The VERITAS Dark Matter Program

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VERITAS Introduction

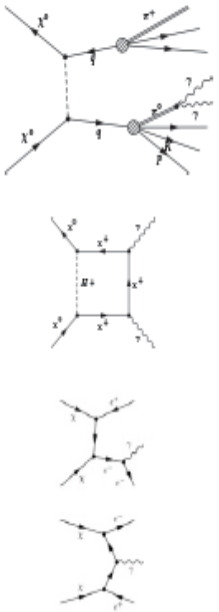
- Very Energetic Radiation Imaging Telescope Array System
- Employs ~100 scientists in five countries
- Full Array Operations since fall 2007
- Four 12m Davies-Cotton Telescopes in Southern AZ
- Upgrades:
  - Move of T1 in Summer 2009
  - Trigger Upgrade in November 2011
  - Camera Upgrade in Summer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

- Support From:
  US DOE
  US NSF
  Smithsonian Inst.
  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 ~10 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	
$\chi\chi \to Z^0Z^0$	$Z^0 \to ll,\ \nu\bar{\nu},\ q\bar{q} \to$ 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
$\chi\chi \to \gamma\gamma$		γ	Loop suppressed
$\chi\chi \to Z^0\gamma$	Z^0 decay	γ	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?)
$\chi\chi \to \phi\phi$	$\phi \to e^+e^-$	$e^{\pm}$	New scalar field with $m_\chi < m_q$ to explain large electron signal and avoid overproduction of p, γ

internal/final state bremms
inverse Compton γ's

(Nearly) All Roads lead to Gamma Rays!

- WIMP annihilation production γ-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:

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

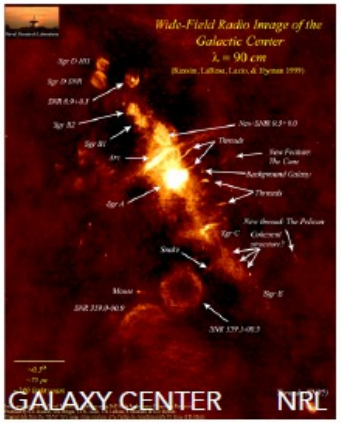
$$= \frac{\langle\sigma v\rangle}{8\pi M^2} \frac{dN_\gamma(E)}{dE} \int d\ell\, \rho^2(\ell\hat{\mathbf{n}})$$

Particle Physics

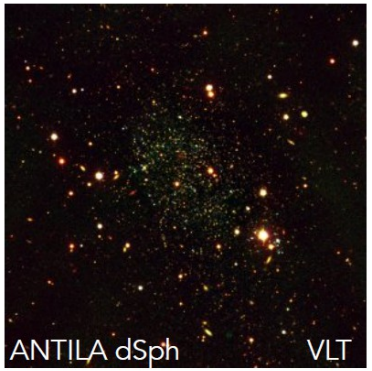
Astrophysical Factor

VERITAS Dark Matter Targets

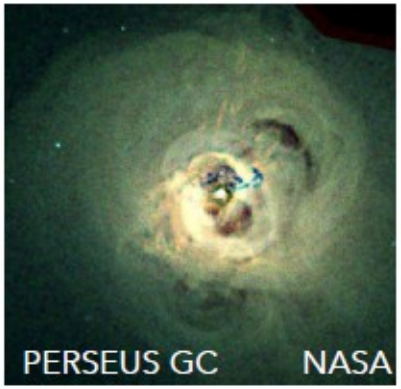
Galactic Center (GC):
- Close by
- Astrophysical backgrounds



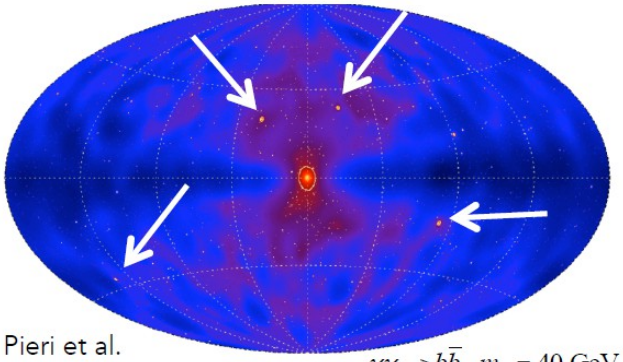
Dwarf Spherioidal Galaxies (DSphs):
- Low Astrophysical Backgrounds
- High M/L
- Low Flux



Galaxy Clusters:
- Large DM Content
- Large Distance
- Potentially Extended
- Astrophysical backgrounds



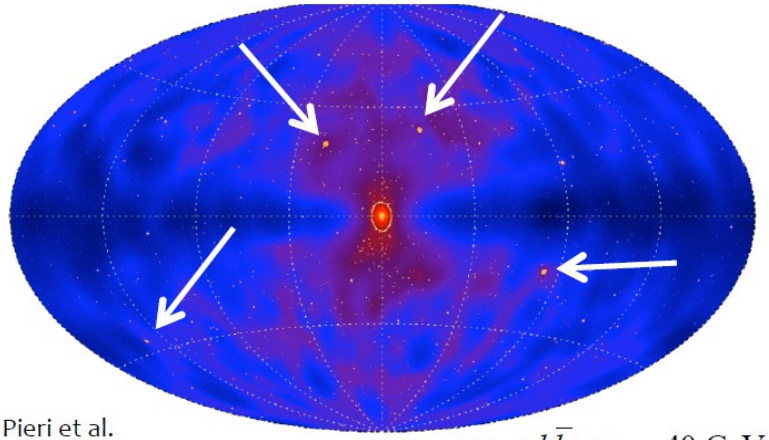
Unassociated Fermi Sources
- Potentially DM Sub-halos?



Pieri et al.
PRD 83:0235, 2008

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

DM Sub-Halo Candidates



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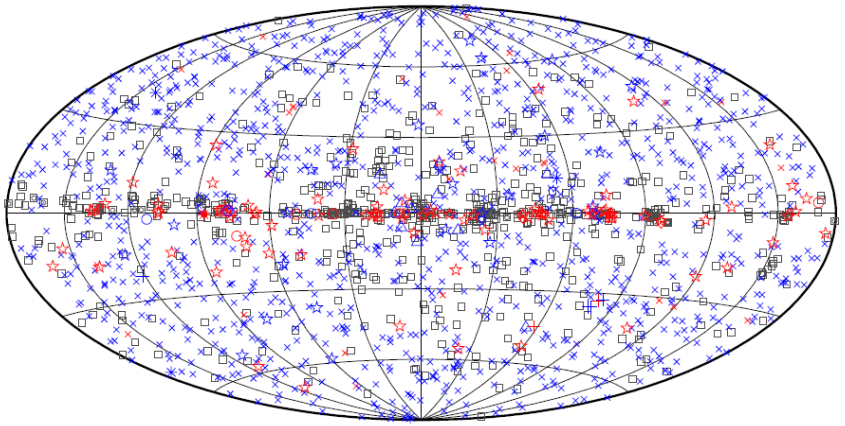


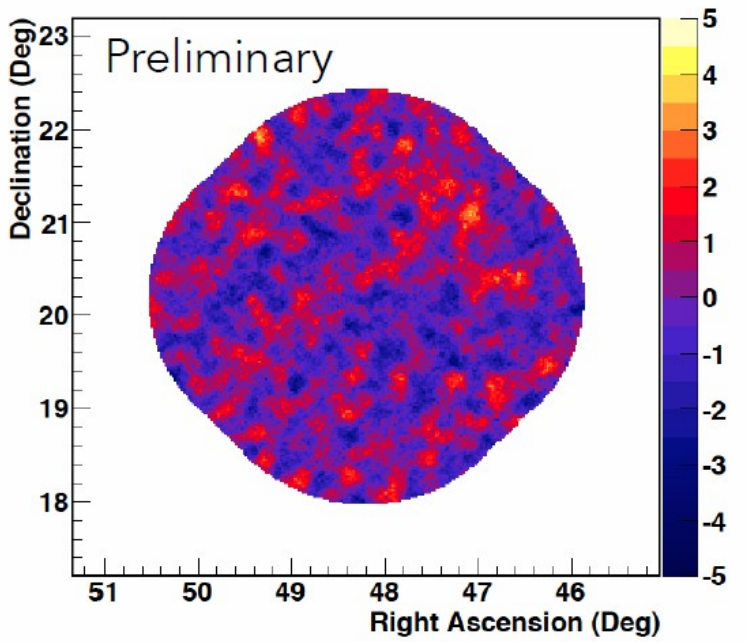
ApJS 199:31, 2012 [arXiv:1108.1435]

No association	Possible association with SNR or PWN	
AGN	Pulsar	Globular cluster
Starburst Gal	PWN	HMB
Galaxy	SNR	Nova

- N-Body simulations predict the existence of DM sub-halos
  - Potentially close enough for VHE detection
  - Too small to attract Baryonic matter for star formation
    - Invisible at other wavelengths
- Selection Criteria for VERITAS Observations:
  - Lies outside the Galactic Plane
  - No variability
  - No spectral curvature
  - Detection feasible by extrapolation of Fermi-LAT spectra to VHE
  - No counterparts at other wavelengths

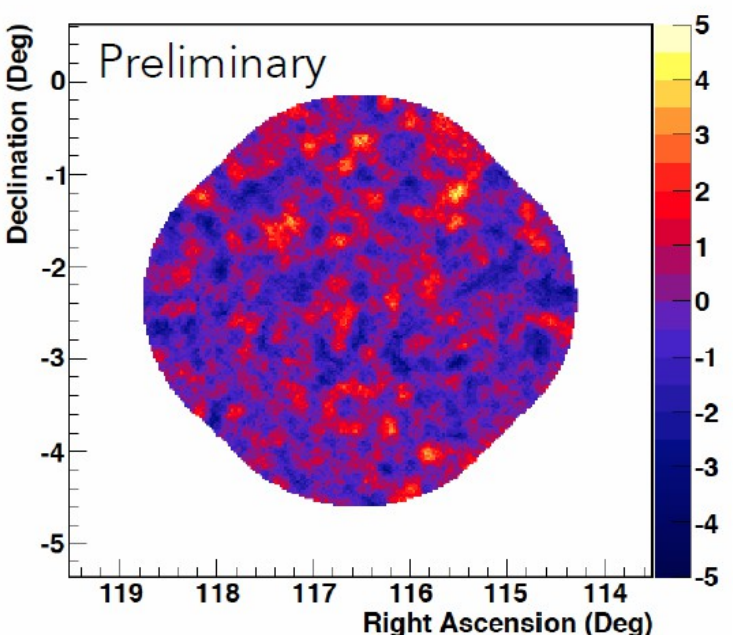
DM Sub-Halo Candidates

2FGL J0312.8+2013



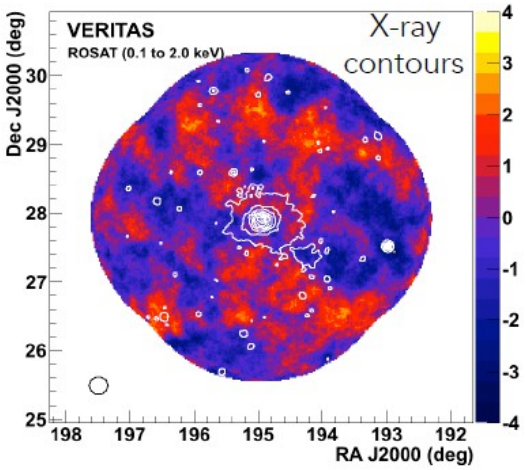
Exposure Time: 9.1 hrs
Excess: -25.7 ± 16.9
Significance: -1.5σ
Energy Threshold: 220 GeV
Flux UL (99% CL): < 1.78x10^{-12} cm^{-2}s^{-1}
< 0.9% Crab Nebula

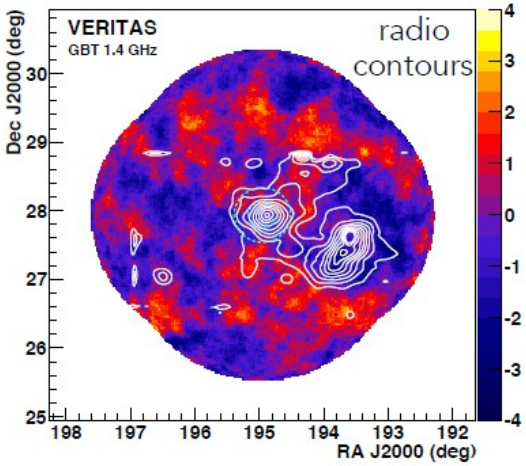
2FGL J0746.0-0222



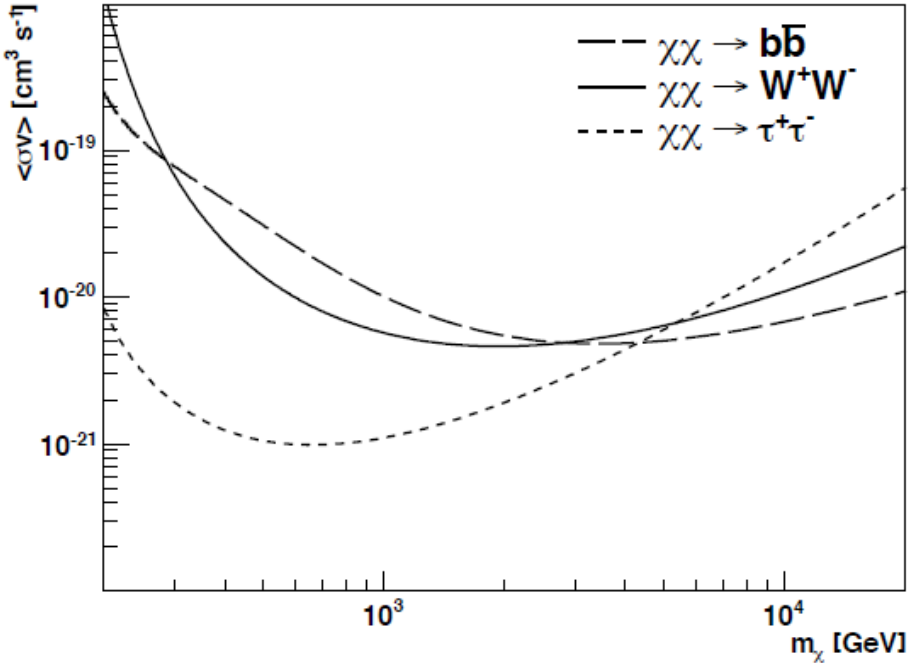
Exposure Time: 9.1 hrs
Excess: -14.5 ± 15.8
Significance: -0.9σ
Energy Threshold: 320 GeV
Flux UL (99% CL): < 1.23x10^{-12} cm^{-2}s^{-1}
< 1.1% Crab Nebula

Galaxy Clusters

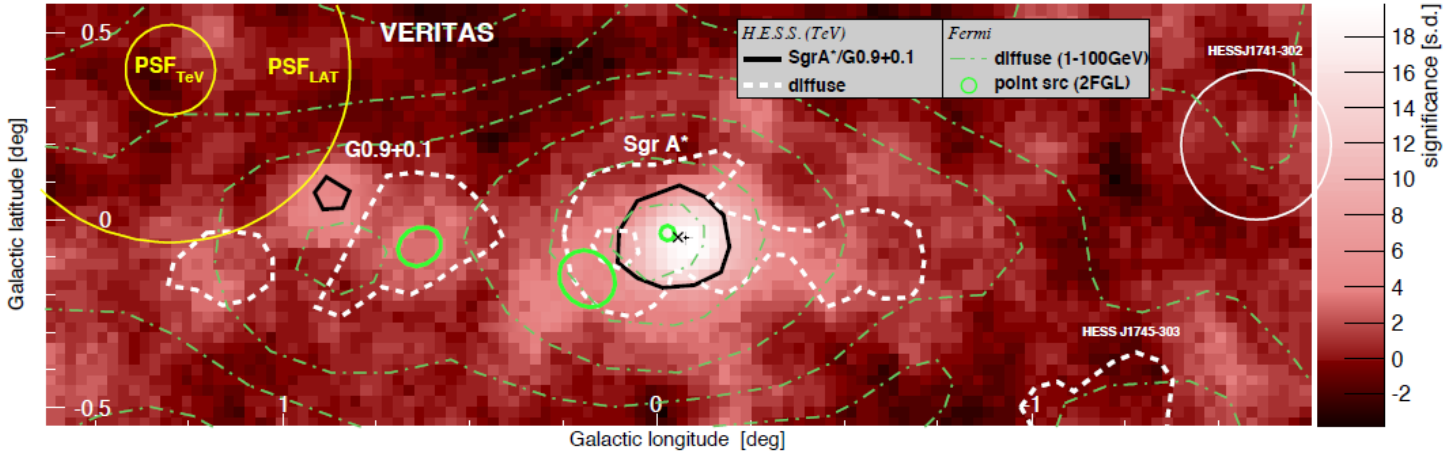




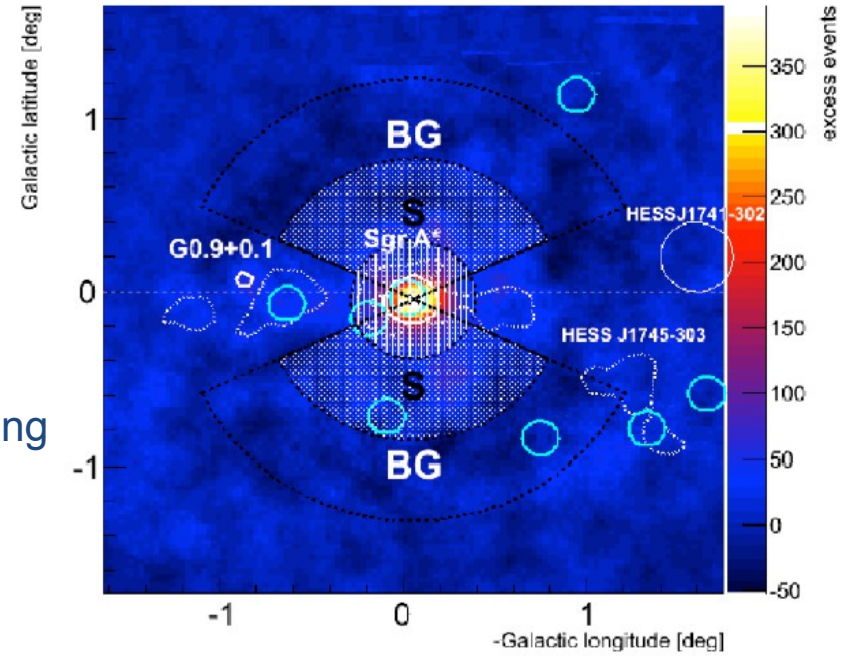
- 21 hrs on Coma Galaxy Cluster, low Zn observations
  - No Detection with VERITAS or Fermi-LAT
  - $\langle\sigma v\rangle^{95\%CL} \sim O(10^{-21})$ $cm^{-3}s^{-1}$
  - ApJ 757 123 (2012) [arXiv:1208.0676]
- Archival Galaxy Cluster search currently underway
  - Search for clusters that have overlapped in same FOV as previous VERITAS observations
  - Cluster list from ROSAT and SDSS



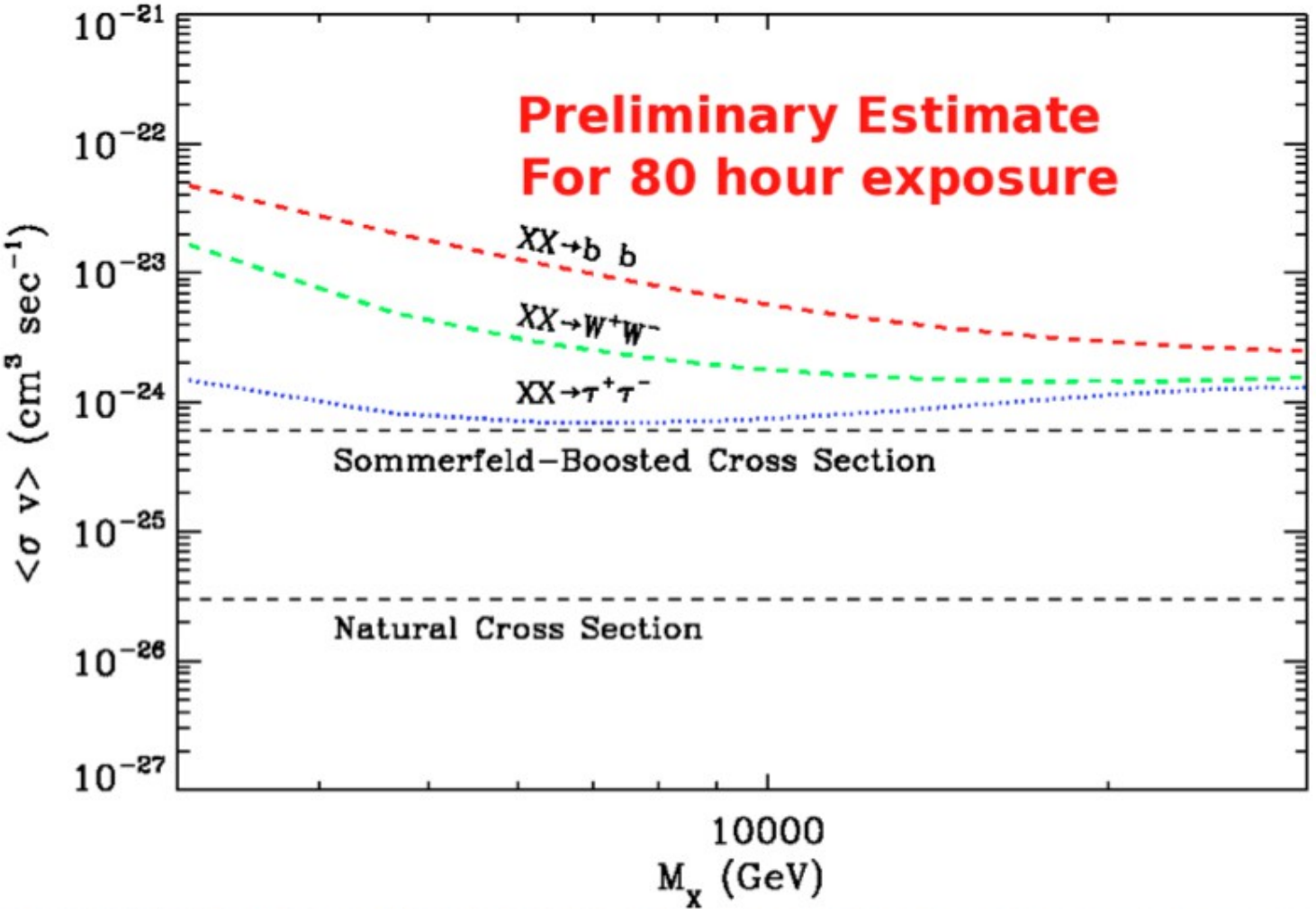
Sgr A* Observation Strategy



- SgrA* Observations paper: ApJ 790 149 [arXiv:1406.6383], Poster by Andy Smith
- 18σ detection of SgrA*, 46 hours observation
- Large Zenith Observations → ~2 TeV threshold
- Increased CR density in GC, diffuse gamma-ray emission, SNR & PWNe in GC
- Two different ON/OFF pointings
  - Define signal/bg regions in ON/OFF maps, excluding SgrA* and other gamma-ray sources
  - Use OFF map to determine energy-dependent acceptance

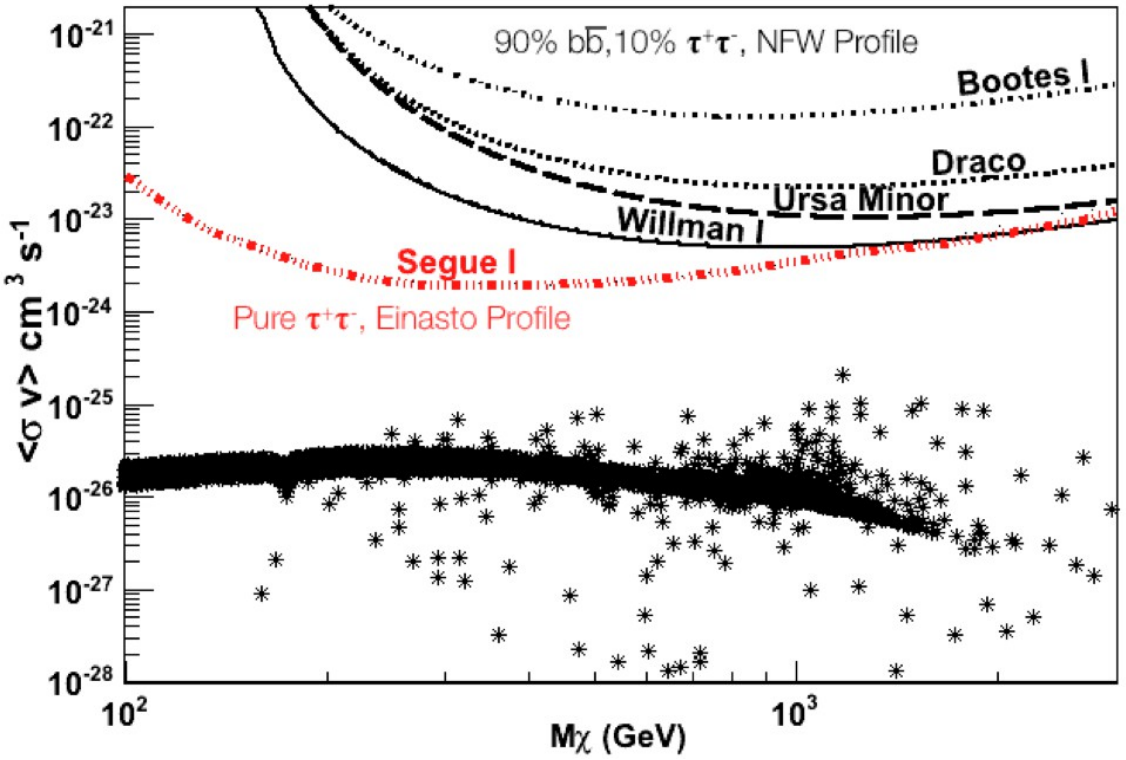


DM Constraints from the Galactic Center



DM Constraints from DSphs

- Already published shown here:
  - 15 hours on four DSphs
    - $\langle\sigma v\rangle \sim 10^{-23}$ cm^{3}s^{-1} at min M_X
    - ApJ 720:1174 (2010) [arXiv:1006.5955]
  - 48 hours Segue 1
    - $\langle\sigma v\rangle \sim 10^{-24}$ cm^{3}s^{-1} at min M_X
    - Phys. Rev. D. 85, 062001 (2012) [arXiv: 1202.2144]



Equation for cross-section:

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

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

$A_{eff}(E)$: Effective area

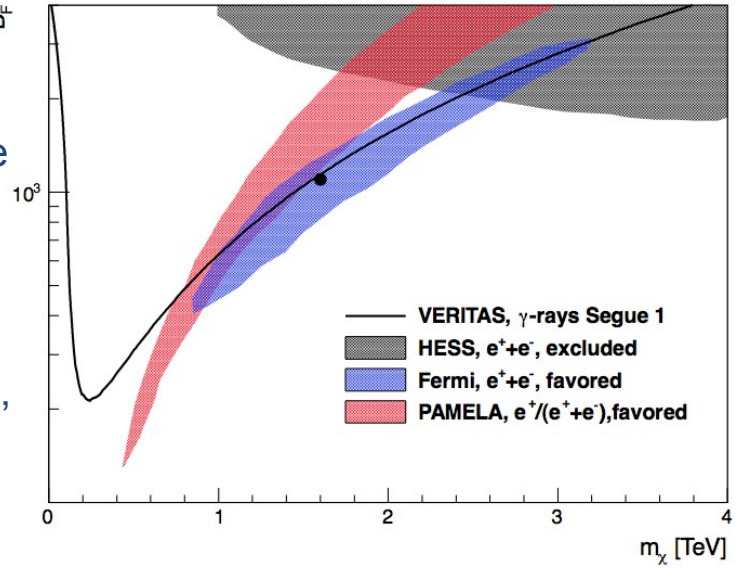
$J(\Delta\Omega)$: line of sight integral of DM density squared

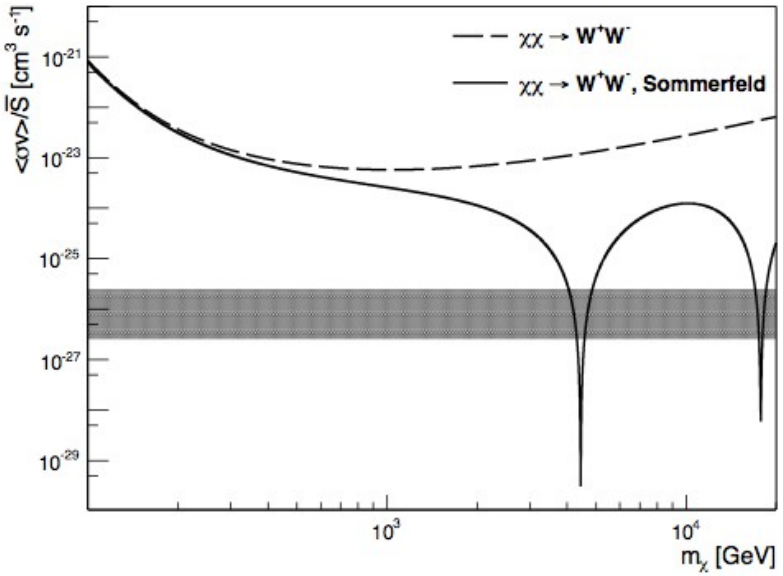
t_{obs}: Observation time on target

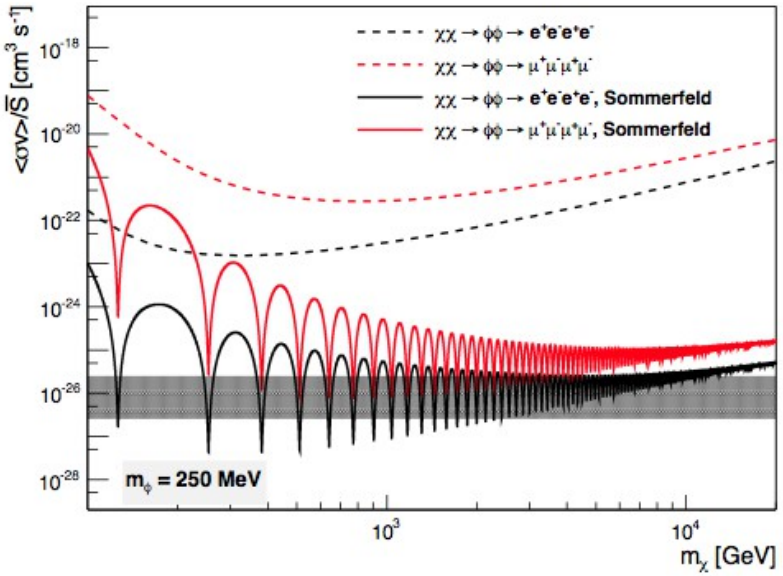
dN_γ/dE: Single annihilation spectra for a WIMP

Segue 1 Results

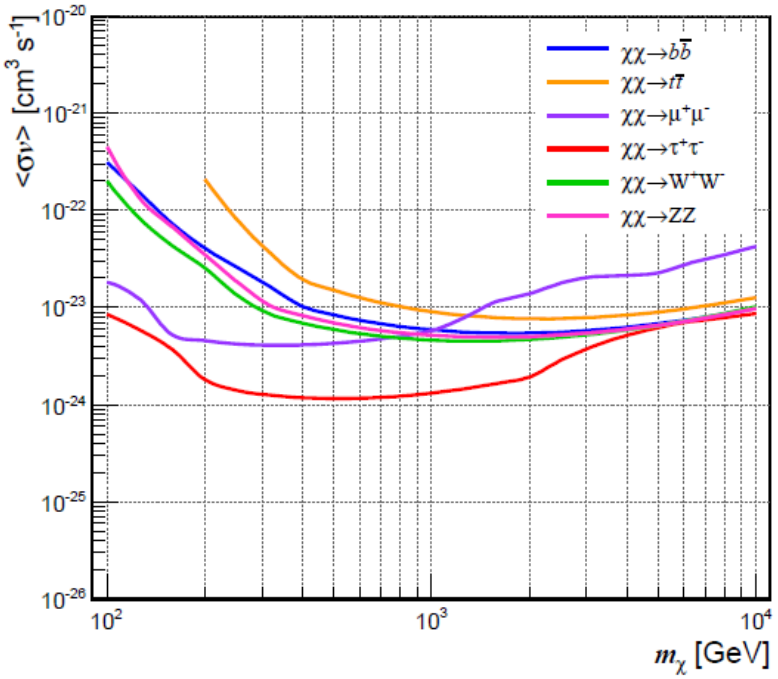
- CR electron excess seen by Pamela/Fermi/HESS could be explained by a Sommerfeld enhancement
  - Arises when two DM particles interact though a attractive potential, mediated by a third particle.
- Velocity dependent, modifying cross-section
- Constraints on models of Lattanzi & Silk (2009), bottom left, and Arkani-Hamed et al (2009), bottom right



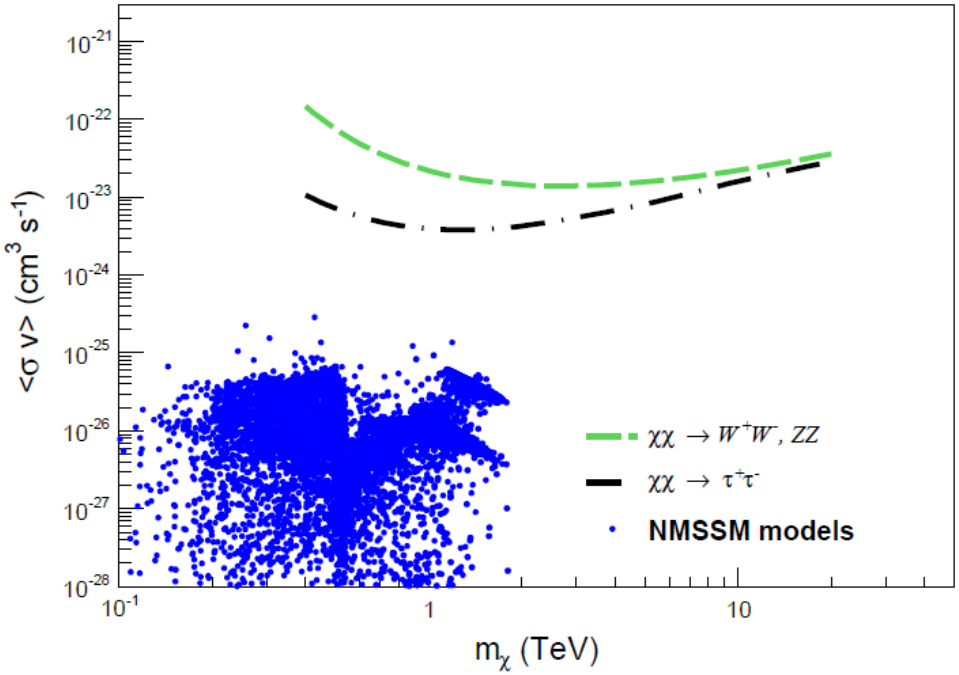




DSph Results of other IACTs

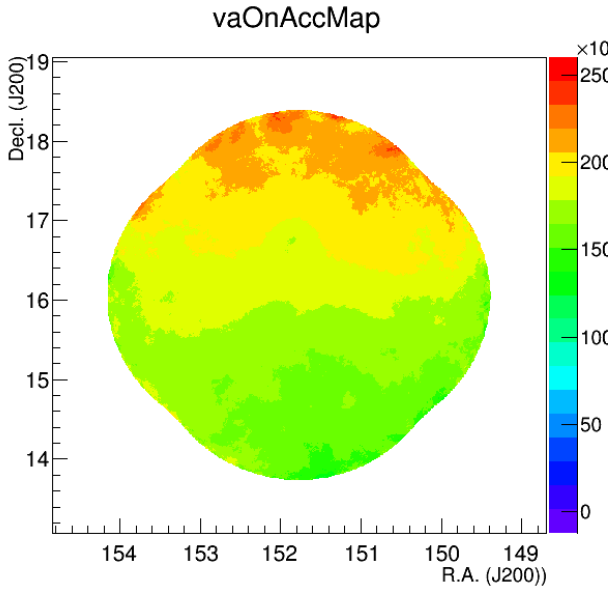


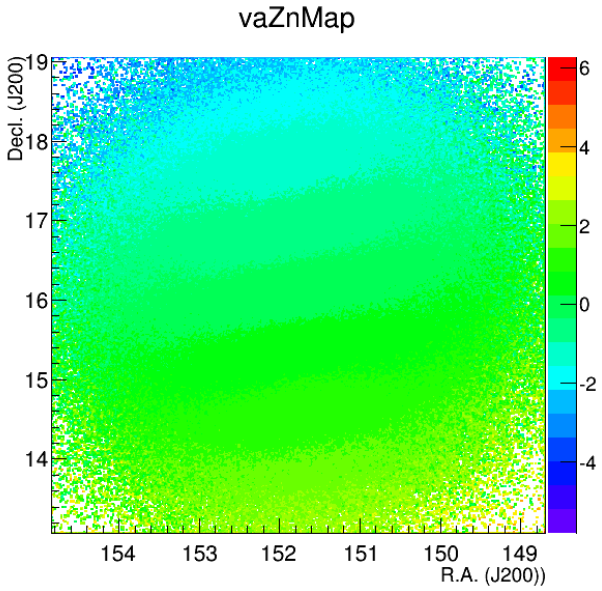
MAGIC: 160 hours on Segue 1
Full Maximum Likelihood method
ArXiv: 1312.1535

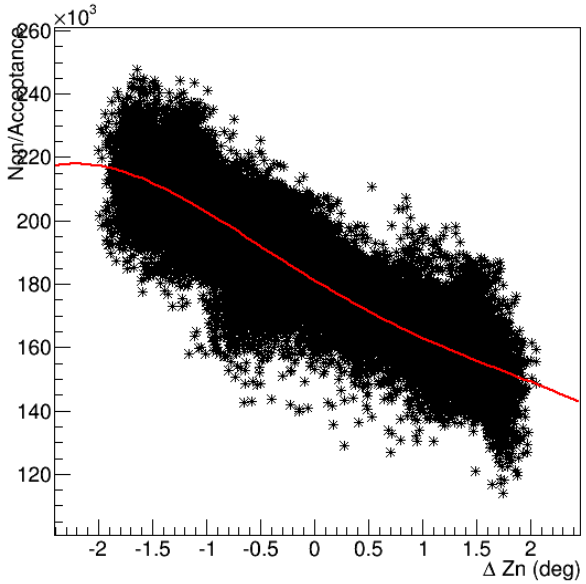


HESS: 141 hours combined on five dSphs
90 hours on Sagittarius
Maximum Likelihood Method
Deep exposure on Galactic Center as well
arXiv: 1410.2589

Deep Exposure Systematics



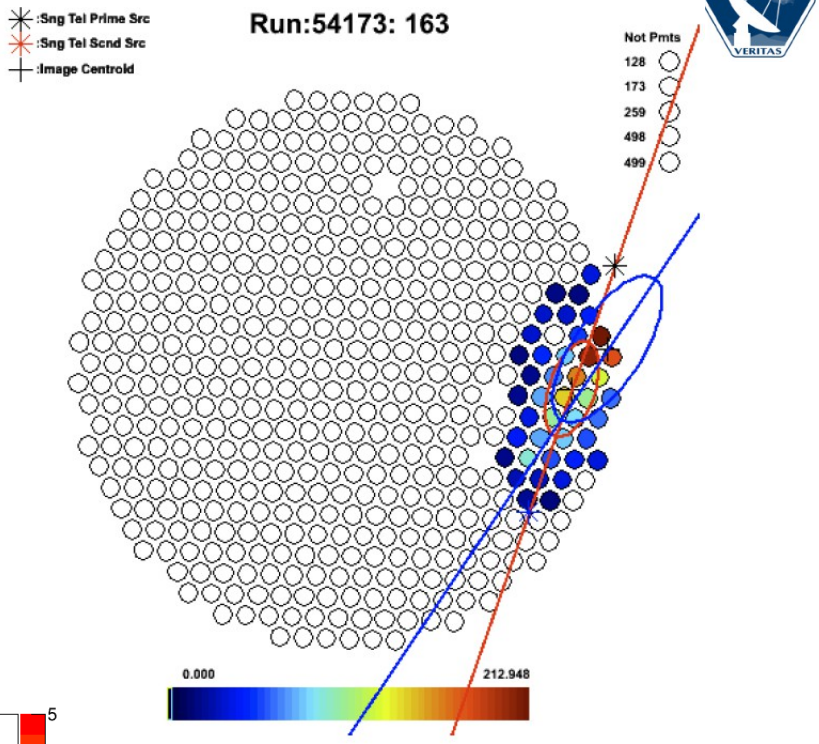


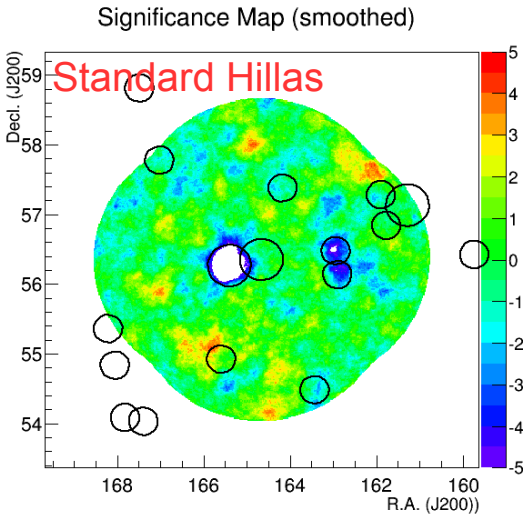


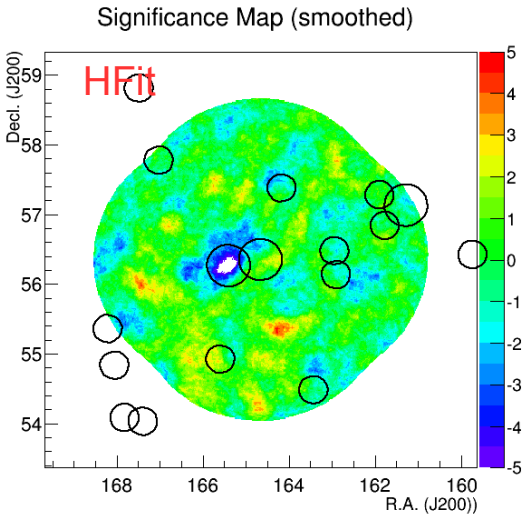
- 92 hours of data quality selection for Segue 1 from period of 2009 to 2013
  - Deepest VERITAS Observation *without* seeing a strong gamma-ray signal
- Softer cuts used, improves statistics, but increases systematics
  - Wider significance distributions of backgrounds (Gaussian sigma > 1.0)
- Gradient correlating with Zenith angle of observations (above, right)
  - Fit of Non/Acc (Flatness) – Zenith curve used to re-weight acceptance

Deep Exposure Systematics (cont.)

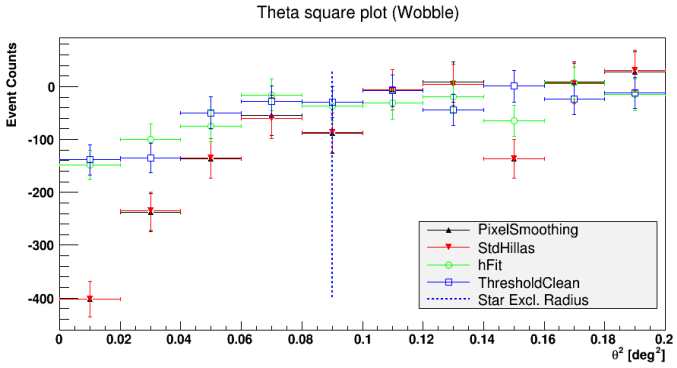
- Bright stars are problematic for IACT data
- Suppressed pixels in cameras for analysis
  - Holes in skymaps
- Segue 1 has bright star (Eta Leonis, 3.8 BMag)
  - located 0.68 deg away
- New HFit algorithm - 2D Gaussian fit of all pixels in camera, no cleaning
- Tested on independent data set - RBG J1058





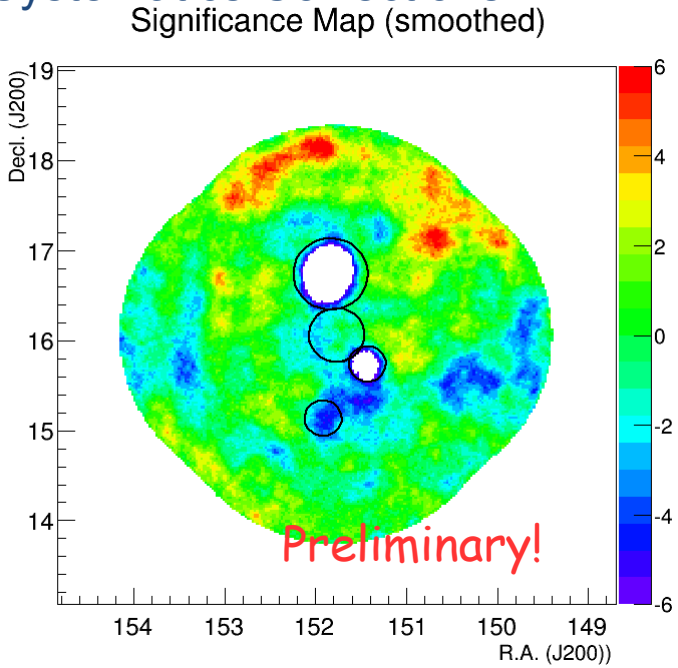


Surface Brightness @ star location

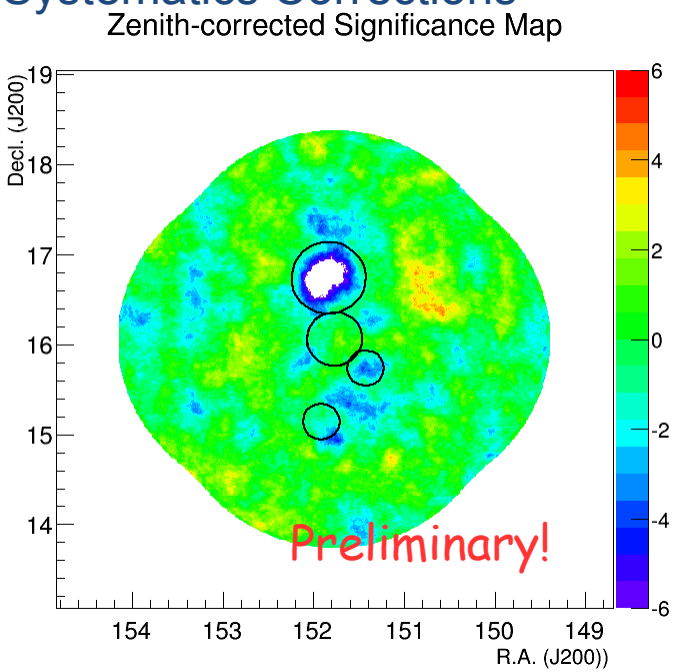


DSph Results Before/After

Before Systematics Corrections



After Systematics Corrections



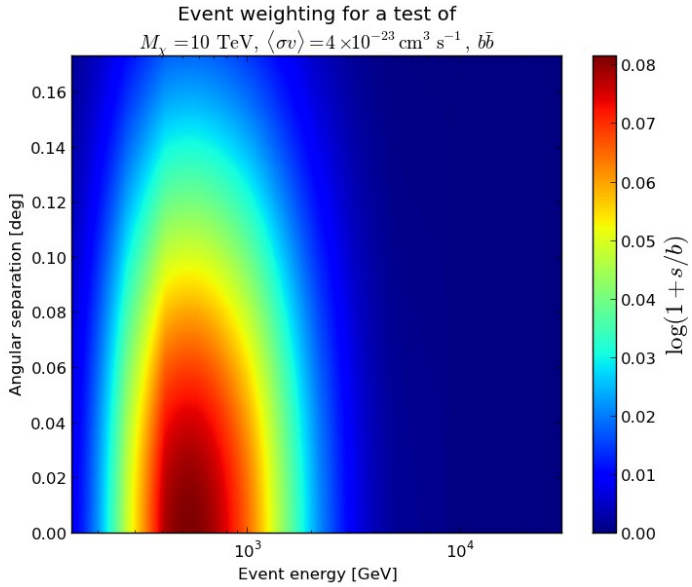
Dsph Results after Systematic corrections:

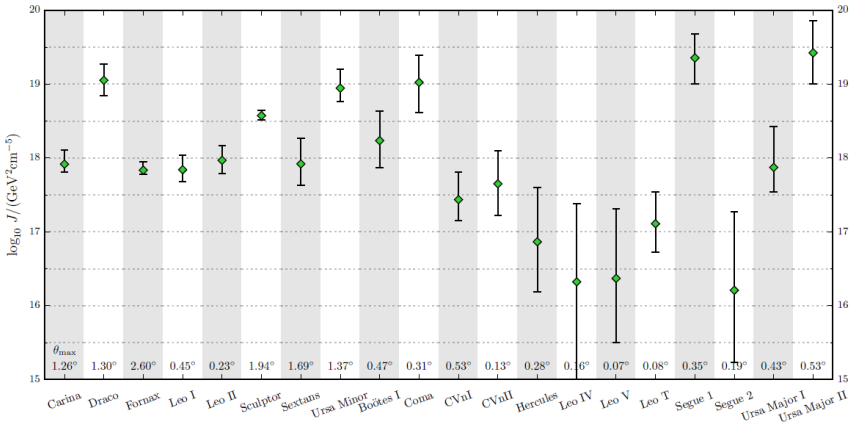
DSph	Exposure (hrs)	Log_{10} J ($\text{GeV}^2\text{cm}^{-5}$)	Significance (σ)	Eth (GeV)	Flux UL, 95% CL (> 300 GeV), Index = -2.4
Segue 1	91.9	19.0	0.7	150	$4.2\text{x}10^{-9}$ $\text{cm}^{-2}\text{s}^{-1}$, ~0.3% CU
Ursa Minor	59.7	18.9	-0.1	290	$3.4\text{x}10^{-9}$ $\text{cm}^{-2}\text{s}^{-1}$, ~0.2% CU
Draco	49.9	18.4	-1.0	220	$3.4\text{x}10^{-9}$ $\text{cm}^{-2}\text{s}^{-1}$, ~0.2% CU
Boötes 1	14.3	17.9	-1.0	170	$5.0\text{x}10^{-9}$ $\text{cm}^{-2}\text{s}^{-1}$, ~0.3% CU
Wilman 1	13.7	18.9	-0.6	180	$1.1\text{x}10^{-8}$ $\text{cm}^{-2}\text{s}^{-1}$, ~0.7% CU

Future Work: Combined DM Analysis

- VERITAS 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 et al. arXiv:1410.2242)
  - 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 M and <σv>
  - Able to combine multiple sources and instruments into a single DM limit
  - Very close to having new DM physics results ready (~1 month)
  - J factors to be used from Geringer-Sameth et al. [arXiv:1408.0002]





arXiv:1408.0002

Concluding Remarks

VERITAS dark matter program is ongoing:

- Observations of dSphs, GC, Fermi UNIDs, galaxy clusters
- No detections of DM (yet!)
- Gaining better understanding of systematics, utilizing new techniques
- Segue 1 Flux UL reduced with longer exposure: ~0.5% Crab → ~0.3% Crab

Future Plans:

- Continuing observations of dark matter targets
- Significant portion of VERITAS observing time (~170 hrs/year)
- Analysis of dSphs for combined analysis paper ongoing (~230 hours!)
  - Gamma-ray analysis/Flux UL complete
  - Dark Matter physics limits soon, including line search
- Galactic center
  - SgrA* detection paper complete
  - Work on DM limits of halo ongoing
- Fermi UNIDs
  - More data to be taken, search for more feasible Fermi UNIDs
- Galaxy Clusters
  - Archival work underway, work on extended source systematics