VERITAS Observations of Active Galactic Nuclei

Stephan O’Brien,
On behalf of the VERITAS Collaboration

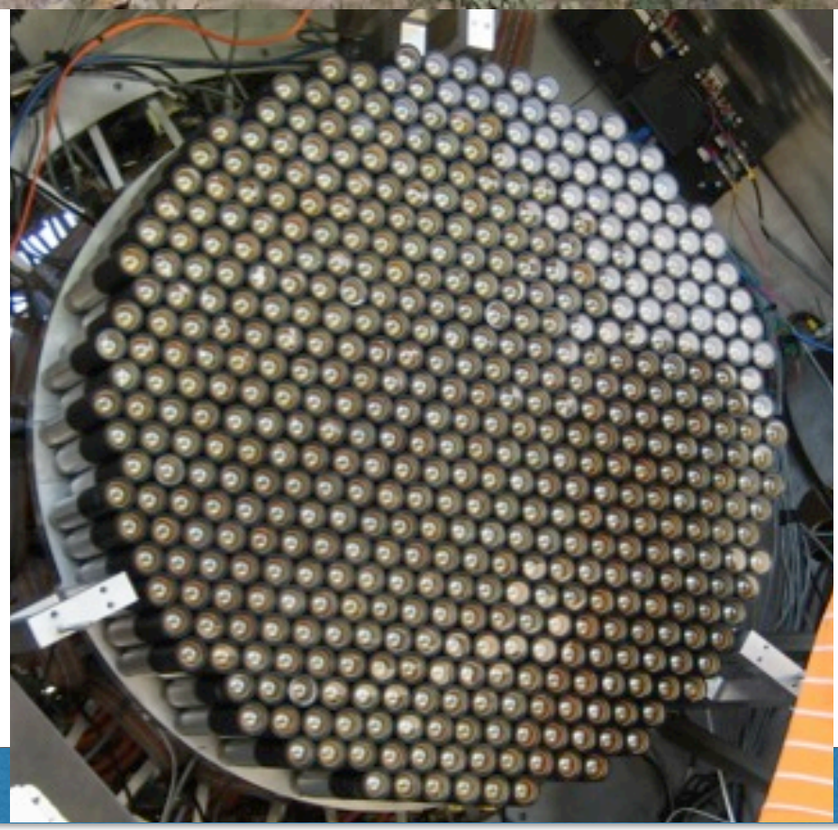
The VERITAS Collaboration

- ~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

Acknowledgements: 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, and by NSERC in Canada. 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.

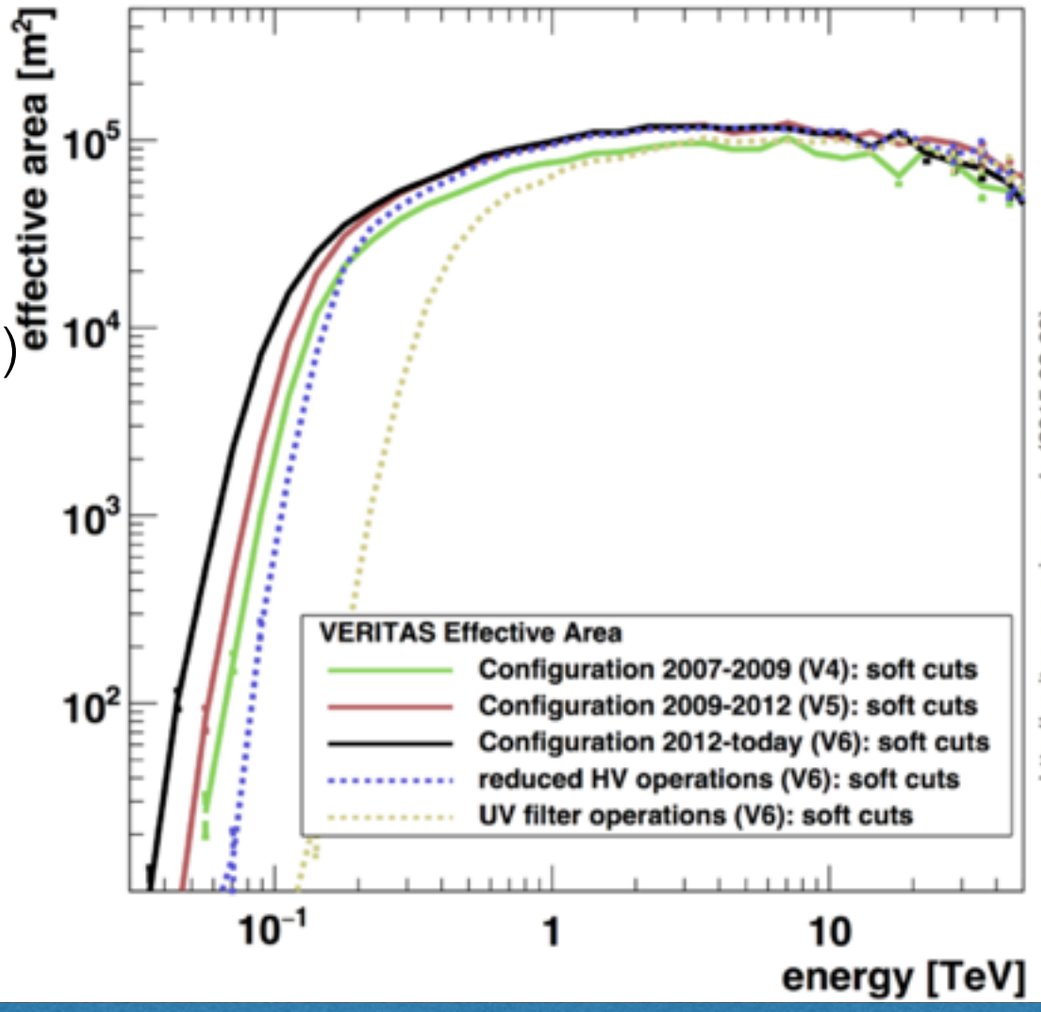
VERITAS

- Array of four 12m IACTs
- Located at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona (31 40N, 110 57W, 1.3km a.s.l.)
- Energy range: **85 GeV - 30 TeV**
- Angular resolution: **$R_{68\%}$ < 0.1° at 1 TeV**
- Pointing accuracy: **< 50”**(including systematics)
- Effective area: **~10^5 m^2 at 1 TeV**
- Field-of-view: **3.5°**
- Can detect **(5 σ) 1% Crab** source in **25 hours**

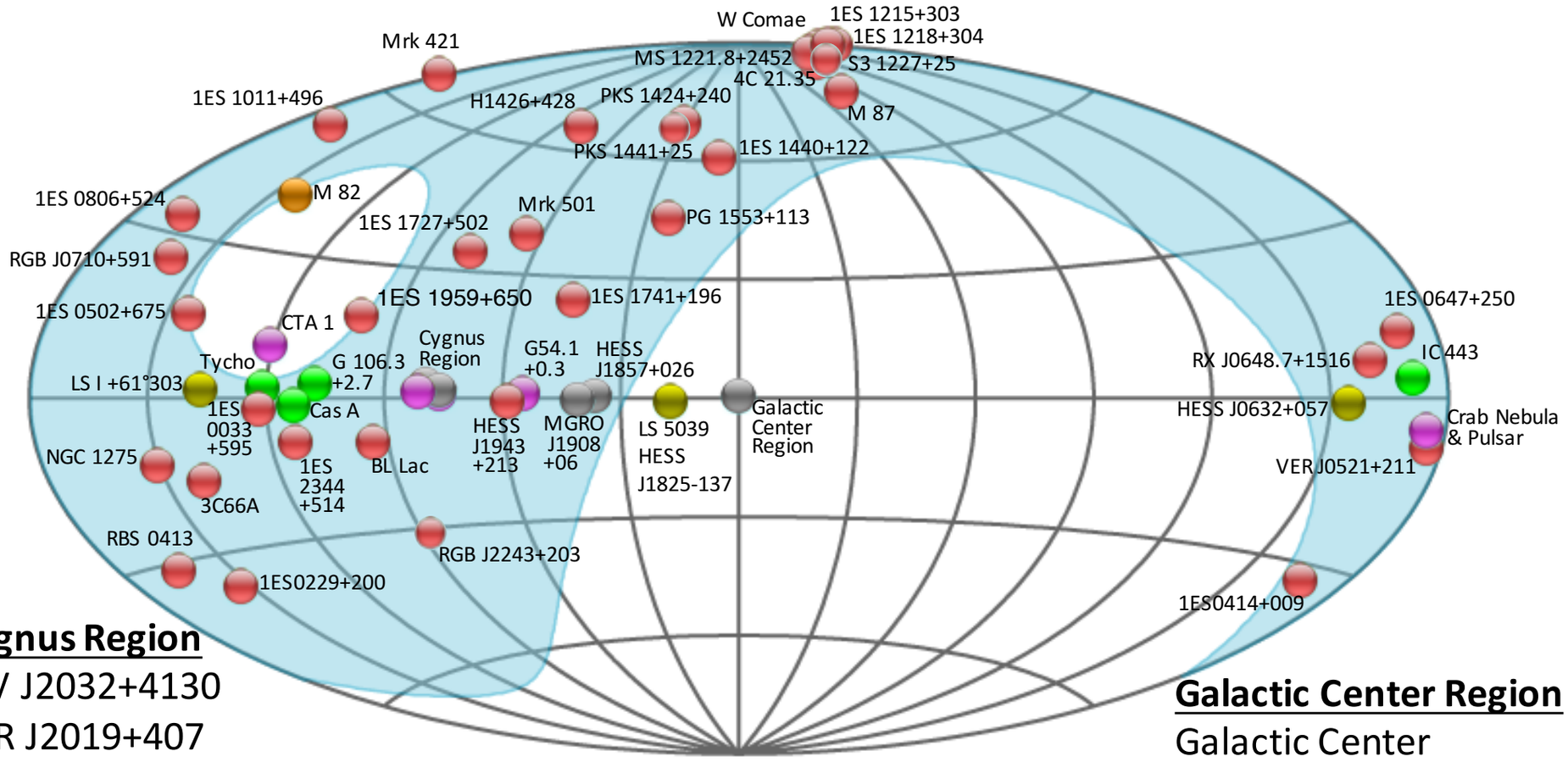


VERITAS

- 4 Telescope Operations began in 2007
- **Funding in place to operate through 2019**
- Major upgrades since 2007:
  - **2009**: T1 Moved to improve the symmetry of the array (**increased sensitivity**)
  - **2009**: Improved mirror alignment system (**reduced instrument PSF by 30%, increased sensitivity**)
  - **2011:** Trigger system upgrade (**improved sensitivity**)
  - **2012:** Camera upgrade (**reduced energy thresholds**)
- Typical VERITAS seasons (Good-weather):
  - **"Dark"** ~1000 hours
  - **"Bright Moon"** (since 2012) + ~300 hours



The VERITAS Source Catalog



Cygnus Region
TeV J2032+4130
VER J2019+407
VER J2019+368
VER J2016+372

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

56 Sources:

35 AGN
8 PWN
3 Shell type SNR
1 Starburst Galaxy
3 Binary, 1 PSR
5 Unidentified

The VERITAS AGN Discovery Program

- Early observations focused on the discovery of VHE Blazars (**~10% of total VERITAS observation time between 2007 and 2012**)
- Discovery candidates chosen based on their **MWL properties** and **VHE extrapolated flux**
- 113 Non-detections published from 2007-2012 as upper limits (Archambault et al., AJ, 151, 142 (2016))
- Stacked analysis shows a **4σ excess** with **3σ coming from nearby (z < 0.6) HBLs**

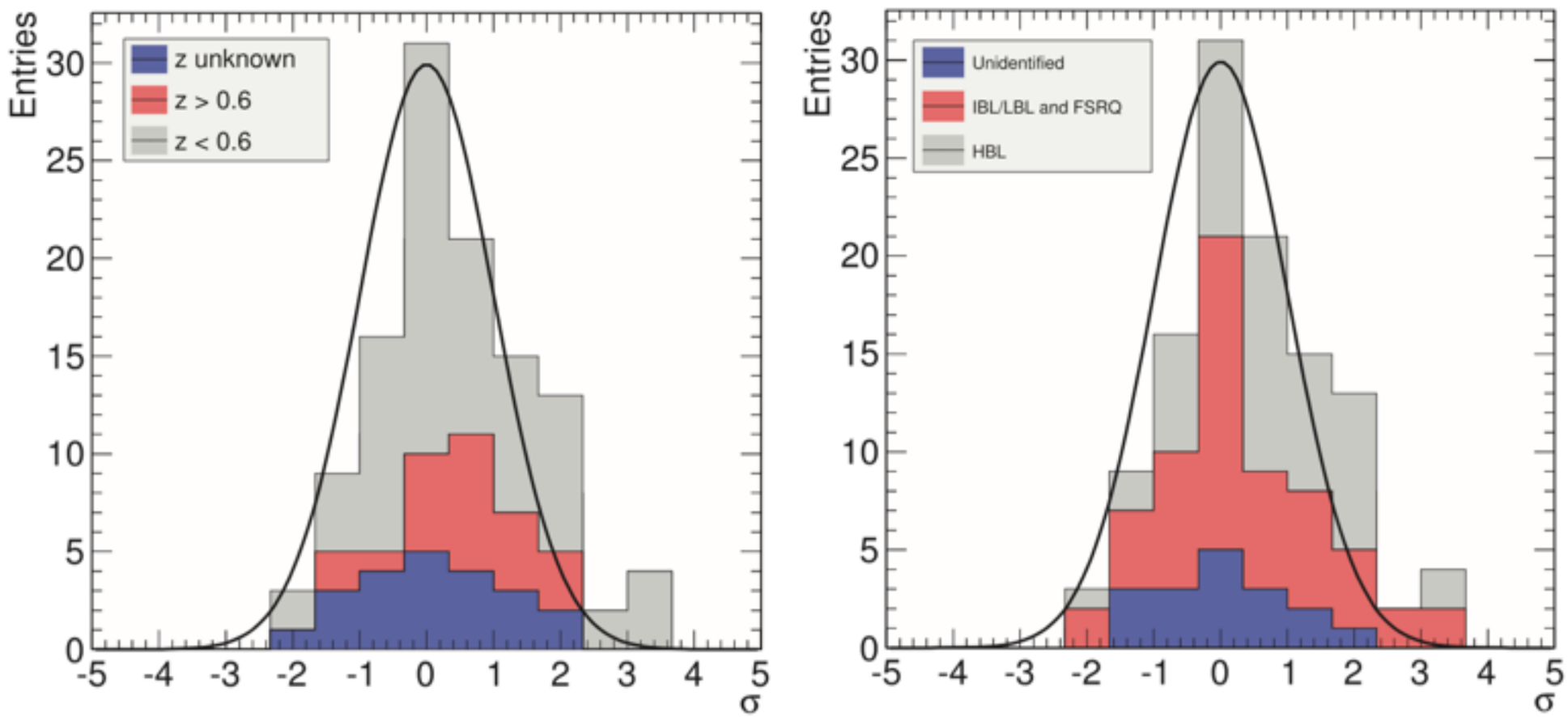


Figure 1. Left: stacked significance distribution of the sources included in our sample, classified according to their redshift. Sources with unknown z are in blue, sources with $z > 0.6$ are in red and sources with $z < 0.6$ are in gray. The Gaussian function represents the expectation from a randomly distributed sample, with mean equal to zero, and variance equal to 1. Right: same as the left panel, but for sources classified according to the AGN type. Unidentified sources are in blue, IBL/LBL/FSRQ in red, and HBL in gray.

The VERITAS AGN Catalog

VERITAS AGN catalog: 35 VHE AGN:

- 26 HBL
- 5 IBL
- 2 FR-I
- 2 FSRQ

All VERITAS AGN are Fermi-LAT detected!

Scientific Objectives:

- Supermassive black holes, jet structure and dynamics
- Cosmology: EBL & IGMF studies
- Fundamental Physics: Lorentz Invariance

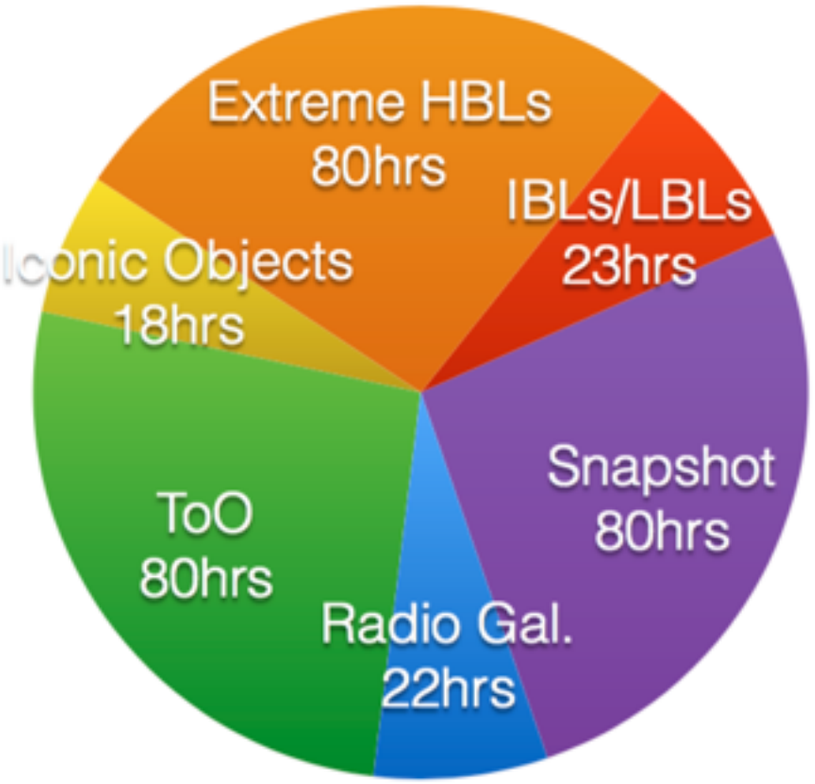
AGN	Type	z
1ES 1440+122	HBL	?
RGB J2243+203	HBL	?
1ES 0033+595	HBL	?
HESS J1943+213	HBL	?
RGB J2056+496	HBL	?
PKS 1424+240	HBL	z > 0.604
3C 66A	IBL	0.33 < z < 0.41
PG 1553+113	HBL	0.43 < z < 0.58

AGN	Type	z
M 87	FR-I	0.0044
NGC 1275	FR-I	0.018
Markarian 421	HBL	0.031
Markarian 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.048
1ES 1727+502	HBL	0.055
BL Lacertae	IBL	0.069
1ES 1741+196	HBL	0.083
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	0.13
S3 1227+25	IBL	0.135
1ES 0806+524	HBL	0.138
1ES 0229+200	HBL	0.139
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
1ES 0502+675	HBL	0.340
PKS 1222+216	FSRQ	0.432
1ES 0647+250	HBL	0.45
PKS 1441+25	FSRQ	0.939

The Current VERITAS AGN Long Term Plan

AGN long term plan receives **~300 hrs of 'dark' time** data per annum (+ **TAC awarded time**)

Focus largely shifted from **discovery → monitoring**



Deep multi-year exposures on:

- **Extreme HBLs** (Distant hard spectrum Blazars)
- **IBLs** (Regular monitoring, low- and flare-state spectra)
- **Iconic Objects** (Mrk 421 and Mrk 501)
- **Simultaneous** with Swift and FLWO 48'' BVri observations

Regular Snapshots taken on all VHE blazars visible to VERITAS

Discovery Snapshots:

- Candidates selected based on VHE extrapolated MWL properties (e.g. 2FHL, WHSP)
- **2nd upper limits paper for non-detections will be produced**

Radio Galaxy monitoring program with MAGIC, HESS and multi-wavelength partners

Pre-approved Target of Opportunity (ToO) time for follow up on flares (Blazar Activity Report(er)highly effective):

- **Daily monitoring** of MWL publicly available resources (ATel, FACT, Swift, etc…)
- **Dedicated Fermi-LAT analysis pipelines**
- **Quick look analysis** allows **real time** estimation of source flux

Monitoring Extreme HBLs

Aim: Obtain deep multi-year exposures on a number of Extreme HBLs

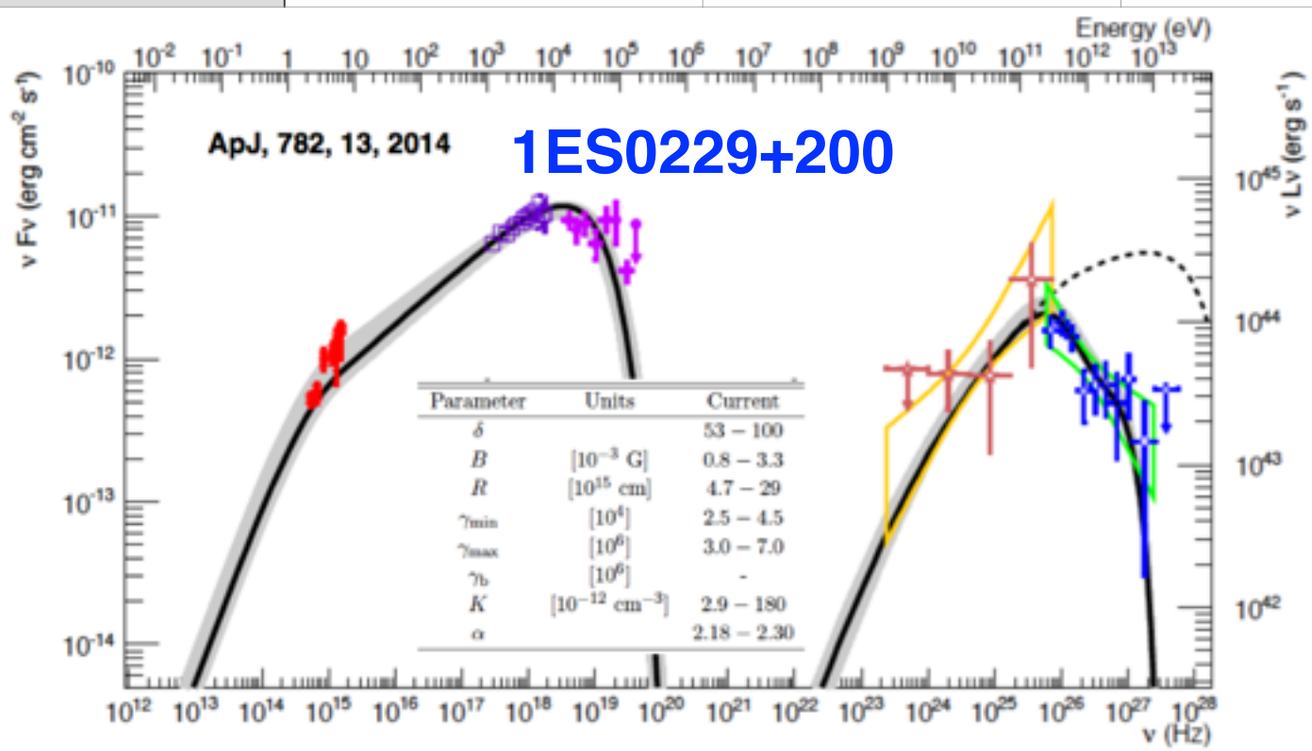
Long term observations allow for **variability studies**

Hard HE spectral indices and **relatively high redshift** make these sources very interesting for **EBL studies**

Aim for **~200 hours** of exposures on each source

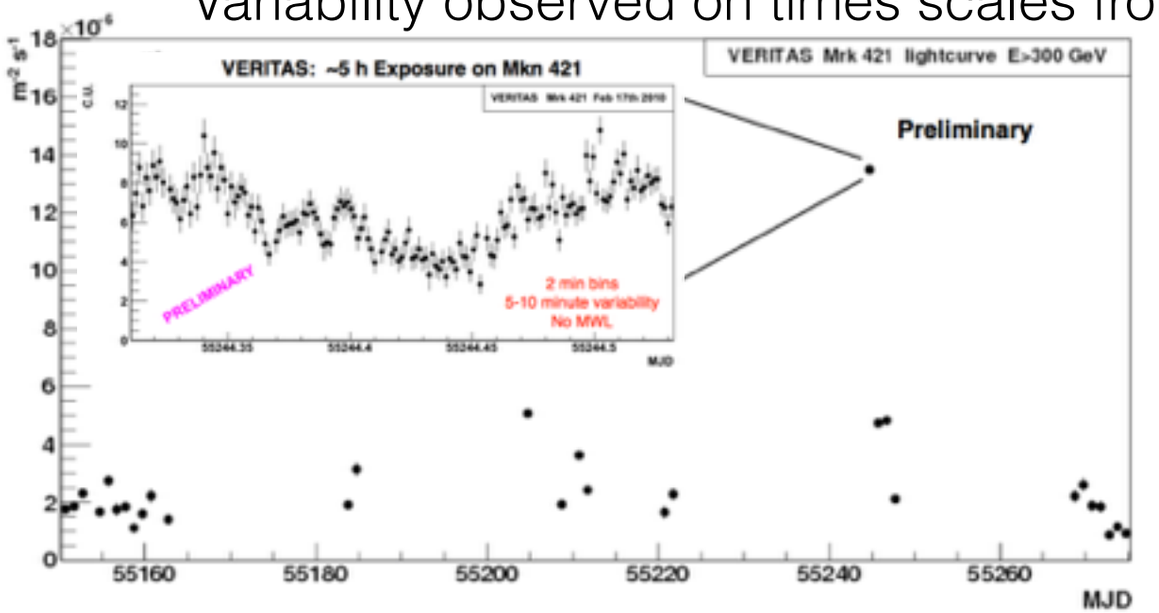
Many snapshots simultaneous with Swift

AGN	z	Typical Flux (% Crab)	Spectral Index
1ES 0229+200	0.140	~1%	~2.9
RGB J0710+591	0.125	~2%	~2.7
H 1426+426	0.129	~2%	~2.9
PKS 1424+240	> 0.6	~3%	~3.7
1ES 1218+304	0.182	~6%	~3.2



HBL Variability: Mrk 421

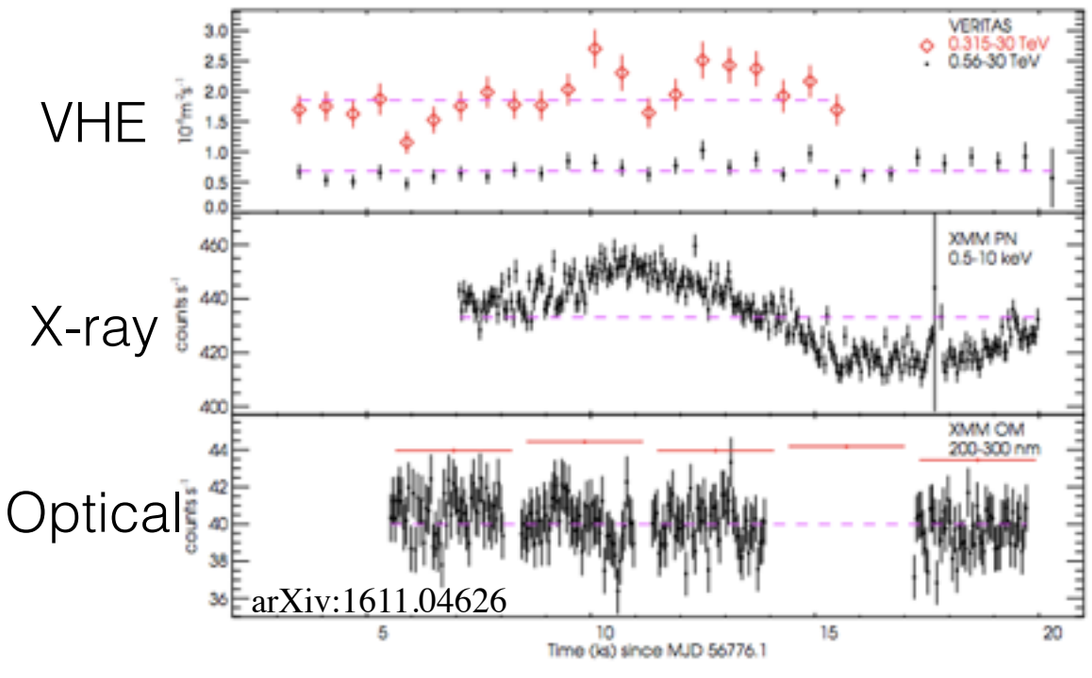
Variability observed on times scales from minutes to years. Flickering common!



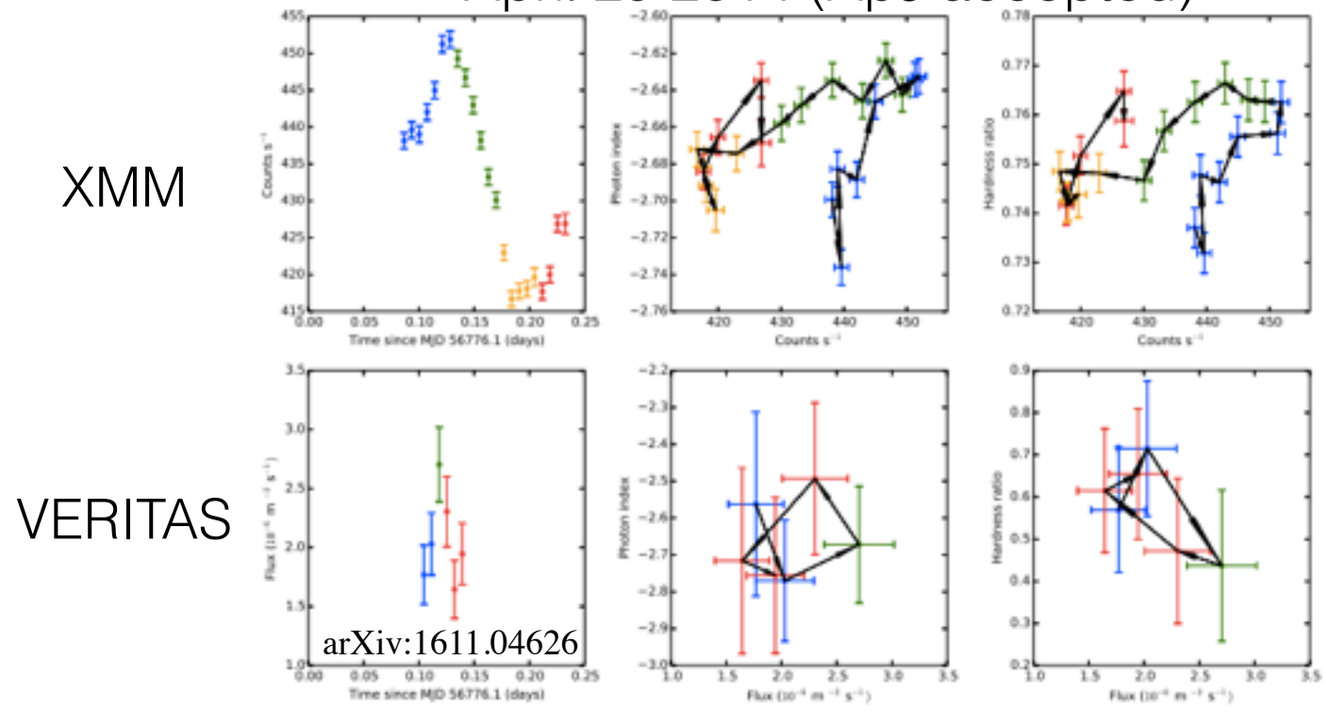
- Mrk 421 large flare observed in February 2010
- Flux ~10 Crab observed
- Variability timescales on the order of 5-10 minutes
- No MWL data

Finely sampled flare states allow for correlation studies with other MWL instruments

April 29 2014 (ApJ accepted)



April 29 2014 (ApJ accepted)

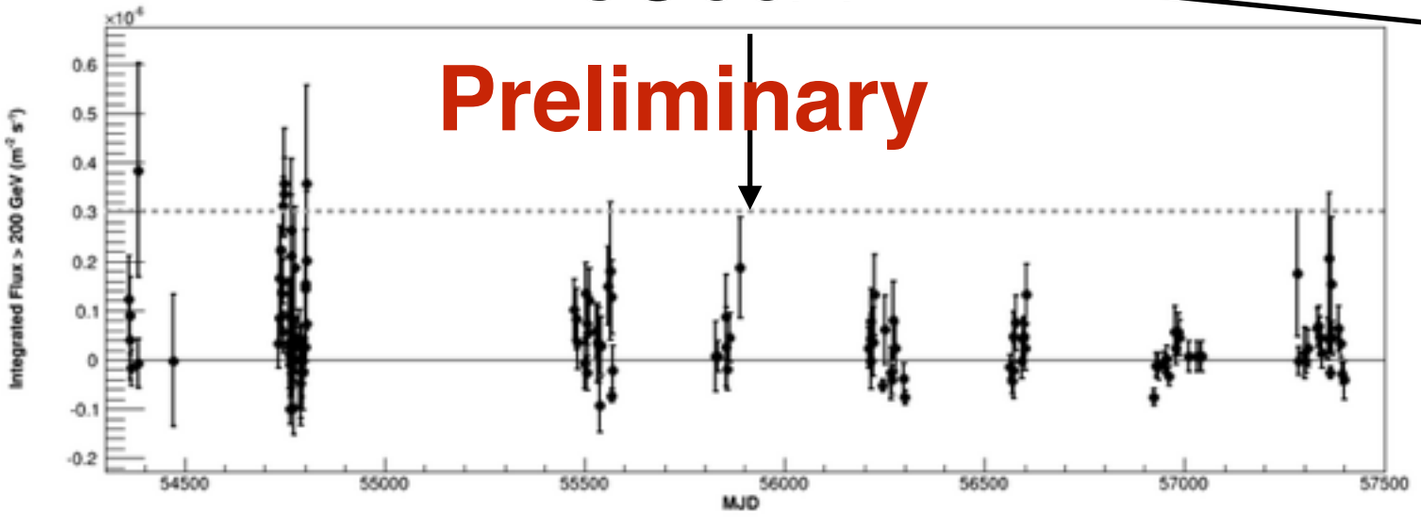


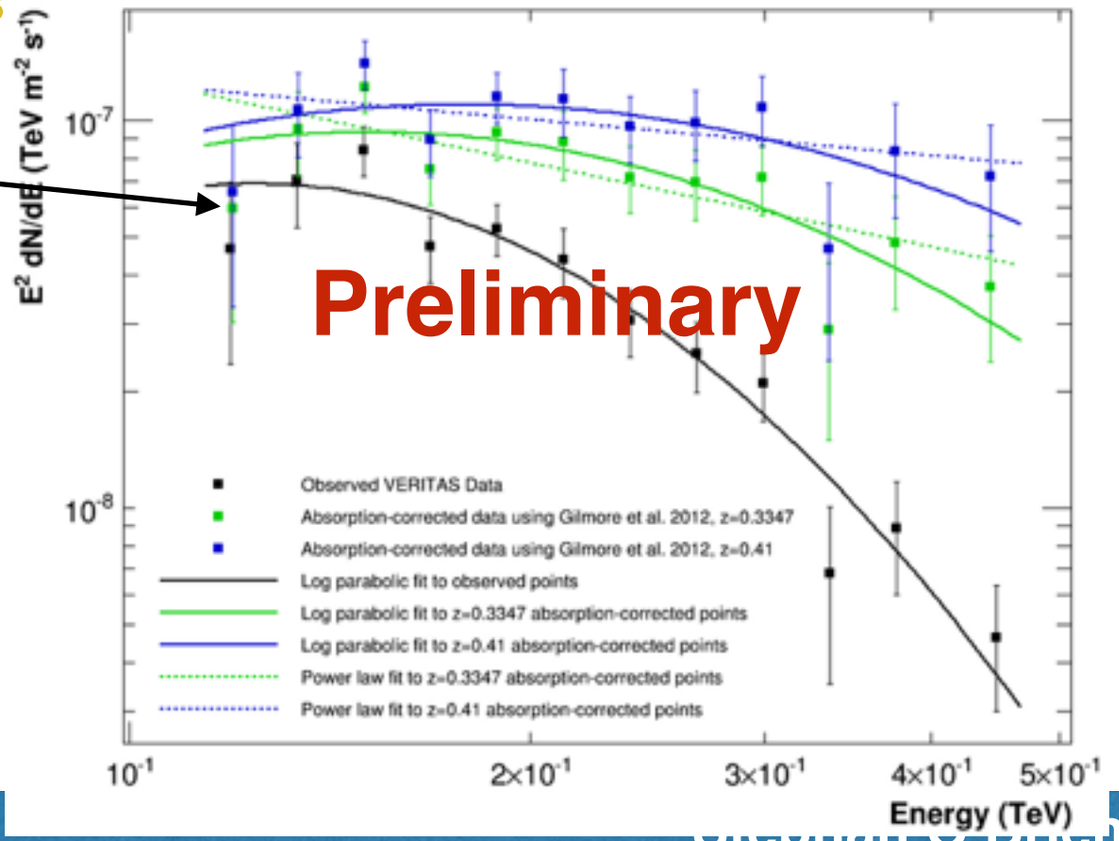
Monitoring of VERITAS IBLs

IBLs generally more difficult to detect a VHE

- To date **8 IBLs** have been detected at VHE, **5 detected by VERITAS**
- **W Comae and 3C66A**: Originally only detected during flares: **Low state detections (1-3% Crab) obtained with deep**, multi-year exposures: **Spectral index $\Gamma \sim 4$**
- **BL Lac**: **Only detected in flaring states**, typically rapid decay timescales, regular snapshots to search for flares, **Spectral index $\Gamma \sim 3.7$**
- **VER J0521+211**: **regularly detected**, variable flux state ~7 % Crab, **Spectral index $\Gamma \sim 3.4$**
- **PKS 1424+240**: **regularly detected**, flux ~1-5%, flux variability x5, **Spectral index $\Gamma \sim 3.7$**, distant source **(z>0.6035) very interesting for EBL studies**

3C66A





BL Lac 5th October 2016

IBL (z = 0.06). Only detected by VERITAS during flaring periods.

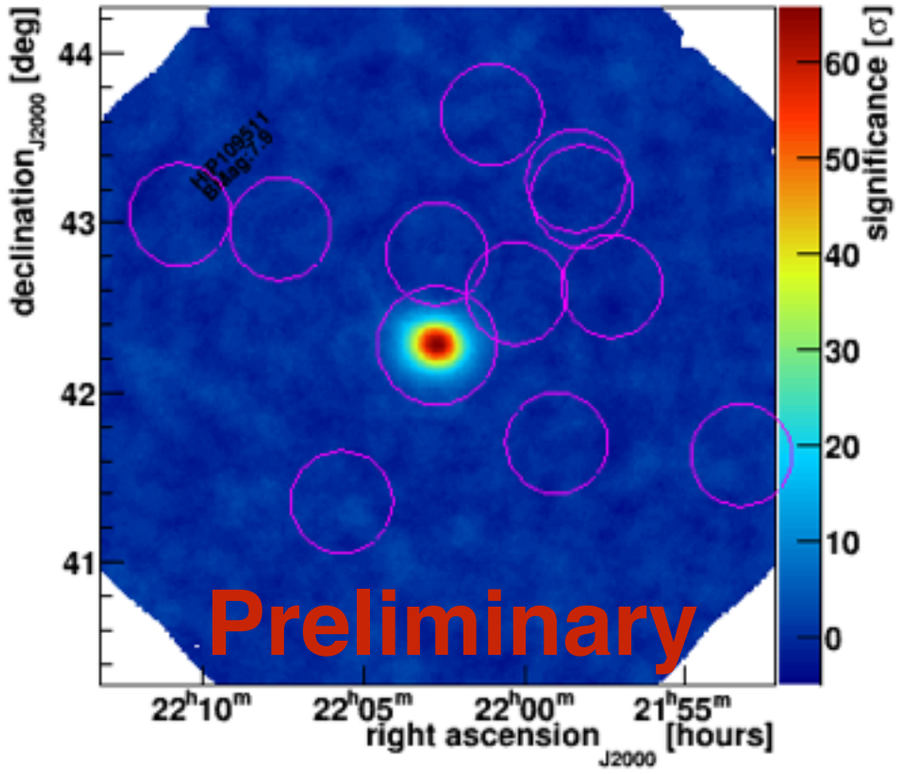
Regular monitoring snapshot on October 5th showed an elevated state of **Flux ~75% Crab**

ToO triggered by observers, monitored for an additional 3 hours

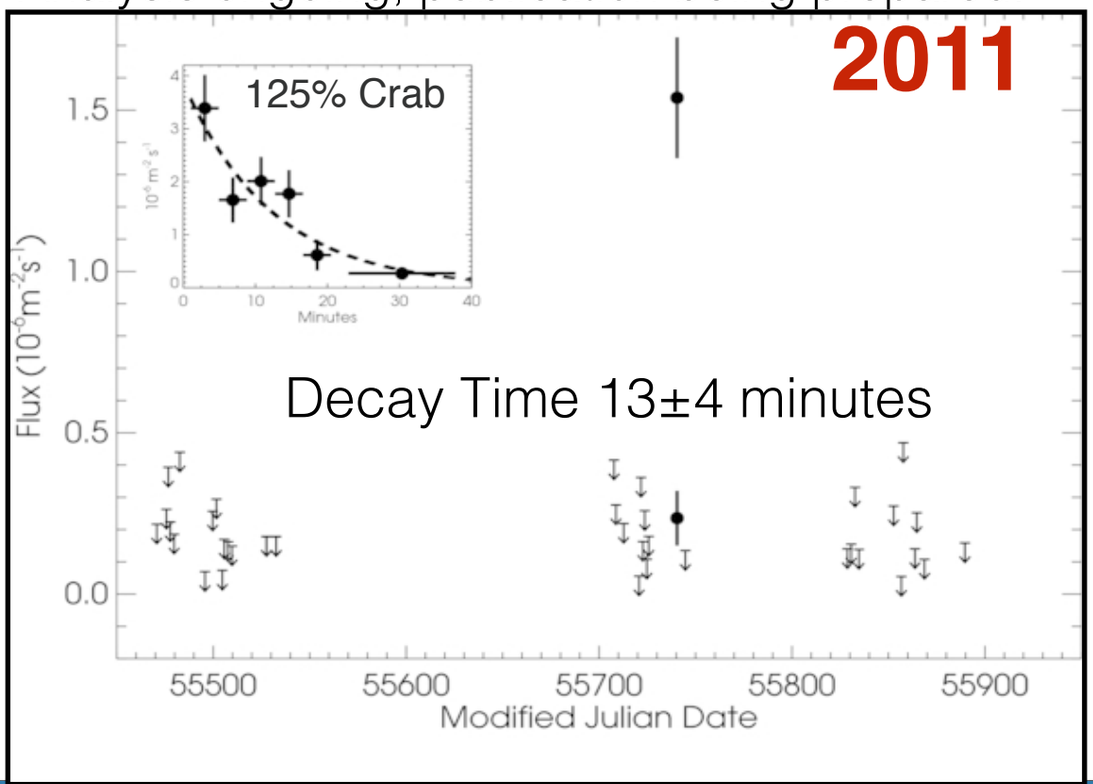
Flux rose to a **peak of ~ 140% Crab** 2 hours into observations

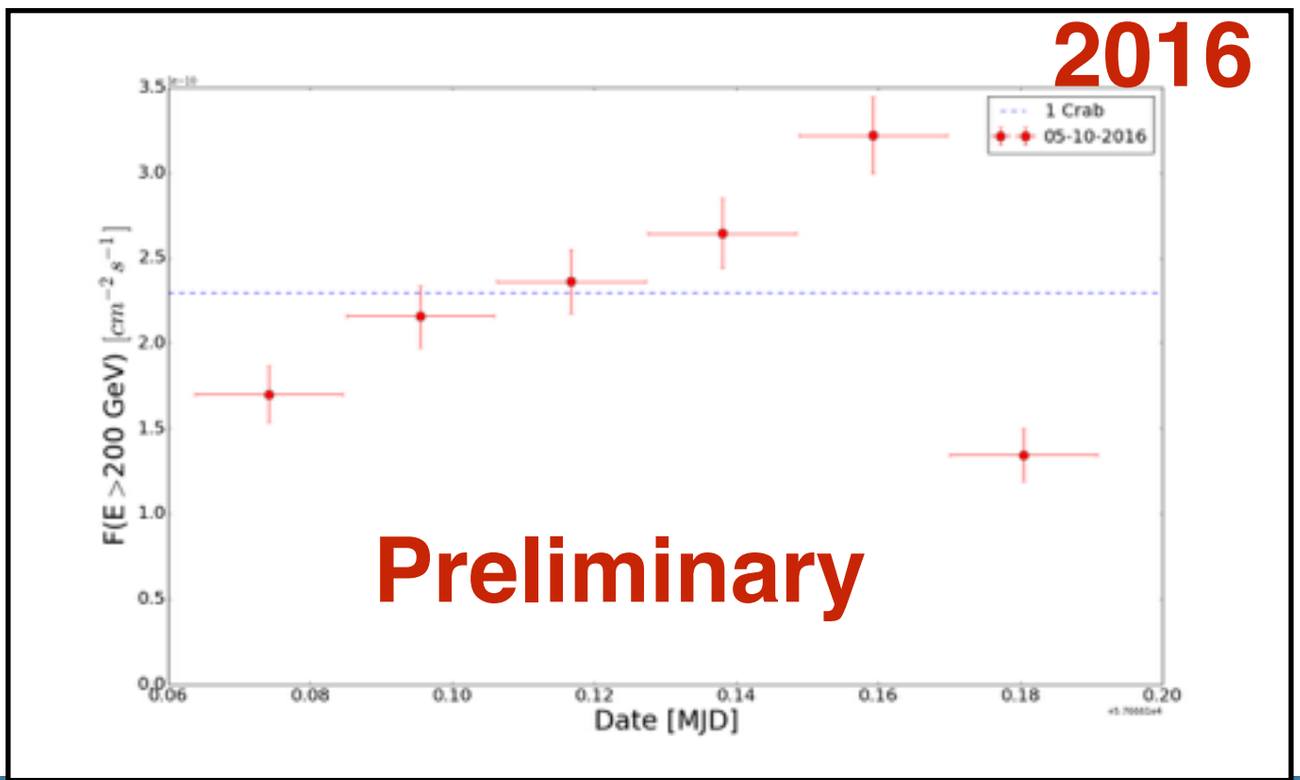
Decay timescale on the order of **1 run (~30 mins)**

Atel (#9599) released on 5th of October



Analysis ongoing, publication being prepared.





Radio Galaxies: NGC 1275

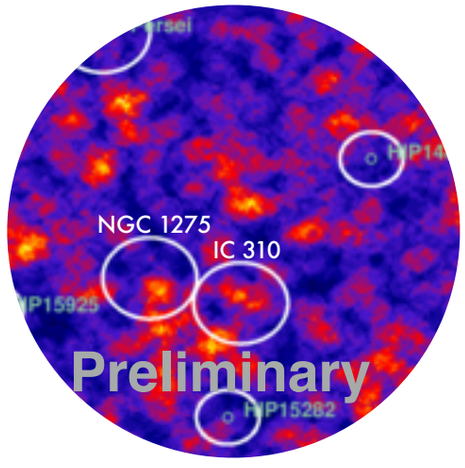
2 Radio galaxies detected by VERITAS: **M 87 (z = 0.0044) and NGC 1275 (z = 0.018)**
IC 310 (MAGIC detected, z = 0.0189) also monitored

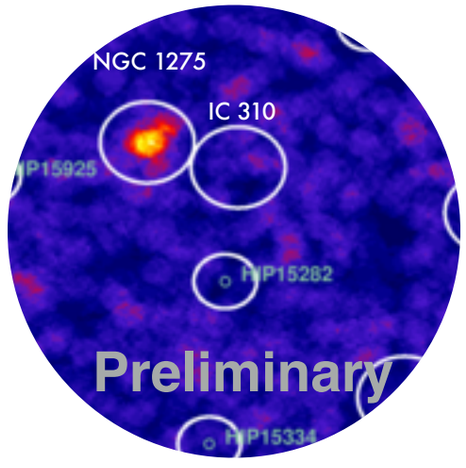
NGC 1275 Previously detected by VERITAS (**~1% Crab**, Benbow et al. 2015) and MAGIC (**~3% Crab**, Aleksic et al. 2014)

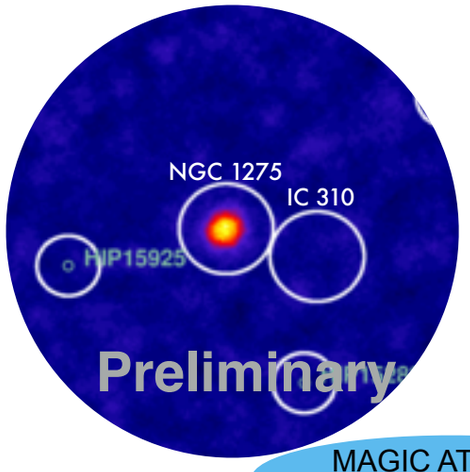
Regular Snapshot 30 minute on 30th of October showed a **strong excess at the location of NGC 1275**
Follow up ToO of 5 hours of observations taken on the 31st of October

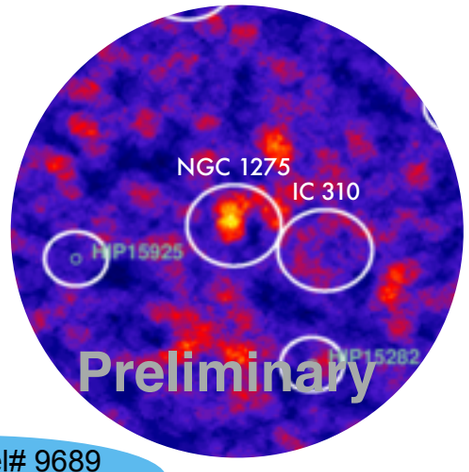
- **17 σ detection**
- Peak run-wise flux > 250 GeV measured to be (2.7 ± 0.67) x 10^{-11}cm^{-2}s^{-1} or **15% Crab** (Preliminary)

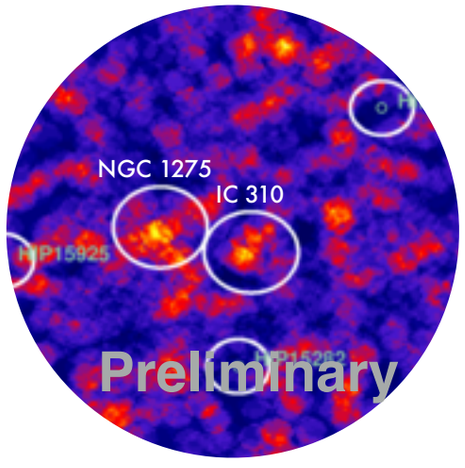
ATel (#9690) released on the 31st of October and follow-up observations taken on the 1st and 3rd of November











MAGIC ATel# 9689
VERITAS ATel# 9690

MJD57687	MJD57690	MJD57691	MJD57692	MJD57694
Significance = 1.40σ Exp. = 25.45 min. Rate = 0.14 ± 0.43 γ / min.	Significance = 6.03σ Exp. = 26.12 min. Rate = 0.69 ± 0.18 γ / min.	Significance = 17.01σ Exp. = 286.06 min. Rate = 0.59 ± 0.05 γ / min.	Significance = 4.26σ Exp. = 51.39 min. Rate = 0.29 ± 0.09 γ / min.	Significance = 2.00σ Exp. = 25.78 min. Rate = 0.20 ± 0.12 γ / min.

Blazar TAC proposals Beyond the LTP

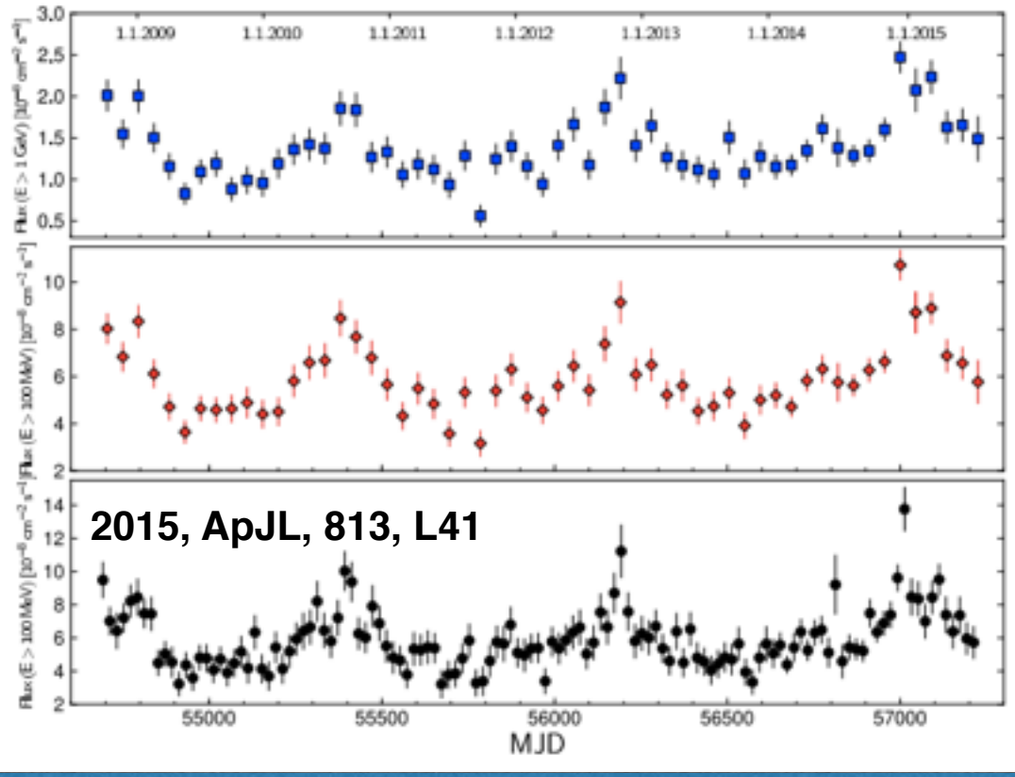
TAC proposals allow for beyond LTP observation

Such proposals range from **source monitoring**, **MWL follow ups and campaigns**, **detection candidates**

Example: **PG 1553+113** subject to an **intense monitoring program** coordinated with MAGIC to **search for VHE periodicity**

Evidence of HE Periodicity reported by Fermi-LAT (2015, ApJL, 813, L41)

Periodicity possibly due to variable helical structure, periodic disk instabilities or presence of a binary of super-massive black-holes



E > 1 GeV (45 day bins)

E > 100 MeV (45 day bins)

E > 100 MeV (20 day bins)

New Detection: RGB J2056+496

Non LTP supplemental TAC proposal

Discovery candidate based on it's 2FHL spectra, also a XMM-Newton and Swift-BAT source.

Unknown redshift

- TeV observations can, potentially, be used to constrain redshift

Observed for **4.2 hours** between **October 10th and November 6th 2016**:

- **Excess of 70 events** above the background detected
- Resulting in a **5.2 σ** detection

Preliminary Flux level > 200 GeV:

- $(9.4 \pm 2.2) \times 10^{-12}$ cm^{-2} s^{-1}
- **4.0 % Crab**

ATel #9721 released on the 6th of November and additional observations taken.

Located 13" away from micro-quasar candidate: LS III +49 13 (not disguise between with VERITAS)

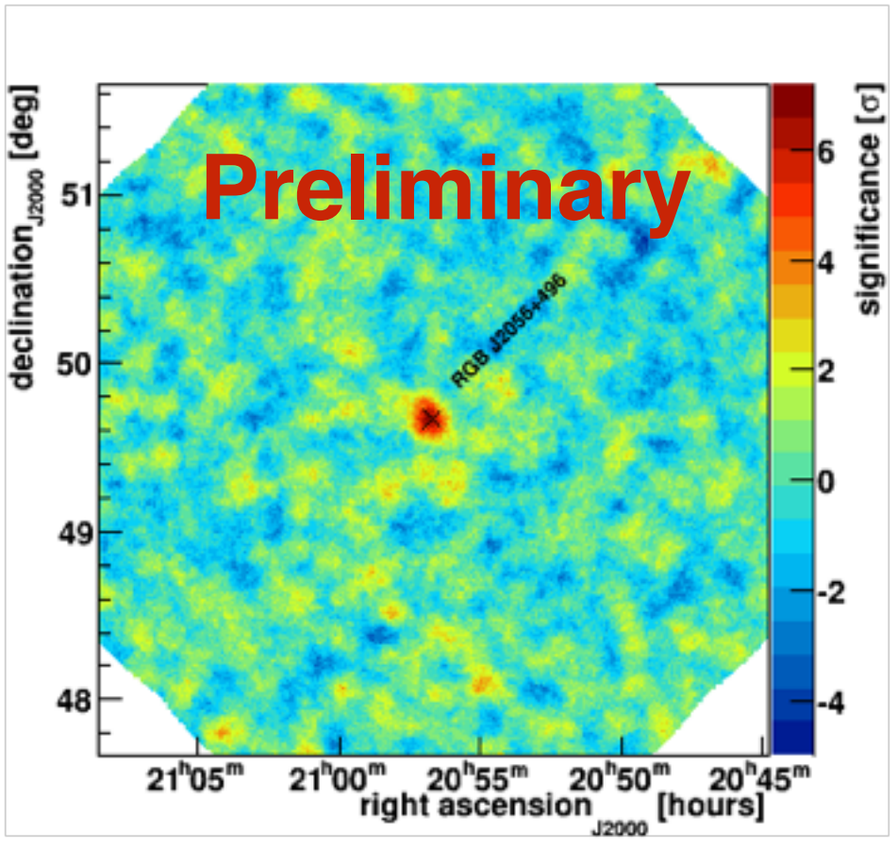
VERITAS Discovery of VHE Emission from RGB J2056+496

ATel #9721; *Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration*
on 6 Nov 2016; 20:55 UT
Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)

Subjects: Gamma Ray, >GeV, TeV, VHE, AGN, Blazar

Tweet Recommend 50

We report the first detection of VHE emission from RGB J2056+496. This blazar, of unknown redshift, was targeted by VERITAS due to its favorable properties above 50 GeV, as described in the Fermi-LAT 2FHL catalog (M. Ackermann, et al., ApJS, Vol. 222, No. 1 (2016).Â The blazar is also an XMM-Newton source and a Swift-BAT source. It was observed for 4.2 h of good-quality live time between October 10, 2016 and November 6, 2016.Â A preliminary analysis of these observations yields an excess of 70 events above the background at the position of the blazar, corresponding to a statistical significance of 5.2 standard deviations.Â We interpret this excess as the discovery of VHE gamma-ray emission from the blazar.Â The corresponding flux observed above 200 GeV is (9.4 +/- 2.2) x10^-12 cm^-2 s^-1, or 4.0% of the Crab Nebula flux above the same threshold. We note that the blazar is 13 arc-seconds distant from the micro-quasar candidate LS III +49 13, and the two objects are effectively co-located for VERITAS. VERITAS will continue to observe RGB J2056+496 and multi-wavelength observations are encouraged. Questions regarding the VERITAS observations should be directed to Reshmi Mukherjee (muk@astro.columbia.edu).Â Contemporaneous target-of-opportunity observations with the Swift satellite have also been scheduled. VERITAS (Very Energetic Radiation Imaging Telescope Array System) is located at the Fred Lawrence Whipple Observatory in southern Arizona, USA, and is most sensitive to gamma rays between ~85 GeV and ~30 TeV (http://veritas.sao.arizona.edu).



Sharing Blazar Observing Schedule

Motivated by MOJAVE:
http://www.physics.purdue.edu/MOJAVE/blazarlist.html

VERITAS will share a list of previous observations (2007-Present) of AGN regularly monitored by VERITAS

VERITAS Blazar Monitoring Program

VERITAS regularly monitors a set of very high energy (VHE) blazars. Our goal is to build a deep archival data set on these sources. Observations will be scheduled at regular intervals, generally once every three nights. Note that observation scheduling may vary depending on the weather conditions, visibility, and for other reasons. The following table shows the list of regularly-monitored blazars. Click on a source name to open the list of VERITAS observation windows since 2009 to present.

Source	RA (J2000) hh mm ss.ss	DEC (J2000) dd mm ss.ss
1ES 0229+200	02 32 48.59	+20 17 16.92
RGB J0710+591	07 10 30.10	+59 08 20.96
1ES 1218+304	12 21 21.9	+30 10 36.99
PKS 1424+240	14 27 00.4	+23 47 59.93
H 1426+428	14 28 32.6	+42 40 28.91
3C 66A	02 22 39.6	+43 02 07.97
W Comae	12 21 31.7	+28 13 59.05
BL Lac	22 02 43.3	+42 16 39.91
Mrk 421	11 04 27.30	+38 12 32.02
Mrk 501	16 53 52.19	+39 45 37.05
M87	12 30 49.40	+12 23 28.10
1ES 0414+009	04 16 53.00	+01 04 54.07
1ES 0502+675	05 07 56.30	+67 37 24.04

VERITAS also performs shallow observations of all VHE blazars with good visibility to VERITAS that are not explicitly summarized above. Our goal is to build at least 10 hours of exposure on each known northern VHE blazar by 2019. Generally VERITAS observes each of these blazars eight times per year. Each observations is typically 15 minutes long.

VERITAS Blazar Monitoring: 1ES0229+200

Click for csv file.

source	ra	dec	start time	end time	duration
1ES0229+200	02h32m48.5944s	+20d17m16.924s	2016-11-23 06:40:04	2016-11-23 07:10:15	0:30:00
1ES0229+200	02h32m48.5944s	+20d17m16.924s	2016-11-23 06:09:24	2016-11-23 06:39:34	0:30:00
1ES0229+200	02h32m48.5944s	+20d17m16.924s	2016-11-23 05:38:41	2016-11-23 06:08:51	0:30:00
1ES0229+200	02h32m48.5944s	+20d17m16.924s	2016-11-23 05:06:43	2016-11-23 05:36:52	0:30:00
1ES0229+200	02h32m48.5944s	+20d17m16.924s	2016-11-19 06:57:45	2016-11-19 07:27:57	0:30:00
1ES0229+200	02h32m48.5944s	+20d17m16.924s	2016-11-09 07:10:36	2016-11-09 07:40:51	0:30:00

Sharing Blazar Observing Schedule

Dates of scheduled upcoming coordinated Swift observations

Subject to changes based on weather and other constraints

Make up observations generally planned in the even of missed simultaneous snapshots

Page not currently live (coming soon!)

Interested collaborators are encouraged to get in contact!

Coordinated observations with Swift

VERITAS and Swift perform coordinated multiwavelength observations on selected blazars. The following table shows the scheduled dates for the upcoming simultaneous observations.

VERITAS Blazars Scheduled for simultaneous observations with Swift

Source Name	Scheduled Date
1ES 0229+200	12/2/2016
RGB J0710+591	12/2/2018
1ES 1218+304	12/2/2018
PKS 1424+240	12/2/2018
H 1426+428	12/2/2017
3C 66A	12/2/2017
W Comae	12/2/2017
BL Lac	12/2/2017
Mrk 421	12/2/2016
Mrk 501	12/2/2016
1ES 0414+009	12/2/2016
VER J0521+211	12/2/2016
1ES 0502+675	12/2/2016
S5 0716	12/2/2016
Test	date

Table Last updated 2016-11-30 03:25:02.401536

Note that the observation schedule might vary dependent on weather conditions and for other reasons. If you are interested in organizing a joint multiwavelength campaign with VERITAS please contact the VERITAS spokesperson

Conclusions

VERITAS is fully funded to **operate until at least 2019**

VERITAS **AGN Long Term Plan** receives **~300 hours** of observations, with **non-LTP AGN observations** making up an additional **~300 hours**.

Shift from discovery orientated observations to deep exposures and monitoring programs, however **discovery program still providing new detections**

Successful monitoring program in place: **Pre-approved ToO time allows for follow up on alerts**

Will continue to monitor **all known Northern VHE AGN** and follow up on MWL alerts

Resource for accessing previous and upcoming VERITAS AGN observations dates will soon be in place