VHE Blazar Studies after a Decade of H.E.S.S., MAGIC & VERITAS

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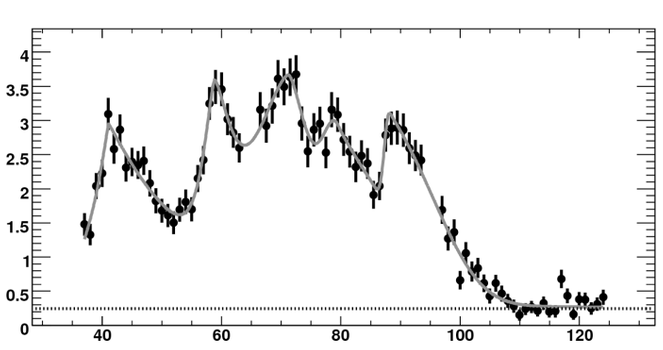
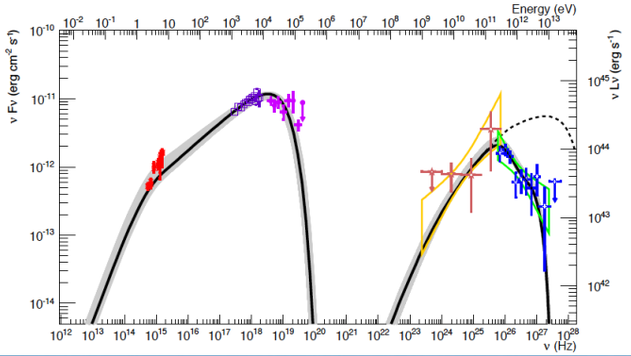
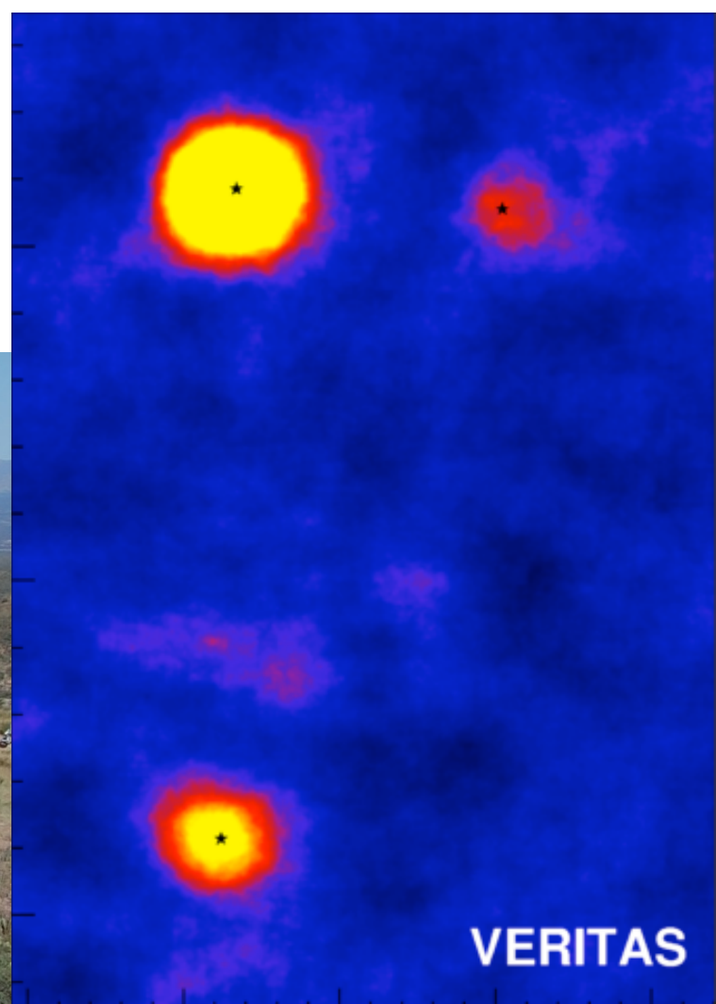
Blazars Through Sharp Multi-Wavelength Eyes, Malaga, Spain, June 2, 2016







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Currently 4 Major Projects: ~600 Scientists

Three major Cherenkov arrays plan to run until at least ~2019; All have AGN Programs

FACT (@MAGIC site): Small (~3 m) Cherenkov telescope; sensitive to >1 Crab events; Monitors AGN

VERITAS, MAGIC & FACT can run through full moon; HAWC runs 24/7

Whipple 10-m decomissioned in 2013

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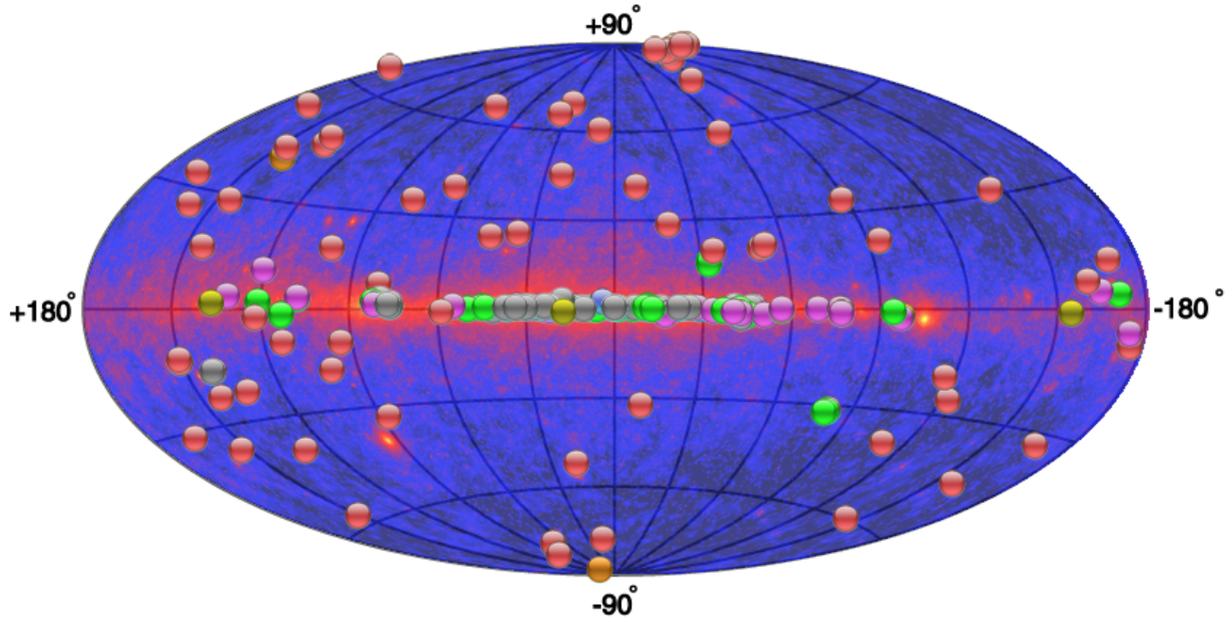
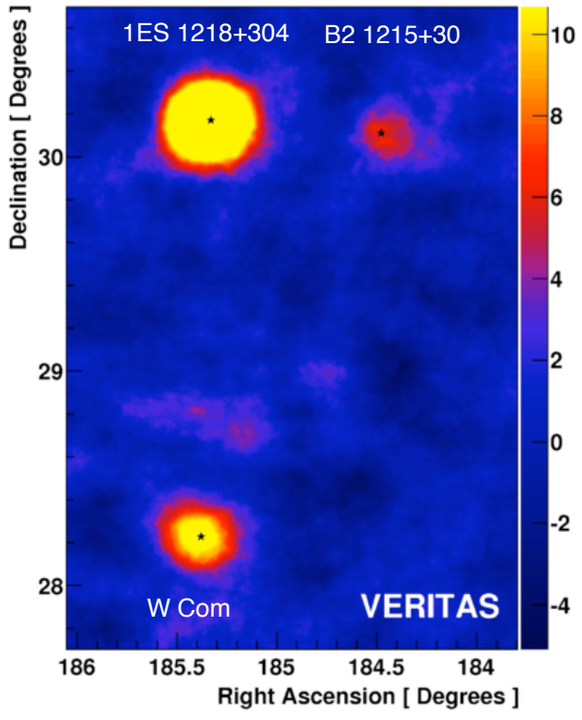
The Extragalactic VHE Gamma-ray Sky

- June 1, 2016: 176 sources in TeVCat
  - Flux range: 0.003 Crab to ~20 Crab flare
  - ~12 different source classes
  - Systematics: ΔΓ ~ 0.1, Flux ~20%
- 67 extragalactic VHE sources (65 AGN)
  - 2 starburst galaxies: M 82 & NGC 253
  - 4 FR I radio galaxies: M 87, Cen A, NGC 1275 & PKS 0625-35
- 61 blazars (c.f. 3EG catalog = 66)
  - 75% are HBL (46 objects)
  - 15 non-HBL: 8 IBL, 1 LBL, 5 FSRQ, 1 lensed BL; ~all are "flare only"
  - z range: 0.030 to 0.94; ~20% w/ z = ?

VHE γ-ray Sky Catalog Overlaid onto Fermi-LAT Sky Map





3 blazars in same FoV!

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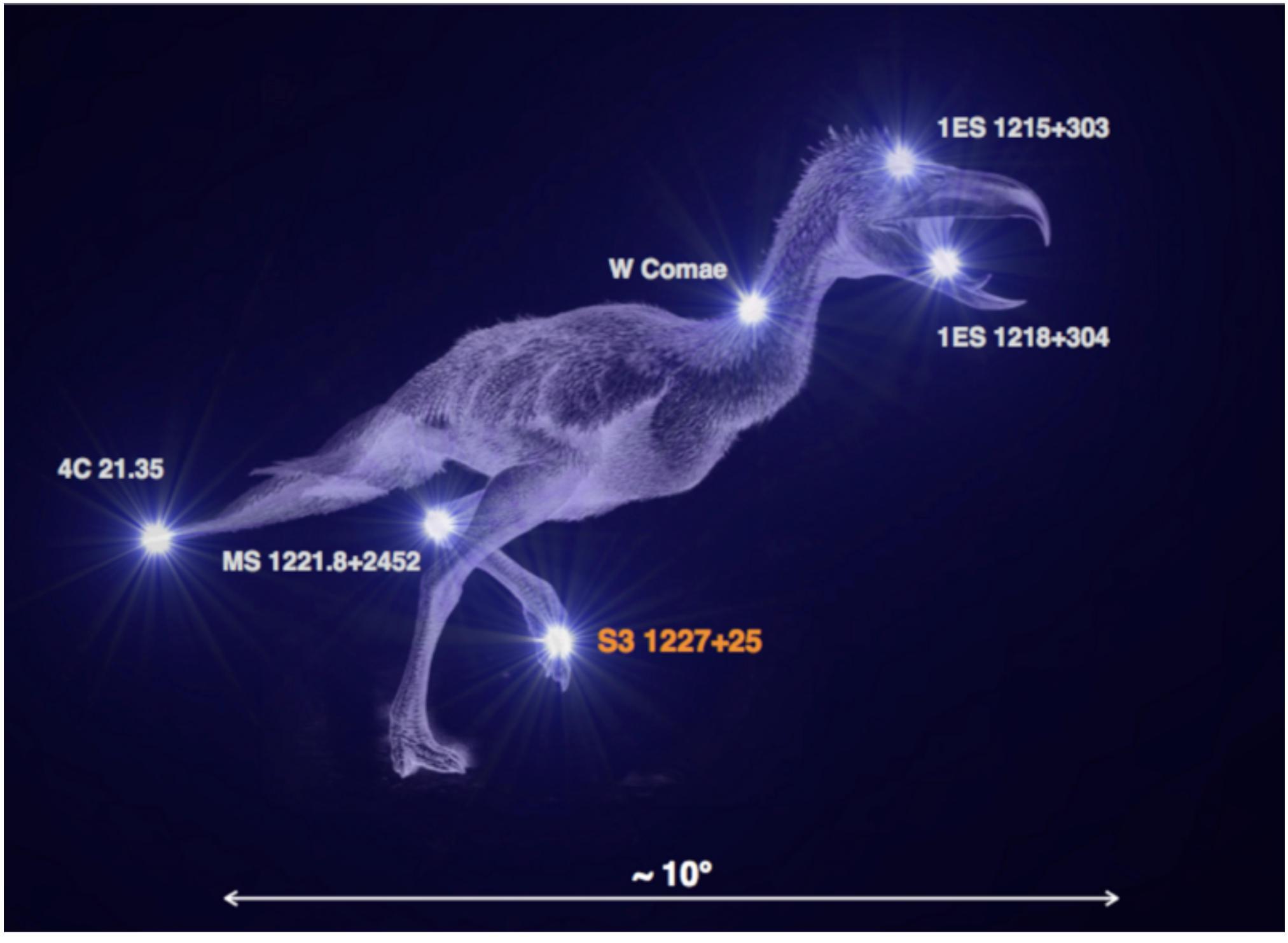
The “Tera-Bird”



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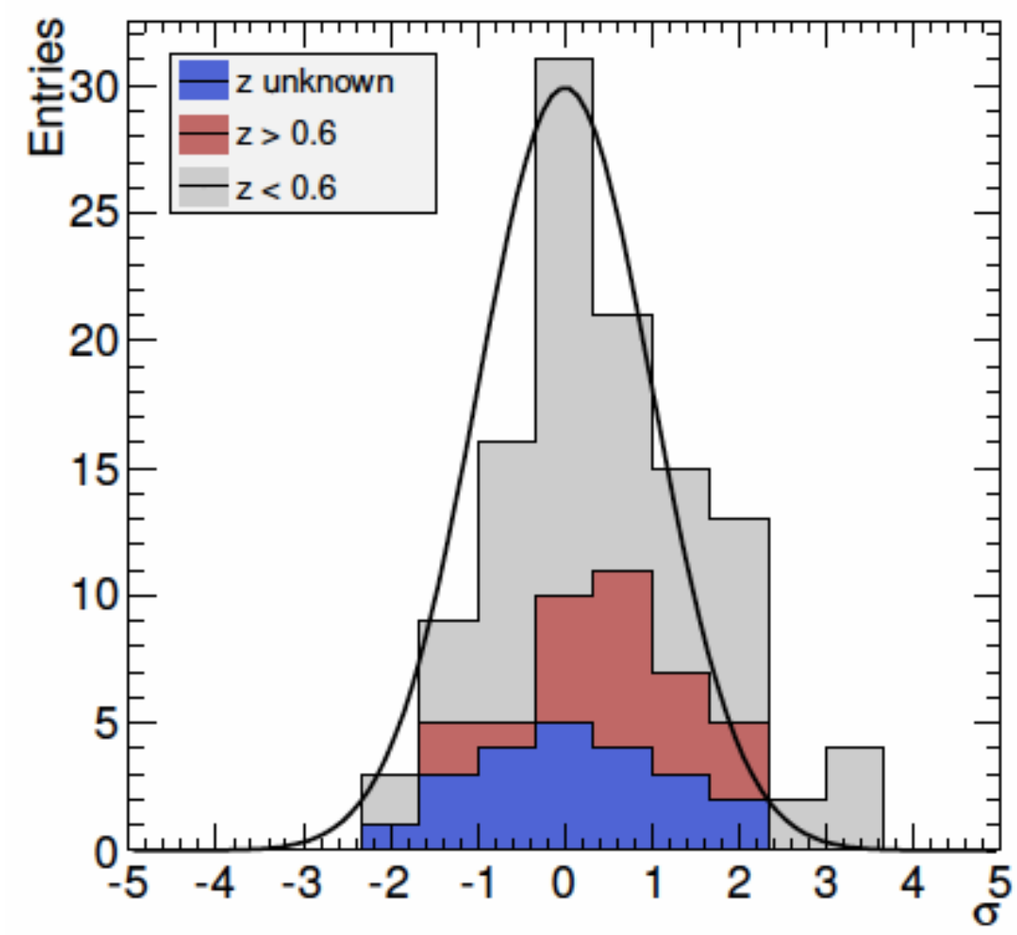
Discoveries: It's not so much where, but when?

- VHE target catalogs are exhausted:
  - Pre-Fermi: Targets sourced from X-ray bright, IBLs/HBLs & 3EG catalog
  - Post-Fermi: Nice-LAT spectra (0FGL, 1FGL, 2FGL, 3FGL, 1FHL, 2FHL) or clusters of HE γ's
- "All" recent discoveries are during flares in objects we have already observed!
  - Knowing when is really tricky!
  - Recent avg. ~2 discoveries / yr
- VERITAS published limits on 113 blazars
  - AJ, 151, 142, 2016
  - Limits pending on ~75 others from 2012-16
- MAGIC published limits on 30 blazars
  - MNRAS, 440, 530, 2014; ApJ, 729, 115, 2011; A&A 498, 83, 2009
- H.E.S.S. published limits on 47, 18 & 19 AGN
  - A&A, 564, 9, 2014; A&A ,478, 387, 2008; A&A, 441, 465, 2005

VERITAS σ Distribution



VERITAS & MAGIC each see stacked excess of γ-rays (~4σ)

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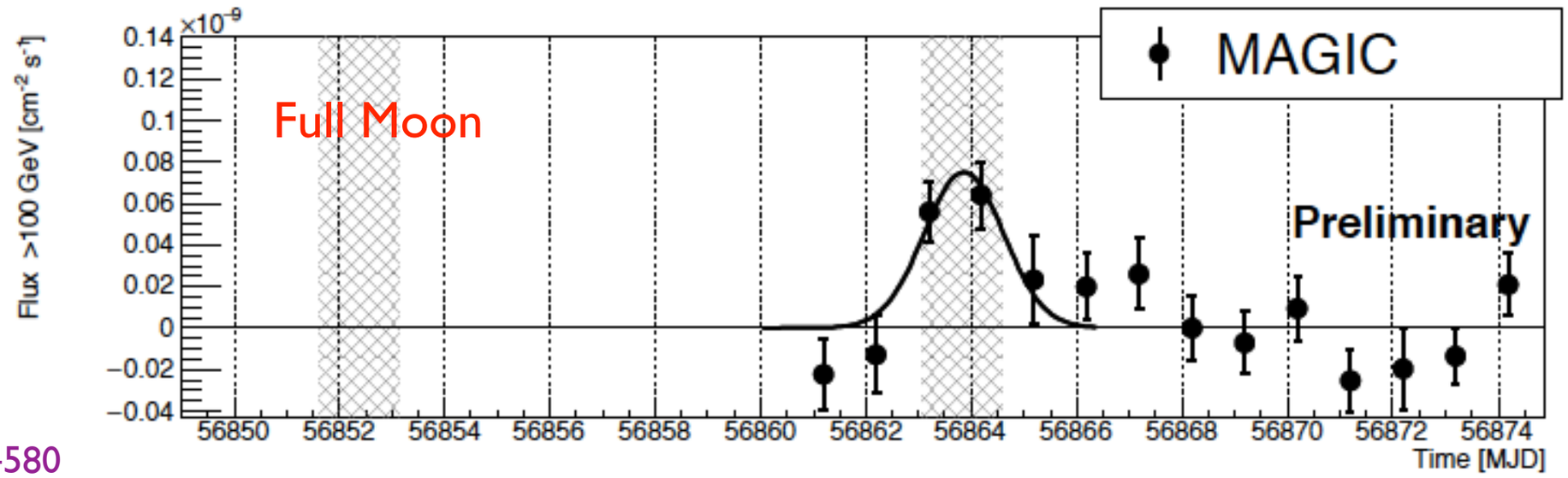
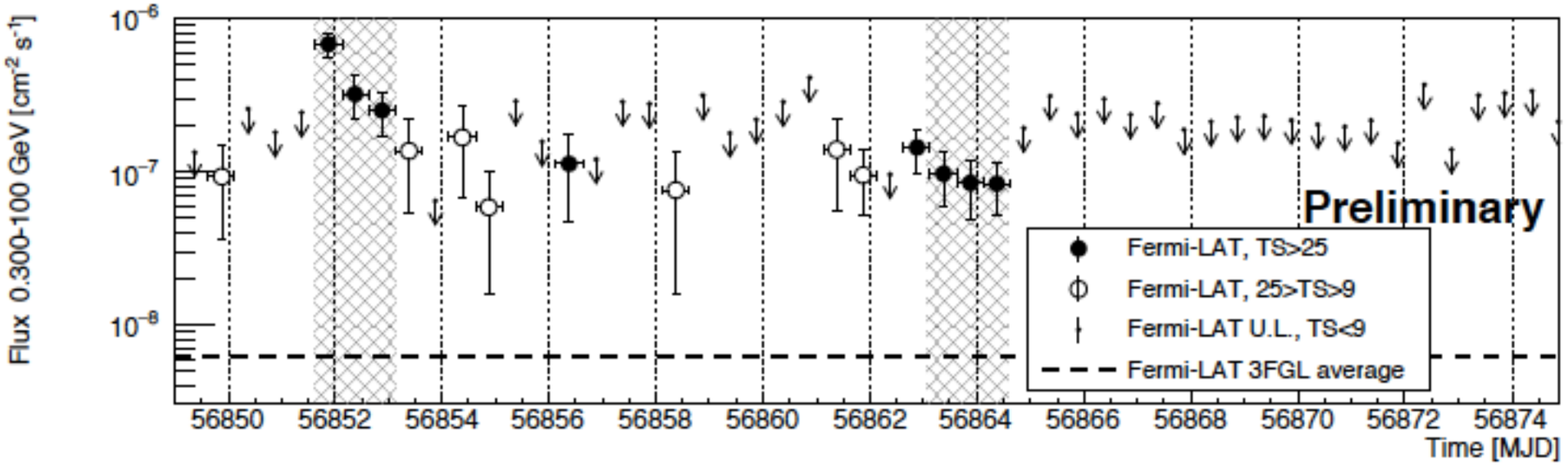
MAGIC Detection of a Lensed Blazar



astro-ph/1508.04580

July 2014



S3 0218+35 is an FSRQ? at z = 0.944, lensed by a galaxy at z = 0.68;
Radio variability => 10-12 day delay on mirrored flares;
Fermi-LAT in 2012 => 11.5 day delay on mirrored gamma-ray flare
Most distant (z = 0.944) blazar detected at VHE; ~10% Crab over 2 nights

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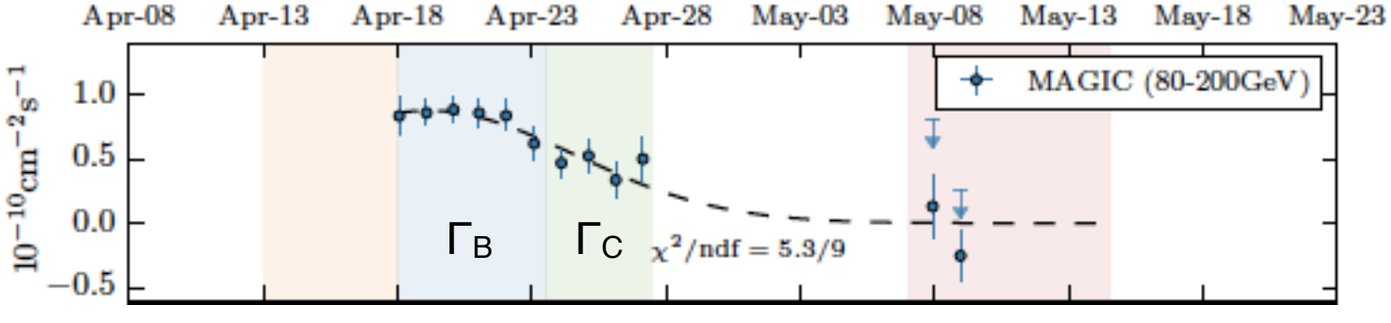
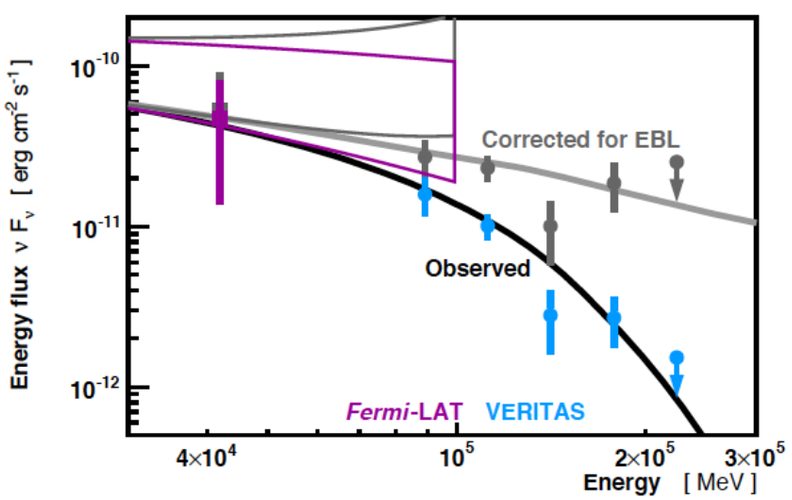
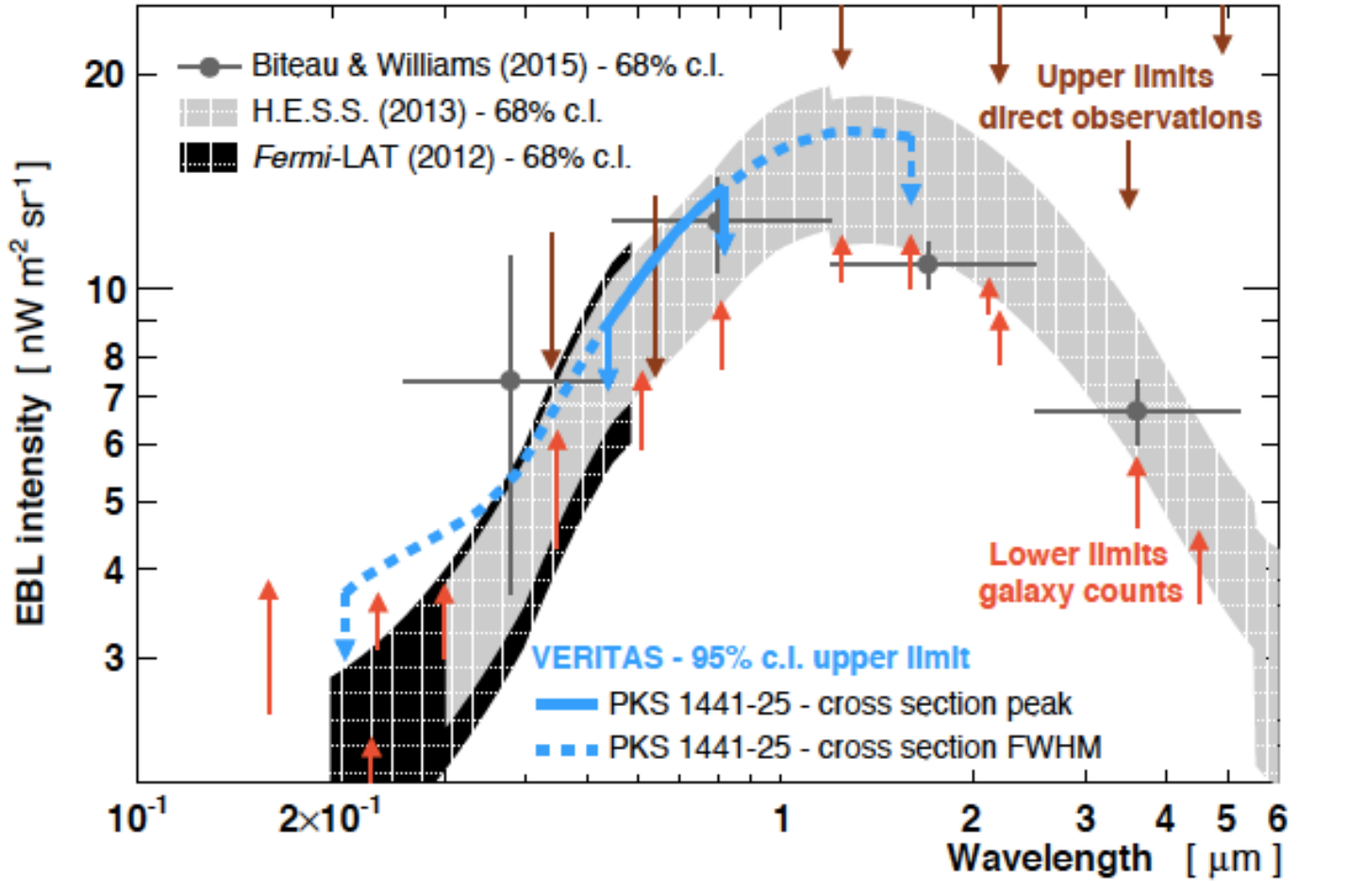
Detection of PKS 1441+25 (z = 0.940)

VERITAS: ApJL, 815, L22, 2015
MAGIC: ApJL,, 815, L23, 2015

- Fermi-LAT Alerts => MAGIC / VERITAS ToOs
  - Both experiments detect ~5% Crab in April
  - VERITAS detected ~400 γ-rays, 8σ in ~15 h
    - $\Gamma_{VHE} = 5.3 \pm 0.5$
  - MAGIC detected ~2600 γ-rays, 26σ in ~30 h
    - $\Gamma_B = 4.6 \pm 0.1$, $\Gamma_C = 3.7 \pm 0.4$
- Neither detect in May 2015
- EBL: De-absorbed VERITAS points connect smoothly to Fermi-LAT spectrum
  - Despite z ~ 1 (light-travel time ~ 7.5 Gyr), it isn't unusual that we saw this <200 GeV!







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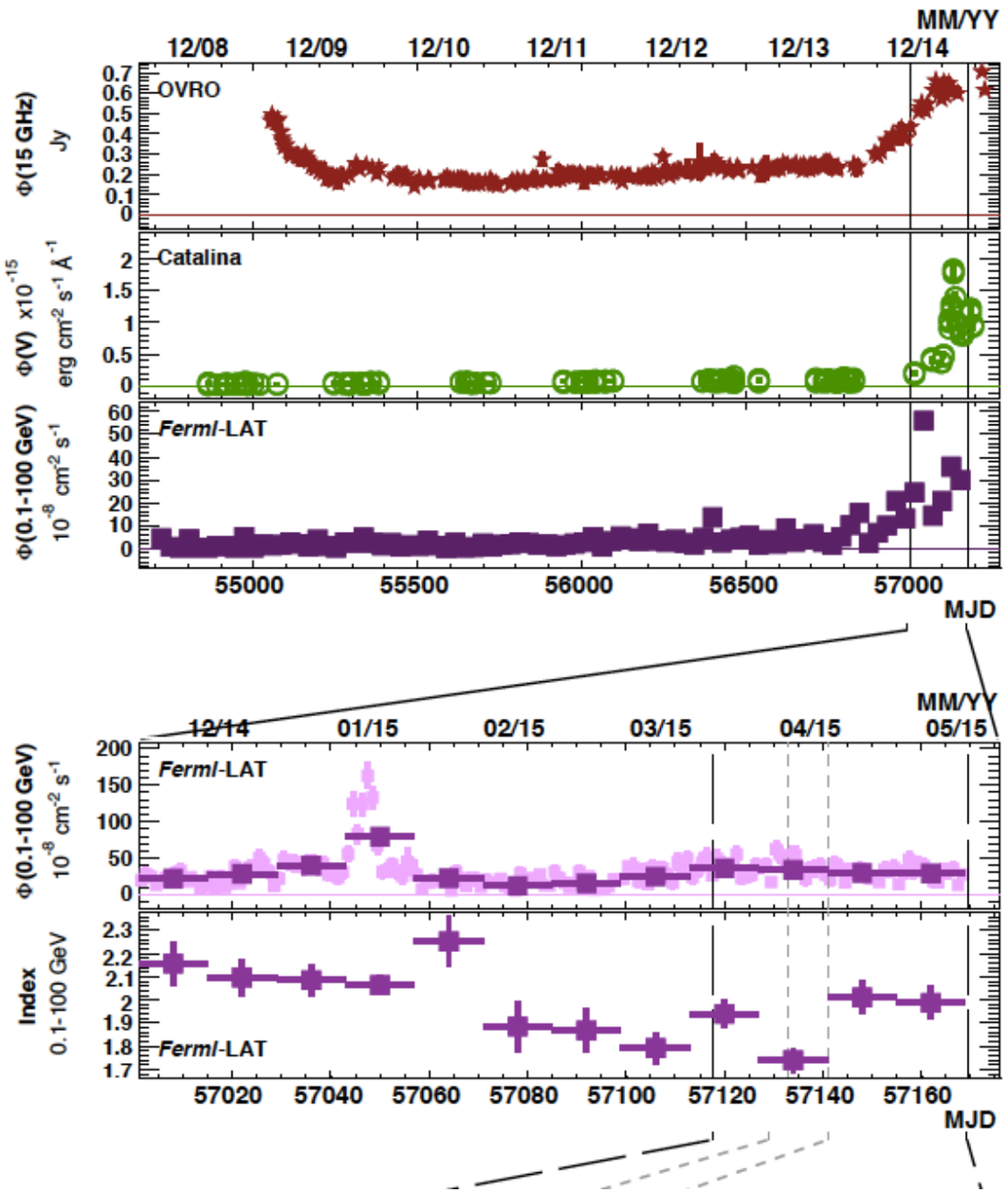
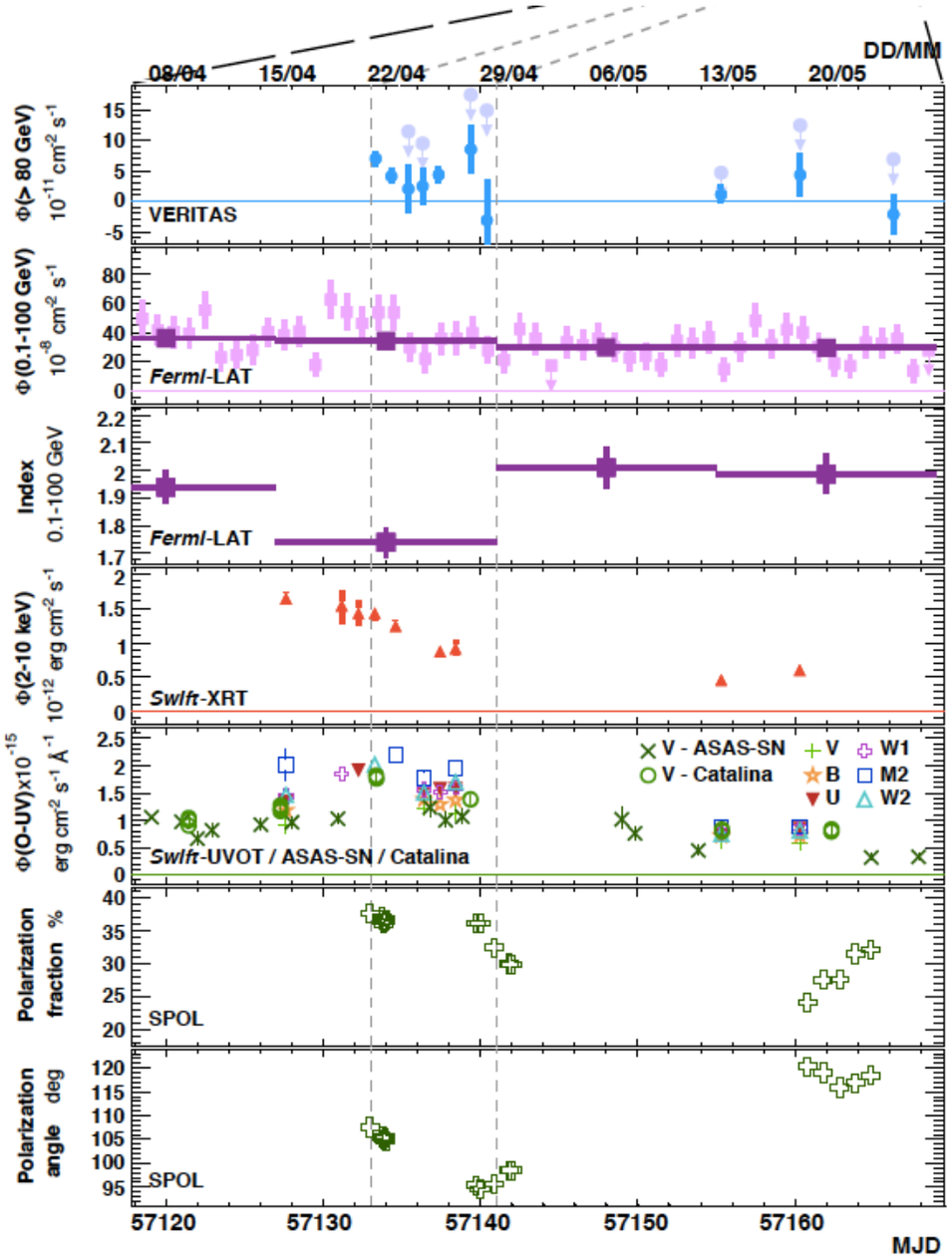
Copious MWL Data during PKS 1441 Flare





Long-term: Radio, optical, Fermi-LAT correlation (no delay) supports single, large-scale emission region

VERITAS detection is contemporaneous with period of high polarization & enhanced MWL emission

Variability time scale (X-ray) < 2 weeks

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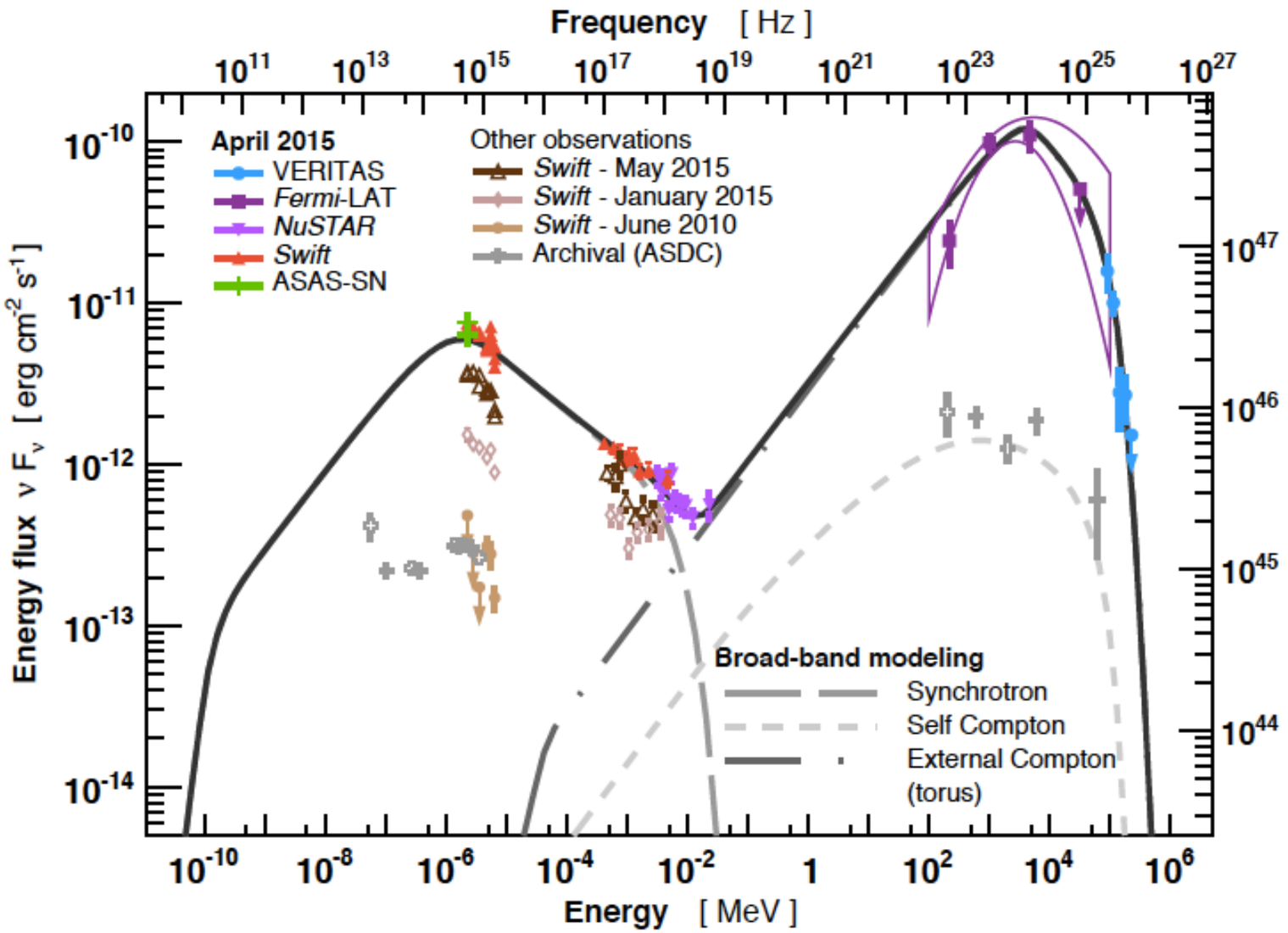
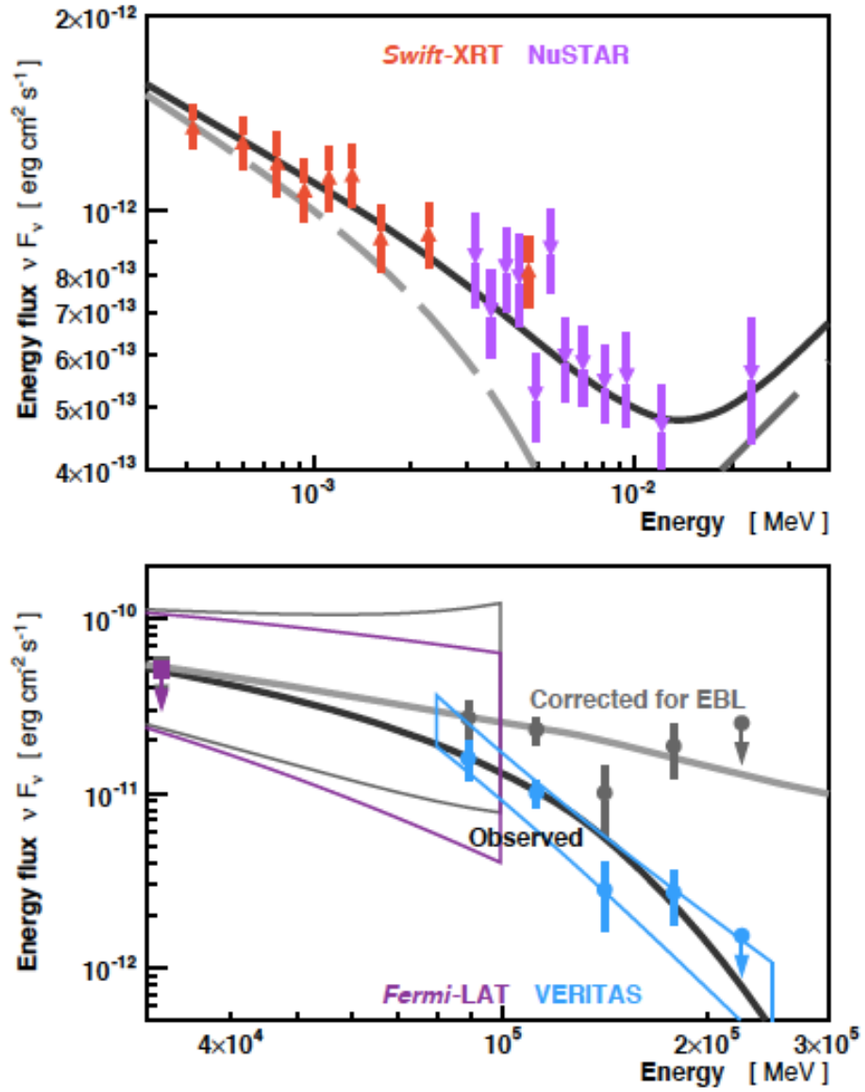
PKS 1441+25: Spectral Energy Distribution





Synchrotron emission seen up to ~30 keV

Gamma-ray emission must be from outside of BLR (τ~9 @ 100 GeV)

Broad-band model: Low doppler factor & close to equipartition => Large-scale emission (R = 200,000 R_{sch})

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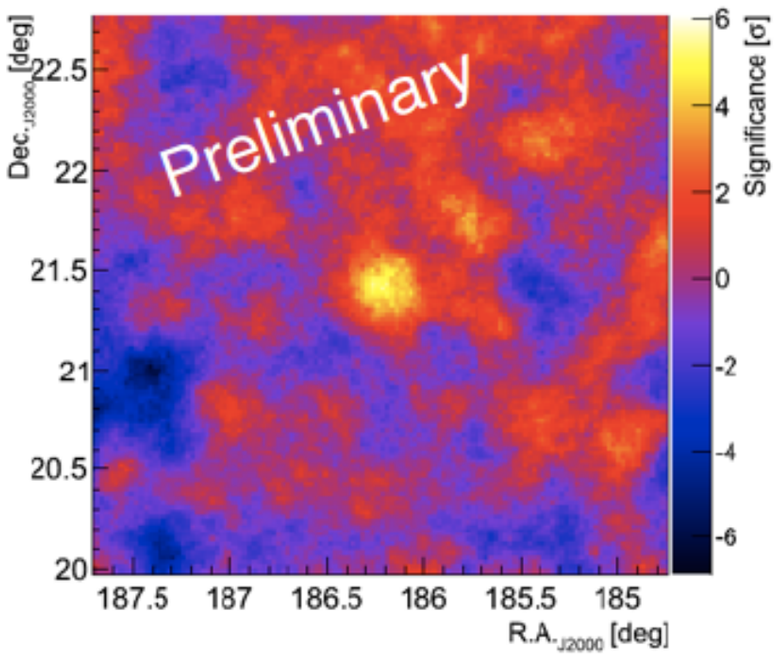
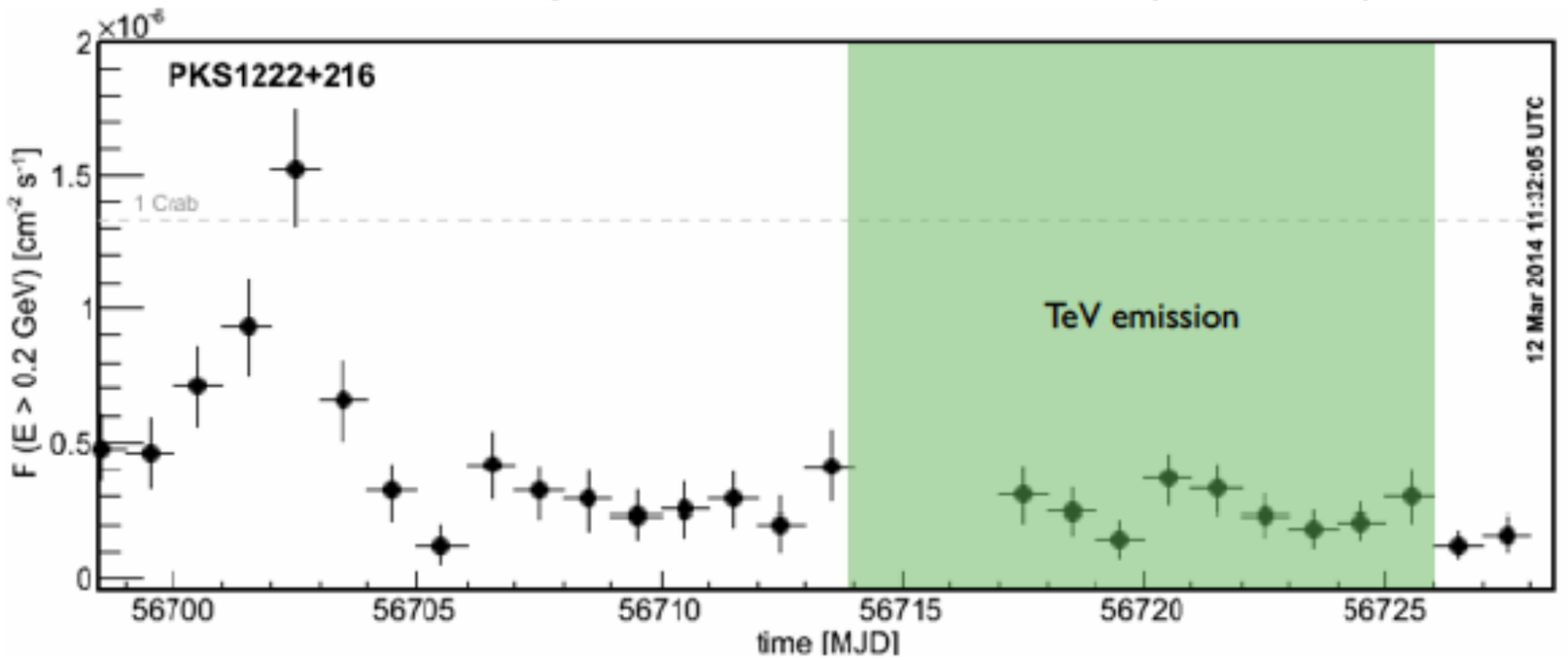
VHE FSRQ's are difficult!

VERITAS: PKS 1222+216 Sky Map



Fermi-LAT Light Curve for PKS 1222+216 (4C +21.35)



- Most FSRQ's usually seen briefly, during bright flares:
  - PKS 1222+216: Originally seen during a 30 minute flare in 2010 (MAGIC); ~10 minute flux doubling
  - 3C 279: MAGIC 2x, 1-night pre-LAT flares; Only deep VERITAS limits during 2014 mega-flare
- PKS 1510-089 exceptional: Seen by HESS & MAGIC during long-lasting flares in 2009 & 2012
  - VERITAS limits during regular observations of LAT / MWL flare in 2015 well below '09 & '12 flux
- VERITAS PKS 1222+216 detection: ~6σ in ~ 6 h of VERITAS ToO data; 10 nights in Feb / March 2014
  - Steady, persistent flux (~3% Crab) & clearly delayed vs LAT flare; ATel #5981
  - Deep observation (~25 h) in prior seasons only yielded limits, including during flare epochs

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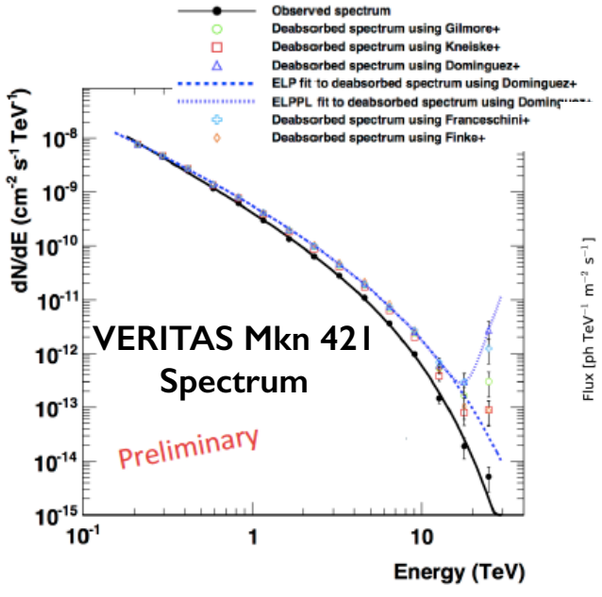
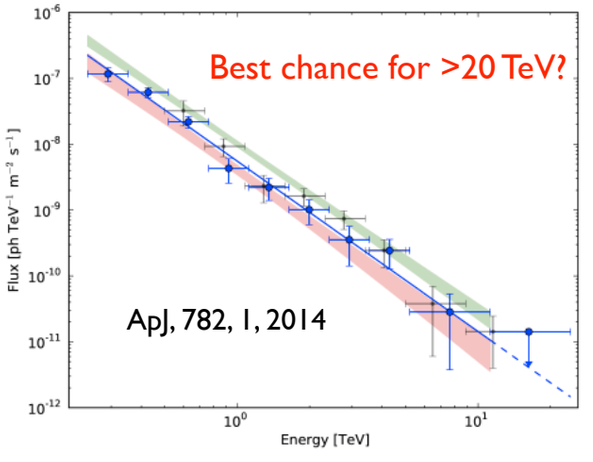
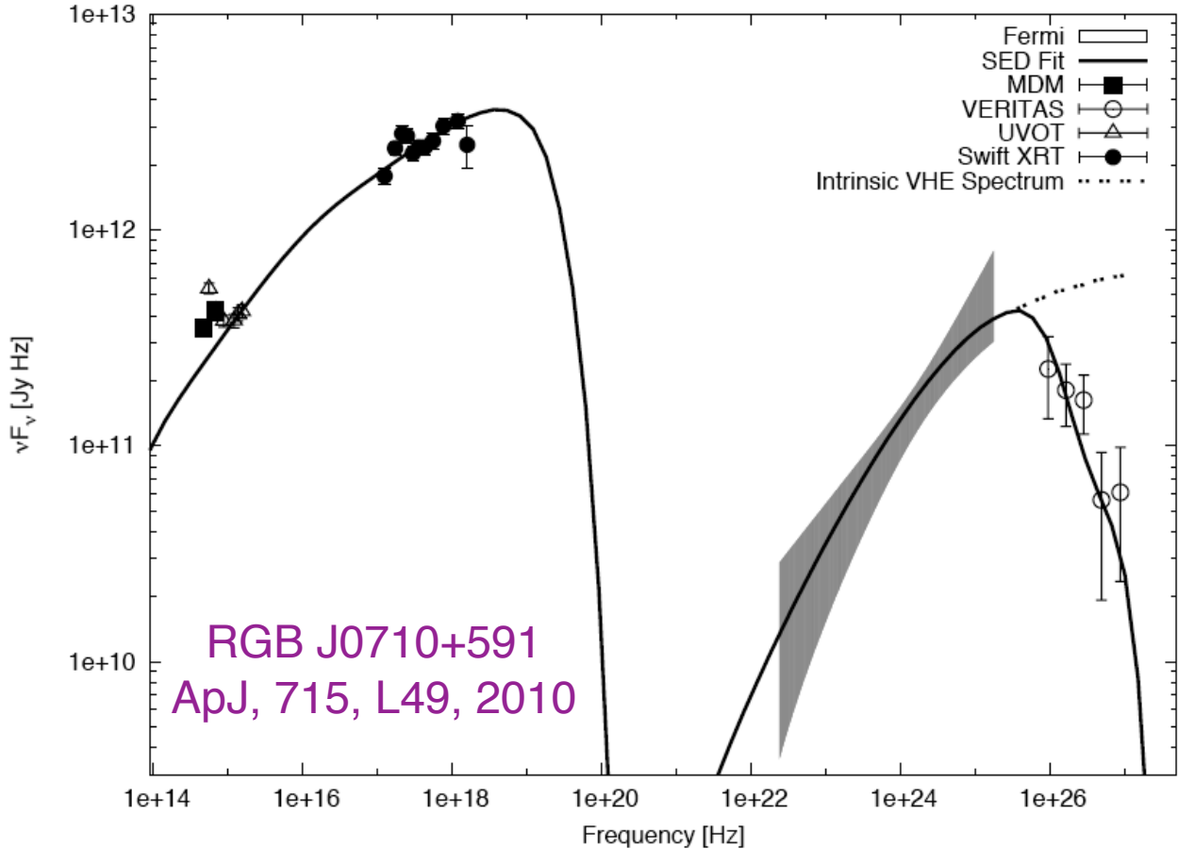
46 HBLs: The Bread & Butter of VHE AGN

- Spectral range: Γ ~ 2.5 to ~ 5; Avg ~ 3.5
- Highest E photons: ~20 TeV (Mkn 421/501)
  - Mkn 421 / 501 E_{cut} @ Ec ~4 / 6 TeV, PKS 2155: Γ ~ 3.5
  - Generally, few are detected >1-2 TeV!
- 67% show some variability, but often weak
  - 13 detected only during flares (often brief & few % Crab)
  - 6 w/ weak, month-scale variations; few % Crab sources
  - 2 have ~1-day factor of few flares in data that is otherwise relatively steady & moderate flux (few % Crab)
- Only 15 are "well-studied"
- Only ~10 w/ "striking" flaring episodes
  - With one exception (IC 310), these are the brightest
- Modeling: 1-zone SSC model usually works very well - even during flares



VERITAS + HESS 1ES 0229+200





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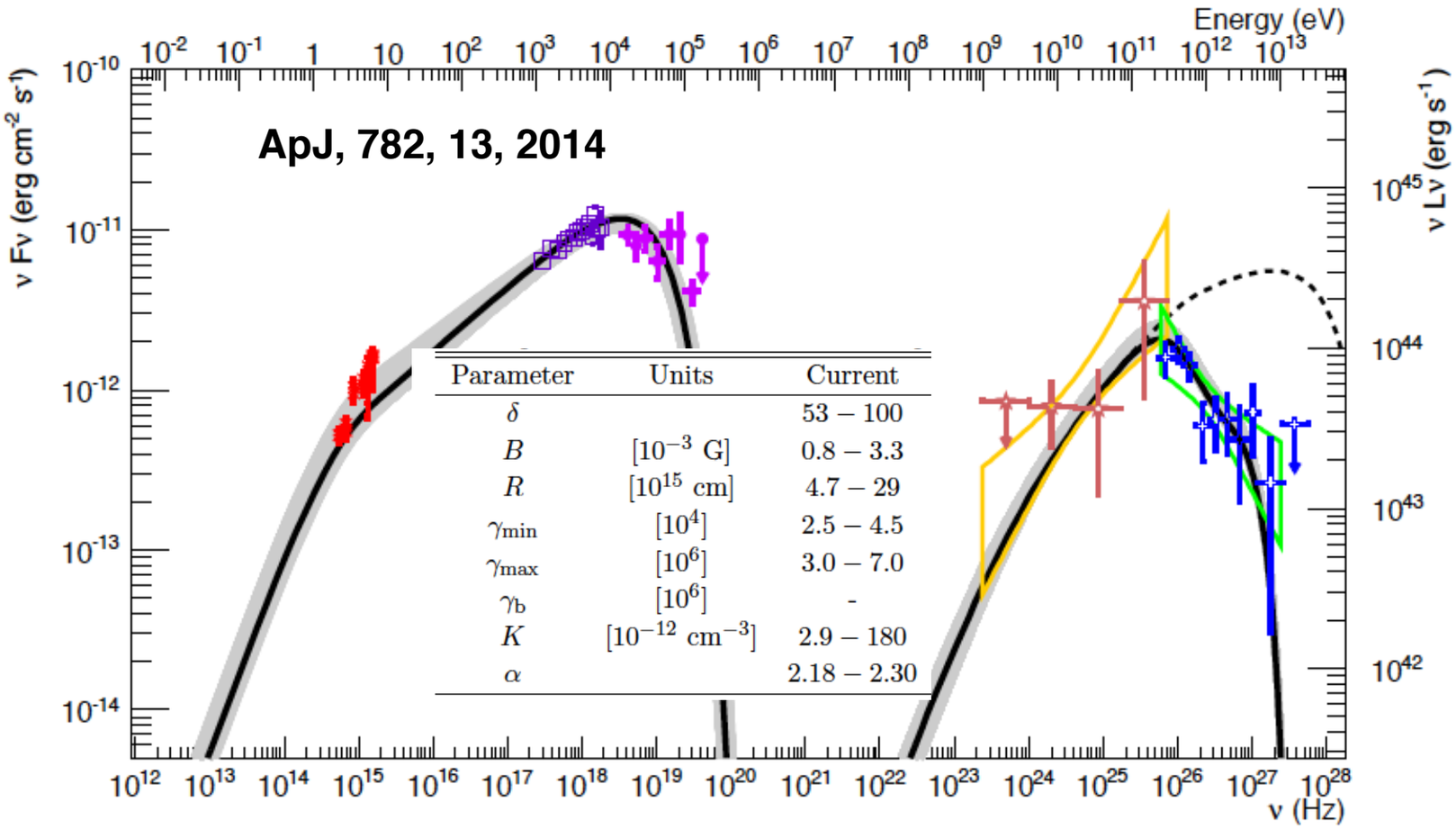
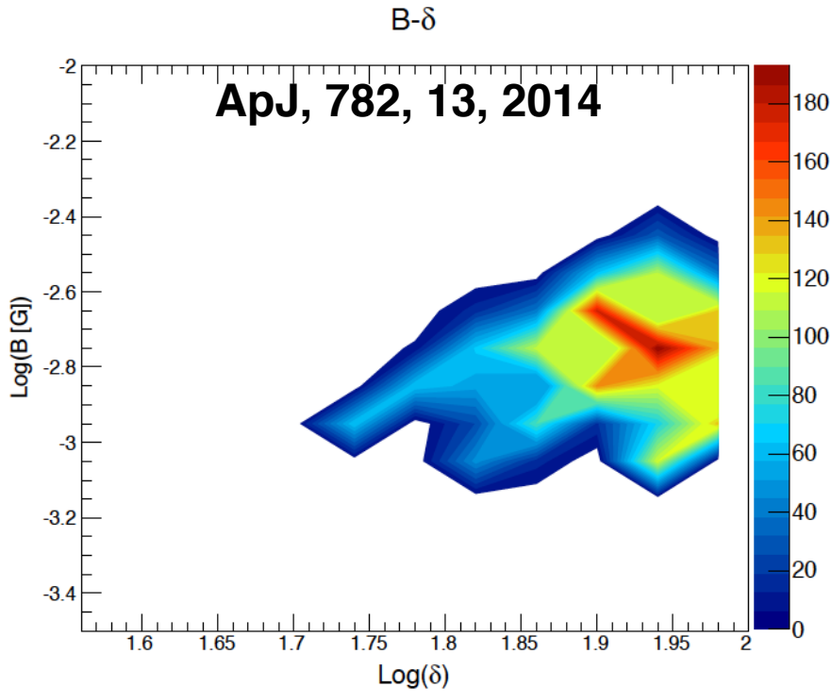
SSC: Reducing the Degeneracies





- 1ES 0229+200 w/ VERITAS (2010-12): 54 h; ~12σ, 1.7% Crab, Γ = 2.59 ± 0.12
  - SED compatible with SSC, <u>but we fully constrained the SSC parameter space</u>
  - δ > 53: Higher than radio & unusual for most blazars; Minimum Lorentz factor is also high: "No" low-E electrons

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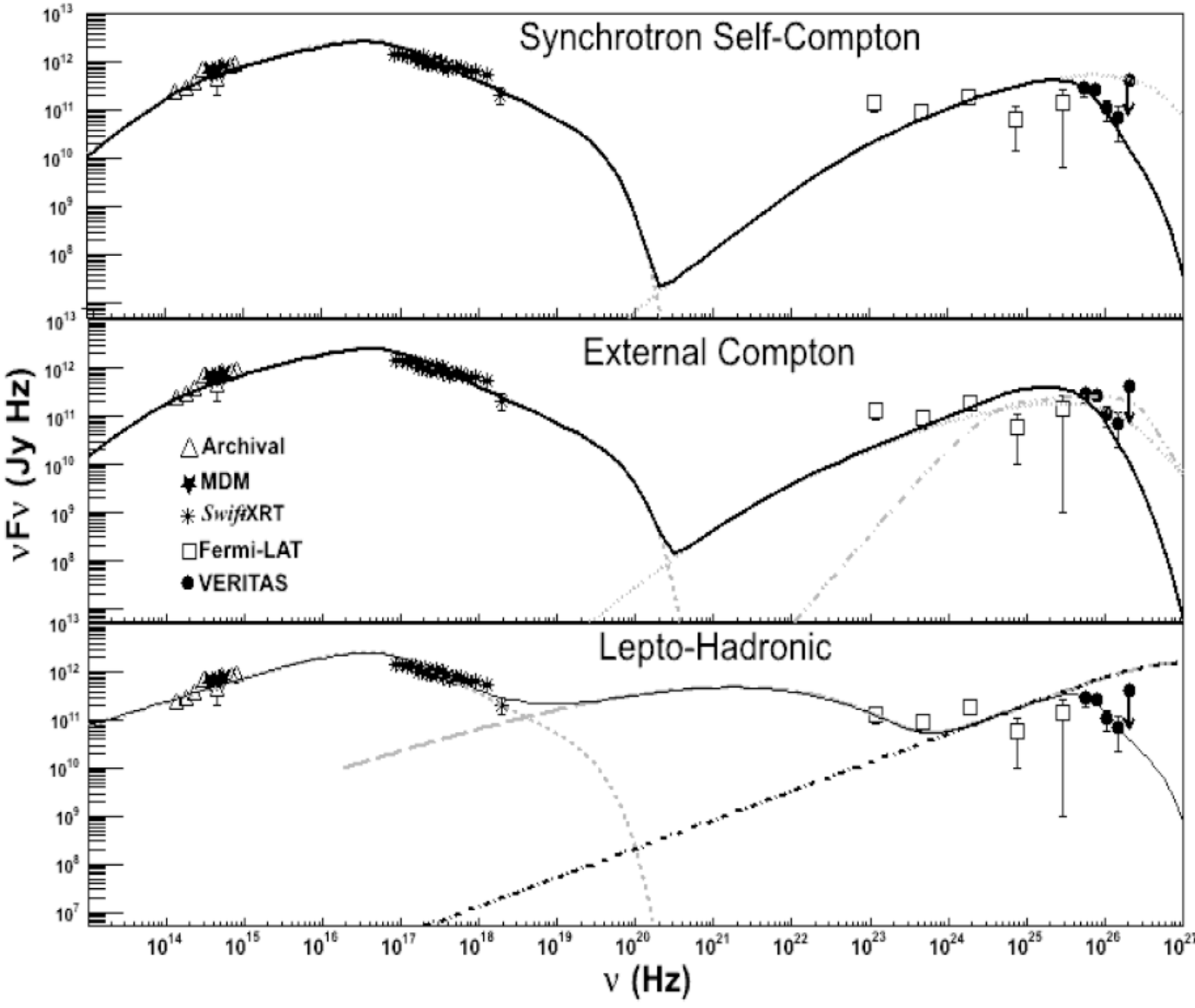
Some HBLs are not well fit by SSC



1ES 0414+009:
ApJ, 755, 118, 2012

However, the statistics are poor & the integration time is long

See also: RX J0648.7+1516: ApJ, 742, 127, 2011 & RBS 0413: ApJ, 750, 94, 2012

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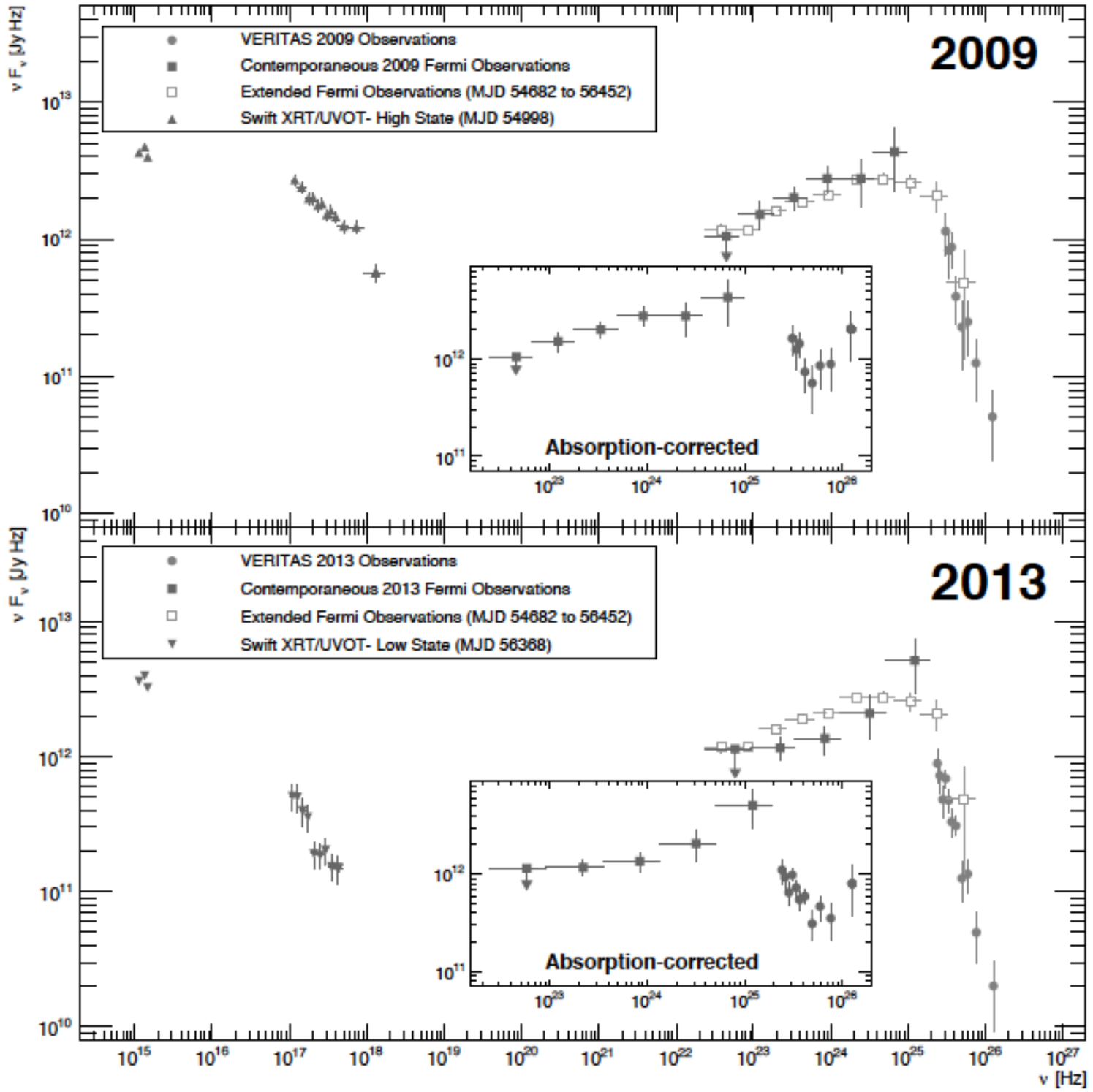
PKS 1424+240: Something Odd?

- Discovered at VHE by VERITAS in 2009
- HST observations clearly show z > 0.6035:
  - Furniss *et al.*, ApJ, 768, L31, 2013
- Intense VERITAS + MWL obs. in 2013:
  - >100 h live time from 2009, 2011 & 2013
  - Strong detection (20σ); $\Gamma = 4.2 \pm 0.3$
  - ApJ, 785, L16, 2014
- Annual VHE flux variability (~factor of 5);
  - Unfortunately flux was low in 2013 & 2014
  - VHE Γ & LAT >1 GeV flux are not variable
- Due to large z & EBL absorption of VHE photons, the VHE spectrum is rather curious



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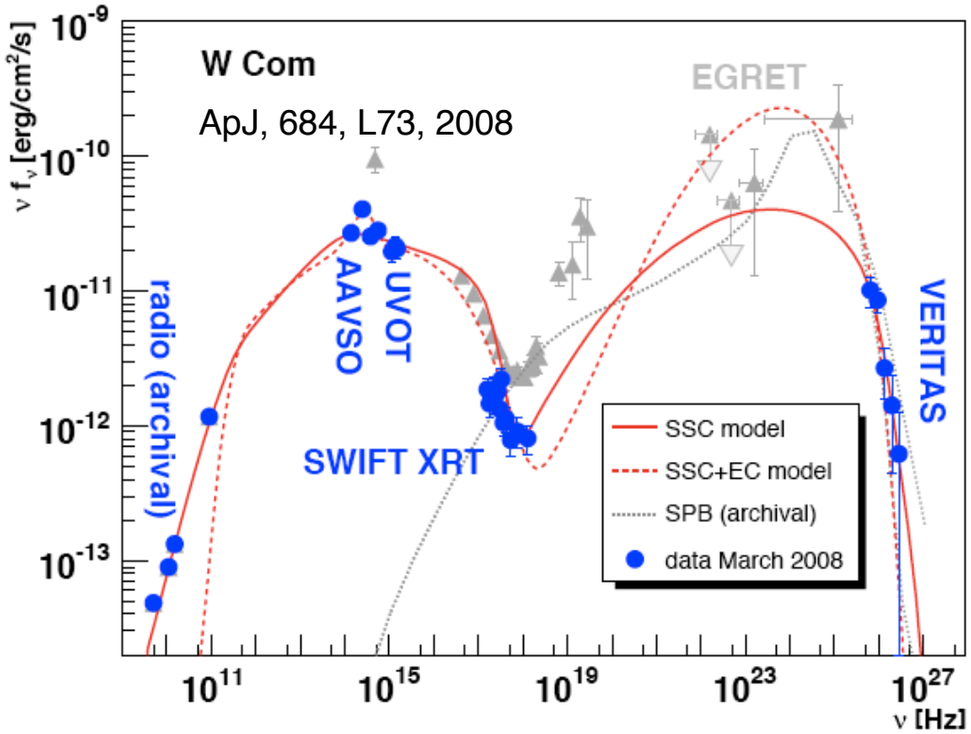
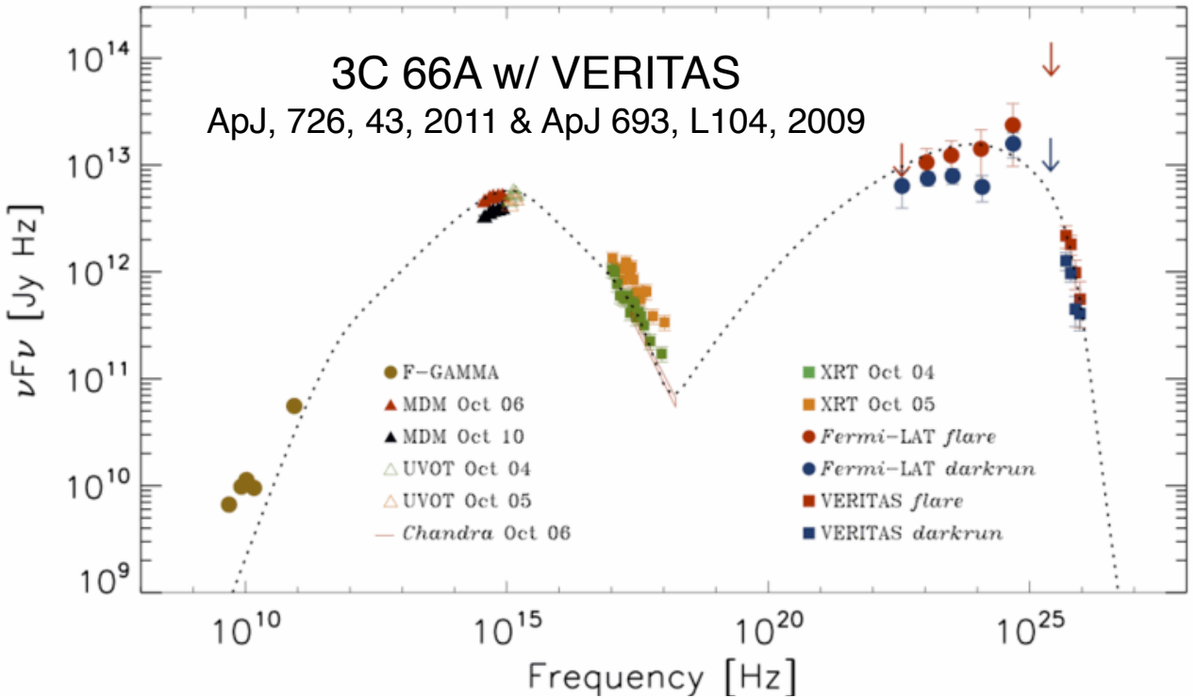
Modeling IBLs

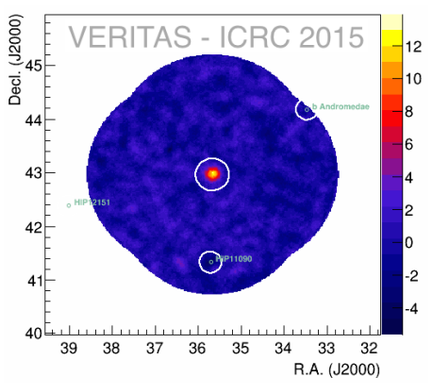


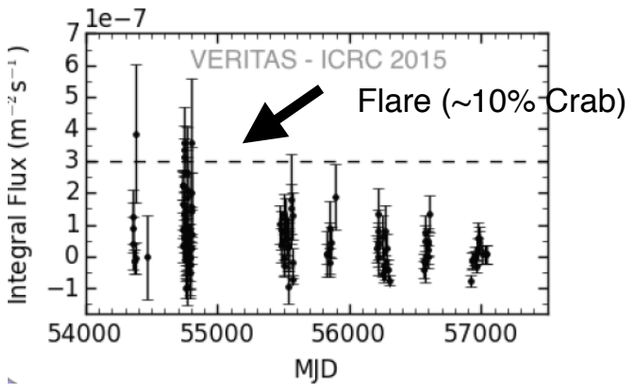


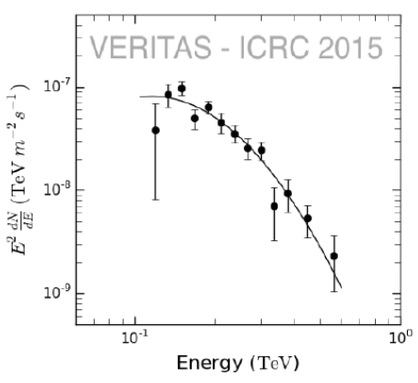
- IBLs: SSC models, can work, but parameters often far from equipartition, or SSC model parameters incompatible with observed variability time scales => SSC + EC preferred
- However, ~all VHE emitting IBLs are only detected during flares. Only VER J0521+211 is easily detected

VERITAS has recently detected low states of 3C 66A & BL Lac
(3C 66A shown)

Spectral shape does not change







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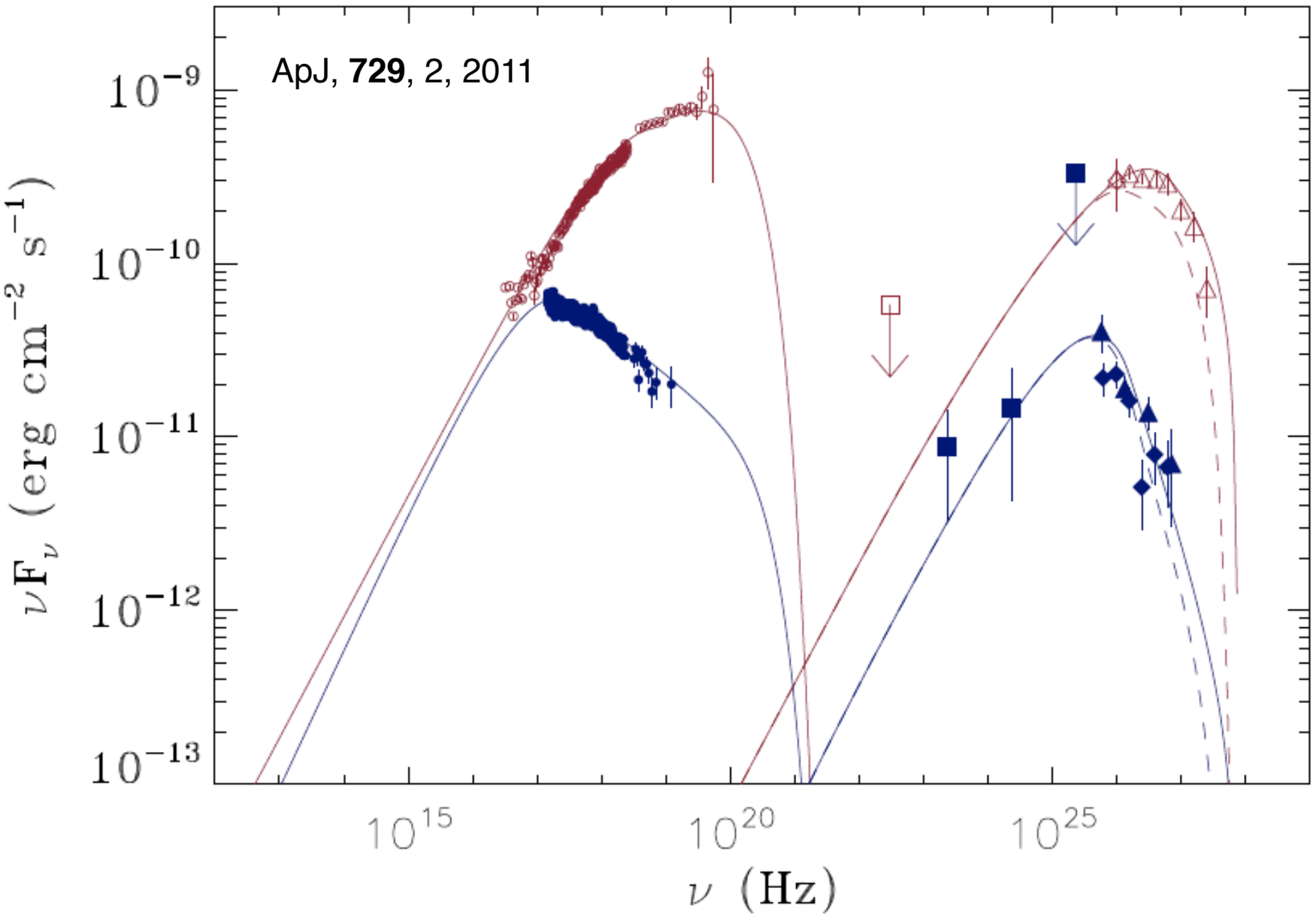
Sub-Classification: Be Cautious



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

Synchrotron peak can move a lot => VHE may detect an IBL, when behaving like an HBL, or an LBL behaving like an IBL, etc

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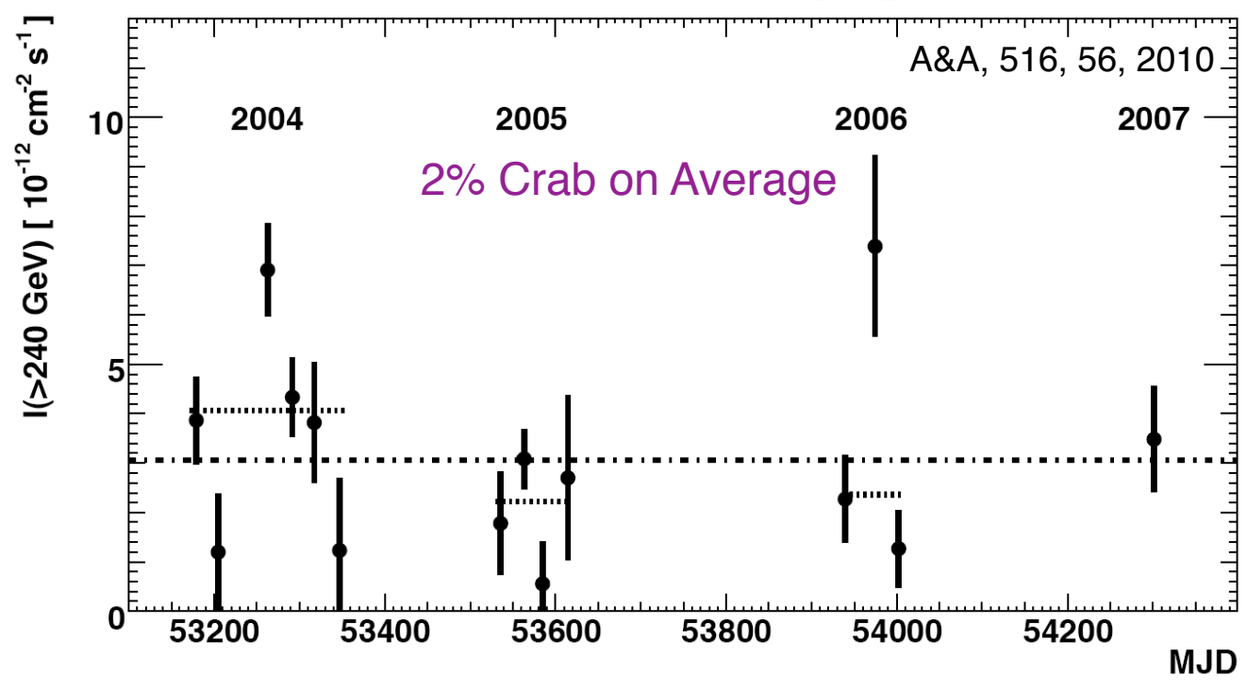
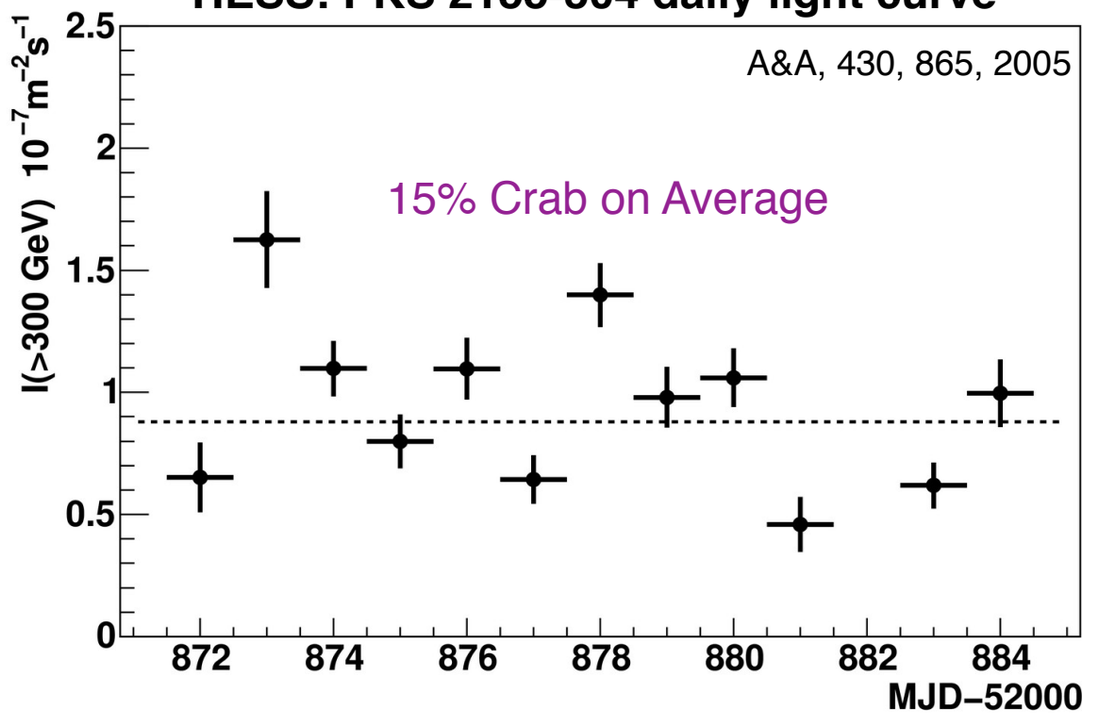
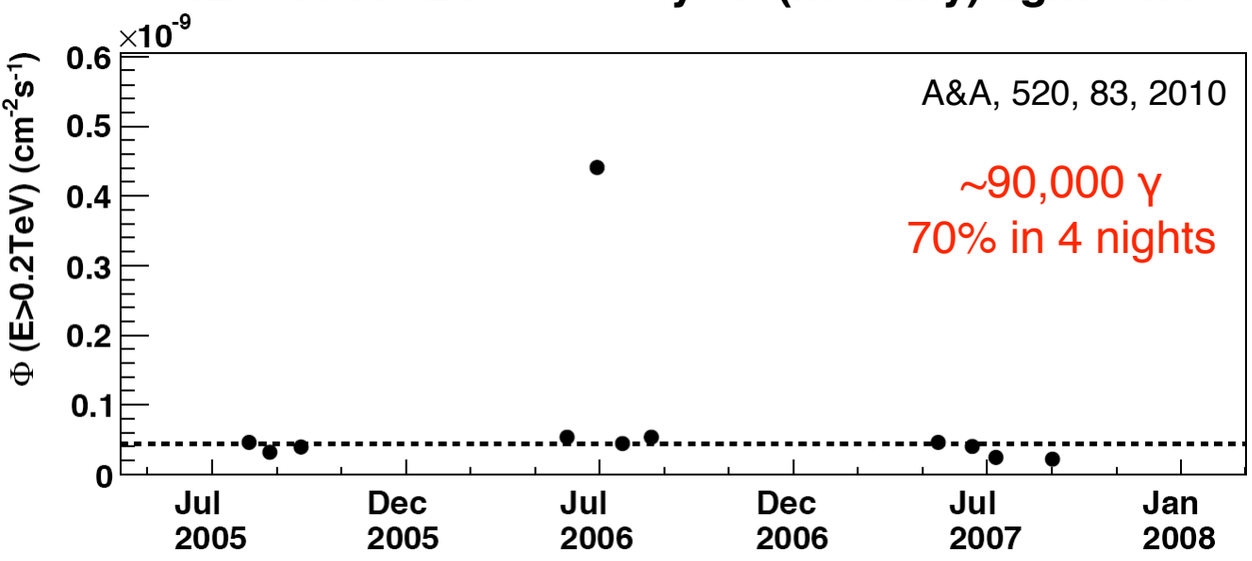
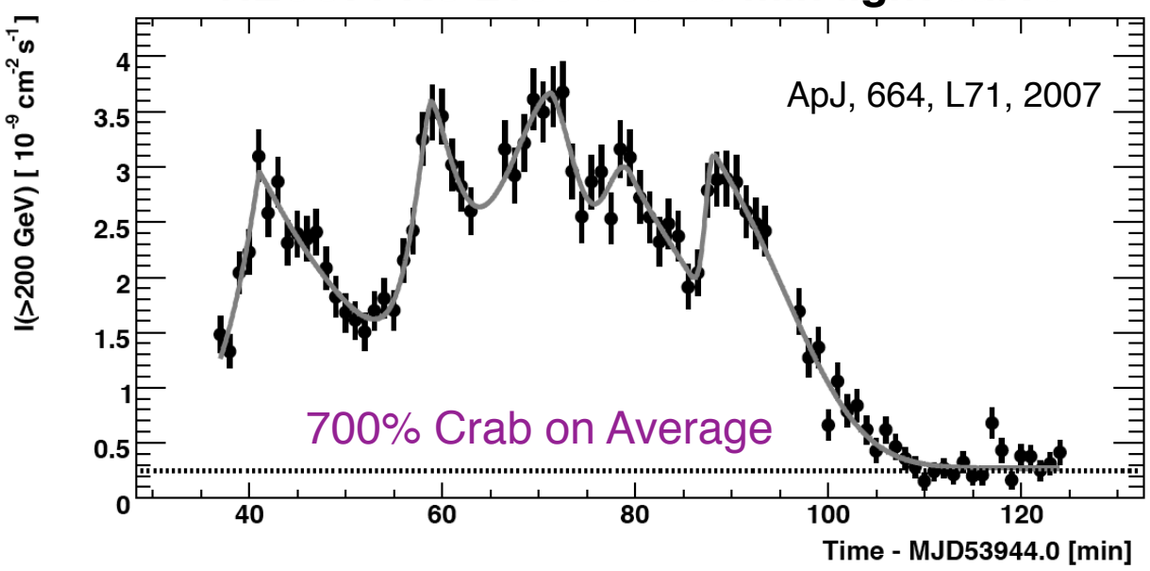
VHE Blazar Flaring: An Overview









Only 4 VHE blazars (1ES 1959+650, PKS 2155, +) have ever been observed >2 Crab;
Only 2 (Mrk 501 +) w/ more than one episode & only Mrk 421 >2 Crab “regularly”

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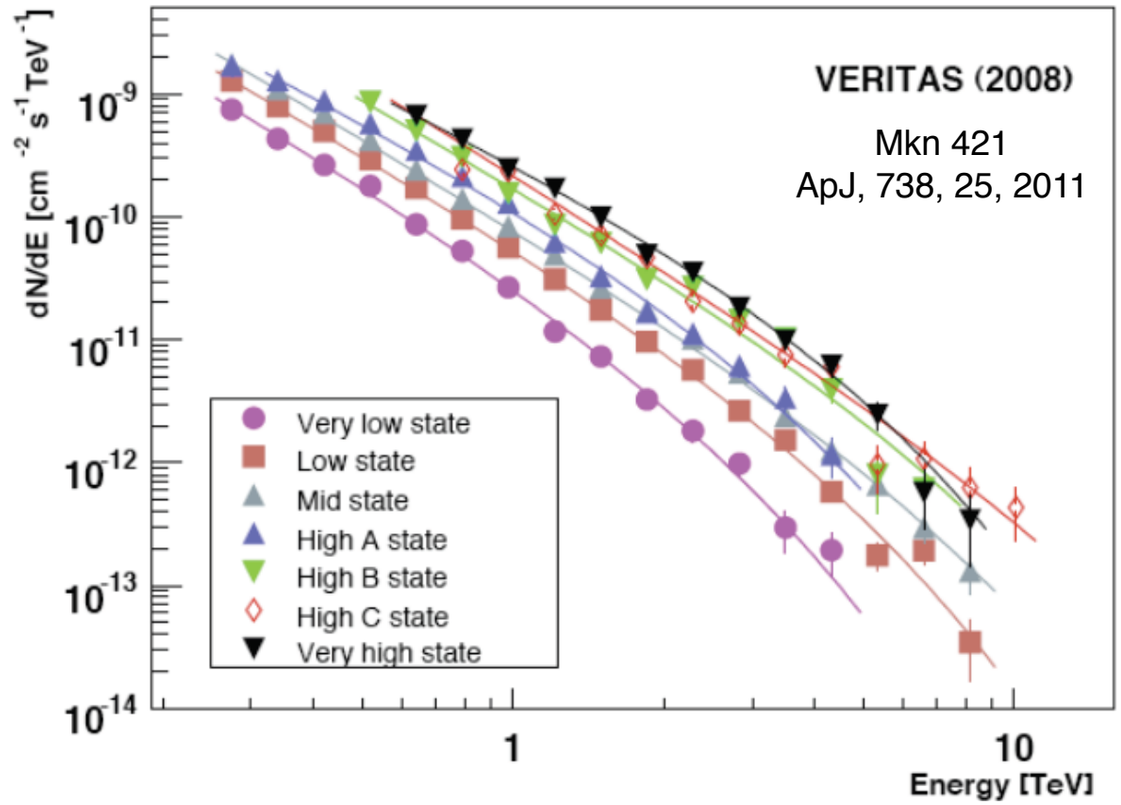
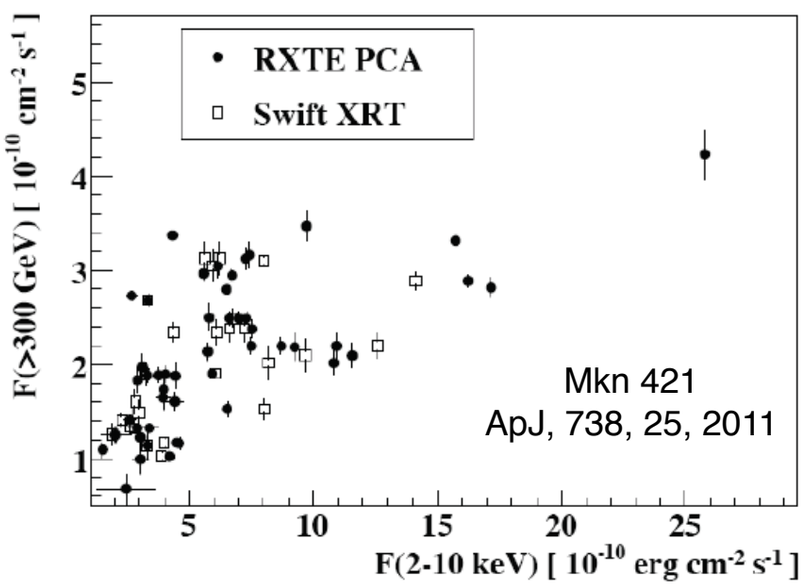
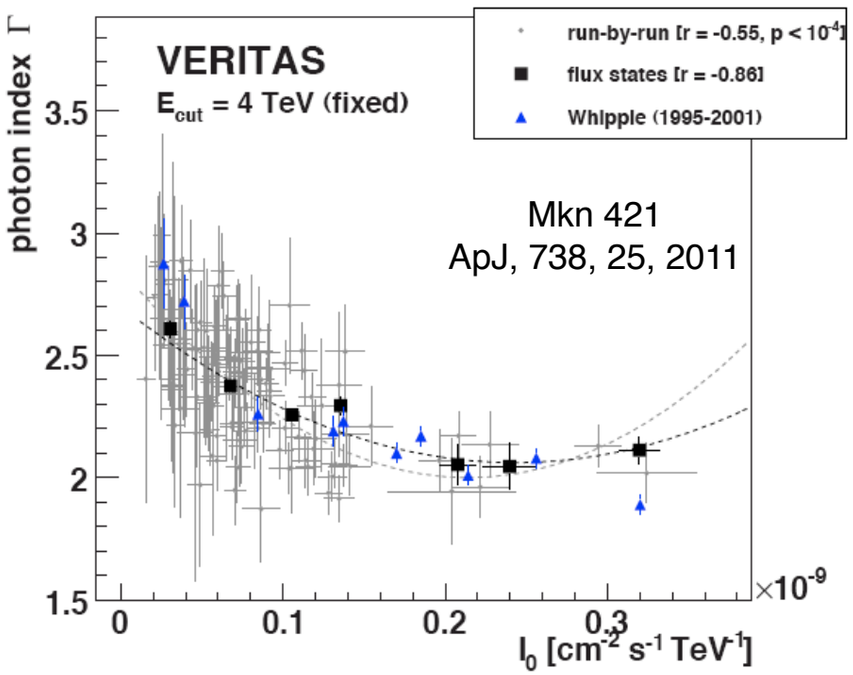
"Common Knowledge" about Flaring HBL

- Illustrative case using Mkn 421 in 2008
  - Same trends seen in long-term studies
  - Similar results seen for a few other VHE HBL
- VHE spectral hardening w/ increased flux
- X-ray & VHE fluxes are linearly correlated
  - VHE/X-ray spectral hardening also correlated
- Low "flicker" states: No correlation seen; or VHE correlation w/ optical & not X-ray







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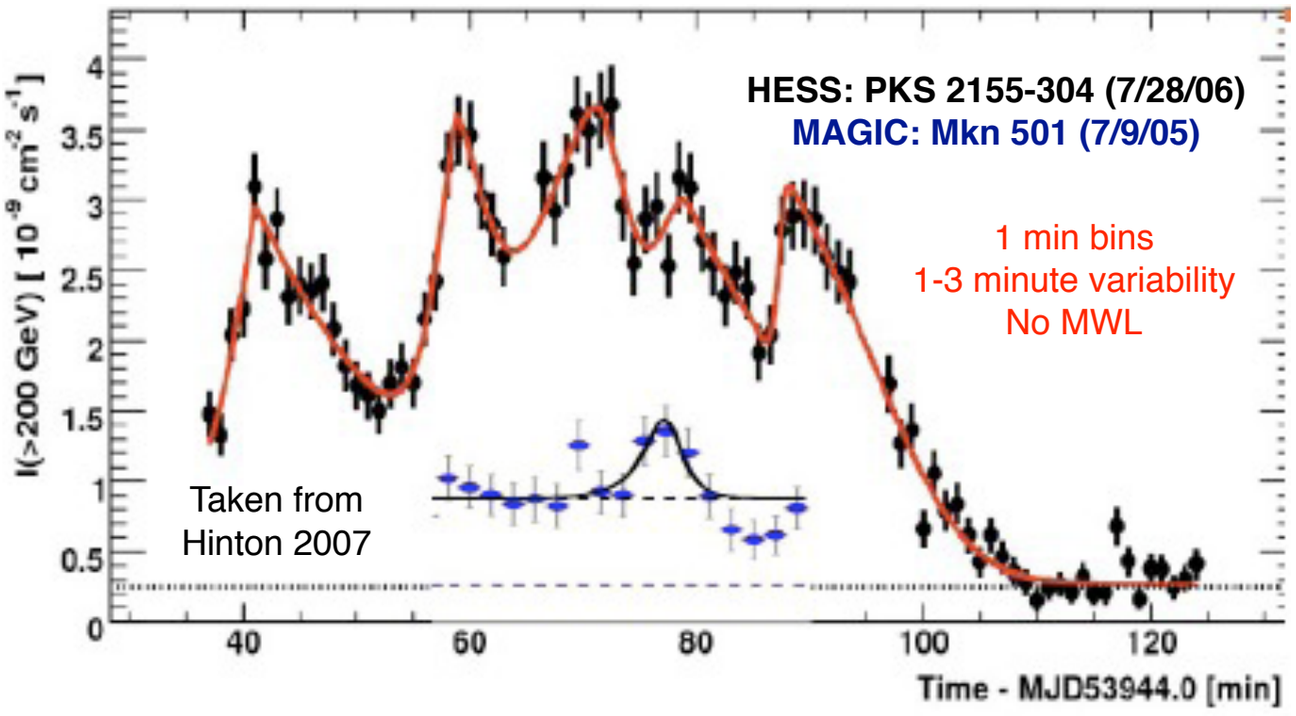
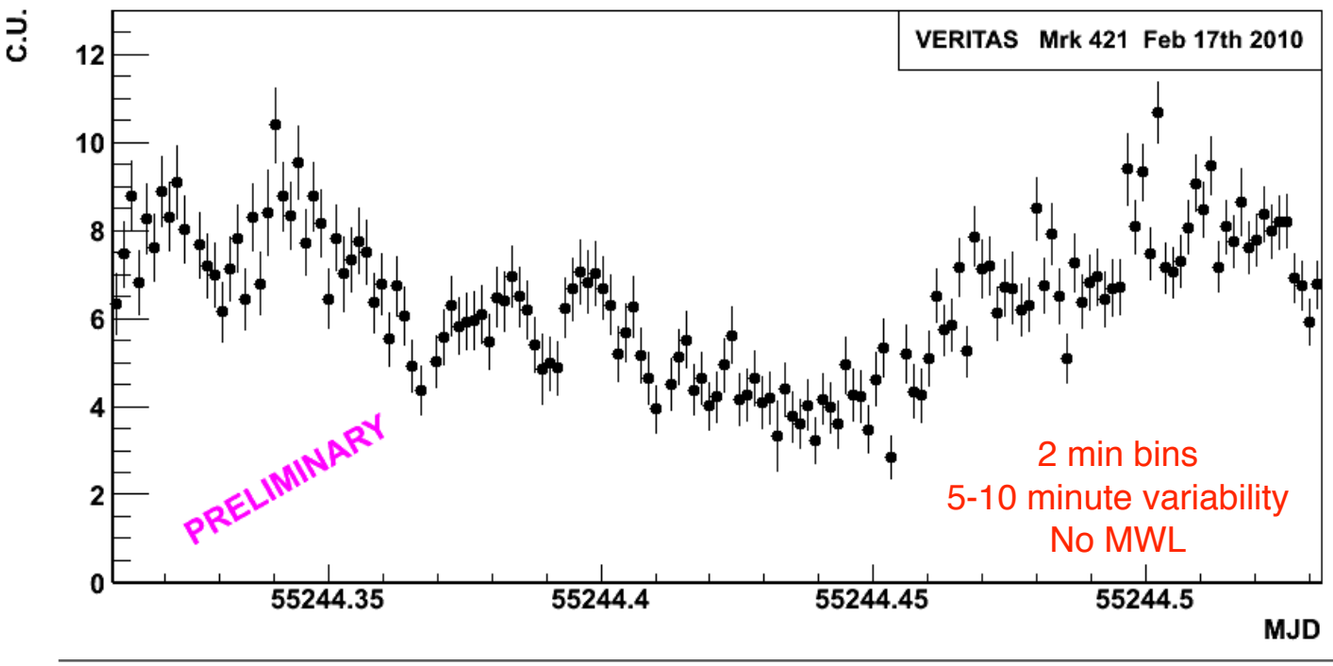
3 Most Extreme Flares w/ 3rd Generation

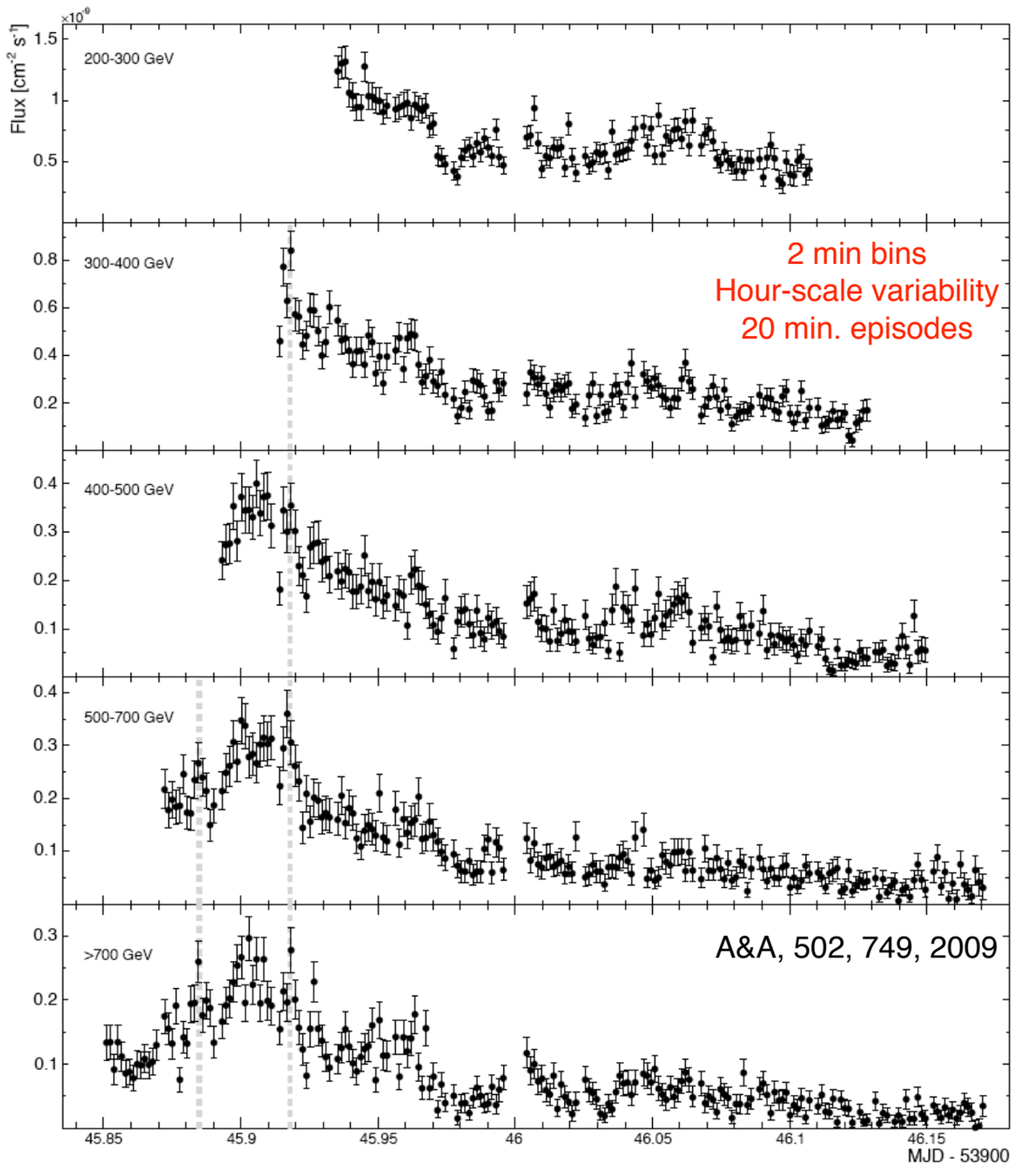
PKS 2155-304 (90 min) & Mkn 501 on Same Scales



VERITAS: ~5 h Exposure on Mkn 421



HESS: PKS 2155-304 Flare on 7/30/06
7.5 h of data - ~6 h Simultaneous w/ Chandra



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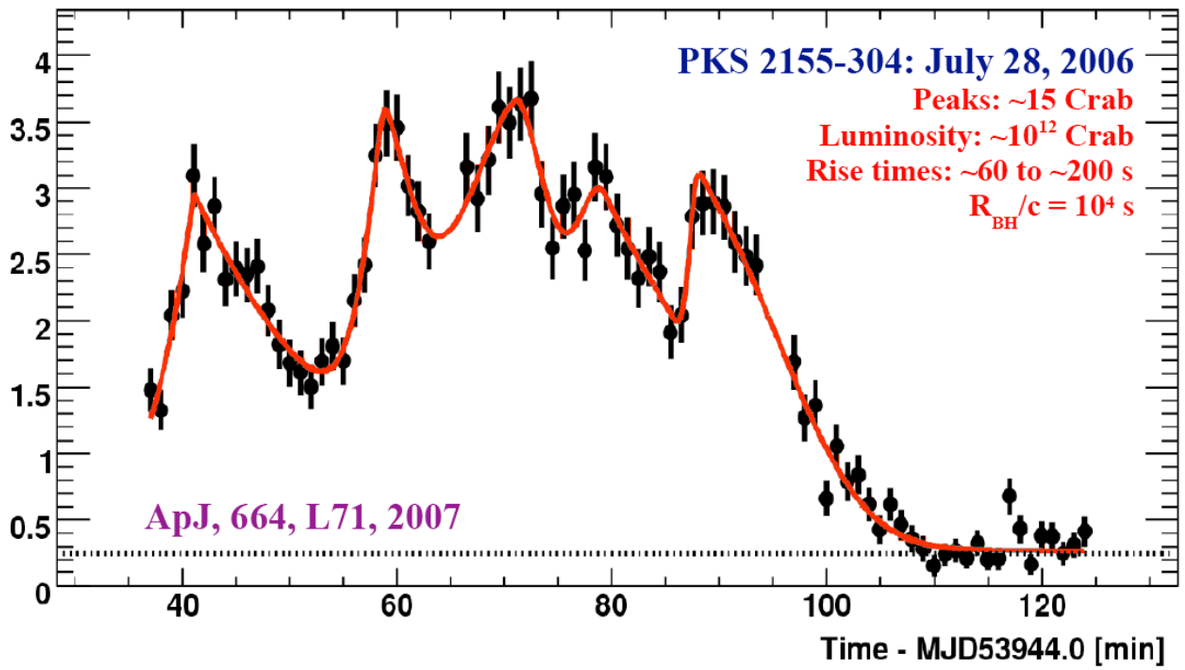
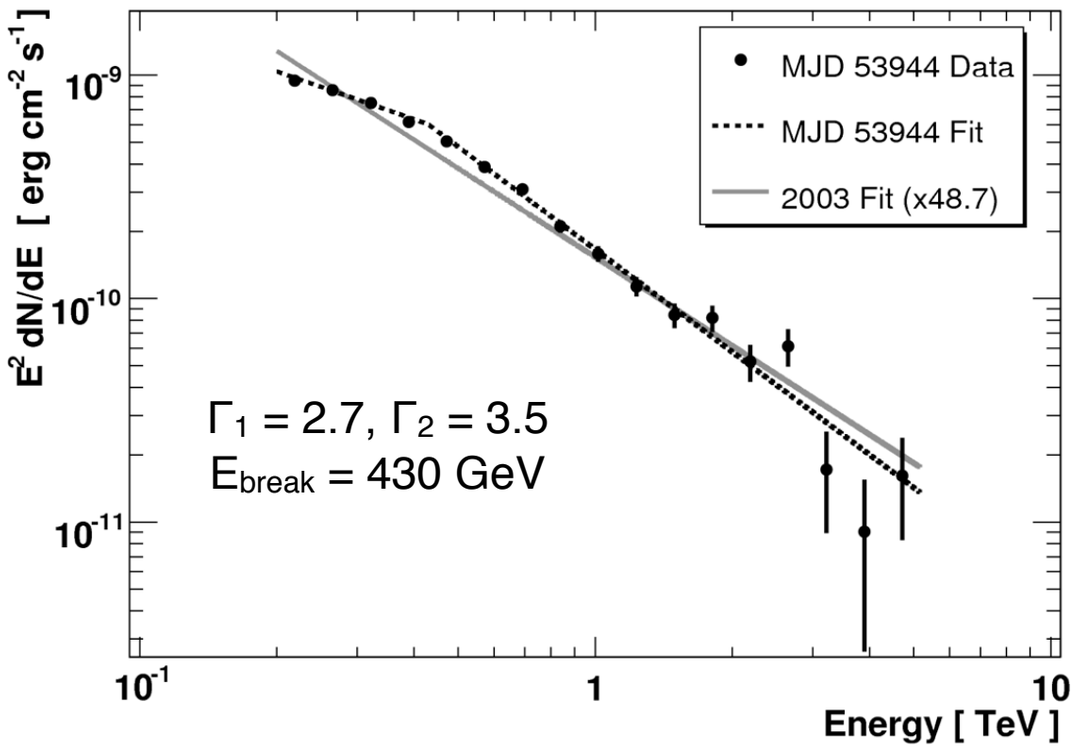
The Big Flare of PKS 2155-304 (z = 0.116)

- 9-yrs HESS monitoring: 4 nights >2 Crab
- 90 min. episode: Factor of 23 flux range
  - ~12000 γ,168σ, γ-rate: 2.5 Hz (after cuts)
  - F_{var} = 0.58 ± 0.03; ~2x higher than X-ray
- Almost no spectral change from low state, despite factor of ~50 flux change



- 5 bursts; Fit GRB "generalized Gaussian"
- Best τ_r = 173 ± 28 s; Fastest τ_r = 67 ± 44 s
  - Best: R < δ x 4.7 x 10^{12} cm < δ x 0.31 AU
- BH is ~10^9 M_{sun}: δ > ~100 R / R_{sch}
  - Energetics + VHE photon escape: Γ > 50
- GRB like Doppler factors or variability not related to black hole



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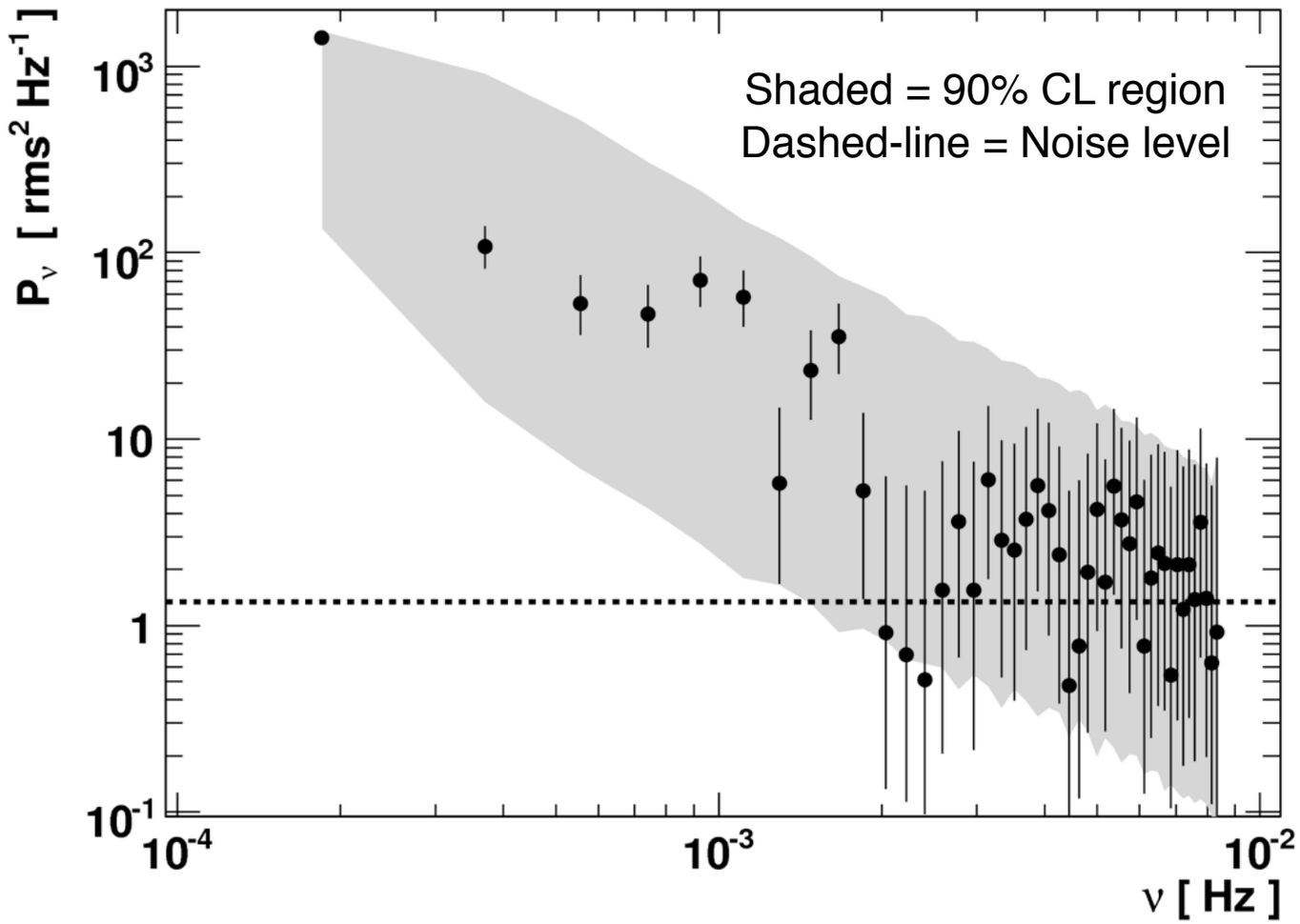
Big Flare: X-ray Timing Techniques

- PDS: Significant power down to 600 s
- P ~ ν^{-2} (red-noise like)
  - ν^{-1} rejected; Too much power at high-ν
  - Remarkably similar to X-ray power spectra
  - Similar behavior seen by H.E.S.S from Mkn 501
- Log-normal process suggests multiplicative (not additive) process
  - 11-yr light curve from H.E.S.S. shows that even quiescent flux is log-normal (intrinsic)
- Typically related to undamped fluctuations in accretion rate
- Alternative fast moving jet w/ several compact (faster moving) sources
  - Simple SSC explanation
  - Larger component dominates “steady state”

Fourier PDS for PKS 2155-304 Flare



No sign of high-ν cutoff suggests even faster variability may be detectable with a more sensitive instrument

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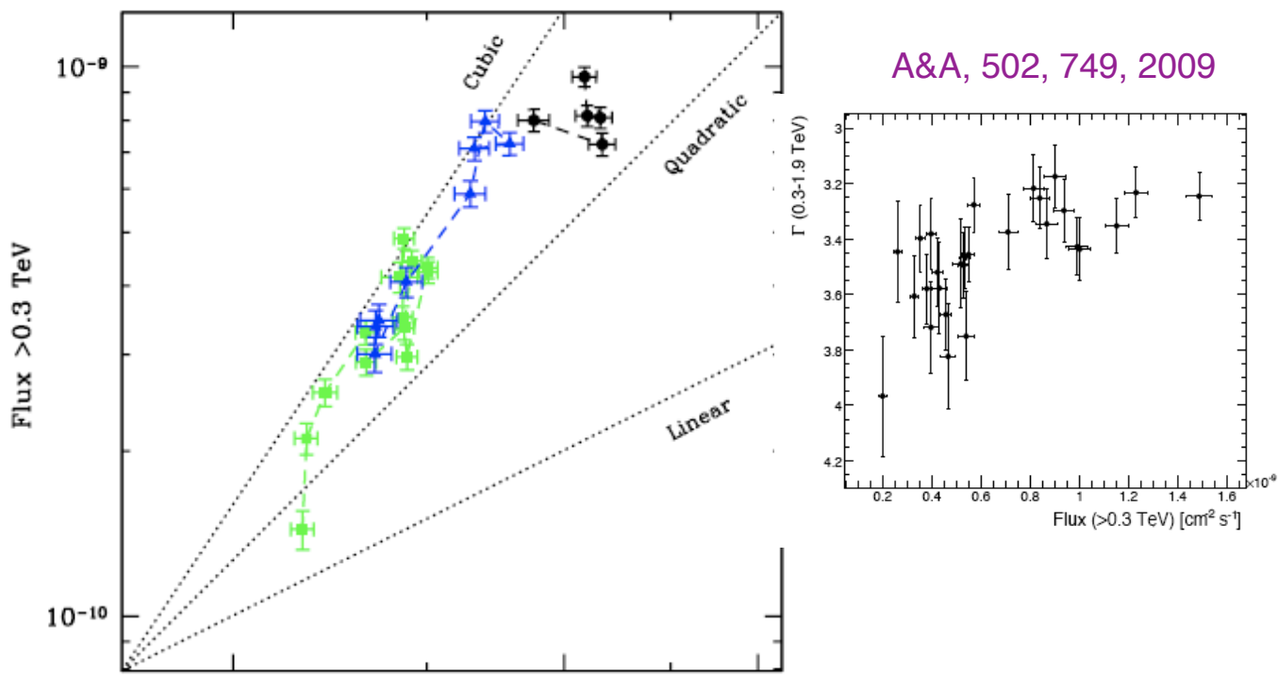
PKS 2155-304: Chandra Flare Highlights

- ~7.5 h HESS exposure, 6 h w/ Chandra
  - Brighter, but slower (~1 h) than “fast flare”
- Changes: 20x VHE, 2x X-ray, 15% optical
  - VHE/X-ray harder when brighter
  - VHE spectra more curved with higher flux
  - Synchrotron & inverse-Compton peaks don’t move
- X-ray/VHE flux correlation strong & cubic
  - No lags between bands or within bands
  - VHE/X-ray spectra correlated; similar time evolution
- No optical corr. aside from rise at flare onset
- Extremely Compton-dominated (10x) flare
  - Never seen before
- Again, multiple SSC components needed



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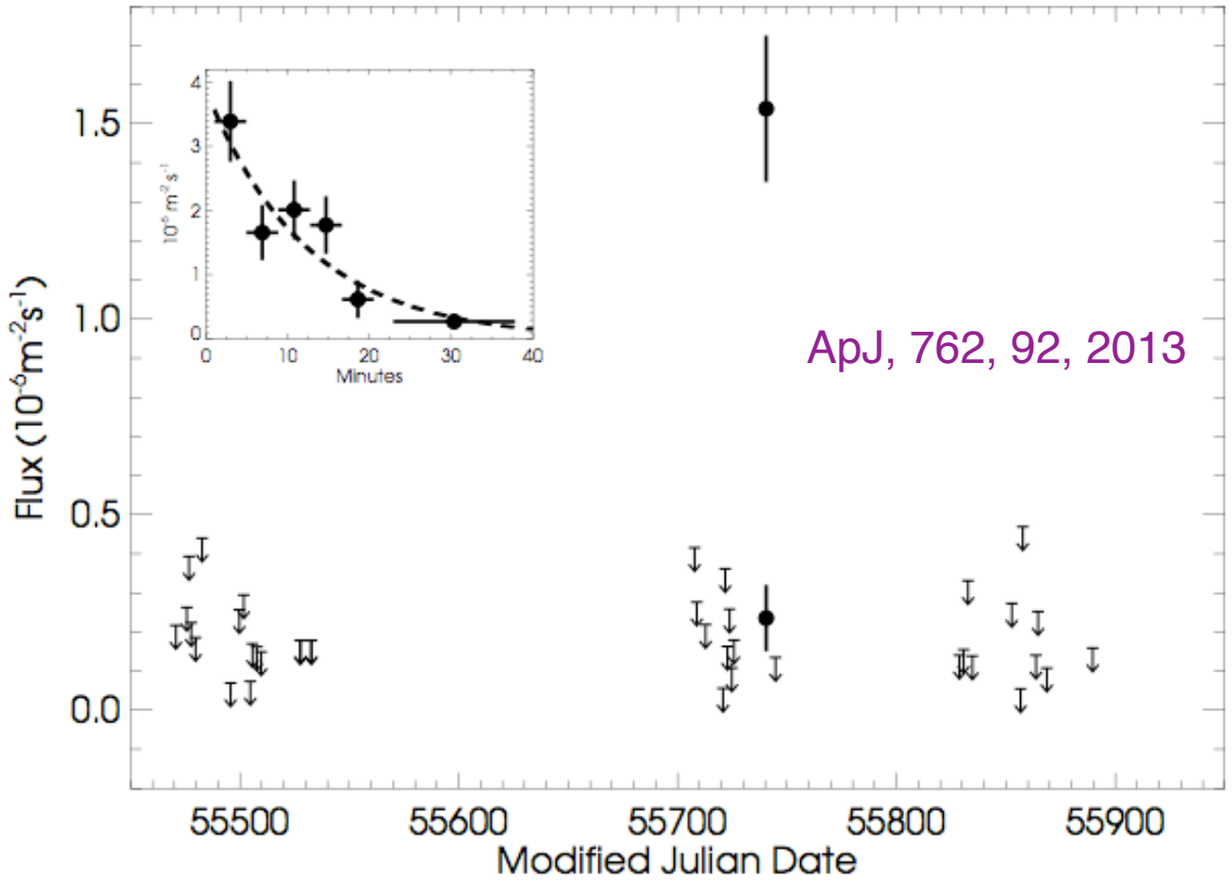
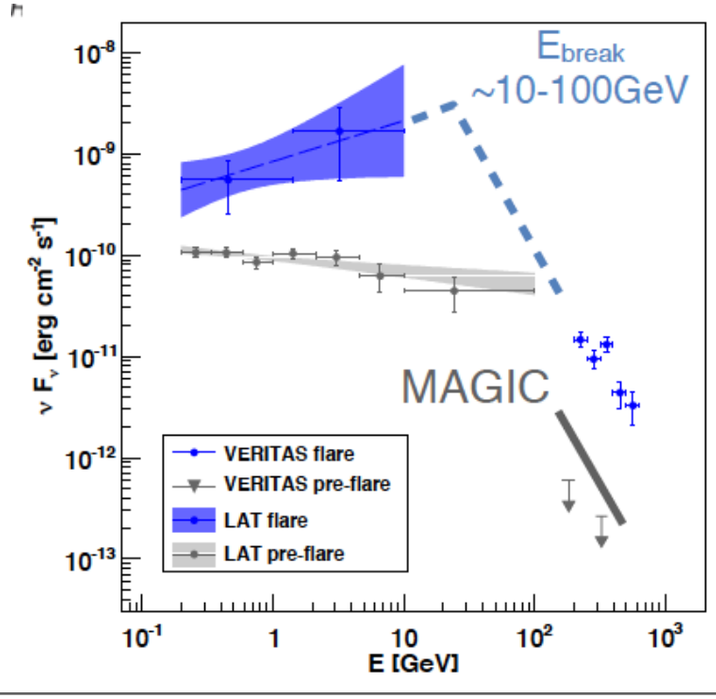
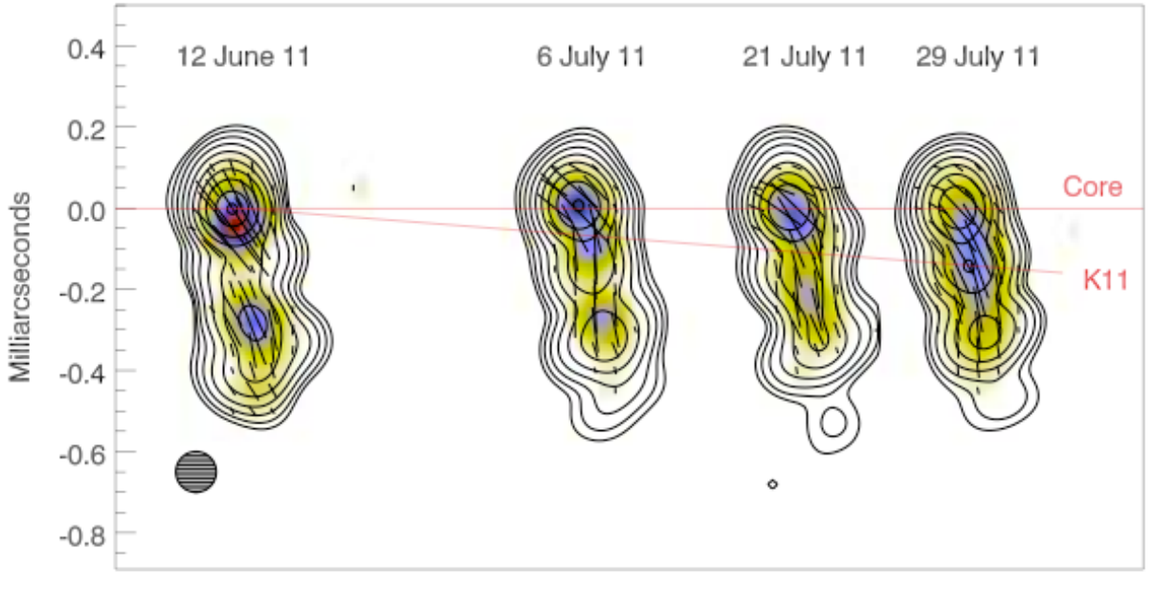
BL Lacertae Flare in 2011

- One of the few non-HBL VHE blazars
- Only detected at VHE during 3 flares (3% Crab by MAGIC in 2005; 15% Crab by VERITAS in 2013)
- Major flare on June 27, 2011
  - Peaked at ~125% Crab; 13 ± 4 min decay
  - Spectral break in Flare: $\Gamma_{LAT} \sim 1.6$, $\Gamma_{VHE} \sim 3.8$
- Emergence of radio knot linked to VHE flare
- Do rapid variations, spectral break & radio correlation indicate emission location?



ApJ, 762, 92, 2013





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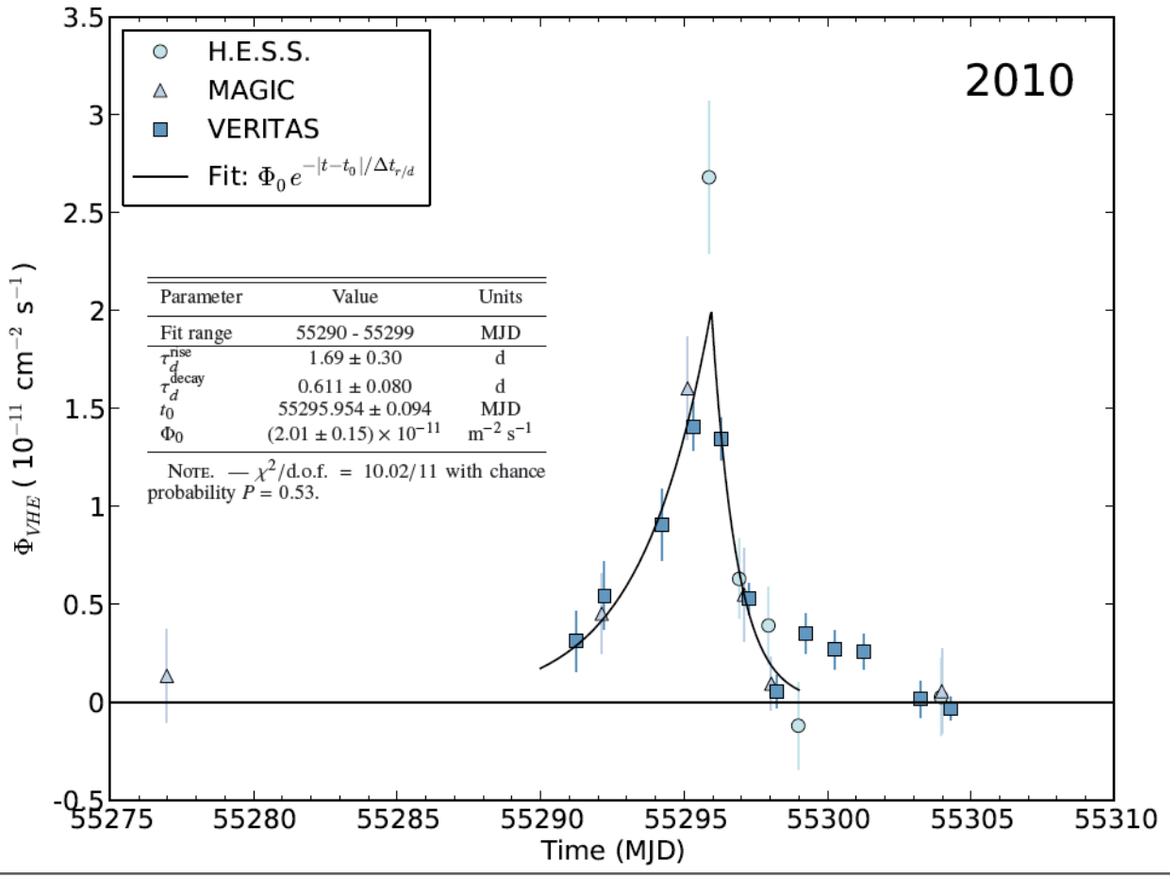
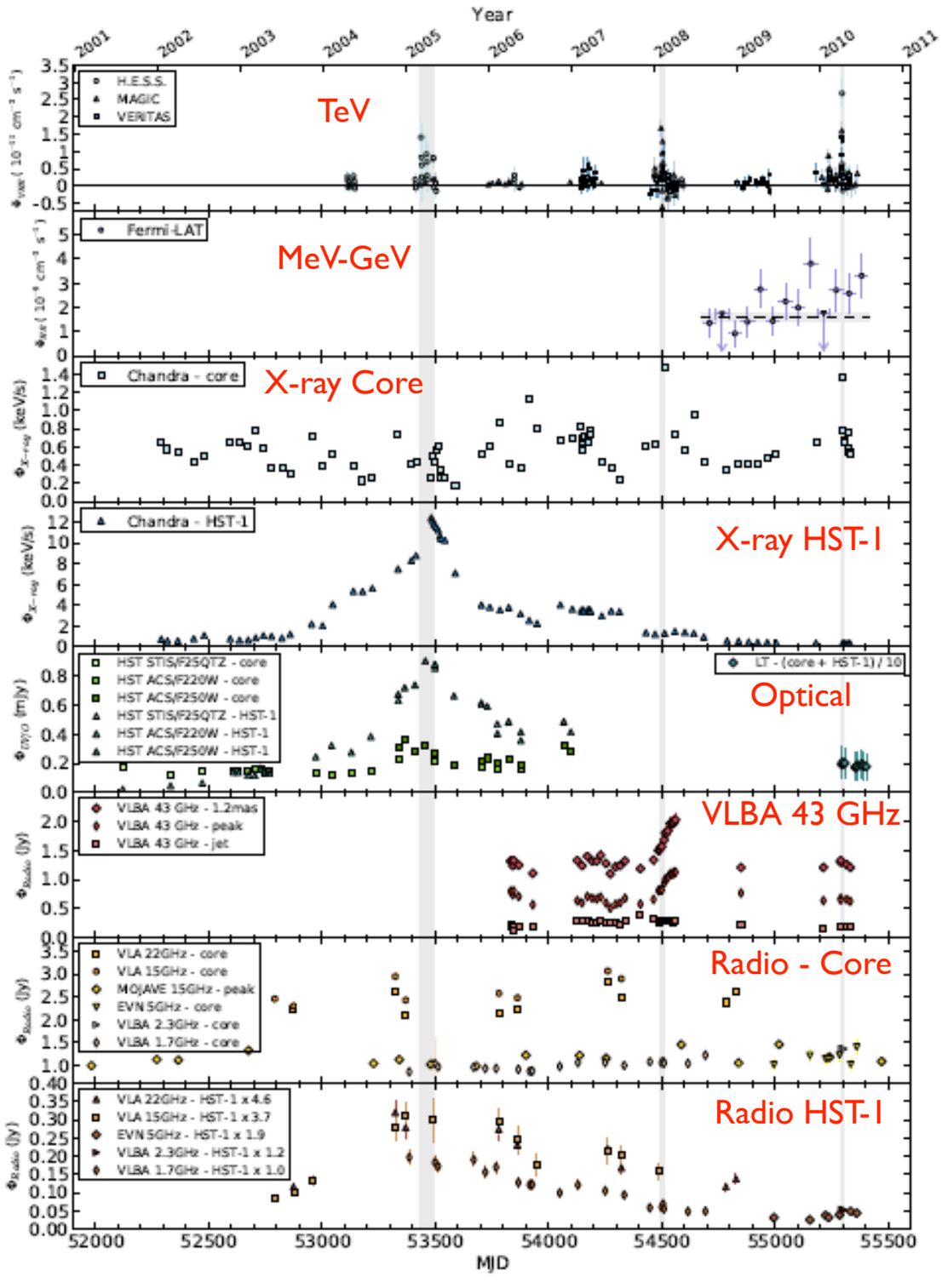
M87: 3 TeV Flares w/ Day-scale Variations

- 2005: TeV flare while HST-1 bright & core low
  - Science, 314, 1424, 2006
- 2008: X-ray / radio core flare; Birth of radio knot; HST-1 quiet
  - Science, 325, 444, 2009
- 2010: Sub-day-scale variability (0.6 days)
  - $R < \delta \times 10^{15}$ cm; (67 AU = 10^{15} cm)
  - ApJ, 746, 151, 2012 & ApJ, 746, 141, 2012
- Very quiet at TeV (i.e. only weakly detected) since 2010 event





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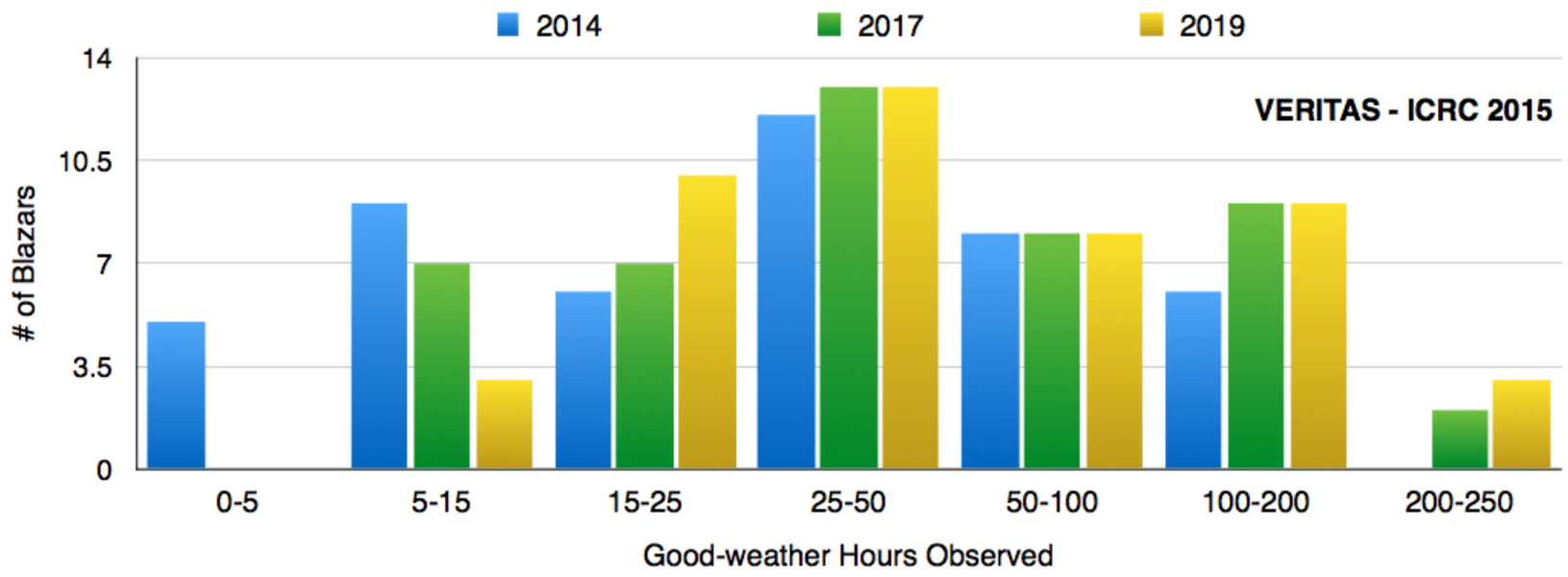
Conclusions

- 65 VHE AGN: ~70% HBL, but growing pop. of IBL, LBL, FSRQs & Radio Galaxies
  - Non HBL “only” detected during flares; ~2/3 of HBL show some variability
  - Extreme variability is very rare: Only a few major events in past decade
- Modeling of HBL w/ SSC is successful; Even during “slow” flares
  - Non-HBL possibly requires SSC+EC or more complex; Extreme variability also more complex
  - As we look in much greater detail (Mkn 421 / Mkn 501), we see perhaps (obviously) SSC is too simple…
- Future of 3rd Generation: AGN source count will probably be > EGRET (67)
  - Deep (~100 h @ VHE) MWL campaigns on ~20 AGN: Duty cycle, low states for some IBL, long MWL corr. studies



VERITAS Exposure on all known VHE AGN