



# VERITAS AND COSMIC RAYS: AN UPDATE

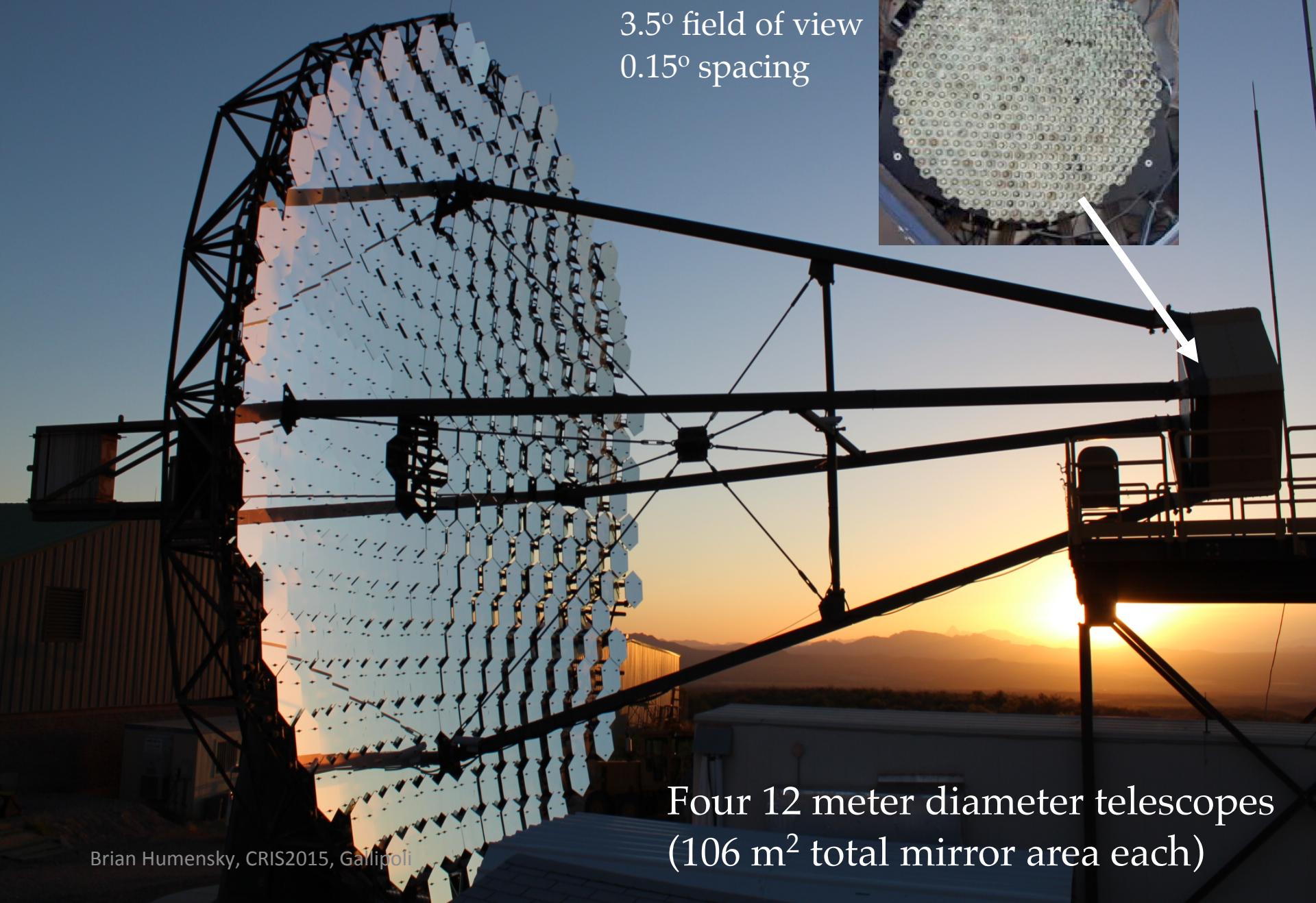
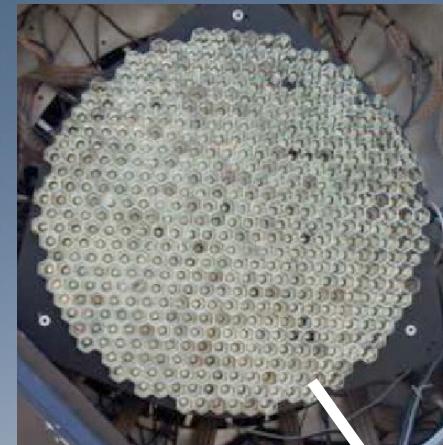
CRIS 2015 GALLIPOLI



**Brian Humensky**  
for the VERITAS Collaboration

 COLUMBIA UNIVERSITY  
IN THE CITY OF NEW YORK

499 PMTs  
3.5° field of view  
0.15° spacing



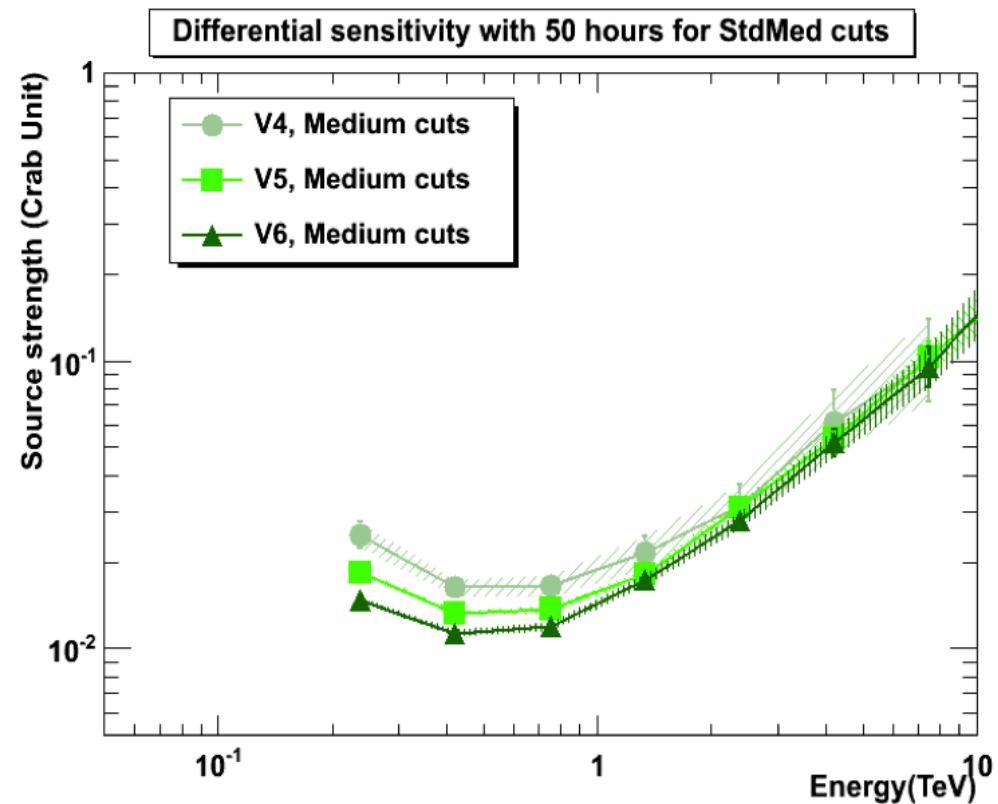
# VERITAS from 2007 to today

- Fully operational since 2007
  - Multiple upgrades: T1 move 2009, L2 Trigger + PMT replacements 2011/12
- Improved sensitivity at low energy
  - critical improvement for science with soft sources (new AGN detections)
  - allow extending the spectrum of known objects to lower energies (i.e. SNRs)

V4: prior to T1 move

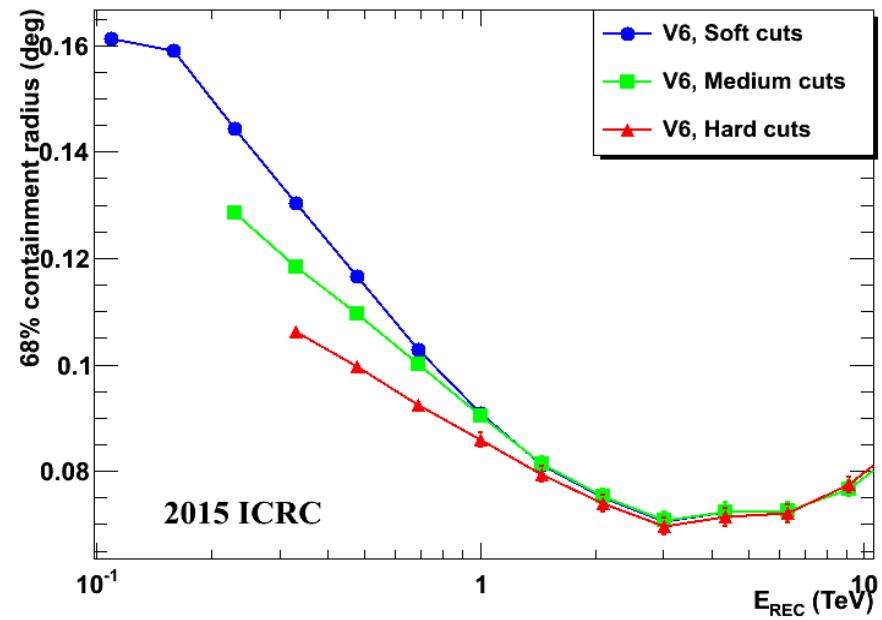
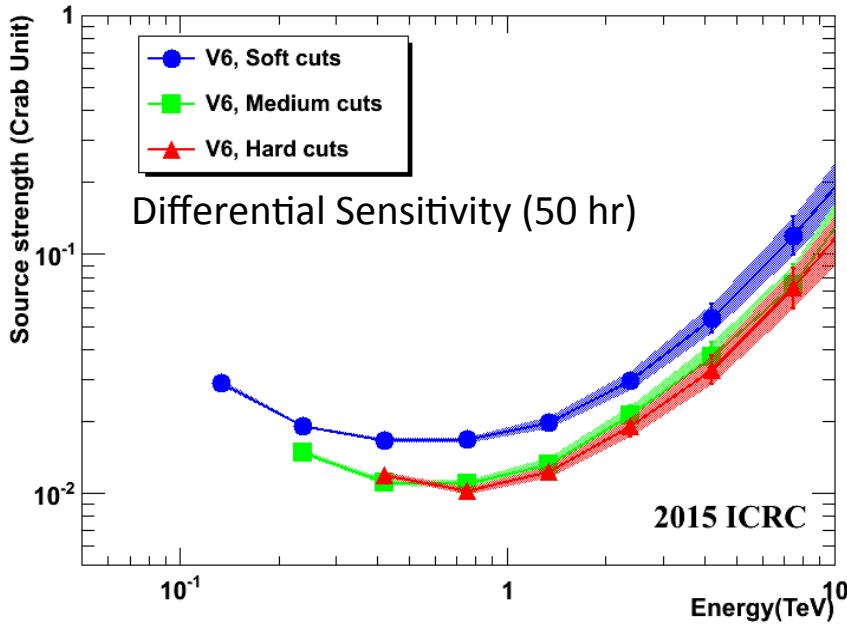
V5: after T1 move, prior to new PMTs

V6: current configuration

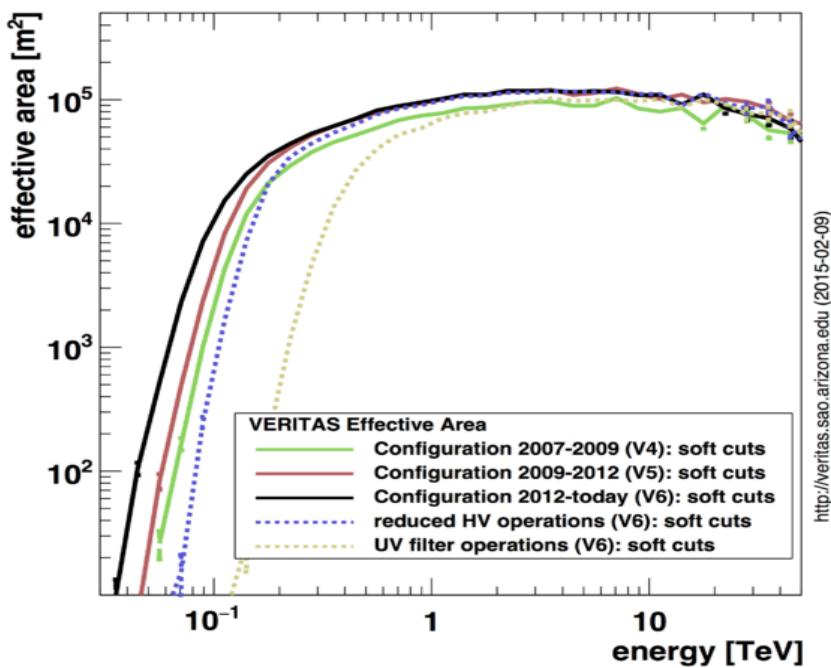
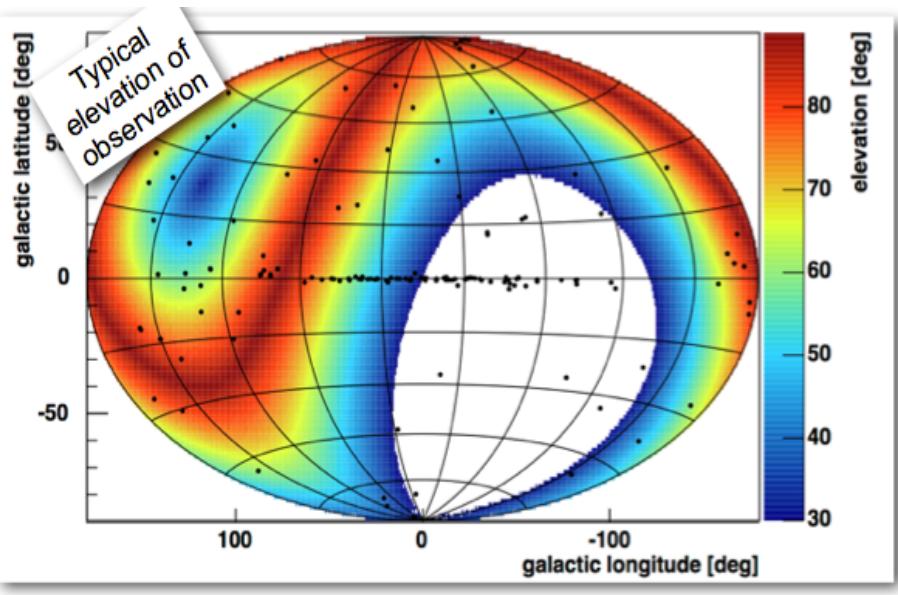


# VERITAS from 2007 to today

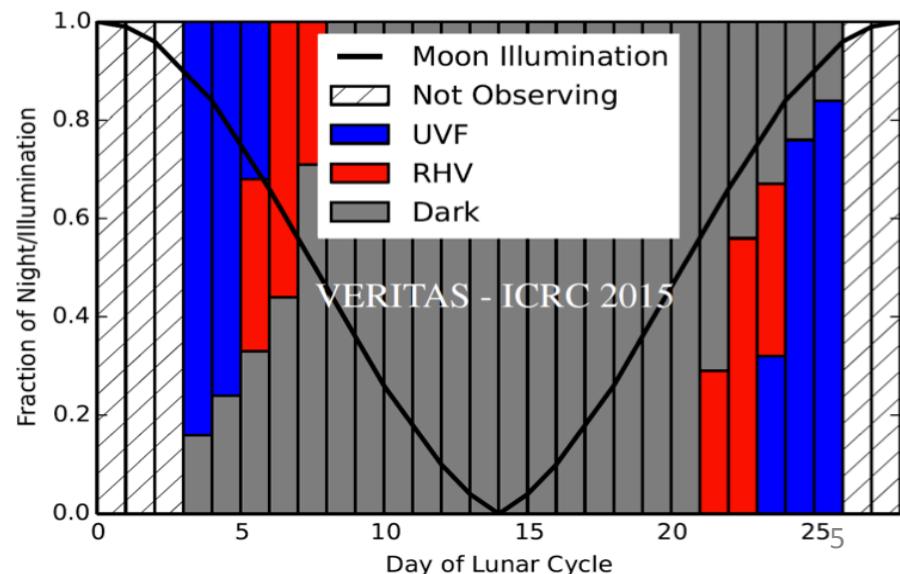
- Energy range: 85 GeV – 30 TeV
- Energy resolution: 15-25%
- Angular Resolution: < 0.1 deg at 1 TeV
- Pointing accuracy error < 50”



# Observing with VERITAS



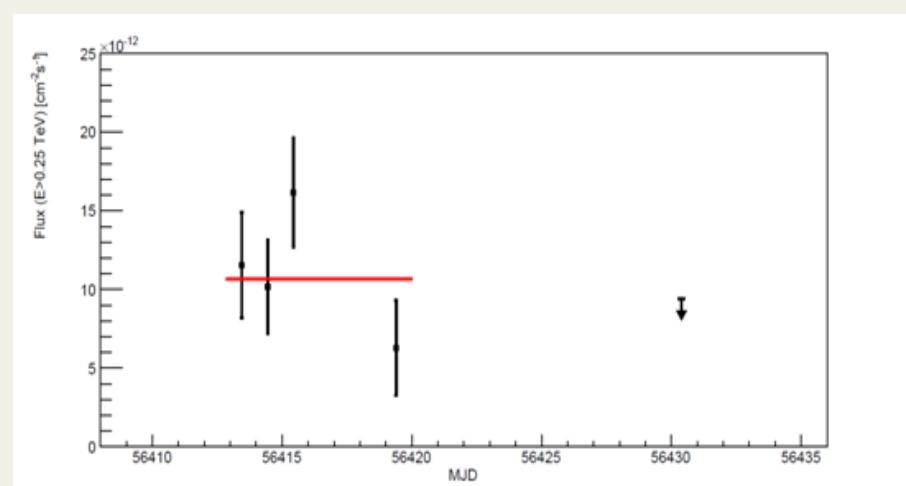
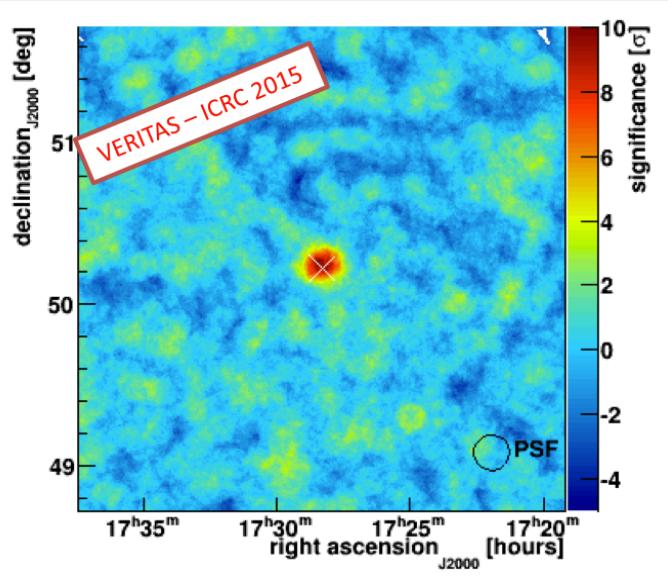
- Northern hemisphere observatory
- Observations cover a large fraction of the moon cycle
  - ~1000 hours in “dark time” conditions per year
  - ~300 hours of bright moonlight data with moon illuminations >30% (using reduced-HV and UV-filter techniques)



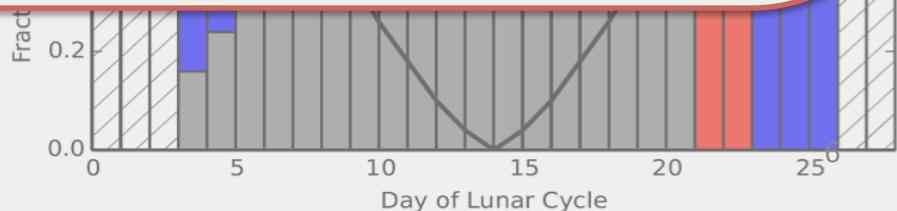
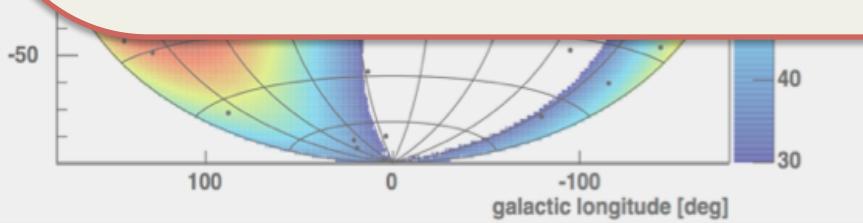
# Observing with VERITAS

- Northern hemisphere observatory

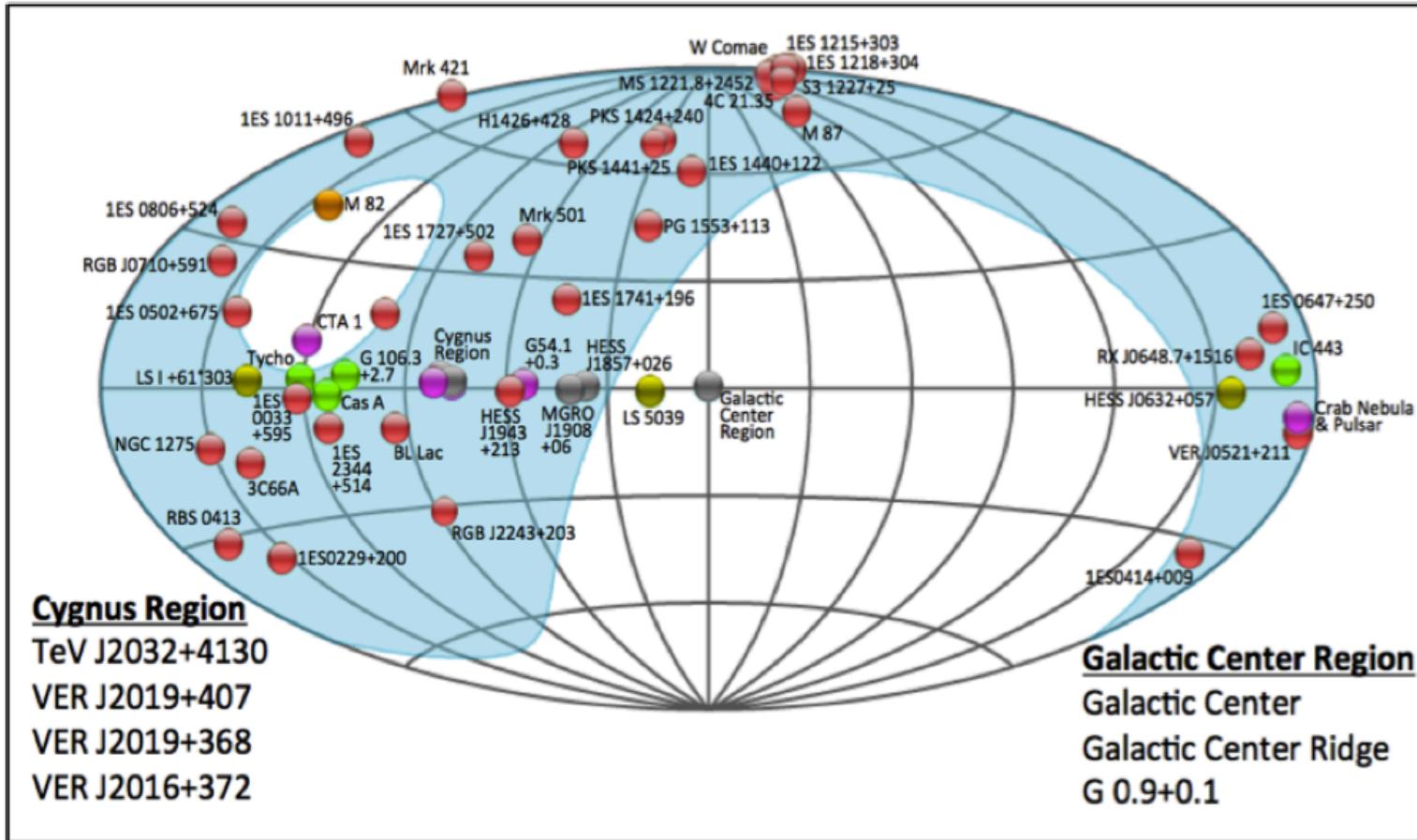
Improving the duty cycle of VERITAS pays off...  
detection of a flare in 1ES 1727+502



*Detected at  $\sim 5x$  archival VHE flux from MAGIC, this detection represents the first evidence of variability in the VHE-band for this source*



# The VERITAS Catalog



54 detections, representing at least 8 source classes

# VERITAS Science

- Many great recent results...
  - Results presented at recent ICRC will be posted on arXiv soon
- What I will cover:
  - New SNR results including Tycho & IC 443
  - Studies of the Galactic Ridge
  - Highlights from the blazar program including PKS 1441+25 & IGMF constraints
  - Cosmic-Ray Electron spectrum
  - IceCube Neutrino follow-up
  - Dark Matter limits

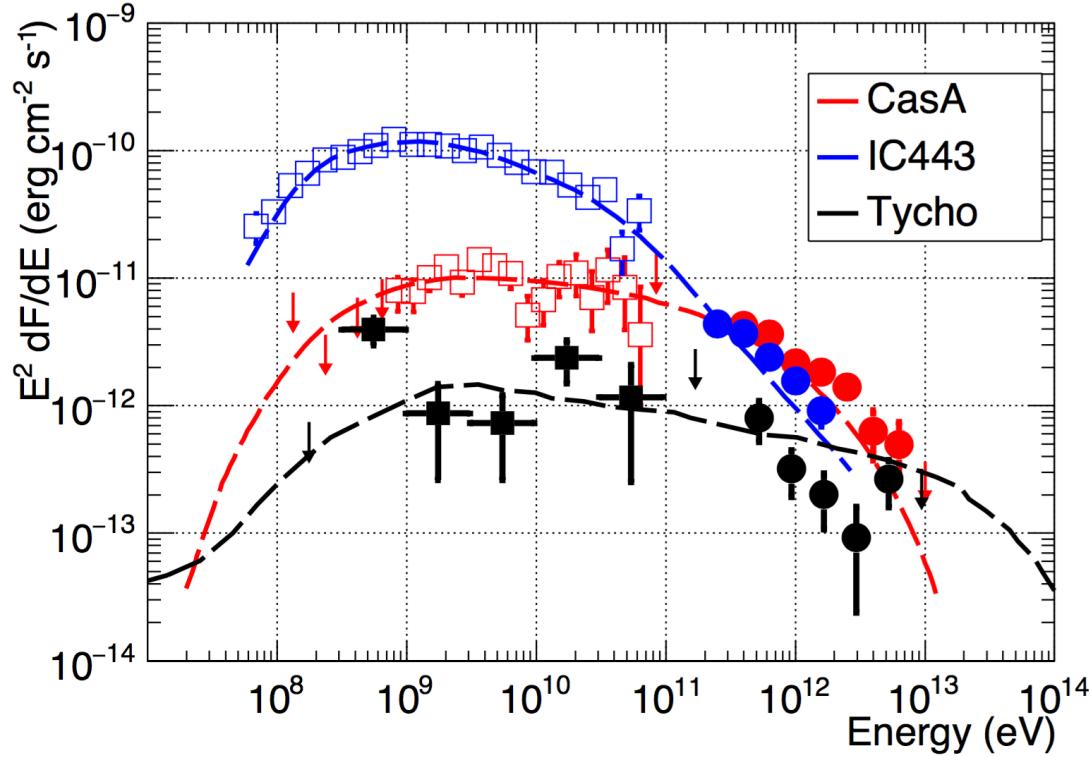


# New VERITAS SNR results

- Deep exposures of three northern SNRs

- Investigate the mechanisms of cosmic-ray acceleration
- Probe the distribution of energetic particles in the acceleration region
- Study the importance of SNR type, age, target material, magnetic fields, progenitor

> 150 hours of exposure for IC443 and Tycho

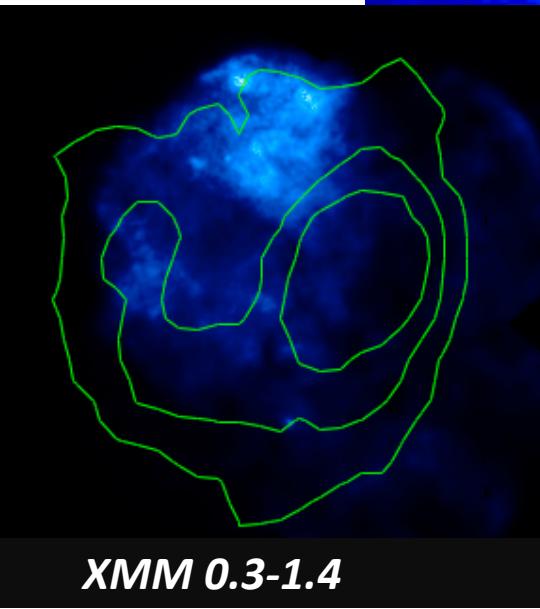
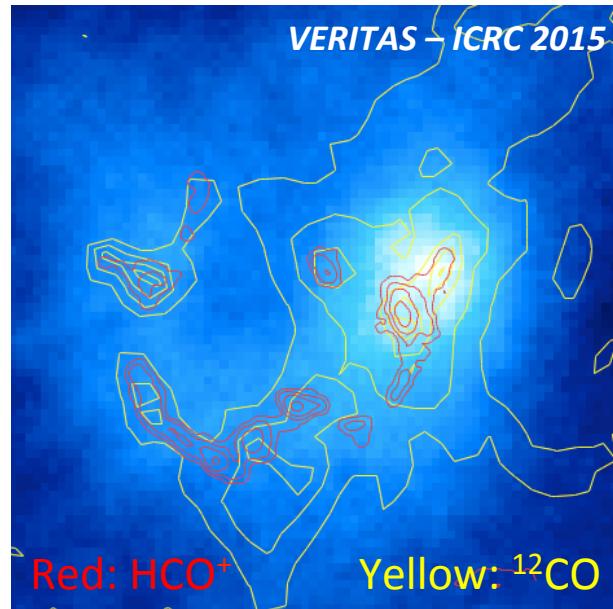
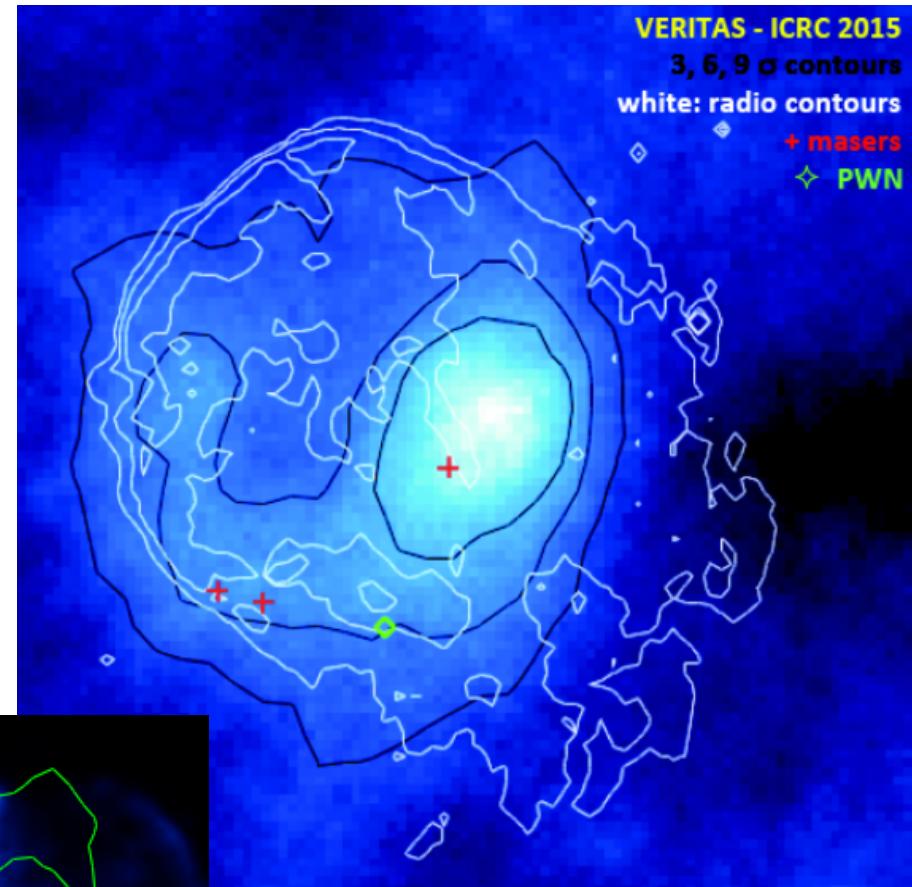


CasA model (Yuan et al., 2013), Fermi (Yuan et al., 2013), VERITAS (ICRC 2015)  
IC443 model (Ackermann et al., 2013), Fermi (Ackermann et al., 2013), VERITAS (ICRC 2015)  
Tycho model (Slane et al., 2014), Fermi (ICRC 2015), VERITAS (ICRC 2015)



# VERITAS RESULTS: IC 443

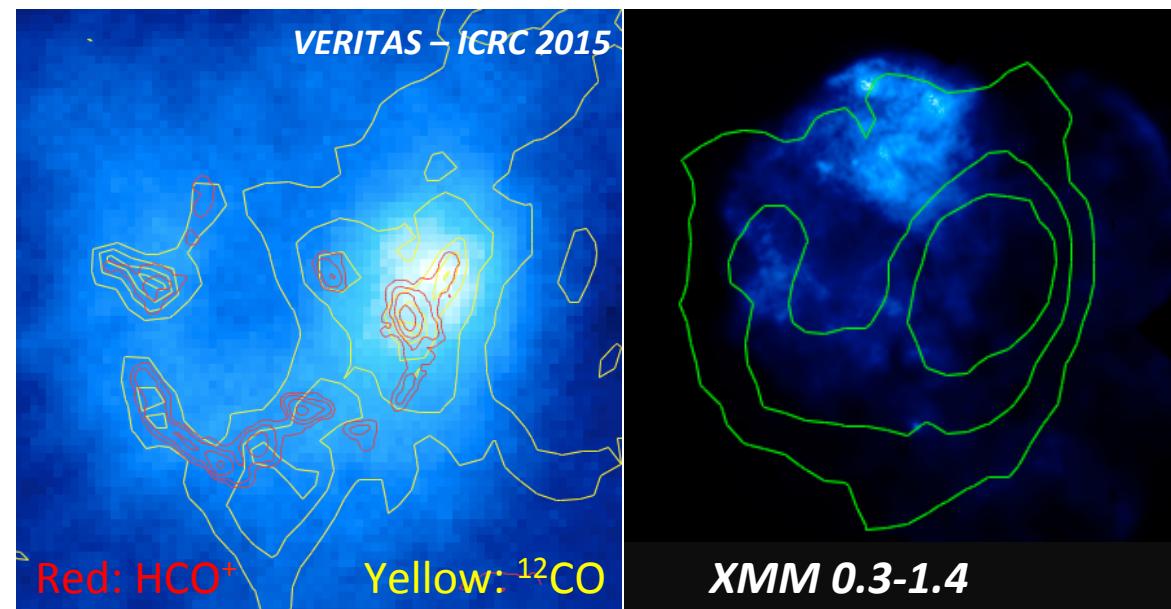
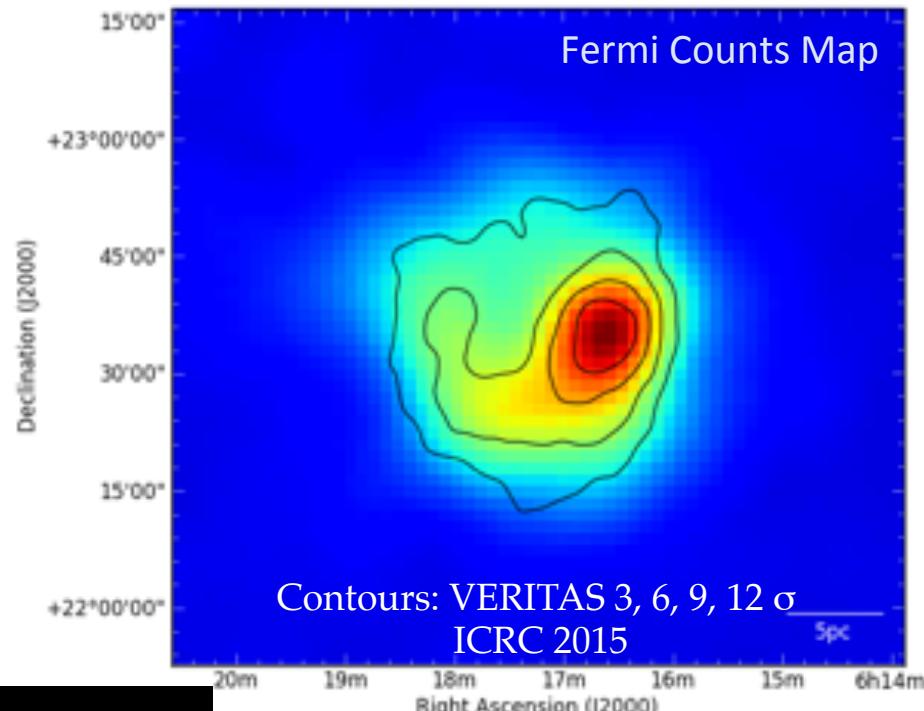
- Strong spatial correlation of  $\gamma$ -ray emission with masers and molecular gas
- GeV/TeV emission show remarkable spatial correlation
- Anticorrelation with thermal X-rays
- Can extract spectra from different regions to probe the environmental dependence of cosmic-ray diffusion



Single population  
of CR interacting  
with swept up /  
shocked gas?

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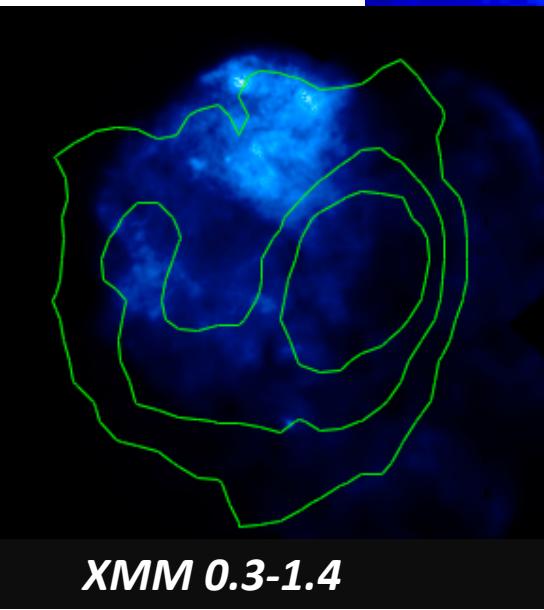
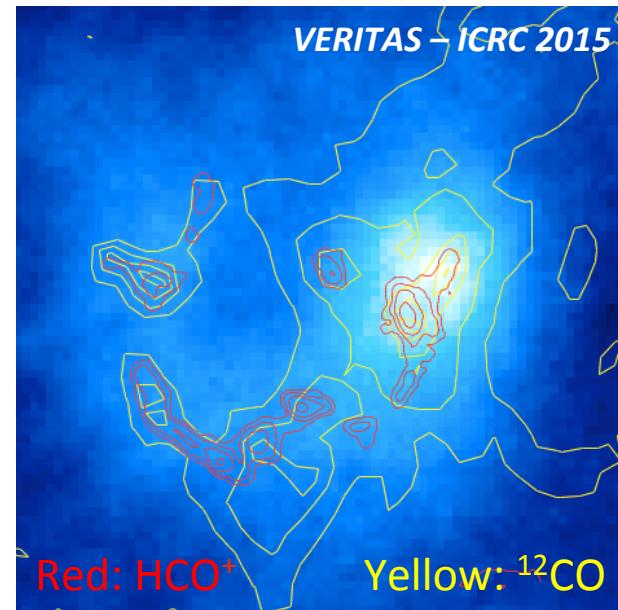
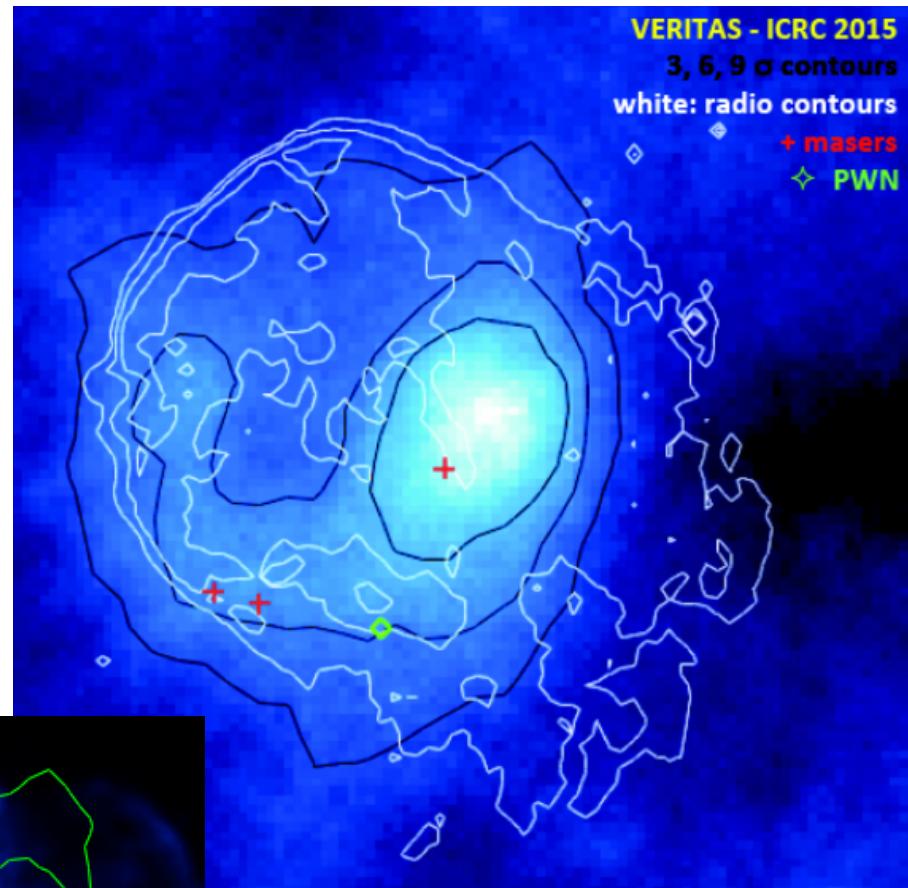
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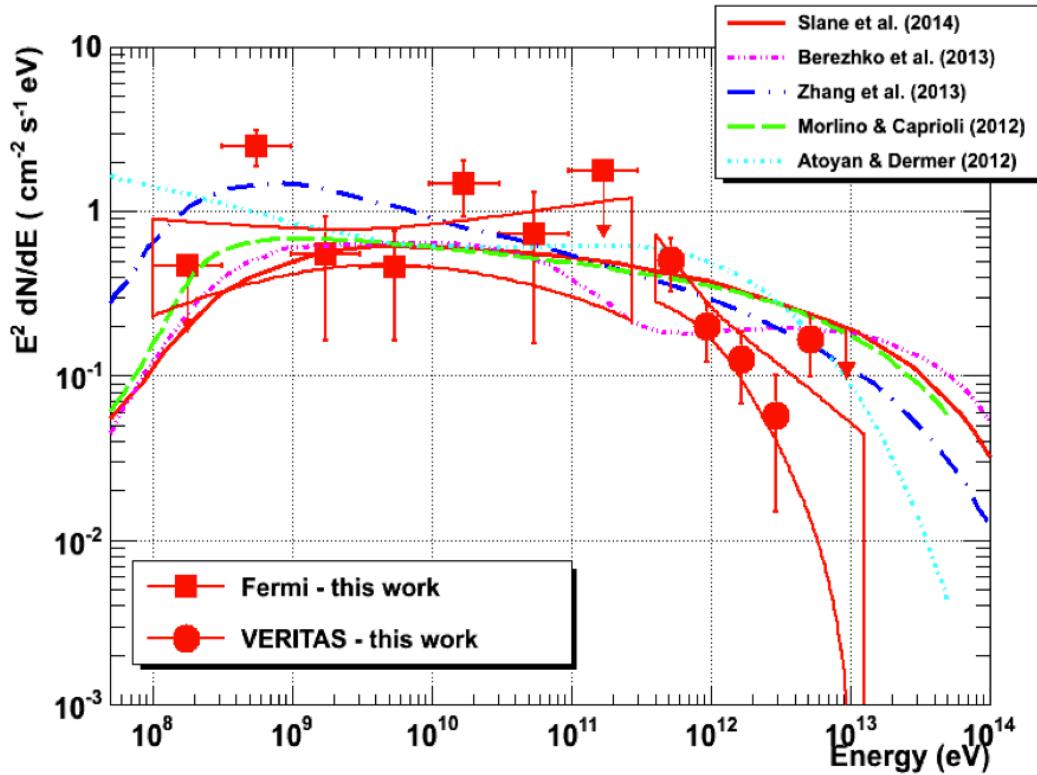
# VERITAS RESULTS: IC 443

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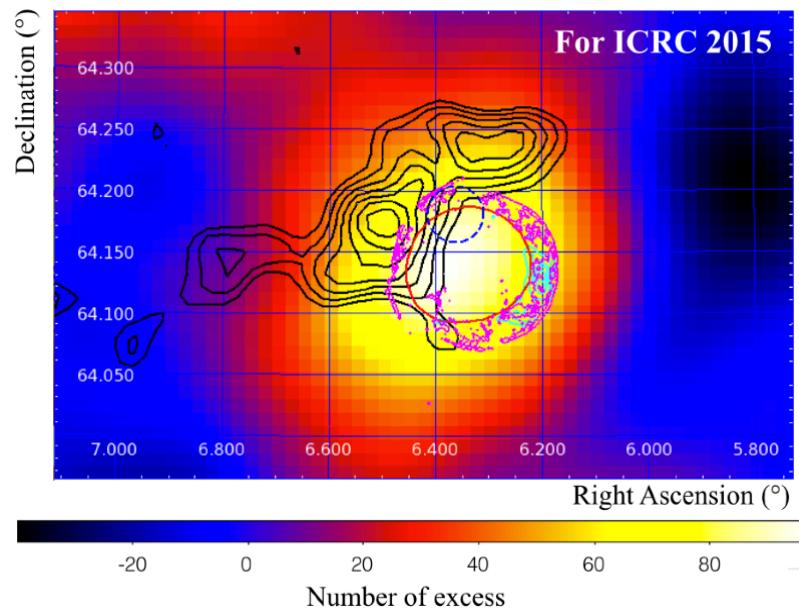
Single population  
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# Tycho: Young Type Ia SNR – 1572



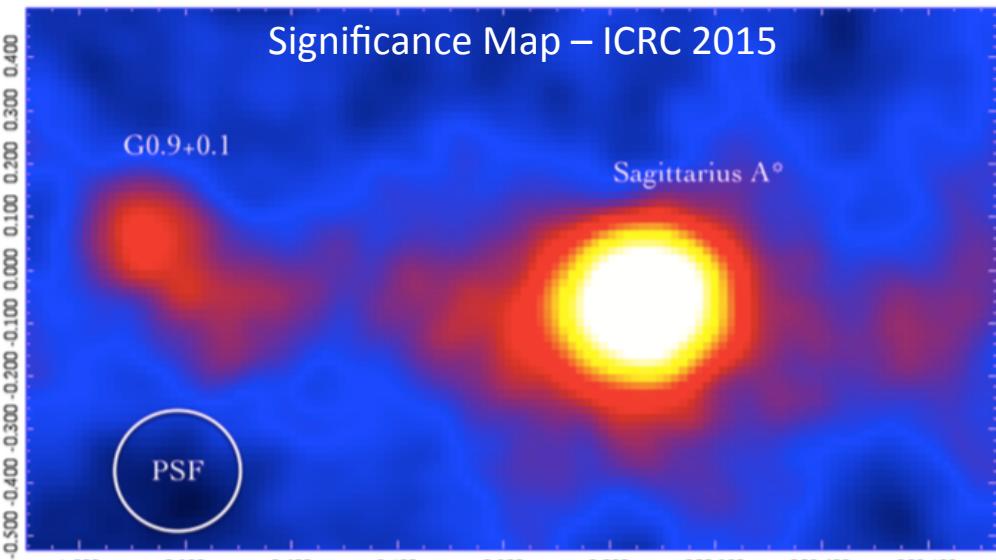
- Updated spectrum extended to lower energies (new PMTs), resulting in a softer best-fit index:  
 $-2.92 \pm 0.42_{\text{stat}} \text{ (new)}$   
versus  
 $-1.95 \pm 0.51_{\text{stat}} \pm 0.30_{\text{sys}} \text{ (published)}$
- Constrains and challenges particle acceleration models

- Good candidate for hadronic emission scenarios
  - exploded in a clean environment
  - young and well studied at other wavelengths
- Discovered by VERITAS in 2010, we now have  $\sim 150$  hours
- Models mainly from hadronic particles with some multi-zone leptonic

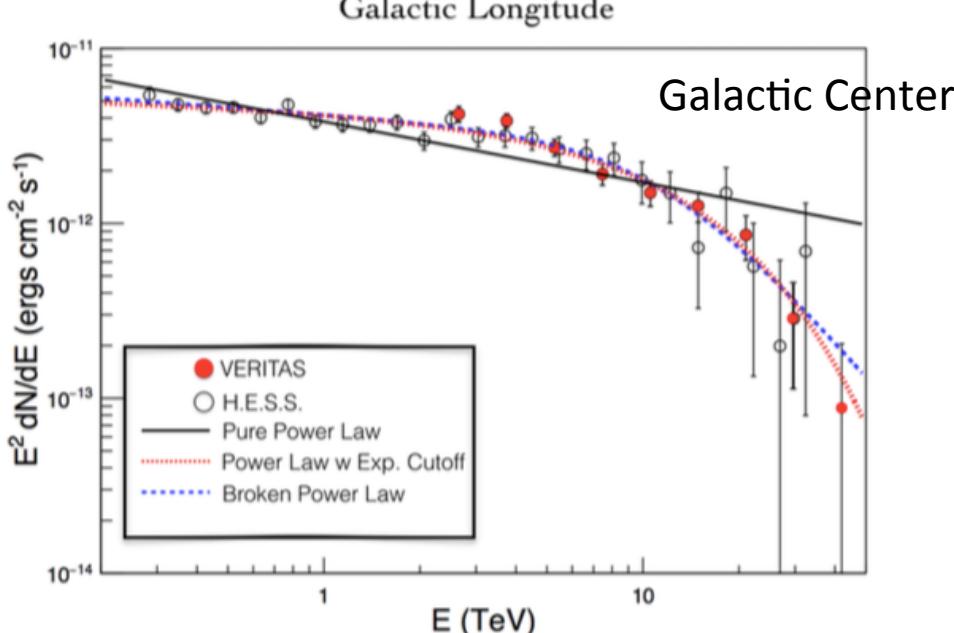


# The Galactic Center and Ridge

Galactic Latitude

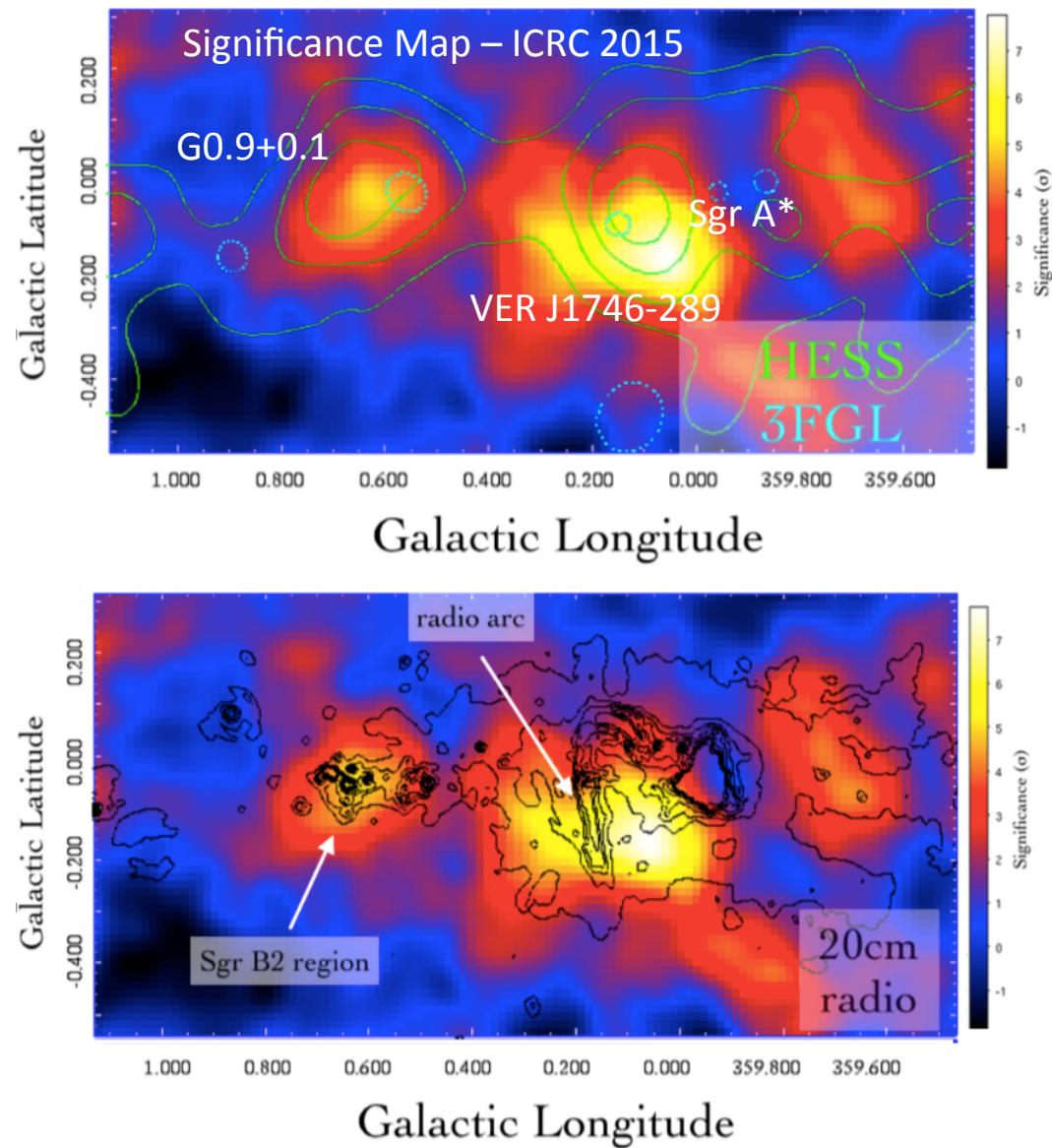


Galactic Longitude



- Observations 2010-2014 > 85 hr.
- 2 point sources within FOV:
  - SgrA\* ( $>25\sigma$ )
    - (HESS + VERITAS) spectral fit favor PL + exp cutoff:  
 $\Gamma = 2.1 \pm 0.04$   
 $E_{\text{cut}} = 12.8 \pm 1.9$  TeV
    - No sign of variability  $> 2$  TeV
  - Composite SNR G.0.9+0.1 ( $>7\sigma$ )
    - Extends power-law spectrum ( $G = 2.3 \pm 0.1$ ) with no cut off below 25 TeV
- Diffuse TeV band also apparent

# The Galactic Center and Ridge



- Remove point-source excesses from Sgr A\*, G0.9+0.1 to study residual diffuse emission
  - VERITAS > 2-TeV residual emission overlaps reasonably well with H.E.S.S >300 GeV
  - Several 3FGL sources nearby
- New VERITAS source VER J1746-289 revealed adjacent to Sgr A\*, detected at 7.8 $\sigma$ 
  - Located near radio arc, but not clearly correlated
- > 2-TeV enhancement correlated with Sgr B2 MC/SFR



# The VERITAS Blazar program

AGN	Type	z
M 87	FR I	0.004
NGC 1275	FR I	0.018
Mkn 421	HBL	0.03
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
1ES 1727+502	HBL	0.055
BL Lac	IBL	0.069
1ES 1741+196	HBL	0.084
W Comae	IBL	0.102
VER J0521+211	HBL	0.108
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
S3 1227+25	IBL	0.135
1ES 0806+524	HBL	0.138
1ES 0229+200	HBL	0.139
1ES 1440+122	HBL	0.163
RX J0648.7+1516	HBL	0.179
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.19
1ES 1011+496	HBL	0.212
MS 1221.8+2452	HBL	0.218
1ES 0414+009	HBL	0.287
PKS 1222+216	FSRQ	0.432
PKS 1441+25	FSRQ	0.939

## Scientific objectives:

- Understand supermassive black holes
- Origin of jet emission, dynamics and evolution of the black hole environment
- Cosmology: EBL/IGMF studies
- Fundamental Physics: Lorentz Invariance

AGN	Type	z
3C 66A	IBL	0.33 < z < 0.41
PKS 1424+240	IBL	>0.604
PG 1553+113	HBL	0.43 < z < 0.58
1ES 0033+595	HBL	?
1ES 0502+675	HBL	?
1ES 0647+250	HBL	?
B2 1215+30	IBL	?
HESS J1943+213	HBL	?
RGB J2243+203	IBL	?

- All VERITAS AGN are Fermi-LAT detected
- All detections have simultaneous MWL data
- ~25% have uncertain redshift

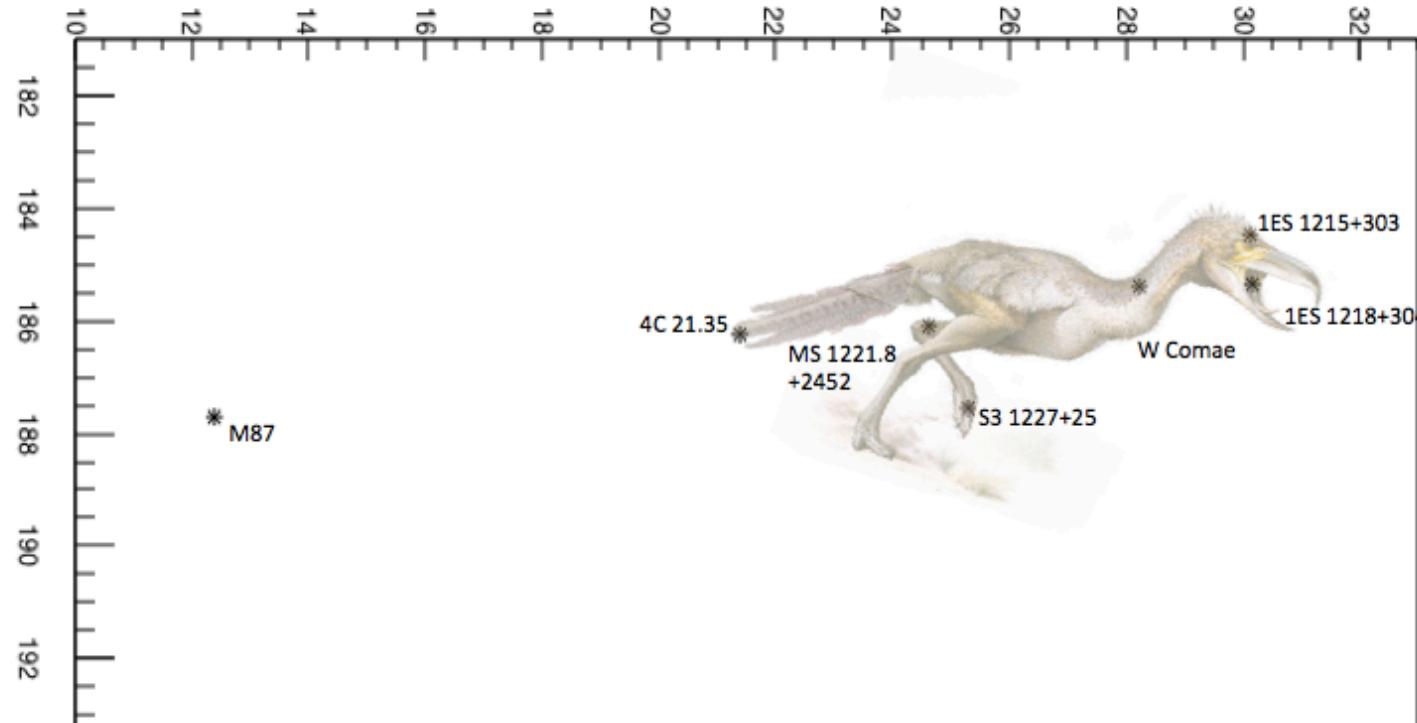
arXiv: 1508.07251

- **34 VHE AGN: 23 HBL, 7 IBL, 2 FSRQ & 2 FR I**
- 2013-14: 1ES 0033+595, MS 1221.8+2452, PKS 1222+216 & HESS J1943+213
- 2014-15: S3 1227+25, PKS 1441+25 & RGB J2243+203

# The VERITAS Blazar program

## Scientific objectives:

- Understand supermassive black holes



*The first VHE constellation?! Introducing Tera-bird (credit Jamie Holder)*

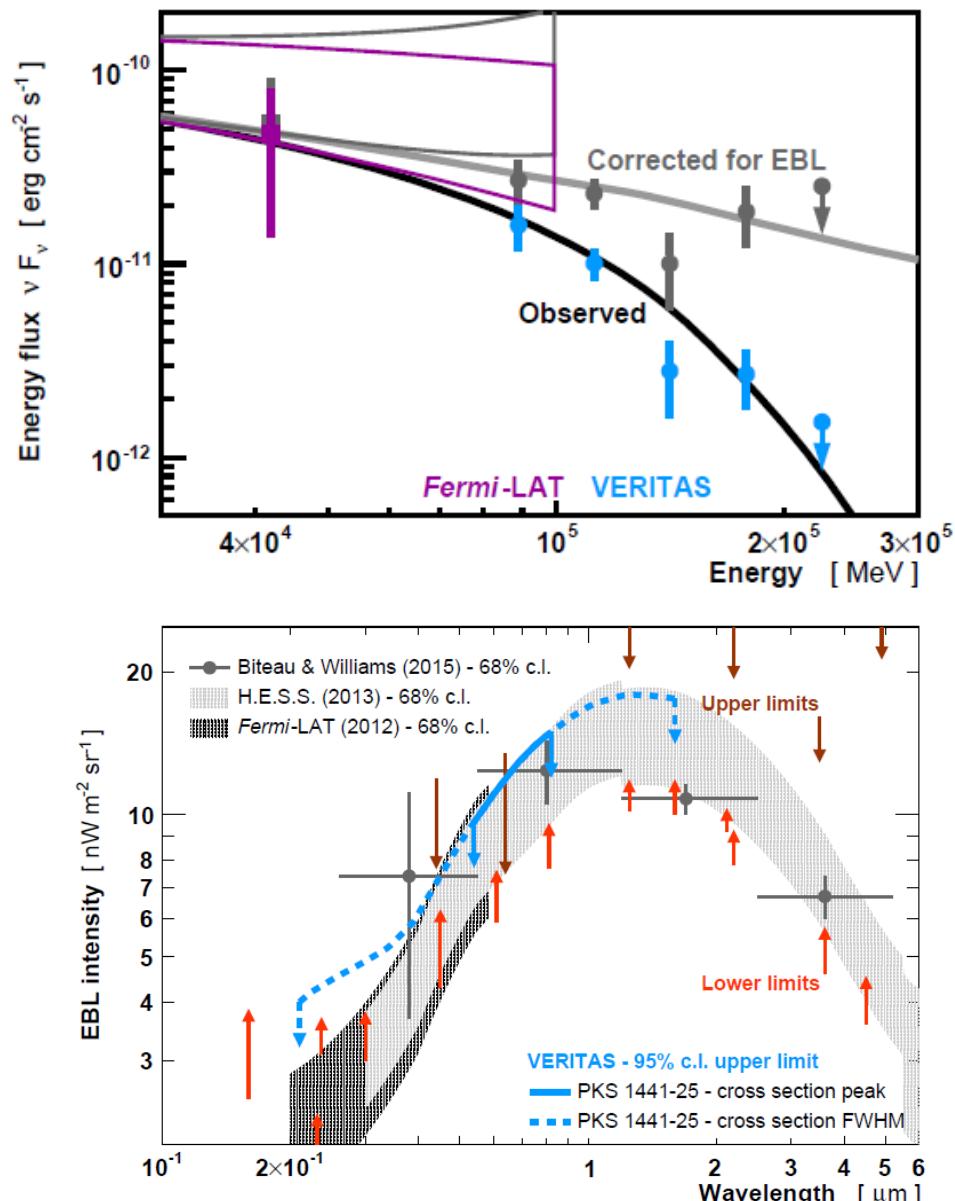
- 2013-14: 1ES 0033+595, MS 1221.8+2452, PKS 1222+216 & HESS J1943+213
- 2014-15: S3 1227+25, PKS 1441+25 & RGB J2243+203

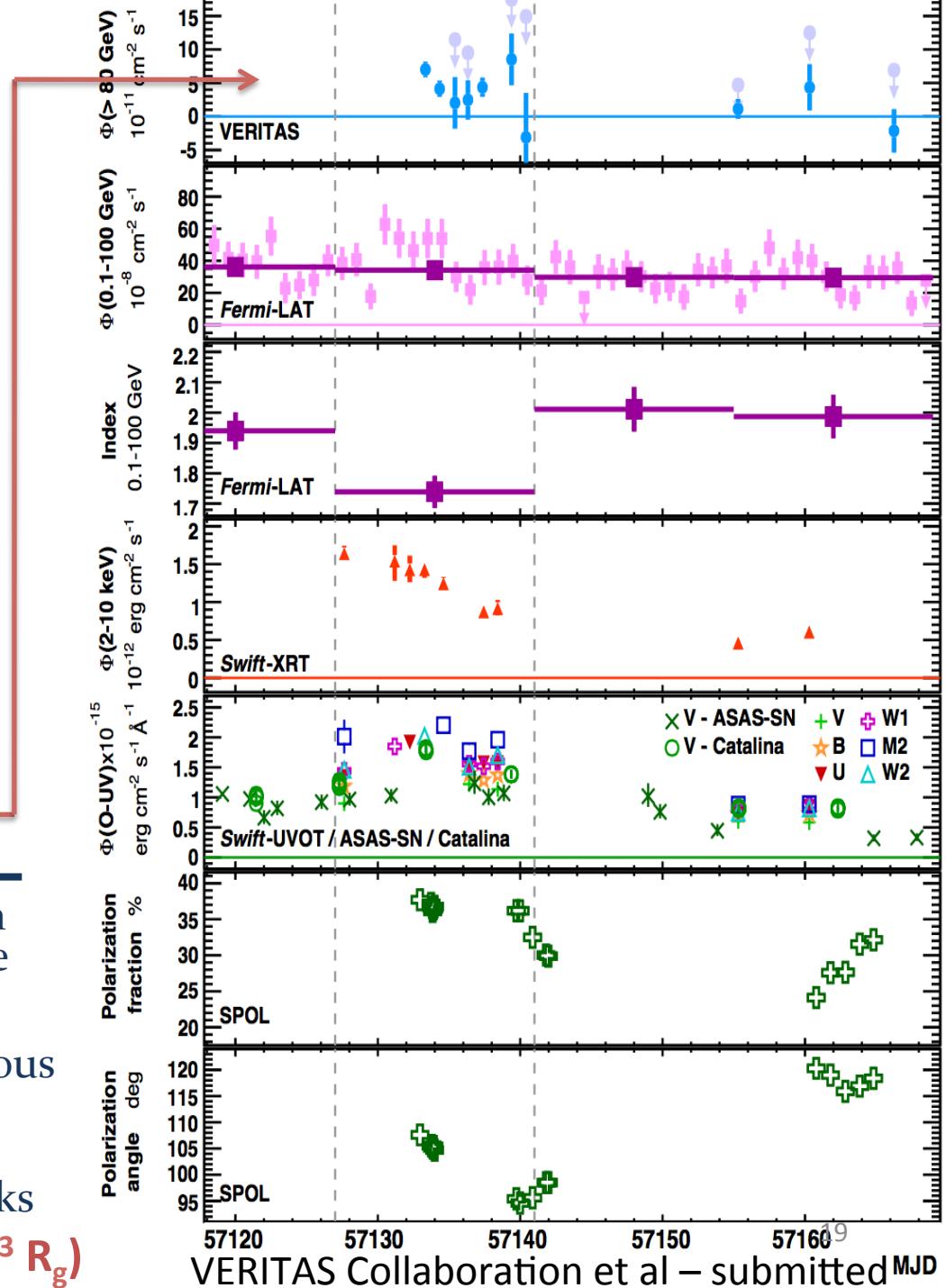
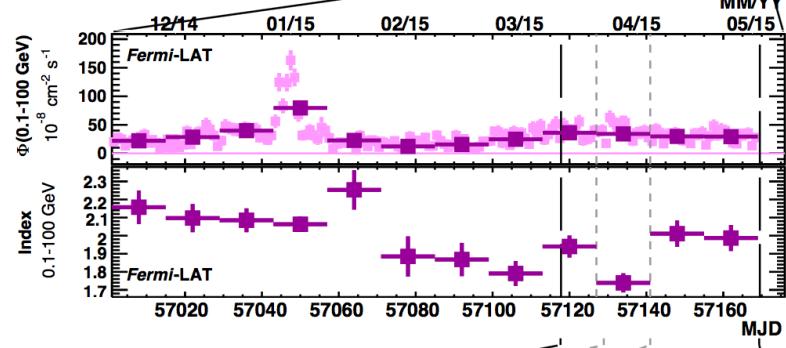
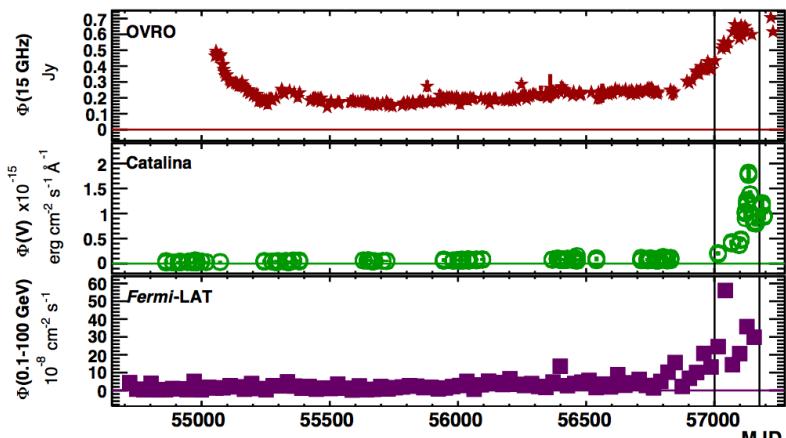
AGN	Type	z
M 87	FR I	0.004
NGC 1275	FR II	0.010

# VERITAS Results: PKS 1441+25

- One of the most distant FSRQs detected in VHE ( **$z=0.939$** )
- Triggered by Fermi/MAGIC alerts
- 15 hours of observations with VERITAS– Apr 2015
- ~400 gamma rays,  $8\sigma$
- 5% Crab above 80 GeV
- Very soft spectral index  $\Gamma=5.3\pm0.5$

**First time that one single source constrains a large fraction of the EBL spectrum.**





# PKS 1441+25: MWL

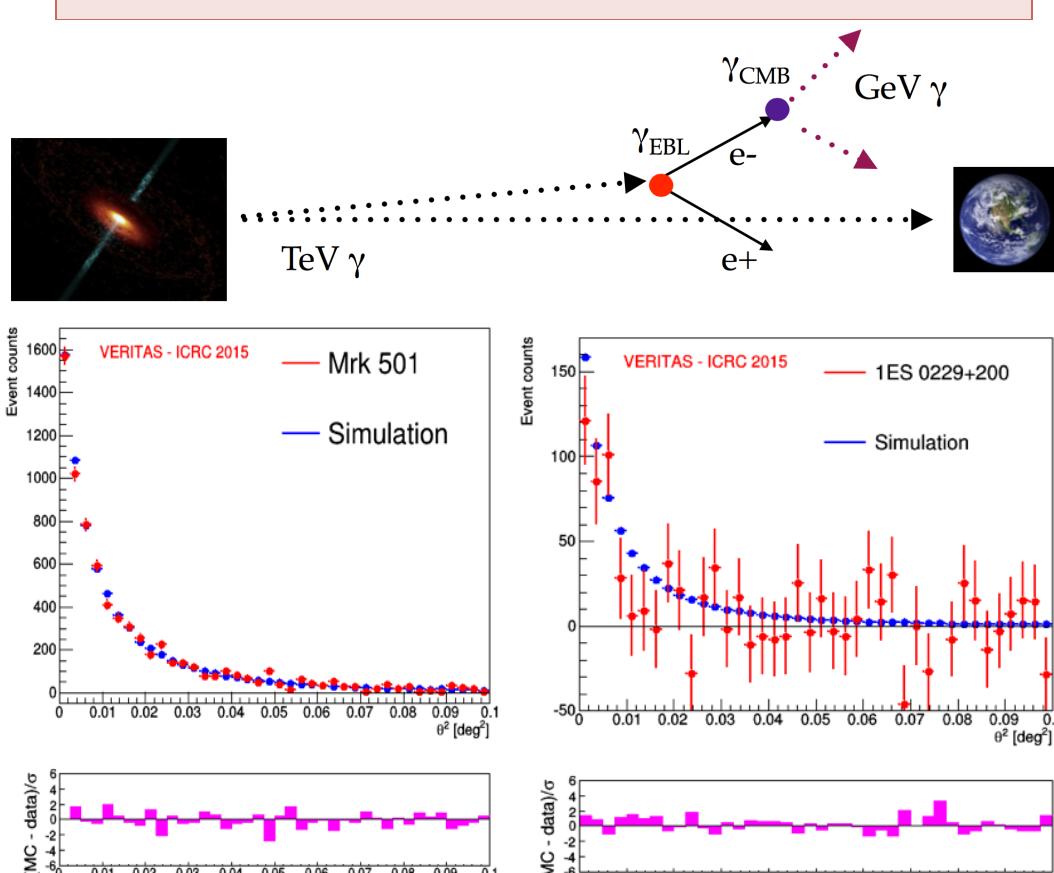
- Radio, optical, Fermi-LAT correlation (no delay) supports single, large-scale emission region
- VERITAS detection is contemporaneous with period of high polarization & enhanced MWL emission
- Variability time scale (X-ray)  $< 2$  weeks

**Emitting region far from SMBH ( $10^3 R_g$ )**

# VERITAS IGMF Constraints

*Unambiguous detection of IGMF remains elusive - important to understand large scale structure formation and to understand the propagation of cosmic rays in cosmic voids*

## Search for IGMF-broadened cascade emission in VHE blazars



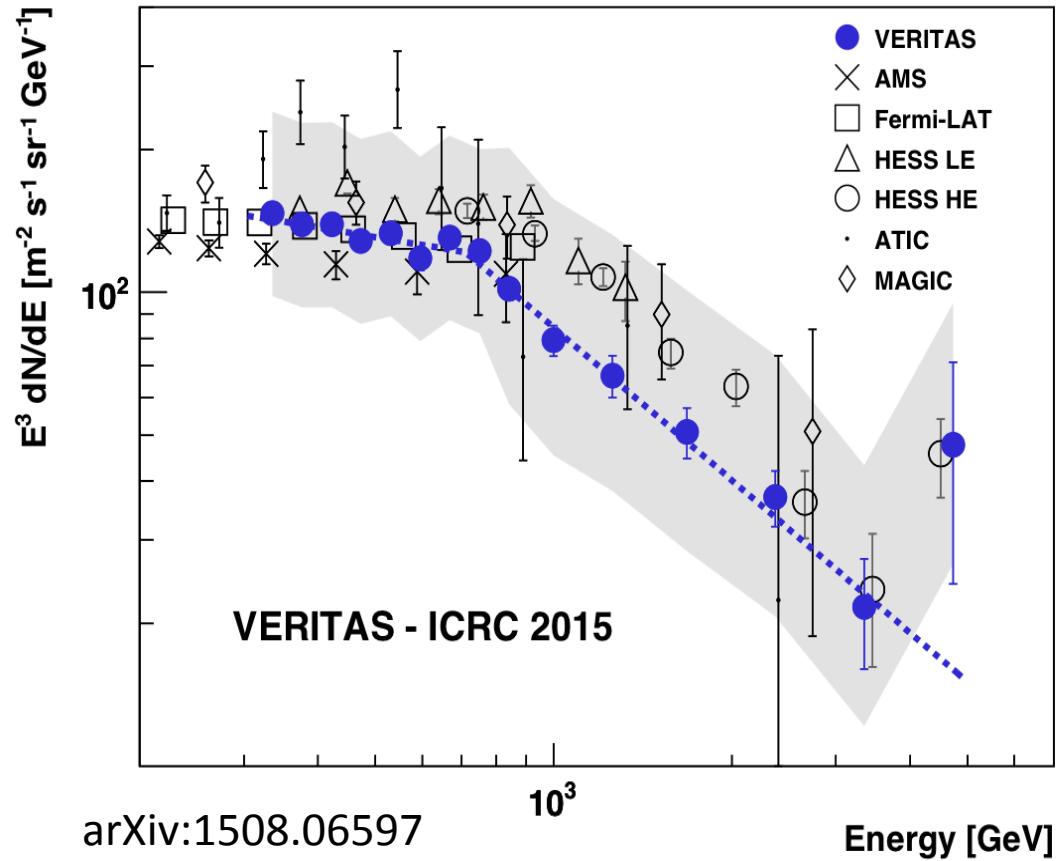
- EBL produces  $e^+e^-$  pair, secondary particles are bent by the IGMF
- **No extension seen in the angular distribution in 7 blazars**
- Flux limits set for model independent case:  
 $(0.17-2.69) \times 10^{-12} \text{ cm}^{-2} \text{TeV}^{-1} \text{s}^{-1}$
- Limits on IGMF magnitude set for model-dependent extended emission by comparing to simulated blazars and using 3D semi-analytical code

# Cosmic Ray Electrons with VERITAS

*Cosmic-ray electrons at TeV energies are a direct probe of nearby ( $\sim 1\text{ kpc}$ ) accelerators*

**296 hours of data  
between 2009 and 2012**

- Electron-like events selected by Boosted Decision Trees and extended likelihood fitting
- Spectrum agrees qualitatively with other experiments within systematic uncertainty
  - Break at  $710 \pm 40$  GeV
  - Index below (above) break of  $-3.2 \pm 0.1_{\text{STAT}}$   
 $(-4.1 \pm 0.1_{\text{STAT}})$



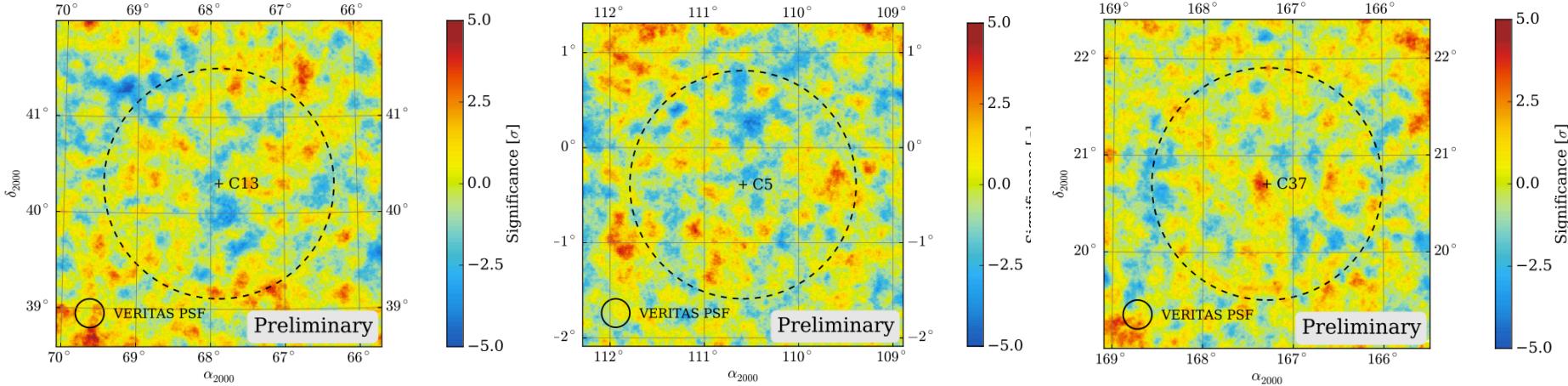
- Confirms evidence of at least one nearby CR electron emitter
- Second high-statistics measurement of a break below  $\sim 1$  TeV



# Follow-up of IceCube Events

*IceCube discovery of astrophysical flux of high-energy neutrinos provides evidence of sites of cosmic ray generation... however, no significant neutrino point sources seen yet (isotropic)*

arXiv:1509.00517



- Observations of 22 IceCube  $\nu_\mu$ -induced muon-track events for a total of 40 hours
  - muon-track events have good localization,  $\sim 1$  degree angular uncertainty
  - 3 positions publicly released, 19 shared by a mutual agreement

No significant signals seen: flux upper limits for each of the positions found in the range of  $\sim 2\text{-}10\%$  Crab Nebula flux



# VERITAS Dark Matter Program

Search for gamma-ray flux of particle DM annihilation or decay from 100 GeV to the multi-TeV scale

$$\frac{d\phi}{dE} = \frac{\langle\sigma v\rangle}{8\pi m_x^2} \left[ \frac{dN(E, m_x)}{dE} \right]_{DM} \langle J \rangle$$

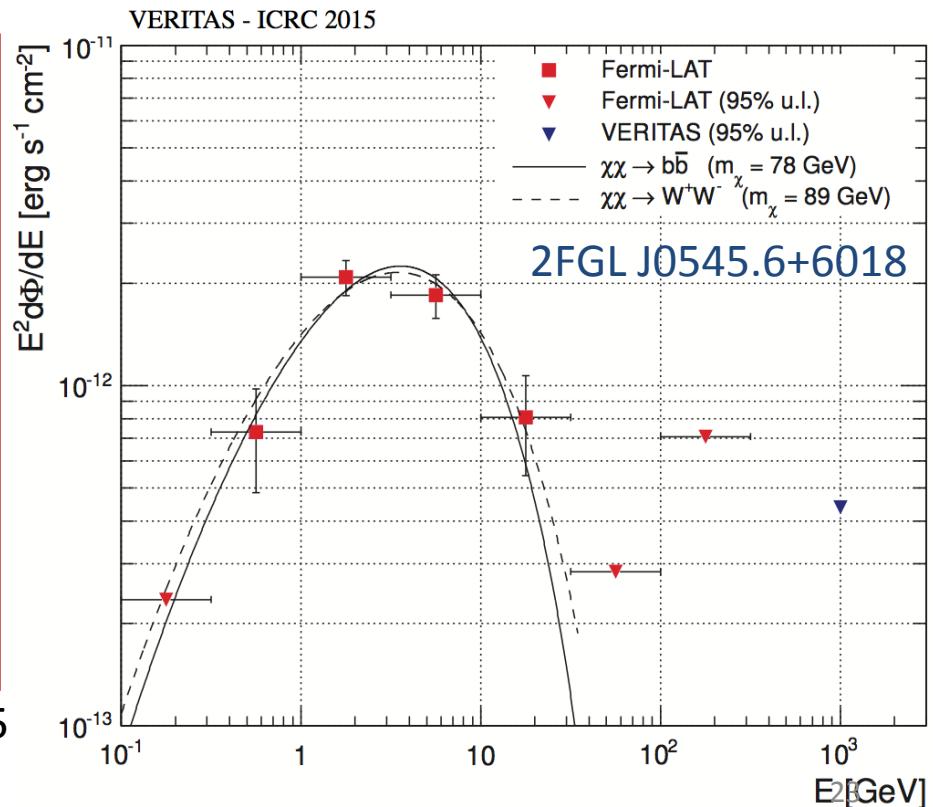
Particle PhysicsAstrophysics

Search for signals in DM-dominated regions: Dwarf Spheroidal Galaxies (dSphs), the Galactic Center, Galaxy Clusters, and Fermi Unassociated Sources

New result on observations of two sub-halo candidates identified from the 2FGL catalog

- Targets identified by lack of variability & MWL counterparts
- **2FGL J0545.6+6018**, **2FGL J1115.0-0701**

arXiv:1509.00085



Brian Humensky, CRIS2015, Gallipoli

# VERITAS Dark Matter Program

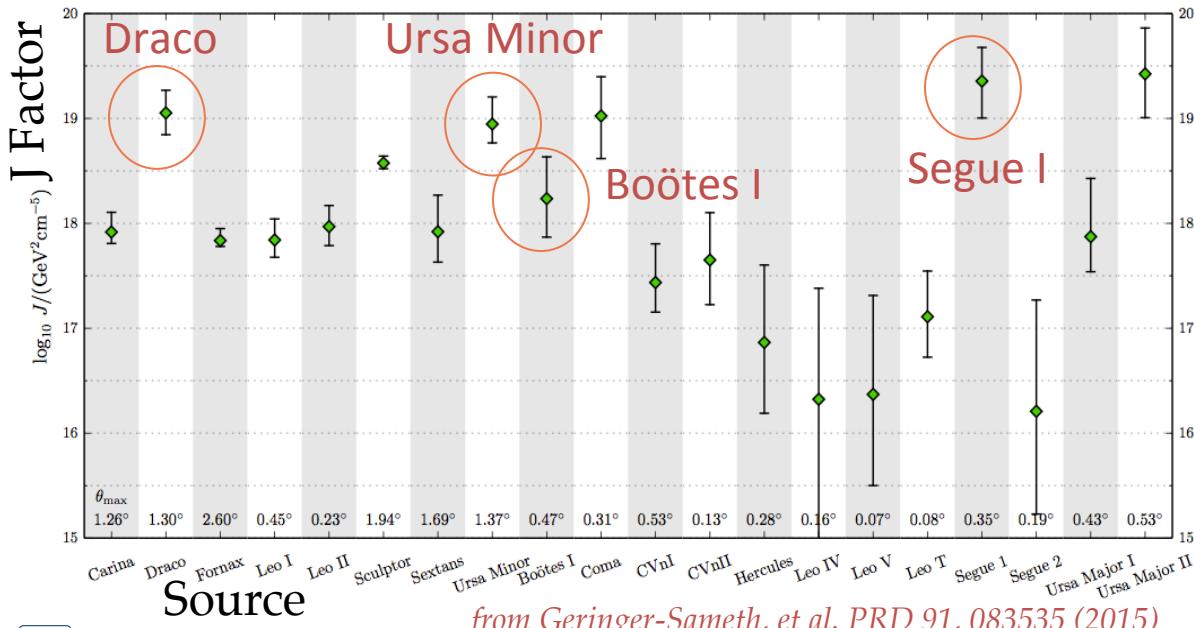
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Particle PhysicsAstrophysics

Search for signals in DM-dominated regions: Dwarf Spheroidal Galaxies (dSphs), the Galactic Center, Galaxy Clusters, and Fermi Unassociated Sources

- New combined result with data from 4 dSphs



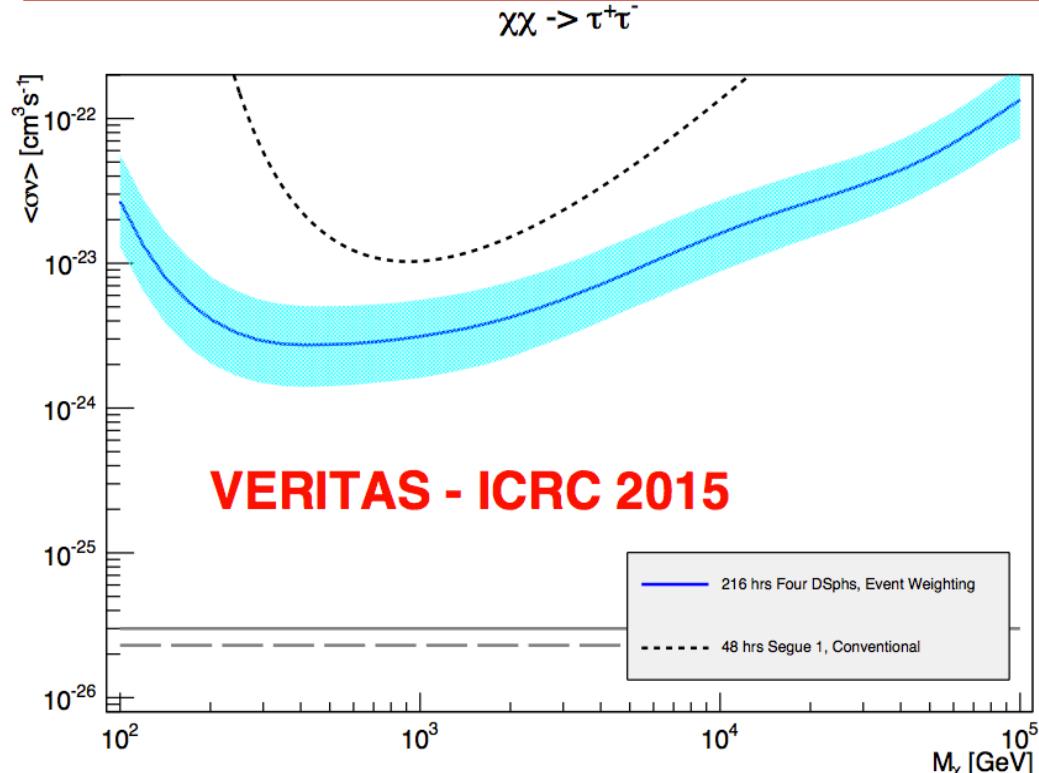
Long-term Plan: 150 hours annually on dSphs, including deep exposures on several high J-factor objects + survey of ~all known northern dSph



# VERITAS dSph Combined DM Limits

*Ideal DM targets: **dSph galaxies** are nearby, with  $O(10^3)$  times more DM mass than visible matter, and little expected astrophysical background*

Dark Matter Search/Limits using  
216 hours of Dwarf Spheroidal data  
from 2007-13.



- Methodology (Geringer-Sameth et al. 2015) utilizes individual event energy, dwarf field and direction information
  - Limits presented as a band to represent systematic uncertainty in J-Factors
- Previous single-source results published by VERITAS: the most constraining from 48-hours on Segue 1

- *Phys. Rev. D. 85, 062001 (2012)*  
*(Erratum) Phys. Rev. D. 91, 129903 (2015)*



# Conclusions

- VERITAS is running very well, is more sensitive than ever, and is extending observations to cover more of the moon cycle
- VERITAS science covers a wide range of topics: astronomy, cosmology, particle physics
  - Lots of data with plenty of sources, both Galactic and extragalactic
  - The source catalog is now at 54 sources from at least 8 source classes
- We are always looking to collaborate, with a fraction of our observation time open to the larger community and funded through the Fermi-VERITAS-GI
- See upcoming arXiv links for compilation of the most recent VERITAS results from the ICRC

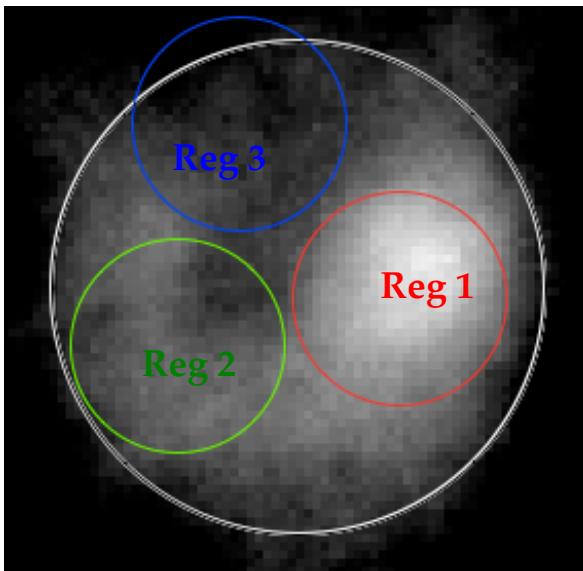


# Backup

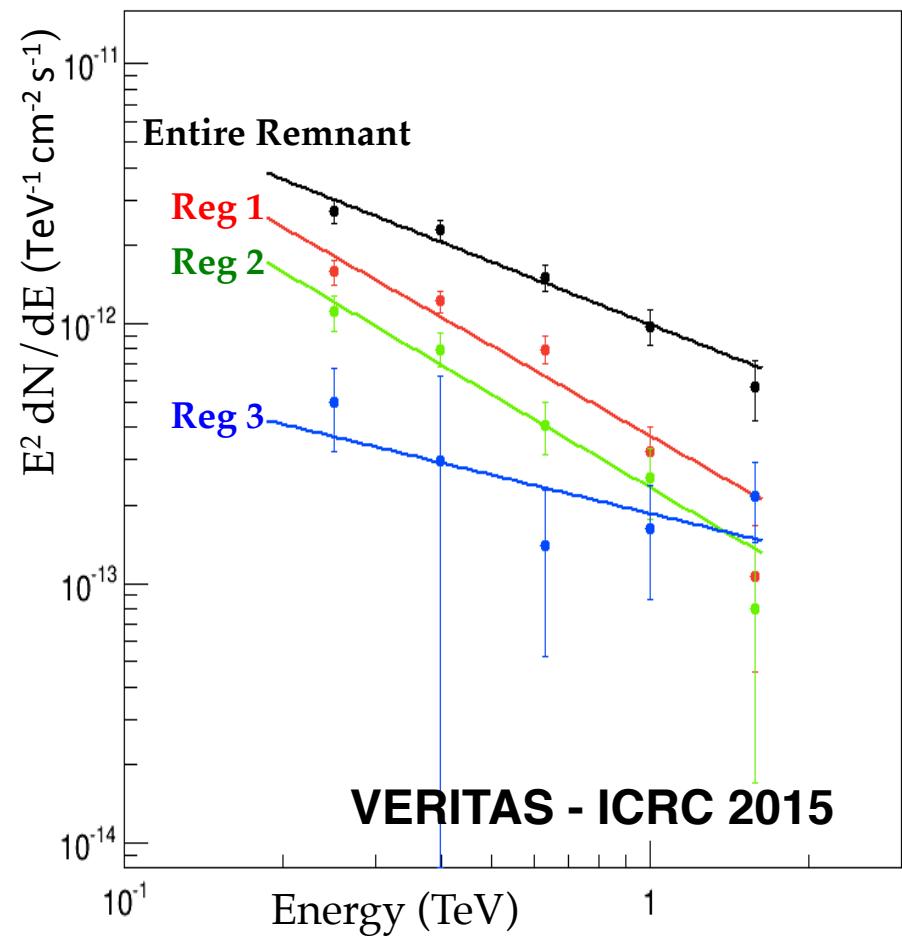


# IC 443 VHE Spectra

- Spectra extracted for entire SNR ( $0.3^\circ$  radius) and three regions ( $0.13^\circ$  radius):
  - Brightest maser emission.
  - Dim, extended maser emission.
  - Swept-up material; no clouds.



Brian Humensky, CRIS2015, Gallipoli



Region	Norm (/550 GeV) * $10^{-13} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$	Index	$\chi^2 / \text{ndf}$
Entire Remnant	$9.92 \pm 0.90$	$-2.80 \pm 0.09$	2.76 / 3
Region 1	$3.69 \pm 0.42$	$-3.15 \pm 0.11$	9.98 / 3
Region 2	$2.33 \pm 0.42$	$-3.19 \pm 0.17$	1.85 / 3
Region 3	$1.86 \pm 0.49$	$-2.49 \pm 0.42$	2.64 / 3

# PKS 1441+25 SED

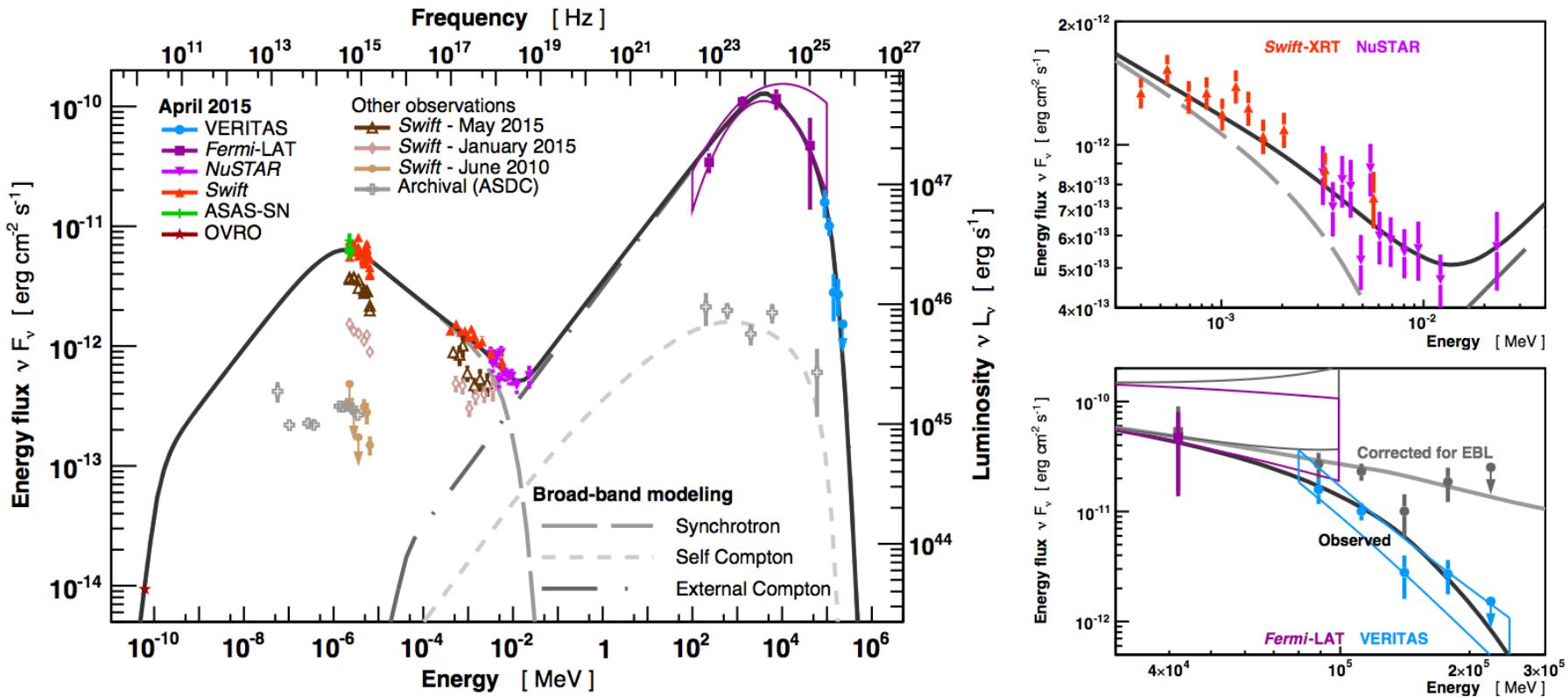


FIG. 2.— Multiwavelength emission of PKS 1441+25. Side panels show the X-ray (top) and gamma-ray emission (bottom) in April 2015 (MJD 57127–57141). The various exposures and the model are discussed in Sec. 2 and 3, respectively.

