: 3.5 deg

Gamma Rays from Dark Matter

Dark Matter is well described theoretically by extensions of the Standard Model of Particle physics (Supersymmetry, Kaluza-Klein) by a Weakly Interacting Massive Particle (WIMP) in the mass range of 50 GeV – 10 TeV.



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	
$\chi\chi \to Z^{0}Z^{0}$	$Z^{0} \to ll,\ \nu\bar{\nu},\ q\bar{q} \to$ pions	p, e, γ, ν	
$\chi\chi \to \tau^{\pm}$	$\tau^{\pm} \to \nu_{\tau}e^{\pm}\nu_{e},\ \tau \to \nu_{\tau}W^{\pm} \to p, \bar{p}$, 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

(Nearly) All Roads lead to Gamma Rays!

- WIMP annihilation production   -rays
  - Gamma-ray line from direct annihilation (higher order process)
  - Gamma-ray continuum from hadronization
  - Enhanced near M_{WIMP} from internal brem
  - DM gamma-ray flux:

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

Particle Physics

Astrophysical Factor

VERITAS Dark Matter Targets

Target	Advantages	Disadvantages
Galactic Center	Close by, lots of DM	Large γ BG
Fermi-LAT UIDs	Possibly local, known gamma-ray sources	Unknown distance, nature
Galaxy Clusters	-Largest DM concentrations in universe	-very distant (weak signal) -very extended -possible γ BG
Dwarf Galaxies	-High Mass/Light -No likely γ BG	DM distribution can be very uncertain

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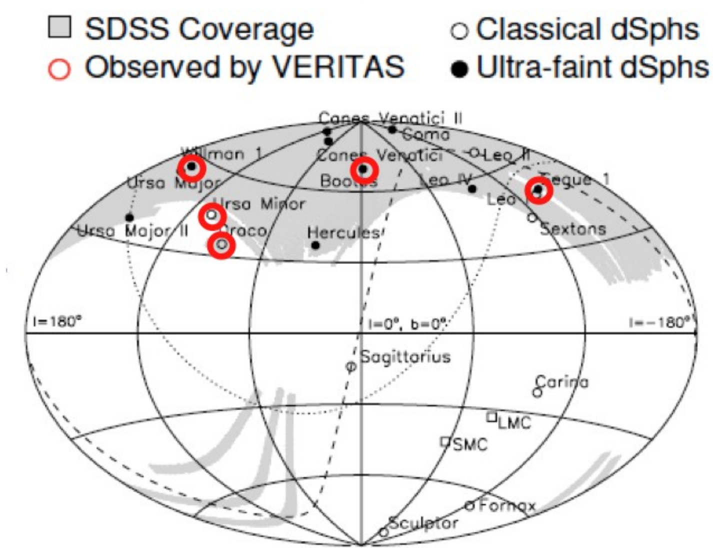
Sorry to fans of Galaxy Clusters and Fermi-LAT Unidentified sources!

Observations of DSph Galaxies



Advantages:

- Dark Matter dominated M/L ~ 200-1000
- Absence of known VHE backgrounds
- Close (10s of kiloparsecs)
- Recent discovery of many dSphs by SDSS
- Segue 1, at 23 +/- 2 kpc, discovered in 2006 in SDSS
- Segue 1 probably most DM dominated dSph known to date

Disadvantages:

- Small expected flux for standard flux modeling (w/smooth NFW, no boost, no velocity-dependent σ)
- Tidal disruption common makes DM estimation difficult.

Results of VERITAS DSph Observations:

Dwarf	Distance [kpc]	Obs. Time [hrs]	Sig. [σ]	$N_\gamma^{95\%CL}$	E_{min} [GeV]	Flux UL [C.U.]
Segue	23	83	-1.34	92.1	150	0.15%
Ursa Minor	80	38	-1.1	64.8	380	0.52%
Draco	66	39	0.71	197.7	290	1.36%
Bootes	38	14	-0.31	65.9	200	0.81%
Wilman1	62	14	-0.15	97.6	200	1.62%

+ 26 hours = 109 hours

+ 27 hours = 65 hours

+ 19 hours = 58 hours

Total Observing time: ~260 hours!

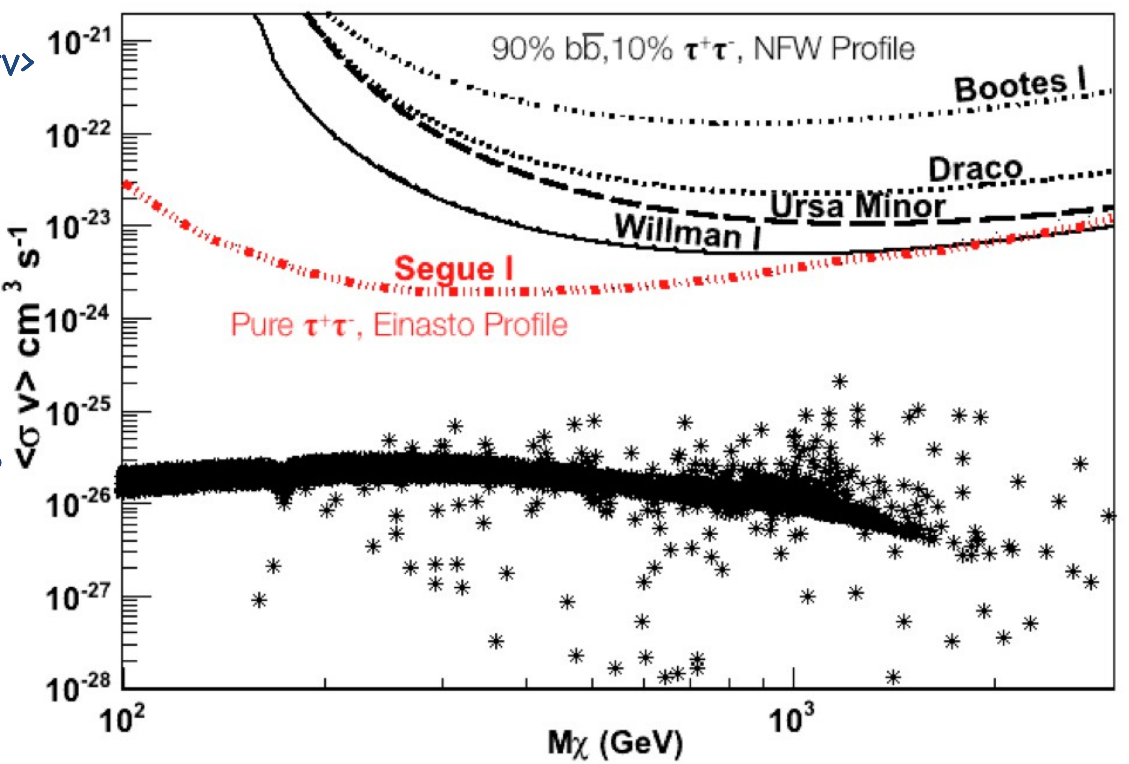
DM Constraints from DSphs

Place constraints on thermally-averaged annihilation cross-section, <σv>

Published results shown here:

- 15 hours on four DSphs
  - <σv> ~ 10^{-23} $cm^3 s^{-1}$ at min M_χ
- 48 hours Segue 1
  - <σv> ~ 10^{-24} $cm^3 s^{-1}$ at min M_χ

Natural cross-section at <σv> ~ 3×10^{-26}



Equation for cross-section:

$$< \sigma v >^{95\%CL} = \frac{8\pi}{J(\Delta\Omega)} \frac{N_\gamma^{95\%CL} m_\chi^2}{t_{obs} \int_0^{m_\chi} A_{eff}(E) \frac{dN_\gamma}{dE} dE}$$

$N_\gamma^{95\%}$: counts UL, calculated from Rolke

$A_{eff}(E)$: Effective area, function of array Elevation, Azimuth, and background noise

$J(\Delta\Omega)$: line of sight integral of DM density squared

t_{obs}: Observation time on target

dN_γ/dE: Single annihilation spectra for a WIMP

Segue 1 Results

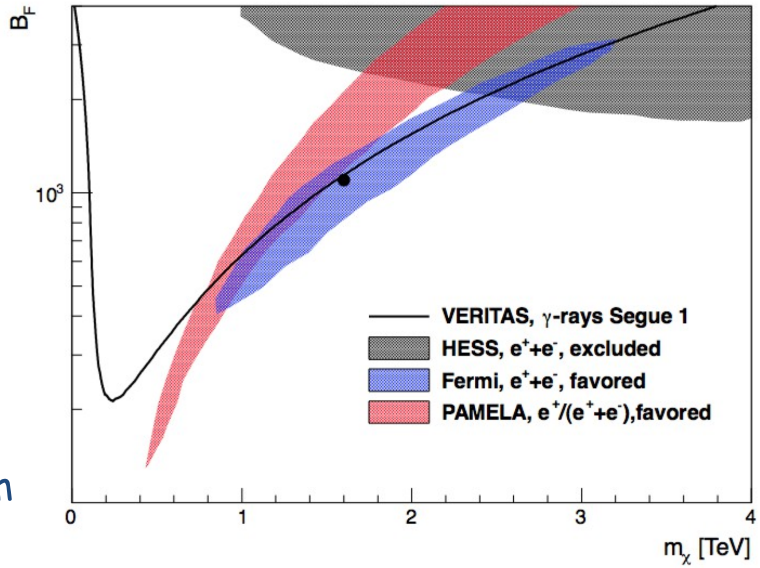
CR electron excess seen by Pamela/Fermi/HESS could be explained by a Sommerfield enhancement

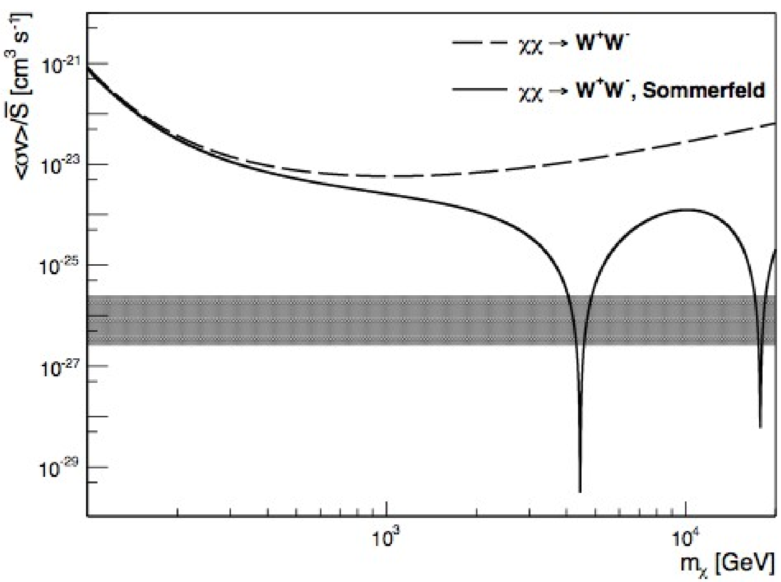
Arises when two DM particles interact though a attractive potential, mediated by a third particle.

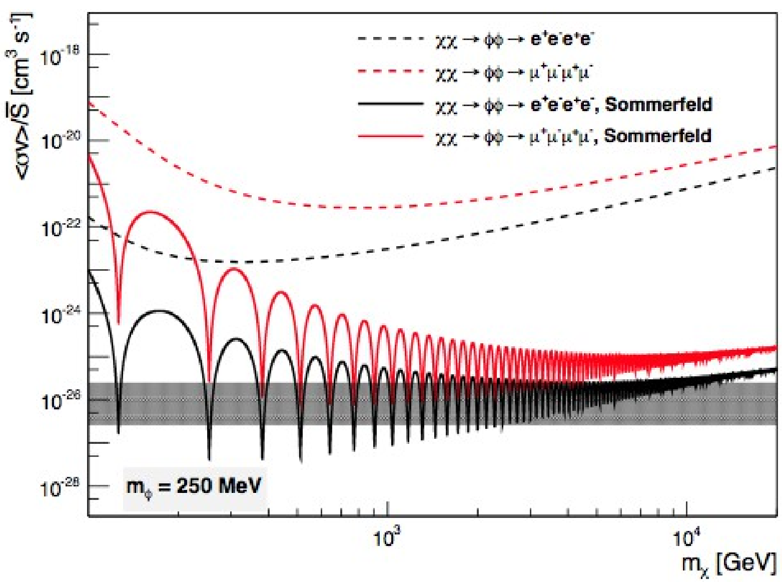
Velocity dependent, modifying cross-section

Constraints on models of Lattanzi & Silk (2009), bottom left, and Arkani-Hamed et al (2009), bottom right

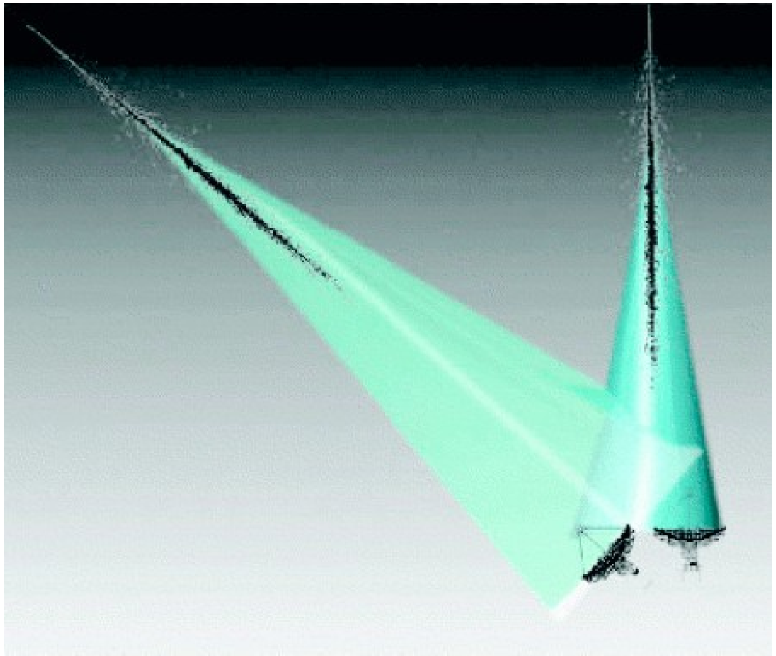
Constraints on overall boost factor, upper right

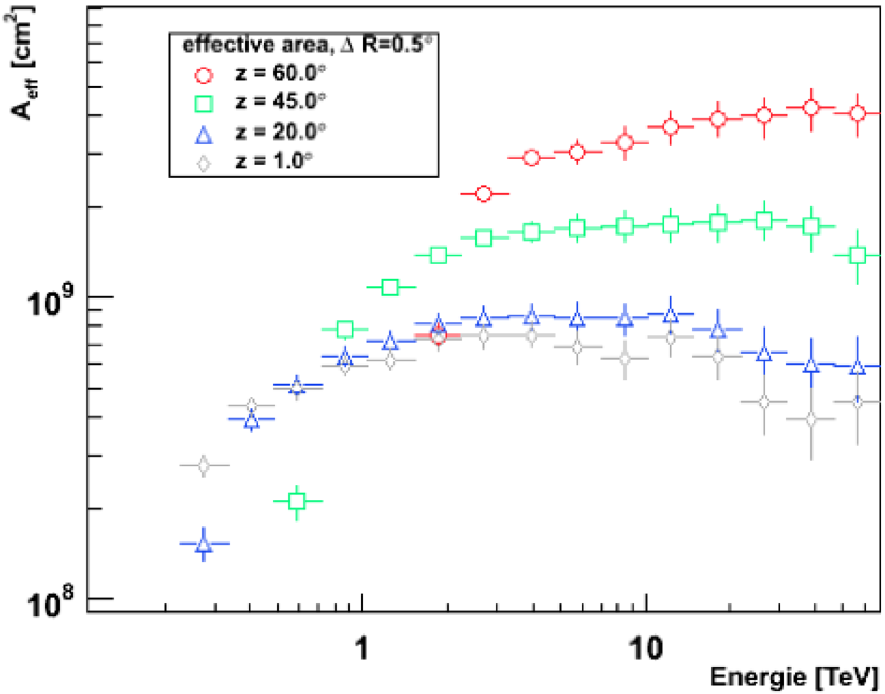






Sgr A* Observations with VERITAS

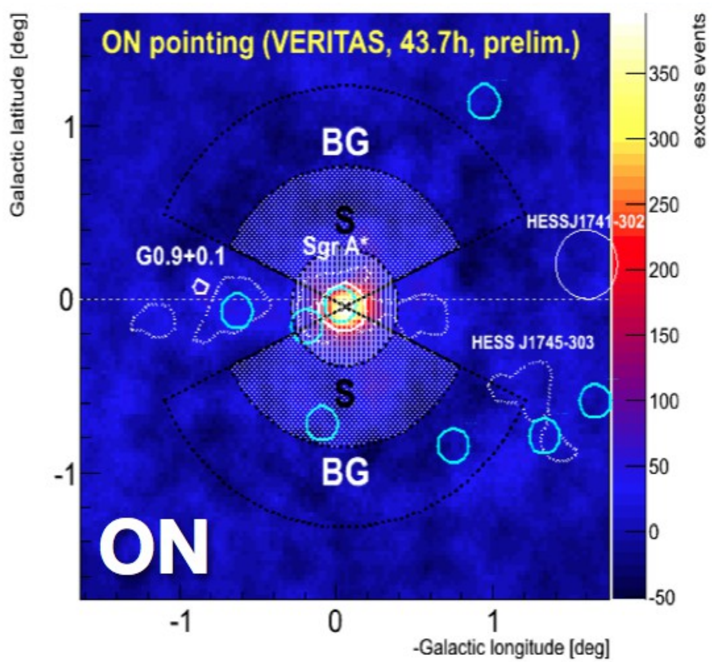


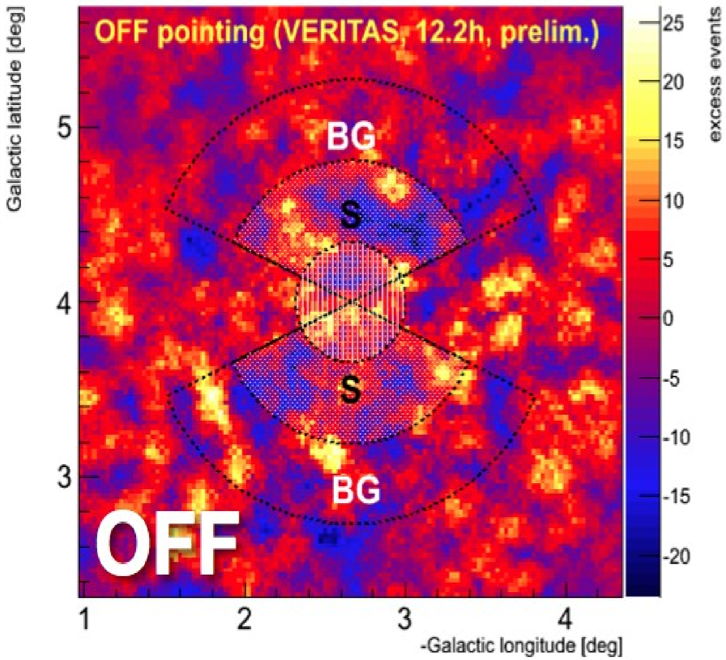


The Galactic Center (SgrA*) is a large zenith angle (LZA) source for VERITAS

- The Bad: This raises the energy threshold for SgrA* Observations
  - E_{th} ~ 2 TeV (possibly lower w/ upgrade data)
- The Good: Increased sensitivity at higher energies
- Drawback of increased angular resolution is offset by 'Disp' method

Sgr A* Observation Strategy



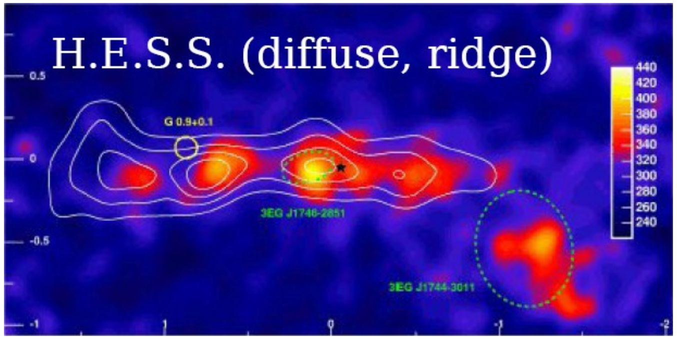


Increased CR density in GC, diffuse gamma-ray emission, SNR & PWNe in GC

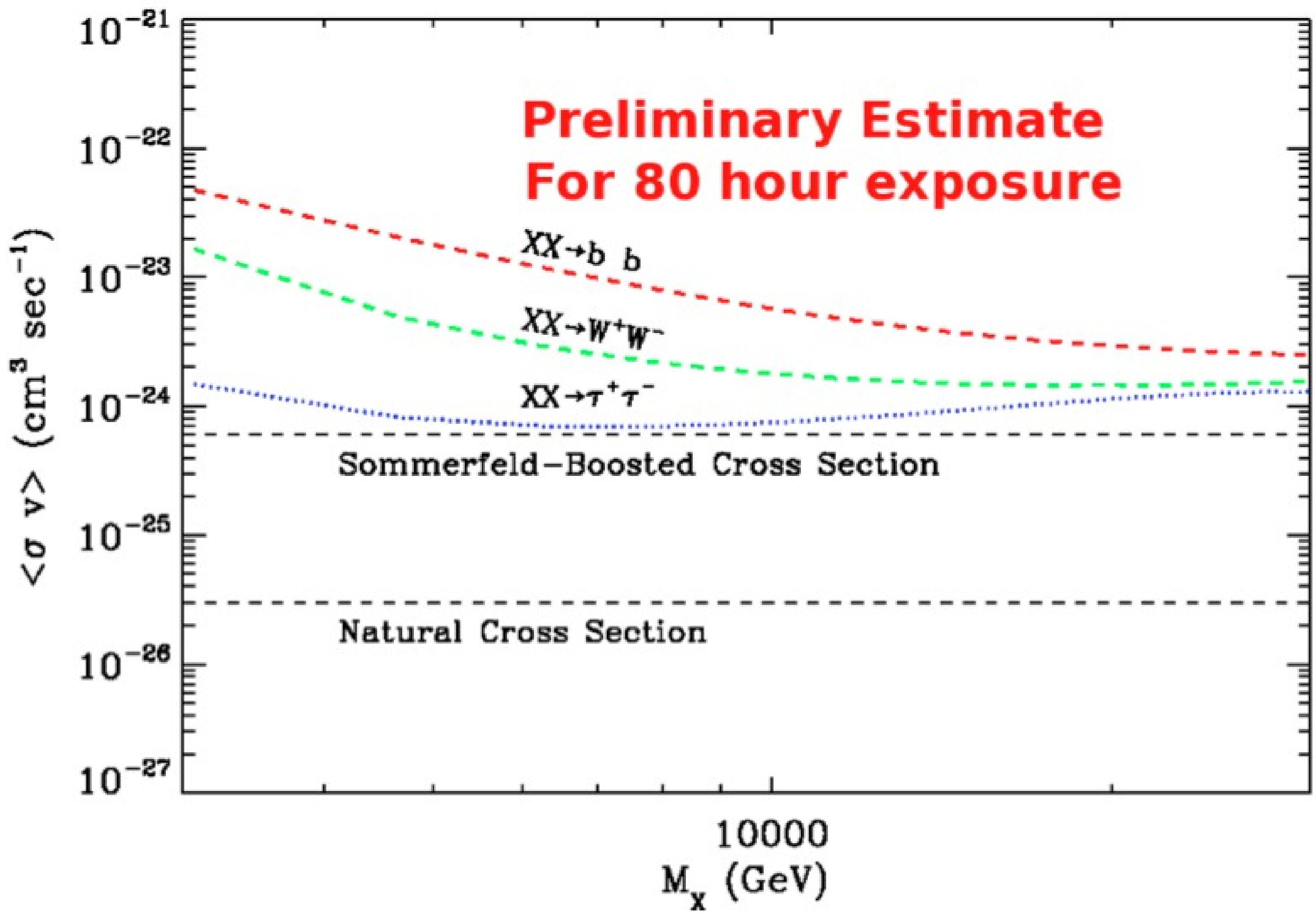
Two different ON/OFF pointing

Define signal/bg regions in ON/OFF maps, excluding SgrA* and other gamma-ray sources

Use OFF map to determine energy-dependent acceptance



DM Constraints from the Galactic Center

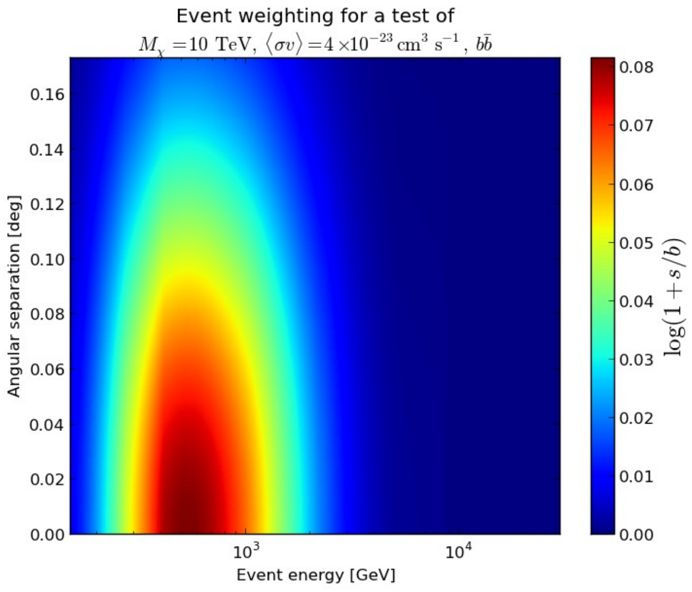


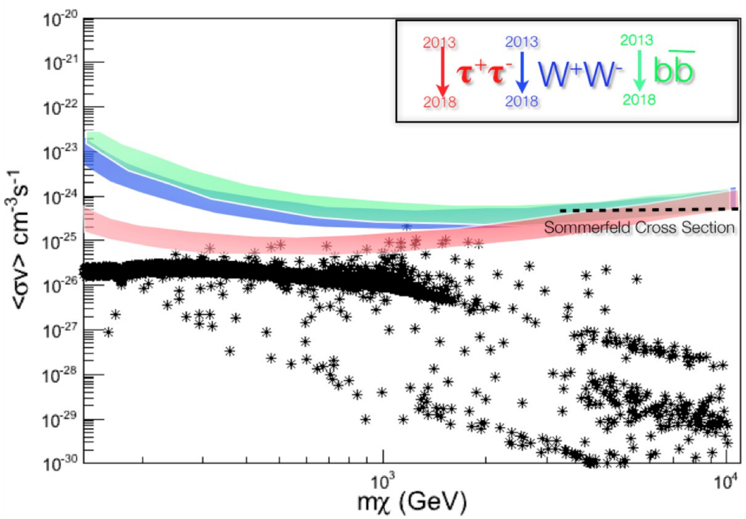
Future Work: Combined DM Analysis

DM results shown previously do not use individual photon information, one limit per source

Event Weighting method used for Fermi-LAT data of DSphs (Geringer-Sameth and Koupishappas, 2011)

- Authors working with VERITAS Collaboration
- Each event is assigned a weight as a function of energy and position, increased sensitivity
- Events closer to target with lower energy more likely to be from DM annihilation
- Sum of weights is test statistic to test hypothesis of events existing due to DM annihilation with given MX and <σv>
- Able to combine multiple sources and instruments into a single DM limit
- Predicted results of completed VERITAS DM program, (left) with 500 hours on a Segue-like DSph





Conclusions

VERITAS dark matter program is ongoing:

- Observations of dSphs, GC, Fermi UNIDs, galaxy clusters
- 2012-2013 observing season finished; first with upgraded cameras
- Lowered energy threshold, improved sensitivity for all DM masses

Future Plans:

- Continuing observations of dark matter targets
- Significant portion of VERITAS observing time
- Analysis of dSphs for combined analysis paper ongoing (260 hours!)
    - ~60 hours of post-upgrade data
    - ~100 hours from Segue 1
    - Limits soon, including line search
- Galactic center analysis ongoing