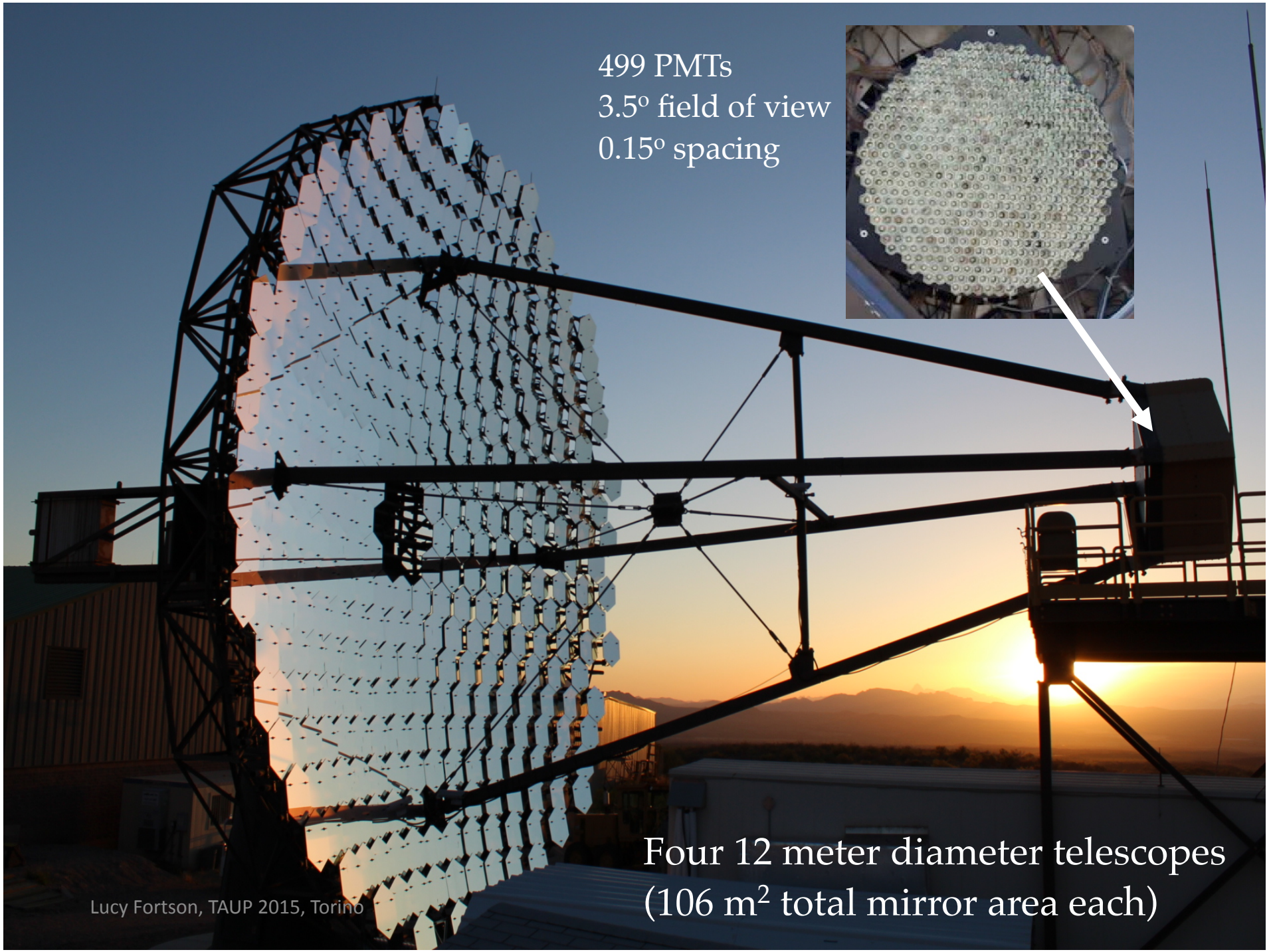
Highlights of recent results from the VERITAS gamma-ray observatory

TAUP-2015 TORINO

Lucy Fortson

for the VERITAS Collaboration

University of Minnesota


499 PMTs
3.5° field of view
0.15° spacing
Four 12 meter diameter telescopes
(106 m² total mirror area each)
Lucy Fortson, TAUP 2015, Torino

VERITAS from 2007 to today

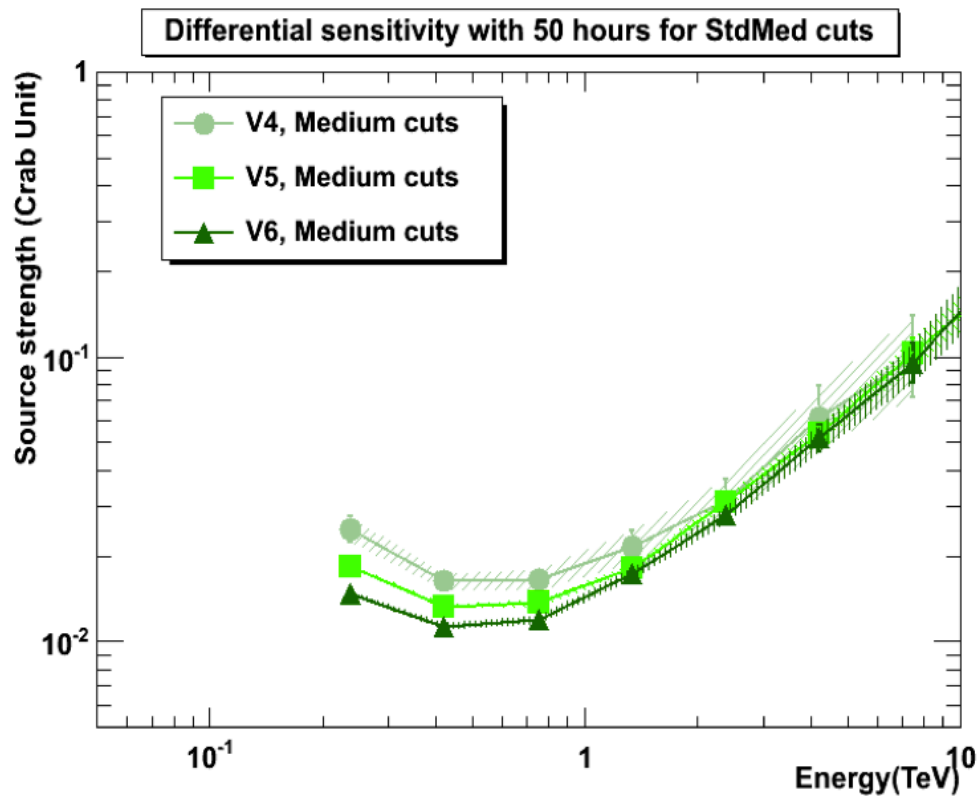
- Fully operational since 2007
  - Multiple upgrades: T1 move 2009, L2 Trigger + PMT replacements 2011/12

V4: *prior to T1 move*

V5: *after T1 move, prior to new PMTs*

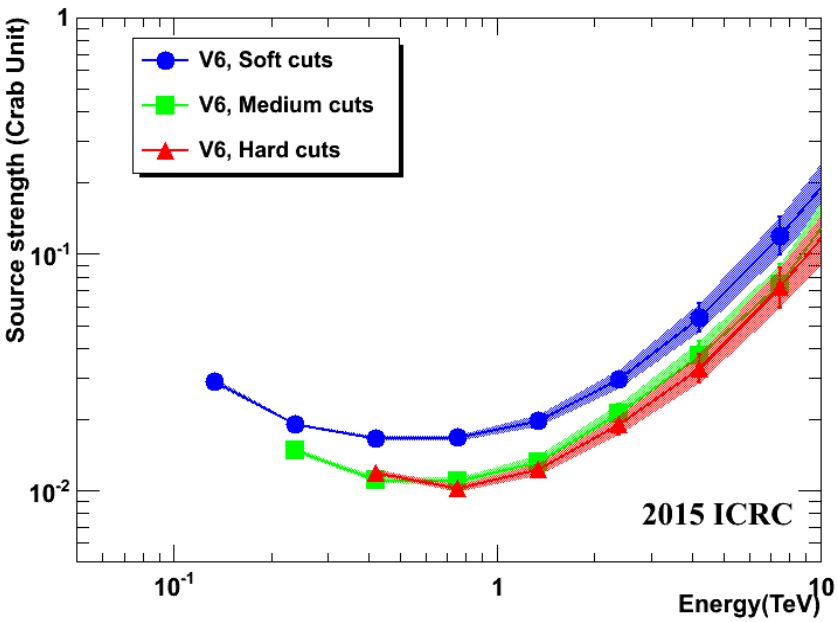
V6: *current configuration*

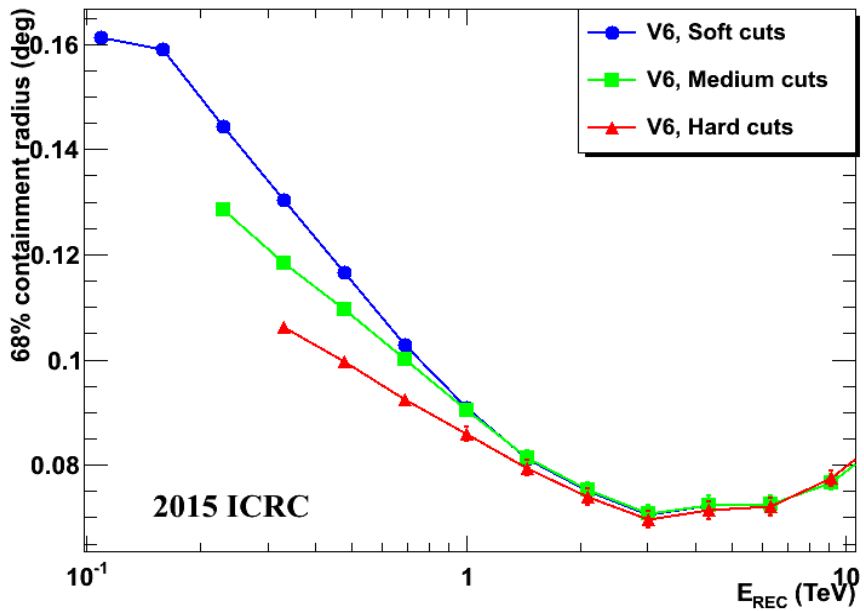
- Improved sensitivity at low energy
  - critical improvement for science with soft sources (new AGN detections)
  - allow extending the spectrum of known objects to lower energies (i.e. SNR)



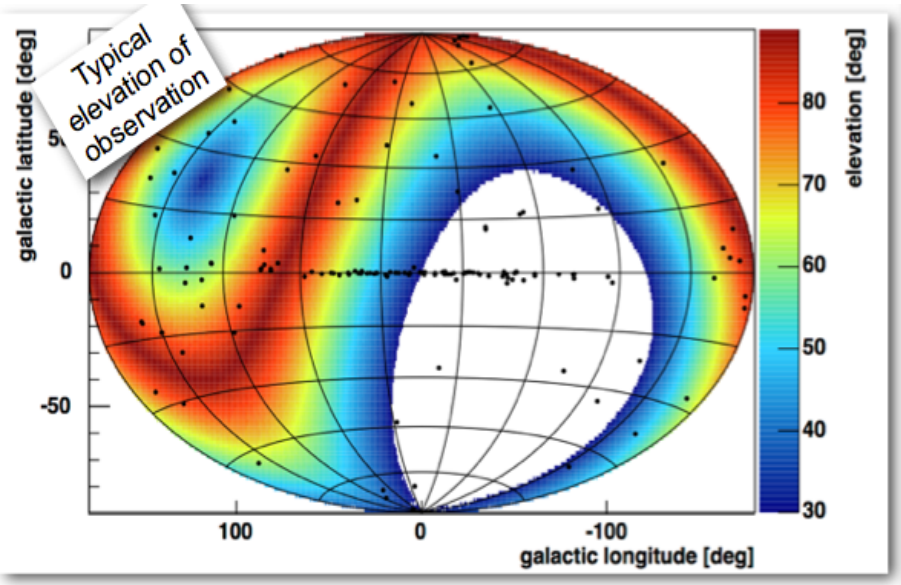
VERITAS from 2007 to today

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

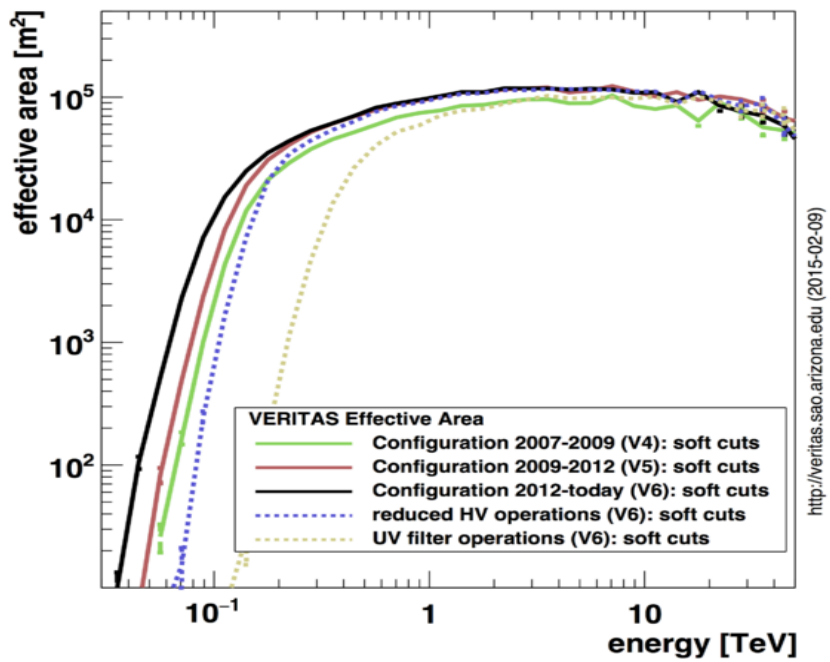


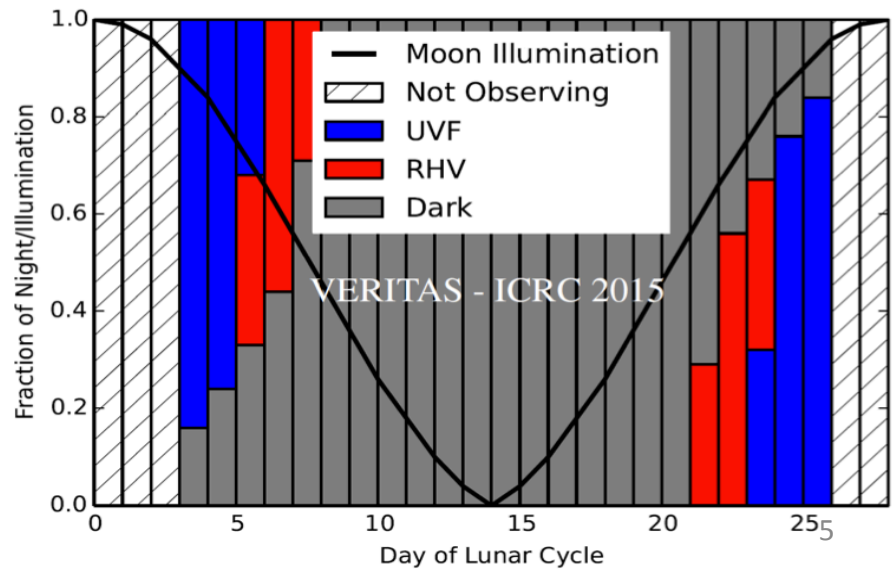


Observing with VERITAS



- 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)

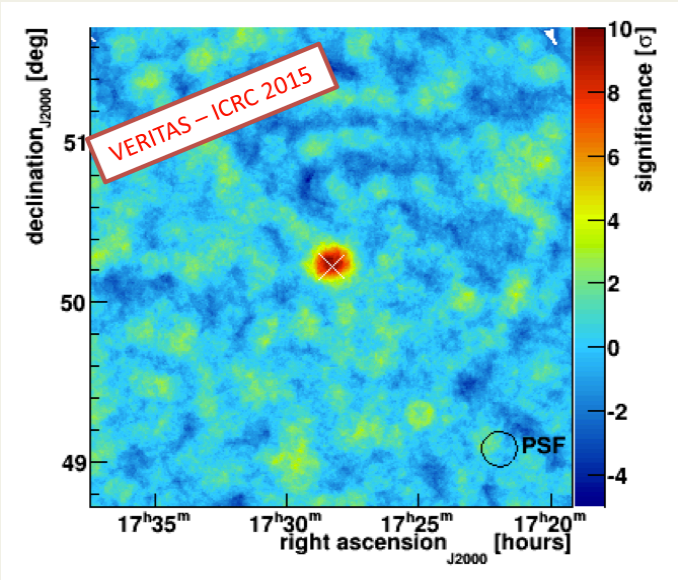




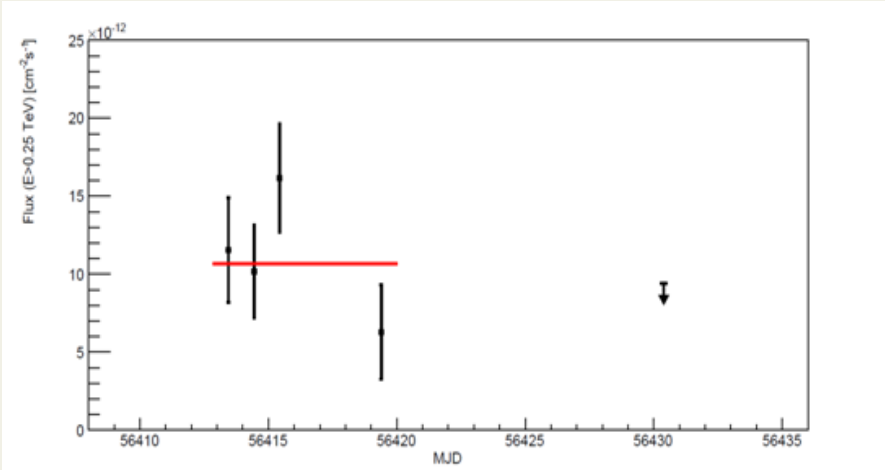
Observing with VERITAS

- Northern hemisphere observatory

Improving the duty cycle of VERITAS pays off…
detection of a flare in 1ES 0727+502

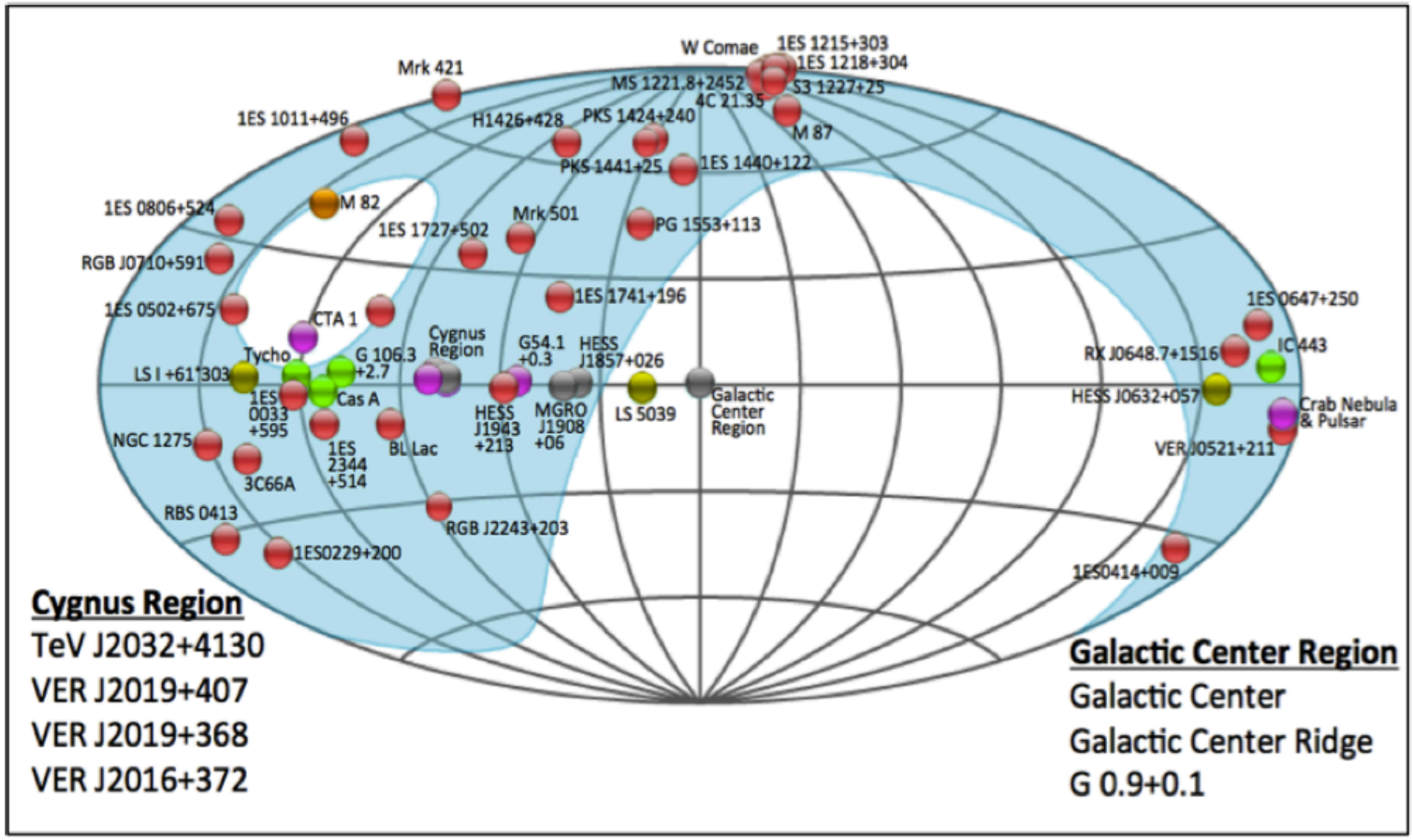


arXiv: 1508.05551



Detected at ~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

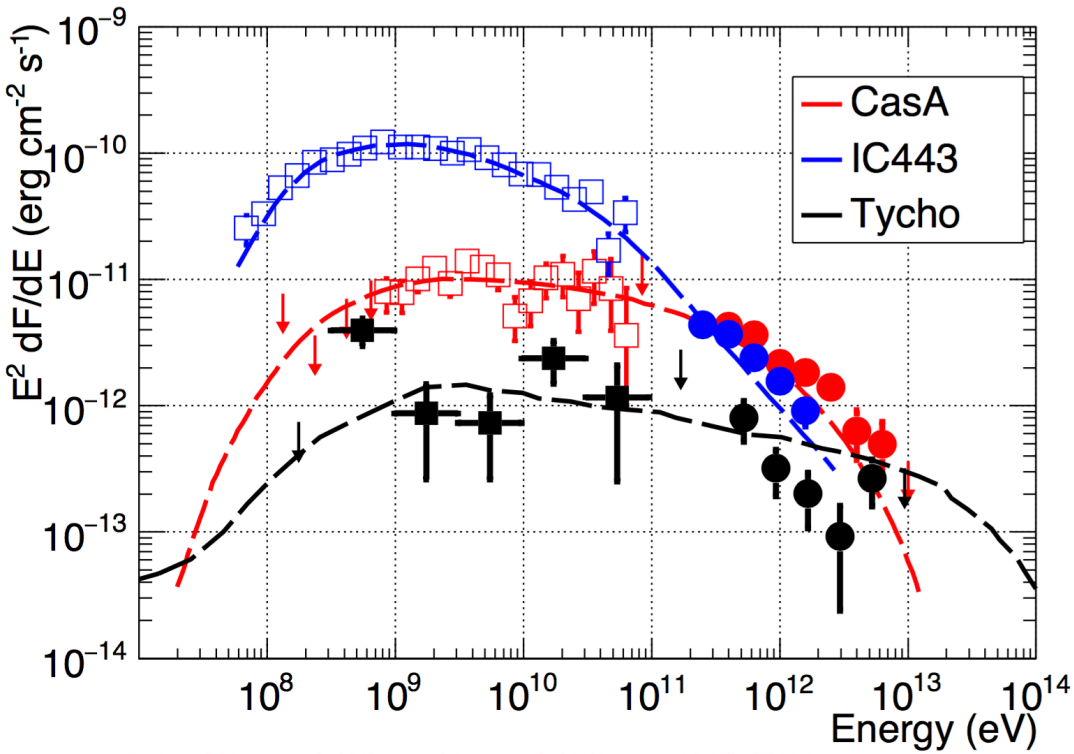
VERITAS Science

- Lots of great results I *won't* talk about today
  - Results presented at recent ICRC will be posted on arXiv soon
- What I will cover:
  - New SNR results including IC 443
  - Highlights from the blazar program including PKS 1441+25
  - Dark Matter limits
  - Electron spectrum
  - IceCube follow-up

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

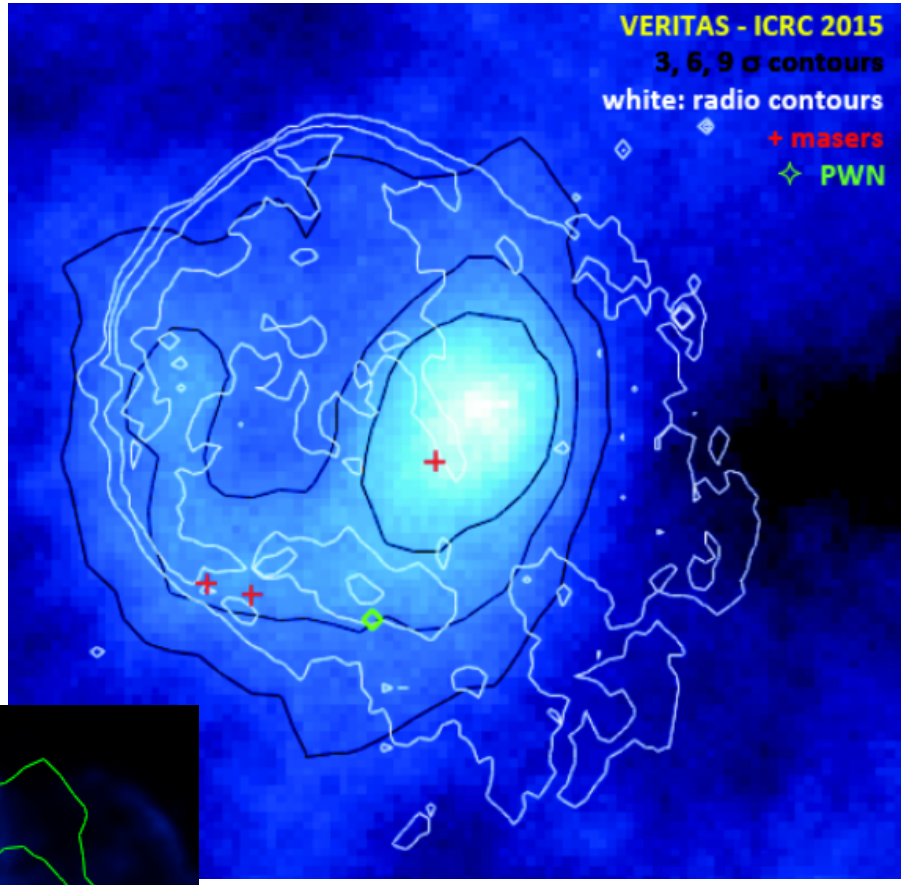
> 150 hours of exposure for IC443 and Tycho

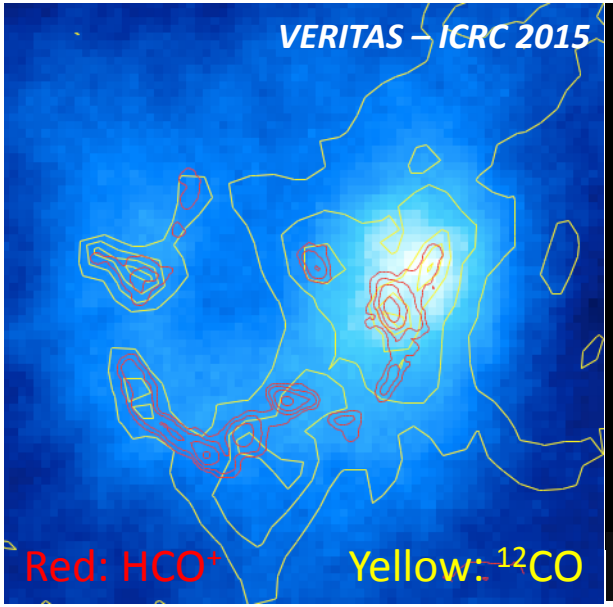


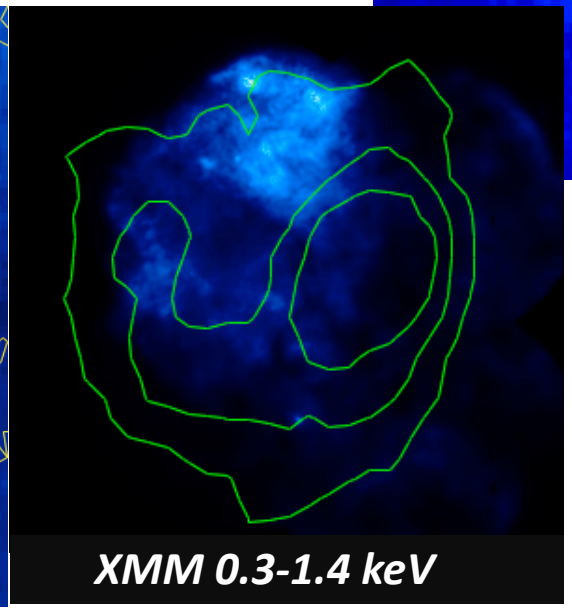
CasA model (Yuan et al., 2013), Fermi (Yuan et al., 2013), VERITAS (ICRC 2015)
IC443 model (Ackermann et al., 2013), Fermi (Ackermann et al., 2013), VERITAS (ICRC 2015)
Tycho model (Slane et al., 2014), Fermi (ICRC 2015), VERITAS (ICRC 2015)

VERITAS RESULTS: IC 443

- Strong spatial correlation with gamma emission, 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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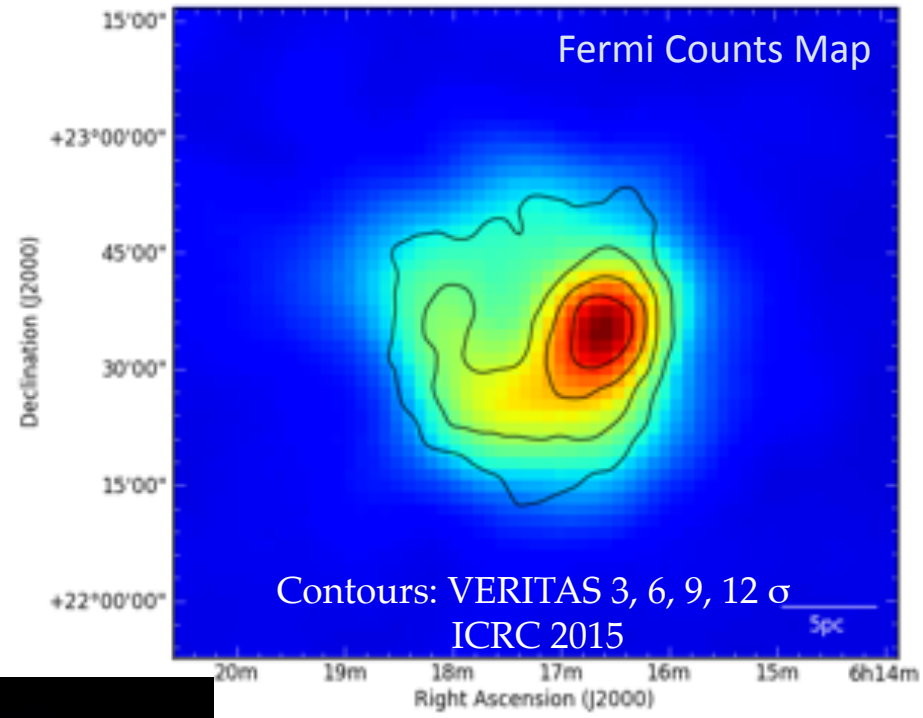

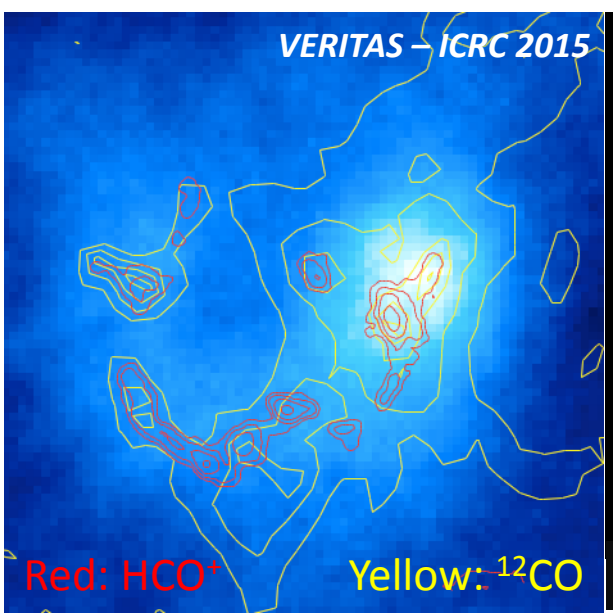

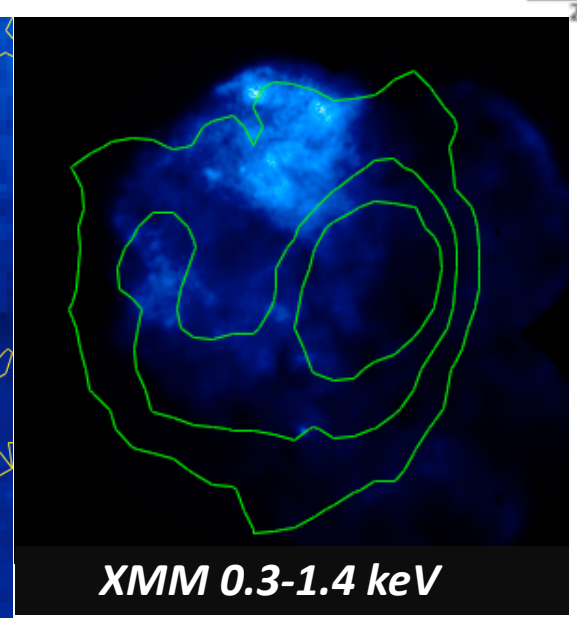

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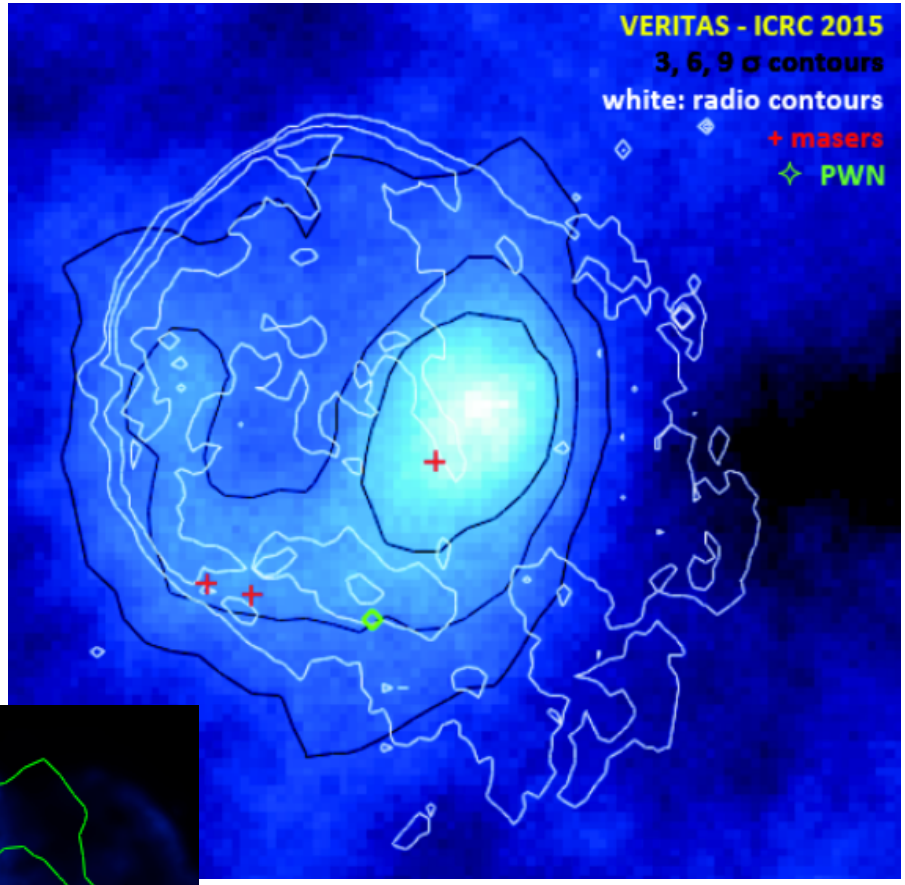
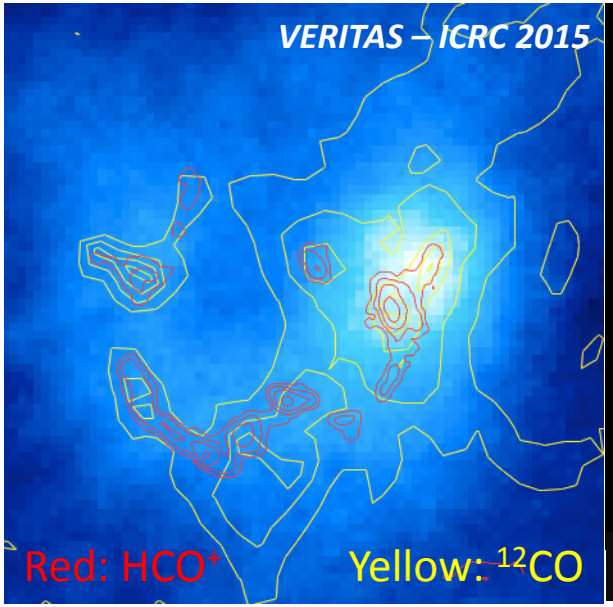
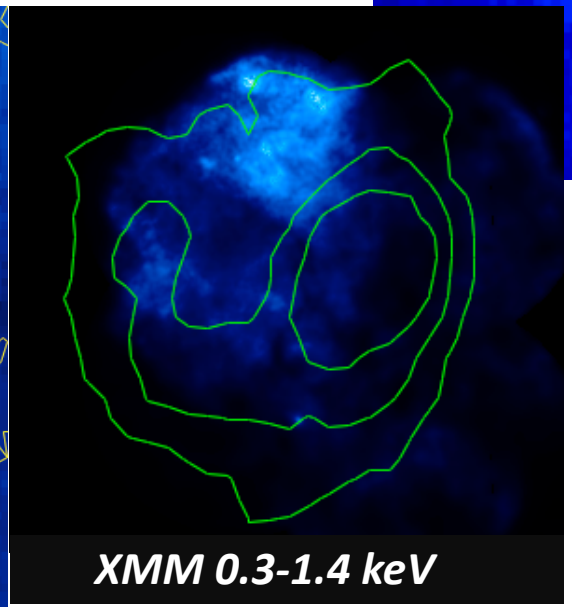






Single population of CR interacting with swept up / shocked gas?

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

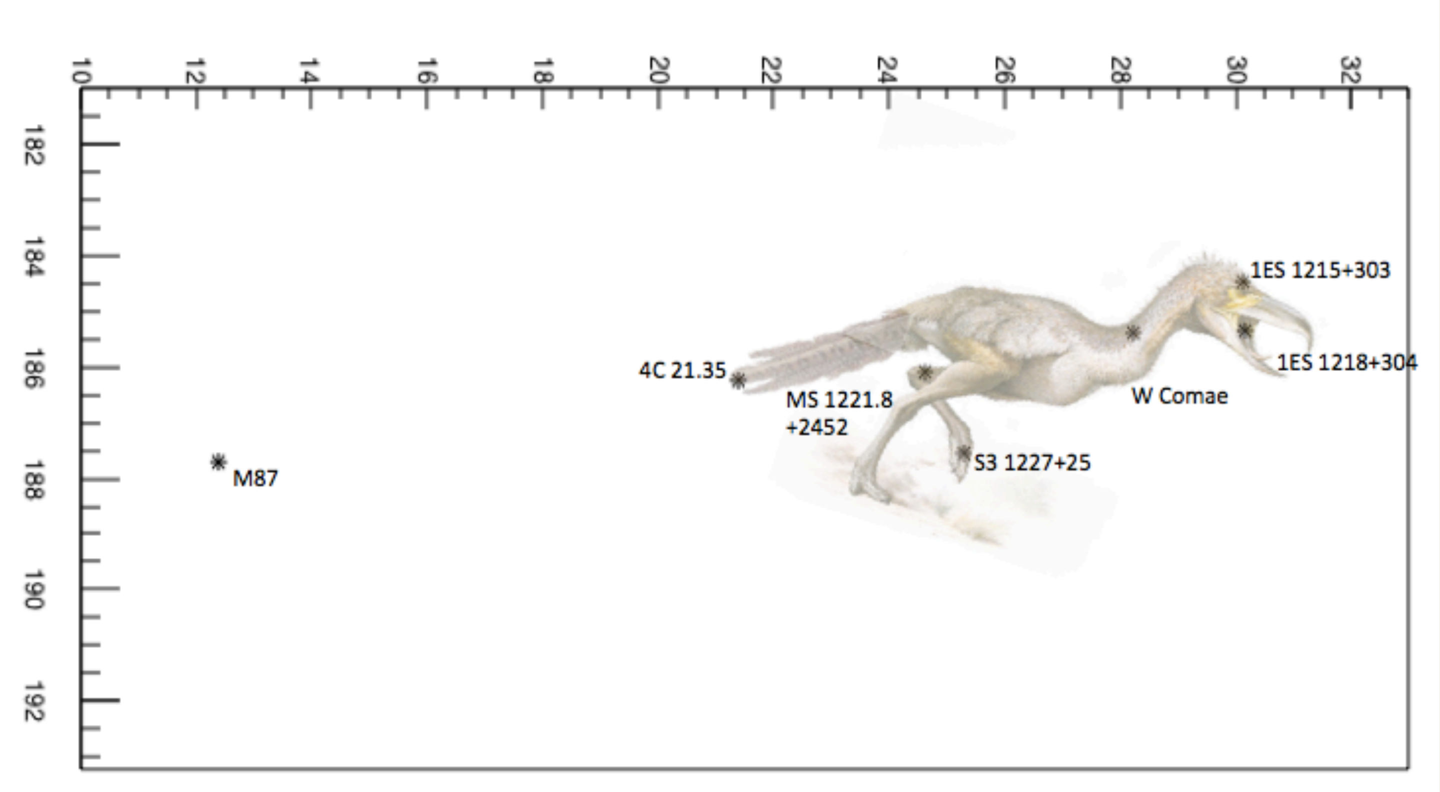
- **34 VHE AGN: 23 HBL, 7 IBL, 2 FSRQ & 2 FR I**
- 2013-14: 1ES 0033+595, MS 1221.8+2452, PKS 1222+216 & HESS J1943+213
- 2014-15: S3 1227+25, PKS 1441+25 & RGB J2243+203

The VERITAS Blazar program

AGN	Type	z
M 87	FR I	0.004
NGC 127		
Ml		
R		
1ES		
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

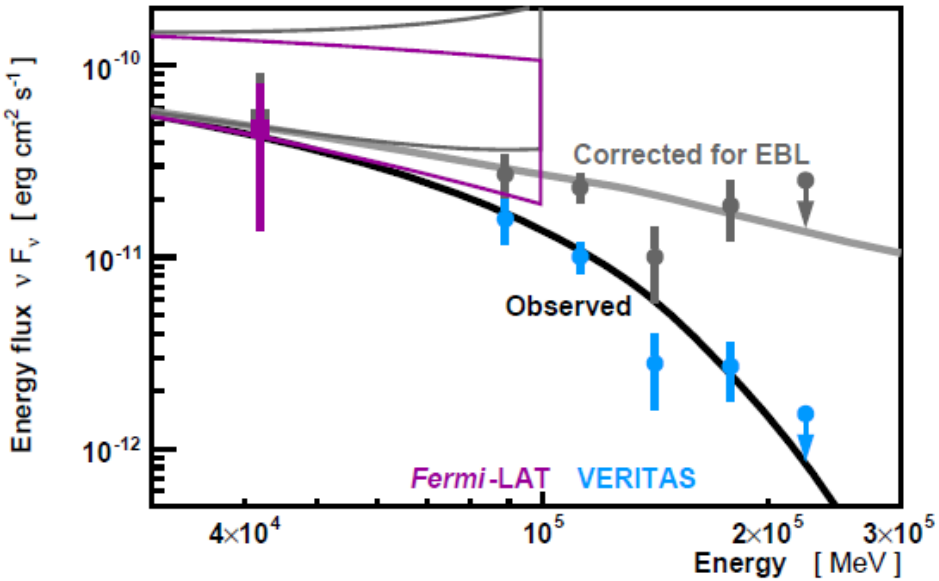


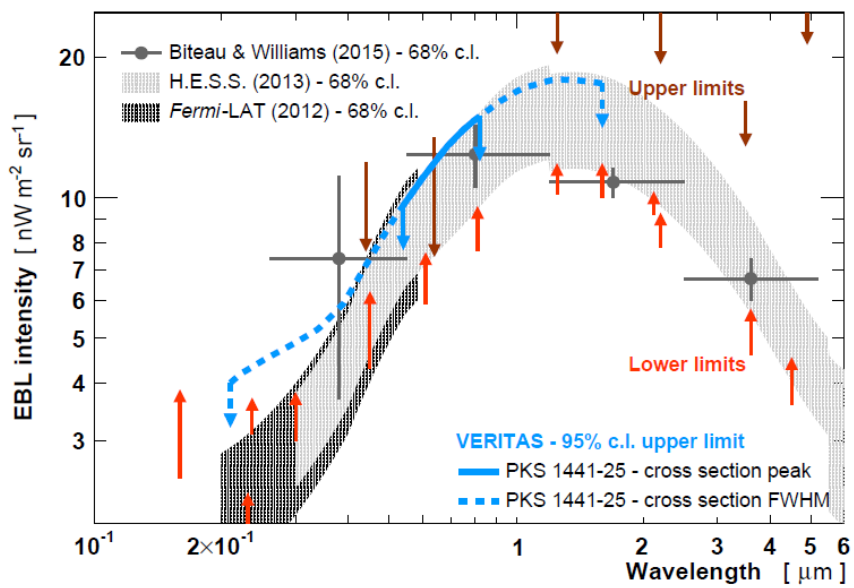
The first VHE constellation?! Introducing Tera-bird (credit Jamie Holder)

- 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

VERITAS Results: PKS 1441+25

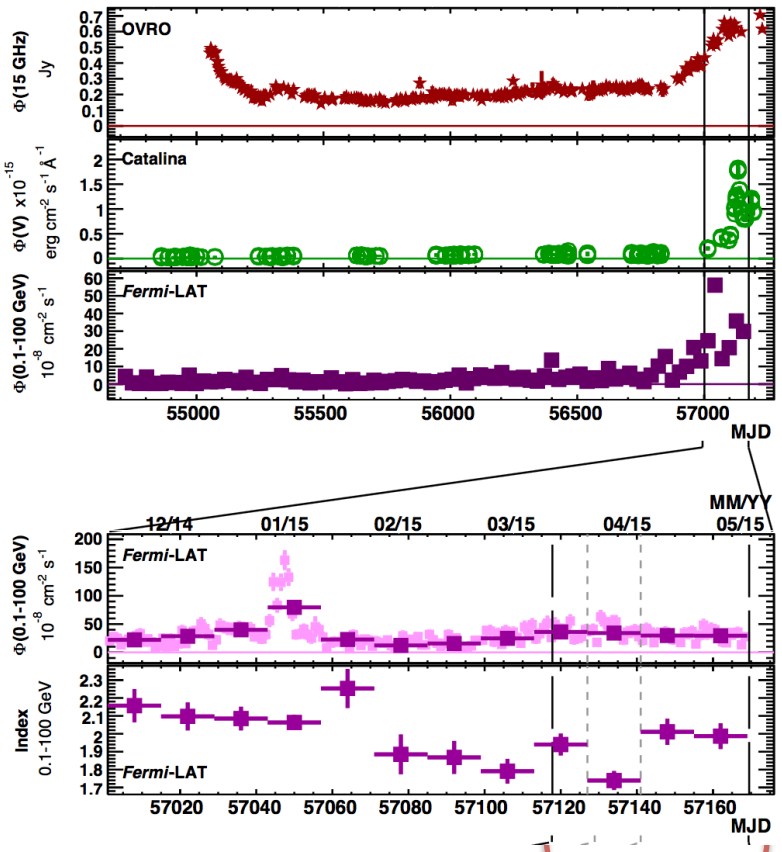
- One of the most distant FSRQs detected in VHE (z=0.939)
- Triggered by Fermi/ MAGIC alerts
- 15 hours of observations with VERITAS– Apr 15, '15
- ~400 gamma rays, 8σ
- 5% Crab above 80 GeV
- Very soft spectral index Γ=5.3±0.5

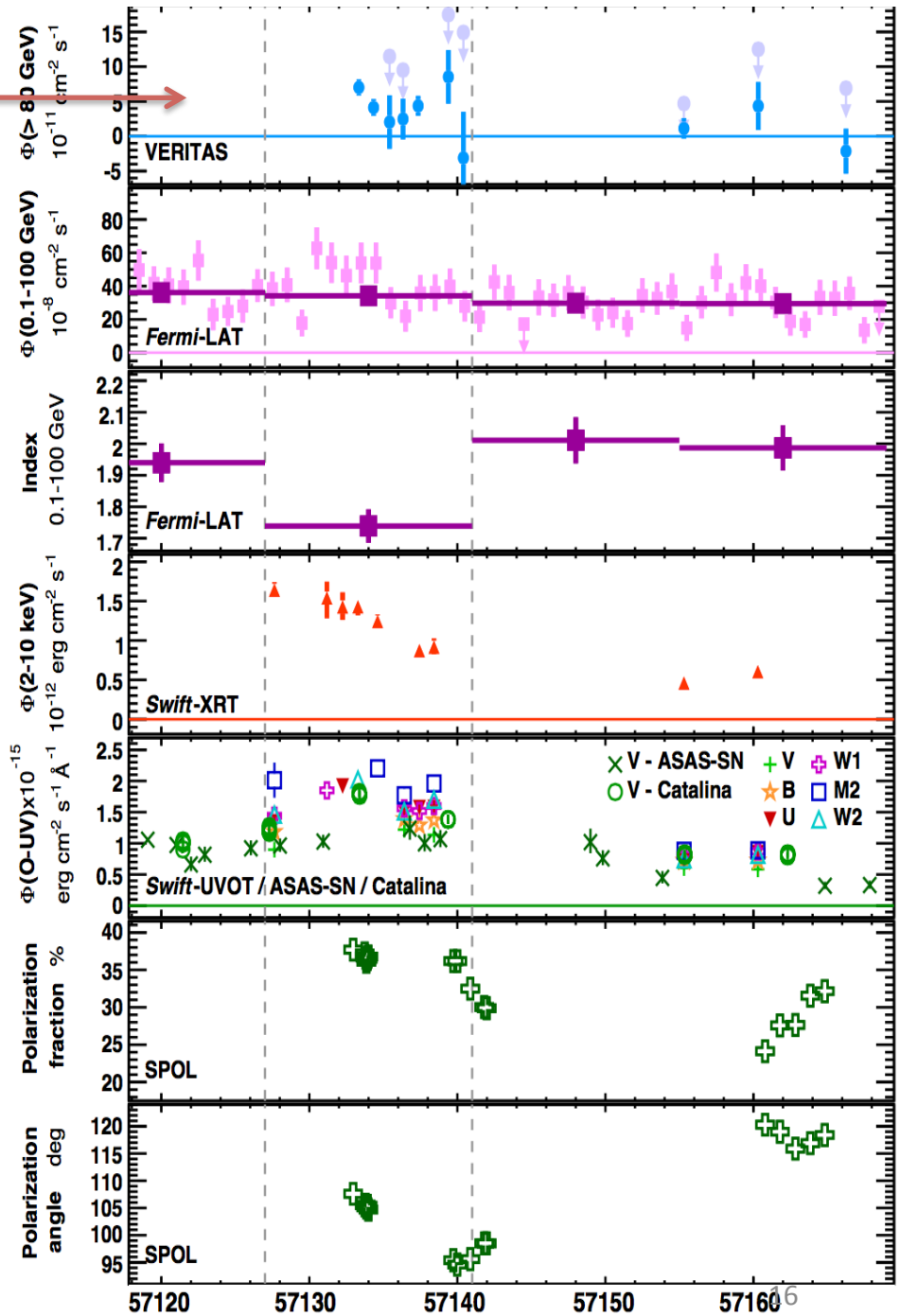




First time that one single source constrains a large fraction of the EBL spectrum.

VERITAS Collaboration et al – submitted





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 Collaboration et al – submitted

VERITAS Dark Matter Program

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

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

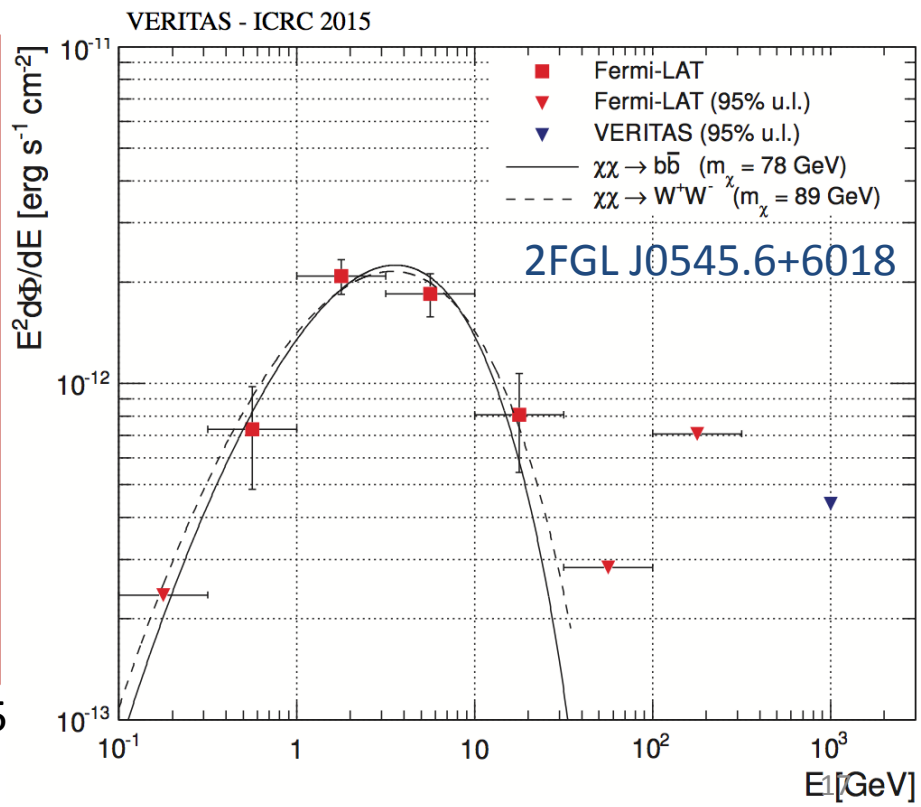
Particle Physics | Astrophysics

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



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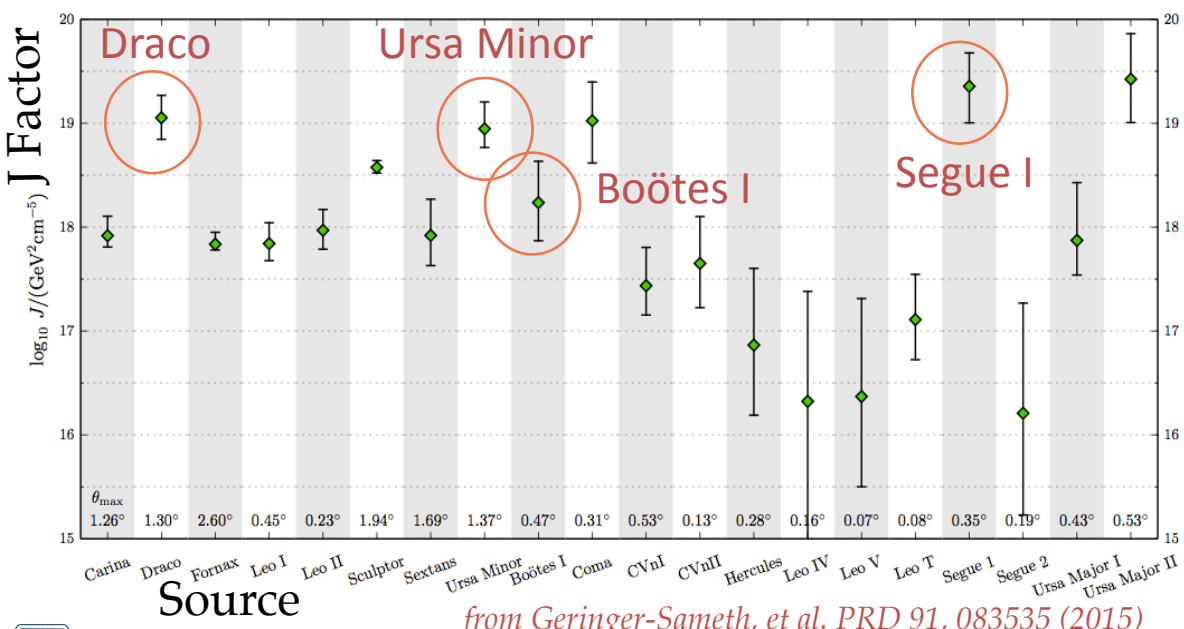
Astrophysics

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



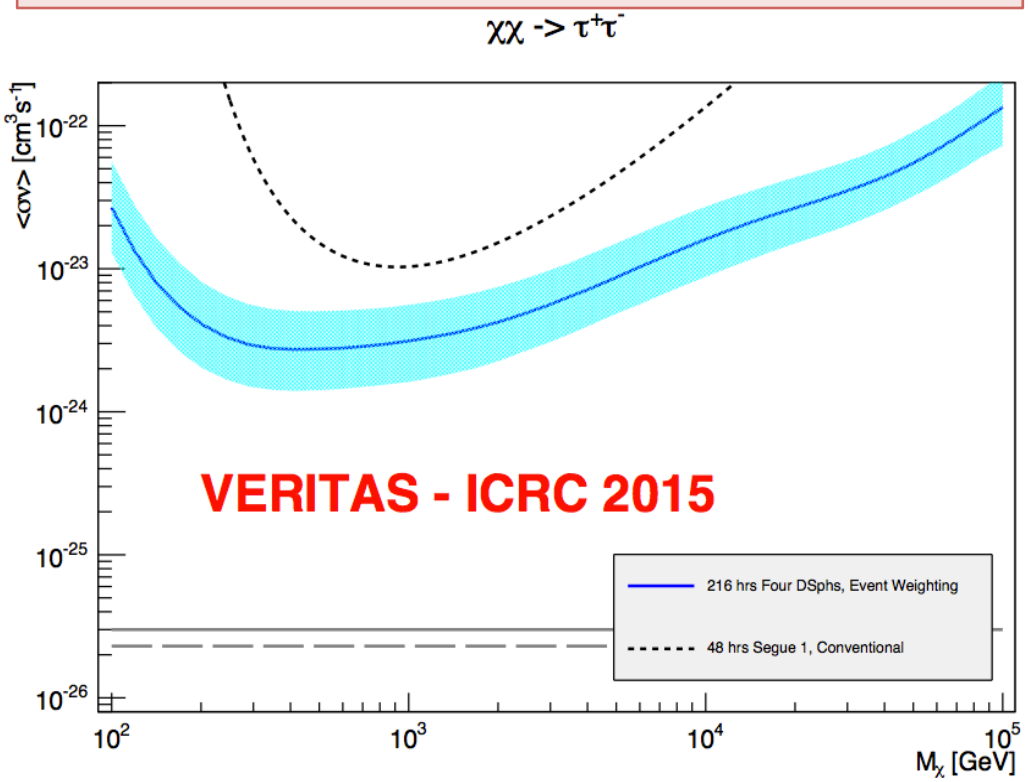
from Geringer-Sameth, et al. PRD 91, 083535 (2015)

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(10³) 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)

arXiv:1509.01105

Cosmic Ray Electrons with VERITAS

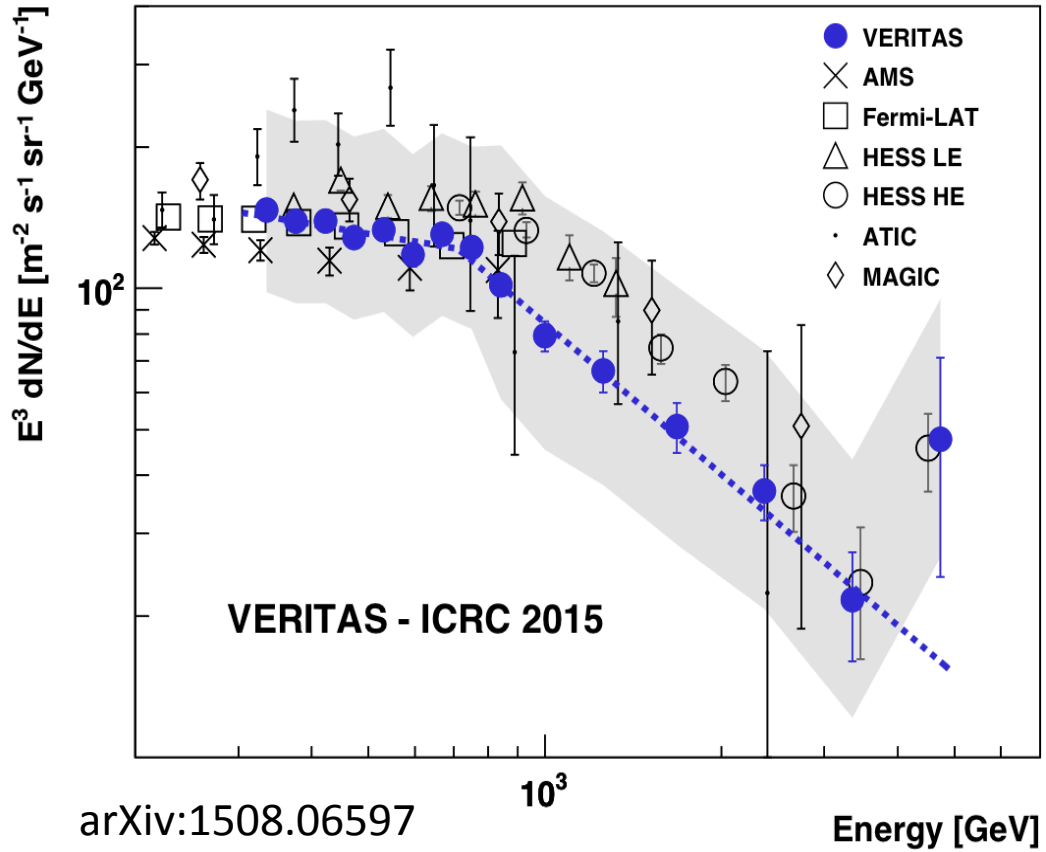
Cosmic-ray electrons at TeV energies are a direct probe of nearby (~1kpc) accelerators

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 ± 40 GeV
  - Index below (above) break of

    $-3.2 \pm 0.1_{STAT}$

    $(-4.1 \pm 0.1_{STAT})$



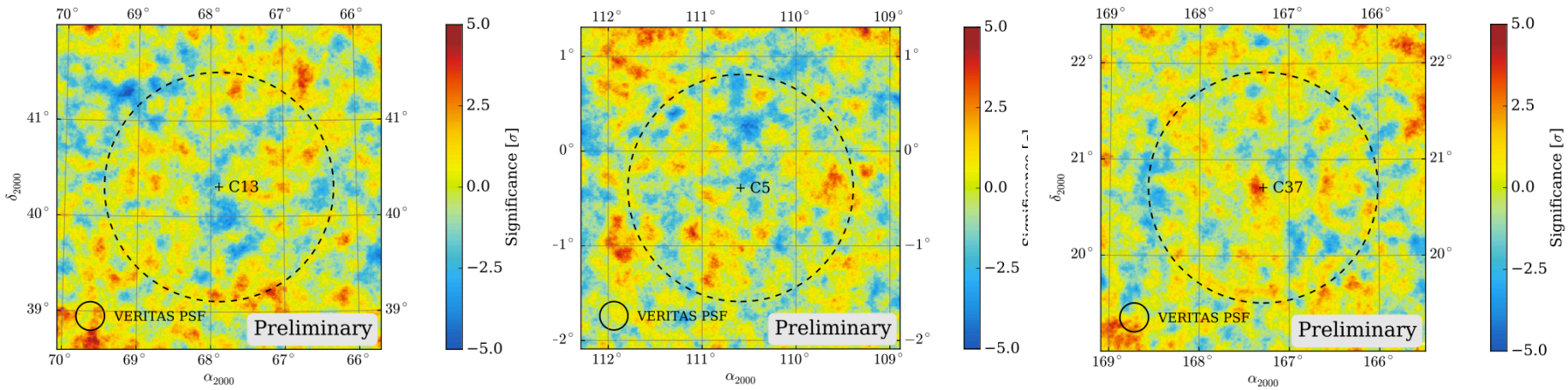
arXiv:1508.06597

- Confirms evidence of at least one nearby CR electron emitter
- Second high-statistics measurement of a break below ~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 ν_μ-induced muon-track events for a total of 40 hours
  - muon-track events have good localization, ~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 ~2-10% Crab Nebula flux

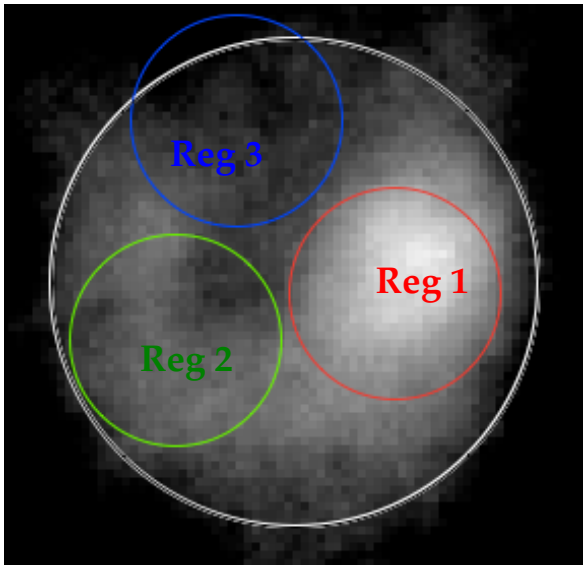
Conclusions

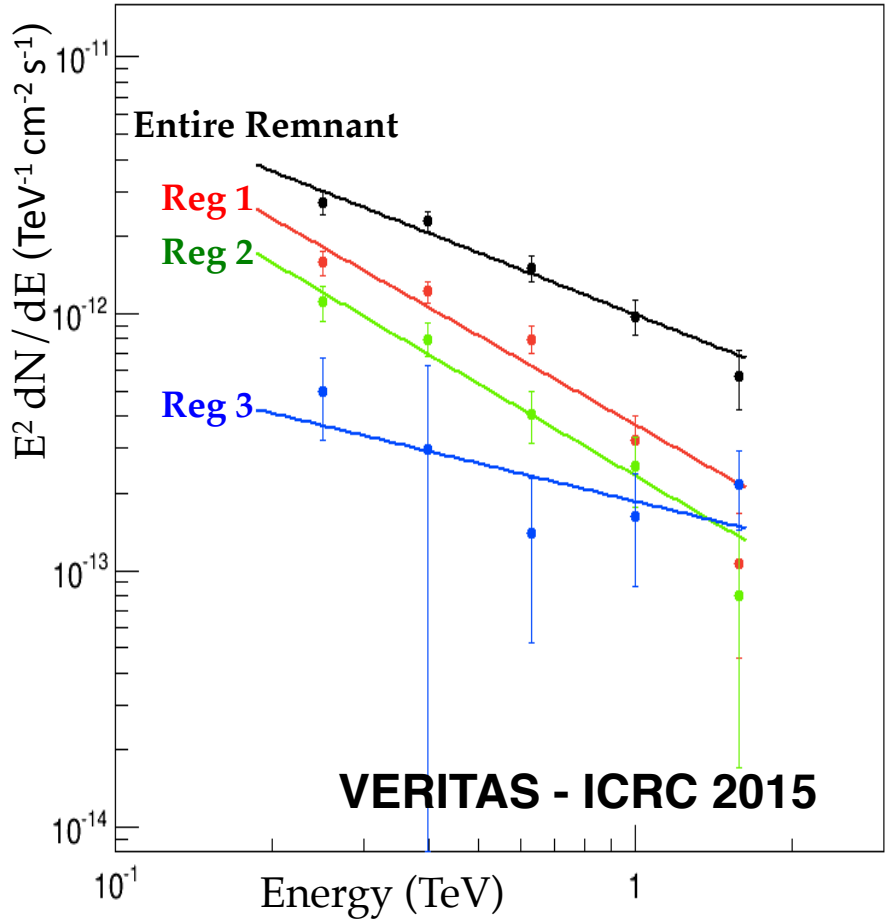
- VERITAS is running very well, is more sensitive than ever, and is extending observations to cover more of the moon cycle
- VERITAS science covers a wide range of topics: astronomy, cosmology, particle physics
  - Lots of data with plenty of sources, both Galactic and extragalactic
  - The source catalog 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° radius) and three regions (0.13° radius):
  1. Brightest maser emission.
  2. Dim, extended maser emission.
  3. Swept-up material; no clouds.





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

PKS 1441+25 SED

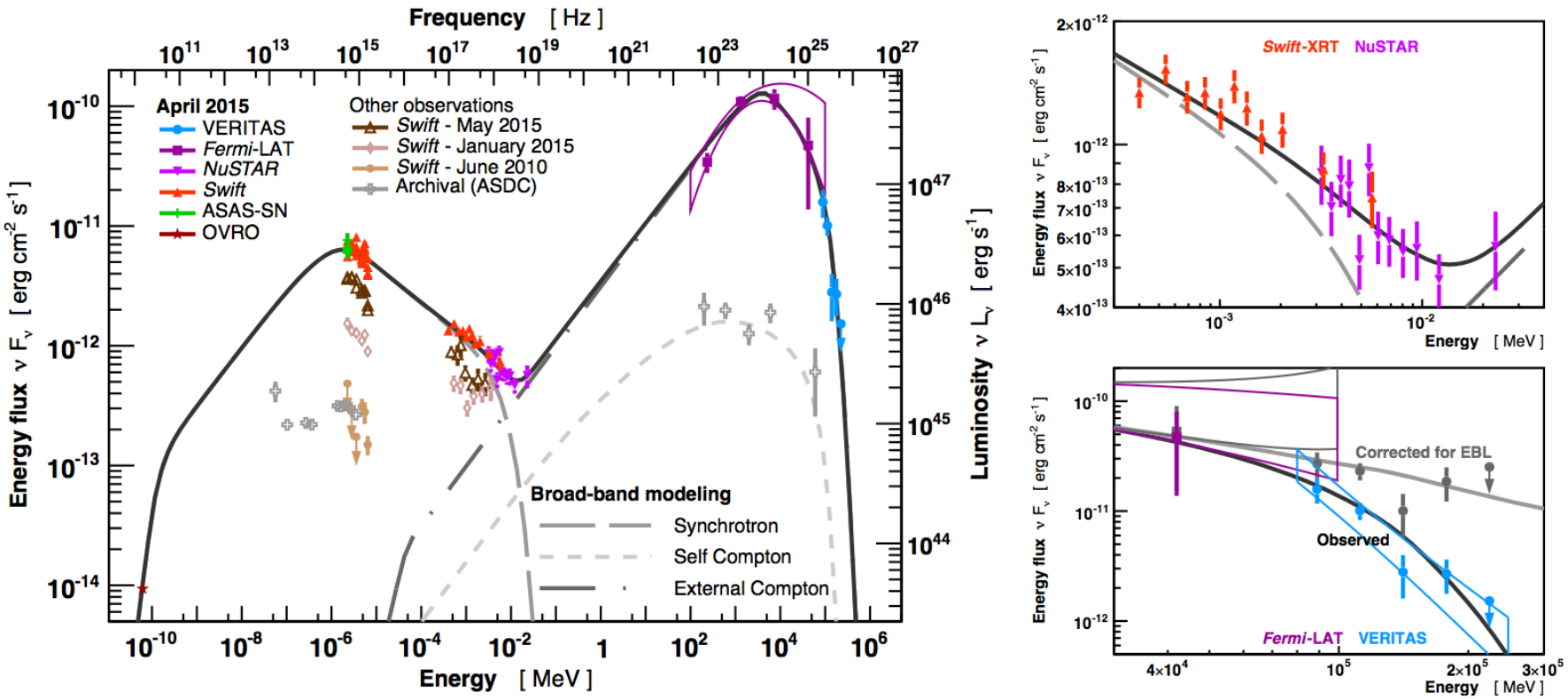
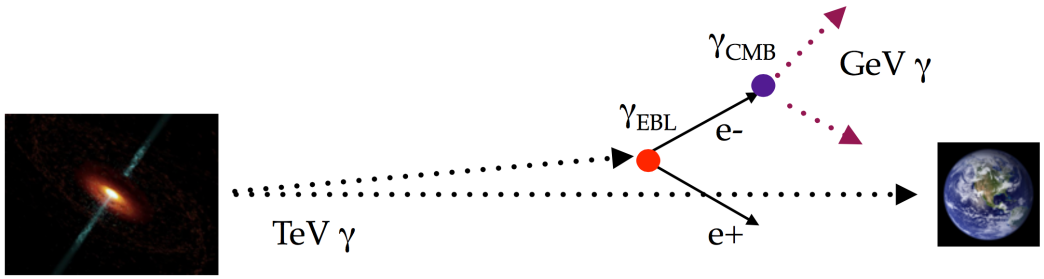


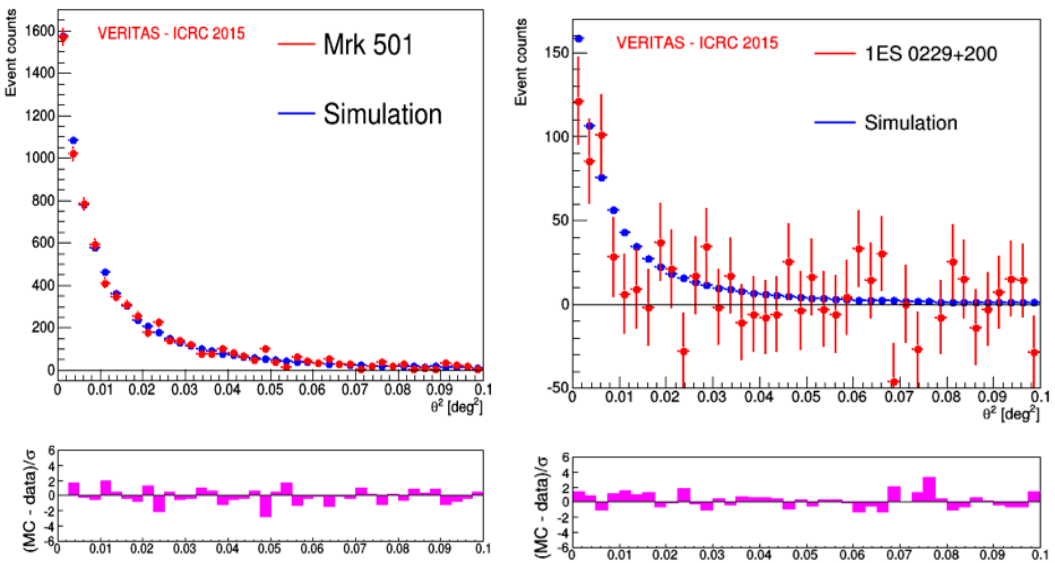
FIG. 2.— Multiwavelength emission of PKS 1441+25. Side panels show the X-ray (top) and gamma-ray emission (bottom) in April 2015 (MJD 57127-57141). The various exposures and the model are discussed in Sec. 2 and 3, respectively.

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:

  $(0.17\text{-}2.69) \times 10^{-12}\ cm^{-1}TeV^{-1}s^{-1}$
- Limits on IGMF magnitude set for model-dependent extended emission by comparing to simulated blazars and using 3D semi-analytical code