Results from VERITAS Extragalactic Observations

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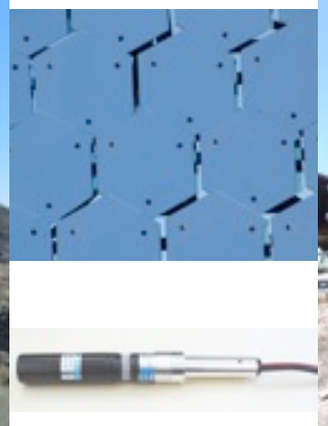
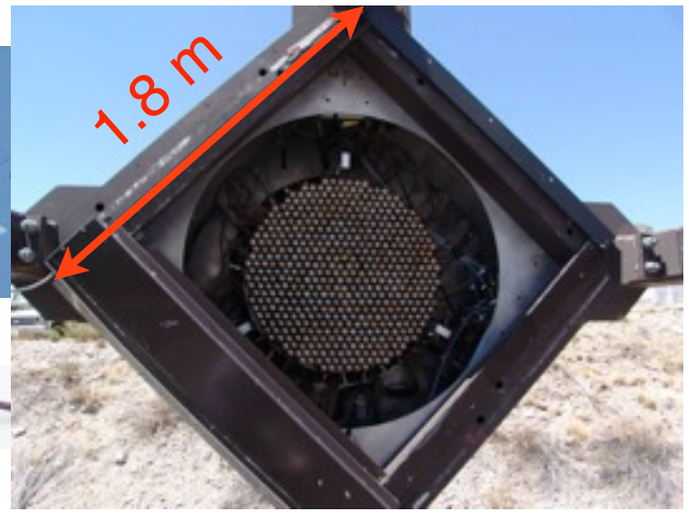
TeVPA 2010; Paris, France; July 19, 2010

VERITAS: A Cherenkov Telescope Array

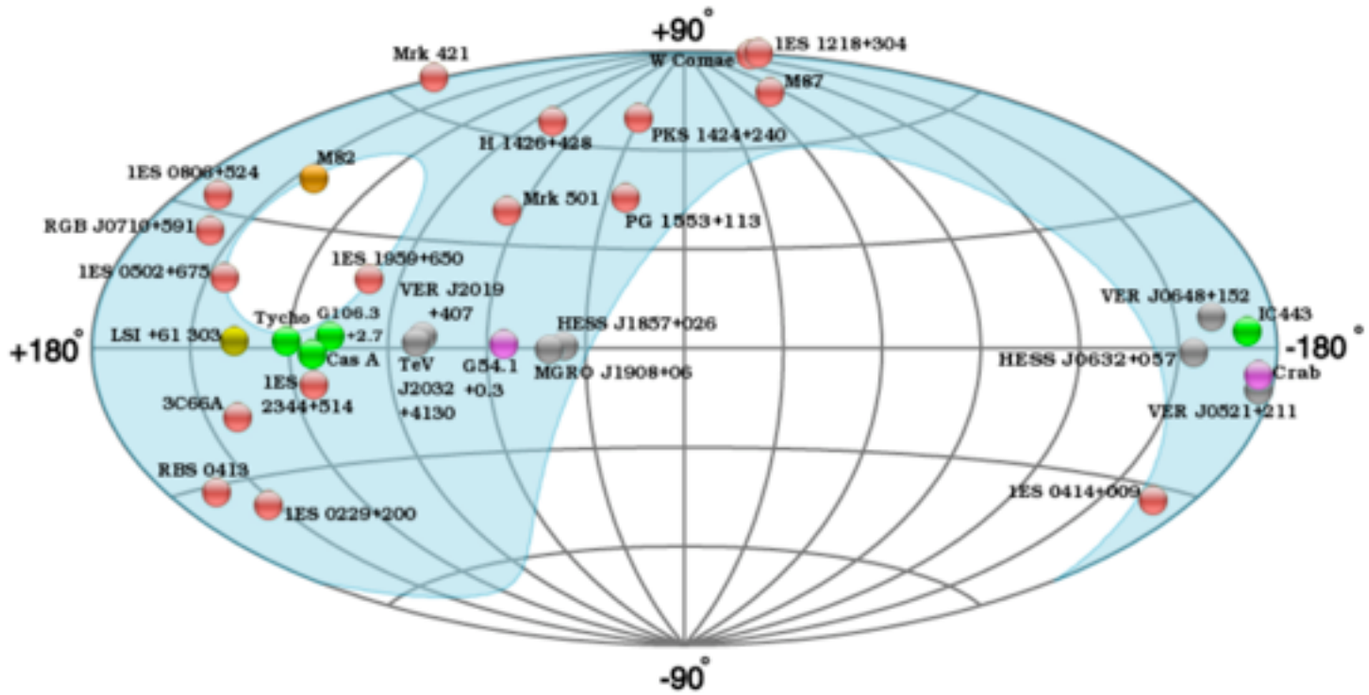
- Arizona: ~32° N, ~111° W, 1268 m a.s.l.
- 4 identical telescopes: ~85 m “square”
  - f/D ~ 1.0; D = 12 m; f = 12 m
- Mirror Area: ~106 m²; 350 mirrors
- Camera: 499 pixels (0.15°) & 3.5° FoV
- 3-level trigger: ~10% dead time; ~300 Hz
- Upgraded in Summer 2009:
  - Telescope relocated & improved mirror alignment
  - 30% increase in sensitivity, fewer systematics
- Further upgrade funded (Summer 2012)
  - New cameras (High QE PMTs) & L2 trigger
  - Optical interferometry capability





VERITAS Scientific Studies

- **Data:** ~1100 h / year (~25% in moonlight)
  - ~70% on extragalactic targets
- **Metrics:** Studies from ~100 GeV to ~30 TeV
  - Detect (5σ) 1% Crab source in <30 h @zenith
  - Angular resolution: $r_{68} < 0.1^{o}$
  - Energy resolution: ~15%
  - Systematic errors: $\Delta\Gamma \sim 0.1$, Flux ~ 20%
- **Extragalactic objects of interest**
  - AGN (blazars & radio galaxies) & starburst galaxies
  - Galaxy clusters & GRB afterglows
  - Dark Matter focused: dwarf galaxies, globular clusters, Local Group objects & galaxy clusters



VERITAS catalog = 32 sources

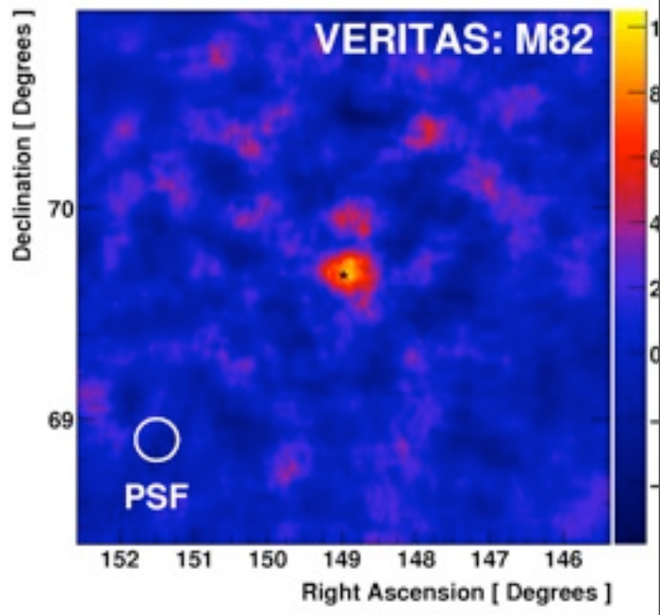
c.f. June 2009 = 18 sources

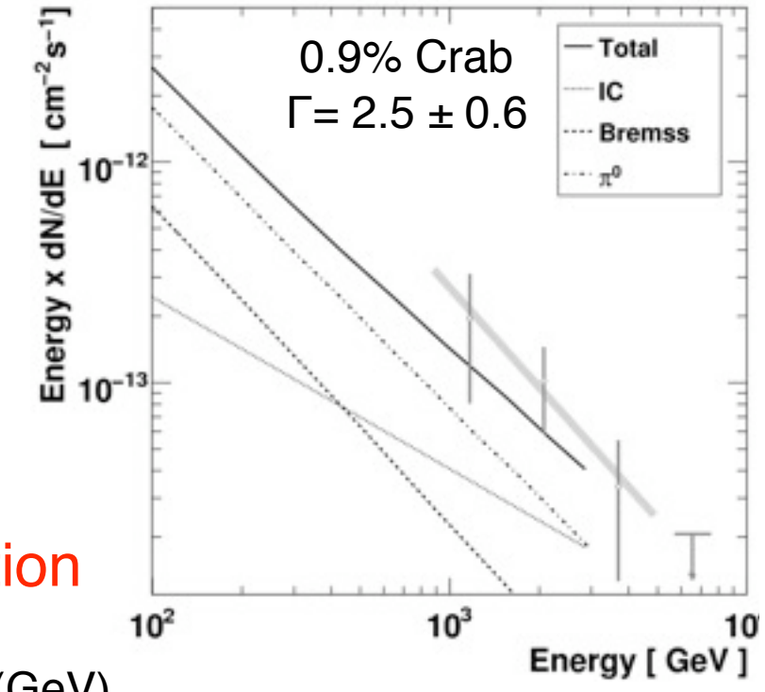
20 extragalactic sources

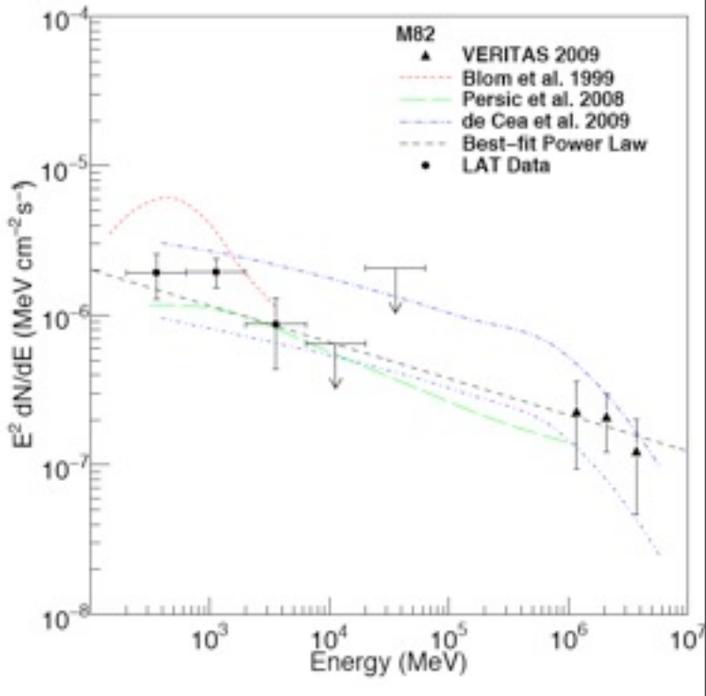
(18 blazars, 1 FR 1 & 1 Starburst)

Starburst Galaxies: "Solving" a 100-yr old mystery

- γ's expected from central regions:
  - High rate of massive star formation => CRs
  - High gas density; CRs + gas => π^o => γ's
- M82 expected to be brightest in VHE
- VERITAS ('07-09): ~137 h live time
  - Discovery: 91γ, 4.8σ post-trials, P = 8 x 10^{-7}
  - Nature, 462, 770, 2009
- VHE flux close to predictions
- CR density: 250 eV cm^{-3}; ~500x Milky Way
- Links CR acceleration to star formation
  - NB: NGC 253 (VHE & GeV) & 30 Doradus (GeV)
- SN+Stellar winds = likely CR accel. sites



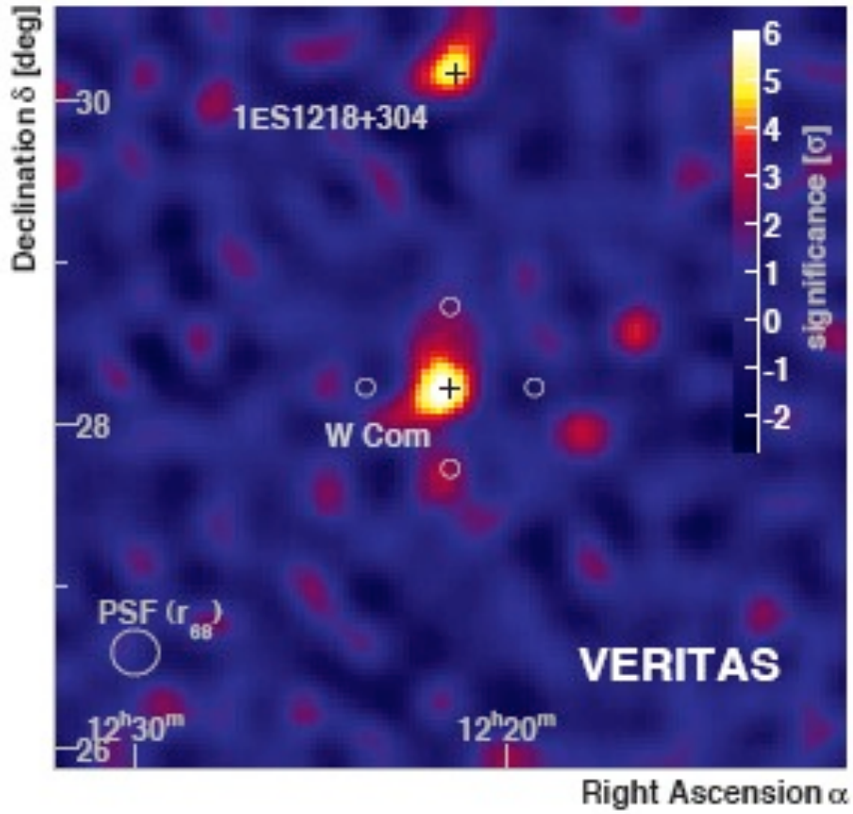


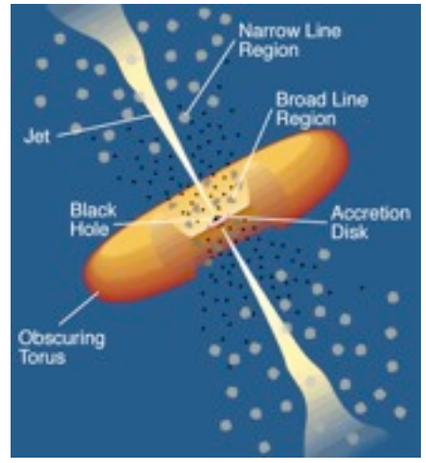


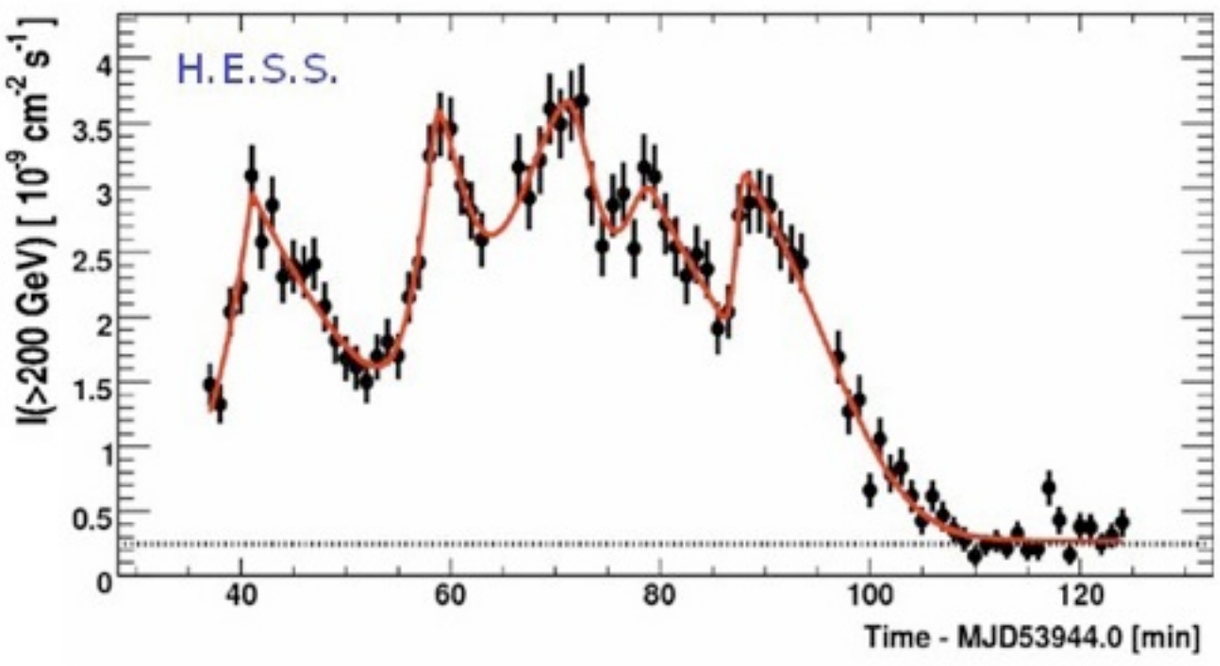
Future seasons: Deepen M82 exposure + look at other SBGs & ULIRGs

VHE (E>100 GeV) Active Galactic Nuclei

- ~30 VHE blazars + 3 radio galaxies
  - ~80% HBL; Most non-HBL only seen during flares
- VHE spectra generally soft ($\Gamma > 3.0$)
- Mostly z<0.25, due to EBL horizon
  - Distant blazars harder than expected => low EBL
  - 3C 279 (z = 0.536) / PG 1553+113 (0.43 < z < 0.47)
- Variability: Only for brightest HBL; non-HBL flares
  - Time scales of ~2 minutes
- VERITAS Key Science Project
  - ~400 h / year incl. moonlight data
  - Discovery, MWL & ToO observations
  - '07-'10 discovery data: ~90 blazars







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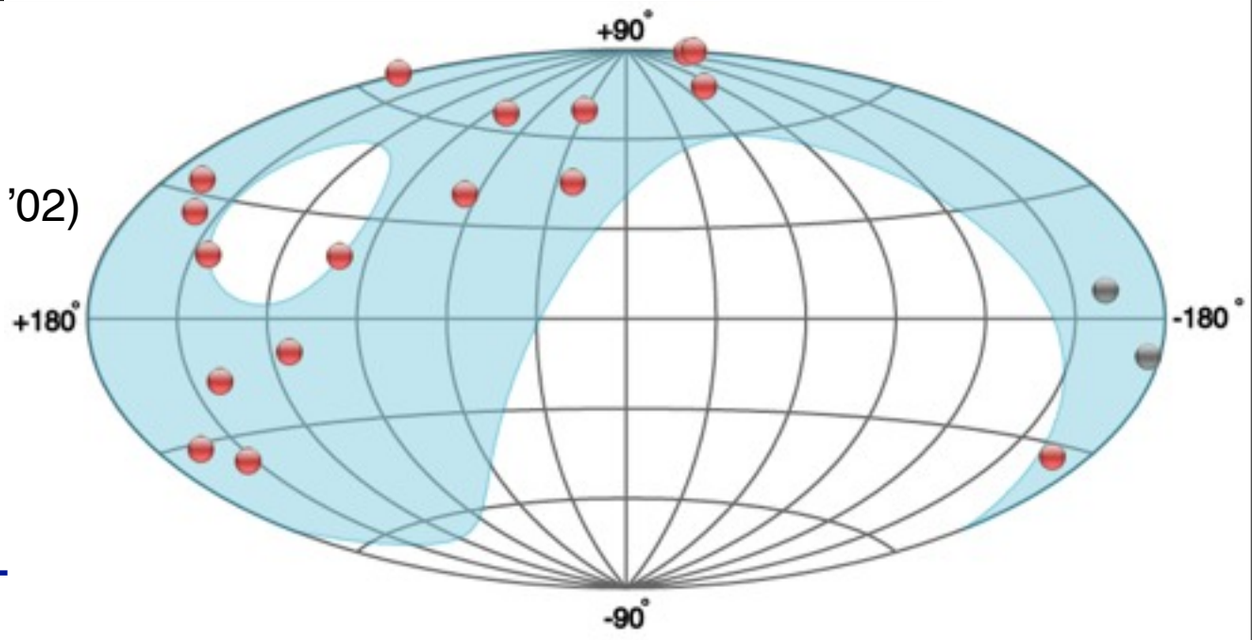
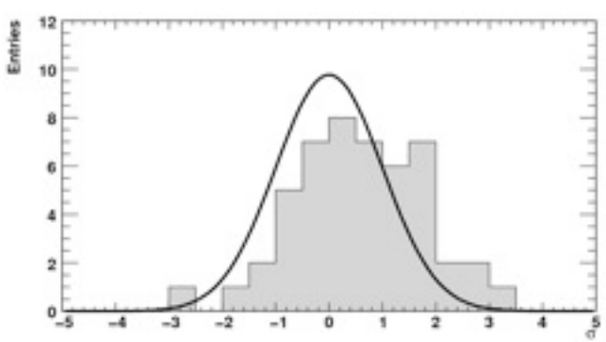
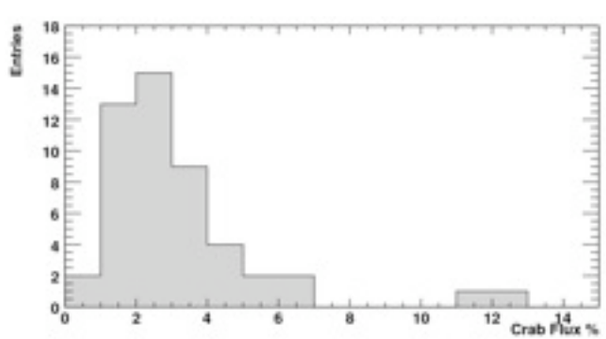
VERITAS AGN Observations

- VERITAS: 9 discoveries + 10 detections
  - More than MAGIC (start in ’04); ~Same as HESS (start in ’02)
  - All discoveries via ATel once >5σ; ApJL in ~6 mo.
- First 3 VHE IBL’s & Most distant BL Lac
- Prior to Fermi: X-ray bright HBL & IBL; EGRET



- 2007-09: Exposures on 80% of “good” X-ray sel. candidates
  - ~5σ “stacked” excess (49 AGN, ~6 h each)
    - 96% from HBL/IBL, albeit 80% of exposure
  - Most UL are best ever; Limits 1st shown at ’09 ICRC





AGN	Type	z
M 87	FR I	0.004
Mkn 421	HBL	0.030
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
W Comae	IBL	0.102
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
1ES 0229+200	HBL	0.139
1ES 0806+524	HBL	0.138
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.190
1ES 0414+009	HBL	0.287
PG 1553+113	HBL	0.43 < z < 0.47
1ES 0502+675	HBL	~~0.341~~ ?
3C 66A	IBL	~~0.444~~ ?
PKS 1424+240	IBL	?
VER J0521+211	Blazar	?
RX J0648.7+1516	Blazar	?

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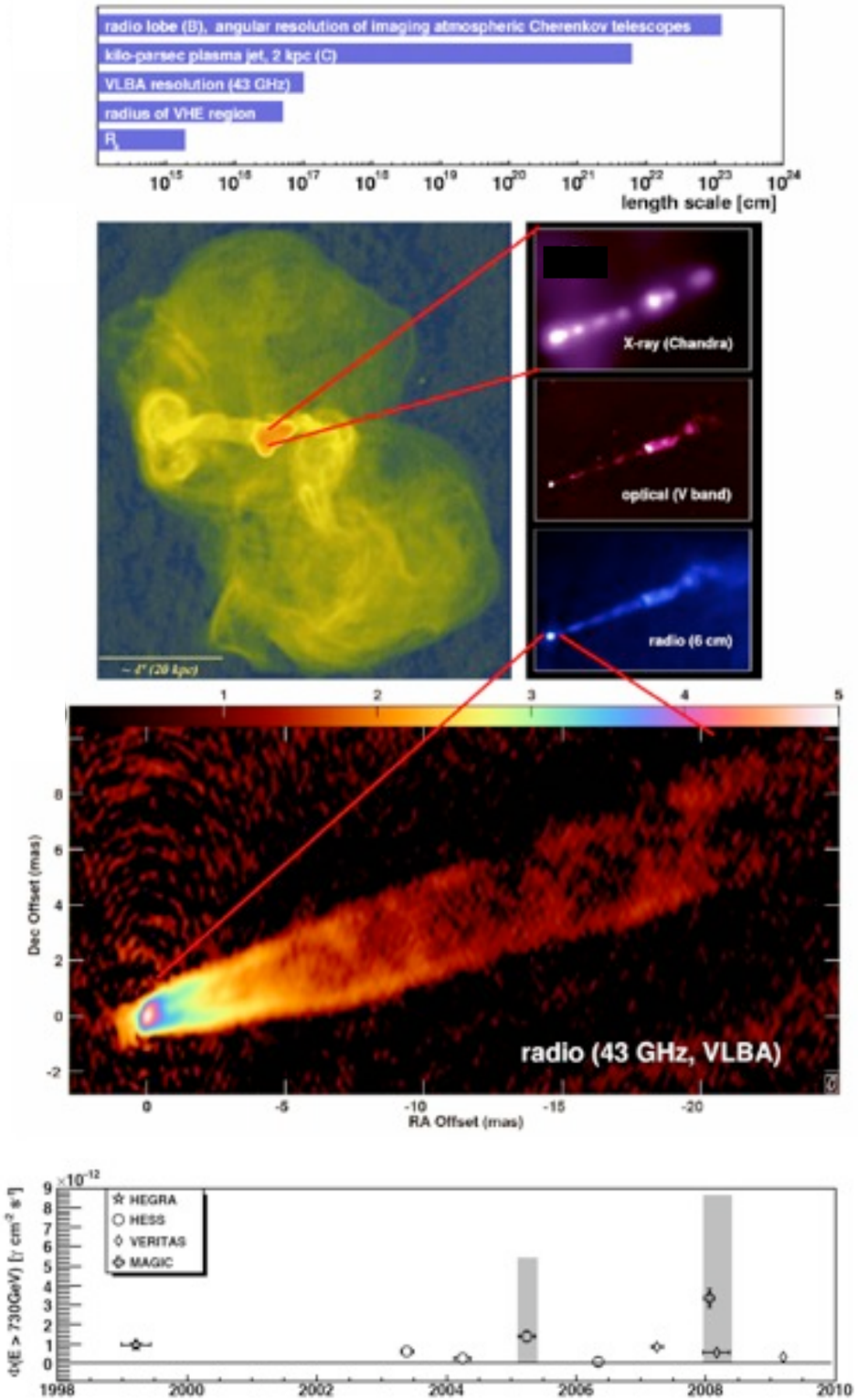
Radio Galaxies

- "Mis-aligned" Blazars: FR I = BL Lacs; FR II = FSRQ
  - View central region (SMBH) & Model w/o beaming effects
- 3 VHE Radio Galaxies (FR I): M 87, Cen A, IC 310
  - M87: 2007 Low state & spectrum => ApJ, 679, 397, 2008
  - M87: 2007-09 VERITAS results: ApJ, 716, 819, 2010
- 13 detected by Fermi-LAT & 3C 111 by EGRET
  - NGC 1275 (FR I): Fermi Bright source; LAT notice in 02/09
    - VERITAS DDT (10 h); Non-detection - but variable flux
    - γ-ray spectrum must cut off: ApJ, 706, L75, 2009
  - 3C 111 (FR II) - Non-detection in 2008 - ApJ, in prep.
    - Exposure during expected flare: RXTE every day
- Future: More M87, NGC 1275, & Survey Fermi detections

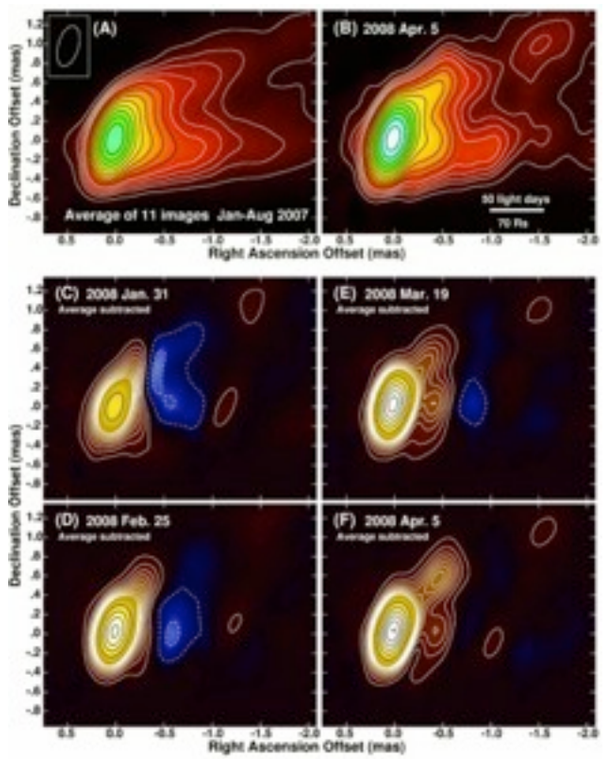


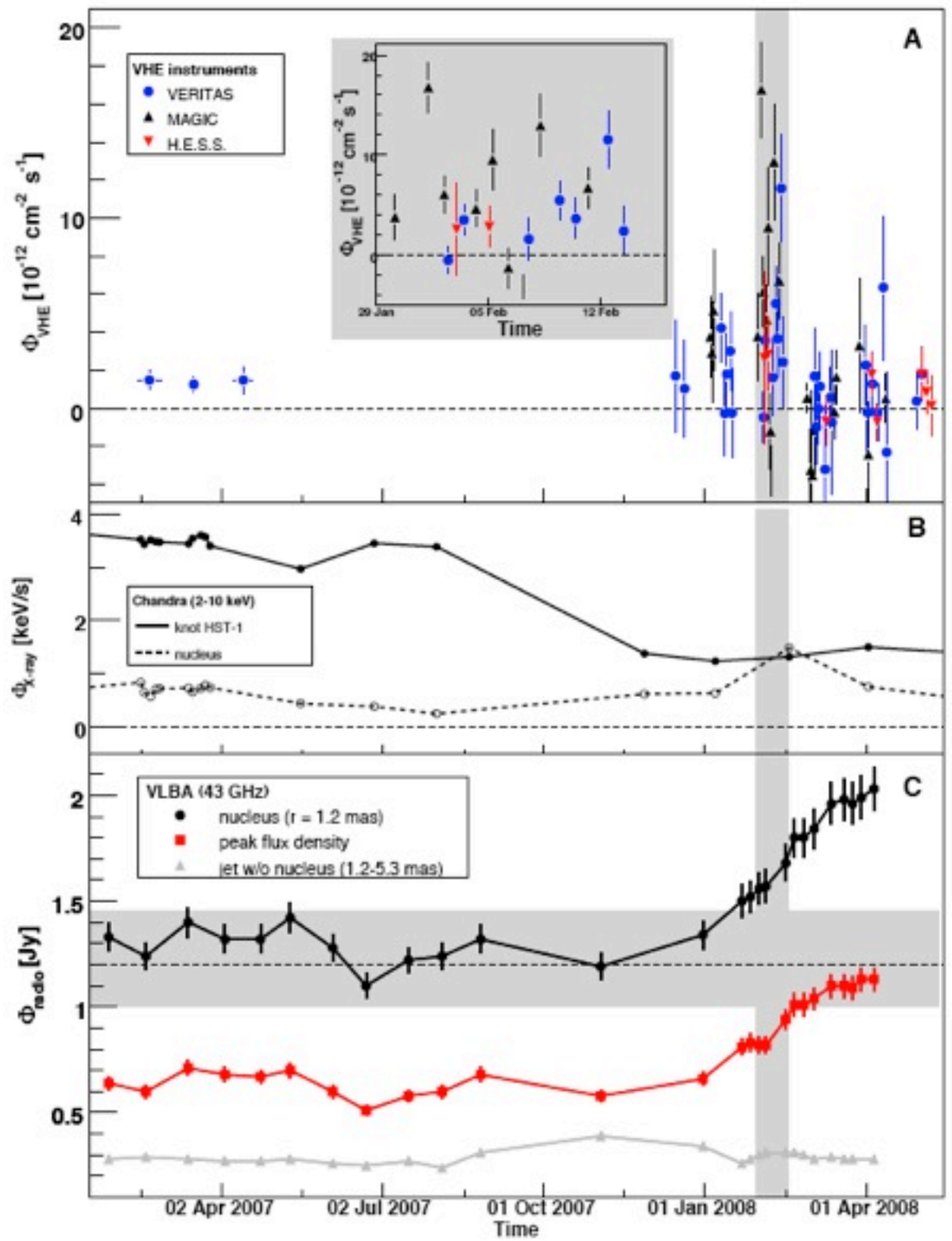
Radio Galaxies: The M87 Flare

- HESS: Day-scale flaring (3σ) in 2005
  - Science article: Emission region near SMBH
  - Knots or core? Knot flare in X-ray
- VERITAS: Day-scale Flaring in 2008
  - Monitoring All VHE instruments (120 h in '08)
  - VERITAS-led paper: Science, 325, 444, 2009

VHE flaring along with simultaneous birth of radio-knot & nuclear X-ray flare

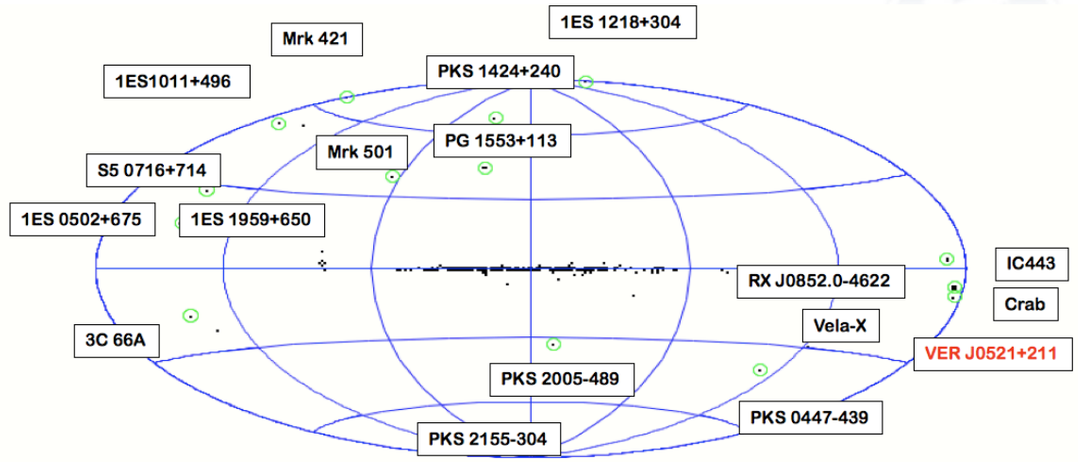
Establishes core as a source of VHE emission



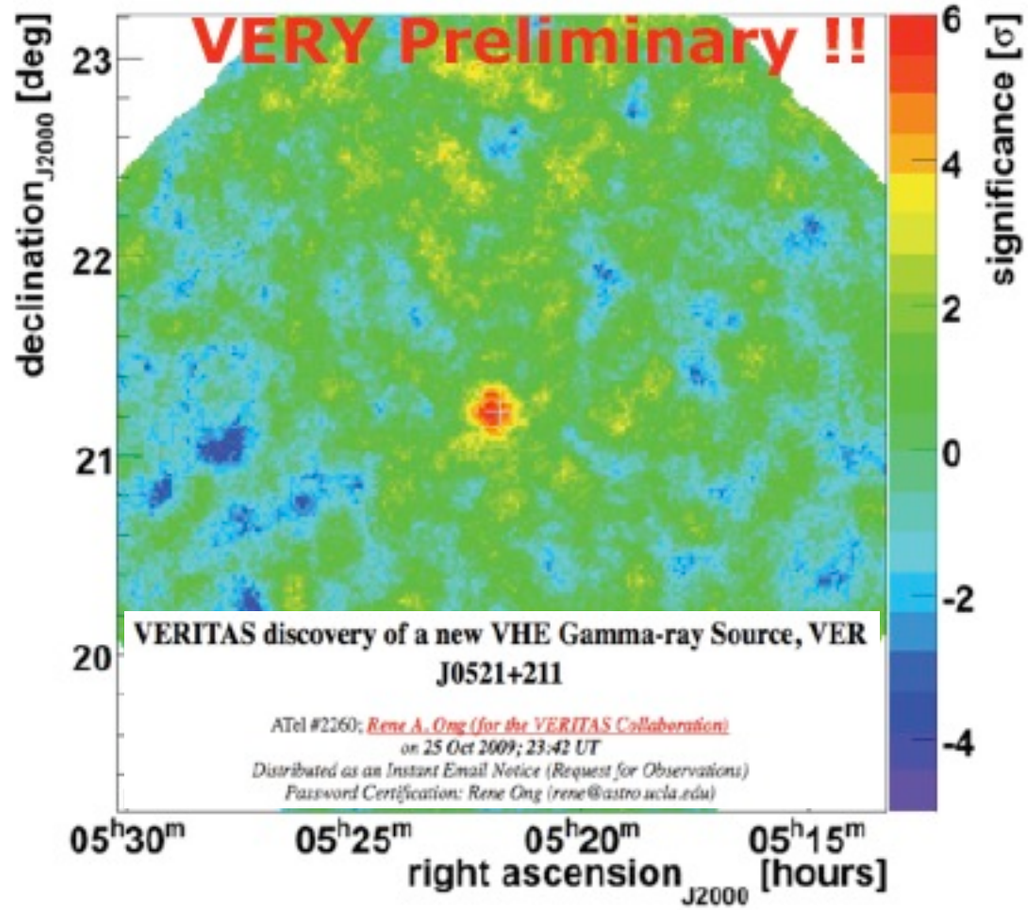


VHE Blazars in the Fermi Era

- 02/09: VERITAS discovers RGB J0710+591
  - ATel => Fermi examines >1 GeV data => LAT detection
- 02/09: Fermi LBAS released => DDT obs. of 3
  - PKS 1424+240: 1st VHE discovery (IBL) via Fermi info.
- 08/09: Fermi-data public => VER J0521+211
- 11/09: Fermi's VHE candidates (1-yr catalog)
  - Top-20 list created w/ input from LAT team
  - #1: RBS 0413 (VERITAS '09 discovery; ~50% '08 data)
  - #5: 1ES 0502+675 (~~z = 0.341~~; VERITAS '09 disc.; LBAS)
- Future: Systematic survey of Fermi candidates
  - NB: Overlap w/ X-ray list; Use LAT for ToO on FSRQ
  - Recent success: VERITAS Discovery of RX J0648.7+1516

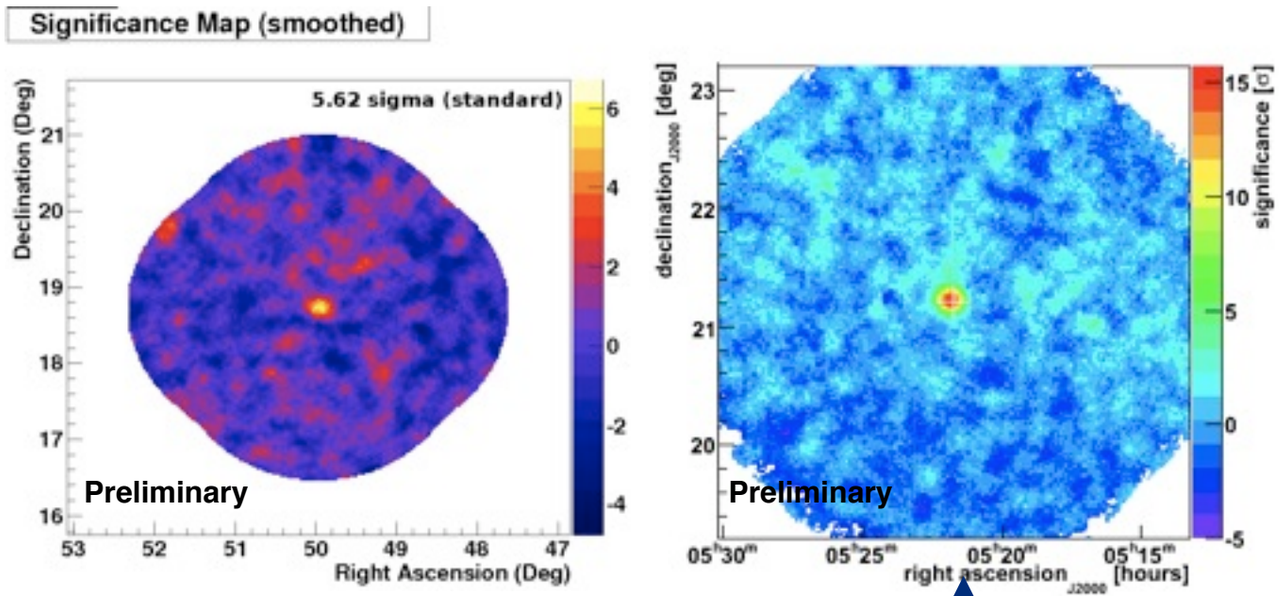


Fermi >30 GeV Sky Map

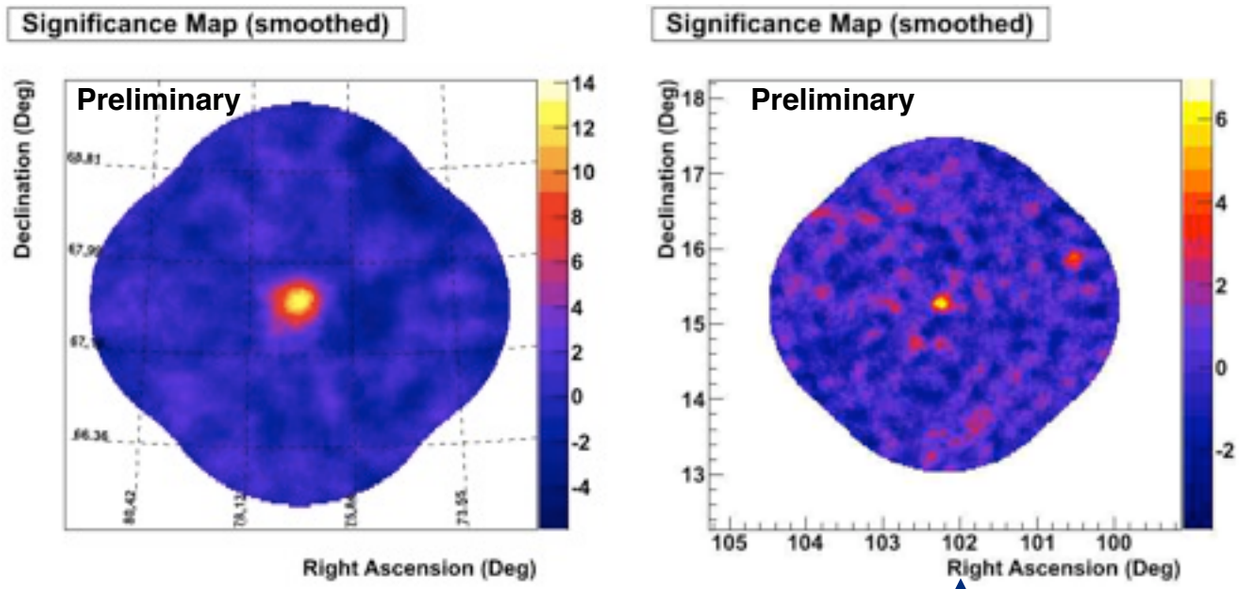


The New Blazar Detections

RBS 0413: ~5.5σ in ~25 h, ~1.6% Crab
X-ray bright HBL @ z = 0.19
Brightest LAT extrapolation



1ES 0502+675: ~12σ in ~30 h, ~7% Crab
z ≠ 0.341; 1 h MMT exposure (10x sens)



VER J0521+211: ~18σ in ~15 h, ~4% Crab
z = ? (unsuccessful MMT, MDM & IR efforts)
Bright flare (~4x brighter; ATel #2309)

RX J0648.7+1516: ~5.2σ in ~18 h; ~2% Crab
Keck: Blazar, but @ z = ?

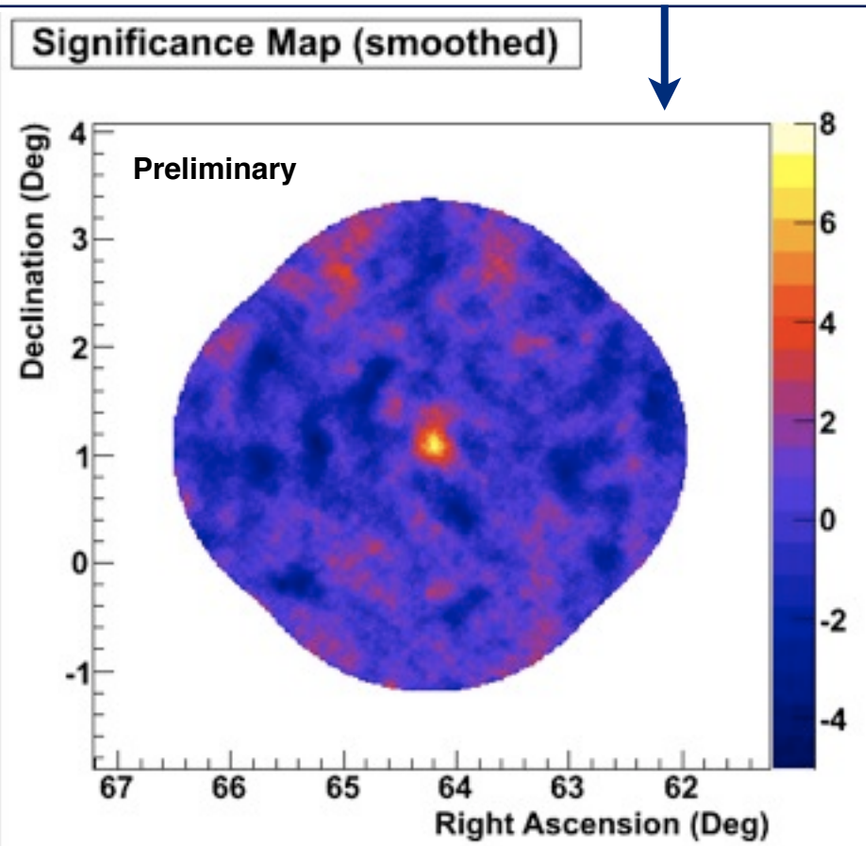
All discoveries initiated MWL observations (Swift + optical & radio)
All will be published as joint VERITAS-LAT collaboration articles

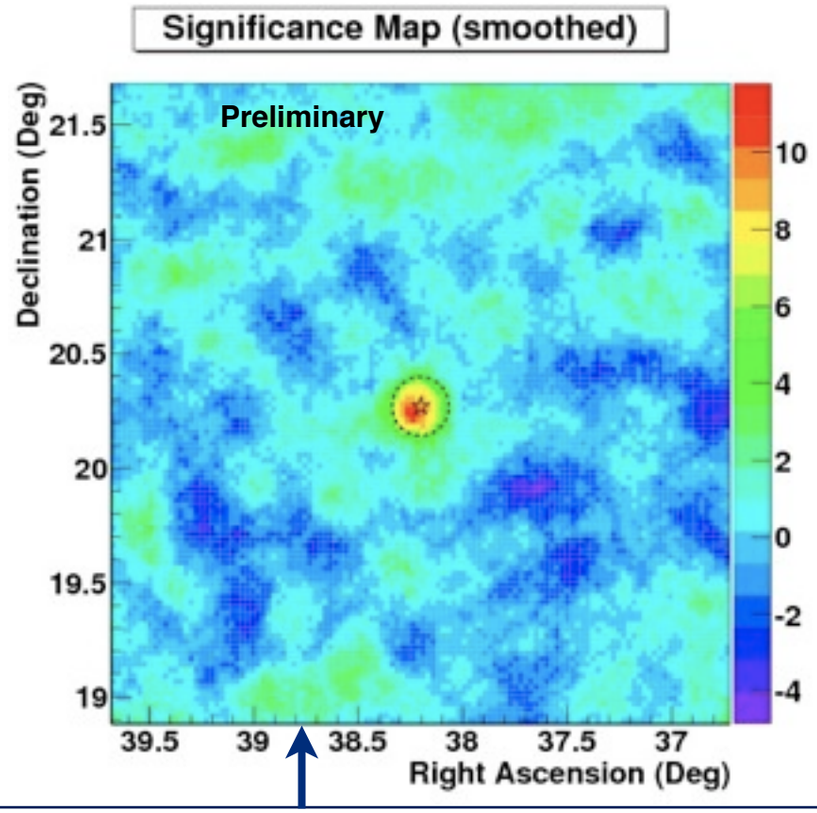
W. Benbow, "VERITAS Extragalactic Observations", TeVPA 2010

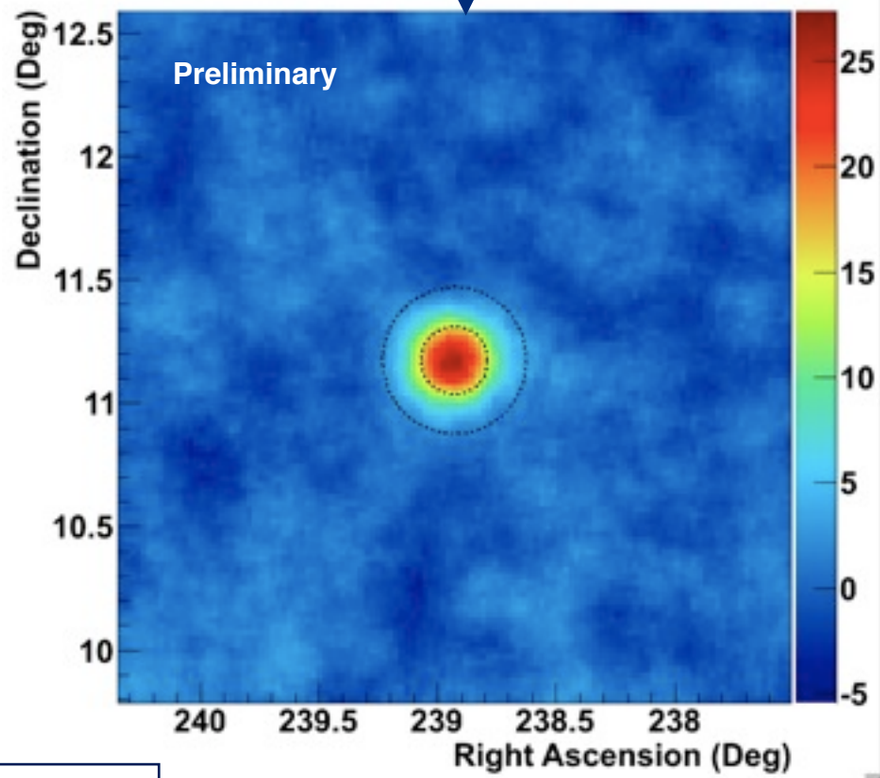
New VERITAS detections: Known VHE HBL

1ES 0414+009: ~7σ in ~45 h, ~2% Crab
Among X-ray brightest HBL; z = 0.287
H.E.S.S. detected at same time

PG 1553+113: ~25σ in ~25 h, ~6% Crab
New redshift info: z = 0.43 - 0.47
Flux/spectrum comparable to HESS in '05







1ES 0229+200: ~9σ in ~28 h, ~2% Crab
z = 0.139; Major-MWL campaign
Flux/spectrum consistent w/ HESS in '06

All measurements are the deepest-ever @ VHE & have significant EBL implications
Use LAT spectrum => VHE extrapolation => See EBL footprint

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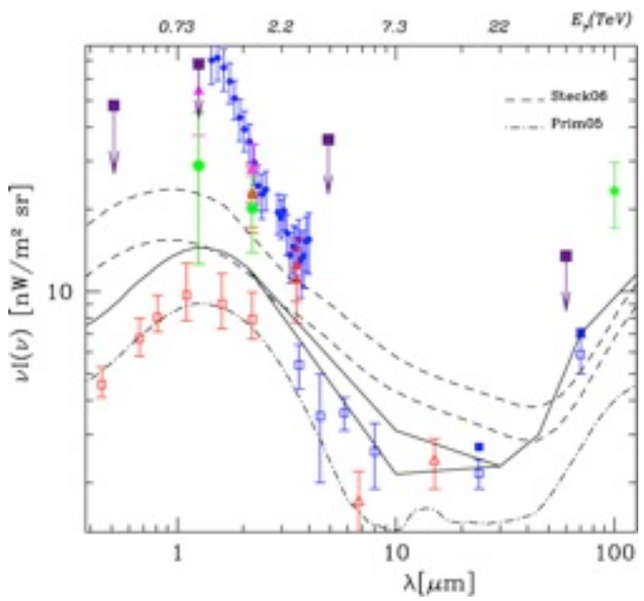
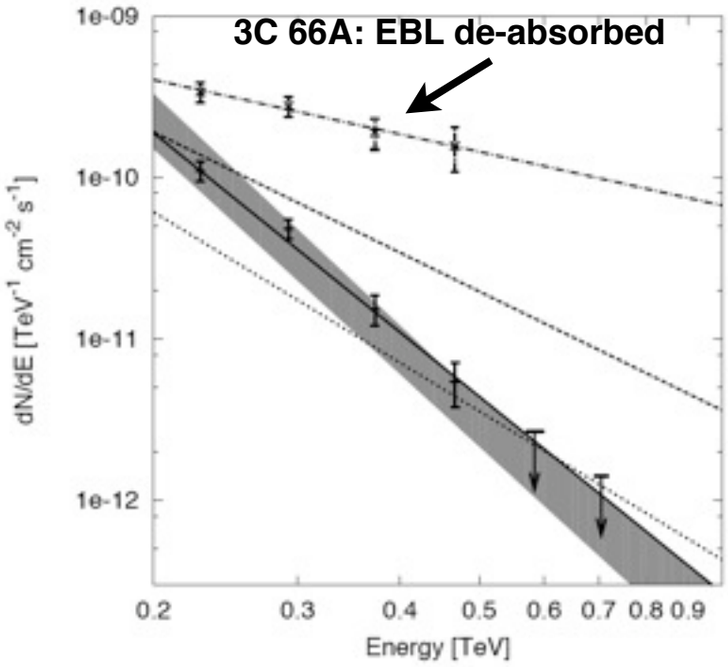
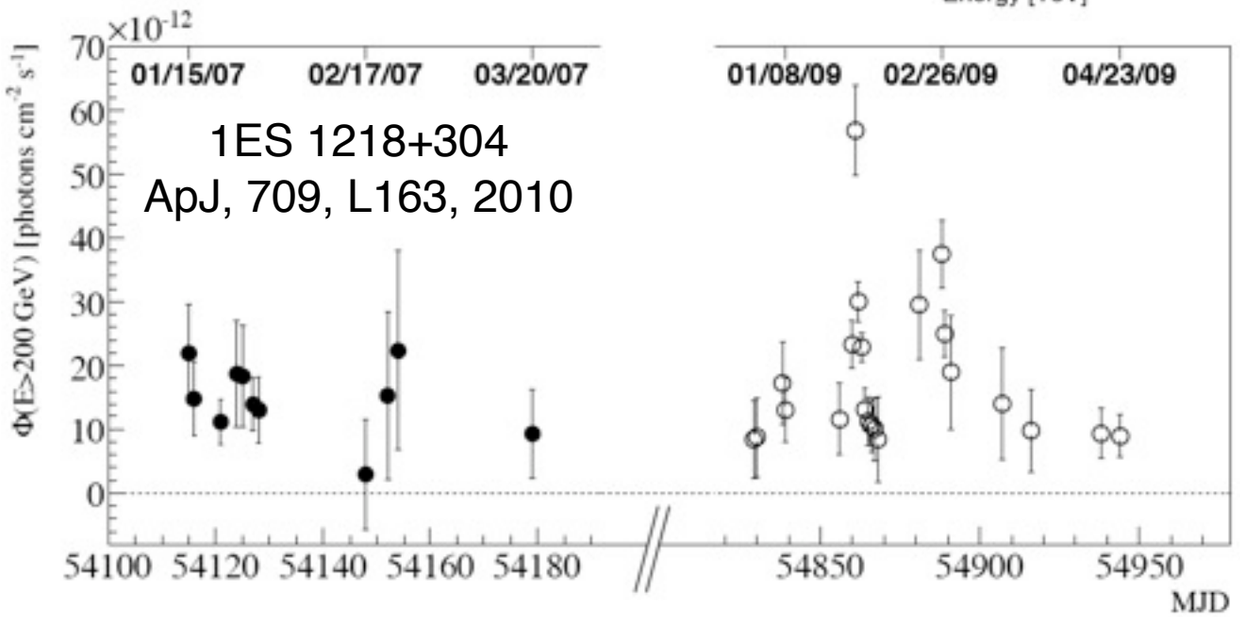
Cosmology: VHE & Extragalactic Background Light

- Diffuse EBL: ~Analogous to CMB
  - Combined flux of all extragalactic sources over entire history of Universe
- EBL absorbs γ's: $F_{int} = F_o\, e^{-T(E, z)}$
  - Softens VHE spectra; eventual horizon
  - Constrain w/ distant hard-spectrum VHE blazars
- Prior to 2009: Only 2 good Northern EBL blazars
  - 1ES 1218+304 (z=0.18): Big MWL in '08 season
    - 2007 data: ApJ, 695, 1370, 2009
    - EBL limits within 20% of best, rules out models
  - 1ES 0229+200 (z=0.14): Big MWL - '09-'10 season
- ~~VERITAS 11/09: Discovery of 1ES 0502+675 (z=0.34)~~
- Use LAT spectrum = > See EBL footprint in 3 distant blazars





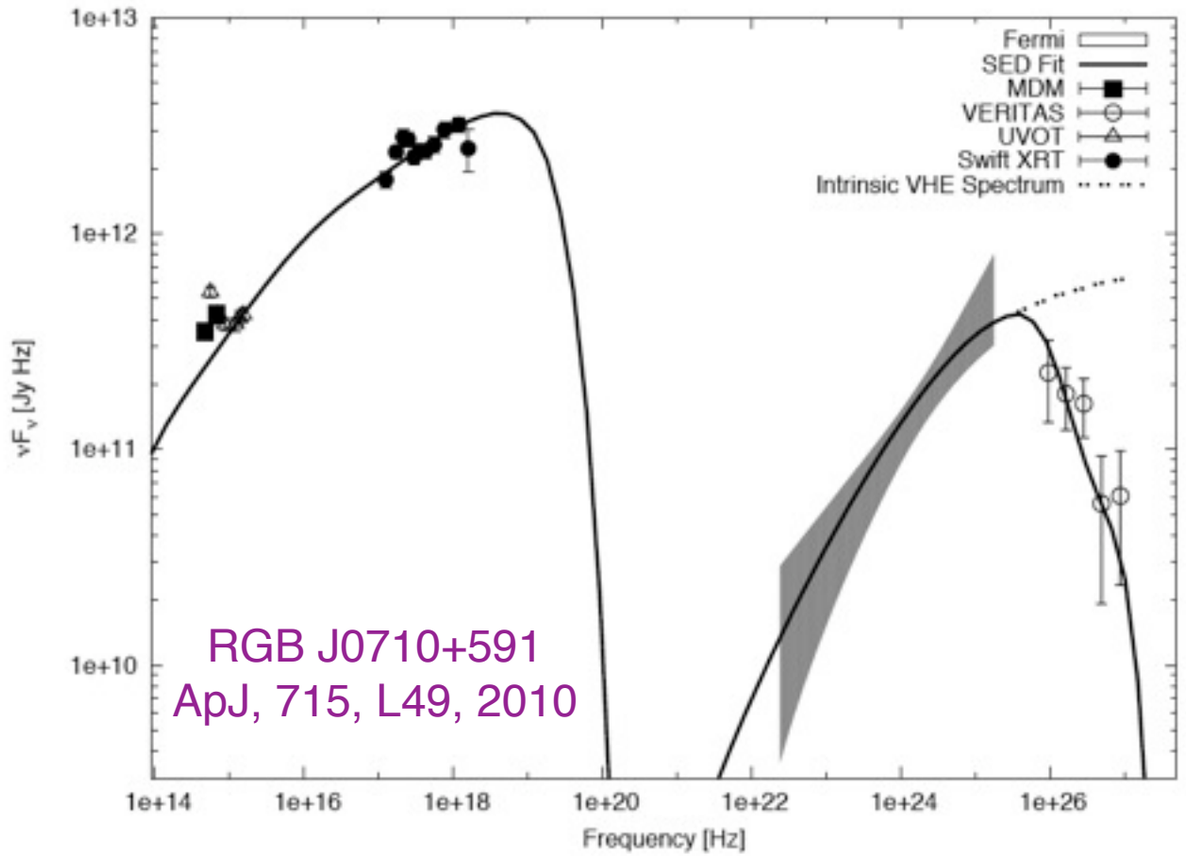


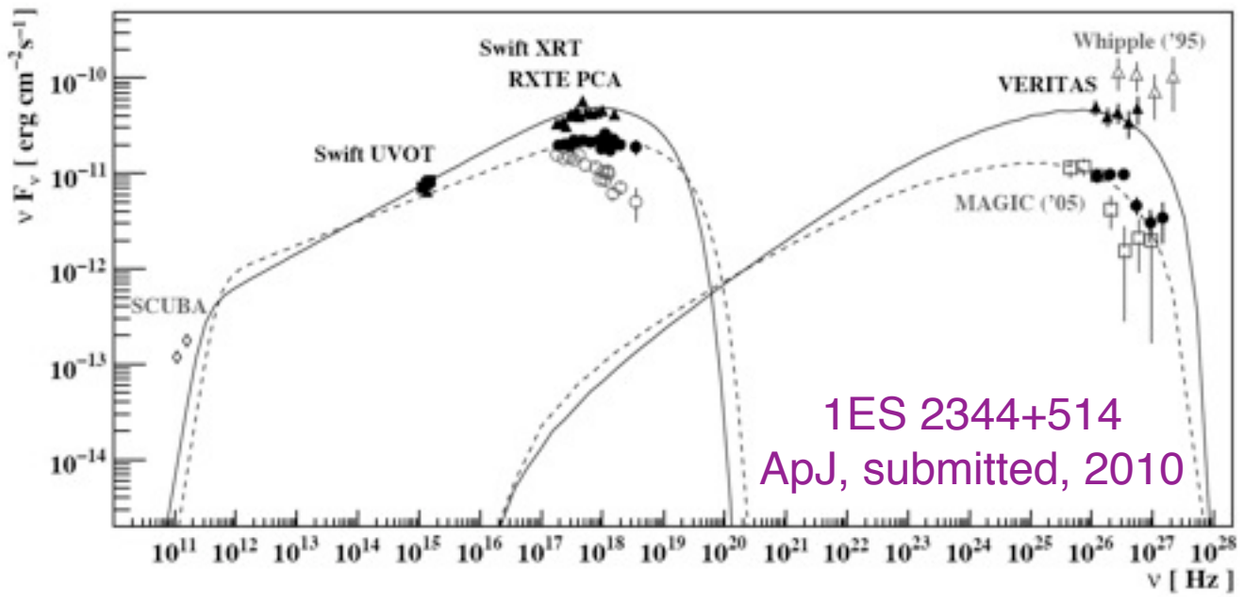
VHE Flare in 1ES 1218 rules out steady-state models that "refute" EBL limits

W. Benbow, "VERITAS Extragalactic Observations", TeVPA 2010

Blazars: Multi-wavelength Modeling

- Blazar modeling requires MWL data
  - Highly variable & SED spans radio => γ-ray
  - Leptonic or hadronic?; Which flavor of leptonic?
- Every VERITAS blazar discovery has contemporaneous MWL data (ToO)
  - Swift, LAT, Chandra, RXTE & XMM + optical & radio
- Major MWL campaign every yr (~50 h)
  - Pick “most-interesting” object
  - 1ES 2344 in ’07, 1ES 1218 in ’08, 1ES 0229 in ’09
  - Also smaller (~10 h) ones: e.g. Mkn 501 in ’08 & 09
- Major ToO campaigns: e.g. Mkn 421 in ’08 & ’10
- Modeling HBL: SSC always works w/ normal pars.





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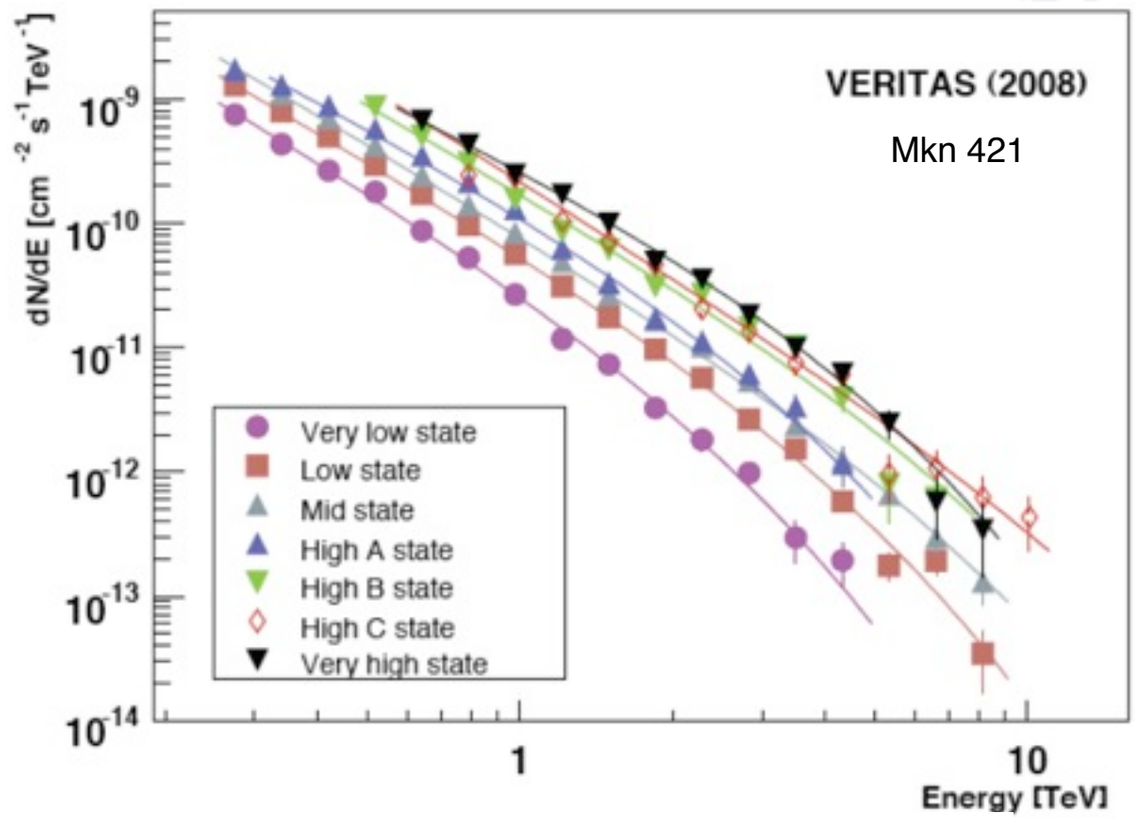
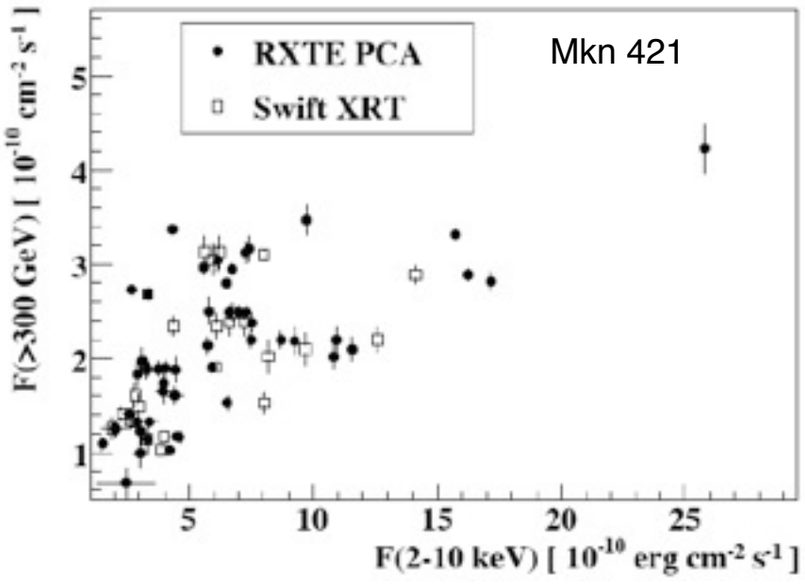
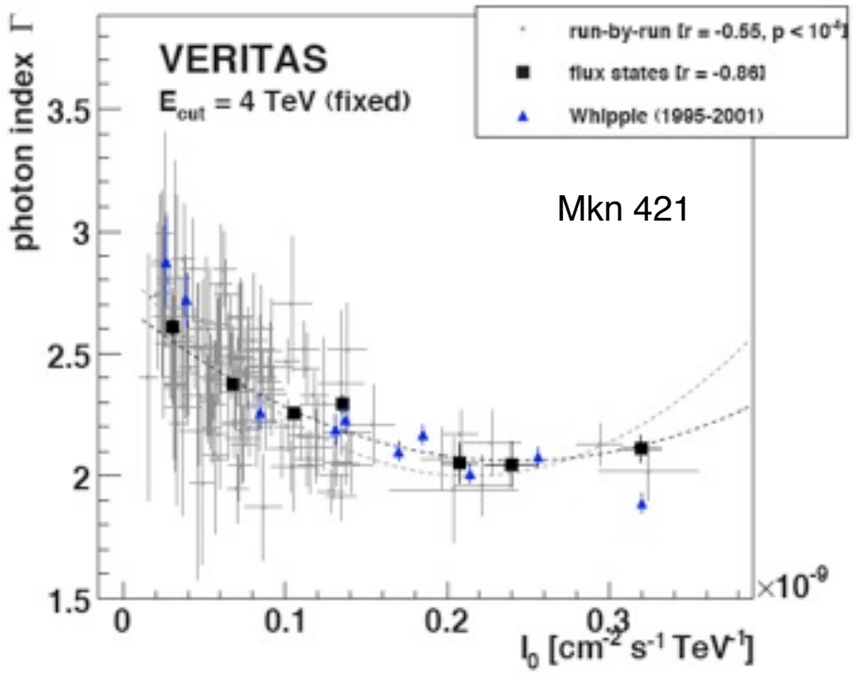
What about flaring HBL?

- Major flares for Mkn 421 in ‘08 & ’10
  - Initiate large MWL efforts
- Mkn 421 in ‘08: ApJ, submitted, 2010
  - Hardening w/ increased flux in X-ray & VHE
  - Correlation w/ X-ray & VHE fluxes
- Brief flares for 2 other HBL - no others
  - 1ES 2344+514: Same trends as Mkn 421
  - Mkn 501: VHE hardens w/ flux; no MWL







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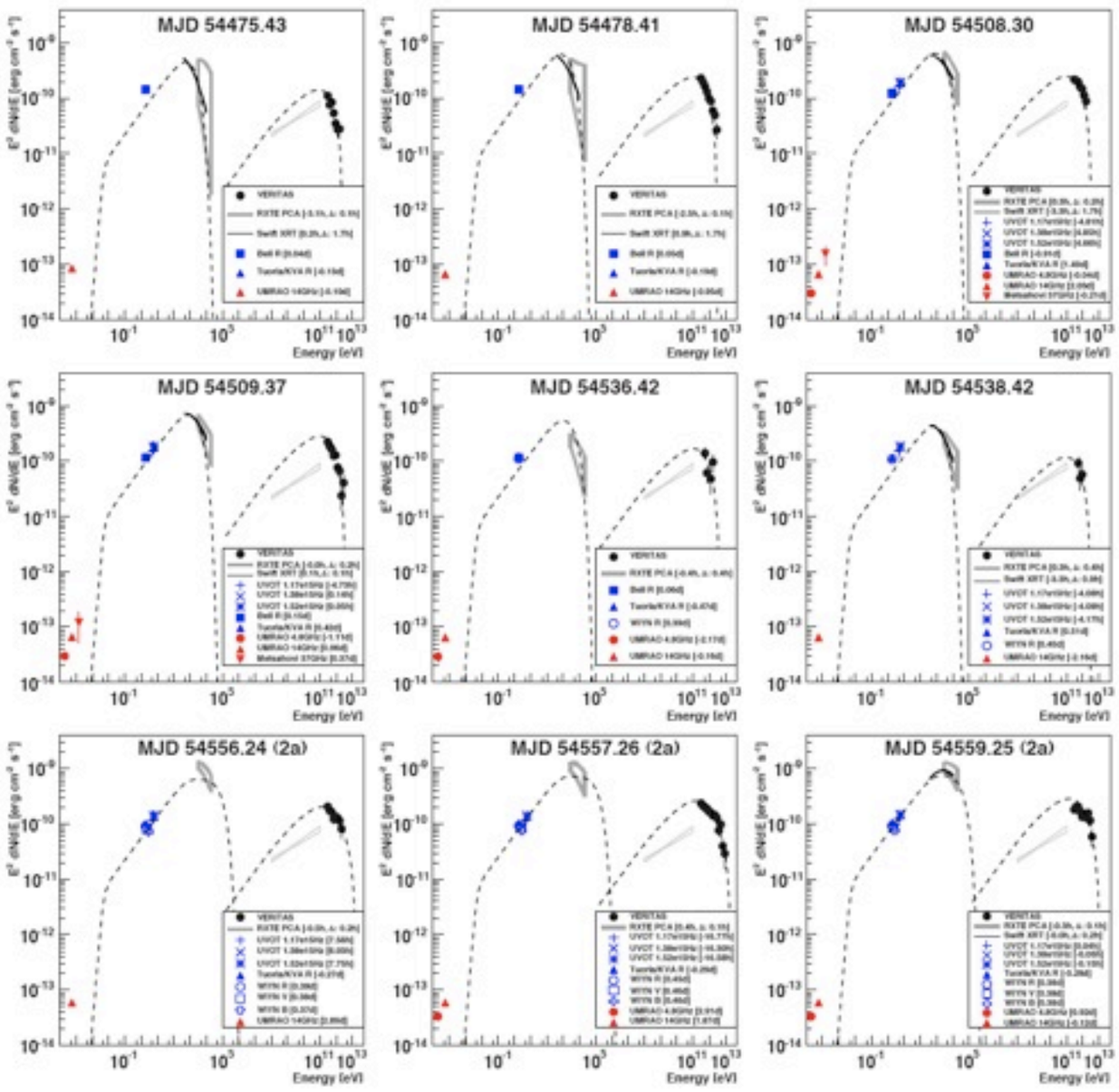
Mkn 421: SED Evolution



118 days

SSC works in all flare states for Mkn 421

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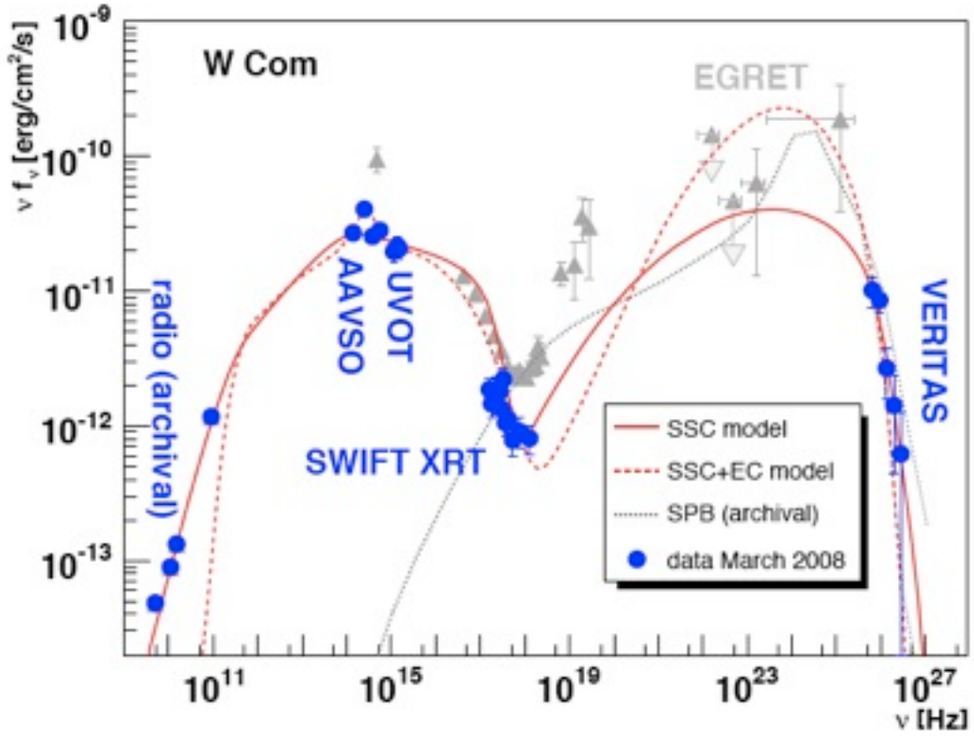
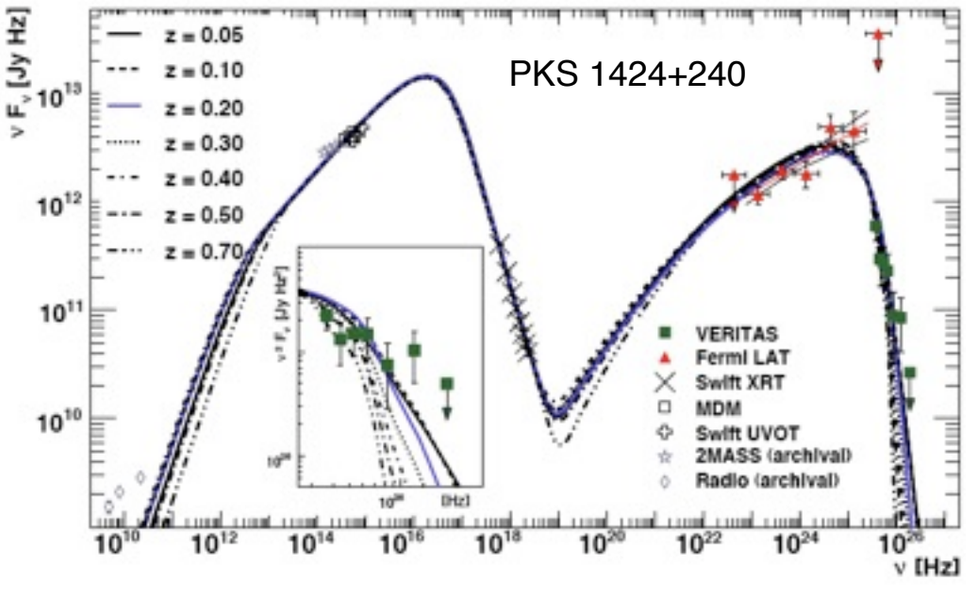
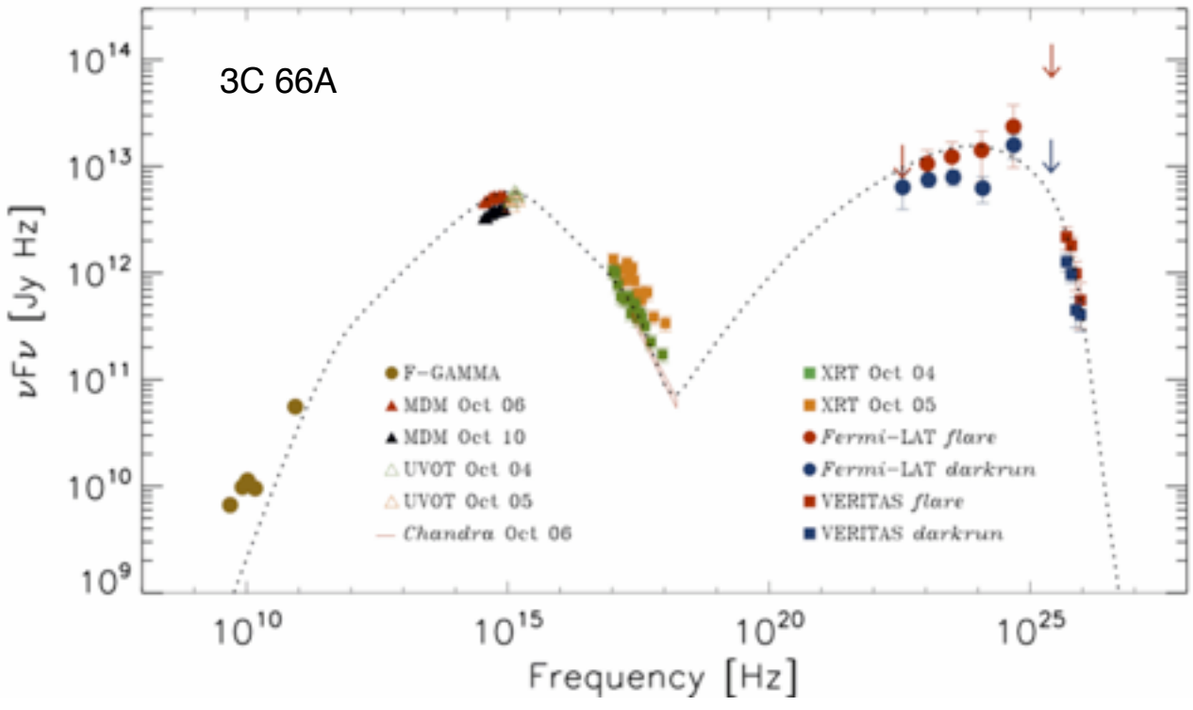
Does IBL modeling differ from HBL?

- 3 VHE IBL - all discovered by VERITAS
  - 3C 66A (ApJ, 693, L104, 2009 & ApJ, submitted, 2010) & W Com (ApJ, 684, L73, 2008 & 707, 612, 2009) in flares
    - SEDs: Needs SSC + EC component
  - PKS 1424+240 - steady flux state (ApJ, 708, L100, 2010)
    - SED: SSC works: No EC needed



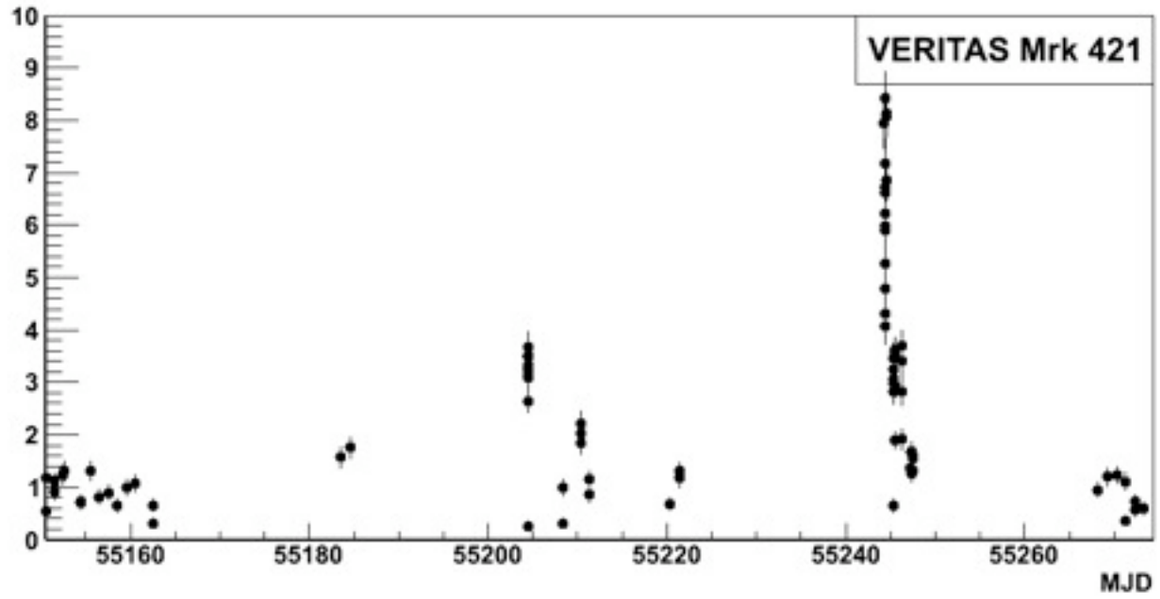
- NB: Borderline HBL w/ z = ?



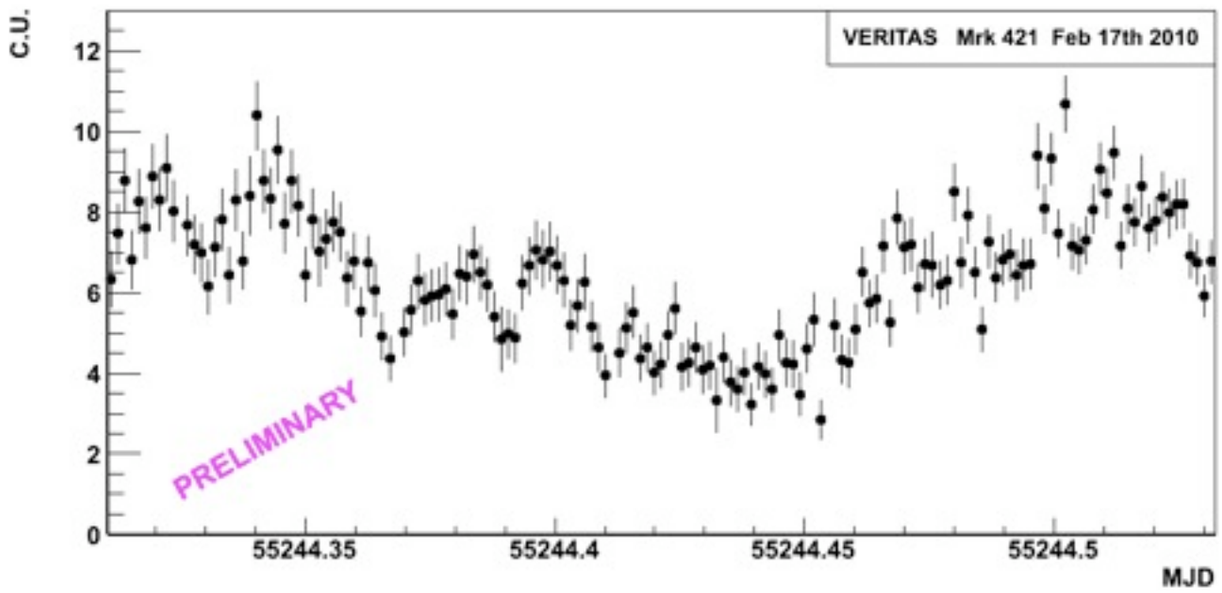


Recent Flaring from VHE AGN

- Mkn 421: Hot in VHE & X-ray since 11/09
  - Season long monitoring + MWL coverage
  - 35 h of data for season; ~400σ
  - Huge flare on 2/17/10 - Massive MWL camp.
    - Variability on 5-10 minute time scales

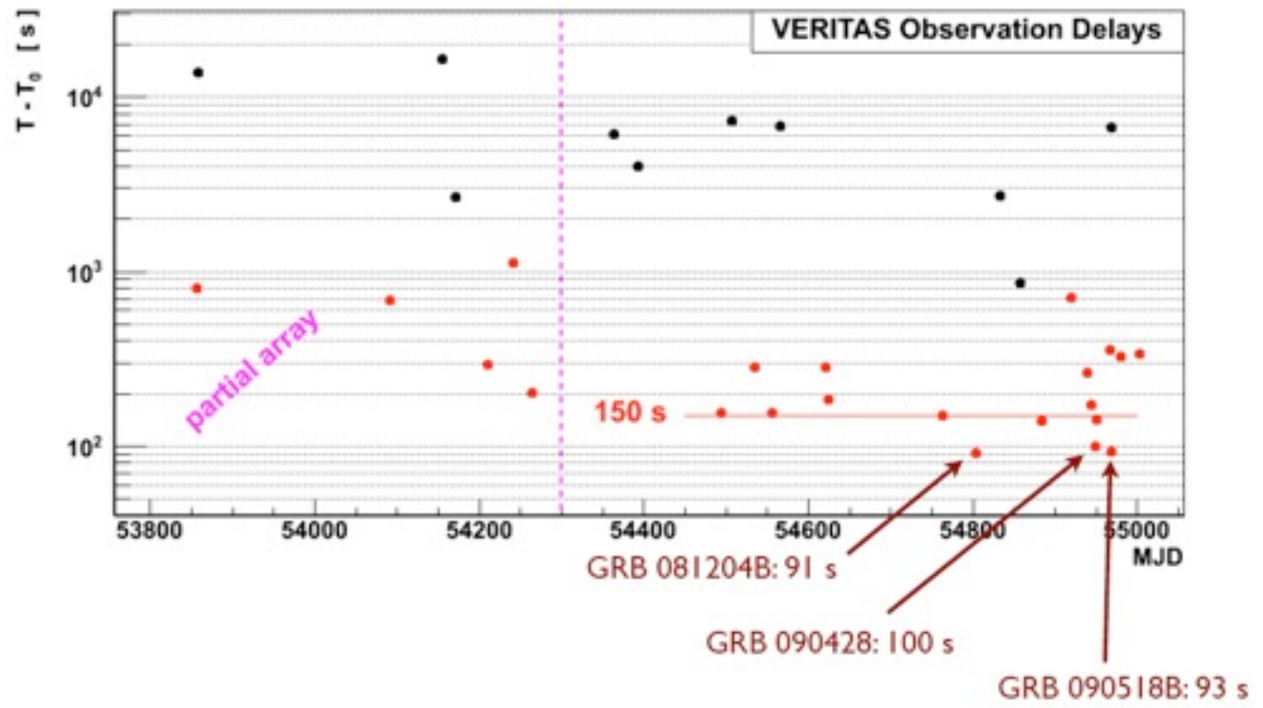


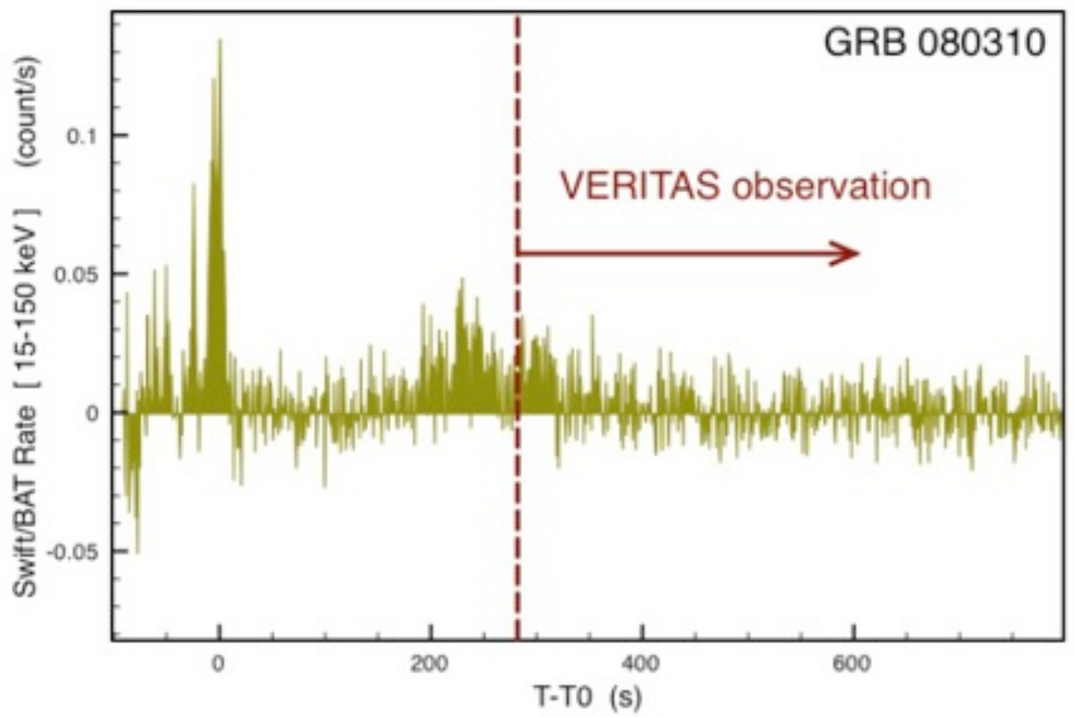
- M 87 monitoring -- Multi-year effort
  - Other VHE, radio & Chandra partners
  - April 8-11: Massive flaring episode
    - April 9: VHE flux 2-3x historical high;
      - Averaged ~20% Crab
    - Triggered Chandra observations of Core / HST-1
  - By far, best VHE signal / spectrum ever



Gamma-ray Bursts (Afterglows)

- Most luminous events in Universe
  - "2" populations; Few ms to several min
- VHE γ's feasible
  - Long-lived afterglows: Models => blazar-like SED
  - Fermi: Observed GeV γ's after powerful GRB
  - Delayed X-ray flares detected by Swift
  - Milagro: ~3σ evidence for >650 GeV emission
- VERITAS: GRB afterglows = highest priority
  - Fermi / Swift / AGILE / INTEGRAL triggers
  - Observe if <3 h old & θ<70°; ~30 h / y
- >35 observed so far; Best ΔT ~ 90 s
  - No detections, but all are high-z or z = ?





Many Other Extragalactic Targets...

- Dwarf Galaxy Survey (~20 total)
  - Extremely dark matter (DM) dominated objects
    - “No” other way to get VHE γ-rays
  - Draco, Ursa Minor, Willman 1 & Bootes 1: ApJ, in press
- Globular Clusters: M13, M15, M5, M92
  - VHE γ-rays from DM annihilation or ms-Pulsars
  - Fermi-LAT detection of 47 Tuc
- Local Group Galaxies: M31, M32, M33
  - Dense DM cores, but also astrophysical channels
- Galaxy Clusters: Coma & Perseus
  - 85% dark matter & non-thermal acceleration site
- VERITAS limits pubs. for all these classes

Conclusions

- M82 discovery provides crucial cosmic-ray origin info: New VHE source class
- VERITAS has made most-sensitive measurements of ~20 AGN (~2/3 the VHE total)
- All VERITAS blazar studies have simultaneous MWL data for SED modeling
  - HBL - SSC works independent of state; VHE & X-ray are correlated & harden w/ flux increase
  - IBL - Modeling hints at need for SSC + EC -- N.B. IBL generally detected in a flaring state
- Distant blazar studies have confirmed strong HESS EBL limits
  - VHE variability in 1ES 1218+304 rules out most models for ultra-hard VHE spectra
  - Big data sets on 1ES 0229+200 (mid-IR EBL), 1ES 0414+009 & PG 1553+113 (optical / near-IR EBL) under analysis
- Several major flares recorded for M 87 & Mkn 421: M87 => emission-zone near nucleus
- VERITAS is actively observing numerous other source classes
- Future of blazar program: More emphasis on long-term monitoring of known VHE sources
  - Build 100/200 h exposures for ~16 particularly interesting VHE AGN in next 5 yrs + Fermi driven discovery program