

# VHE Galactic Source Highlights from VERITAS



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**SACLAY Seminar, 28 July 2011**

# OUTLINE

- Scientific Motivations
- The atmospheric Cherenkov technique and VERITAS
- Bonus: Latest DM Results (Segue 1)
- Selection of new Galactic source results
  - Galactic Center
  - Supernova Remnants (SNRs) – Tycho
  - Pulsar Wind Nebulae (PWN) – CTA1
  - Cygnus region
  - Crab Pulsar
- Future Prospects and Summary

# Scientific Motivations

Some of many motivations for Galactic VHE  $\gamma$ -ray sources:

## PHYSICS Motivations

- Origin of Cosmic Rays
  - energy balance of Galaxy
- Physics of compact objects
- Dark matter

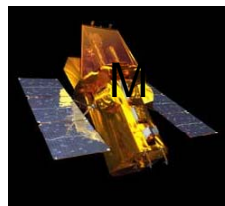
## ASTRONOMICAL Motivations

- New observational window !  
(non-thermal Universe)
- High energy particle (e,p) accel.
  - shocks, stellar winds, jets, etc.

Multiwavelength Observations



Radio



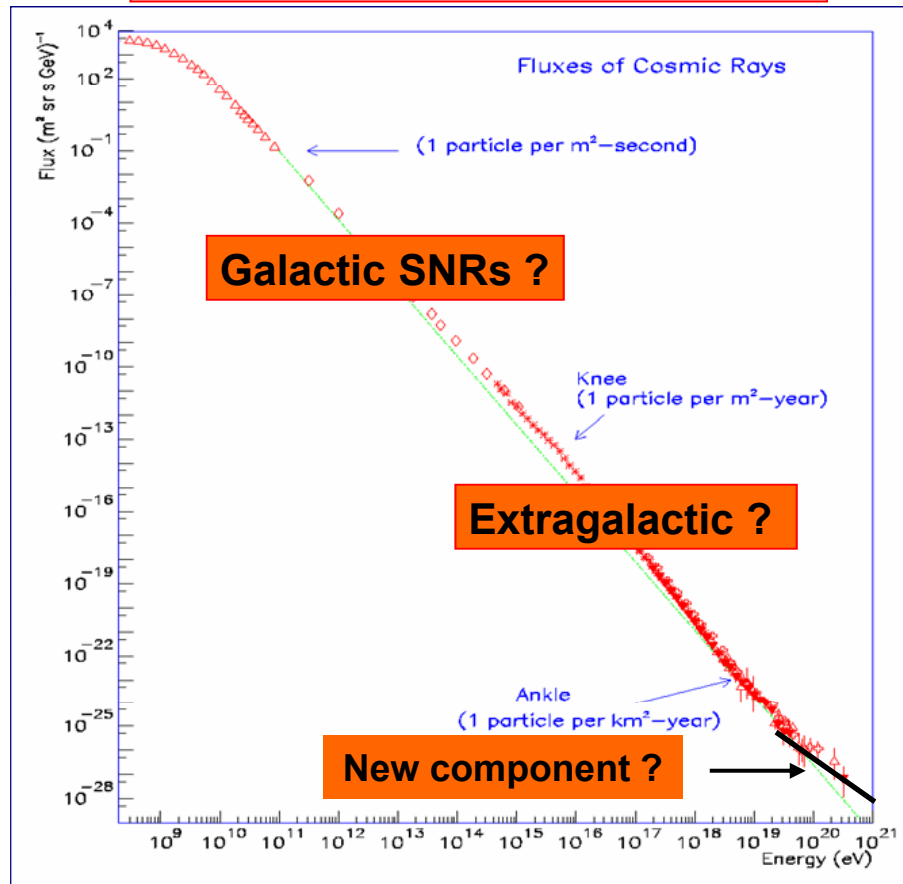
X-rays



Fermi LAT

# Origin of Cosmic Rays

Diffuse, all particle spectrum



S. Swordy

90 year old mystery !

- Enormous E range
- Mostly charged particles
- E density  $\sim 1 \text{ eV/cm}^3$

Neutral messengers:

$\gamma, \nu$

are required to directly observe cosmic accelerators.

# Variety of VHE Galactic Sources

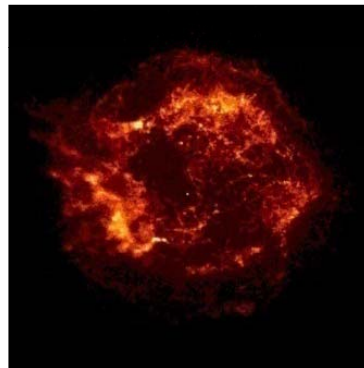
## Pulsars

### Pulsar Wind Nebulae



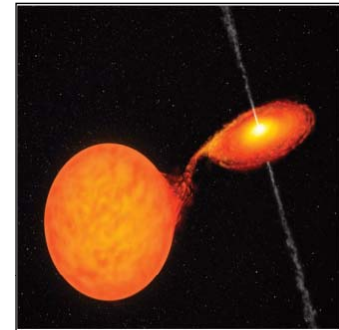
NS dynamo  
Winds

## Supernova Remnants



Shocks  
Fermi mechanism

## Binary systems



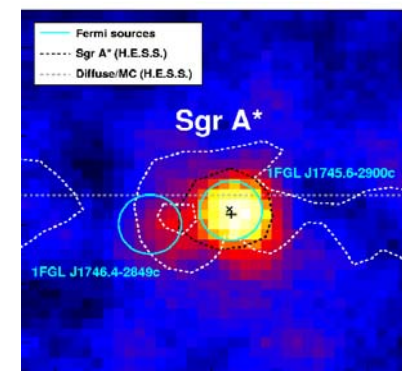
Accretion-powered jets,  
Colliding winds, or ...?

## Star Forming Regions



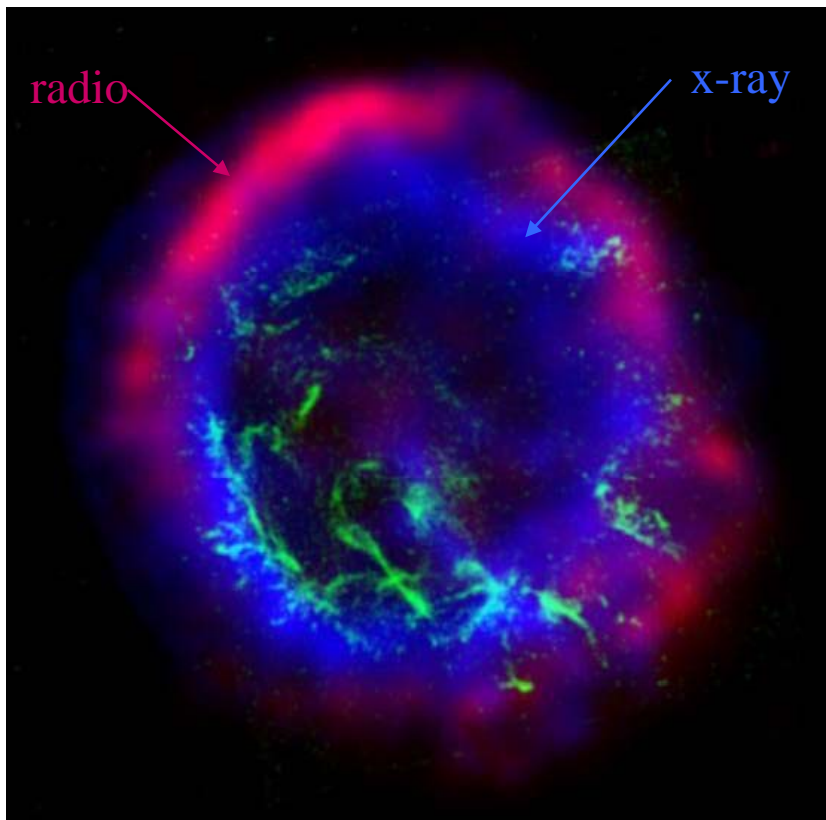
OB Assoc., WR stars  
HII regions, molecular clouds

## Un-Identifieds



???

# Supernova Remnants (SNRs)



SNR E102

- Collapse of massive star or detonation of white dwarf.
- Outer layers ejected with  $v \sim 3 \times 10^3$  km/s.
- Shell expands and shock front forms as it sweeps up material from ISM.
- Acceleration of particles via “canonical” Fermi process – or diffusive shock acceleration.
- In  $\sim 10^4$  yrs, blast wave decelerates and dissipates.
- Can supply and replenish CR's if  $\varepsilon \sim 5\text{-}10\%$ .



# Electrons or Protons ?

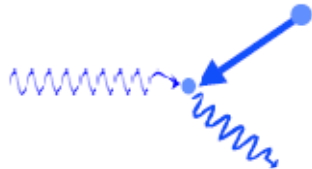
VHE  $\gamma$ -rays are:

- *Not deflected* by interstellar magnetic fields.
- *Tracers* of parent particle populations – those particles accelerated by shocks, combined with possible target material.

*But both electrons and protons produce  $\gamma$ -rays.*

Accelerated electrons  
→ TeV  $\gamma$ -rays

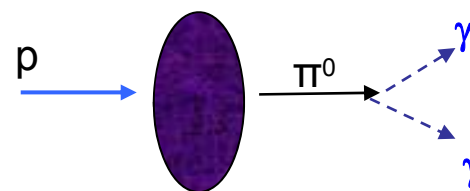
Up-scattering of soft photons



Inverse Compton  
Scattering

Accelerated protons  
→ TeV  $\gamma$ -rays

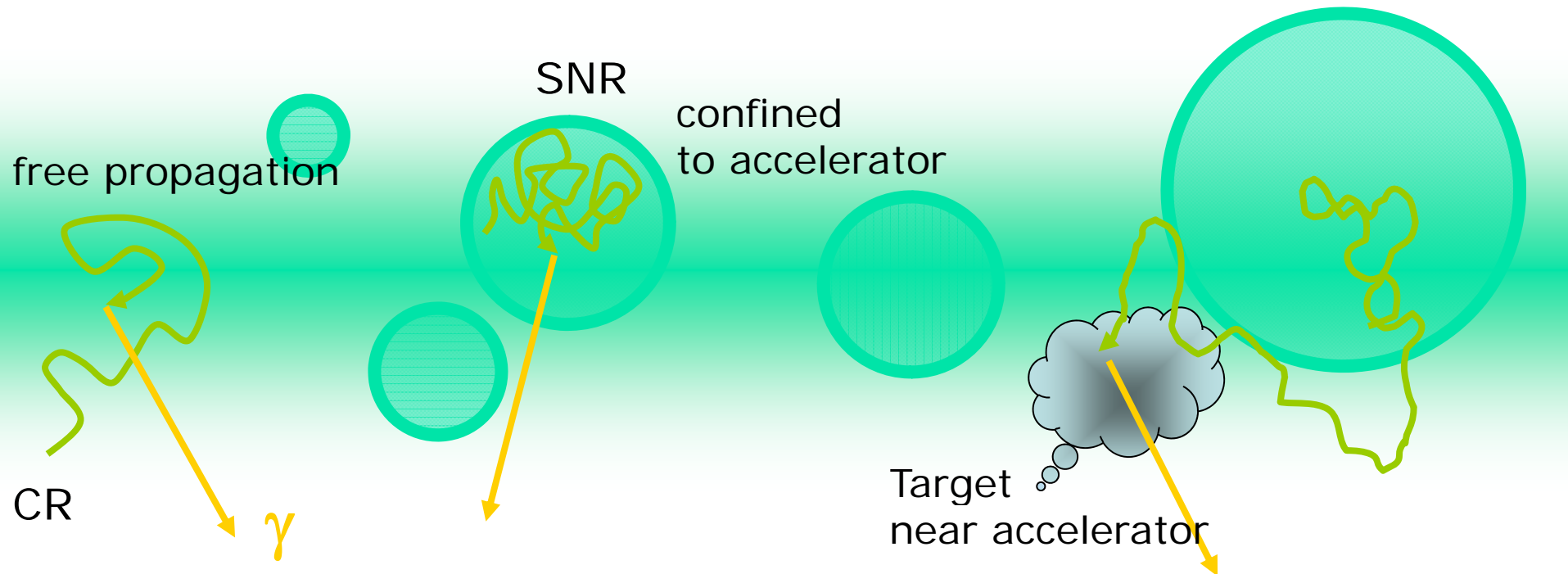
Target interaction,  $\pi^0$  decay



$\pi^0$  and target material

There is now good evidence for SNR acceleration of CRs, but the case is not yet ironclad.

# Tracing the HE Particles



VHE  $\gamma$ -rays come from secondary interactions:

p:  $p^0$  production and decay

e: Inverse Compton scattering and Bremsstrahlung

Trace beam density x target density

Need to disentangle e, p components  $\rightarrow$  MWL observations are crucial



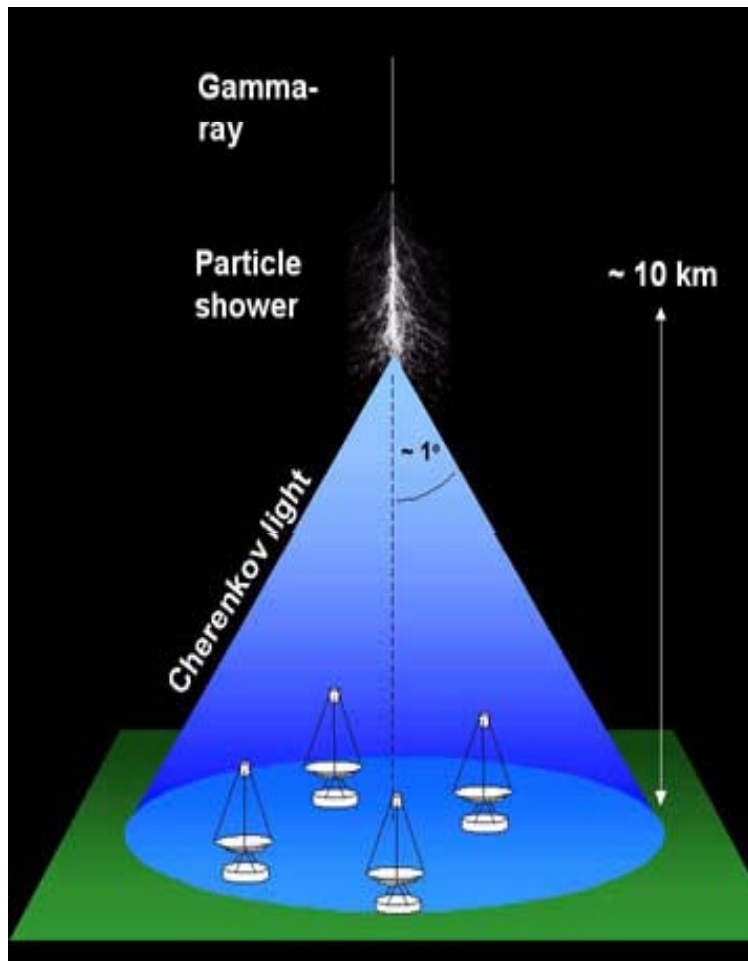


# Atmospheric Cherenkov Technique

&

# VERITAS Instrument

# Atmospheric Cherenkov Technique



Reconstruct IMAGE in camera of each telescope:

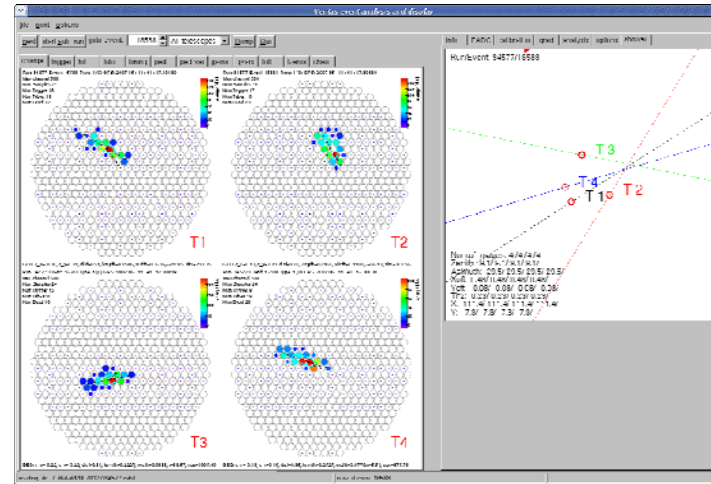


Image axis →  $\gamma$ -ray direction

Intensity →  $\gamma$ -ray energy

Image shape → particle type

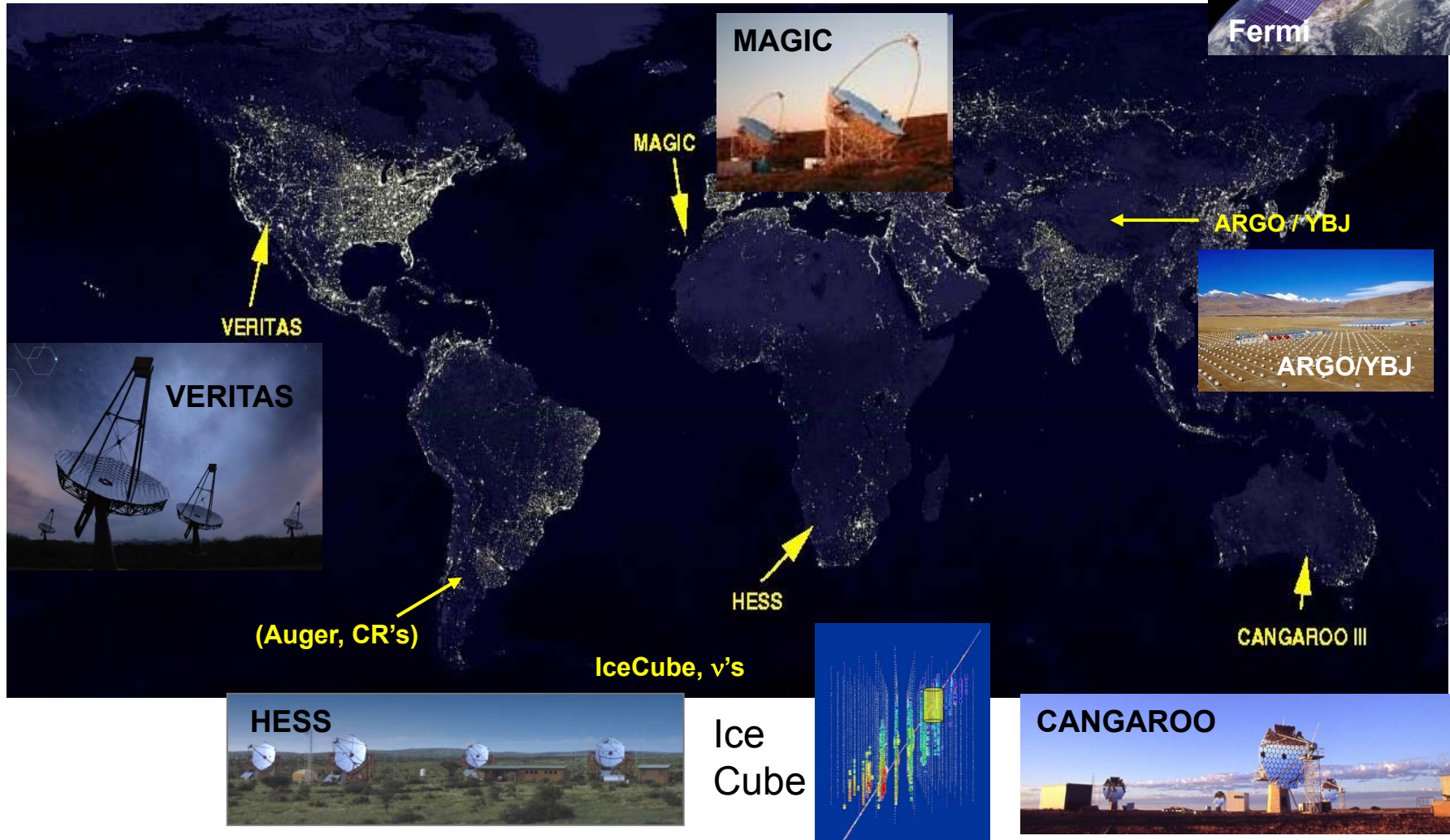
Stereoscopy gives greatly improved

**ang. resolution, E resolution,**

**$\gamma$  / had separation, SENSITIVITY**

# VHE Telescopes World-Wide

Multi-messenger Astronomy ( $\gamma, \nu, CR$ )



# VERITAS



Collaboration of ~95 scientists  
24 Institutions in five countries

## Detector Design:

- Four 12m telescopes
- 500 pixel cameras ( $3.5^\circ$ )
- Site in southern Az (1300m)

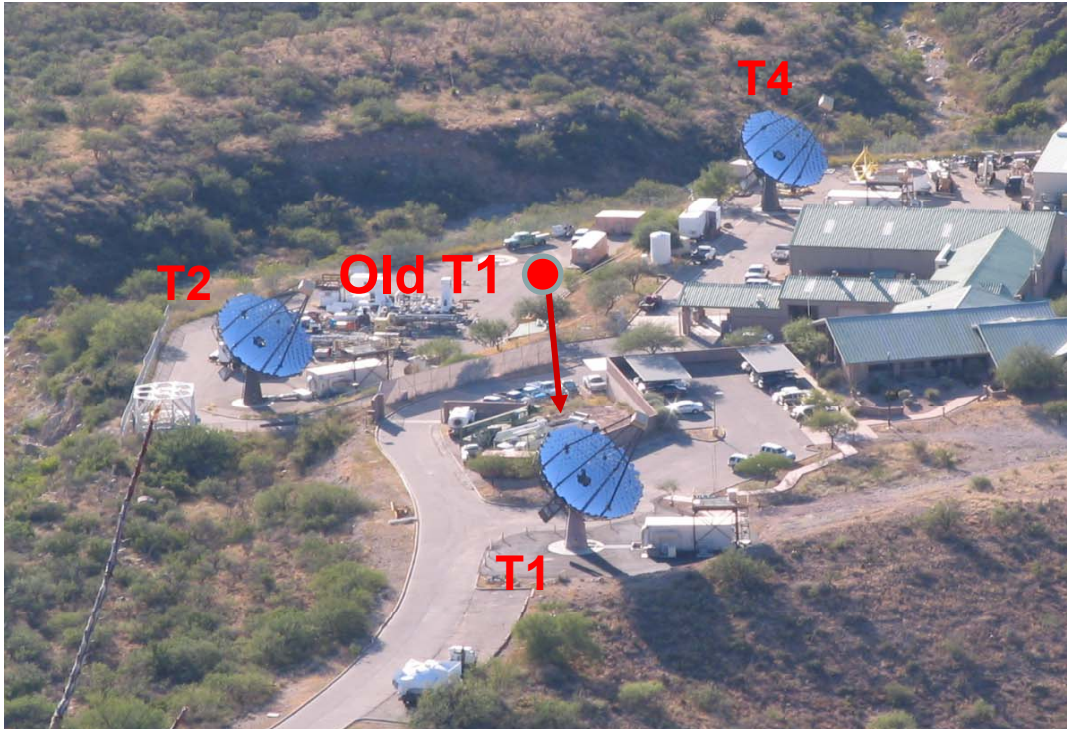
## Performance:

- Energy threshold  $\sim 100$  GeV
- Ang. resolution  $\sim 4-6'$
- **1% Crab sensitivity (<30 hrs)**

**Very Energy Radiation Imaging  
Telescope Array System (VERITAS)**



# VERITAS @ Mt Hopkins, AZ USA



## Support from:

U.S. DOE  
U.S. NSF  
Smithsonian  
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  
U. of Chicago  
U. of Delaware  
U. of Iowa  
U. of Minnesota  
U. of Utah  
Washington U.

## Canada

McGill Univ.

## U.K.

Leeds Univ.

## Non-Affiliated Members

DESY/Potsdam  
Penn State U.

## Ireland

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

## Collaboration Mtg.

July 2011, McGill University

**+ 35 Associate Members**  
**Theorists, MWL partners,**  
**IceCube, Fermi, Swift, etc.**

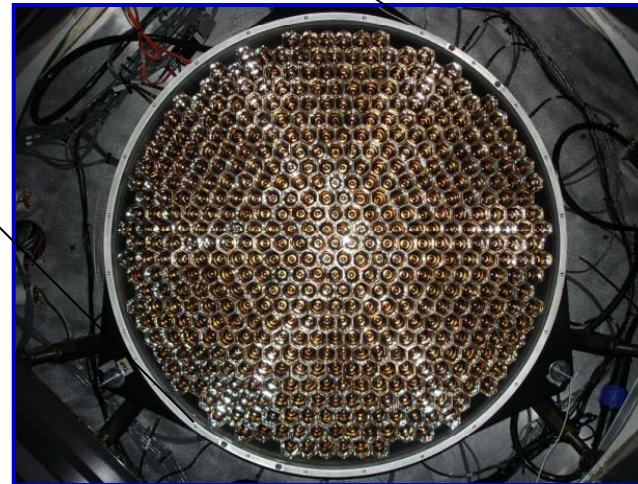
# A VERITAS Telescope



12m reflector, f1.0 optics



350 Mirror Facets



500 pixel Camera



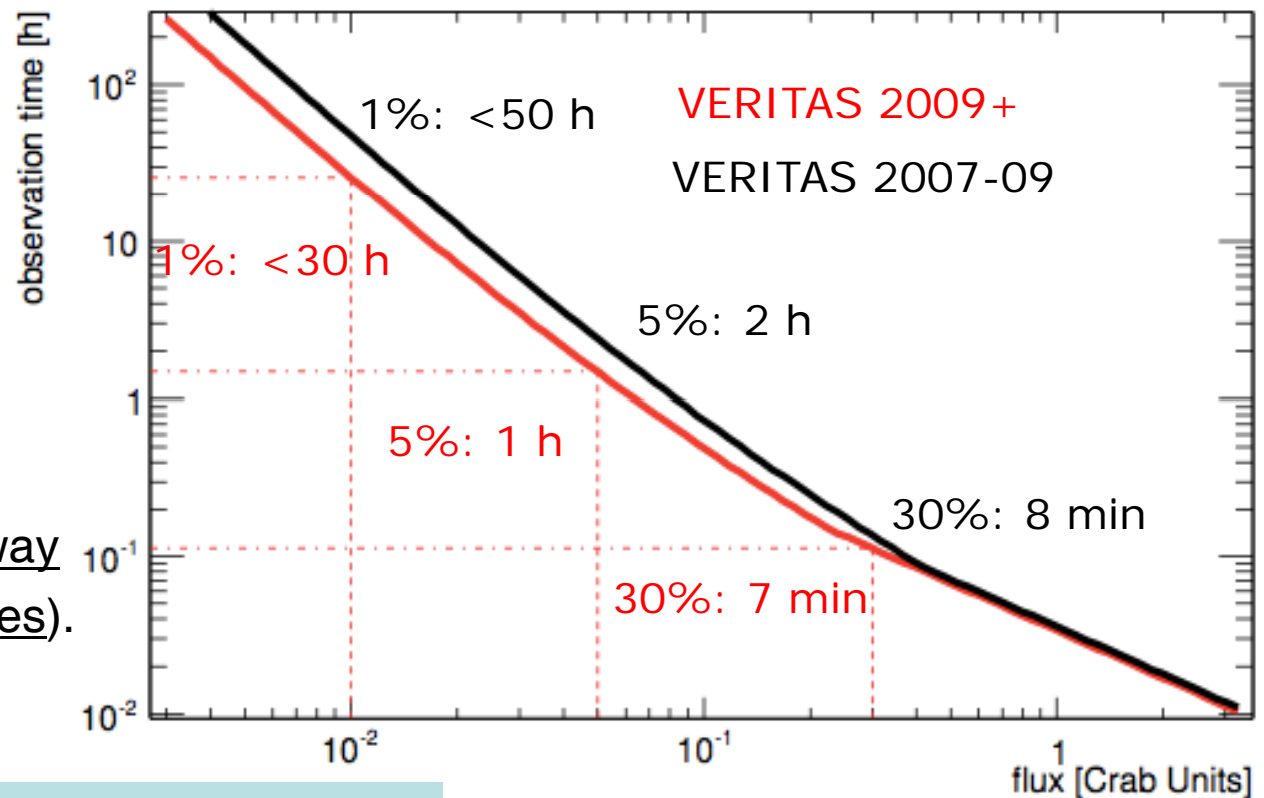
# VERITAS Performance



## Sensitivity

(% Crab detection,  $5\sigma$ )

Using a standard Hillas moment analysis  
(Improvements on the way with advanced techniques).



- Energy range: 100 GeV – 30 TeV
  - Energy resolution: 15%-25%
  - Angular resolution:  $r_{68} < 0.1^\circ$
  - Pointing accuracy:  $< 50''$
- Crab Nebula  $\gamma$ -ray rate  $\sim 0.9$  Hz (trigger)

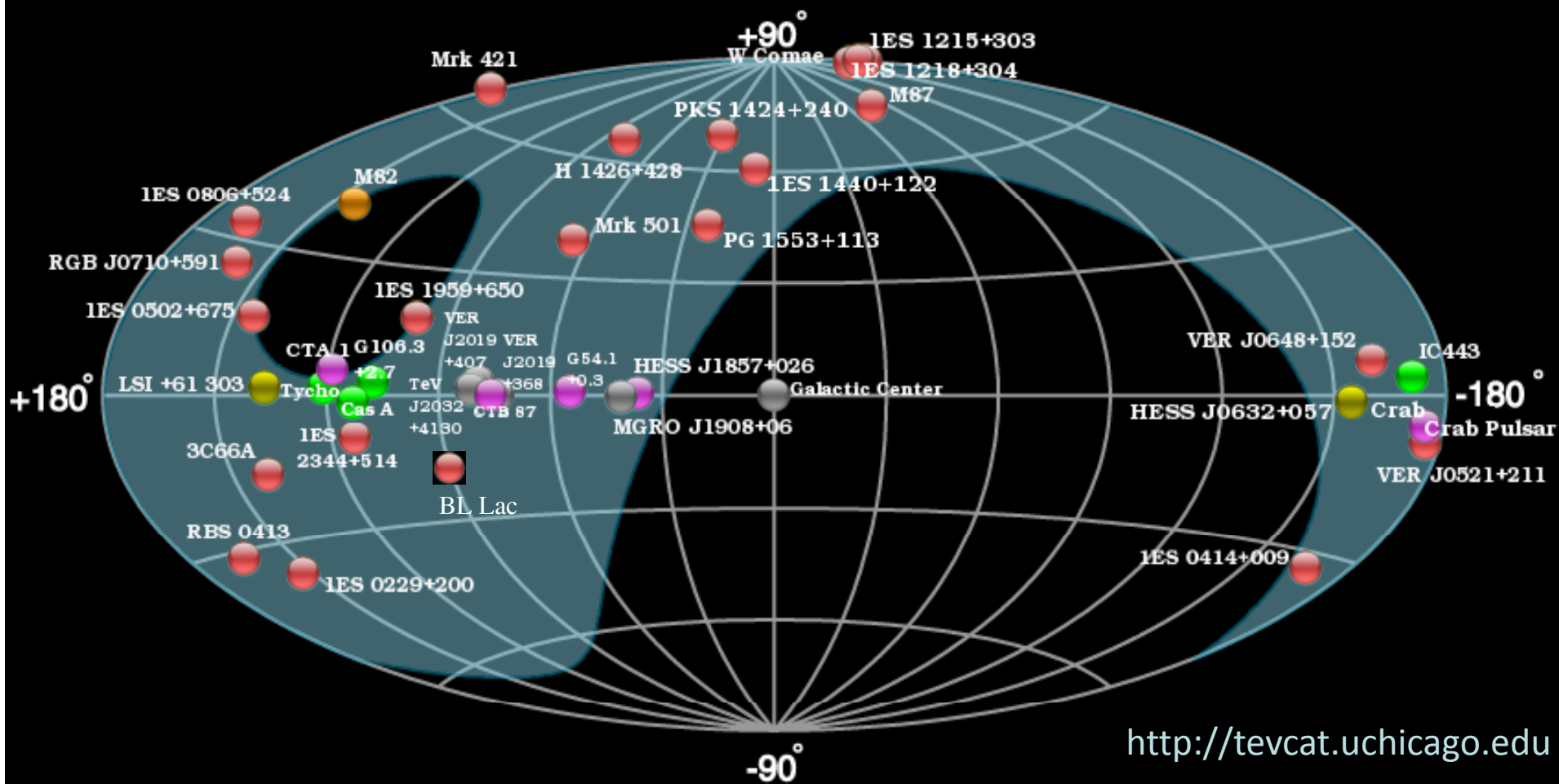
## Observing (quality data)

- $\sim 825$  dark hrs/year
- $\sim 200$  partial moon hrs/year

# VERITAS Sky Map (2011)



**40+ sources covering 8 source classes**  
**At least 17 sources are likely Galactic (SNRs, PWNe, Binaries, Unlds, Pulsars)**

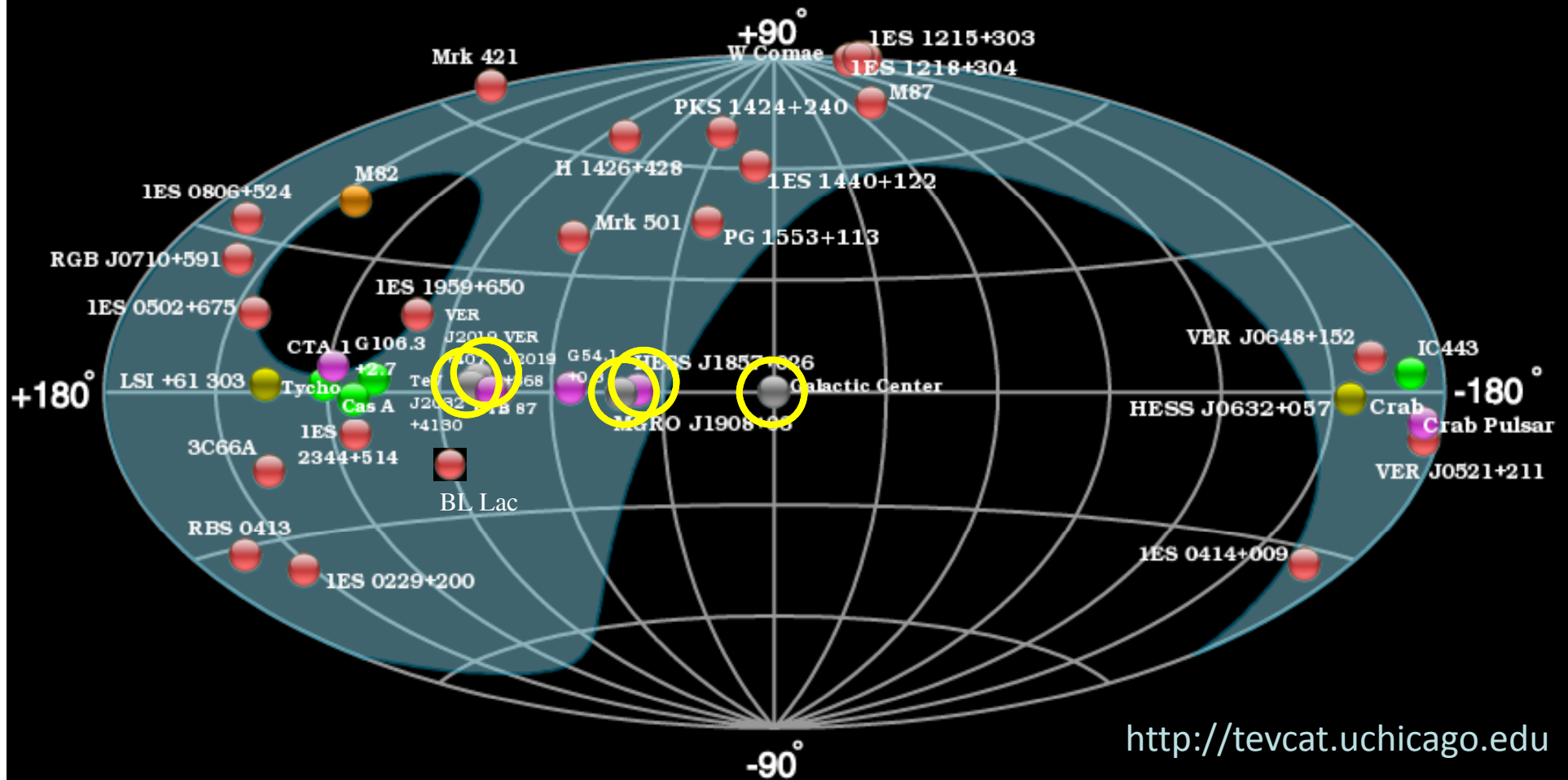


<http://tevcat.uchicago.edu>

# VERITAS UnID Sources



**Galactic Center, HESS J1857+026, MGRO J1908+06,  
TeV 2032+4130, VER J2019+407**



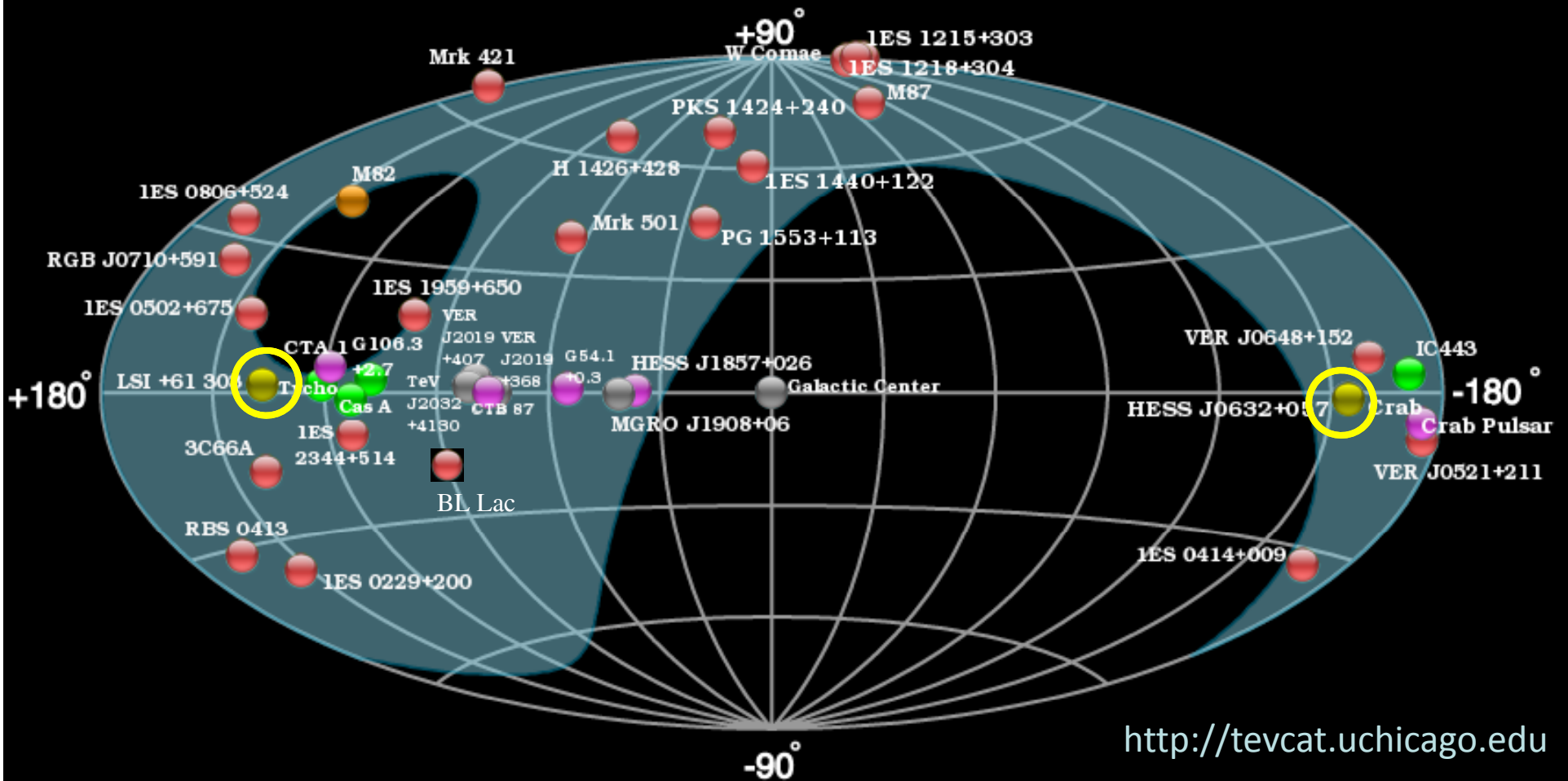
<http://tevcat.uchicago.edu>

# VERITAS Binaries



**LSI +61 303**

**HESS J0632+303 ? (stay tuned for ICRC 2011)**

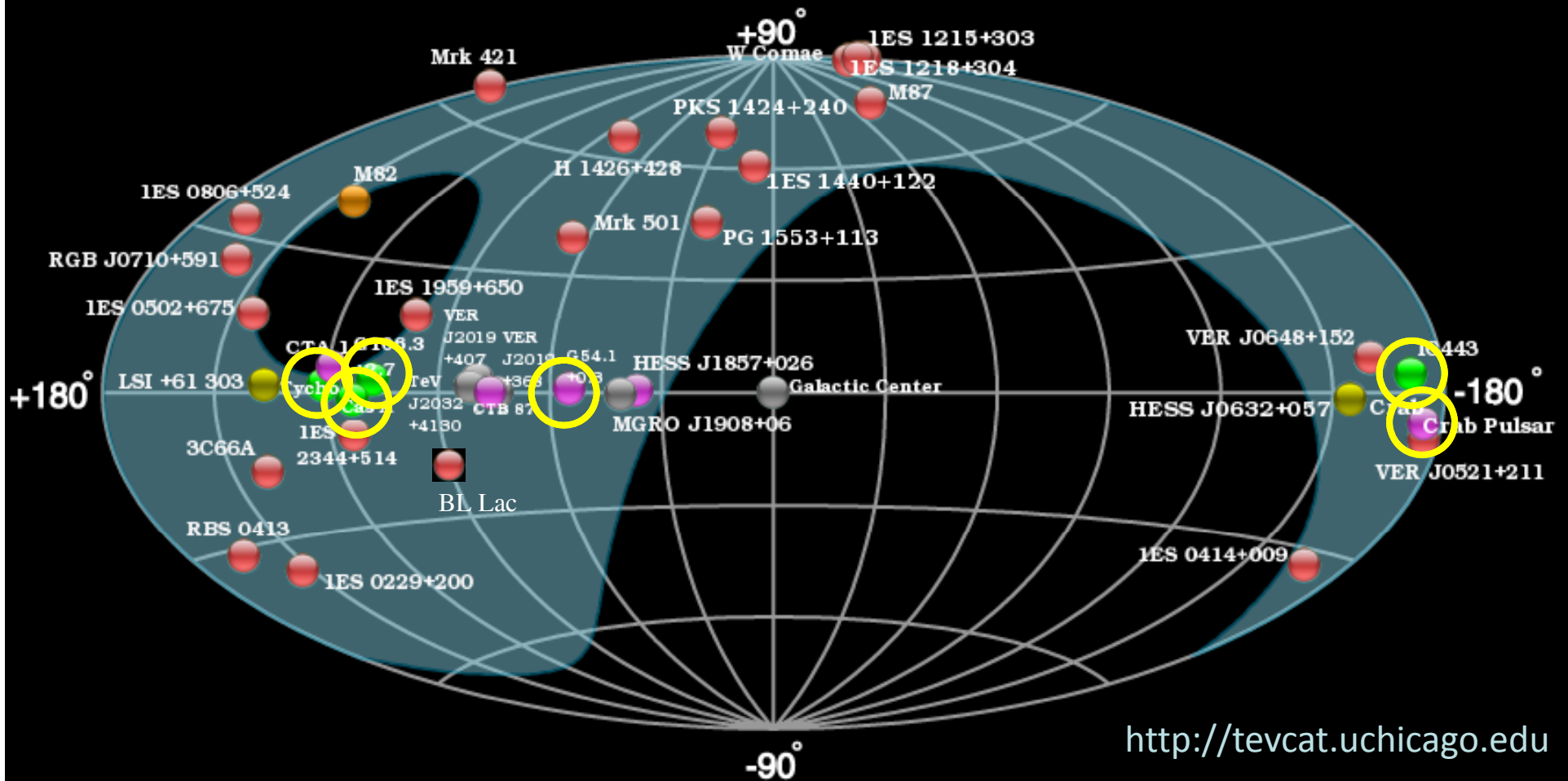


<http://tevcat.uchicago.edu>

# VERITAS SNRs and PWN



*Crab Nebula, Cassiopeia A, IC 443, G54.1+0.3, G106.3+2.7, Tycho's SNR*



<http://tevcat.uchicago.edu>

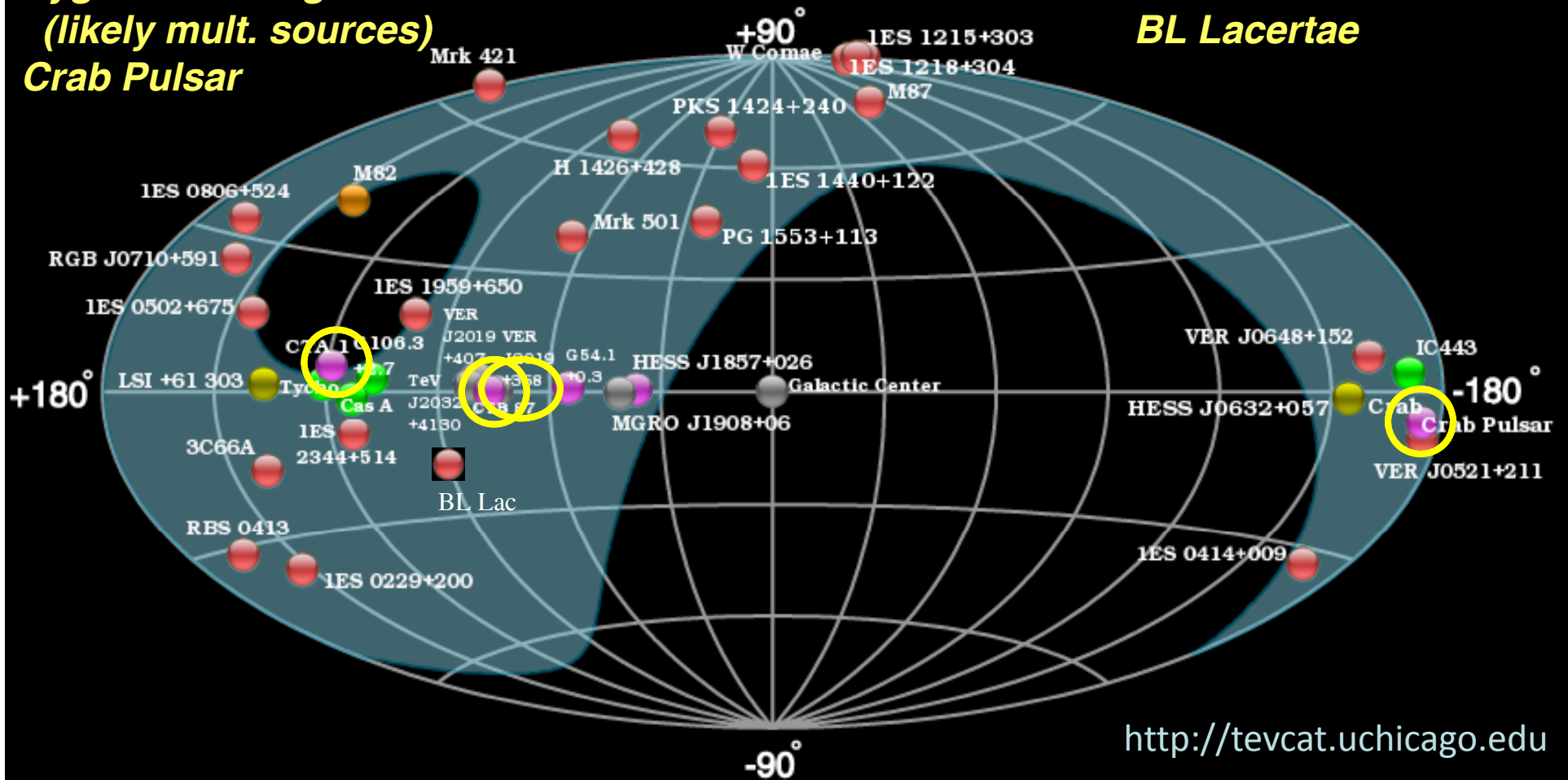


# VERITAS New Sources (2011)



**CTA 1**  
**VER J2016+372: CTB 87**  
**Cygnus OB1 region**  
*(likely mult. sources)*  
**Crab Pulsar**

**Other new Detections:**  
**Galactic Center**  
**H1426+428**  
**BL Lacertae**



<http://tevcat.uchicago.edu>



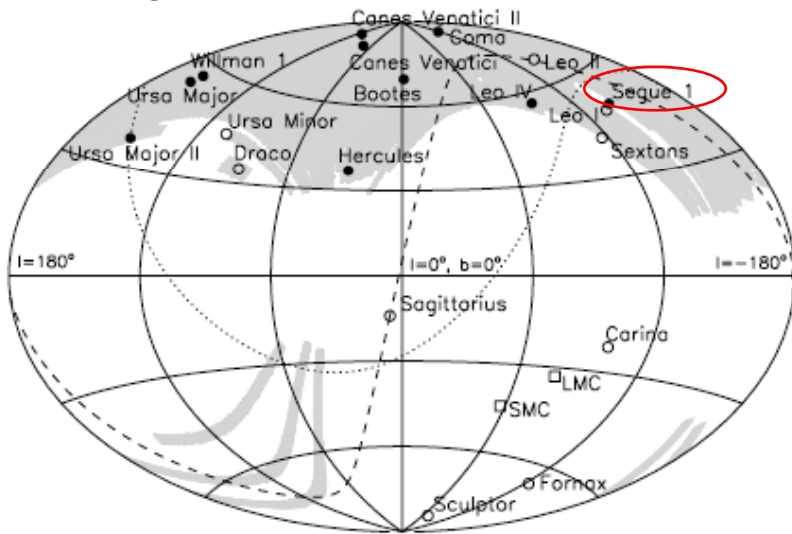


# Latest VERITAS Results

## Dark Matter

# New result on Segue 1

Segue1: dSph, DM dominated



Belokurov et al. (2007)

VERITAS Data set and analysis:  
(M. Vivier)

- 168 runs taken between Jan 2010 and May 2011.
- Standard quality selection.
- Mean zenith angle: 19.4 deg.
- **Final dataset 47.8 hrs of livetime → best sensitivity reported so far on a dSph**
- No signal seen, set flux limits at  $E = 300$  GeV, energy above which  $E(\text{bias}) < 5\%$ .
- Paper in preparation (results preliminary now).

$$\Phi_{\gamma}(E > E_{\min}) \leq 0.5 \% \text{ Crab (95\% CL)}$$

$\gamma$ -ray flux limit set based on power-law spectra and DM annihilation spectra

Spectral index	$\Phi_{\gamma}^{95\% \text{ CL}}(E \geq 300 \text{ GeV})$ [ $10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ ]
1.8	7.6
2.2	7.7
2.6	8.0
3.0	8.2

Power-law spectra

**Preliminary**

TABLE II. The 95% CL ULs on the integrated  $\gamma$ -ray flux above  $E_{\min} = 300$  GeV for power-law spectra with various spectral index. For comparison, 1% of the integrated Crab Nebula flux above  $E_{\min} = 300$  GeV is  $1.5 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ .

# New Result on Segue 1

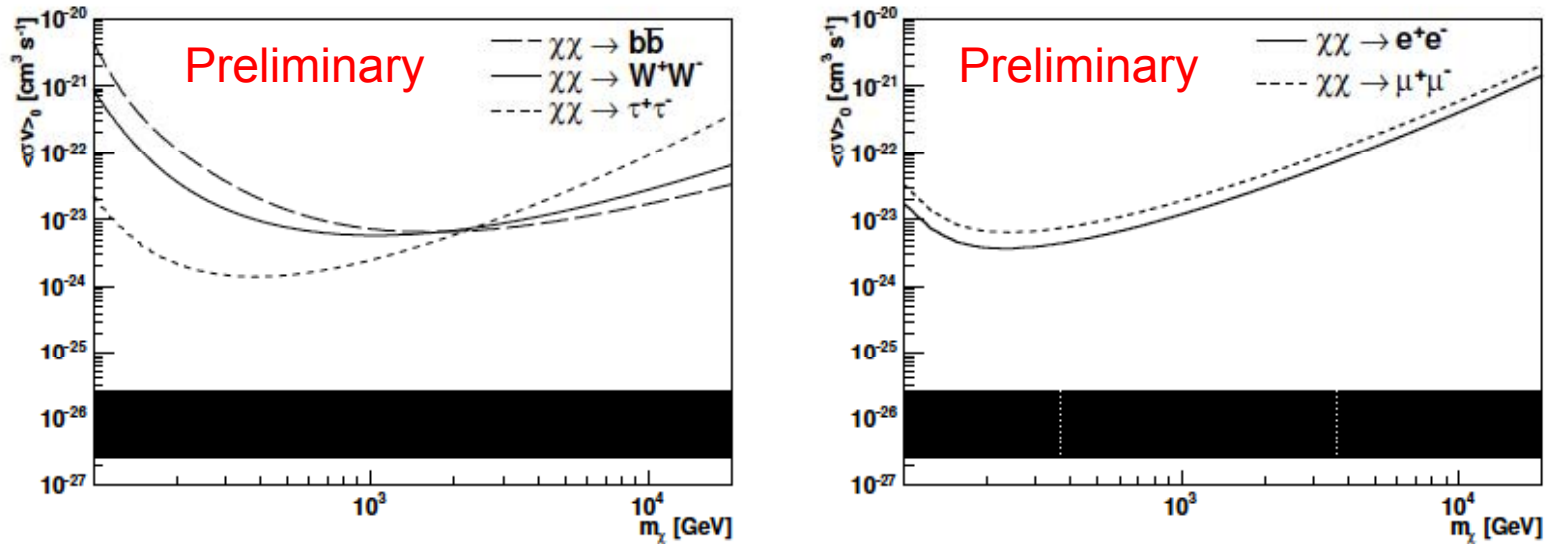


FIG. 3. 95% CL ULs on the WIMP velocity-weighted annihilation cross-section  $\langle\sigma v\rangle_0$  as a function of the WIMP mass, considering different final state particles. The grey band area represents a range of generic values for the annihilation cross-section in the case of thermally produced DM. Left: hadronic channels  $W^+W^-$ ,  $b\bar{b}$  and  $\tau^+\tau^-$ . Right: leptonic channels  $e^+e^-$  and  $\mu^+\mu^-$ .

$$\langle\sigma v\rangle_{\min} \leq 1-8 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1}$$

**Limits are factor of 4-5x better than our previous dSph results and best on dSph reported so far.**

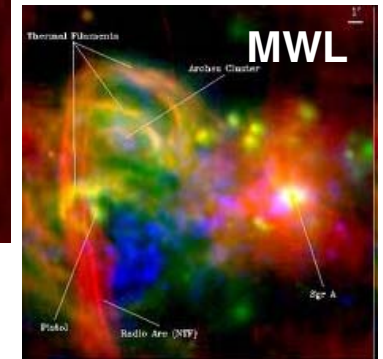
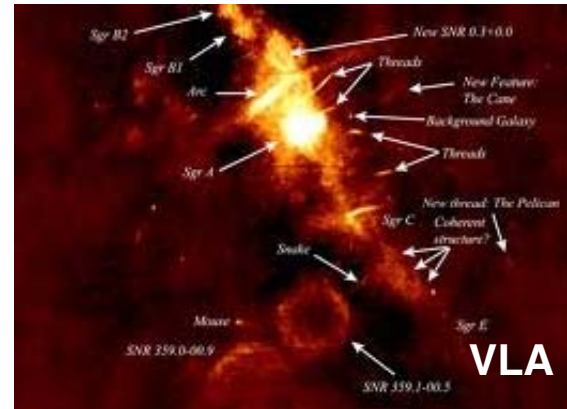


# New VERITAS Results on Galactic VHE Sources

# Galactic Center

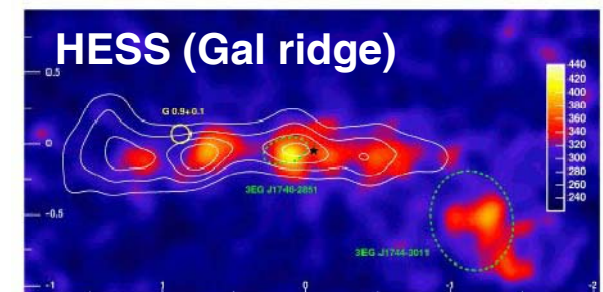
## Complex region:

- Sgr A\*,  $\sim 3 \times 10^6$  solar mass BH.
- Possible SNRs or PWN  
- increased level of CR density.
- Transients seen in X-rays, GeV  $\gamma$ -rays.
- Dark matter ?



## GeV / TeV Observations:

- **EGRET**: strong source 3EG 1746-2851.
- **CANGAROO-II (2001/2)**: 10% Crab, steep spect.
- **Whipple 10m (1995-2003, LZA)** :  $\sim 4\sigma$  evidence. (Kosack et al.)
- **H.E.S.S. (2004-2006)**: strong detection, hard spectrum  $E^{-2.1}$  with cutoff  $\sim 15$  TeV consistent with SGR A\*; also diffuse emission.
- **MAGIC (2004-2005, LZA)**: 25h,  $7.3\sigma$ , confirm H.E.S.S. spectrum.
- **Fermi-LAT**: Numerous sources in region.



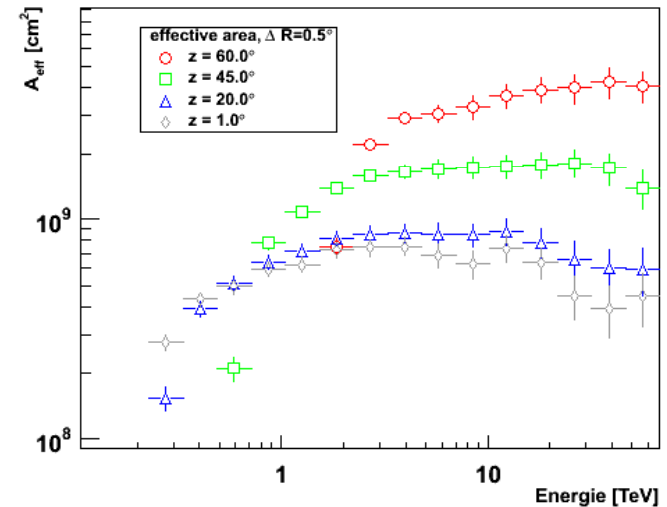
# LZA Observations

## Large Zenith Angle (LZA) method:

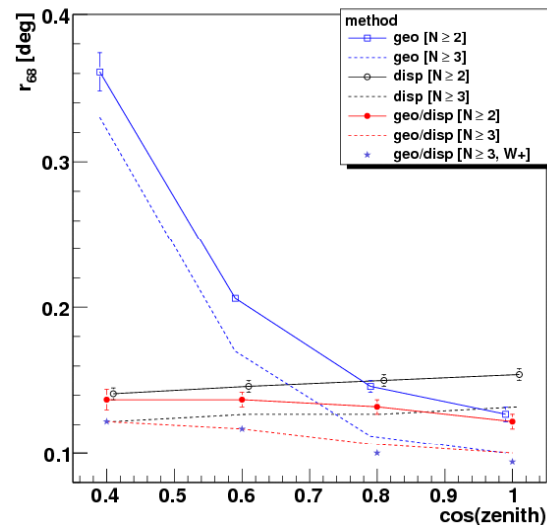
- Large effective area at high energies.
- Increased  $E_{th}$  and poorer angular recon.

## Displacement method:

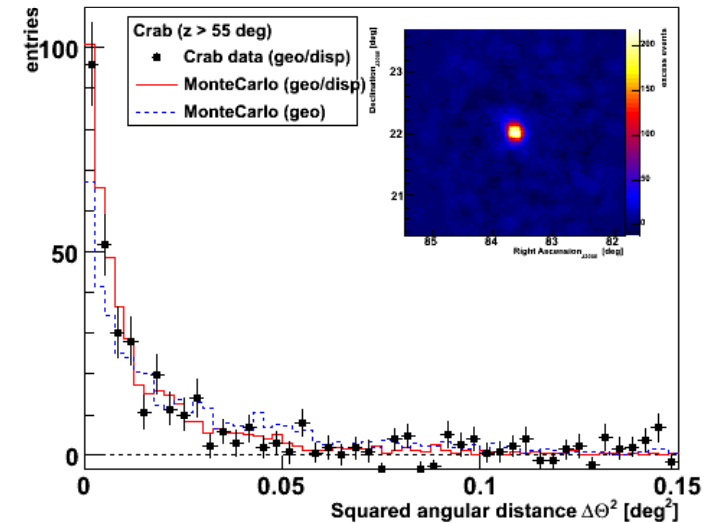
- New parameter into 6-dim lookup table.
- Combine with standard geometric method.
- Test using LZA observations of Crab.



Significantly improved angular resolution and sensitivity



M. Beilicke, G. Senturk

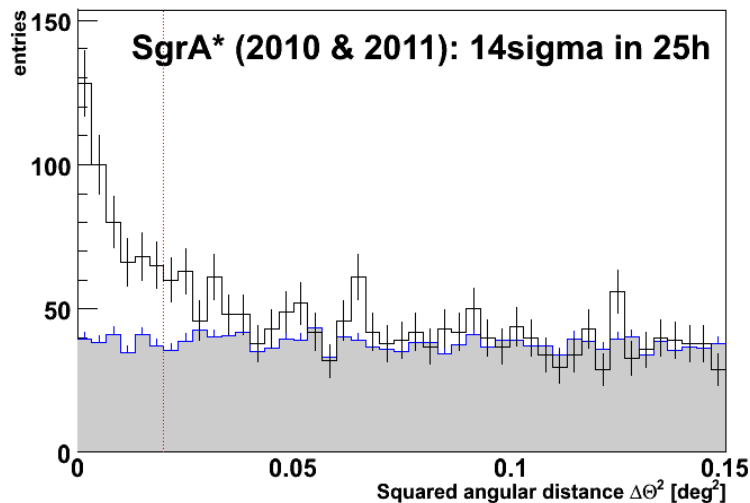




# VERITAS GC Observations

## 2010-11 Observations:

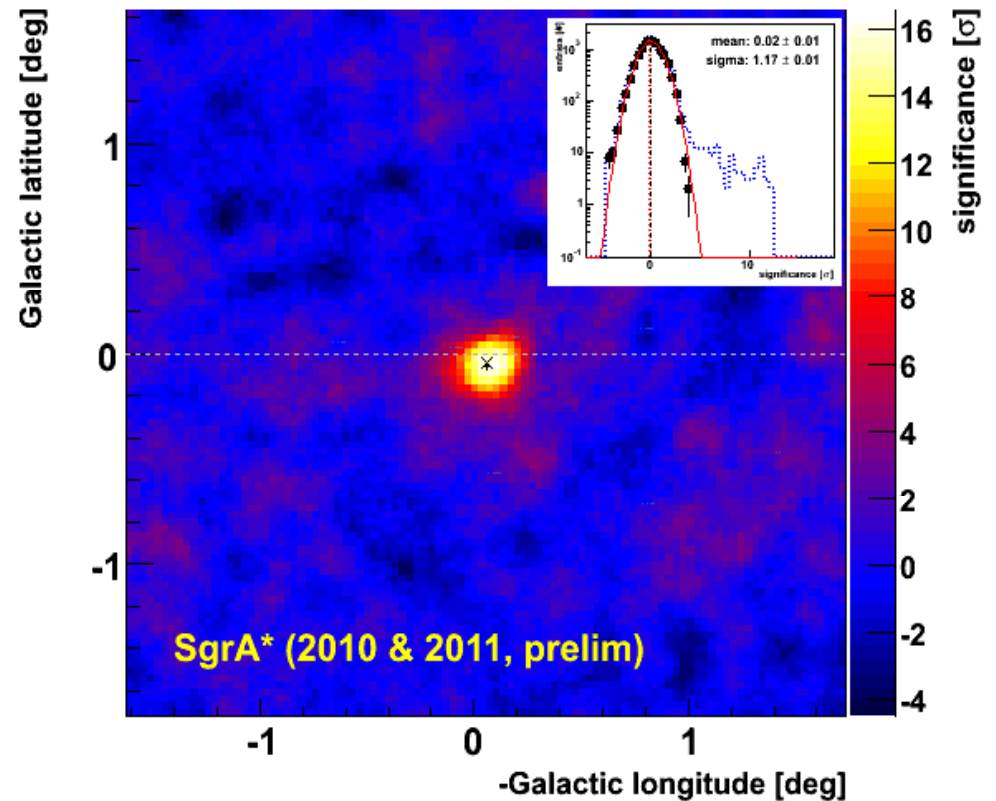
- 24.7 hrs, zenith  $\sim 65^\circ$ ,  $E > 2$  TeV
- $14\sigma$  detection
- No evidence for variability



$5\sigma$  detection possible in  $\sim 3$ h

## Sky map:

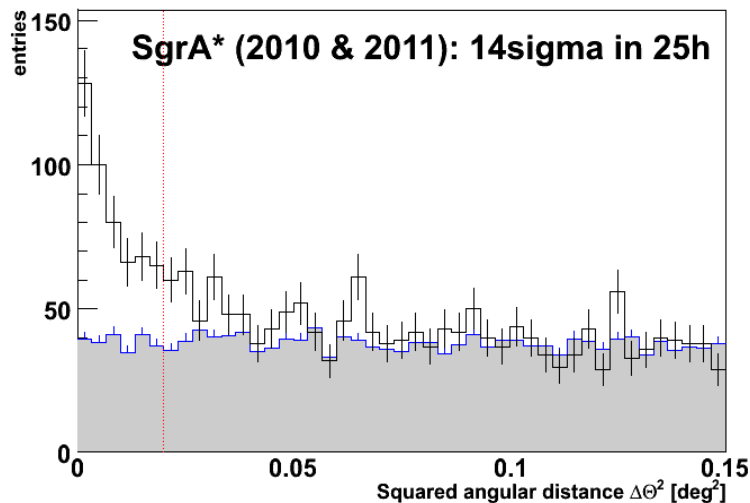
- Excess at GC, fit position:  
 $l = -0.06 \pm 0.02$ ;  $b = -0.06 \pm 0.01$
- Consistent with H.E.S.S. (overlay)



# VERITAS GC Observations

## 2010-11 Observations:

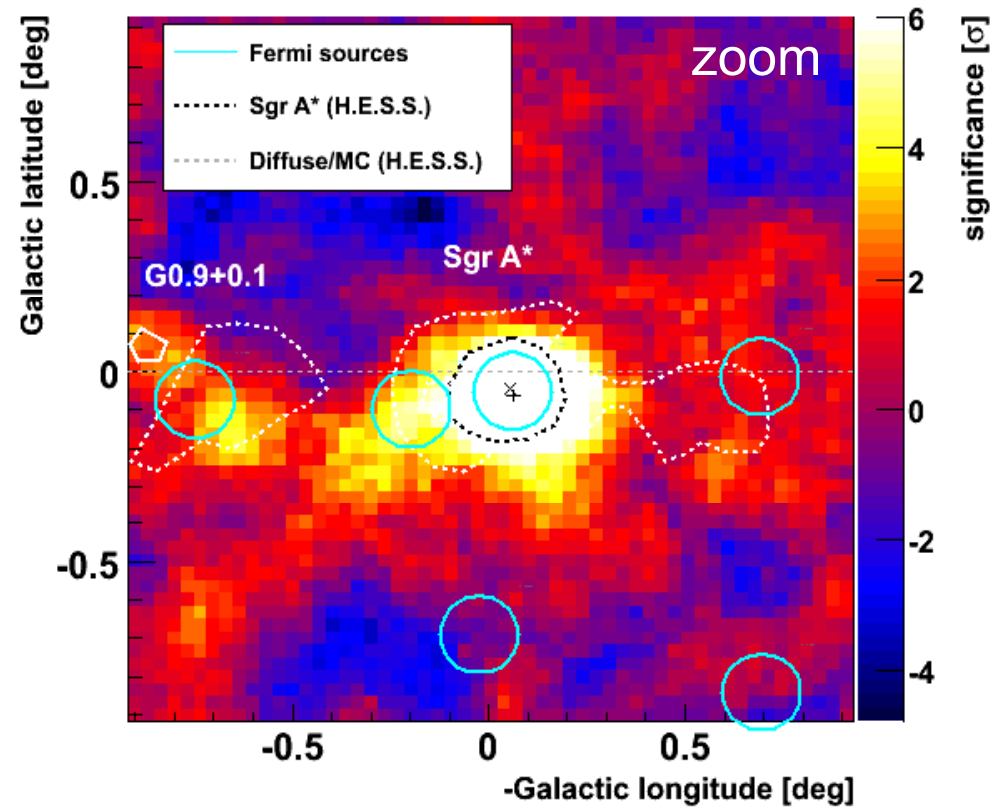
- 24.7 hrs, zenith  $\sim 65^\circ$ ,  $E > 2$  TeV
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## Sky map:

- Excess at GC, fit position:  
 $l = -0.06 \pm 0.02$ ;  $b = -0.06 \pm 0.01$
- Consistent with H.E.S.S. (overlay)



# VERITAS GC Energy Spectrum

## Spectrum (preliminary):

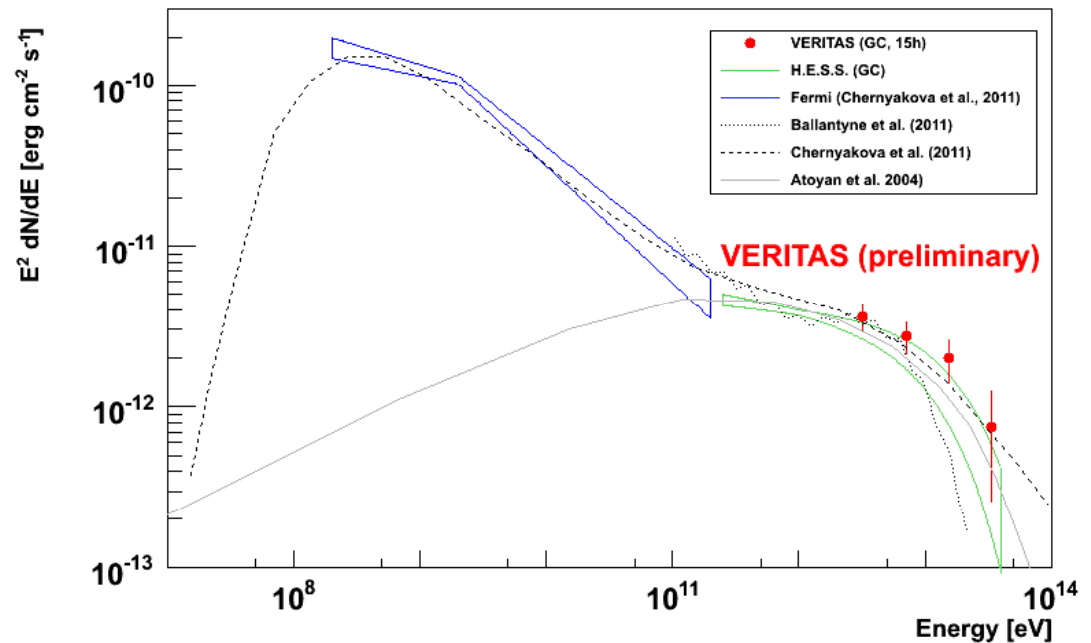
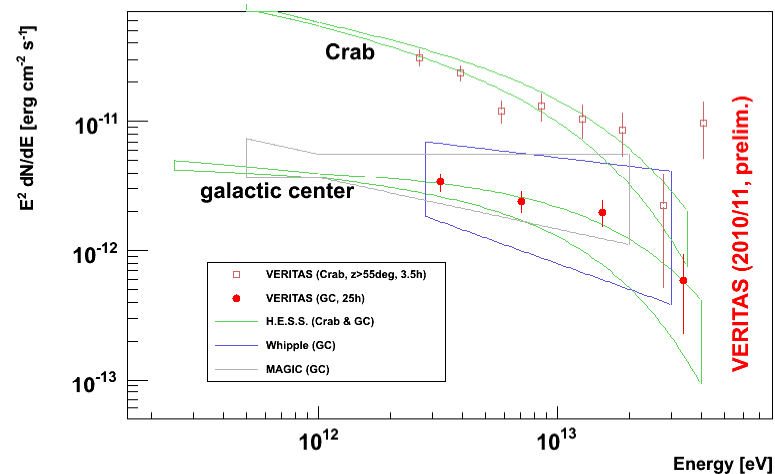
- Compatible with Whipple, H.E.S.S. and MAGIC.
- Conservative flux systematic  $\sim 40\%$  (from Crab LZA).

## Comparison to some models:

- Hadronic accelerator models near BH - (Chernyakova et al. 2011) and (Ballantyne et al. 2011).
- Plerion wind model of (Atoyan et al 2004).

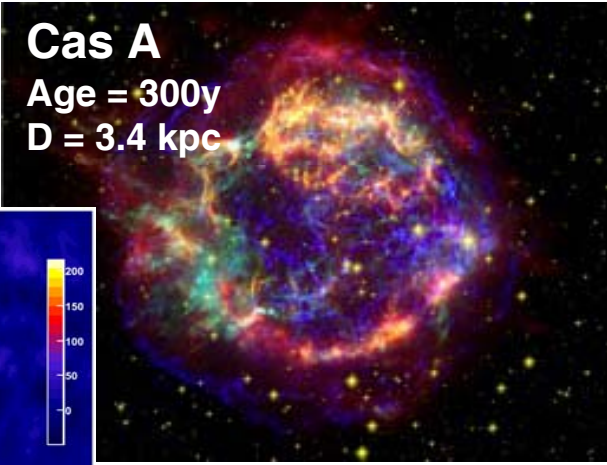
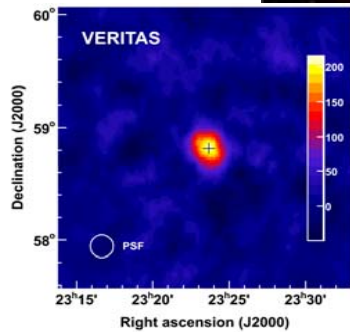
### Future:

Improved  $>10$  TeV data (spectrum & variability) to constrain cut-off.

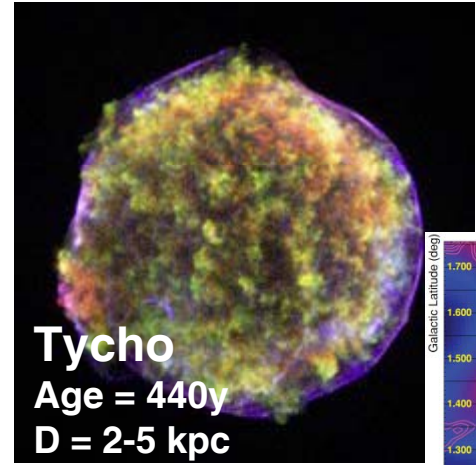


# VERITAS Supernova Remnants

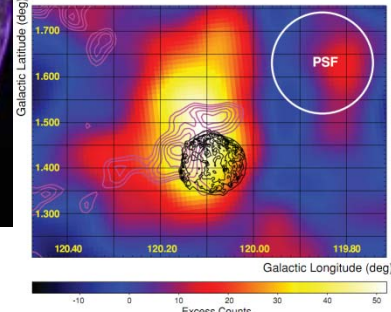
**Cas A**  
~3% Crab



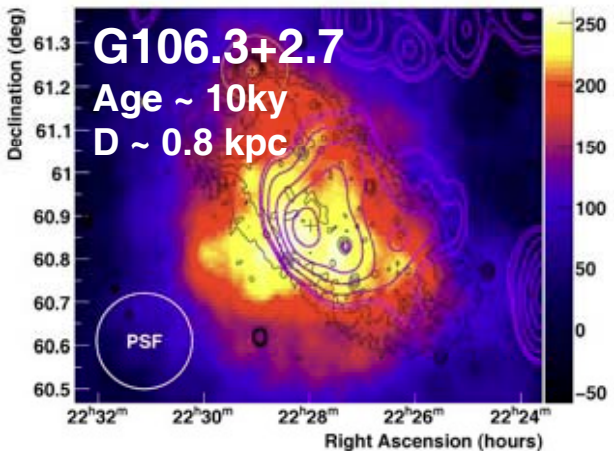
**Cas A**  
Age = 300y  
D = 3.4 kpc



**Tycho**  
Age = 440y  
D = 2-5 kpc

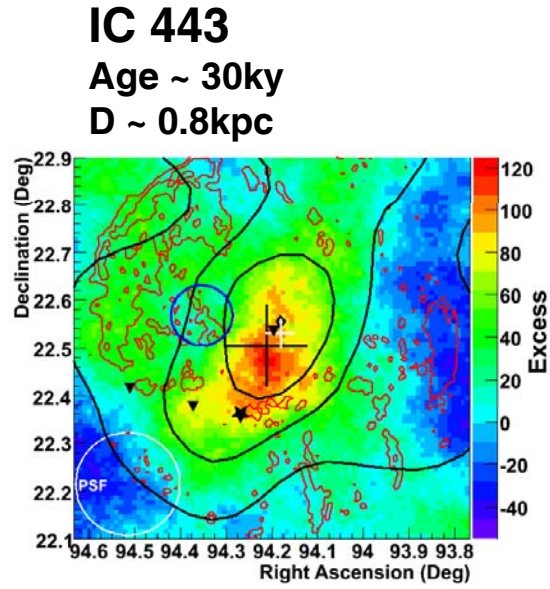


**Tycho**  
~1% Crab

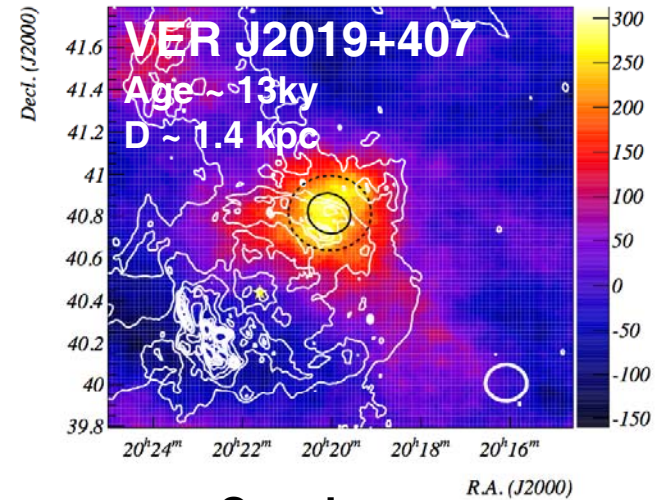


**G106.3+2.7**  
Age ~ 10ky  
D ~ 0.8 kpc

**Boomerang**



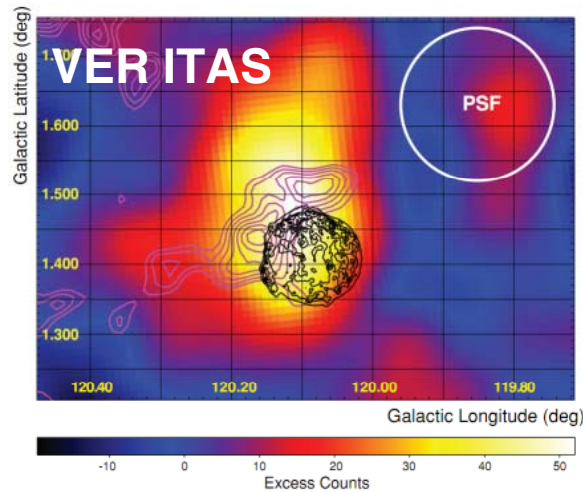
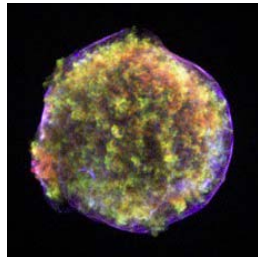
**IC 443**  
Age ~ 30ky  
D ~ 0.8kpc



**VER J2019+407**  
Age ~ 13ky  
D ~ 1.4 kpc

**γ-Cygni**

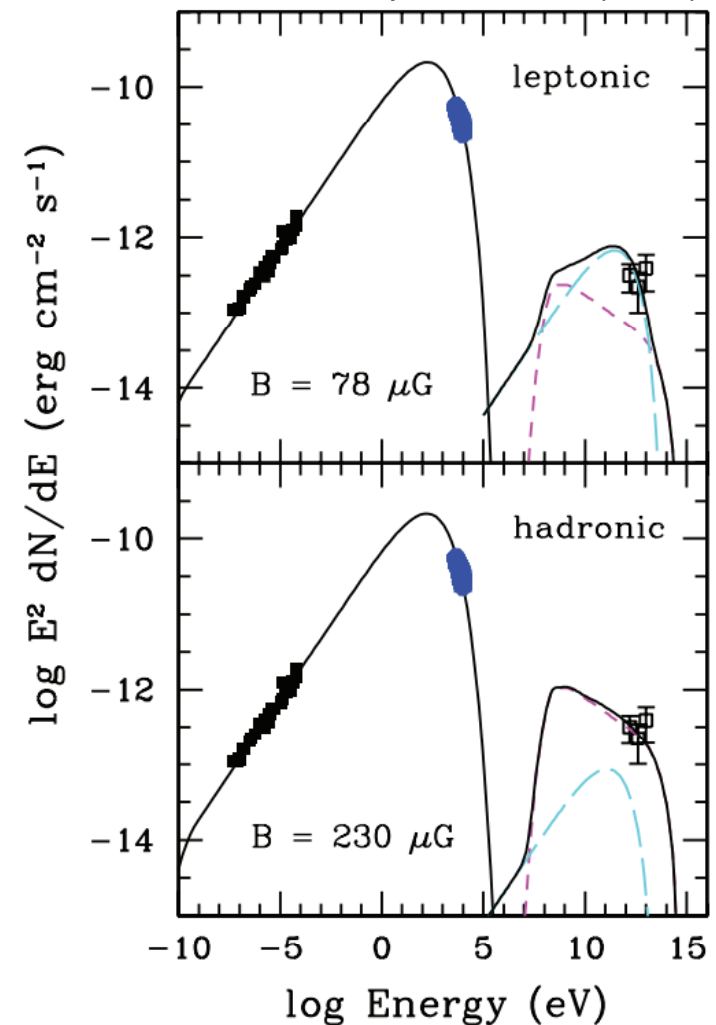
# Tycho's SNR: VERITAS Discovery



## Tycho's SNR:

- Historical Type 1a SN of 1572.
- X-ray morphology argued for hadronic acceleration (Warren et al. 2005).
- VERITAS discovery in 2010 with 68 hrs.
- Weak source (0.9% Crab) with hard power-law spectrum  $\Gamma = 1.95 \pm 0.51 \pm 0.30$ .
- Consistent with leptonic or hadronic models.

V.A. Acciari et al., ApJ 720, L20 (2011)





# Tycho with Fermi-LAT, Hadrons ?

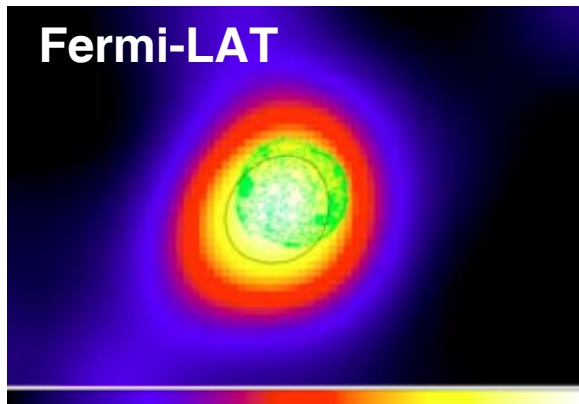
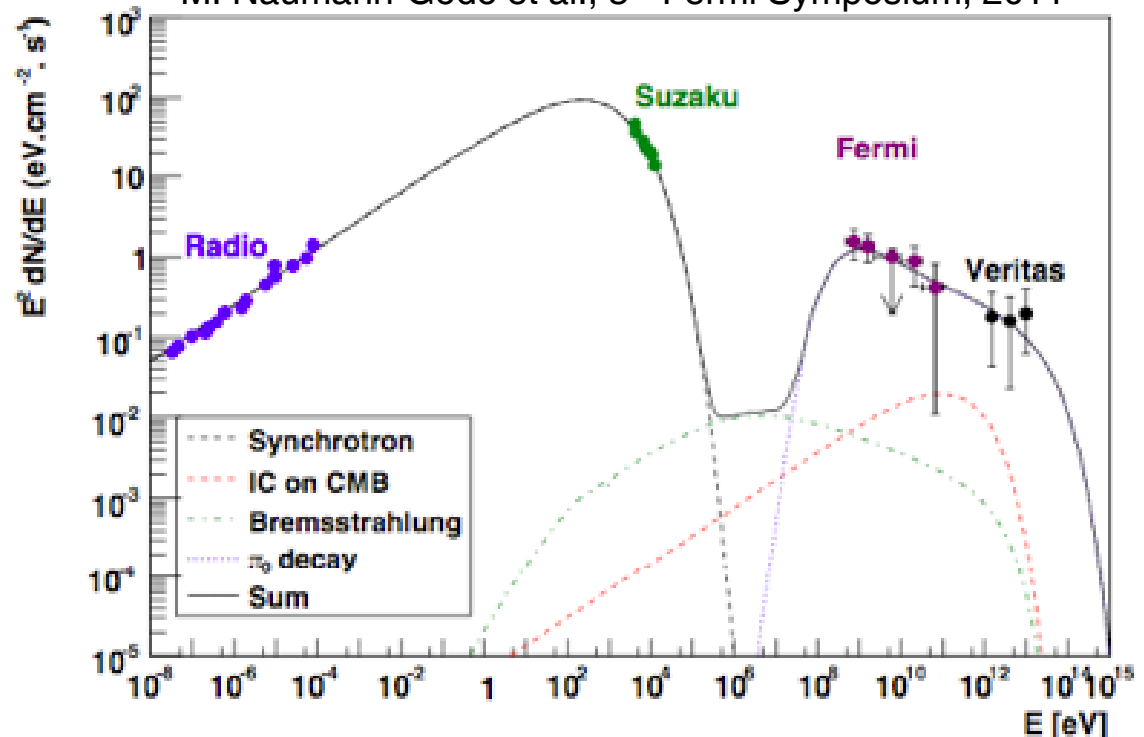


Figure 2: Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.

M. Naumann-Godo et al., 3<sup>rd</sup> Fermi Symposium, 2011



## Fermi-LAT & VERITAS:

- New Fermi-LAT detection ( $5\sigma$ ).
- Hard photon index of  $2.3 \pm 0.1$  favors hadronic origin.
- 6-8% of  $E_{sn}$  transferred to CR acceleration ( $D \sim 2.8 \text{ kpc}$ ).

Good evidence for hadron accelerator; similar for Cas A



# CTA 1: First Blind-Search Fermi Pulsar

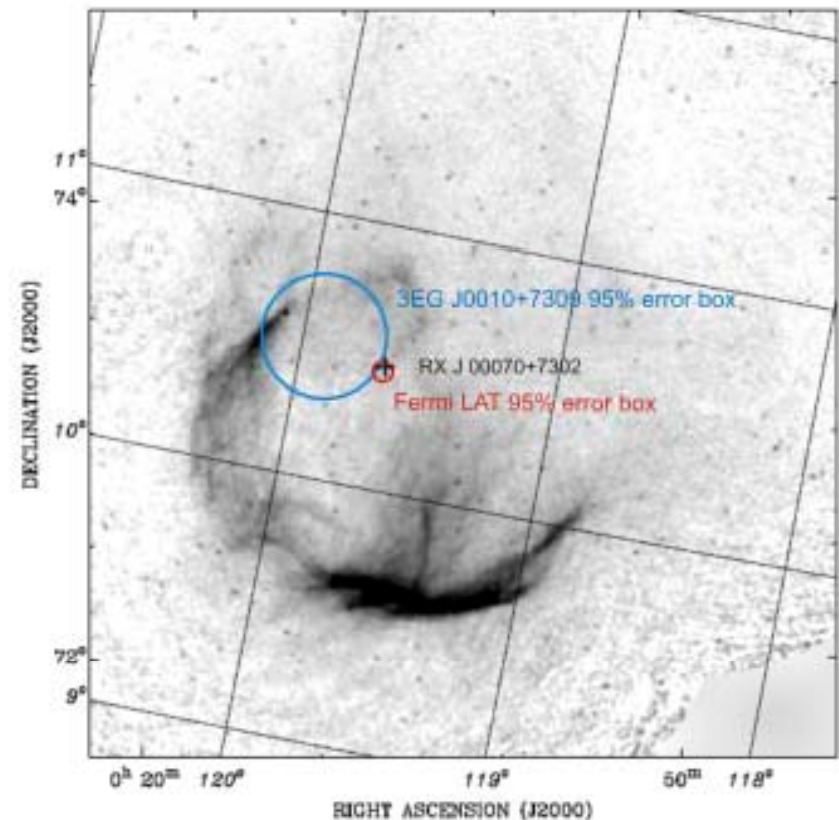
## CTA 1:

- Composite SNR with an X-ray filled radio shell  $\sim 1.8^\circ$  diameter.
- Age  $\sim 13$ ky,  $D \sim 1.4 \pm 0.3$  kpc .
- No known pulsar (before Fermi).

## Fermi-LAT Observations (2008):

- Pulsar discovered in blind search in first four months of data – coincident with X-ray source, presumed PWN.
- Period = 316.9ms,  $E_{\text{cutoff}} \sim 5$  GeV; characteristic pulsar age  $\sim$  SNR age.
- X-ray pulsar subsequently detected with Chandra (P. Caraveo et al. 2010).

A. Abdo et al., Science 322, 1218 (2008)



Fermi-LAT source (red), X-ray PWN), EGRET source (blue) and radio contours.

# CTA 1: VERITAS Detection

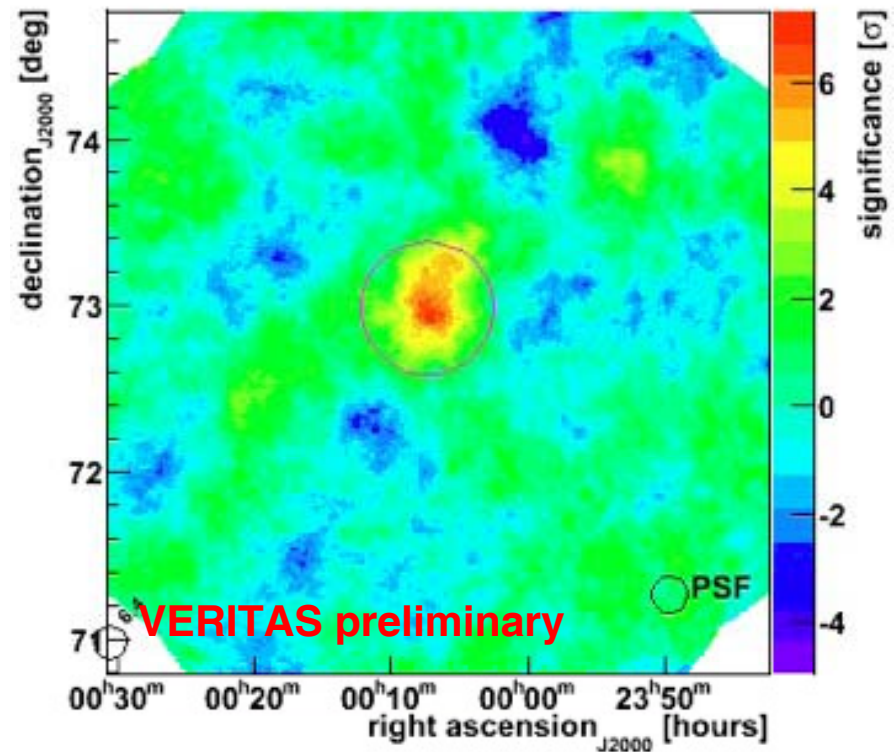
## VERITAS Observations:

- 26 hrs, Oct 2010-Jan 2011 at  $0.7^\circ$  wobble.
- Search region: circle of  $r=0.4^\circ$ , tiled in  $0.04^\circ$  square sections; pt-source & ext cuts.
- Trials factor  $\sim 1300$ .

## Detection:

- Significance  $\sim 6.3\sigma$  post-trials.
- $F (> 1 \text{ TeV}) \sim 4\%$  Crab Nebula.
- Clearly extended source.

S. McArthur, R. Mukherjee



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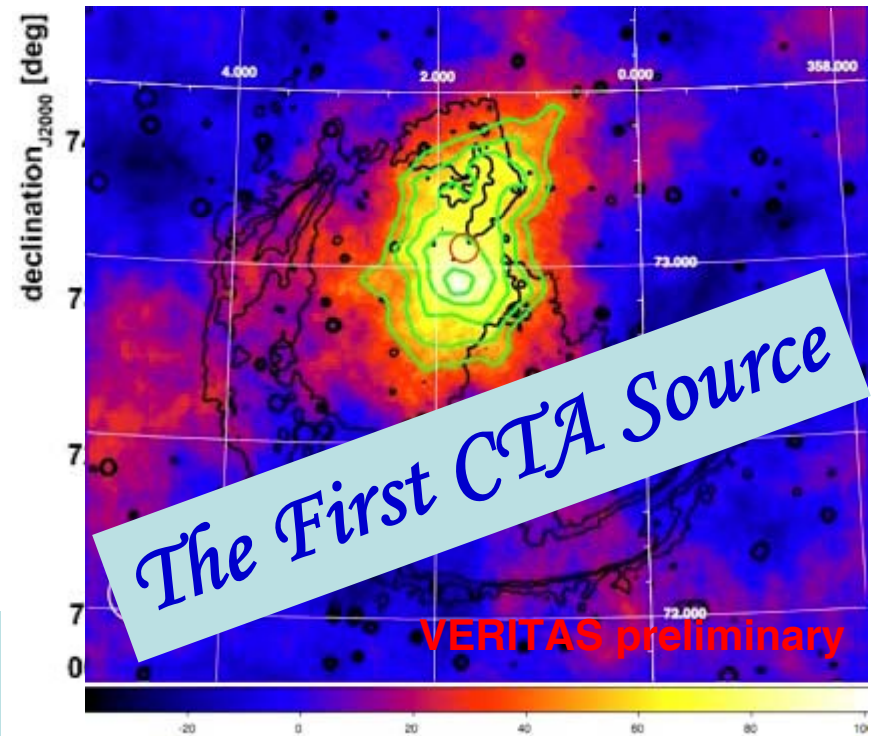
- Significance  $\sim 6.3\sigma$  post-trials.
- $F (> 1 \text{ TeV}) \sim 4\%$  Crab Nebula.
- Clearly extended source.

## MWL Picture:

- VERITAS emission surrounds the Fermi-LAT pulsar.
- Properties of CTA 1 in middle range of known TeV/X-ray PWN.

Good evidence that CTA 1 is a PWN  
(new indications from Fermi-LAT too)

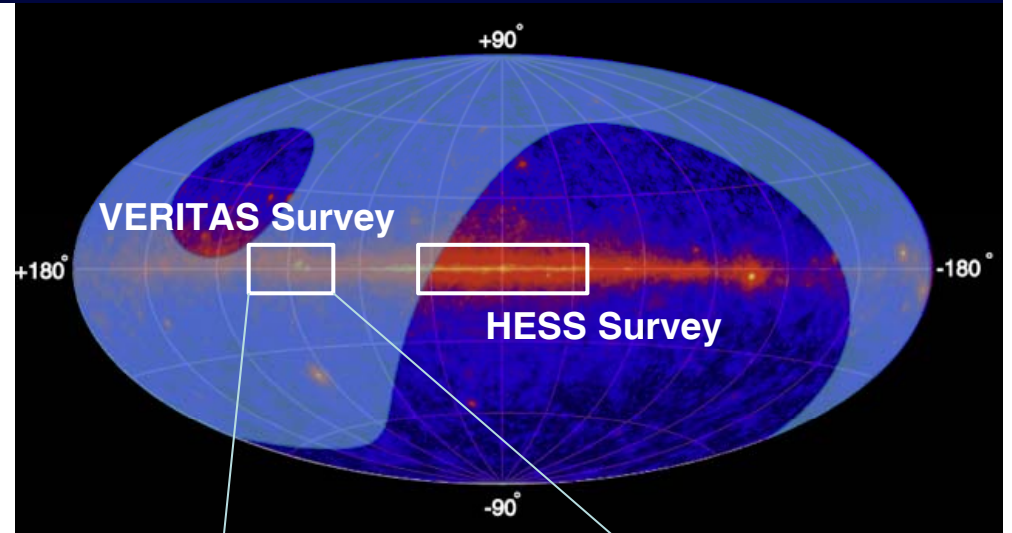
Color: VERITAS excess map with green contours from  $3-7\sigma$ .  
Black: Radio 1420 MHz (T. Landecker).  
Red: Fermi-LAT error circle.



# VERITAS Cygnus Sky Survey

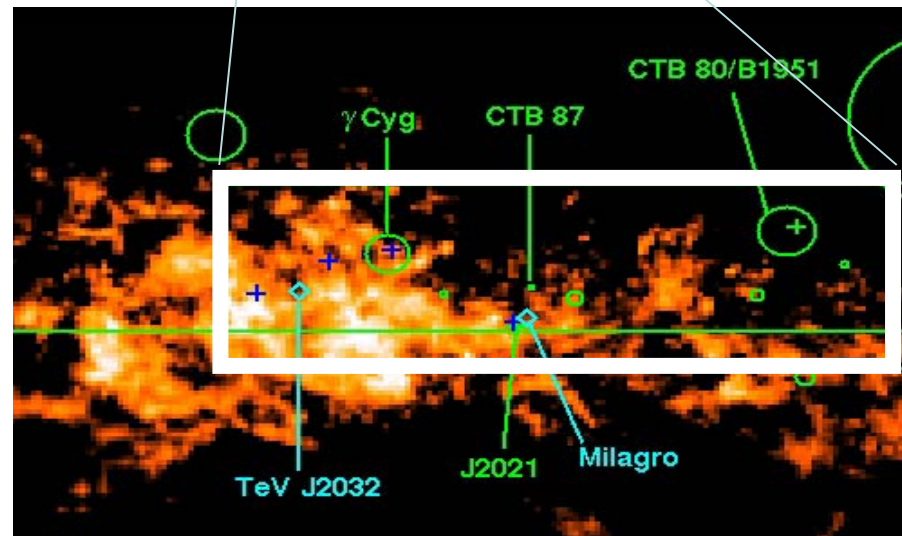
## VHE Sky Surveys:

- **HEGRA (97-02):** North, ~25% Crab.
- **HESS (03-04):** South, ~3% Crab. and extended (05-08).
- **Milagro (01-07):** North, ~35% Crab at  $E > 10$  TeV.



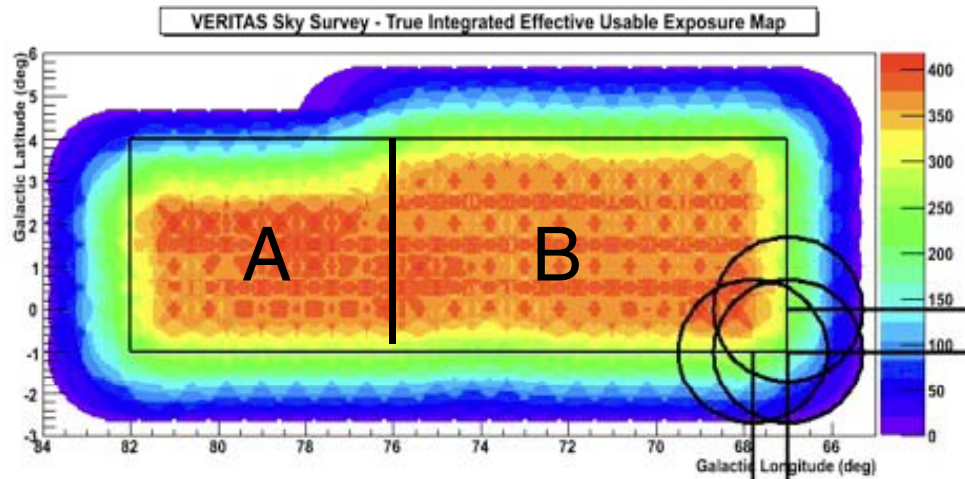
## VERITAS Sky Survey (07-09):

- N. Hemisphere – Cygnus arm.
- 115h + 55h follow-up; done before improvements to sensitivity.
- ~3% Crab (99%) for  $E > 200$  GeV.





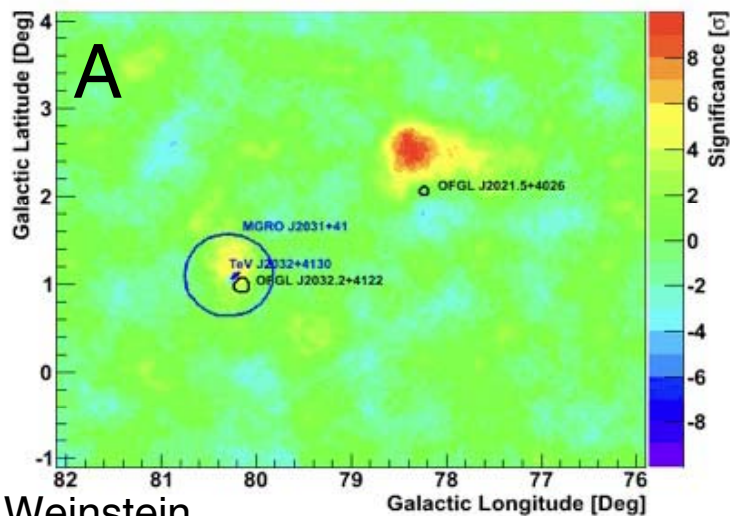
# VERITAS Cygnus Sky Survey



## Survey exposure map

- Survey done by pointings spaced by  $0.8^\circ$  in  $l$  and  $1.2^\circ$  in  $b$ .
- Overall scope limited by summer and weather conditions.

## Left side region (2010)



## TeV J2032+4130

- First UnID TeV source

## VER J2019+407

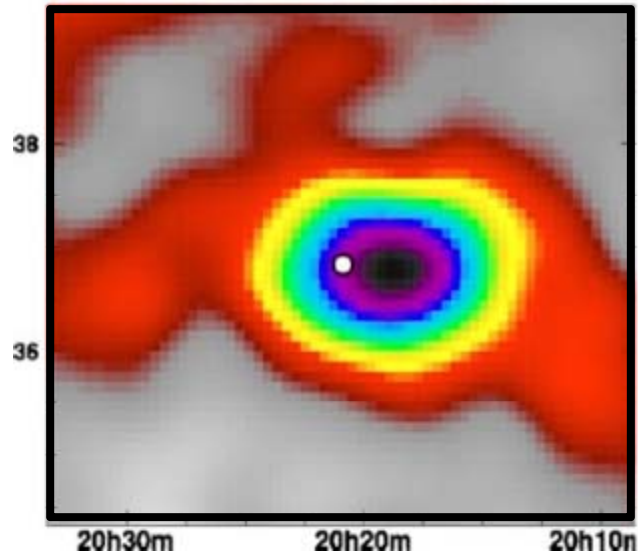
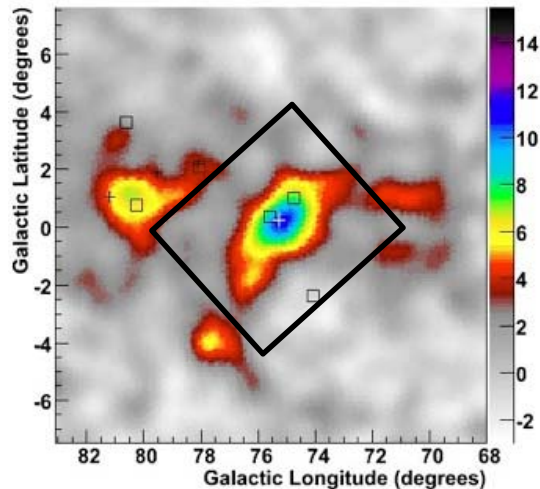
- New source near  $\gamma$ -Cygni.
- SNR interaction with HI shell ?

Now, discuss some results from region B.

A. Weinstein



# Cygnus OB1 (“Cisne”, “Dragonfly”)



A. Abdo et al.,  
ApJ 664, L91 (2007)

## MGRO J2019+37

- Brightest new source in Milagro survey, ~80% Crab,  $E > 15$  TeV (A. Abdo et al. 2007). (But not seen by ARGO/YBJ... ?).
- Coincident with two EGRET sources – one proposed as blazar (Mukherjee et al., 2000) and other proposed as PSR J2021+3651 (Roberts et al. 2002) – both sources confirmed by Fermi-LAT.
- Large effort to look for counterparts in radio (Parades 2009) and X-ray (Zabalza & Parades 2010).
- Origin of 10 TeV emission not clear – PWN ? Shocks from WR stars in OB1 complex (Bednarek 2009)?

# VERITAS Observations of Cygnus OB1

## Observations and Analysis:

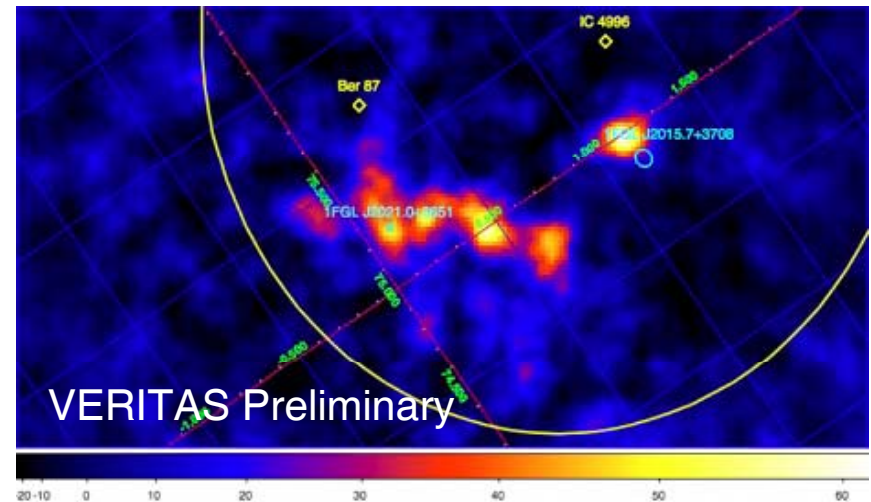
- 75h, May-Dec 2010.
- $0.7^\circ$  wobble around PSR J2021+3651.
- Pt-source and extended search ( $0.25^\circ$ ).
- Hard cuts,  $E_{\text{th}} \sim 600$  GeV.

## Results:

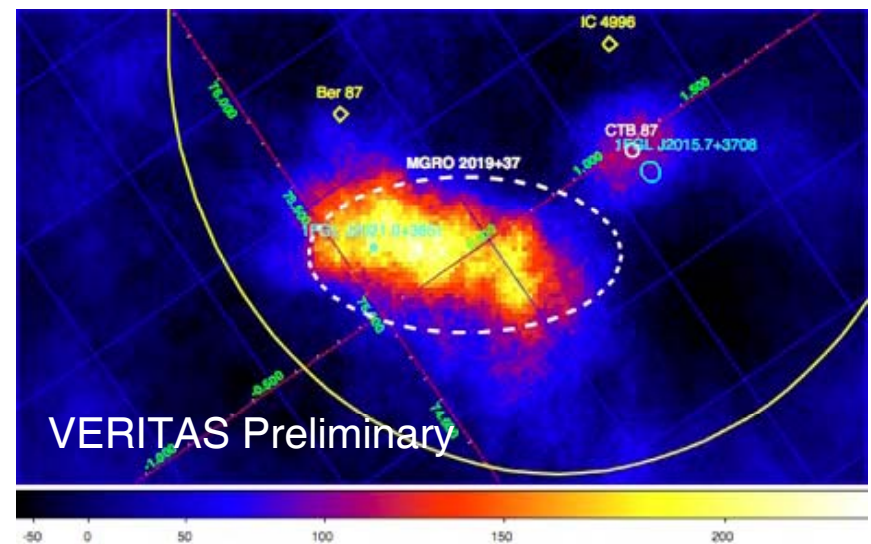
- Point source and extended source both detected above  $6\sigma$ , post-trials.
- The extended source is a complex region, most likely made up of multiple sources.

E. Aliu et al.,  
3<sup>rd</sup> Fermi Symposium (2011)

Pt-source



Extended source

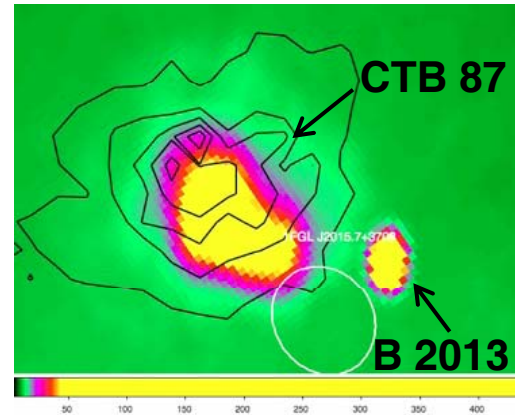


# VER J2016+372 and Cisne

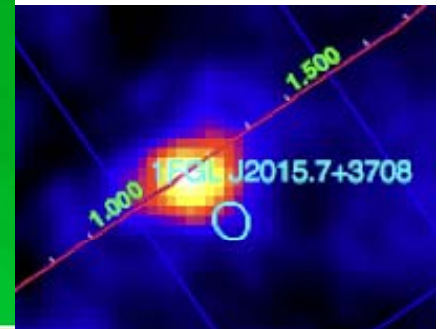
## VER J2016+372:

- Consistent with CTB 87 (PWN candidate).
- At edge of B 2013+379 (blazar).
- 1FGL J2015.7+3708 most consistent with blazar (variability seen).
- VERITAS source is likely a new TeV PWN, not seen at GeV energies.

CGPS (1420 MHz)  
VERITAS  $3\sigma$  to  $7\sigma$  contours

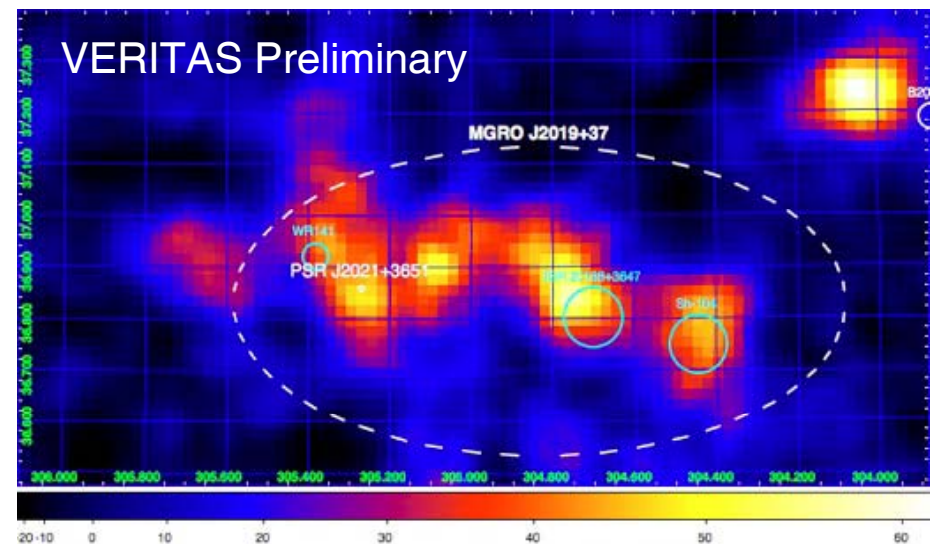


VERITAS Emission &  
1FGL J2015.7+3708



## Cisne:

- VERITAS data consistent with MGRO J2019+37, but reveals more detail.
- Most likely multiple (possibly extended) sources.
- Need more VHE and lower energy data; Fermi-LAT analysis to be presented at ICRC 2011 (Beijing).



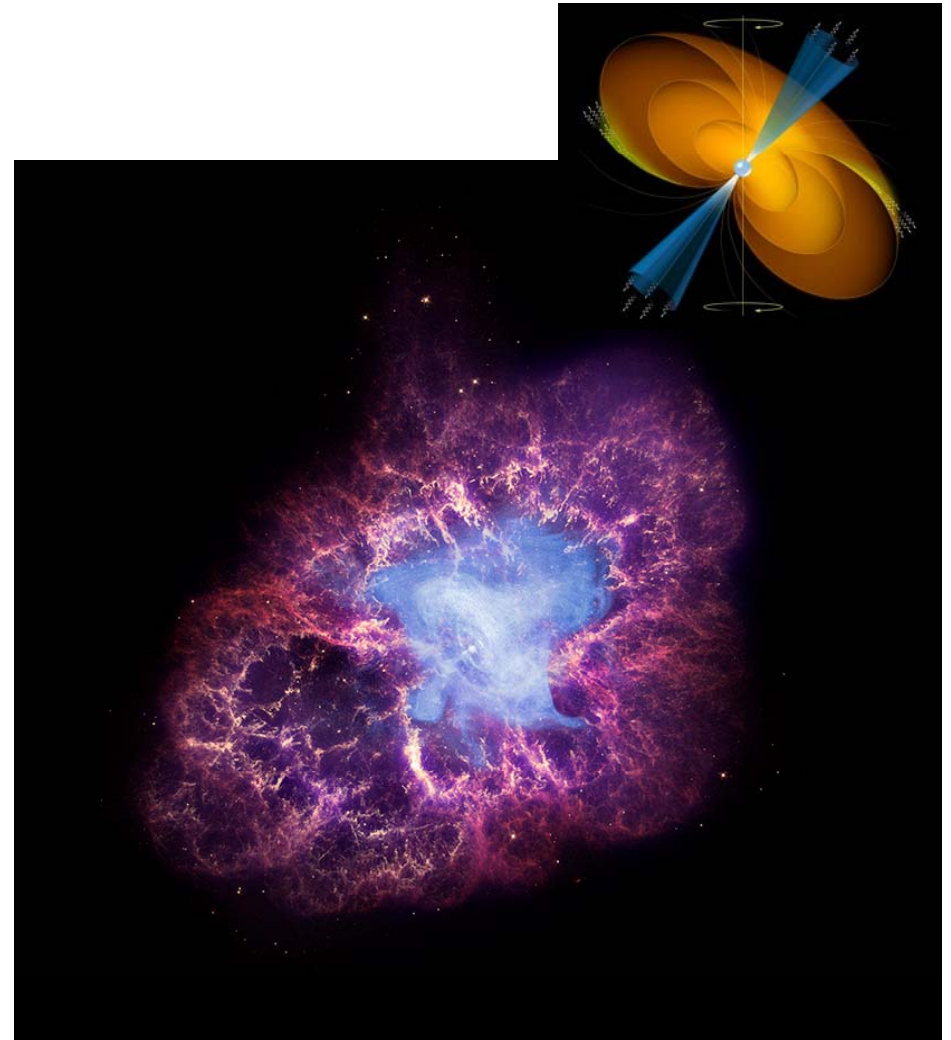
# Crab

## Crab Nebula and Pulsar

- Remnant from historical SN in 1054.
- One of the most energetic pulsars and brightest  $\gamma$ -ray pulsars.
- Nebula is the brightest, steady VHE source.

## $\gamma$ -ray observations of Pulsar

- **Fermi-LAT (first EGRET):** exquisite measurements around spectral break near few GeV.
- **MAGIC:** detection at 25 GeV and hint at 60 GeV.
- Numerous, constraining limits from **many VHE experiments.**
- 30-year effort to detect at VHE.

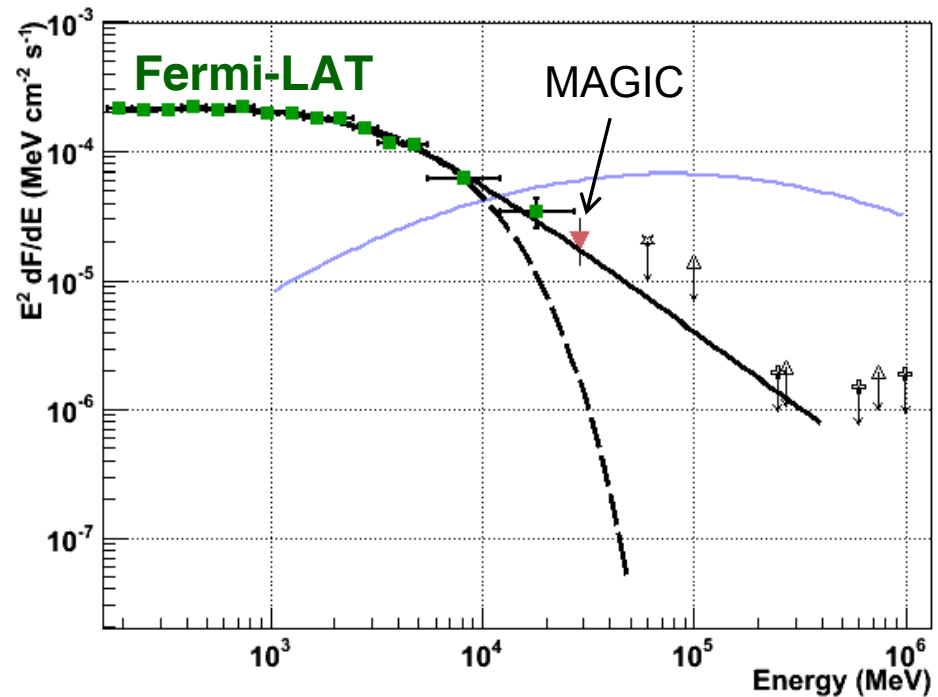




# Crab Pulsar at HE and VHE

## MAGIC Result at 25 GeV (Aliu et al., 2008)

- Special trigger to lower  $E_{th}$ .
- Similar pulse profile to EGRET.
- Exponential  $E_{cutoff} \sim 18$  GeV.
- Rule out polar cap model.



## Conventional view:

- Spectral break is described by exponential cut off; i.e. there is a single component.
- Curvature radiation – most-favored  $\gamma$ -ray production mechanism.
- Emission come from outer regions  $>6$  stellar radii. Outer-gap or slot-gap models favored.



# VERITAS Observations & Analysis

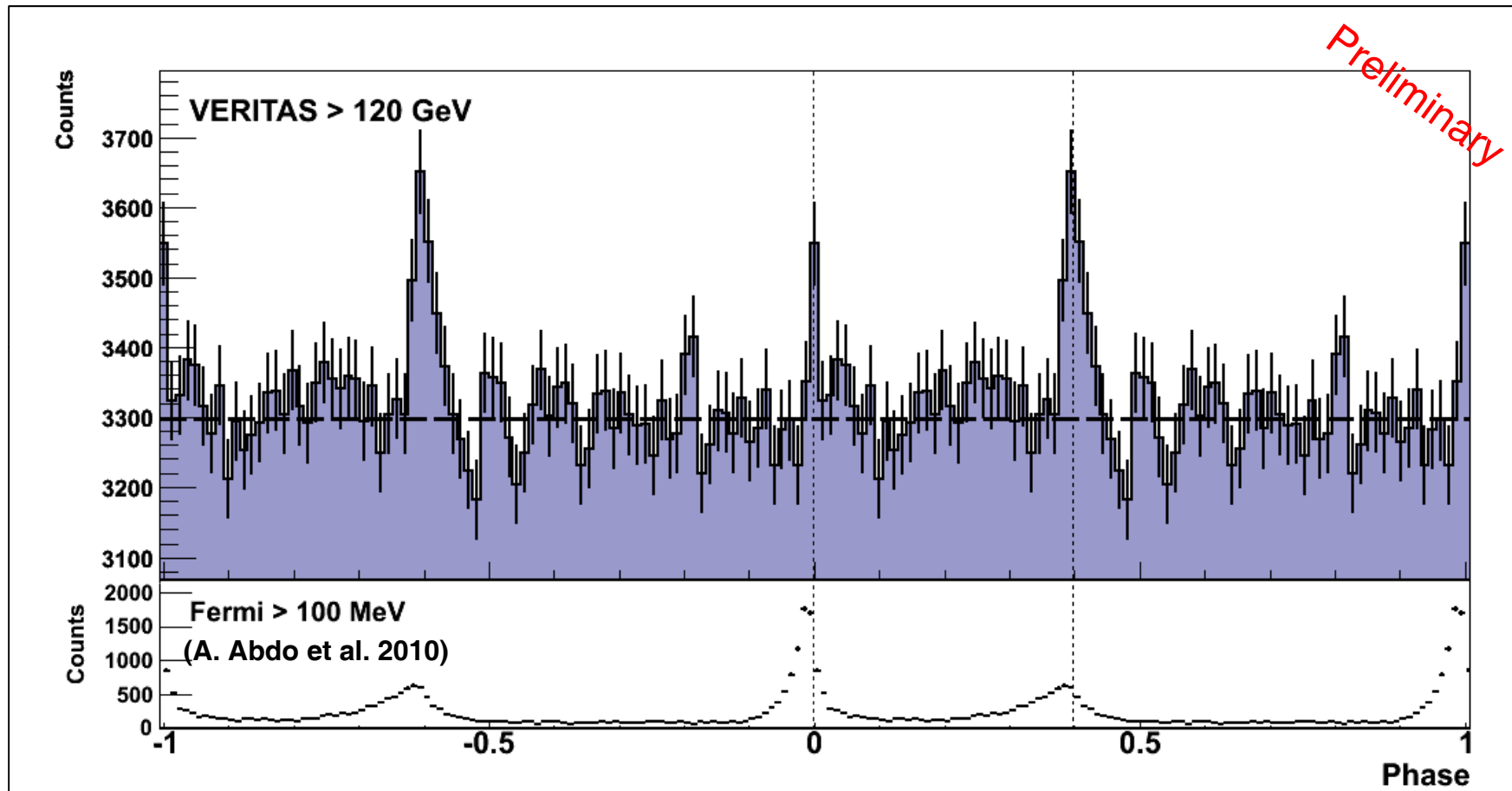
## VERITAS Observations:

- Total of 107h of data (2007-09: 45h, 2010: 62 h), taken with 4 telescopes.
- Wobble with  $0.5^\circ$  offset.
- Zenith angle  $< 25^\circ$ .
- Event times from four independent GPS receivers ( $1 \mu\text{s}$  accuracy).

## Analysis (N. Otte, A. McCann, M. Schroedter):

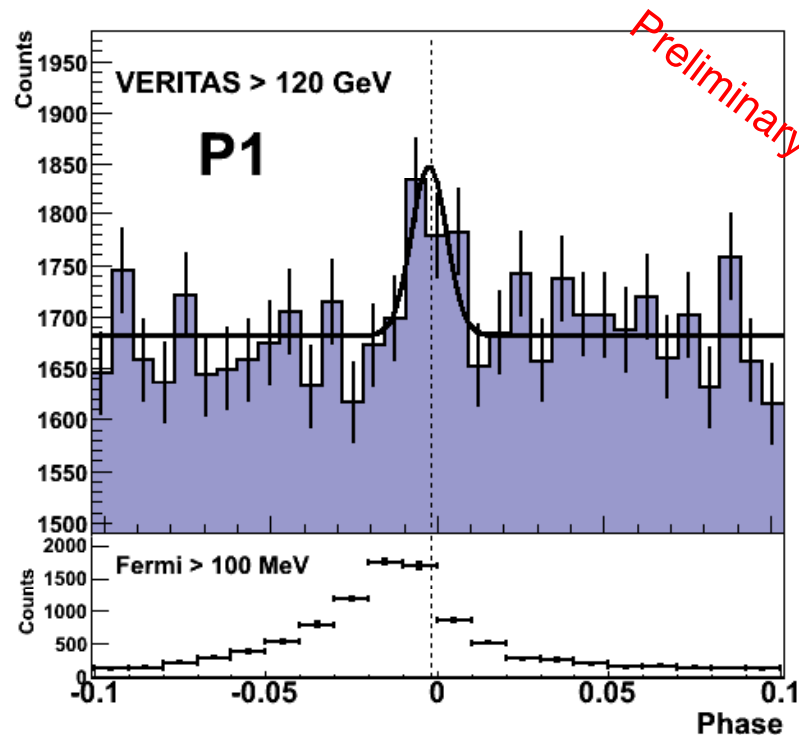
- Standard trigger, standard analysis tools (two independent packages).
  - Hillas image analysis with stereo reconstruction.
  - Analysis selection set *a priori* for weak (few % Crab Nebula) source with soft spectrum,  $\Gamma = 4$ .
  - Event time barycentering with two custom codes and tempo2.
  - Phase folding of data using Jodrell Bank empherides.
-

# VERITAS Pulsed Signal



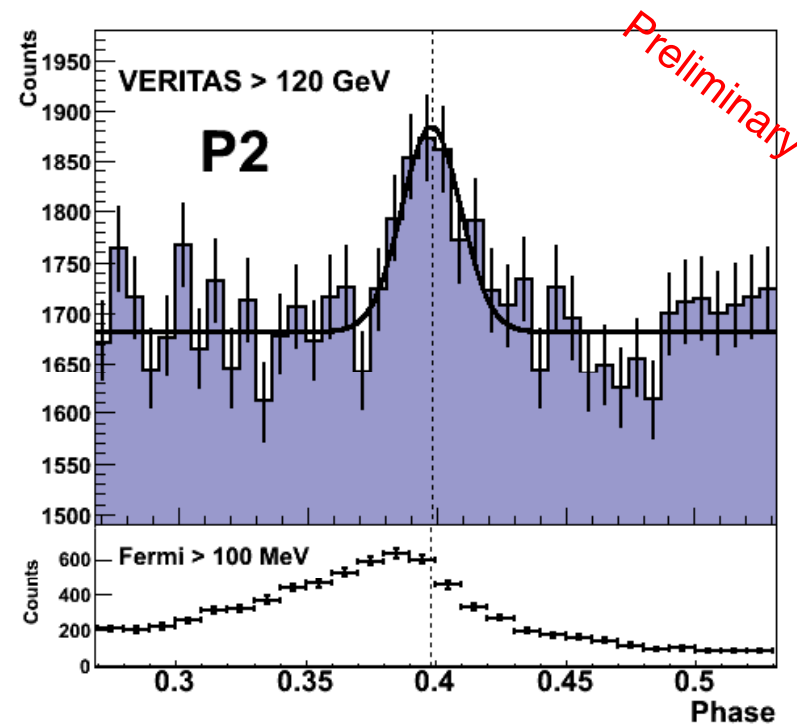
Statistical significance of pulsed signal:  
H-Test value of 50, i.e.  $6.0\sigma$ .

# A Closer Look at the Peaks



Position:  $-0.0023 \pm 0.0020$

Width:  $0.0132 \pm 0.0035$  FWHM



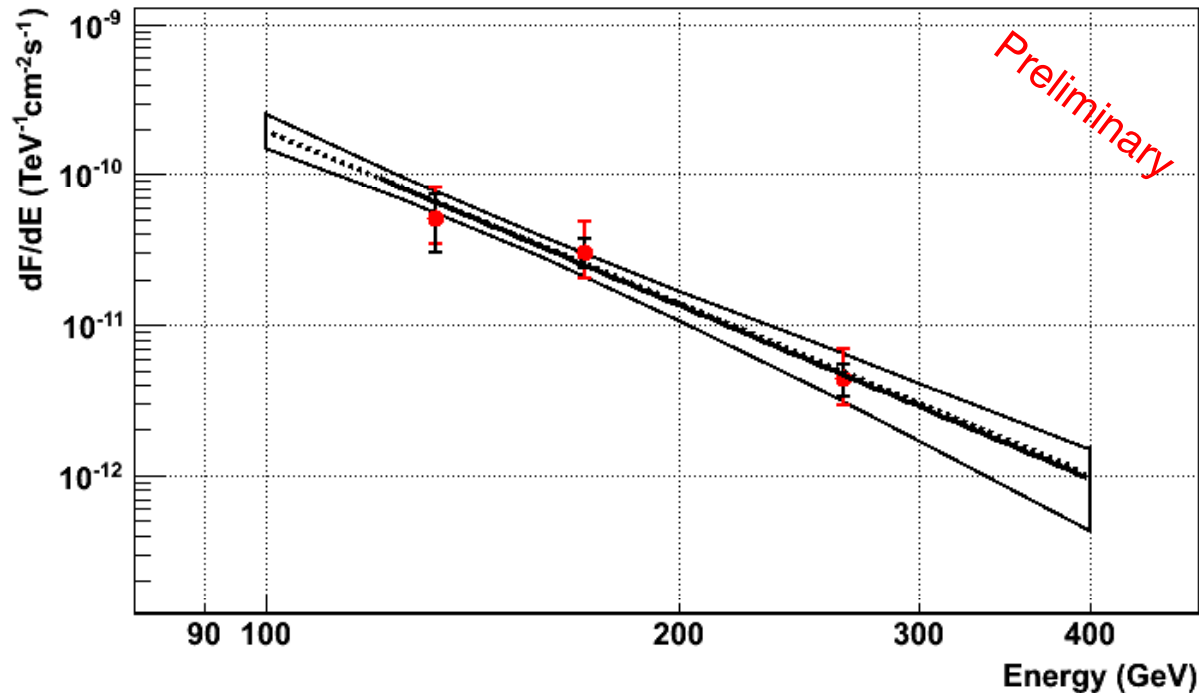
Position:  $0.3975 \pm 0.0020$

Width:  $0.0268 \pm 0.0052$  FWHM

Peak positions **aligned with peak positions in radio**. The shift with respect to Fermi-LAT data is an analysis effect

Pulses above 120 GeV **2-3 times narrower than in Fermi-LAT data**  
→ possible interpretation: the acceleration zone tapers

# VHE Spectrum of Crab Pulsar

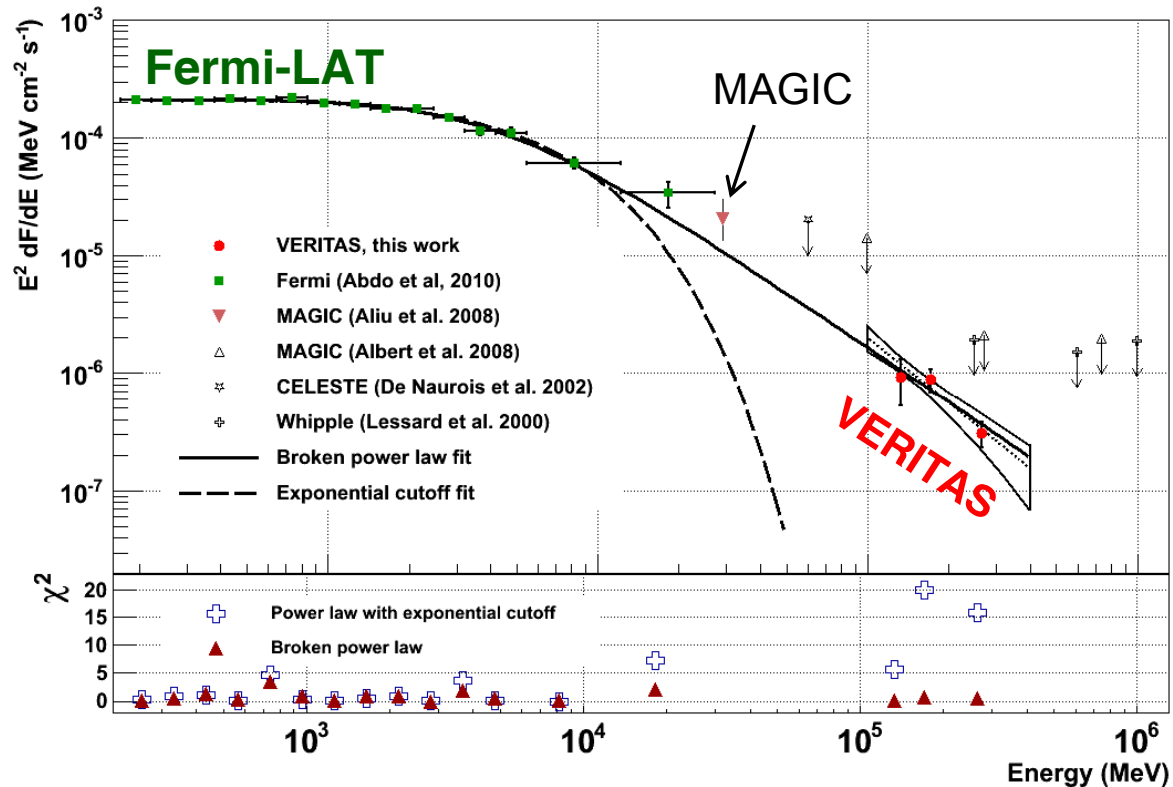


## VERITAS VHE Spectrum:

- Combine P1 and P2 regions – good approx. of phase-averaged spectrum.
- Highest energy point at 280 GeV.
- Crab Pulsar  $\sim 1\%$  Nebula flux at 150 GeV.
- **Power-law form !**

$$dN/dE = A(E/150 \text{ GeV})^\alpha \quad \text{for } \alpha = -3.8 \pm 0.5_{\text{stat}} \pm 0.2_{\text{syst}}$$

# The New Picture of the Crab Pulsar



- **First detection of a pulsar above 100 GeV.**
- VERITAS detection @ 280 GeV  $\rightarrow$  emission region  $> 10$  stellar radii.
- Absence of exponential cutoff  $\rightarrow$  rules out curv. radiation as dominant mech.
- Narrowing of pulses  $\rightarrow$  tapered acceleration region ?
- What other pulsars are out there at  $E > 100$  GeV ?

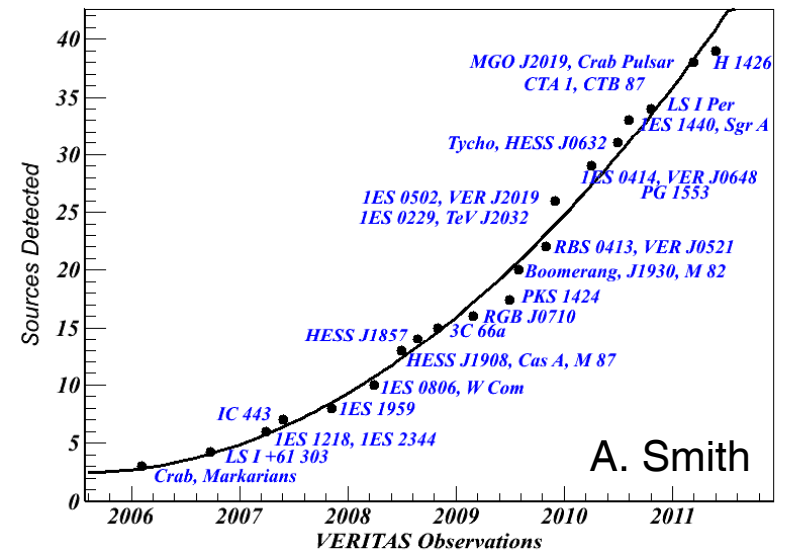


# Future Prospects: VERITAS Upgrade

## VERITAS in 2011:

- Operating smoothly in excellent sensitivity and science output.
- With excitement of field (and power of Fermi), we want to improve sensitivity – especially at  $\sim 100$  GeV.

VERITAS Detections vs time



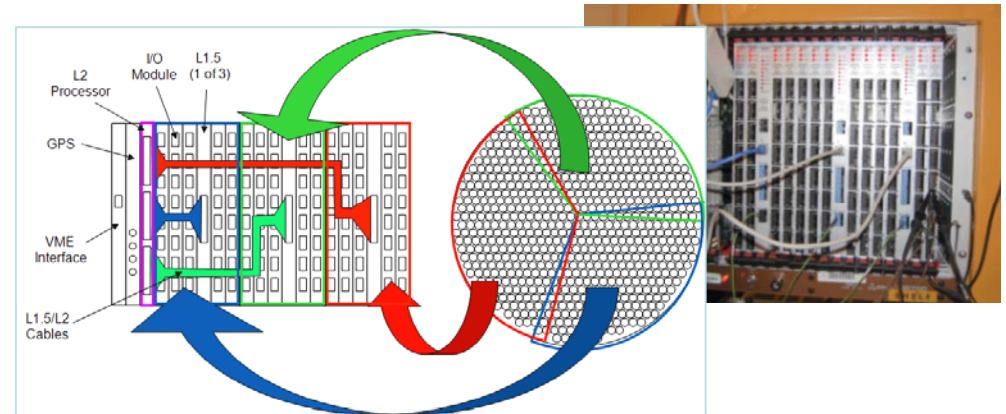
## VERITAS UPGRADE (2009-2012):

1. Improved optical point spread function ← completed
2. Relocating telescope T1 ← completed
3. Upgrading cameras with high efficiency PMTs ← ongoing
4. New trigger system ← ongoing
5. An additional telescope T5 ← possible in the future

# VERITAS Trigger & PMT Upgrade

## Trigger upgrade (2009-2011):

- Camera trigger processing done by special (L1.5) FPGA-trigger cards.
- L2 processor combines L1.5 signals.
- Deployed June-Sept 2011.



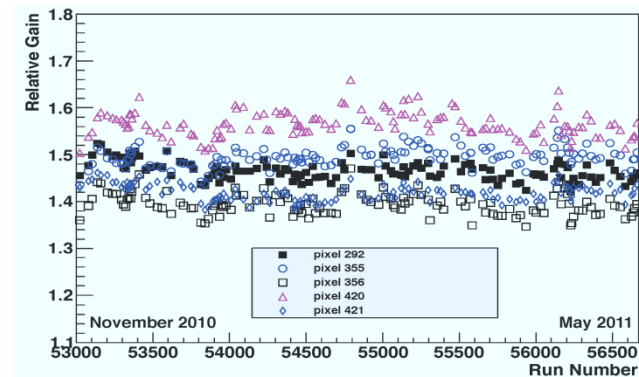
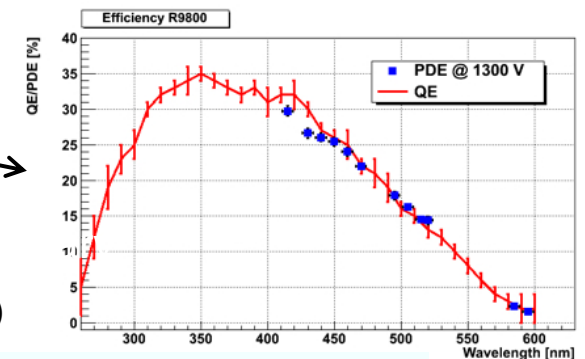
## Camera upgrade (2010-2012):

- Replace all PMTs with HQE ones (Hamamatsu R9800 SBA); new mount tube and pre-amp.
- Improve sensitivity and lower E threshold ( $120 \text{ GeV} \rightarrow 80 \text{ GeV}$ ).
- Installed Summer 2012.



Measured  
QE/PDE  
(50% increase)

PMT stability (*in situ*)



# Summary

## Lots of new results from VERITAS:

- **Dark Matter:** New result by VERITAS from **Segue 1**.
- Galactic Center: competitive observations possible using LZA technique.
- SNRs: we detect young shell-type SNRs directly and older ones through interaction with material. **Tycho** is a relatively clean system that supports hadronic acceleration picture.
- **CTA 1:** VHE discovery by VERITAS; indicates a likely PWN.
- Cygnus Region: new sources: **VER J2019+407** ( $\gamma$ -cygni, OB2) and – **VER J2016+372** (CTB 87, OB1) neither seen (yet) by Fermi-LAT. **MGRO J2019** is complex object likely containing multiple sources.
- **Crab Pulsar:** detected for first time above 100 GeV. Pulse profile is different than at lower energies – new understanding of pulsars needed !
- VERITAS is operating well and will further improve with upgrade (2012).