Recent Results from VERITAS AGN Observations

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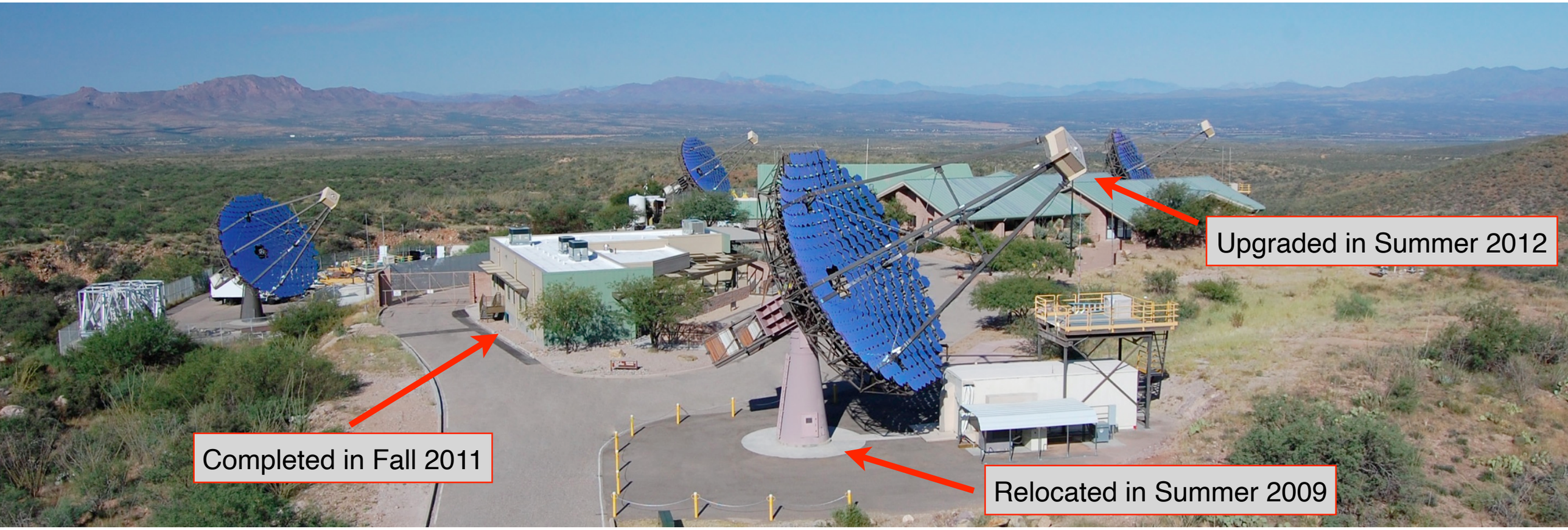
1. Smithsonian Astrophysical Observatory
2. http://veritas.sao.arizona.edu

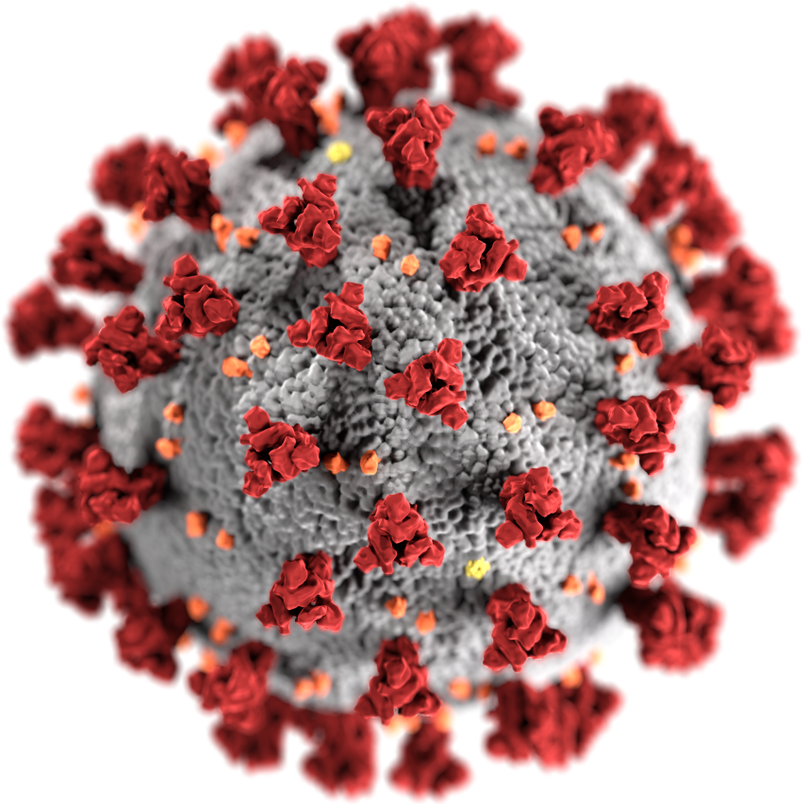
37th ICRC
Berlin, Germany (Online); July 15, 2021

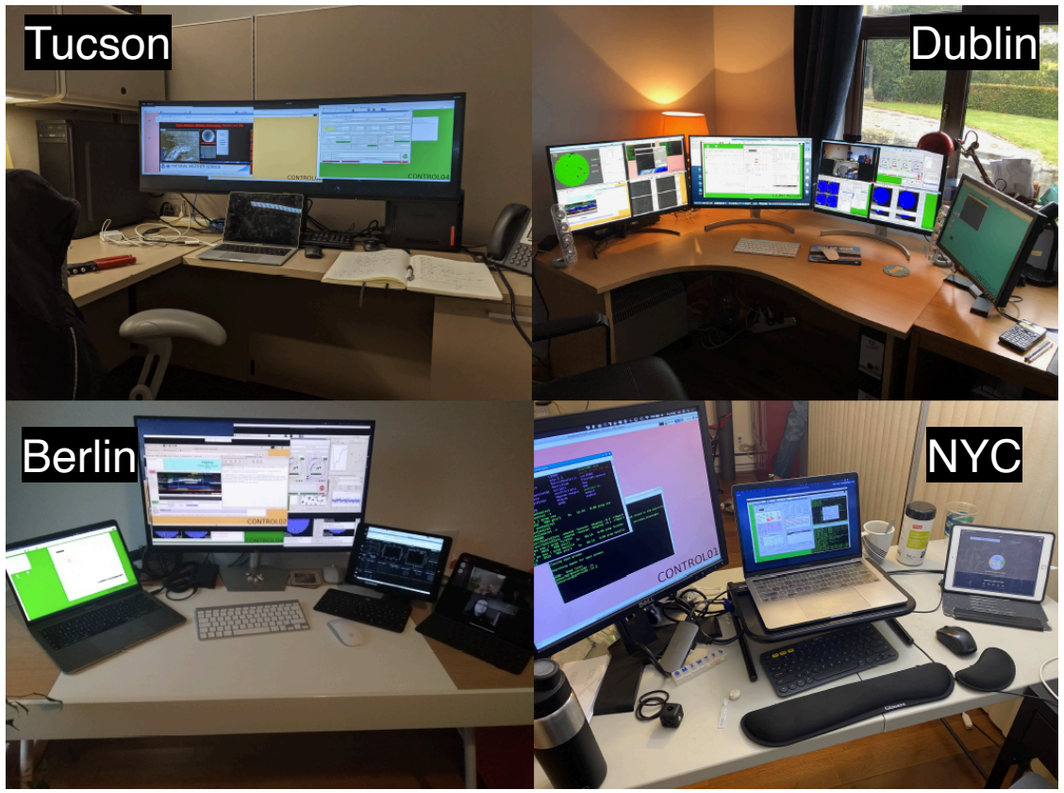
VERITAS: Observatory Overview



- Study very-high-energy (~85 GeV to ~30 TeV) γ-rays from astrophysical sources
- Full-scale operations since 2007; Upgrade completed in 2012; ~16,300 h of data
- Good-weather data / yr: ~930 h in “dark time” + ~200 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: ~85 GeV
  - Spectral reconstruction > 100 GeV
  - Systematic errors: Flux ~20%; Γ ~ 0.1

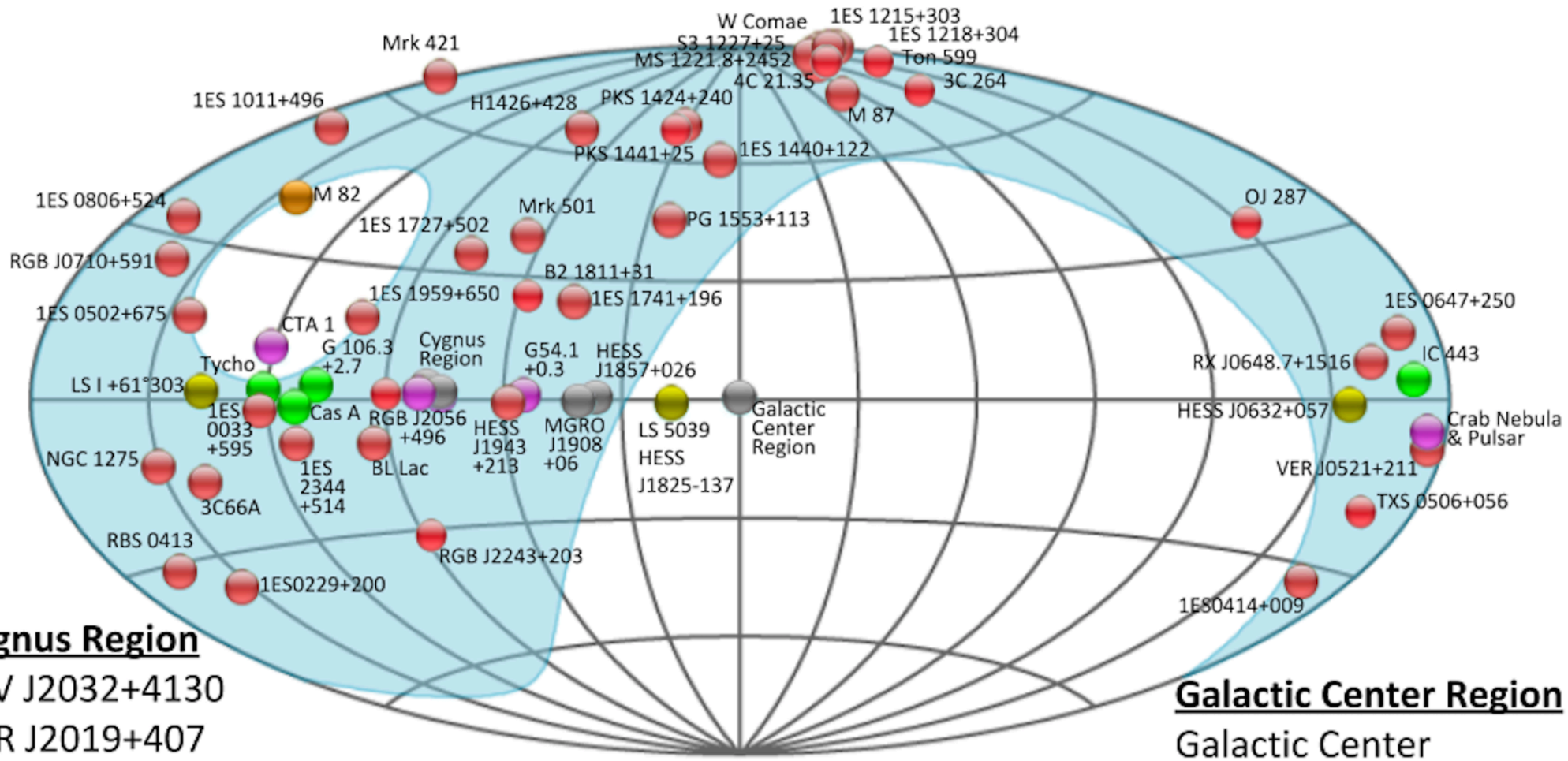
VERITAS & COVID





- Remote observing capability developed & full-scale, remote observing now possible
- 2019-21 VERITAS AGN yields are ~25% below 2-year average
  - VERITAS observing suspended for March - June 2020 (est. ~500 h lost)
  - Bright-moon observing suspended for most of 2020-21 season (est. ~160 h lost)

The VERITAS Source Catalog



Cygnus Region

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

Galactic Center Region

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

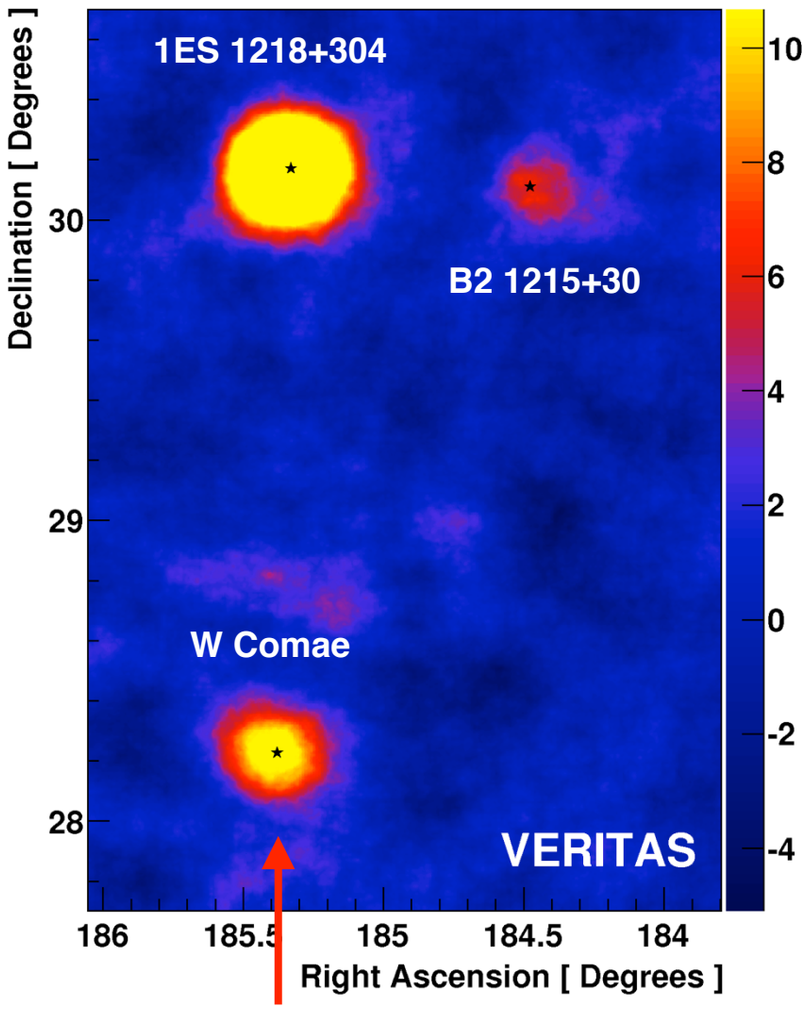
64 sources from 8 astrophysical classes

41 Extragalactic (64%) & 23 Galactic (36%) objects

Extragalactic: 40 AGN & a starburst galaxy (M82)

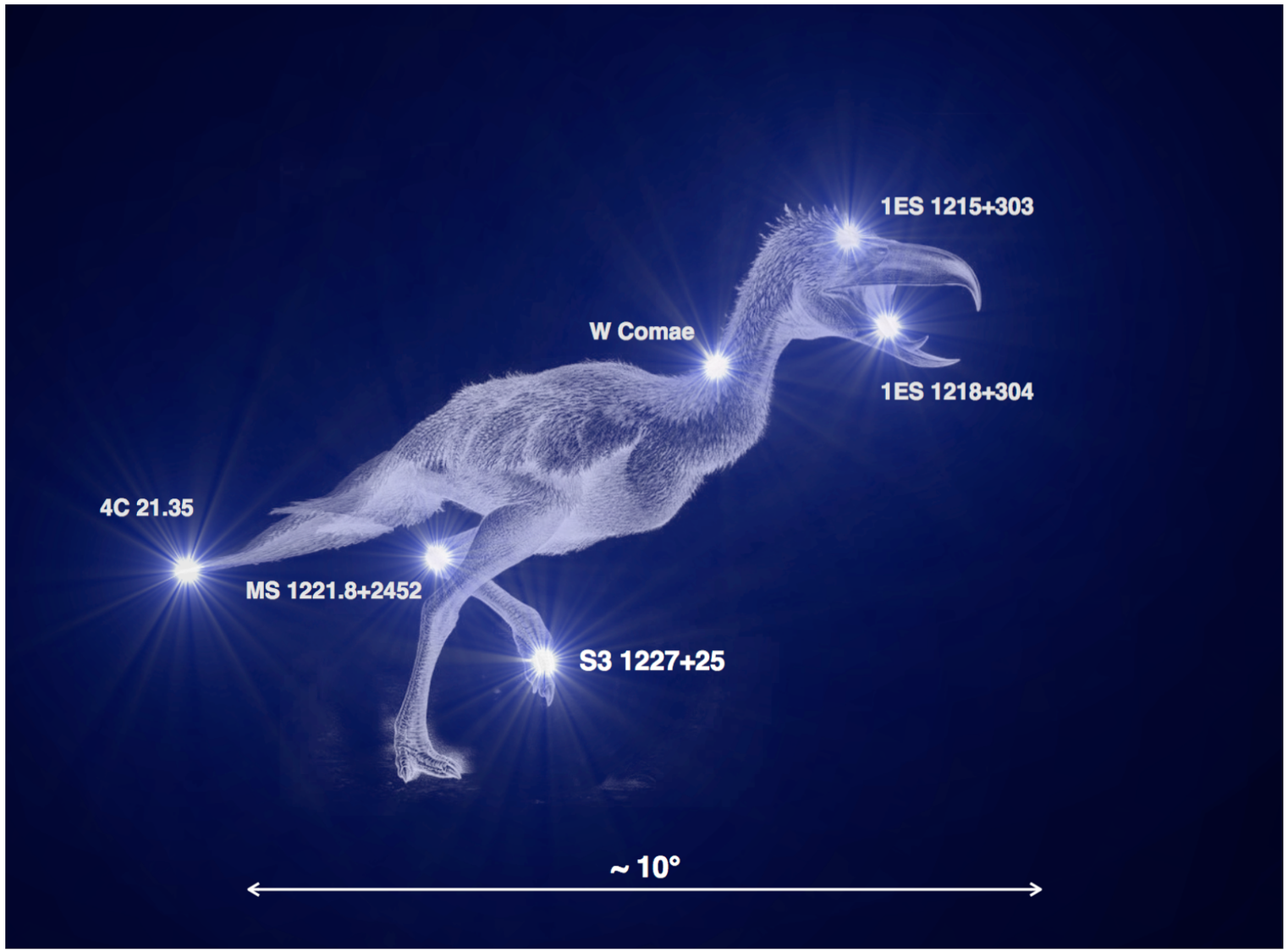
The VERITAS AGN Catalog is Plentiful!

2011: 3 VHE blazars in 1 FoV



First VHE IBL

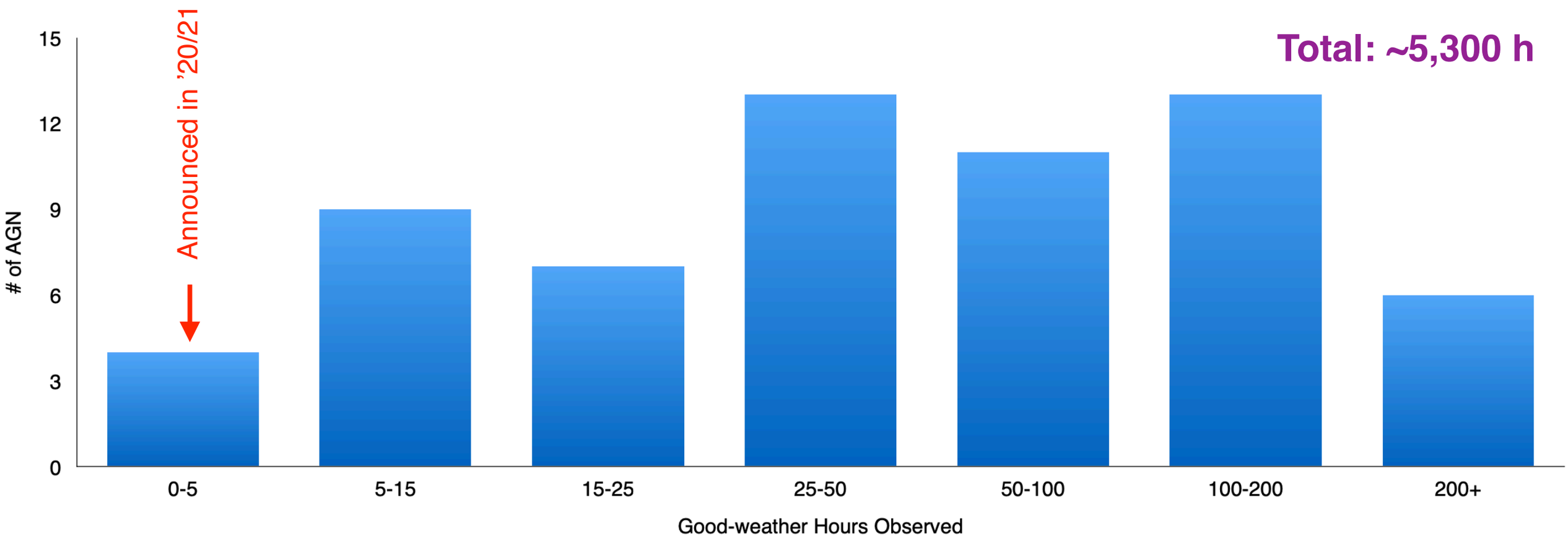
2021: 6 blazars (HBLs, IBLs, FSRQ) in 1 CTA FoV



VERITAS AGN Program: ~560 h / yr

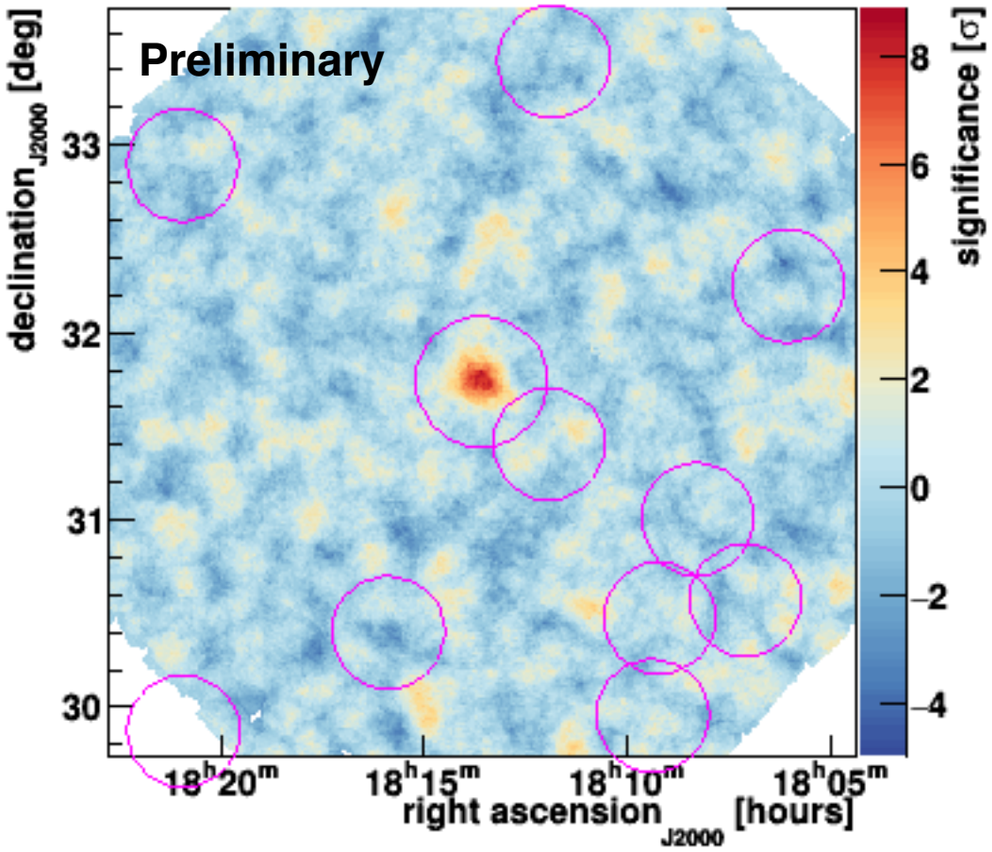
- 2007-2021: ~5,900 h of good-weather "normal" AGN data; Average ~420 h / yr
  - Typically 90% blazars / 10% radio galaxies; Recently ~50% more radio galaxy data
- 2012-2021: ~1,100 h of good-weather "bright moon" AGN data; Average ~140 h / yr
  - Similar sensitivity (>250 GeV) => Study hard-spectrum AGN & flare monitoring
- Blazar program: Primarily BL Lac objects
  - Priority (~15%): Target of Opportunity (ToO) observations
  - ~35% are VHE discovery observations
  - Major effort is regular monitoring of ~23 known VHE blazars
    - Depth / cadence depends on "importance"
    - MWL coordination => Long-term MWL + VHE light curves
    - Target list streamlined in 2018: All Northern AGN => ~23
  - Intense follow-up observations of discoveries & flares is key!
- Radio galaxy (RG) program
  - Recently: ~40% discovery / ~60% known VHE

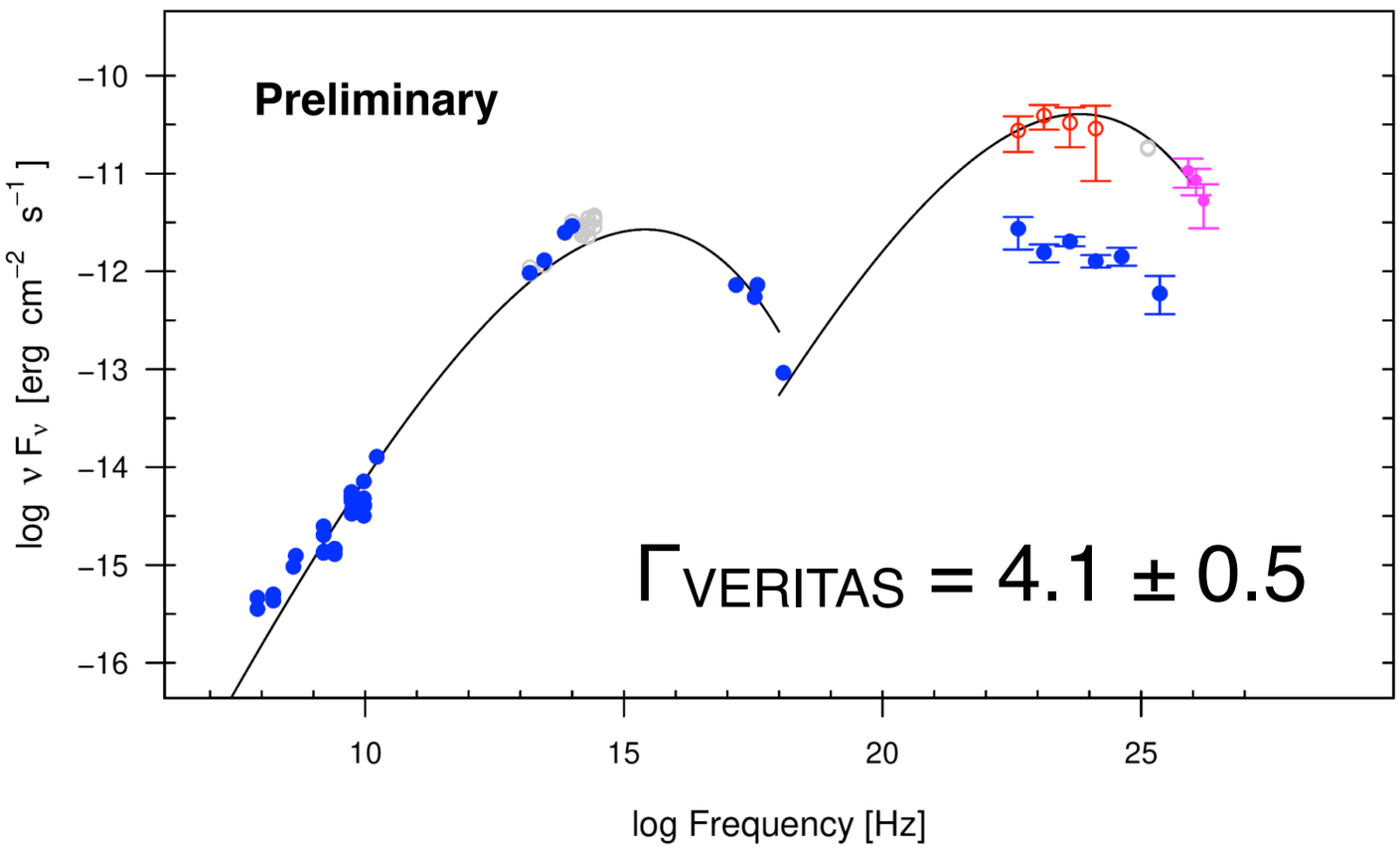
Deep VHE Monitoring = Deep VHE Catalog



- Northern VHE AGN: VERITAS has observed ~50% for >50 h & ~70% for >25 h
- VERITAS is developing a VHE AGN catalog paper:
  - All have significant, contemporaneous MWL data: Swift, Fermi-LAT & FLWO 48”

B2 1811+31: A New VHE IBL (z = 0.117)

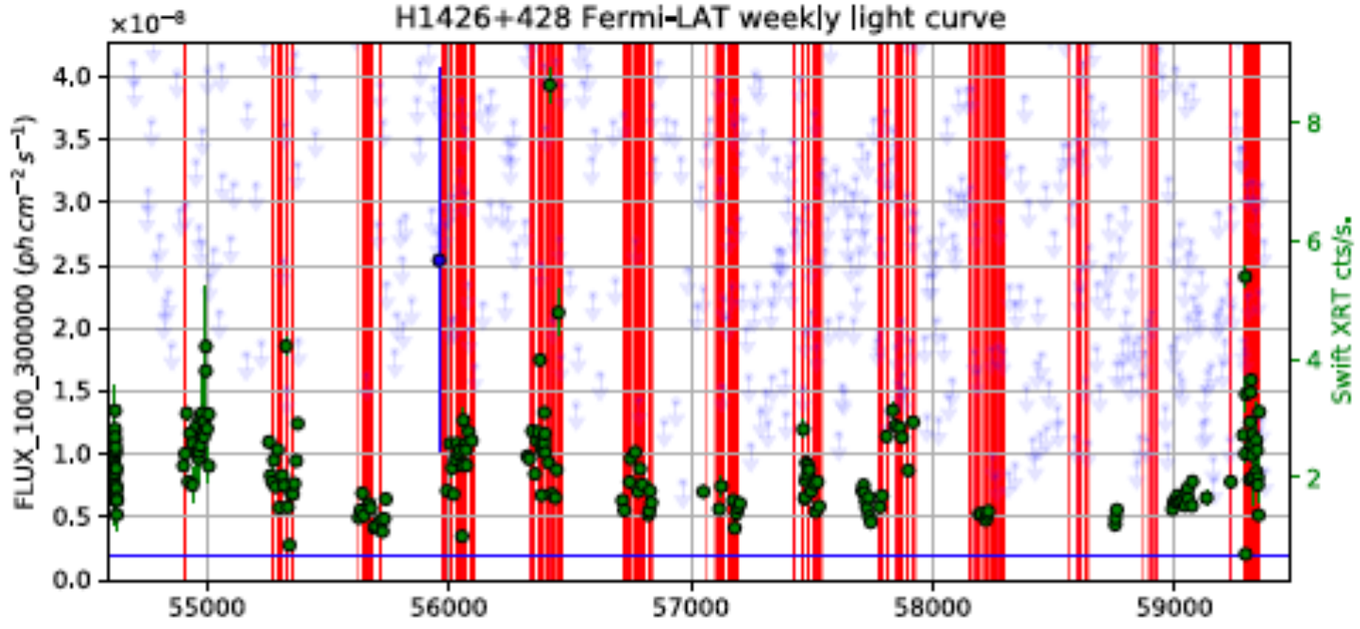


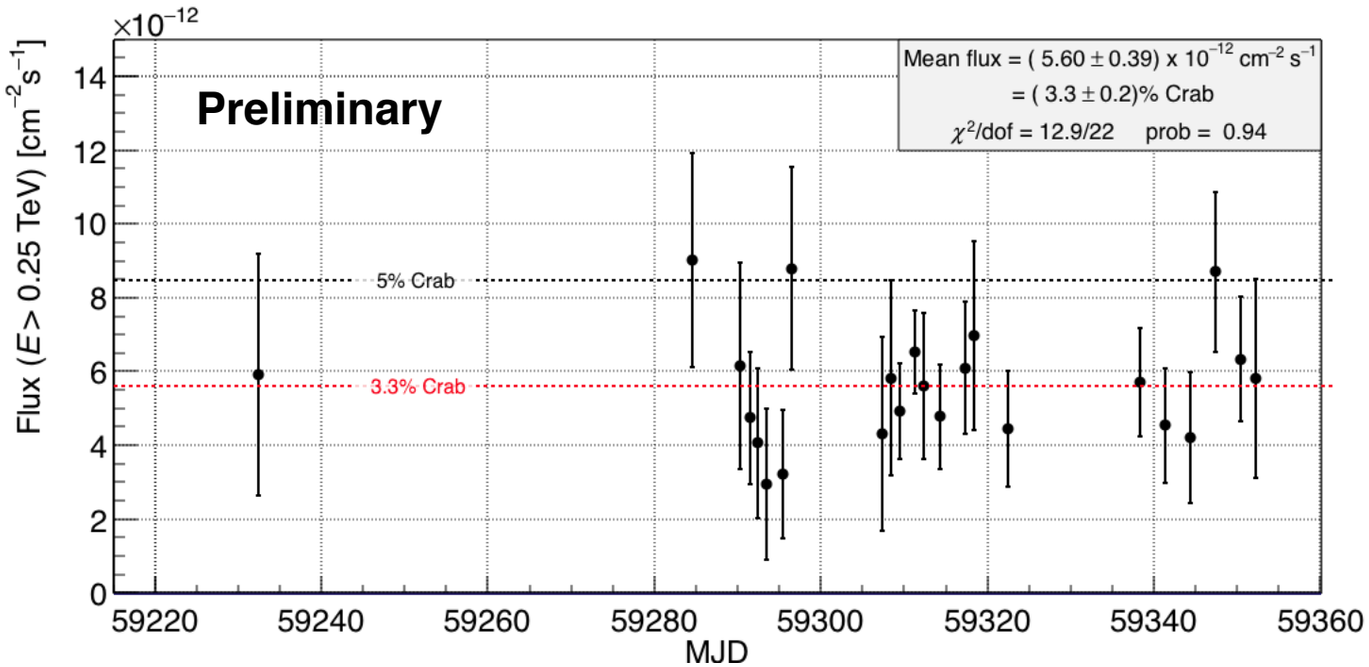


- Strong VERITAS detection (~8σ) in ~5 h from Oct. 15-19, 2020
  - LAT: Elevated flux (~11x brighter) & harder Γ_{LAT} (1.4 vs. 2.1) in Oct. 2020; ATel #14060
  - MAGIC VHE detection (~5% Crab from Oct. 4-10; ATel #14090) & enhanced optical activity (ATel # 14103)
- $F(>250\ GeV) = (1.10 \pm 0.18_{stat} \pm 0.22_{syst}) \times 10^{-11}\ cm^{-2}\ s^{-1}$ (~6% Crab)

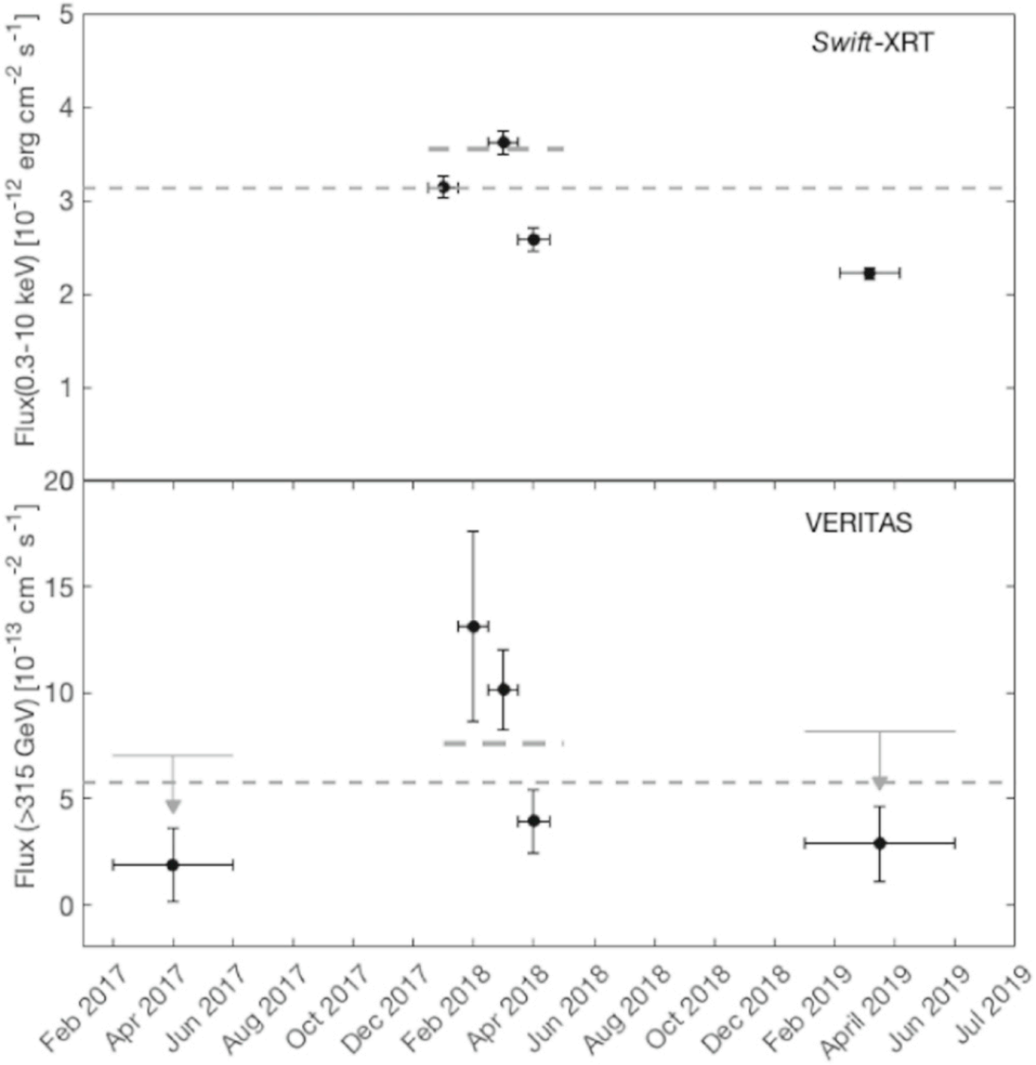
H 1426+428: Flare in 2021

- Extreme HBL: $\nu_{synch} \sim 10^{18.1}$ Hz
  - EBL interest: Hard Γ & z = 0.129
  - Before 2002: Routinely 5-20% Crab
  - Very dim since (<2% Crab)
- VERITAS: ~200 h + MWL coverage
- 2008-16: ~13σ in ~82 h
  - Steady: F(>250 GeV) = (1.9 ± 0.2)% Crab
  - $\Gamma_{VERITAS}$ = 2.8 ± 0.1
- 2021 flare: ~19σ in ~45 h
  - Steady: F(>250 GeV) = (3.3 ± 0.2)% Crab
    - Contrasts w/ Swift variations
  - No clear hardening ($\Gamma_{VERITAS}$ ~ 2.6 to high-E)

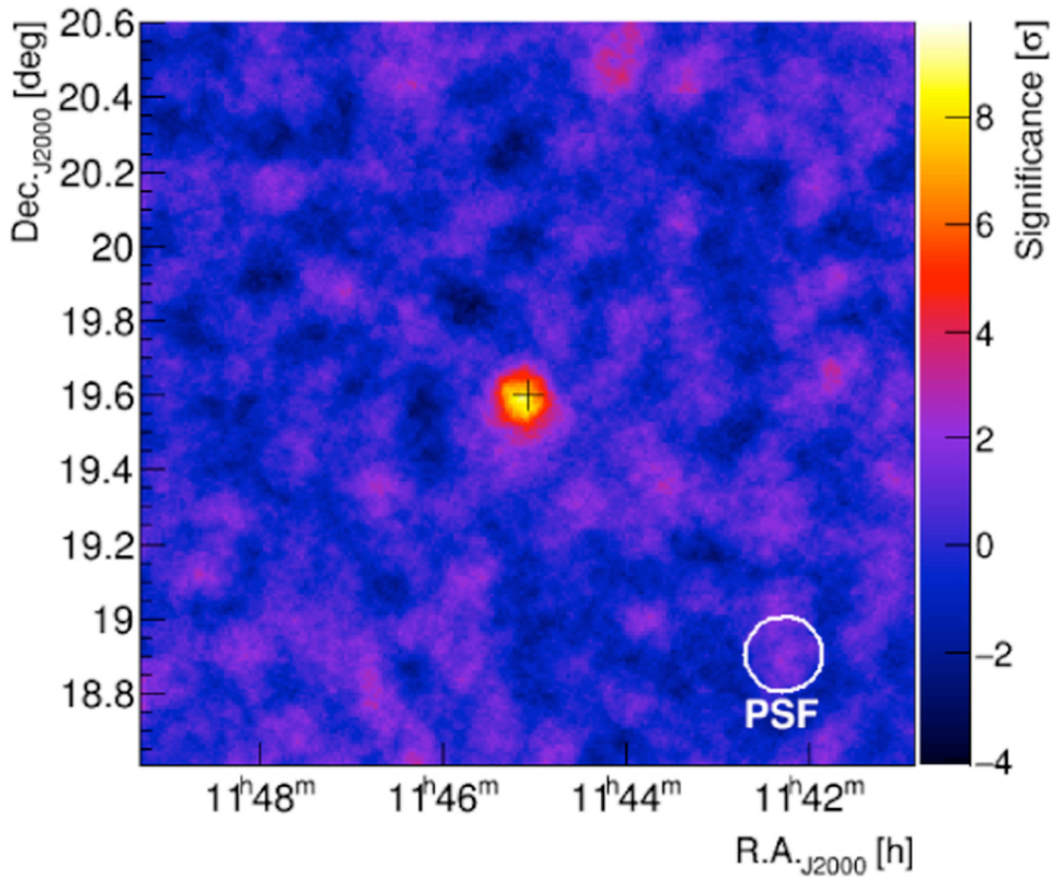




VERITAS VHE Discovery of 3C 264



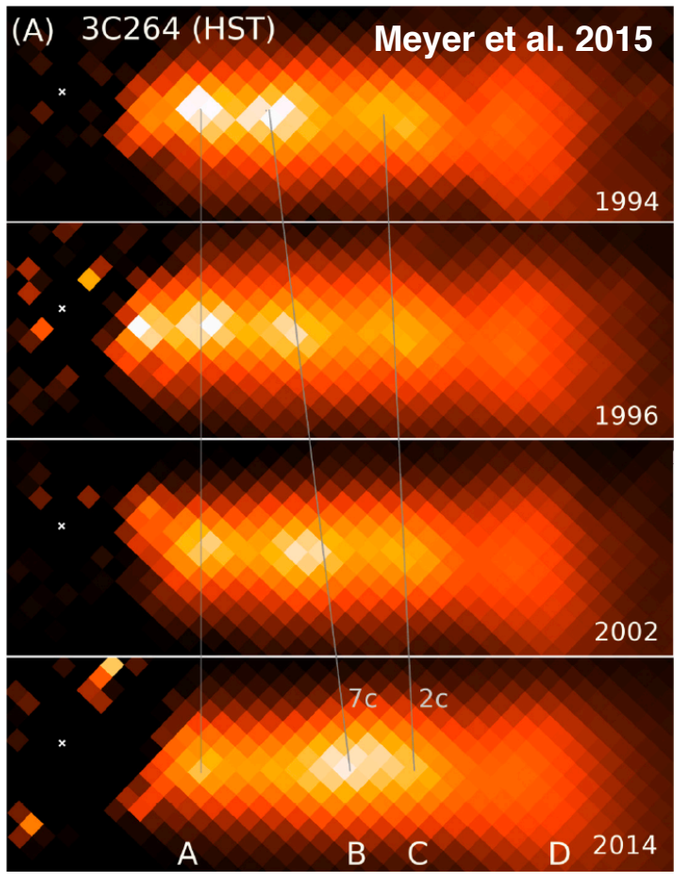
Significance map for 3C 264

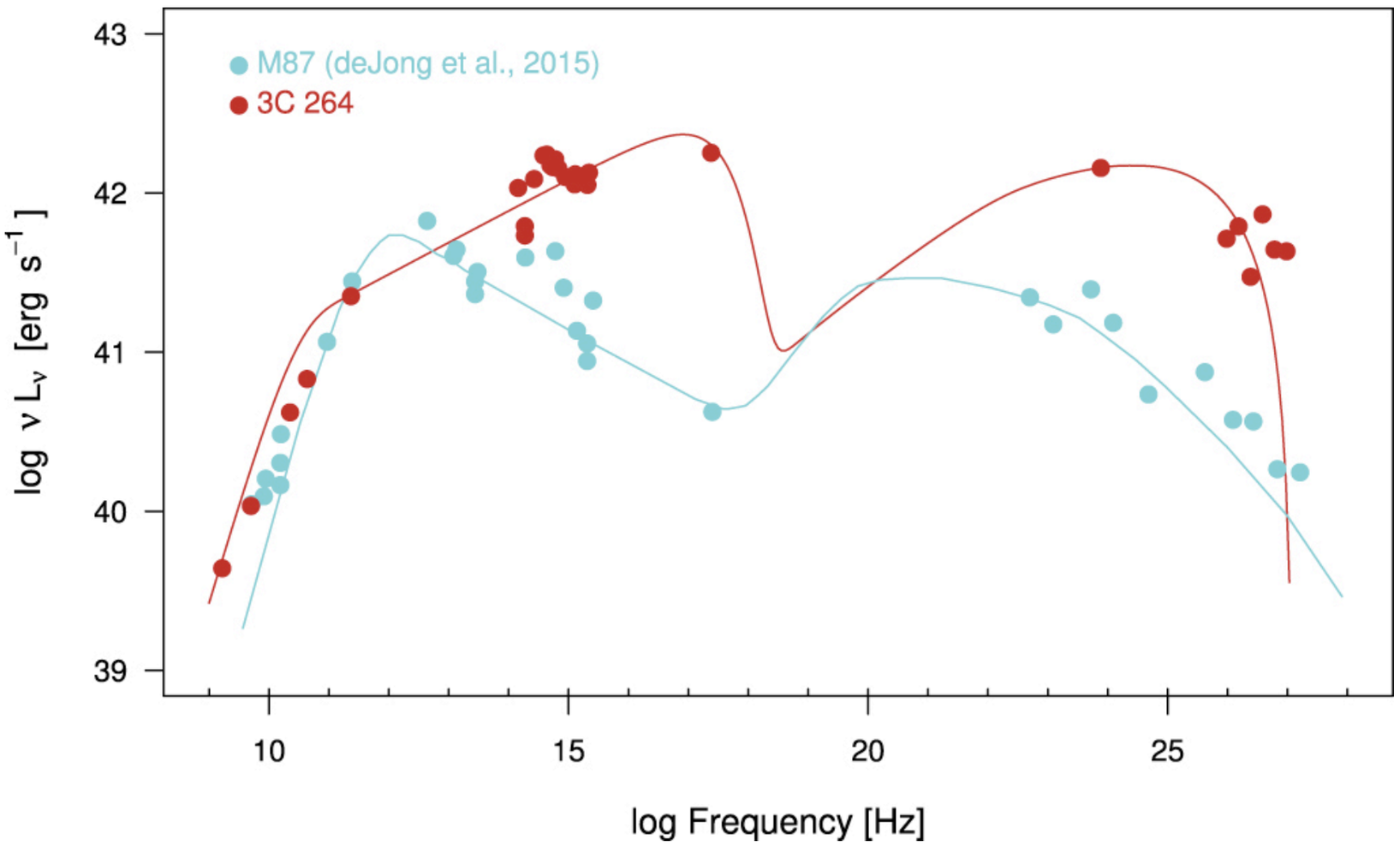


Astrophysical Journal, **896**, 41, 2020

- VERITAS discovered 4th VHE radio galaxy: ~7.8σ in ~57 h from 2017-19
- Low, Variable VHE flux: F(>315 GeV) = $(7.6 \pm 1.2_{stat} \pm 2.3_{syst})$ x 10^{-13} cm^{-2} s^{-1}; ~0.7% Crab
  - Bright in 2018; ~Month-scale variations at VHE & X-ray

3C 264: A Multi-wavelength View



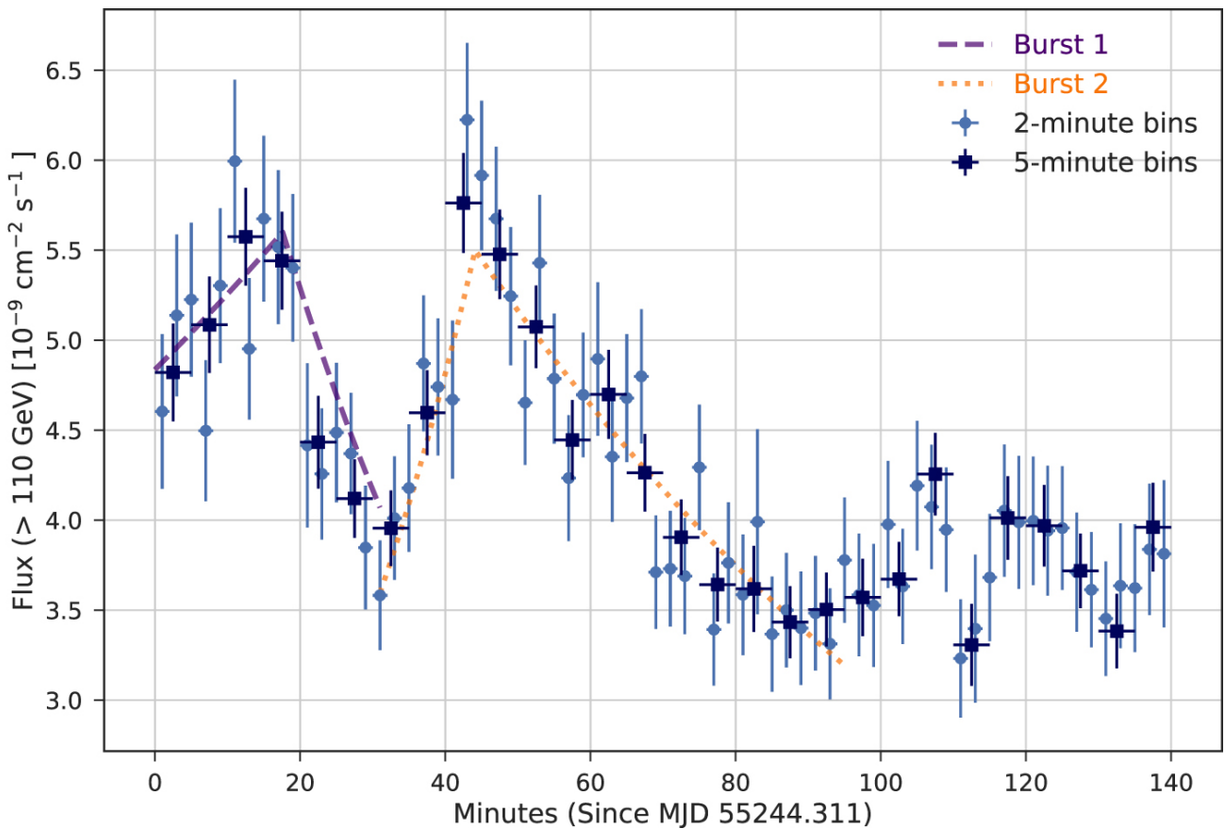


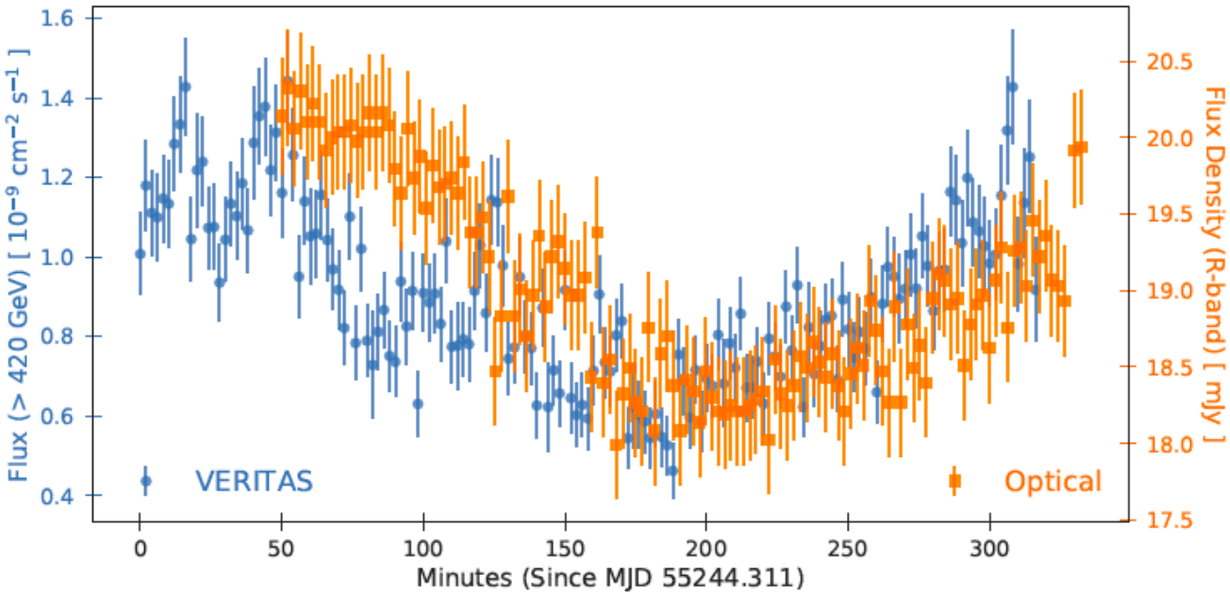
- Major MWL effort incl. high-resolution imaging (e.g. VLA, VLBI, HST, Chandra)
  - No major activity in knot sub-structure; No clearly identifiable source of emission
  - Hard VHE ($\Gamma = 2.2 \pm 0.3$) & Fermi-LAT ($\Gamma_{10\text{-yr}} = 1.9 \pm 0.1$) spectra
- Unusual SED for RG: High-peaked & broad; SSC w/ typical BL Lac parameters works
- 3C 264 & M 87 SED differences: Plausibly from 3C 264 oriented closer to line of sight

Extraordinary Flare of Mrk 421

- Feb. 2010: Mrk 421 bright => MWL
- Extraordinary flare: Feb. 17, 2010
  - F(>110 GeV) ~ 11 Crab in VERITAS
  - F(>1 TeV) ~ 27 Crab in VERITAS
    - Brightest VHE AGN flare ever!
- Fit exponential to rise & fall of 2 bursts
  - Doubling (84 & 22 min); Halving (28 & 65 min)
  - Limits: $\delta \gtrsim 33$; $R_B / \delta \gtrsim 3.8 \times 10^{13}$ cm
- VHE & Optical Correlated (3σ) on short time scales w/ 25-55 m lag
- VHE & X-ray: linear & quadratic correlations; also anti-correlations
- Difficult for single-zone SSC model

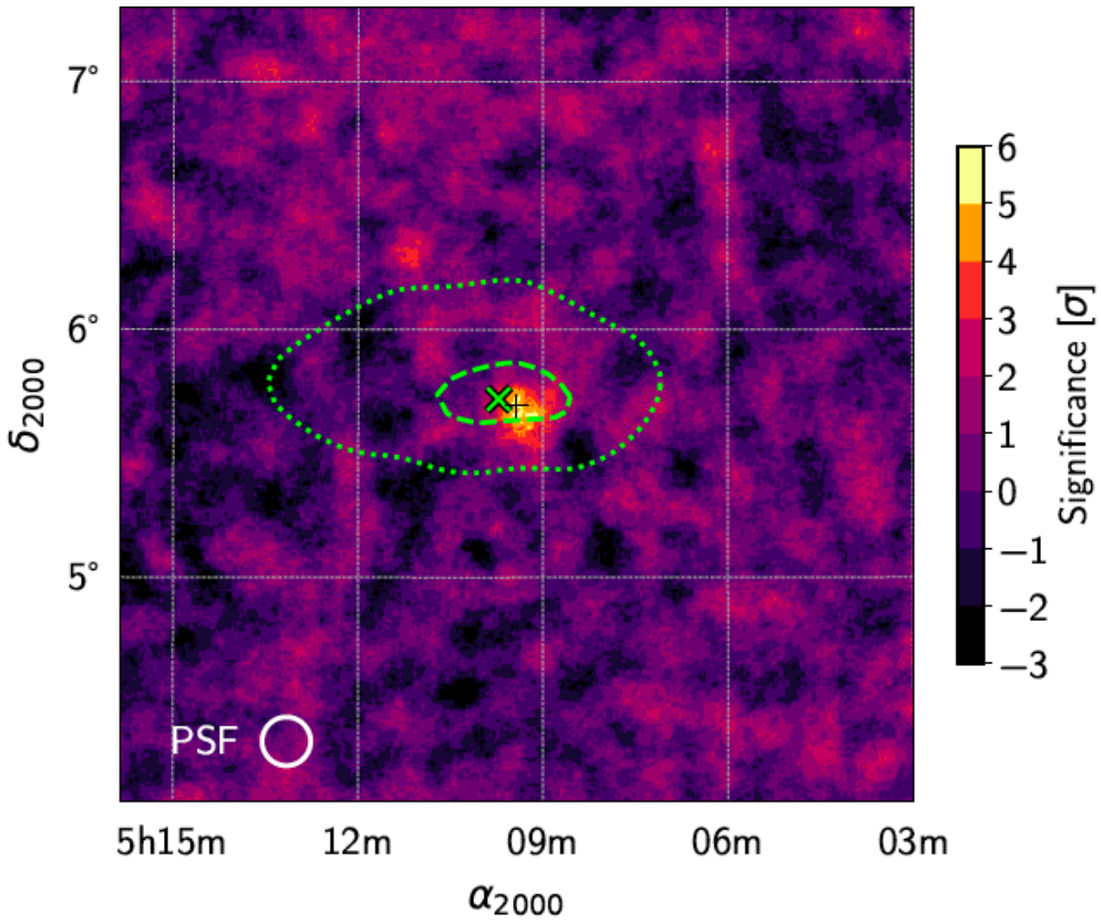
Astrophysical Journal, **890**, 97, 2020

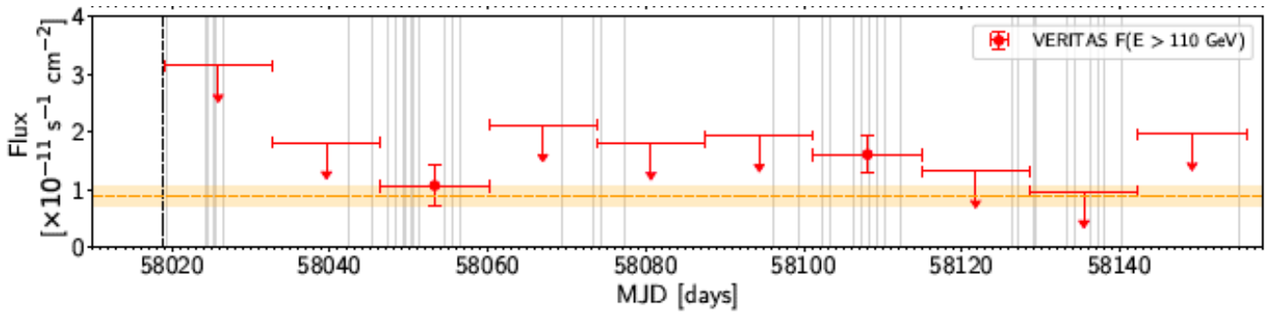


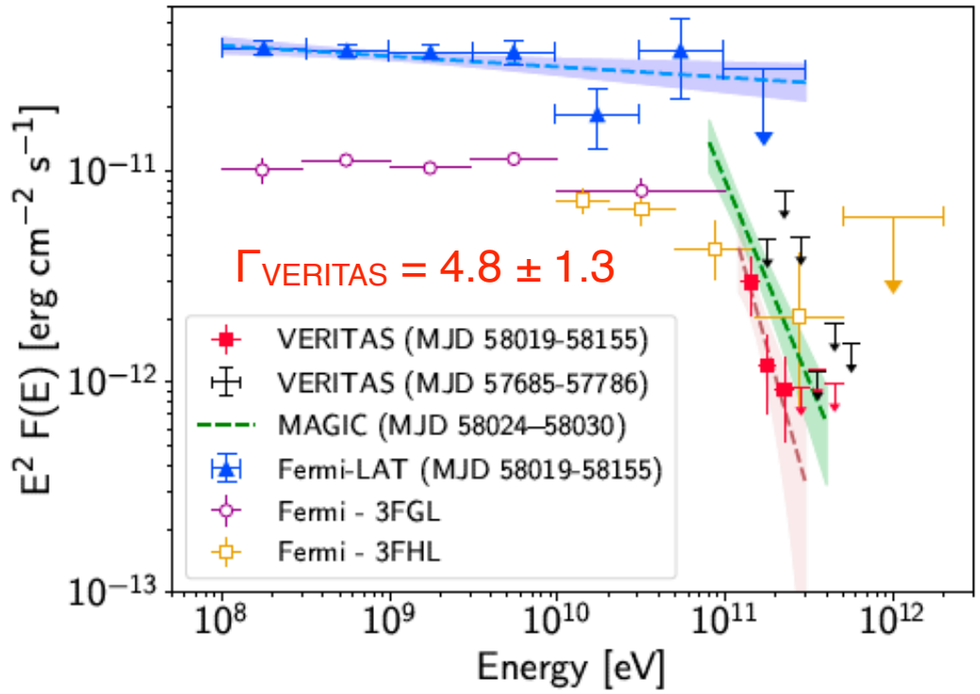


TXS 0506+056: A Multi-messenger Blazar

Astrophysical Journal, **861**, L20, 2018





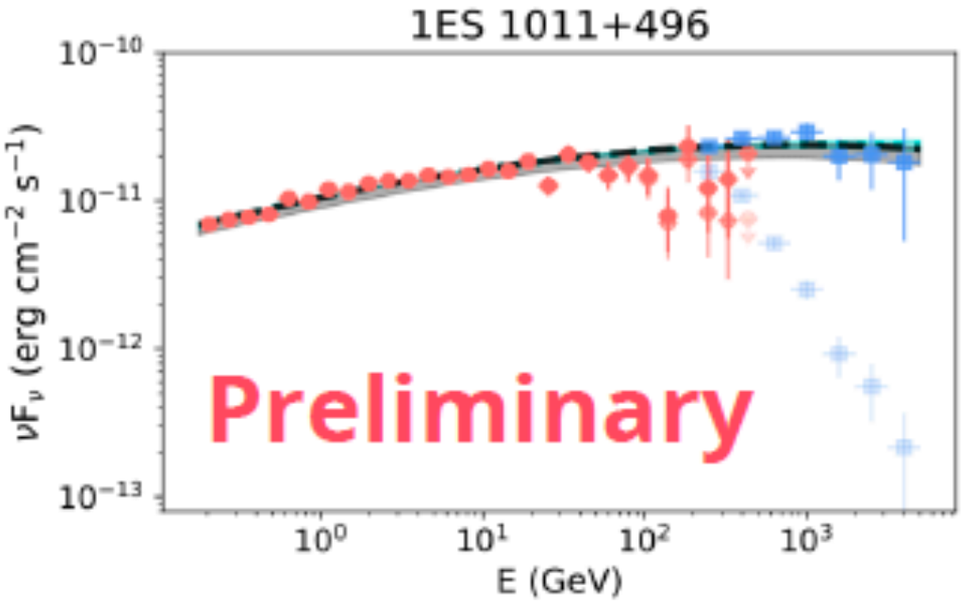


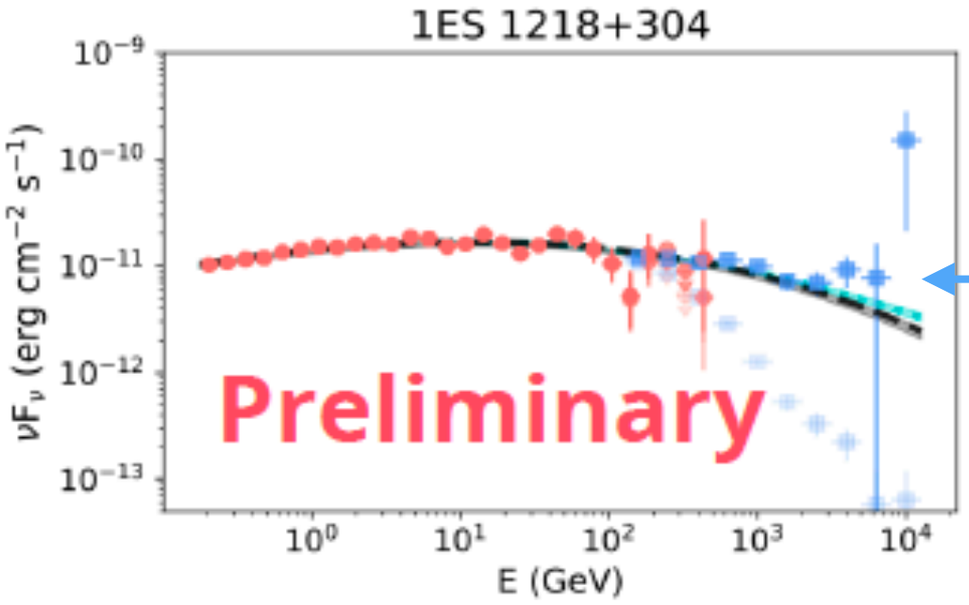
- Temporal & spatial correlation w/ γ-ray flare of TXS 0506 & IceCube-170922A
  - 3σ effect (Science, 361, 147, 2018); IceCube pre-flare, 3.5σ neutrino excess: (Science, 361, 141, 2018)
- VERITAS: 5.8σ in 35 h (Sept. ’17 - Feb. ’18); F(>190 GeV) = (0.7 ± 0.2)% Crab
- VERITAS: 3.4σ in 61 h (Oct. ’18 - Mar. ’21); F(>190 GeV) = (0.5 ± 0.2)% Crab

TeV Luminosity Function of HBLs

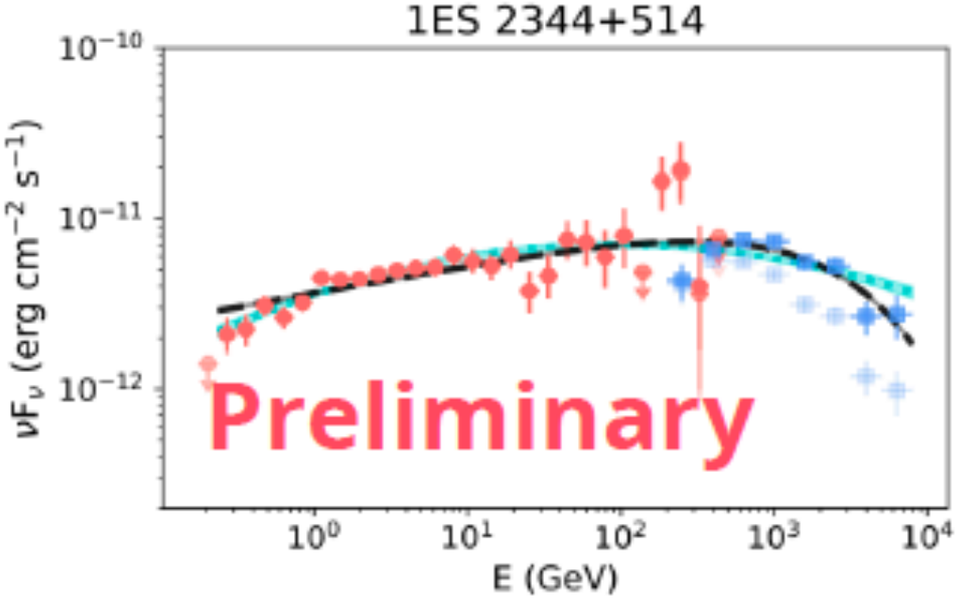
- HBL: ~65% of VHE AGN; Dominate extragalactic VHE sky & total cosmic VHE radiation
- Luminosity Function: Number of HBLs, per unit volume, per unit luminosity
  - Key to understanding HBL properties, their relationship with other sources, & their contributions to unresolved radiation fields
    - Enables studies of hadronic/neutrino production in jets, the IGMF, and AGN evolution
  - Measurement is challenging due to observational biases
- VERITAS will measure using 36 HBLs selected from the 3HSP catalog
  - Measuring the VHE fluxes at times not weighted towards high-fluxes
- VERITAS observations complete: ~1800 h of archival data & ~150 h of 2019-21 data
  - Each target has at least 8 h of exposure; ~1% Crab sensitivity
  - 22 targets are in TeVCat
- Please see Errando's Contribution (GAI#980)

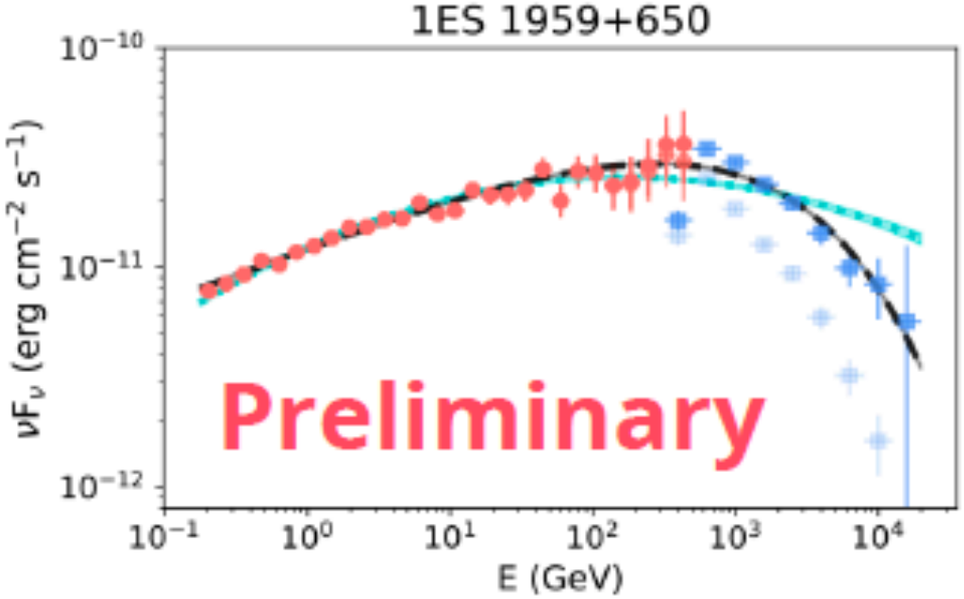
Hard Spectrum Blazars





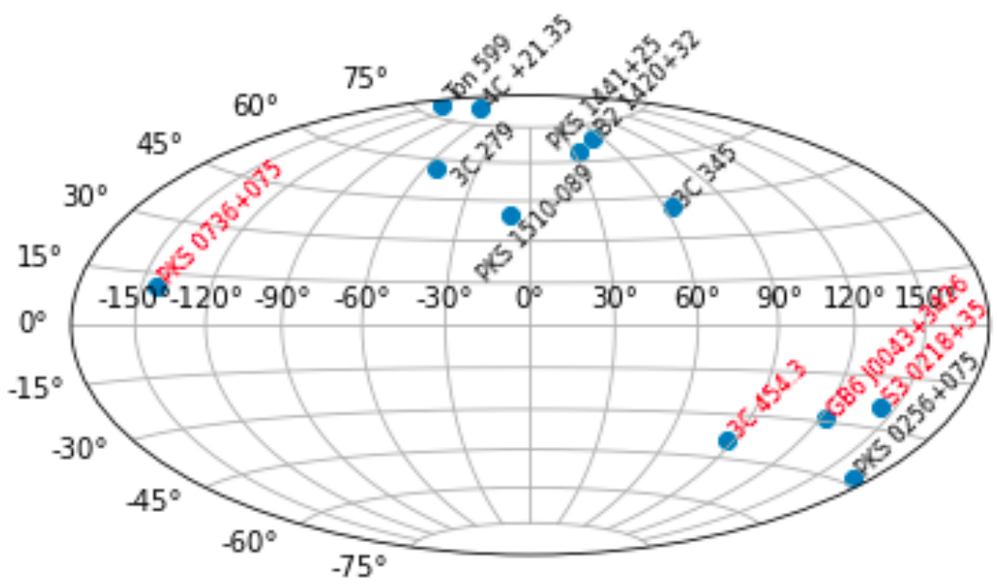
EBL de-absorbed

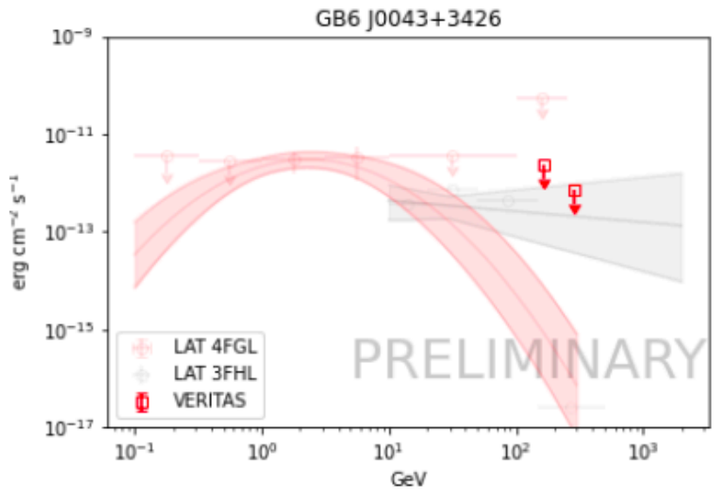


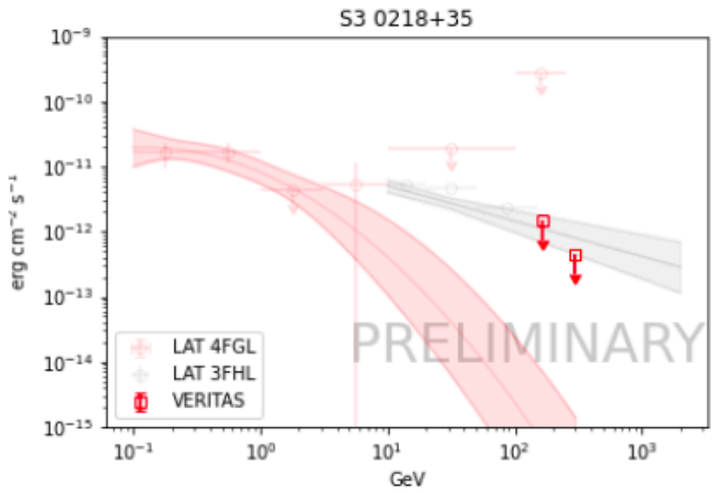


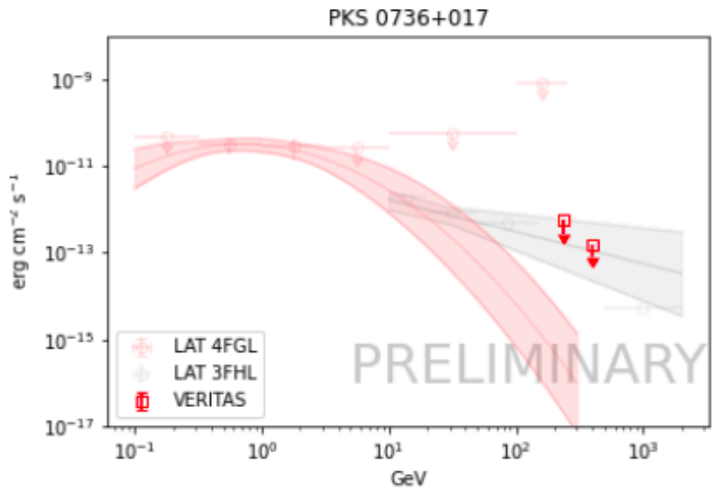
- VERITAS generating joint LAT-VHE spectra for 17 HBLs: Feng; GAI#367
- 4 brightest: Cut-off visible; No preference for log parabola vs. stretched exponential

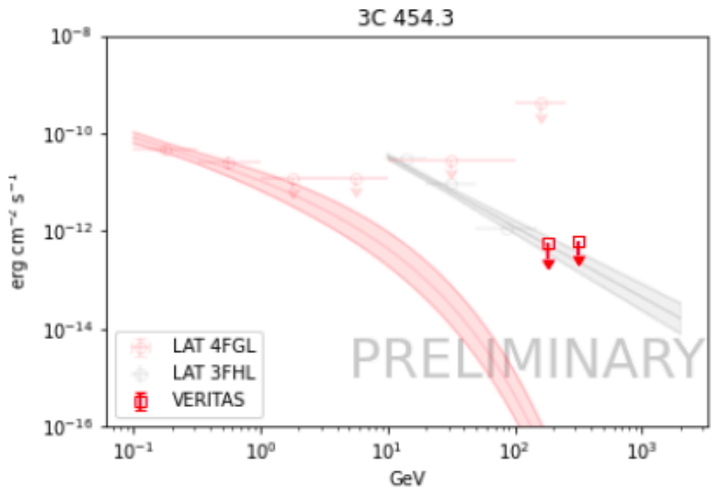
VHE FSRQ Survey











- VERITAS: >500 h of FSRQ data but heavily biased towards flaring states
  - 3 detections: PKS 1222+216 ($z \sim 0.43$), Ton 599 ($z \sim 0.73$), PKS 1441+25 ($z \sim 0.94$)
- Unbiased survey (8 h each) of 12 FSRQs => VHE duty cycle!
  - 8 w/ 3FHL extrap. + EBL => Flux >1% Crab; 4 are VHE sources - not yet detected by VERITAS
  - Patel (GAI#592): Results from first 4 targets; None detected; Targeted limit sensitivity (<1% Crab) achieved

Conclusions

- VERITAS is running very well & plans to operate until Summer 2025
- The VERITAS source catalog is now at 64 sources from 8 classes: 40 are AGN
- Discovery program has 2 approaches: ToO & pre-planned observations
  - Pre-planned: Comprehensive survey of hardest 2FHL & 2WHSP objects; Follow-up on old (>3σ) excesses
- Major program: Monitoring select Northern VHE AGN & intense follow up on any flares
  - Cadence / annual exposures & simultaneous MWL coverage varies by “importance”
  - Recent major results involve ToO follow-up of flares: B2 1811+31, H 1426+428, 3C 264, Mrk 421
  - We have a deep, multi-year VERITAS exposure for every known VHE blazar => Catalogs
- Multi-messenger physics a major aspect of VERITAS: TXS 0506+056 is only one part
- We are always looking to collaborate!
- Please see other VERITAS AGN Contributions: Patel (FSRQ Survey, GAI#592, 7/13), Jin (TXS 0506+056, MM#331, 7/16), Errando (TeV luminosity function of HBLs; GAI#980, 7/13), Feng (High-E spectra of VHE blazars, GAI#367, 7/13)

VERITAS AGN Catalog

Blazar	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
S3 1227+25	IBL	0.135
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
1ES 0414+009	HBL	0.287
OJ 287	BL Lac	0.306
TXS 0506+056	Blazar	0.337
1ES 0502+675	HBL	0.341
PKS 1222+216	FSRQ	0.432
1ES 0033+595	HBL	0.467
PKS 1424+240	HBL	0.604
Ton 599	FSRQ	0.725
PKS 1441+25	FSRQ	0.939

- 40 VHE AGN: 25 HBL, 6 IBL, 3 FSRQ, 3 uncertain & 3 FR I
  - ~60% have $z < 0.2$ & 85% have $z < 0.4$
- All VERITAS AGN are Fermi-LAT detected
- All VERITAS detections have simultaneous 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

AGN	Type	z
M 87	FR I	0.004
NGC 1275	FR I	0.018
3C 264	FR I	0.022

Blazar	Type	z
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	?

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

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VERITAS Acknowledgments

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.