Highlights of Gamma-ray Astronomy with VERITAS

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*University of Chicago, ^http://veritas.sao.arizona.edu/conferences/authors?icrc2009

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
Univ. of Chicago
Univ. of Delaware
Univ. of Iowa
Univ. of Massachusetts
Univ. of Utah
Washington Univ.

Canada

McGill Univ.

U.K.

Leeds Univ.

Ireland

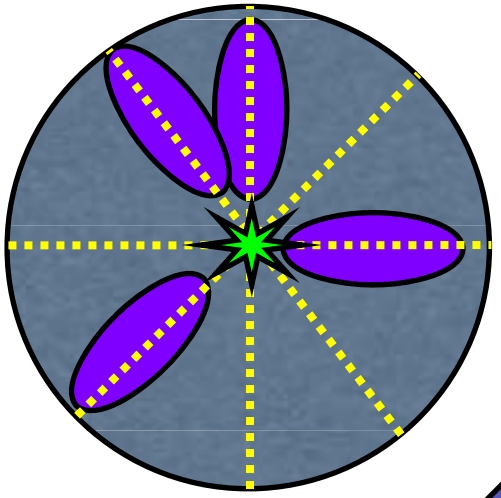
Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
Univ. College Dublin

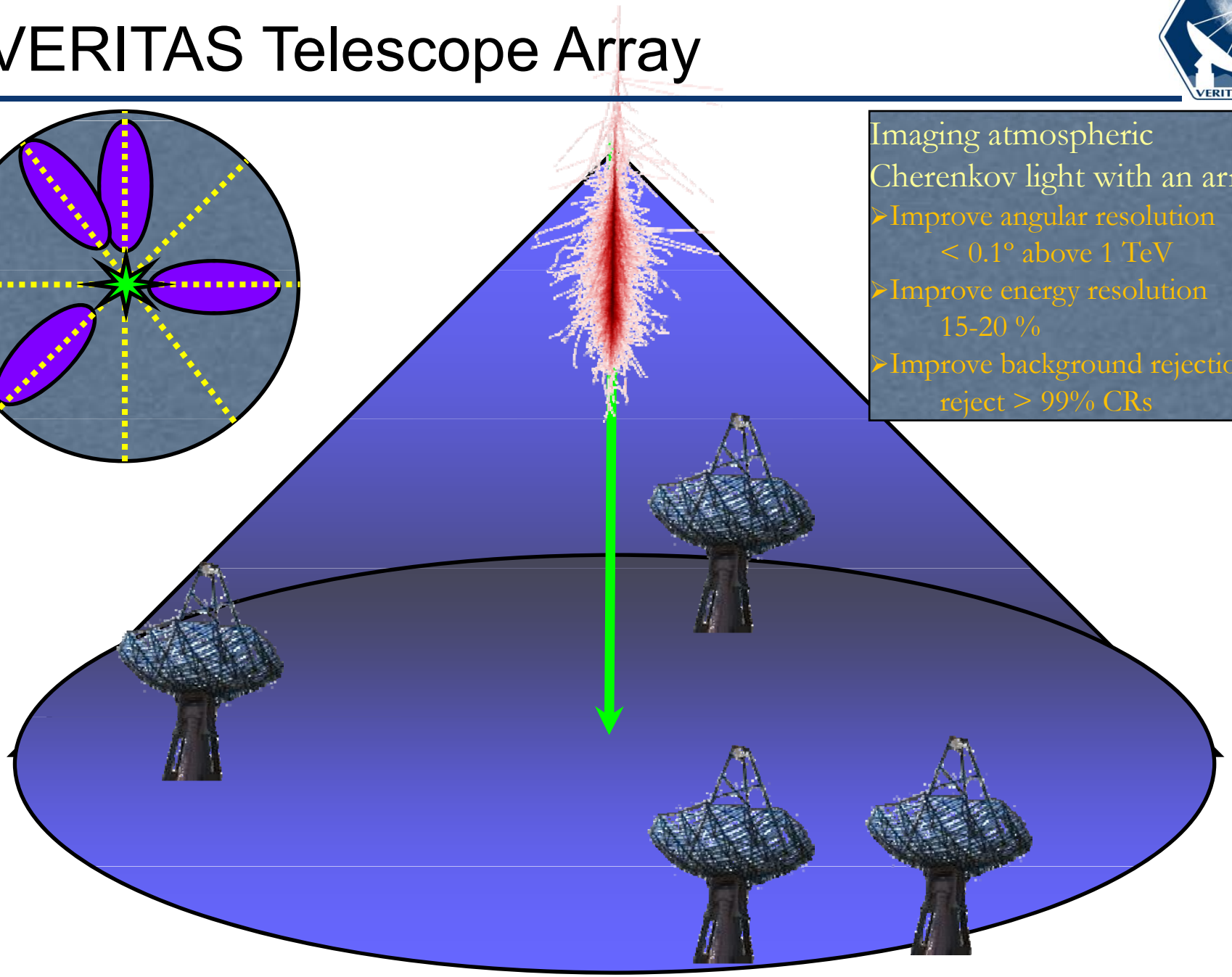
+ 25 Associate Members

Outline

- VERITAS Telescope Array
  - **Layout, technical details, performance**
- Observation Strategy and Summary
- Science:
  - **Starburst Galaxy: M 82**
  - **Galactic Plane Survey**
  - **Extragalactic Source Highlights**
  - **Galactic Source Highlights**
- VERITAS Upgrade Plans

VERITAS Telescope Array

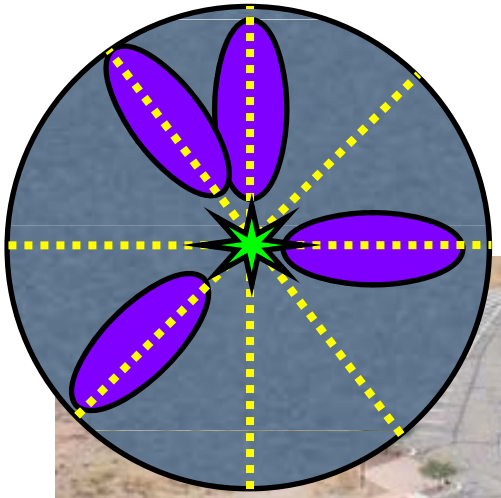


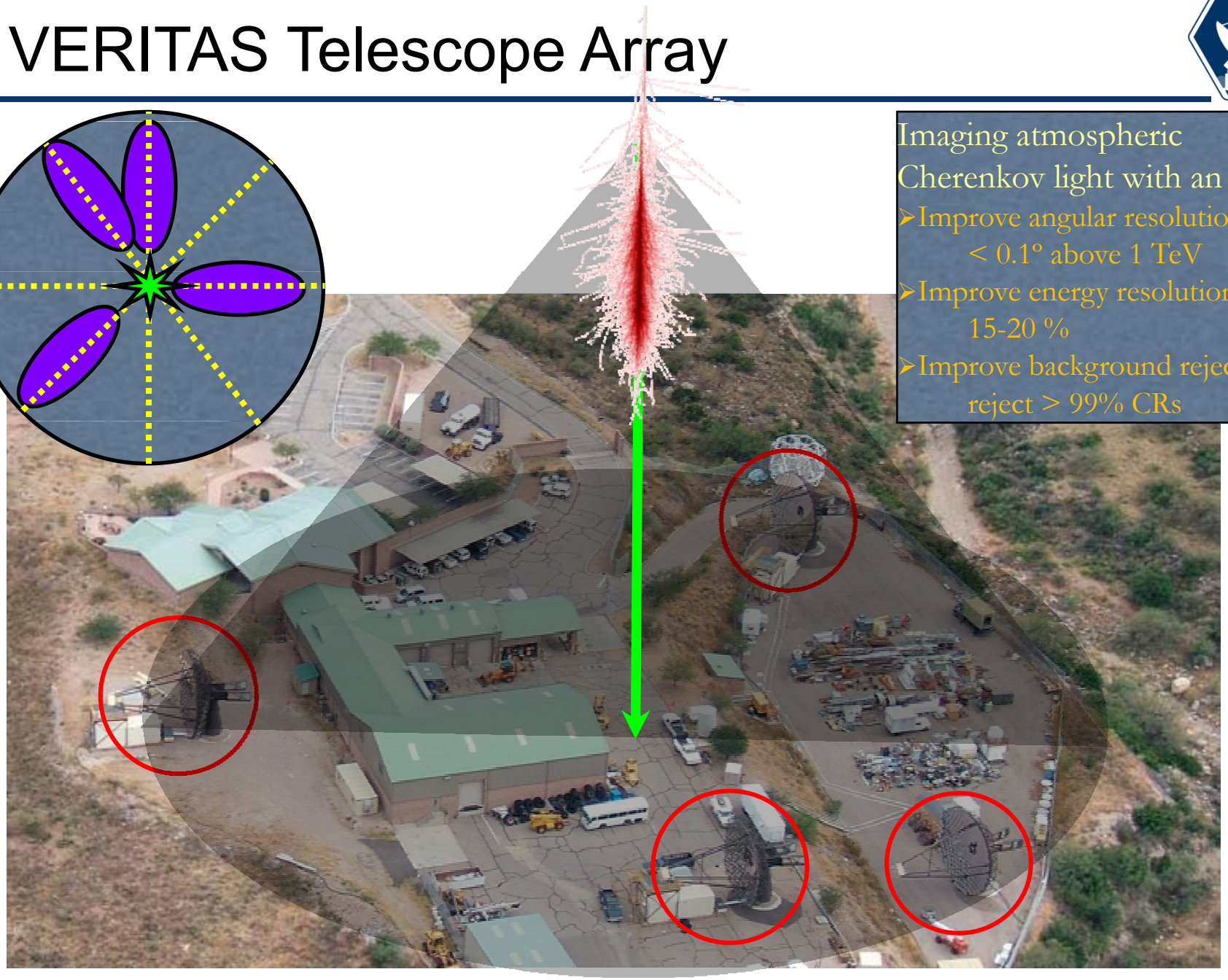


Imaging atmospheric Cherenkov light with an array:

- Improve angular resolution
  < 0.1° above 1 TeV
- Improve energy resolution
  15-20 %
- Improve background rejection
  reject > 99% CRs

VERITAS Telescope Array





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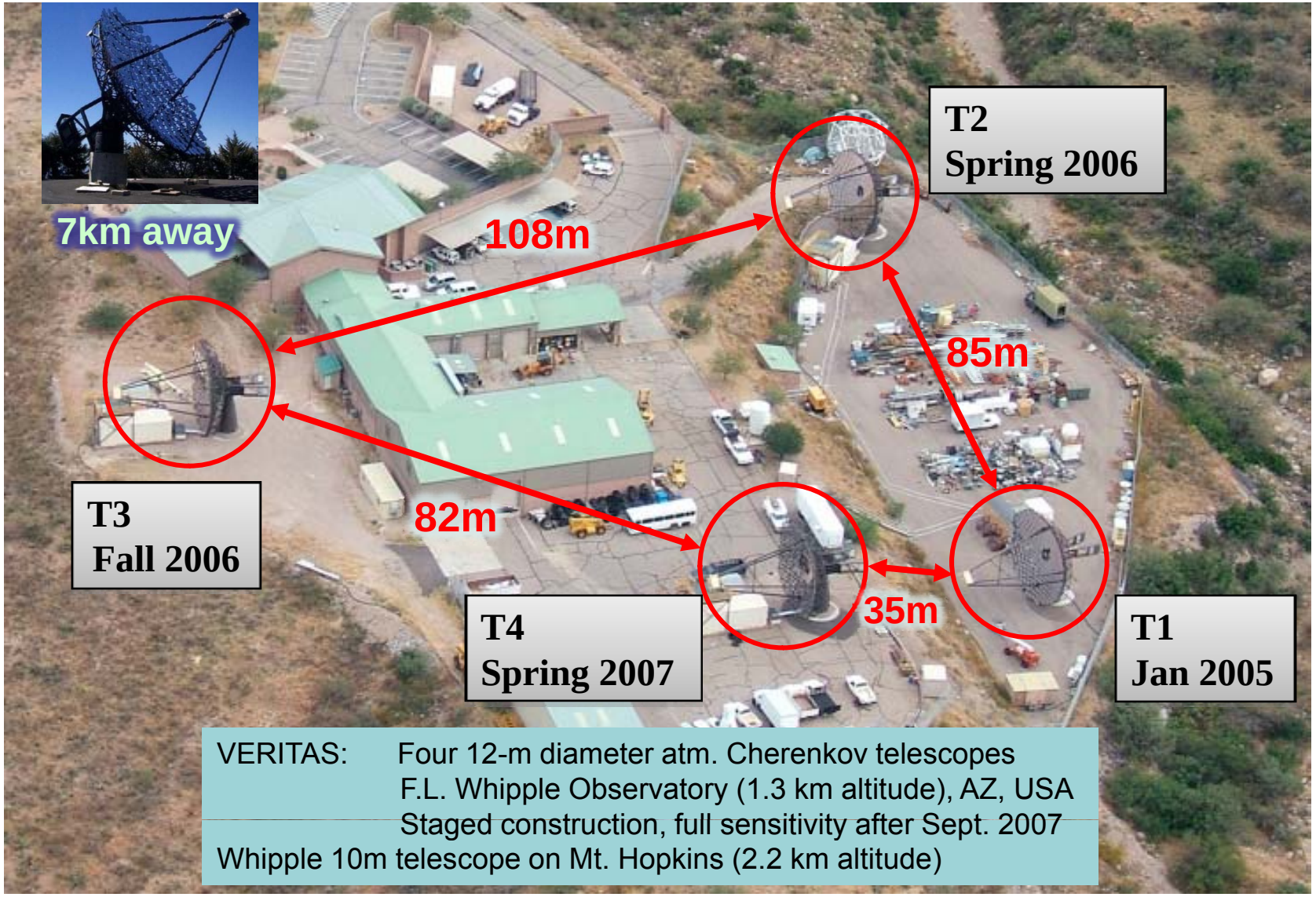
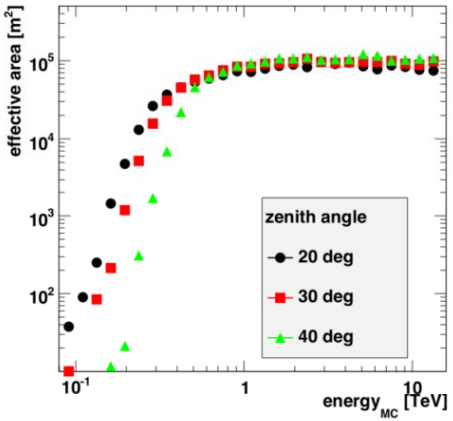
VERITAS Telescope Array



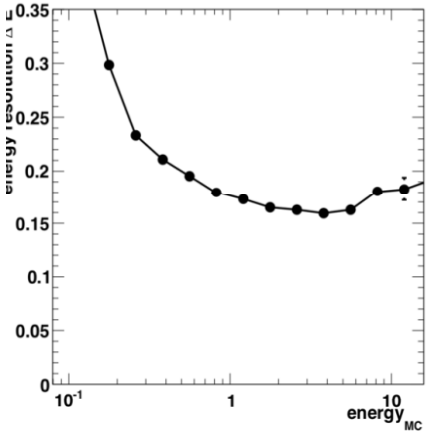
VERITAS: Four 12-m diameter atm. Cherenkov telescopes
F.L. Whipple Observatory (1.3 km altitude), AZ, USA
Staged construction, full sensitivity after Sept. 2007
Whipple 10m telescope on Mt. Hopkins (2.2 km altitude)

VERITAS Performance

- Energy Range: 100 GeV – 30 TeV (spectra >150 GeV)
- Energy Resolution: 15% – 20%



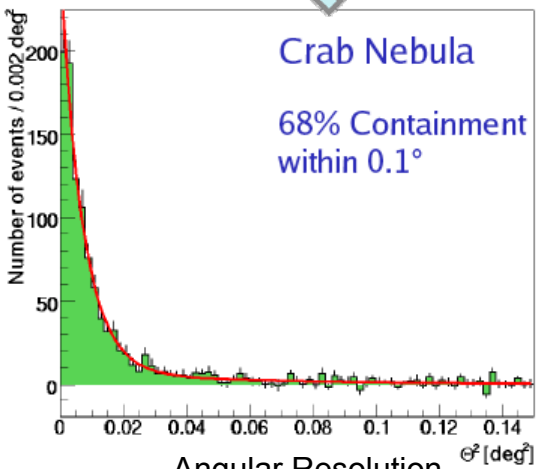
Effective Area (std. cuts)



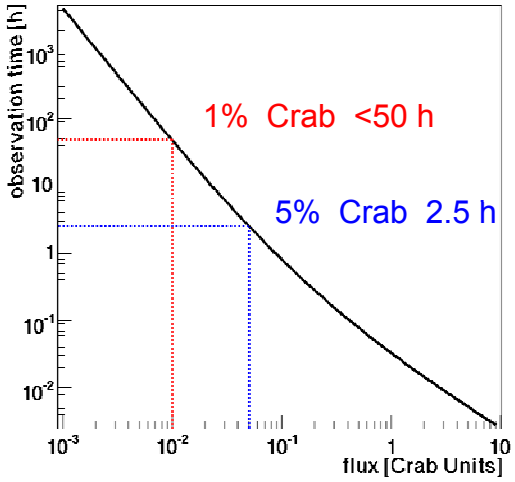
Energy Resolution

- Crab Rate ~ 40 / min (trigger)
- Sensitivity: 5% Crab in < 2.5 h
  1% Crab in < 50 h

- Angular Resolution: r_{68} < 0.1°
- Pointing Accuracy: < 50″



Angular Resolution



Pt. Source Sensitivity

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.

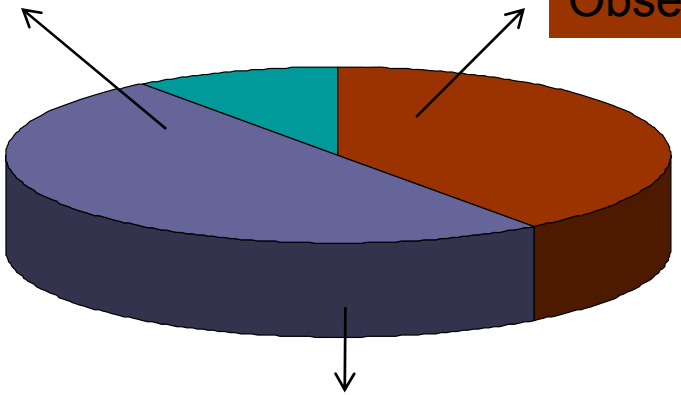
Observation Strategy 2007-09

Discretionary (10%)

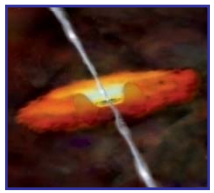
- ToO's, GRBs
- Higher risk sources

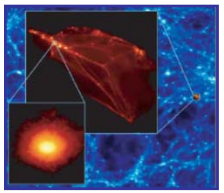
Observing Proposals (40%)

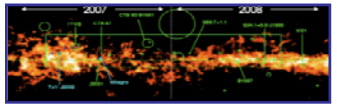
- Science WG's & TAC

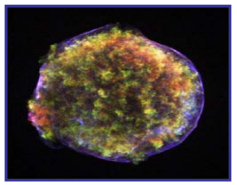


Key Science Projects (50%)


BLAZARS


Dark Matter


Galactic Plane Survey

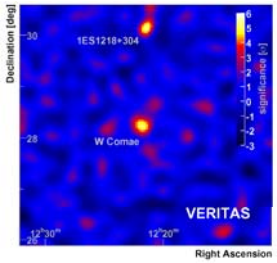

SNRs/PWN

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

VERITAS Science Highlights (so far)

2007:

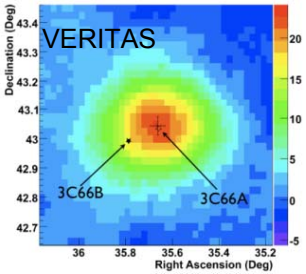
- **Detection of SNR IC 443 (w. MAGIC).**
- Detection of binary LS I +61 303, confirming variability.
- Detection of blazar 1ES 1218+304 and radio galaxy M87.



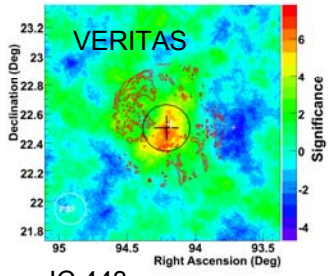
W Comae & 1ES 1218+304

2008:

- 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.**



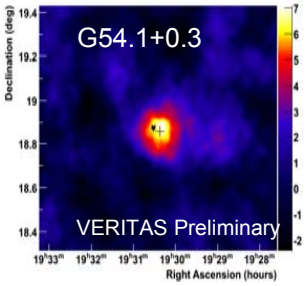
3C 66A

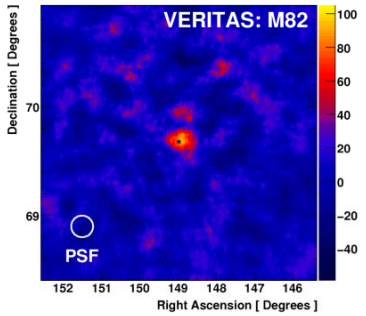


IC 443

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).**
- **Discovery of blazar PKS 1424+240 (ATEL #2084, Fermi trig).**
- 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.
- **Discovery of TeV emission from starburst galaxy M82.**



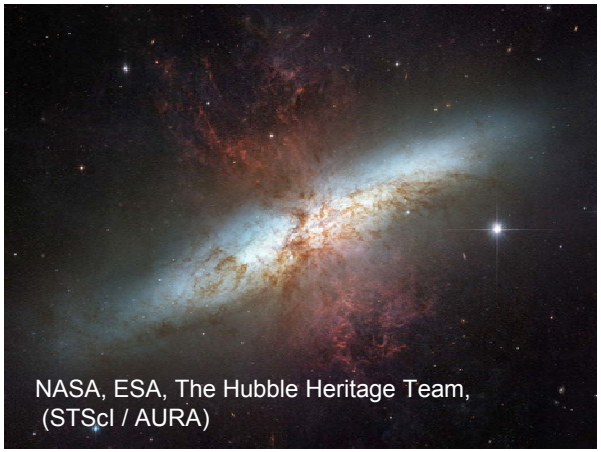


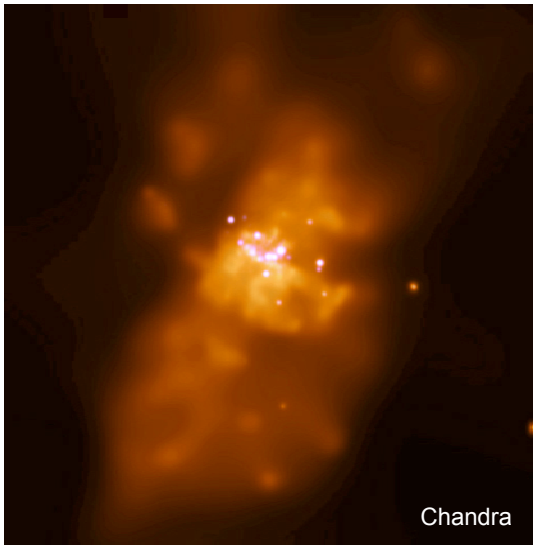
Highlight: Detection of Starburst Galaxy M82

Highlight: Galactic Plane Survey

Highlight: Starburst Galaxy M82

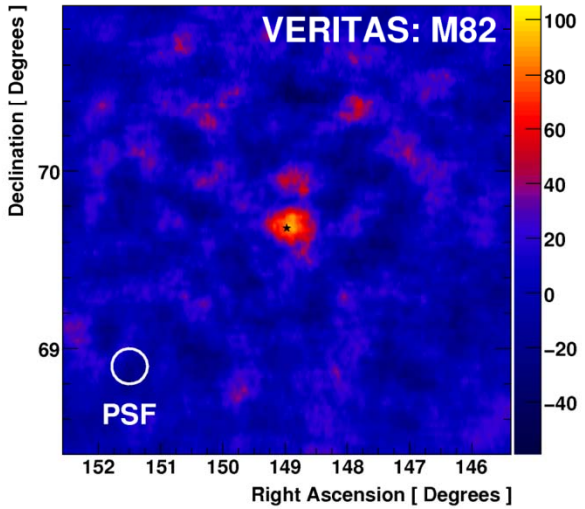
- M82: Prototype starburst galaxy
  - Interacting with group of galaxies over hundreds of Myrs.
  - Tidal forces → active starburst region (HST shows > 200 massive star clusters.
  - SMBH < 3 x 10^7 M_{sun}, no AGN activity.
- Starburst Region
  - High star formation and SNR rate.
  - High CR density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

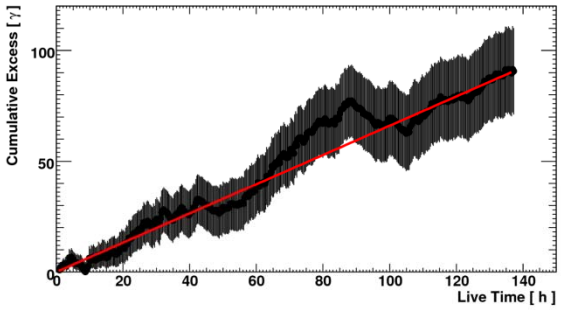




Highlight: Starburst Galaxy M82

- 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 (θ ~ 40º).
- Detection !
  - 5.0 σ excess (pre-trials), 4.8 σ (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 ~0.9% Crab.
- Interpretation
  - **First detection of an extragalactic VHE source not clearly associated with AGN activity.**
  - Consistent with predictions, general nature of CR interactions.



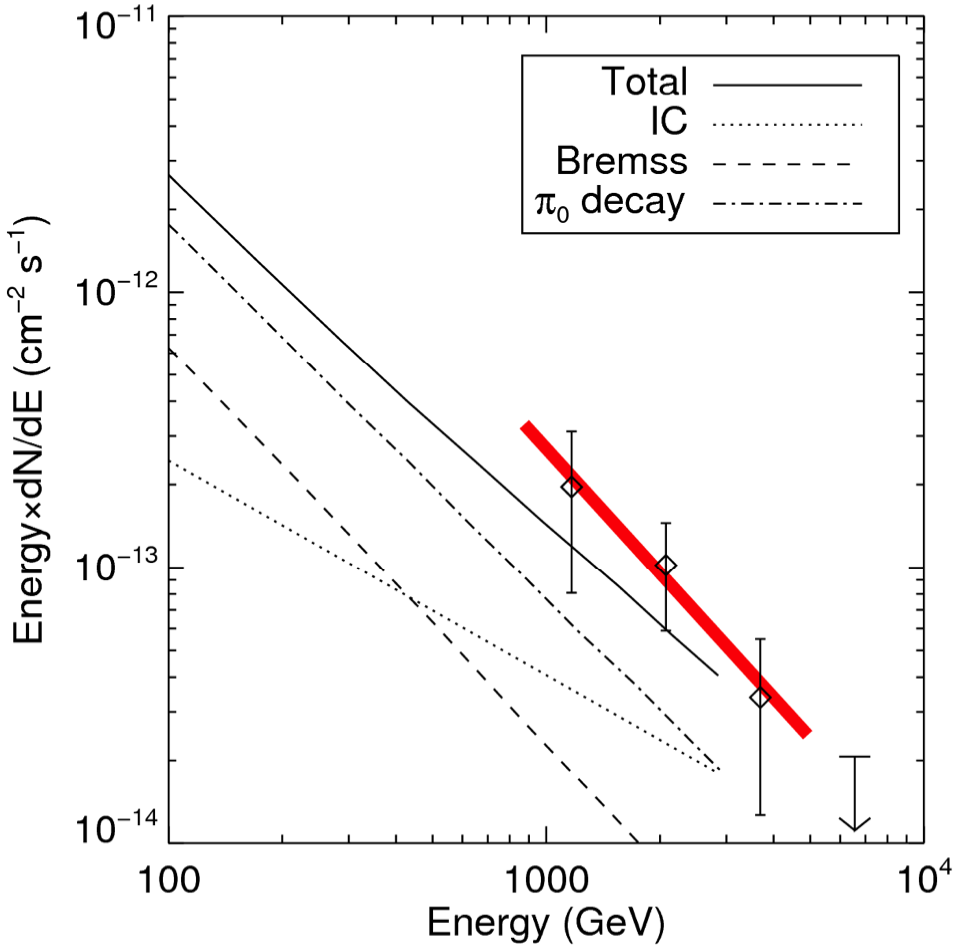


"Discovery of Gamma-ray Emission from a Starburst Galaxy,"
Acciari et al., submitted to Nature.

Highlight: Starburst Galaxy M82

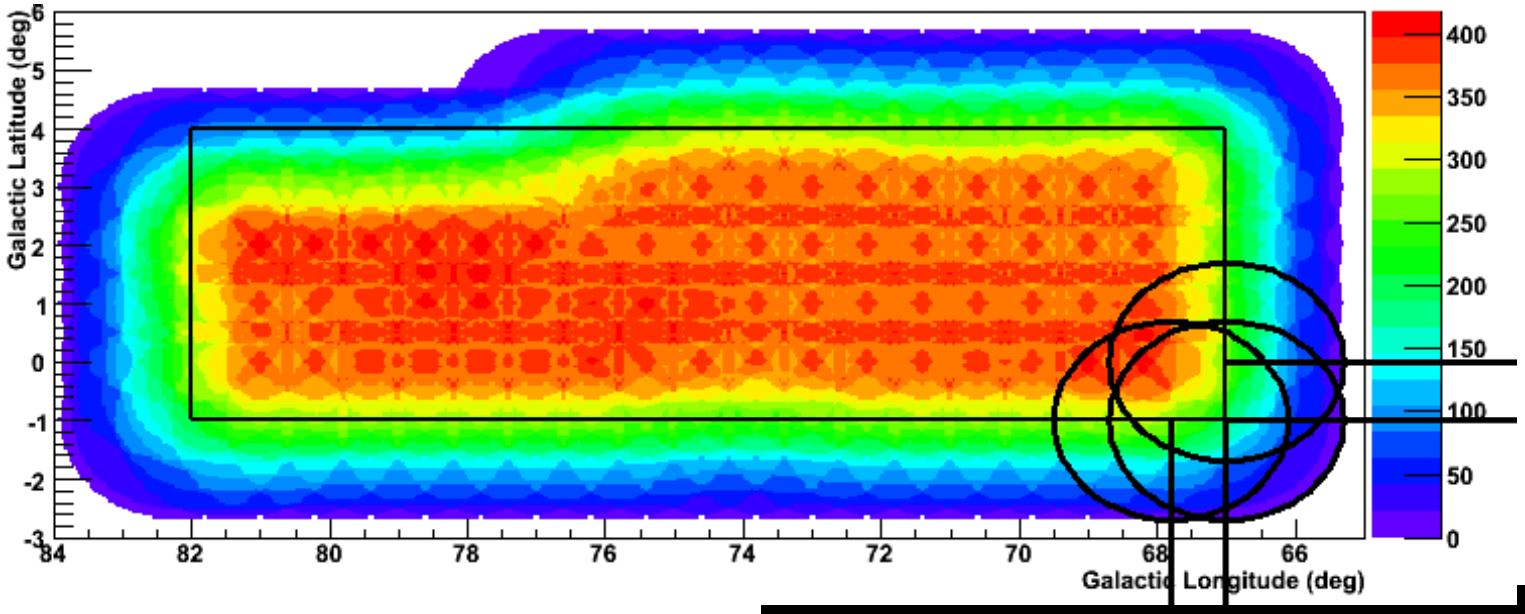
- Fit Range:

  875 GeV to ~5 TeV
  - Fit to dN/dE ~ (E / TeV)$^{-\Gamma}$
  - χ^2 = 0.1, 1 NDF; P($\chi^{2)}$ = 0.7
- Γ= 2.5 ± 0.6
- VHE flux close to predictions
  - Incl. both leptonic & hadronic channels
    - Pohl 1994
    - Völk et al. 1996
    - Persic et al. 2008
    - de Cea del Pozo et al. 2009

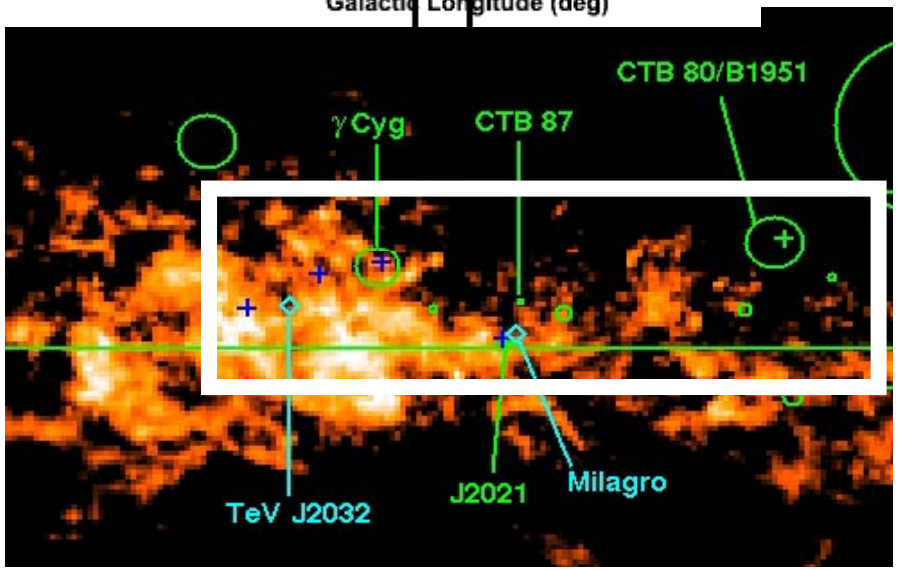


Model of Persic et al. 2008

Highlight: Galactic Plane Survey



- VERITAS Survey of Cygnus Region
  - 2007-09, 112 h (base survey) + 32 h (follow-up).
  - Grid pointings covering $67^o < l < 82^o$, $-1^o < b < 4^o$
  - Region of numerous SNRs, PWNe, XRBs, dense gas, massive stars



Highlight: Galactic Plane Survey

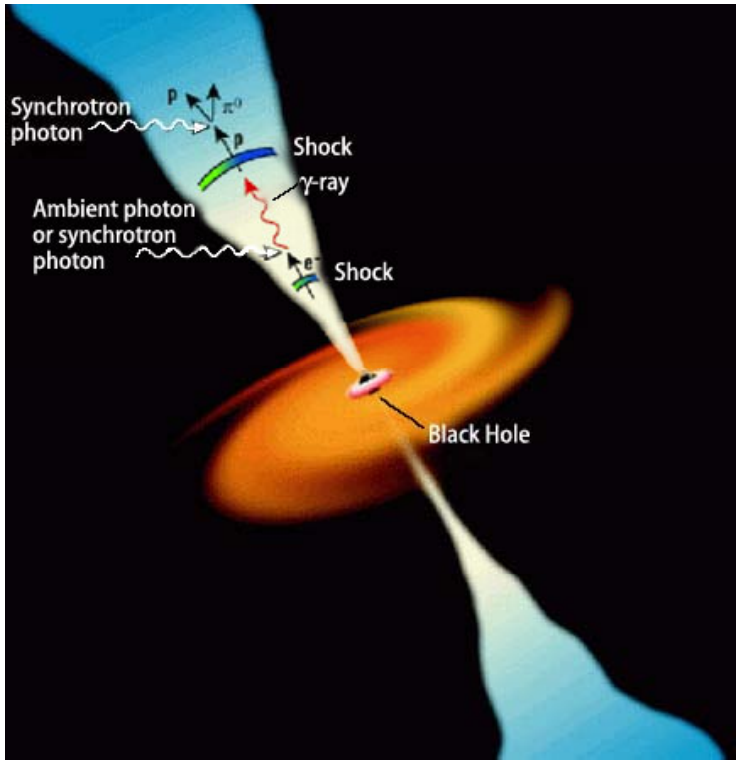
- Sensitivity Estimate
  - Comes from injecting simulated γ-rays into background survey fields taken from data.
    - Blank survey fields for background
    - Spectra between 2.5 and 2.0, varied source extent
  - Estimates are
    - Conservative (zenith angle, configuration variations)
    - Consistent with VERITAS sensitivity curve & "effective" exposure time.
- New Result (Preliminary):
  - **No sources > 5.0σ (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.

Extragalactic Sources

Extragalactic Sources

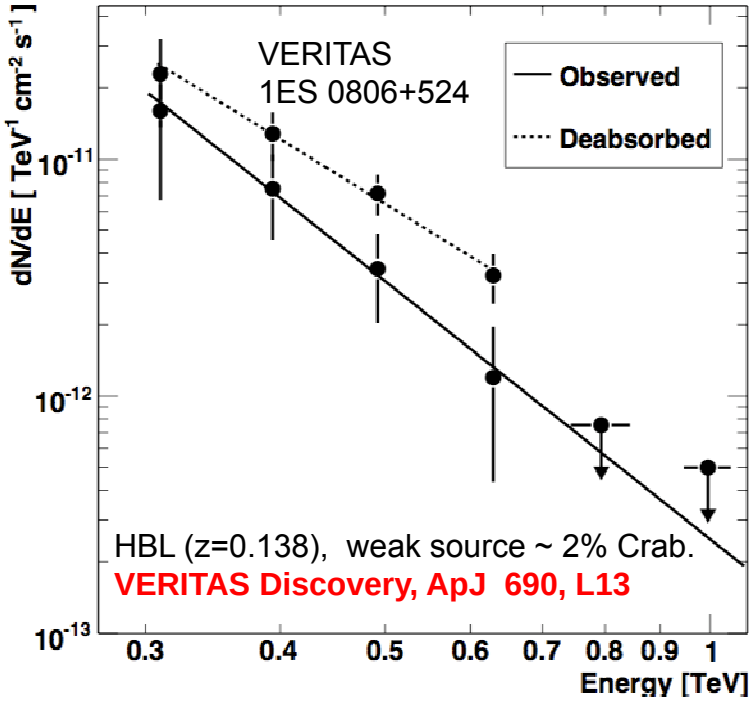
- Active Galactic Nuclei
  - BH accretion powers relativistic jet & VHE particle acceleration.
  - Science goals: emission mechanism, jet physics, BH accretion, etc.
- Blazars
  - Dominant VHE extragalactic source class (so far).
  - "Double-peaked" SED. Simultaneous MWL data crucial.
  - Probe EBL from spectra via: $\gamma_{VHE} + \gamma_{EBL} \rightarrow e^+ e^-$
- Radio Galaxies: M87, Cen-A
  - Closer, so structure can be better resolved.
- Gamma-Ray Bursts (GRBs)
  - Most powerful γ-ray events known.

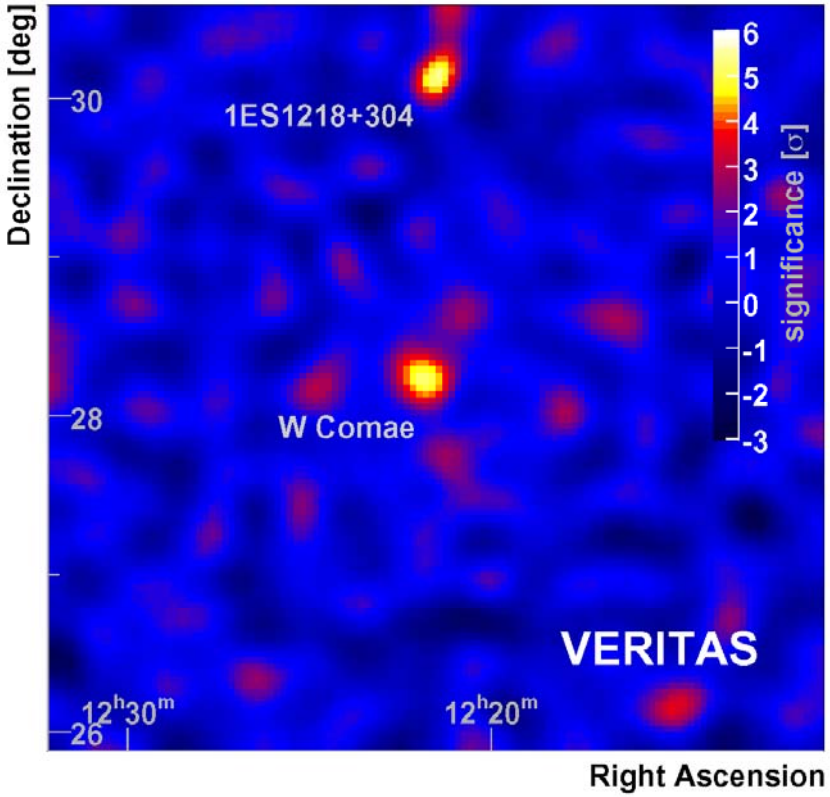


- Starburst Galaxies
- Searches for Dark Matter
  - See talk by R. Dickherber, Tues 2:40pm

VERITAS Blazar Program

- Strategy and Results
  - 1/3 Discovery, 1/3 MWL Campaigns, 1/3 ToO's
  - >60 Blazars observed, so far.
  - **11 Detections, 5 Discoveries. New LBL's and IBL's.**



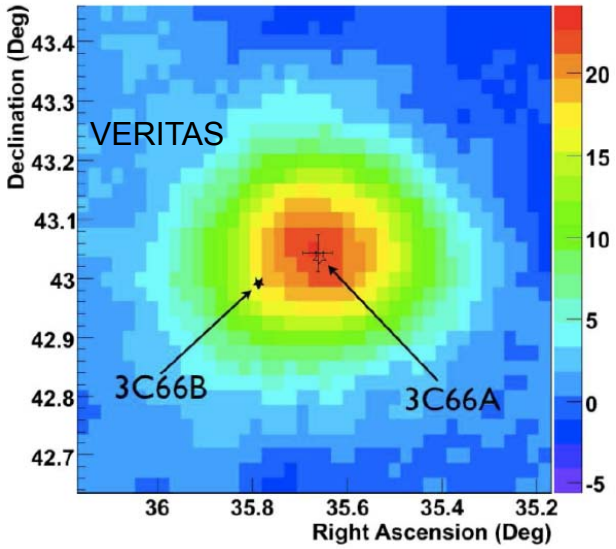


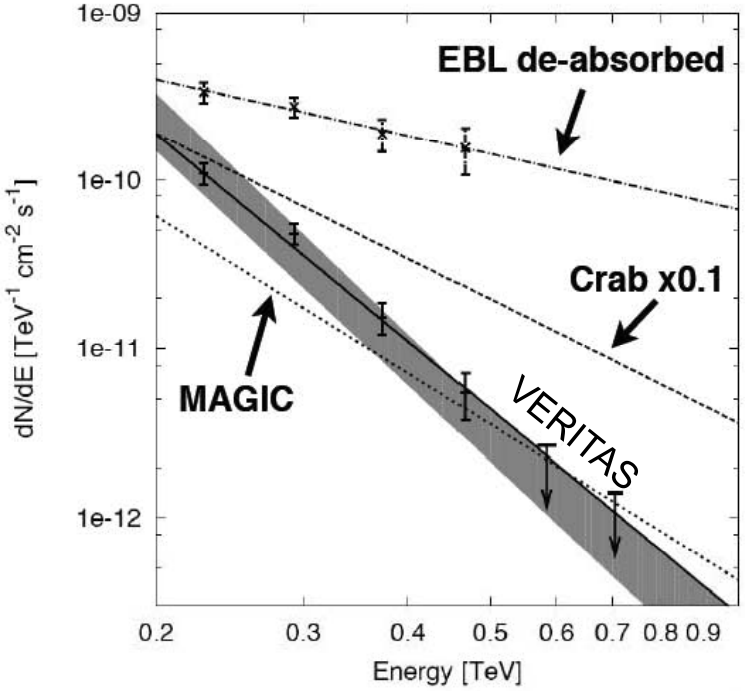
W Comae: IBL (z=0.102)
VERITAS Discovery, ApJ 684, L73

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

Highlight: 3C 66A

- 3C 66A
  - IBL at nominal z=0.44 (uncertain).
  - **VERITAS flare discovery, 2008**
    21σ, 33h, E_{th} ~ 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 paper in preparation:
    SSC-only model disfavored.

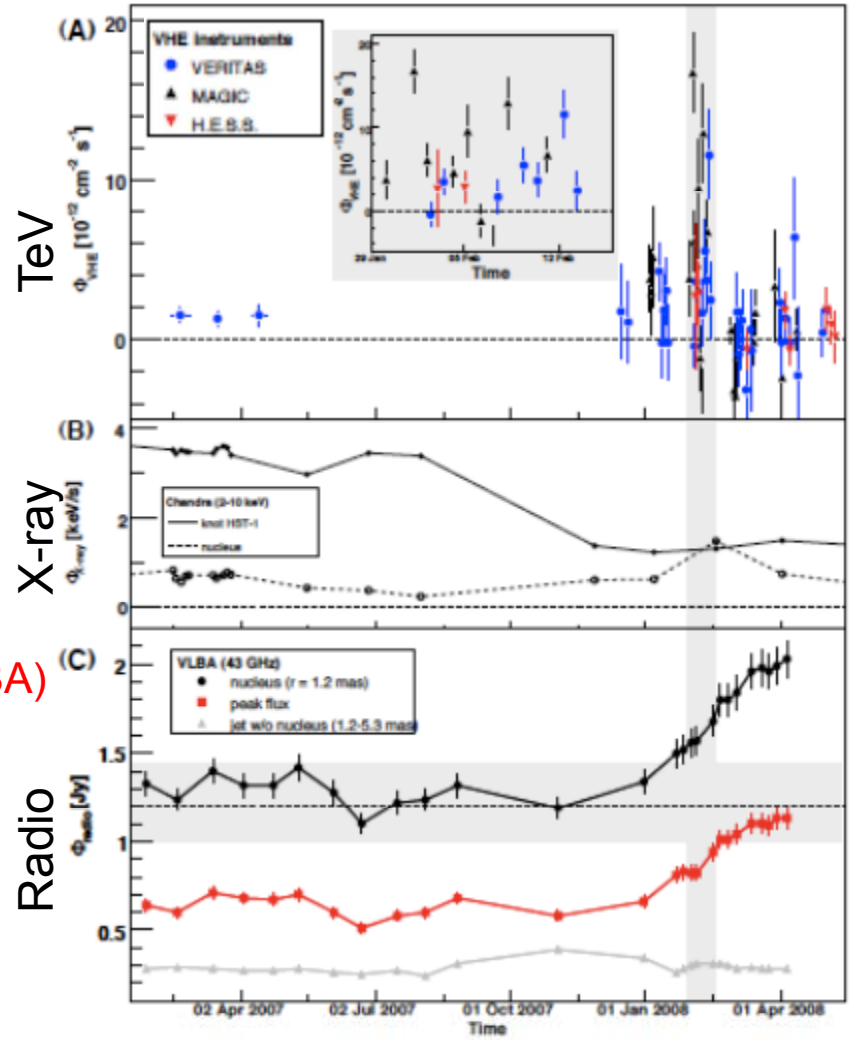




- MAGIC reported 3C66B 0.12° away.
  5.4σ in 54 h from 2007 data.
- VERITAS data excludes 3C66B at 4.3σ.

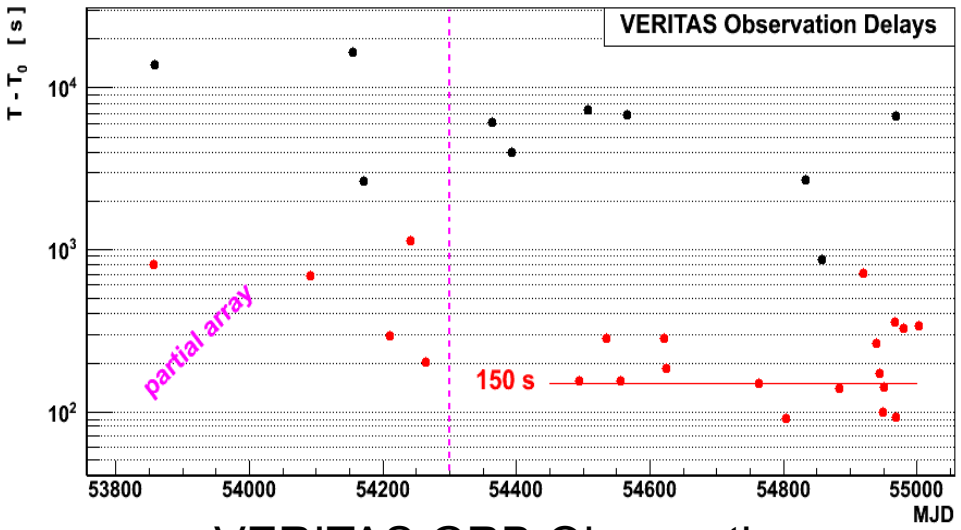
M 87: A Beautiful Laboratory

- 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 γ-ray telescopes.
- VERITAS observations
  - 2007, 2009: detected at 1-2% Crab.
  - 2008: joint campaign with MAGIC, H.E.S.S. TeV flaring correlated with radio emission (VLBA) from M87 core.



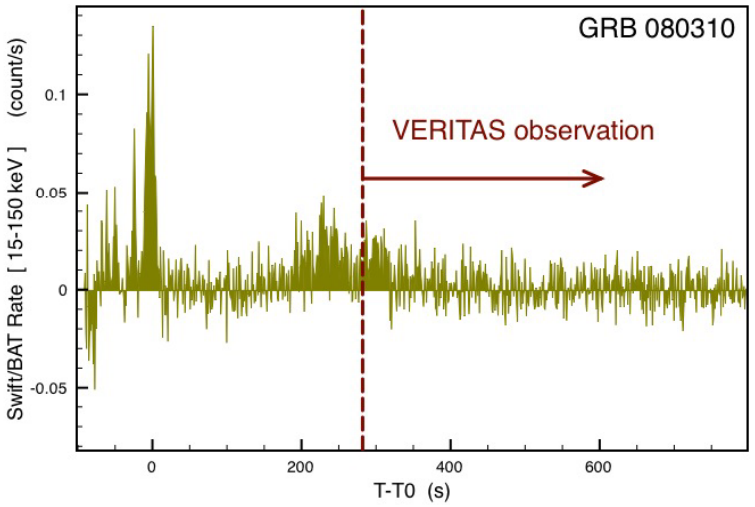
GRBs

- 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 γ-rays).



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

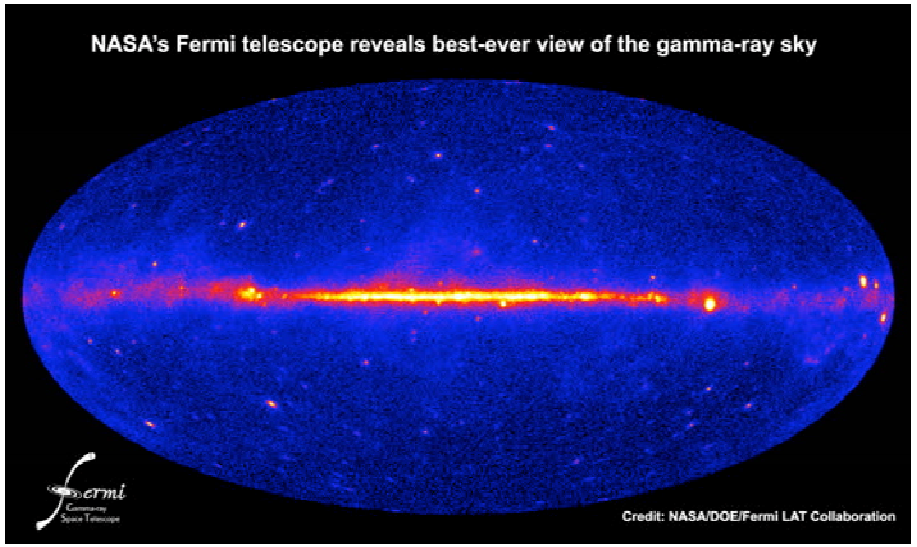
VERITAS GRB Observations
(red= GRBs immediately observable)



Galactic Sources

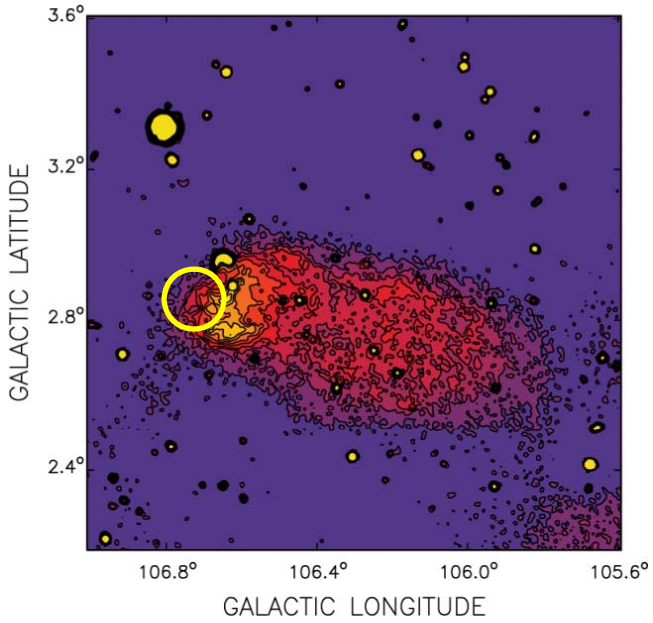
VHE Galactic Sources

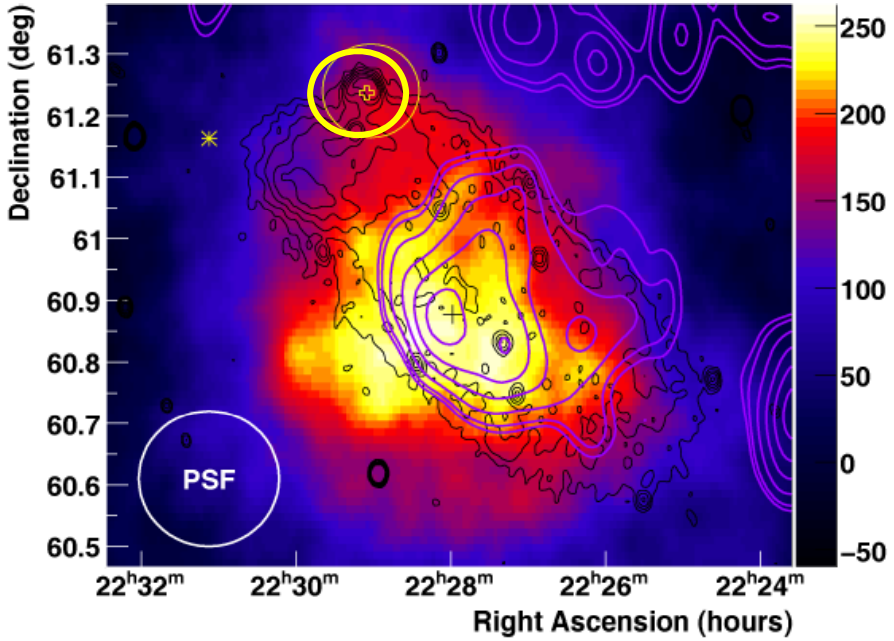
- Galactic plane is rich in γ-ray emission:
  - 90% photons seen in GeV range.
  - Variety of VHE sources:
    - Pulsars/PWN
    - SNRs
    - Binaries
    - Unidentifieds
  - Probe acceleration of e, p in shock fronts, colliding winds, superbubbles, etc.
    Hope to pin down CR Origin (at last!).



- Recent VERITAS Results
  - Discovery of TeV emission associated with two PWNe
  - Studies of the SNRs IC 443 and Cas A
  - Discovery of variability in HESS J0632+057

Highlight: G106.3 +2.7 (“Boomerang”)





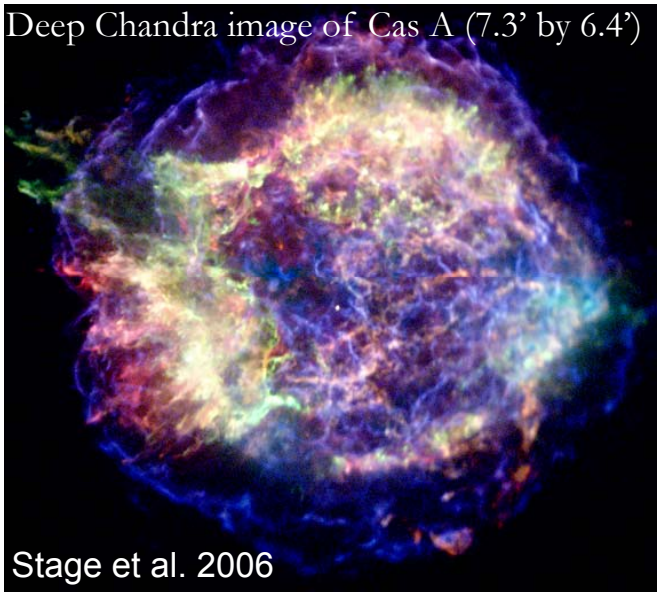
- G106.3 +2.7
  - Energetic pulsar PSR J2229+6114 and SNR/PWN with E-dot ~ 2 x 10^{37} erg/s, age ~ 10 ky.
  - 3EG J2227+6112 error ellipse. Fermi-LAT source J2229.0+6114.
  - Milagro reports > 10 TeV emission from region (Abdo et al., 2009).

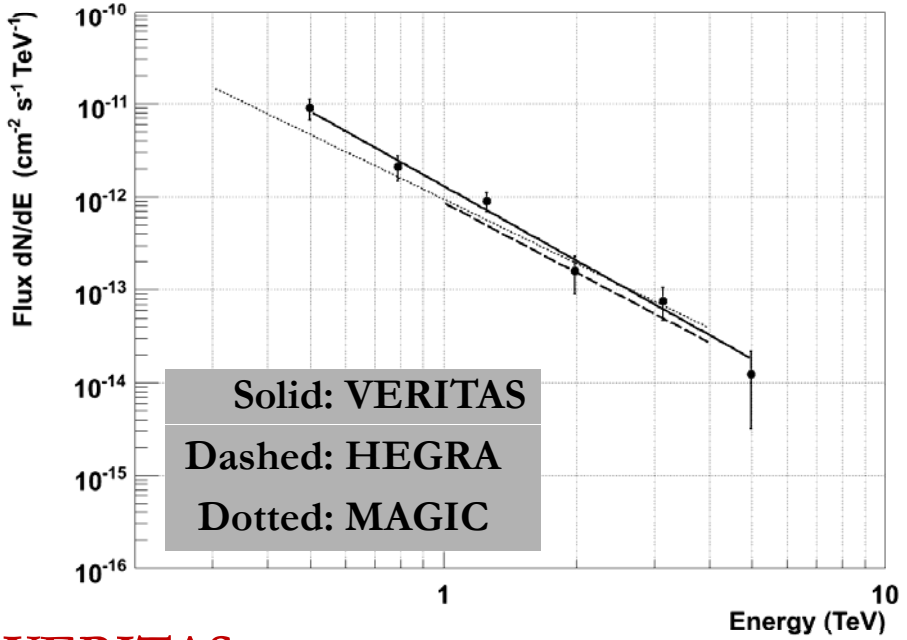
- VERITAS Results
  (V. A. Acciari et al., sub. to Astrophys. J, 2009)
  (E > 1 TeV)
  - 33 hr data in 2008, 6.0σ , ~5% Crab.
  - Clearly extended, peak overlaps CO.
  - Γ = 2.3 ± 0.3stat ± 0.3sys, consistent w. power-law to 35 TeV.

  Hadronic Origin ?

Cassiopeia A

- Young (330 yr), well studied shell-type SNR at a distance of ~3.4 kpc.
- 5' diameter (~TeV angular resolution)
- Discovered in TeV by HEGRA (232 hrs, 5 σ), confirmed by MAGIC (47 hrs, 5.3 σ)
  - Flux ~ 3.3 % Crab above 1 TeV





VERITAS:

- 22 hr data in 2007, 8.3 σ
- Size comparable to PSF

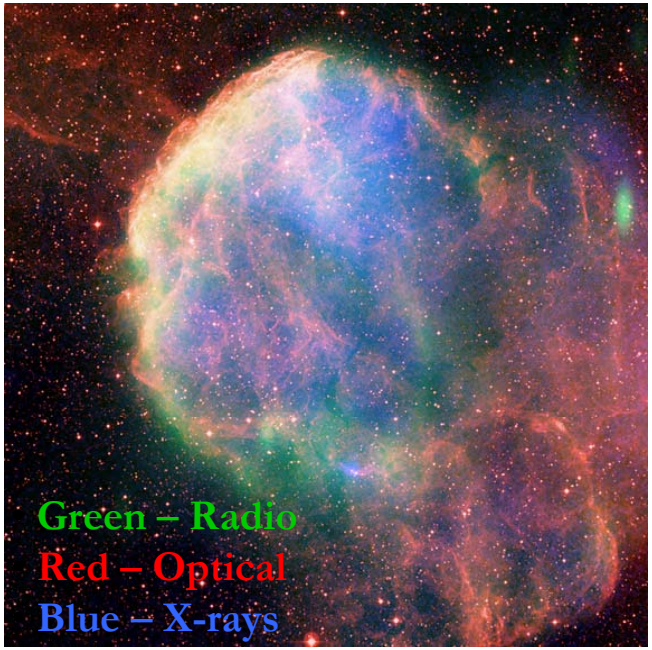
- Well fit by a power-law spectrum:

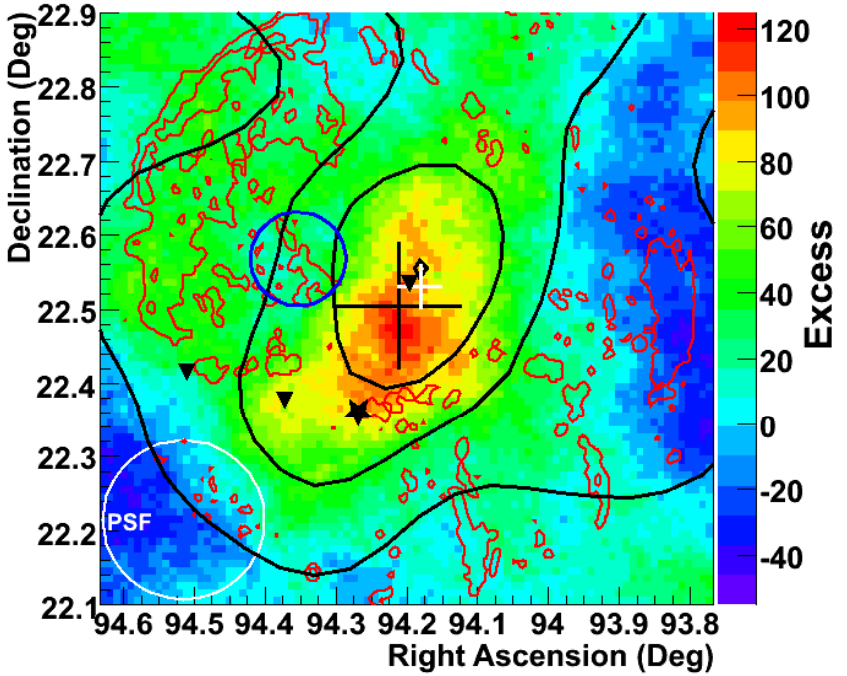
$$\Gamma = 2.61 \pm 0.24_{stat} \pm 0.20_{sys}$$

$$F(E > 1\ TeV) = (7.76 \pm 1.10_{stat} \pm 1.55_{sys}) \times 10^{-13}\ cm^{-2}\ s^{-1}\ (3.5\%\ Crab)$$

- No sign of a cut-off at high energy.

IC 443

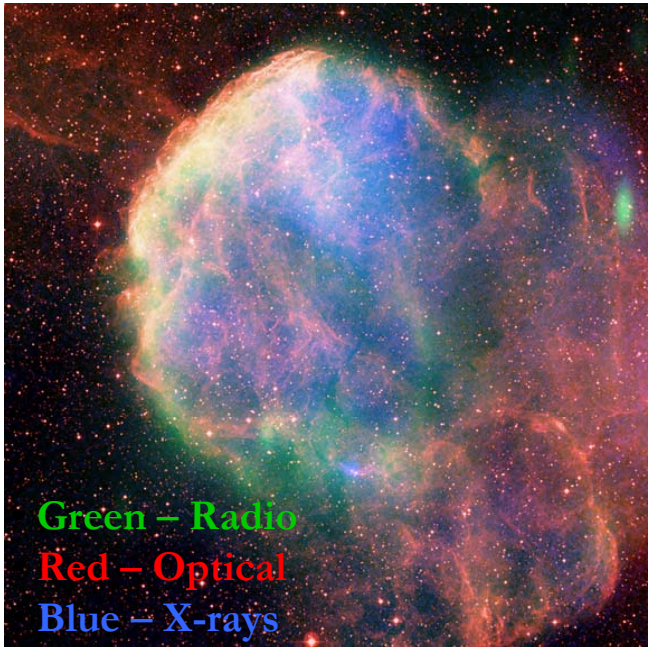


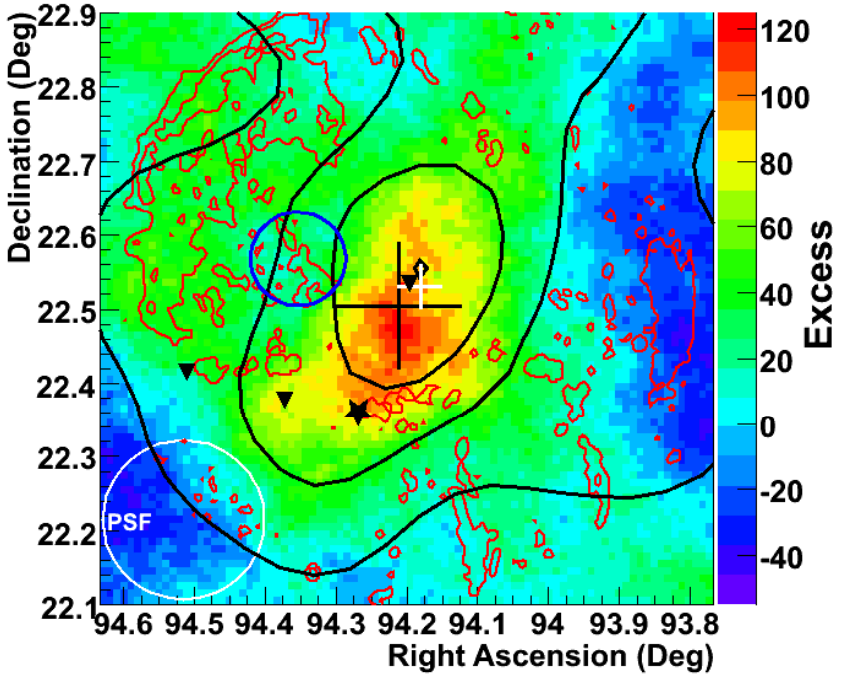


- Shell interacting with molecular cloud → potential target material
  - 30 kyr age, 45 arcmin diameter
  - Fermi emission centered on remnant, overlaps cloud
  - MAGIC emission centered on cloud
- PWN at southern edge of shell

- Discovered in TeV in 2007
  - by MAGIC (5.7 σ in 29 hrs)
  - by VERITAS (7.1/6.0 σ pre/post-trials in 15.9 hrs)
- Total livetime: 37.9 hrs.
- 8.3 σ peak significance pre-trials

IC 443





- Power-law fit 0.3 – 2 TeV:

  $\Gamma = 2.99 \pm 0.38_{stat} \pm 0.30_{sys}$

- F(E > 300 GeV): 3.2% Crab

  $(4.63 \pm 0.90_{stat} \pm 0.93_{sys}) \times 10^{-12}\ cm^{-2}\ s^{-1}$

2-D Gaussian profile fit:

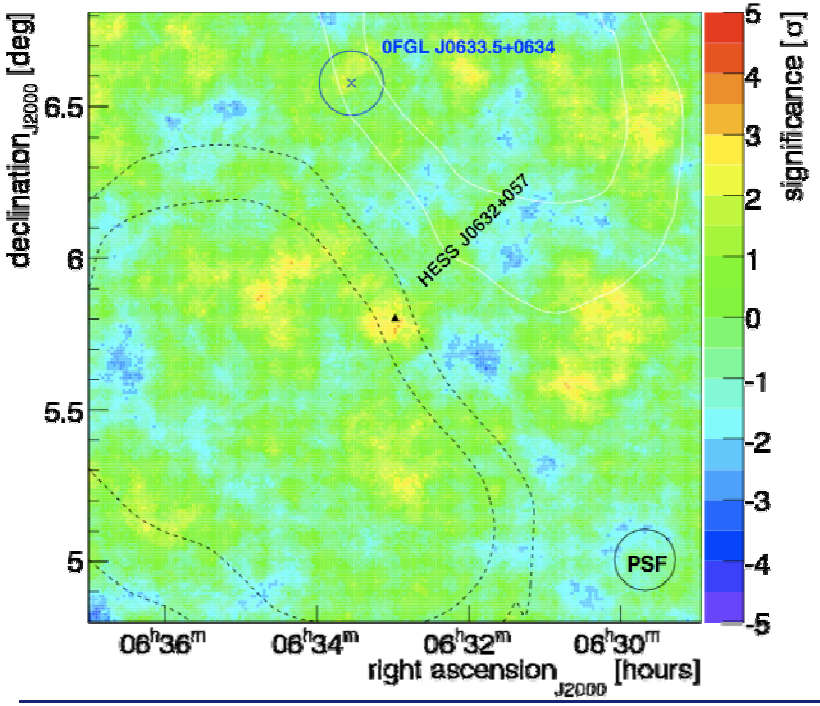
Centroid: 06 16.9 +22 32.4 $\pm\ 0.03^{o}_{stat} \pm 0.07^{o}_{sys}$

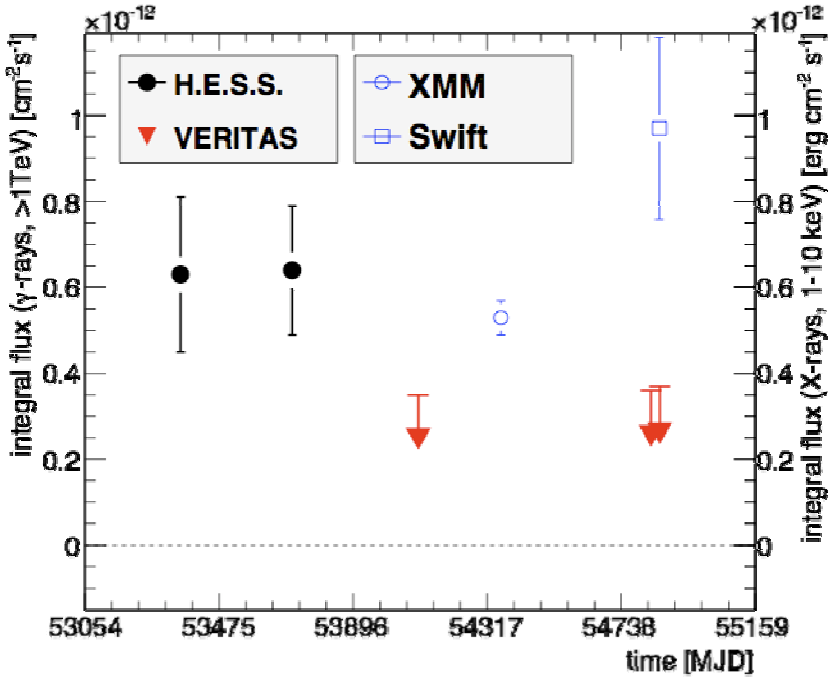
Extension: $\sigma \sim 0.17^{o} \pm 0.02^{o}_{stat} \pm 0.04^{o}_{sys}$

- TeV emission may be
  - CR-induced pion production in cloud
  - associated with the pulsar wind nebula to the south
- GeV and TeV emission spatially separated

Variability in HESS J0632+057

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

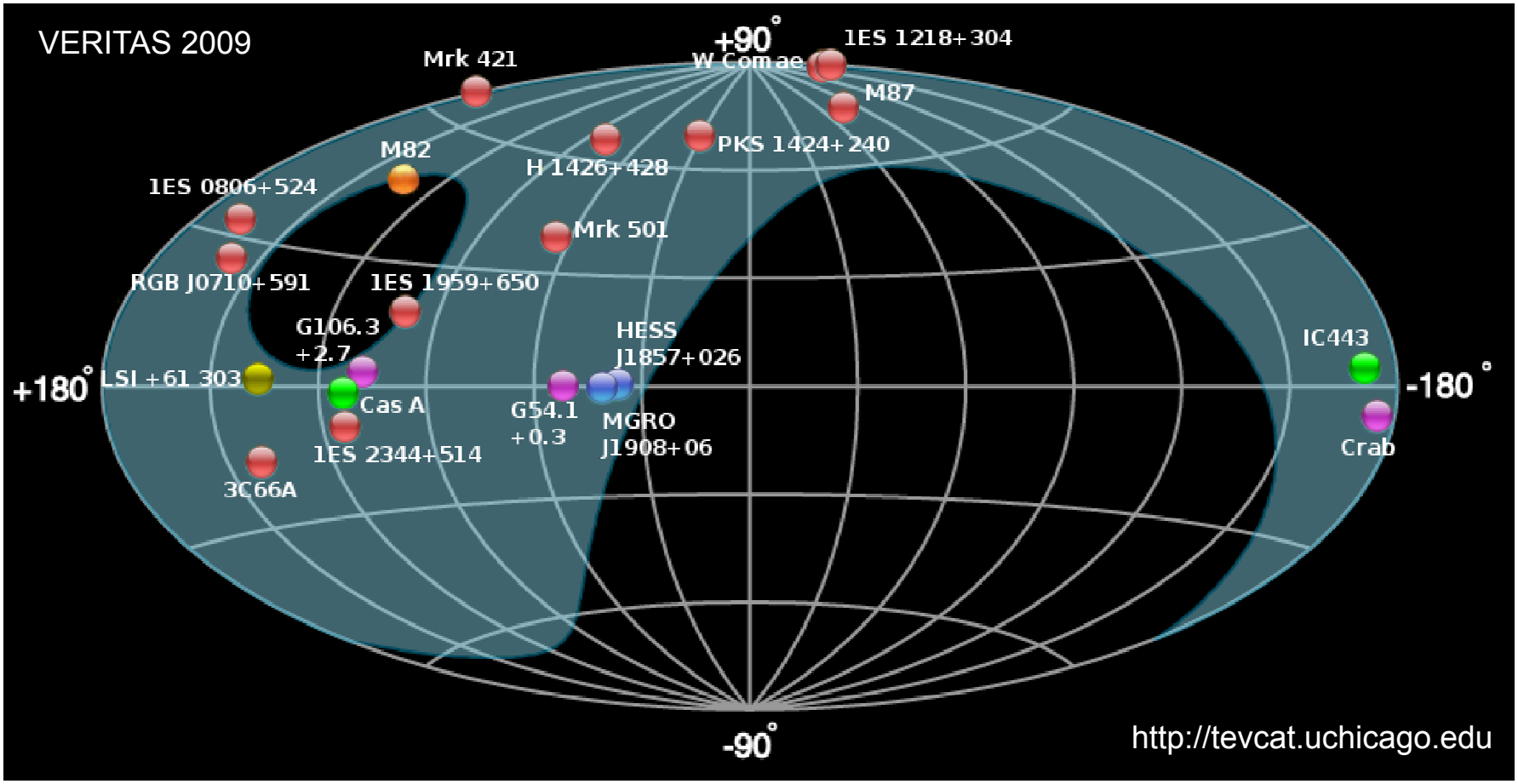




- VERITAS Observations, ~30hrs over 3 years
  - No emission detected, excludes steady flux measured by HESS at 4σ.

➢ New TeV binary or a new source class ?

VERITAS VHE Sky (July 2009)



21 Source Detections in 6 source classes

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.

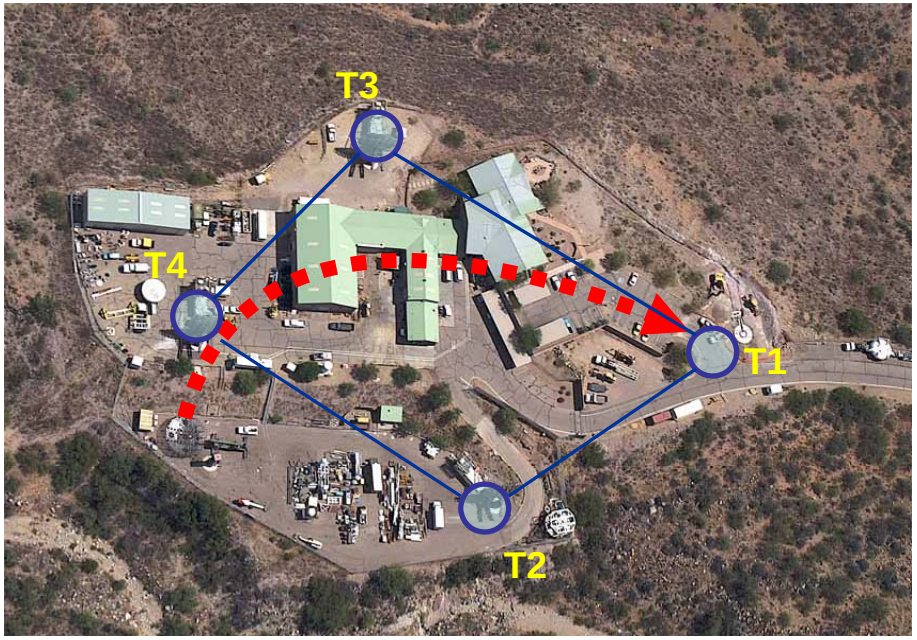
Plans to improve the sensitivity and to extend the energy range are ongoing or discussed:

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

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)

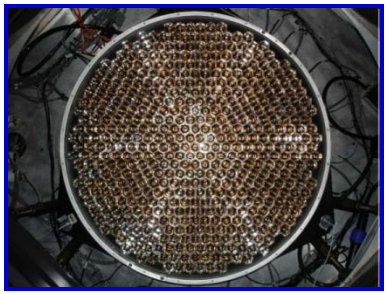
Baseline Upgrade Plan (2009-2011)

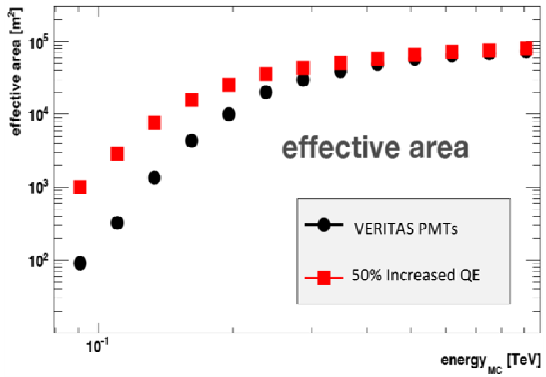
- We plan to replace the PMT cameras and L2 trigger system to significant improve the sensitivity and energy threshold.

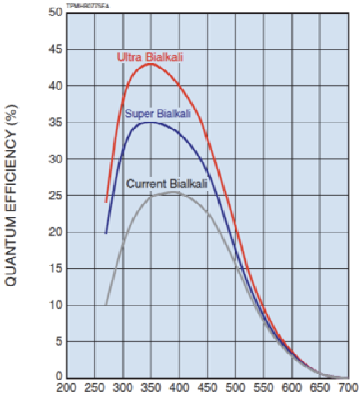
CAMERA Upgrade
PMT replacement with high efficiency PMTs.

Increase photon collection by ~35%.

Improves background rejection, E_{th}, sensitivity.

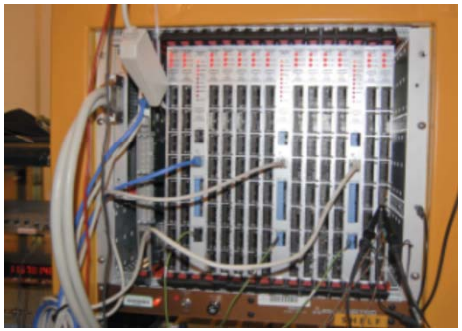


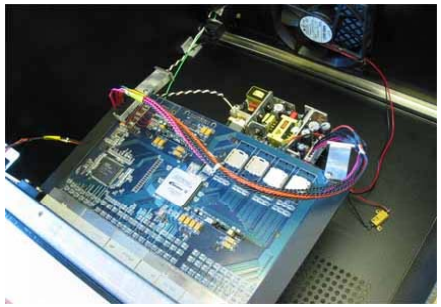




TRIGGER Upgrade
Smaller coincidence window
Topological Trigger

Improves E_{th} and CR event rejection.





Prototype Trigger Systems

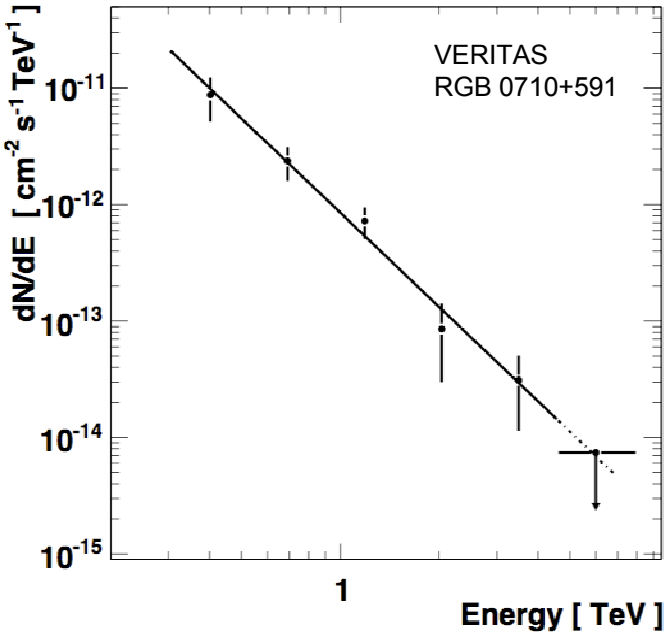
Summary

- VERITAS is operating very well (> 95% uptime) with two good years of data in hand.
- Many new results, including:
  - **Discovery of γ-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 γ-rays from 6 targets.**
    - **See talk by R. Dickherber, Tues 2:40pm**
- VERITAS Upgrade will significantly improve sensitivity.
- Coordinated work with Fermi immediately fruitful!
- Future will require even closer collaboration and cooperation between major GeV, TeV γ-ray and ν telescopes.

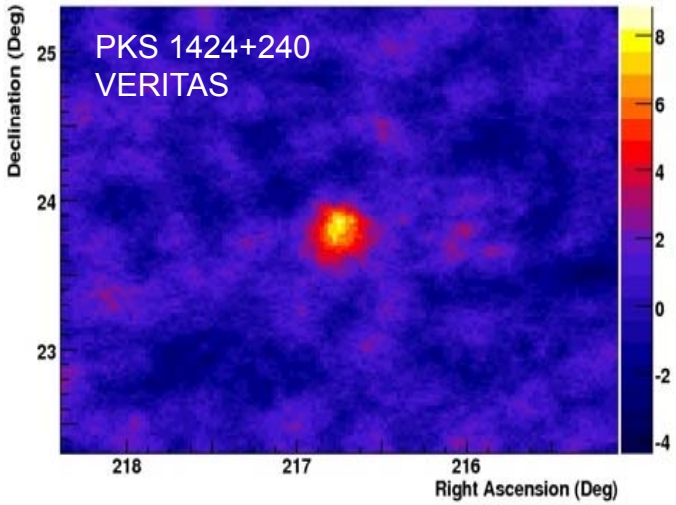
BACKUP

Highlight: Two New Blazars

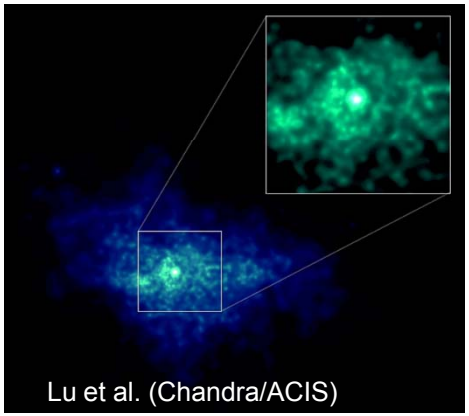
- RGB 0710+591
  - HBL at z = 0.125.
  - **5.5σ discovery in 2009 from 22h (ATEL #1941).**
  - Hard spectrum will constrain EBL.
  - MWL SED modeling (w. Fermi-LAT).

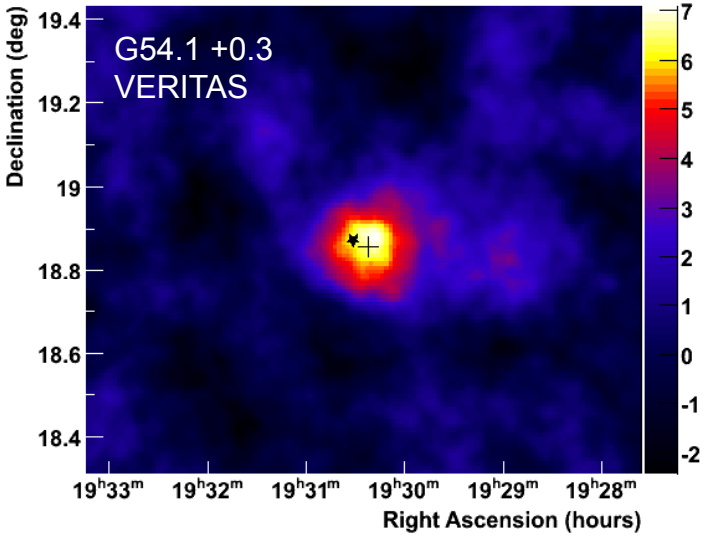


- PKS 1424+240
  - IBL at z = 0.16.
  - Detected by Fermi-LAT (Abdo et al. 2009).
  - **VHE discovery by VERITAS (ATEL #2084). 7.5σ in full data set. MAGIC detection (ATEL #2098).**
  - 1st VHE discovery motivated by Fermi !

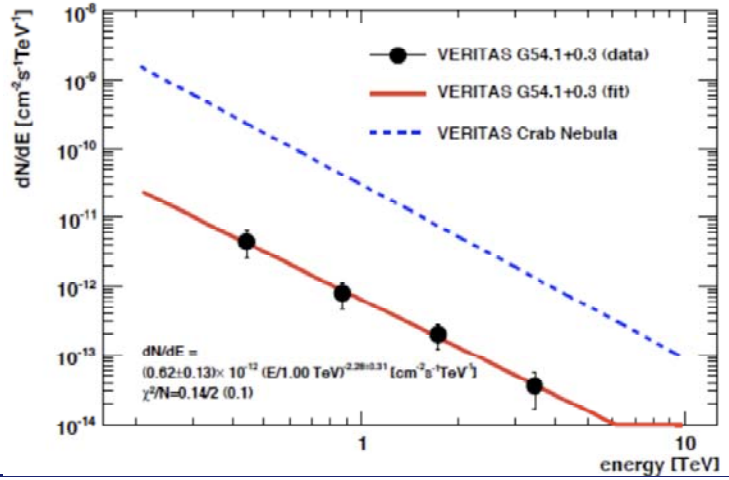


Highlight: G54.1 +0.3 (PWN)

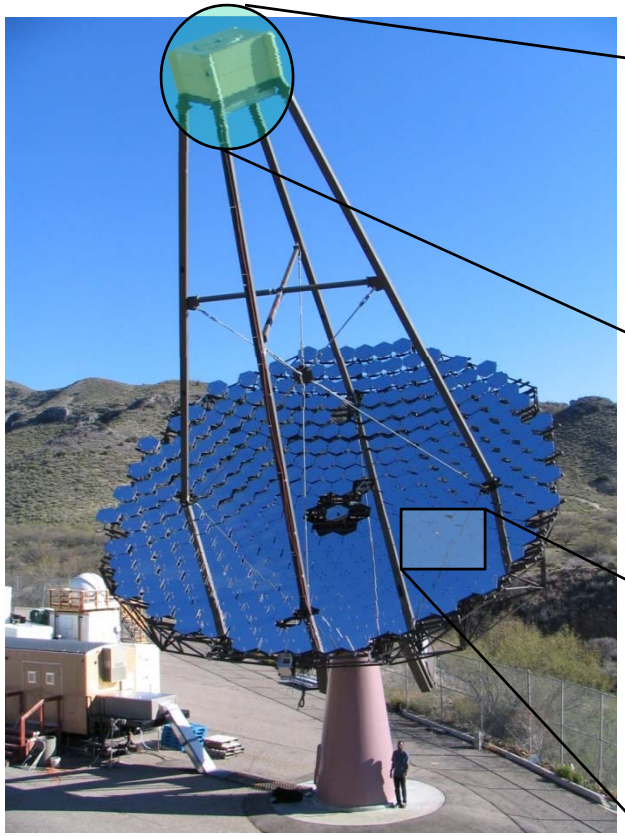




- G54.1 +0.3 (PSR J1930 +1852)
  - Similar to Crab; X-ray jet and torus.
  - E-dot ~ 10^{37} erg/s, age ~ 3 ky.
  - Nearby molecular cloud.
- VERITAS Detection
  - 31 h, 7.0σ detection, ~3% Crab (E > 1 TeV).
  - Consistent with point source at pulsar location.
  - $\Gamma = 2.3 \pm 0.3_{stat} \pm 0.3_{sys}$ (preliminary)

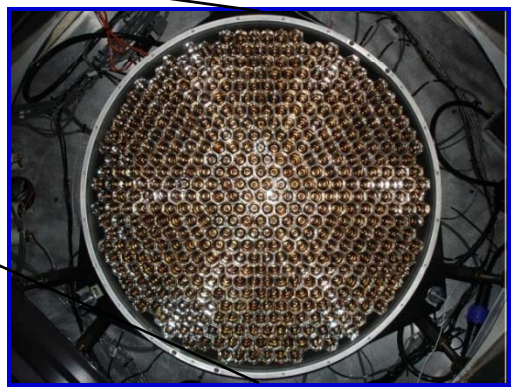


Technical Details



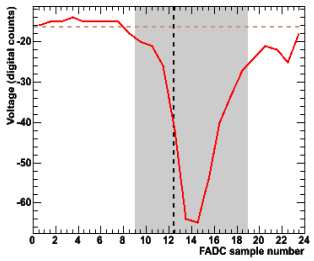
Telescope (x 4)
12-m diameter Davies-Cotton
f 1.0, 110 m2 area

PMT Assembly



Camera (x 4)
499 PMTs, 3.5^{o} FOV

Mirror Facets (x 350)
Reflectivity ~ 88%
(Recoated every 2 years)



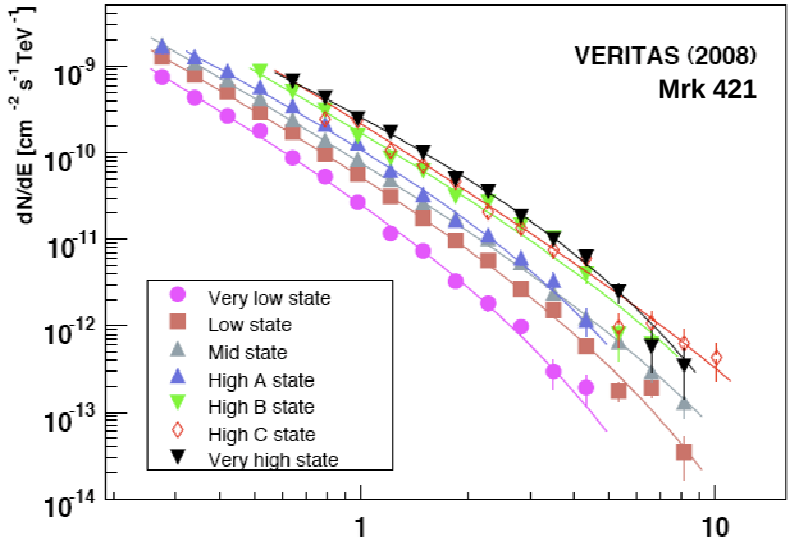
FADC Board & Trace

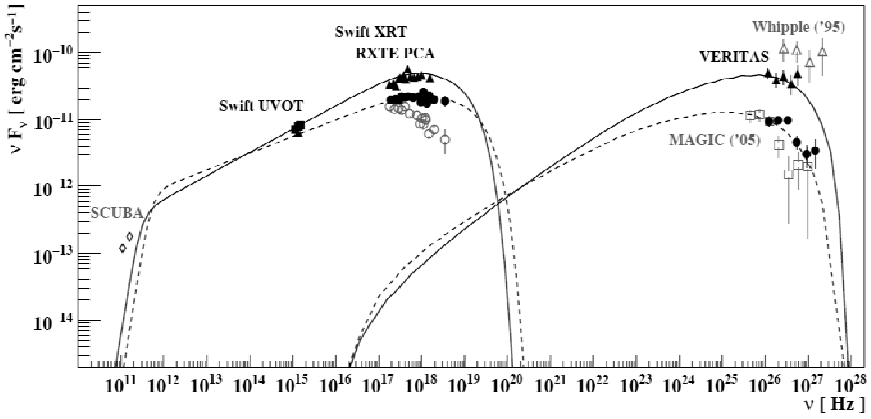
FADC Readout
500 Msps, dual-gain

3-Level Trigger
Pixel, Telescope, Array
Deadtime ~10% @ 300 Hz

Old Favorites and MWL Studies

- Mrk 421
  - 2008 flare, Whipple 10m (ATEL #1506).
  - VERITAS data, Jan – Jun 2008
    Strong signal ~280σ, > 30,000 γ-rays.
    Clear spectral hardening.
    MWL coverage with Swift, RXTE, optical.
  - June 2008: Broad MWL coverage of Mrk 421 led by AGILE and MAGIC.
    (Donnarumma et al., ApJ 691, L13).
    See ICRC poster by R. Wagner (#0926).
- Mrk 501
  - March-May 2008, extended campaign from radio to TeV.
    See ICRC poster by D. Krannich (#1346).
- 1ES 2355+514
  - VERITAS detection ~20σ in 18h in late 2007.
    0.5 Crab flare on 07 Dec 2007, well fit by one-zone SSC model.
    (Acciari et al., Submitted to ApJ, 2009)





Other Science Results

IceCube Hotspot

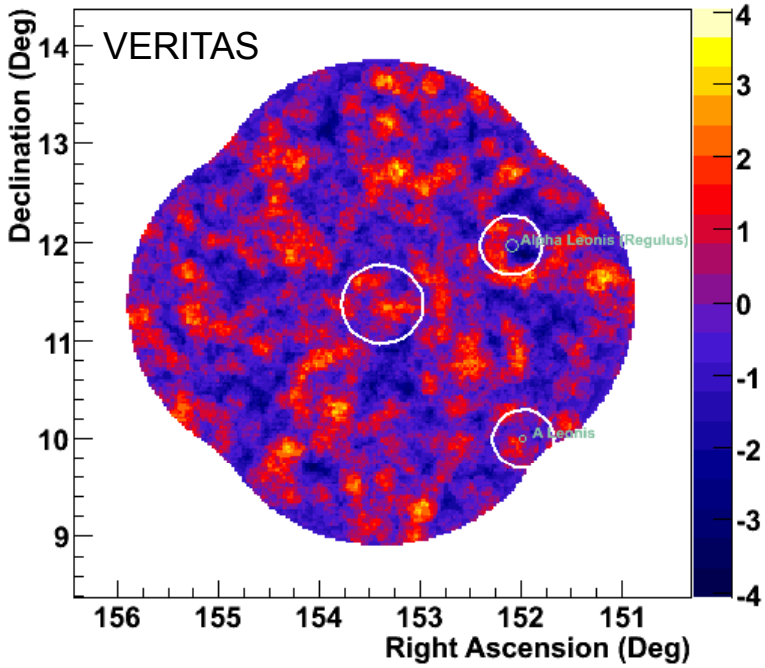
❑ IceCube Hotspot

- All-sky neutrino map from 22-string detector reveals “hotspot” at (10h13m30s,+11d22m30s). (T. Montaruli, private communication).
- 7.7 excess events (4.8σ/2.2σ pre/post trials).
- Collaboration between IceCube & VERITAS
  → DDT request to observe with VERITAS.

❑ VERITAS Observations

- 2.5h in moonlight in April 2009.
- No signal observed, fluctuations consistent with background.

γ-ray Flux Limit (E>1 TeV) < 4.0% Crab
(at hotspot position)



Useful exercise – keep sending interesting candidates!

Dark Matter Searches

❑ Dark Matter (DM)

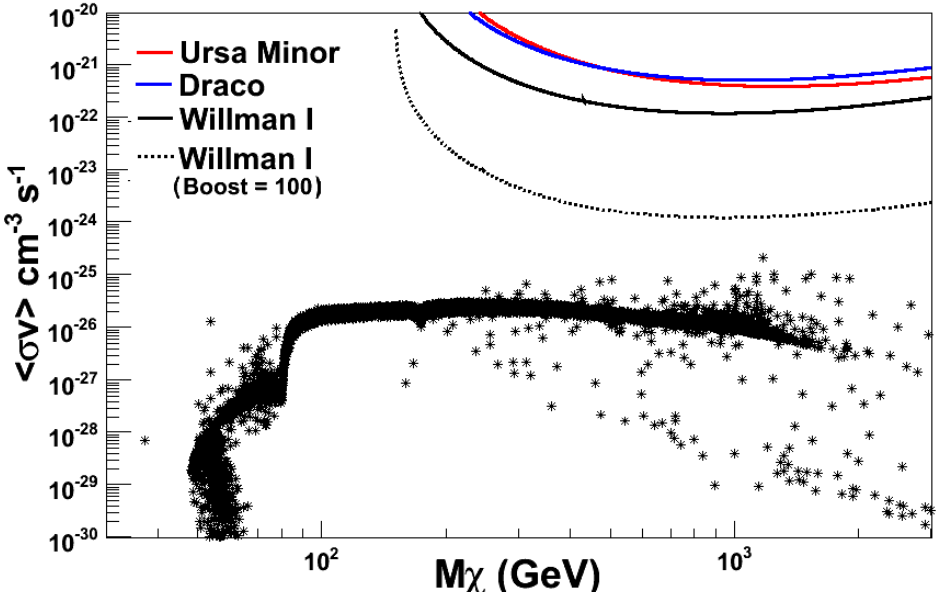
- A major scientific puzzle, inferred from a variety of measurements.
- Particle DM candidates (SUSY, KK) → unique HE γ-ray signatures.

❑ 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

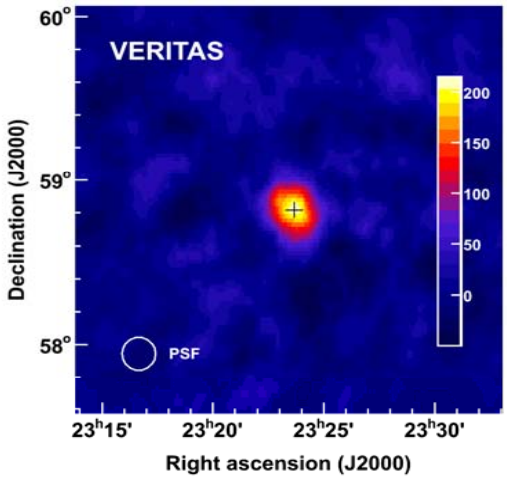


VERITAS limits on dwarf galaxies

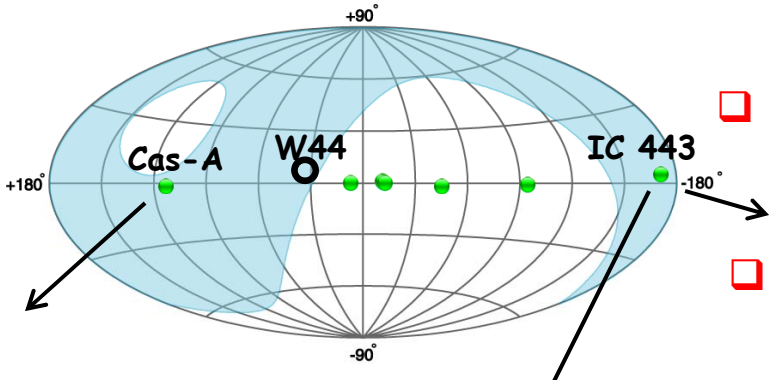
Other VERITAS Results @ ICRC 2009

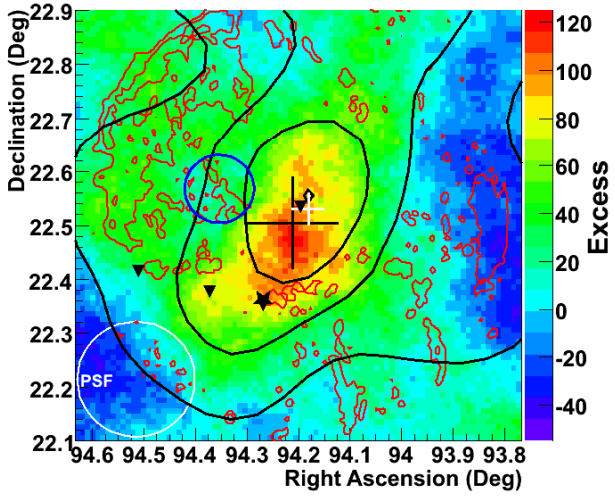
Presenter	Title	Session	Paper #
Talks:			
J. Grube	**Highlights of MWL Observations of VHE Blazars with VERITAS**	OG 2.3	0782
J. Holder	**VERITAS Observations of LS I +61 303 in the Fermi Era**	OG 2.2	1155
A. Imran	**VERITAS Discovery of Variability in the VHE gamma-ray Emission of 1ES 1218+304**	OG 2.3	0510
D. Mazin (MAGIC)	**A First Joint M87 Campaign in 2008 from Radio to TeV γ-Rays**	OG 2.3	1313
A. Pichel	**Highlights from the Whipple 10m Blazar Monitoring Program**	OG 2.3	0636
Posters:			
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 Observatons 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

SNRs ICR 443 & Cas-A



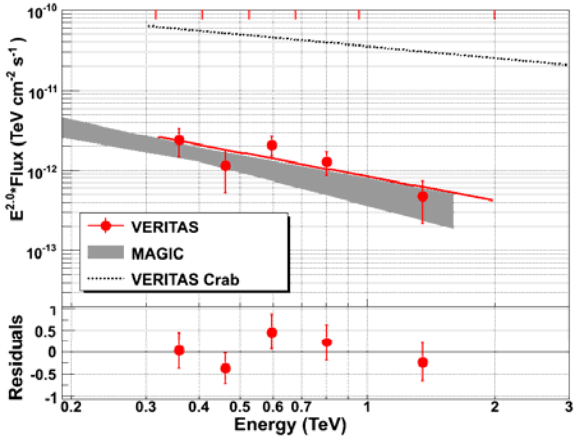
- VERITAS Cas-A Detection
  - 22h, 8.3σ in 2007.
  - 3.5% Crab, power-law $\Gamma = 2.61 \pm 0.24_{stat} \pm 0.20_{sys}$
  - No evidence for cut-off.



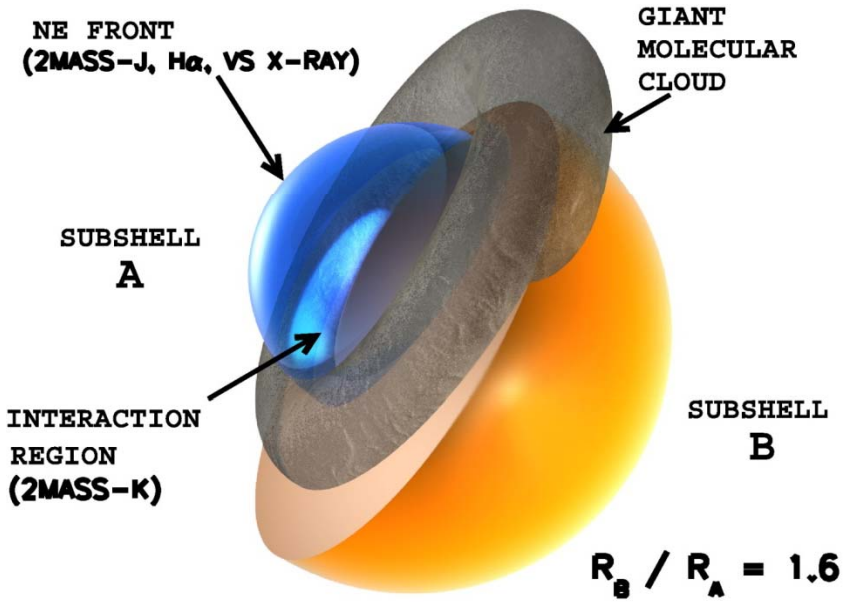


Acciari et al. ApJ 698, L133

- IC 443
  - Co-discovery in 2007
- Latest Results
  - 37h, 8.2σ, 3.2% Crab.
  - Clear extension overlap with CO (molecular cloud).
  - $\Gamma = 2.99 \pm 0.38_{stat} \pm 0.30_{sys}$



IC 443

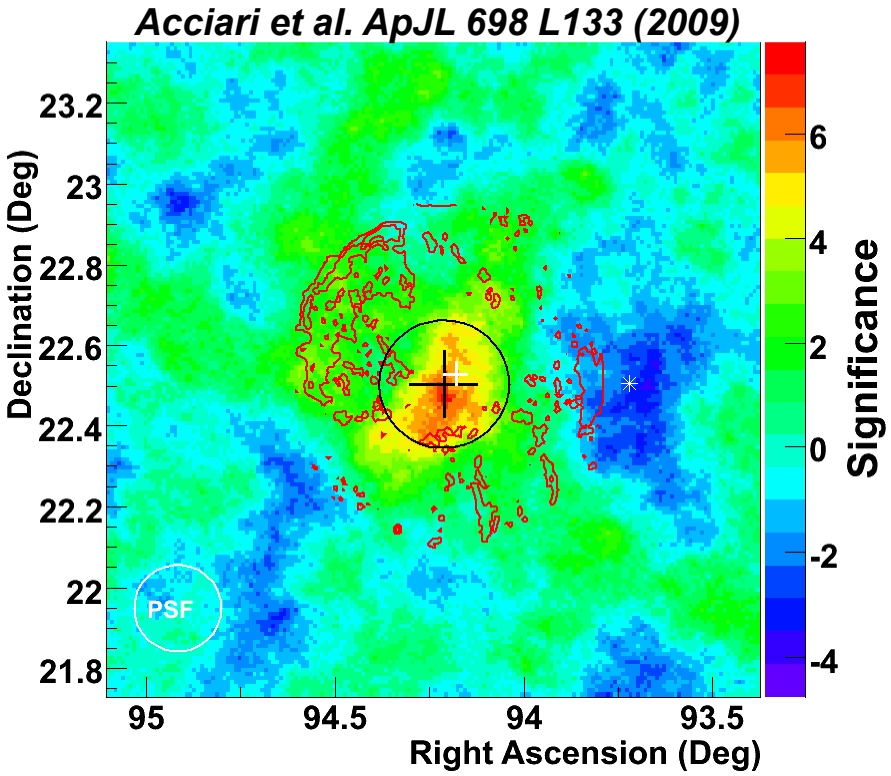


- Shell interacting with molecular cloud → potential target material
  - EGRET emission centered on remnant, overlaps cloud
  - MAGIC emission centered on cloud
- PWN at southern edge of shell

- Distance ~ 1.5 kpc
- Age ~ 30,000 years
- Diameter 45'
- Distinct shell in radio, optical

Compelling reasons to study TeV emission from IC 443: γs from cosmic rays, or from the PWN?

IC 443



- Discovered in TeV in 2007
  - by MAGIC (5.7 σ in 29 hrs)
  - by VERITAS (7.1/6.0 σ pre/post-trials in 15.9 hrs)
- Wobble-mode observations, 0.5° offset
- Observed during two epochs:
  - Feb / Mar 2007 with 3 telescopes
    - PWN location, CXOU J061705.3+222127
  - Oct / Nov 2007 with 4 telescopes
    - Center of Feb/Mar hot spot: 06 16.9 +22 33

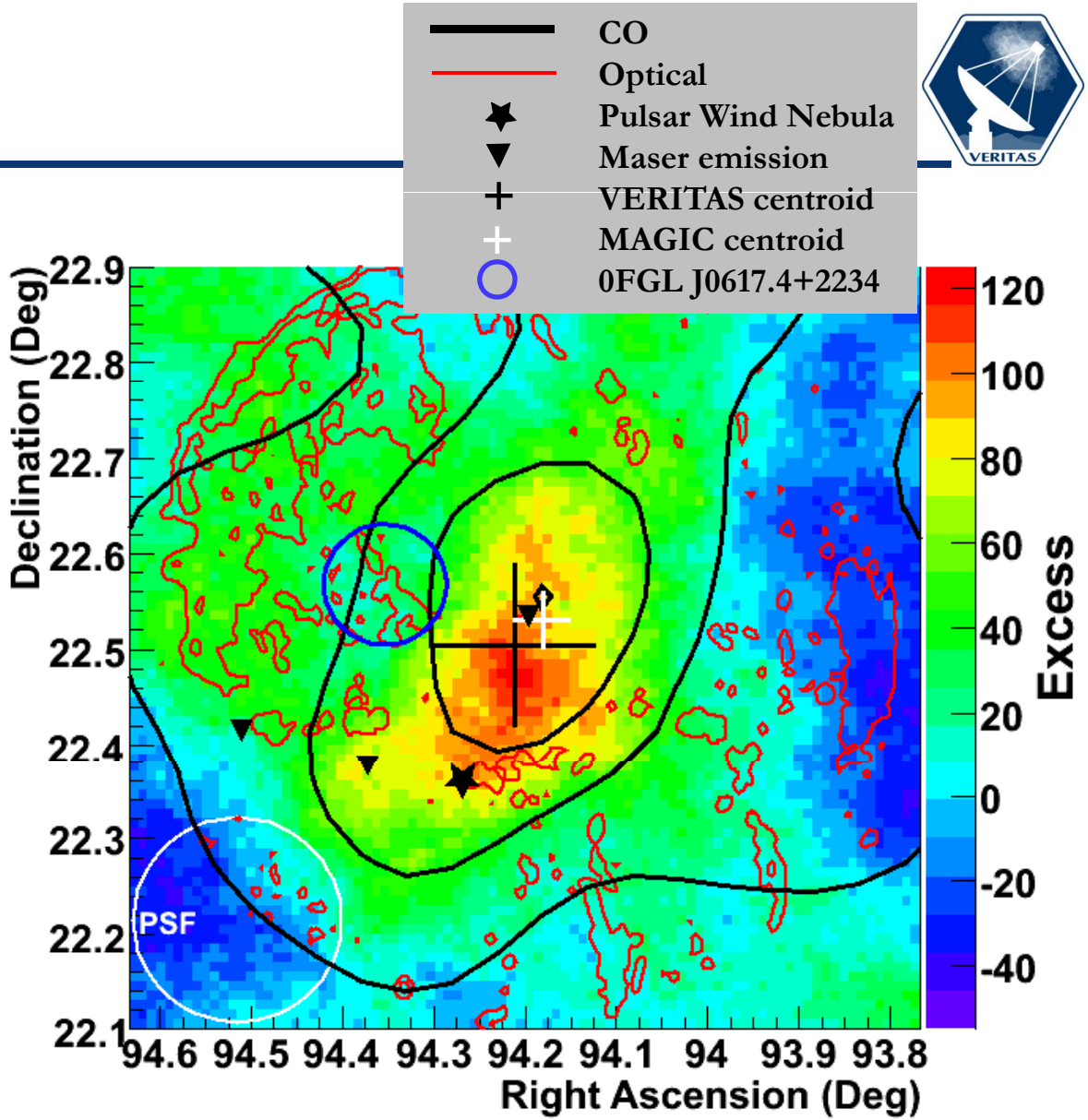
2-D Gaussian profile fit:
Centroid: 06 16.9 +22 32.4 ± 0.03°(stat) ± 0.07°(syst)
Extension: σ ~ 0.17° ± 0.02°(stat) ± 0.04°(syst)

- Total livetime: 37.9 hrs.
- 8.3 σ peak significance pre-trials

IC 443

Multiwavelength Picture

- Overlap with CO indicating molecular cloud along line of sight
- Maser emission suggests SNR shock interacting with cloud
- TeV emission could be
  - CR-induced pion production in cloud
  - associated with the pulsar wind nebula to the south
- GeV and TeV emission spatially separated?



- Power-law fit 0.3 – 2 TeV: $\Gamma = 2.99 \pm 0.38_{stat} \pm 0.30_{sys}$
- $F(E > 300\ GeV)$: $(4.63 \pm 0.90_{stat} \pm 0.93_{sys}) \times 10^{-12}\ cm^{-2}\ s^{-1}$ (3.2% Crab)