Highlights from the VERITAS AGN Observation Program

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The VERITAS Collaboration

- **~100 members, 20 institutions**
  - 24 non-affiliated members
  - +35 associate members
- Managing Organization: Smithsonian Astrophysical Observatory
- Adler Planetarium
- Argonne National Lab
- Barnard College / Columbia University
- Bartol Research Institute / University of Delaware
- Georgia Institute of Technology
- Iowa State University
- Purdue University
- University of California, Los Angeles
- University of California, Santa Cruz
- University of Chicago
- University of Iowa
- University of Minnesota
- University of Utah
- Washington University in St. Louis
- McGill University, Montreal
- University College Dublin
- Cork Institute of Technology
- Galway-Mayo Institute of Technology
- National University of Ireland, Galway

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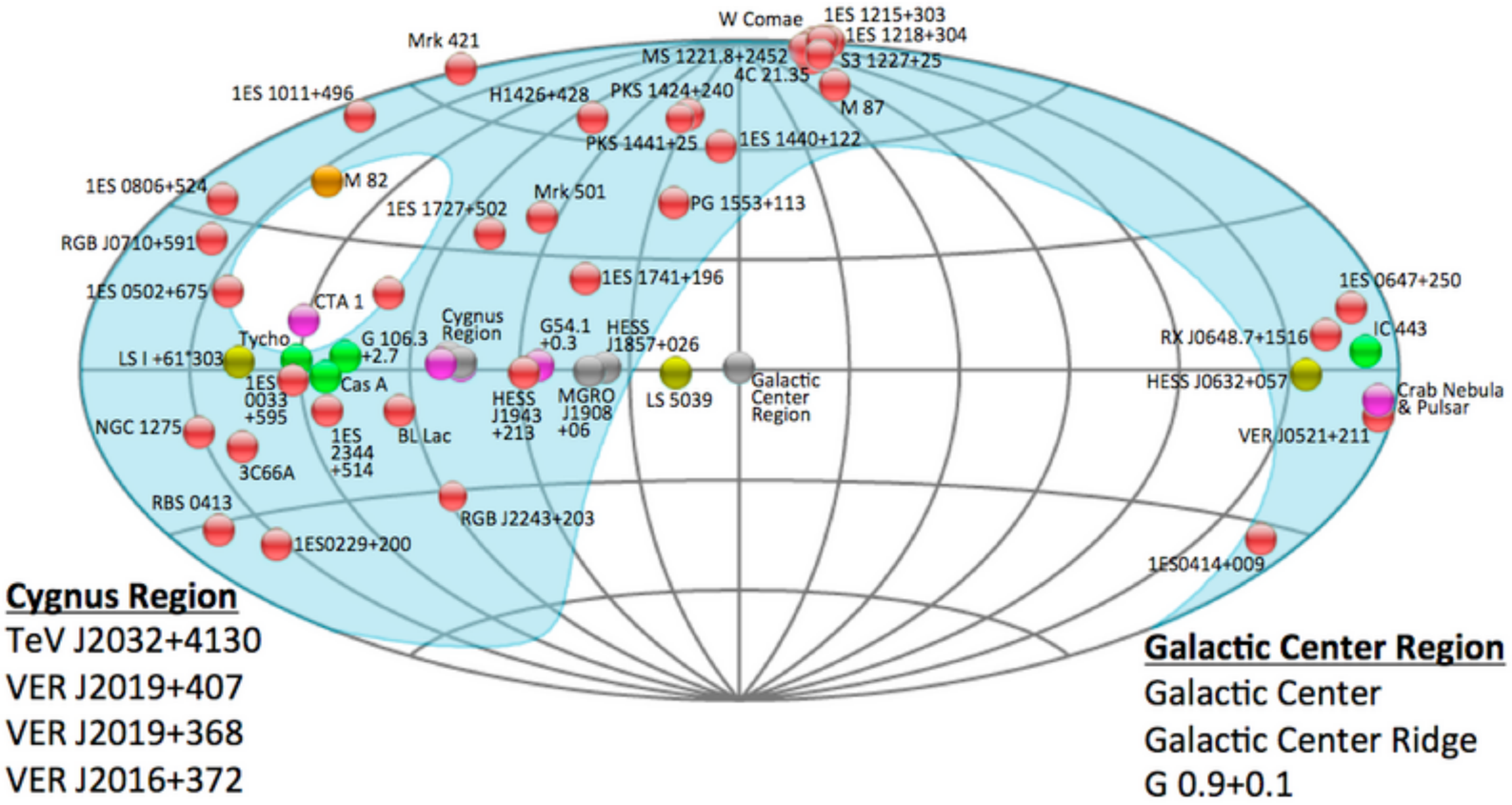
VERITAS: Observatory Overview

- Study very-high-energy (~80 GeV to ~30 TeV) γ-rays from astrophysical sources
- Full-scale operations since 2007; Major upgrade completed in 2012
- Good-weather data / yr: ~1000 h in "dark time" + 300 h in "bright moon" (illum. >30%)

  - Sensitivity: 1% Crab in ~25 h
  - Angular resolution: r_{68} ~ 0.08° @ 1 TeV
  - Energy resolution: ~17%
  - Energy Threshold: ~80 GeV
  - Spectral reconstruction > 100 GeV
  - Systematic errors: Flux ~20%; Γ ~ 0.1

The VERITAS Source Catalog



55 sources from 8 astrophysical classes

35 Extragalactic (64%): 32 blazars, 2 radio galaxies & a starburst galaxy (M82)

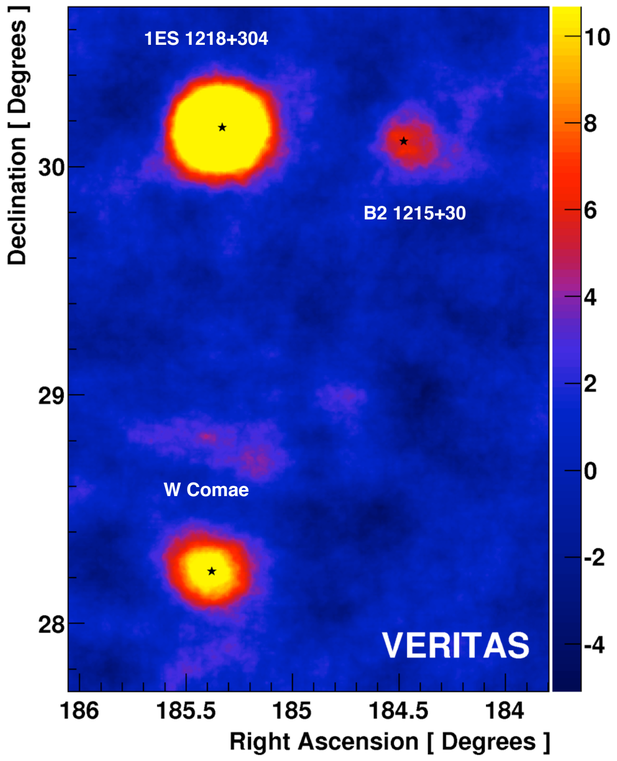
20 Galactic (36%): Crab pulsar, 3 gamma-ray binaries, 7 pulsar wind nebulae, 3 SNRs & 6 unidentified objects

The VERITAS AGN Program

- 2007-2015: ~3400 h of good-weather "normal" AGN data; Average ~ 430 h / yr
  - 90% Blazars / 10% Radio galaxies; Blazar studies are mostly focused on BL Lac objects
  - Since 2012: Another 200 h / yr of AGN data being taken in bright moonlight, but >200 GeV threshold
    - First publication w/ bright moonlight data (arXiv:1506.06246): Detection of a flare of 1ES 1727+502 (see Cerruti #762, GA08)
- Blazar program:
  - ~30% Target of Opportunity (ToO) observations: Focus of ToO's has shifted; Initially mostly follow-up campaigns on our VHE discoveries, now mostly follow-up campaigns on VHE / MWL flaring
  - ~20% are VHE discovery observations: c.f. ~40% in 2010-12 & ~80% in 2007-10
  - >50% is for regular monitoring of all known VHE blazars; Most get snapshots; ~10 others w/ longer shots (deep exposures)
    - Monitoring coordinated with MWL partners => Long-term MWL light curves
    - Observations intensified during any VHE (or MWL) flaring
- Radio galaxy (RG) program
  - Historically dominated by M 87 (~50%), with rest of emphasis on "discovery" observations of LAT-detected RG
  - Now = Monitor VHE flux of M87 & ToO's during VHE flares of M87 or LAT flares of other RG (e.g. NGC 1275)

The VERITAS AGN Catalog

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



All VERITAS AGN are Fermi-LAT detected

All detections have simultaneous MWL data

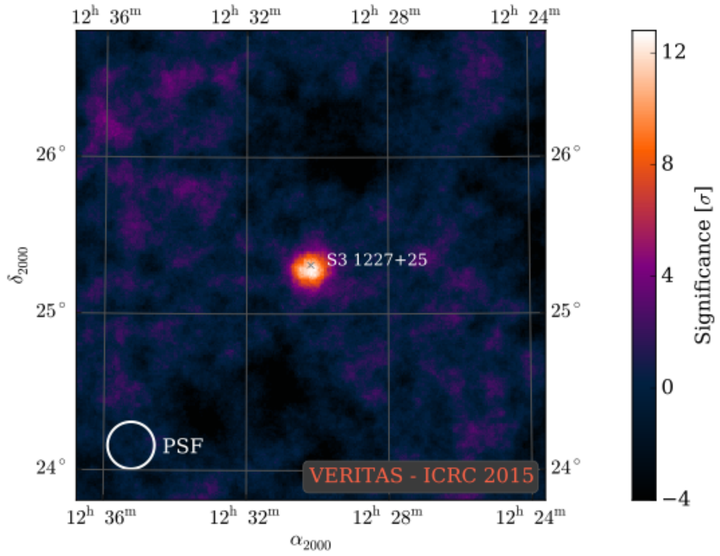
~25% have uncertain redshift

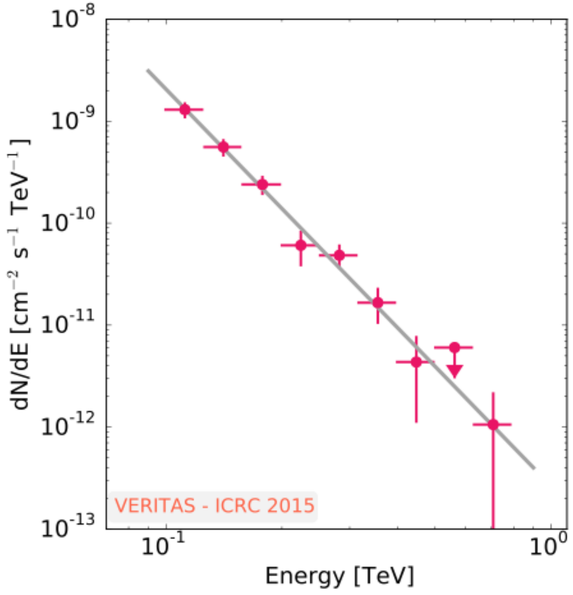
AGN	Type	z
3C 66A	IBL	0.33 < z < 0.41
PKS 1424+240	IBL	>0.604
PG 1553+113	HBL	0.43 < z < 0.58
1ES 0033+595	HBL	?
1ES 0502+675	HBL	?
1ES 0647+250	HBL	?
B2 1215+30	IBL	?
HESS J1943+213	HBL	?
RGB J2243+203	IBL	?

- 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
- Catalog has grown by 7, 13 & 22 AGN since the 2013, 2011 & 2009 ICRC's, respectively

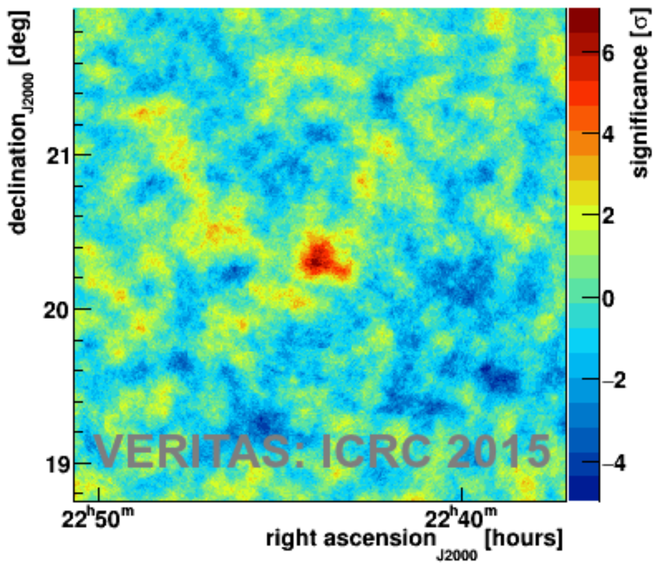
Discovery of VHE Emission from S3 1227+25

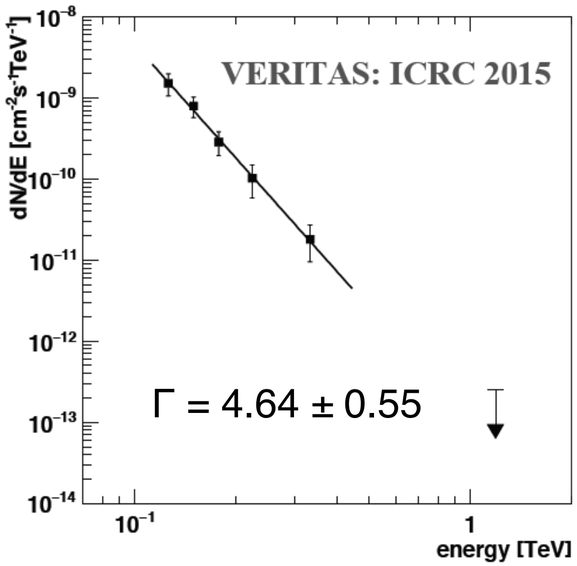
- Fermi-detected LBL / IBL @ z = 0.135
  - $\Gamma_{3FGL} \sim 2.24$; $\Gamma_{1FHL} \sim 3.3$; F(>10 GeV) ~ 1% Crab
  - Unlikely VHE source
- January 2015: No VHE detection in ~3 h
  - LAT-based ToO (~30x brighter than 3FGL & $\Gamma_{LAT} \sim 2.2$)
- May 2015: ~420 γ-rays, ~13σ in ~6 h
  - LAT-based ToO (~40x brighter & $\Gamma_{LAT} \sim 1.9$)
  - Detected on May 16, 18 & 21; Weather issues
  - Variable flux; Peaks of ~6-8% Crab flux
  - $\Gamma = 3.89 \pm 0.24$
- Contemporaneous MWL data: Swift, Fermi-LAT, optical & polarization





Discovery of VHE Emission from RGB J2243+203



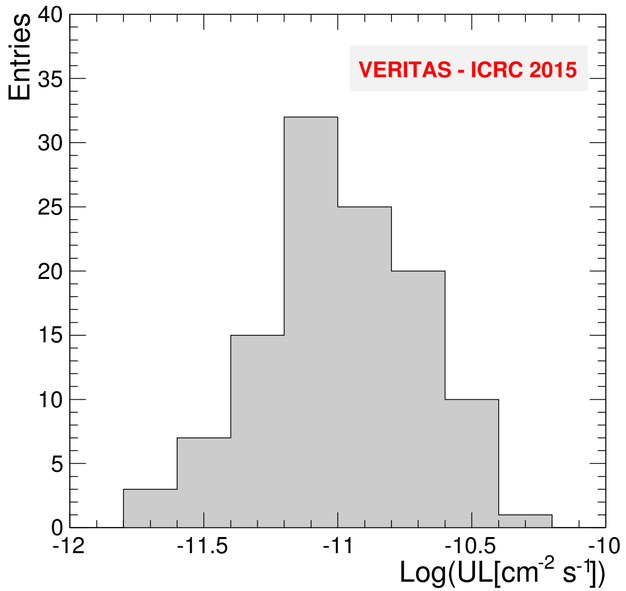


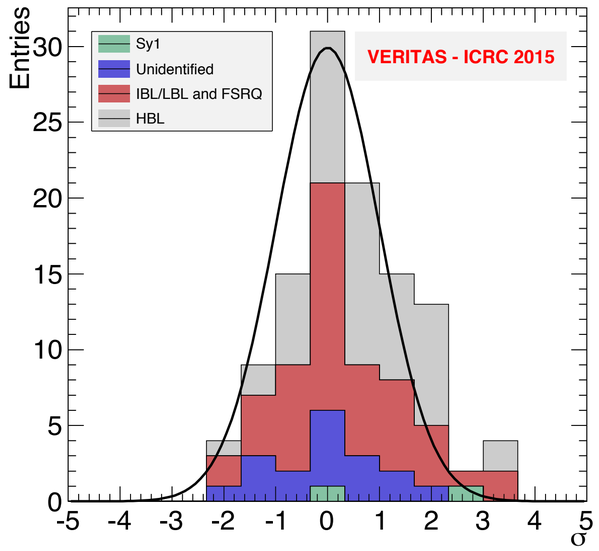
- Fermi-detected IBL / HBL at $z_{imaging} > 0.39$
  - $\Gamma_{2FGL} \sim 1.75$; $\Gamma_{1FHL} \sim 2.4$
- VERITAS observed in 2009
  - No signal in ~5 h; Flux $UL_{99\%} < 2\%$ Crab
- VERITAS monitors Fermi-LAT flux & Γ from hundred VHE candidates in ~real-time
  - Many timescales (0.25 - 28 days)
  - Alerted on Dec. 20, 2014; Sub-LAT-team threshold
- ToO Observations on Dec 21-24, 2014:
  - ~4 h good-quality data; ~6σ detection, 190 γ-rays
  - Steady flux, ~6% Crab >160 GeV
- Contemporaneous Swift ToO campaign

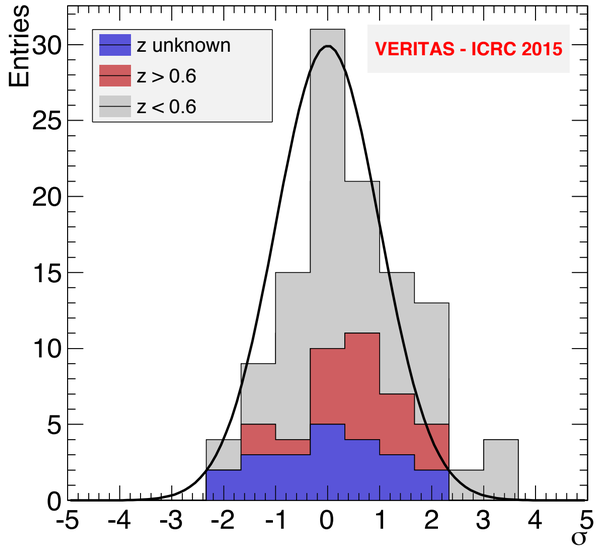
Abeysekara #731, GA 01 Poster #73

Blazar Upper Limits

- ~160 blazars observed since 2007
- 32 blazars are detected at VHE by VERITAS
- Limits for 114 objects: 93 targeted blazars (many are 2FGL sources) & all 21 2FGL sources serendipitously in 3.5° FoV
  - Limits are generally the most constraining to date; 570 h total data
- Stacked excess: 4.6σ from the 36 HBL at z < 0.6
  - 0.6σ from the remaining 78 objects

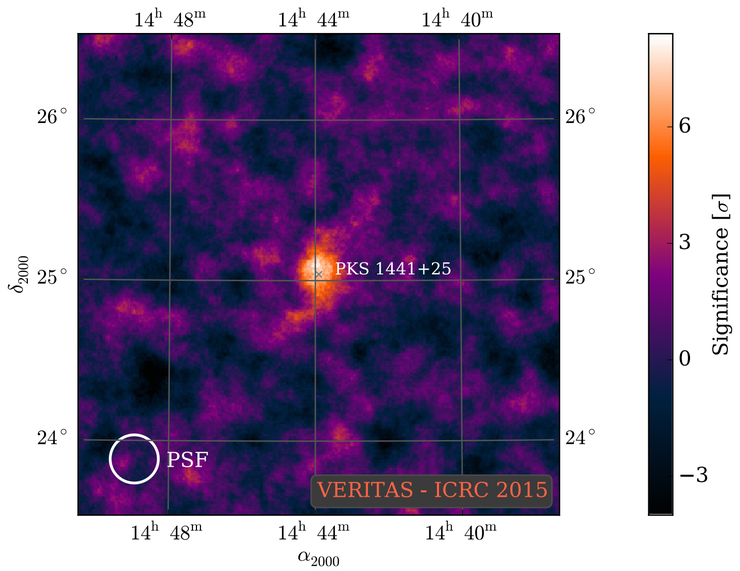


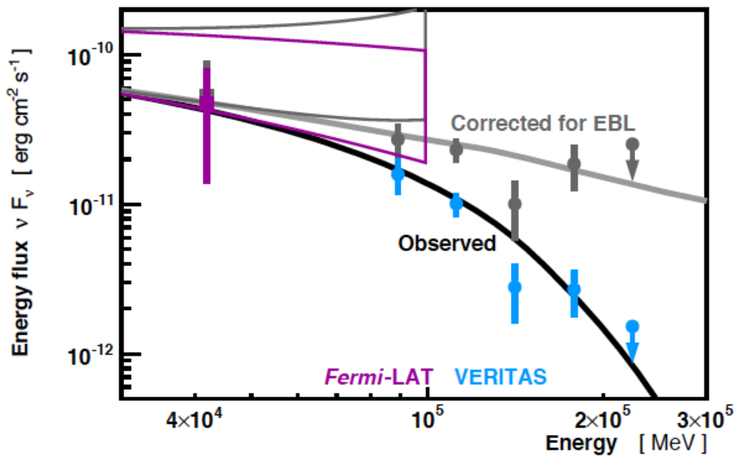


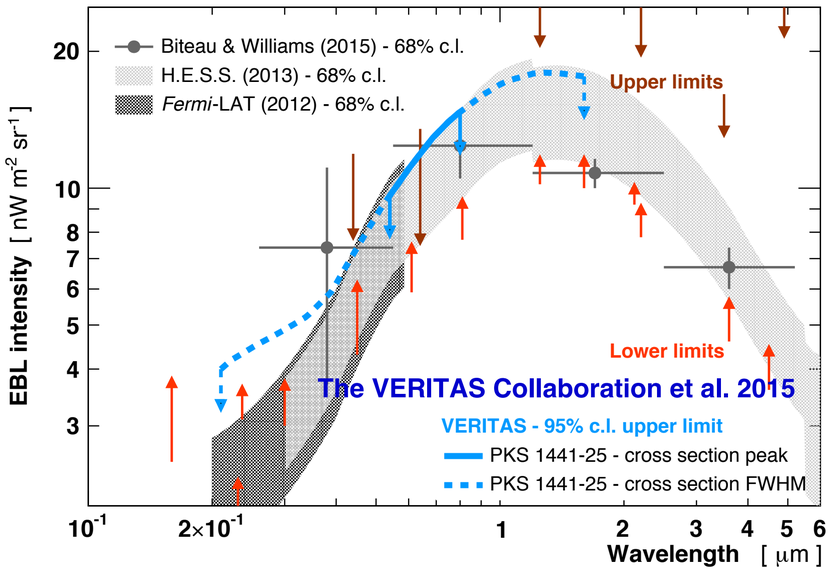


VERITAS Detection of PKS 1441+25 (z = 0.939)

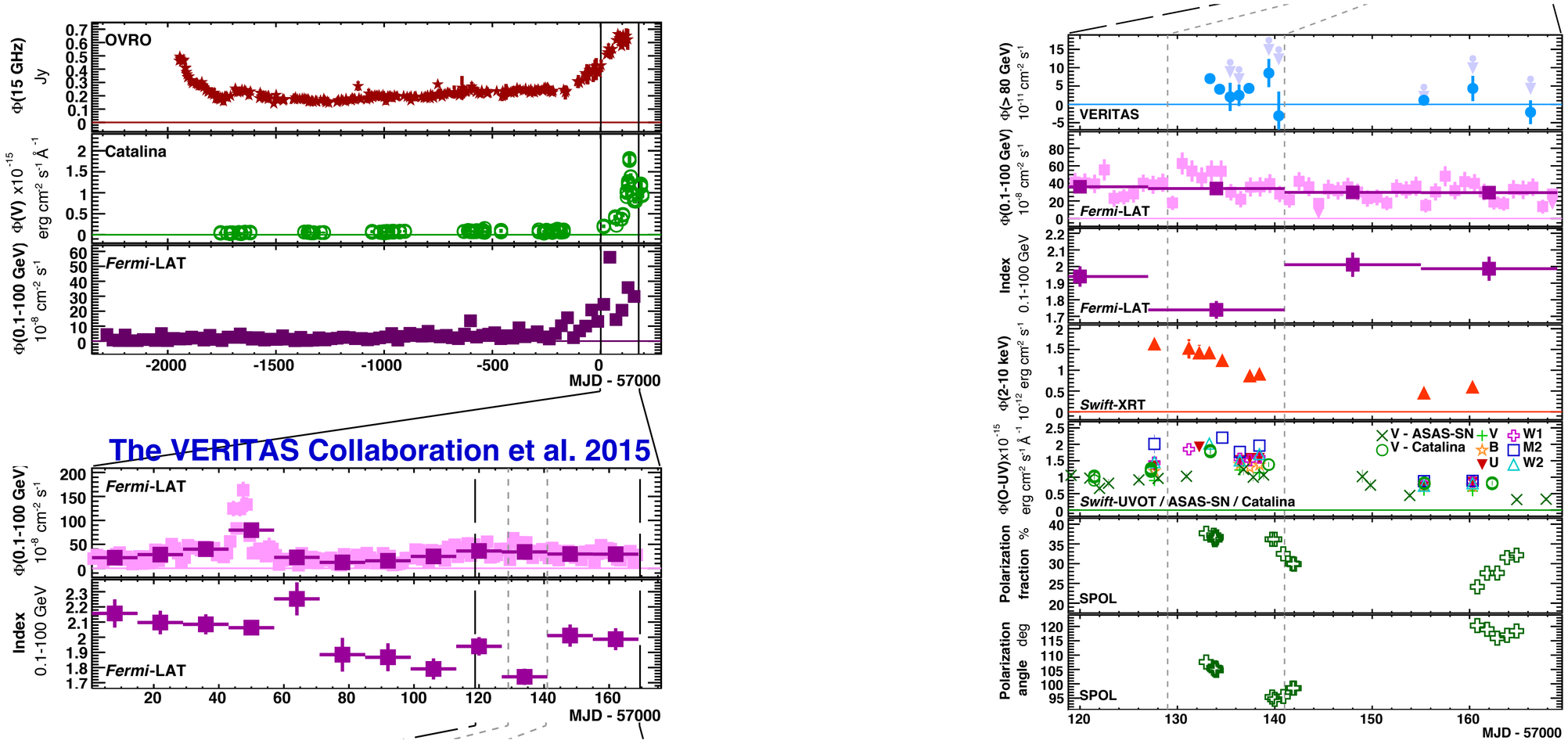
- 5th VHE FSRQ: 2nd for VERITAS
- Most-distant FSRQ detected at VHE
  - Light travel time = 7.5 Gyr
- ToO in April 2015: ~1 week, ~15 h
  - Triggered by MAGIC / Fermi alerts
  - VERITAS detected ~400 γ-rays, 8σ
  - Steady flux (>80 GeV) of ~5% Crab
  - $\Gamma_{VHE} = 5.3 \pm 0.5$
- May 2015 follow-up: Not detected in ~4 h
- EBL: De-absorbed VERITAS points connect smoothly to Fermi-LAT spectrum
  - Despite z ~ 1, it isn't unusual that we saw this <200 GeV!
  - Competitive EBL limits from Fermi-VERITAS spectrum





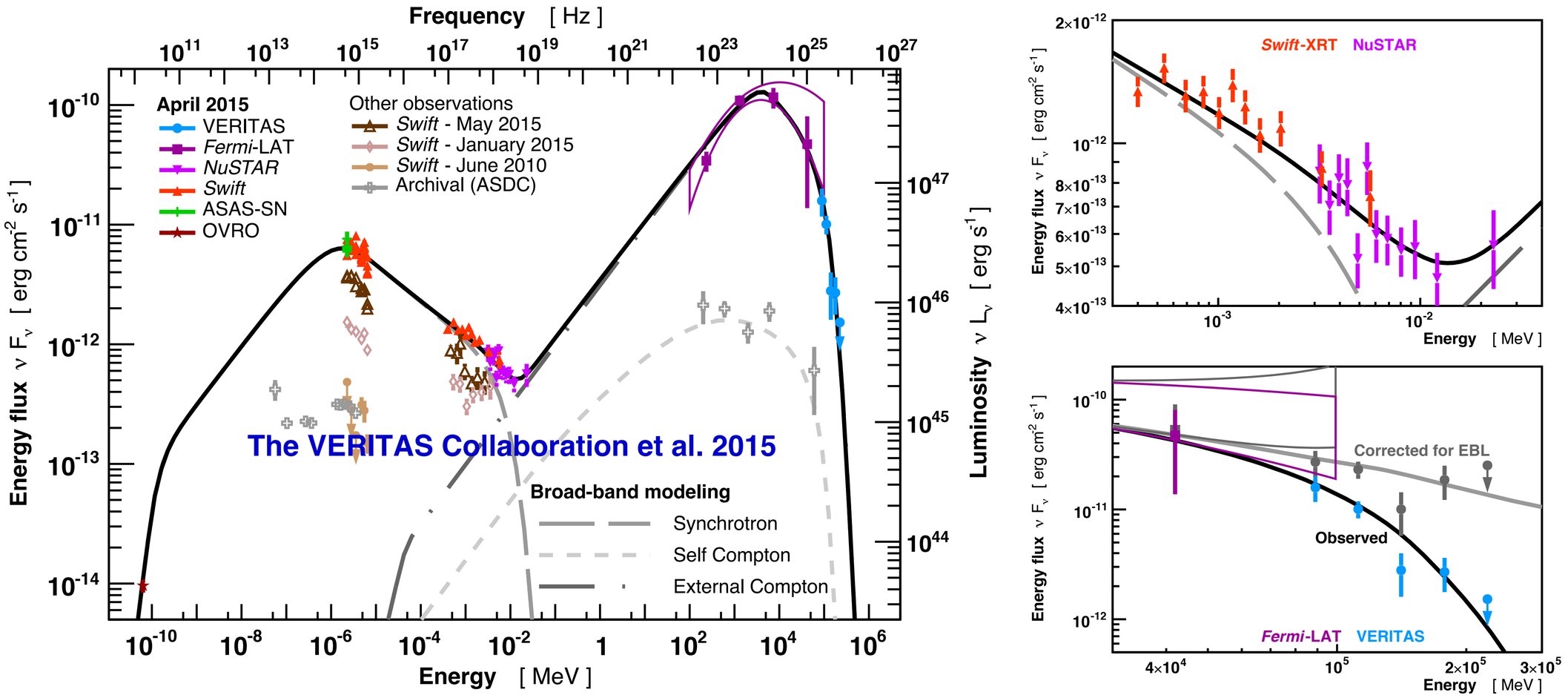


Copious MWL Data During Flare of PKS 1441+25



Long-term: 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

PKS 1441+25: Spectral Energy Distribution

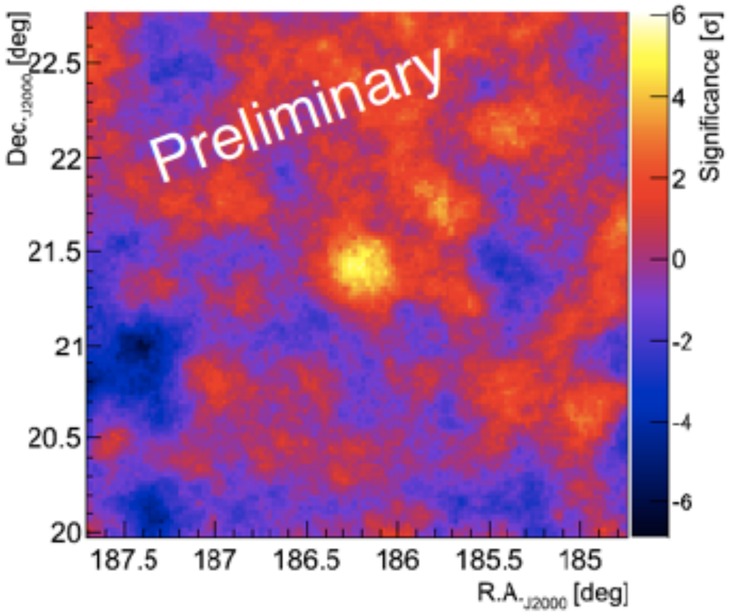


Synchrotron emission seen up to ~30 keV

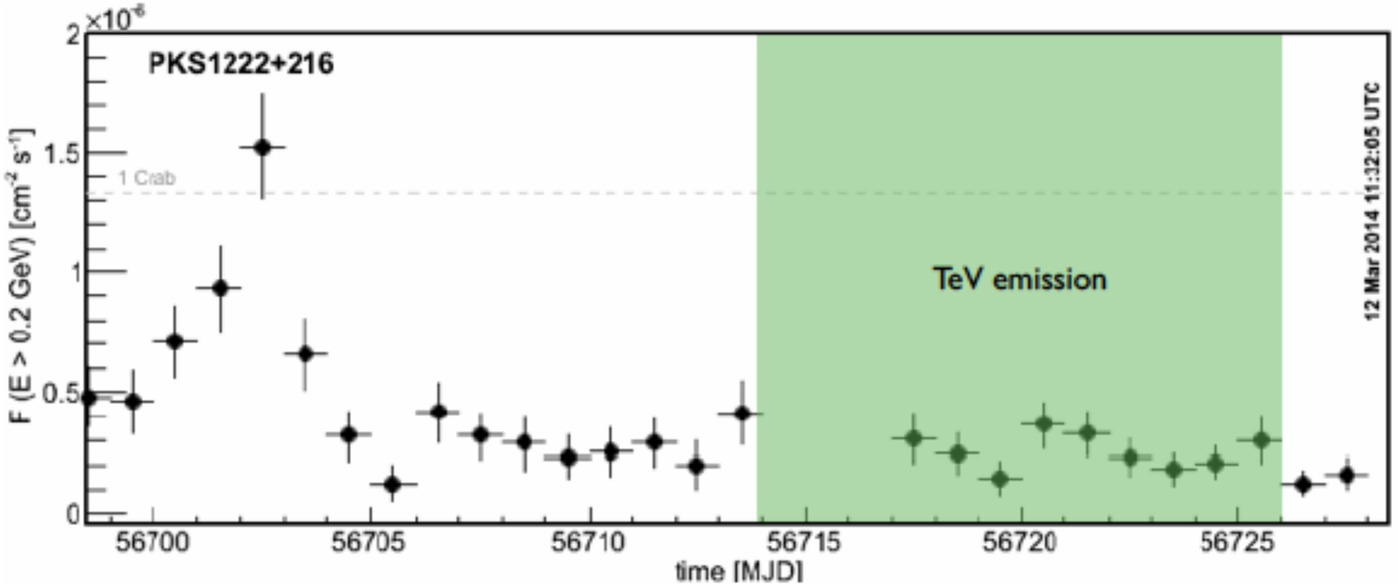
Gamma-ray emission must be from outside of BLR (τ~9 @ 100 GeV)

Broad-band model: Low doppler factor & close to equipartition => Large-scale emission (R = 200,000 R_{sch})

VERITAS Detection of PKS 1222+216 (FSRQ)



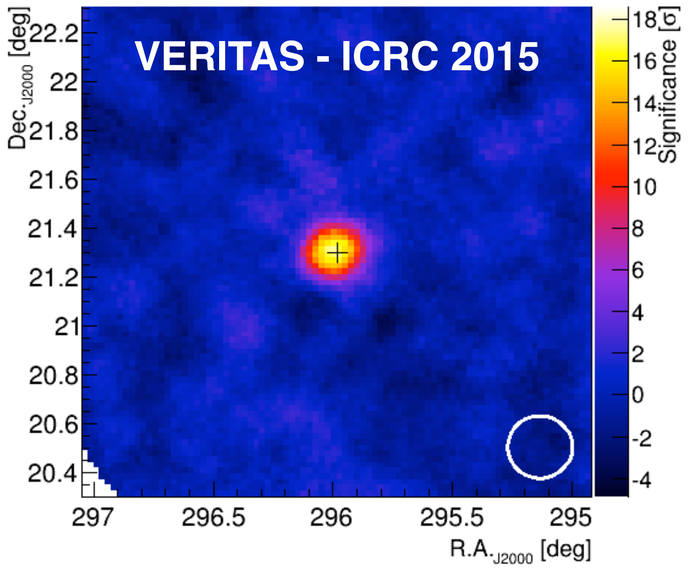
Fermi-LAT Light Curve for PKS 1222+216 (4C +21.35)

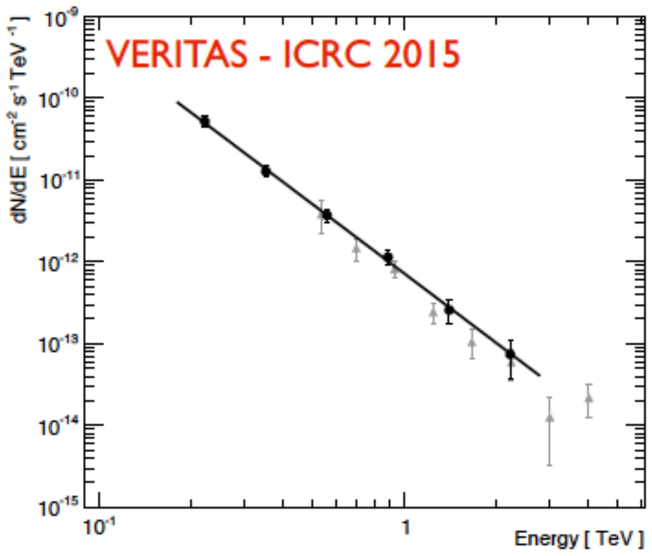


- Detection in ~6 h of VERITAS ToO data: ~6σ over 10 nights in Feb / March 2014
- Steady, persistent flux (~3% Crab) & clearly delayed vs LAT flare; ATel #5981
  - Deep observation (~25 h) in prior seasons only yielded limits
- Most VERITAS FSRQ observations are ToO-based (primarily Fermi-LAT triggered)
  - VERITAS flux limits during nightly observations of unprecedented LAT flare of 3C 279 in 2014
  - VERITAS flux limits during regular observations of LAT / MWL flare of PKS 1510-089 in 2015

Detection of HESS J1943+213: A blazar?

- Found during HESS Galactic Plane scan
  - Point-like, >500 GeV emitter; Soft ($\Gamma \sim 3.1 \pm 0.3$)
  - Possibly a blazar, but no redshift; PWN?
    - Soft spectrum a key blazar motivator
    - Variations would be key evidence
  - Detected in 5 yrs of LAT data ($\Gamma \sim 1.6$)
- VERITAS: ~28 h live time in 2014
  - 18σ excess >200 GeV
- Spectrum ($\Gamma \sim 2.81 \pm 0.13$) consistent with HESS, but on the harder side
- Flux consistent w/ HESS & consistent with constant on daily & weekly time scale!
  - VERITAS: 3.7 $\sigma\ h^{-0.5}$ vs HESS: 1.8 $\sigma\ h^{-0.5}$

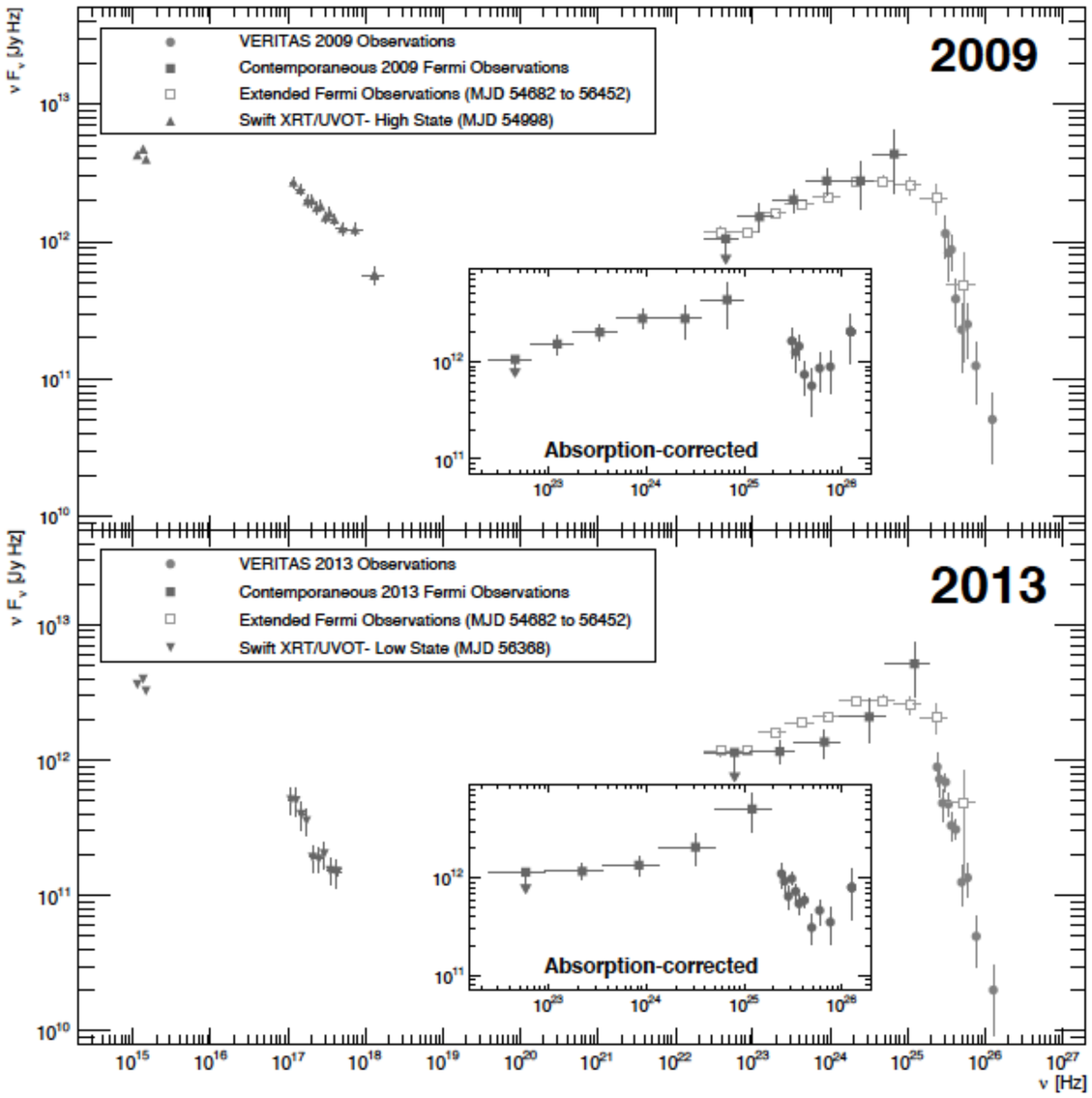




Shahinyan #1232, GA 01 Poster #54

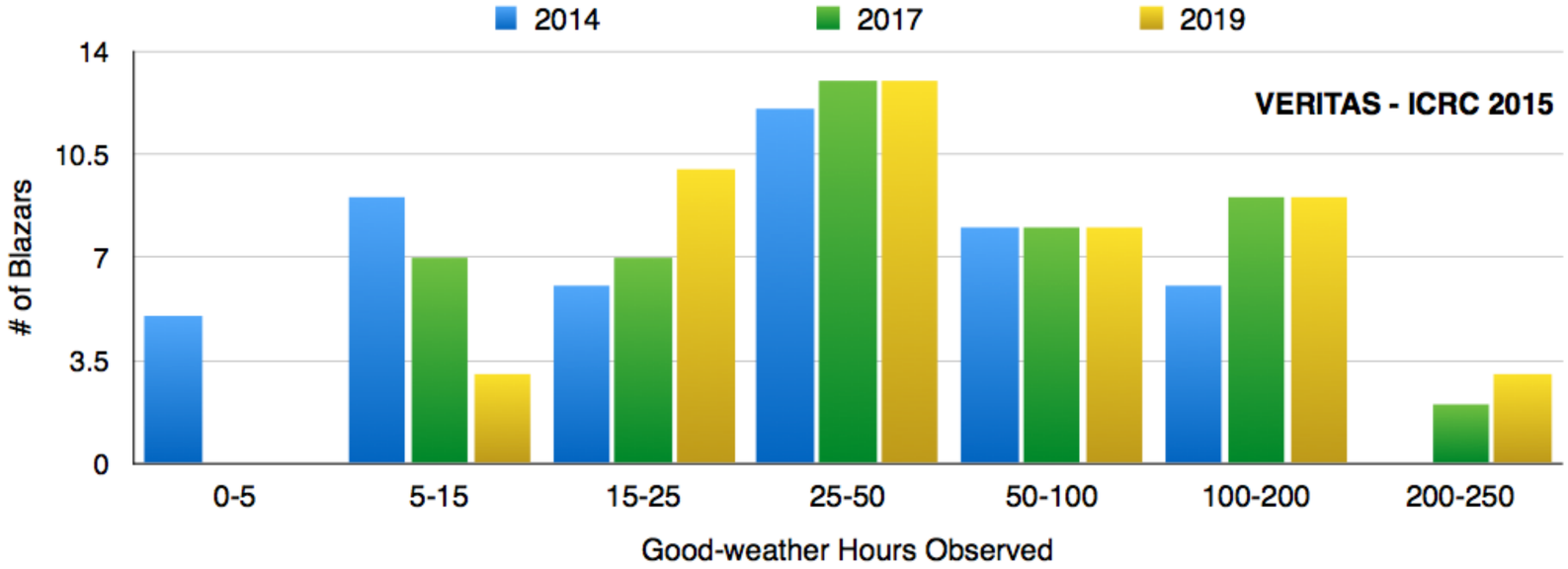
PKS 1424+240: Most-distant regular VHE emitter

- Discovered at VHE by VERITAS in 2009
- HST observations clearly show z > 0.6035:
  - Furniss *et al.*, ApJ, 768, L31, 2013
- Intense VERITAS + MWL observations in 2013:
  - >100 h live time from 2009, 2011 & 2013
  - Strong detection (20σ) >120 GeV; Γ = 4.2 ± 0.3
  - ApJ, 785, L16, 2014
- VHE flux variable on annual time scales (~factor of 5);
  - Unfortunately flux was low in 2013 & 2014
  - VHE Γ & Fermi-LAT >1 GeV flux are not variable
- Due to large redshift & EBL absorption of VHE photons, the VHE spectrum is rather curious



Updated AGN Long-Term Plan

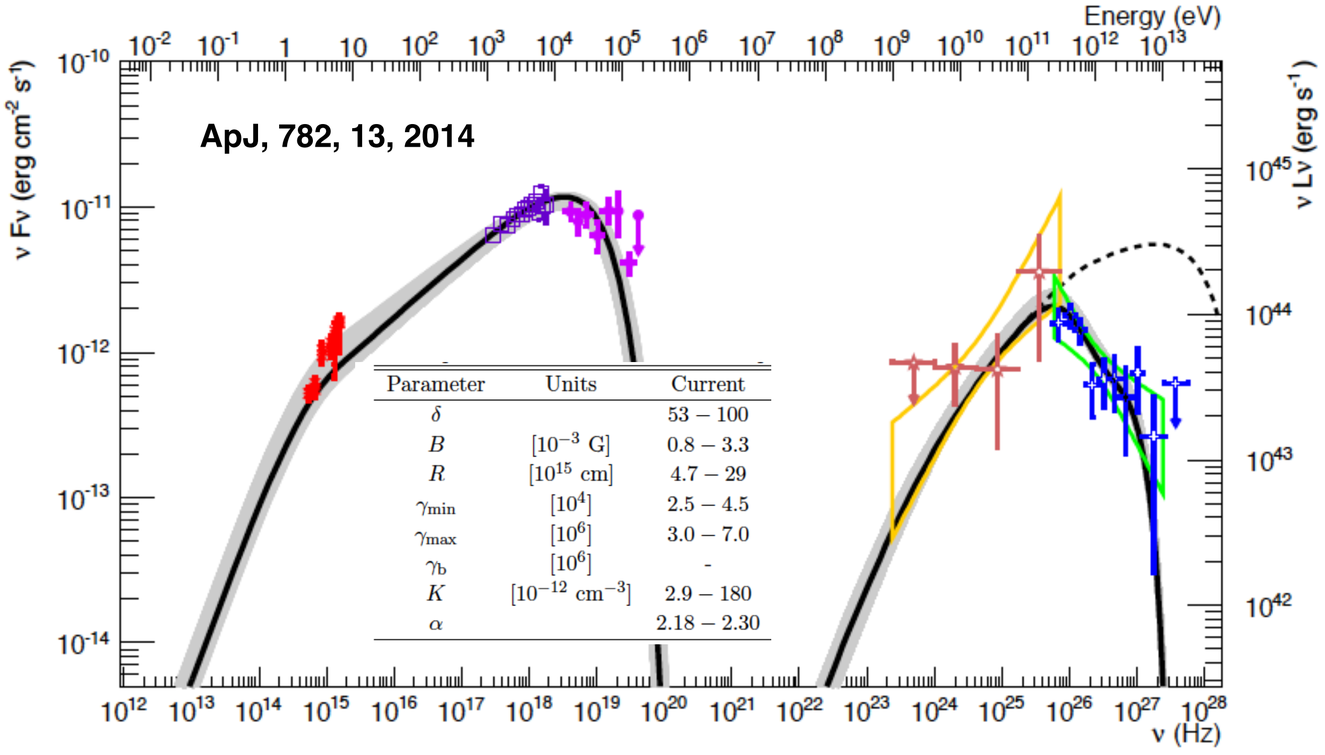
- Deep exposures via intense monitoring of blazars: All w/ simultaneous Swift & intense FLWO 48" BVri coverage
  - EBL / CR Line-of-sight Program: Make precision spectra up to high energy for 5 "distant", hard-spectrum blazars
  - Understanding Variations at all Wavelengths: Find flares & detect low states for 3C 66A & W Comae
  - Iconic Objects: Spectrum each night of observations for Mkn 501 & Mkn 421
- Regular "weekly" snapshots for all remaining Northern VHE blazars: Sensitivity to at least 10% Crab flux
  - Each with Intense FLWO BVri coverage & 8 high-priority targets also with simultaneous Swift data
- Radio Galaxies: Intense M87 monitoring (~20 h / year) as part of a major, world-wide multi-wavelength effort
- Flare follow-up is the key => Pre-approved ToO data



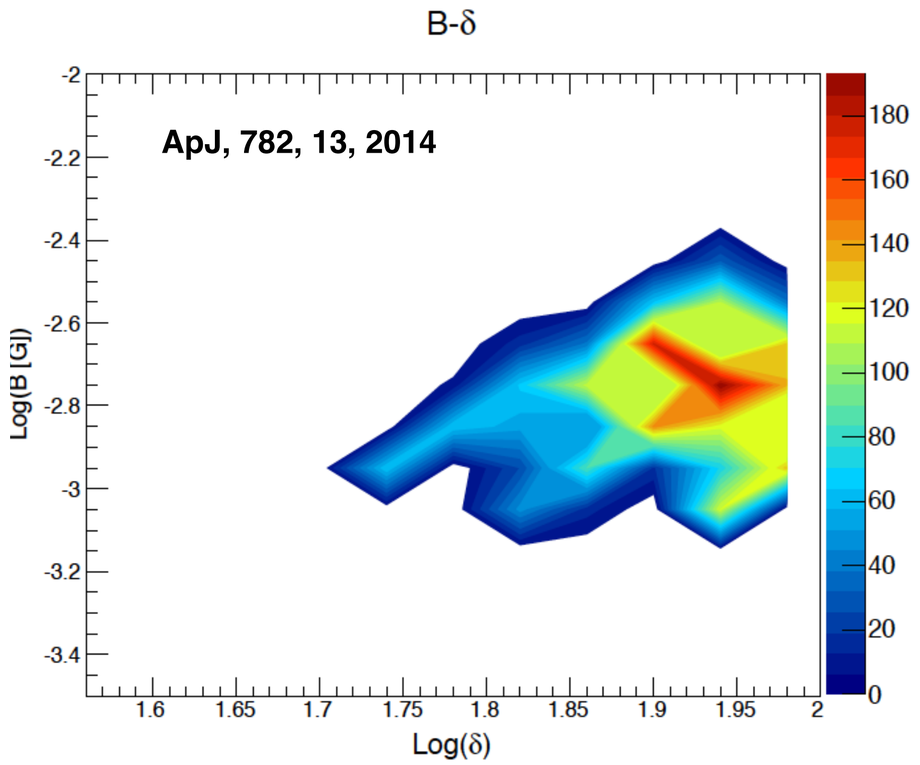
Histogram of minimal VERITAS exposure

N.B.: >100 h / yr for other blazar projects

VERITAS Modeling: Decreasing Degeneracy



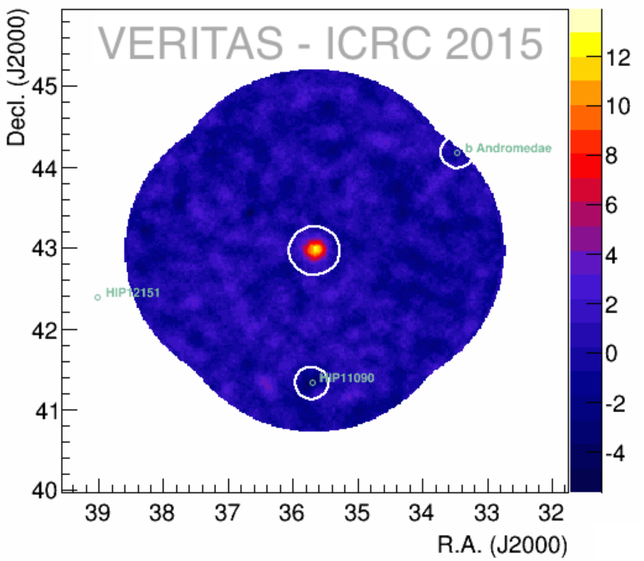
Parameter	Units	Current
δ		53 – 100
B	[10^{-3} G]	0.8 – 3.3
R	[10^{15} cm]	4.7 – 29
γ_{min}	[10^{4}]	2.5 – 4.5
γ_{max}	[10^{6}]	3.0 – 7.0
γ_b	[10^{6}]	-
K	[10^{-12} cm^{-3}]	2.9 – 180
α		2.18 – 2.30

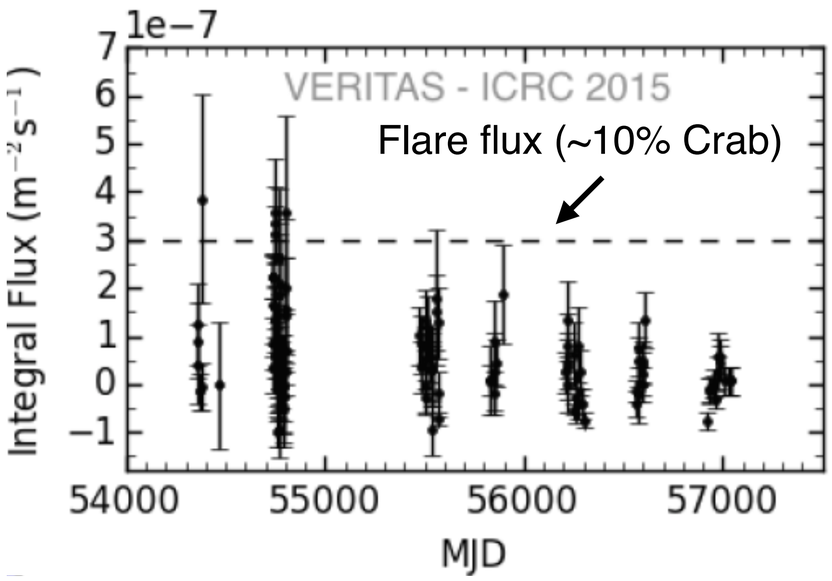


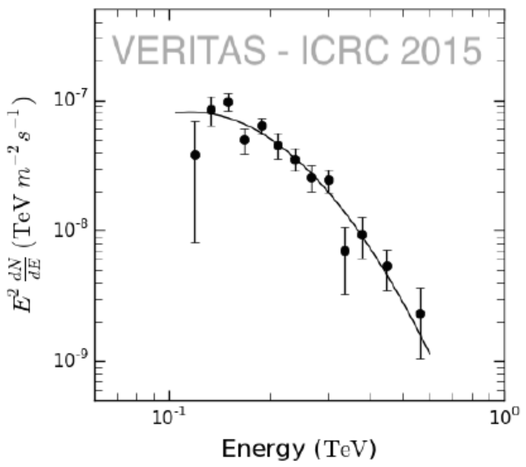
- VERITAS blazars: We ensure all have SEDs. Generally compatible with an SSC model
  - Some exceptions where SSC + EC (e.g. some IBLs), or lepto-hadronic (e.g. some UHBLs), scenarios are preferred
- 1ES 0229+200 w/ VERITAS (2010-12): 54 h; ~12σ, 1.7% Crab, Γ = 2.59 ± 0.12
- SED compatible with SSC, <u>but we fully constrained the SSC parameter space</u>
  - δ > 53: Higher than radio & unusual for most blazars; Minimum Lorentz factor is also high: "No" low-E electrons

Detection of the “Low States” of VHE IBLs

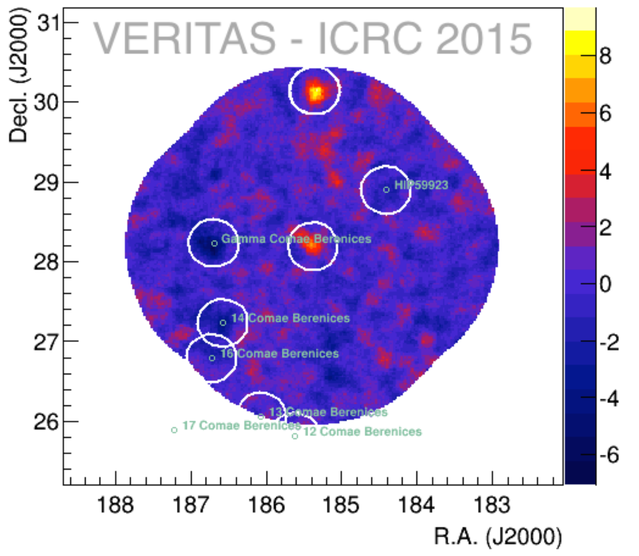
3C 66A

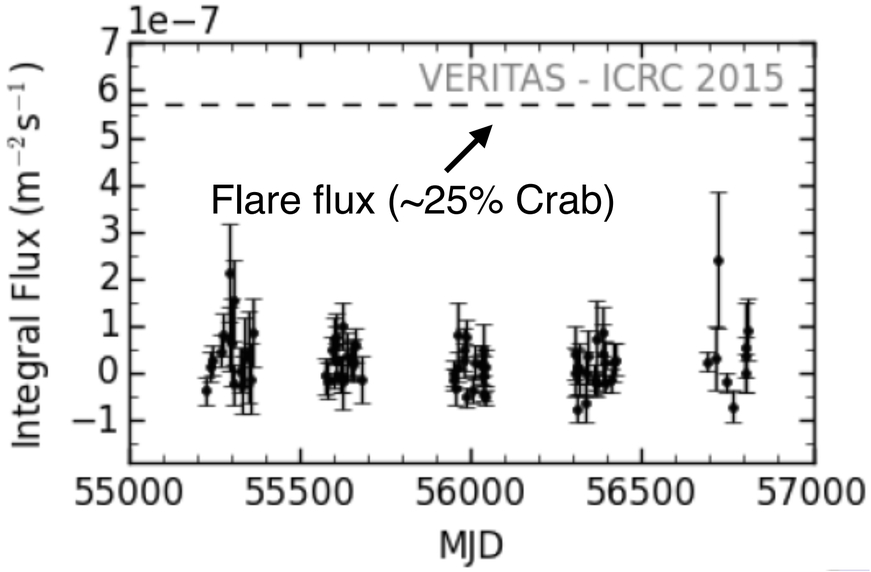


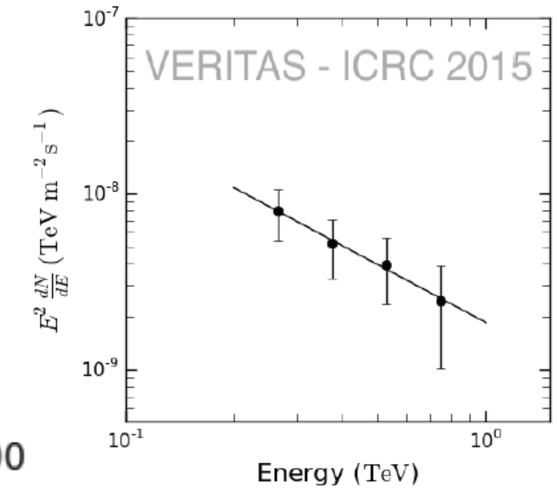




W Comae







Vievering #745, GA 01 Poster #63

Flares from the VERITAS Snapshot Program

- Tested viability of "snapshot" program in 2013-14 season; Monthly 15 minute exposures on ~20 VHE blazars
  - NB: VERITAS was already performing deep monitoring of 15 VHE blazars of interest
- We caught flares from 5 blazars; arguably much of the highlights from 2013-14
  - 1ES 0033+595: ~20σ, ~15% Crab; Factor of ~15 flare with intense MWL coverage
  - VER J0521+211: ~60σ; Flux peaks at ~40% Crab, intense MWL coverage (see Prokoph #1134, GA03 Poster #66)
  - 1ES 1011+496: Flux peaks at ~70% Crab (z ~ 0.2!); Intense MWL coverage; ATel #5887
  - MS 1221.8+216: ~20% Crab; Factor of 5 flare; VERITAS hadn't previously detected
  - 1ES 1727+502: ~10% Crab; Similar to 2013 event (see Cerruti #762, GA08)
- Complements 2 flares from MWL ToOs or from "Deep Monitoring" program:
  - BL Lac: ~15% Crab during a 1-night event
  - B2 1215+30: >200% Crab flare serendipitously found in F.o.V. of 1ES 1218+304: (see Zefi #591, GA08)
- We also now know that many other VHE blazars were relatively quiet on ~monthly time scales
  - N.B. it would not have caught the PKS 1222+216 event
- 2014-15 was quieter, but some small flares: 1ES 0033+595, 1ES 1011+496, B2 1215+30, 1ES 1727+502, BL Lac

Conclusions

- VERITAS is running very well & plans to operate until ~2019
  - Recent upgrades: Sensitivity to AGN 2x better & E_{th} 40% less than in mid-2009 & we can observe on any good-weather night
- The VERITAS source catalog is now at 55 sources from 8 classes: 34 are AGN
  - Growth in catalog now driven by new detections of soft-spectrum AGN after our instrument upgrade
- AGN are ~50% of VERITAS observations; Many significant results & dozens of VERITAS AGN papers
- Most recent blazar highlights are based on the detection of flares or the results of deep (MWL) exposures
- Radio galaxy highlights:
  - ~230 h on M87: Very quiet since 2010 flare; Minor (~2x) brightening in 2012; ~1.5% Crab in both 2013-14 & 2014-15
  - VERITAS detected NGC 1275 during two flaring episodes in 2013: 7σ, 1% Crab, $\Gamma \sim 4.0$
- Long-term plan: Focus on monitoring <u>all</u> Northern VHE blazars & M87 to identify flares & quickly follow up on those with "pre-approved" ToOs; Also follow-up on MWL ToOs
  - Cadence / annual exposures & simultaneous MWL coverage varies for the known VHE blazars
- By 2019, we plan to have a deep, multi-year VHE exposure for every known VHE AGN

VERITAS AGN Publications #1

(1)V. Acciari et al., “VERITAS Discovery of >200 GeV Gamma-ray Emission from the IBL Object W Comae”, *Astrophysical Journal Letters*, **684,** L73, 2008
(2)V. Acciari et al., “Discovery of Very High-Energy Gamma-Ray Radiation from the BL Lac 1ES 0806+524”, *Astrophysical Journal Letters*, **690**, L126, 2009
(3)I. Donnarumma et al., “The June 2008 Flare of Markarian 421 from Optical to TeV Energies”, *Astrophysical Journal Letters*, **691**, L13, 2009
(4)V. Acciari et al., “VERITAS Observations of a Very High Energy Gamma-ray Flare from the Blazar 3C 66A”, *Astrophysical Journal Letters*, **693**, L104, 2009
(5)V. Acciari et al., “VERITAS Observations of the BL Lac Object 1ES 1218+304”, *Astrophysical Journal*, **695**, 1370, 2009
(6)V. Acciari et al., “Radio imaging of the very-high-energy gamma-ray emission region in the central engine of a radio galaxy”, *Science,* **325**, 444, 2009
(7)V. Acciari et al., “Simultaneous Multiwavelength Observations of Markarian 421 During Outburst”, *Astrophysical Journal*, **703**, 169, 2009
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(14) A. Abdo et al., “Multi-wavelength Observations of Flaring Gamma-ray Blazar 3C 66A in October 2008”, *Astrophysical Journal*, **726**, 43, 2011
(15) A. Abdo et al., “Insights Into the HE γ-ray Emission of Markarian 501 from Extensive Multifrequency Observations in the Fermi Era”, *Astrophysical Journal*, **727**, 129, 2011
(16) V. Acciari et al., “Spectral Energy Distribution of Markarian 501: Quiescent State vs. Extreme Outburst”, *Astrophysical Journal*, **729**, 2, 2011
(17) V. Acciari et al., “TeV and Multi-wavelength Observations of Mrk 421 in 2006-2008”, *Astrophysical Journal*, **738**, 25, 2011
(18) V. Acciari et al., “Multiwavelength Observations of the VHE Blazar 1ES 2344+514”, *Astrophysical Journal*, **738**, 169, 2011
(19) E. Aliu et al., “Multiwavelength Observations of the Previously Unidentified Blazar RXJ0648.7+1516”, *Astrophysical Journal*, **742**, 127, 2011
(20) A. Abramowski et al., “The 2010 VHE Flare & 10 Years of Multi-Wavelength Observations of M87” *Astrophysical Journal*, **746**, 151, 2012
(21) E. Aliu et al., “VERITAS observations of day-scale flaring of M87 in April 2010”, *Astrophysical Journal*, **746**, 141, 2012
(22)E. Aliu et al., “ Discovery of High-energy and Very High Energy γ-Ray Emission from the Blazar RBS 0413” *Astrophysical Journal*, **750**, 94, 2012
(23)E. Aliu et al., “ Multiwavelength Observations of the AGN 1ES 0414+009 with VERITAS, Fermi-LAT, Swift-XRT, and MDM”, *Astrophysical Journal*, **755**, 118, 2012
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(26)E. Aliu et al., “Multiwavelength Observations and Modelling of 1ES 1959+650”, *Astrophysical Journal*, **775**, 3, 2013

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(31)S. Archambault et al., “Deep Broadband Observations of the Distant Gamma-ray Blazar PKS 1424+240”, *Astrophysical Journal Letters,* **785,** L16, 2014

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