VERITAS – Status and Results

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Physics Department and McDonnell Center for the Space Sciences

Science with the New Generation of
High Energy Gamma-Ray Experiments
6th workshop, October 8-10, Padova, Italy

- Status of VERITAS
- Galactic Observations
- Extragalactic Observations
- Summary and Conclusions

McDonnell Center for the Space Sciences

Washington University in St.Louis
Arts & Sciences

STATUS OF VERITAS

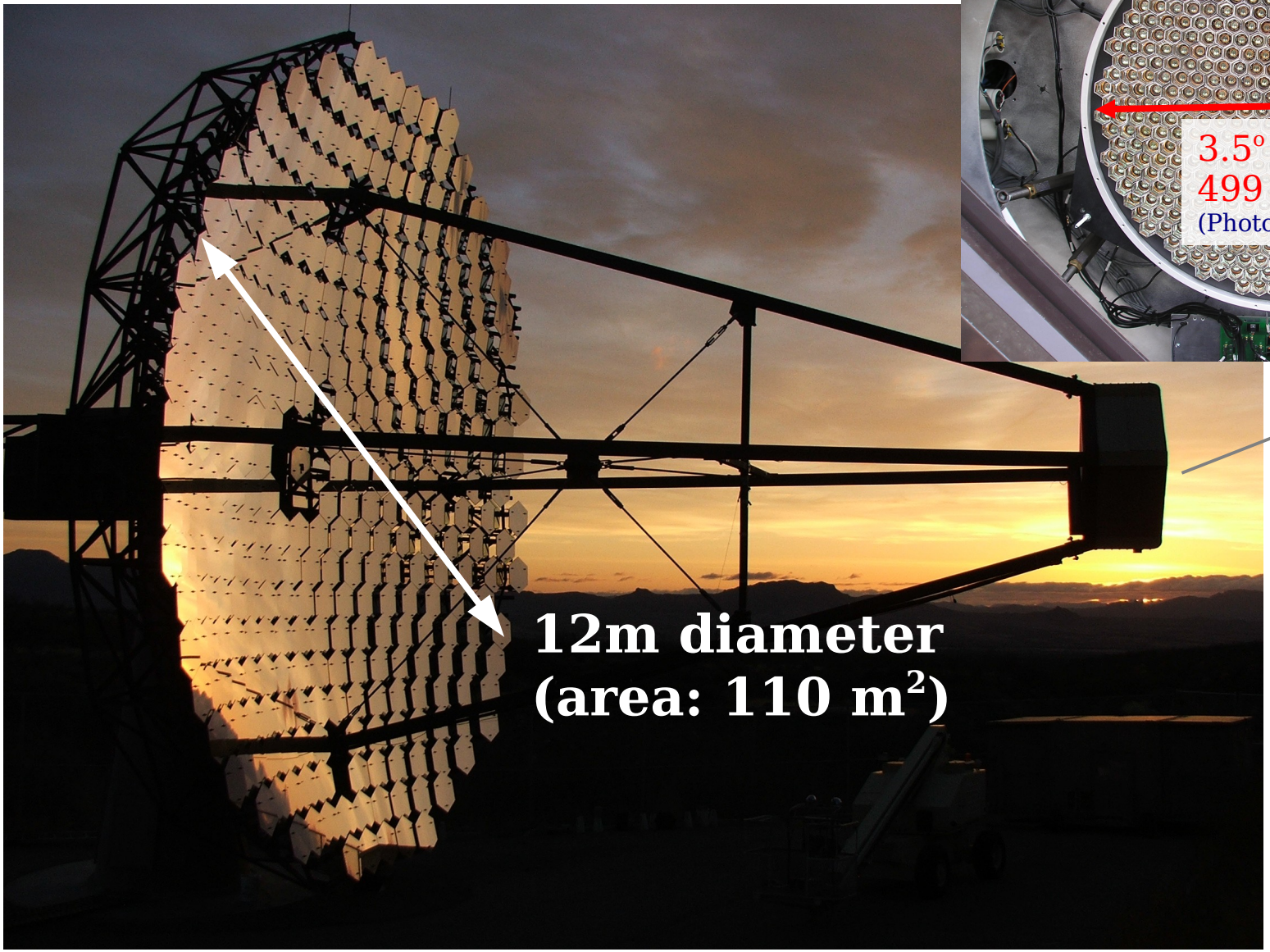
The VERITAS Collaboration

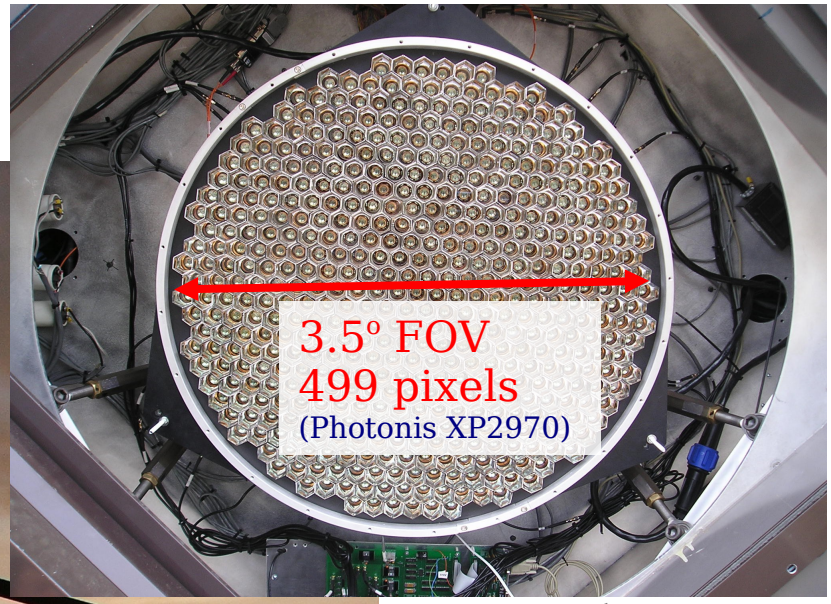
- Smithsonian Astrophysical Observatory
- Purdue University
- Iowa State University
- Washington University in St. Louis
- University of Chicago
- University of Utah
- University of California, Los Angeles
- McGill University, Montreal
- University College Dublin
- University of Leeds
- Adler Planetarium
- Argonne National Laboratory
- Barnard College
- dePauw University
- Bartol Research Institute/ University of Delaware
- Grinnell College
- University of California, Santa Cruz
- University of Iowa
- University of Massachusetts
- Cork Institute of Technology
- Galway Mayo Institute of Technology
- National University of Ireland Galway

- ~25 Associate Members

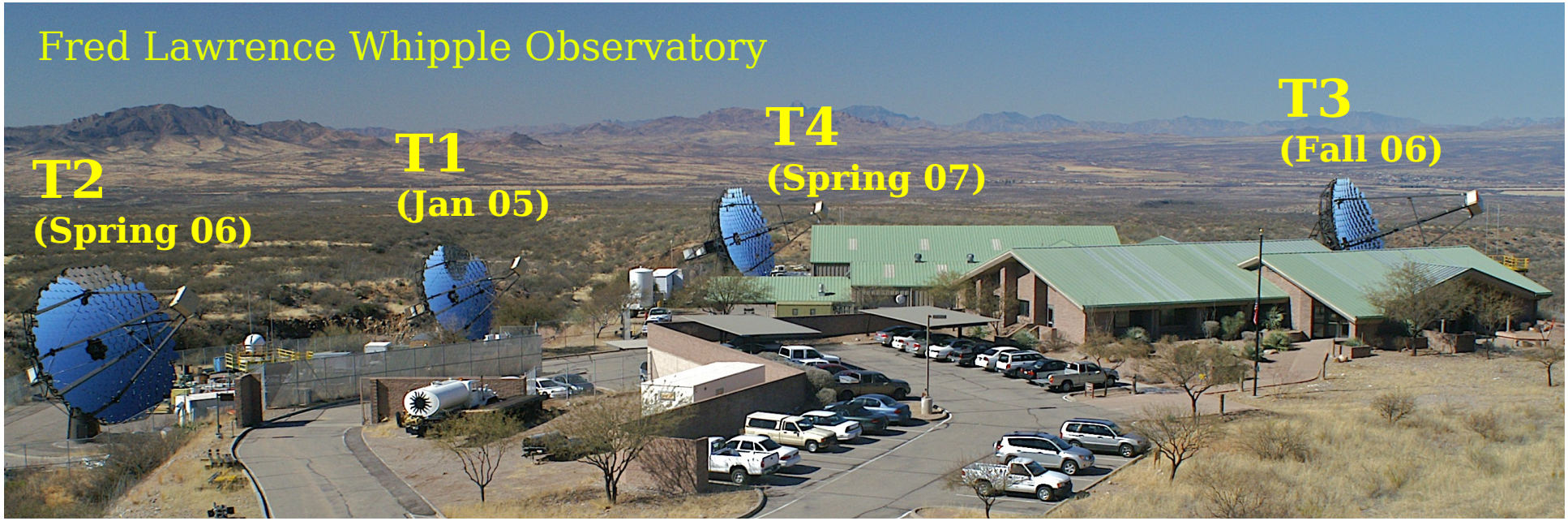
A VERITAS Cherenkov Telescope

PMT camera



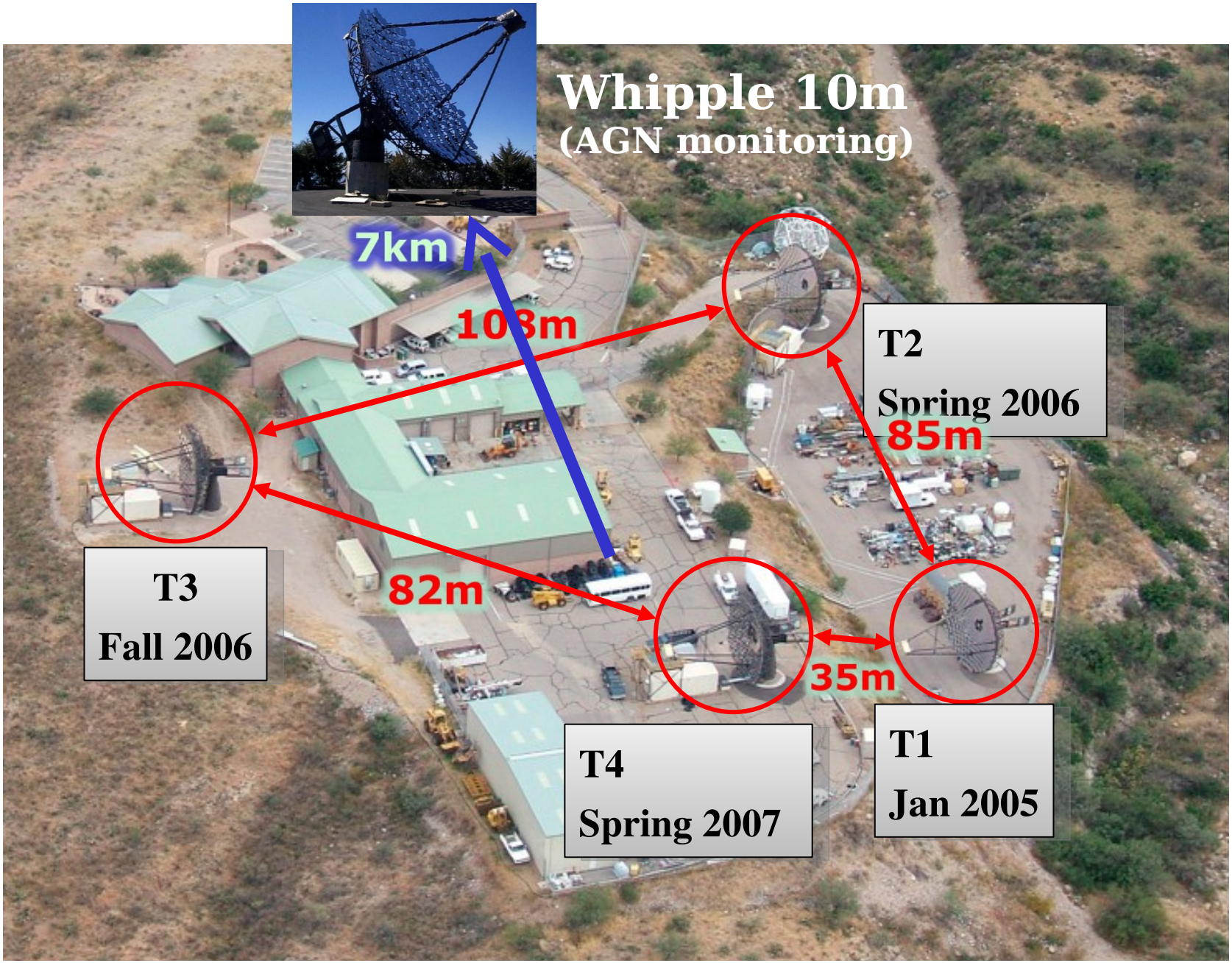


The VERITAS Cherenkov Telescope Array



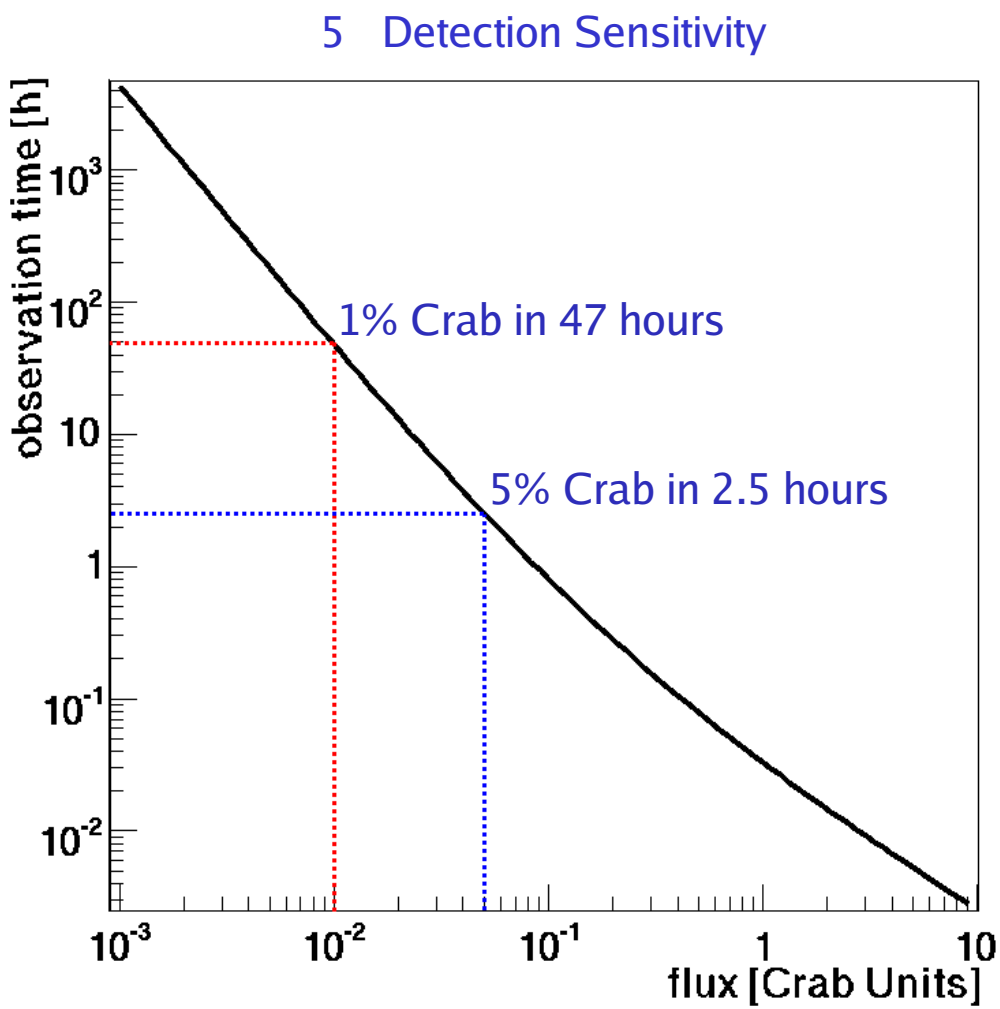
- Very Energetic Radiation Imaging Telescope Array System
- Array fully operational since Spring 2007
- Energy range: 100 GeV up to ~30 TeV (resolution: <20%)
- Sensitivity: 10% (1%) Crab in <1h (<50h)

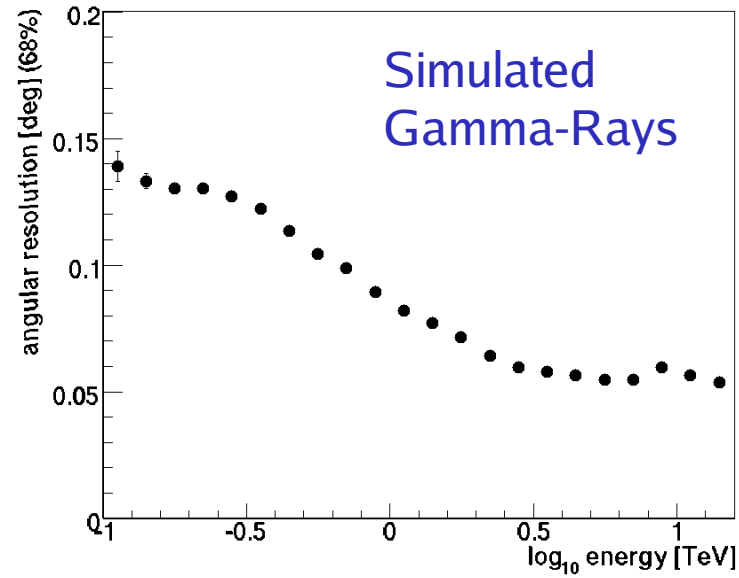
The VERITAS Cherenkov Telescope Array++

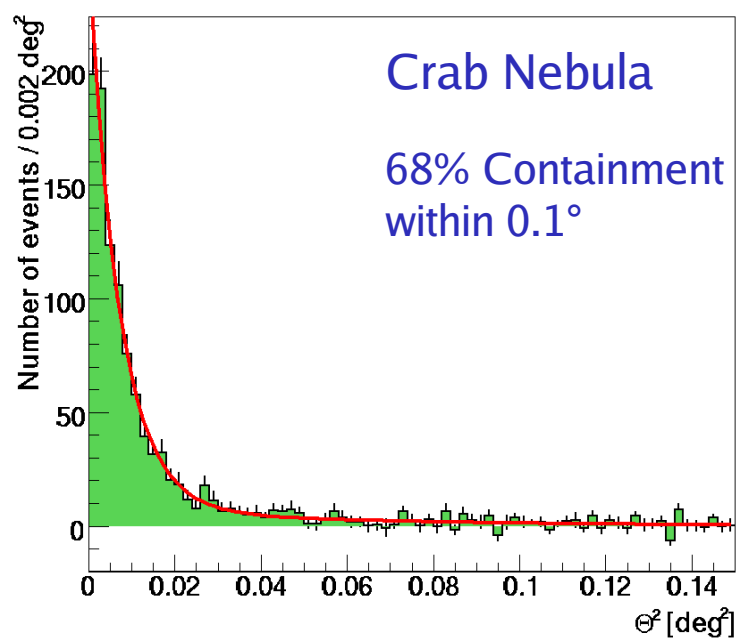


Array: Angular Resolution & Sensitivity

- Tight cuts (weak source sensitivity):
  size>400dc (~75p.e.), $\Delta\theta^2$<0.015deg^2, N_{mult} = 4

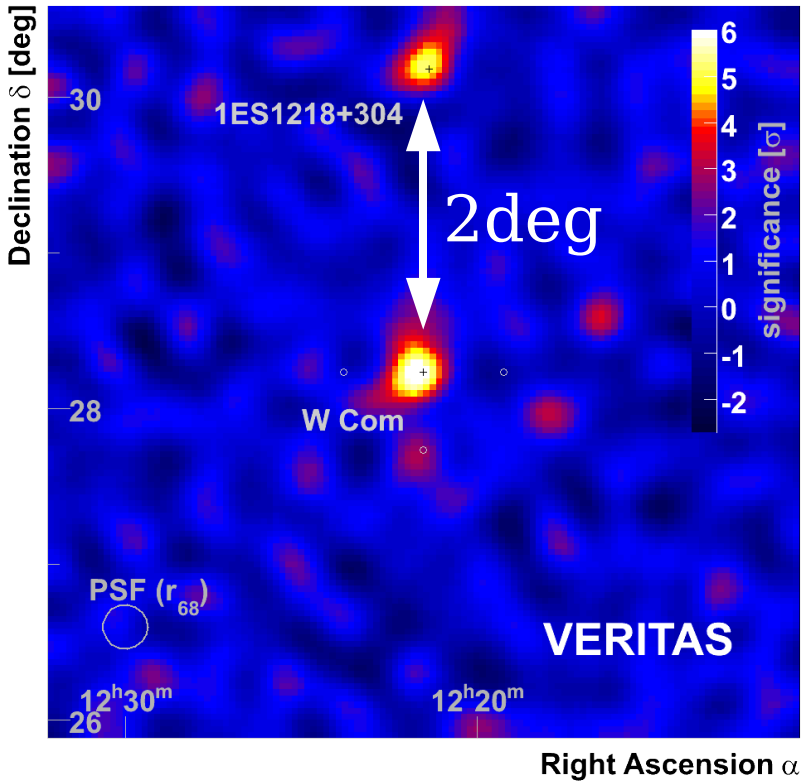


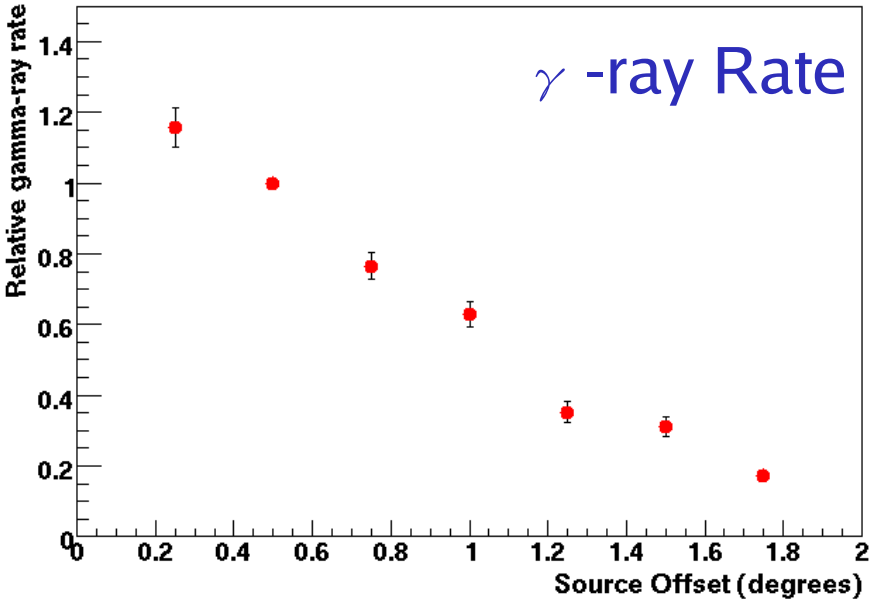


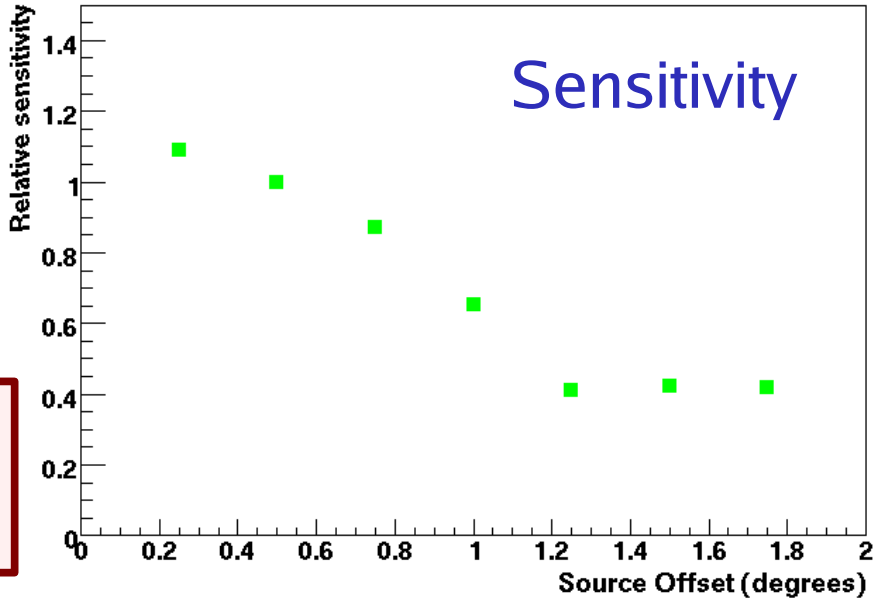


Array: Off-axis Sensitivity

- Measured on Crab Nebula
- Physical camera radius: 1.75deg



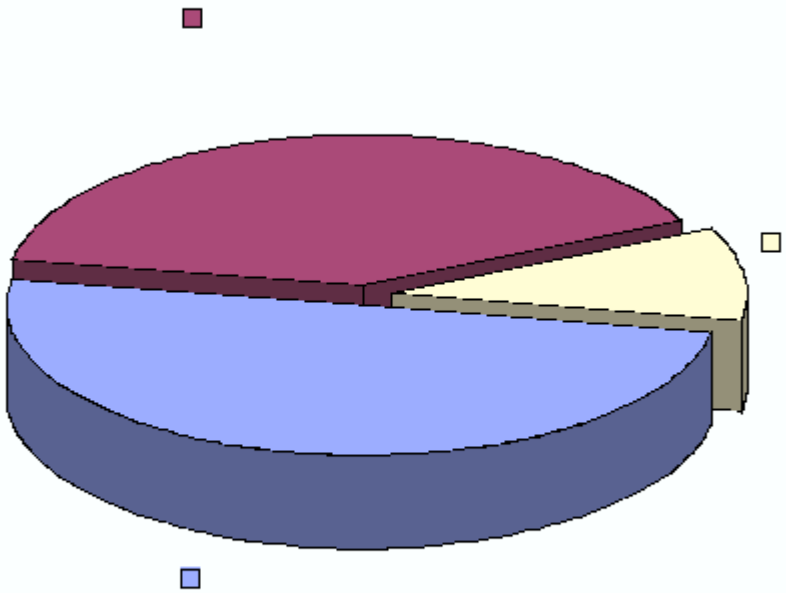




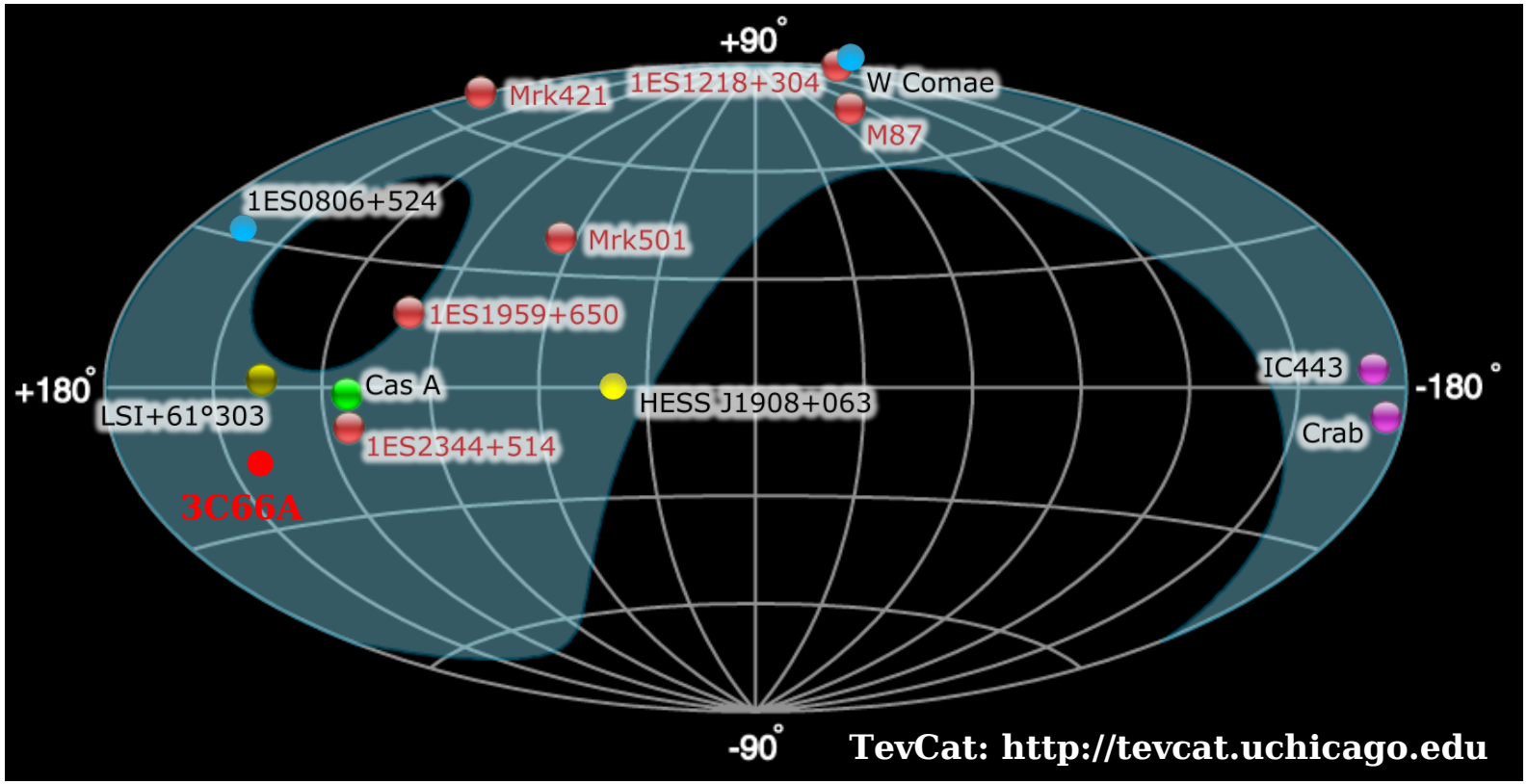
Capability: source detections beyond physical camera extension

Observation Planing & Key Science Projects

- Key Science Projects
  - Blazars
  - Dark Matter
  - Galactic Plane Survey
  - Supernova Remnants
- Open time for SWG proposals, administered by the VERTIAS TAC
- Spokesperson's Discretionary Time for Engineering and ToOs



The 2007/2008 Observing Season

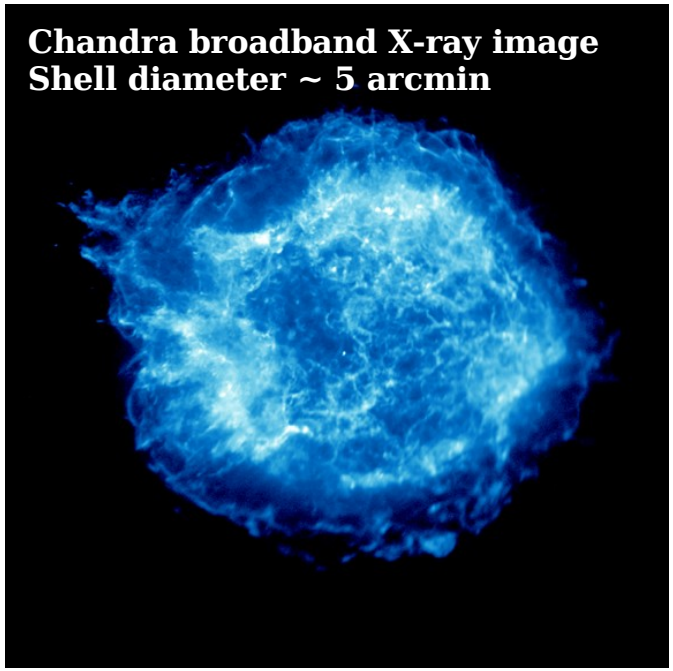


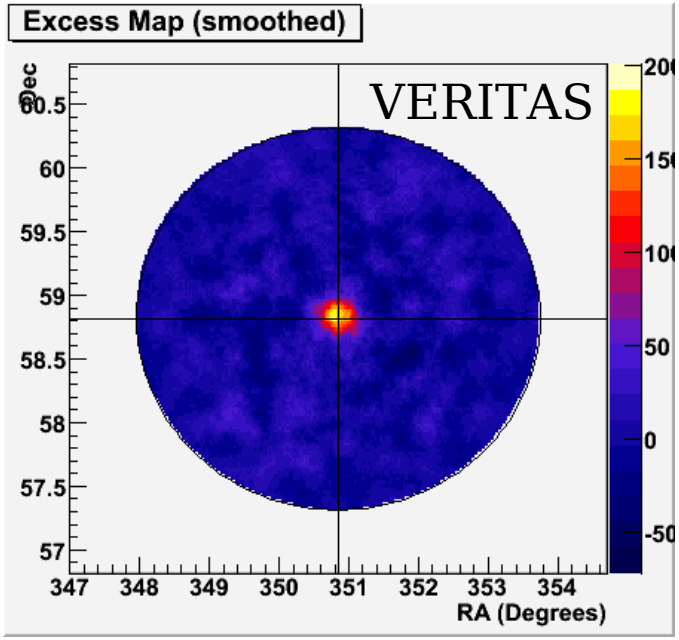
- Oct07–Jun08 season: Good weather, 4tels: ~700h + moon data (~100h)
- Discoveries: 1ES0806+524 (Atel 1415), W Com (Atel 1422) & 3C66A (Atel 1753)
- Flaring sources: Mrk421 (Atel #1506), W Comae (Atel #1565) & M 87
- Source observations (partially including MWL coverage): Crab, Cas A, IC 443, LSI+61, HESSJ1908, Mrk421, Mrk501, 1ES2344, 1ES1959, 1ES0806, 1ES1218, WComae, M87, and many more...

GALACTIC OBSERVATIONS

Cas A

- Young SNR (330 years), 5 arcmin
- Discovered by HEGRA (232h, 5σ)
  confirmed by MAGIC (47h, 5.3σ)
- VERITAS observations:
  => Oct/Nov 2007 (20h, 9.8σ)
  => Flux level: ~3% of the Crab
  => no indication for extension (ongoing)
  => Energy spectrum: work in progress
- Open question: hadronic or leptonic accelerator



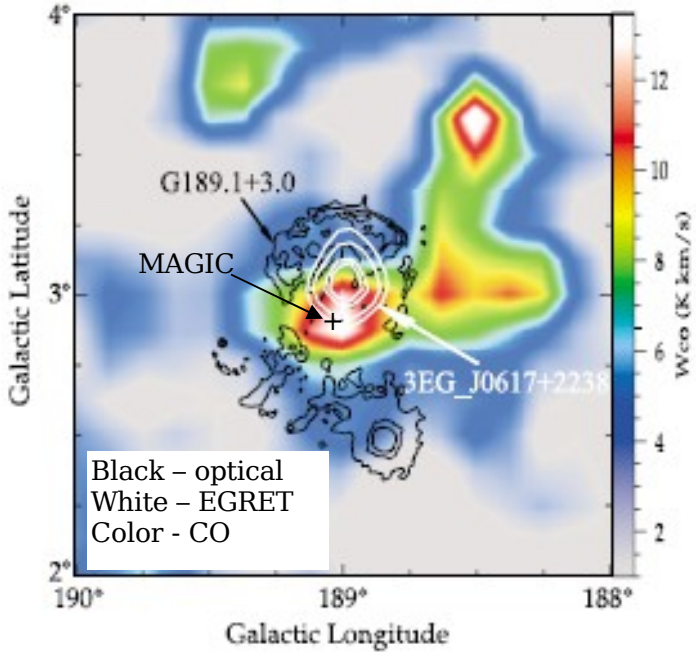


VERITAS data will allow most accurate energy spectrum

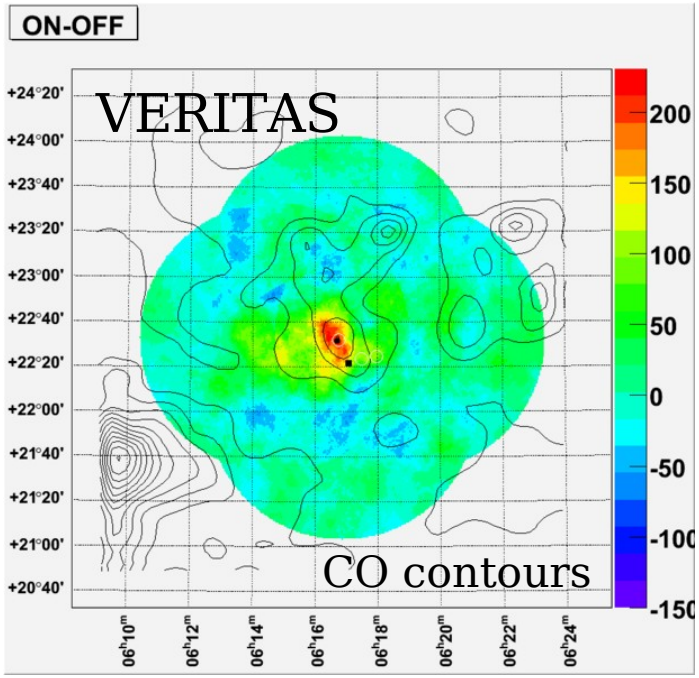
Contact: A.Konopelko, B.Humensky, T.Ergin

IC 443

- SNR shell, mol. cloud interaction & PWN
- Discovered at VHE in 2007 by:
  => MAGIC (29h, 5.7σ) [Albert et al. 2007]
  => VERITAS (16h, 6σ)
- Total VERITAS observations (31h, 8.2σ):
  -> Feb/Mar 2007 (3 telescopes)
  -> Oct/Nov 2007 (4 telescopes)
- Position compatible with MAGIC,
  Extension: $\sigma=(0.17\pm0.02_{stat}\pm0.04_{syst})$ deg
- Bright star: different BG models, MC
- VHE emission:
  => CR interaction with molecular cloud?
  => associated with PWN in the north?



[Torres et al. 2003]

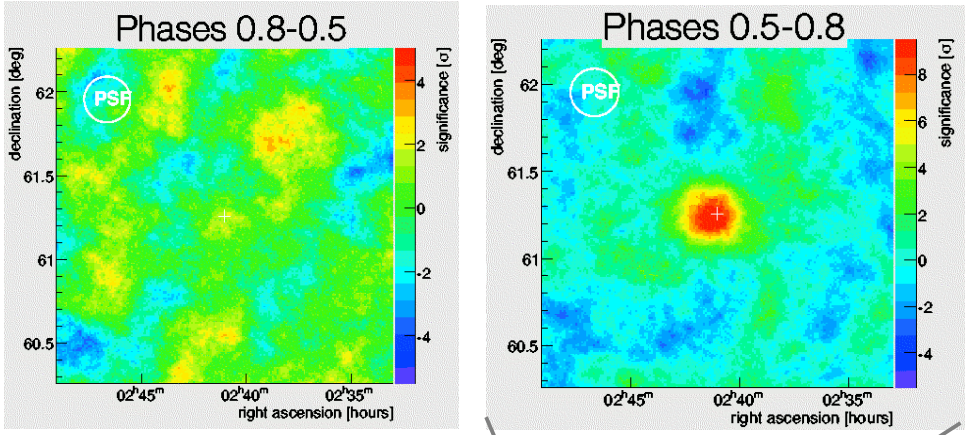


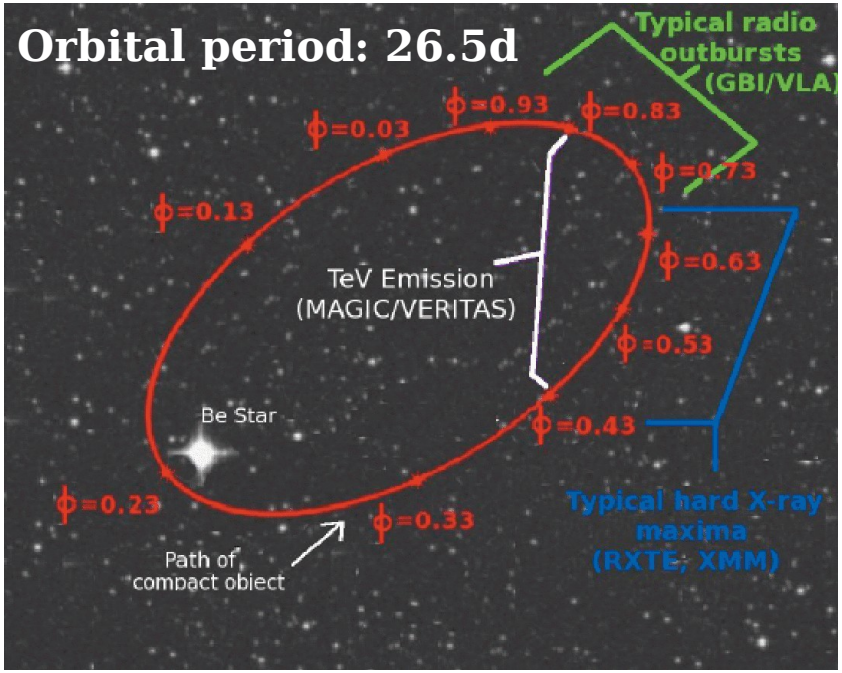
Energy spectrum: Work ongoing

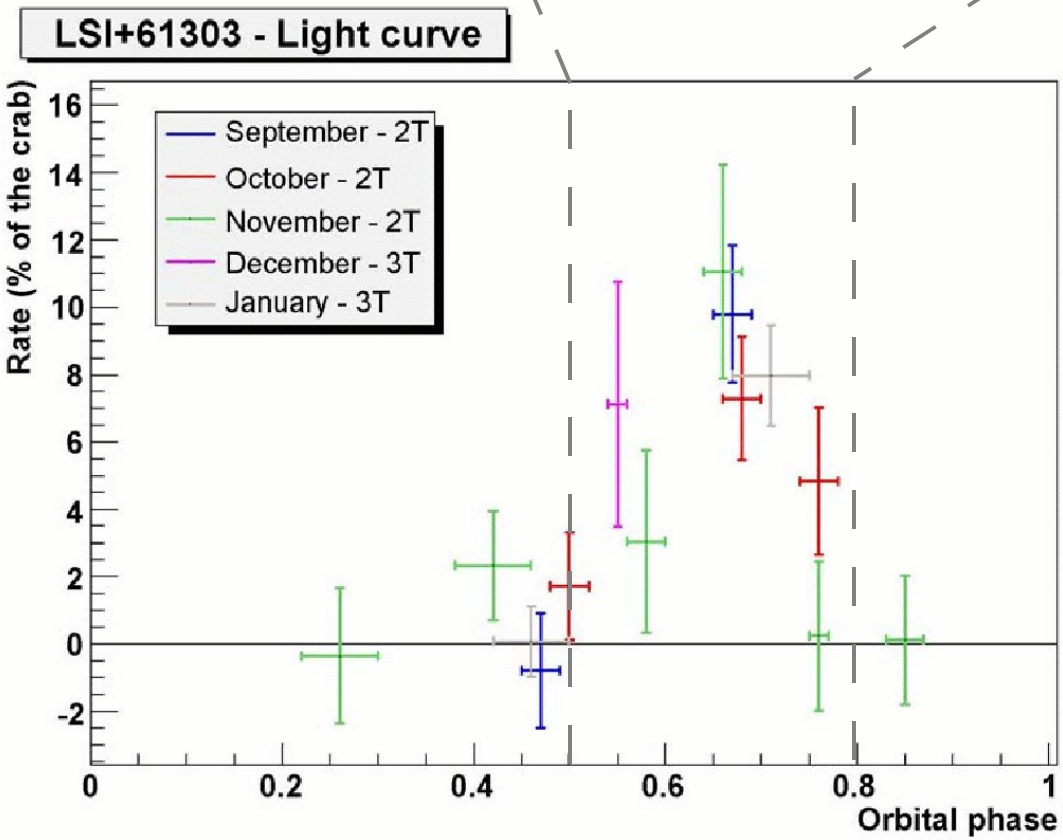
Contact: B.Humensky, S.Bugaev

LSI +61 303

- High-mass X-ray binary
- Variable VHE γ-ray source
  (seen by MAGIC/VERITAS)
- Emission mechanism unknown:
  Microquasar or interacting PWN?
  (+strong propagation/absorption effects)
- Acciari et al., ApJ, 679, 1427 (2008)







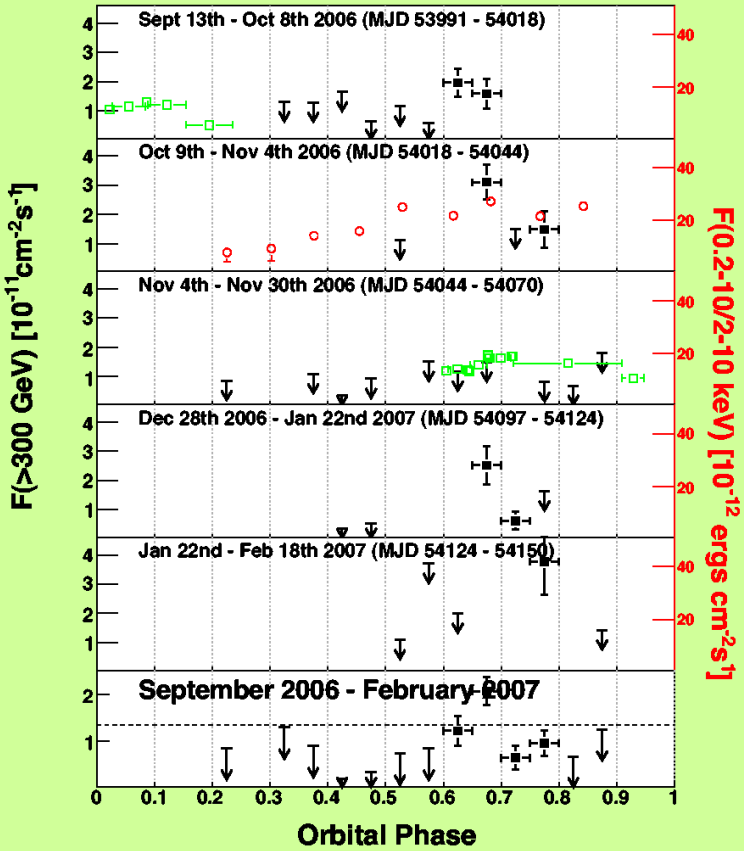
Contact: G.Maier

VERITAS observations of LSI +61 303 (2 years)

2006-2007

45 h of 2/3-telescope data

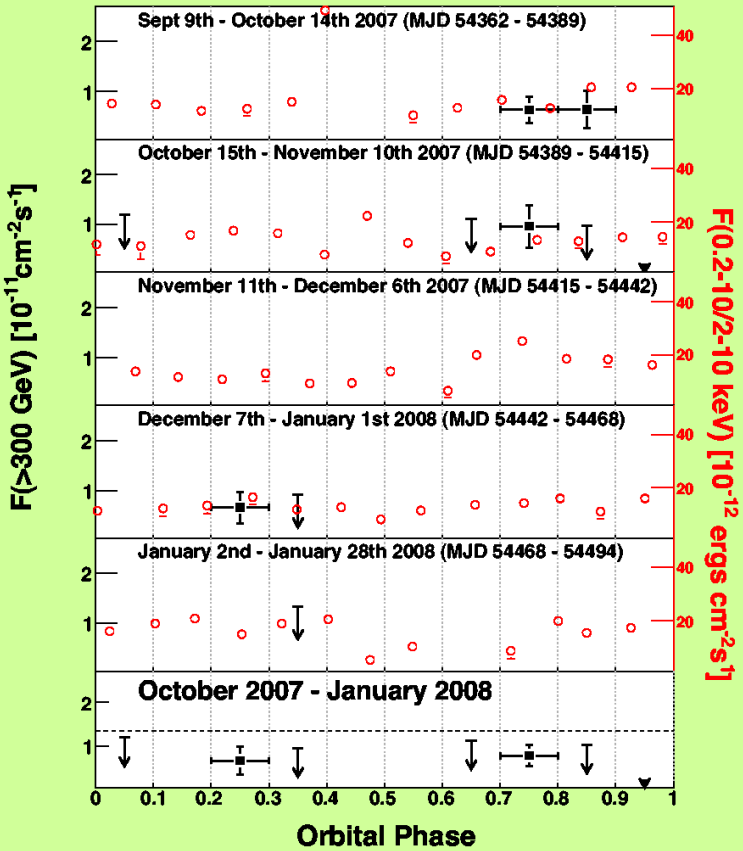
(VERITAS: Acciari ApJ 679, 1427 (2008))



2007-2008

12 h of 4-telescope data

(analysis of data taken in moonlight conditions still ongoing)

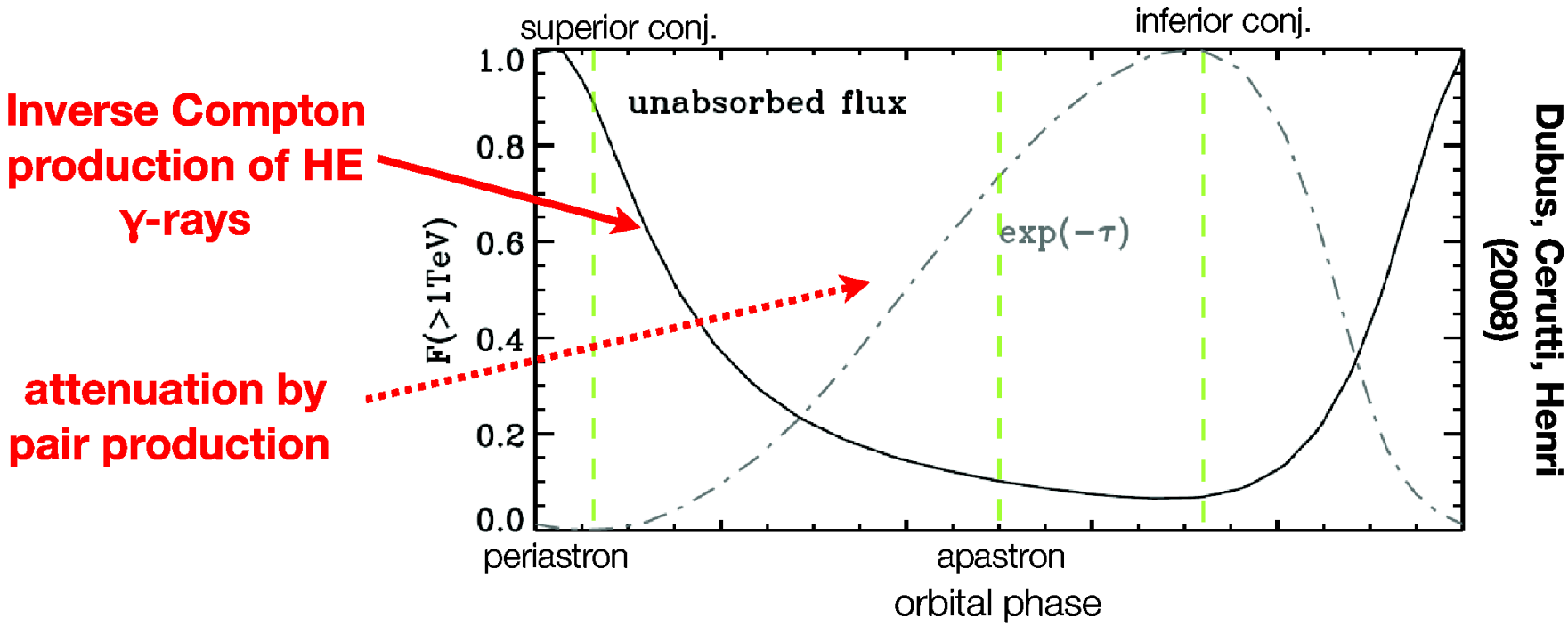


Rich set of X-ray and γ-ray data:
Correlation between γ-ray emission and X-ray emission?

Contact: G.Maier

GeV/TeV (anti)correlation in VHE binaries

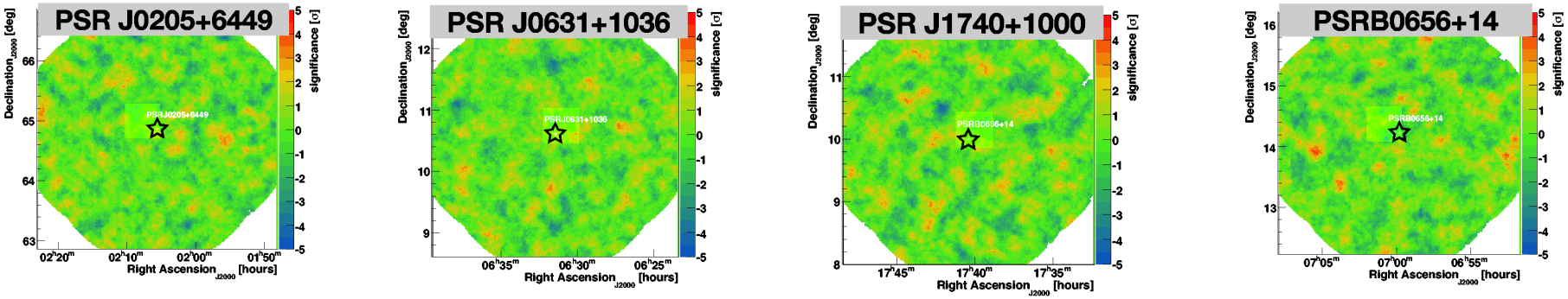
- Photon fields (dense and anisotropic):
  => phase-dependent VHE emission (pair productions)



(for LS 5039, but similar for LS I +61 303)

Different flux modulation vs. orbital phase expected for GeV and TeV energies

VERITAS observations of Pulsar Wind Nebula



PWNe are largest class of galactic γ-ray sources

Evidence for acceleration of electrons up to 100 TeV

VERITAS observed selection of pulsars with large energy loss:

$(dE/dt)/d^2 > 10^{35}$ ergs/s/kpc^2

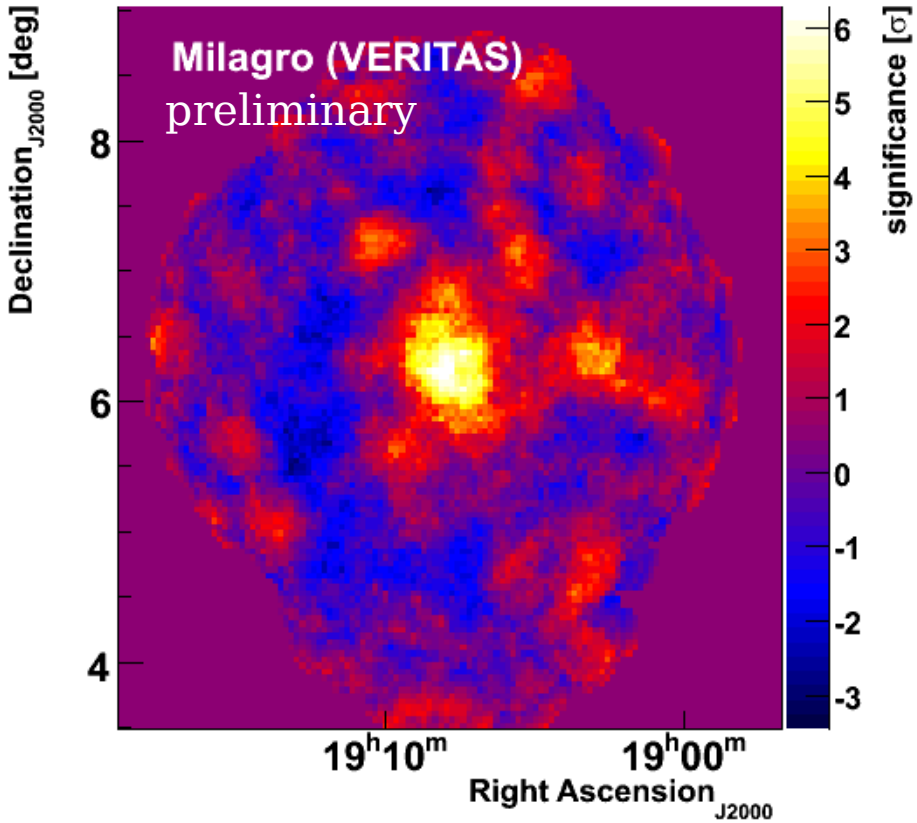
Object	$\log_{10}\dot{E}/d^2$ [erg/s/kpc^2]	T [hrs]	<Z> [deg]	Significance [σ]	$F(E_{th})$ [% Crab]
Crab Nebula	38.1	11	15	100	100
PSRJ0205+6449	36.4	12.8	35.2	1.1 (1.5)	<2.3 (4.1)
PSRJ0631+1036	33.6	13.0	24.5	0.3 (0.4)	<1.3 (2.1)
PSRJ0633+1746	36.1	13.3	17.6	-0.1 (0.6)	<1.0 (2.2)
PSRB0656+14	35.6	9.4	22.4	-1.8 (-2.6)	<0.2 (0.7)
PSRJ1740+1000	35.1	10.5	24.6	0.2 (0.0)	<1.0 (1.4)

99% upper limits, flux above 300 GeV

Contact: E.Aliu

VERITAS observations of MGRO J1908+06

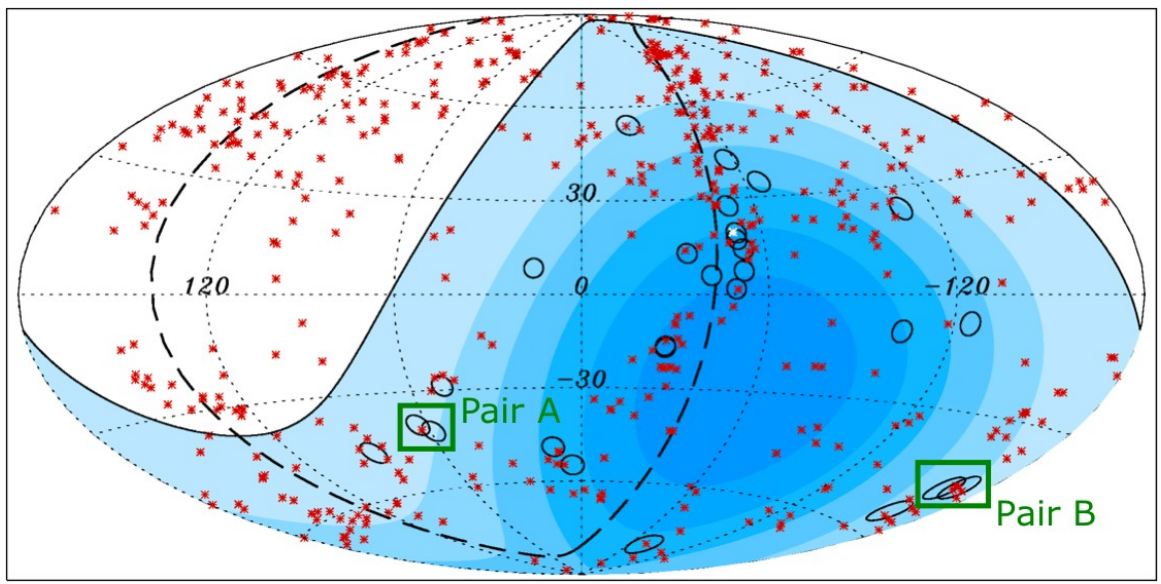
- Unidentified Milagro source (80% Crab @ 20 TeV)
- Detected at VHE energies by H.E.S.S
- No counterpart identified, candidates:
  => SNR G40.5-0.5
  => EGRET 3EG J1903+063
- VERITAS observations (22h):
  => Detection at ~5σ level
  => Position: compatible with position reported by H.E.S.S.
  => Extension: ~0.2deg

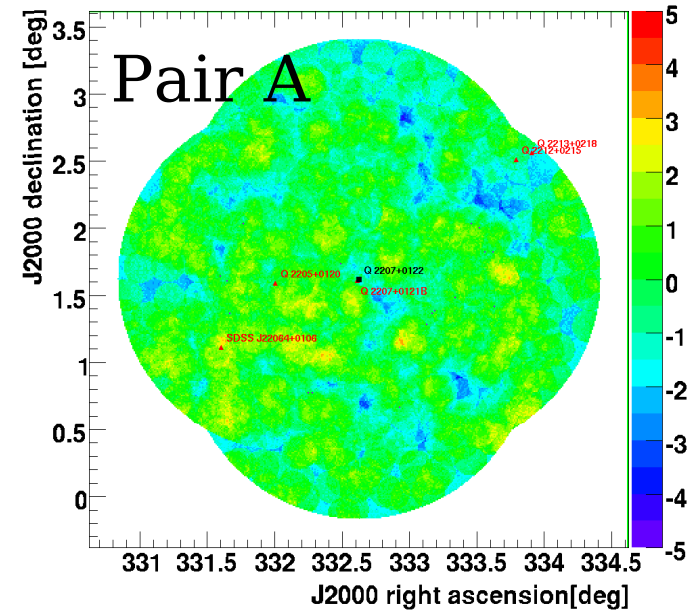


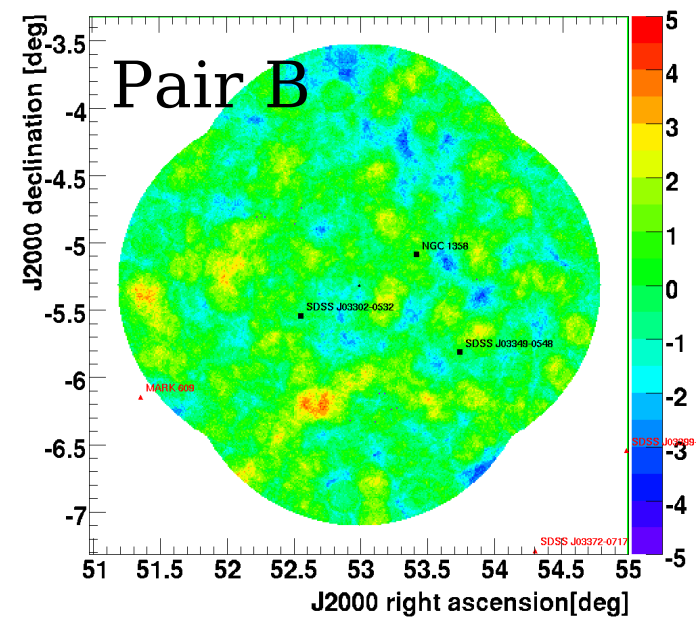
Contact: J.E.Ward, A.Weinstein, A.Konopelko, T.Ergin, M.Beilicke

The Auger Cosmic Ray / AGN correlation

- Auger: Anisotropy in CR arrival directions (E>50EeV), correlated with AGN (Veron/Cetty, z<0.018) [Science, 318, 939 (2007)]
- Encouraged VERITAS observations:
  => Pair A (3.3h) & Pair B (10.1h)
- No significant excess found



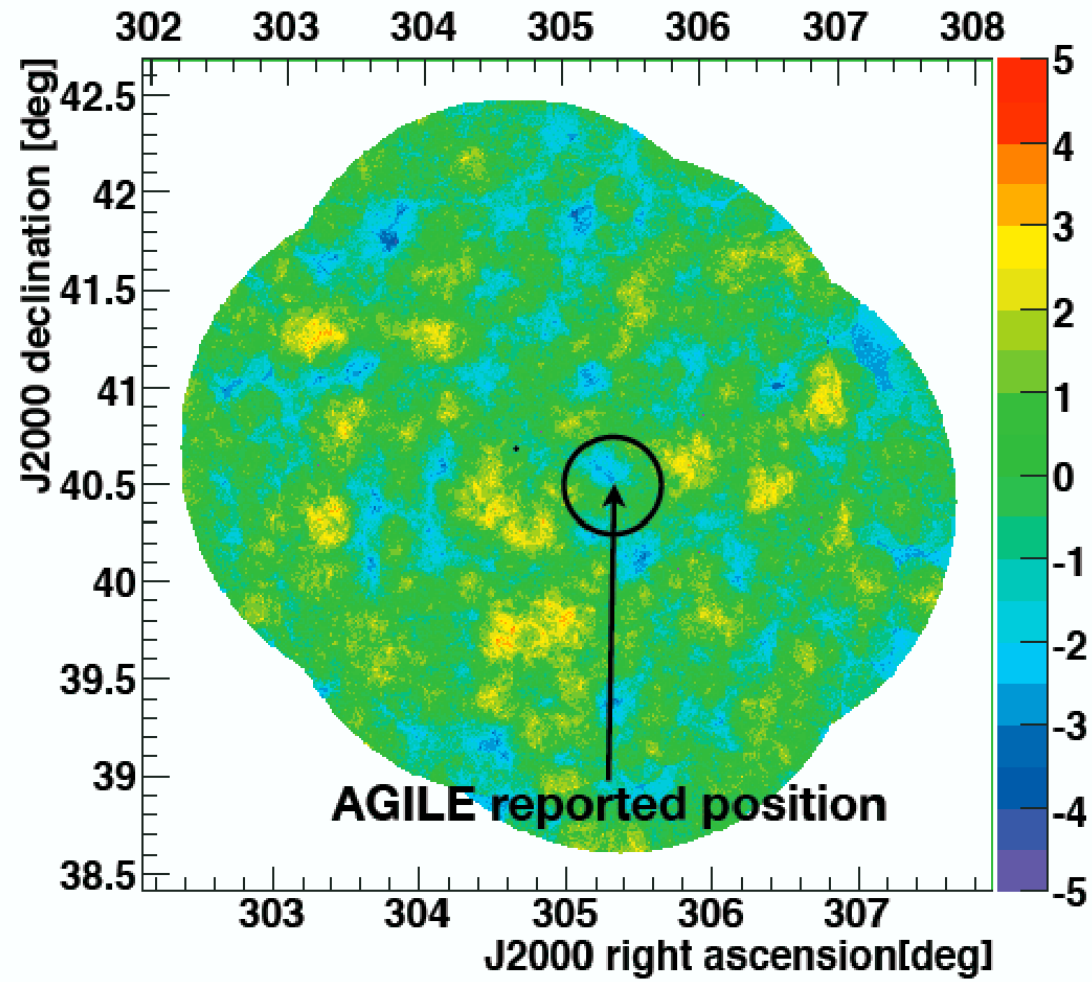




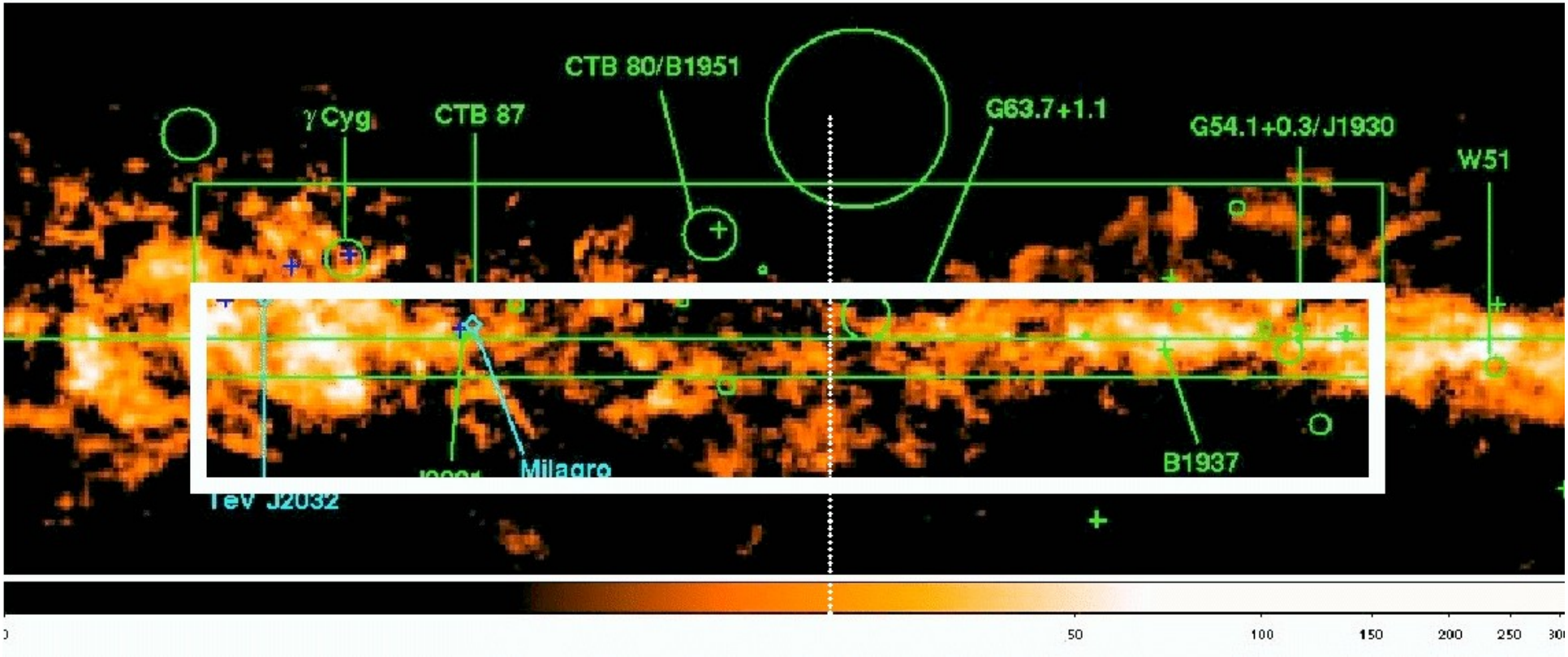
Contact: J.Holder

The AGILE transient

- AGILE reported strong transient
  => E>100MeV
  => comp. with 3EG J2020+4017
  => variable emission (April 2008)
  => ATel#1492
  => AGILE J2021+4024
- VERITAS observations: ~7h
- UL (99%): ~2% Crab (non-simultaneous)



The VERITAS sky survey



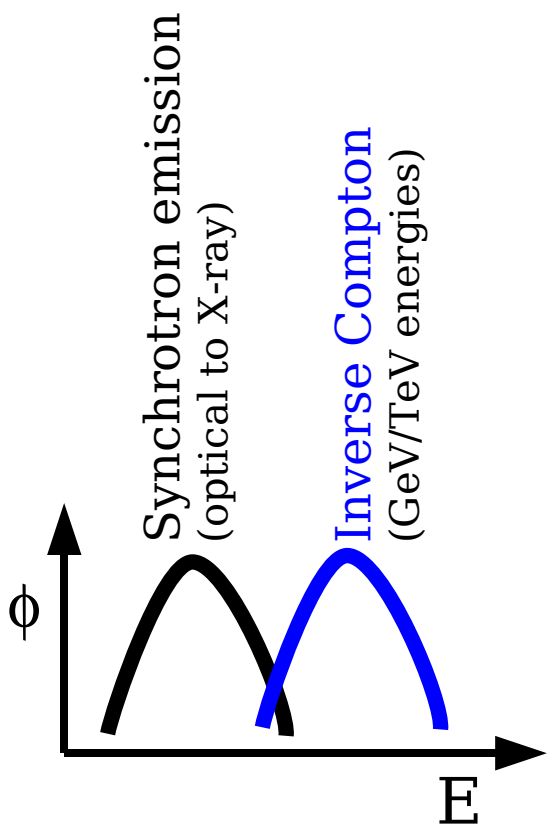
ongoing...

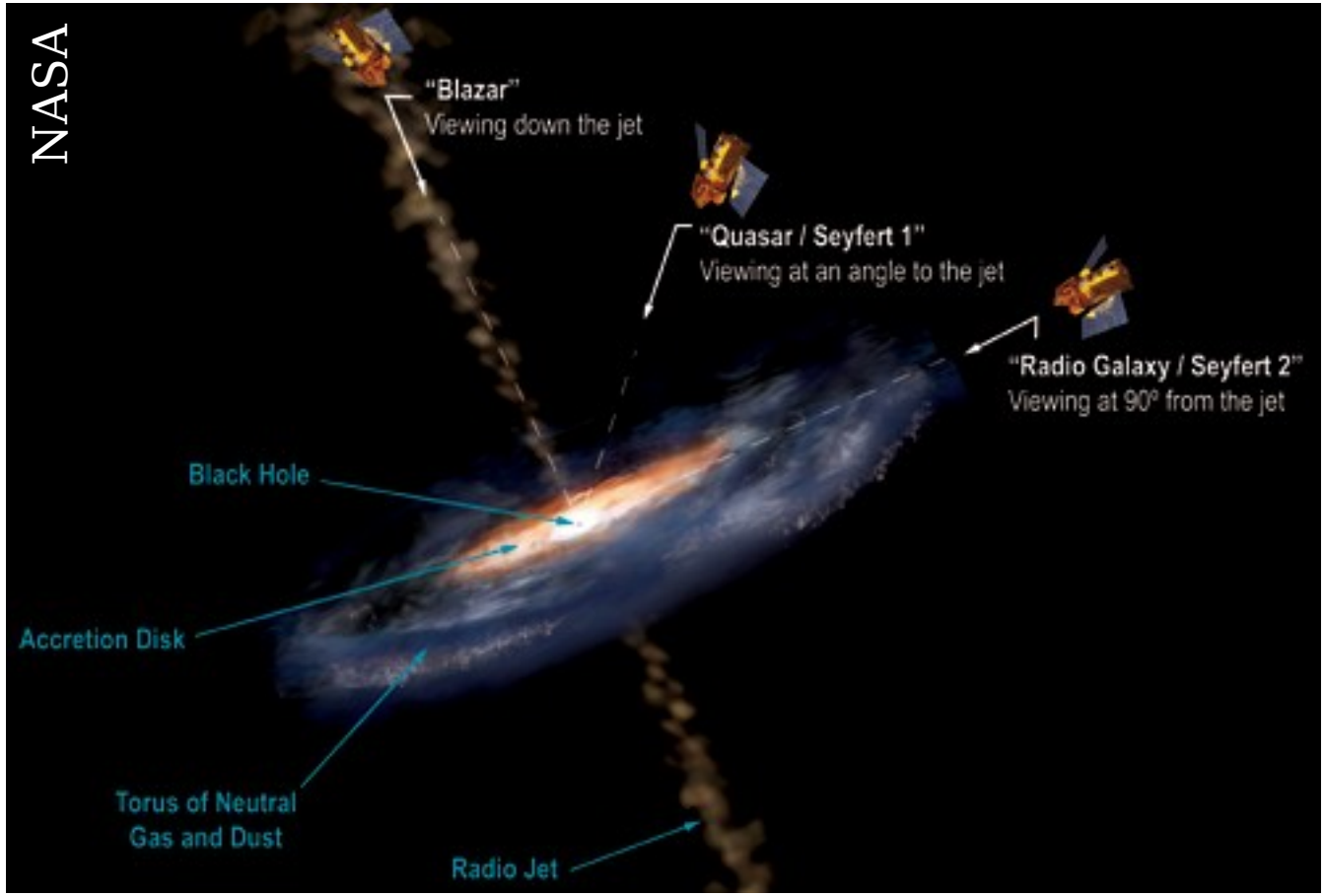
Contact: R.Ong

EXTRAGALACTIC OBSERVATIONS

Active Galactic Nuclei (AGN) and Blazars

- AGN: Black hole and accretion disk power relativistic plasma jet
- SSC model:



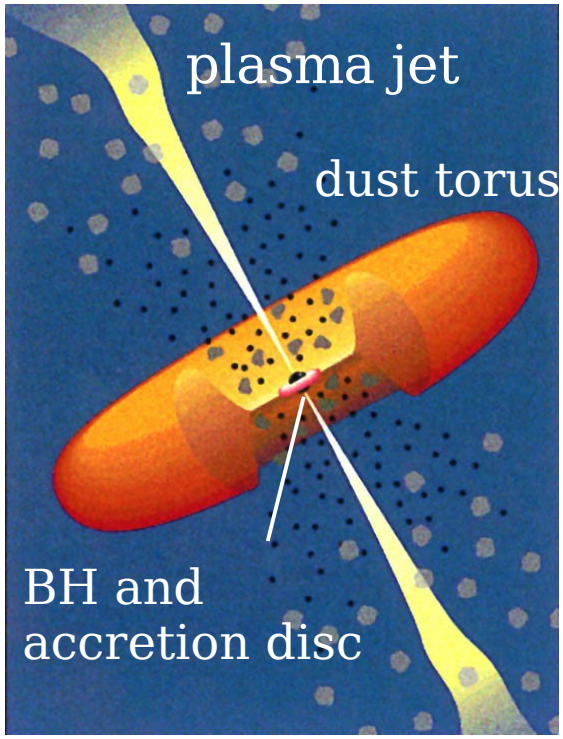


Open question: TeV emission: hadronic vs. leptonic models

The Extragalactic VHE sky: AGN and Blazars

Name	redshift	reference
M 87	0.004	Aharonian et al, A&A, 403, L1 (2003)
Markarian 421	0.030	Punch et al., Nature, 358, 477 (1992)
Markarian 501	0.034	Quinn et al., ApJ, 456, L83 (1996)
1ES 2344+514	0.044	Catanese et al., ApJ, 501, 616 (1998)
Markarian 180	0.045	Albert et al., astro-ph/0606630 (2006)
1ES 1959+650	0.047	Nishiyama et al., 29th ICRC, 3, 370 (1999)
PKS 548-322	0.067	Proc. Of ICRC 2007
BL Lacertae	0.069	Albert et al., astro-ph/0703084 (2007)
PKS 2005-489	0.071	Aharonian et al, A&A, 436, L17 (2005)
W Comae	0.102	Swordy et al 2008, ATel #1422
PKS 2155-304	0.116	Chadwick et al., ApJ, 513, 161 (1999)
H 1426+428	0.129	Horan et al., ApJ, 571, 753 (2002)
1ES 0806+524	0.138	Swordy et al 2008, ATel #1415
1ES 0229+200	0.139	Proc. Of ICRC 2007
H 2356-309	0.165	Aharonian et al, Nature, 440, 1018 (2006)
1ES 1218+304	0.182	Albert et al., ApJ, 642, L119 (2006)
1ES 1101-232	0.186	Aharonian et al, Nature, 440, 1018 (2006)
1ES 0347-121	0.188	Proc. Of ICRC 2007
PG 1553+113	>0.09?	Aharonian et al, A&A, 448, L19 (2006)
S50716+714	???	Teshima et al 2008, Atel #1500
3C 66A	>0.096	Swordy et al 2008, ATel #1753

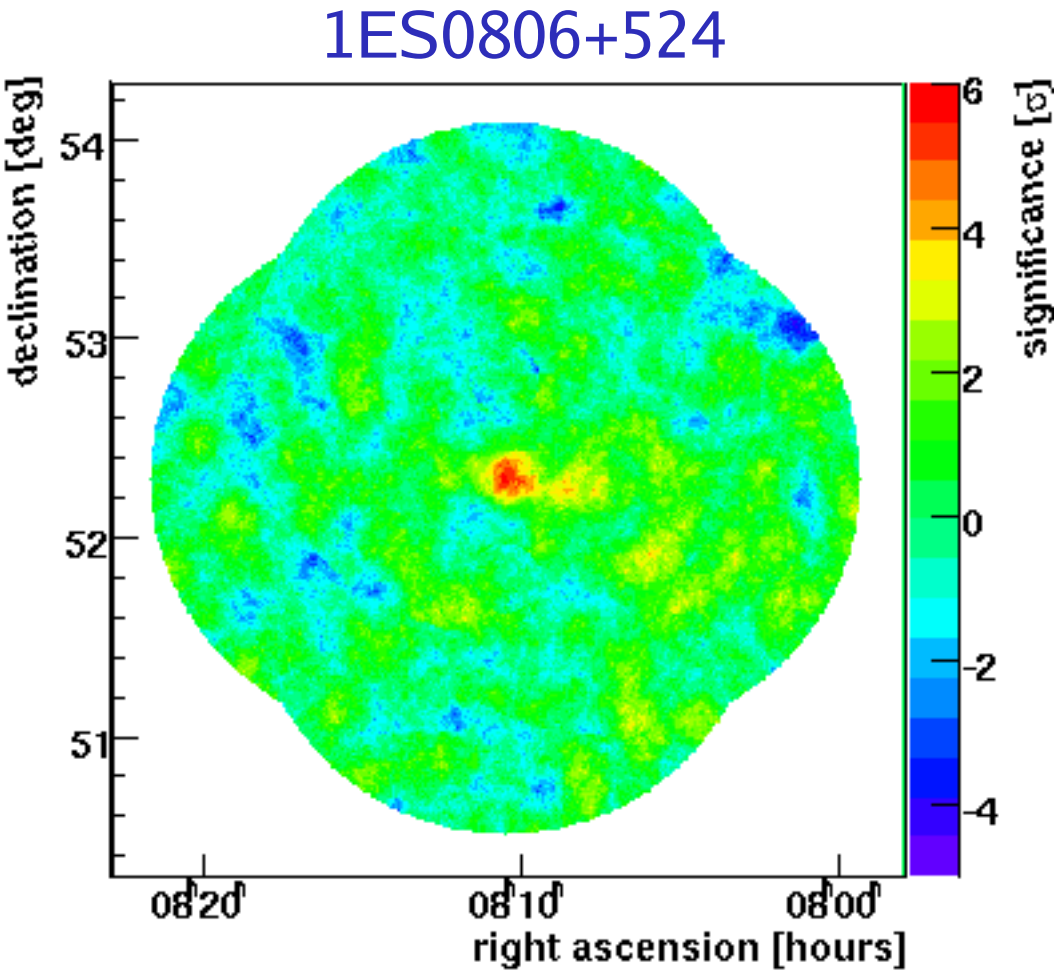
Seen by VERITAS
Discovered by VERITAS



Except for M87, all extragalactic TeV γ-ray sources are blazars

Discovery of 1ES0806+524

- HBL (redshift z=0.138)
- Predicted VHE emission
  [Costamante 2002]
- VERITAS detection:
  40h, 5.8σ, ATel#1415
- Photon flux:
  $(1.1 \pm 0.2_{stat})$ % of Crab
  [good weak source sensitivity]

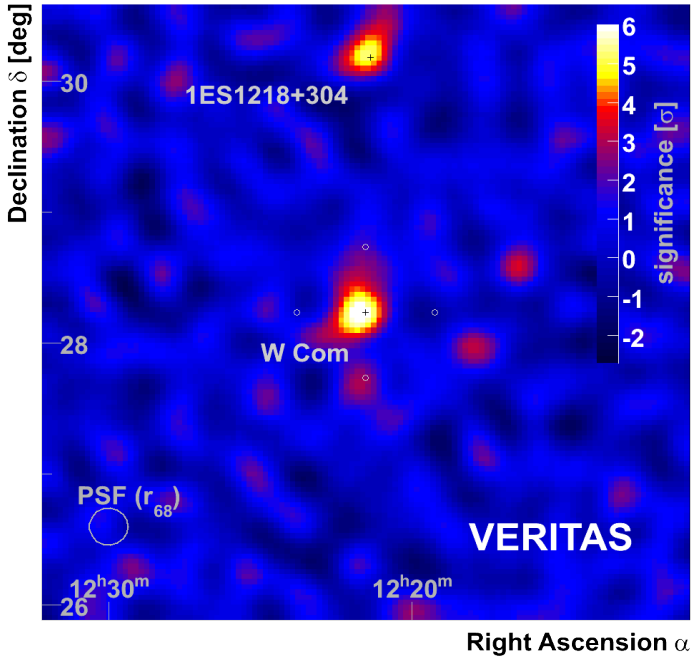


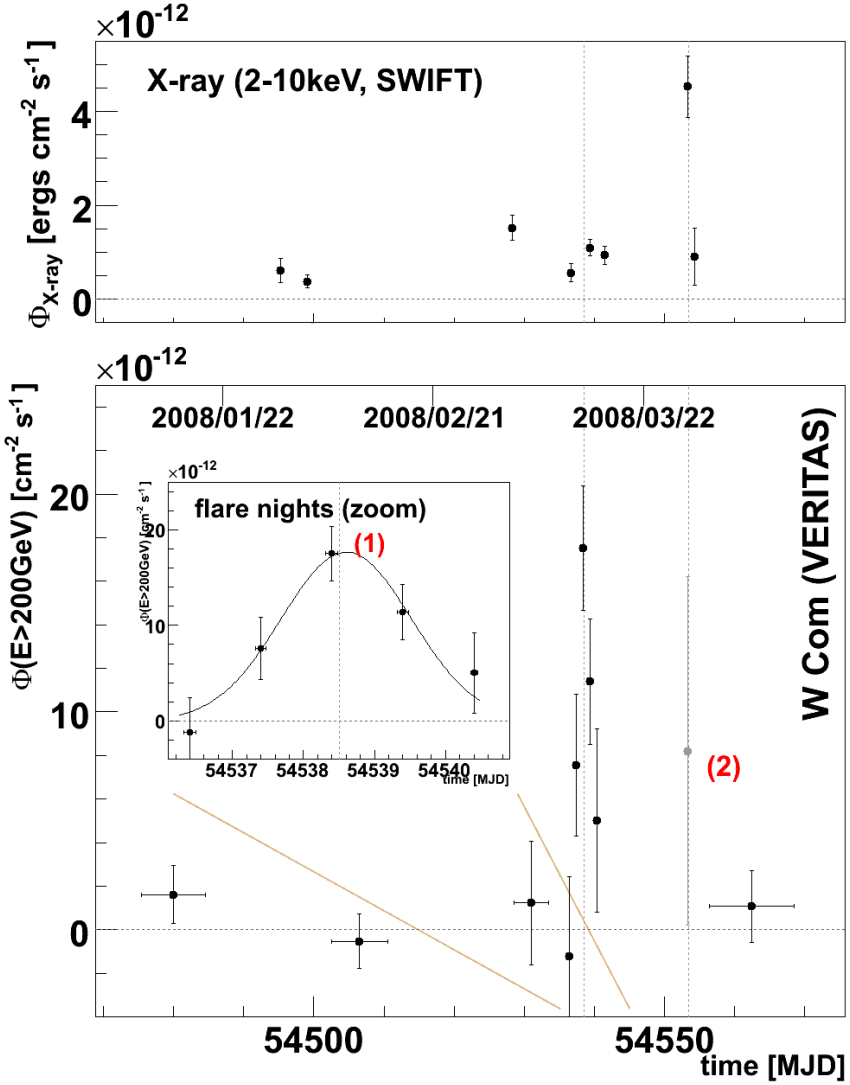
First 'VERITAS discovery': 1ES0806+524

Contact: P.Cogan

Detection of the IBL W Comae

- Intermediate-frequency-peaked BL Lac (IBL, z=0.102)
- VERITAS obs. in 2008 (39.5h)
- Detected with 4.9 std.dev.
- Strong flare (March): ATel#1422
- First time: 2 extragalactic VHE sources in one FoV.

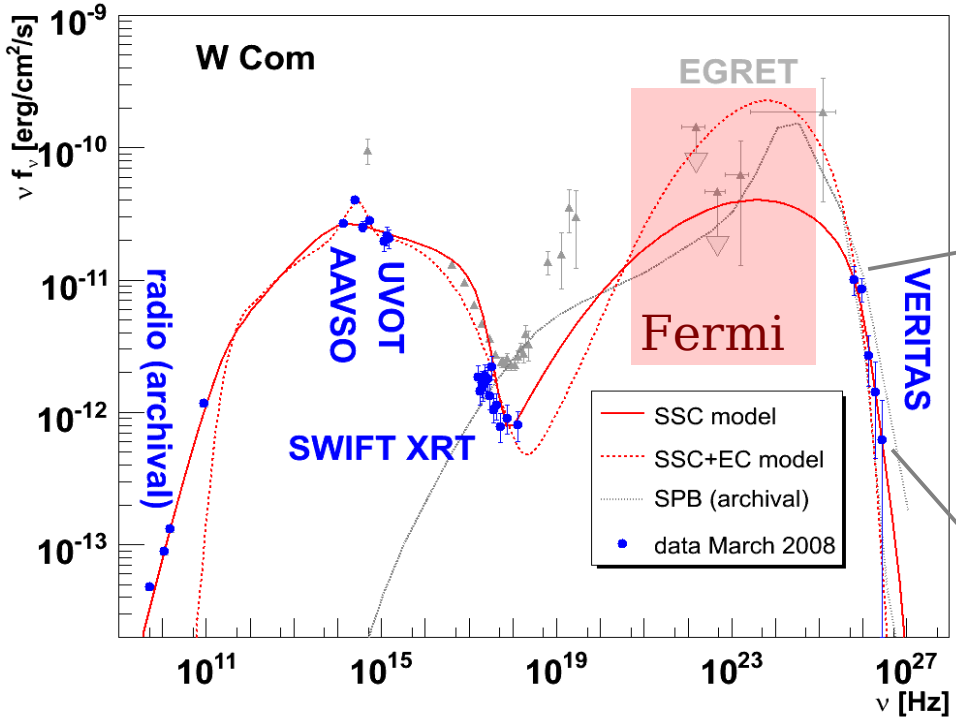


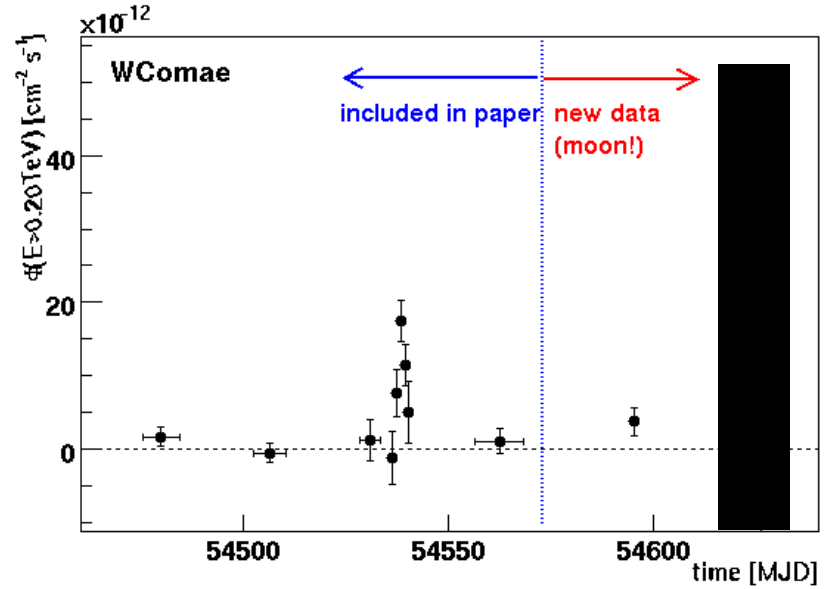


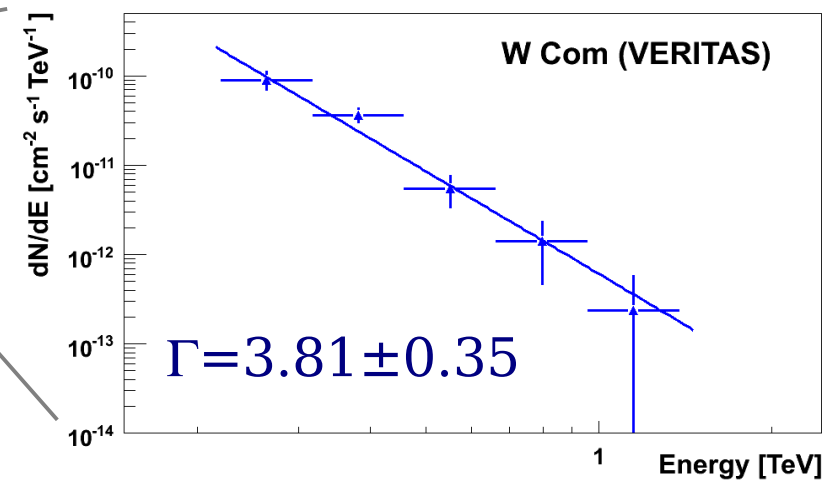
Contact: M.Beilicke

Detection of the IBL W Comae

- Steep energy spectrum, modeling:
  => SSC (unusual low B-field: 0.007G)
  => SSC+EC (more realistic parameters)
- Second VHE flare (June, Atel#1565)
  => triggered Agile (ATel#1582)



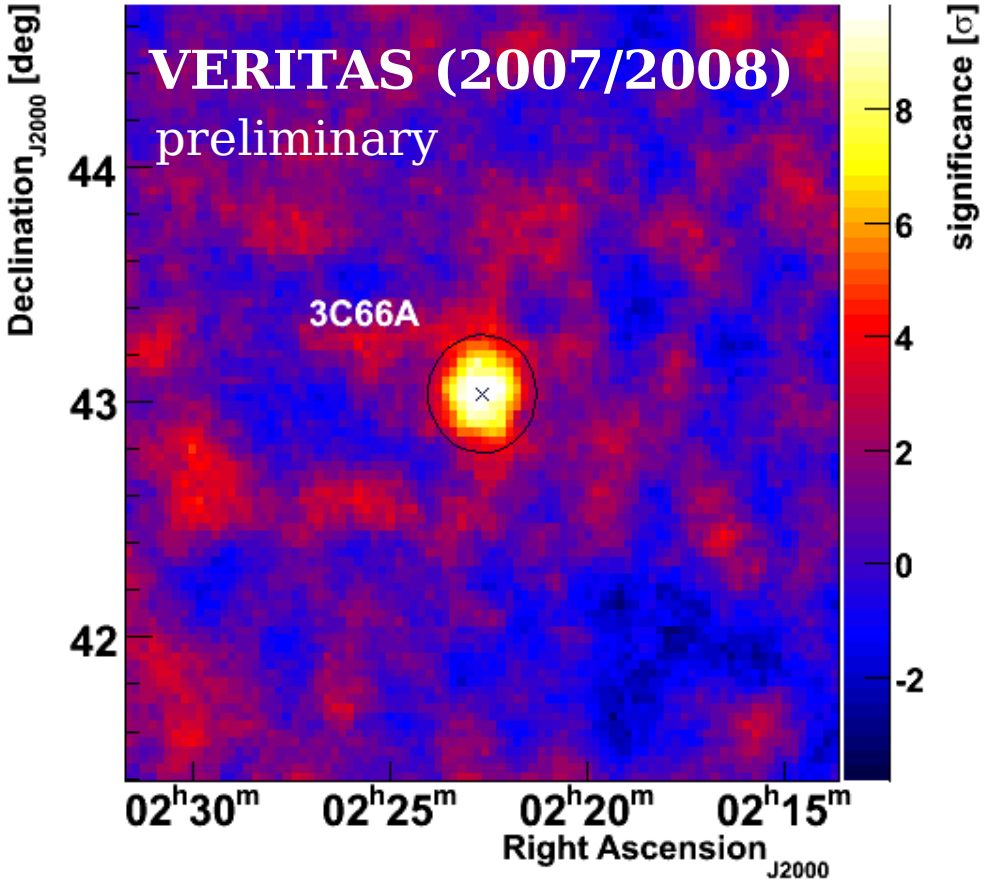




Second 'VERITAS discovery': W Comae (ApJL,684,L73,2008)

Discovery of 3C 66A

- First evidence: Crimean IACT
  [Neshpor et al (1998)]
- VERITAS detection (2007/08):
  >8σ, ATel#1753
- Spectrum: soft
  Integral flux: ~10% Crab
- Redshift uncertain:
  o) Weak line (Mg II?) => z = 0.444
  [Miller, French & Hawley (1978)]
  o) Weak Ly-alpha line
  [Lanzetta et al. (1993), ApJS, 84, 109]
  o) Limit (photometric z): z > 0.096
  [Finke et al. (2007), A&A, 447, 513]
- => GASP: Optical/near-IR brightening (Atel#1755)
- => Fermi detection (ATel#1759)



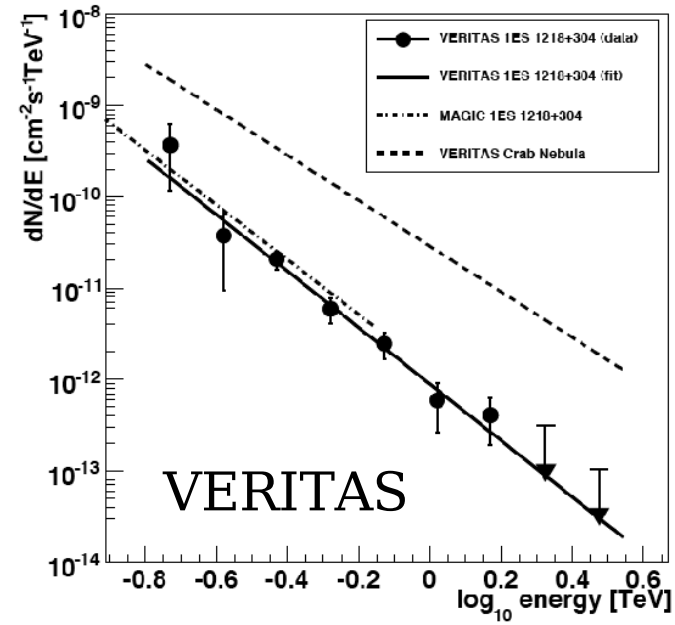
Third 'VERITAS discovery': 3C 66A

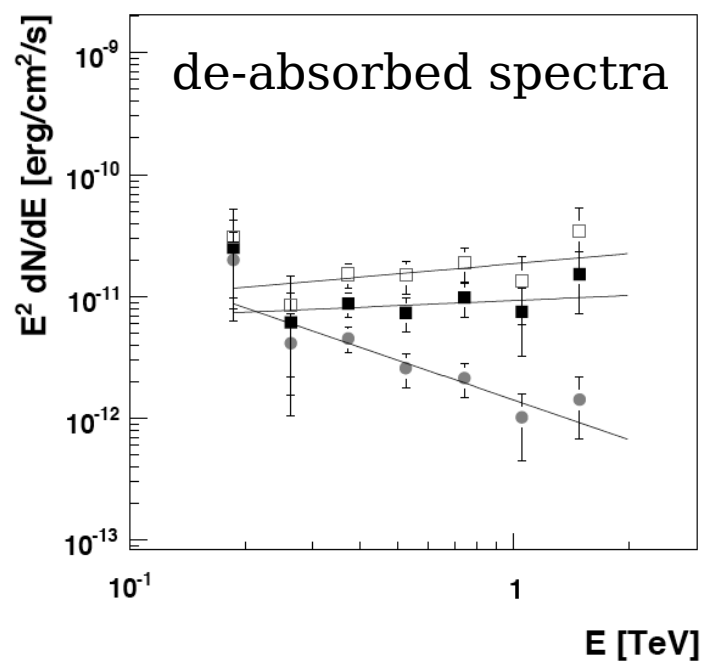
Contact: L.Reyes, J.Perkins

VERITAS observations of 1ES1218+304

- HBL (redshift z=0.182)
- Discovered by MAGIC [Albert et al. 2006]
- VERITAS observations: 17h, 10.4σ
  => Photon flux: ~6% Crab (no variability)
  => Photon index: $\Gamma = 3.08 \pm 0.34_{stat} \pm 0.2_{syst}$
- De-absorbed energy spectrum:
  => EBL limit (gal. count): $\Gamma_{int} < 2.32 \pm 0.37$
  => +blazar constraints: $\Gamma_{int} < 1.86 \pm 0.37$
  => HE peak beyond 2 TeV

Extending the 1ES1218 spectrum to 10 TeV: constrain EBL

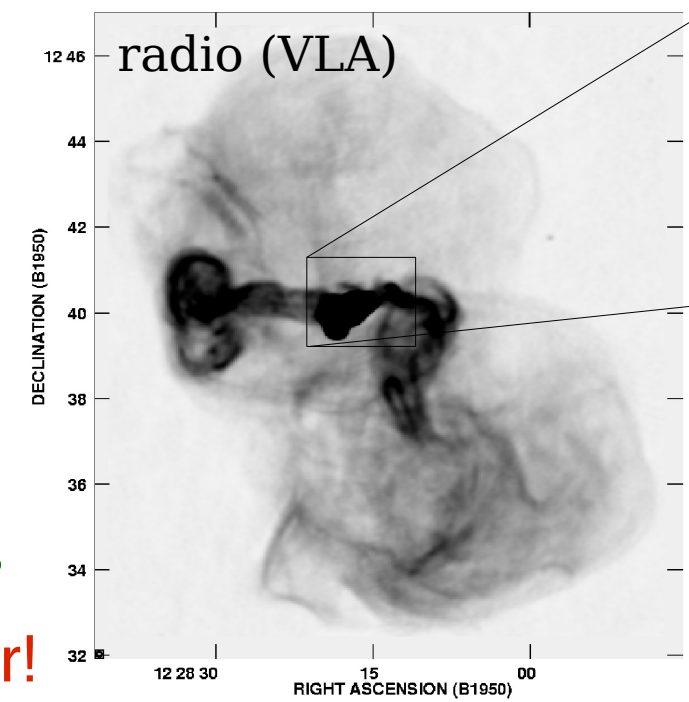


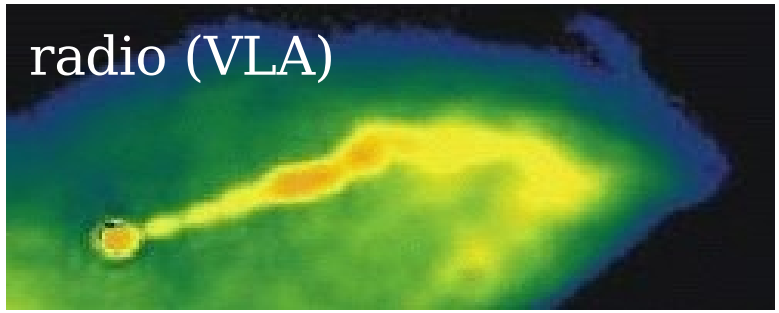


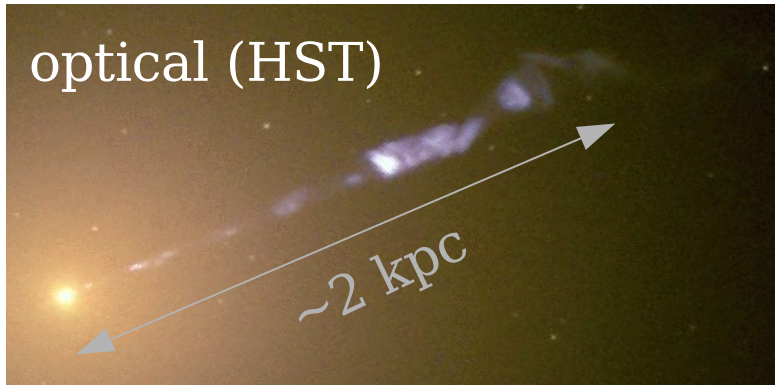
Contact: P.Fortin, F.Krennich

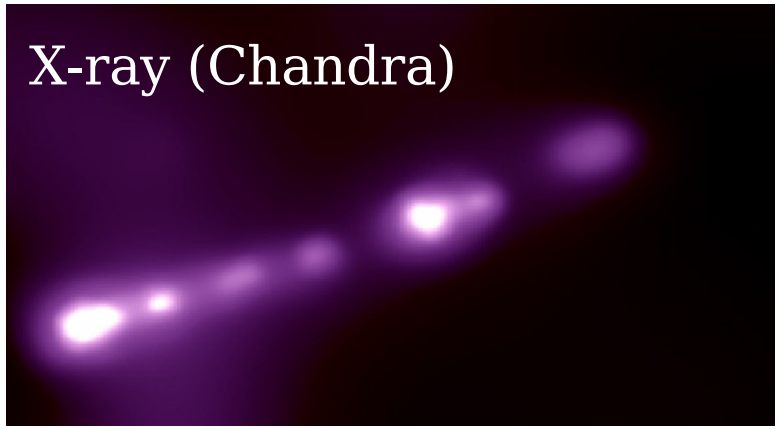
The Giant Elliptical Radiogalaxy M 87

- Distance:
  ~16 Mpc
  (z=0.00436)
- Central BH:
  $M_{BH} \sim 3 \cdot 10^9 M_{sun}$
- Jet angle: ~30°
  ⇒ not a blazar!









- Structures of the jet resolved at radio, optical and X-ray energies
- Predictions of TeV γ-ray emission and charged 10^{20} eV particles (UHECR)

M87: 10 Years of VHE Observations

History:

HEGRA (>4σ excess):
[Aharonian et al. 2003]

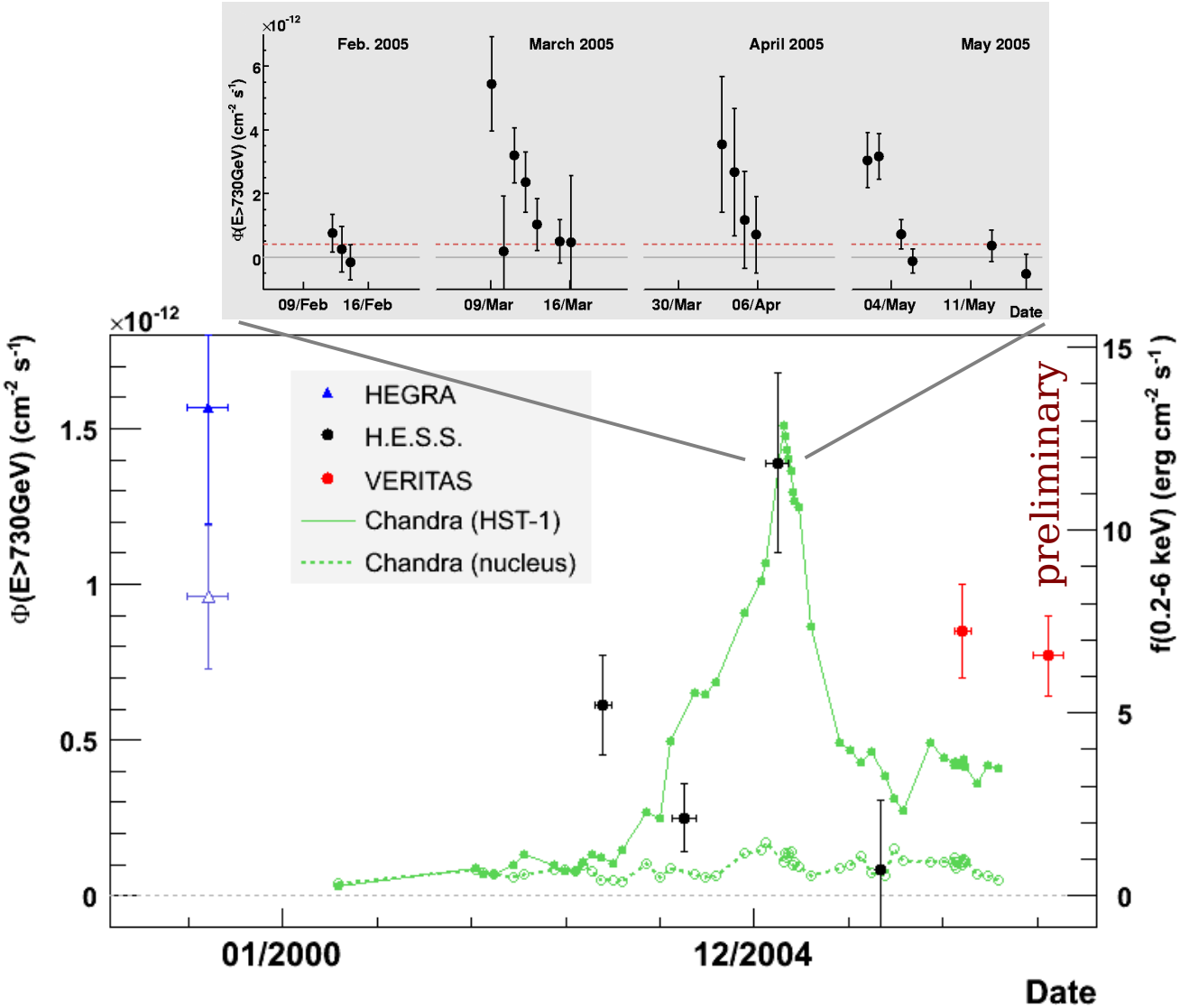
Whipple (upper limit):
[Lebohec et al. 2003]

H.E.S.S. (11σ confirmation, short-term variability):
[Aharonian et al. 2006]

VERITAS (detection):
[Acciari et al. 2008]

MAGIC (confirmation of short-term variability):
[Albert et al. 2008]

Thanks to D.Harris!
(Chandra light curves)



Contact: M.Beilicke

A joint M87 Observation Campaign in 2008

- Coordinated campaign: H.E.S.S./MAGIC/VERITAS
- More than 120h (>50 nights)
- Outburst in February 2008
  (triggered by MAGIC, occurred during X-ray low-state of HST-1)
- 5 Chandra pointings in 2008

Key question: origin/location of the TeV emission

To be published soon

Contact: M.Hui, M.Beilicke, H.E.S.S. And MAGIC

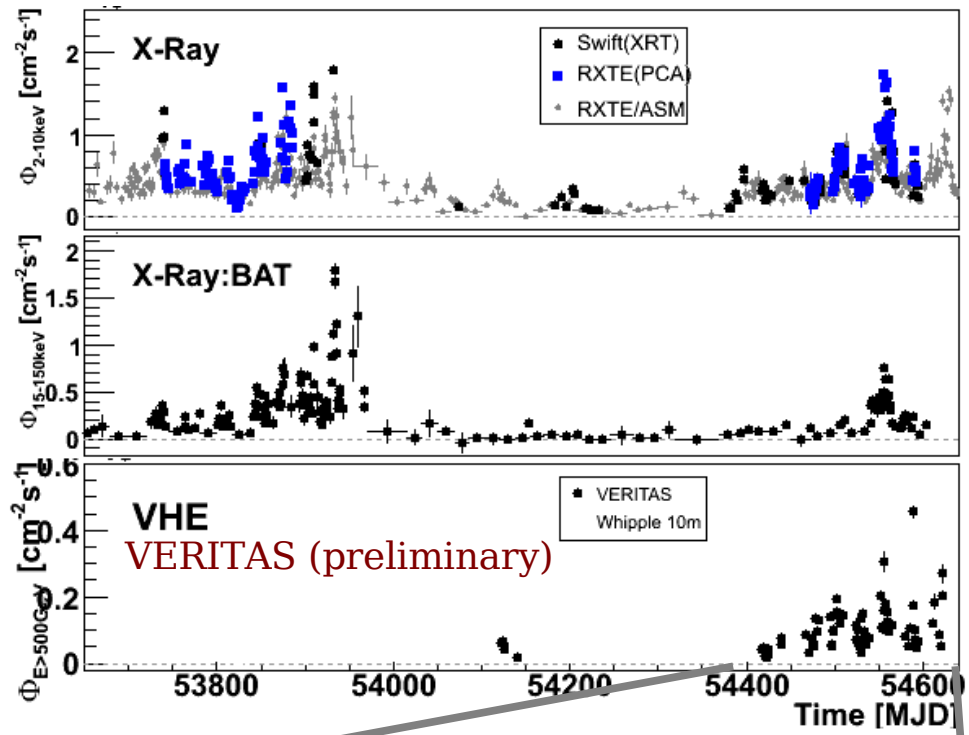
Mrk421: 2007/08 MWL Campaign

MWL data:

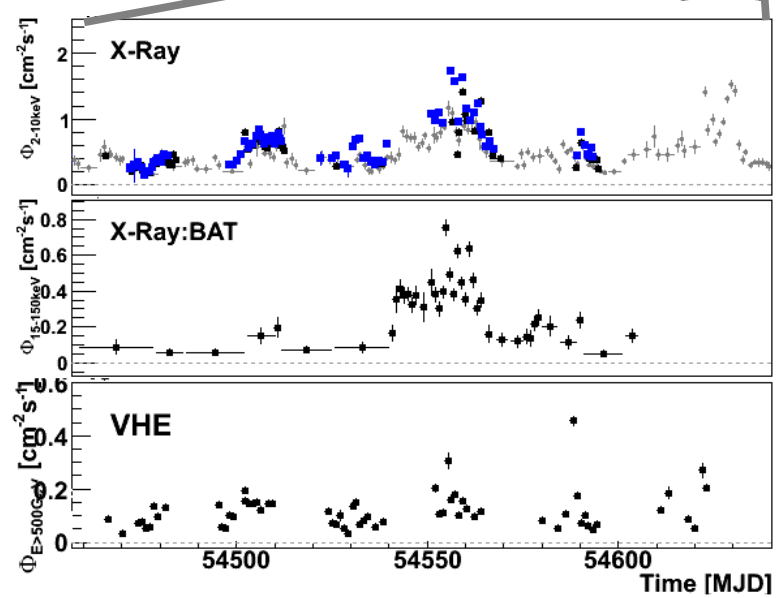
- **Radio:** Metsahovi, UMRAO (tbd)
- **Optical:** BRT/NMS, UVOT, RCT/Bell/CRAO, WIYN, Turola/KVA (tbd)
- **X-ray:** RXTE (ASM&PCA), Swift (BAT&XRT), Suzaku (tbd)

VERITAS data:

- 42h of data in 2008
- Night-by-night light curve (assuming dN/dE ~ $E^{-2.5}$)
- Whipple results will follow



Thanks to the RXTE and Swift teams



preliminary

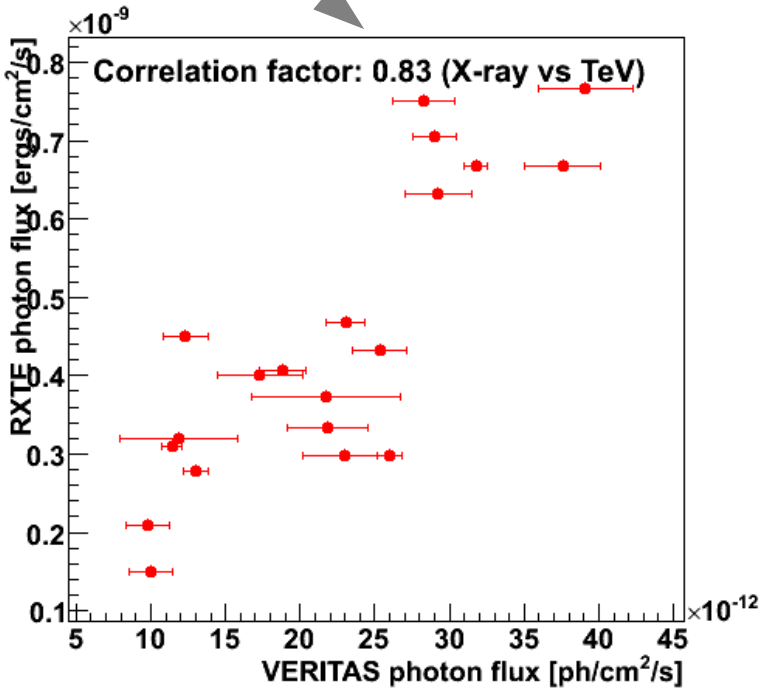
Underway: Spectral variability, MWL flux correlations

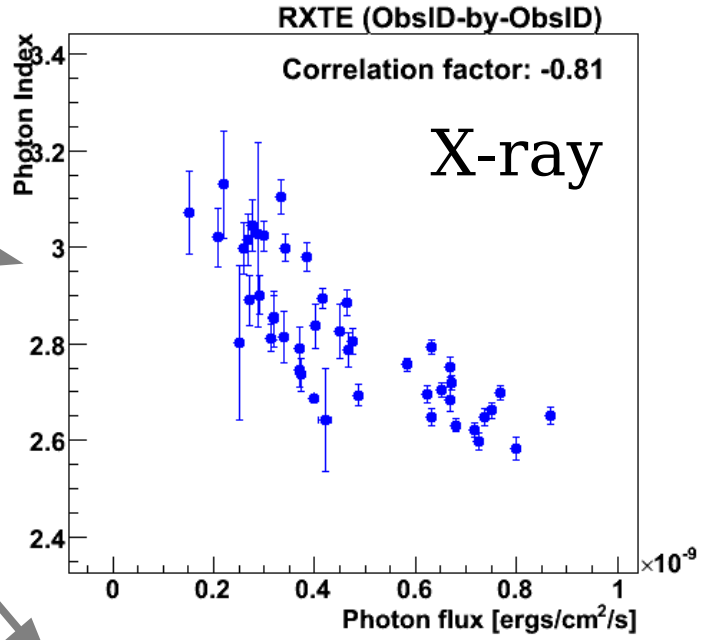
Contact: J.Grube, L.Reyes, M.Daniel, M.Beilicke

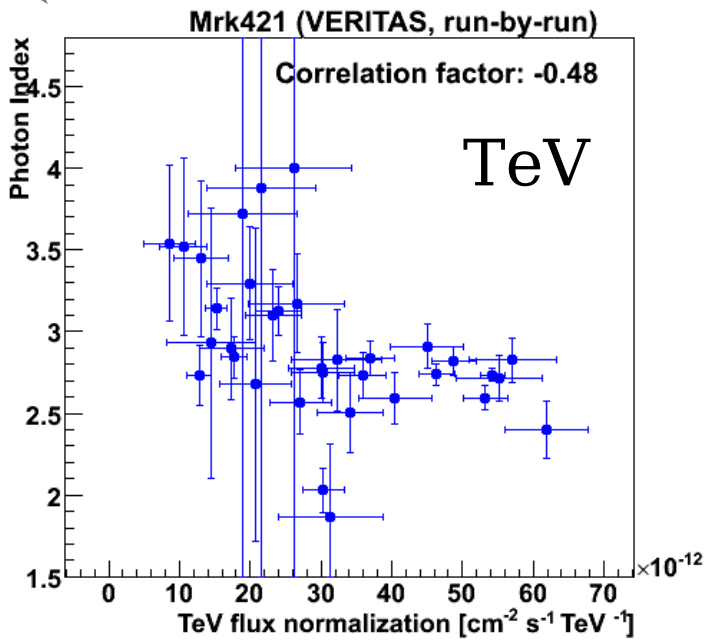
Mrk421: TeV & X-ray Correlations

Correlation studies (preliminary):

- Flux vs. index (X-ray & TeV)
- X-ray/TeV flux





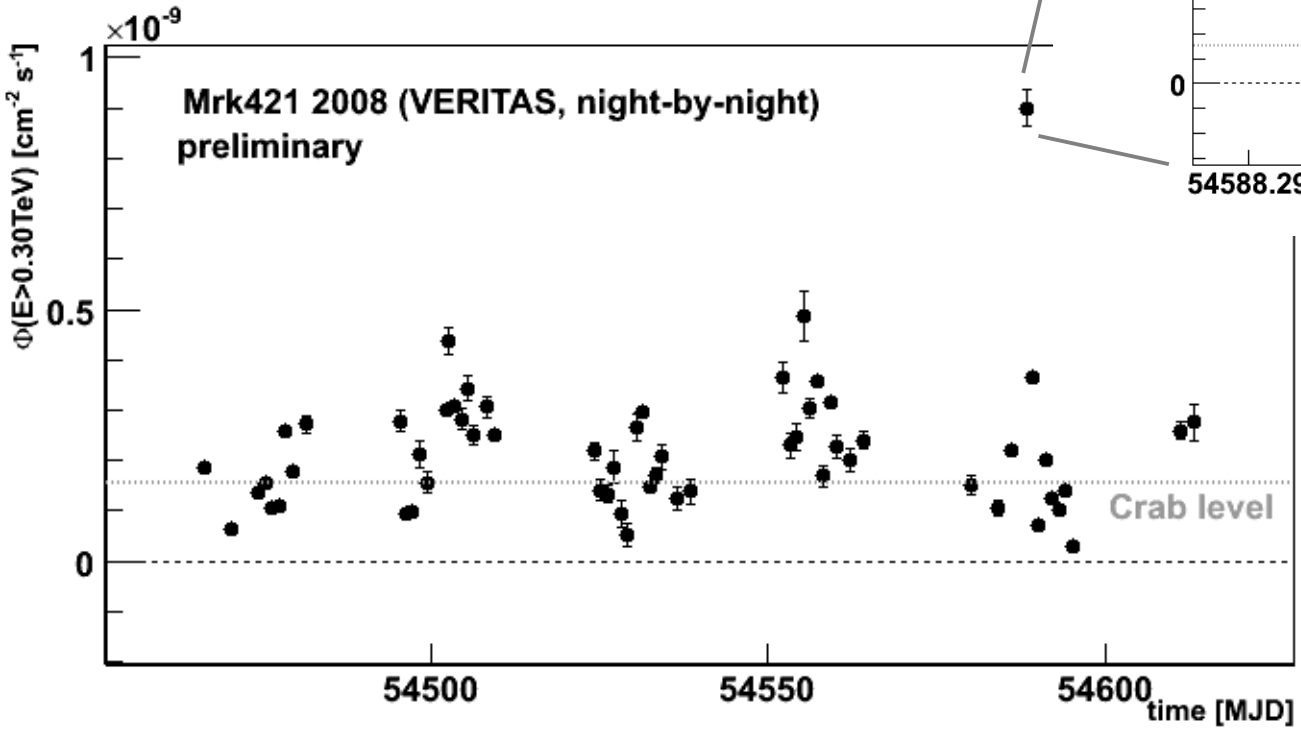


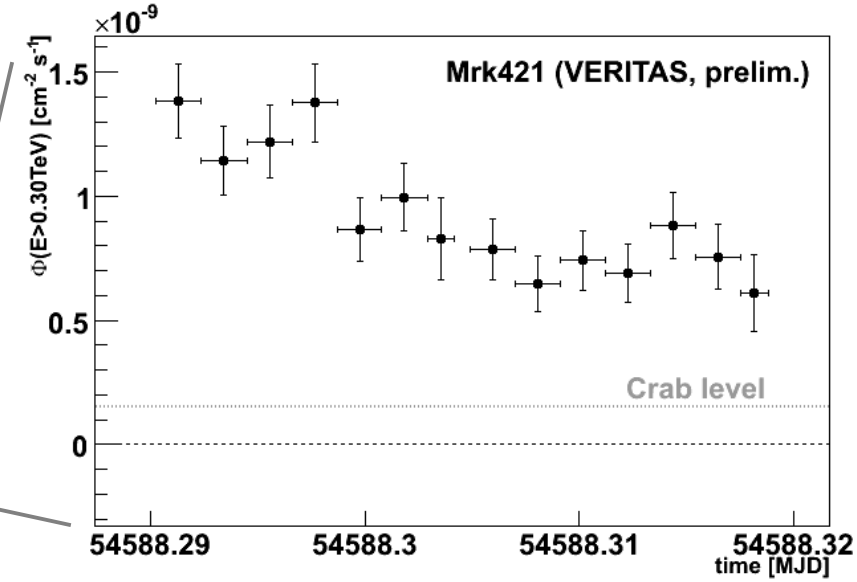
Underway: Spectral variability, MWL flux correlations

Contact: L.Reyes, M.Daniel, M.Beilicke

Mrk421: The big Flare (May 2008)

- Big flare recorded begin of May '08
  Flux level up to 10 Crab
  [Swordy et al 2008, ATel#1506]
- 5σ-detection in ~15s(!)





More studies underway...

Contact: L.Reyes, M.Daniel, M.Beilicke

1ES 2344+514 (z=0.044): TeV/X-ray Light Curve

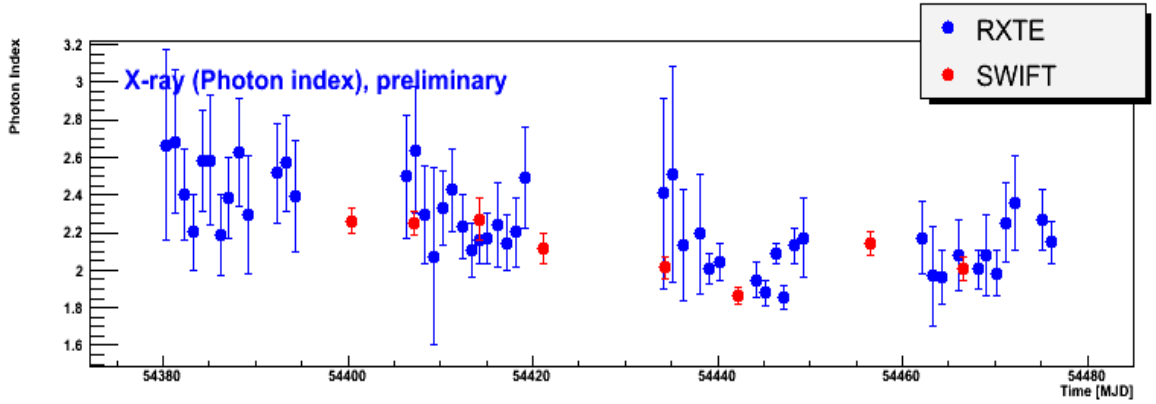
X-ray data:

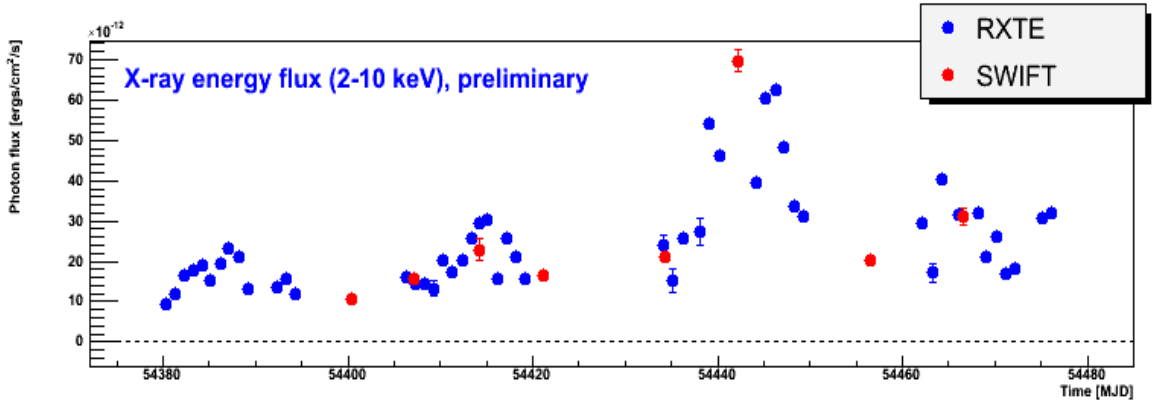
- 53 RXTE/PCA pointings
  - STD QL selection
  - RXTE faint BG model
  - Fit data with power law
- Swift data
  - power-law fit (0.6-10keV)

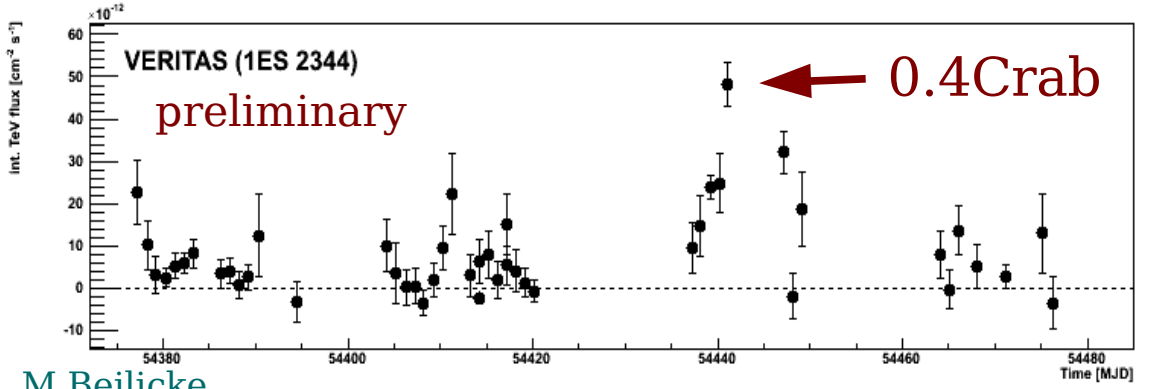
VERITAS data:

- 23h of data in 2007/2008
- Night-by-night light curve

4th VHE blazar with good MWL coverage

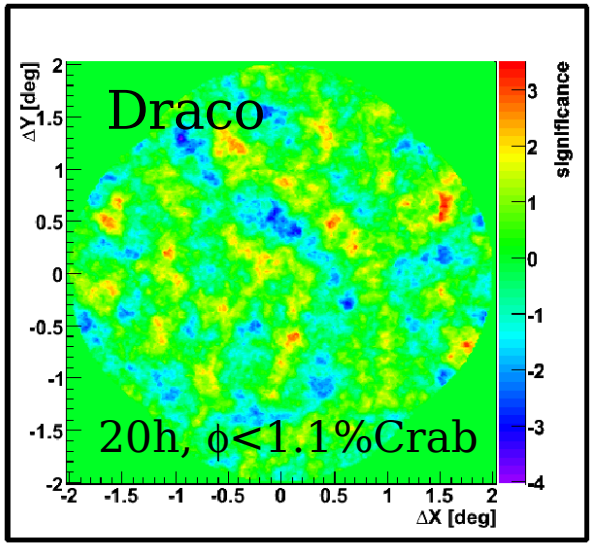


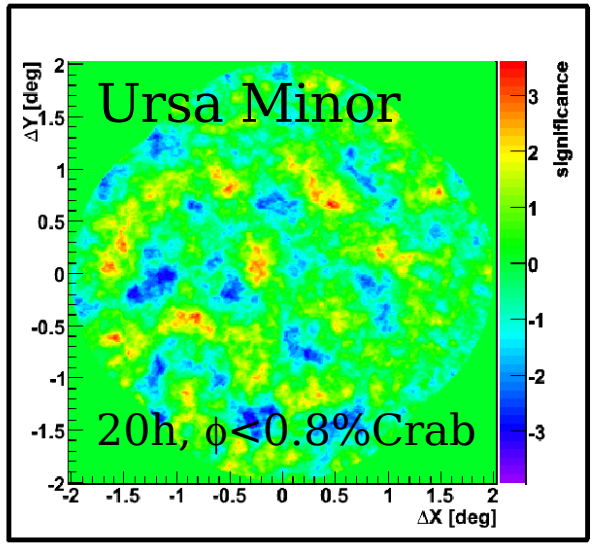


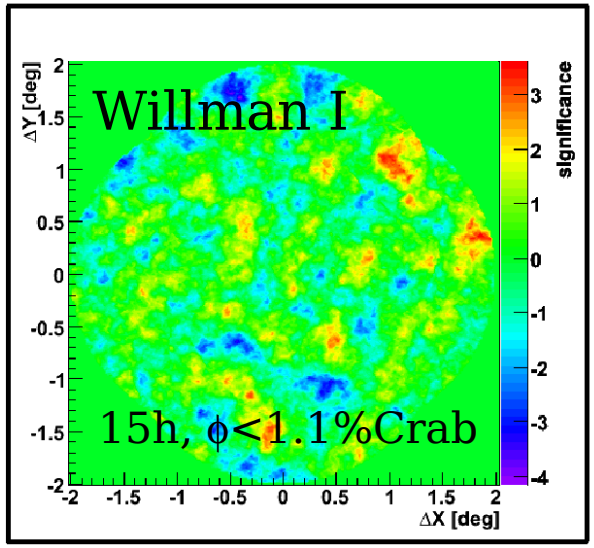


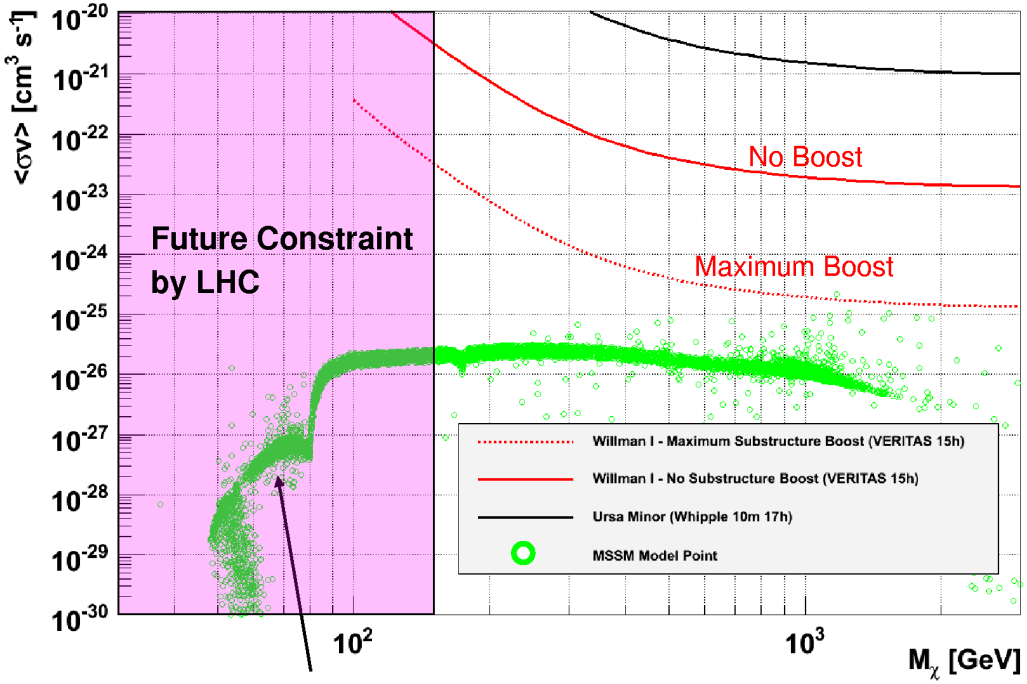
Contact: J.Grube, L.Reyes, D.Horan, M.Wood, M.Beilicke

Observation of Dwarf Galaxies (DM)









Whipple 10m
Ursa Minor constraint

VERITAS
Willman I constraints
derived from
Strigari et al. 2007

Minimal Supersymmetric extensions to Standard Model (MSSM) allowed by WMAP

Contact: M.Hui

SUMMARY & CONCLUSION

Summary and Conclusion

- **Total observations in 2007/2008 season:** 700h (+100h moon)
- **Galactic objects**
  - **Detected:** Crab, Cas A, MGRO J1908+06
  - **LSI+61:** flux modulation with orbital phase, MWL observations
  - **IC443:** detected in 2007/2008 (~8σ), extended
- **Extragalactic observations**
  - **Discoveries:** 1ES0806, W Comae (IBL) and 3C 66A
  - **M87:** detected in 2007/2008 (joint campaign with H.E.S.S. And MAGIC)
  - **Mrk421:** Extensive VERITAS/RXTE/Swift campaign in 2008
  - **1ES2344:** VERITAS/RXTE/Swift MWL, flaring up to 0.4 Crab
  - **More AGN/blazars:** observed/analyzed (not addressed here)

Thanks go to the RXTE, SWIFT and AAVSO teams