VERITAS Observations of Dwarf Galaxies

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For The VERITAS Collaboration

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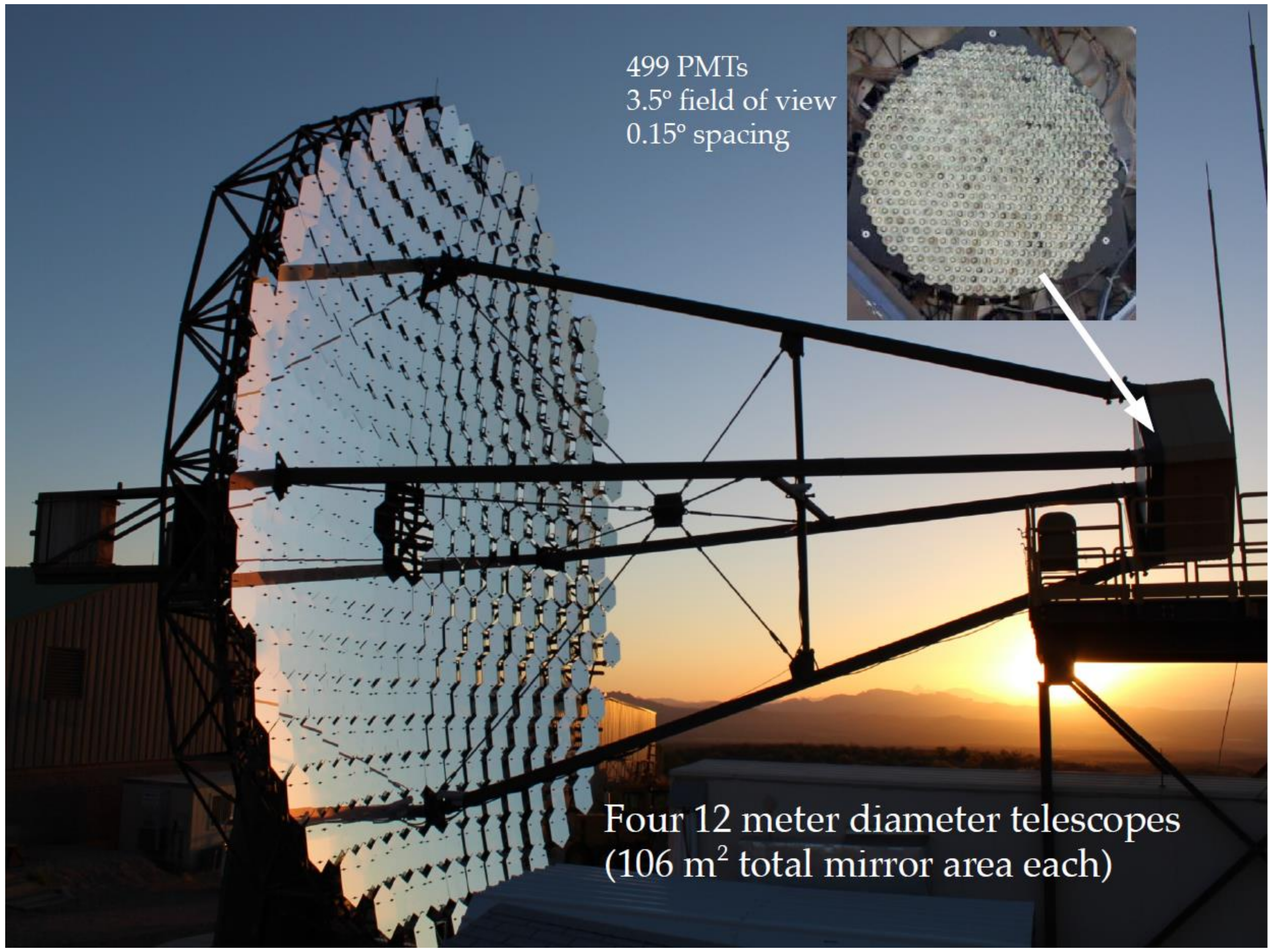
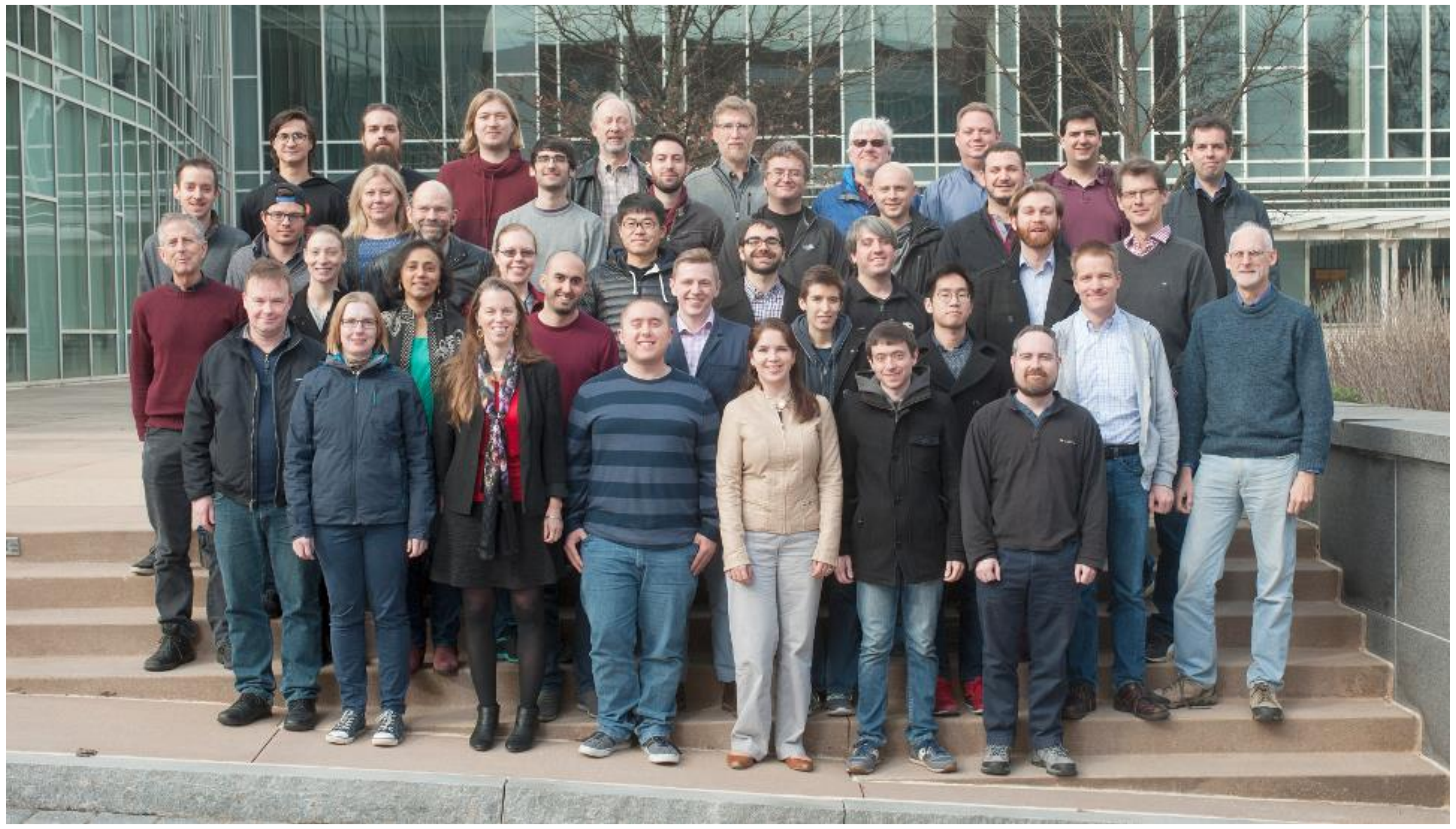
Introduction to VERITAS

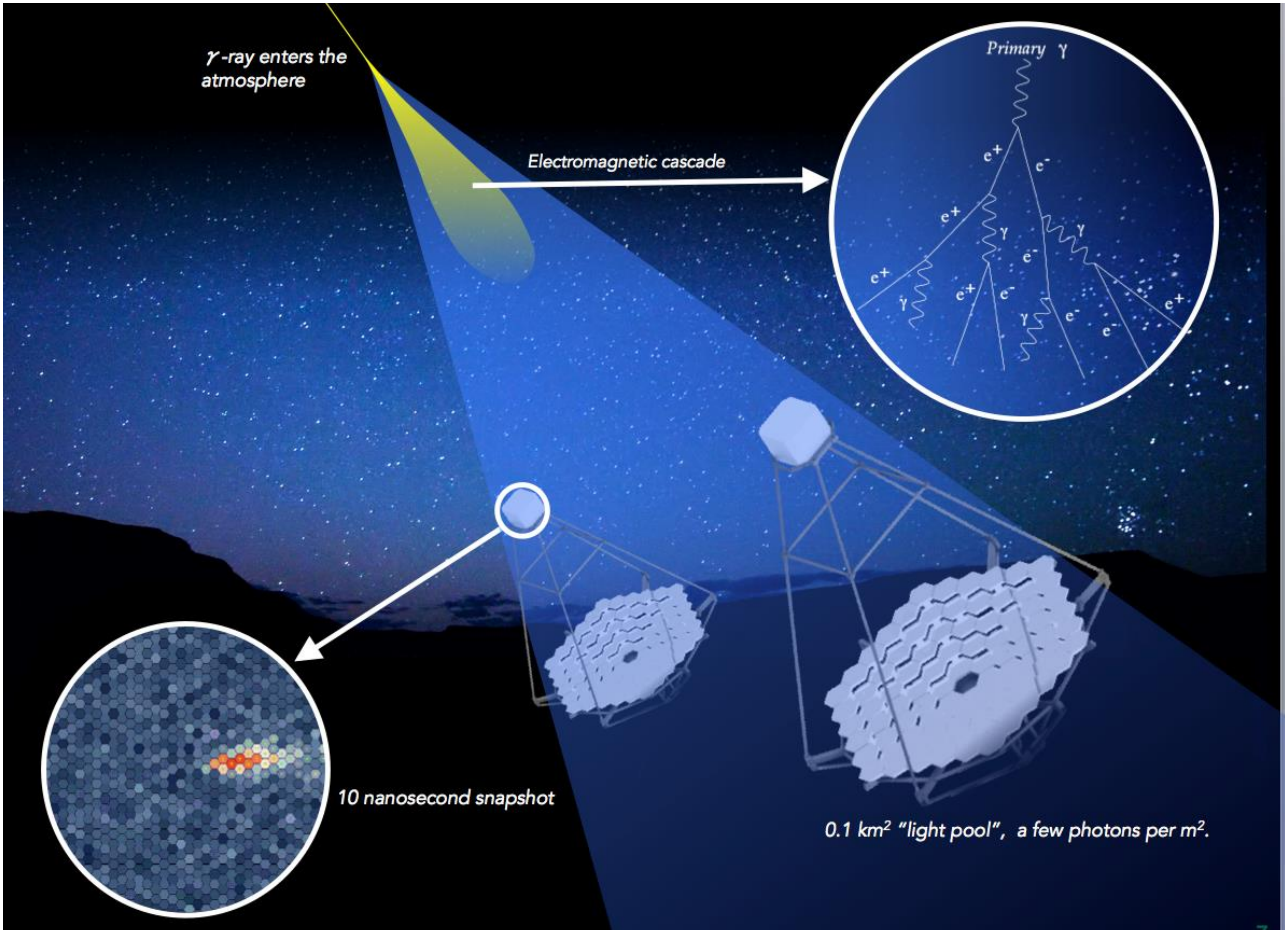


- Array of four IACTs in southern Arizona, USA
- Employs ~100 scientists in five countries
- Full Array operations started in 2007
- Upgrades:
  - Move of telescope 1 in Summer 2009 and improved mirror alignment system
  - FPGA-based camera trigger upgrade in 2Fall 2011
  - Camera Upgrade with High-QE PMTs in Summer 2012



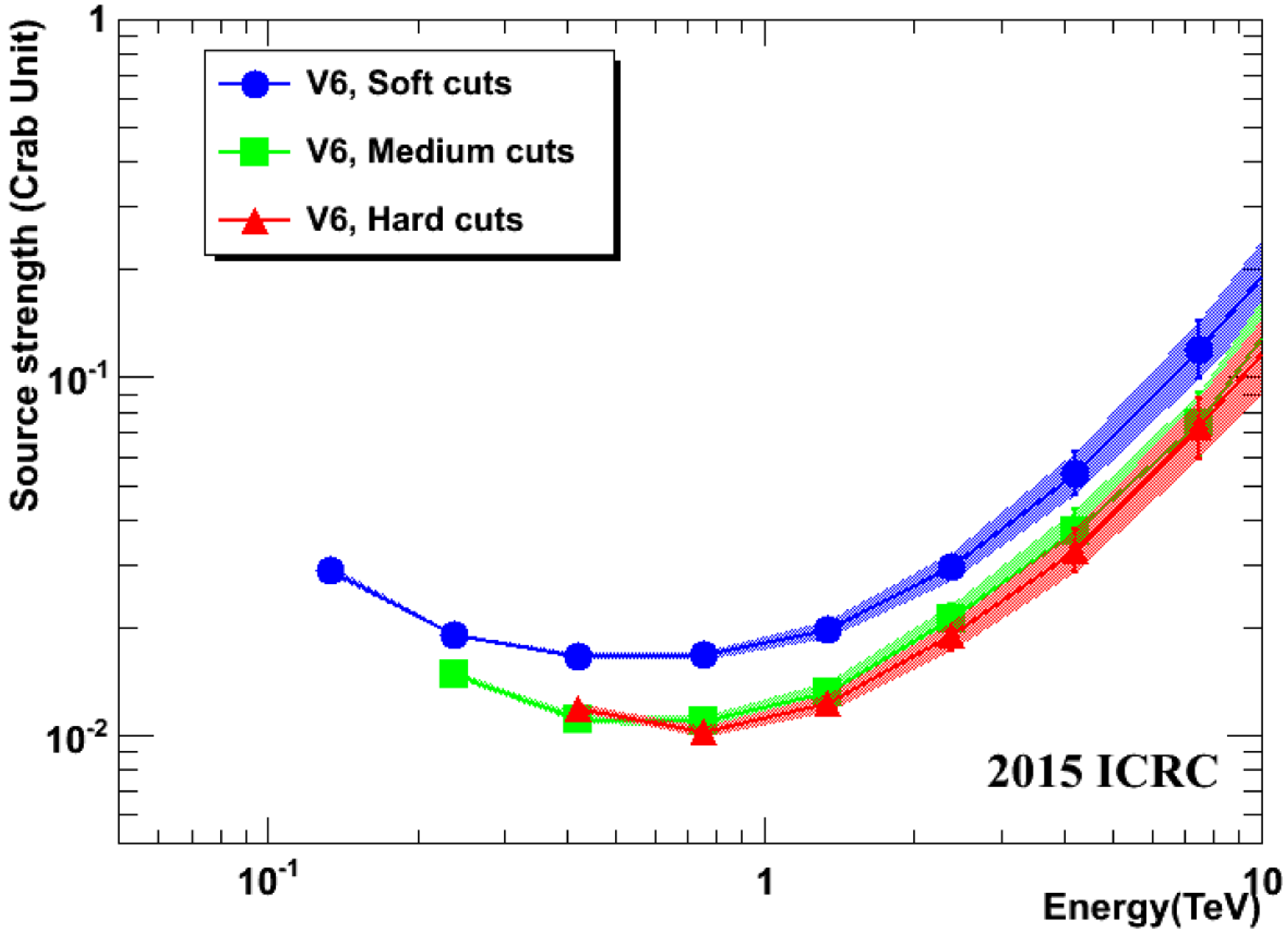
- Support From:
  - NSF (USA)
  - DOE (USA)
  - Smithsonian Institution (USA)
  - NSERC (Canada)

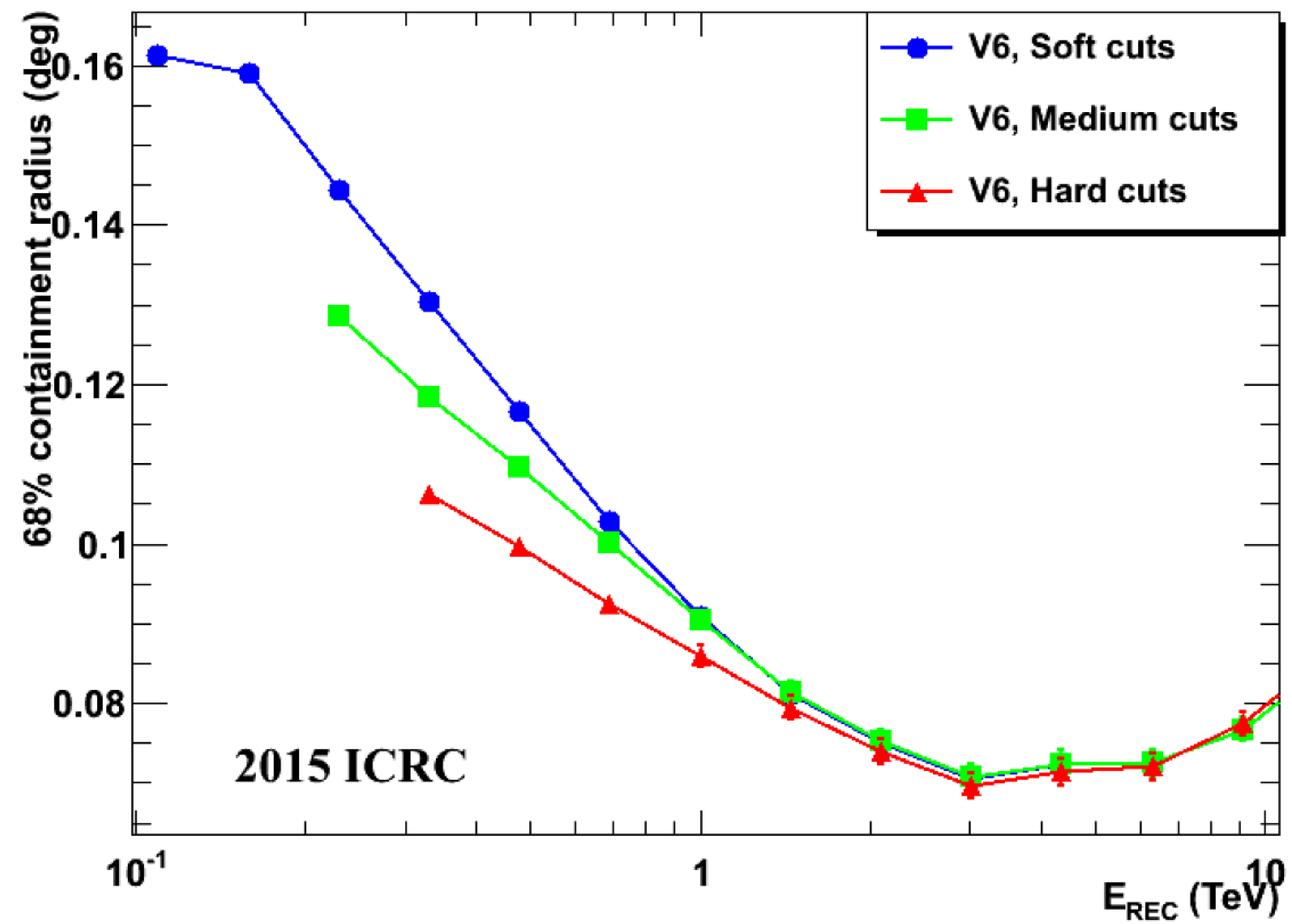
Atmospheric Cherenkov Technique



www.cta-observatory.org

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	
$\chi\chi \to \tau^{\pm}$	$\tau^{\pm} \to \nu_{\tau}e^{\pm}\nu_e,\ \tau \to \nu_{\tau}W^{\pm} \to p, \bar{p}$, 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?)
$\chi\chi \to \phi\bar{\phi}$	$\phi \to e^+e^-$ internal/final state bremms inverse Compton γ's	$e^{\pm}$	New scalar field with $m_{\chi} < m_{\phi}$ to explain large electron signal and avoid overproduction of p, γ

Almost all roads lead to gamma rays!

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

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

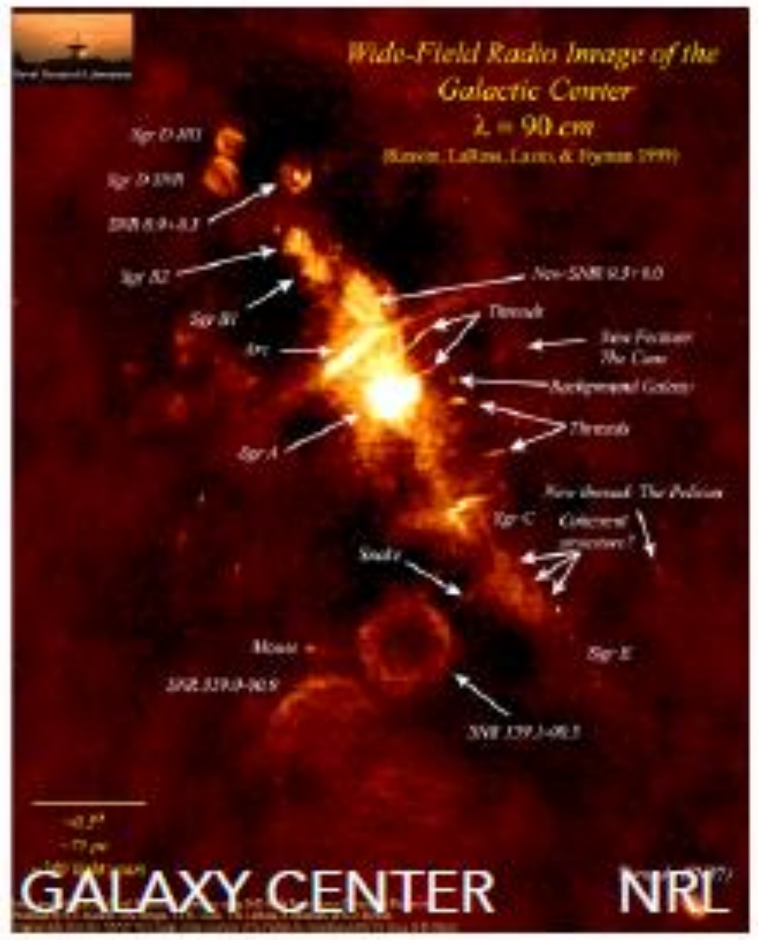
$$= \boxed{\frac{\langle\sigma v\rangle}{8\pi M^2}\frac{dN_\gamma(E)}{dE}}\ \boxed{\int d\ell\,\rho^2(\ell\hat{\mathbf{n}})}$$

Particle Physics

Astrophysics (J factor)

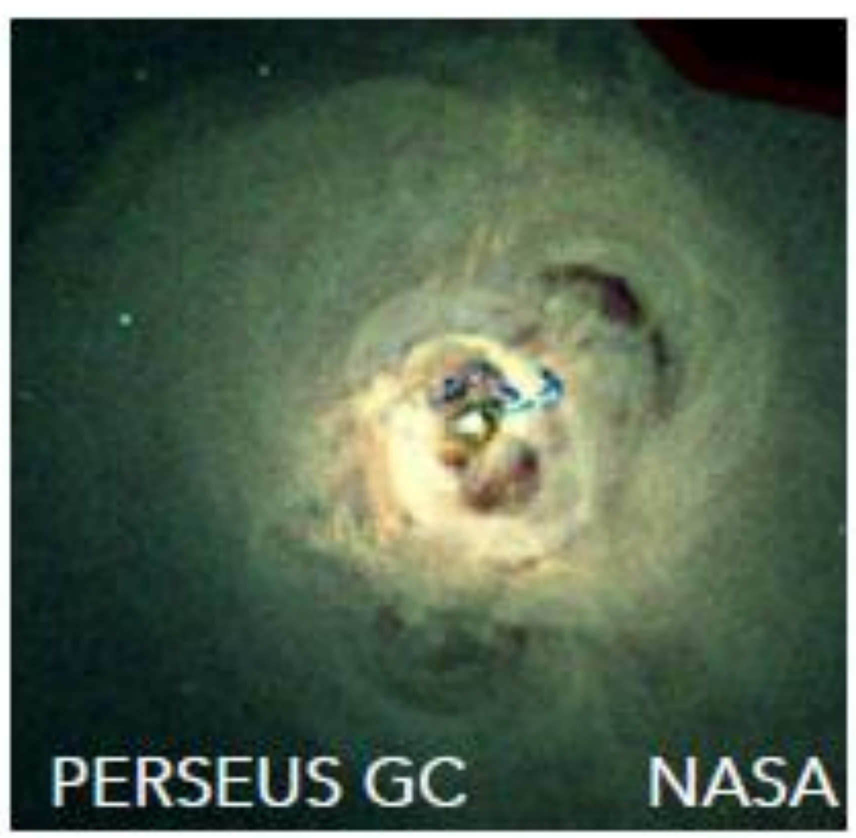
VERITAS Dark Matter Targets

Galactic Center (GC)
- Close by (~8kpc)
- Large DM content
- Astrophysical backgrounds

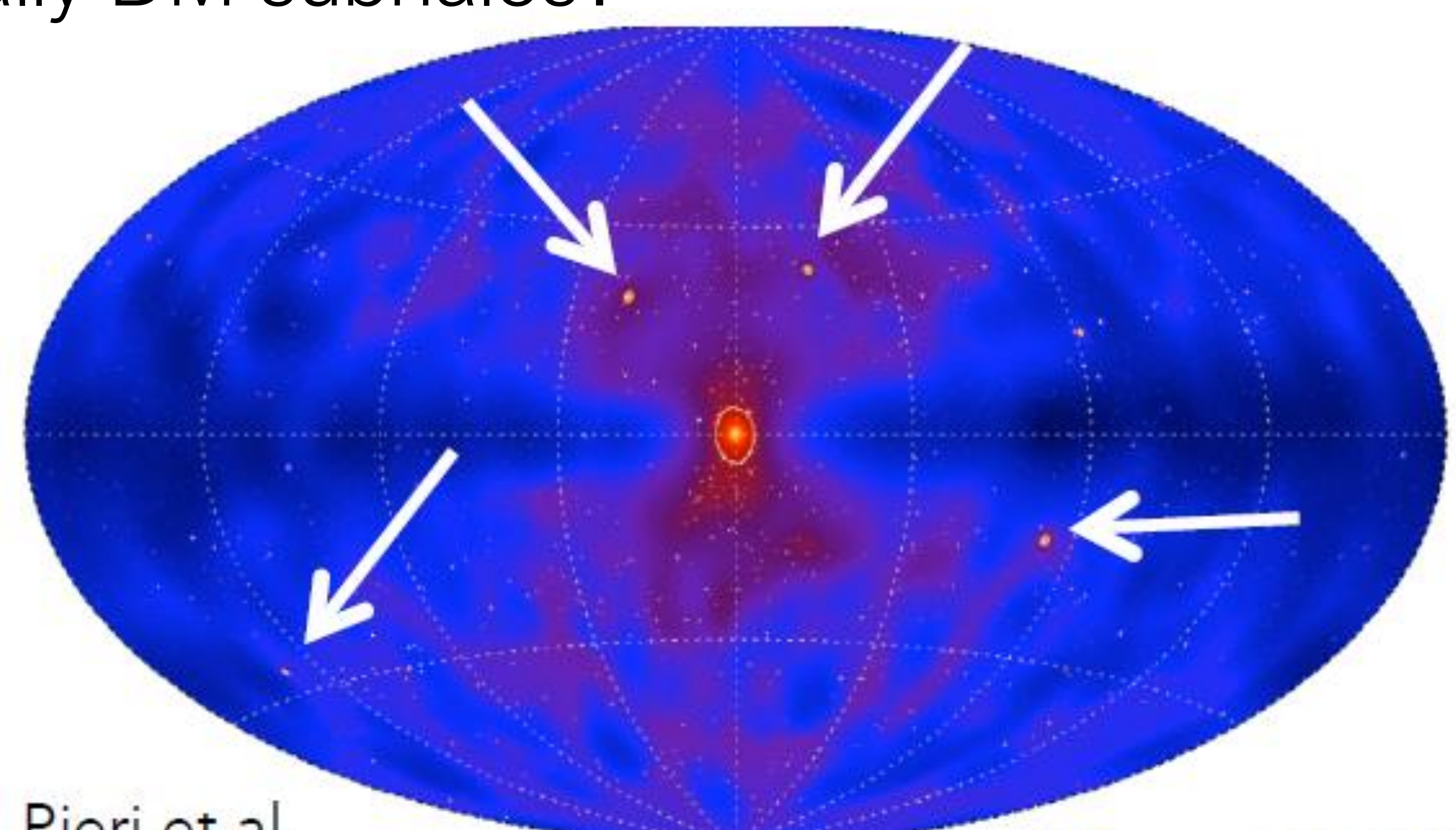


Dwarf Galaxies (DSphs)
- No known astrophysical backgrounds
- Close by (~10's kpc)
- High mass/light ratio

Galaxy Clusters
- Distant
- Large DM content
- Many are extended
- Astrophysical backgrounds (?)



Fermi Unidentified Objects
- Potentially DM subhalos?



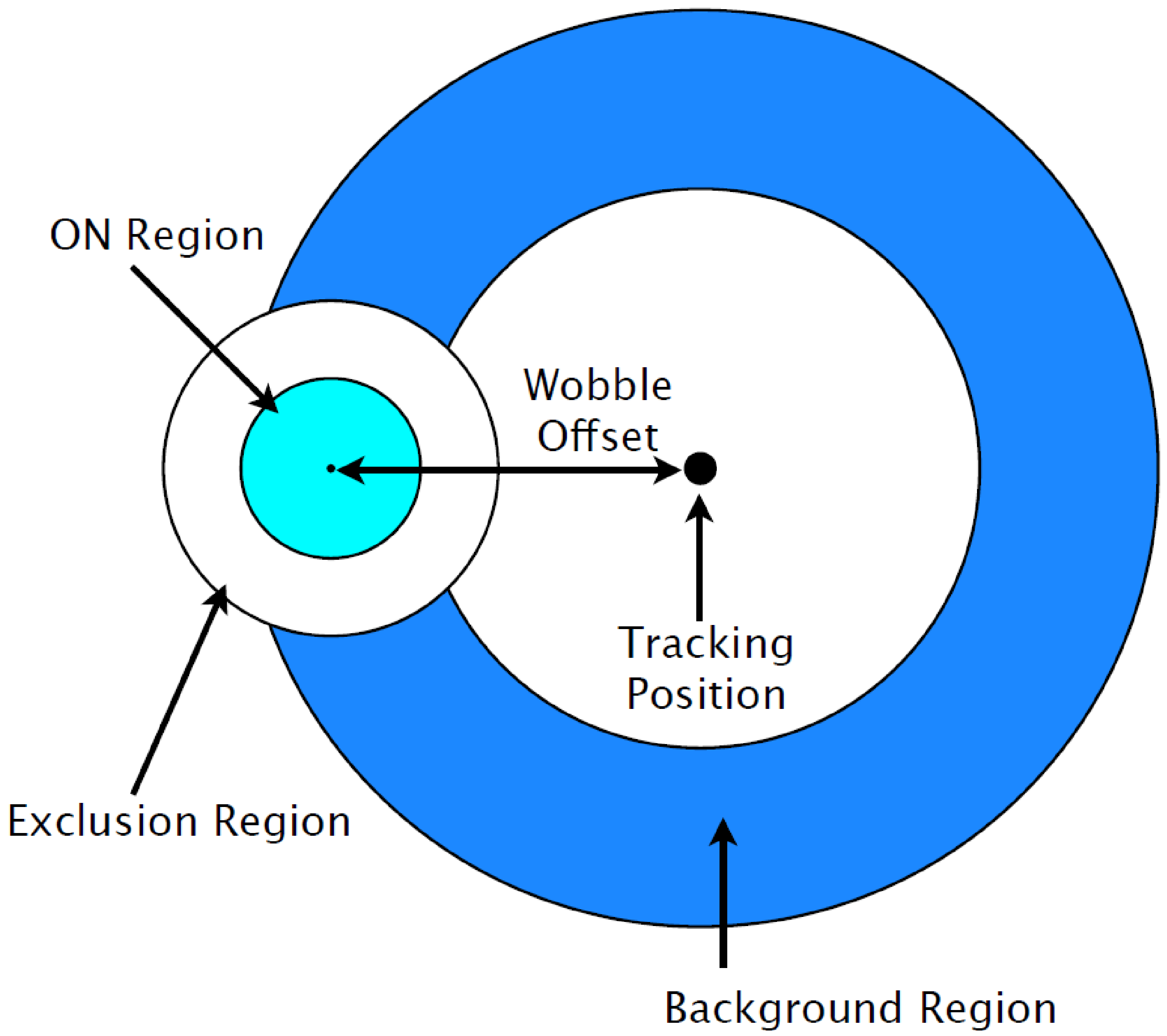
Pieri et al.
PRD 83:0235, 2008

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

VERITAS Dwarf Galaxy Observations: 2007 to 2013

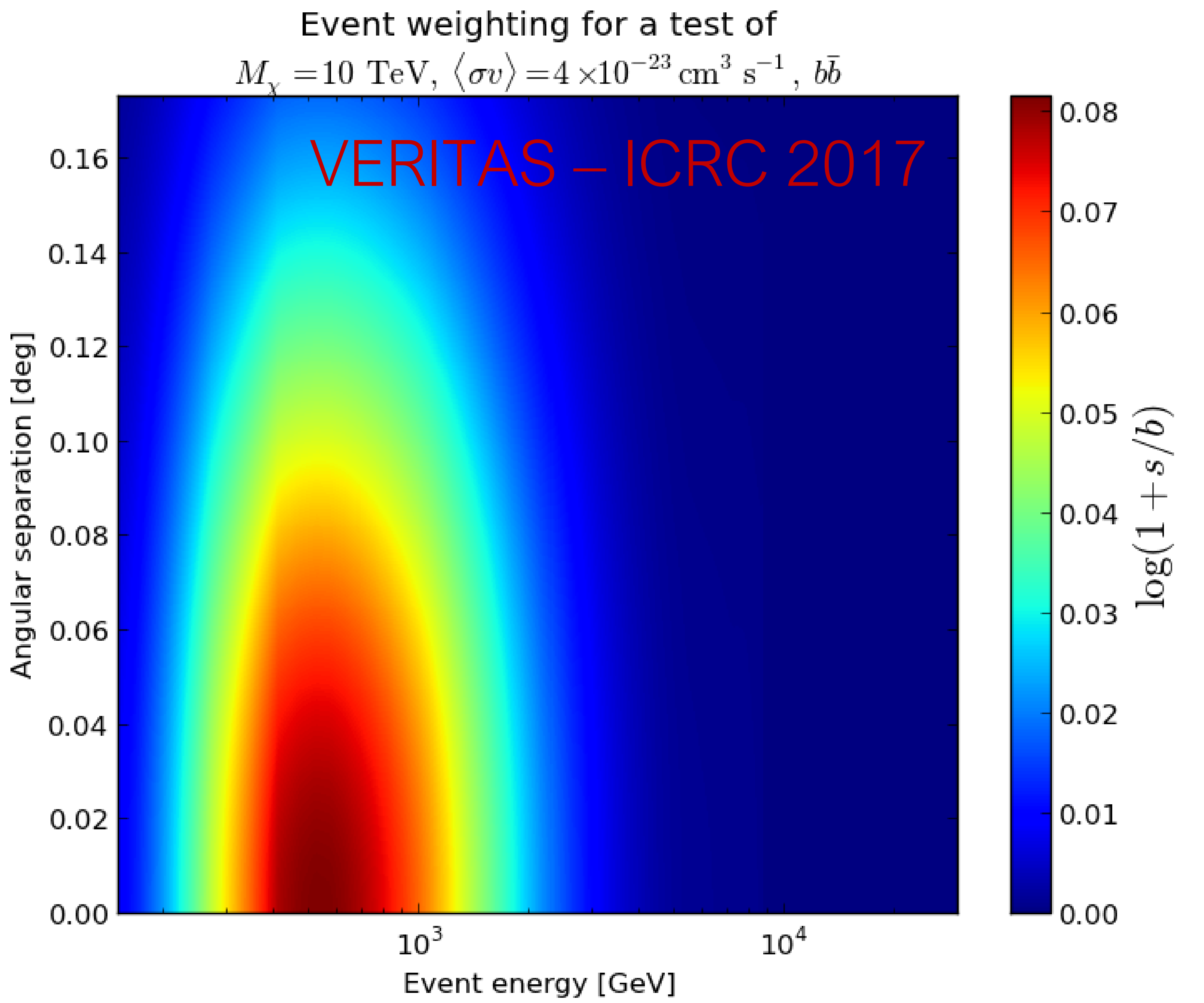
DSph	N_{ON} [counts]	N_{OFF} [counts]	$\bar{\alpha}$	Significance [σ]	$N^{95\%}$ [counts]	$\Phi^{95\%}$ [$10^{-12}\text{cm}^2\text{s}^{-1}$]	Distance [kpc]	$\log_{10} J(0.17°)$ [$\text{GeV}^2\ \text{cm}^{-5}$]
Segue 1	15895	120826	0.131	0.7	235.8	0.34	23	$19.2^{+0.3}_{-0.3}$
Draco	4297	39472	0.111	-1.0	33.5	0.15	76	$18.3^{+0.1}_{-0.1}$
Ursa Minor	4181	35790	0.119	-0.1	91.6	0.37	76	$18.9^{+0.3}_{-0.3}$
Boötes 1	1206	10836	0.116	-1.0	34.5	0.40	66	$18.3^{+0.3}_{-0.4}$
Willman 1	1926	18187	0.108	-0.6	23.5	0.39	38	N/A

- Recent VERITAS Publication:
  - Archambault et al. Phys. Rev. D 95, 082001
- Five dSphs observed by VERITAS between 2007 and 2013
  - Total of 230 hours after data quality selection
  - 92 hours Segue 1
- Crescent-shaped region used for background subtraction
- No gamma-ray detection
- Integral flux upper limits above 300 GeV for each dSph



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, angular distance from dwarf center and dwarf field
  - proportional to likelihood 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>
  - Limits on plots where DM hypothesis is rejected at 95% confidence for a given mass



Weight

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

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

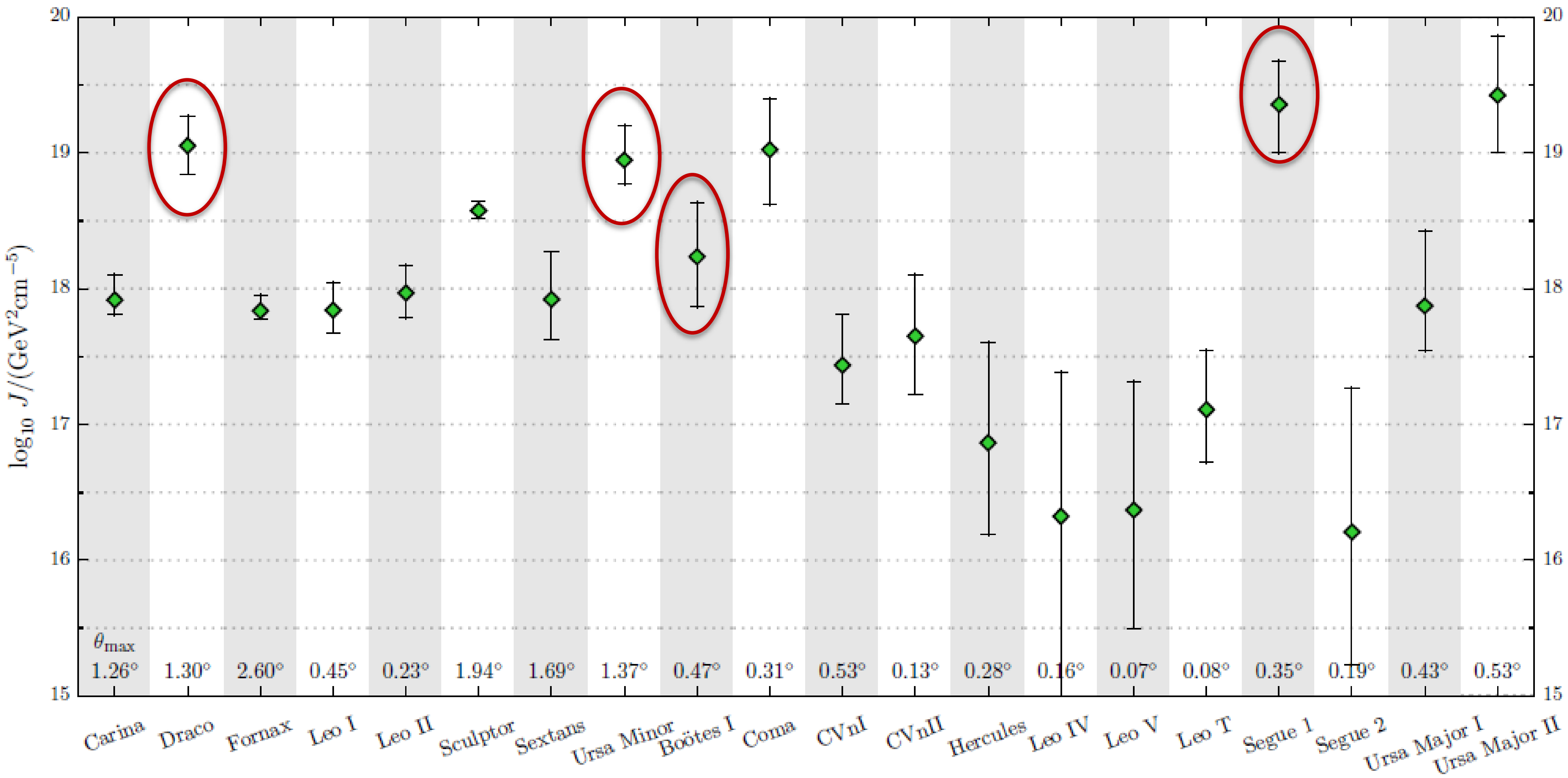
Particle Physics

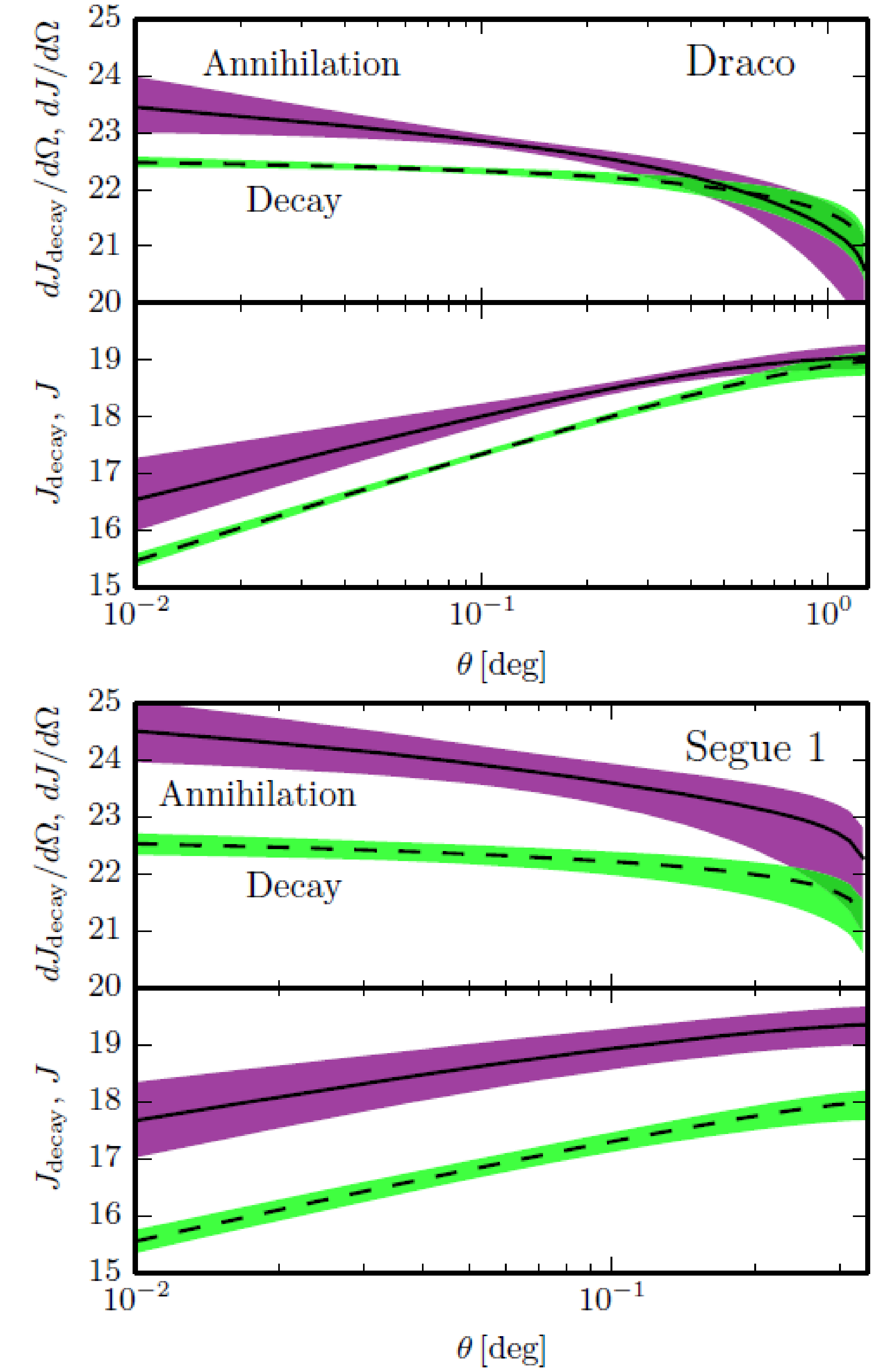
$$\frac{dF(E, \hat{\mathbf{n}})}{dE d\Omega} = \frac{\langle\sigma v\rangle}{8\pi M^2} \frac{dN_\gamma(E)}{dE} \frac{dJ(\hat{\mathbf{n}})}{d\Omega}$$

Detector Response

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

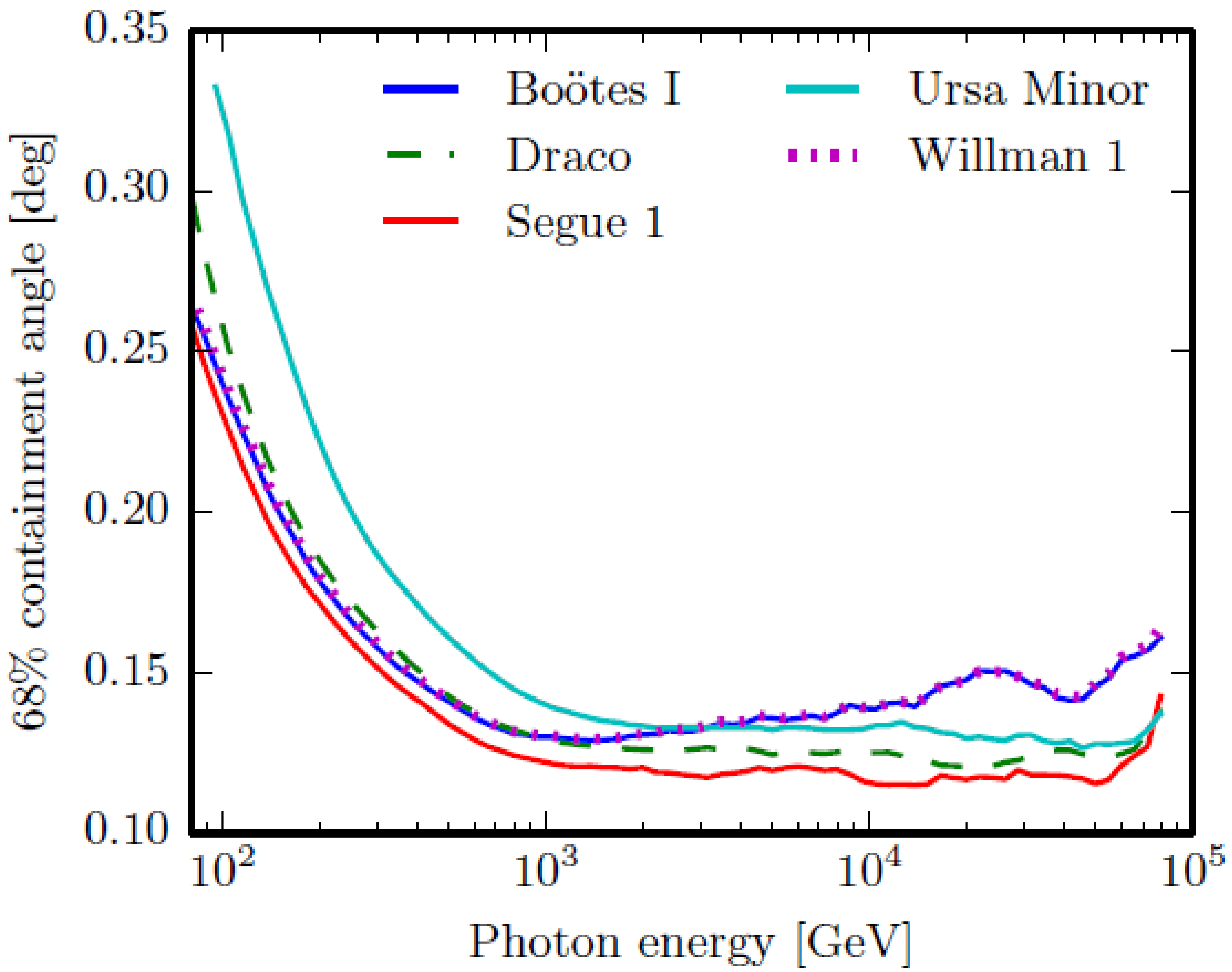
Dark Matter Distribution in Dwarf Galaxies

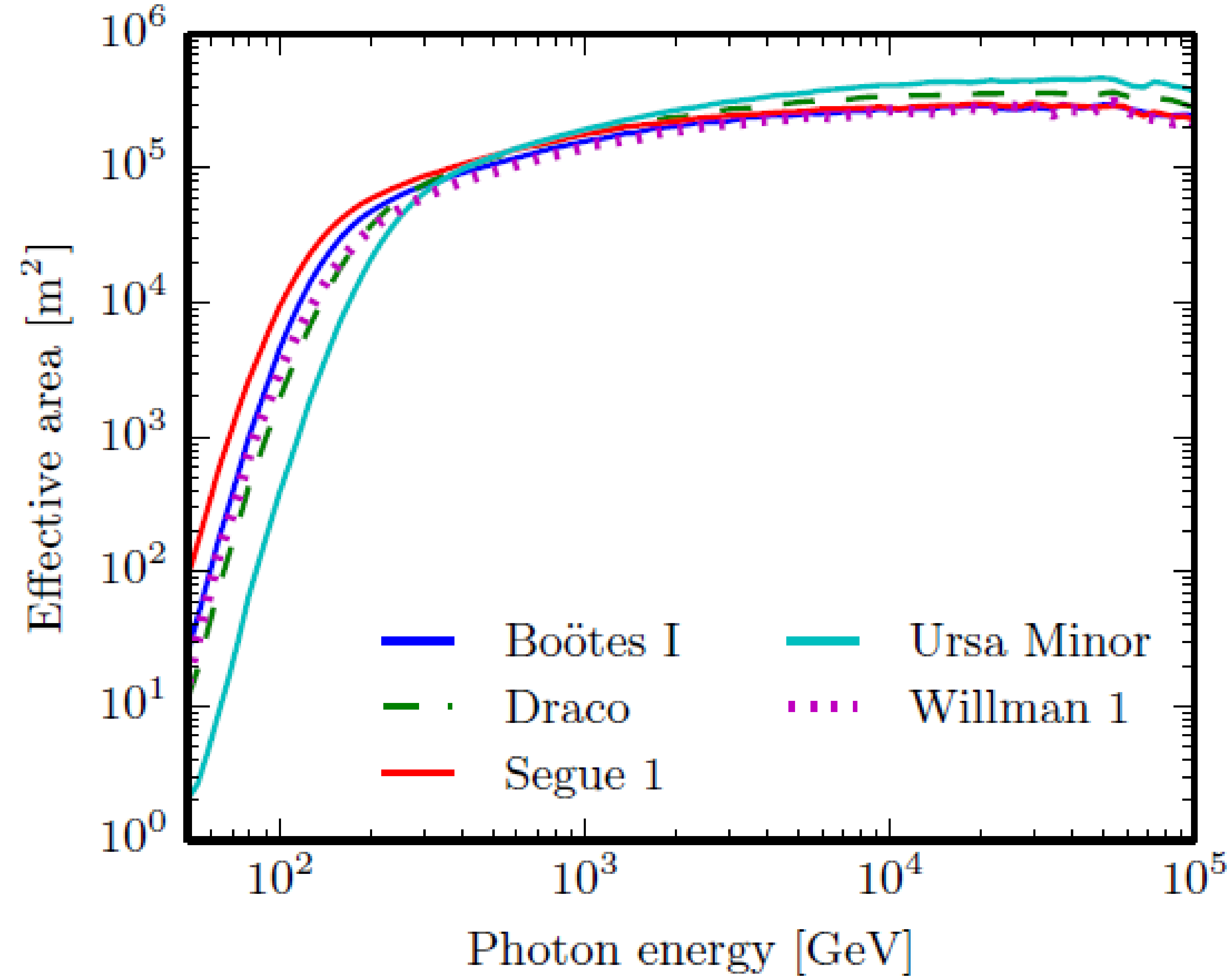




- J factor per unit solid angle needed for event weights, which is mass density squared integrated along the line of sight:
- Velocities and positions of stars gravitationally bound to the dSphs are obtained and used to find mass density
- A likelihood function relates the star velocities to the mass density through the Jean's equation
- Mass density best fit to a generalized NFW profile: $\rho(r) = \rho_s [r/r_s]^{-\gamma} [1 + (r/r_s)^{\alpha}]^{(\gamma-\beta)/\alpha}$
- Figures and J factors used from Geringer-Sameth et al. ApJ, Vol. 801, Issue 2 (2015)

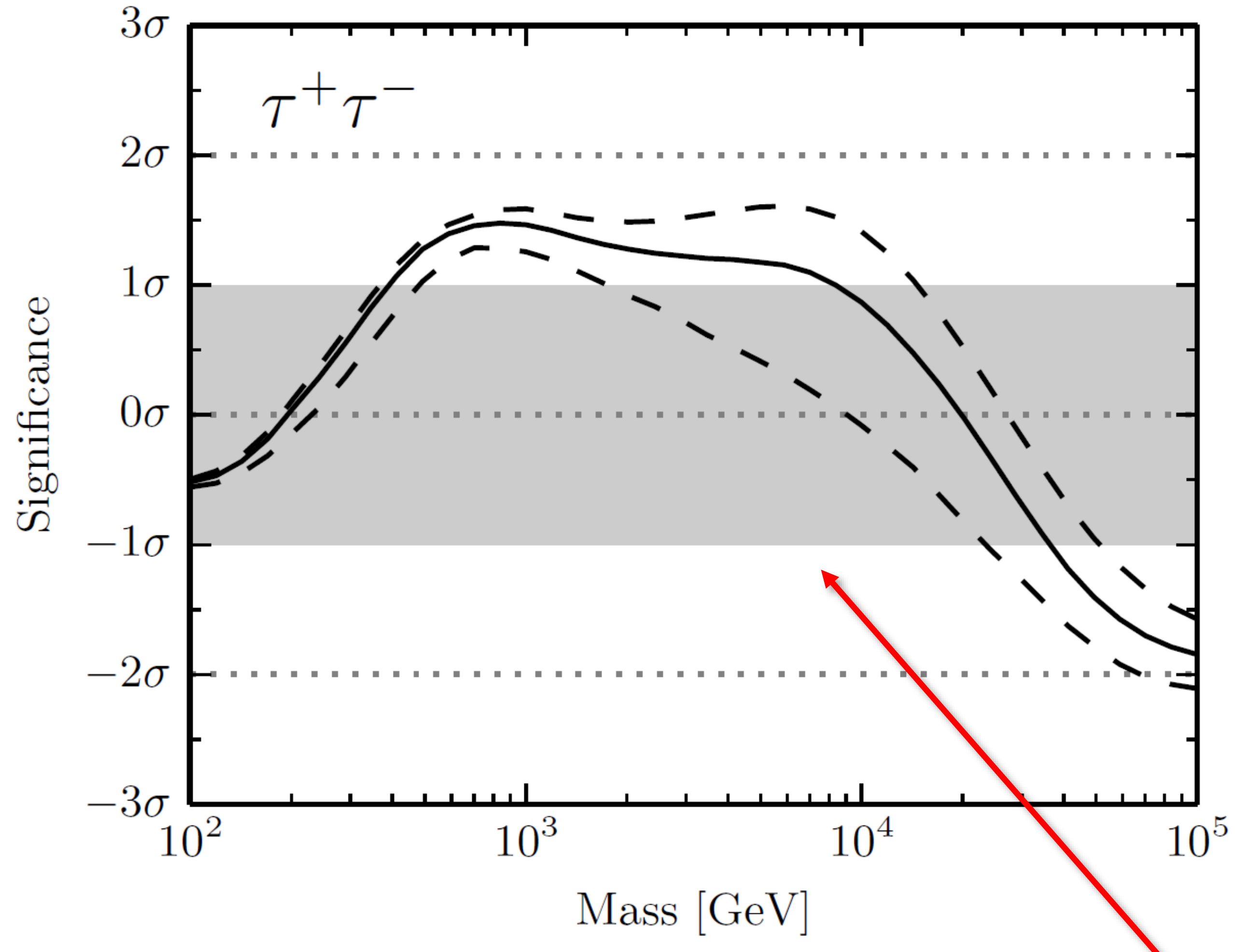
VERITAS Detector Response

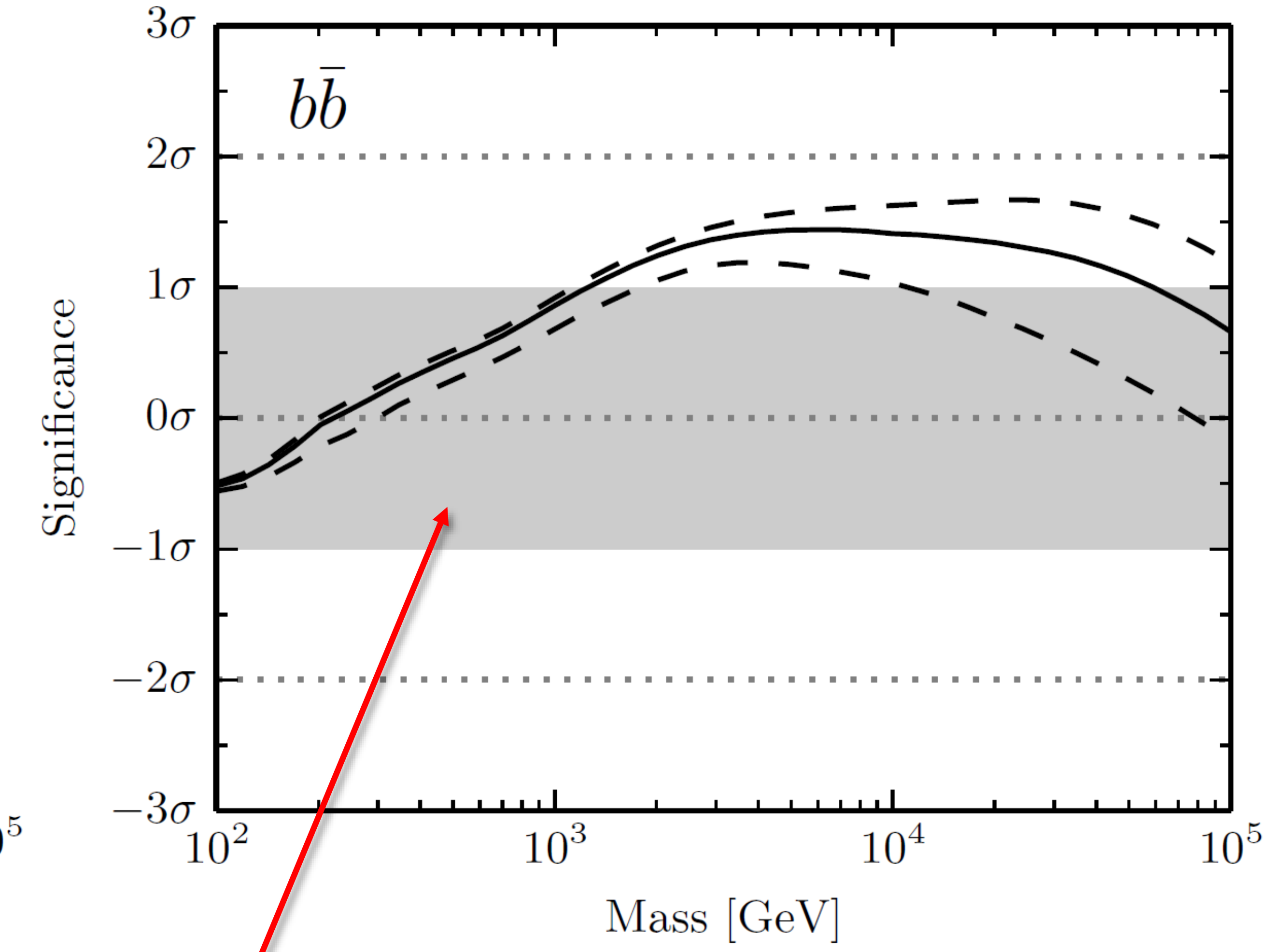


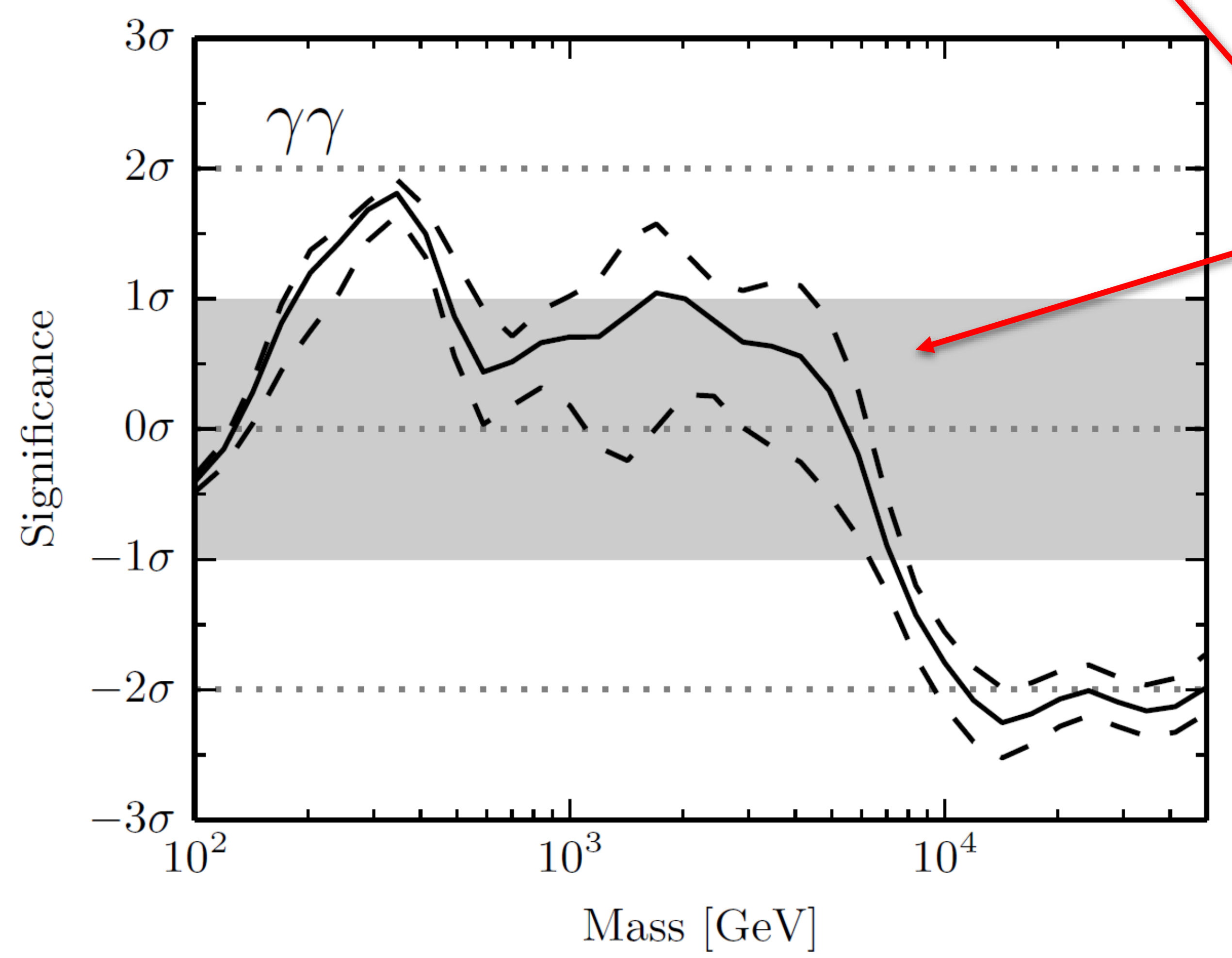


- VERITAS detector response required for event weighting
- PSF convolved with dJ/dΩ to determine weights as a function of direction
- Effective areas, PSF and Energy Dispersion (i.e $P(E \mid E_{tr})$) determined from γ-ray simulations produced by Corsika and put through VERITAS detector response functions
- Variations due to observing conditions for each dSph (e.g. observed zenith angle)

Dark Matter Search from Dwarf Galaxies

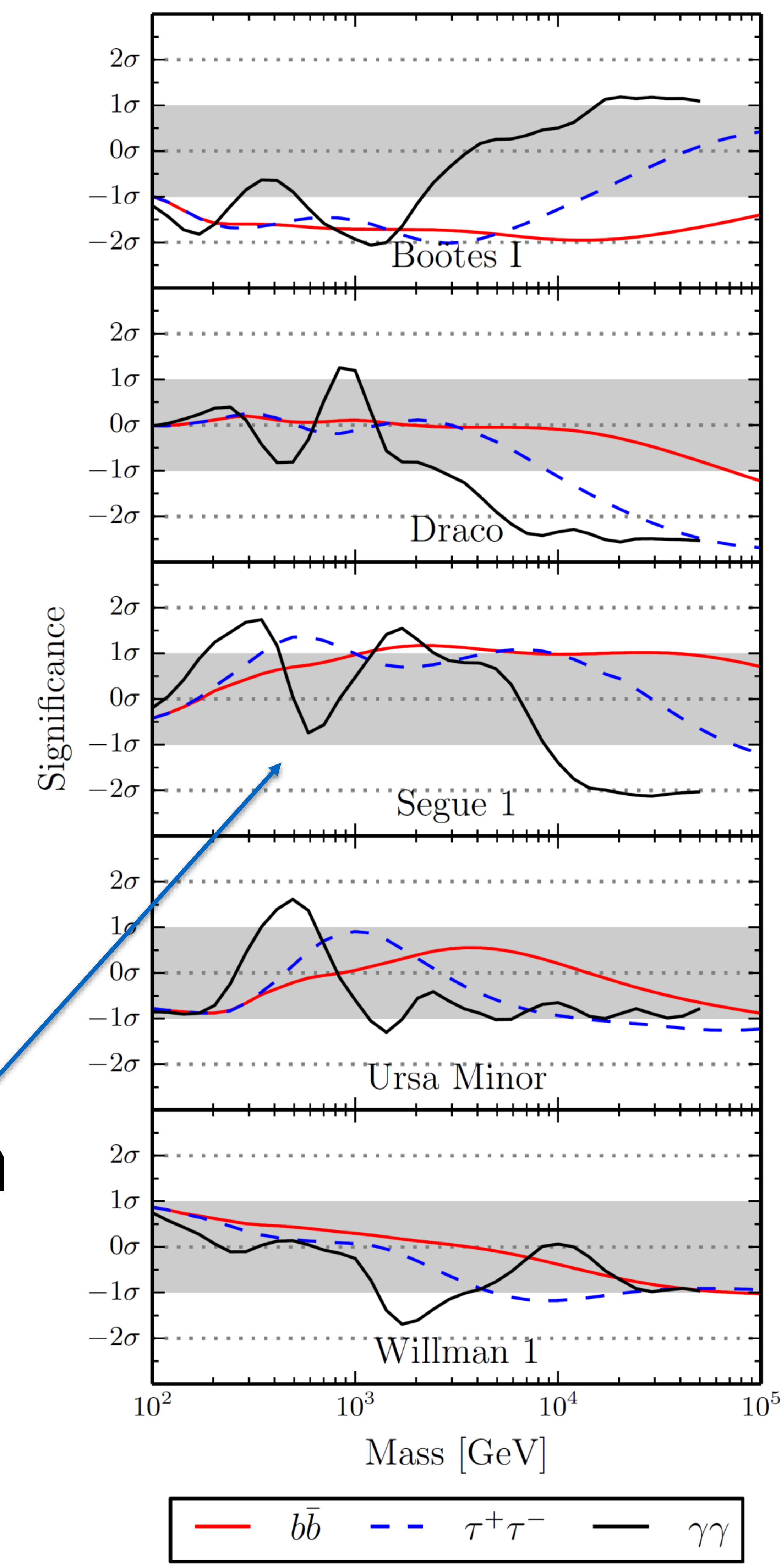




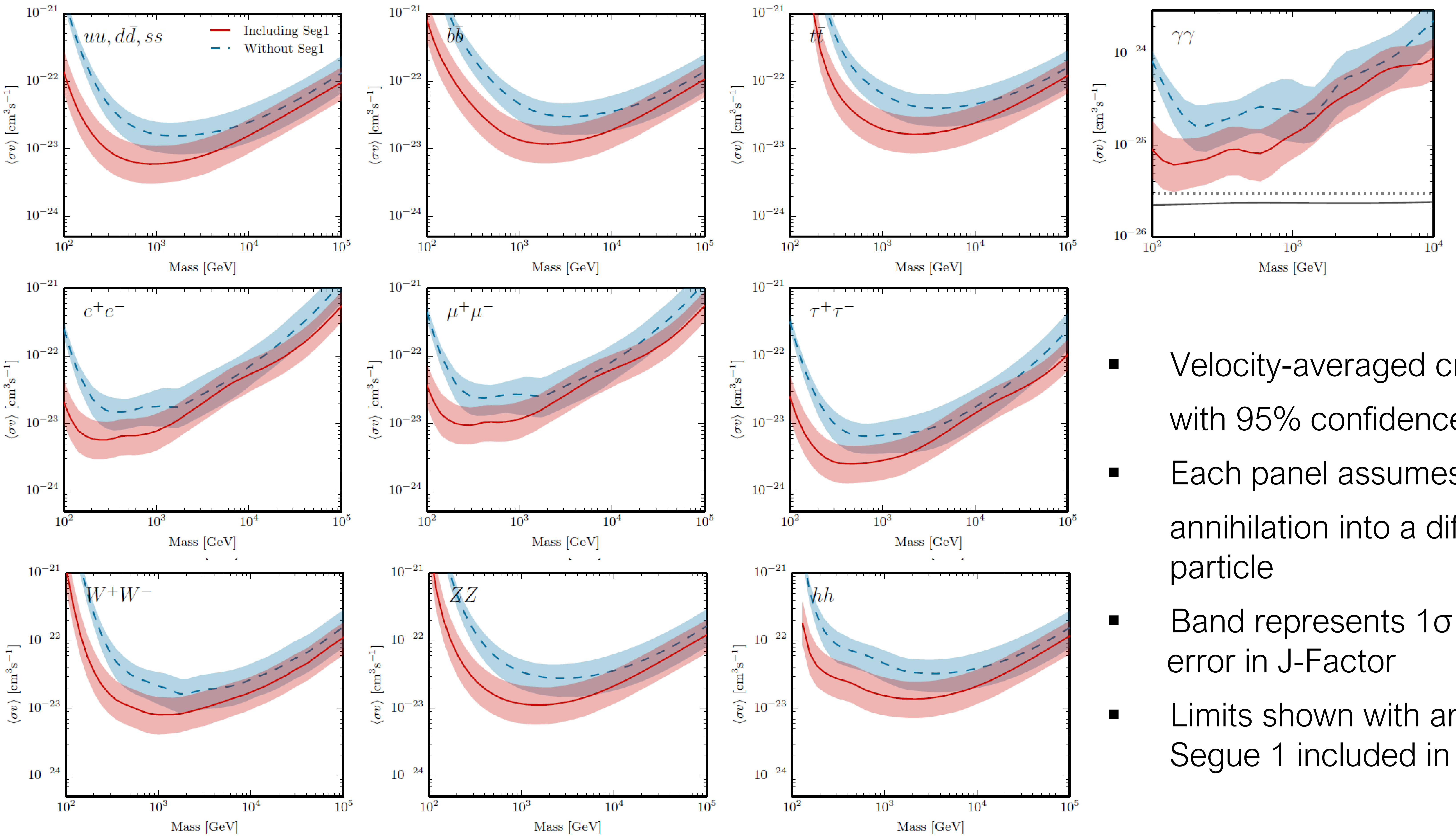


Combined Search

Individual Dwarf Search

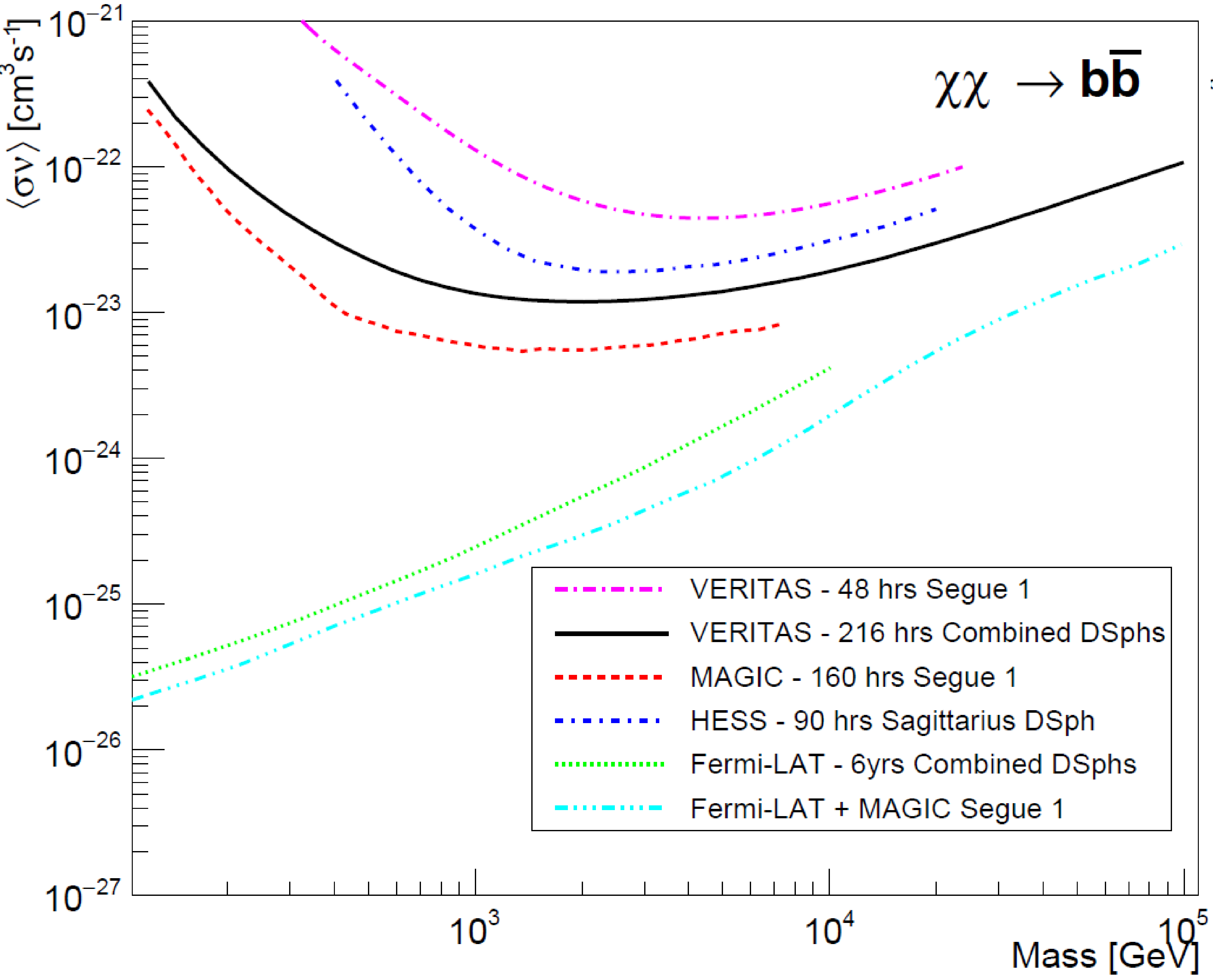


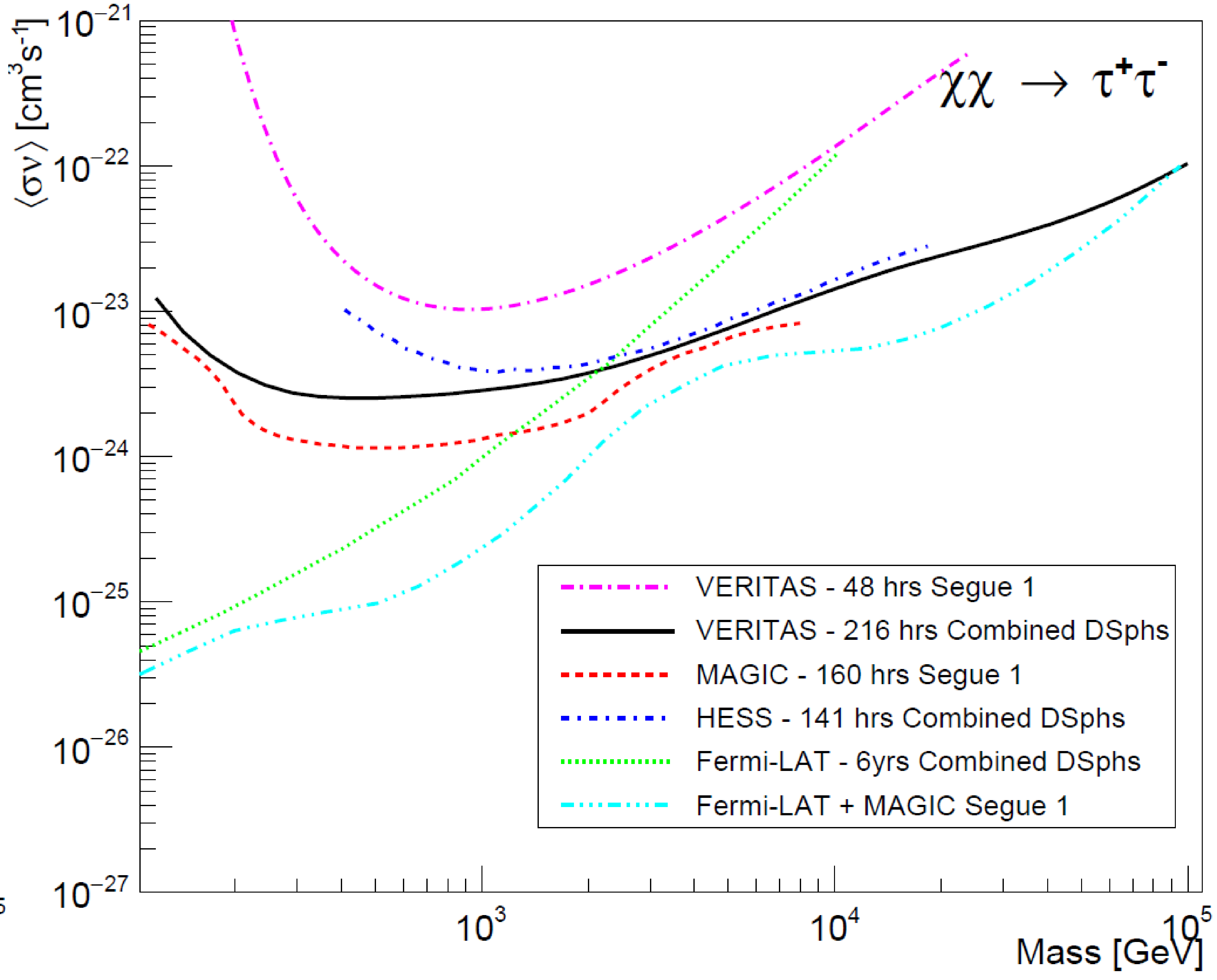
Dark Matter Search from Dwarf Galaxies



- Velocity-averaged cross section with 95% confidence level
- Each panel assumes 100% annihilation into a different SM particle
- Band represents 1σ systematic error in J-Factor
- Limits shown with and without Segue 1 included in combined limit

Comparison with other Experiments





A Decade of VERITAS Dwarf Observations

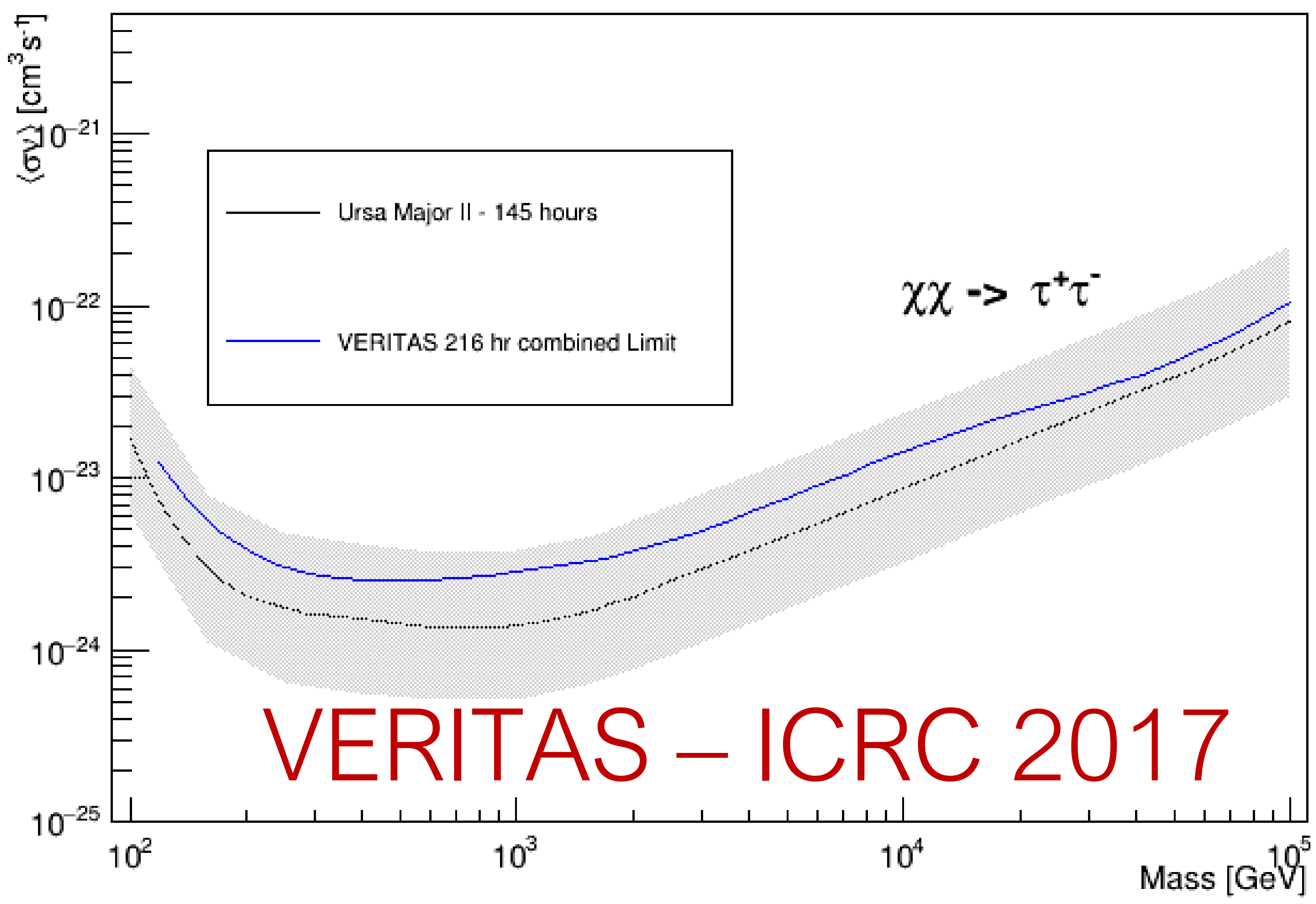
- VERITAS Dwarf Observations Divided into two Classes:
  - **Deep Exposure** – dSphs with typically the best J-Factors in the literature to get best DM sensitivity
  - Deep Exposure dSphs are a combination of 'Classical' (i.e. Draco, Ursa Minor) and 'Ultra-faint' (i.e. Segue I, Ursa Major II) dSphs
  - **Survey** - dSphs covering nearly all Northern Hemisphere dSphs
  - This strategy ensures the program is not severely impacted if one of the dSphs is no longer considered a viable indirect DM target.
    - Example: Segue 1 from Bonnivard et al. 2015

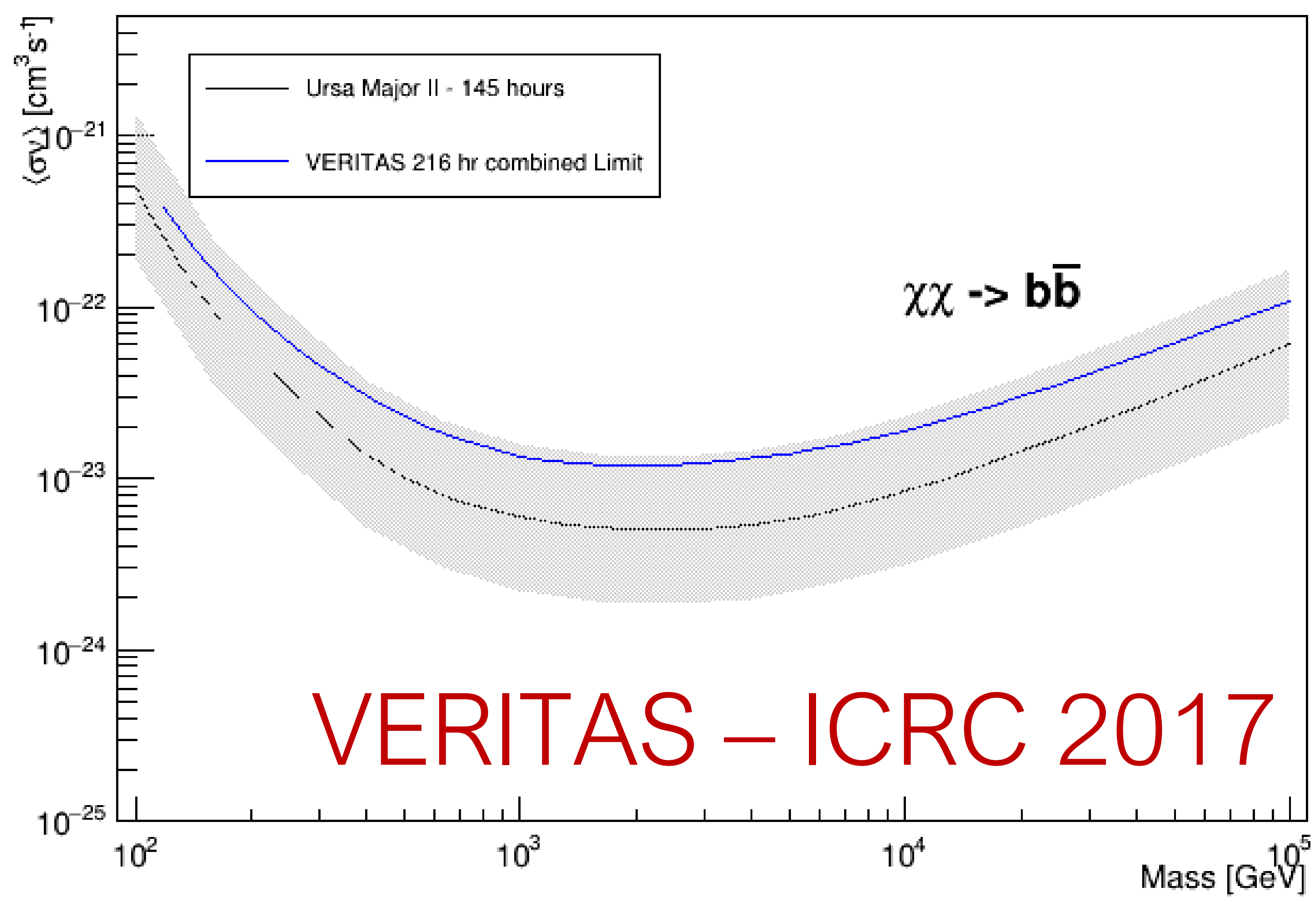
A Decade of VERITAS Dwarf Observations

Dwarf	$\log_{10} J_1(0.5°)$ [GeV^2 cm^{-5}]	$\log_{10} J_2(0.5°)$ [GeV^2 cm^{-5}]	$\log_{10} D_1(0.5°)$ [GeV cm^{-2}]	Exposure v4 [min]	Exposure v5 [min]	Exposure v6 [min]	Total Exposure [min]
Segue 1	$19.4^{+0.3}_{-0.4}$	$17.0^{+2.1}_{-2.2}$	$18.0^{+0.2}_{-0.3}$	0	6121	4921	11042
Ursa Major II	$19.4^{+0.4}_{-0.4}$	$19.9^{+0.7}_{-0.5}$	$18.4^{+0.3}_{-0.3}$	0	0	10869	10869
Ursa Minor	$18.9^{+0.3}_{-0.2}$	$19.0^{+0.1}_{-0.1}$	$18.0^{+0.2}_{-0.1}$	711	2209	6844	9724
Draco	$18.8^{+0.1}_{-0.1}$	$19.1^{+0.4}_{-0.2}$	$18.5^{+0.1}_{-0.1}$	1169	2170	3435	6813
Coma Berencies	$19.0^{+0.4}_{-0.4}$	$19.6^{+0.8}_{-0.7}$	$18.0^{+0.2}_{-0.3}$	0	0	2204	2204
Segue II	$16.2^{+1.1}_{-1.0}$	$18.9^{+1.1}_{-1.1}$	$15.9^{+0.4}_{-0.4}$	0	0	1128	1128
Boötes 1	$18.2^{+0.4}_{-0.4}$	$18.5^{+0.6}_{-0.4}$	$17.9^{+0.2}_{-0.3}$	960	0	0	960
Leo II	$18.0^{+0.2}_{-0.2}$	$17.8^{+0.2}_{-0.2}$	$17.2^{+0.4}_{-0.5}$	0	0	946	946
Willman 1	N/A	N/A	N/A	931	0	0	931
Triangulum II	N/A	N/A	N/A	0	0	909	909
Canes Ver. II	$17.7^{+0.5}_{-0.4}$	$18.5^{+1.2}_{-0.9}$	$17.0^{+0.2}_{-0.2}$	0	0	864	864
Canes Ver. I	$17.4^{+0.4}_{-0.3}$	$17.5^{+0.4}_{-0.2}$	$17.6^{+0.4}_{-0.7}$	0	0	850	850
Hercules I	$16.9^{+0.7}_{-0.7}$	$17.5^{+0.7}_{-0.7}$	$16.7^{+0.4}_{-0.4}$	0	0	794	794
Sextans I	$18.0^{+0.2}_{-0.2}$	$17.6^{+0.2}_{-0.2}$	$17.9^{+0.1}_{-0.2}$	0	0	783	783
Draco II	N/A	N/A	N/A	0	0	598	598
Ursa Major I	$17.9^{+0.6}_{-0.3}$	$18.7^{+0.6}_{-0.5}$	$17.6^{+0.2}_{-0.4}$	0	0	482	482
Leo I	$17.8^{+0.2}_{-0.2}$	$17.8^{+0.5}_{-0.2}$	$17.9^{+0.2}_{-0.2}$	0	0	409	409
Leo V	$16.4^{+0.9}_{-0.9}$	$16.1^{+1.2}_{-1.0}$	$15.9^{+0.5}_{-0.5}$	0	0	167	167
Leo IV	$16.3^{+1.1}_{-1.7}$	$16.2^{+1.5}_{-1.6}$	$16.1^{+0.7}_{-1.1}$	0	0	151	151

- V4 – before T1 move, V5 – after T1 move, V6 – after camera upgrade
- J factors from ApJ, Vol. 801, Issue 2 (2015), integrated within 0.5 deg

Ursa Major II – Preliminary Results





- Dwarf Spheroidal Galaxy discovered by SDSS (Zucker et al. 2007)
- 145 hours of quality-selected data between 2013 and 2017
- J Factors from Geringer-Sameth et al. ApJ, Vol. 801, Issue 2 (2015)
- Limit computed using unbinned maximum likelihood (Aleksic, Rico and Martinez, 2012, jcap, 10, 32)
- band represents 1sigma uncertainty in the J factor
- Preliminary limit exceeds 216 hour combined limit at all masses for tau lepton and b quark channels

Conclusions and Future Work

- VERITAS Observations of 230 hours of dwarf galaxies between 2007 and 2013
- Combined search and limits using 216 hours from 100 GeV to 100 TeV
- Method for DM search and computing limits utilizing individual event energies and directions
- VERITAS has a larger data set with data taken after 2013, including a large exposure on Ursa Major II
- VERITAS now working with other gamma-ray experiments for standardization and combination of DM searches