



The VERITAS Dark Matter and Astroparticle Programs

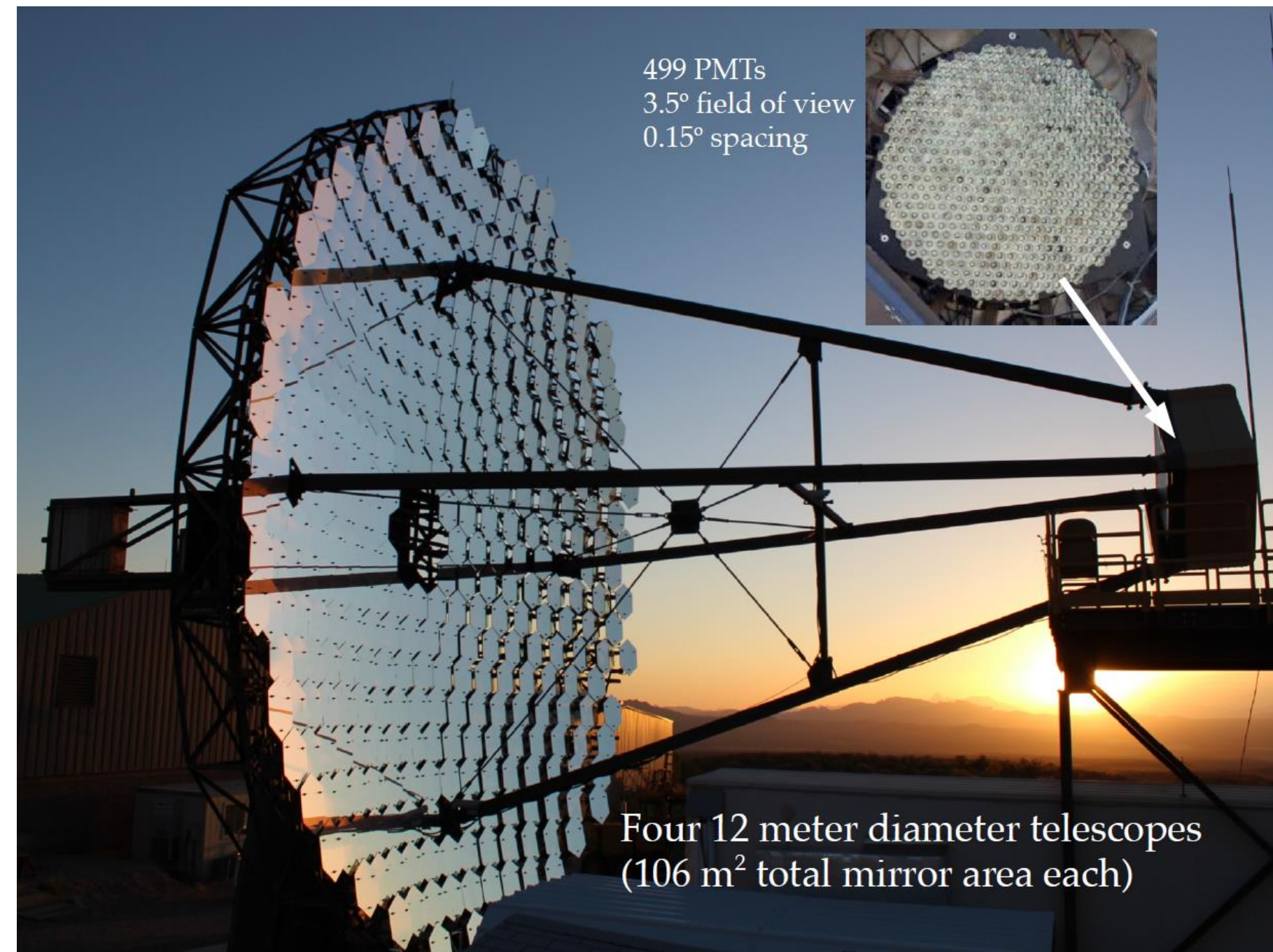


Benjamin Zitzer
For The VERITAS Collaboration



McGill
UNIVERSITY

Introduction to VERITAS



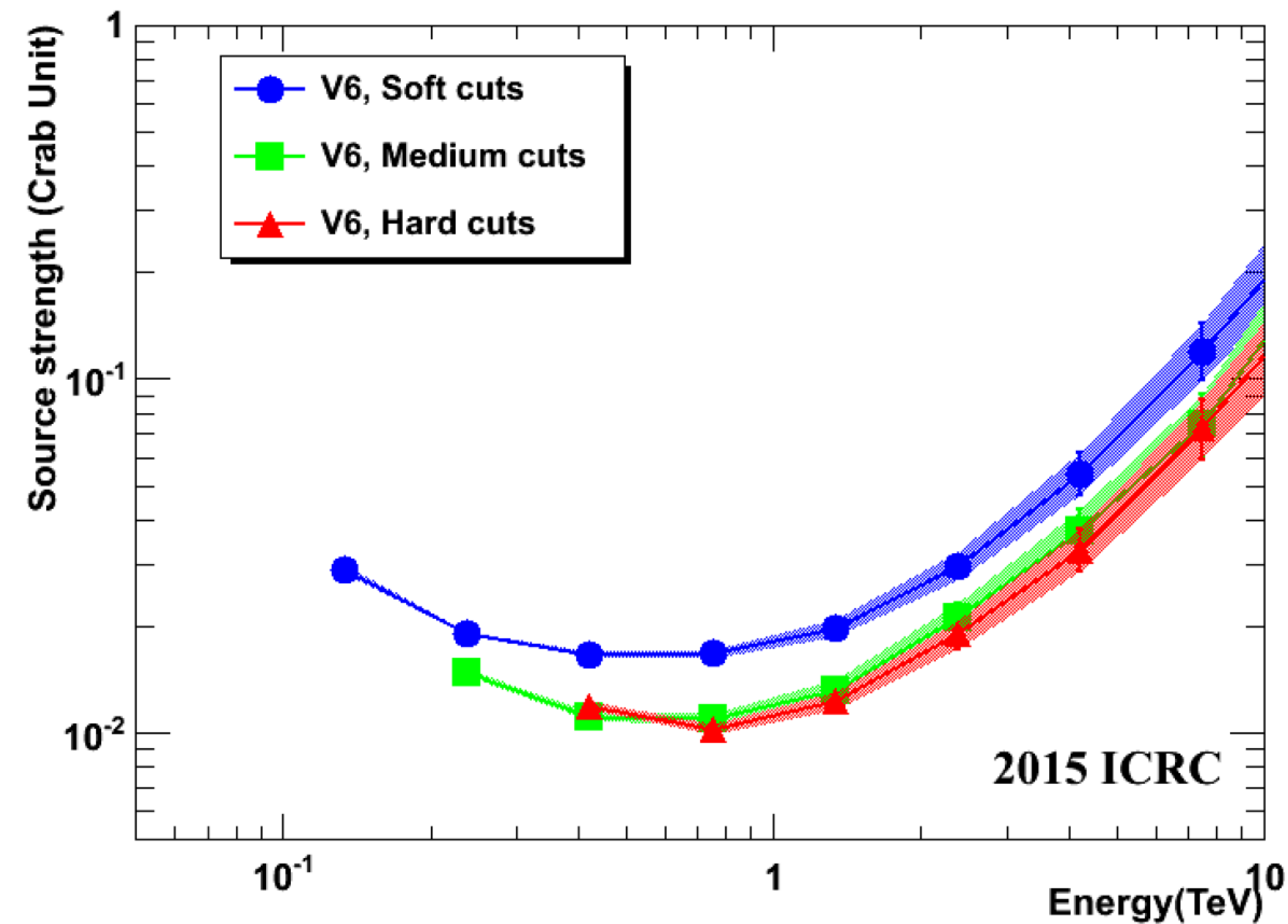
- Array of four IACTs in Southern AZ, USA
- Employs ~100 Scientists in five countries
- Full Array Operations in Fall 2007
- Upgrades:
 - Move of T1 in Summer 2009
 - Level-2 Trigger upgrade in Fall 2011
 - Camera Upgrade with High-QE PMTs in Summer 2012
- See overview talk by Nahee Park



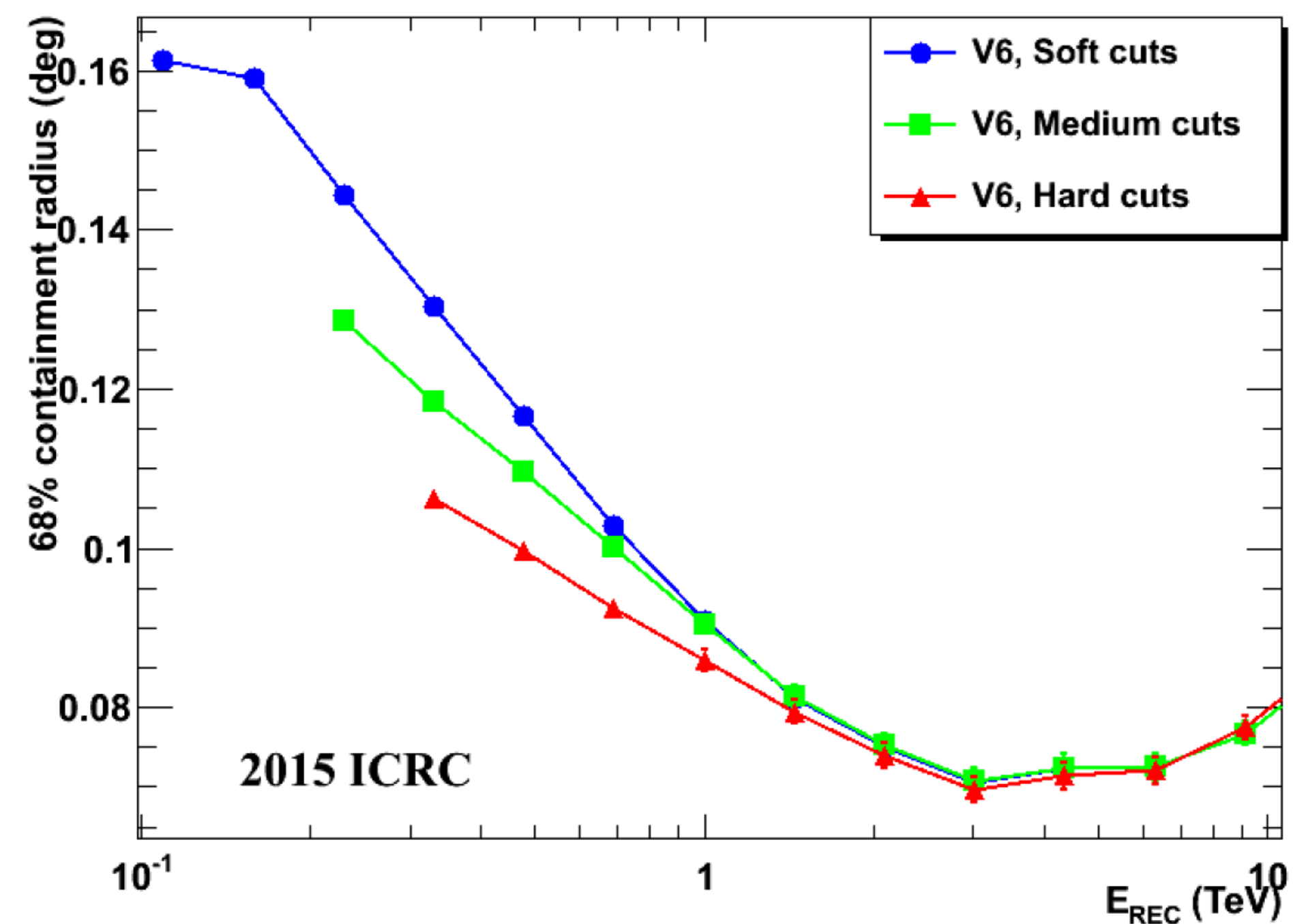
- Support From:
 - NSF (USA)
 - DOE (USA)
 - Smithsonian Institution
 - NSERC (Canada)



VERITAS Performance



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



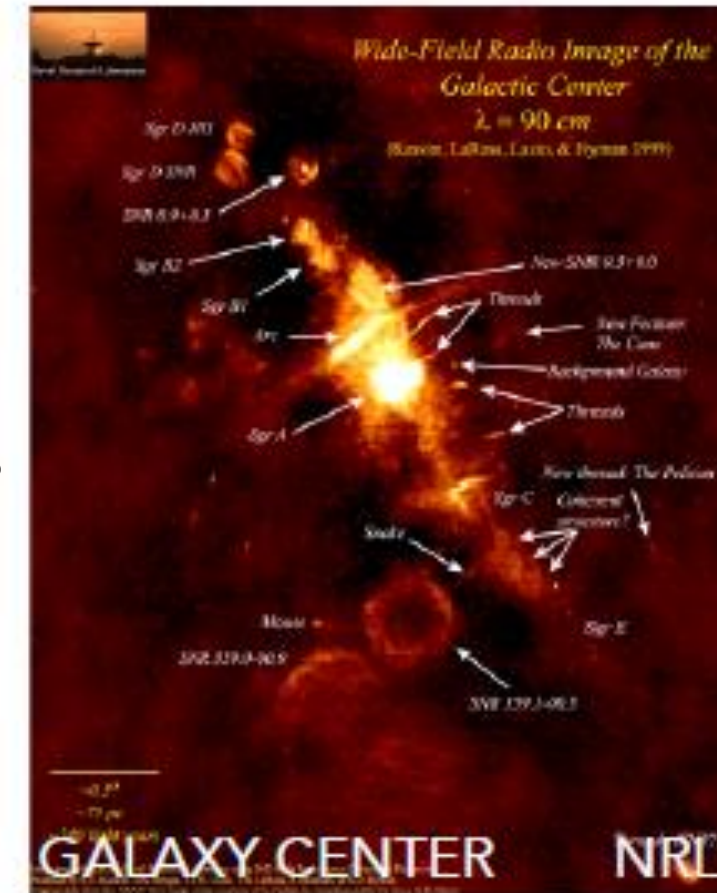
- Sensitivity: 1% Crab in ~ 25 hrs
- Angular Resolution: < 0.1 at 1 TeV (68%)
- Pointing Accuracy: Error < 50 arcsec



VERITAS Dark Matter Targets

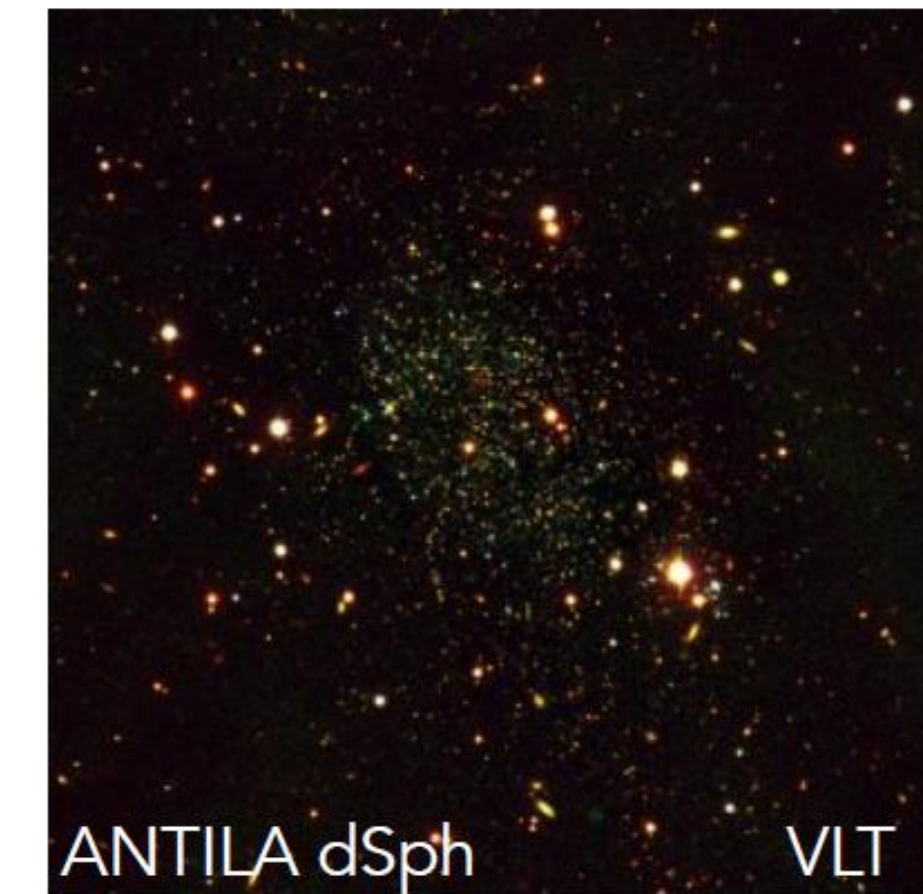
Galactic Center (GC)

- Close By
- Large DM Content
- Astrophysical Backgrounds



Dwarf Galaxies (DSphs)

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

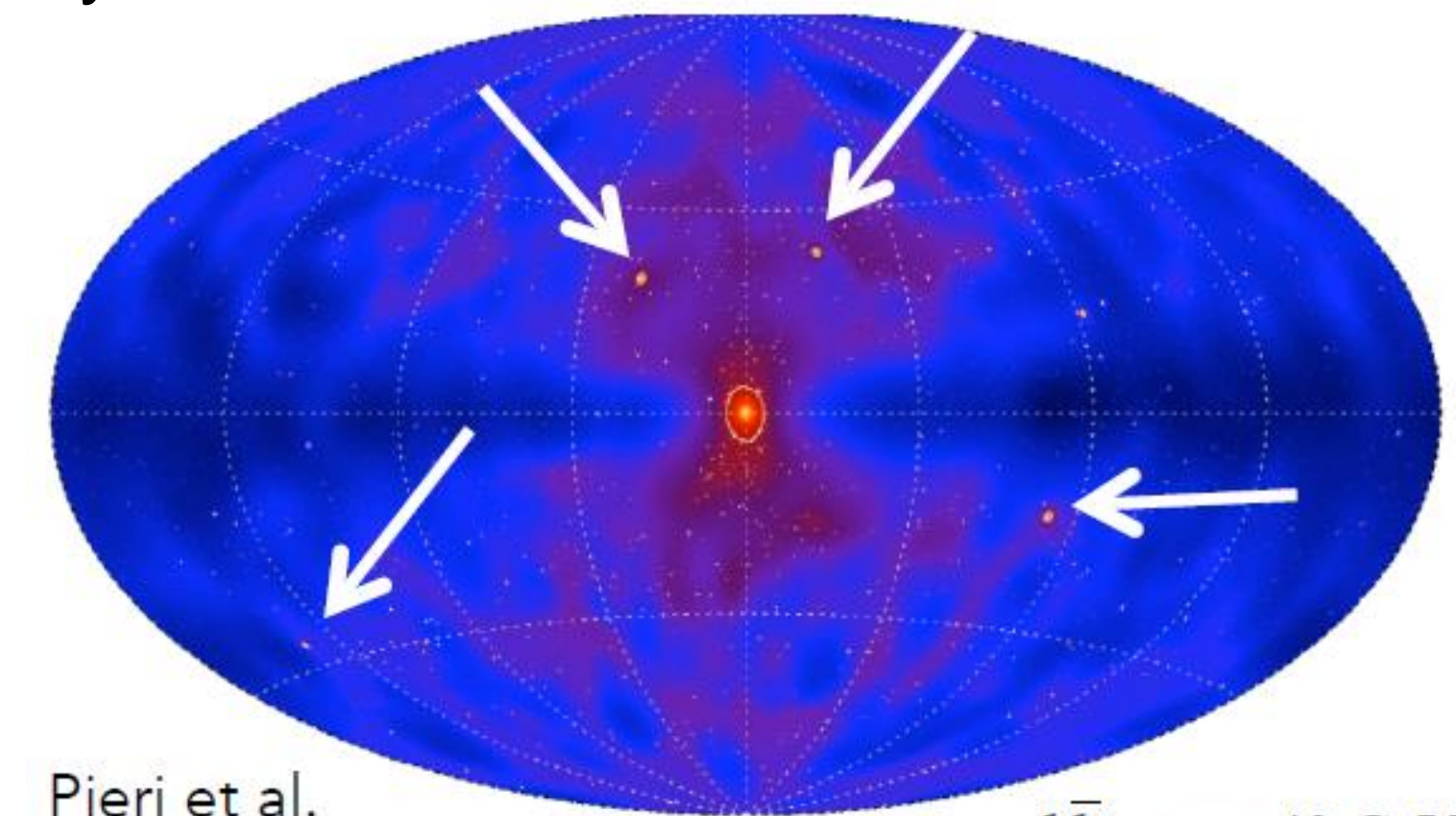
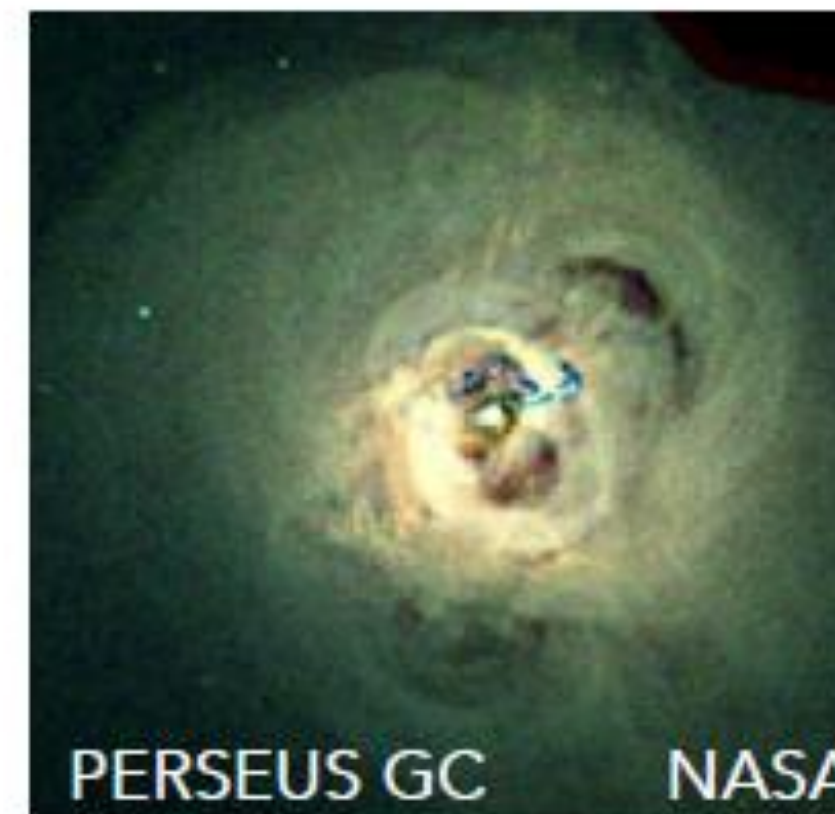


Fermi Unidentified Objects

- Potentially DM Subhalos?

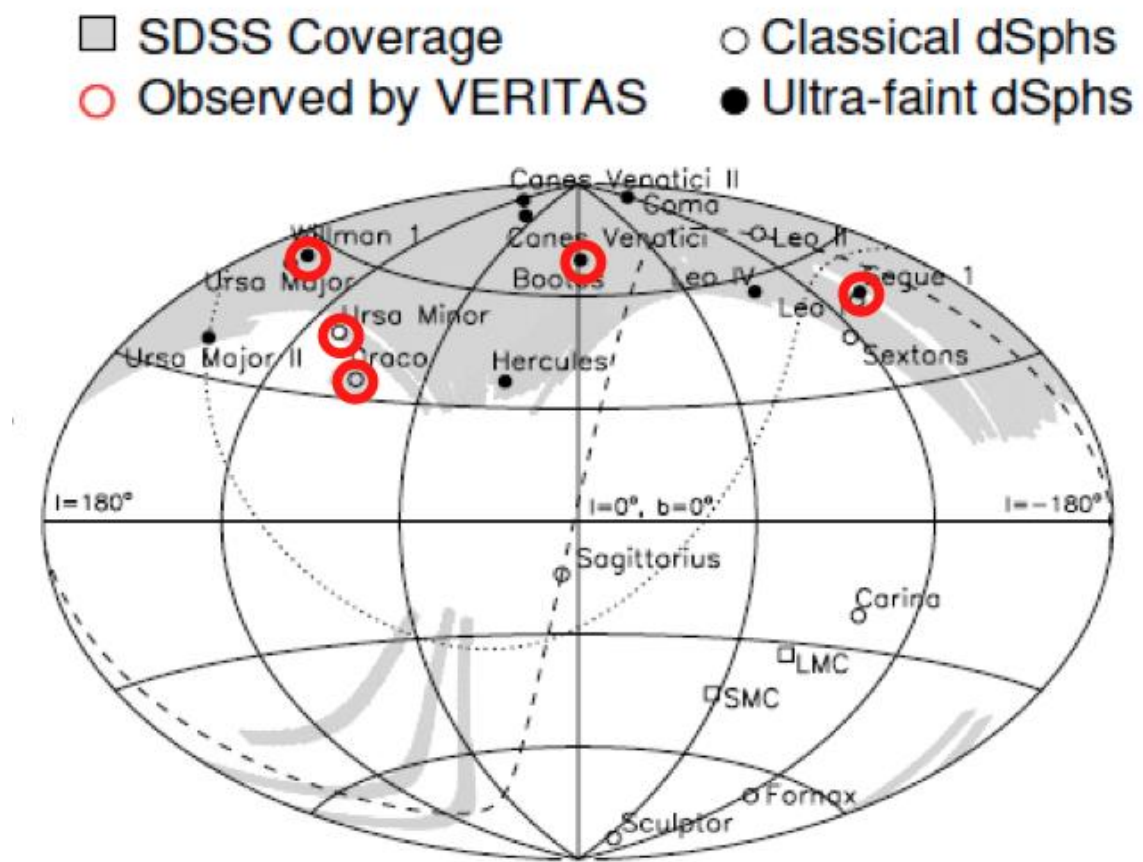
Galaxy Clusters

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

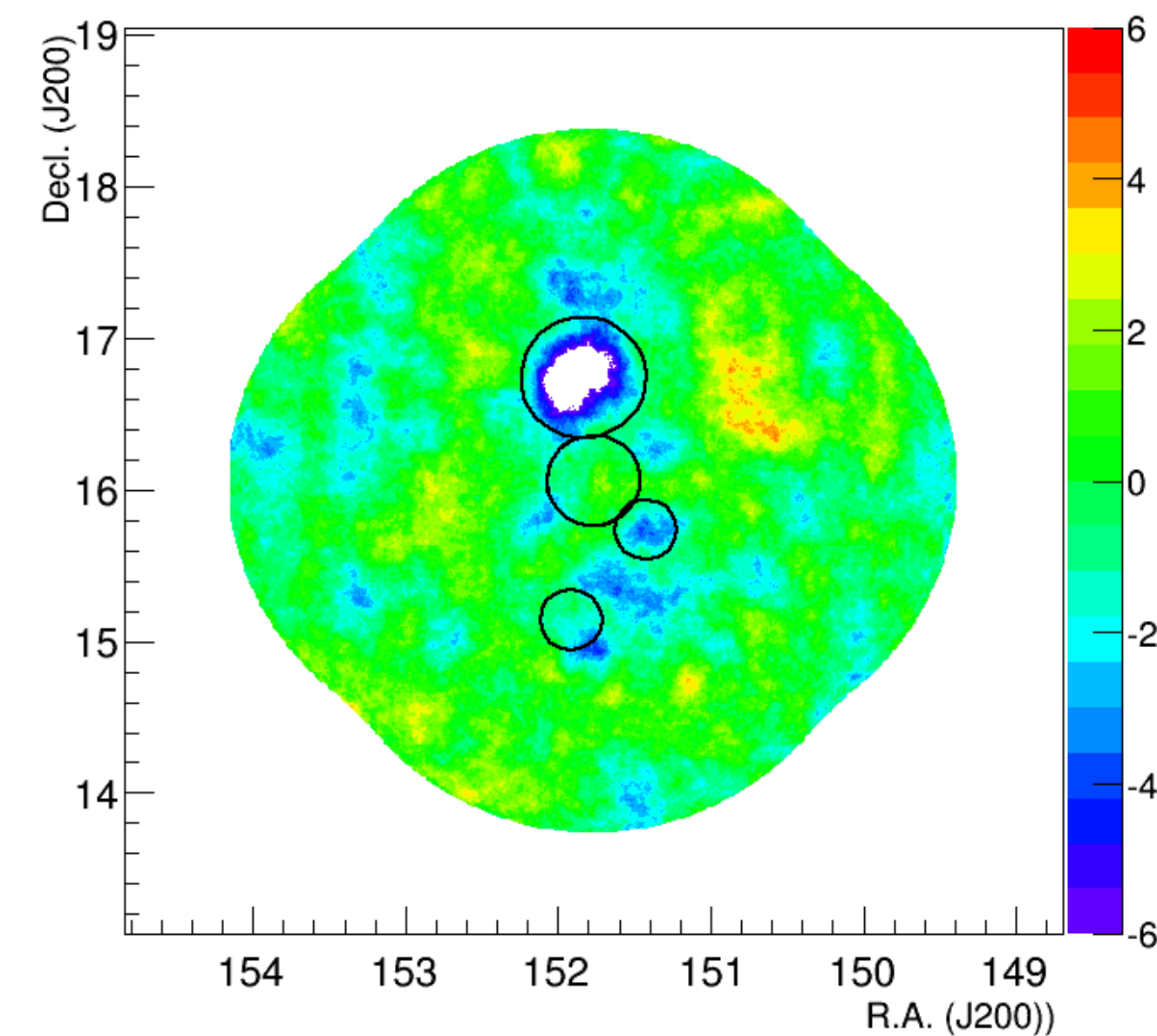


VERITAS Dwarf Galaxy Observations

Dwarf	Live time [hrs]	$\log_{10} J$ [GeV ² cm ⁻⁵]	Significance [σ]	$F_{-12}^{95\%}$ [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 \pm 0.1	-1.0	0.15
Boötes	14.0	18.2 \pm 0.4	-1.0	0.40
Willman 1	13.7	N/A	-0.6	0.39

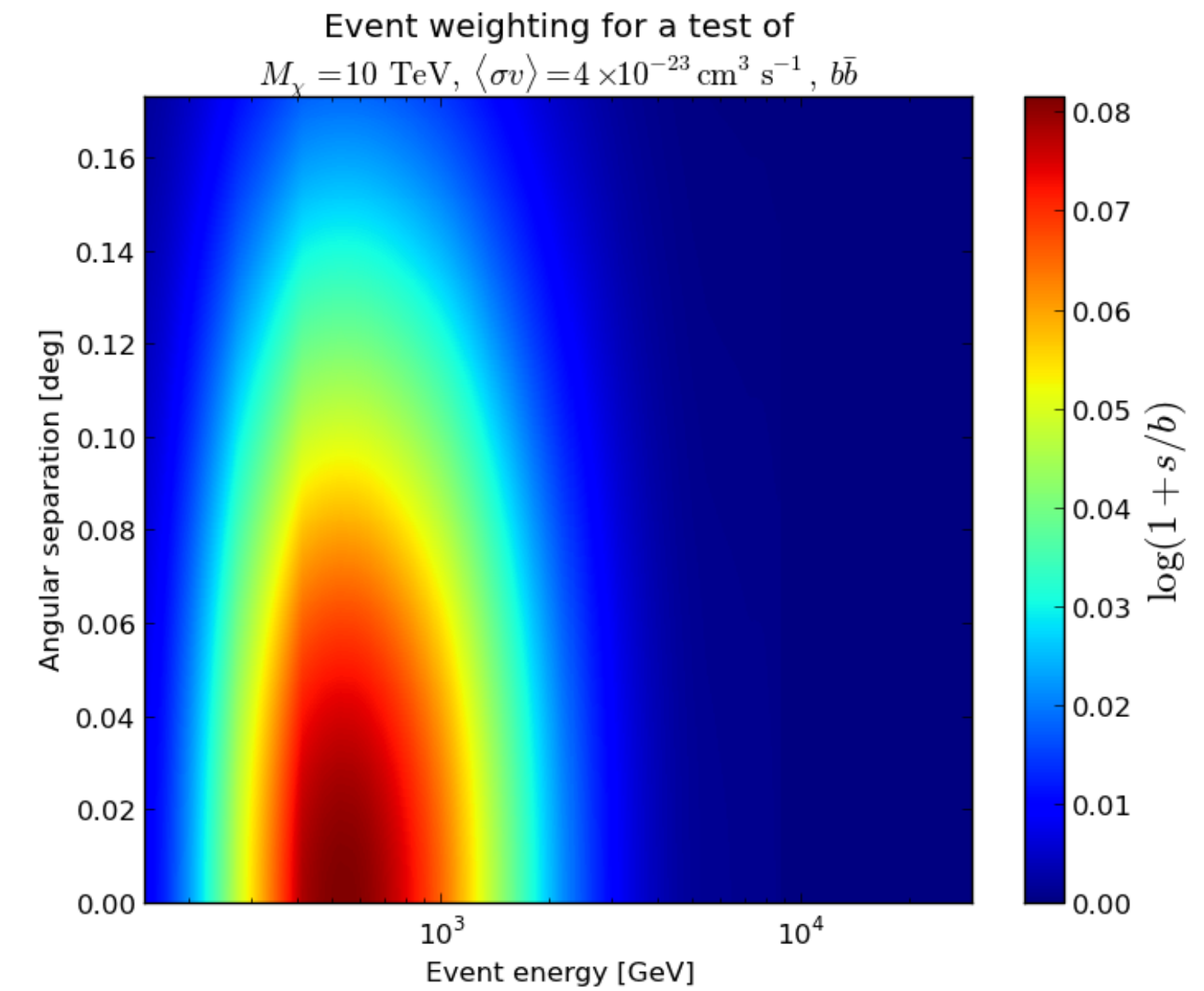
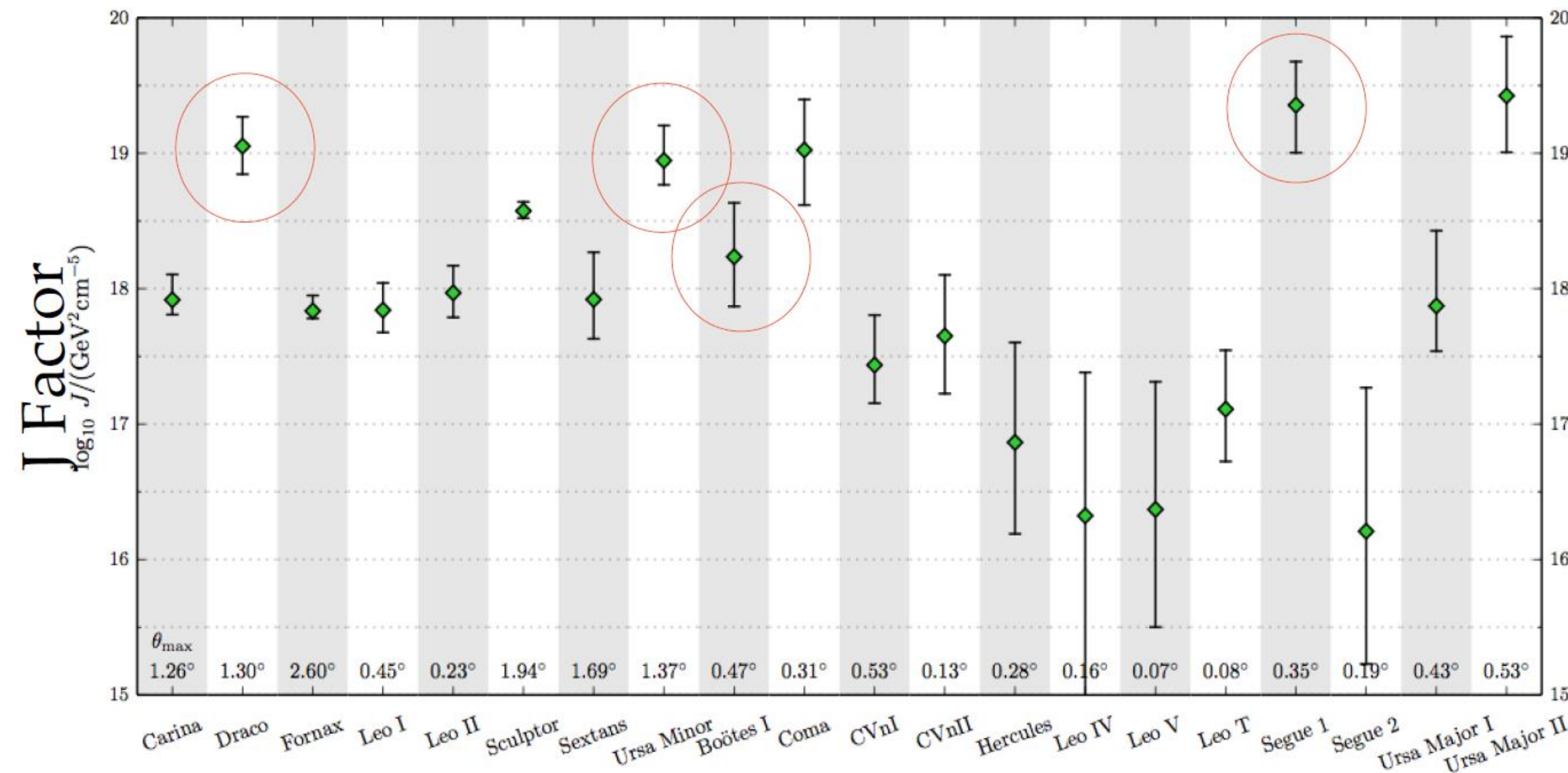


- Five dSphs observed by VERITAS between 2007 and 2013
- Total of 230 hours
 - Deepest exposure on Segue 1: 92 hours
- No gamma-ray detection
- Flux upper limits above 300 GeV



Dark Matter Search/ Limits from Dwarf Galaxies

- Using Methodology of Geringer-Sameth et al.
 - Phys. Rev. D 91, 083535 (2015)
 - Each event is assigned a weight which is proportional to the probability of photon originating from DM annihilation
 - Function of Energy and angular distance from dwarf galaxy
- J Factors from Geringer-Sameth et al.
 - ApJ, Vol. 801, Issue 2 (2015)



$$w(\nu, E, \theta) = \log \left[1 + \frac{s(\nu, E, \theta)}{b(\nu, E, \theta)} \right]$$

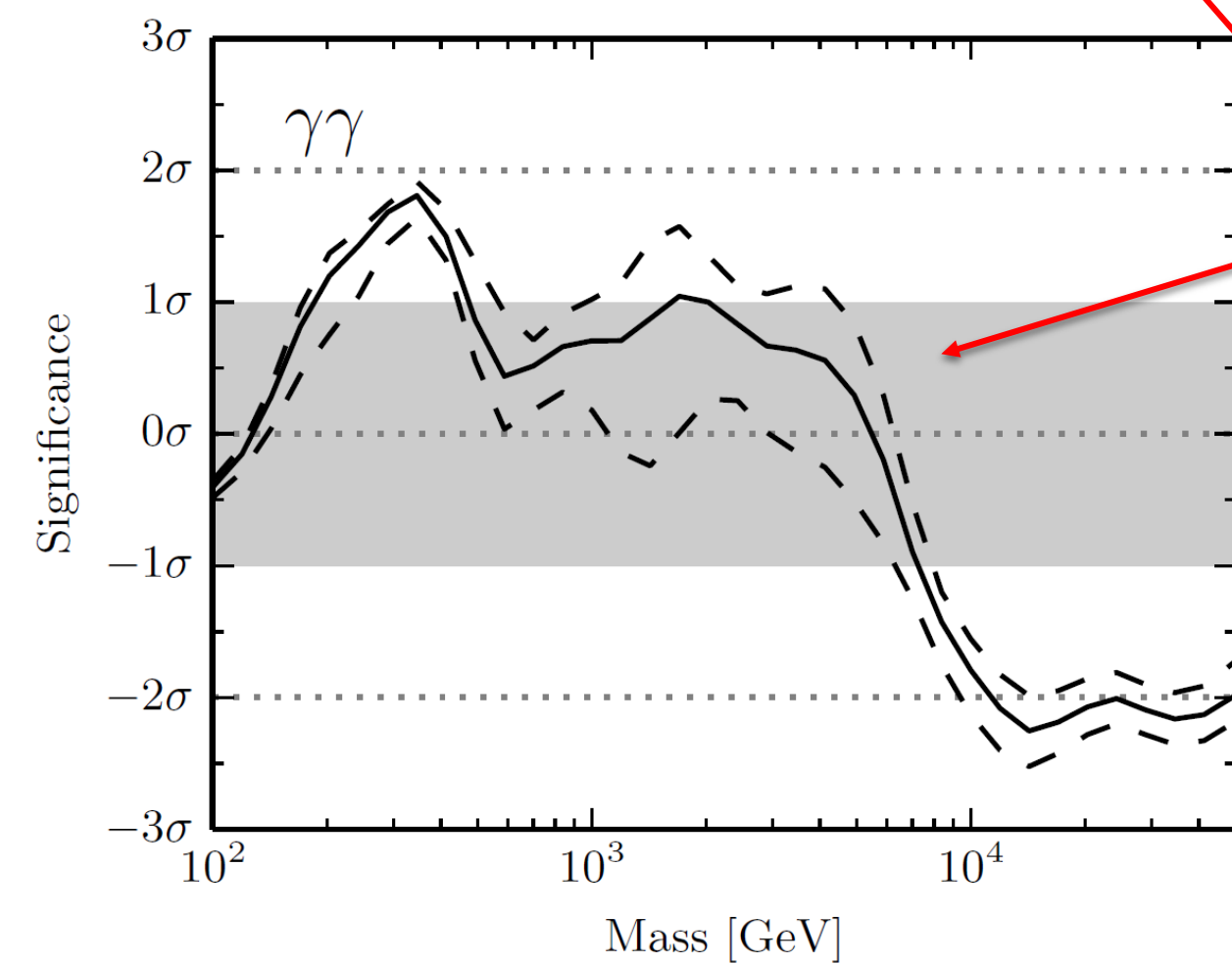
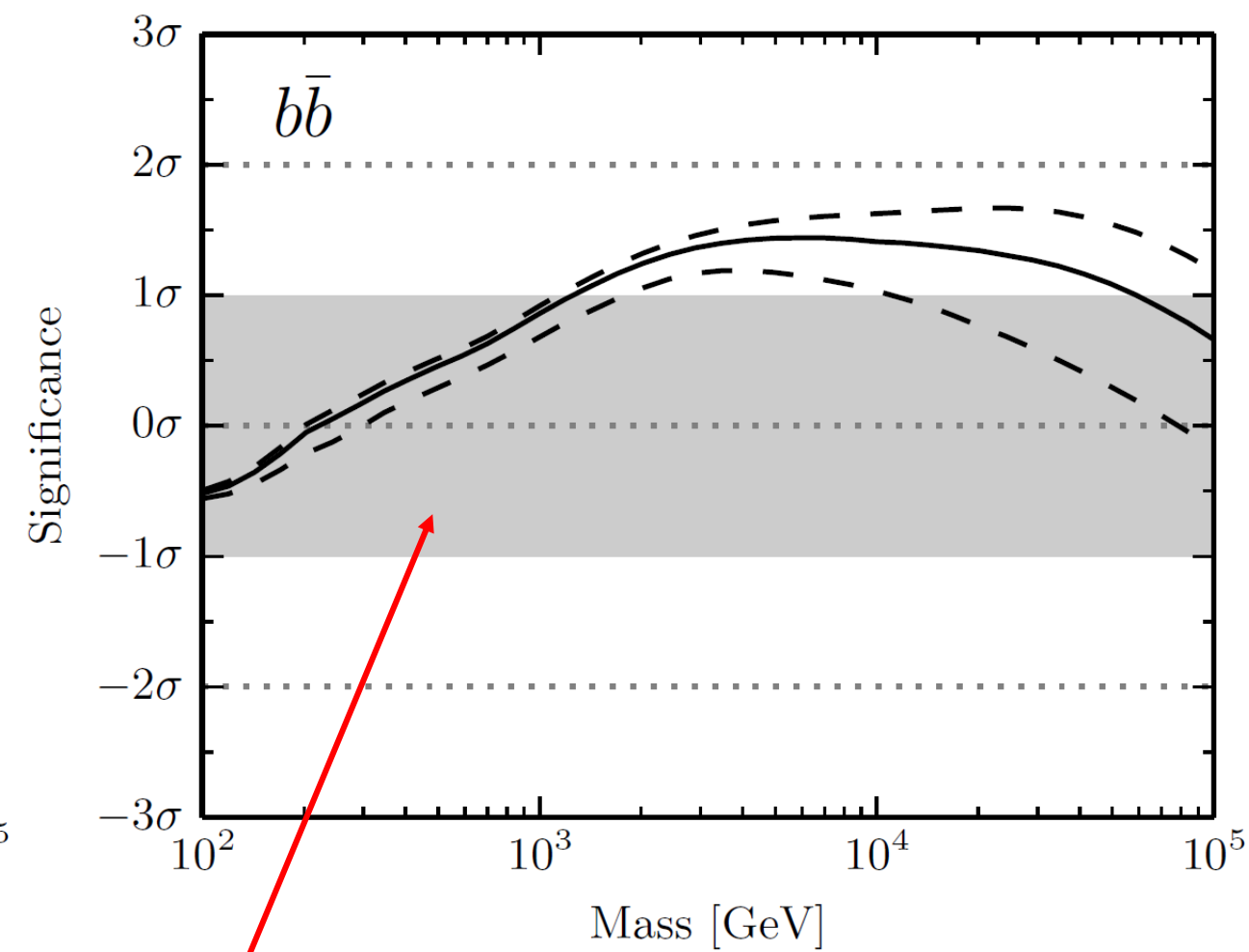
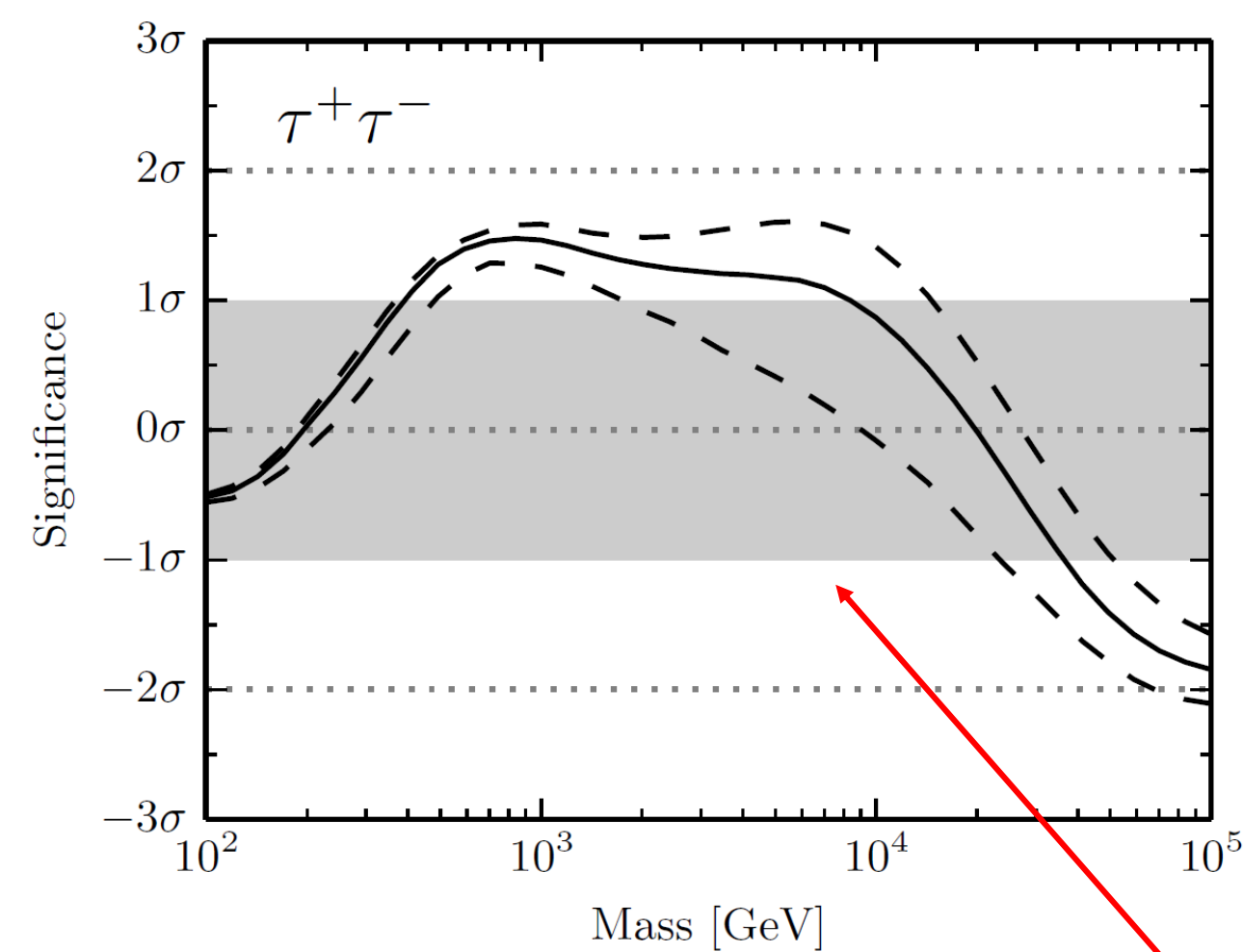
$$s(\nu, E, \theta) = \frac{dN(\nu, E, \theta)}{dE d\Omega} dE 2\pi \sin(\theta) d\theta$$

$$\frac{dN(\nu, E, \theta)}{dE d\Omega} = \int_{E_t} \int_{\Omega_t} dE_t d\Omega_t \frac{F(E_t, \theta_t)}{dE_t d\Omega_t} R(E, \theta | E_t, \theta_t)$$

$$\frac{F(E_t, \theta_t)}{dE_t d\Omega_t} = \frac{\langle \sigma v \rangle}{8\pi M^2} \frac{dN_\gamma(E)}{dE} \frac{dJ(\theta)}{d\Omega}$$

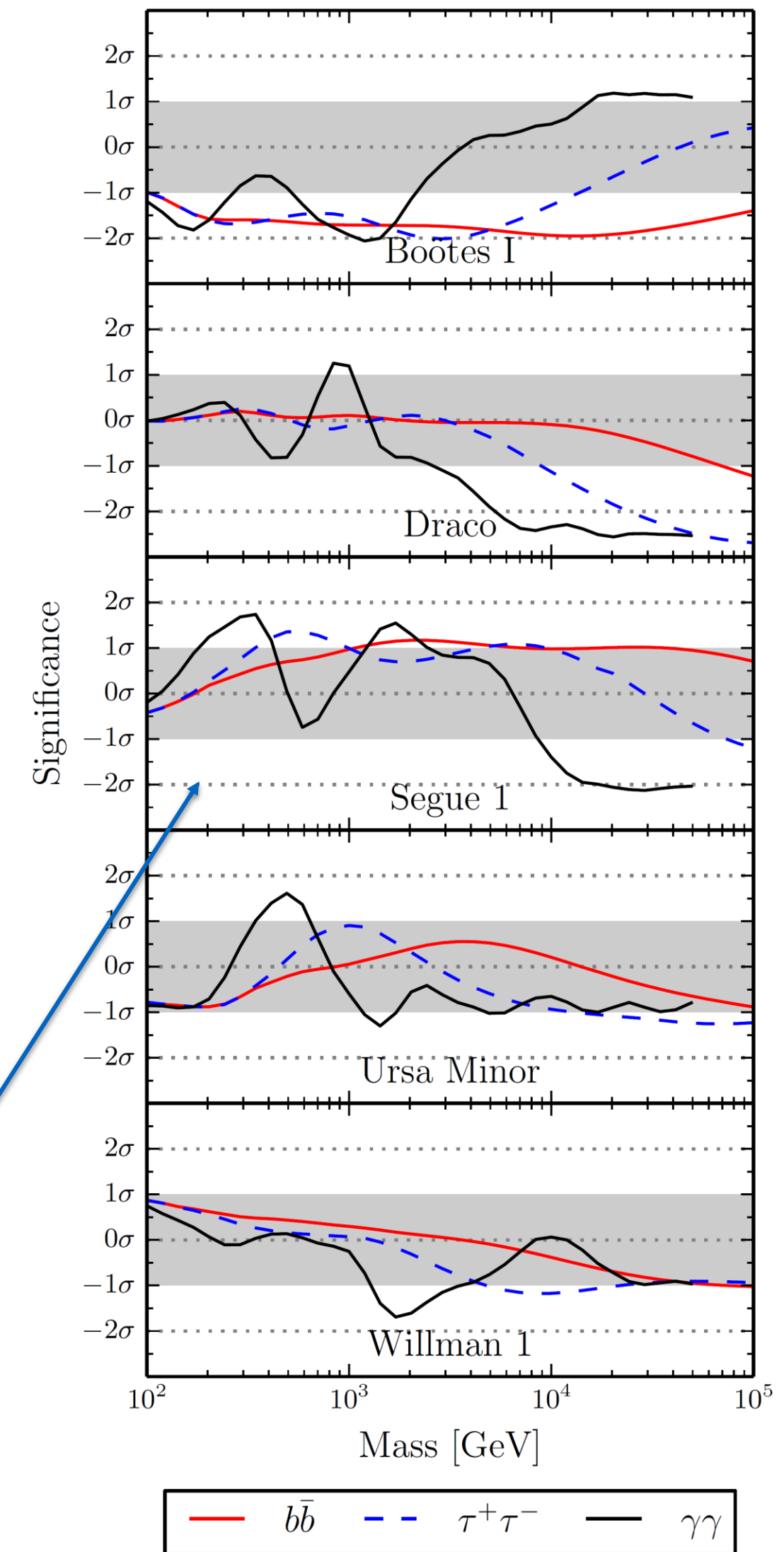


Dark Matter Search/ Limits from Dwarf Galaxies

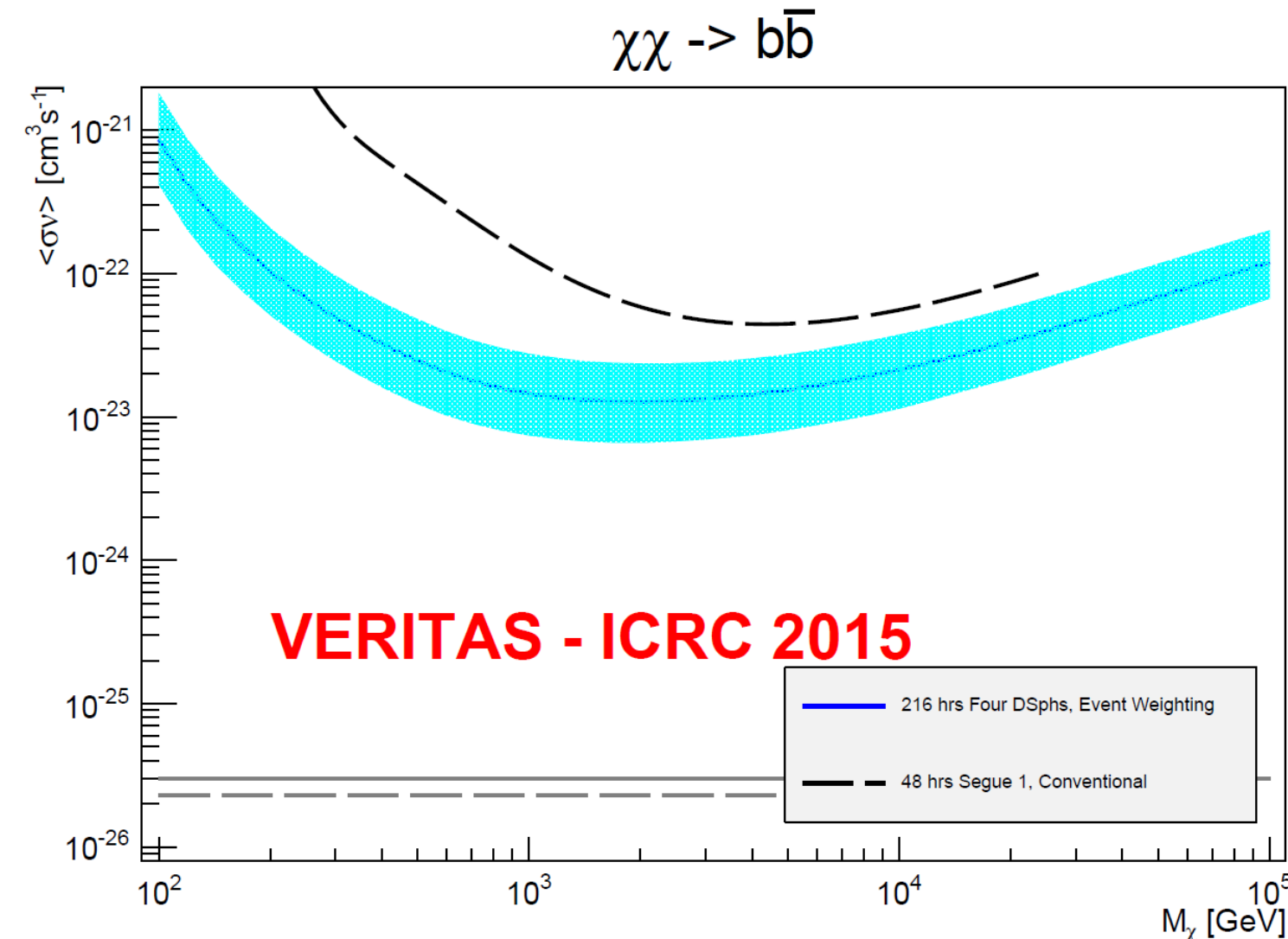
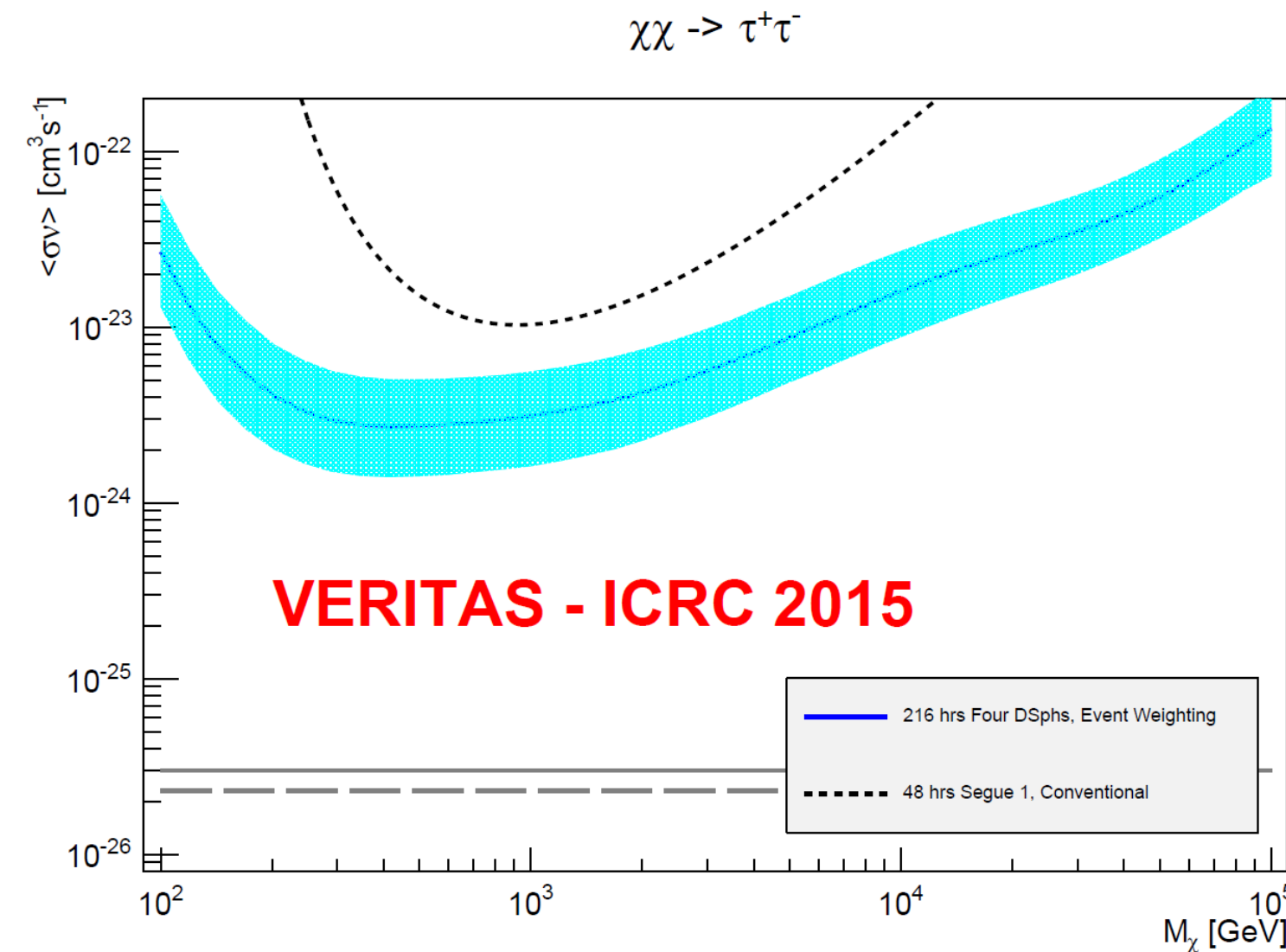


Combined Search

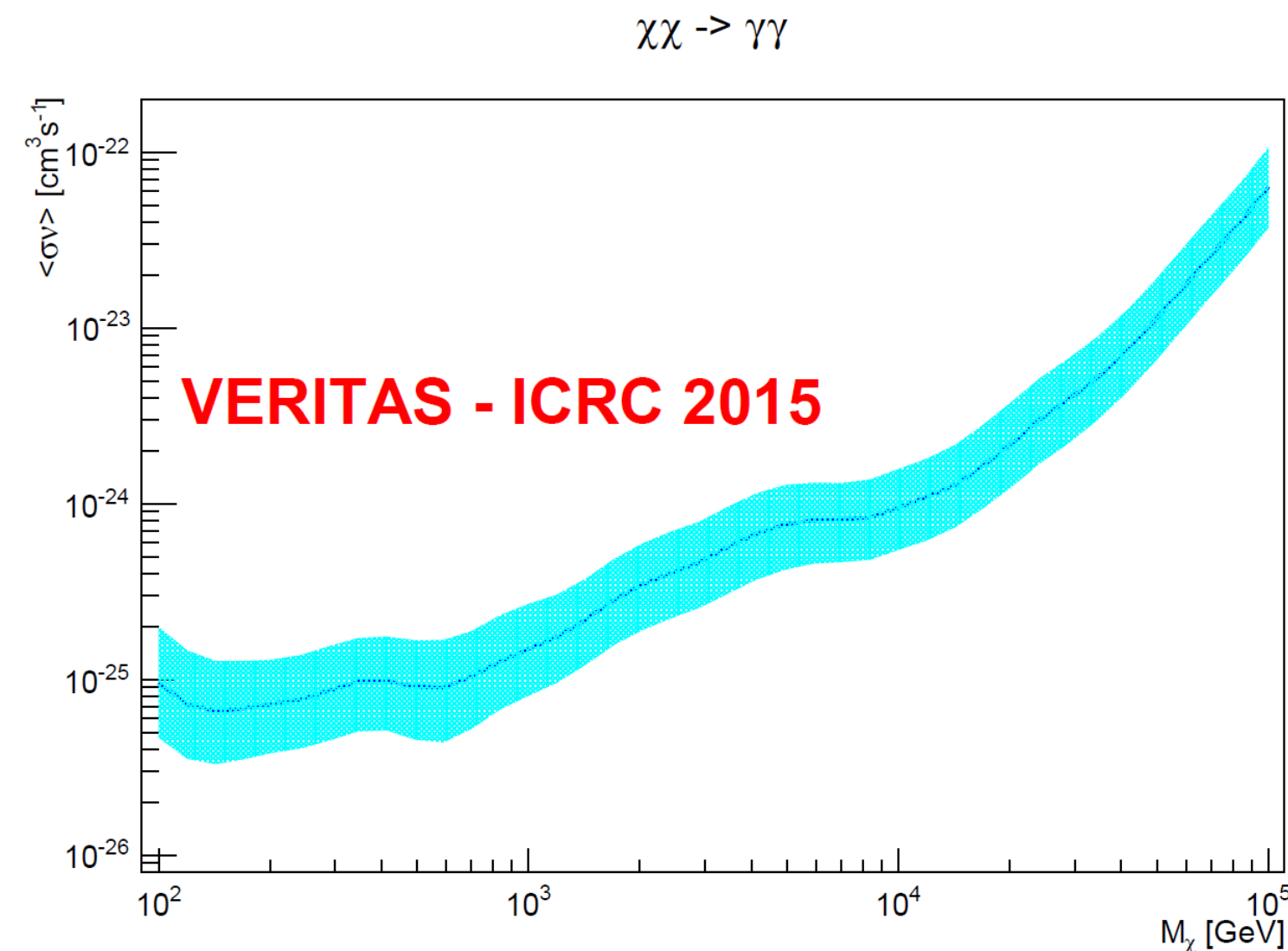
Individual Dwarf Search



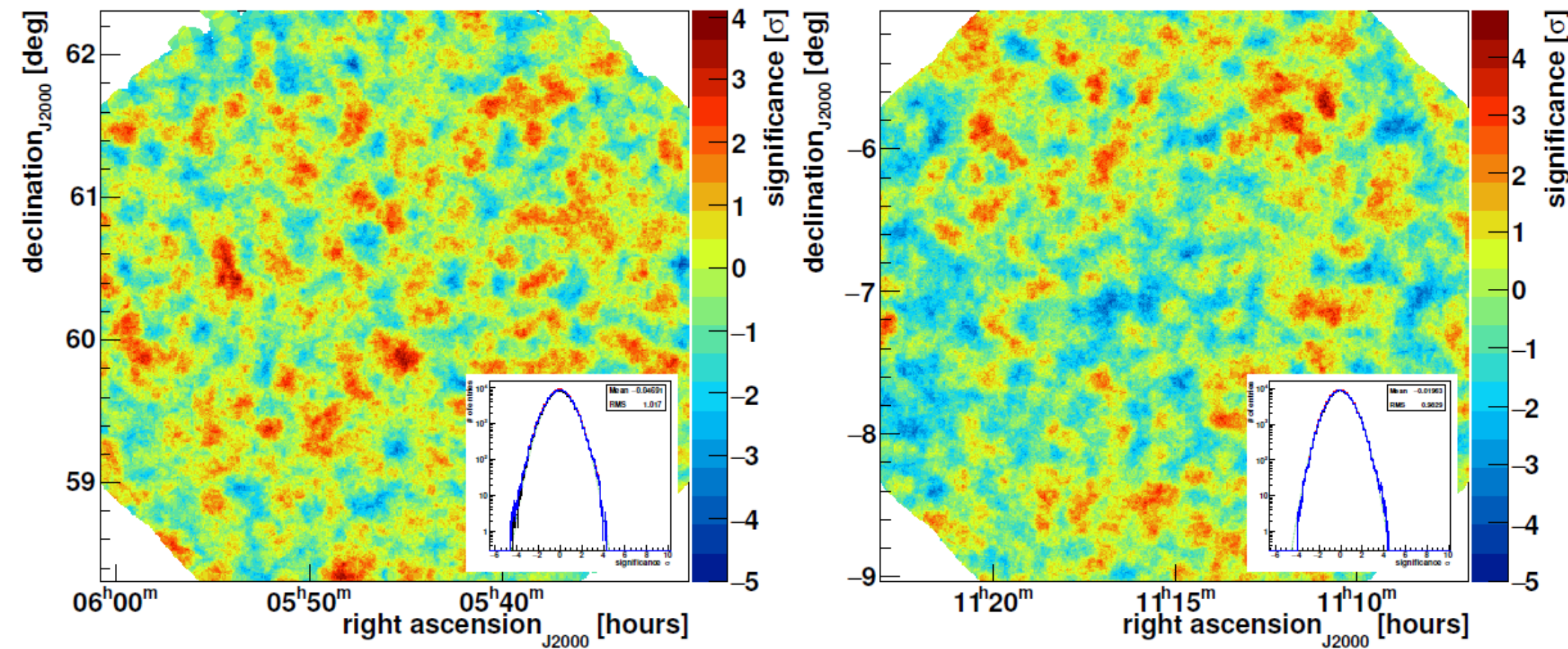
Dark Matter Search/ Limits from Dwarf Galaxies



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

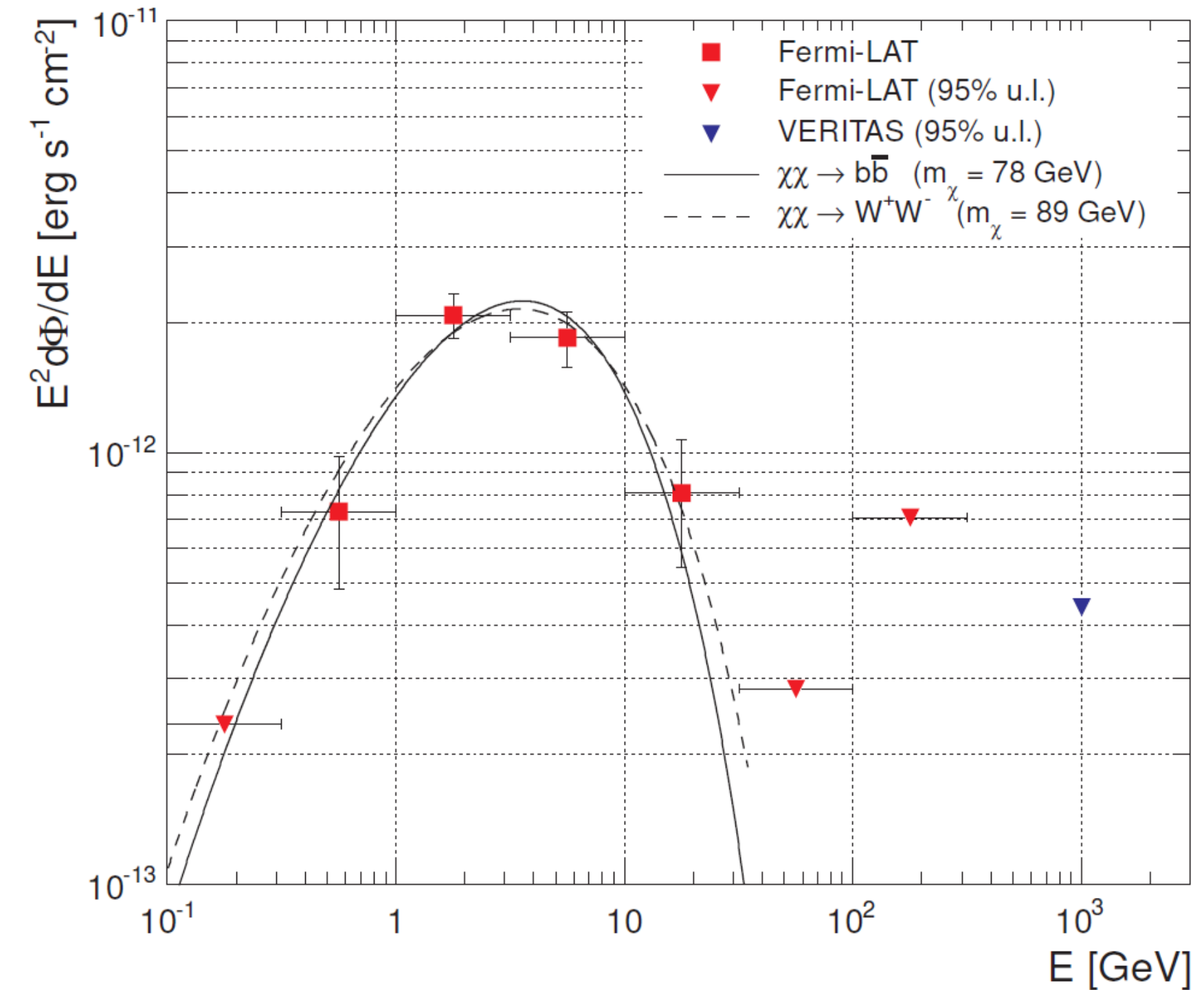


Dark Matter Subhalos

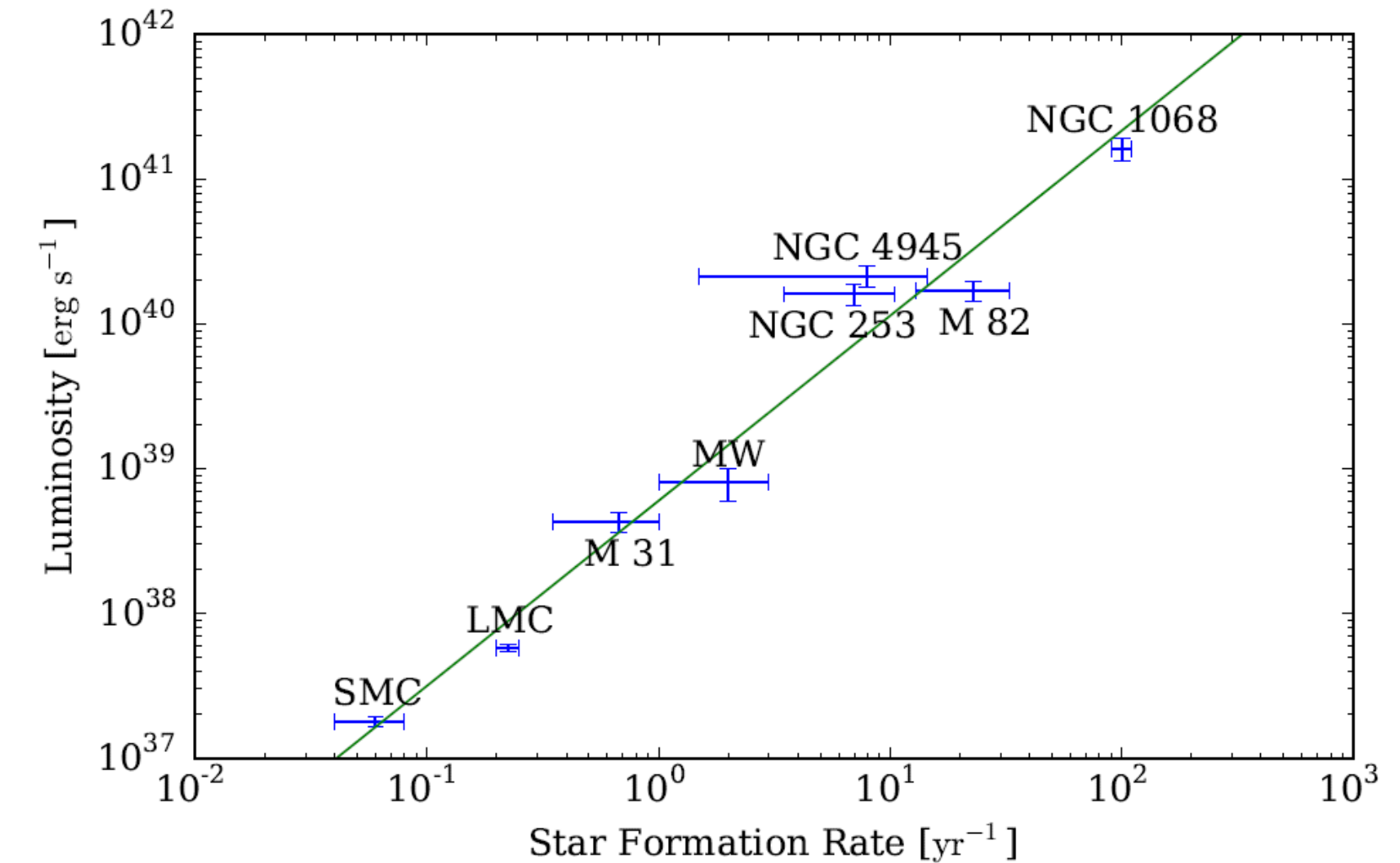
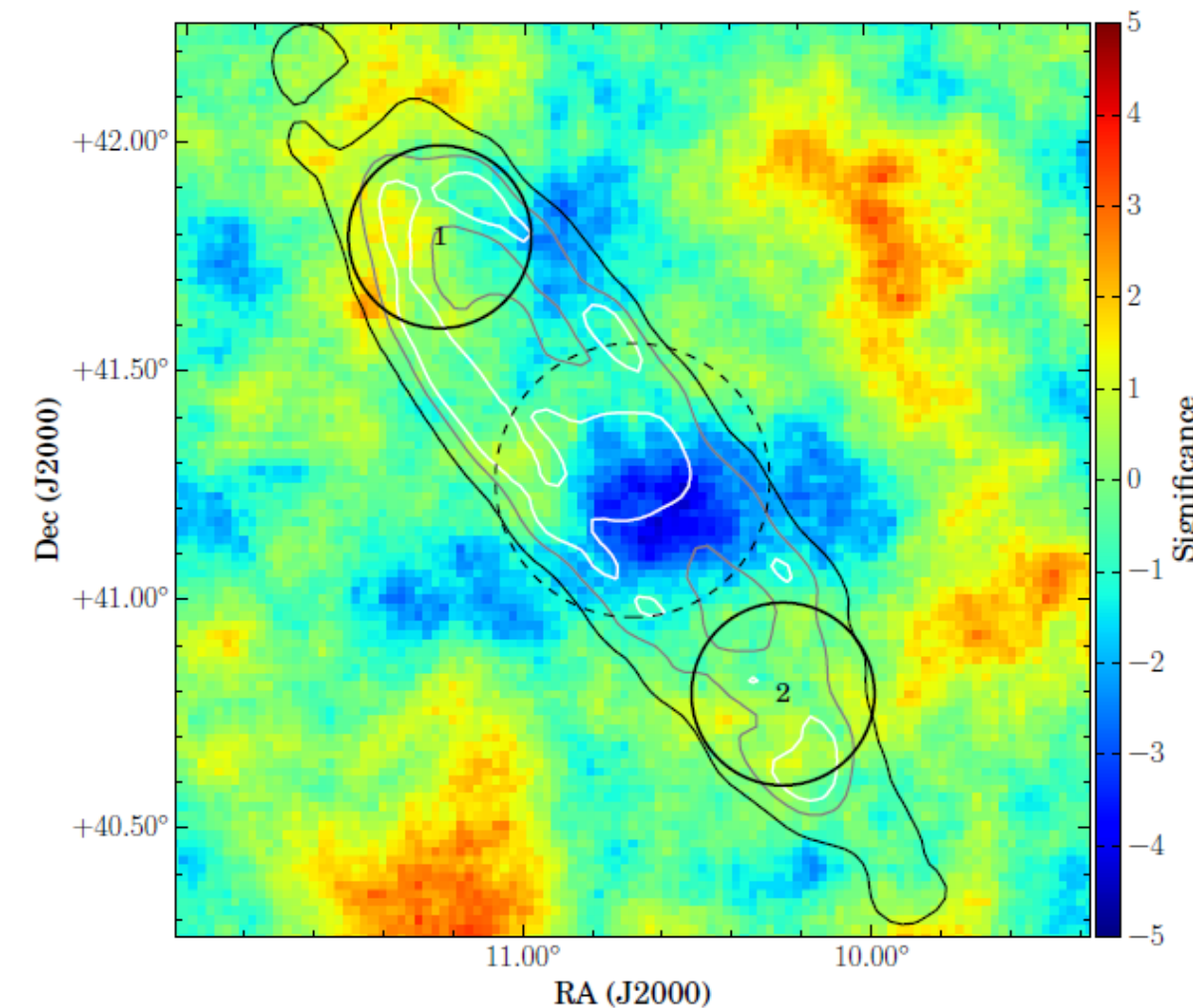
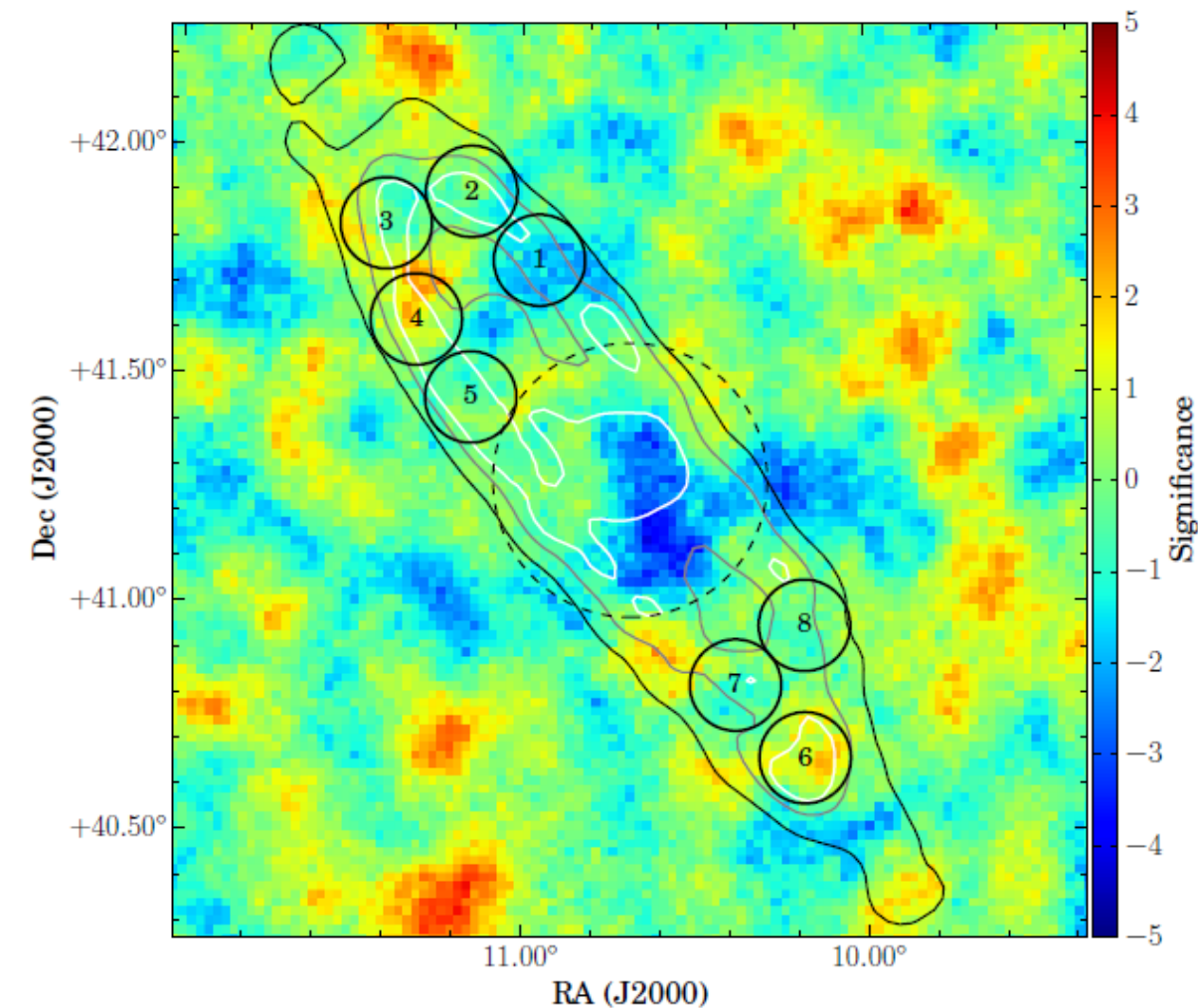


- Observations of two Fermi-LAT UNIDs from 2FGL
 - Selection criteria: Power-law spectra, not variable, no counterparts, observable by VERITAS
- 2FGL J1115.0-0701 found to be variable in 3FGL catalog, likely a blazar
- 2FGL J0545.6+6018 curved power-law in 3FGL
- Fit of 2FGL J0545.6+6018 with Dark Matter model
 - Assume $\langle\sigma v\rangle=2.2\times 10^{-26} \text{ cm}^3\text{s}^{-1}$
 - Mass and J factors are free fit parameters

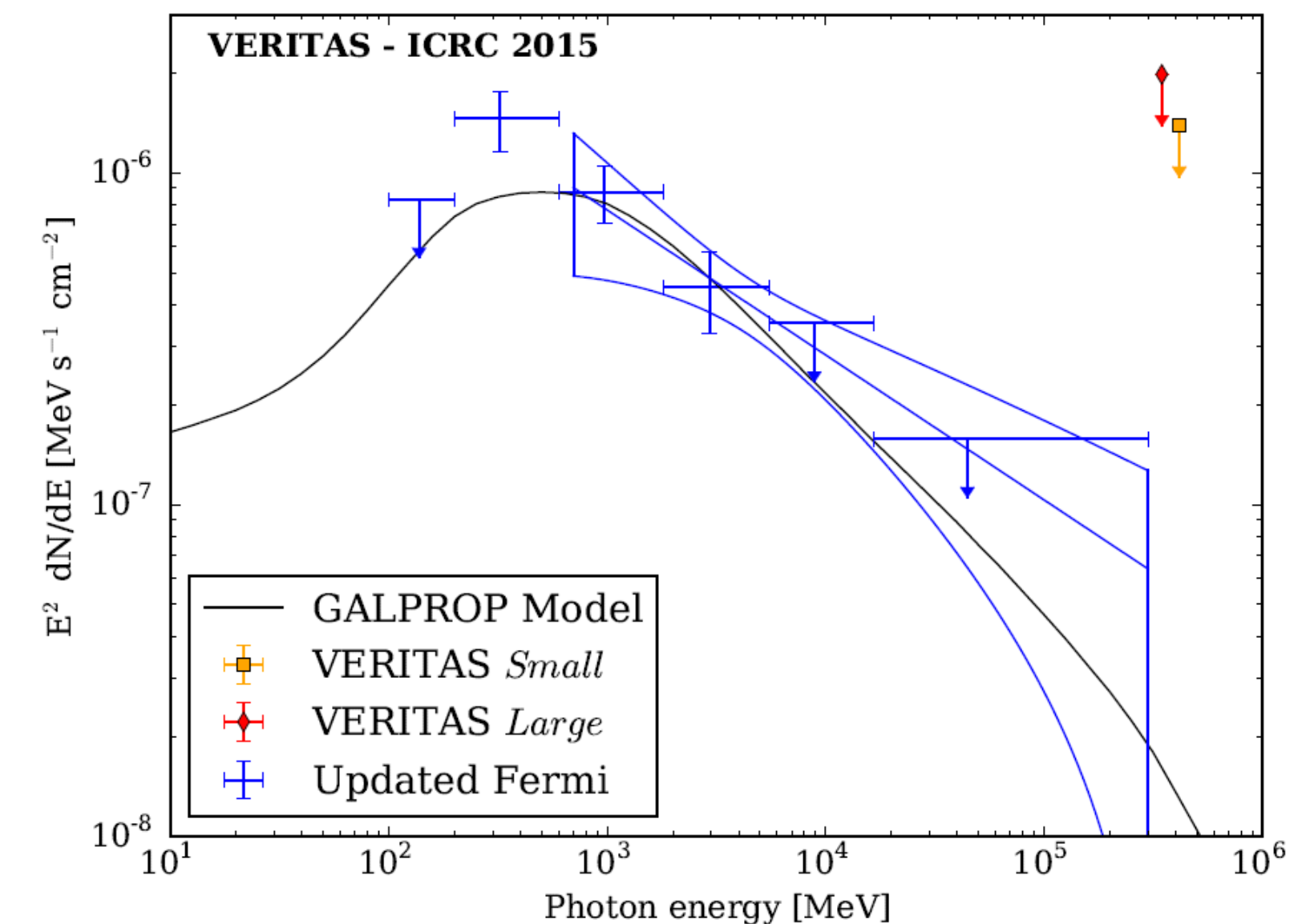
	c.l.	E>150 GeV		Integral E>250 GeV		E>450 GeV		Differential E ₀ = 1 TeV
		[cm ⁻² s ⁻¹]	[C.U.]	[cm ⁻² s ⁻¹]	[C.U.]	[cm ⁻² s ⁻¹]	[C.U.]	[TeV ⁻¹ cm ⁻² s ⁻¹]
2FGL J0545.6+6018	95%	1.95×10^{-12}	0.6%	0.95×10^{-12}	0.6%	0.16×10^{-12}	0.2%	1.88×10^{-13}
	99%	3.57×10^{-12}	1.0%	1.69×10^{-12}	1.0%	0.42×10^{-12}	0.6%	2.38×10^{-13}
2FGL J1115.0-0701	95%	2.15×10^{-12}	0.6%	0.88×10^{-12}	0.5%	0.31×10^{-12}	0.4%	2.11×10^{-13}
	99%	3.62×10^{-12}	1.0%	1.48×10^{-12}	0.9%	0.53×10^{-12}	0.8%	3.54×10^{-13}



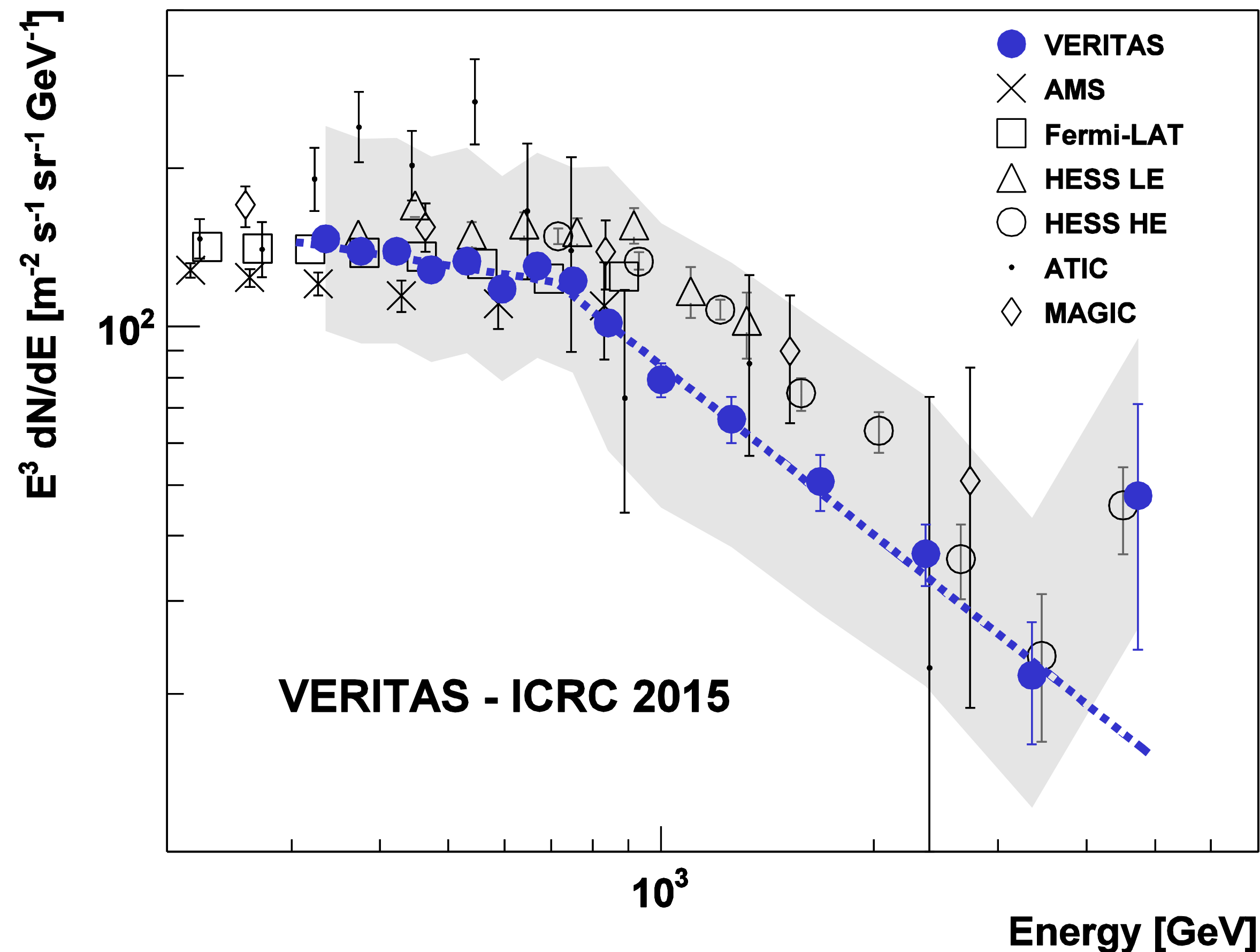
Observations of Andromeda/ M31



- Interaction of CRs with the interstellar medium and unresolved point source leads to predictions of VHE emission from M31
- Number of CR accelerators scales with star formation rate
- M31 is extended and optically bright, both of which have been issues for IACTs
- Upper limits in several test regions of interest
 - Extended and point-like test regions

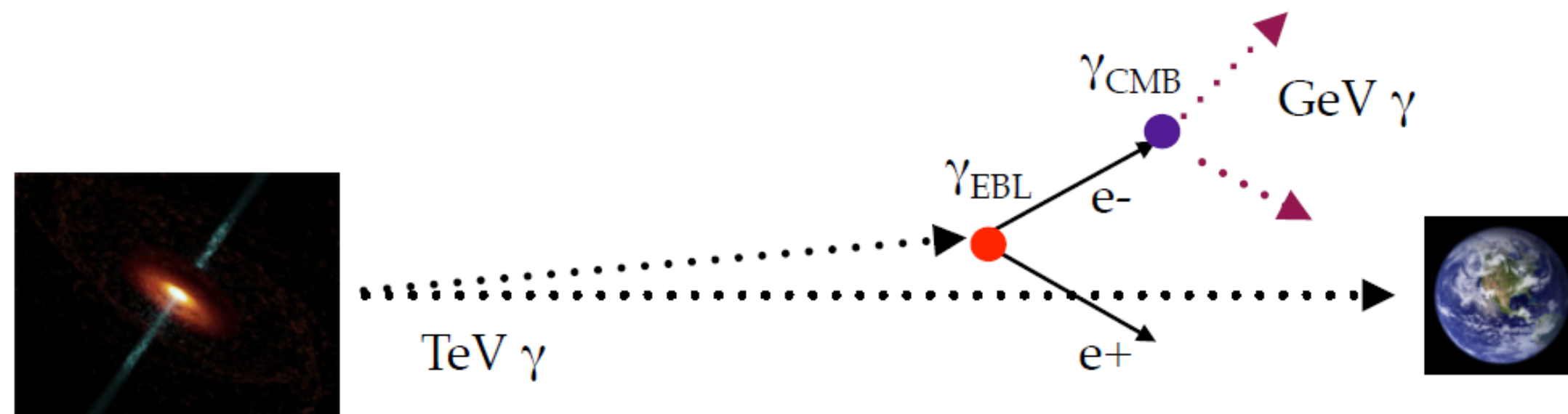


VERITAS Electron Spectrum

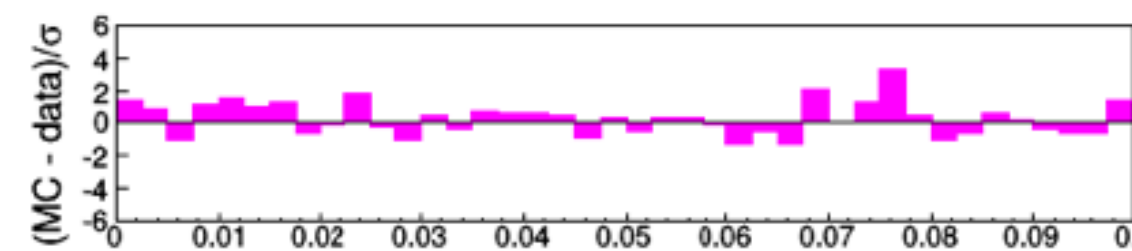
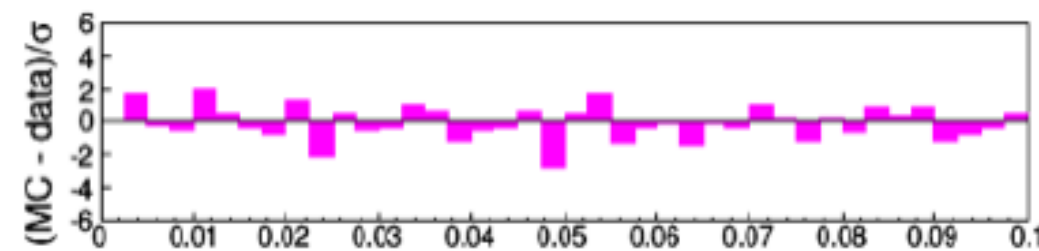
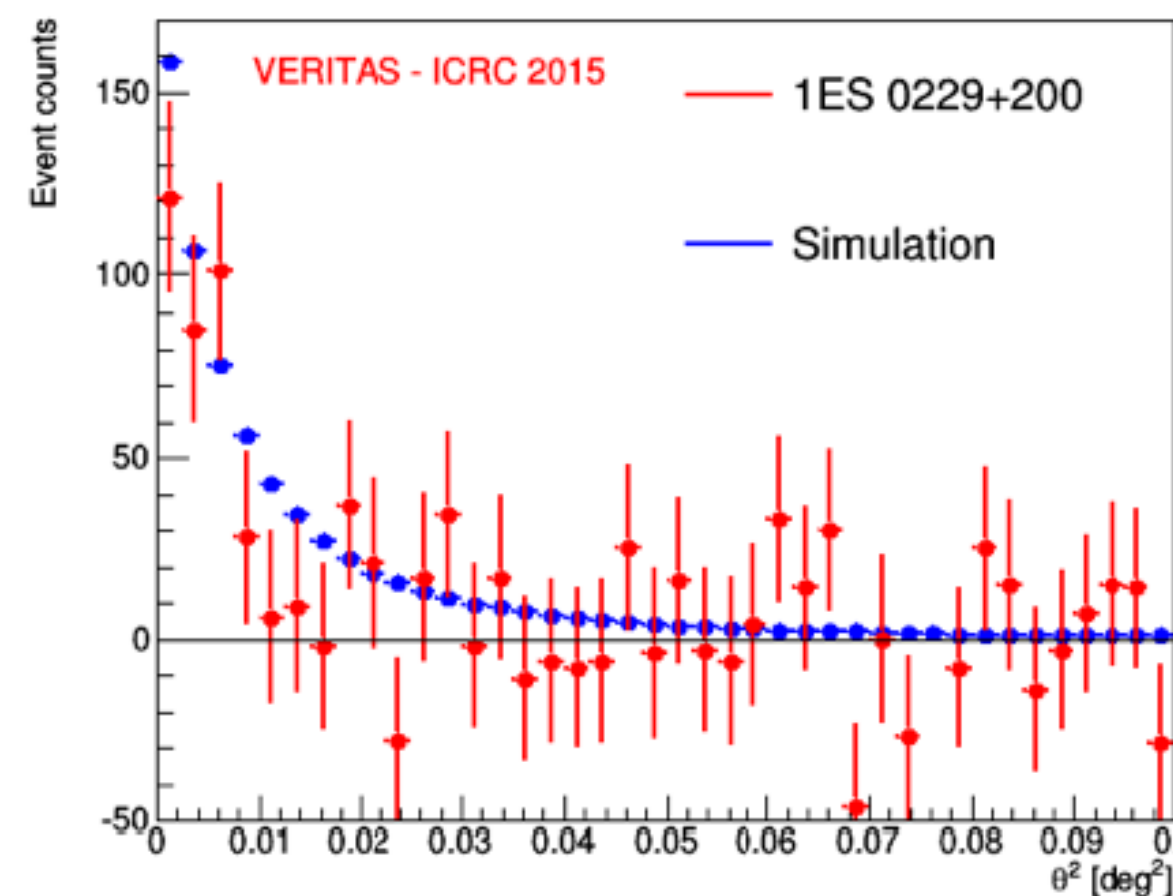
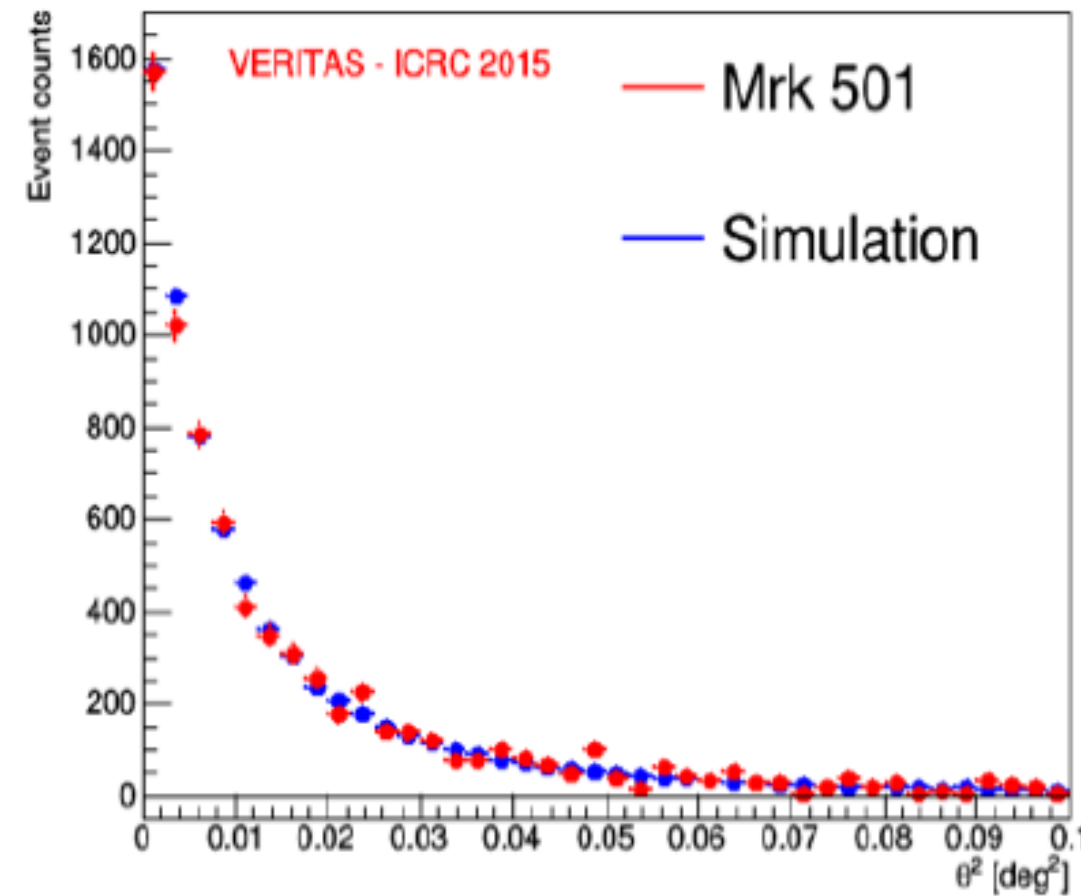


- 296 hours of data between 2009 and 2012
- Electron-like events selected by boosted decision trees and extended likelihood fitting
- Agreement with other experiments within systematic uncertainties
 - Break at 710 ± 40 GeV
 - Index below break: $-3.2 \pm 0.1_{\text{stat}}$
 - Index above break: $-4.1 \pm 0.1_{\text{stat}}$
- Confirms the existence of at least one nearby CRE emitter
- Second high-statistics measurement of a break above 1 TeV

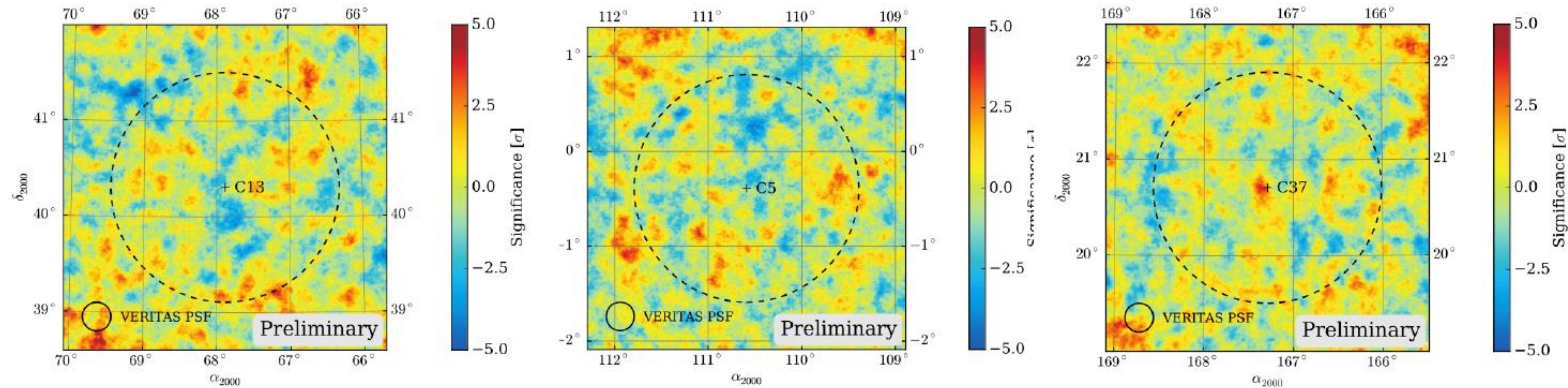
IGMF Measurements



- IGMF provides clues for large-scale structure and CR propagation
- Pair production with EBL produces cascade
 - Secondary particles bent by IGMF
 - Broadening of Blazar VHE emission
- No extension seen in 7 blazars
- Limits on IGMF magnitude set for model-dependent extended emission by comparing to simulated blazars and using 3D semi-analytical code
 - T. Weisgarber 2012
- VERITAS disfavors IGMF strength of $\sim 10^{-14}$ G



Follow-up of Icecube events



- TeV emission associated with astrophysical flux of high-energy neutrino events provides evidence of the site of CR acceleration
- Observation of 22 ν_{μ} –induced muon-track showers for combined 40 hours exposure
 - Muon tracks have good angular reconstruction: ~ 1 deg
- Flux upper limits in the 2-10% Crab level

Other VERITAS Dark Matter/ Astroparticle Projects

- Dark Matter:
 - Archival Galaxy cluster search ([arXiv: 1508.07197](#))
 - Galactic Center ([arXiv: 1508.07197](#))
- Astroparticle topics:
 - Lorentz Invariance Violations (arXiv: 1307.8382)
 - Measurement of positron fraction with Moon Shadow Observations ([arXiv: 1508.07197](#))
 - Iron Spectrum measurements via Direct Cherenkov Method ([arXiv: 1508.05823](#))
 - Ultra-Luminous Radio Galaxies ([arXiv: 1508.05807](#))



Conclusions

- Dark Matter/Astroparticle physics is a key science topic for VERITAS
- Active and diverse group within the collaboration
- VERITAS (and IACTs in general) can provide important dark matter physics constraints (or possible detection) at masses of ~ 1 TeV and above, particularly with Sommerfeld boosts
- Provide input on many areas of New/Fundamental physics

