



# Highlight Talk: Recent Results from VERITAS

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# VERITAS Collaboration



~ 100 Scientists

22 Institutions in  
4 Countries

Support from:

Smithsonian Inst.  
U.S. NSF  
U.S. DOE  
STFC (U.K.)  
NSERC (Canada)  
SFI (Ireland)

## U.S.

Adler Planetarium  
Argonne Nat. Lab  
Barnard College  
DePauw Univ.  
Grinnell College  
Iowa St. Univ.

Purdue Univ.  
SAO  
UCLA  
UCSC  
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## Canada

McGill Univ.

## U.K.

Leeds Univ.

## Ireland

Cork Inst. Tech.  
Galway-Mayo Inst.  
N.U.I. Galway  
Univ. College Dublin

**+ 25 Associate Members**

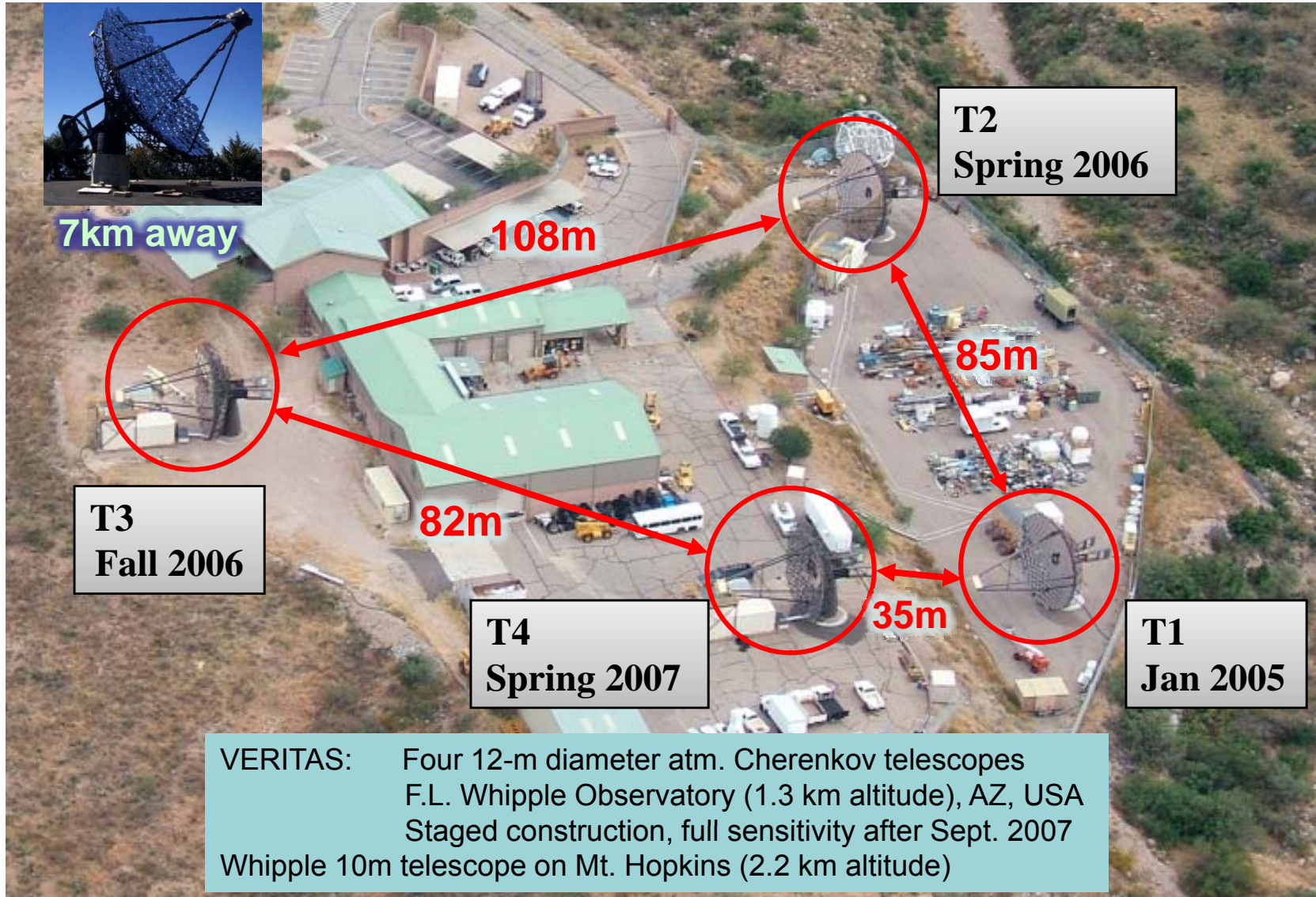
# Outline

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- ❑ VERITAS Telescope Array
  - **Layout, technical details, performance**
- ❑ Observation Strategy and Summary
- ❑ Science: Many new results since ICRC 2007 (Merida)
  - **Starburst Galaxy: M 82**
  - **Galactic Plane Survey**
  - **Extragalactic Source Highlights**
  - **Galactic Source Highlights**
  - **Other Science Results**
- ❑ VERITAS Upgrade Plans
- ❑ Summary of ICRC Presentations

# VERITAS Telescope Array

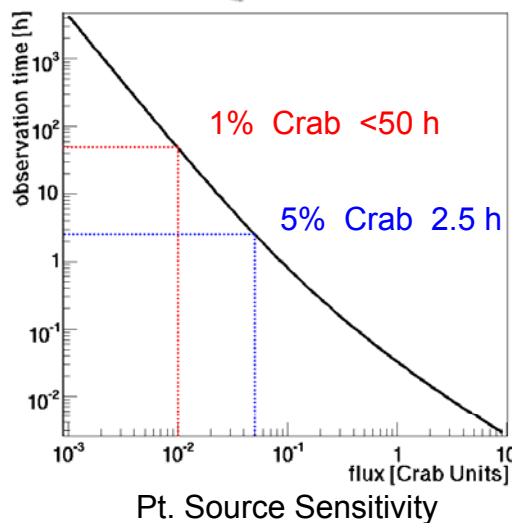
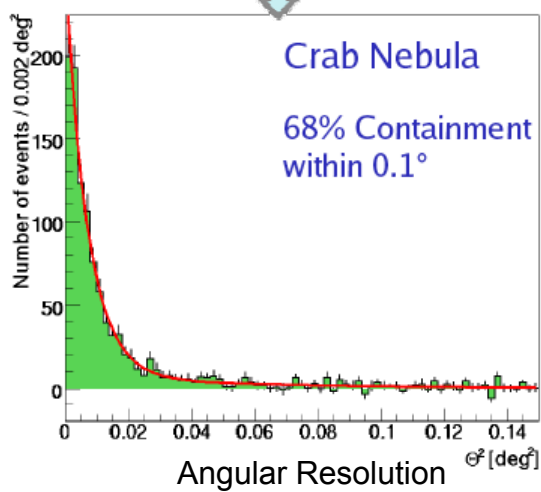
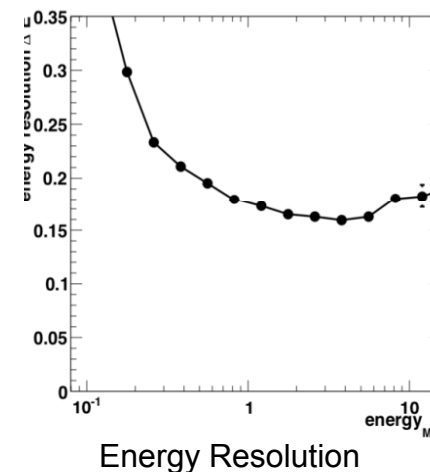
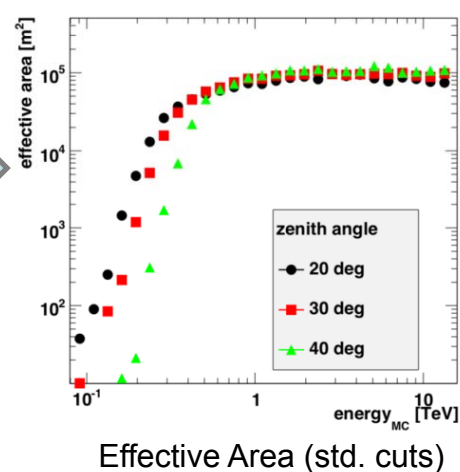




# VERITAS Performance

## Canonical Performance Values:

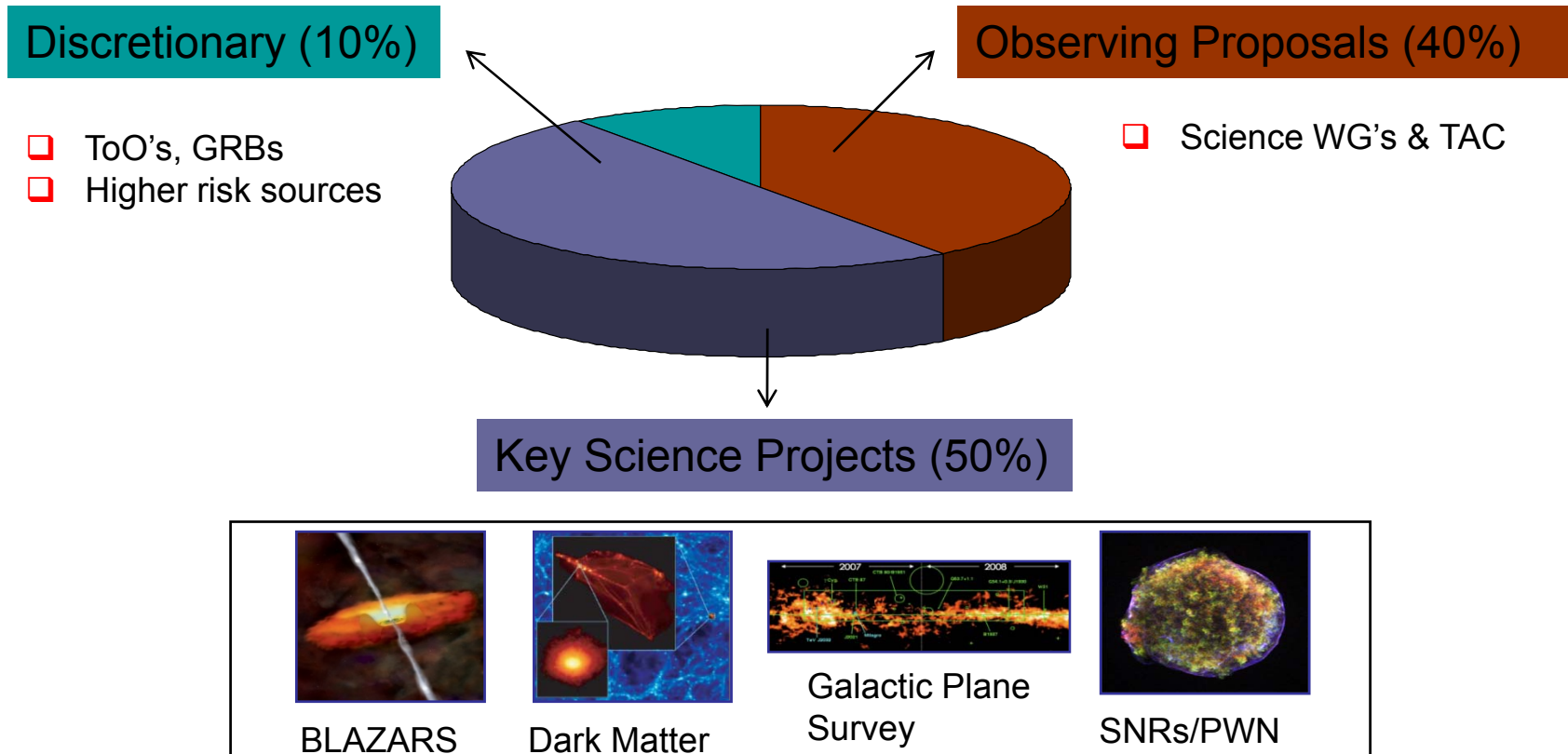
- Energy Range: 100 GeV – 30 TeV (spectra >150 GeV)
- Energy Resolution: 15% – 20%
- Crab Rate ~ 40 / min (trigger)
- Sensitivity: 5% Crab in < 2.5 h  
1% Crab in < 50 h
- Angular Resolution:  $r_{68} < 0.1^\circ$
- Pointing Accuracy: < 50''



## Operational & Analysis Improvements:

- “Hard” and “Soft” cuts permit improved E range, sensitivity.
- Enhanced reconstruction techniques give better sensitivity: **1% Crab ~ 40 h.**
- Future improvement: better PSF & new array configuration.

# Observation Strategy 2007-09



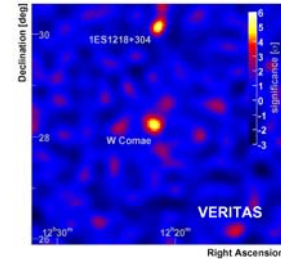
- ❑ **750 hours/year Dark Time + 30% Moonlight (= 975 hours total).**
- ❑ **> 95% Data taken with all four telescopes operational.**

# VERITAS Science Highlights (so far)



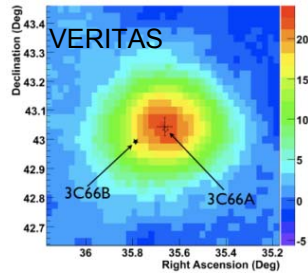
## 2007:

- ❑ **Detection of SNR IC 443 (w. MAGIC).**
- ❑ Detection binary LS I +61 303, confirming variability.
- ❑ Detection of blazar 1ES 1218+304 and radio galaxy M87.



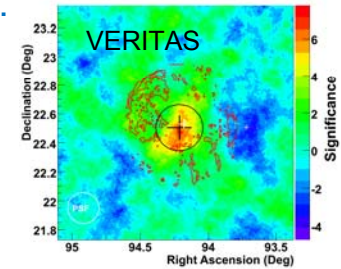
W Comae & 1ES 1218+304

## 2008:



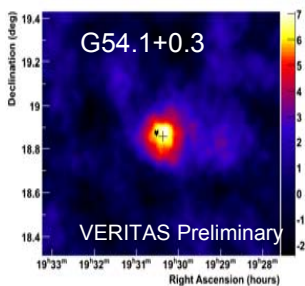
3C 66A

- ❑ Detection of blazar 1ES 2344+514, correlated TeV flare with X-ray.
- ❑ **Discovery of blazar 1ES 0806+524 (ATEL #1415).**
- ❑ **Discovery of blazar W Comae (ATEL #1422), a new LBL.**
- ❑ Detection of SNR Cas-A.
- ❑ **Discovery of blazar 3C 66A (ATEL #1753), the first IBL.**

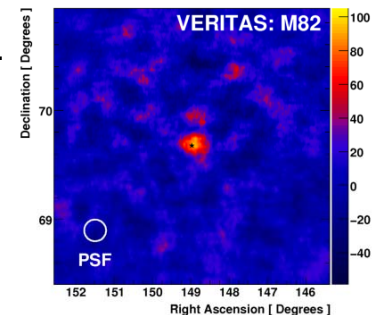


IC 443

## 2009:



- ❑ Measurement of source extent of SNR IC 443.
- ❑ Simultaneous MWL observations of Mrk 421 reported (w. MAGIC).
- ❑ **Discovery of blazar RGB 0710 (ATEL #1941).**
- ❑ MWL observations of LS I +61 303 (w. Swift, RXTE).
- ❑ **Radio imaging of TeV emission region of M87 (w. MAGIC, HESS, VLBA).**
- ❑ Evidence for variability in HESS J0632+057.



- ❑ **ICRC 2009:**  
**Many new results, including 5 New Source Detections.**



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Highlight: Detection of  
Starburst Galaxy M82

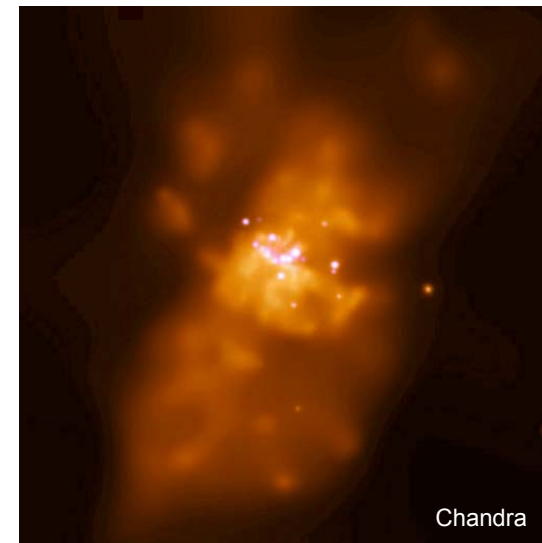
Highlight:  
Galactic Plane Survey





# Highlight: Starburst Galaxy M82

- ❑ M82: Prototype starburst galaxy
  - Interacting with group of galaxies over hundreds of Myrs.
  - Tidal forces → active starburst region (HST shows > 200 massive star clusters).
  - SMBH <  $3 \times 10^7 M_{\text{sun}}$ , no AGN activity.
  
- ❑ Starburst Region
  - High star formation and SNR rate.
  - High CR density (from radio emission).
  - High gas density  $\sim 150 /\text{cm}^3$ .
  - $\gamma$ -rays from cosmic rays (hadrons and e) interacting with gas and photon fields. Clues on origin of CR's.
  - Previous limits < 10% Crab (HEGRA, Whipple). Also limits on NGC 253.





# Highlight: Starburst Galaxy M82

## ❑ VERITAS Data & Analysis

- 2007-09: 137 h live time.  
Only dark time (no moonlight).
- “Hard cuts” from *a priori* study of Crab data at similar zenith ( $\theta \sim 40^\circ$ ).

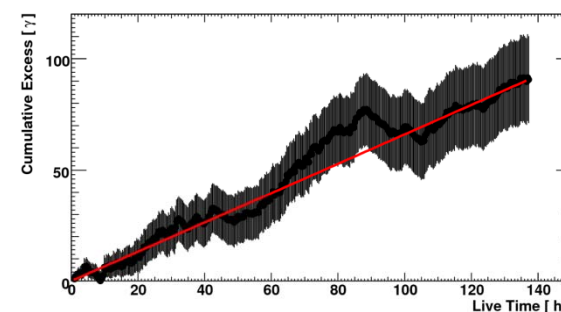
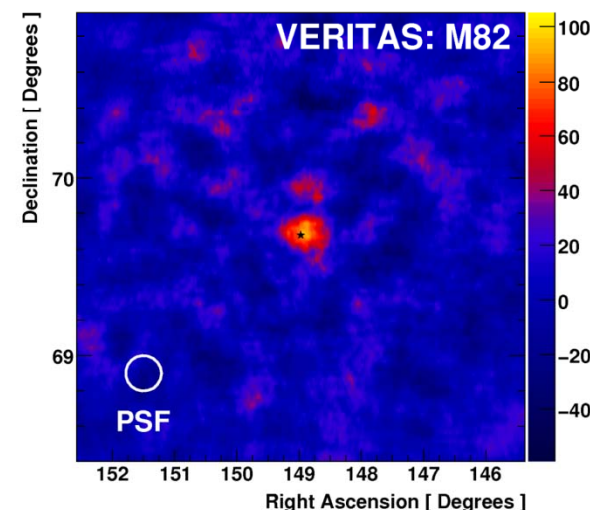
## ❑ Detection !

- $5.0 \sigma$  excess (pre-trials),  $4.8 \sigma$  (post-trials).  
Consistent with point source at M82.
- Many systematic checks of analysis procedure, background method, and potential biases.  
( $E > 700$  GeV)
- Among weakest VHE sources  $\sim 0.9\%$  Crab.  
(Power-law spectrum: upcoming talk).

## ❑ Interpretation

- **First detection of an extragalactic VHE source not clearly associated with AGN activity.**
- Consistent with predictions, general nature of CR interactions.

ICRC Talk: W. Benbow OG 2.3 (#0656)

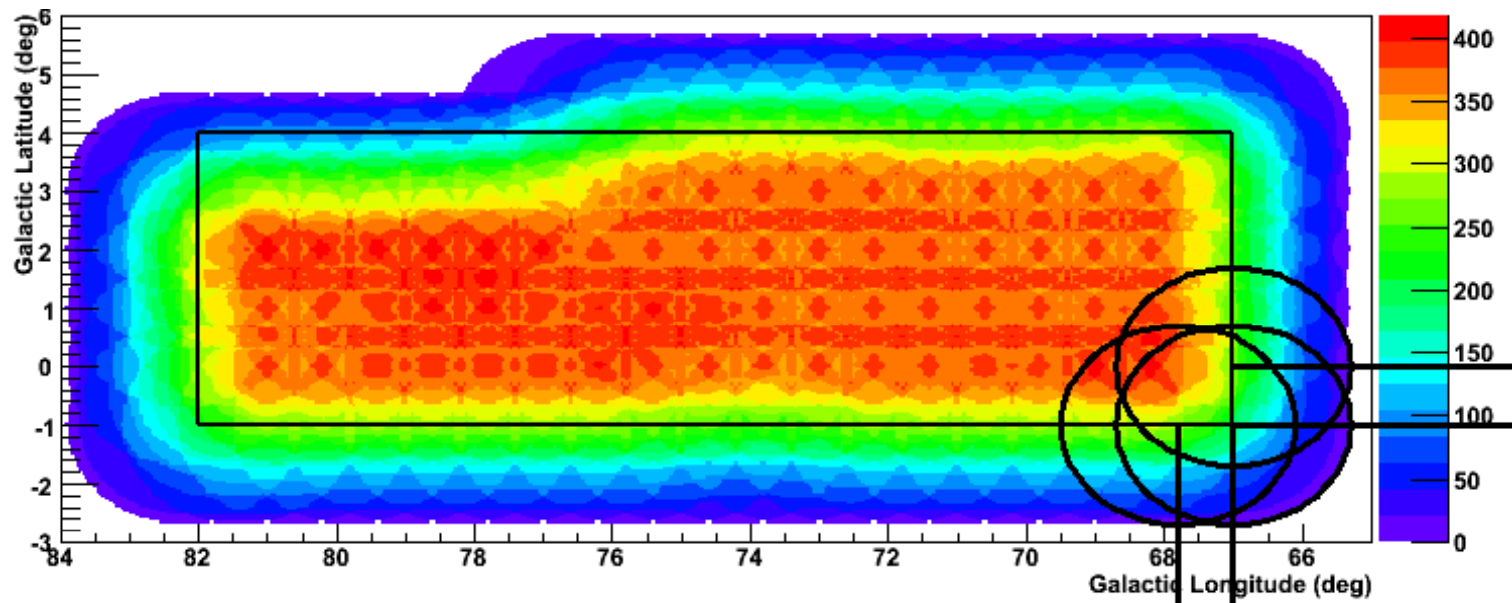


“Discovery of Gamma-ray Emission from a Starburst Galaxy,”  
Acciari et al., submitted to Nature.



# Highlight: Galactic Plane Survey

ICRC Talk: A. Weinstein OG 2.2 (#0665)



## ❑ VERITAS Survey of Cygnus Region

- 2007-09, 112 h (base survey) + 32 h (follow-up).
- Data at various zeniths and using 3,4-telescope configuration.
- Grid pointings covering  $67^\circ < l < 82^\circ$ ,  $-1^\circ < b < 4^\circ$
- Analysis using 4 pre-defined cuts (hard/soft, pt src./extended).



# Highlight: Galactic Plane Survey

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## □ Sensitivity Estimate

- Comes from injecting simulated  $\gamma$ -rays into background survey fields taken from data.
- Depends on specific analysis.

## □ New Result (Preliminary):

- **No sources  $> 5.0\sigma$  (post-trials) in the base survey.**  
→ **Limits (99% CL)  $< 3\%$  Crab (pt. src),  $< 8.5\%$  Crab (ext) at 200 GeV.**

**VERITAS survey is much deeper than previous work (HEGRA).**

- **Cygnus region is qualitatively different than S. Hemisphere (H.E.S.S. survey saw 12 sources above 5% Crab).**
- Work is continuing.  
Correlation with Fermi-LAT & Milagro data will be valuable.



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# Extragalactic Sources



# Extragalactic Sources

## ❑ Active Galactic Nuclei

- BH accretion powers relativistic jet & VHE particle acceleration.
- Science goals: emission mech., jet physics, BH accretion, etc.

## ❑ Blazars

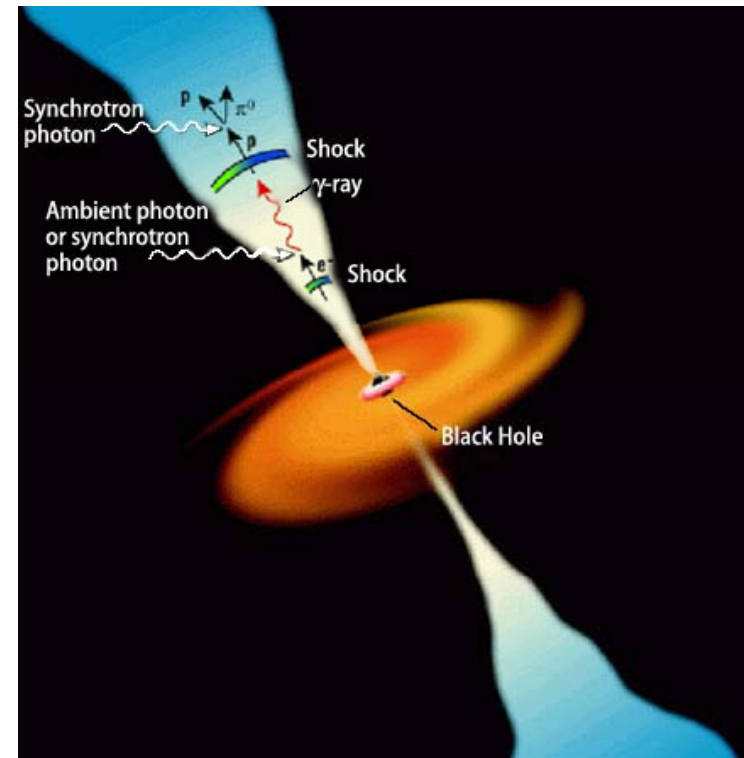
- Dominant VHE extragalactic source class (so far).
- “Double-peaked” SED. Simultaneous MWL data crucial.
- Probe EBL from spectra via:  
$$\gamma_{\text{VHE}} + \gamma_{\text{EBL}} \rightarrow e^+ e^-$$

## ❑ Radio Galaxies: M87, Cen-A

- Closer, so structure can be better resolved.

## ❑ Gamma-Ray Bursts (GRBs)

- Most powerful  $\gamma$ -ray events known.



## ❑ Starburst Galaxies



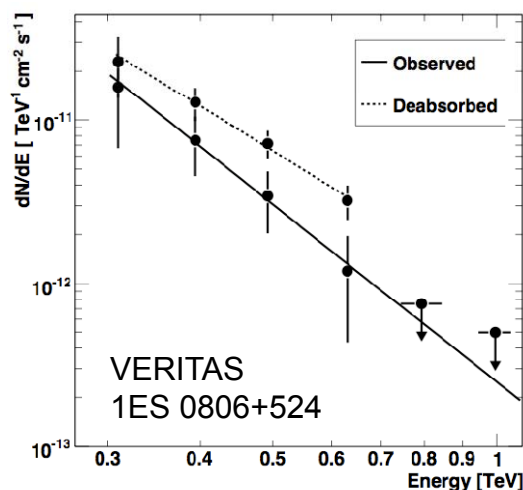
# VERITAS Blazar Program

## □ Strategy and Results

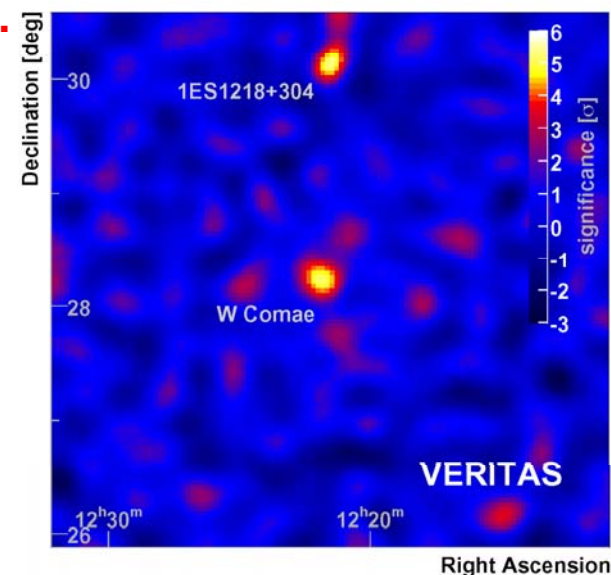
- 1/3 Discovery  
1/3 MWL Campaigns,  
1/3 ToO's
- 49 Blazars observed, so far.
- **11 Detections, 5 Discoveries. New LBL's and IBL's.**
- Comprehensive results in other talks and posters.

ICRC Talk: J. Perkins OG 2.3 (#0490)

ICRC Poster: W. Benbow OG 2.3 (#0655)



VERITAS  
1ES 0806+524  
HBL ( $z=0.138$ ), weak source  $\sim 2\%$  Crab.  
**VERITAS Discovery, ApJ 690, L13**



W Comae: IBL ( $z=0.102$ )  
**VERITAS Discovery, ApJ 684, L73**

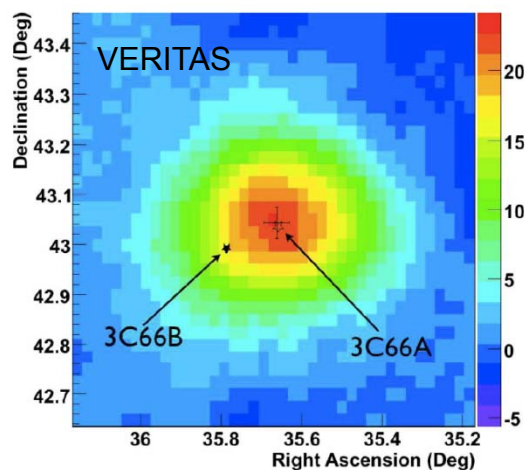
1ES 1218+304: HBL ( $z=0.182$ ), ApJ 695, 1370



# Highlight: 3C 66A

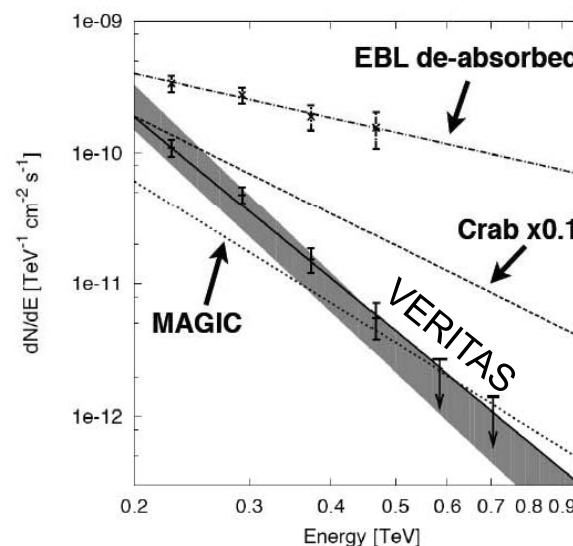
## □ 3C 66A

- IBL at nominal  $z=0.44$ .
- **VERITAS flare discovery, 2008**  
 **$21\sigma$ , 33h,  $E_{th} \sim 120$  GeV.**  
**(ATEL #1753, ApJ 693, L104).**
- Soft spectrum:  $\Gamma = 4.1 \pm 0.4_{stat} \pm 0.6_{sys}$   
(due to EBL ?) .
- Fermi-LAT detection (ATEL #1759).  
Joint Fermi-VERITAS study;  
SSC model disfavored (see L. Reyes' talk).



ICRC Talk: J. Perkins OG 2.3 (#0490)

ICRC Talk: L. Reyes OG 2.3 (#0637)



- MAGIC reported 3C66B  $0.12^\circ$  away.  
 $5.4\sigma$  in 54 h from 2007 data.
- VERITAS data excludes 3C66B at  $4.3\sigma$ .

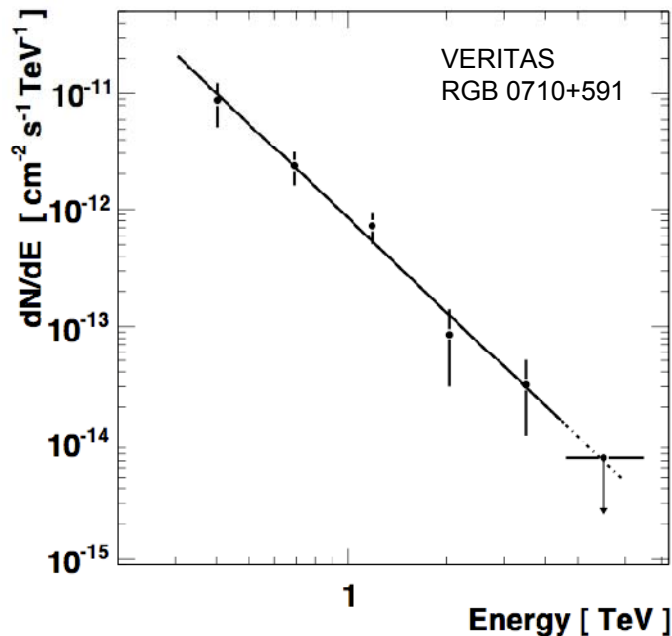




# Highlight: Two New Blazars

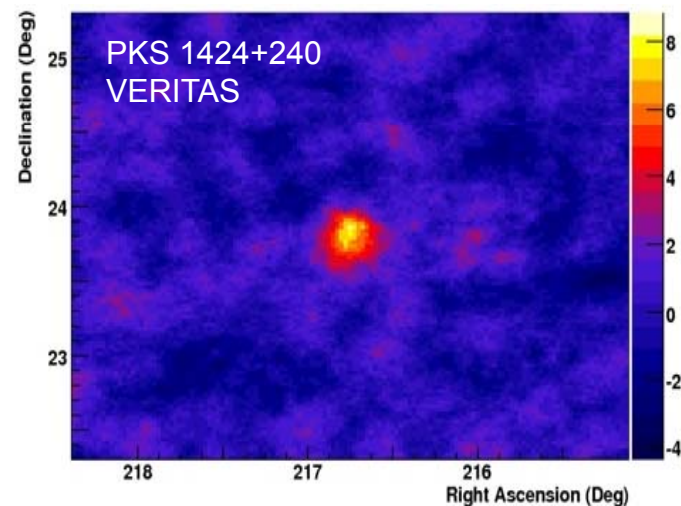
## RGB 0710+591

- HBL at  $z = 0.125$ .
- **5.5 $\sigma$  discovery in 2009 from 22h (ATEL #1941).**
- Hard spectrum will contain EBL.
- MWL SED modeling (w. Fermi-LAT).



## PKS 1424+240

- IBL at  $z = 0.16$ .
- Detected by Fermi-LAT (Abdo et al. 2009).
- **VHE discovery by VERITAS (ATEL #2084). 7.5 $\sigma$  in full data set. MAGIC detection (ATEL #2098).**
- 1<sup>st</sup> VHE discovery motivated by Fermi !



ICRC Talk: J. Perkins OG 2.3 (#0490)

# M 87: A Beautiful Laboratory



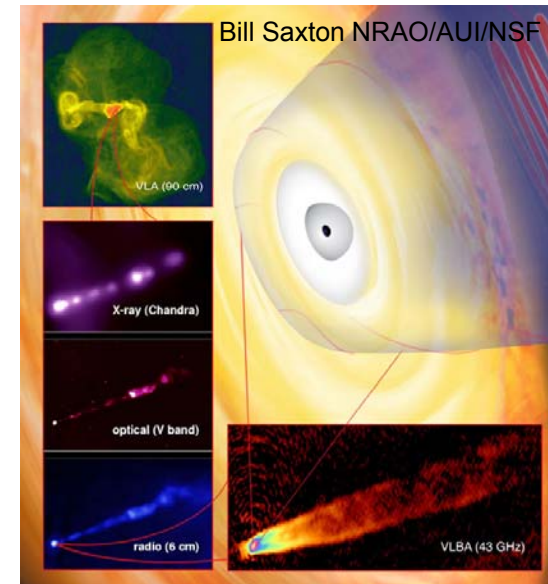
## □ M87

- Giant radio galaxy in Virgo ( $z = 0.004$ ).
- Misalignment and distance allow jet to be imaged in radio, optical and X-ray.
- After first detection by HEGRA, M87 is now well studied by major TeV  $\gamma$ -ray telescopes.

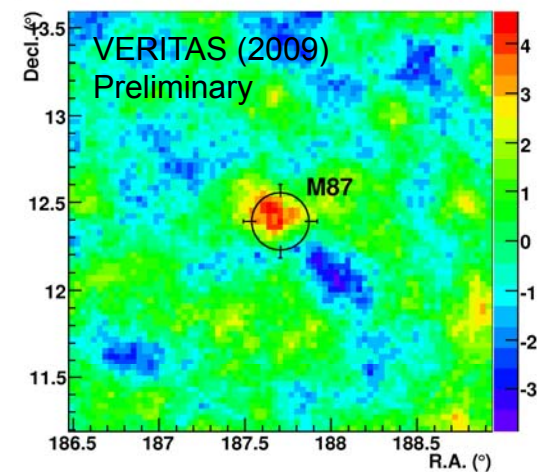
## □ VERITAS observations

- 2007: detected at  $\sim 2\%$  Crab, no variability.
- 2008: joint campaign with MAGIC, H.E.S.S. TeV flaring correlated with radio emission (VLBA) from M87 core. See talk by D. Mazin (MAGIC), OG 2.3 (#1254).
- 2009: source appears to be weaker, Marginal detection with 21 h data.

ICRC Talk: M. Hui OG 2.3 (#1254)



Significance



# GRBs

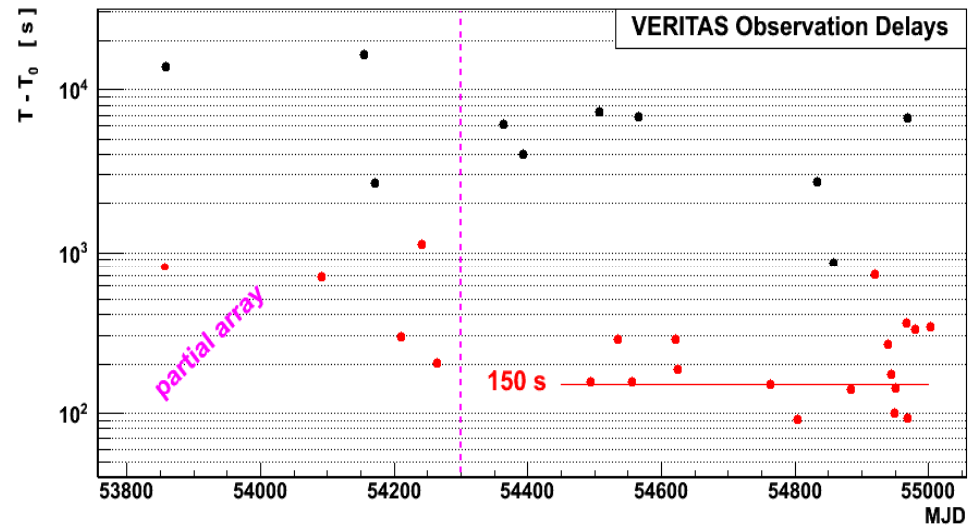


## GRBs

- Most powerful explosions known. Complex acceleration mechanisms, possibly involving shocks in a relativistic jet.
- VHE emission not yet detected (EGRET/Fermi see 10's GeV  $\gamma$ -rays).

## VERITAS observations

- 31 GRBs observed since 2006.  
**No Detections.**
- Rapid response time allows for observations during delay emission phase of GRB.
- Improved sensitivity and energy threshold with upgraded VERITAS.



VERITAS GRB Observations  
(red= GRBs immediately observable)

ICRC Talk: N. Galante OG 2.4 (#0772)



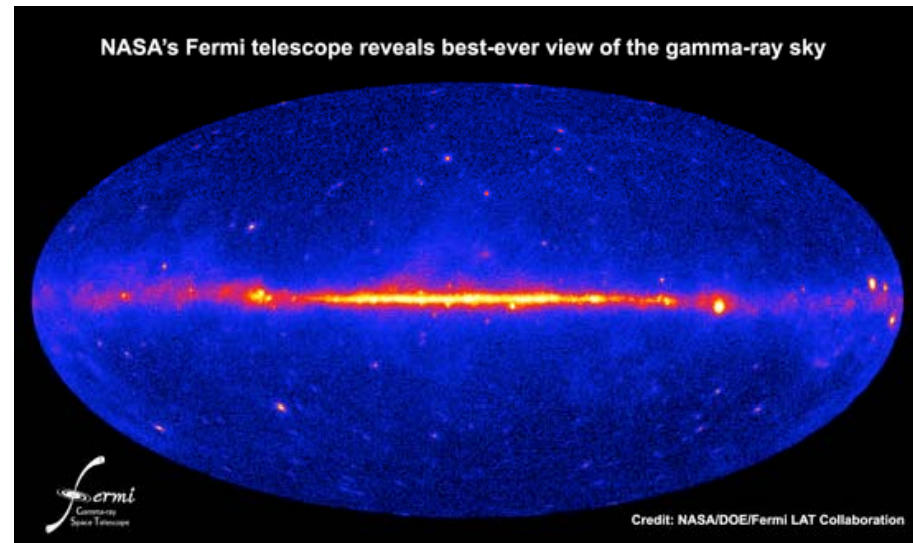
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# Galactic Sources

# VHE Galactic Sources



- Galactic plane is rich in  $\gamma$ -ray emission:
  - 90% photons seen at GeV energies.
  - Variety of VHE sources in 4 classes:
    - Pulsars/PWN
    - SNRs
    - Binaries
    - Unidentifieds
  - Probe acceleration of e, p in shock fronts, colliding winds, superbubbles, etc.  
**Hope to pin down CR Origin (at last!).**



## VERITAS Results at ICRC 2009

- Wide range of galactic source observations:
  - Galactic plane survey
  - SNRs & PWN (Key Science Project)
  - Binaries, Unid's, Magnetars, FVW objects, etc.

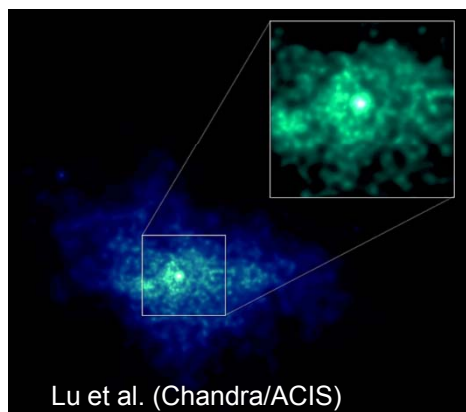
ICRC Poster:  
B. Humensky OG 2.2 (#1490)

**Here we report on new detections of four Galactic sources.**



# Highlight: G54.1 +0.3 (PWN)

ICRC Talk: S. Wakely, OG 2.2 (#0457)

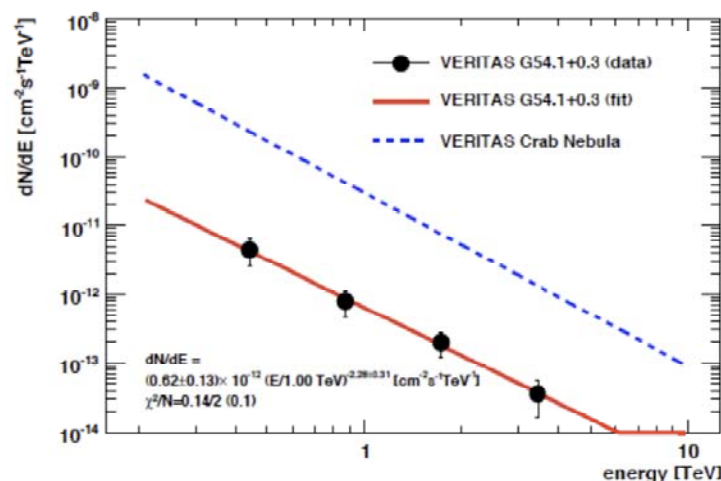
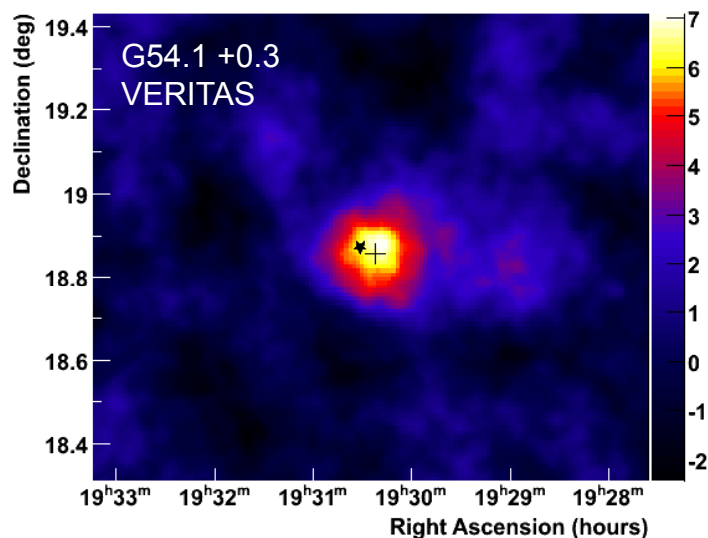


## □ G54.1 +0.3 (PSR J1930 +1852)

- Similar to Crab; X-ray jet and torus.
- $\dot{E} \sim 10^{37}$  erg/s, age  $\sim 3$  ky.
- Nearby molecular cloud.

## □ VERITAS Detection

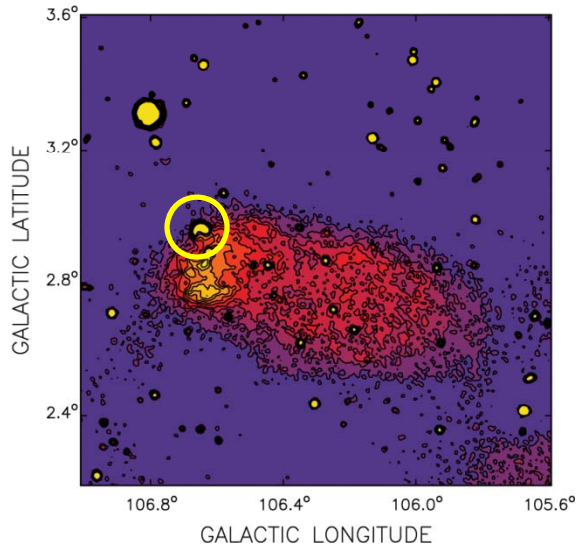
- 31 h,  $7.0\sigma$  detection,  $\sim 3\%$  Crab ( $E > 1$  TeV).
- Consistent with pt. src. at pulsar location.
- $\Gamma = 2.3 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$  (preliminary)



# Highlight: G106.3 +2.7 (“Boomerang”)

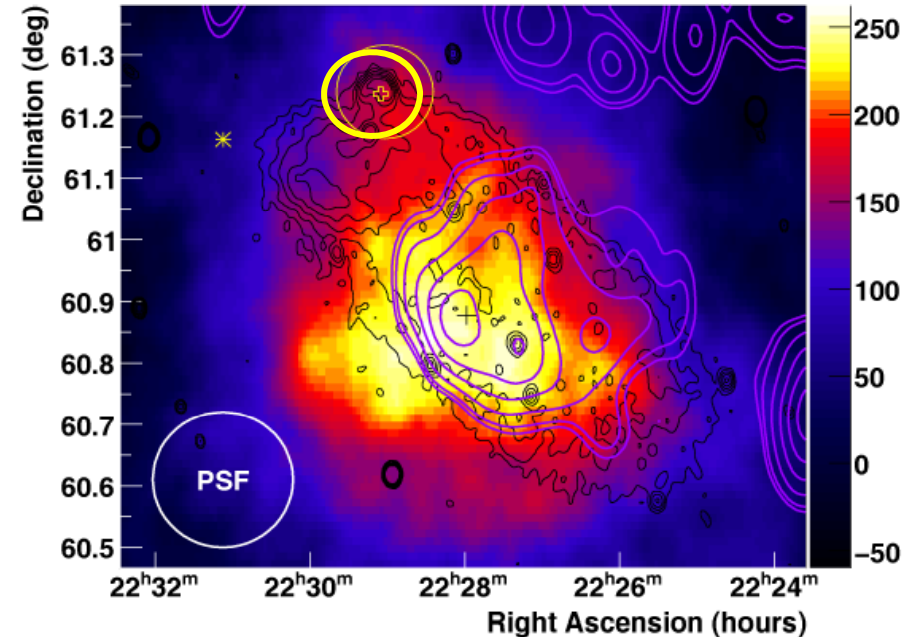


ICRC Talk: S. Wakely, OG 2.2 (#0457)



## □ G106.3 +2.7

- Energetic pulsar PSR J2229+6114 and SNR/PWN with  $\dot{E} \sim 2 \times 10^{37}$  erg/s, age  $\sim 10$  ky.
- 3EG J2227+6112 error ellipse. Fermi-LAT source J2229.0+6114.
- Milagro reports  $> 10$  TeV emission from region (Abdo et al., 2009).



## □ VERITAS Results

(V. A. Acciari et al., sub. to *Astrophys. J.*, 2009)  
( $E > 1$  TeV)

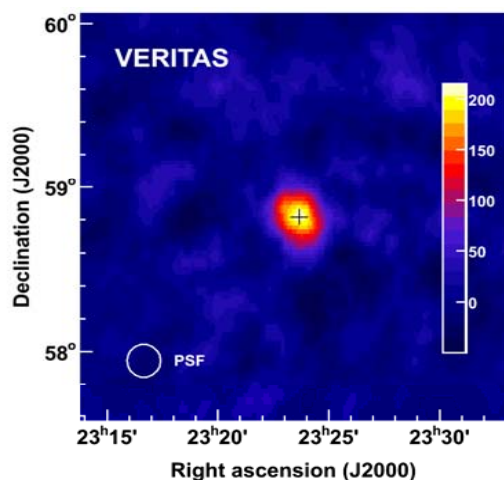
- 33 h data in 2008,  $6.0\sigma$ ,  $\sim 5\%$  Crab.
- Clearly extended, peak overlaps CO.
- $\Gamma = 2.3 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$ , consistent w. power-law to 35 TeV.

**Hadronic Origin ?**



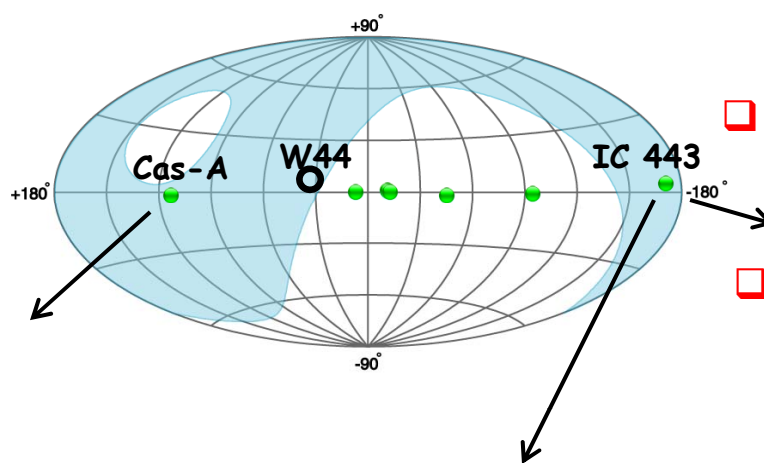
# SNRs ICR 443 & Cas-A

ICRC Talk: B. Humensky  
OG 2.2 (#1489)



## VERITAS Cas-A Detection

- 22h,  $8.3\sigma$  in 2007.
- 3.5% Crab, power-law  
 $\Gamma = 2.61 \pm 0.24_{\text{stat}} \pm 0.20_{\text{sys}}$
- No evidence for cut-off.

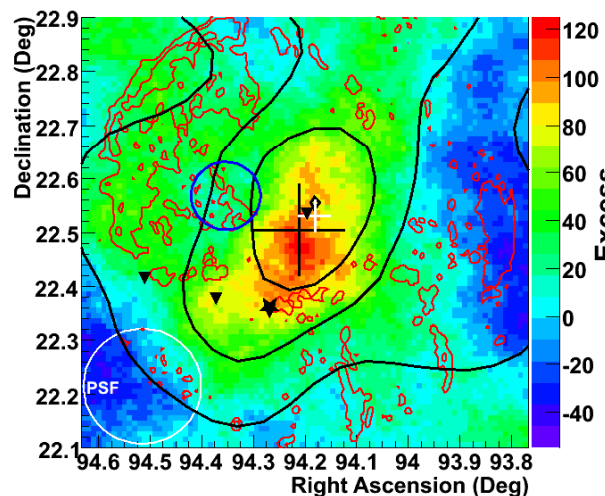


## IC 443

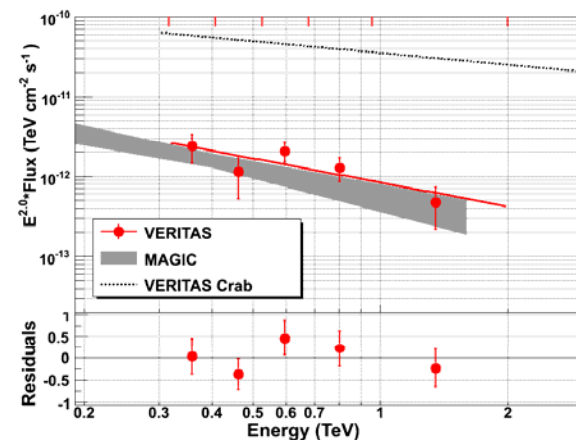
- Co-discovery in 2007

## Latest Results

- 37h,  $8.2\sigma$ , 3.2% Crab.
- Clear extension overlap with CO (molecular cloud).
- $\Gamma = 2.99 \pm 0.38_{\text{stat}} \pm 0.30_{\text{sys}}$



Acciari et al. ApJ 698, L133



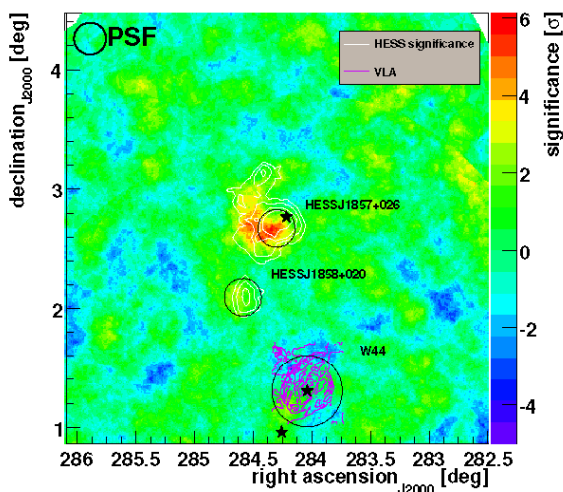




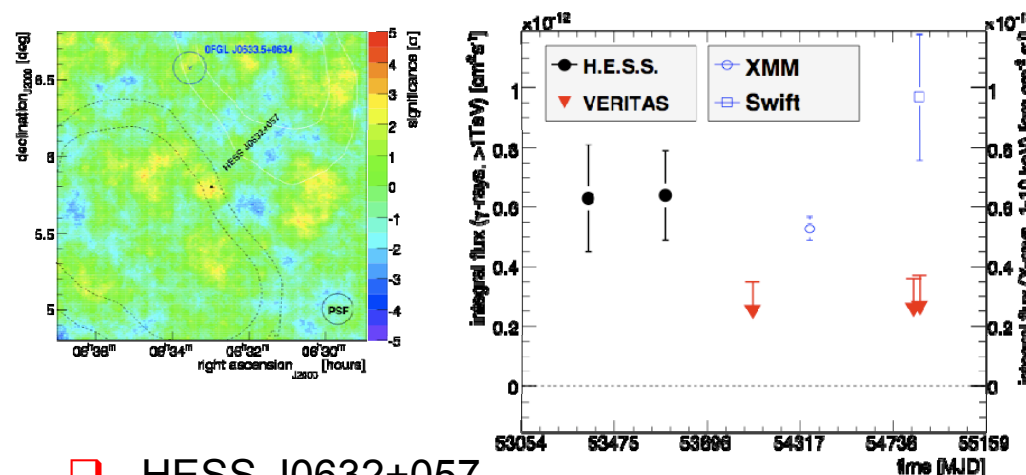
# A Tale of Two Unidentifieds

## W44 Region

- SNR long a candidate for TeV emission.
- H.E.S.S. detected two unid. sources in the region, but not W44.



## ICRC Talk: G. Maier, OG 2.2 (#0512)



## HESS J0632+057

- Discovered by H.E.S.S. @ ~ 3% Crab Unidentified consistent with pt. source. Region of Monoceros Loop and Rosette Nebula.
- Postulated as new  $\gamma$ -ray binary (Hinton et al., 2008).

## VERITAS Observations, ~30hrs over 3 years

- No emission detected, excludes steady HESS at > 99.99% CL.

New TeV binary or a new source class ?

## VERITAS Results, 13h in 2008

- Detection of HESS J1857+026, comparable spectrum and position.
- Marginal excess at HESS J1858+020; Limit at W44 < 2.0% Crab (> 300 GeV)

ICRC Talk: S. Bugaev, OG 2.2 (#0791)



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## Other Science Results

# Dark Matter Searches



ICRC Talk: R. Wagner, HE 2.3 (#0625)

## □ Dark Matter (DM)

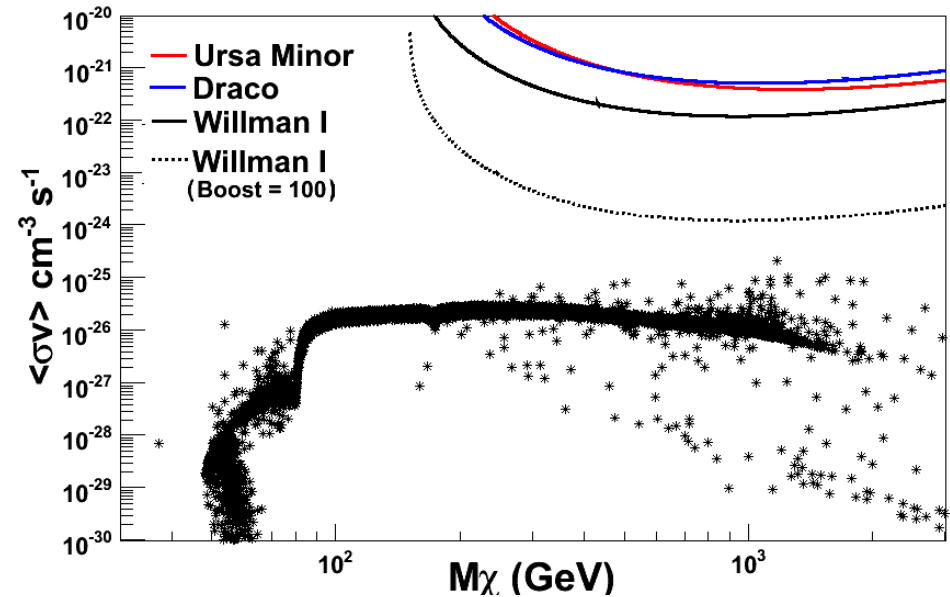
- A major scientific puzzle, inferred from a variety of measurements.
- Particle DM candidates (SUSY, KK)  
→ unique HE  $\gamma$ -ray signatures.

## □ VERITAS DM Program

- Comprehensive program, ~ 7% of observing time, variety of classes:

Dwarf Galaxies (e.g. Draco...)  
Local Galaxies (e.g. M32, M33)  
Globular Clusters (e.g. M5)  
Galaxy Clusters (e.g. Coma)

- **So far, no Detections**  
→ **Limits on 7 candidate sources**



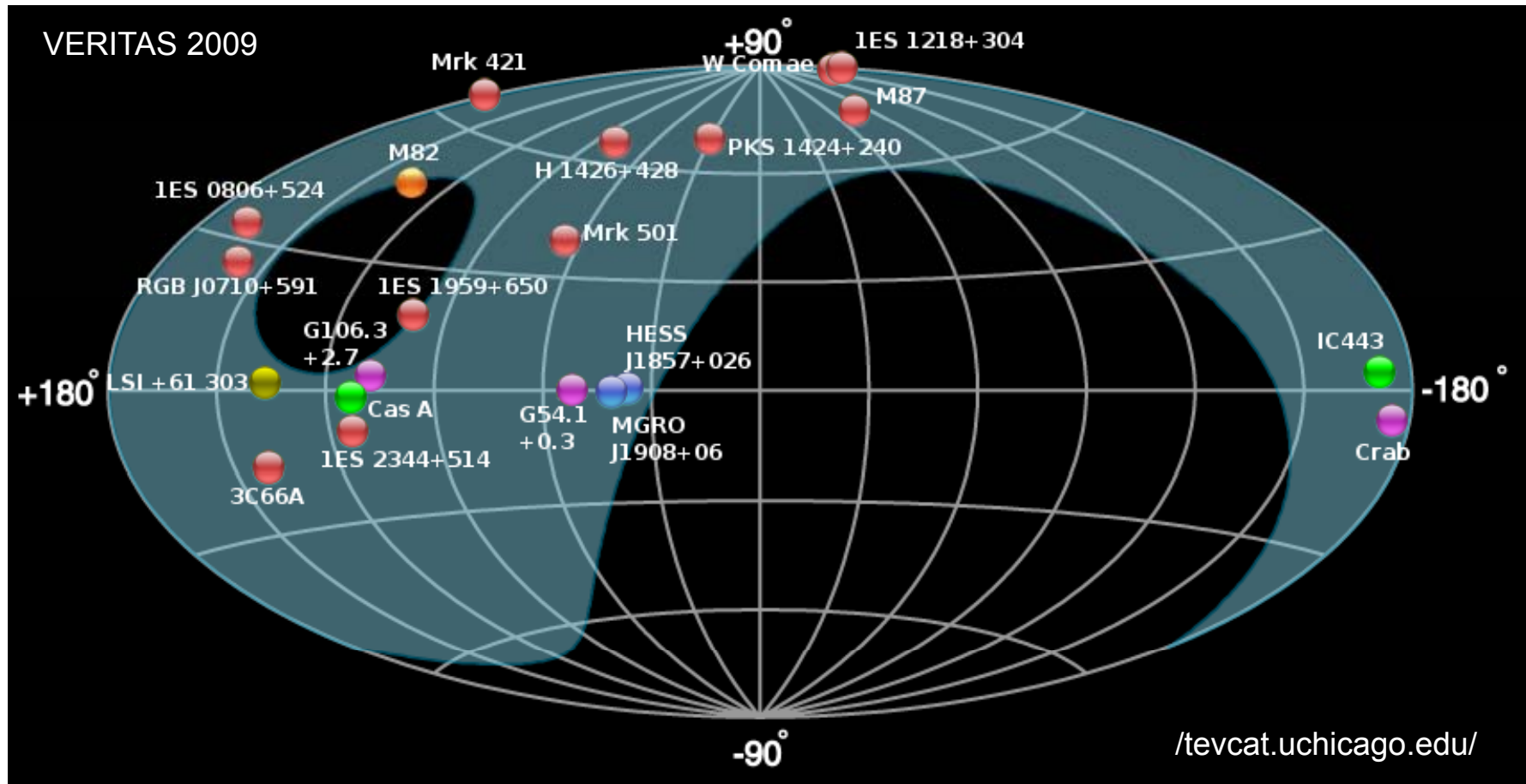
VERITAS limits on dwarf galaxies

# Other VERITAS Results @ ICRC 2009



Presenter	Title	Session	Paper #
<b>Talks:</b>			
J. Grube	Highlights of MWL Observations of VHE Blazars with VERITAS	OG 2.3	0782
J. Holder	VERITAS Observations of LS I +61 303 in the Fermi Era	OG 2.2	1155
A. Imran	VERITAS Discovery of Variability in the VHE gamma-ray Emission of 1ES 1218+304	OG 2.3	0510
D. Mazin (MAGIC)	A First Joint M87 Campaign in 2008 from Radio to TeV $\gamma$ -Rays	OG 2.3	1313
A. Pichel	Highlights from the Whipple 10m Blazar Monitoring Program	OG 2.3	0636
<b>Posters:</b>			
G. Finnegan	Search for TeV Emission from Geminga by VERITAS	OG 2.2	1348
N. Galante	Observation of Radio Galaxies and Clusters of Galaxies with VERITAS	OG 2.3	0774
R. Guenette	VERITAS Observations of X-ray Binaries	OG 2.2	0521
R. Guenette	VERITAS Observations of Magnetars	OG 2.2	0632
J. Holder	VERITAS Observations of a "Forbidden Velocity Wing"	OG 2.2	1157
D. Krannich (MAGIC)	MWL Observations of Mrk 501 in 2008	OG 2.3	
G. Maier	Multiwavelength Observations of a TeV Flare from W Com	OG 2.3	0511
A. McCann	An Alignment System for IACTs	OG 2.7	0650
M. McCutcheon	VERITAS Observations of Globular Clusters	OG 2.2	1316
M. Schroedter	Search for Short Bursts of Gamma Rays above 100 MeV from the Crab using VERITAS and SGARFACE	OG 2.2	1301
M. Schroedter	A Topological Trigger System for IACTs	OG 2.7	1312
R. Wagner (MAGIC)	The June 2008 Flare of Mrk 421 from Optical to TeV Energies	OG 2.3	0926

# VERITAS VHE Sky (July 2009)



21 Source Detections in 6 source classes



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# FUTURE

# VERITAS Upgrade Plans



- ❑ VERITAS operates very well with excellent sensitivity.
- ❑ With the excitement in the field and the unique capabilities of Fermi, we want to improve VERITAS.

Plans to improve the sensitivity and to extend the energy range are ongoing or discussed:

likely in  
this  
order

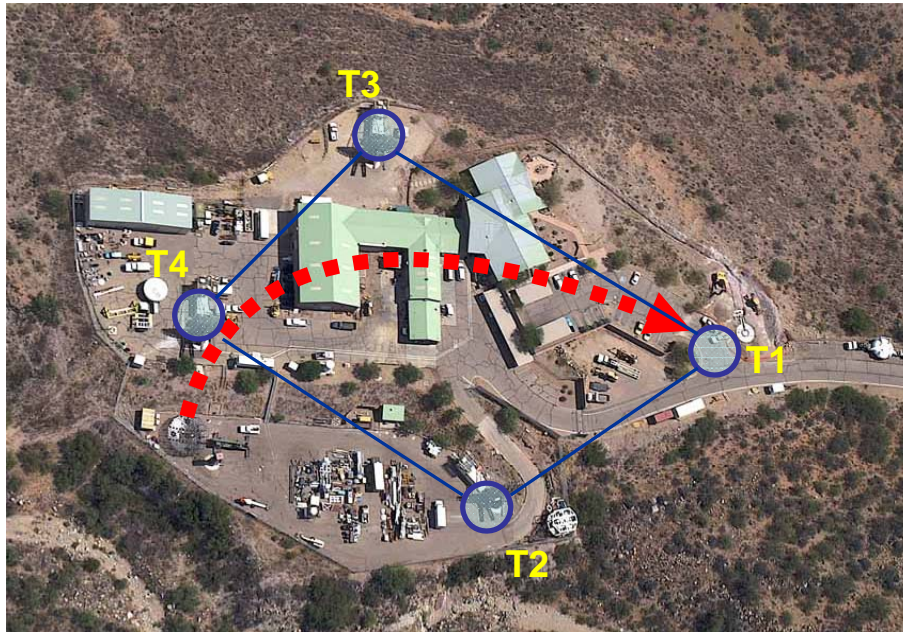
1. Improved optical point spread function - **accomplished**
2. Relocating telescope T1 ← **ongoing**
3. Upgrading cameras with high efficiency PMTs ← **proposed**
4. New trigger system ← **proposed**
5. An automatic mirror alignment system ← **possible in the future**
6. An additional telescope T5 ← **possible in the future**

ICRC Talk: N. Otte, OG 2.7 (#1408)  
Presented by J. Holder

# Telescope 1 Relocation



- ❑ T1 Relocation will significantly improve baseline.



24 June 2009

- ❑ Move is well underway with completion expected by September 2009.
- ❑ Expected improvement in sensitivity ~20% (equivalent to additional ~400 h/year)







# Baseline Upgrade Plan (2009-2011)

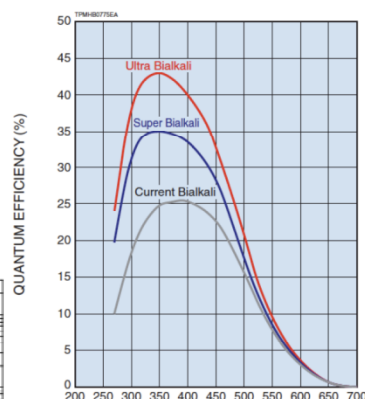
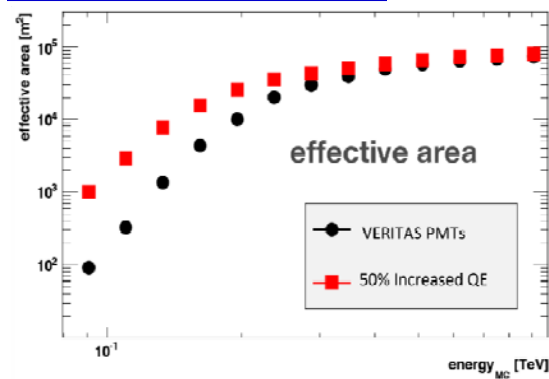
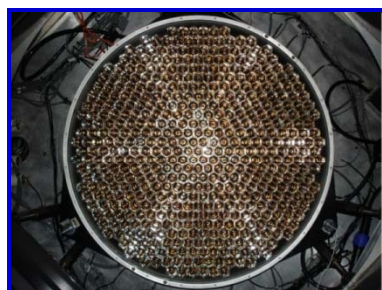
- We plan to replace the PMT cameras and L2 trigger system to significantly improve the sensitivity and energy threshold.

## CAMERA Upgrade

PMT replacement with high efficiency PMTs.

Increase photon collection by ~35%.

Improves background rejection,  $E_{th}$ , sensitivity.

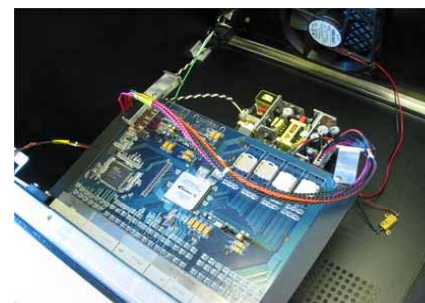
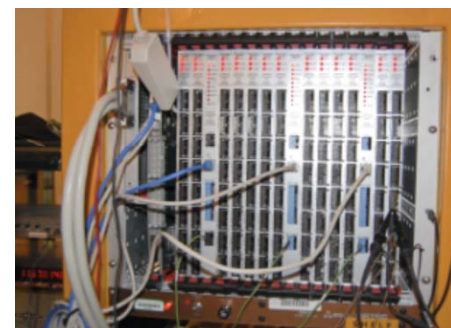


## TRIGGER Upgrade

Smaller coincidence window

Topological Trigger

Improves  $E_{th}$  and CR event rejection.



Prototype  
Trigger  
Systems



# Summary

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- ❑ VERITAS is operating very well (> 95% uptime) with two good years of data in hand.
- ❑ At Merida, we had 31 papers, 16 with science results. At Lodz, we have 34 papers, 31 with science results.
- ❑ Many new results presented here, including:
  - **Discovery of  $\gamma$ -ray emission from starburst galaxy M82.**
  - **Stringent limits from Galactic plane survey.**
  - **Detection of 5 new blazars:**  
**(1ES0806+524, W Com, 3C 66A, RGB 0170+541, PKS 1424+240)**
  - **Correlated radio-TeV emission from M87 (w. MAGIC, HESS).**
  - **Detection of 2 new PWN/SNR: G106.3+2.7, G54.1+0.3.**
  - **Detailed studies of SNRs: IC 443 and Cas-A.**
  - **Limits on Dark Matter annihilation to  $\gamma$ -rays from 7 targets.**
- ❑ VERITAS Upgrade will significantly improve sensitivity.
- ❑ Future will require even closer collaboration and cooperation between major GeV, TeV  $\gamma$ -ray and  $\nu$  telescopes.