Recent Highlights from the VERITAS AGN Discovery Program

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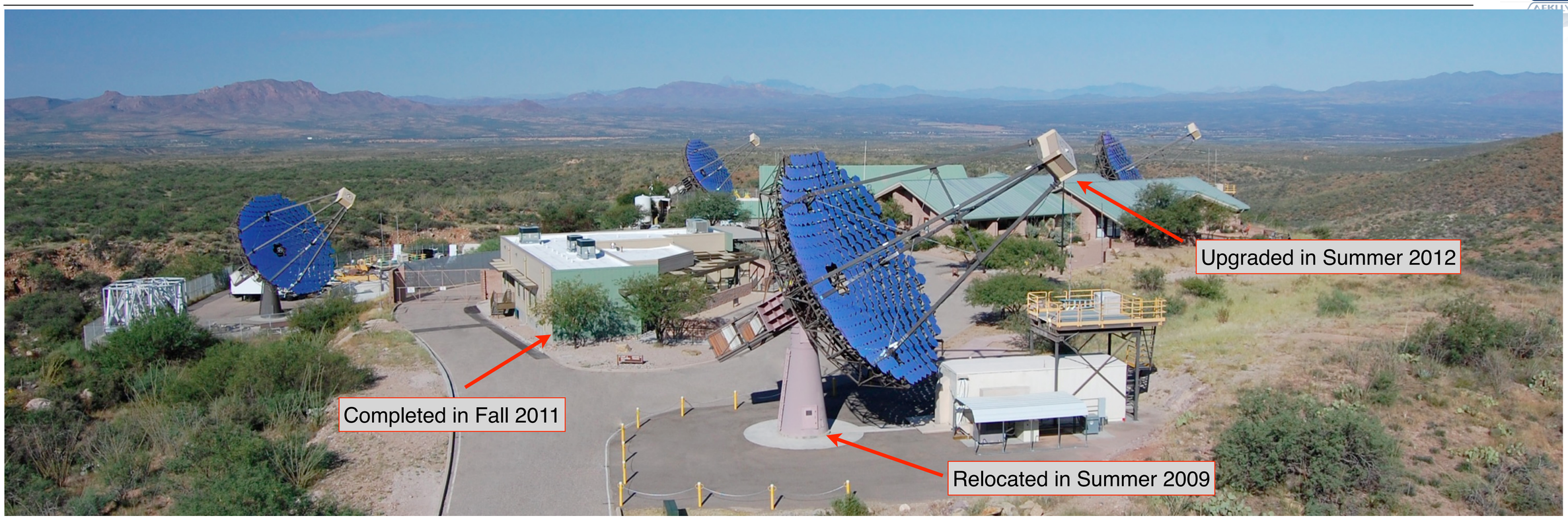
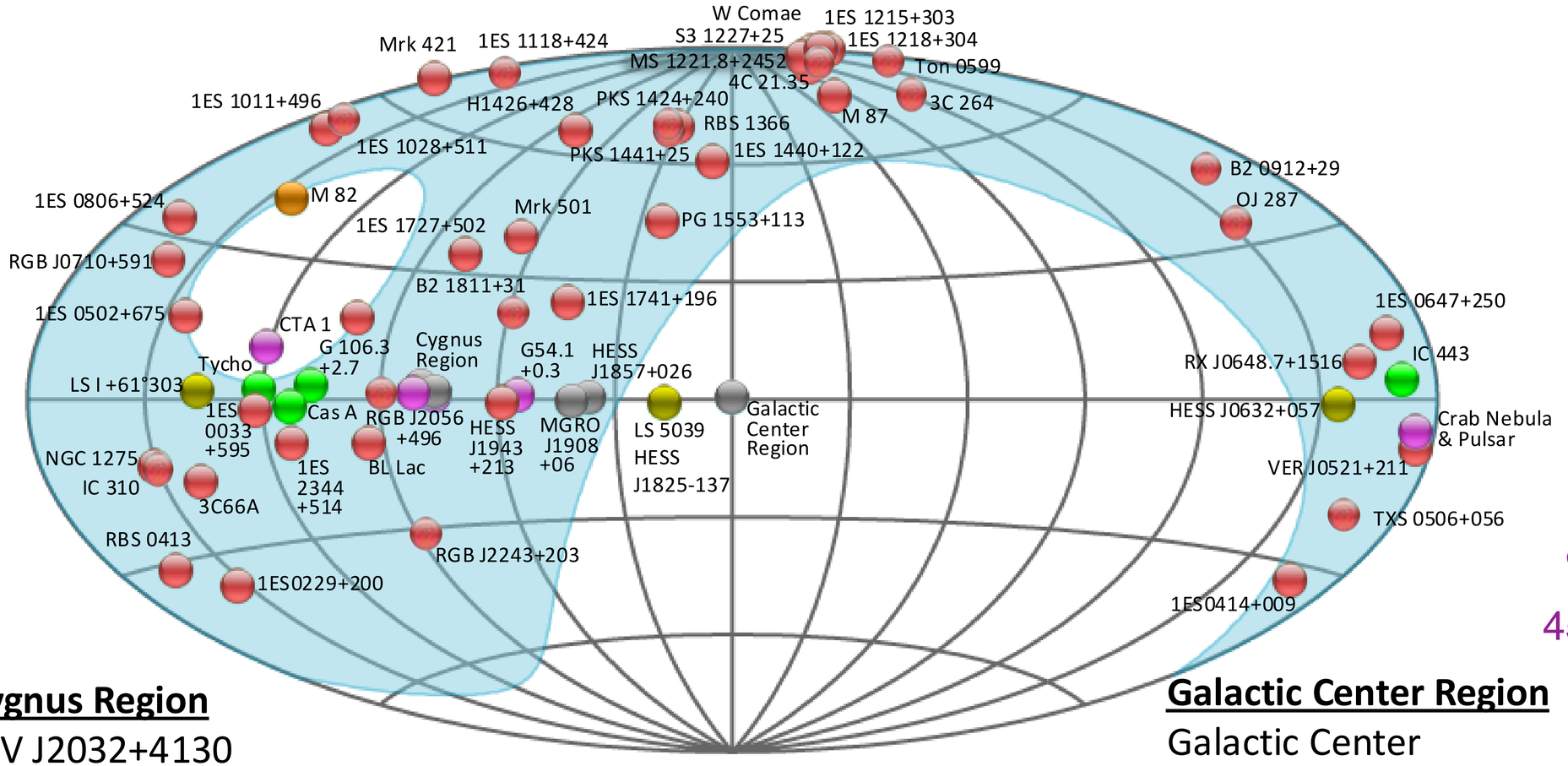
Gamma-2024, Milan, Italy; September 3, 2024

VERITAS: Observatory Overview



- Very-high-energy (~100 GeV to ~30 TeV) γ-ray studies since 2007 (~19,400 h data)
  - Operations funded through 2025; Applying for funding to operate through 2028
- Good-weather data / yr: ~910 h in “dark time” + ~140 h in “bright moon” (illum. >30%)
  - Sensitivity: 1% Crab in <25 h
  - Systematic errors: Flux ~20%; Γ ~ 0.1
  - Angular resolution: r_{68} ~ 0.08° @ 1 TeV
  - Energy resolution: ~17%

The VERITAS Source Catalog



69 sources

46 Extragalactic (67%)

23 Galactic (33%)

8 astrophysical classes

45 AGN (42 blazars & 3 RGs)

Cygnus Region

TeV J2032+4130
VER J2019+407
VER J2019+368
VER J2016+372
VER J2034+414

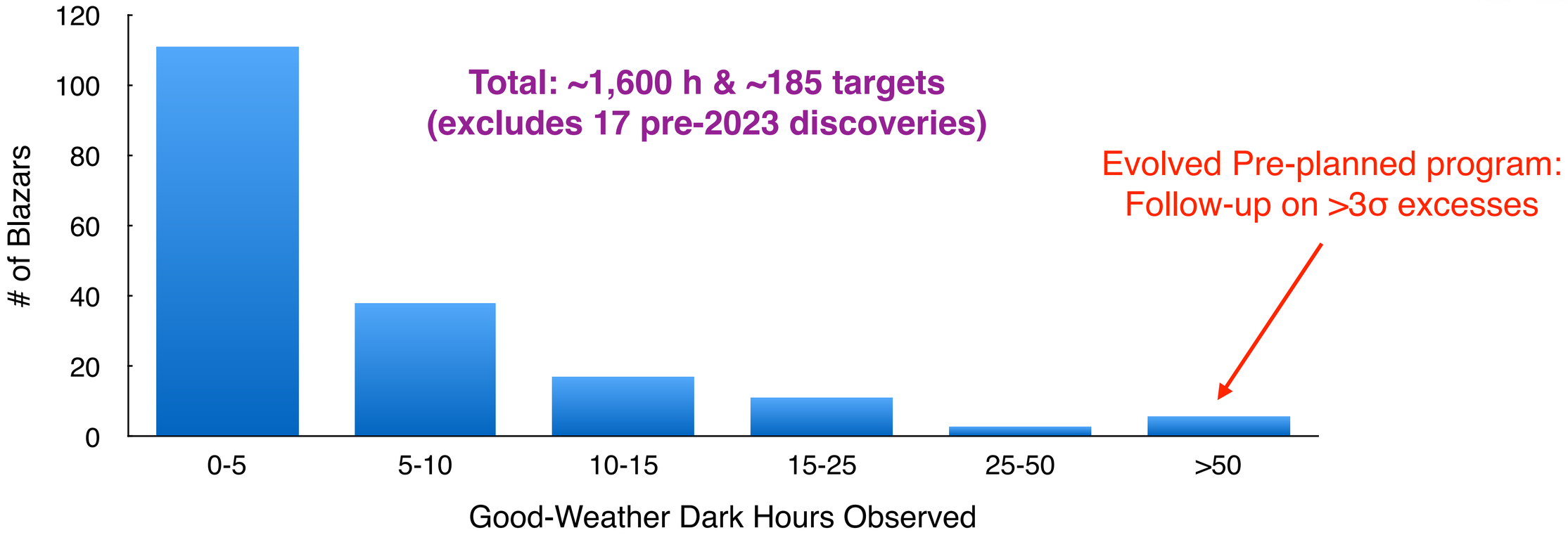
Galactic Center Region

Galactic Center
Galactic Center Ridge
VER J1746-289
G 0.9+0.1

The VERITAS AGN Program

- 2007-2024: ~7,000 h of good-weather “normal” AGN data; Average ~410 h / yr
  - Recently ~25% radio galaxy exposures; Historically ~90% blazars / ~10% radio galaxies
- 2012-2024: ~1,350 h of good-weather “bright moon” AGN data; Average ~110 h / yr
  - Bright-time AGN program shrinking; Now used to monitor HBLs for flares since similar sensitivity >250 GeV
- AGN program: Focus remains BL Lac objects
  - Discovery of new blazars at VHE (~35%)
    - Recent focus: Deep exposures of several weak (3-5σ) excesses
  - Target of Opportunity (ToO) observations (~15%; Top priority!)
    - Includes response to IceCube alerts
  - High-cadence monitoring of bright VHE blazars (e.g., Mrk 421 & Mrk 501)
    - Reduced target list; Prev. all Northern VHE AGN (2014-2021)
  - Simultaneous MWL observations of AGN
    - Leverage instruments such as the Swift-XRT, IXPE, NuSTAR, and the EHT.
  - Observations of VHE-emitting radio galaxies to better characterize SEDs
    - Radio galaxy program: ~65% discovery / ~35% known VHE

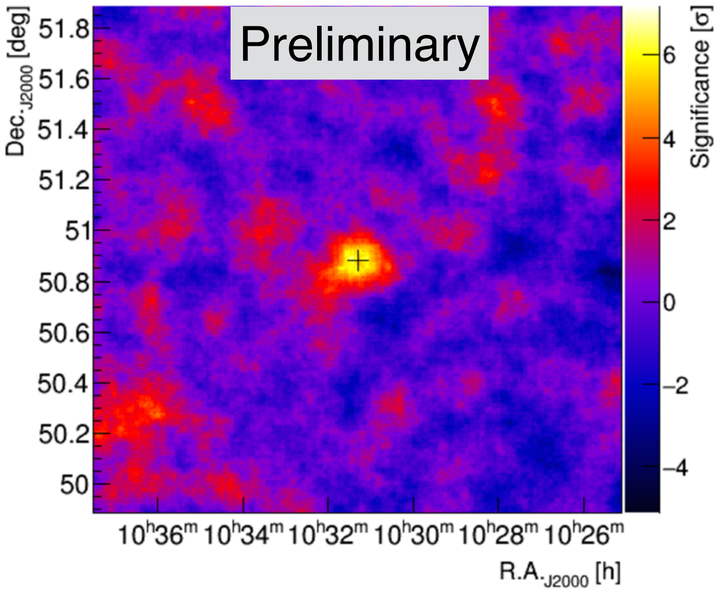
Building the VHE Catalog: Discovery Program



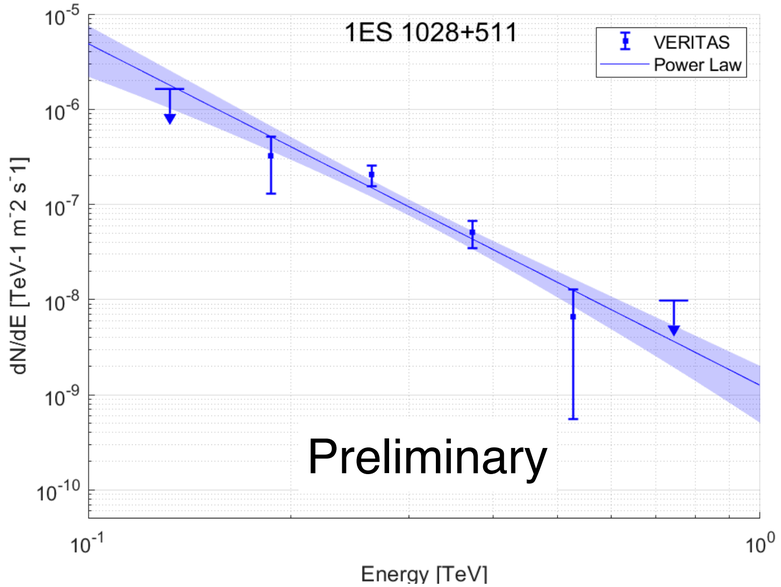
- VERITAS discovery program has 2 approaches: Pre-planned observations & ToOs
- Pre-planned program: Comprehensive survey of X-ray brightest 2WHSP & hardest 2FHL objects
  - 2WHSP FOM ≥ 1.0 & 2FHL Γ ≤ 2.8; Historical oddities: Favor z < 0.3, but some higher-z searches & other additions (e.g. IBLs & LBLs)
- ToO triggers: Gamma-ray (e.g. Fermi-LAT, VERITAS), multi-messenger (e.g. IceCube) & optical facilities

VERITAS VHE Discovery of 1ES 1028+511

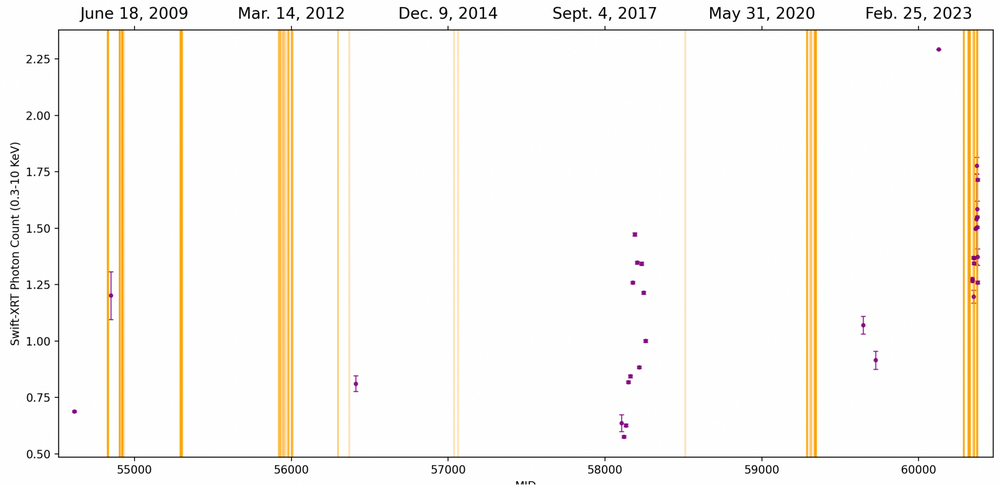
Sky map of Observed Significance



Observed Photon Spectrum



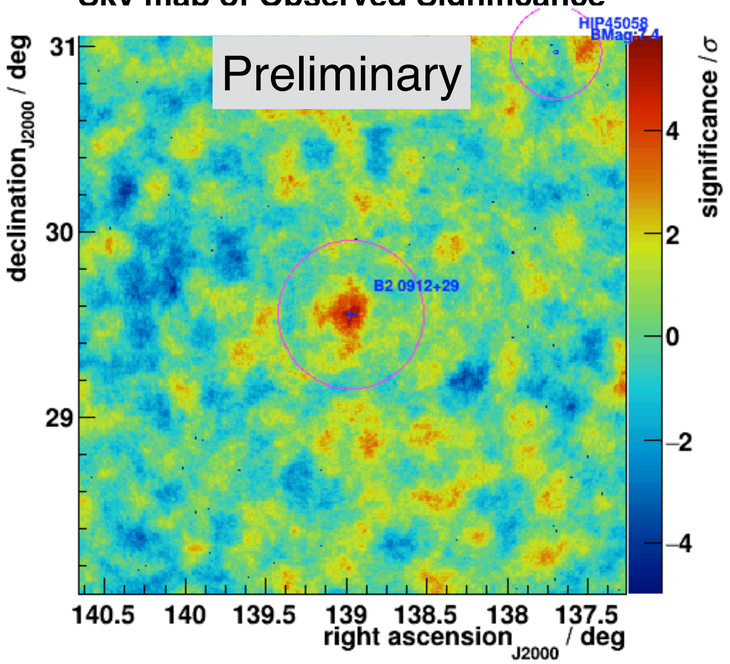
Swift Light Curve w/ VERITAS Exposures



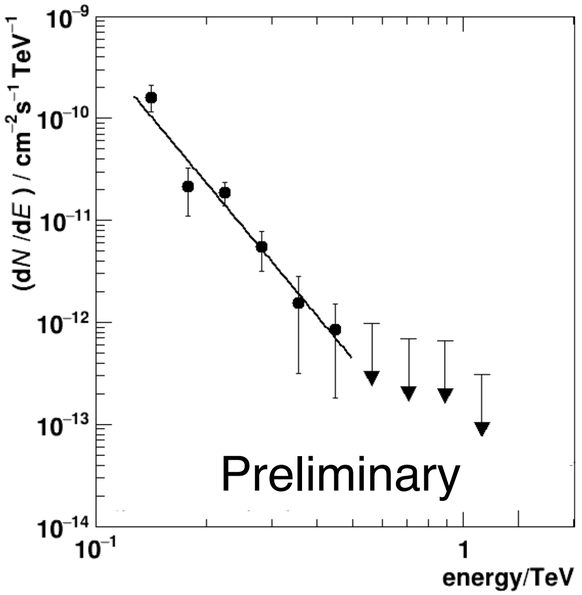
- Distant (z = 0.361), extreme HBL (3HSP => $\nu_{synch} \sim 10^{16.9}$); Long-considered a likely VHE source
  - 3HSP TeV FOM ~ 4; Steady, hard-spectrum Fermi source: $\Gamma_{4FGL} \sim 1.76$; $\Gamma_{3FHL} \sim 1.9$; $\Gamma_{2FHL} \sim 2.6$; F(50 - 150 GeV) ~ 1% Crab
- Extensive VHE observations (~49 h; 2007-24) with VERITAS => VHE discovery (6.1σ, ~320 γ)
- F(>200 GeV) = (2.4 ± 0.5) x 10^{-12} cm^{-2} s^{-1} (~1.0% Crab); Soft spectrum (Γ = 3.6 ± 0.5)
- 33 Swift XRT observations: Factor ~4 variation; Higher X-ray flux during 2024 campaign; also NuStar

VERITAS VHE Discovery of B2 0912+29

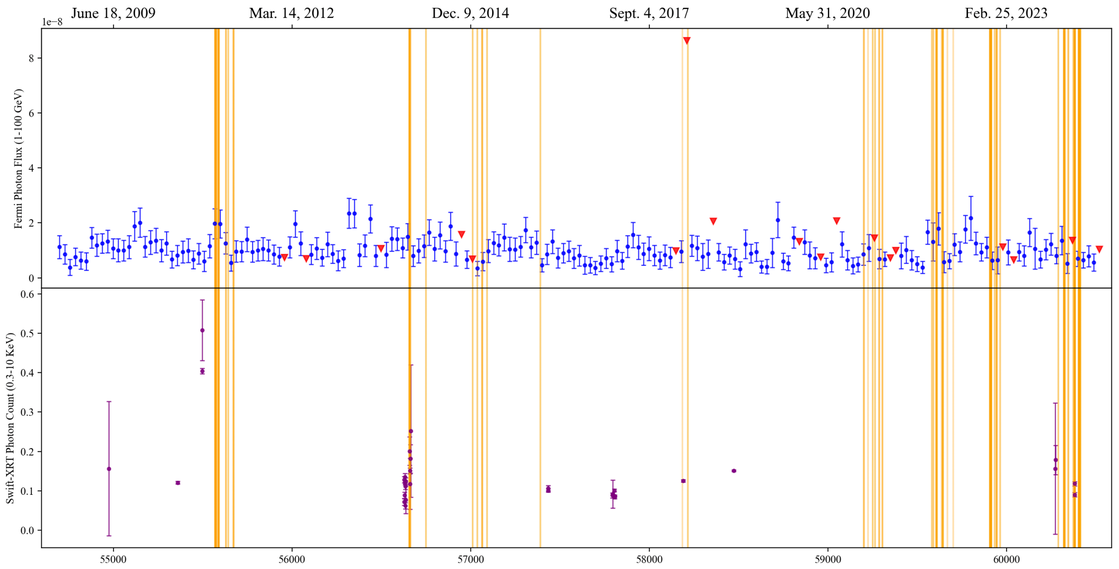
Sky map of Observed Significance



Observed Photon Spectrum



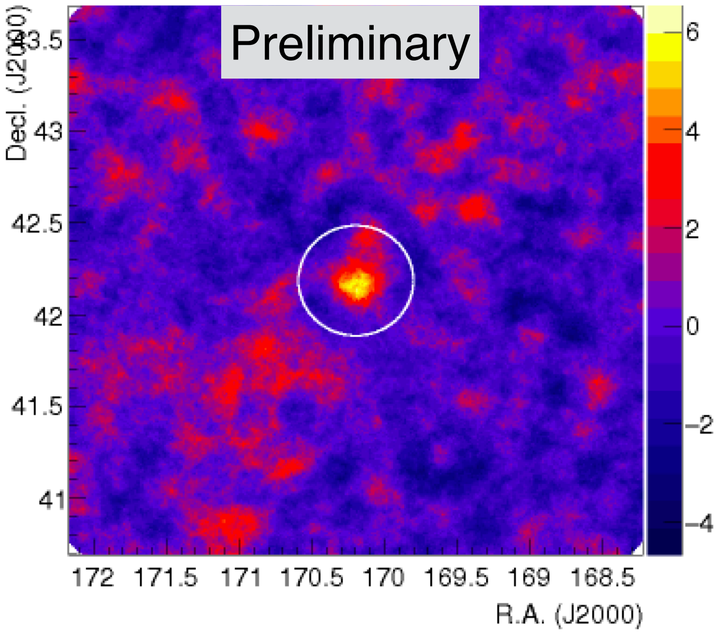
Fermi + Swift Light Curve w/ VERITAS Exposures



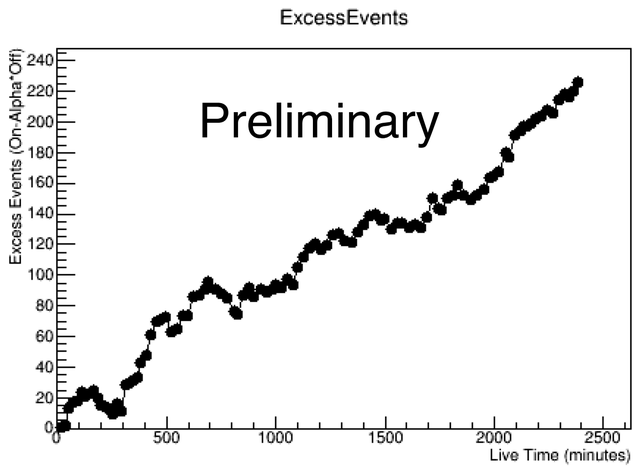
- Distant ($z > 0.19$) HBL (3HSP => $\nu_{synch} \sim 10^{15.4}$); Long-considered a likely VHE source
  - Variable, hard-spectrum Fermi source: $\Gamma_{4FGL} \sim 1.88$; $\Gamma_{3FHL} \sim 2.4$; $\Gamma_{2FHL} \sim 4.5$; F(50 - 150 GeV) ~ 3% Crab; 3HSP TeV FOM ~ 3;
- Extensive VHE observations (~62 h; 2011-24) with VERITAS => VHE discovery (5.8σ, 322 γ)
- Steady flux; F(>200 GeV) = (1.3 ± 0.3) x 10^{-12} cm^{-2} s^{-1} (~0.5% Crab); Soft spectrum (Γ = 4.3 ± 0.6)
- 32 Swift XRT observations: Factor ~10 variation; Lower X-ray flux during VERITAS campaign

VERITAS VHE Discovery of 1ES 1118+424

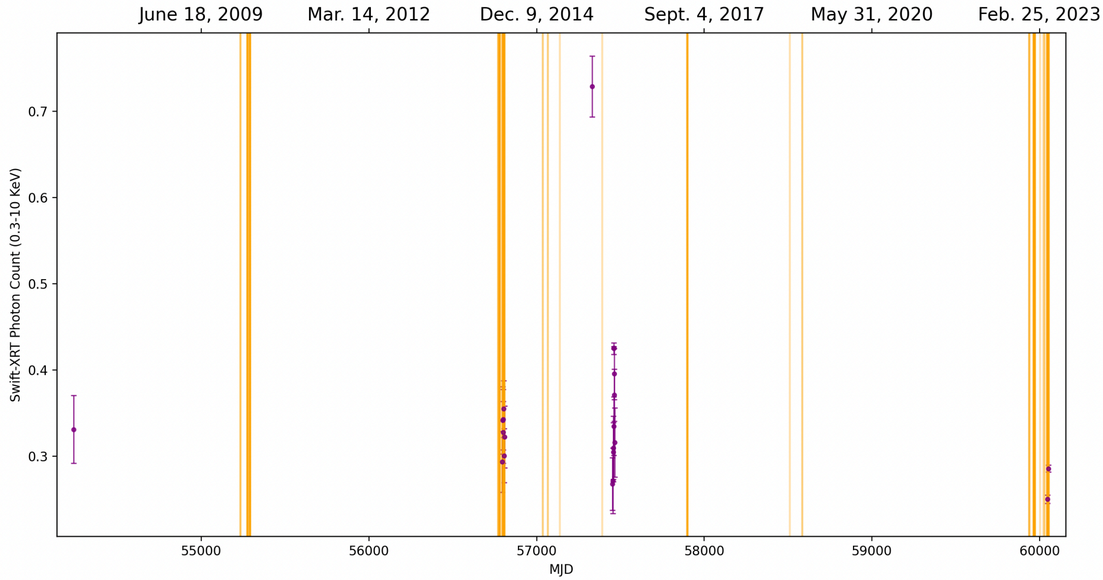
Sky map of Observed Significance



Cumulative Excess

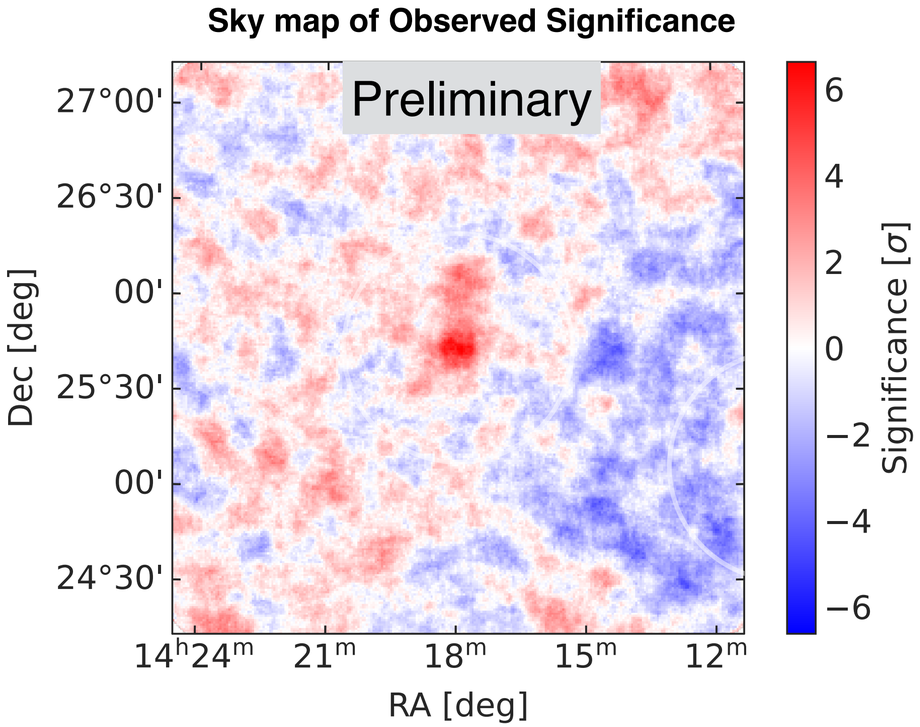


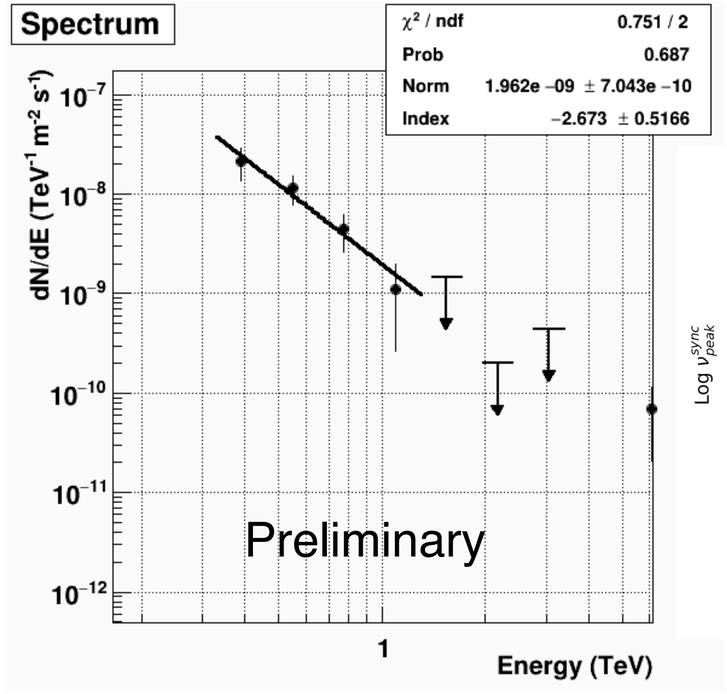
Swift Light Curve w/ VERITAS Exposures

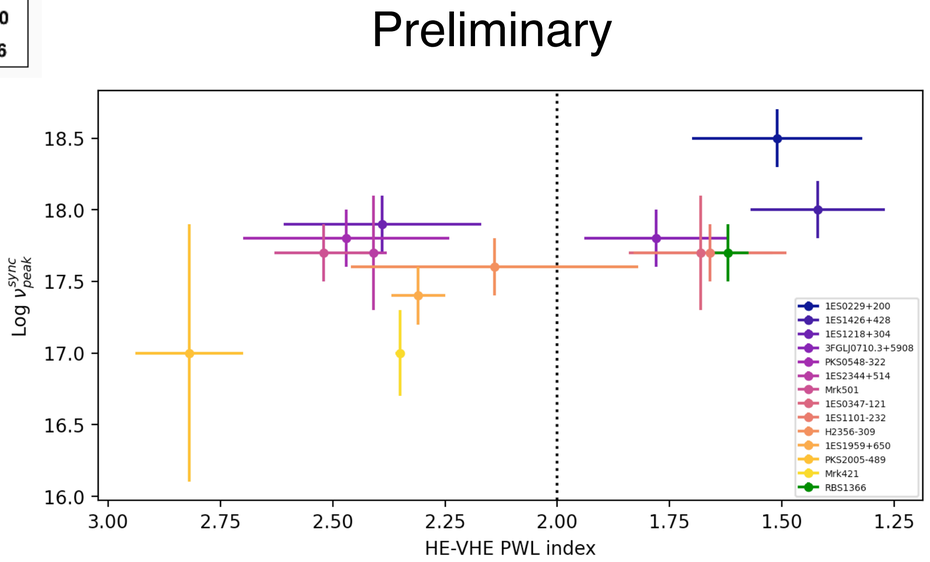


- Distant ($z > 0.28$), HBL (3HSP => $\nu_{synch} \sim 10^{16.2}$); Considered a likely VHE source
  - Variable, hard-spectrum Fermi source: $\Gamma_{4FGL} \sim 1.62$; $\Gamma_{3FHL} \sim 2.1$; $\Gamma_{2FHL} \sim 2.5$; F(50 - 150 GeV) ~ 3% Crab; 3HSP TeV FOM ~ 2
- Extensive VHE observations (~40 h; 2007-24) with VERITAS => VHE discovery (5.2σ, 247 γ)
- $F(>200\ GeV) = (1.9 \pm 0.4) \times 10^{-12}\ cm^{-2}\ s^{-1}$ (~0.8% Crab); Soft spectrum ($\Gamma \sim 3.9$)
- 21 Swift XRT observations: Factor ~3 variation; Lower X-ray flux during VERITAS campaign

VERITAS VHE Discovery of RBS 1366



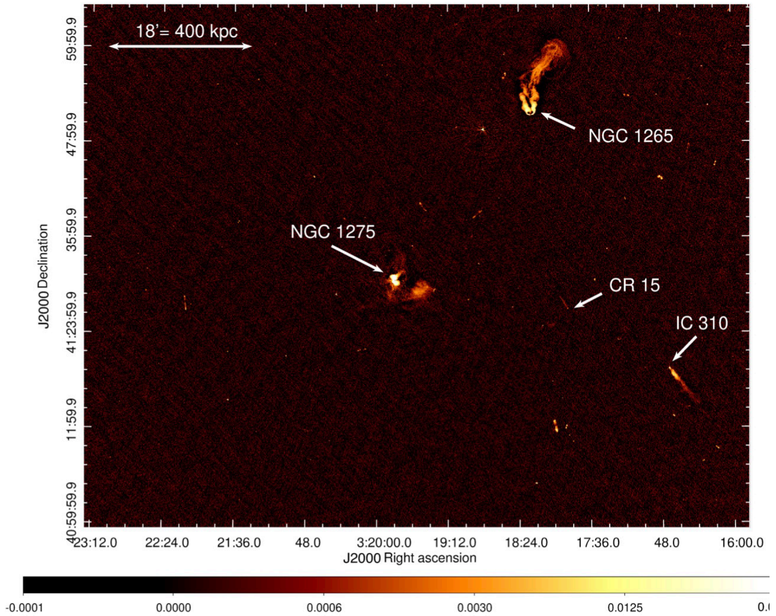




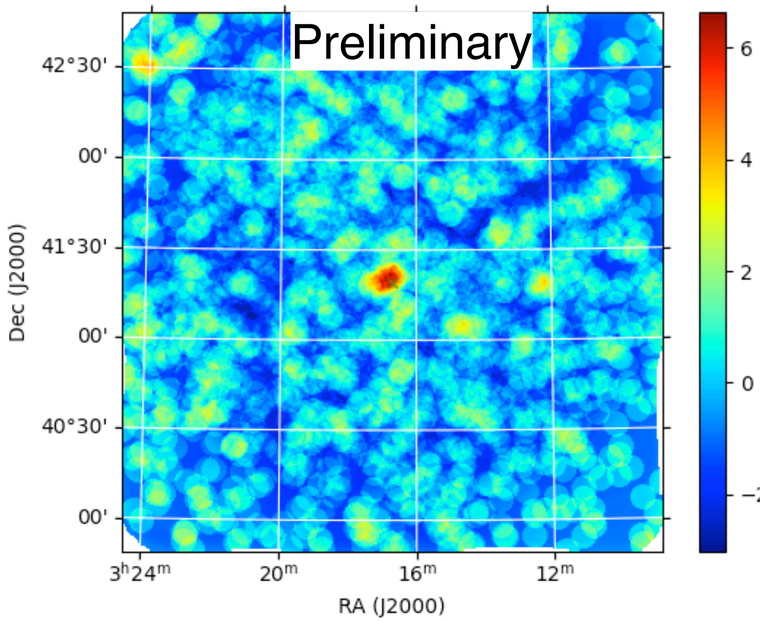
- Extreme high-frequency-peaked (3HSP => $\nu_{synch} \sim 10^{17.6}$) BL Lac; Relatively distant (z = 0.237)
- Extensive VHE observations (~80 h; 2008-24) with VERITAS => VHE discovery (6.9σ, ~440 γ)
- Unusually hard VHE spectrum ($\Gamma = 2.7 \pm 0.5$) & steady flux F(>200 GeV) ~ 0.7% Crab
- Fermi + VHE spectrum => $\Gamma = 1.6$; Another hard, luminous, steady EHBL (hadronic?, MMA?)

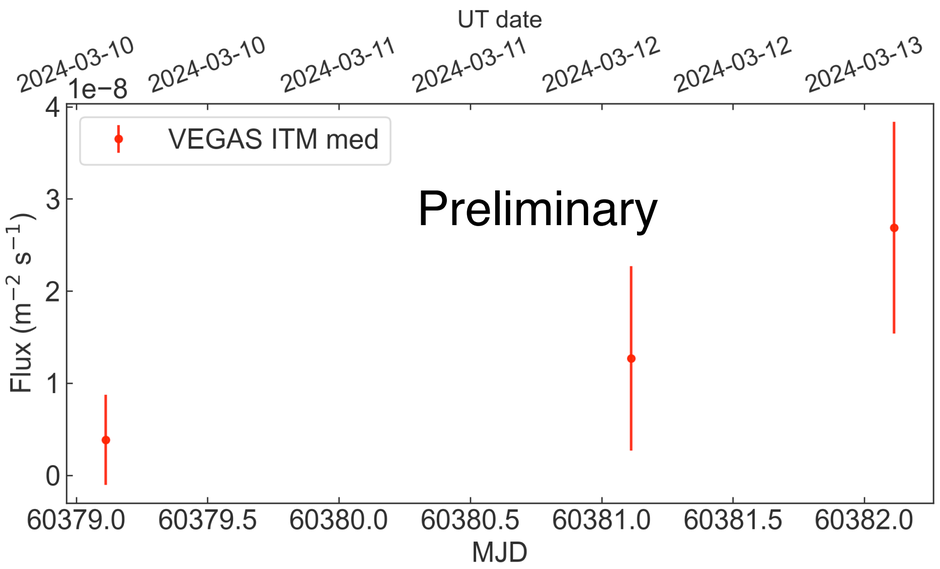
VERITAS VHE Detection of IC 310

VLA Map of Perseus Cluster (central region)



Sky map of Observed Significance





- IC 310: Head-tail radio galaxy @ z = 0.0189; Detected by VERITAS in 2009-17 (7σ; ~80 h; ~1% Crab)
  - Previous studies by MAGIC => Generally low flux, but a ~50% Crab flare with 10-min variability time scale
- LHASSO: ~50% Crab flare (3/6/24) at energies >1 TeV (ATel #16513; 3/8); ATel #16540 (brighter) on 3/20
- VERITAS follow-up observations (@ large zenith angle) => Detection (~7σ in ~2 h) at ~15% Crab
  - Follow-up campaign included X-ray satellites (Swift & NuStar); Followed-up second ATel too (no detection; ~1.5h @ LZA)

Conclusions

- VERITAS is running very well & is funded to operate until at least Summer 2025; Planning at least 2028
- The VERITAS source catalog is now at 69 sources from 8 classes: 45 are AGN (~45% are discoveries)
- Discovery program has 2 successful approaches:
  - Pre-planned observations: Comprehensive survey of hardest 2FHL & 2WHSP objects complete
  - ToO observations: VERITAS & Fermi-LAT main drivers; hopeful MM & optical triggers will be successful
- Several recent discoveries from deep follow-up on previous weak (3-5σ) excesses (more to come)
  - 1ES 1028+511 (eHBL @ $z = 0.361$): 6.1σ in ~49 h; ~1.0% Crab; $\Gamma = 3.6 \pm 0.5$
  - B2 0912+29 (HBL @ $z > 0.19$): 5.8σ in ~62 h; ~0.5% Crab; $\Gamma = 4.3 \pm 0.6$
  - 1ES 1118+424 (HBL @ $z > 0.28$): 5.2σ in ~40 h; ~0.8% Crab; $\Gamma \sim 3.9$
  - RBS 1366 (eHBL @ $z = 0.237$): 6.9σ in ~80 h; ~0.7% Crab; $\Gamma = 2.7 \pm 0.5$
- Limits from ~180 objects & a measurement of TeV Blazar Luminosity Function in preparation

The VERITAS AGN Catalog

BL Lac Object	Type	z
Mkn 421	HBL	0.030
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	IBL	0.108
B2 1811+31	IBL	0.117
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
B2 1215+30	HBL	0.131
1ES 0806+524	HBL	0.138
1ES 0229+200	HBL	0.140
1ES 1440+122	HBL	0.163
RX J0648.7+1516	HBL	0.179
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.190
1ES 1011+496	HBL	0.212
MS 1221.8+2452	HBL	0.218
RBS 1366	HBL	0.237
1ES 0414+009	HBL	0.287
OJ 287	BL Lac	0.306
S3 1227+25	IBL	0.325
1ES 1028+511	HBL	0.361
1ES 0502+675	HBL	0.341
1ES 0033+595	HBL	0.467
PKS 1424+240	HBL	0.604

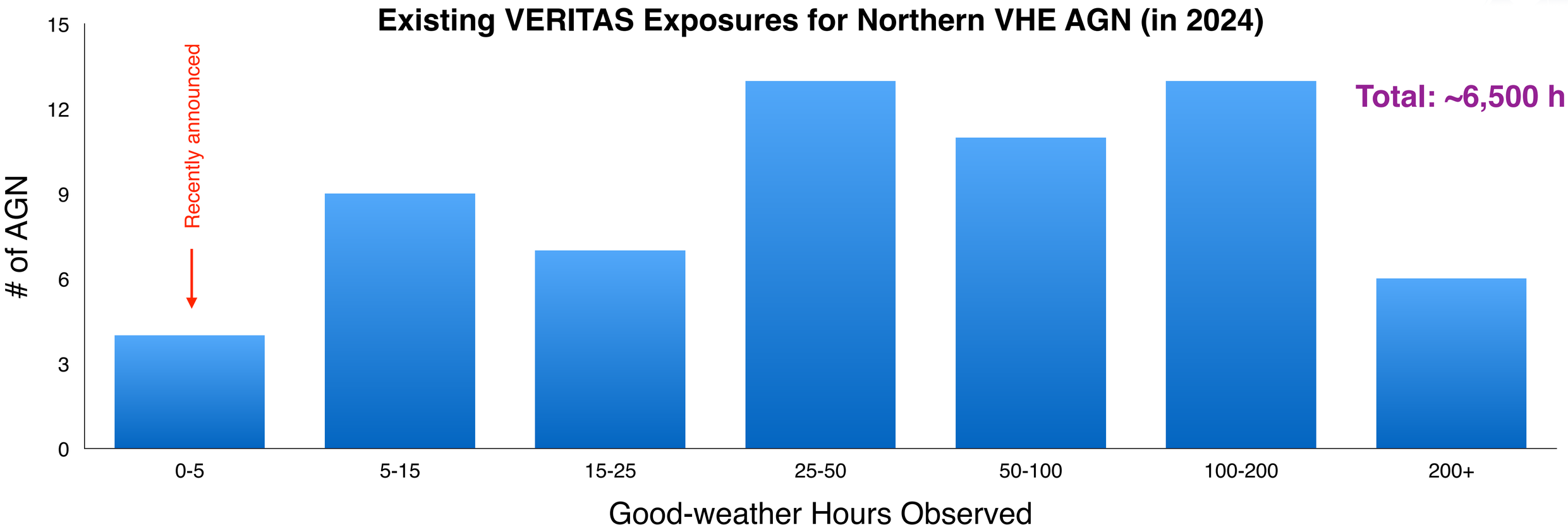
- 45 VHE AGN: 26 HBL, 6 IBL, 3 FSRQ, 3 uncertain & 3 FR I
  - 83% w/ known z: ~60% have $z < 0.2$ & 85% have $z < 0.4$;
- All VERITAS AGN are Fermi-LAT detected
- All detections have significant MWL data to enable modeling
  - 1-zone SSC model generally works, even during flares
  - Hints that IBLs may need SSC + external-Compton
  - Hints some “UHBLs” may favor lepto-hadronic models

20 AGN Discoveries

BL Lac Object	Type	z
B2 0912+29	HBL	>0.19
1ES 1118+424	HBL	>0.28
3C 66A	IBL	$0.33 < z < 0.41$
PG 1553+113	HBL	$0.43 < z < 0.58$
1ES 0647+250	HBL	?
HESS J1943+213	HBL	?
RGB J2056+496	Blazar	?
RGB J2243+203	HBL	?

AGN	Type	z
M 87	FR I	0.004
NGC 1275	FR I	0.018
IC 310	Blazar / RG	0.019
3C 264	FR I	0.022
TXS 0506+056	Blazar	0.337
PKS 1222+216	FSRQ	0.432
Ton 599	FSRQ	0.725
PKS 1441+25	FSRQ	0.939

VERITAS AGN Catalog



- Northern VHE AGN: VERITAS has observed ~60% for >50 h & ~80% for >25 h
  - All have significant, contemporaneous MWL data: Swift, Fermi-LAT & FLWO 48”
- VERITAS is starting to develop the VERITAS AGN catalog paper(s)
  - Long-term flux calibration resolved: *Astronomy & Astrophysics,* **658,** 83, 2022

VERITAS AGN Publications

(1) V. Acciari et al., “VERITAS Discovery of >200 GeV Gamma-ray Emission from the Intermediate-frequency-peaked BL Lac 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

(8) V. Acciari et al., “VERITAS Upper Limit on the VHE Emission from the Radio Galaxy NGC 1275”, *Astrophysical Journal Letters*, **706**, L275, 2009

(9) V. Acciari et al., “Multiwavelength observations of a TeV-Flare from W Com”, *Astrophysical Journal*, **707**, 612, 2009

(10) V. Acciari et al., “Discovery of very high energy gamma rays from PKS 1424+240 and multiwavelength constraints on its redshift”, *Astrophysical Journal Letters*, **708**, L100, 2010

(11) V. Acciari et al., “Discovery of Variability in the Very High Energy Gamma-Ray Emission of 1ES 1218+304 with VERITAS”, *Astrophysical Journal Letters*, **709**, L163, 2010

(12) V. Acciari et al., “The Discovery of γ-ray emission from the Blazar RGB J0710+591”, *Astrophysical Journal Letters,* **715**, L49, 2010

(13) V. Acciari et al., “VERITAS 2008 - 2009 monitoring of the variable gamma-ray source M87”, *Astrophysical Journal*, **716**, 819, 2010

(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 High-energy 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

(24) E. Aliu et al., “VERITAS Observations of Six Bright Hard-Spectrum Fermi-LAT Blazars”, *Astrophysical Journal*, **759**, 102, 2012

(25) T. Arlen et al., “Rapid TeV Gamma-ray Flaring of BL Lacertae”, *Astrophysical Journal*, **762**, 92, 2013

VERITAS AGN Publications

(26) E. Aliu et al., “Multiwavelength Observations and Modelling of 1ES 1959+650”, *Astrophysical Journal*, **775**, 3, 2013

(27) S. Archambault et al., “Discovery of a New TeV Gamma-ray Source: VER J0521+211”, *Astrophysical Journal,* **776,** 69, 2013

(28) E. Aliu et al., “Long term observations of B2 1215+30 with VERITAS”, *Astrophysical Journal,* **779,** 92, 2013

(29) V. Acciari et al., “Observation of Markarian 421 in TeV gamma rays over a 14-year time span”, Astroparticle Physics, **54**, 1, 2014

(30) E. Aliu et al., “A Three-Year Multi-Wavelength Study of the Very High Energy gamma-ray Blazar 1ES 0229+200”, *Astrophysical Journal,* **782,** 13, 2014

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

(32) S. Archambault et al., “Test of Models of the Cosmic Infrared Background with Multi-wavelength Observations of the Blazar 1ES 1218+30.4 in 2009”, *Astrophysical Journal,* **788,** 158, 2014

(33) E. Aliu et al., ”Investigating Broadband Variability of the TeV Blazar 1ES1959+650”, *Astrophysical Journal,* **797**, 89, 2014

(34) E. Aliu et al., ”VERITAS Observations of the BL Lac Object PG 1553+113”, *Astrophysical Journal,* **799**, 7, 2015

(35) F.D. Ammando et al., “The most powerful flaring activity from the NLSy1 PMNJ0948+0022”, *Monthly Notices of the Royal Astronomical Society*, **446**, 2456, 2015

(36) J. Aleksic et al., “Multiwavelength Observations of Mrk 501 in 2008”, *Astronomy & Astrophysics*, **573**, 50, 2015

(37) J. Aleksic et al., “The 2009 multiwavelength campaign on Mrk 421: Variability and correlation studies”, *Astronomy & Astrophysics*, **576**, 123, 2015

(38) J. Aleksic et al., “Unprecedented Study of the Broadband Emission of Mrk 421 during Flaring Activity in March 2010”, *Astronomy & Astrophysics*, **578**, 22, 2015

(39) S. Archambault et al., “VERITAS Detection of γ-ray Flaring Activity from the BL Lac Object 1ES 1727+502 During Bright Moonlight Observations”, *Astrophysical Journal,* **808**, 110, 2015

(40) A. Furniss et al., “First NuSTAR Observations of Mrk 501 within a Radio to TeV Multi-Instrument Campaign”, *Astrophysical Journal,* **812**, 65, 2015

(41) A. Abeysekara et al., “Gamma Rays from the Quasar PKS 1441+25: Story of an Escape”, *Astrophysical Journal Letters,* **815**, L22, 2015

(42) M. Balaokovic et al., “Multiwavelength study of quiescent states of Mrk 421 with unprecedented hard X-ray coverage provided by NuSTAR in 2013”, *Astrophysical Journal,* **819**, 156, 2016

(43) A. U. Abeysekara et al., “Multiwavelength Observations of the BL Lac 1ES 1741+196”, *Monthly Notices of the Royal Astronomical Society*, **459**, 2550, 2016

(44) S. Archambault et al., “Upper Limits from Five Years of Blazar Observations with the VERITAS Cherenkov Telescopes”, *Astronomical Journal*, **151**, 142, 2016

(45) S. Archambault et al., “Discovery of Very High Energy Gamma Rays from 1ES 1440+122”, *Monthly Notices of the Royal Astronomical Society,* **461**, 202, 2016

(46) E. Aliu et al., “Very-High-Energy Outburst of Markarian 501 in May 2009”, Astronomy & Astrophysics, **594**, 76, 2016

(47) A. U. Abeysekara et al., “A search for spectral hysteresis and energy-dependent time lags from X-ray and TeV gamma-ray observations of Mrk 421”, *Astrophysical Journal*, **834**, 2, 2017

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VERITAS Acknowledgments

This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, and by the Helmholtz Association in Germany. This research used resources provided by the Open Science Grid, which is supported by the National Science Foundation and the U.S. Department of Energy's Office of Science, and resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE AC02-05CH11231. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument.