Very-High-Energy γ-Ray Observations of Active Galactic Nuclei with VERITAS

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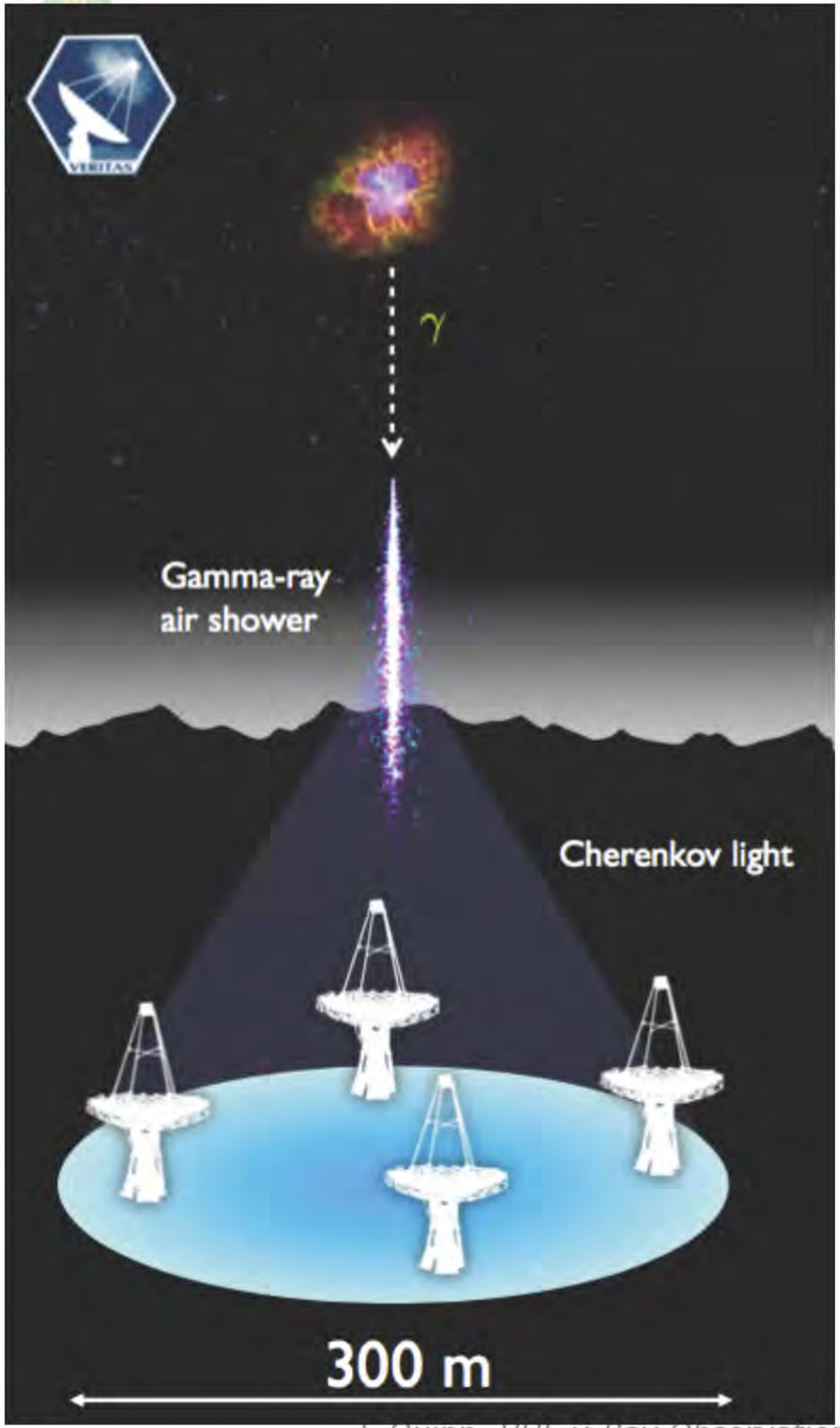
& on behalf of the VERITAS Collaboration

VERITAS Status & Performance



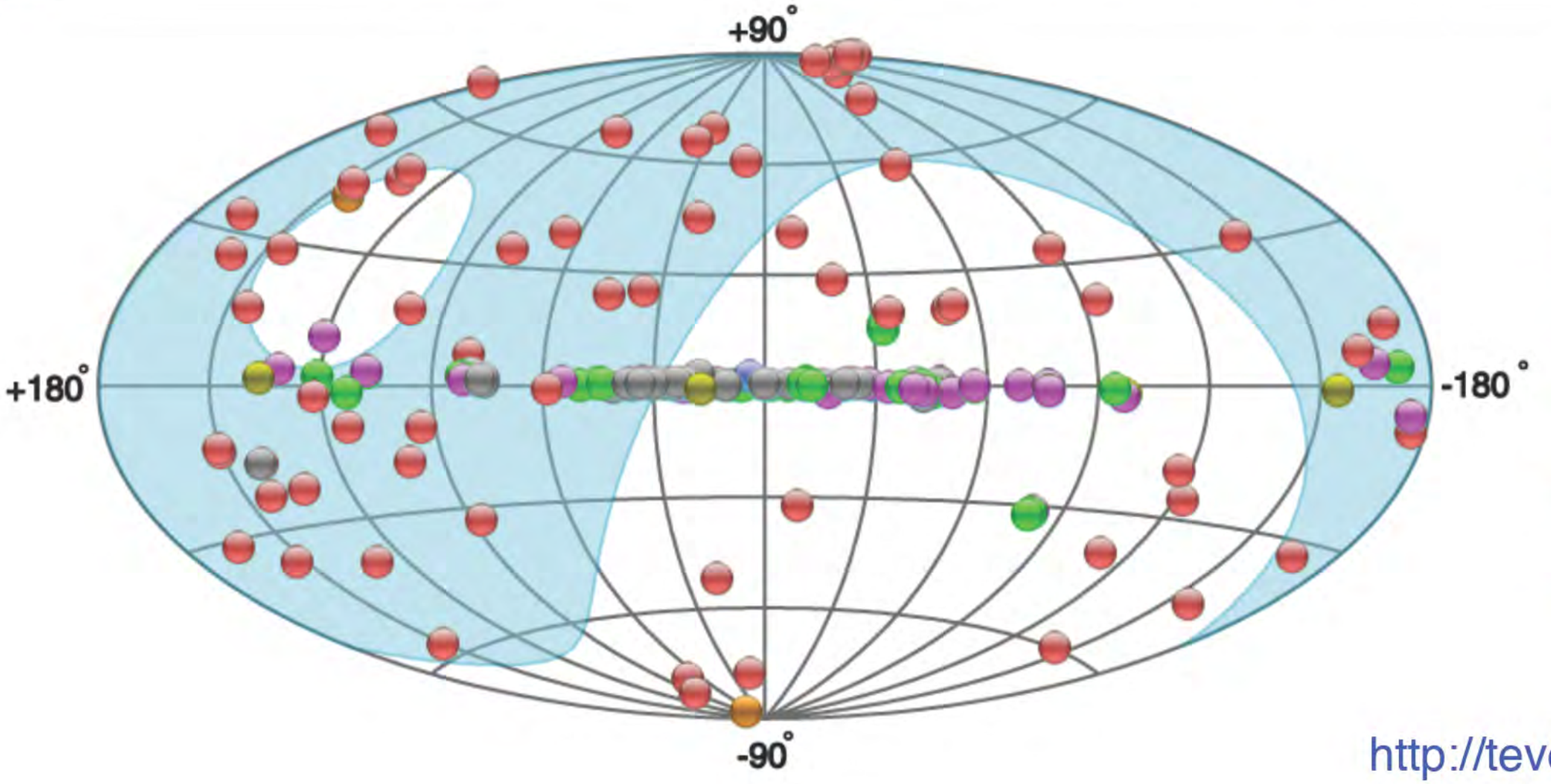
- Entered full 4-telescope operation in 2007.
- Funding is in place to operate through 2019.
- Major hardware upgrades 2009 & 2012 + improved analysis techniques → increased sensitivity (2x) and reduced energy threshold (by 40%).
- Good-weather science data:
  - "Dark": ~1,000 hrs per year
  - "Bright Moon" (since 2012): + ~300 hrs per year >350 GeV

VERITAS Current Performance

Energy Range:	85 GeV - 30 TeV
Energy Resolution:	15 - 25%
Angular Resolution:	~ 0.08° at 1 TeV
Pointing Accuracy:	< 50"
Effective Area:	~10^5 m^2 at 1 TeV
Field-of-view:	3.5°

Can detect (5σ) 1% Crab source in 25 hrs

The VHE sky - 176 objects



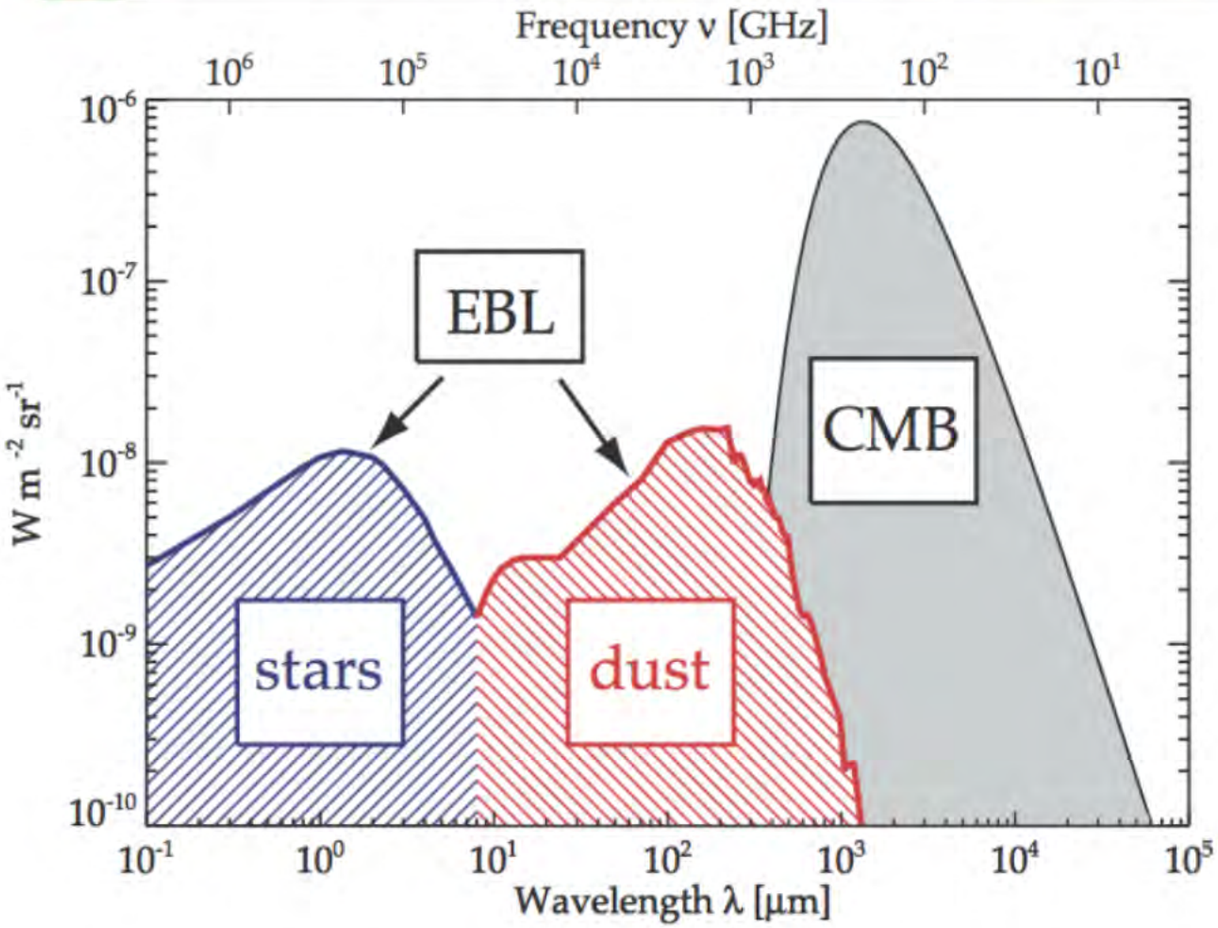
http://tevcat.uchicago.edu

The Extragalactic VHE sky (as of 21/06/2016):

- 8 LBL/IBL
- 46 HBL
- 5 FSRQ
- 4 FRI
- 2 Starburst

} 63 AGN - number comparable to that of EGRET AGN catalogue

The EBL and the γ-ray Horizon



Extragalactic Background Light (EBL):

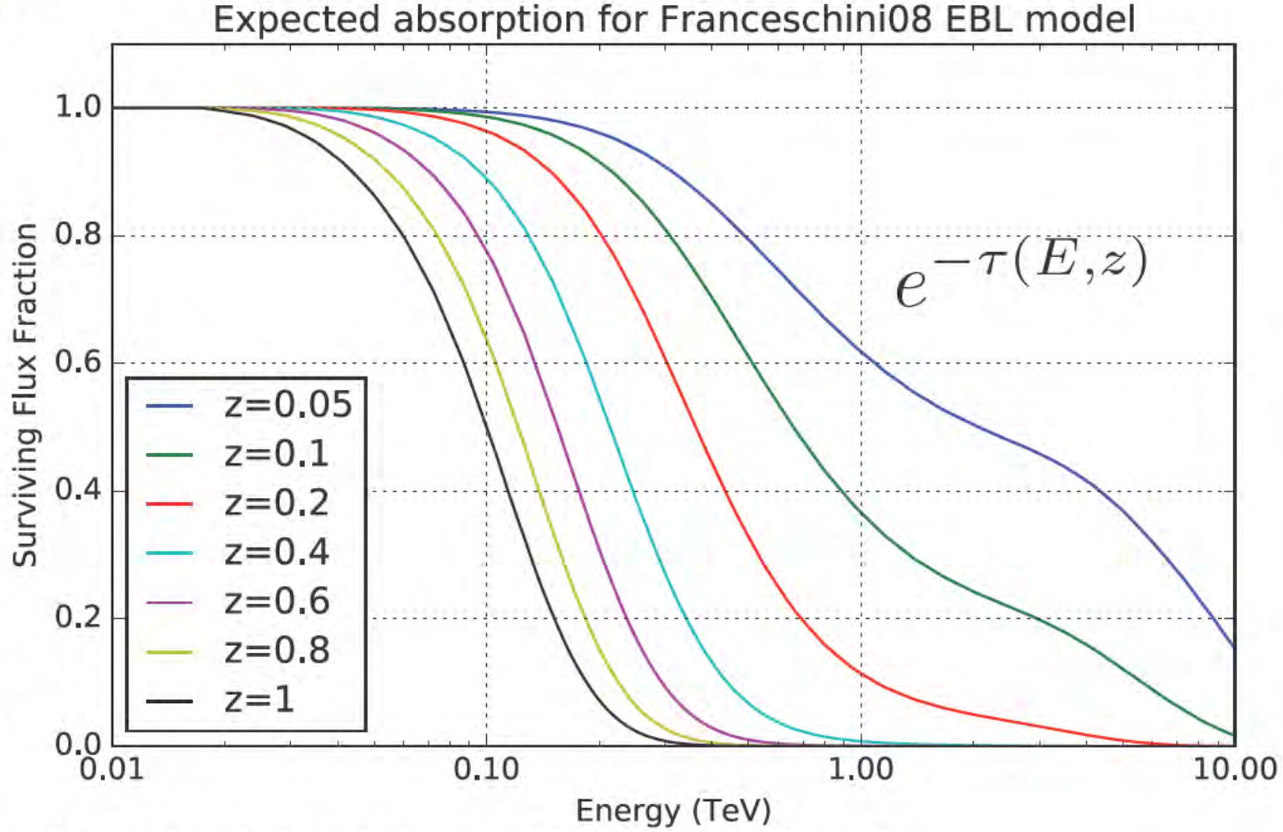
- of cosmological interest but difficult to measure directly due to foreground contamination.
  - Use VHE observations to constrain EBL…
- Places an effective horizon from beyond which we will see no TeV gamma rays
- Measured spectrum modified by $e^{-\tau(E,z)}$

VHE γ-ray photons interact with low-energy photons to produce electron-positron pairs:

$$\gamma_{HE} + \gamma_{EBL} \rightarrow e^+ + e^-$$

Cross section maximum when:

$$\lambda = 1.33\ \mu m \left(\frac{E}{TeV}\right)$$



VERITAS Blazar Discovery Program

- **2007-2012**: Focus on Blazar discovery (~75%) + ToO (~25%)
  - X-ray-selected BL Lacs (Costamante & Ghisellini 2002, Costamante 2007, Perlman 2000, Stecker 1996)
  - X-ray-brightest nearby HBLs in Sedentary (Giommi et al. 2005) ROXA (Turriziani et al. 2007)
  - High-Frequency FSRQs (Perlman 2000, Padovani 2002, Falcone et al. 2004)
  - EGRET & *Fermi*-LAT: 0FGL, 1FGL,& 2FGL, photon clusters
  - Reasonable redshift: generally $z < 0.3$ but good candidates with $z > 0.3$
  - Almost all data has been published as discoveries or in U.L. paper
- **2012-**
  - Discovery reduced to ~20% of "Dark" time + "Bright-Moon" observations
  - New discovery targets:
    - Fermi-LAT: 1FHL and 2FHL, >100 GeV photon clustering (Armstrong et al. 2015)
    - Ultra-high-frequency BL Lac objects (Nieppola et al. 2006)
    - Highest-frequency-peak BL Lacs from SDSS sample
    - Extend redshift range to z~1
    - ToOs triggered by our snapshot program and by other instruments…

The VERITAS AGN Catalogue

2007-2015: 3,400 hrs of 'dark' obs.

+

2012-2015: 530 hrs 'bright moon' obs.

=

~ 600 hrs. per year dedicated to AGN

(time: 90% Blazars, 10% Radio Galaxies)

Catalogue: 34 VHE AGN:

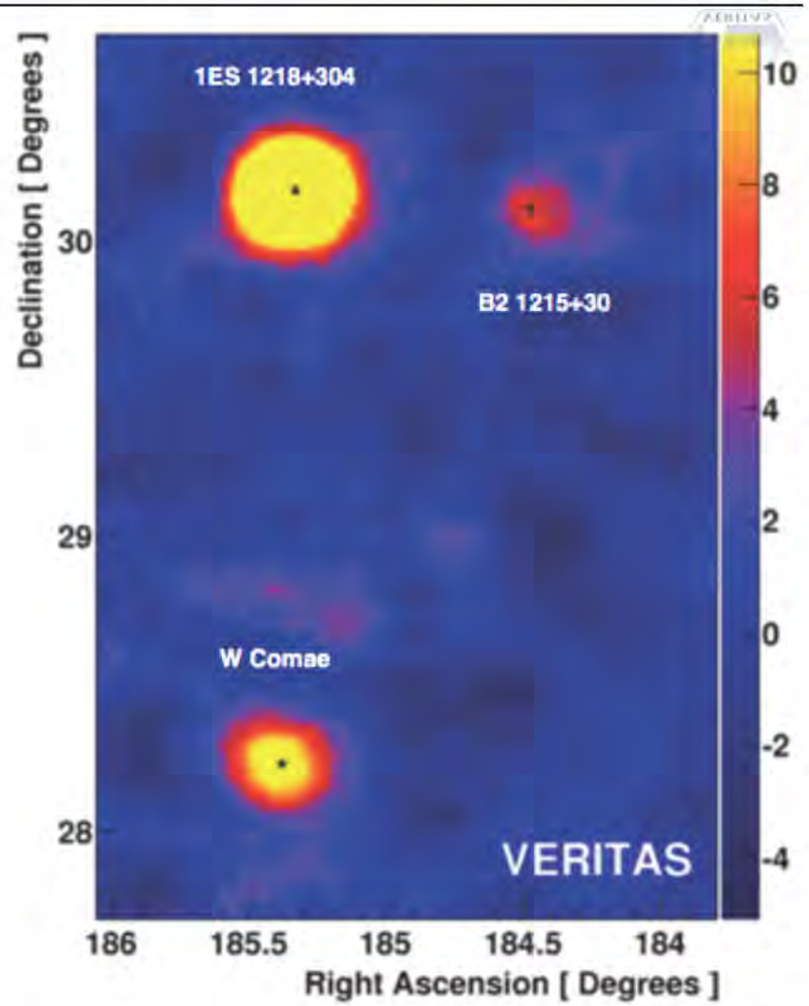
- 24 x HBL
- 6 x IBL
- 2 x FSRQ
- 2 x FR I

2013-2015: 7 new detections

All VERITAS AGN are Fermi-LAT detected.

We have multi-wavelength observations coincident with the majority of our observations.

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	IBL	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



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	HBL	?
HESS J1943+213	HBL	?
RGB J2243+203	IBL	?

VERITAS Blazar Limits 2007-2012

- VERITAS observed 130 Blazars in the period 2007-2012
  - 114 not detected: "*Upper Limits from Five Years of Blazar Observations with the VERITAS Cherenkov Telescopes*", Archambault et al., AJ, 151, 142 (2016) (+16 optical spectra from which there were 4 redshift determinations)
  - Stacked analysis yields a 4σ excess with 3σ coming from nearby (z<0.6) HBLs

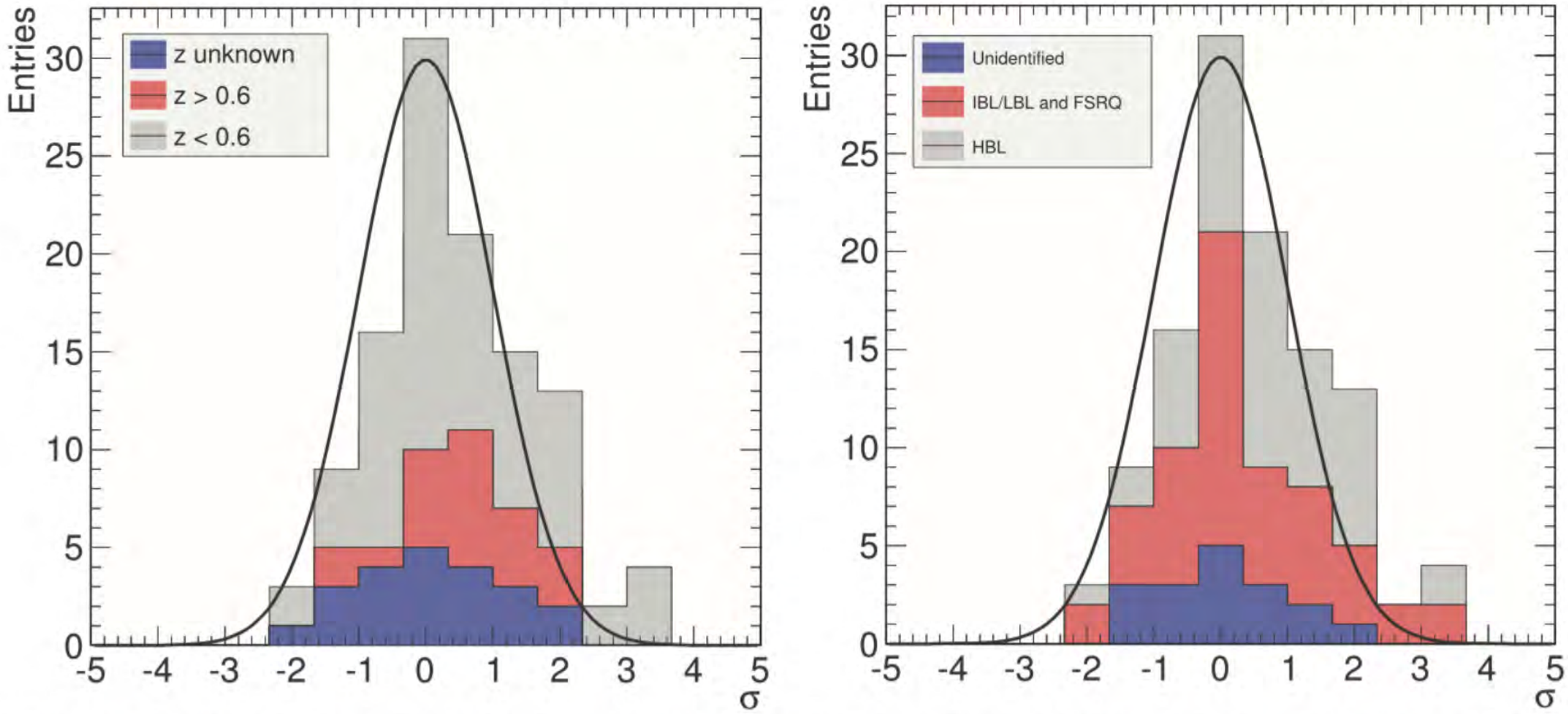


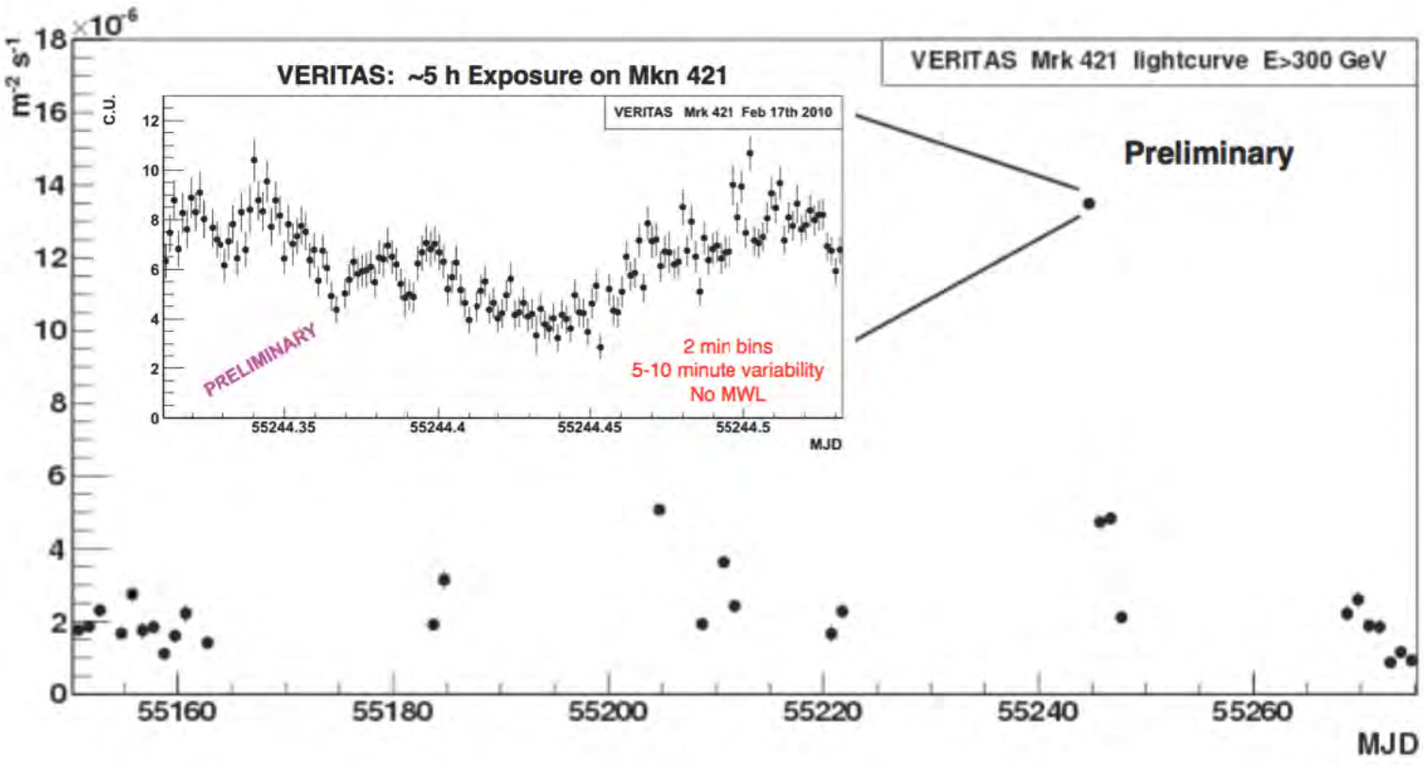
Figure 1. Left: stacked significance distribution of the sources included in our sample, classified according to their redshift. Sources with unknown z are in blue, sources with $z > 0.6$ are in red and sources with $z < 0.6$ are in gray. The Gaussian function represents the expectation from a randomly 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.

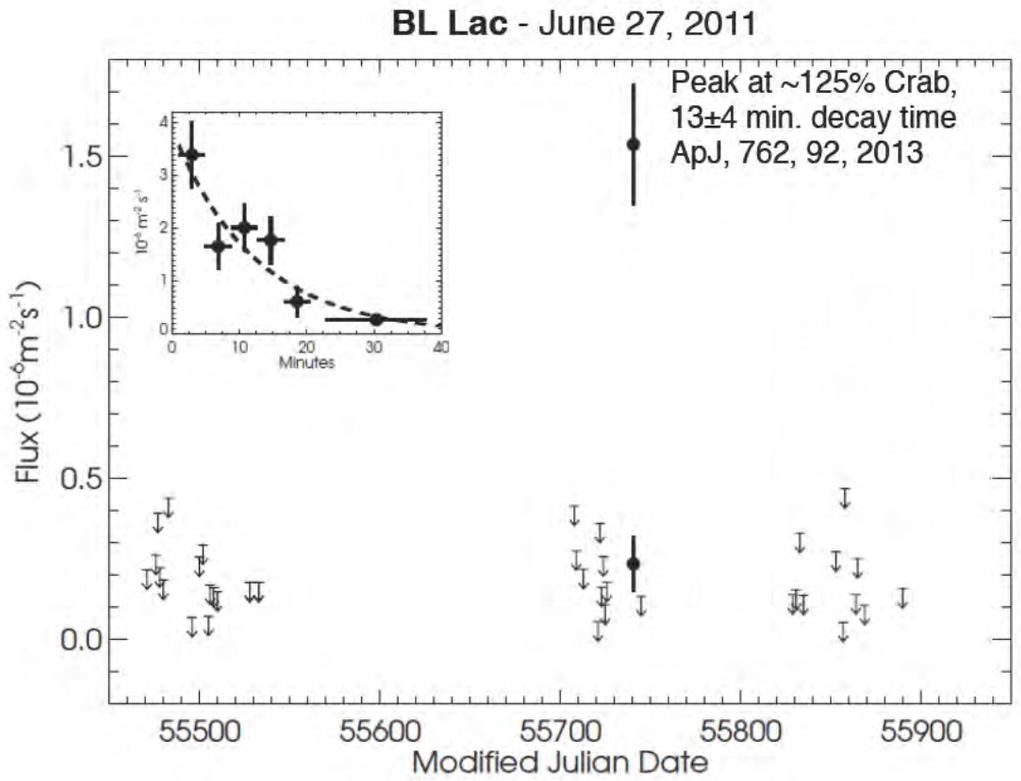
Properties of VERITAS-detected Blazars

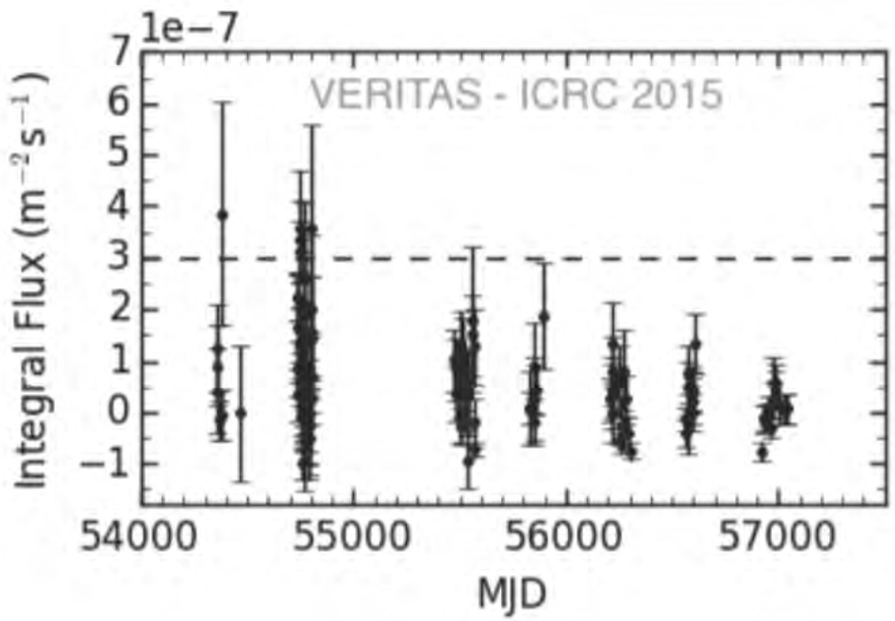
- **HBLs**:
  - Markarian 421 & Markarian 501: highly variable (variability as short as 10 mins, flares to 10 x Crab), spectra to ~ 20 TeV, evidence for curved spectra (intrinsic)
  - 1ES 1959+650: generally ~0.25 Crab, isolated hour-scale flare to 1.2 x Crab, but **2015-2016 enhanced activity** (multiple >1 Crab flares, hour-scale variability, multiple VHE & X-ray ATELs). Previous extended outburst (2002-2003) and historic "Orphan Flare" → leading candidate for neutrino detection.
  - Other HBLs: weak, fluxes typically 2-10% of Crab Nebula, variability x2-3 on timescales of days to years, Crab-scale flares rare.
- **IBLs**:
  - Weak or only detected during flares.
    - 3C66A & W Comae were originally only detected during flares (>6% Crab), now with deep exposures starting to detect low states (~1% Crab).
    - BL Lac - only detected during a once-off flare of 125% Crab (13-minute decay time)
    - VERJ0521 & PKS 1424+240 (z>0.6035, most distant consistently-detected source) variable but regularly detected.
- **FSRQs**:
  - Only detected during flares.

VERITAS Blazar: Variability

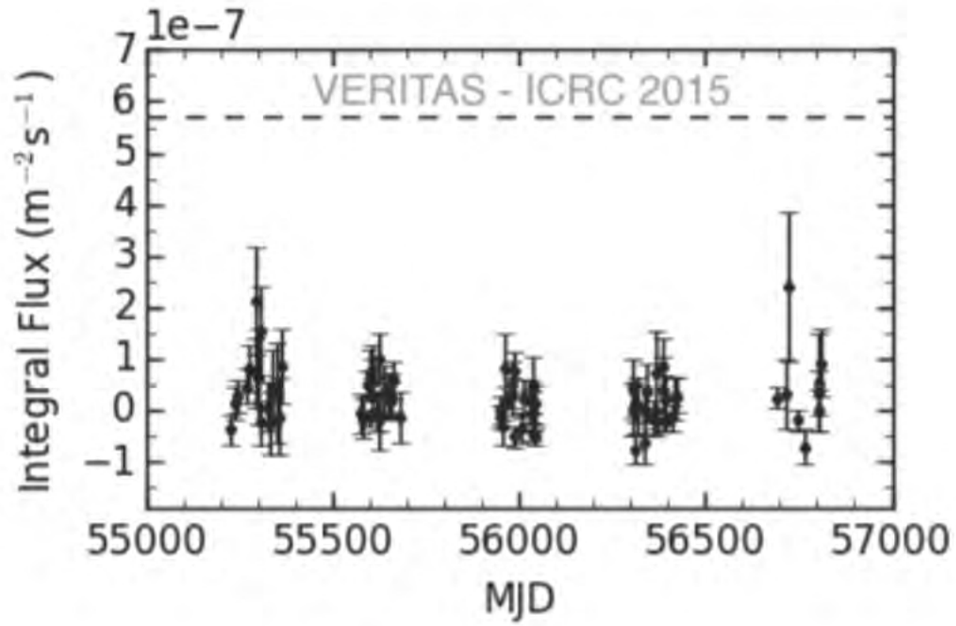
- Blazars exhibit variability on timescales of years to ~10 minutes (brightest) - flickering common.







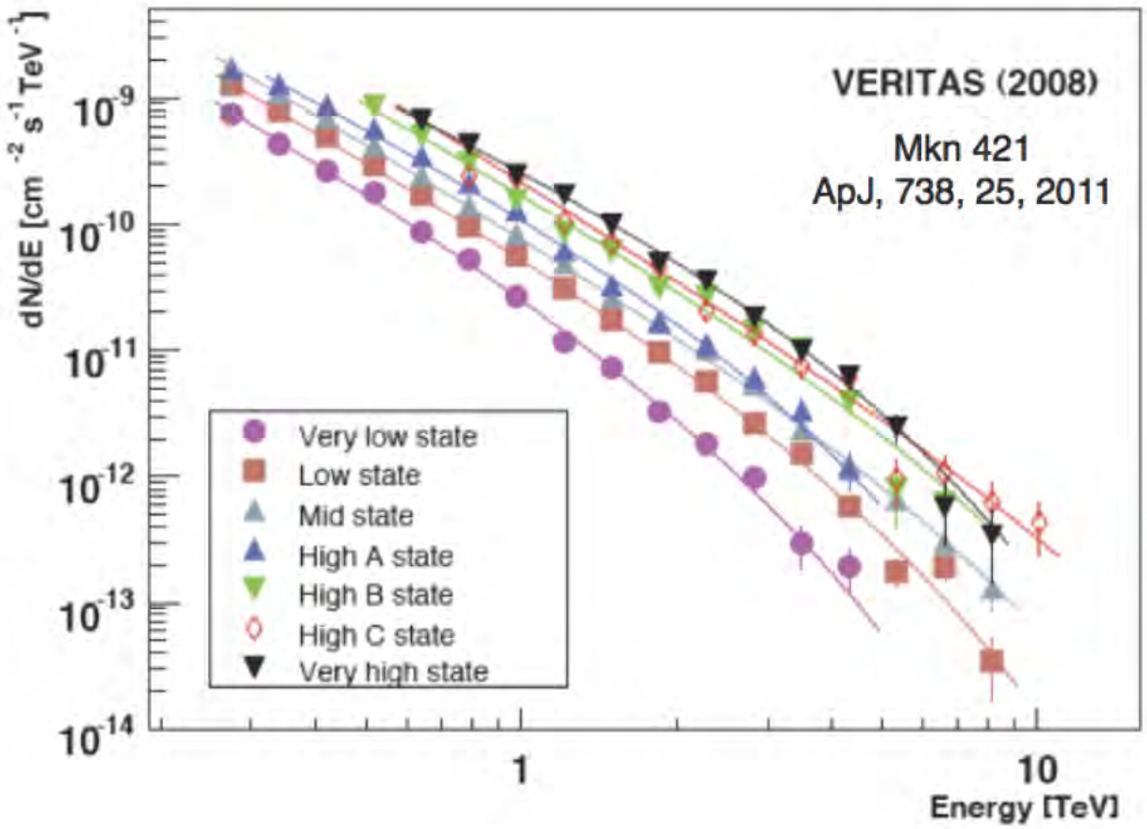
(a) 3C 66A

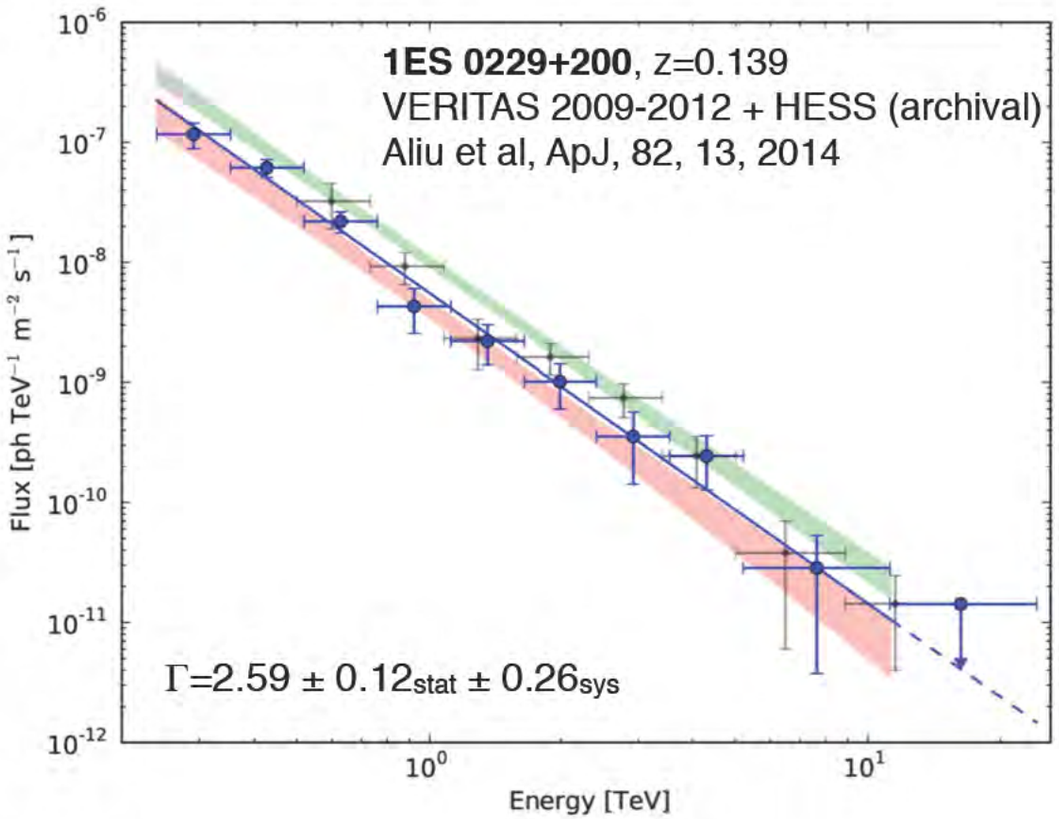


(b) W Comae

VERITAS Blazar: Spectra

- VHE spectra (dN/dE) generally characterised by a power law ($E^{-\Gamma}$) (sometimes with cut-off or curvature).
- Spectral index Γ tends to harden with increased flux and to be softer for more distant sources.





- HBLs: Γ ranges from ~2.5 to ~5.
- IBLs: Γ typically ~3.5 - 4
- Markarian 421/501 have been detected to ~20 TeV, but most objects don't get above a few TeV.
- Some objects have hard spectra for their redshifts, which makes their 'intrinsic' spectra interesting.

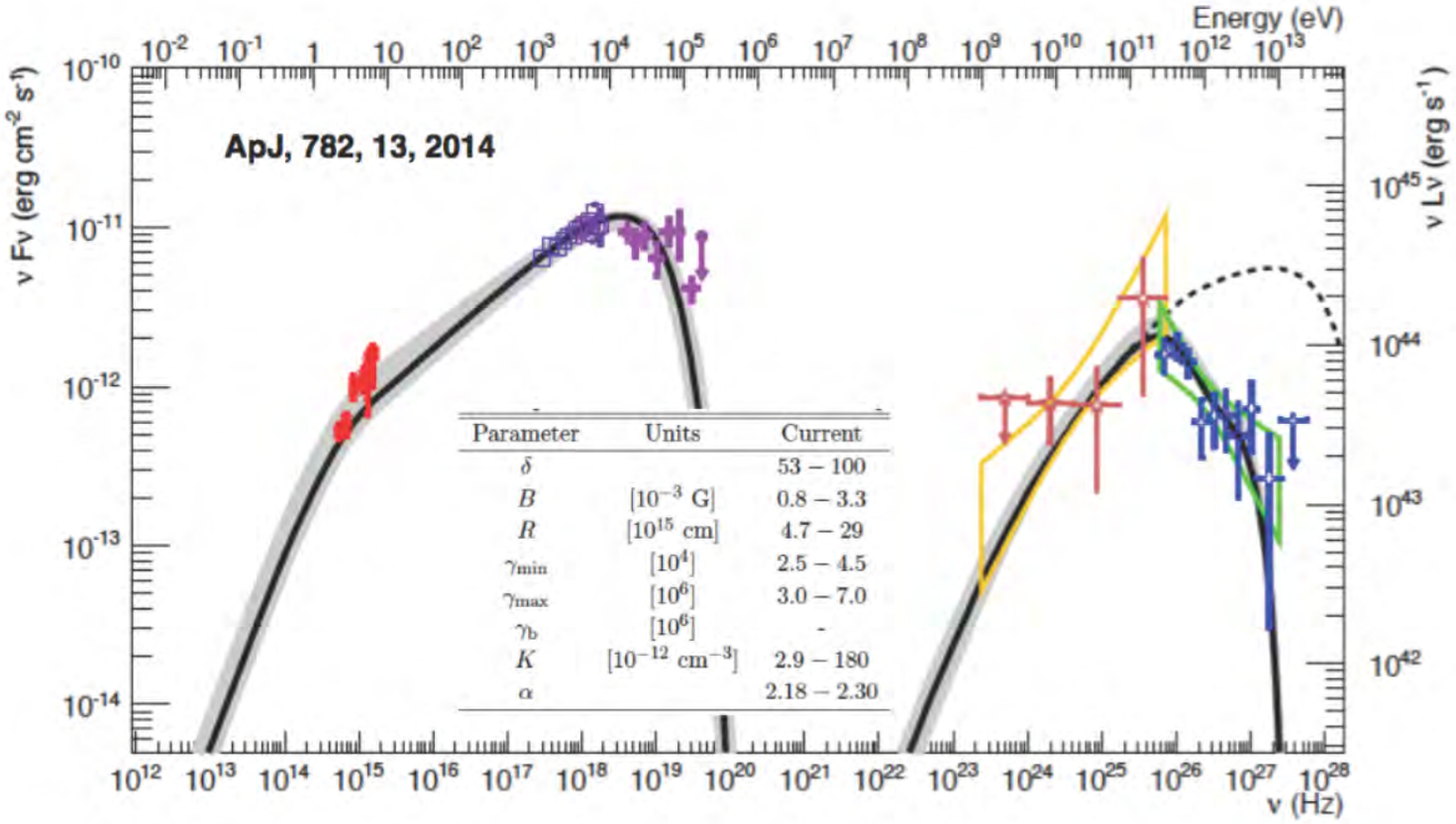
VERITAS SED Modelling

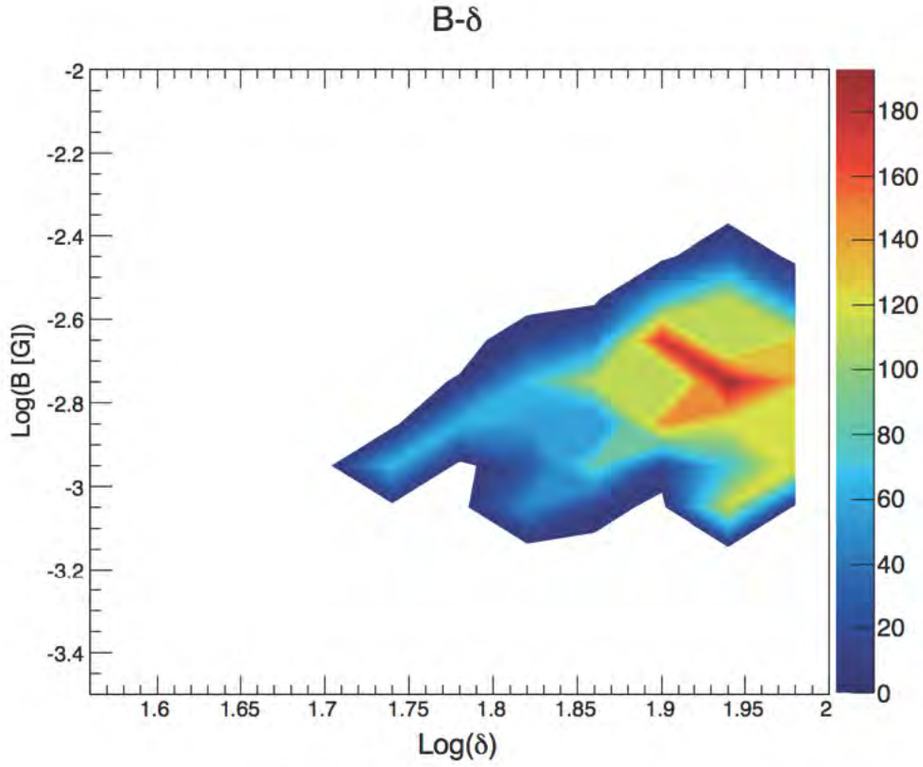
HBLs: tend to be reasonably modelled by SSC, but not always

IBLs: SSC not adequate - generally need EIC too.

FSRQs: PKS 1441+25: adequately described by EIC

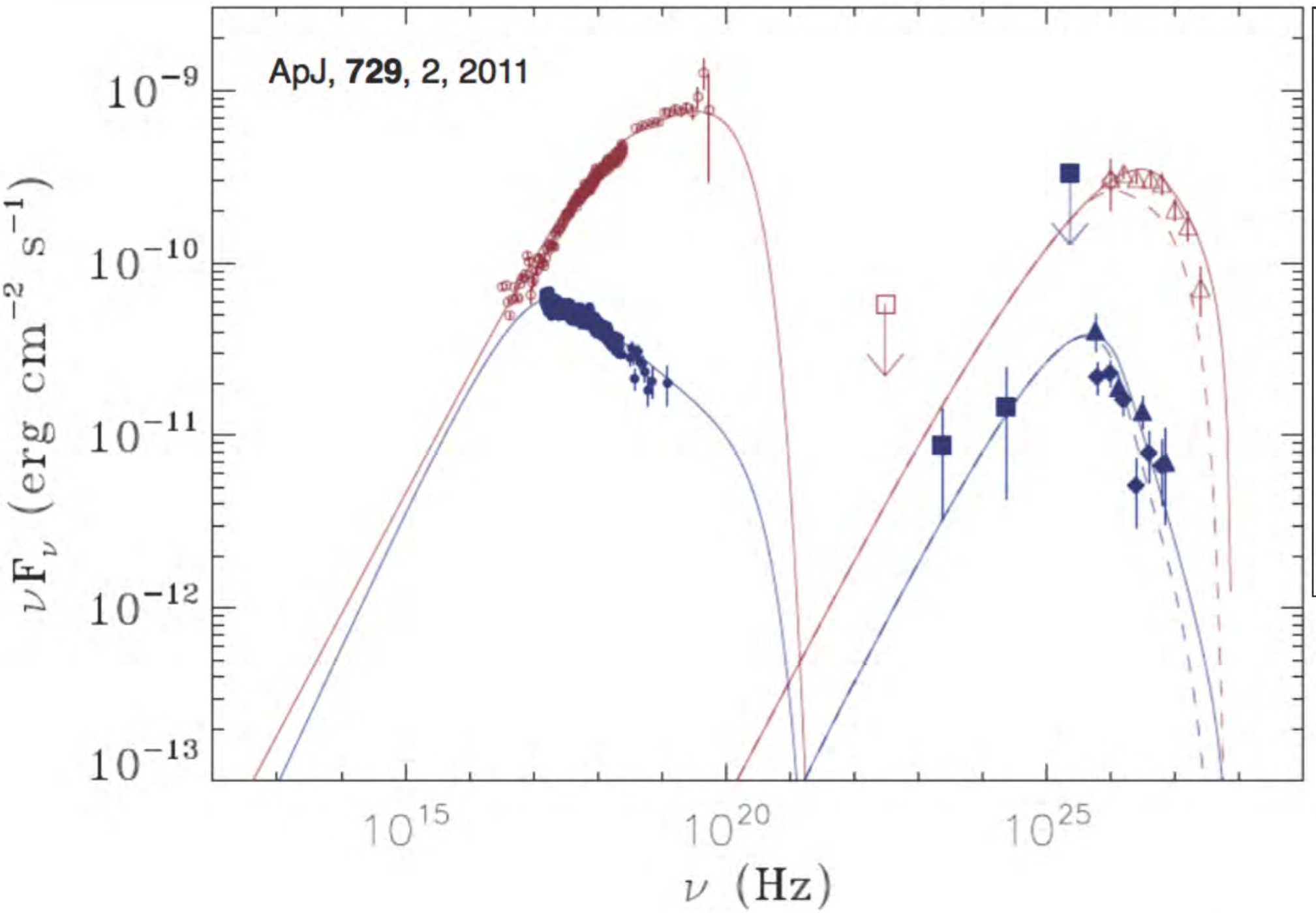
Example: **1ES0229+200**, z=0.139





- VERITAS Observations 2010-2012: 54 h; ~12σ, 1.7% Crab, $\Gamma = 2.59 \pm 0.12$
- MW SED: Swift UVOT, Swift XRT, Swift BAT, Fermi-LAT, VERITAS
- SED compatible with SSC,and SSC parameter space constrained.

Extreme Variability: e.g. Markarian 421 & 501



Mkn 501

1997 Flare

2009 low state

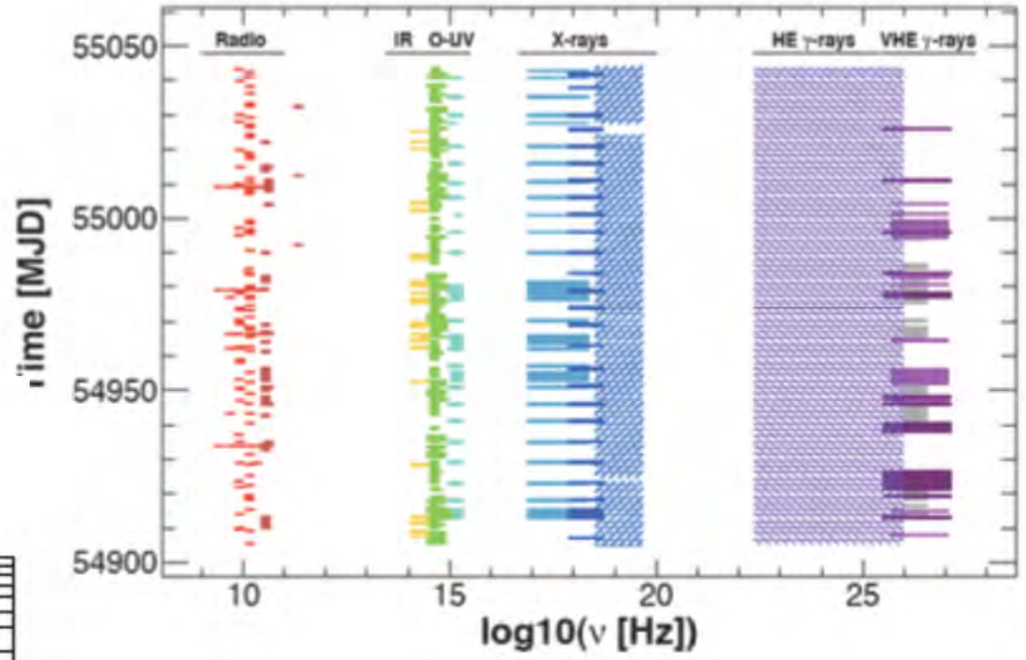
Synch. peak moves by 2 orders of mag.

Mkn 501: SSC scenario successful for both states: Transition ~due to change in electron distribution

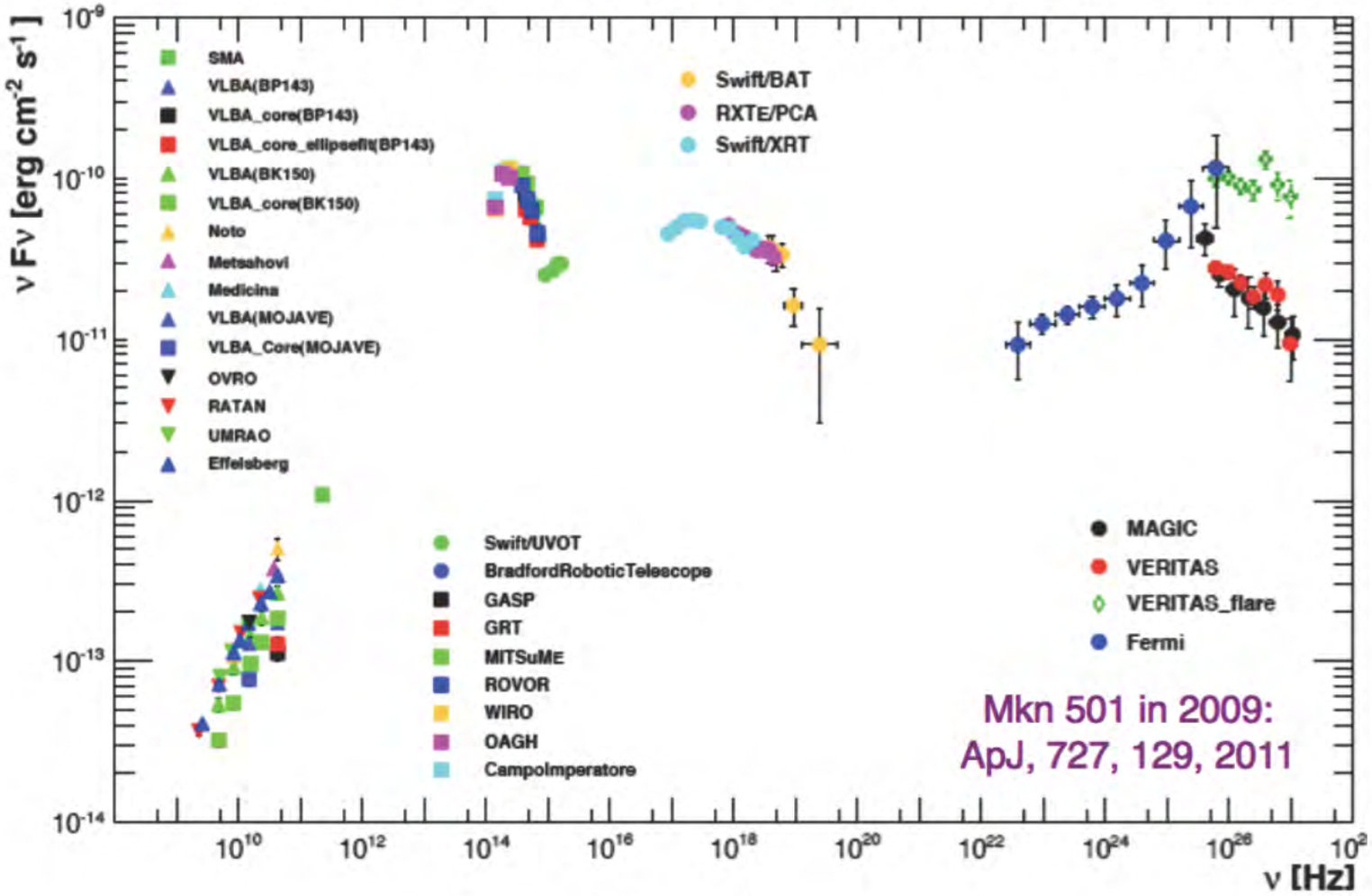
VHE peak moves little: Onset of Klein-Nishina effects

HBL ⇔ LBL ⇔ IBL (time dependent?)

Markarian 421 & 501: Intense MW Coverage



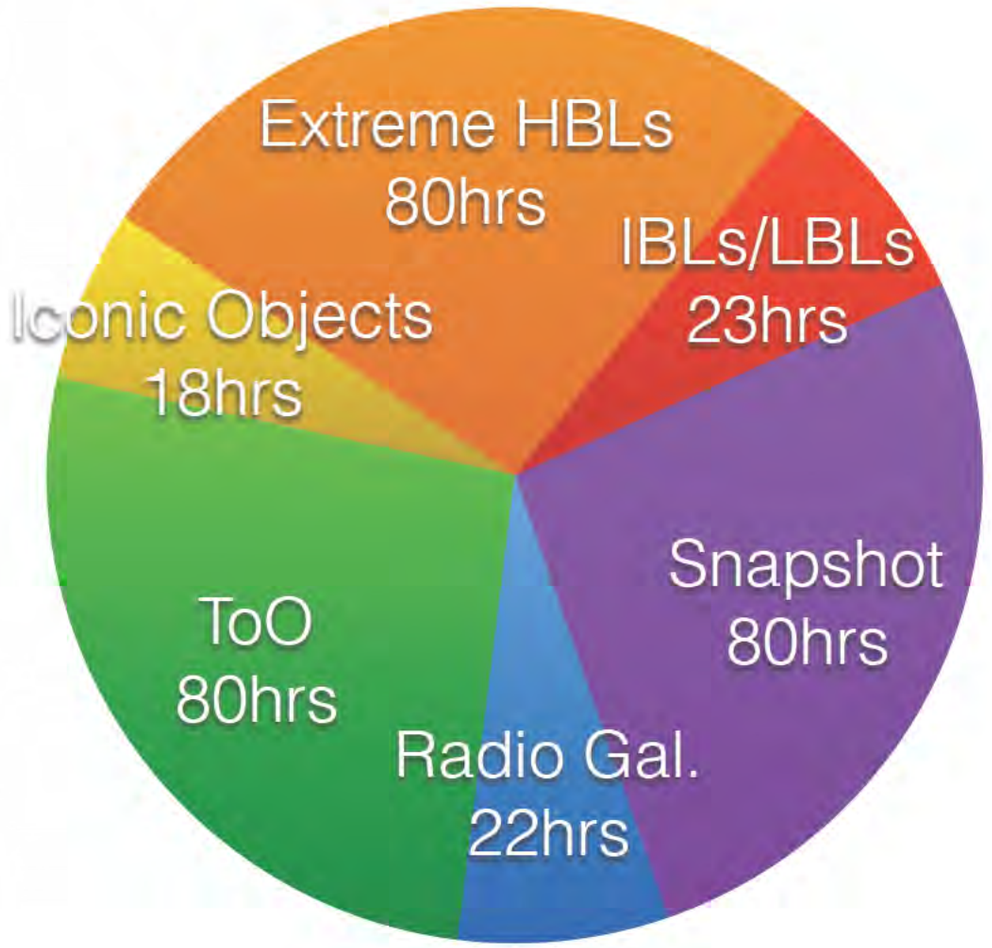
Simultaneous X-ray & VHE every 2 days;
LAT is always on; + optical/radio



VERITAS AGN Long-Term Plan

- Deep exposures via intense monitoring:
  - Extreme HBLs: Make precision measurements of spectra of 5 distant hard-spectrum blazars (1ES0229+200, RGBJ0710+591, H1426+428, PKS1424+240, 1ES1218+304) - aim is for 200 hrs each.
  - IBLs: Regular monitoring to determine low-state spectra and to find flares.
  - Intense monitoring of the iconic objects Markarian 421 and 501 with nightly spectra.
  - All with simultaneous Swift & intense FLWO 48" BVri coverage
- Regular snapshots on all remaining VHE blazars and top blazar candidates visible to VERITAS with multi wavelength coverage.
- Dedicated M87 monitoring program with MAGIC, HESS and multi wavelength partners.
- Pre-approved ToO for following up on flares - triggers from MWL alerts and our own observations.

Annual LTP (~300 hrs) breakdown

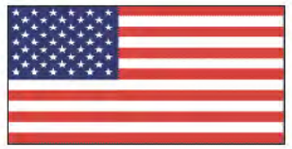


\+ 'Bright Moon' observations
\+ Competitive Time-Allocation-Committee Proposals

Summary and Conclusions

- VERITAS is fully funded to operate through 2019.
- The study of AGN is one of the VERITAS collaboration's key science goals and we currently dedicate ~600 hrs/year to this study.
- Aims:
  - to get extensive multi-year exposures with MWL data on all VHE AGN visible to VERITAS
  - increase the catalogue of VHE AGN via ToOs and new targets.
- After two hardware and analysis software upgrades VERITAS has increased its sensitivity and lowered its energy threshold, enhancing our AGN study program.
- VERITAS has now detected 34 VHE AGN, and we can detect objects out to z~1 and conducted multi wavelength and variability studies.
- We are always interested in new partnerships for AGN studies, including MWL observations and theoretical interpretation.

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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