# Highlights from the VERITAS AGN Observation Program

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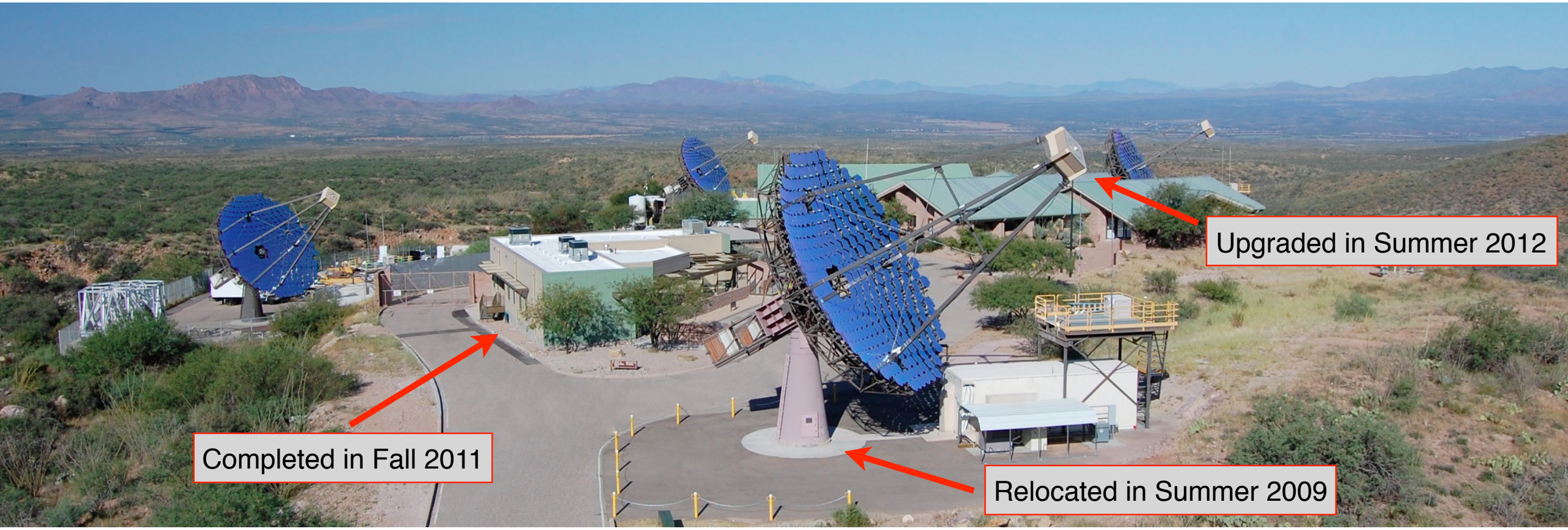
2. http://veritas.sao.arizona.edu

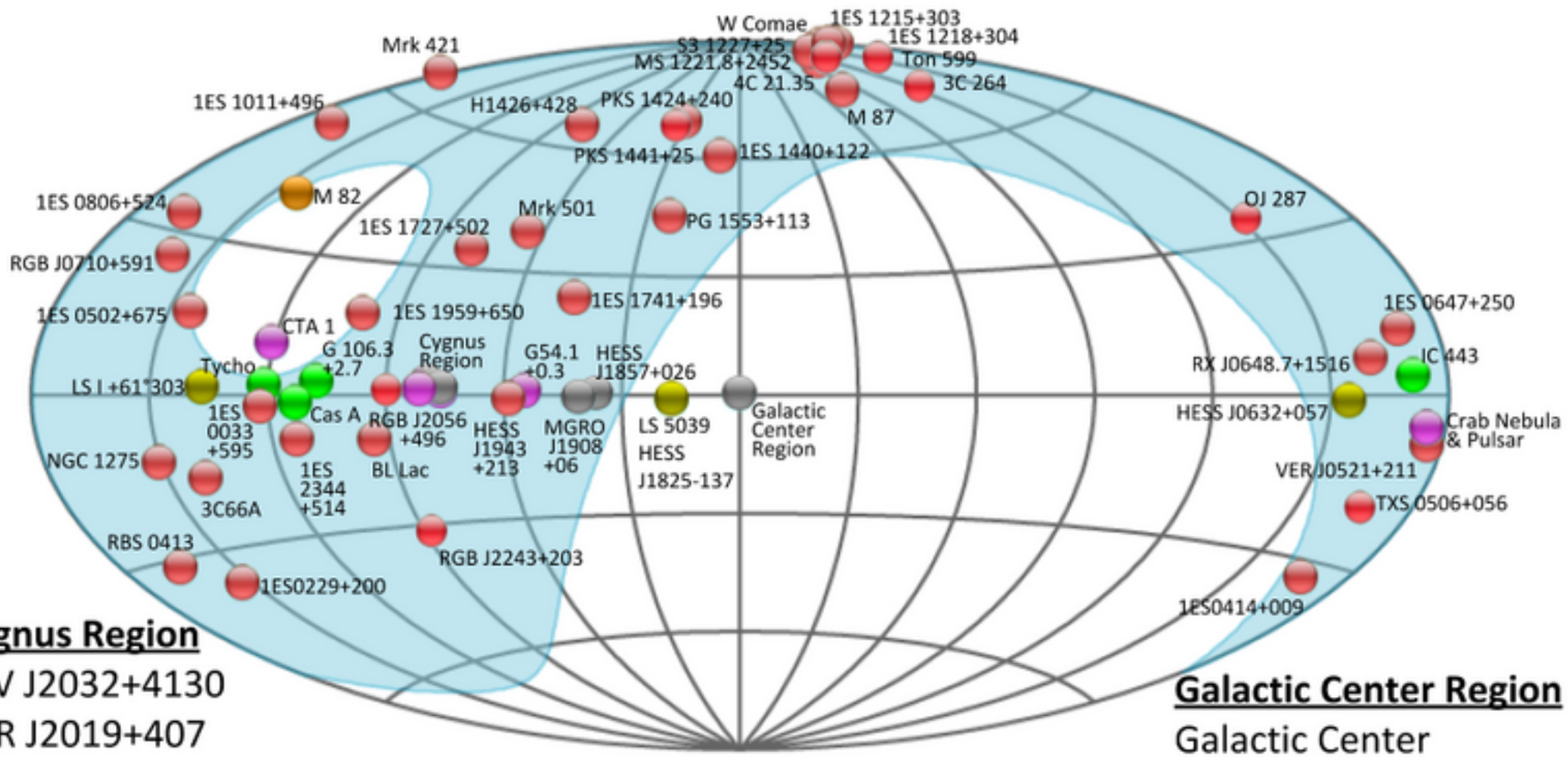
36th ICRC
Madison, WI, USA; July 29, 2019

# 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; ~14,600 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

# The VERITAS Source Catalog




**Cygnus Region**

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

**Galactic Center Region**

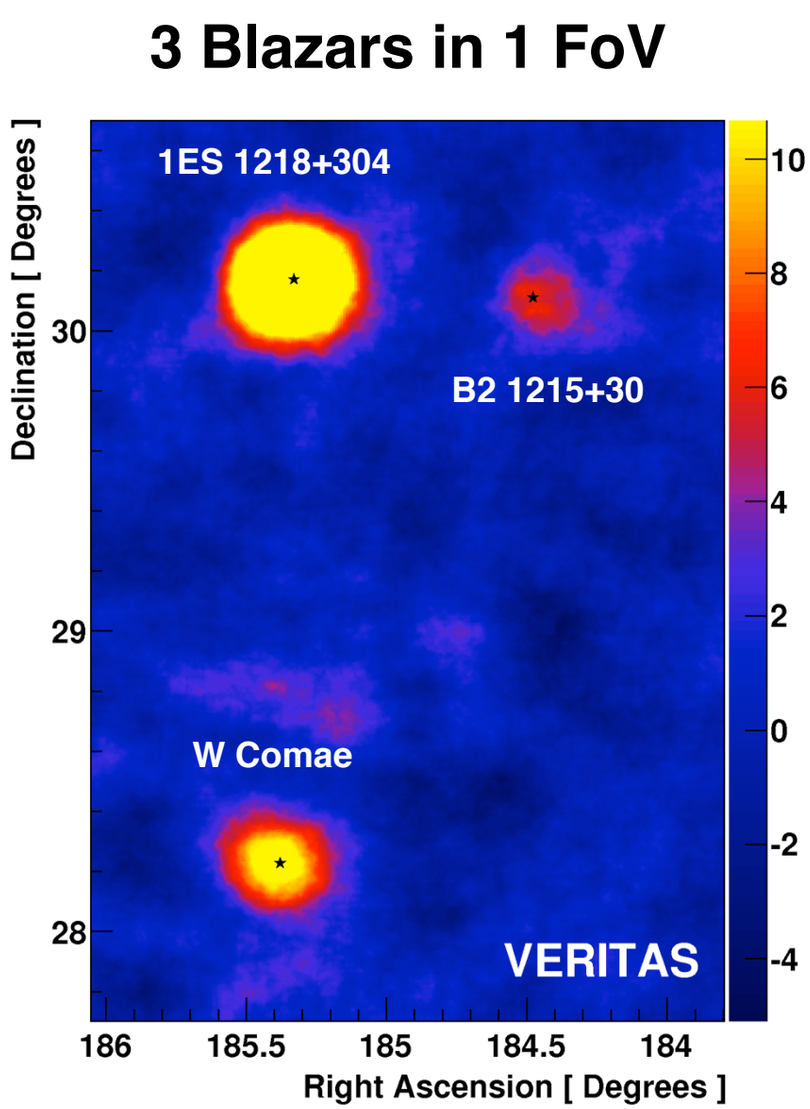
Galactic Center
Galactic Center Ridge
VER J1746-289
G 0.9+0.1

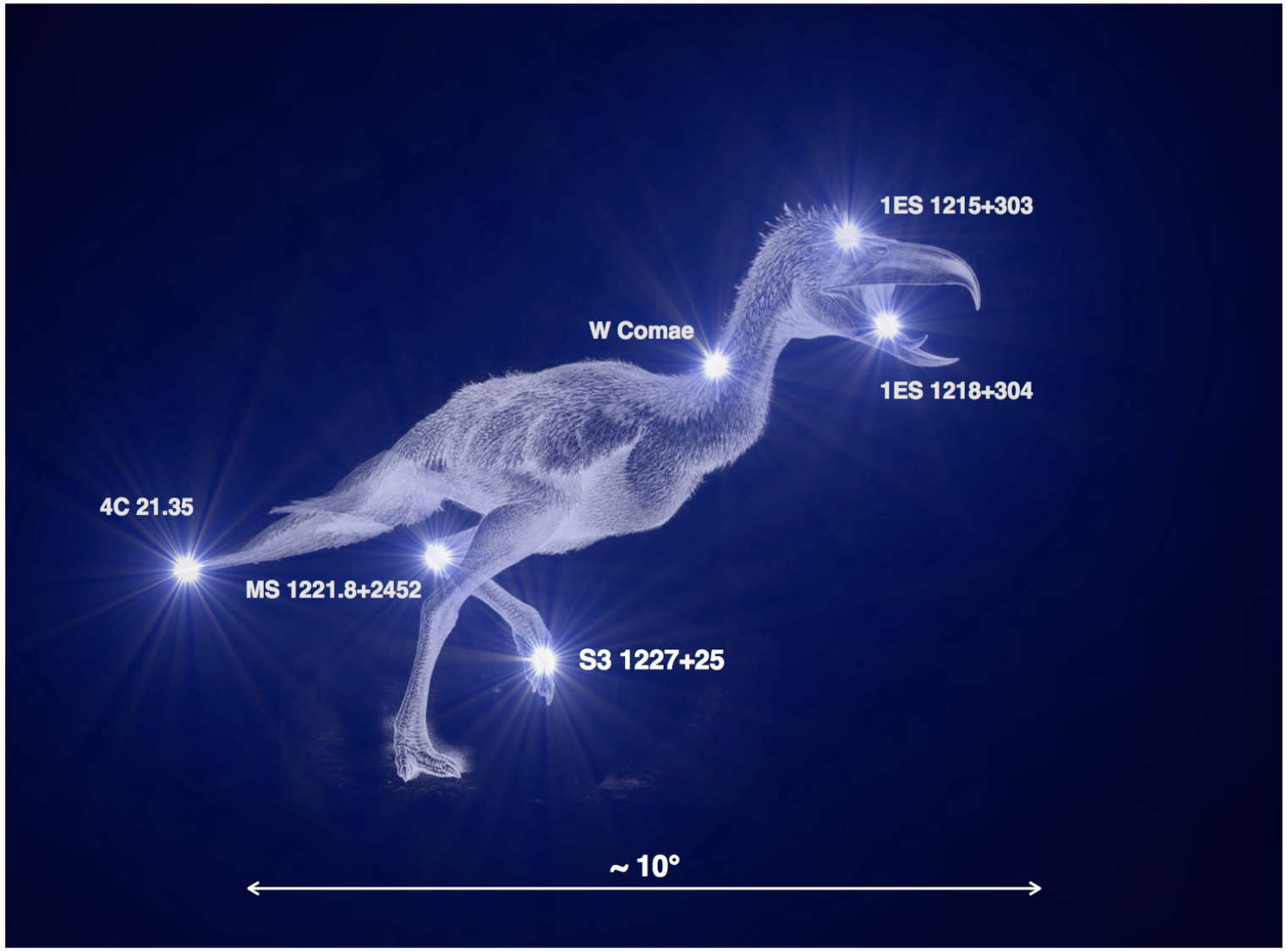
## 63 sources from 8 astrophysical classes

40 Extragalactic (63%) & 23 Galactic (37%) objects

Extragalactic: 39 AGN & a starburst galaxy (M82)

# The VERITAS AGN Catalog is Plentiful!

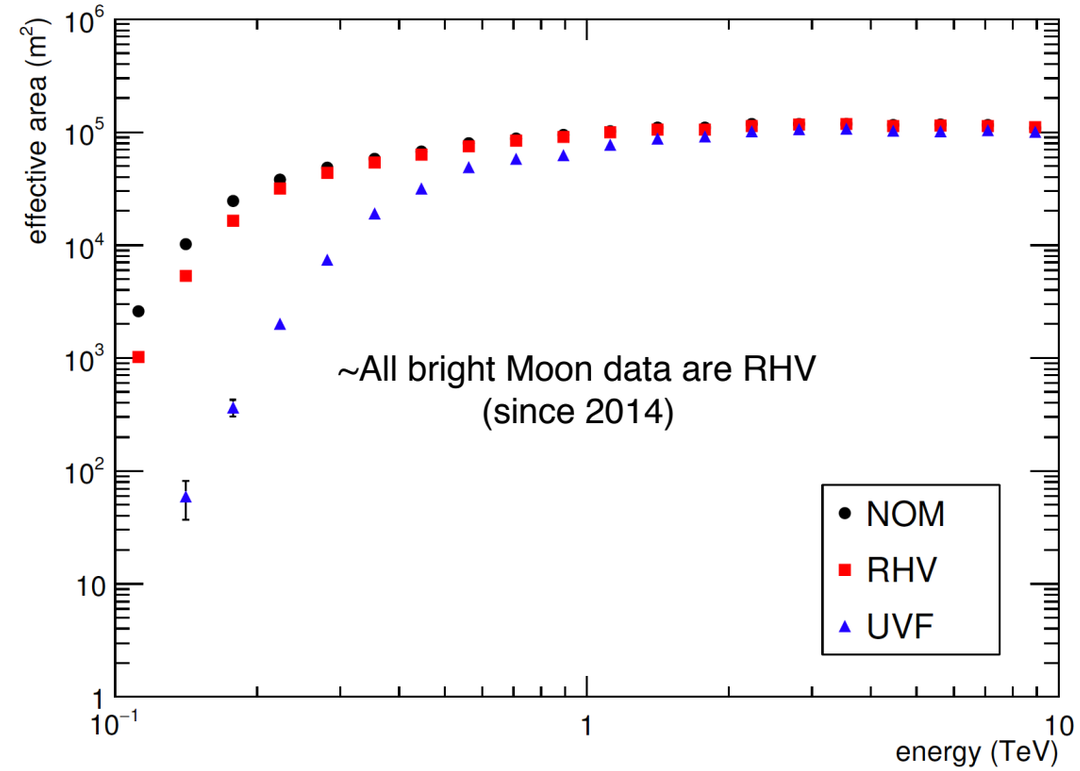


# VERITAS AGN Program: ~560 h / yr

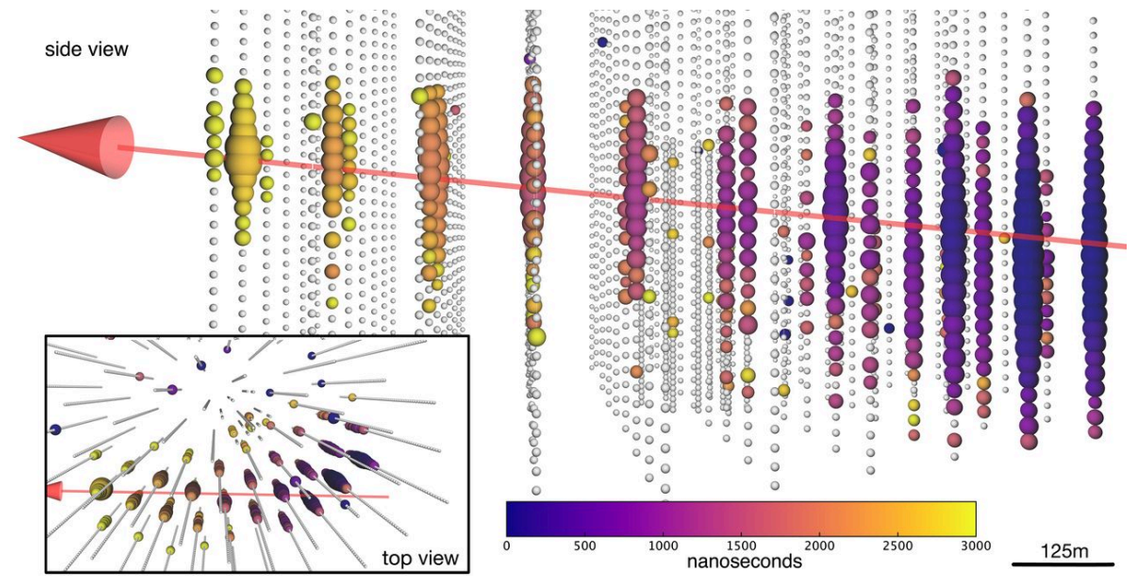
- 2007-2019: ~5100 h of good-weather "normal" AGN data; Average ~420 h / yr
  - 90% blazars / 10% radio galaxies
- 2012-2019: ~1000 h of good-weather "bright moon" AGN data; Average ~140 h / yr
  - Similar sensitivity (>250 GeV) & several blazars detected; S. Archambault et al., *Astroparticle Physics*, **91,** 34, 2017
- Blazar program: Primarily BL Lac objects
  - ~25% Target of Opportunity (ToO) observations
  - Major effort is regular monitoring of known VHE blazars
    - Depth / cadence depends on "importance"
    - Strong MWL coordination => Long-term MWL light curves
    - Observations intensified during any VHE (or MWL) flaring
    - Target list streamlined in 2018: All 59 in North => 22
  - Recently (>2017): ~45% are VHE discovery observations
- Radio galaxy (RG) program
  - Recently (>2017): ~60% discovery / ~40% known VHE

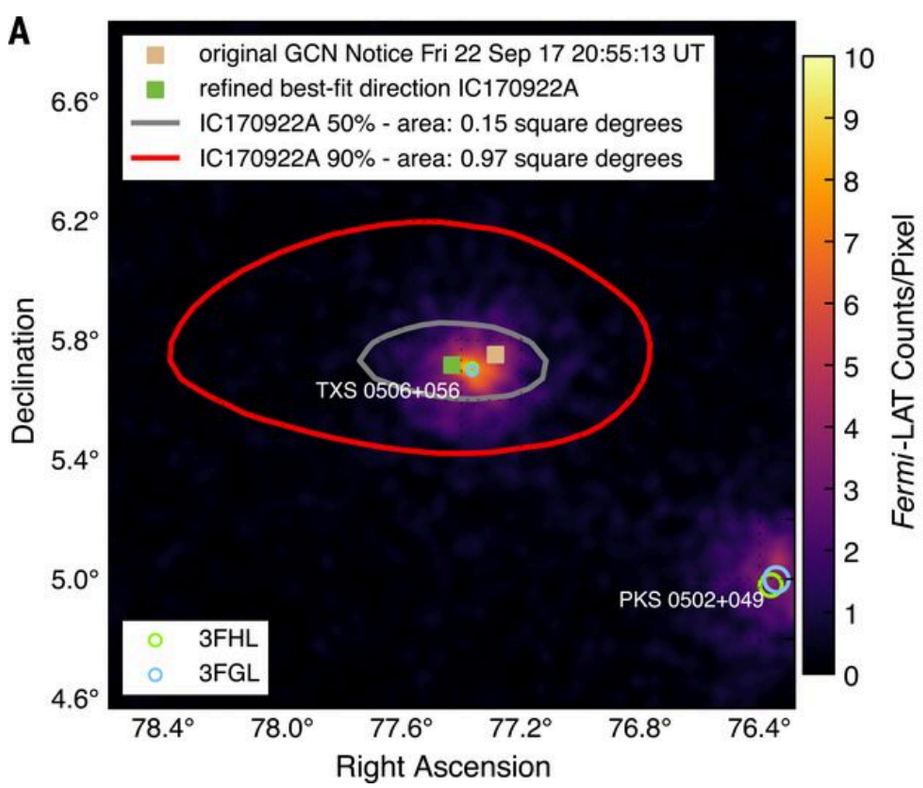
**Post-Analysis Effective Area**
**Normal vs Bright Moon**

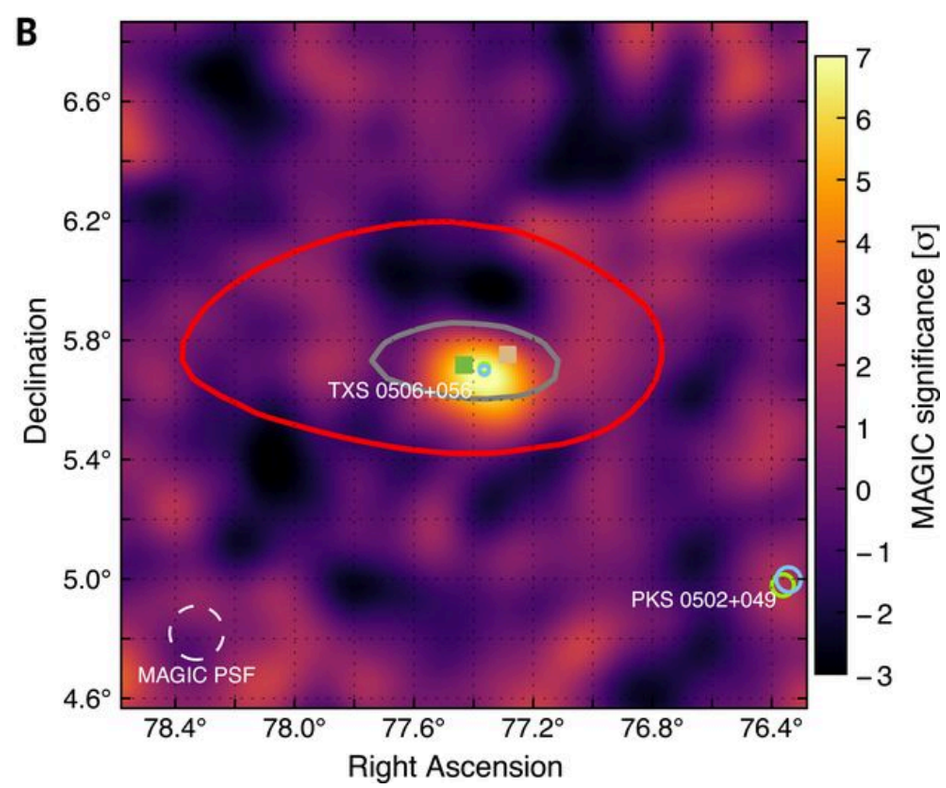


# TXS 0506+056: A Multi-messenger Blazar

- IceCube-170922A: E ~ 290 TeV, $P_{astro}$ ~ 0.6
- VERITAS: Upper Limit on Sept. 22 (~1 h)
  - HESS, VERITAS, MAGIC => ULs on 9/23 & 9/24
- LAT (ATel #10791): 6x 3FGL flux in ±1 week
- MAGIC: ~6σ, 13 h; 9/28 - 10/4; Variable
  - VERITAS (~5 h; 9/28-30) & HESS (~3 h; 9/27-28) ULs



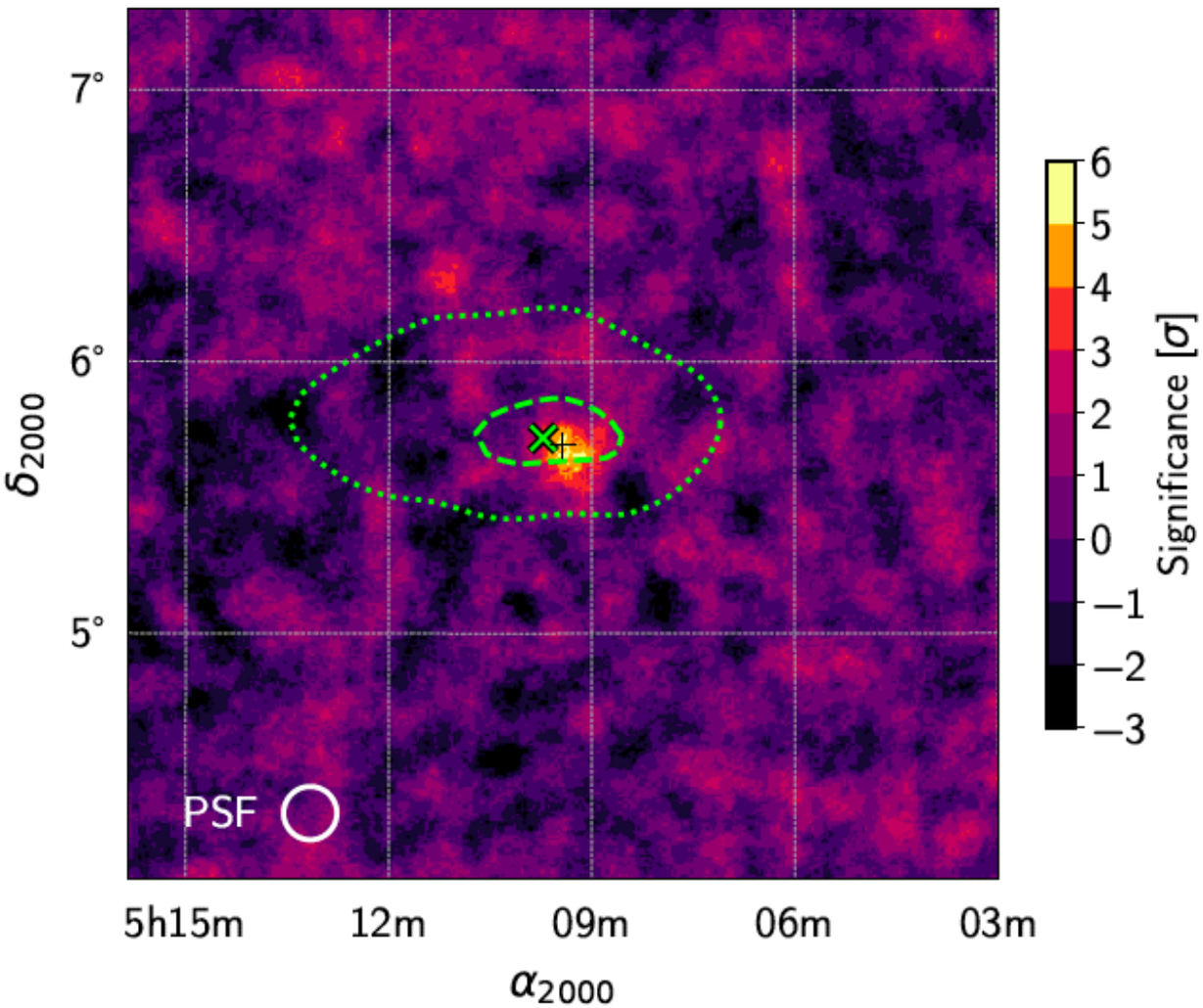



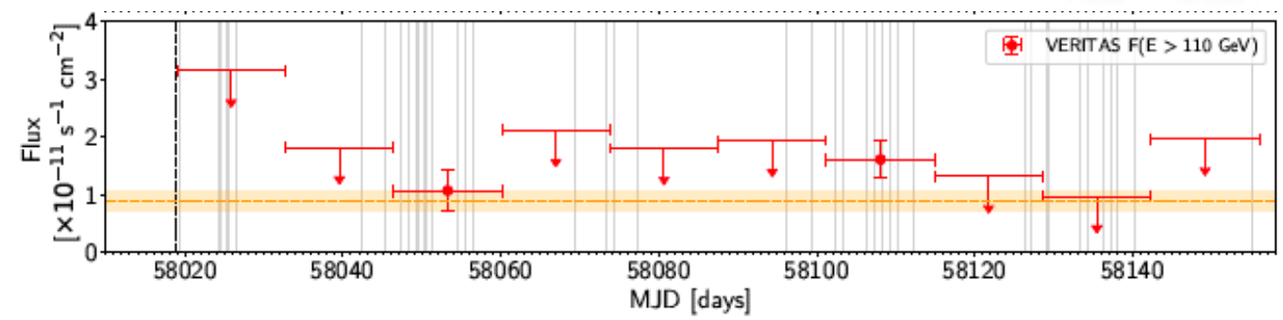



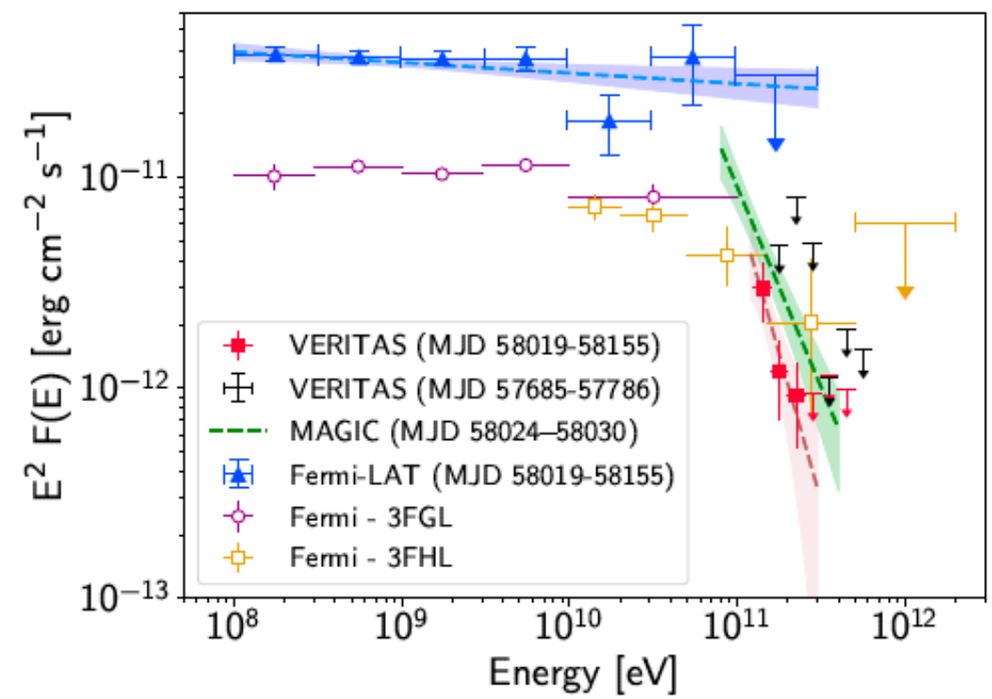

Correlation: 3σ effect
Science, 361, 147, 2018

Pre-flare,
3.5σ neutrino excess:
Science, 361, 141, 2018

# TXS 0506+056 (z = 0.337): VERITAS Detection



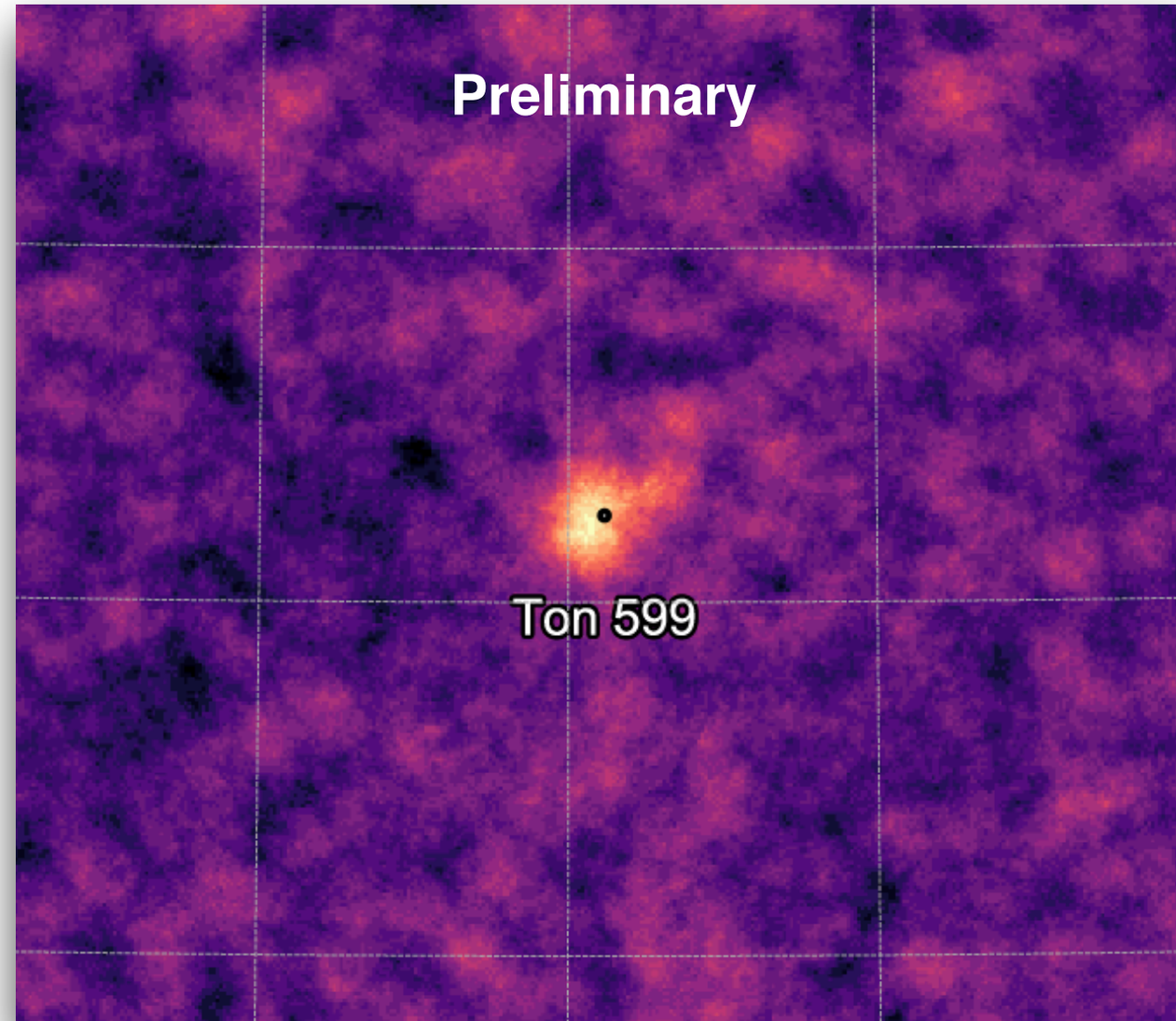




- VERITAS detection: 5.8σ in 35 h of good-quality data from Sept. ’17 - Feb. ’18
- Weak flux: F(>110 GeV) ~ 1.6% Crab; Soft VHE spectrum: Γ = 4.8 ± 1.3
  - Flux is ~60% of MAGIC flux; Spectrum ($\Gamma_{MAGIC}$ ~ 4.9) also consistent
- TXS 0506+056 faded in Fermi-LAT & Swift XRT over course of VERITAS campaign

# VHE “Co-Discovery” of Ton 599

- FSRQ @ z = 0.72
- Fermi-LAT flare in early Nov. 2017
  - ATel #10931: ~20x 3FGL flux
- Exceptional NIR flares in Nov. 2017
  - ATel #10949: 0.5 mag. after 10x flux
- VERITAS observes on 12/15-16
  - ~8σ in ~2 h; Γ ~ 5
  - F(>100 GeV) ~ 12% Crab
- MAGIC also detects on 12/15: ATel #11061

**Significance map for Ton 599**

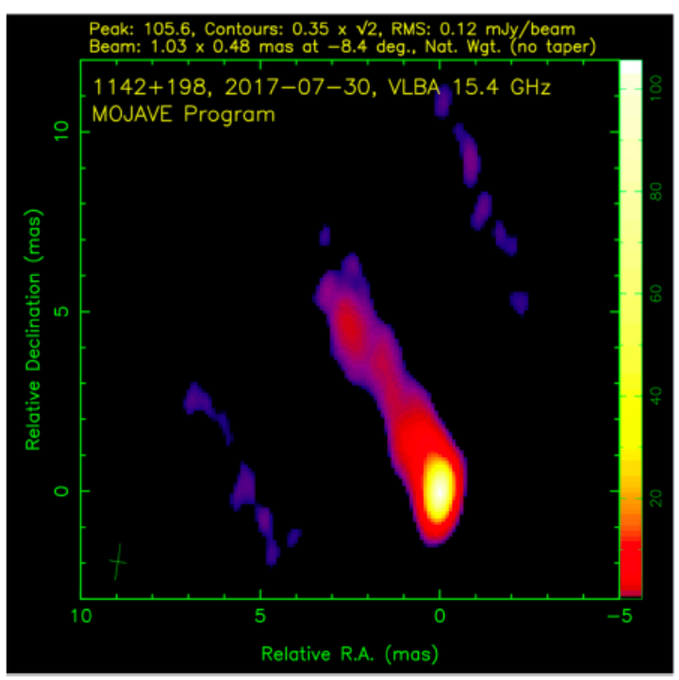


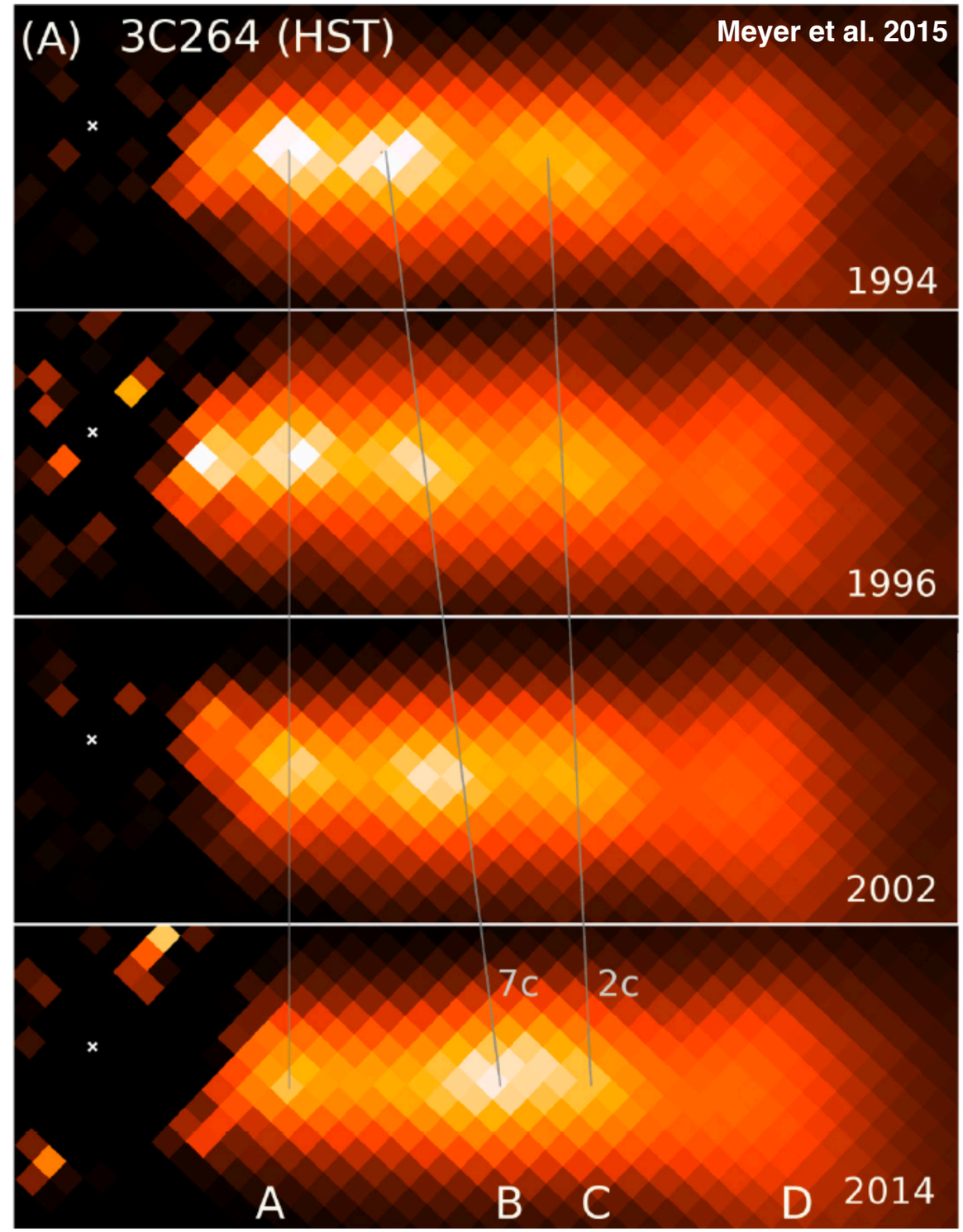

VERITAS’ 3rd FSRQ & 7th in VHE

PKS 1441+25 (z ~ 0.94) & 4C +21.35 (z ~0.43)

# VERITAS Observations of 3C 264

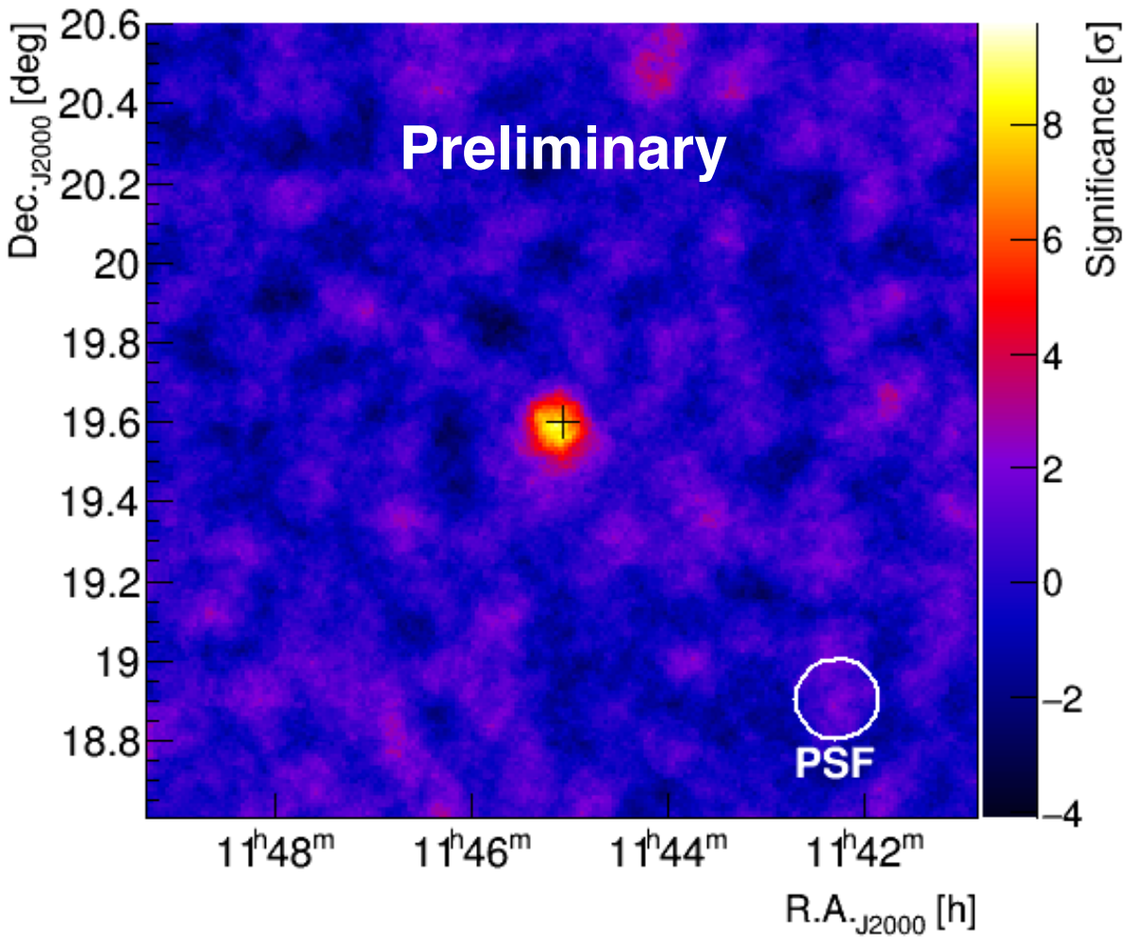
- More distant (~6x) “M87” analog
  - FR-I radio galaxy, z = 0.0216
- MeV-GeV source: 3FGL, 2FHL & 3FHL
  - $\Gamma_{3FHL}$ ~ 1.65 => F(>200 GeV) ~ 1.6% Crab
- Rapidly evolving knot-structure
- VERITAS ~10 h observation in 2017
  - Curious ~2σ excess => 2018 follow-up



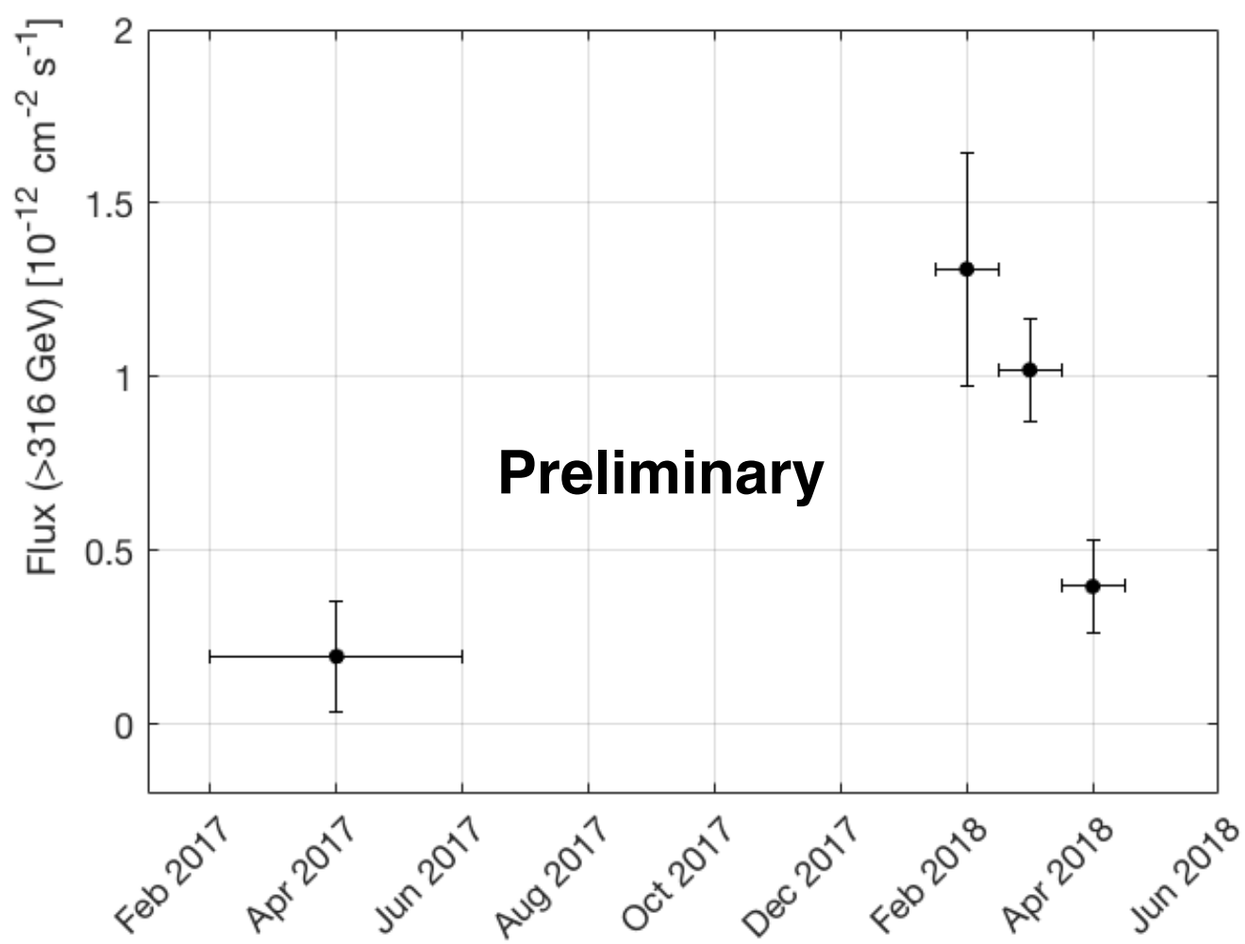



# VERITAS VHE Discovery of 3C 264

**Significance map for 3C 264**



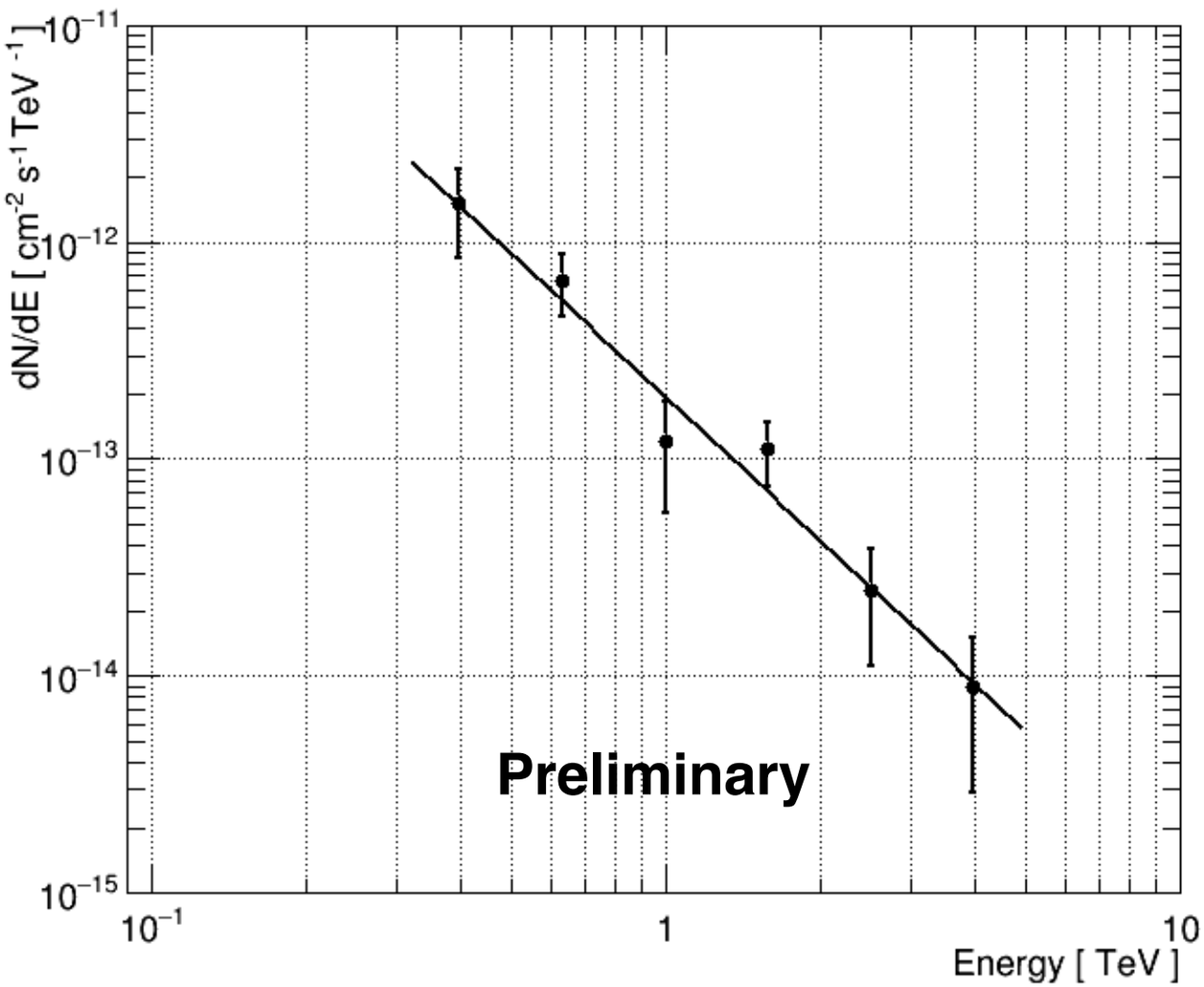

**Preliminary Light Curve for 3C 264**



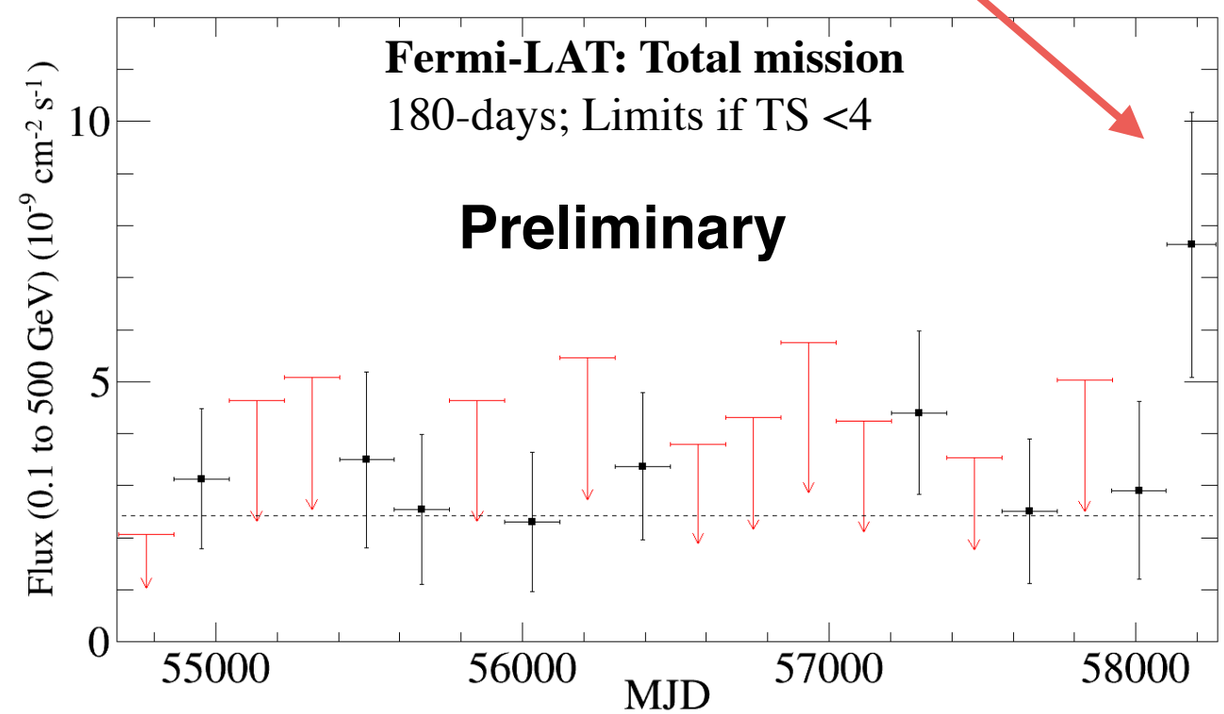

- Strong detection of 4th VHE radio galaxy: ~8.6σ in ~38 h
- Low, weakly variable VHE flux: ~0.6% Crab; ~Month-scale variations
- Major VERITAS + MWL effort: Radio (e.g. VLA, VLBI), Optical (HST, ground-based), X-ray (Chandra + Swift), Fermi-LAT => No major activity in knot sub-structure

# More 3C 264 Results

**Preliminary Spectrum for 3C 264**



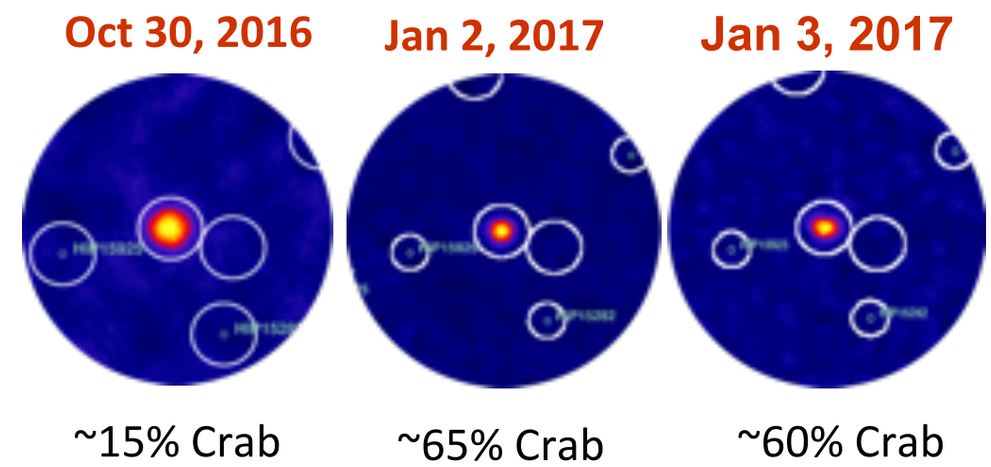

**Time period corresponding to VHE flux increase**

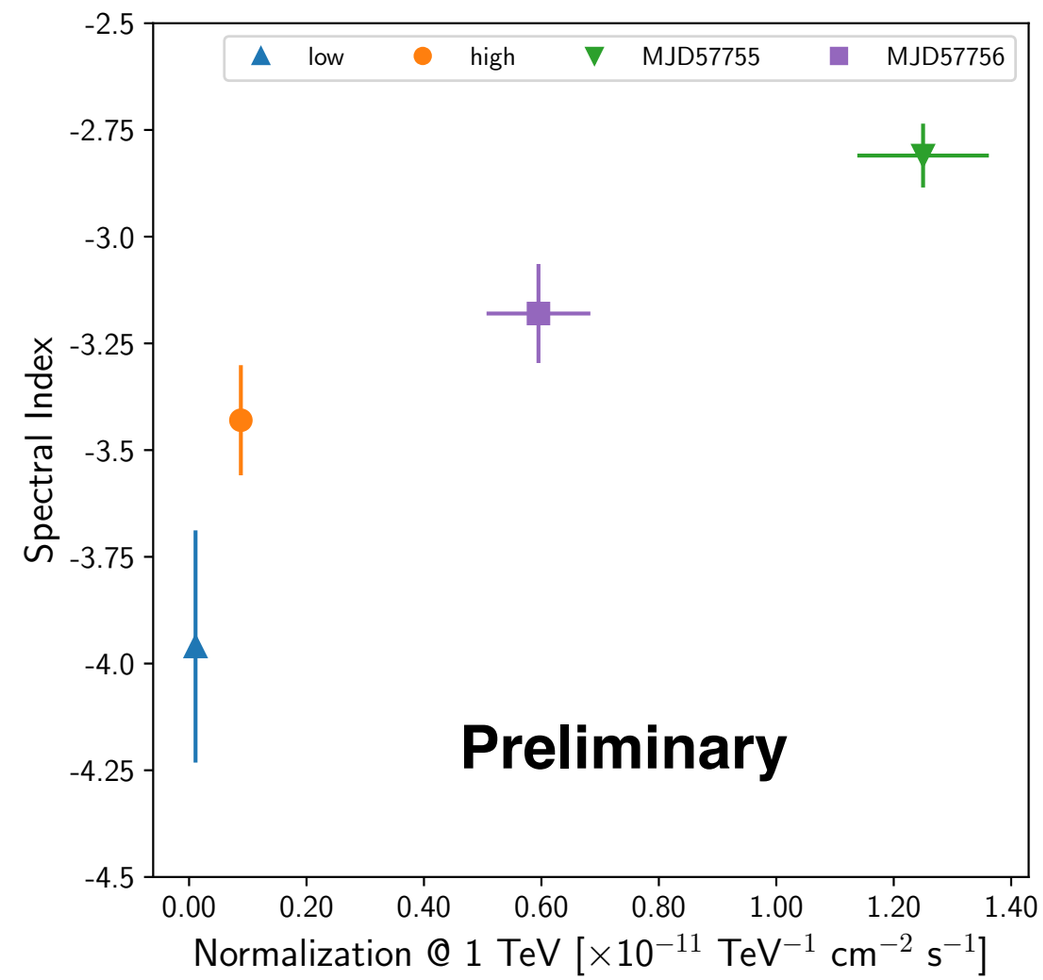



- Hard VHE ($\Gamma = 2.2 \pm 0.3$) & Fermi-LAT ($\Gamma_{10\text{-yr}} = 1.9 \pm 0.1$) spectra
- Preliminary SED shows a broad synchrotron peak
- Please see J. Christiansen: GAI5g, 7/27

# NGC 1275: A Decade of VERITAS Data

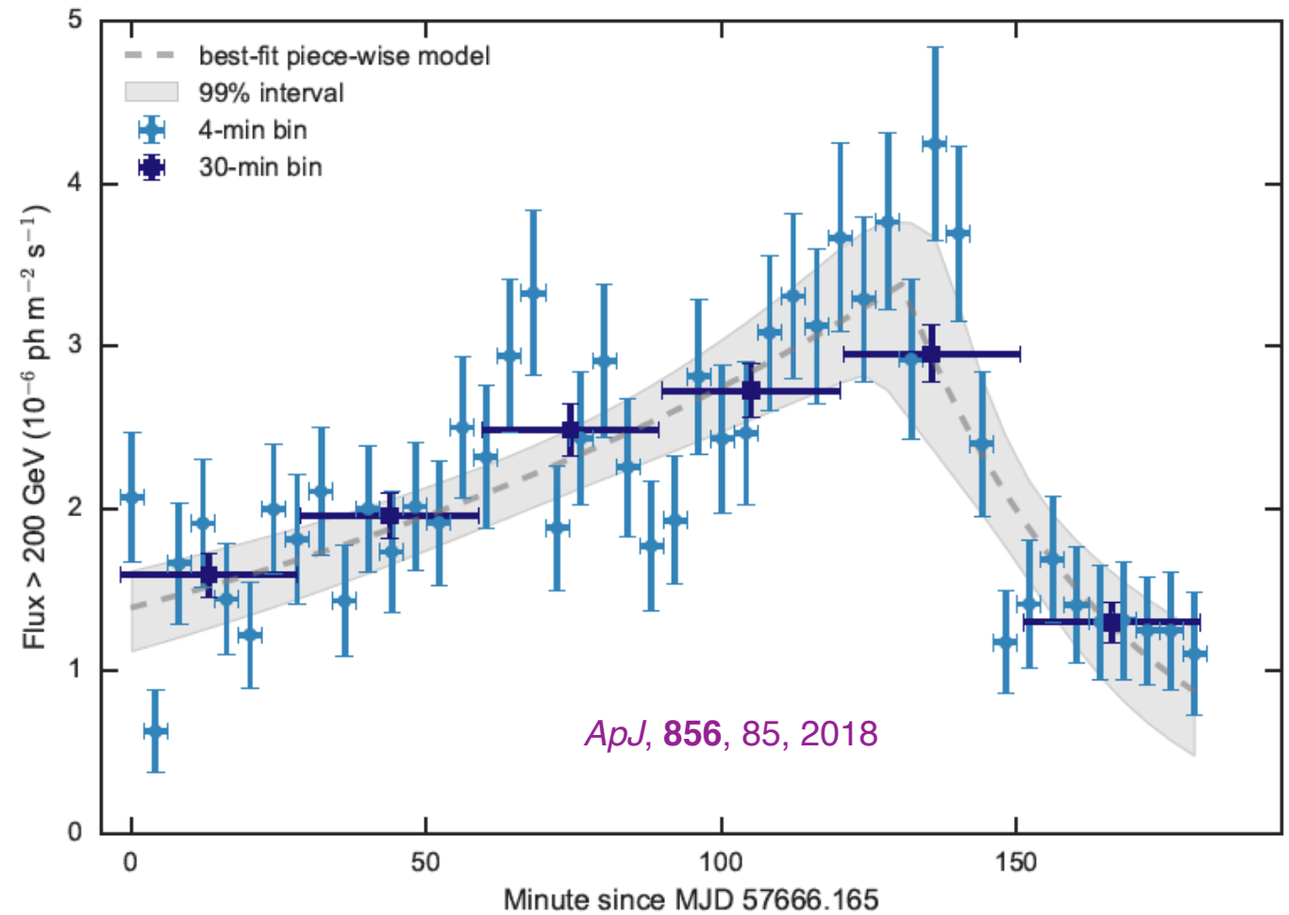
- Central radio galaxy (FR I) of the Perseus Cluster: $\Gamma_{3FGL} \sim 2.0$; $\Gamma_{2FHL} \sim 3.0$
- MAGIC VHE discovery (2010-12): ~2% Crab >100 GeV; $\Gamma \sim 4.1$
- VERITAS data: Limits in 2009, detected during LAT flares in 2013 & monitored since
  - Three major VHE flares for VERITAS
    - Oct. 2016 via monitoring
    - Jan. 2017 via LAT alert
  - Other high-states observed
- Clear evolution of VHE spectrum with flux
- Copious MWL data for SED modeling



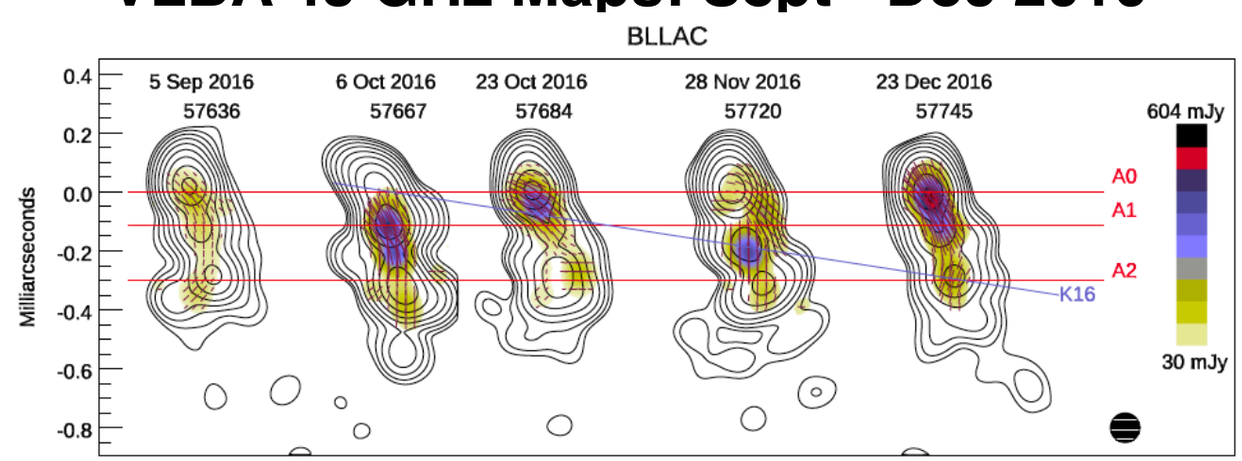



# BL Lacertae: Major Flare in October 2016

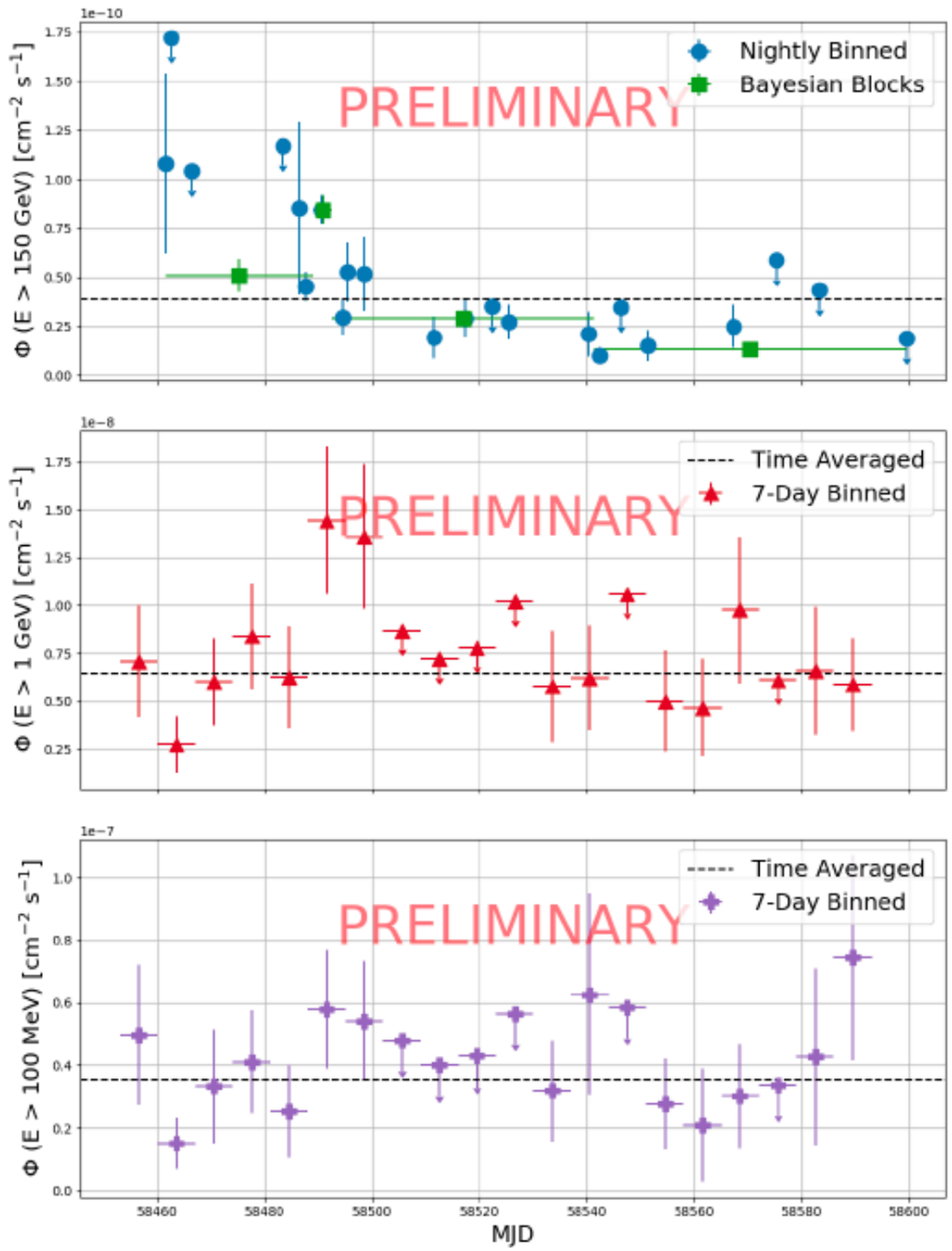
- MAGIC flare in 2005 (3% Crab)
- VERITAS: 80 h of data since 2010
- Brief, rapid flare in 2011: ApJ, **762**, 92, 2013
  - Peak: ~125% Crab; Exp. decay: $\tau = 13 \pm 4$ min
  - Associated w/ birth of superluminal radio knot
- Several, single-night flares
  - 16% Crab on 6/21/15, 9% Crab on 11/30/15
  - ~65% Crab (prelim.) on 5/5/19; low level on others
- Major flare on Oct. 5, 2016
  - Monitoring => 2.6 h, 71σ, Peak ~ 180% Crab
  - Slow rise ($t_{rise}$ ~ 140 min) & rapid fall ($t_{fall}$ ~ 36 min)
  - Another candidate superluminal knot appears



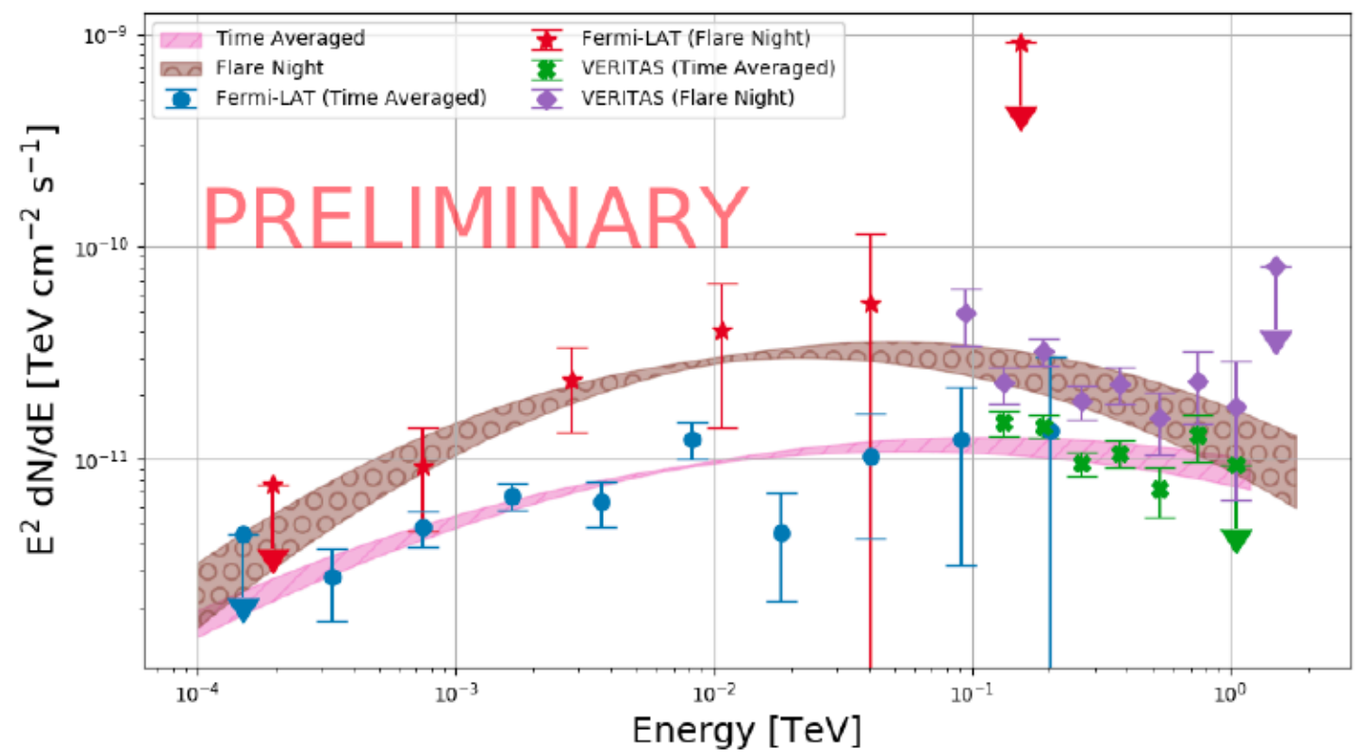

**VLBA 43 GHz Maps: Sept - Dec 2016**



# 2019: Day-scale Flare of 1ES 1218+304 (z=0.182)

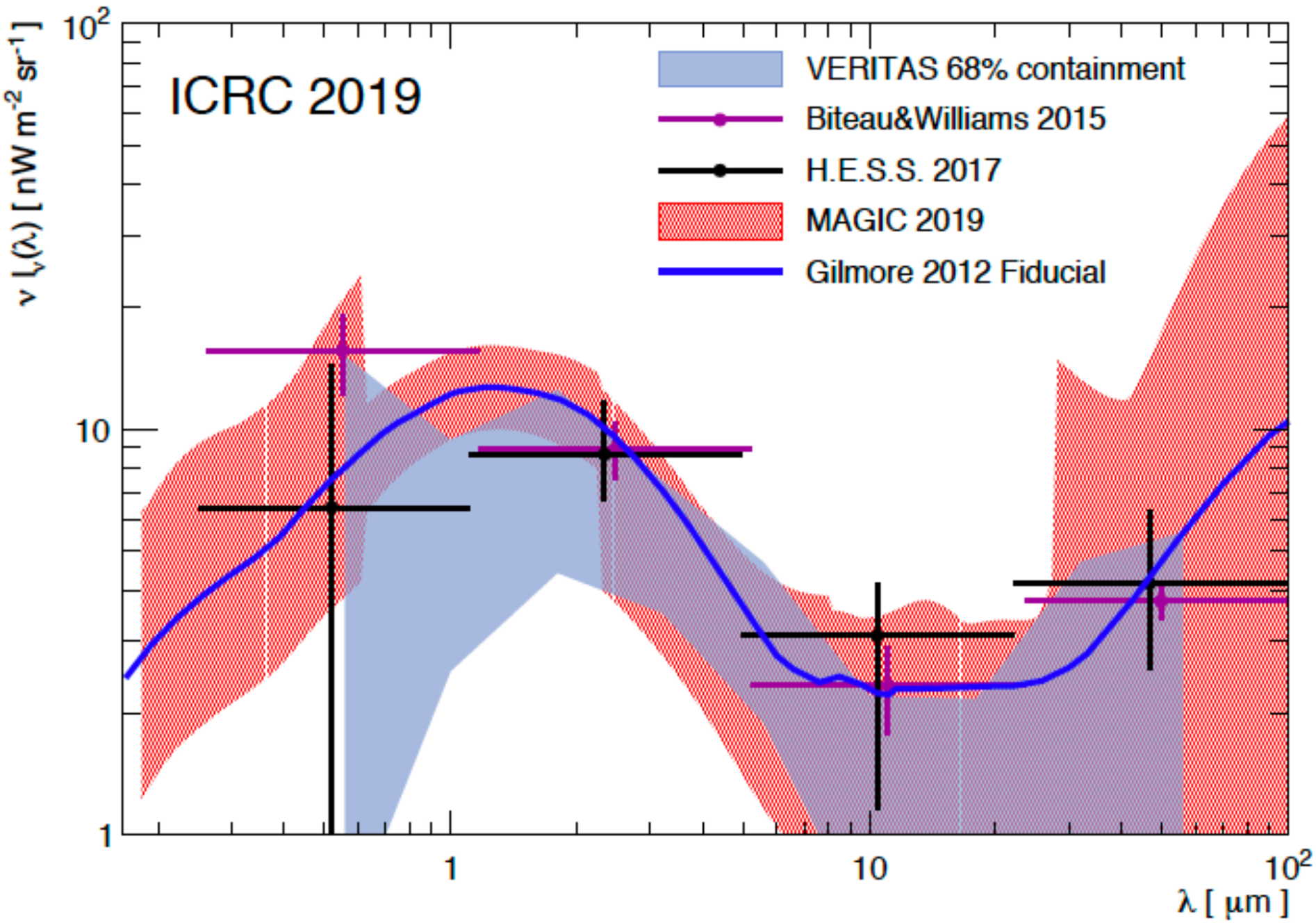



- Among most useful HBL for EBL / IGMF work
  - VERITAS ~20% Crab flare on 1/3/09: ApJ, **709**, L163, 2010
  - Typically ~4% Crab
- Flare night: Slight hardening (LAT & VERITAS)
  - See O'Brien Poster #PS2-71




VERITAS long lasting high-state (11% Crab) & another bright flare (23% Crab) on 1/7/19

# The VERITAS EBL Measurement




Good agreement with lower limits from Galaxy counts

Full treatment of systematic errors

Please see:
E. Pueschel
GAI11b
Wed, 7/31

Uses 16 spectra from 14 blazers observed by VERITAS

# Conclusions

- VERITAS is running very well & is funded to operate until Oct. 2022
- The VERITAS source catalog is now at 63 sources from 8 classes: 39 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
- Long-term plan: Monitoring select Northern VHE AGN & quickly follow up on any flares
  - Cadence / annual exposures & simultaneous MWL coverage varies by "importance"
  - ToO follow-up (VERITAS / MWL triggers) for known VHE blazars is very important & supplements exposures
  - We have a deep, multi-year VERITAS exposure for every known VHE blazar (as of Sept. 2018)
- Multi-messenger physics taking on major role in VERITAS future
  - VERITAS detected TXS 0506+056 following IceCube HE neutrino alert: Deep monitoring + More deep campaigns
- We are always looking to collaborate!
- Please see other VERITAS AGN Contributions: Gueta (~"Study of extreme HBL", GAI5d, 7/27), O'Brien (~"New methods for EBL constraints", PS3-72), Brill ("Towards a luminosity function of TeV gamma-ray blazars"; PS2-50)

# 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 |
| 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 |

- 39 VHE AGN: 25 HBL, 5 IBL, 3 FSRQ, 3 uncertain & 3 FR I
  - ~25% have uncertain redshift
  - 17 new AGN since VERITAS upgrade
- 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 even favor lepto-hadronic model

| 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

(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

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