VHE Galactic Source Highlights from VERITAS

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OUTLINE

- Scientific Motivations
- The atmospheric Cherenkov technique and the VERITAS instrument
- 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

Contributions

This talk summarizes work from a collaboration of scientists, of which many contributed to these results, especially:

E. Aliu (Barnard)
B. Humensky (U. Chicago)
P. Majumdar (UCLA)
R. Mukherjee (Barnard)
A. McCann (McGill)
S. McArthur (Wash U.)
N. Otte (UCSC)
M. Schroedter (SAO)
G. Senturk (Barnard)
A. Weinstein (ISU)

Scientific Motivations

Some of many motivations for Galactic VHE γ-ray sources:

PHYSICS Motivations

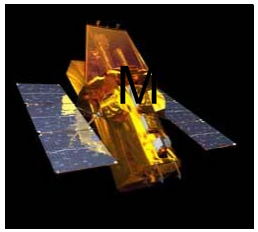
- Origin of Cosmic Rays
  - energy balance of Galaxy
- Physics of compact objects
- Dark matter

ASTRONOMICAL Motivations

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

Multiwavelength Observations

Radio

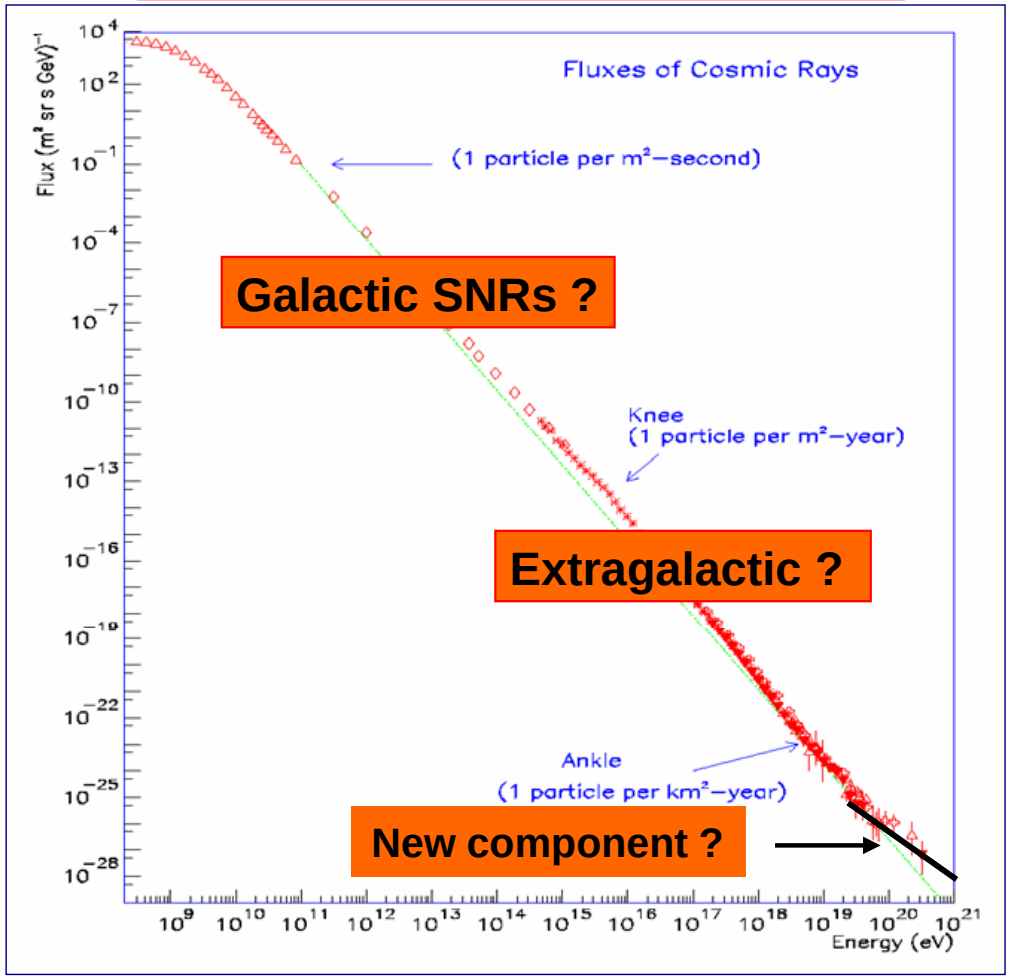


X-rays

Fermi LAT

Origin of Cosmic Rays

Diffuse, all particle spectrum



S. Swordy

90 year old mystery !

- Enormous E range
- Mostly charged particles
- E density ~ 1 eV/cm^3

Neutral messengers:

γ, ν

are required to directly observe cosmic accelerators.

Variety of VHE Galactic Sources

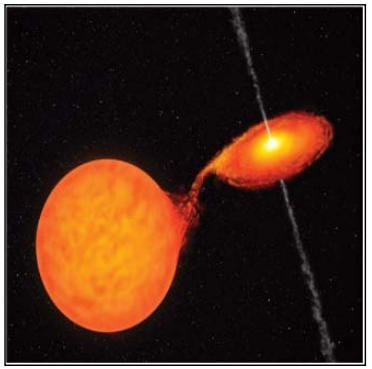
Pulsars
Pulsar Wind Nebulae

NS dynamo
Winds

Supernova Remnants

Shocks
Fermi mechanism

Binary systems

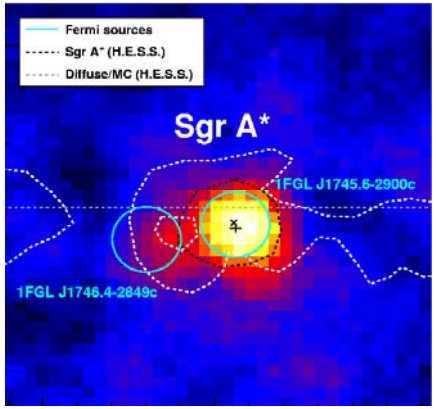


Accretion-powered jets,
Colliding winds, or …?

Star Forming Regions

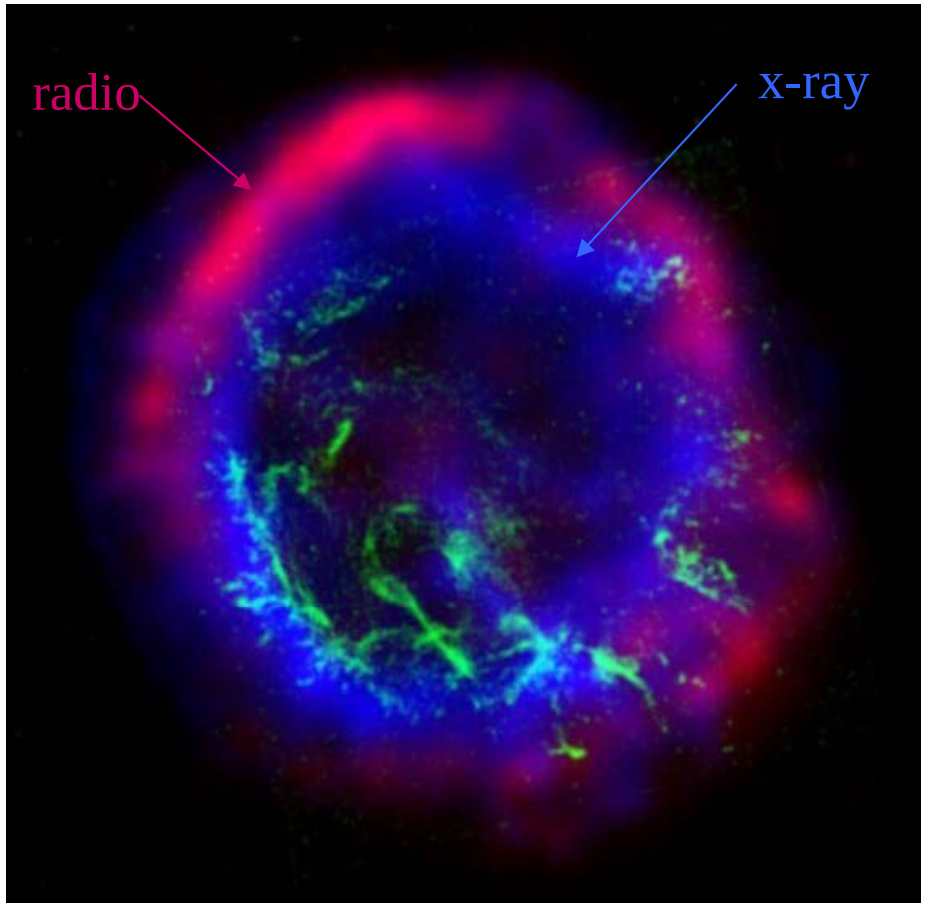
OB Assoc., WR stars
HII regions, molcular clouds

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 ~ 10^4 yrs, blast wave deccelerates and dissipates.
- Can supply and replenish CR's if ε ~ 5-10%.

Electrons or Protons ?

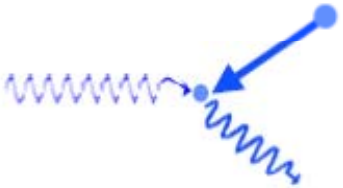
VHE γ-rays are:

- *Not deflected* by interstellar magnetic fields.
- *Tracers* of parent particle populations – those particles accelerated by shocks.

But both electrons and protons produce γ-rays.

Accelerated electrons
→ TeV γ-rays

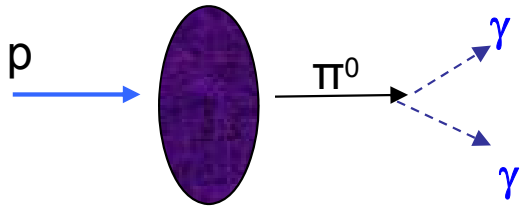
Up-scattering of soft photons



Inverse Compton Scattering

Accelerated protons
→ TeV γ-rays

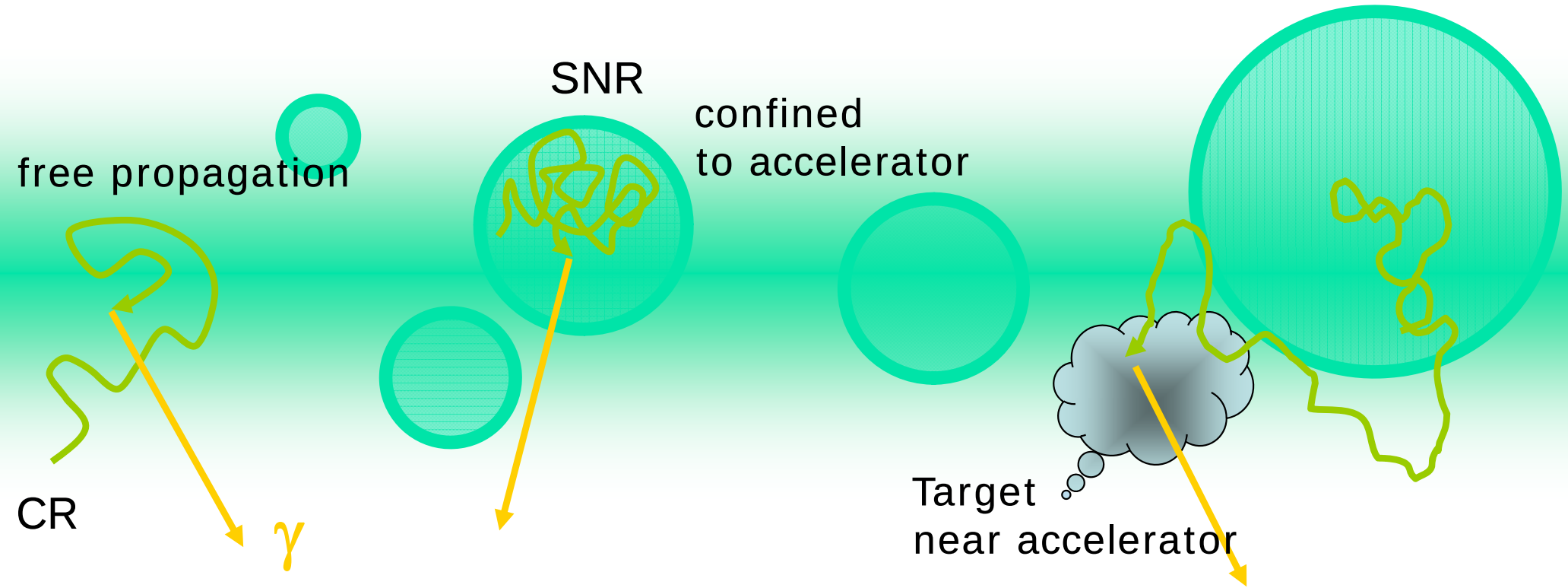
Target interaction, π^0 decay



π^o 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 γ-rays come from secondary interactions:

p: p^o production and decay

e: Inverse Compton scattering and Bremsstrahlung

Trace beam density x target density

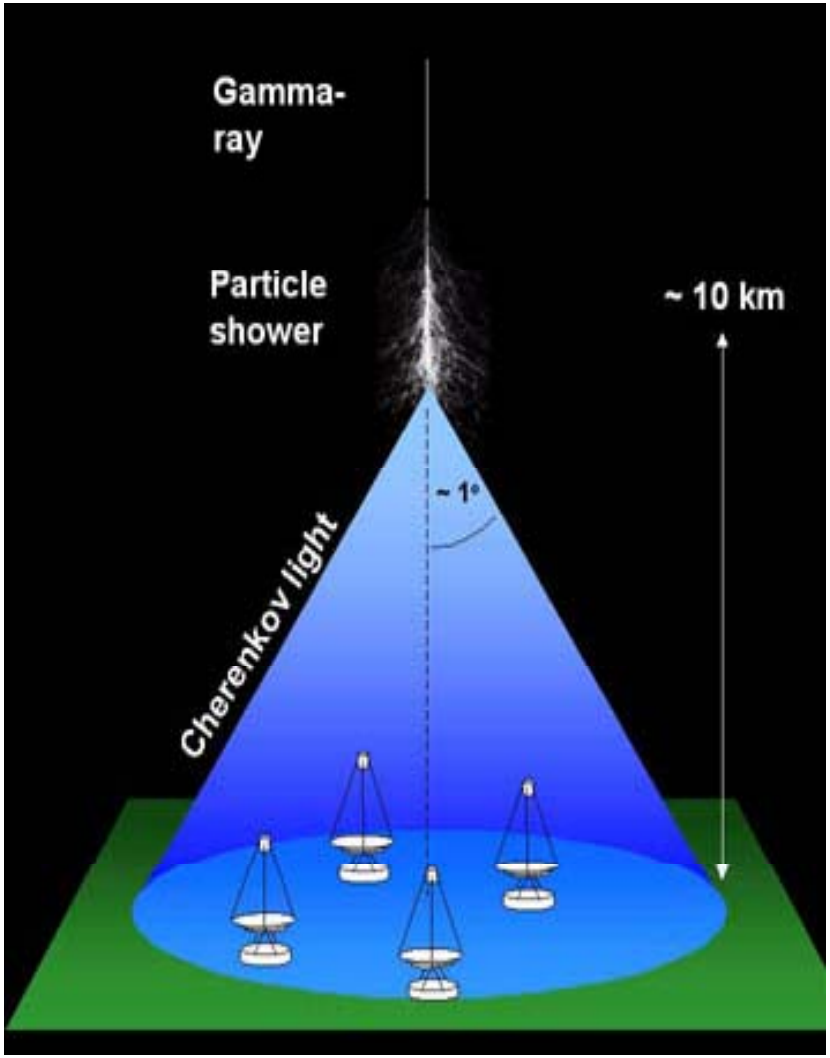
Need to disentangle e, p components → MWL obsevations are crucial

Atmospheric Cherenkov Technique

&

VERITAS Instrument

Atmospheric Cherenkov Technique



Reconstruct IMAGE in camera of each telescope:

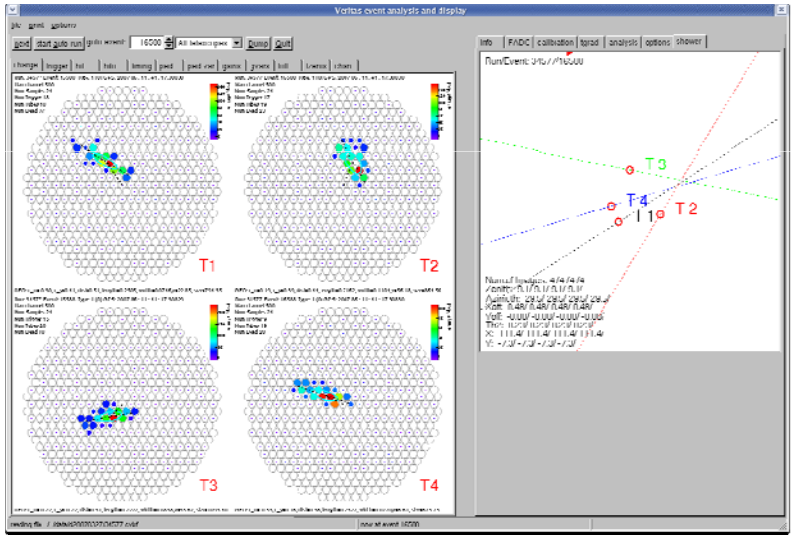


Image axis → **γ-ray direction**

Intensity → **γ-ray energy**

Image shape → **particle type**

Stereoscopy gives greatly improved

ang. resolution, E resolution,

γ / had separation, SENSITIVITY

VHE Telescopes World-Wide

Multi-messenger Astronomy (γ,ν,CR)

MAGIC

ARGO / YBJ

VERITAS

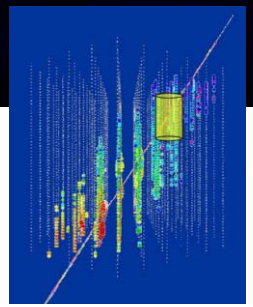
HESS

(Auger, CR's)

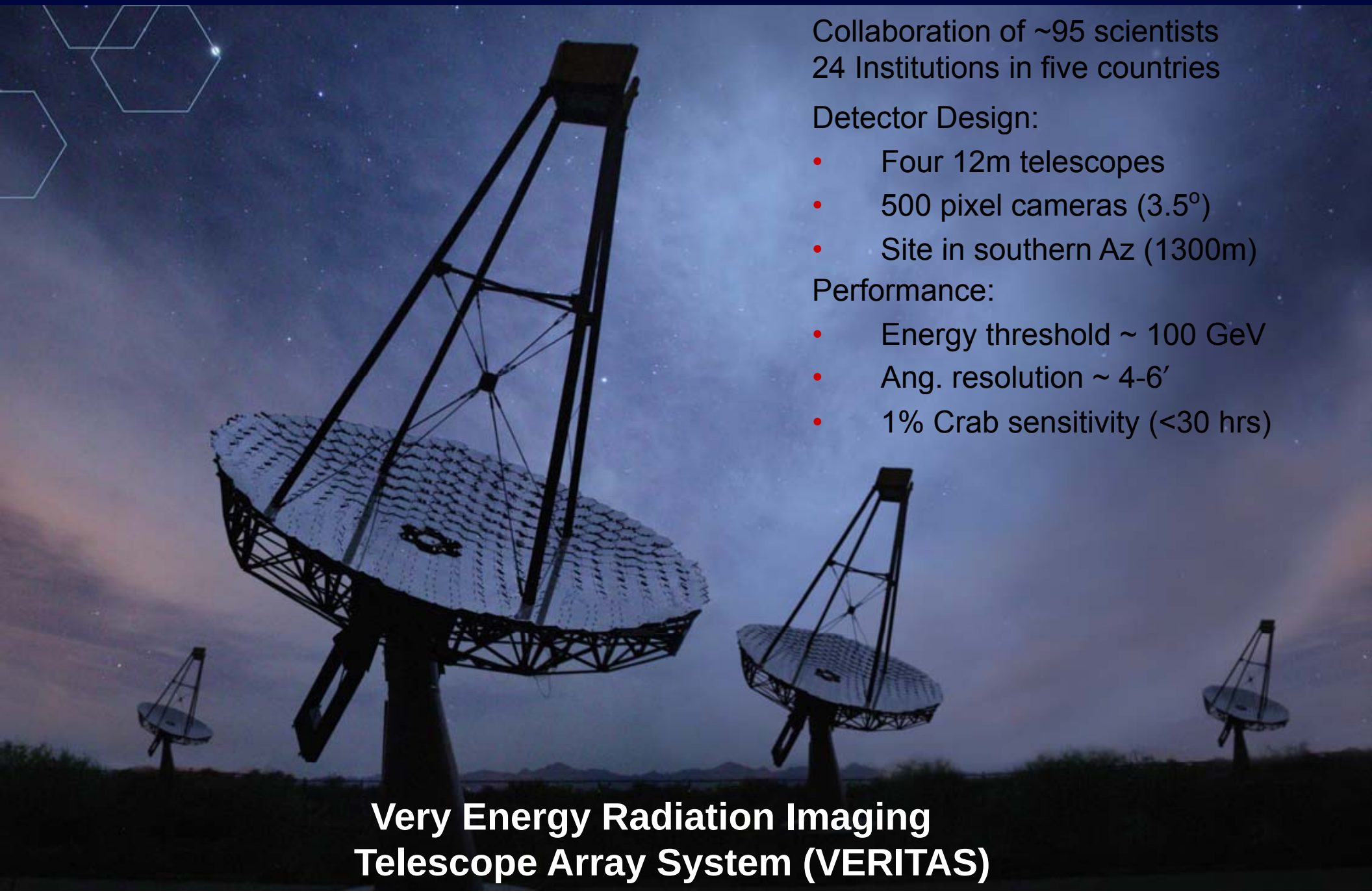
CANGAROO III

IceCube, ν's

Ice Cube



VERITAS



Collaboration of ~95 scientists
24 Institutions in five countries

Detector Design:

- Four 12m telescopes
- 500 pixel cameras (3.5°)
- Site in southern Az (1300m)

Performance:

- Energy threshold ~ 100 GeV
- Ang. resolution ~ 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.

Adl
Arg
Bar
DePauw Univ.
Grinnell College
Iowa St. Univ.
Purdue Univ.
SAO

U. of Delaware
U. of Iowa
U, of Minnesota
U. of Utah
Washington U.

U.K.

Leeds Univ.

Univ. College Dublin

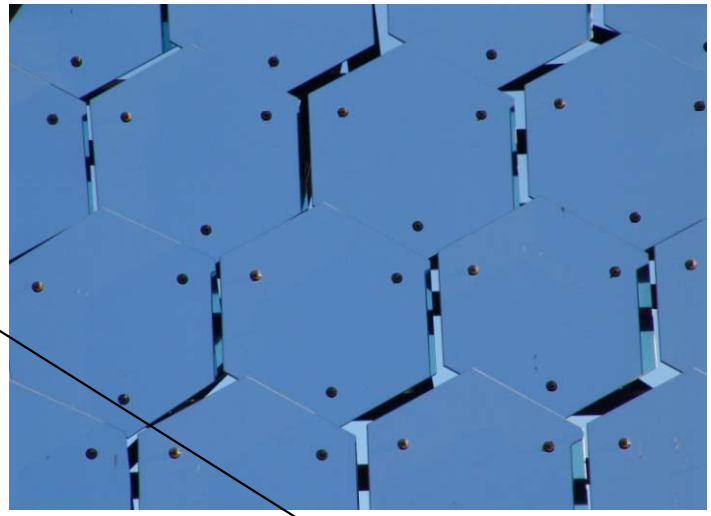
Non-Affiliated Members

DESY/Potsdam
Penn State U.

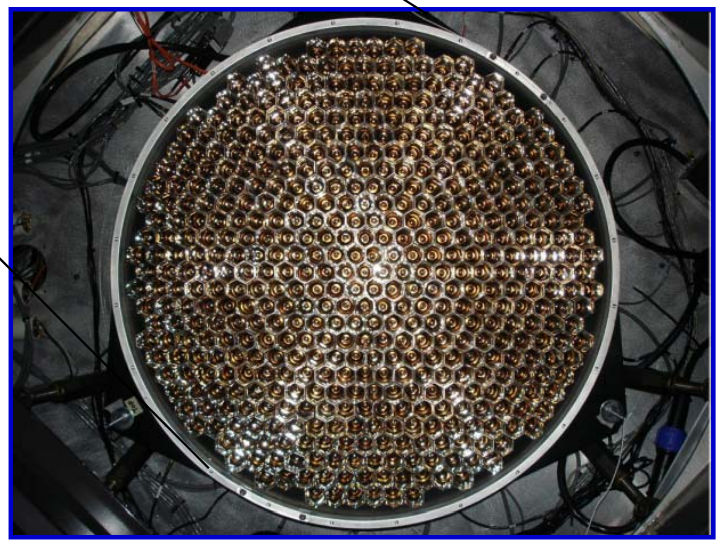
+ 35 Associate Members
Theorists, MWL partners, IceCube, Fermi, Swift, etc.

A VERITAS Telescope

12m reflector, f1.0 optics



350 Mirror Facets



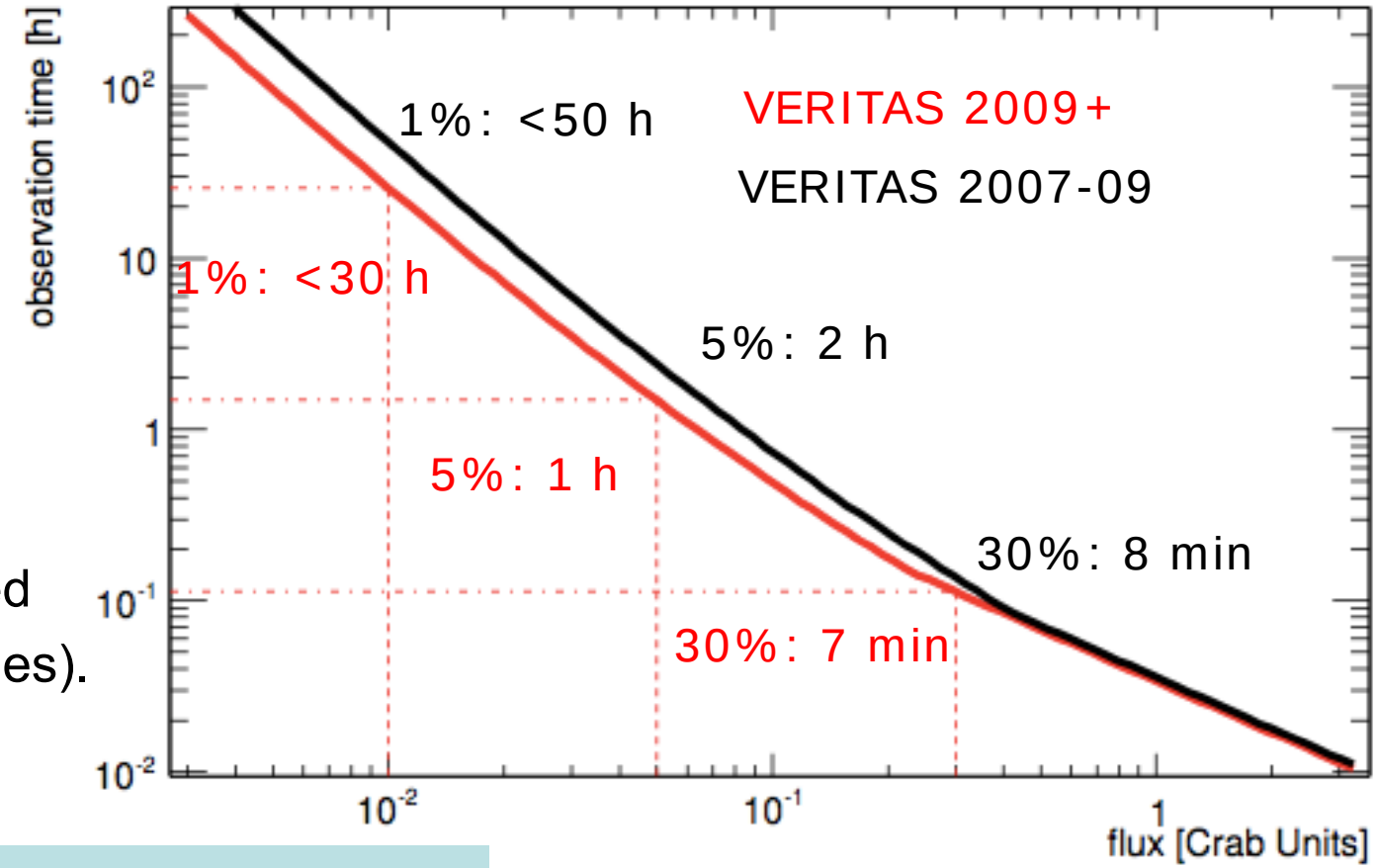
500 pixel Camera

VERITAS Performance

Sensitivity

(% Crab detection, 5σ)

Using a standard Hillas moment analysis (Improvements expected with advanced techniques).



- Energy range: 100 GeV – 30 TeV
- Energy resolution: 15%-25%
- Angular resolution: $r_{68} < 0.1^o$
- Pointing accuracy: < 50″

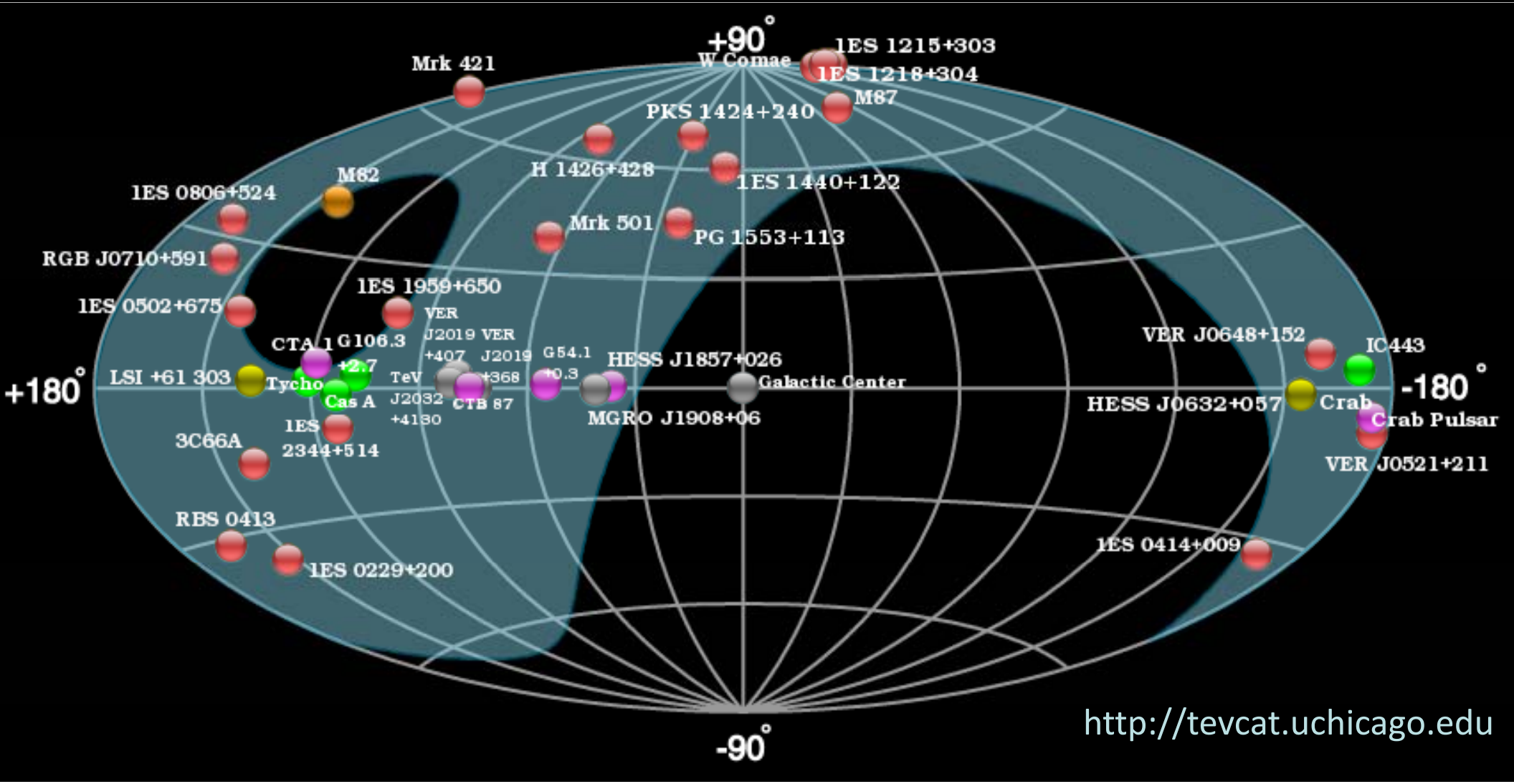
Crab Nebula γ–ray rate ~ 0.9 Hz (trigger)

Observing (quality data)

- ~825 dark hrs/year
- ~200 partial moon hrs/year

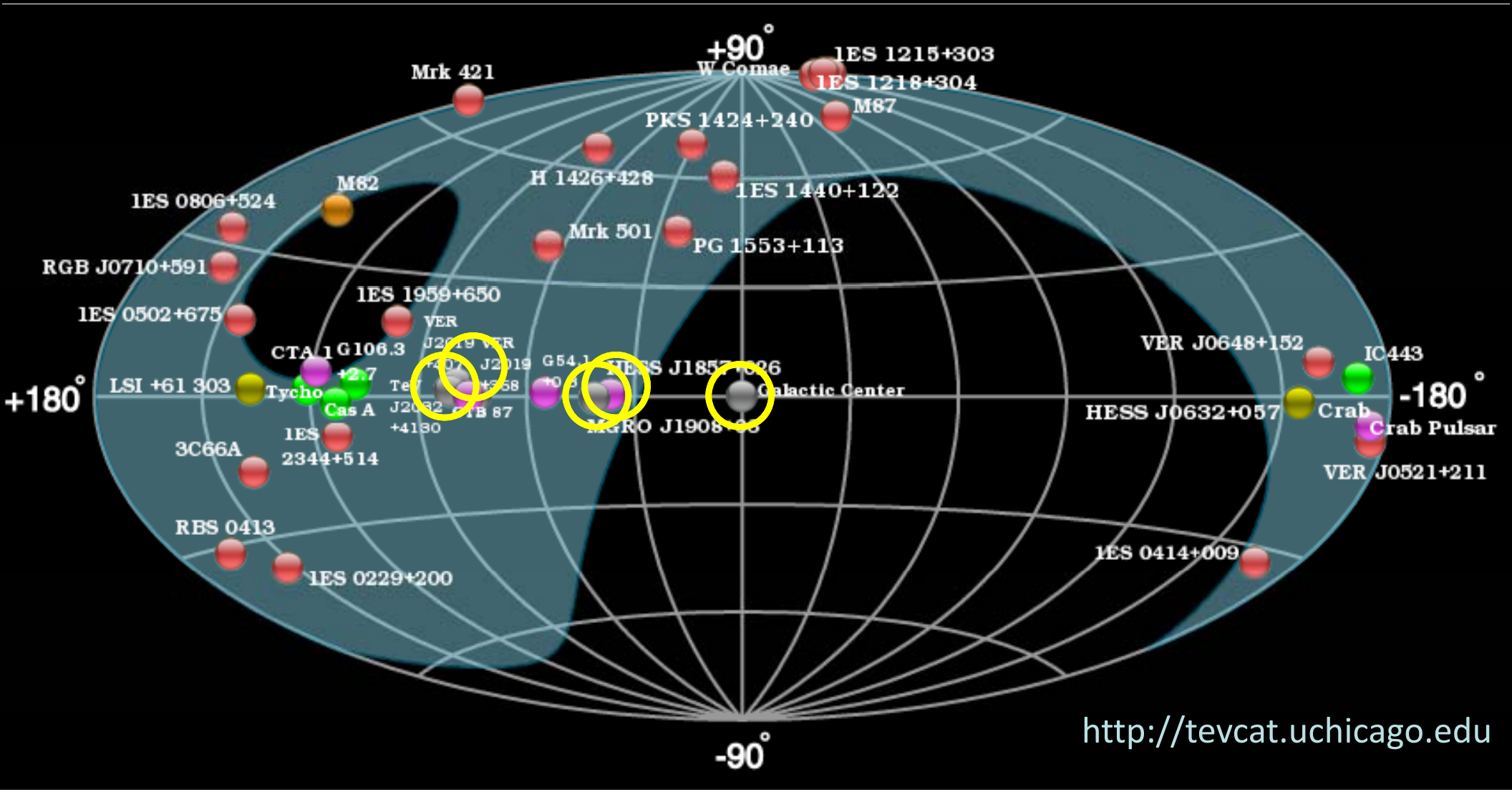
VERITAS Sky Map (2011)

39+ sources covering 8 source classes
At least 17 sources are likely Galactic (SNRs, PWNe, Binaries, Unids, Pulsars)



VERITAS UnID Sources

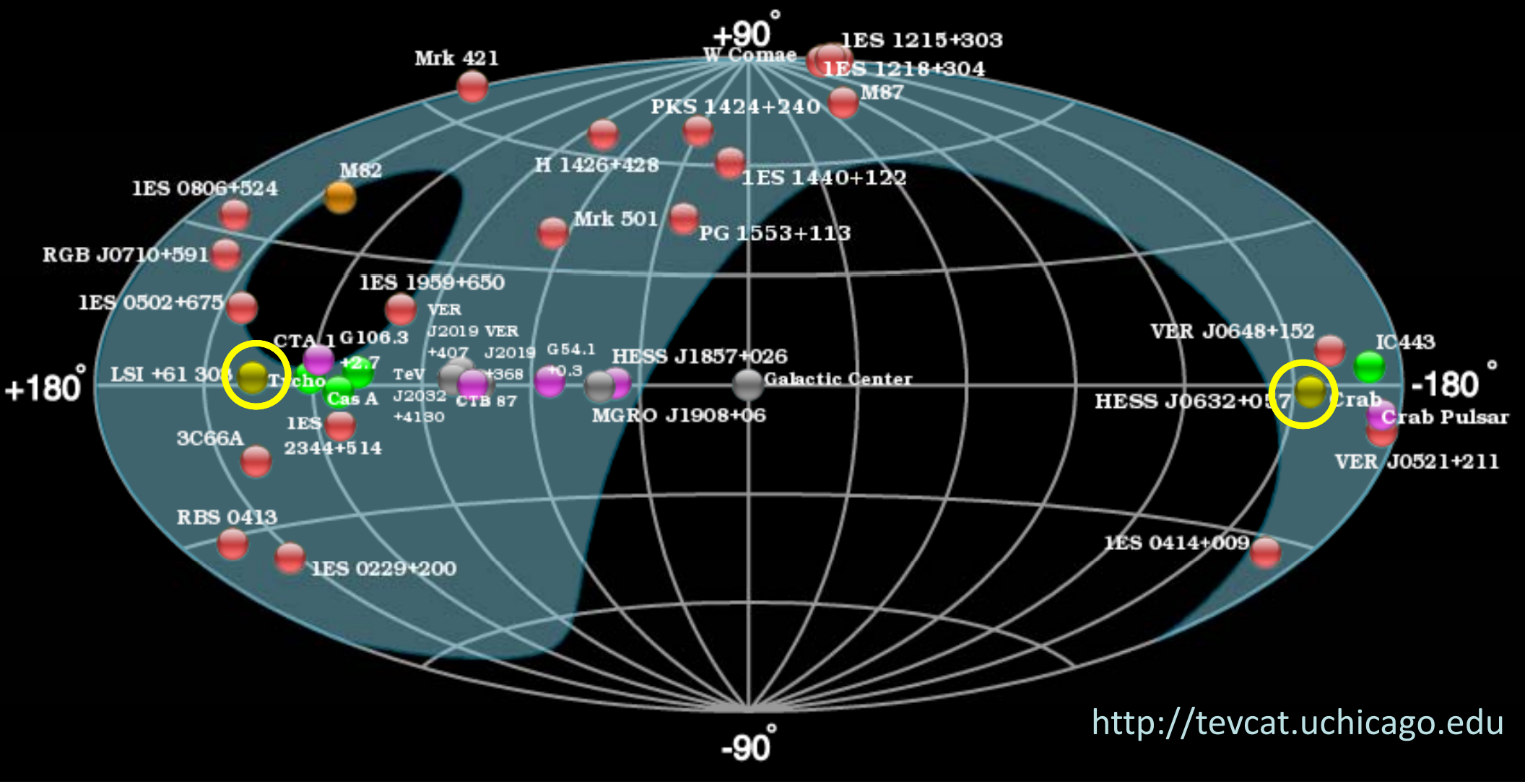
Galactic Center, HESS J1857+026, MGRO J1908+06, TeV 2032+4130, VER J2019+407



http://tevcat.uchicago.edu

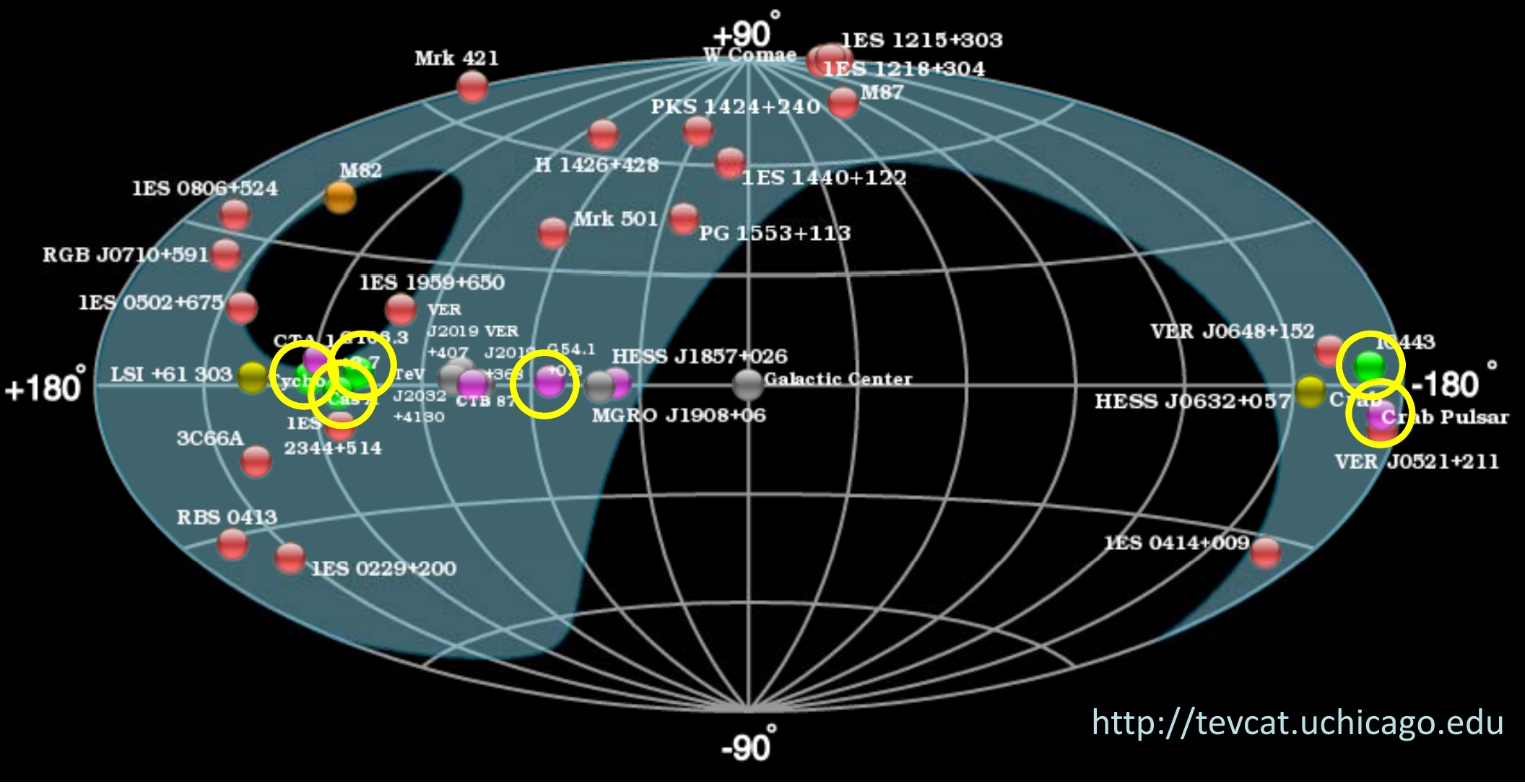
VERITAS Binaries

LS I +61 303
HESS J0632+303 ? (stay tuned for ICRC 2011)

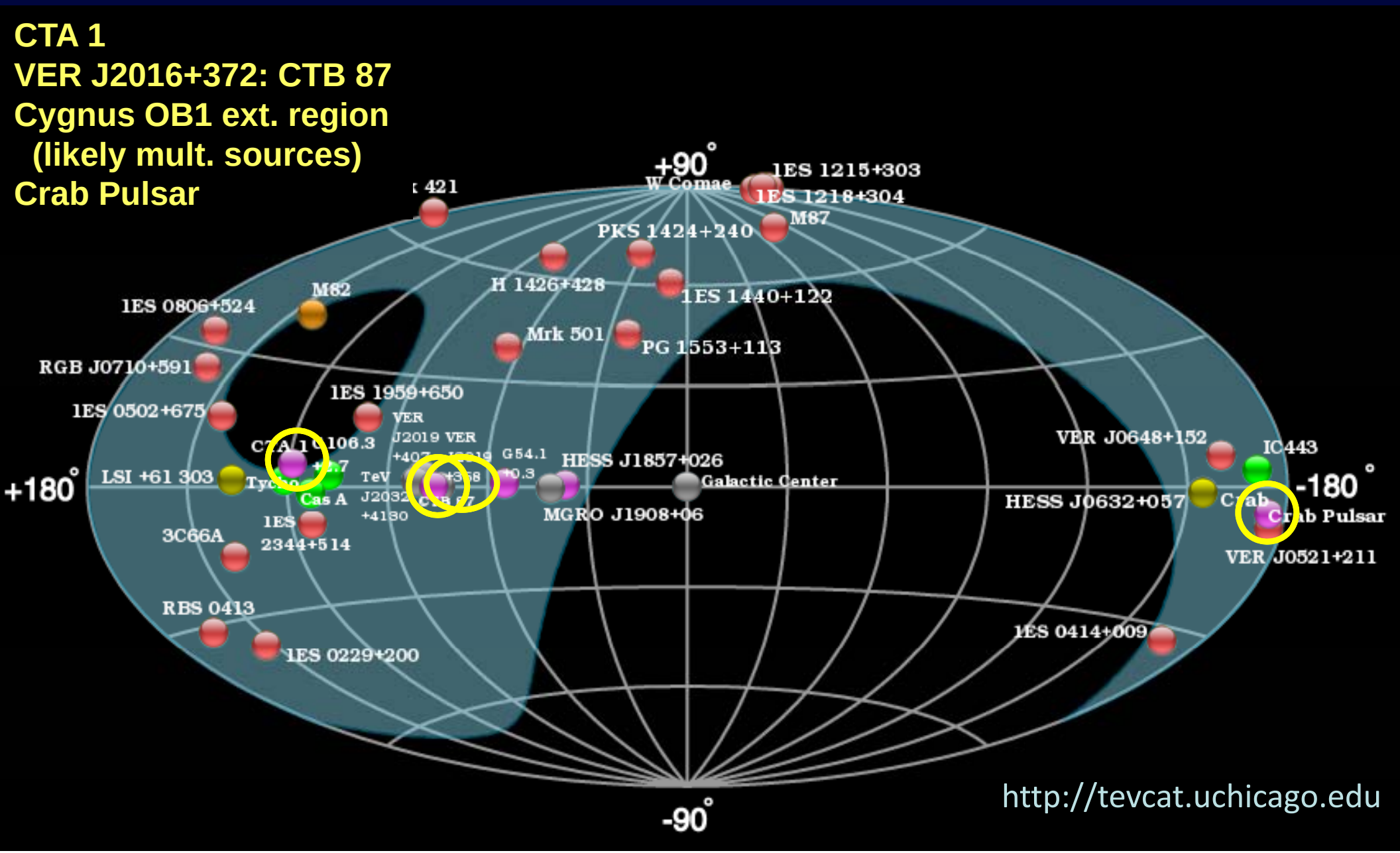


VERITAS SNRs and PWN

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



VERITAS New Sources (2011)

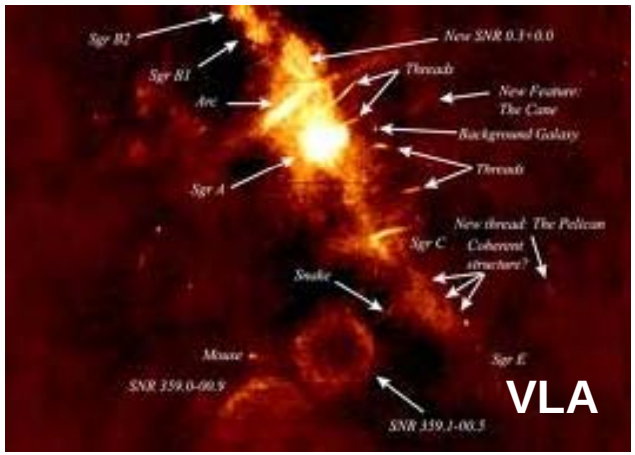


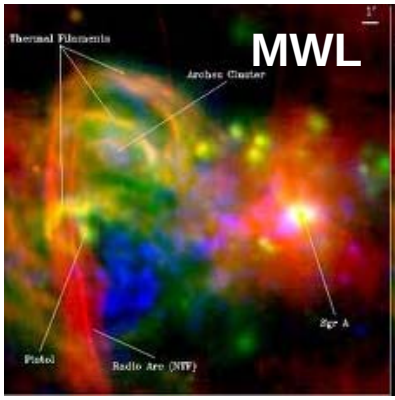
New VERITAS Results on Galactic VHE Sources

Galactic Center

Complex region:

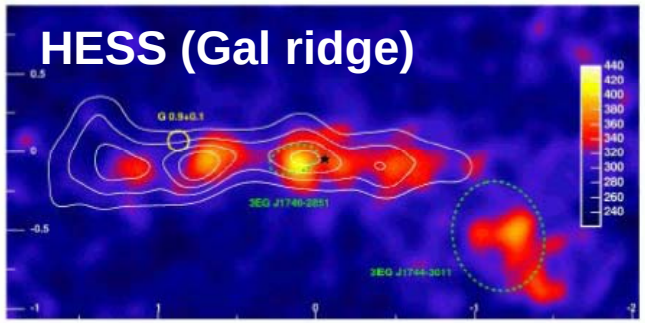
- Sgr A*, ~3x10^6 solar mass BH.
- Possible SNRs or PWN
  - increased level of CR density.
- Transients seen in X-rays, GeV γ-rays.
- Dark matter ?





GeV / TeV Observations:

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



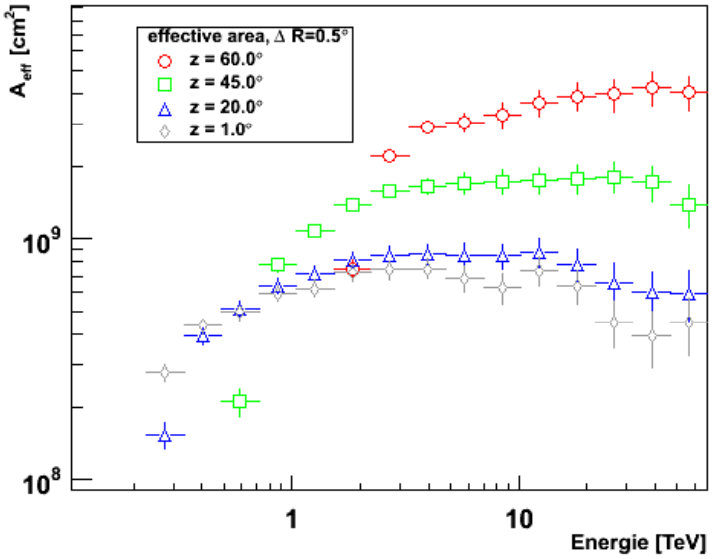
LZA Observations

Large Zenith Angle (LZA) method:

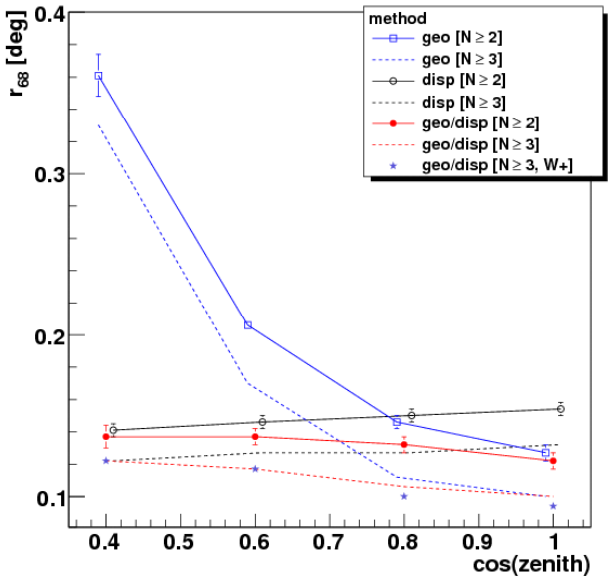
- Large effective area at high energies.
- Increased E_{th} and poorer angular recon.

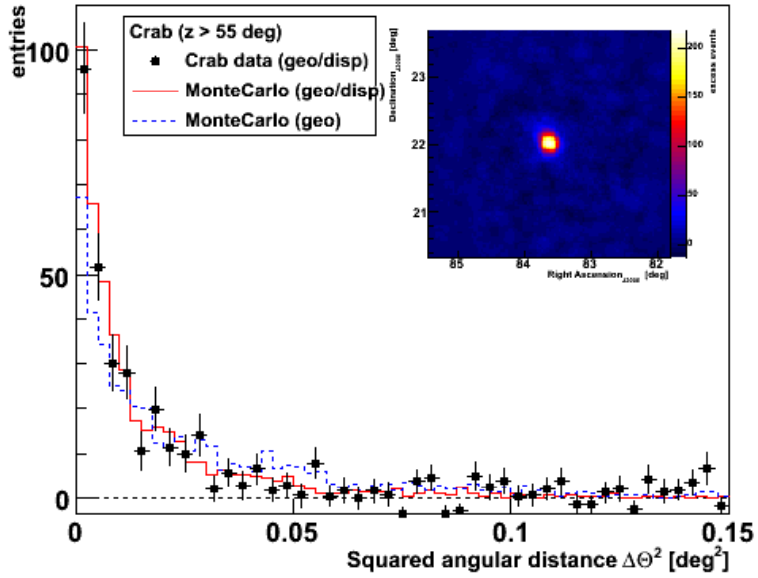
Displacement method (Buckley et al. 1998):

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



Significantly improved angular resolution and sensitivity



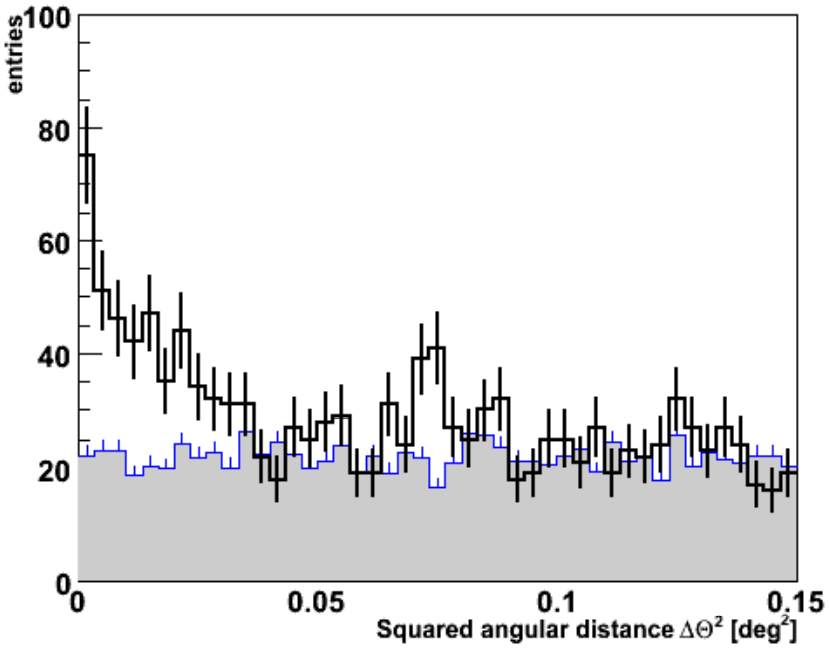


M. Beilicke,G. Senturk

VERITAS GC Observations

2010 Observations:

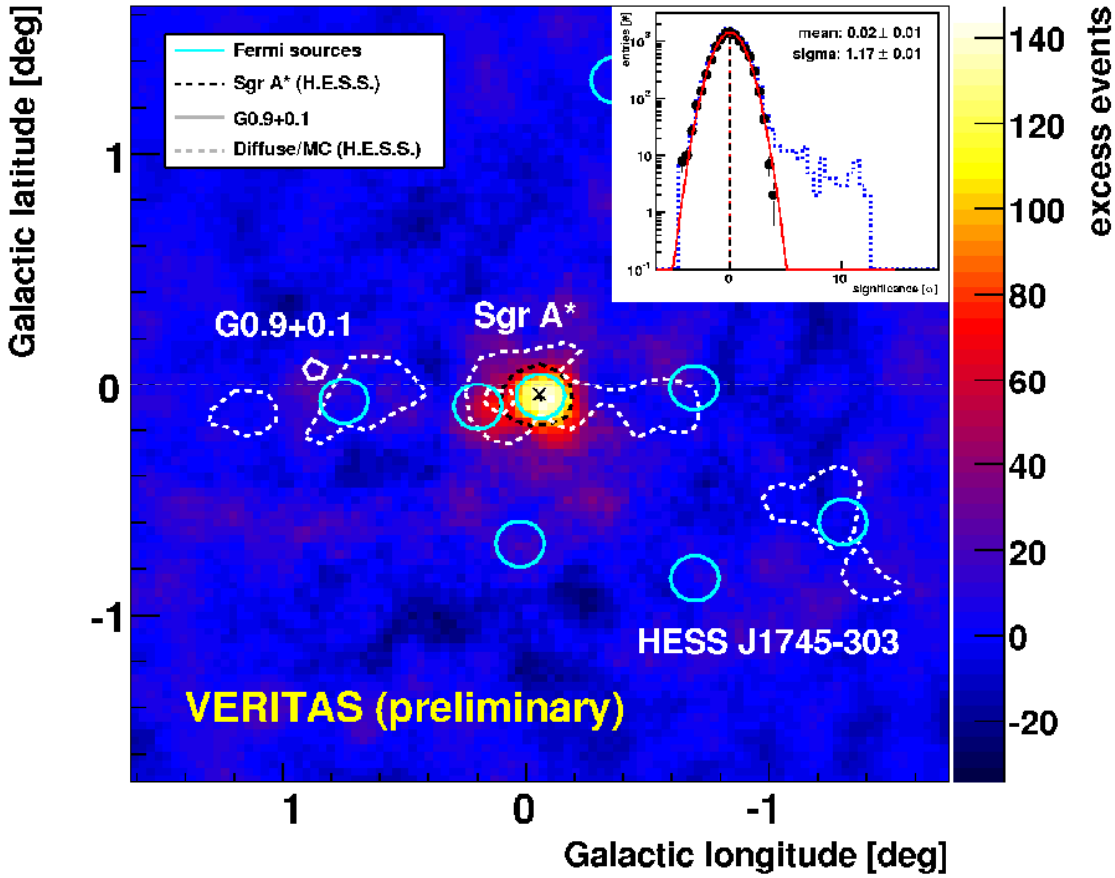
- 14.7 hrs, zenith ~65°, E > 2 TeV
- 12σ detection
- No evidence for variability



5σ detection possible in ~3h

Sky map:

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



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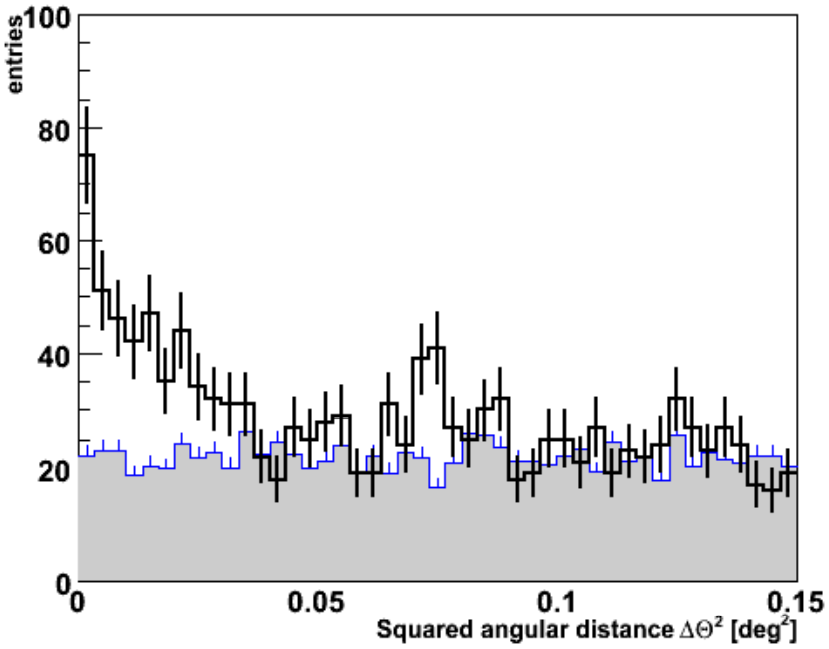

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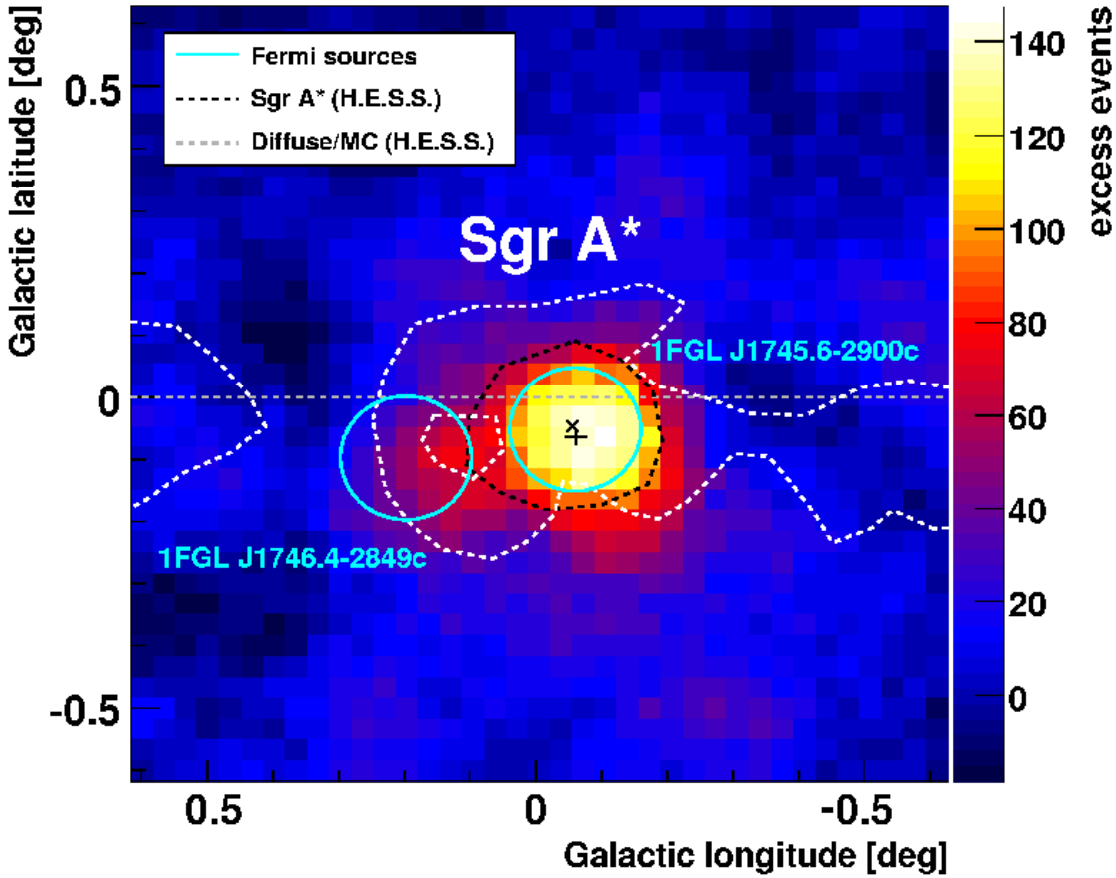


VERITAS GC Energy Spectrum

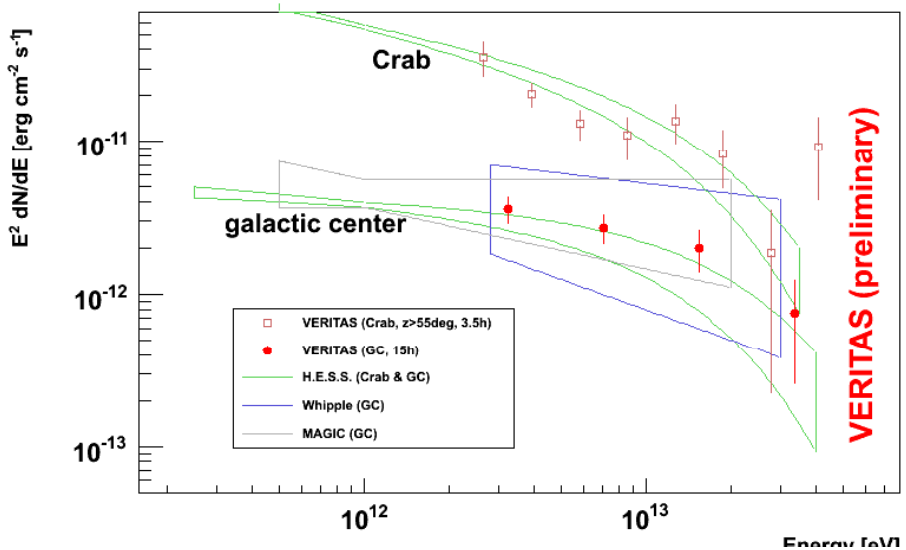
Spectrum (preliminary):

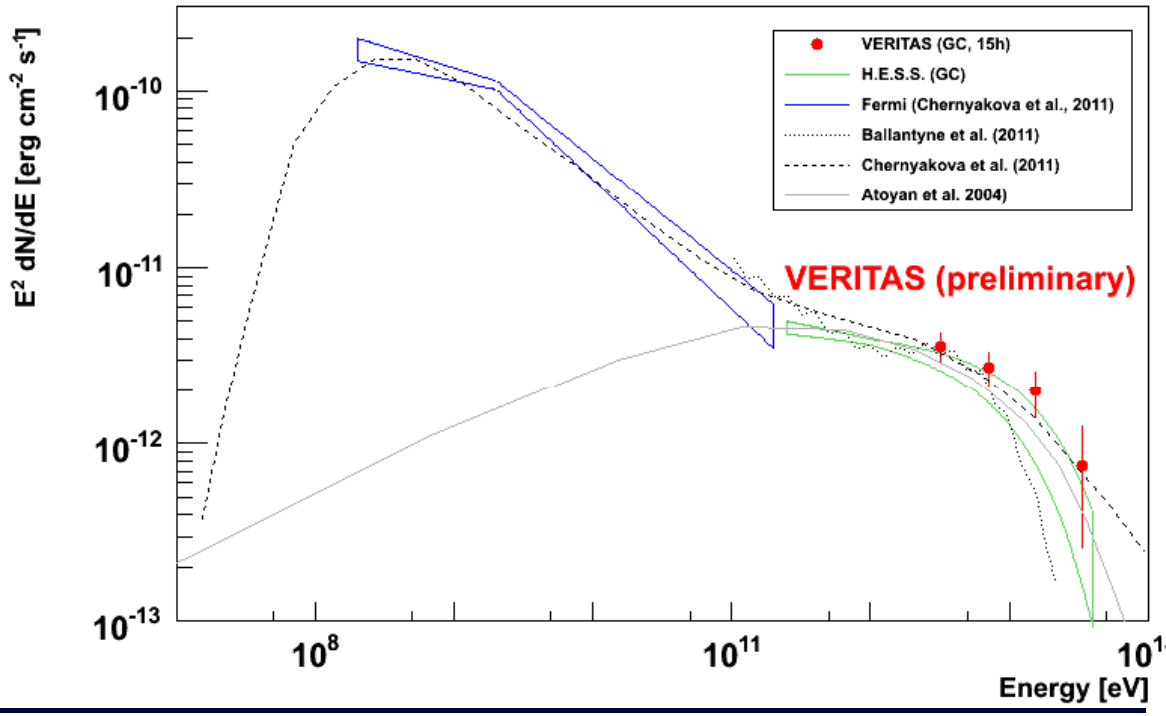
- Compatible with Whipple, H.E.S.S. and MAGIC.
- Conservative flux systematic ~40% (from Crab LZA).

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).

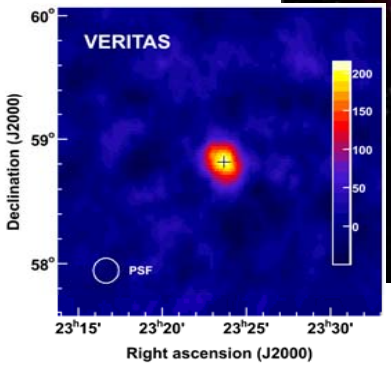
Future:
Improved >10 TeV data (spectrum & variability) to constrain cut-off.

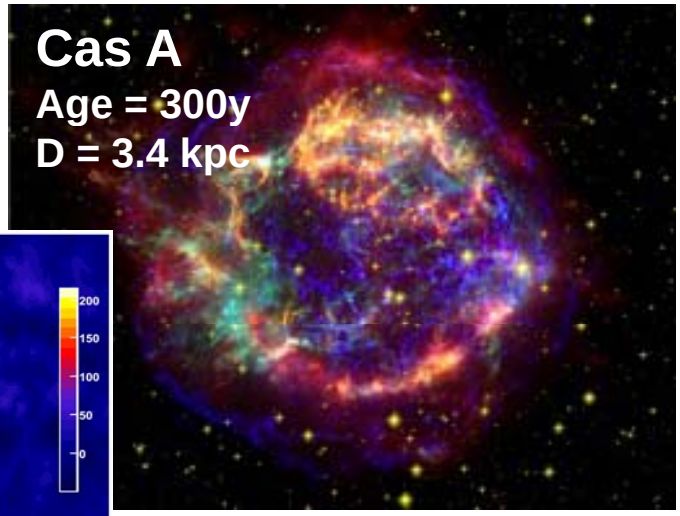


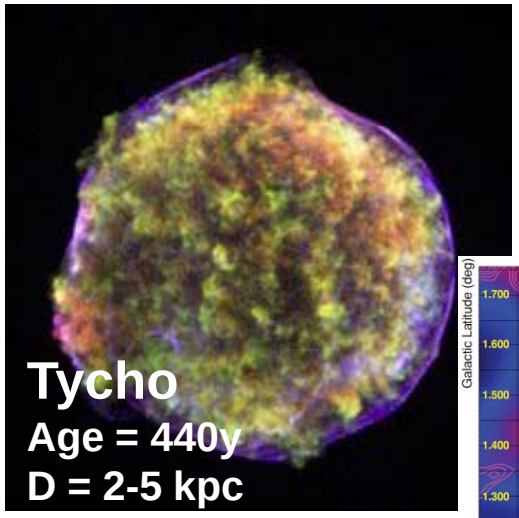


VERITAS Supernova Remnants

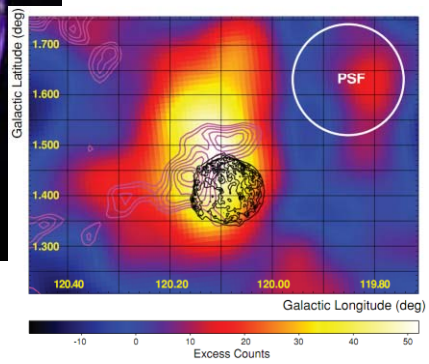
Cas A
~3% Crab

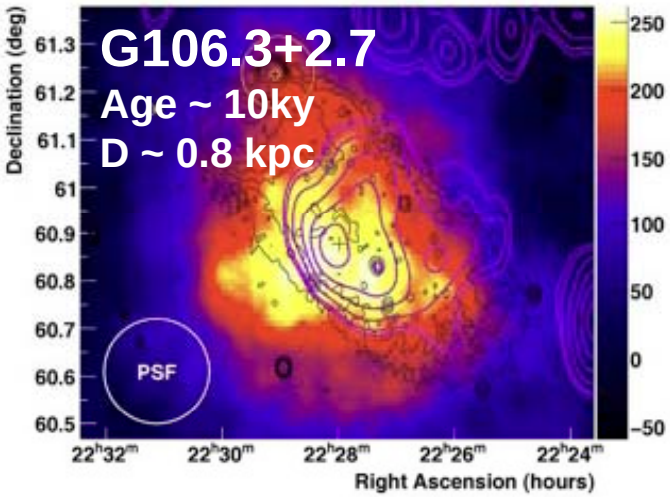






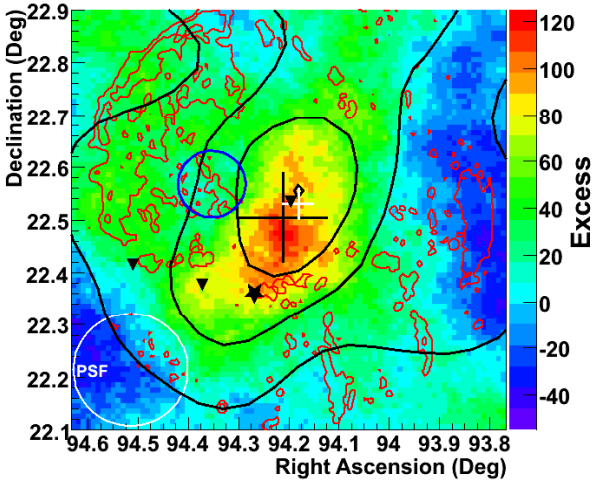
Tycho
~1% Crab

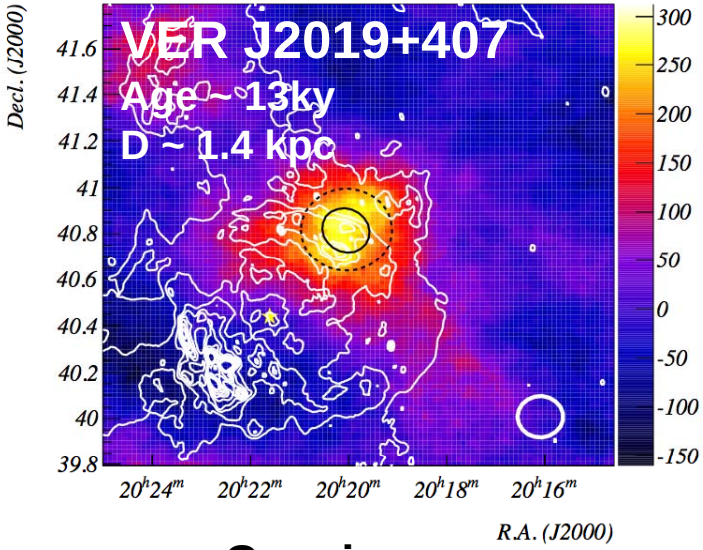




Boomerang

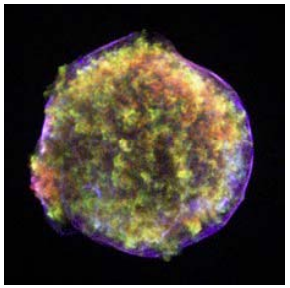
IC 443
Age ~ 30ky
D ~ 0.8kpc

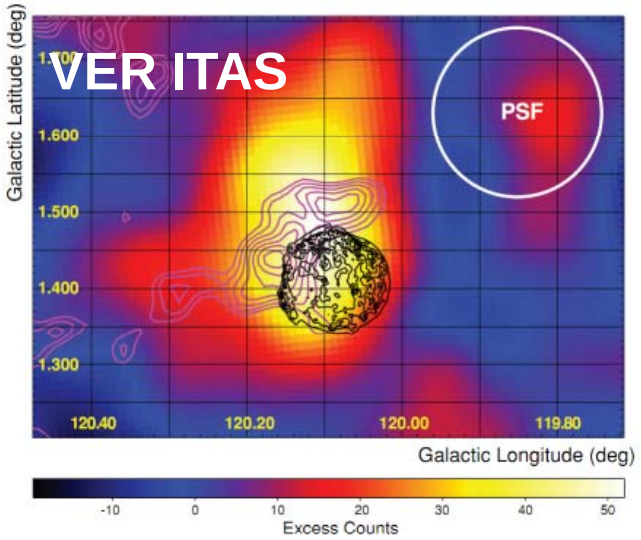




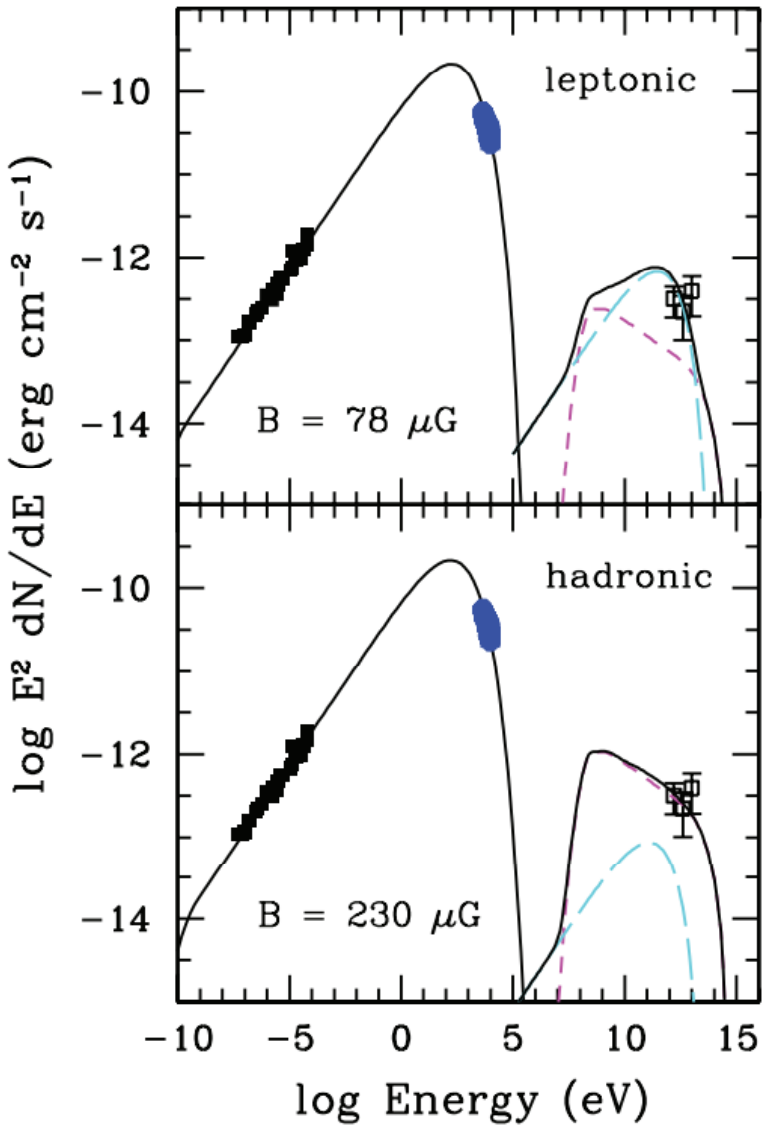
γ-Cygni

Tycho's SNR: VERITAS Discovery





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



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.

Tycho with Fermi-LAT, Hadrons ?

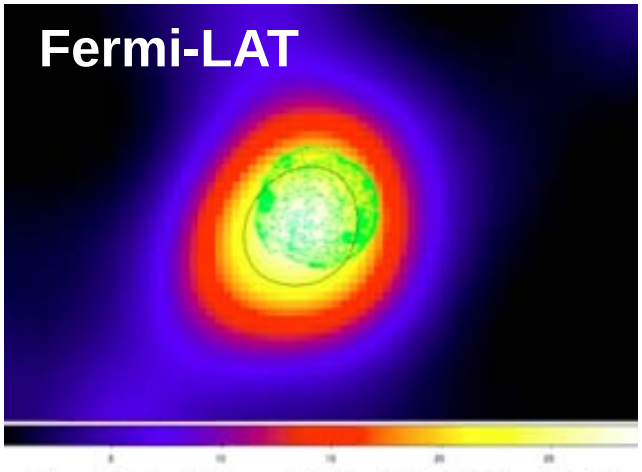
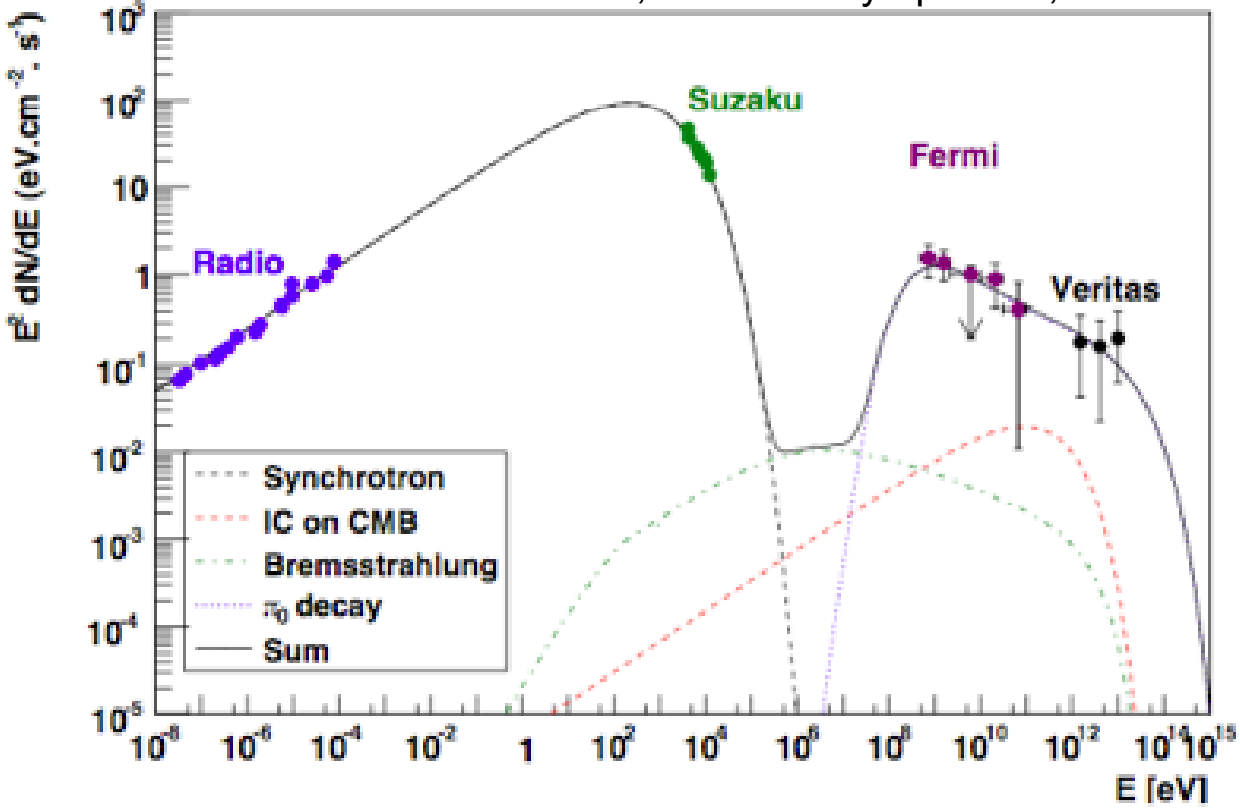


Figure 2: *Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.*

M. Naumann-Godo et al., 3rd Fermi Symposium, 2011



Fermi-LAT & VERITAS:

- New Fermi-LAT detection (5σ).
- Hard photon index of 2.3 ± 0.1 favors hadronic origin.
- 6-8% of E_{sn} transferred to CR acceleration (D~2.8kpc).

Good evidence for hadron accelerator; similar for Cas A

CTA 1: First Blind-Search Fermi Pulsar

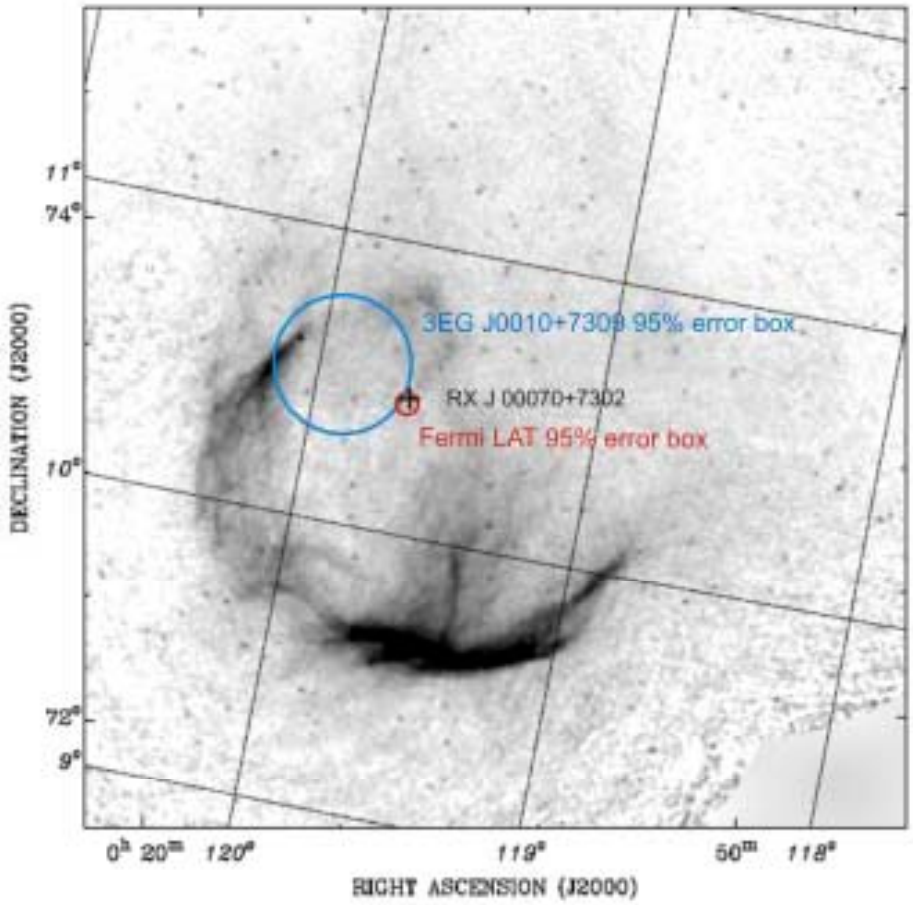
CTA 1:

- Composite SNR with an X-ray filled radio shell ~1.8^{o} diameter.
- Age ~ 13ky, D~ 1.4 ± 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_{cutoff} ~ 5 GeV; characteristic pulsar age ~ 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

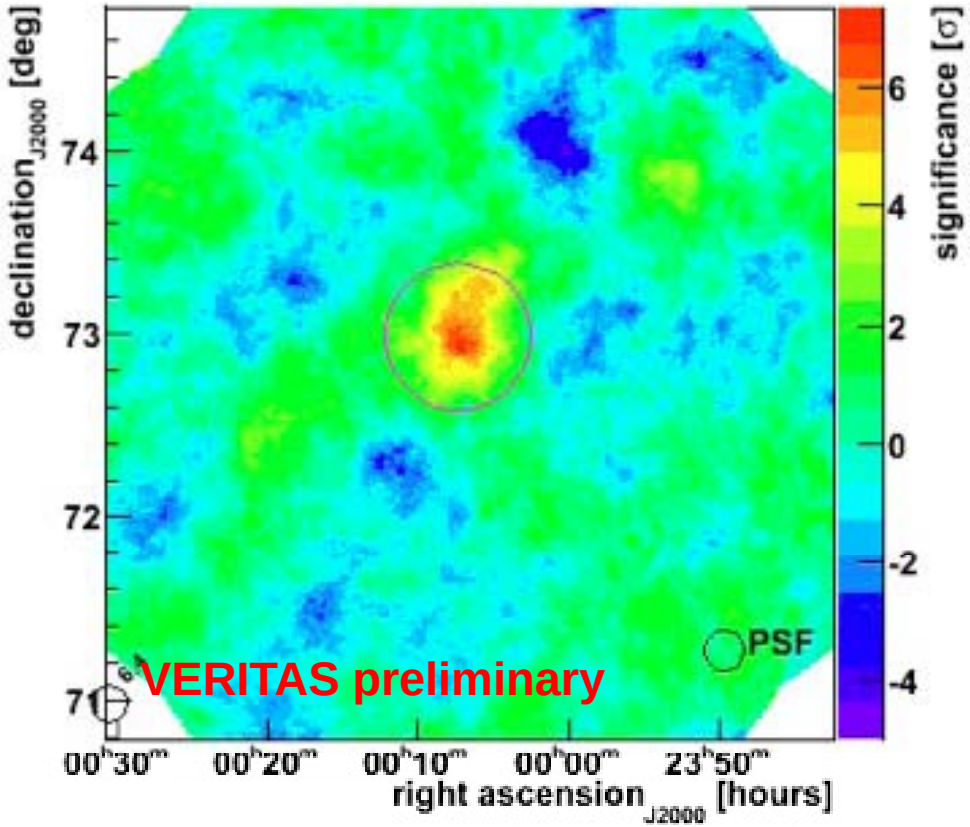
VERITAS Observations:

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

Detection:

- Significance ~6.3σ post-trials.
- F (> 1 TeV) ~ 4% Crab Nebula.
- Clearly extended source.

S. McArthur, R. Mukherjee



CTA 1: VERITAS Detection

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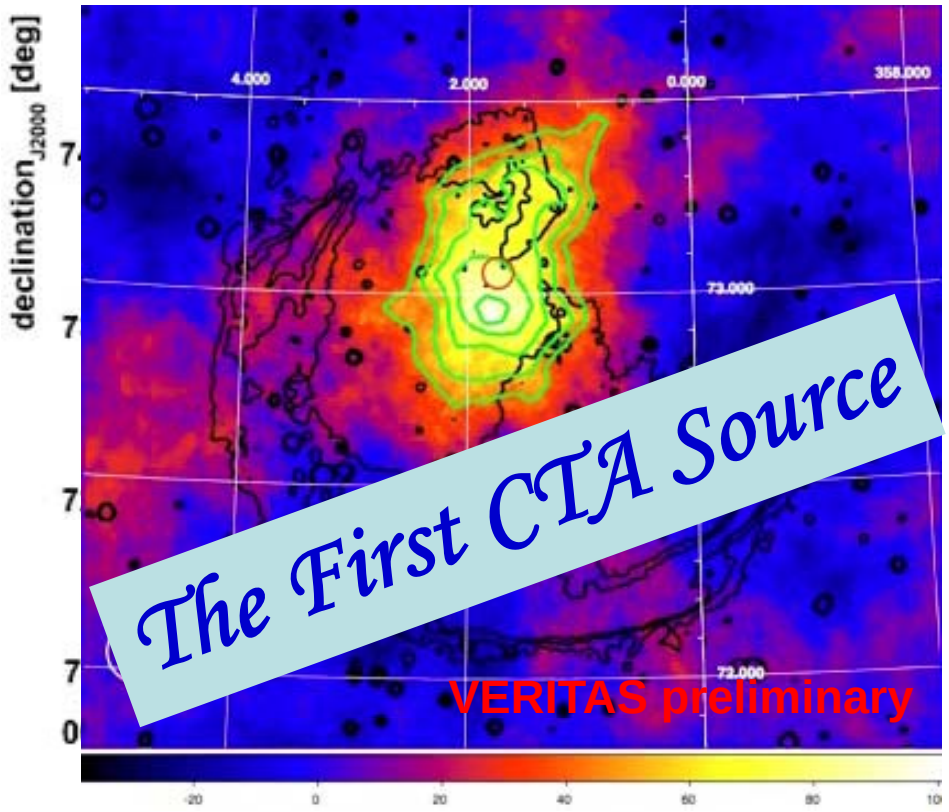
- F (> 1 TeV) ~ 4% Crab Nebula.
- Clearly extended source.

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)

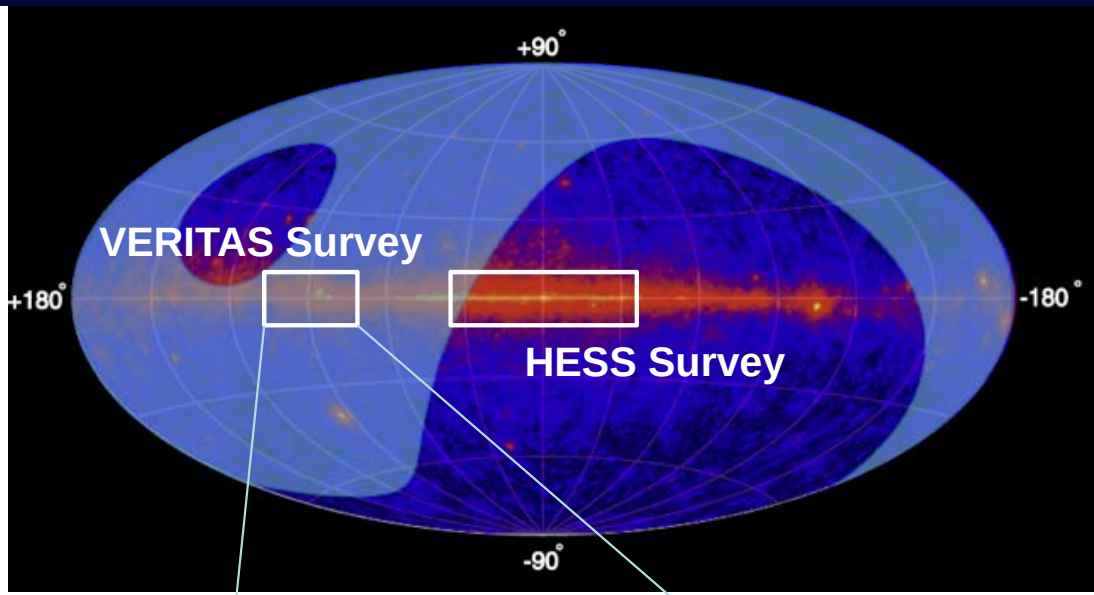
Color: VERITAS excess map with green contours from 3-7σ.
Black: Radio 1420 MHz (T. Landecker).
Red: Fermi-LAT error circle.



VERITAS Cygnus Sky Survey

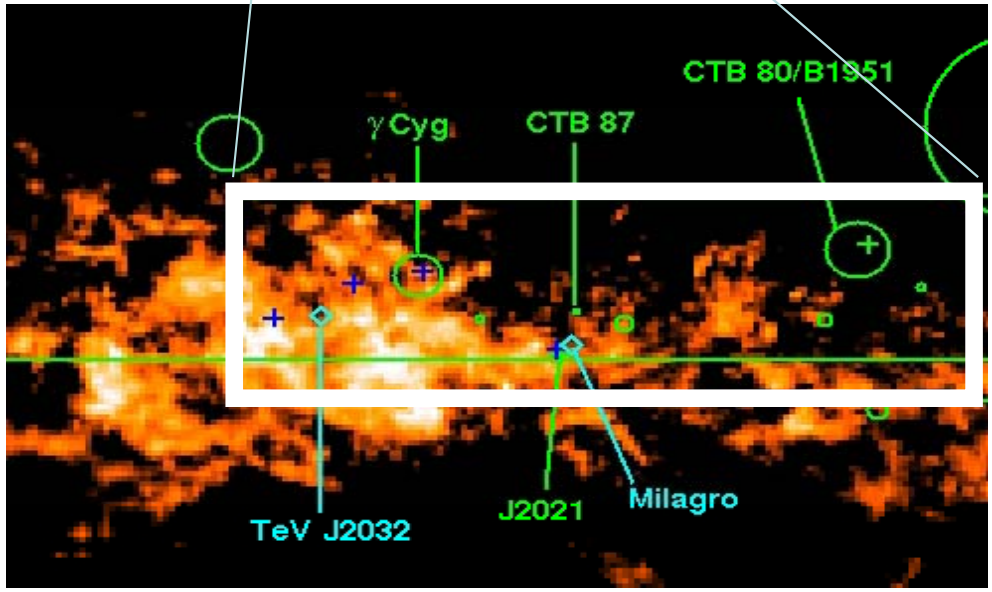
VHE Sky Surveys:

- **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.

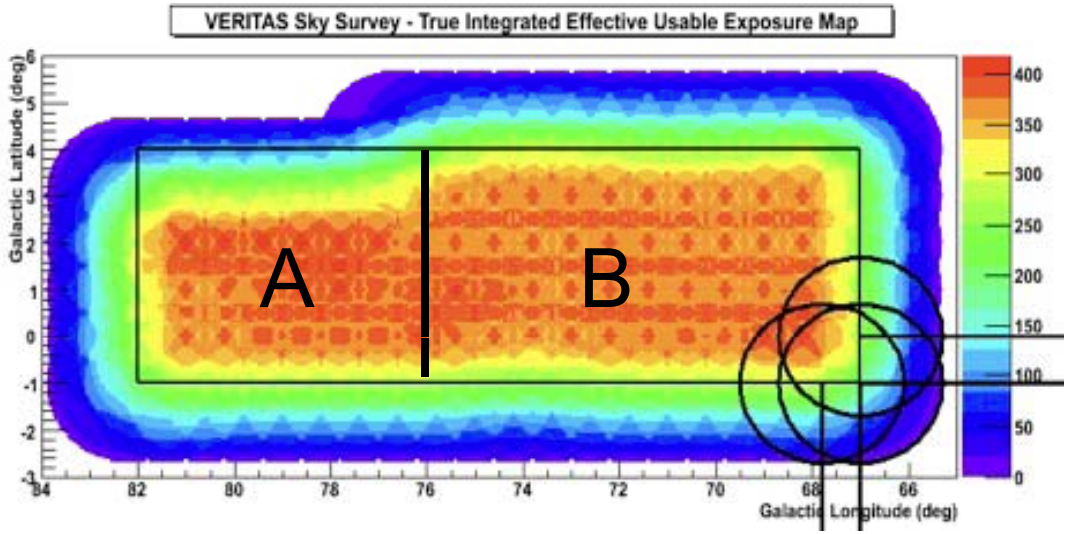


VERITAS Sky Survey (07-09):

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



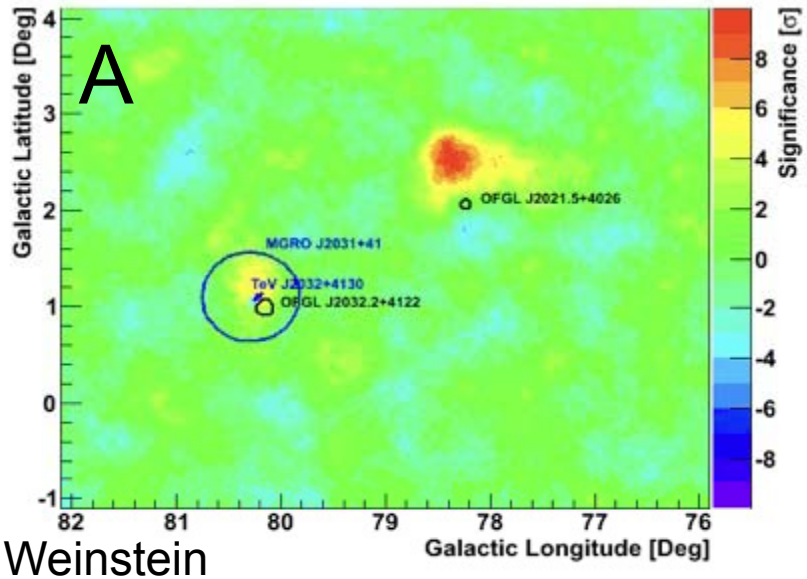
VERITAS Cygnus Sky Survey



Survey exposure map

- Survey done by pointings spaced by 0.8° in l and 1.2° in b.
- Overall scope limited by summer and weather conditions.

Left side region (2010)



TeV J2032+4130

- First UnID TeV source

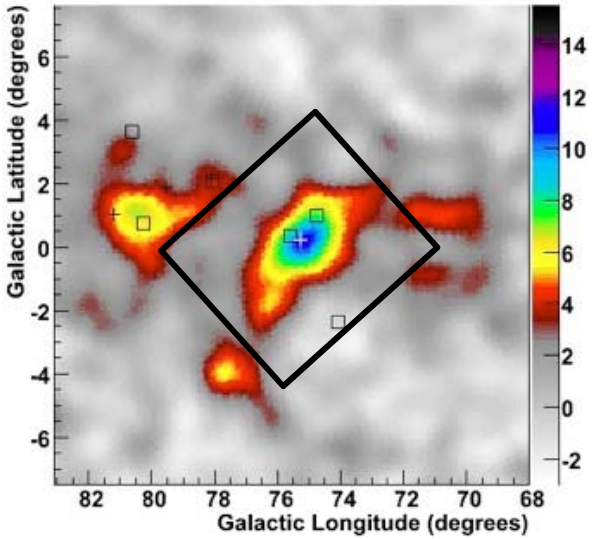
VER J2019+407

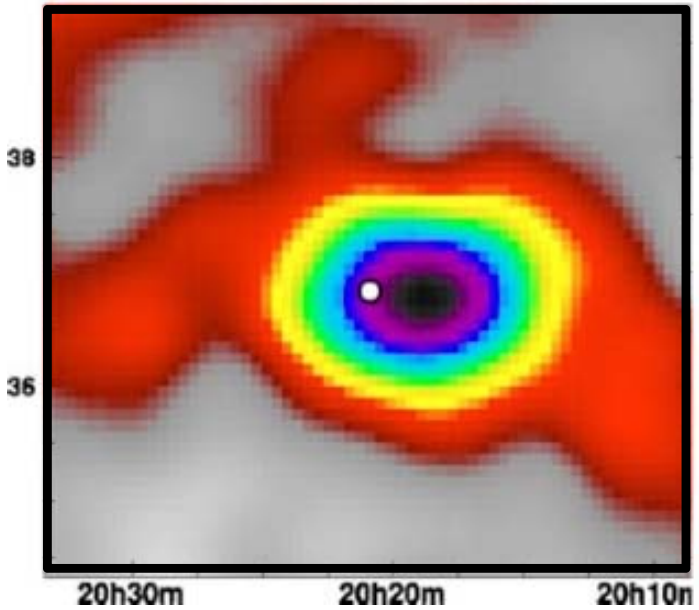
- New source near γ-Cygni.
- SNR interaction with HI shell ?

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:

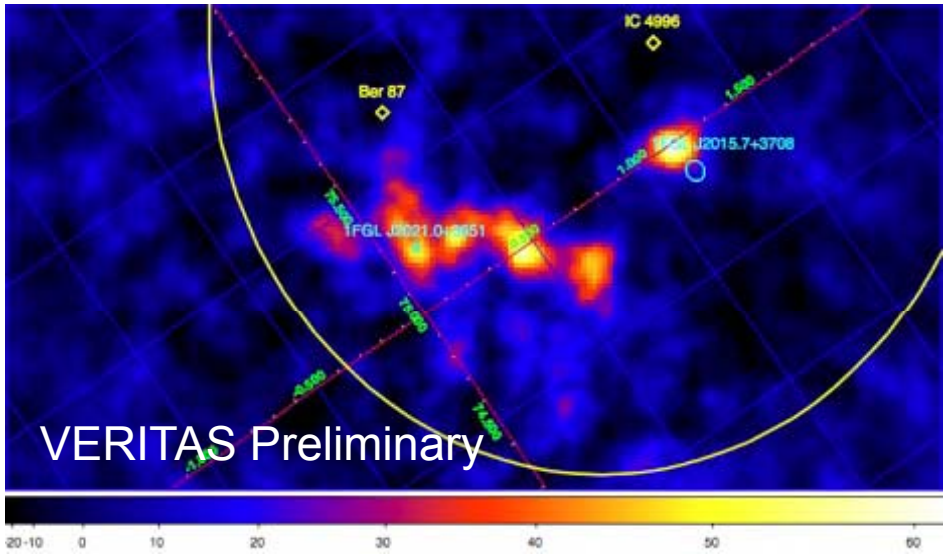
- 75h, May-Dec 2010.
- 0.7^{o} wobble around PSR J2021+3651.
- Pt-source and extended search (0.25^{o}).
- Hard cuts, E_{th} ~ 600 GeV.

Results:

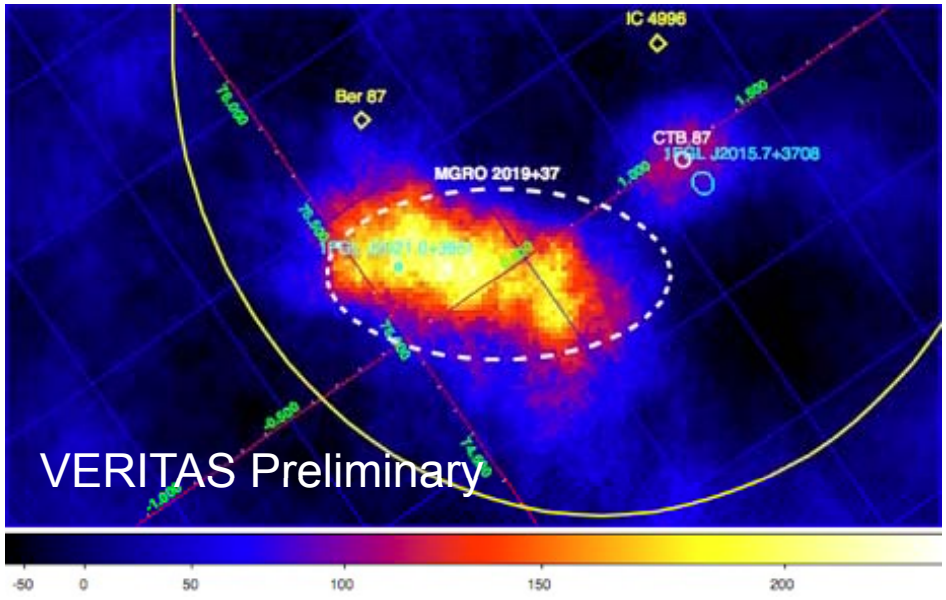
- Point source and extended source both detected above 6σ, post-trials.
- The extended source is a complex region, most likely made up of multiple sources.

E. Aliu et al.,
3rd Fermi Symposium (2011)

Pt-source



Extended source

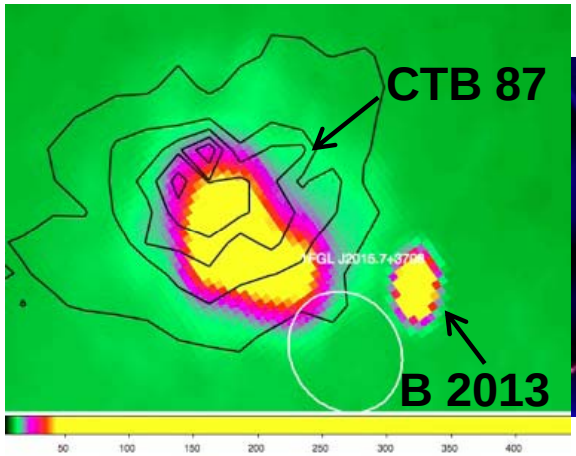


VER J2016+372 and Cisne

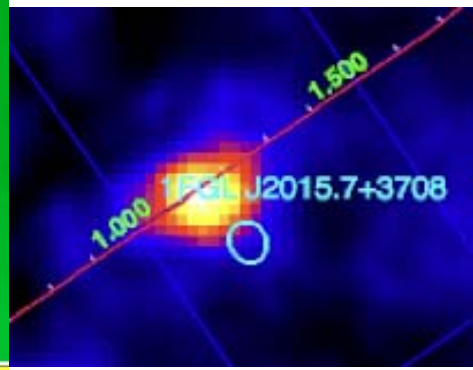
VER J2016+372:

- 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 3σ to 7σ contours

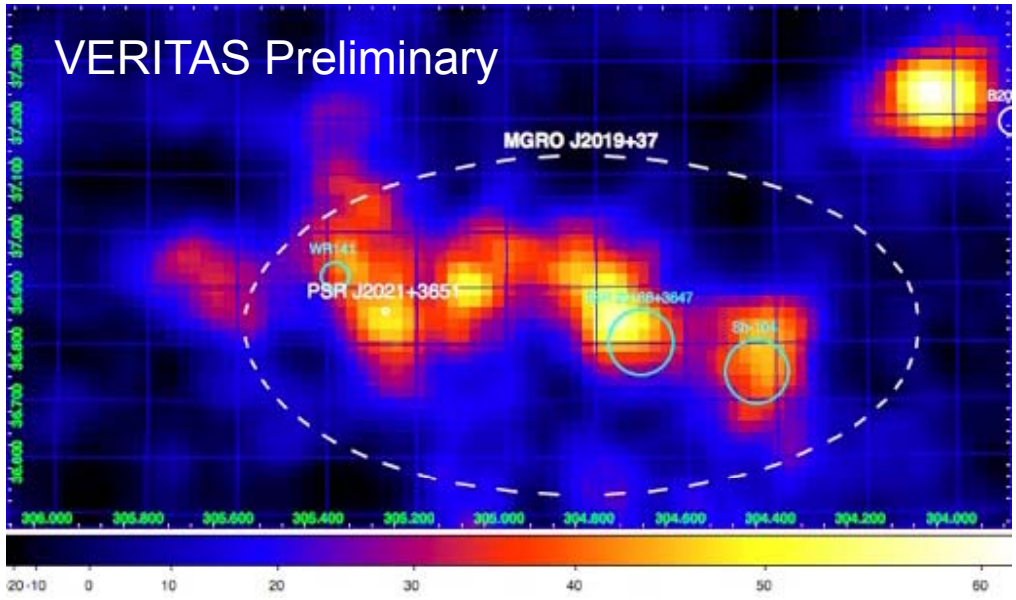


VERITAS Emission &
1FGL J2015.7+3708



Cisne:

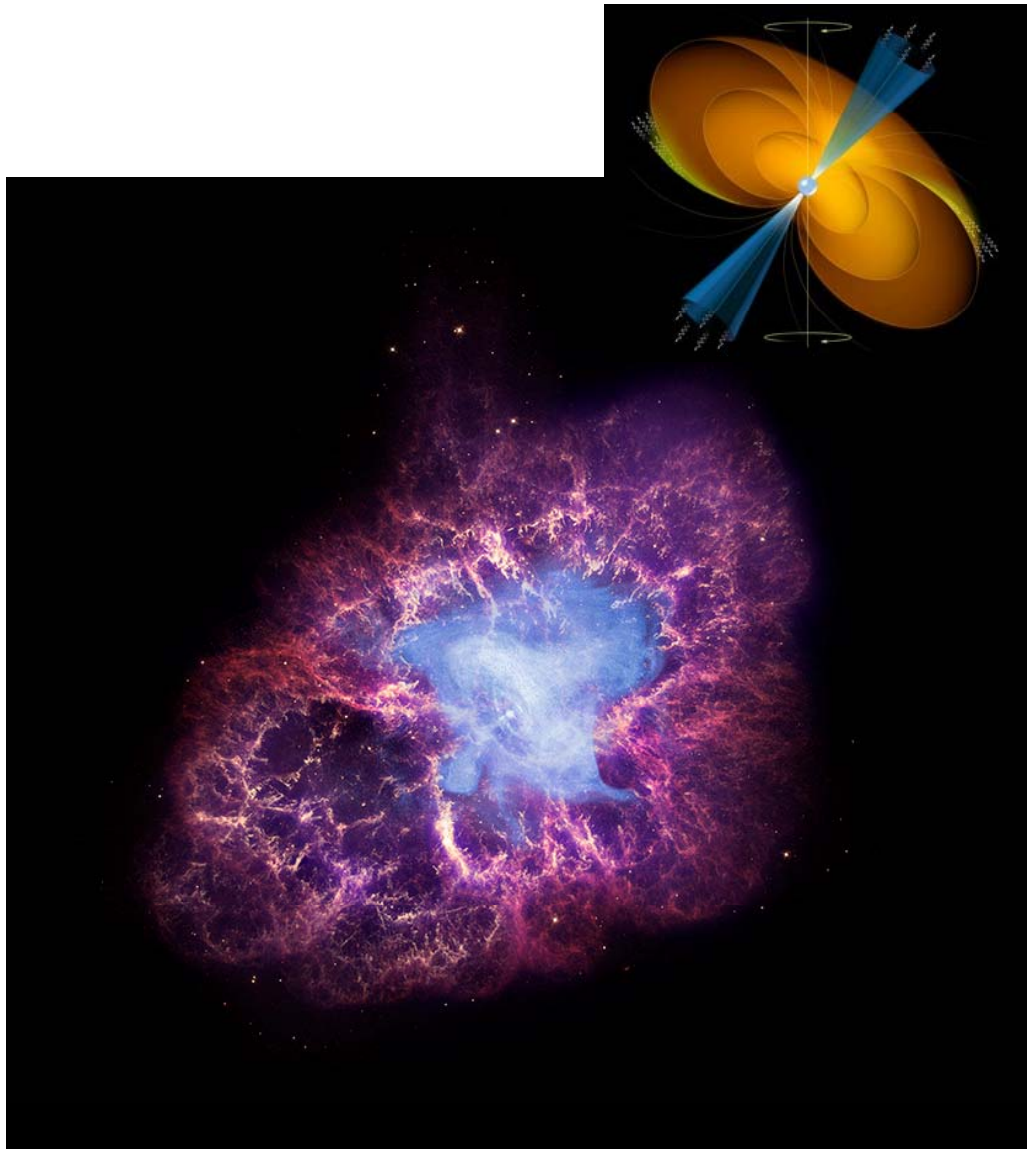
- VERITAS data consistent with MGRO J2019+37, but reveals more detail.
- Most likely multiple (possibly extended) sources.
- Need more VHE and lower energy data; Fermi-LAT analysis to be presented at ICRC 2011 (Beijing).



Crab

Crab Nebula and Pulsar

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



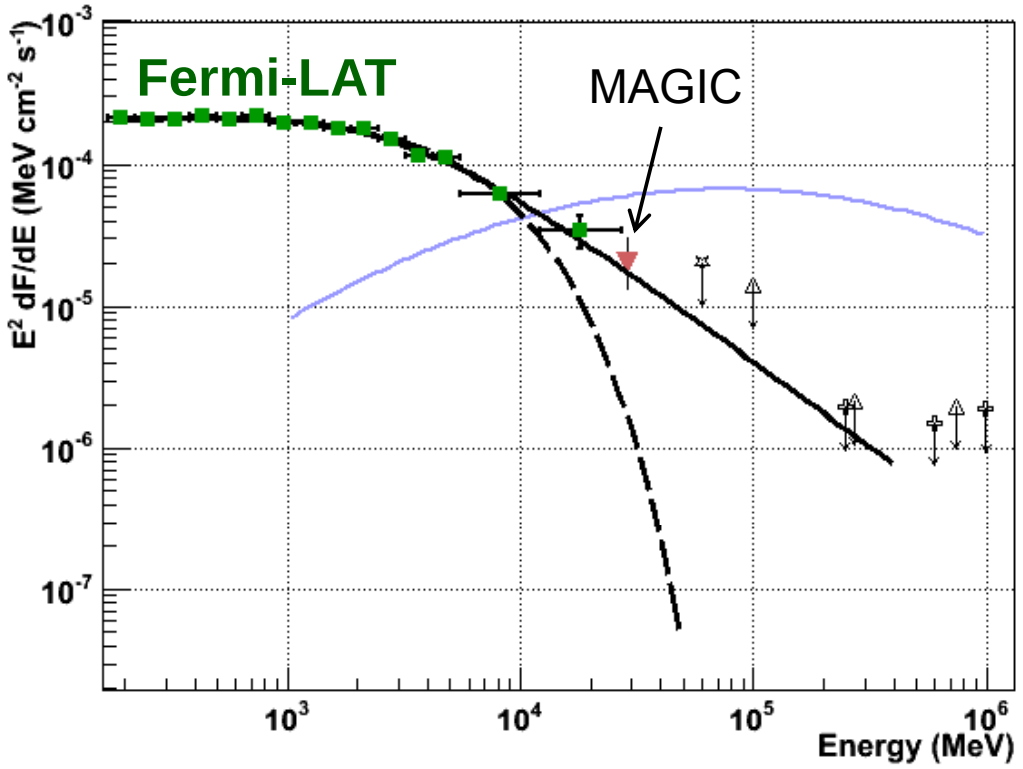
γ-ray observations of Pulsar

- **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} ~ 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 γ-ray production mechanism.
- Emission come from outer regions >6 stellar radii. Outer-gap or slot-gap models favored.

VERITAS Observations & Analysis

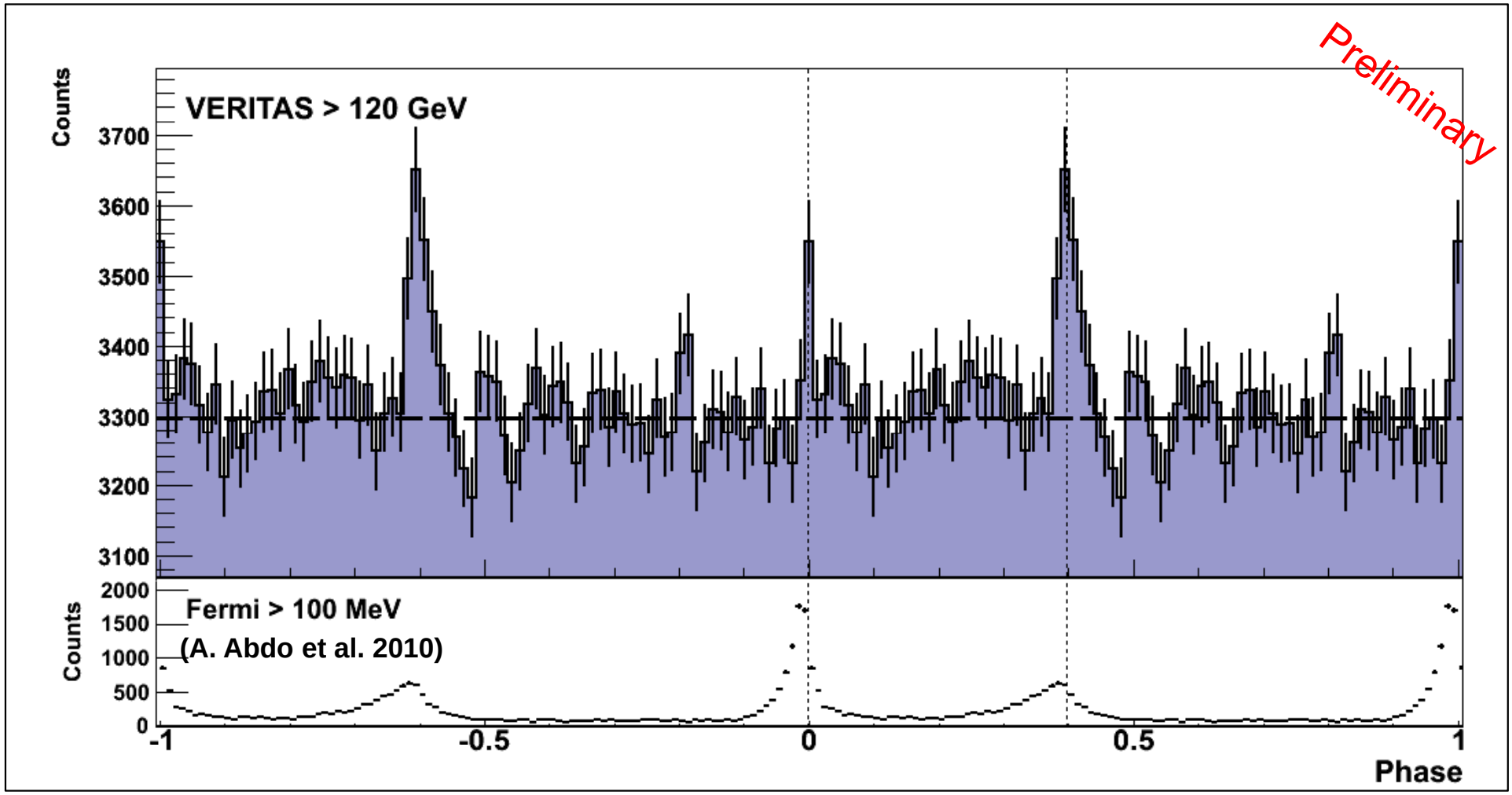
VERITAS Observations:

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

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

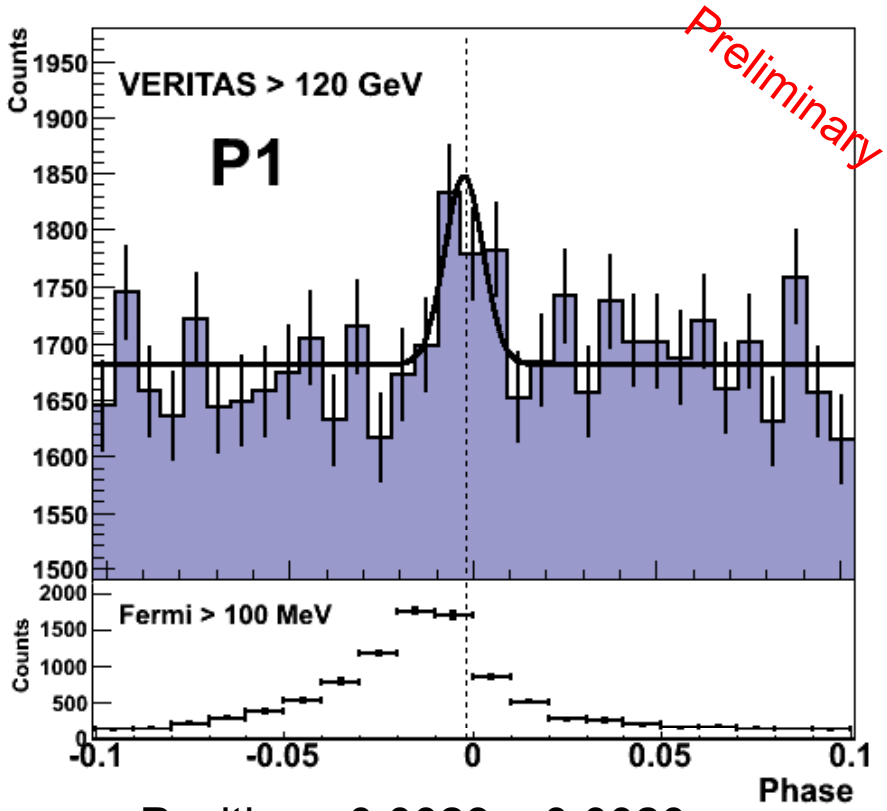
- Standard trigger, standard analysis tools (two independent packages).
- Hillas image analysis with stereo reconstruction.
- Analysis selection set *a priori* for weak (few % Crab Nebula) source with soft spectrum, Γ = 4.
- Event time barycentering with two custom codes and tempo2.
- Phase folding of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

VERITAS Pulsed Signal



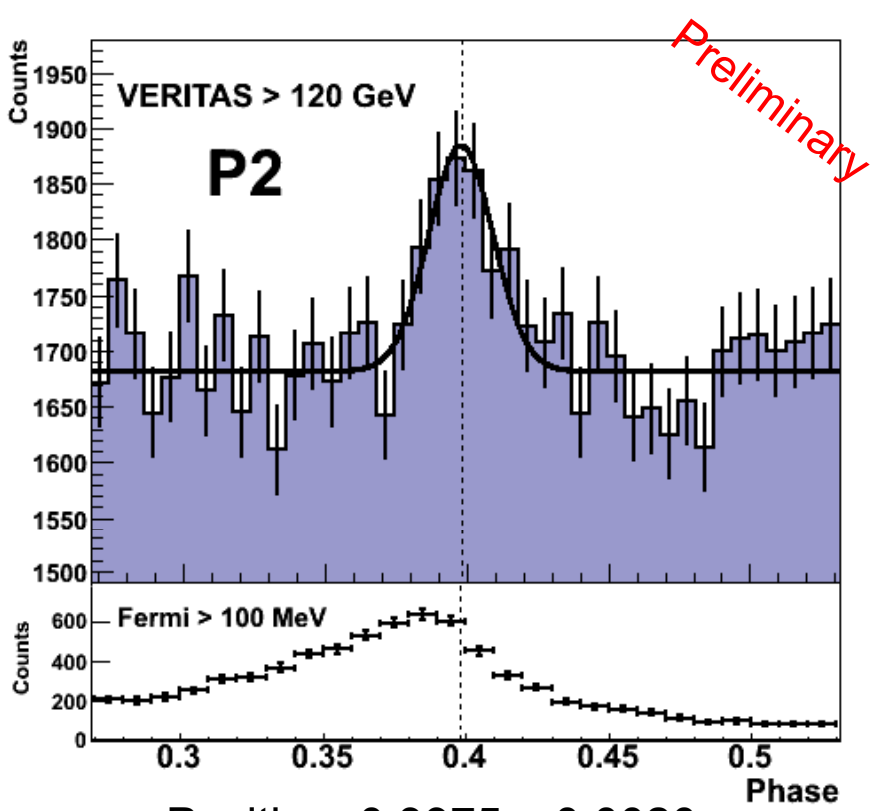
Statistical significance of pulsed signal:
H-Test value of 50, i.e. 6.0σ.

A Closer Look at the Peaks



Position: -0.0023 ± 0.0020

Width: 0.0132 ± 0.0035 FWHM



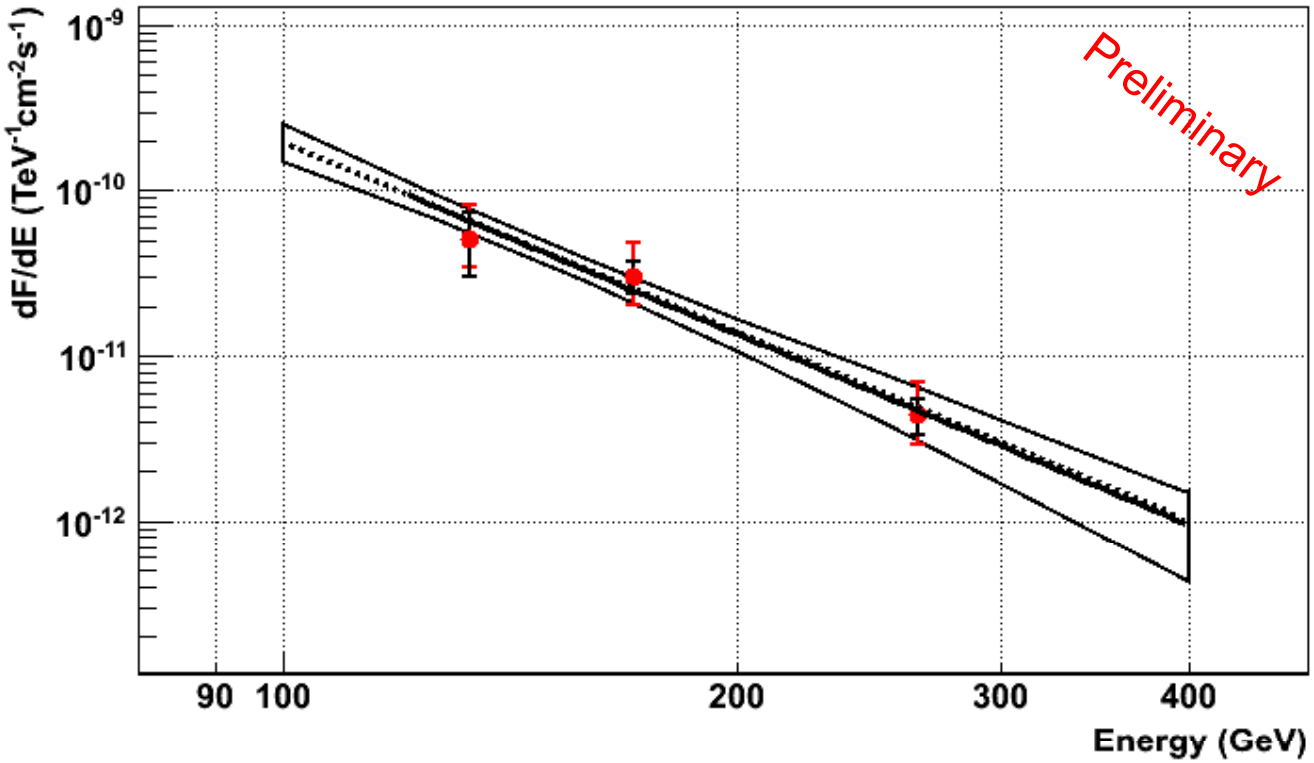
Position: 0.3975 ± 0.0020

Width: 0.0268 ± 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 **five times narrower than in Fermi-LAT data** → possible interpretation: the acceleration zone tapers

VHE Spectrum of Crab Pulsar

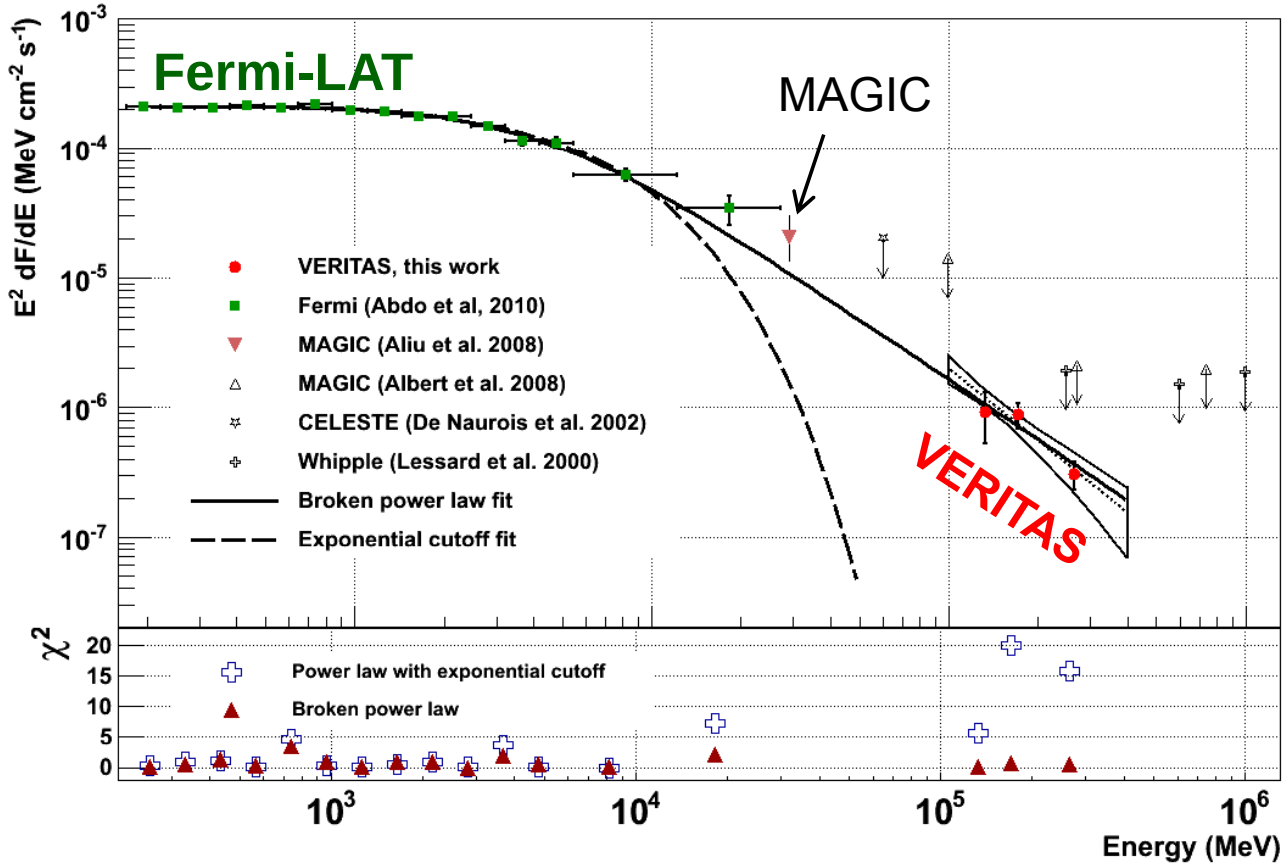


VERITAS VHE Spectrum:

- Combine P1 and P2 regions – good approx.of phase-averaged spectrum.
- Highest energy point at 280 GeV.
- Crab Pulsar ~ 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



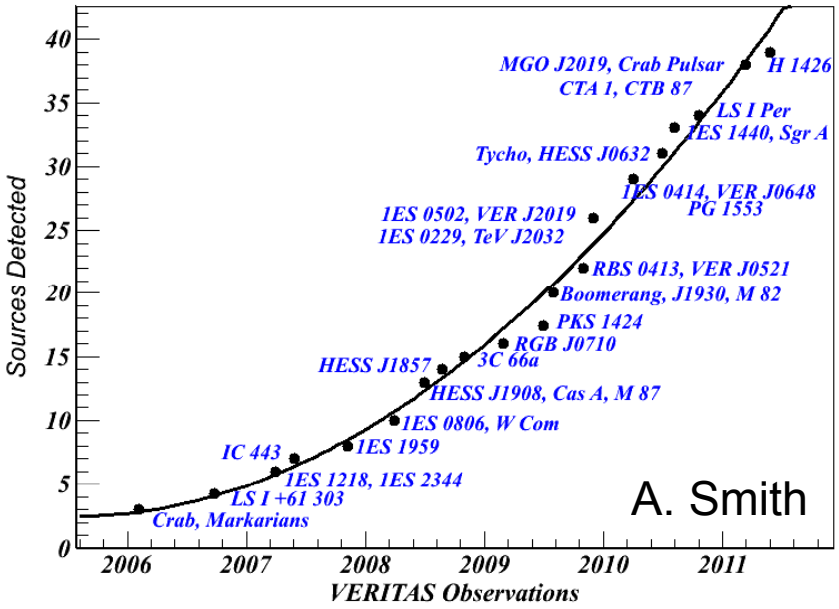
- **First detection of a pulsar above 100 GeV.**
- VERITAS detection @ 280 GeV → emission region > 10 stellar radii.
- Absence of exponential cutoff → rules out curv. radiation as dominant mech.
- Narrowing of pulses → tapered acceleration region ?
- What other pulsars are out there at E > 100 GeV ?

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 ~100 GeV.

VERITAS Detections vs time



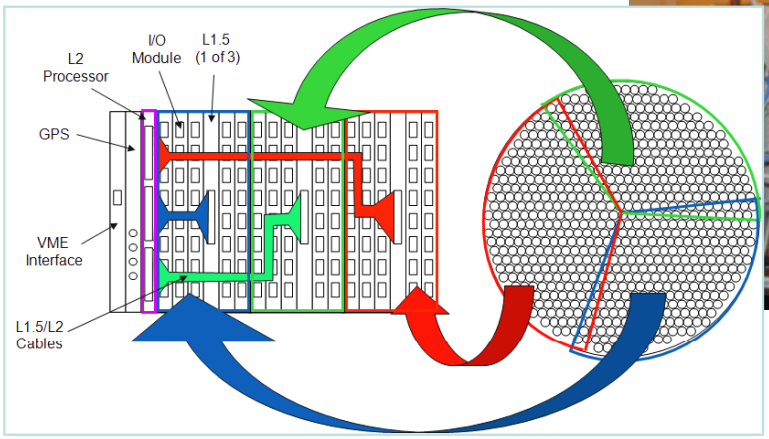
VERITAS UPGRADE (2009-2012):

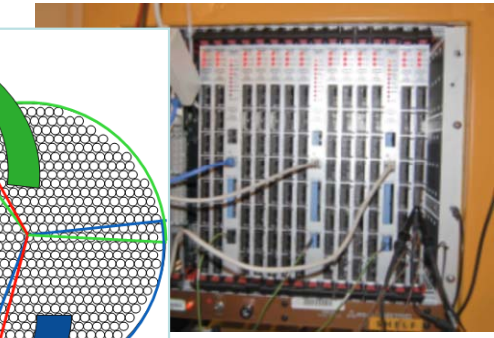
1. Improved optical point spread function ← completed
2. Relocating telescope T1 ← completed
3. Upgrading cameras with high efficiency PMTs ← ongoing
4. New trigger system ← ongoing
5. An additional telescope T5 ← possible in the future

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.

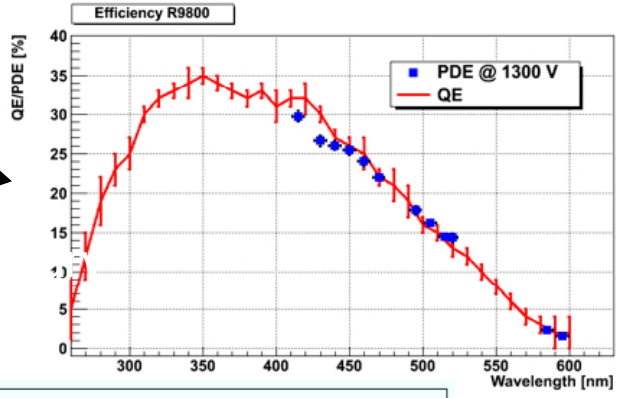




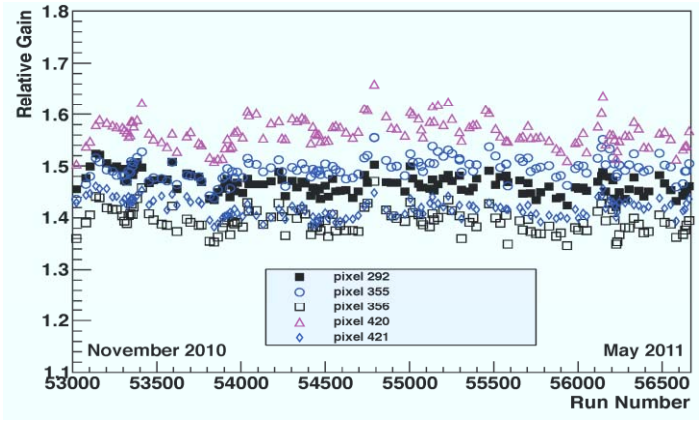
Camera upgrade (2010-2012):

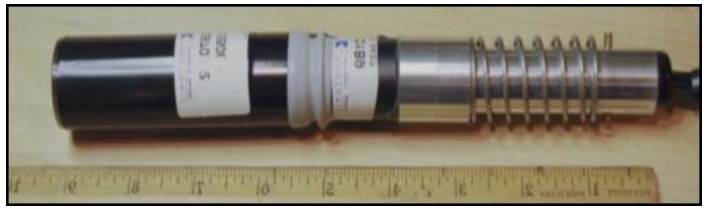
- Replace all PMTs with HQE ones (Hamamatsu R9800 SBA); new mount tube and pre-amp.
- Improve sensitivity and lower E threshold (120 GeV→ 80 GeV) .
- Installed Summer 2012.

Measured QE/PDE (50% increase)



PMT stability (*in situ*)





Summary

Lots of new Galactic results from VERITAS:

- **Galactic Center**: competitve observations possible using LZA technique.
- SNRs: we seem to detect young shell-type SNRs directly and older ones through interaction with material. **Tycho**, a young SNR, 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** (γ-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 clearly different than at lower energies – new understanding of pulsars needed !
- VERITAS is operating well and will further improve with upgrade (2012).