# THE GALAXY IN GAMMA RAYS: RESULTS FROM VERITAS

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for the VERITAS Collaboration
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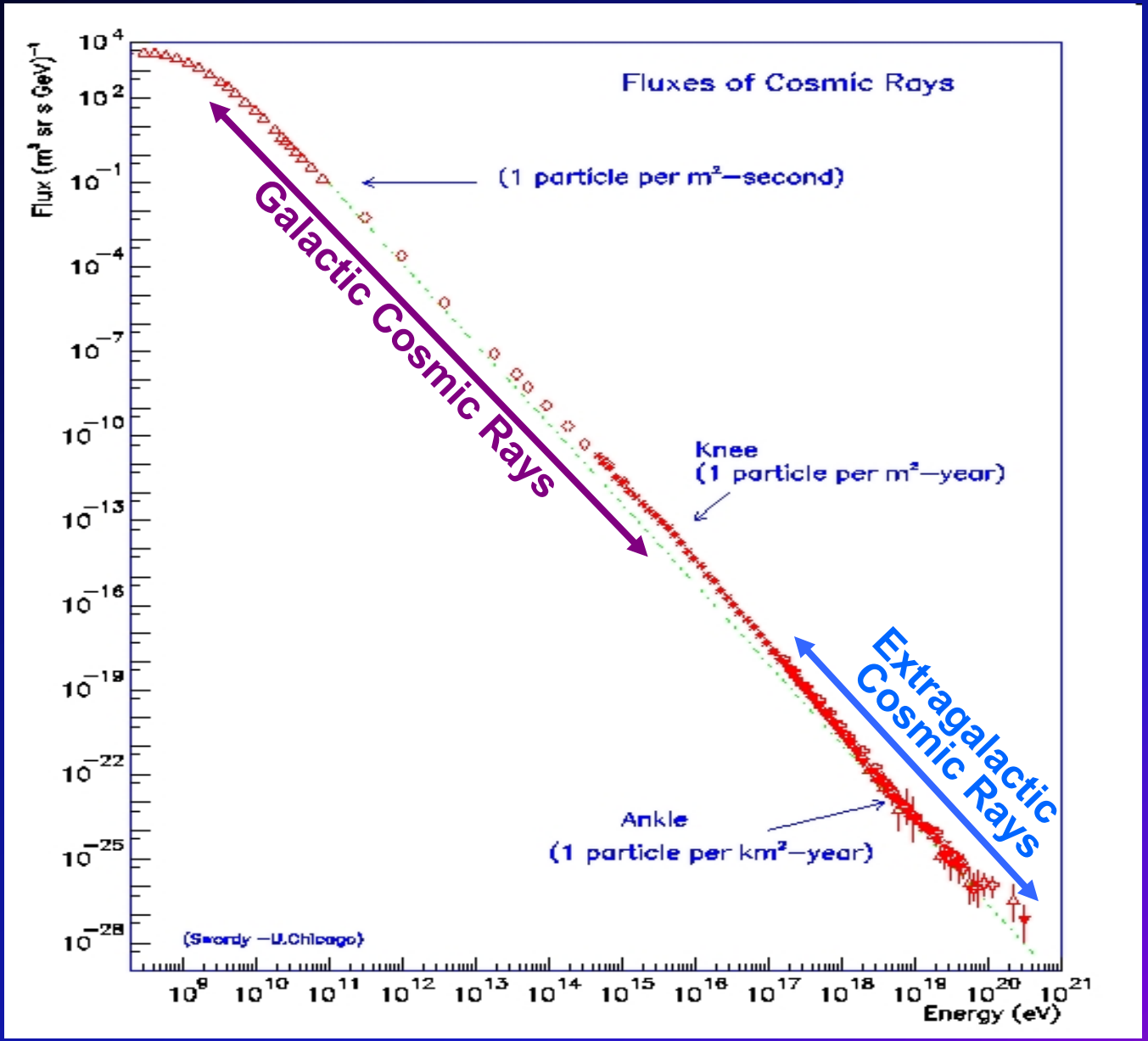
# Outline


- Background
  - Cosmic rays and astrophysical accelerators
- VERITAS (and Fermi)
- Starburst Galaxy M82
- Sky Survey of the Cygnus Region
- Pointed Observations of SNRs and PWNe
- The Future
  - VERITAS upgrade plans
  - AGIS

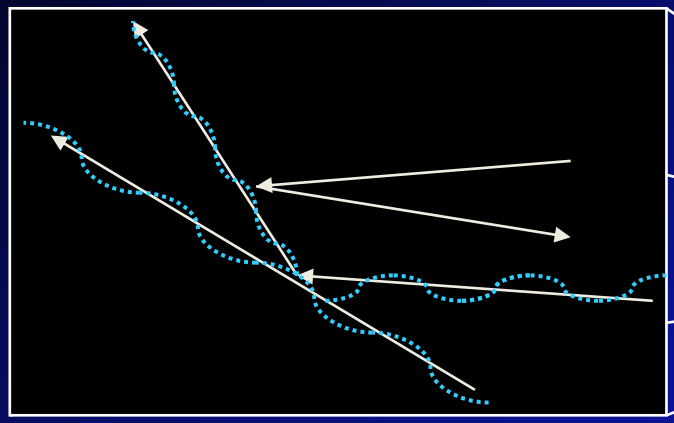
# Cosmic Ray Energy Spectrum

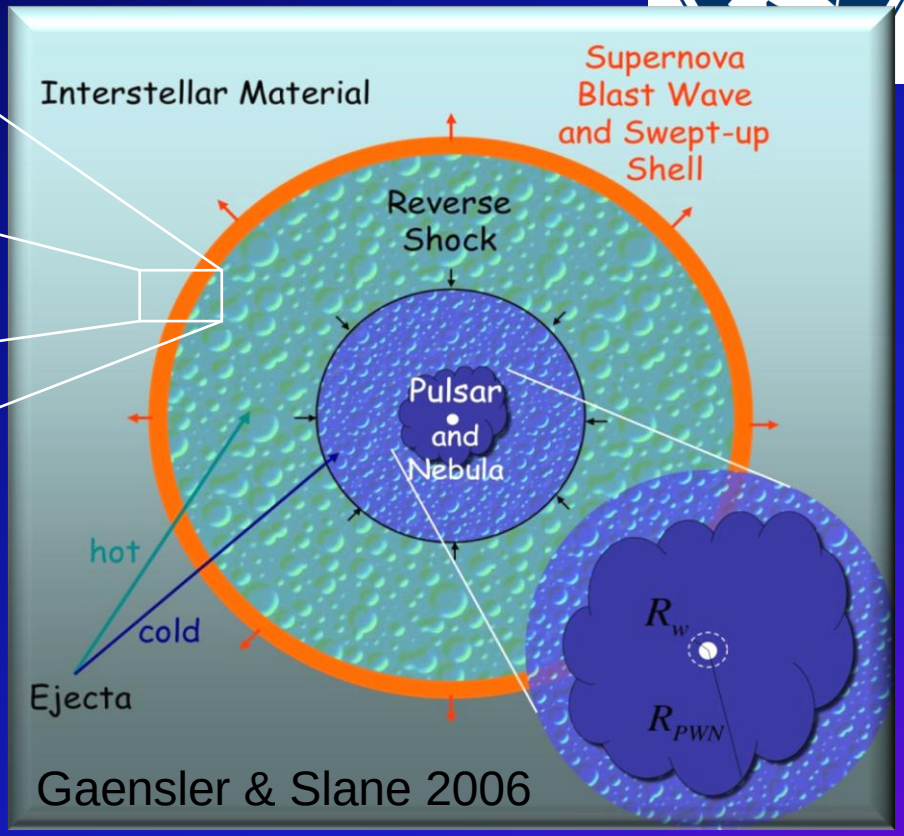


# Cosmic Rays – Origins?

- Cosmic rays gradually leak out of the galaxy, with a typical timescale of ~ 10 million years
  - ⇒ CR power loss ~ 5 * $10^{40}$ erg/s
- *Can* be supplied by supernova remnants – enough energy:
  - ~$10^{51}$ erg released in SN / 50 yrs ~ $10^{9}$ s ⇒ $10^{42}$ erg/s
  - Mechanism exists: diffusive shock acceleration
- Evidence that SNRs accelerate electrons – what about ions?
  - Overall efficiency? Isolated SNRs vs. Superbubbles?
- Other possibilities exist
  - Stellar winds, Superbubbles, Pulsars, Microquasars, Galactic wind…

# Supernova Remnants & Pulsar Wind Nebulae





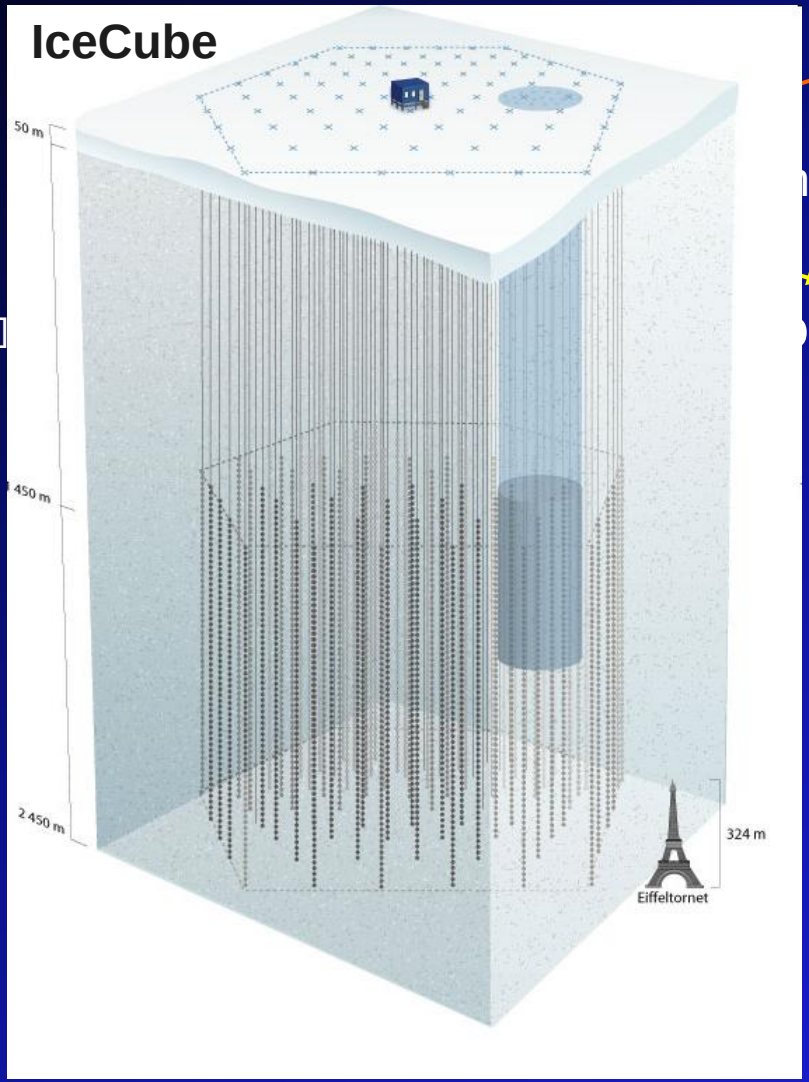

- Pulsar Wind
  - sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms

- Supernova Remnant
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN
  - self-generated turbulence by streaming particles, along with magnetic field amplification, promote diffusive shock acceleration of electrons and ions to energies exceeding 10-100 TeV

(courtesy Pat Slane, CfA)

# Gamma Rays from SNRs

- Inverse Compton Scattering: cosmic-ray electrons




…hoton


- …smic-ray nuclei

  - Gamma rays and neutrinos provide a smoking gun for acceleration of cosmic ray nuclei in SNRs!

    Caveats:

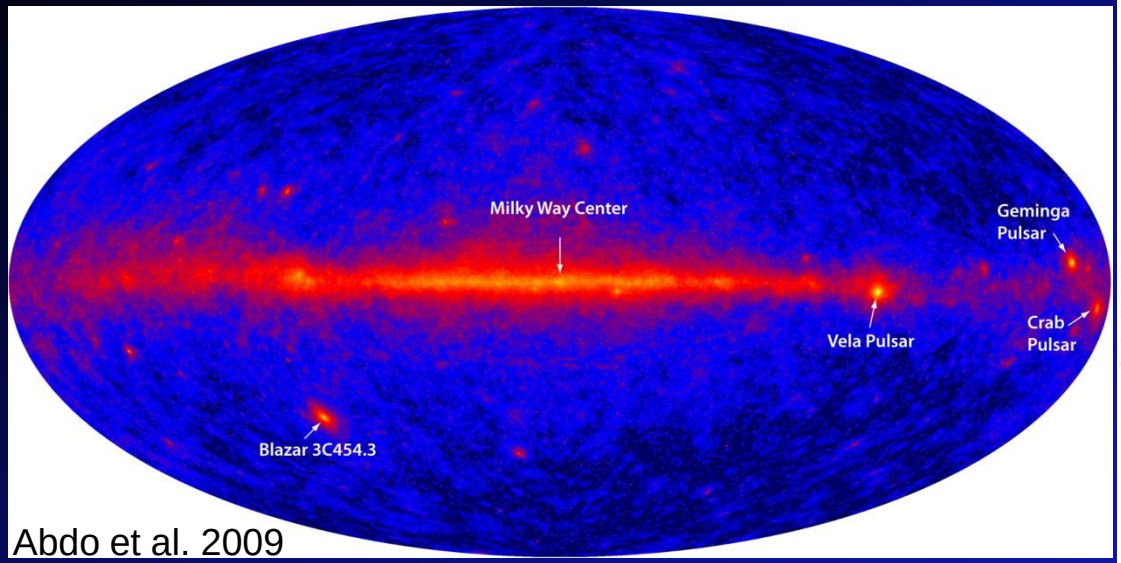
    ⇒ Gamma signal can be faked by cosmic-ray electrons

    ⇒ Still searching for neutrino signal!

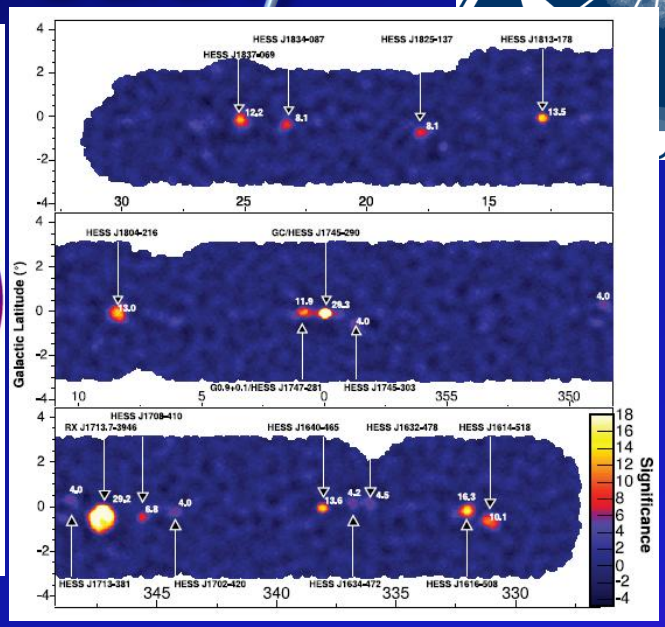
# GeV / TeV Connections

- Broad-band γ-ray spectral and morphological studies of Supernova Remnants and Pulsar Wind Nebulae
  - Spatially resolved properties of nonthermal populations
  - Common population of objects across GeV / TeV
    - ➢ Also different objects! (cut-offs, spectral shapes, …)
- Supernova Remnant / Cosmic Ray science
  - Interactions with dense clouds ⇒ target material
  - Nature & maximum energy of emitting population (electrons vs ions)
  - Propagation / diffusion of cosmic rays in interstellar medium
- Pulsar Wind Nebula science
  - Measure magnetic field strength
  - Study cooling breaks and cut-offs in broad-band spectra

# GeV vs TeV Views of the Galaxy



Abdo et al. 2009

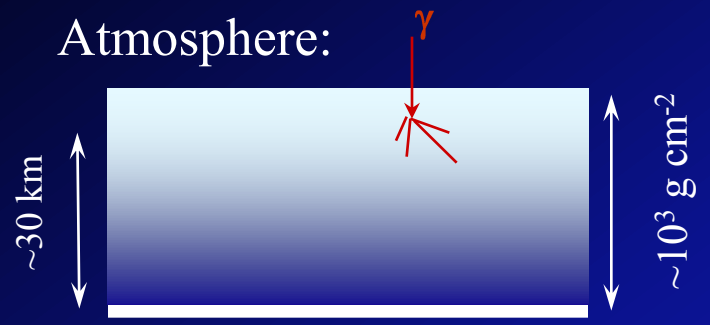


Aharonian et al. 2006

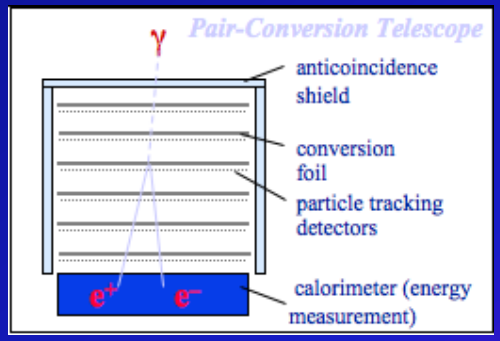
- Fermi all-sky view – strong diffuse emission across entire galactic plane
  - Cosmic rays interacting with ambient gas, photons
  - Identifying, localizing GeV emission from sources is a challenge!
- TeV Instruments – small galactic diffuse component
  - Better angular resolution, less source confusion
  - Morphological studies of cosmic-ray accelerators

# Detecting Gamma Rays

Atmosphere:



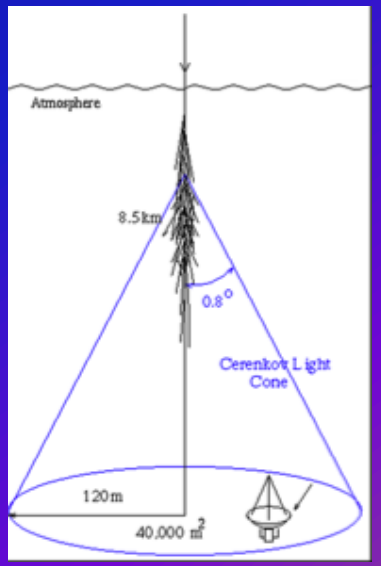

Space-based detectors: EGRET/Fermi




For $E_\gamma \lesssim 100$ GeV, must detect above atmosphere (balloons, satellites)

For $E_\gamma > 100$ GeV, enough information from showers penetrates to the ground (Cherenkov light, particle showers)

Ground-based detectors:

# 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.**

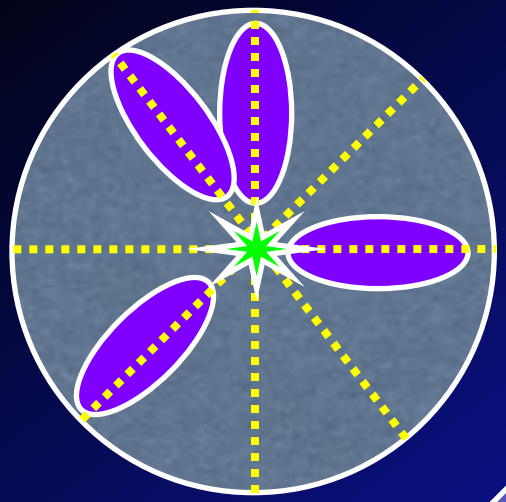
Leeds Univ.

**Ireland**

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

**+ 25 Associate Members**

# VERITAS Telescope Array



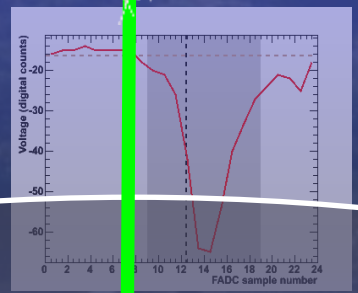


Imaging atmospheric Cherenkov light with an array:

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

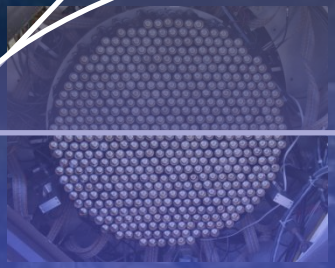
# VERITAS

(Very Energetic Radiation Imaging Telescope Array System)




**FADC Readout**

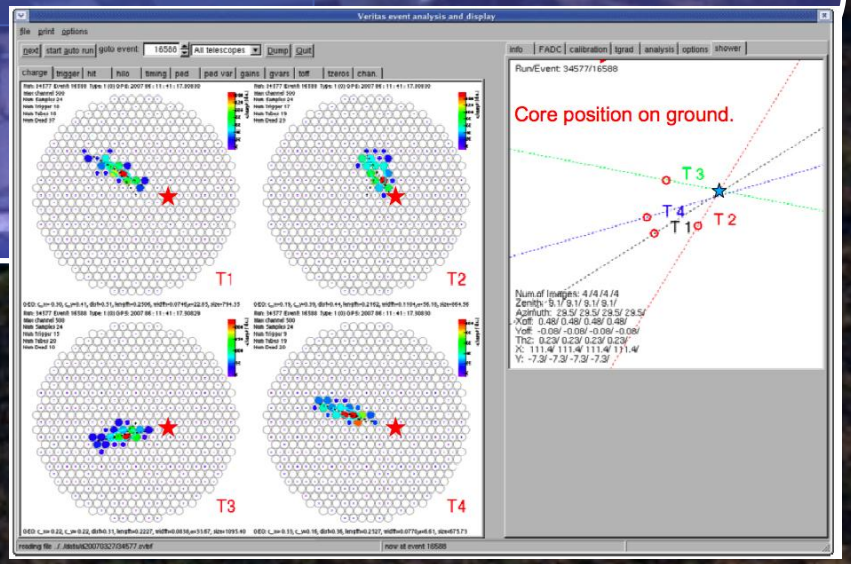
500 Msps, dual-gain



FOV ~ 3.5º.

Pix. ~ 0.15º

499 Pixels



# 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)

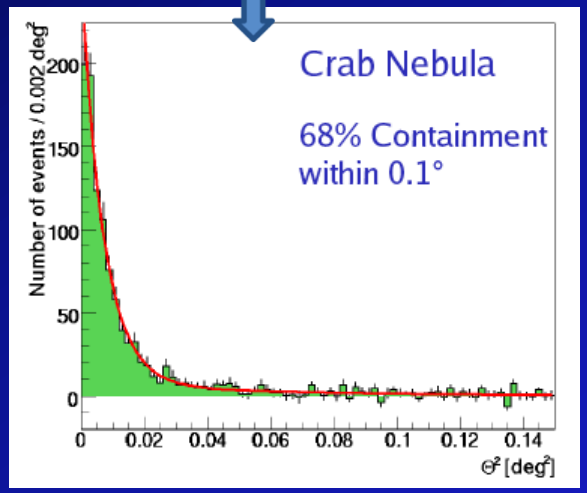
7km away

# VERITAS Performance 2007-09

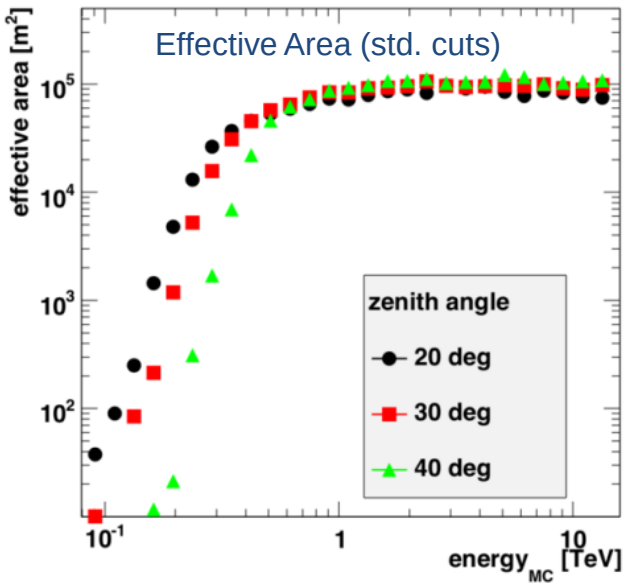
- Energy Range: 100 GeV – 30 TeV (spectra >150 GeV)
- Energy Resolution: 15% – 20%

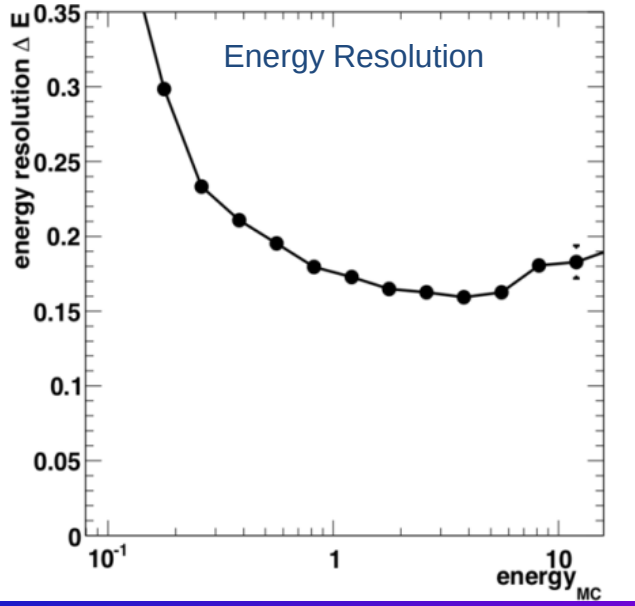
- Crab Rate ~ 40 / min (trigger)
- Sensitivity: 5% Crab in < 2.5 h
  1% Crab in < 50 h

- Angular Resolution: $r_{68} < 0.1^{o}$
- Pointing Accuracy: < 50''

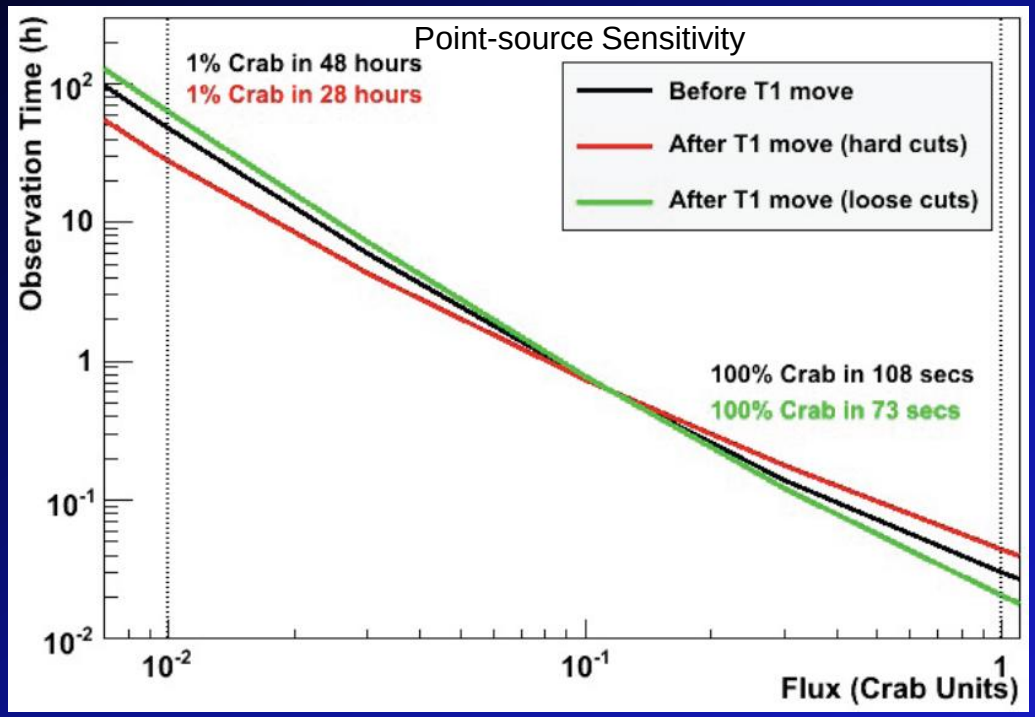


Angular Resolution



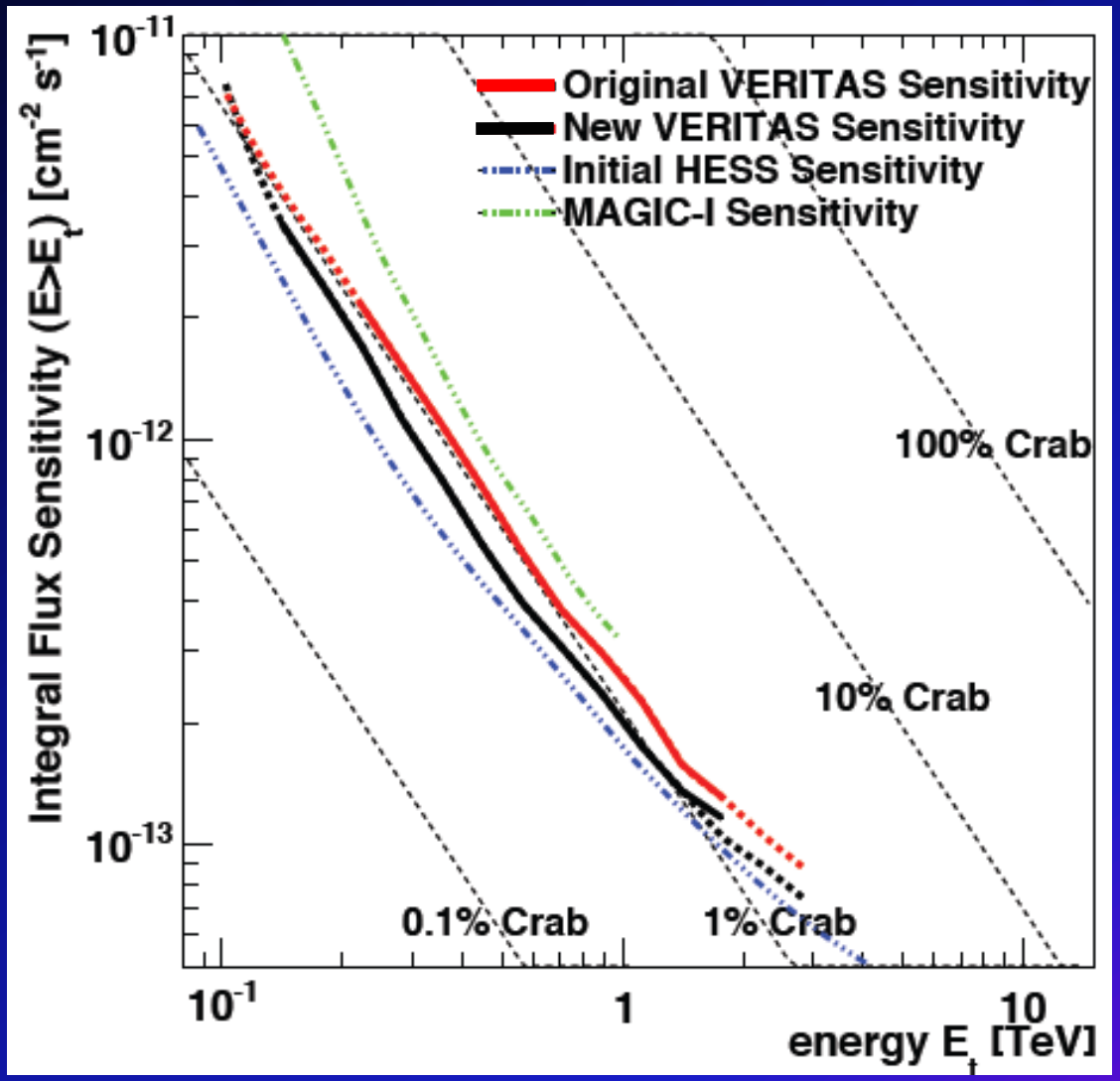
# VERITAS Performance Fall 2009




Operational & Analysis Improvements:

- "Hard" and "Soft" cuts permit improved E range, sensitivity.
- Enhanced reconstruction techniques give better sensitivity: **1% Crab ~ 40 hr.**
- Recent improvements: better PSF & new array configuration.
  **⇒1% Crab < 30 hr.**

# Integral Flux Sensitivity




**Currently the most sensitive VHE instrument in the world!**

# The Fermi Large Area Telescope (LAT)

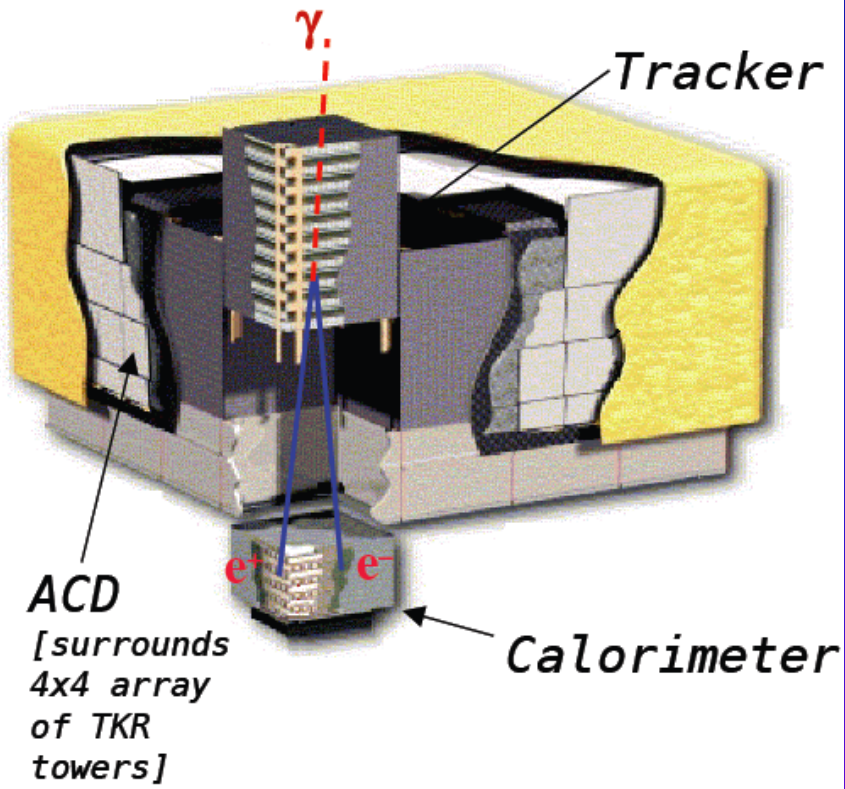
## Overall LAT Design:

- 4x4 array of identical towers
- 3000 kg, 650 W (allocation)
- 1.8 m × 1.8 m × 1.0 m
- **Design choices are based on detailed Monte Carlo simulations**

- **Precision Si-strip Tracker (TKR) Module**
  18 XY tracking planes. 228 μm pitch.
  High efficiency. Good position resolution
  12 layers x 3% rad. length in front end
  4 layers x 18% rad length in back-end

- **CsI Calorimeter(CAL) Module**
  Array of 96 CsI(Tl) crystals in 8 layers.
  Hodoscopic design => Cosmic ray rejection, shower leakage correction
  8.5 X0 => Shower max contained <100 GeV

- **Anticoincidence Detector (ACD)**
  Segmented (89 plastic scintillator tiles)
  => minimize self veto



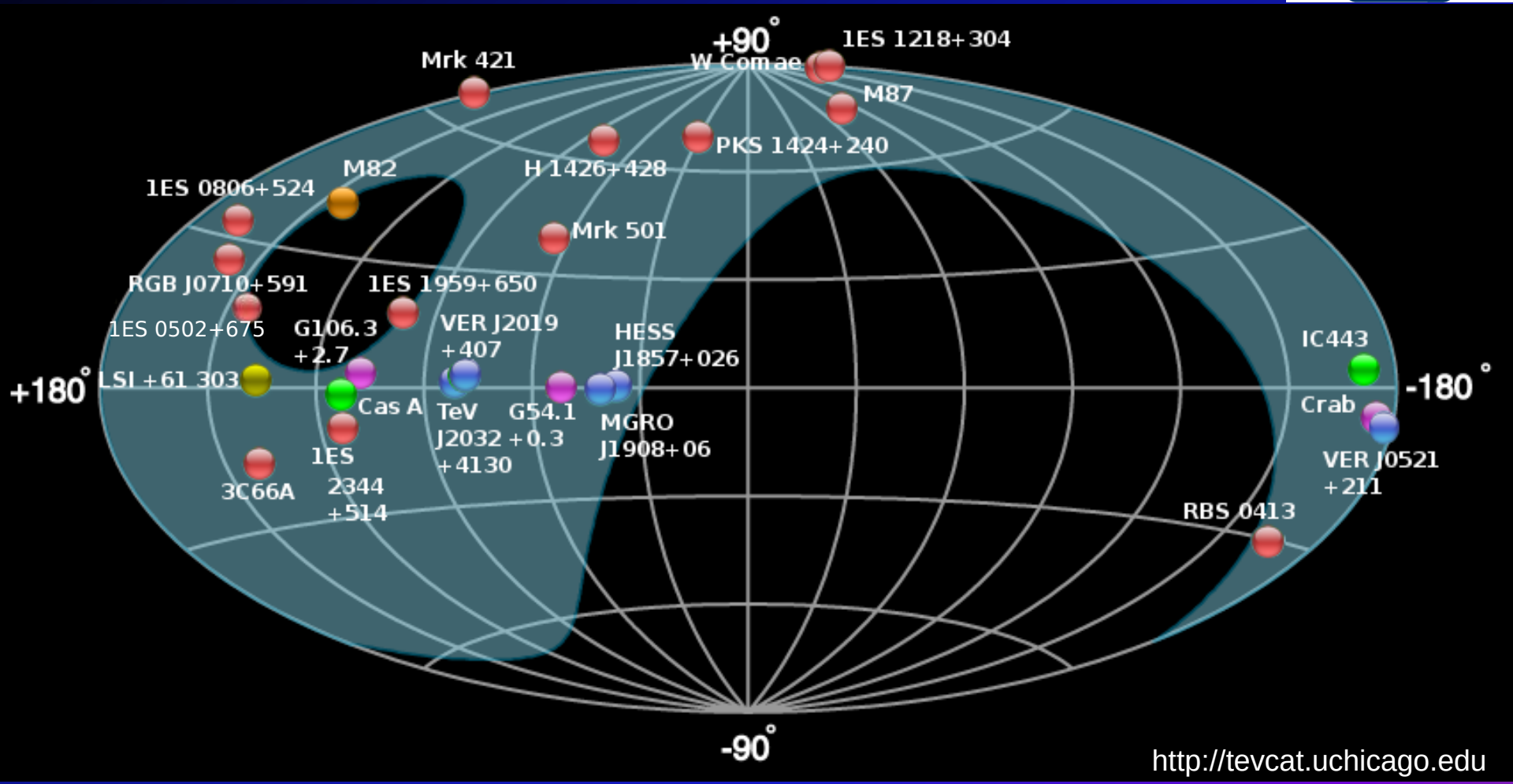

**Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV**

# Synergy Between VERITAS and Fermi

| Parameter | Fermi LAT | VERITAS |
|---|---|---|
| Energy Range | 20 MeV - >300 GeV | ~100 GeV - >50 TeV |
| Energy Resolution | <10% | 15% |
| Duty Cycle | ~ 90% | 12% |
| Field of View | ~2.4 sr (20% of the sky) | 3.5° |
| Angular Resolution | 0.1 deg @ 10 GeV | 0.1 deg |
| Effective area | ~1 $m^2$ | ~$10^5$ $m^2$ |
| Point Source sensitivity | $1.5 \times 10^{-10}$ $cm^2 s^{-1}$ (1 year) | $10^{-11}$ $cm^2 s^{-1}$ (50h) |

- Together, Fermi and VERITAS cover about ~7 decades in energy
- Overlap in the 100 GeV - 300 GeV energy range
- Fermi is an all-sky monitor, VERITAS is a very sensitive pointed instrument

# The VERITAS VHE Sky

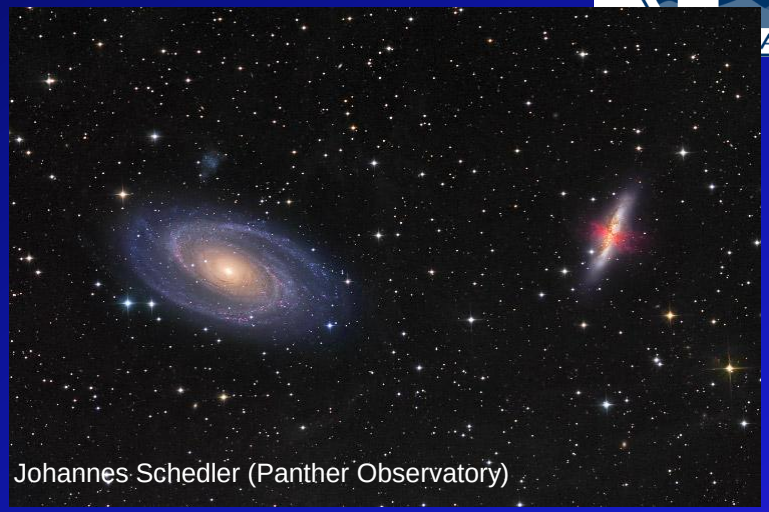



26 Source Detections in 6+ source classes, at least 10 in the Galactic Plane

# STARBURST GALAXY M82

# M 82: A Starburst Galaxy

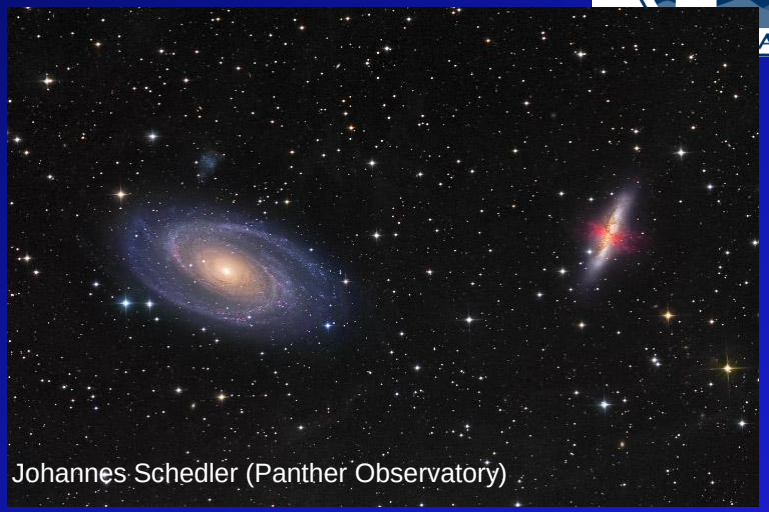
- M 82 is the prototype starburst galaxy
  - $\delta \sim 70º \rightarrow$ Culminates at $\theta \sim 40º$
  - D ~ 3.9 Mpc towards Ursa Major
    - EBL a non-issue
  - Diameter ~1'
    - point-like for VHE γ-ray studies
  - Central SMBH: $<3 \times 10^7 M_\odot$;
    - No evidence of an AGN


Johannes Schedler (Panther Observatory)


NASA, ESA, The Hubble Heritage Team, (STScI / AURA)

# M 82: A Starburst Galaxy

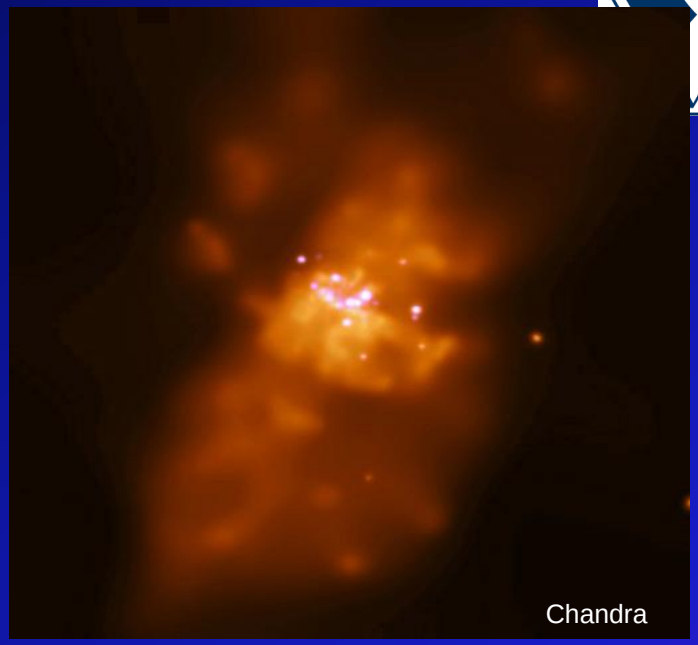
- M 82 interacting with group of galaxies
  - Over hundreds of millions of years
  - At least one major interaction with larger spiral M 81
- Tidal forces → Active starburst region
  - Diameter ~ 1000 light years
  - HST → Contains >200 massive star clusters
    - $10^4$ -$10^6$ $M_\odot$; brighter than most in Local Group

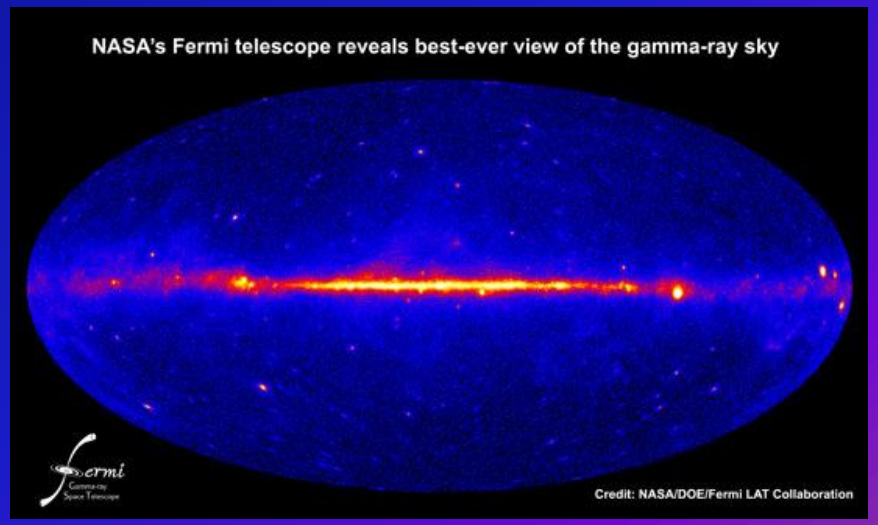

Johannes Schedler (Panther Observatory)


NASA, ESA, The Hubble Heritage Team, (STScI / AURA)

# The Starburst Region of M 82

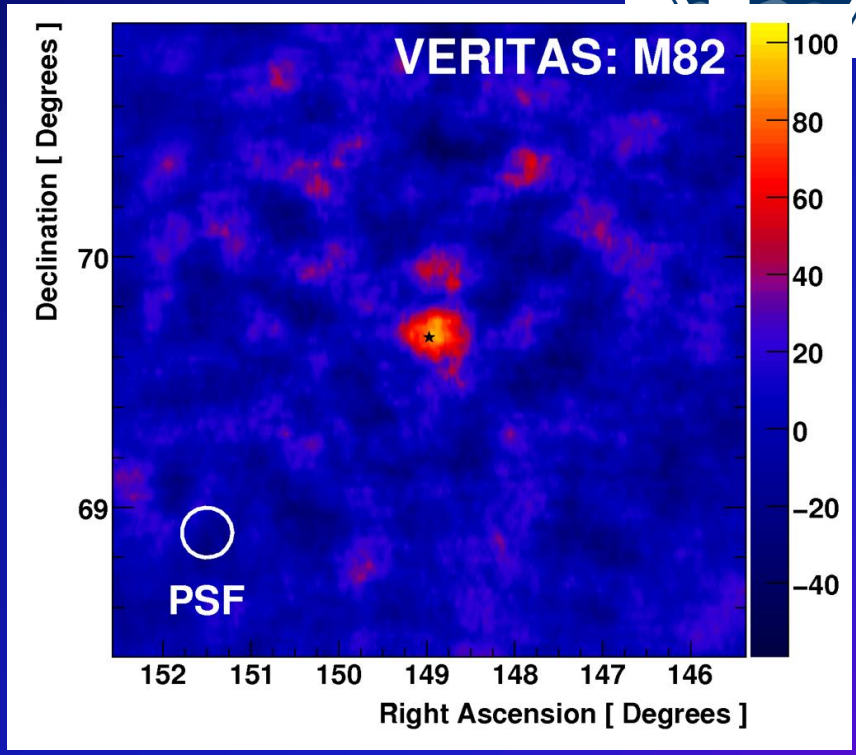
- Cosmic-ray (CR) origin?
  - Preferred theory: SNR & wind-zones of massive stars
- Star formation rate: ~10 × MW
- Supernova rate: ~0.1-0.3 $yr^{-1}$
- High CR density: ~100 × MW
  - Inferred from intense radio-synchrotron emission
- High gas density: ~150 $cm^{-3}$
- CR ions + gas → pions → γ-rays
- CR $e^{\pm}$ + photons → γ-rays
- HEGRA & Whipple: VHE flux <10% Crab

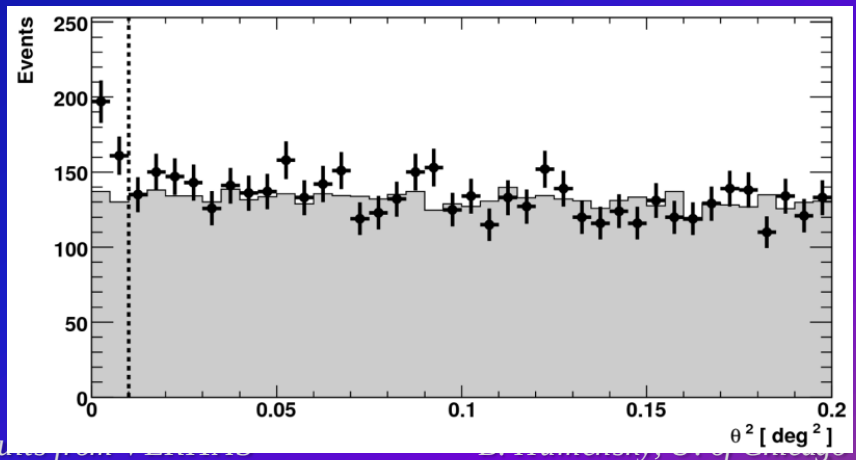


# VERITAS Discovery of VHE γ-rays

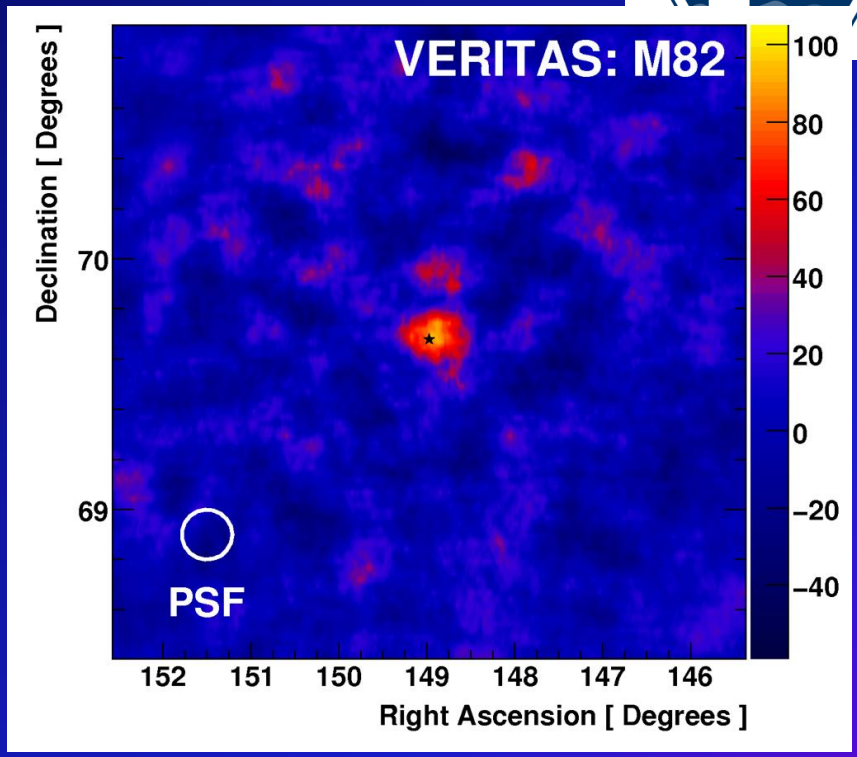
- VERITAS (2007-09): ~137 h
  - Only in astronomical darkness; Mean θ ~ 39º
  - Bad weather data removed (via FIR data)

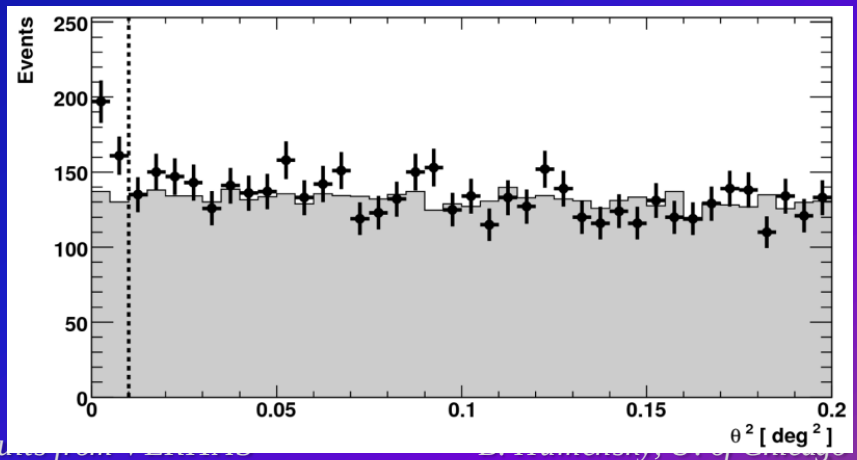


# VERITAS Discovery of VHE γ-rays

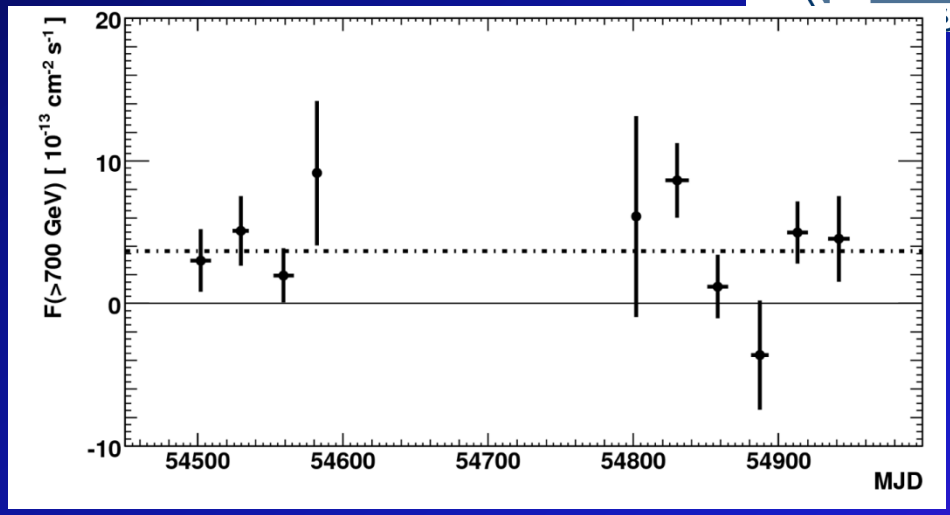
- Standard VERITAS analysis + "hard cuts"
  - $E_{th} \sim 700$ GeV; NB: Sensitivity less at $\theta \sim 39º$
  - Cuts a priori optimized using Crab at $\theta \sim 40º$
    - For detection of weak, hard-spectrum sources
      - Theoretical expectation for M 82
  - Standard practice, but 3 trials: "std" & "soft" cuts
- Point-like excess of 91 γ; 5.0σ pre-trials
- Post-trials significance of 4.8σ
  - Chance probability of 7.7 x 10-7

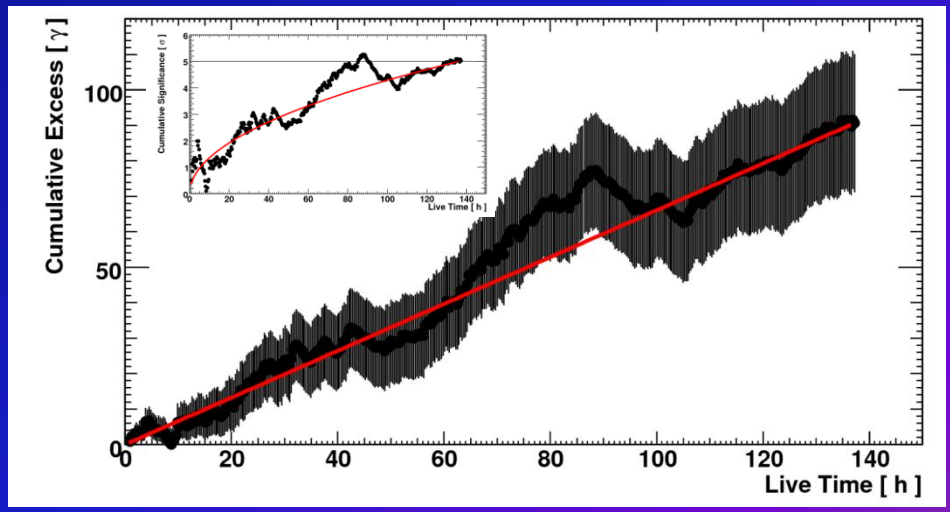


# M 82: A Steady VHE Flux

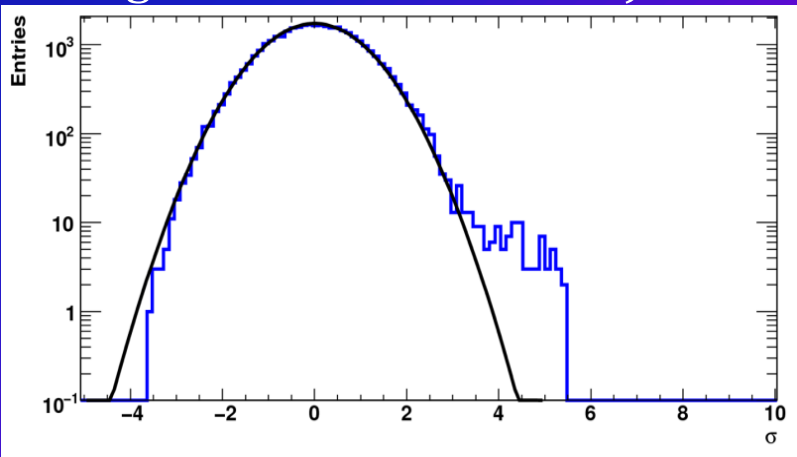
- Among weakest-ever VHE sources
- F(>700 GeV) =
  $(3.7 \pm 0.8_{stat} \pm 0.7_{syst}) \times 10^{-13}$ cm$^{-2}$s$^{-1}$
  - 0.9% of Crab Nebula (>700 GeV)
  - Gamma-ray rate: 0.7 / hour
- No variations in monthly flux
  - $\chi^2$/ndf = 11.5/9 (24%)
  - Factor of "a few" variations not ruled out
- Steady signal accumulation



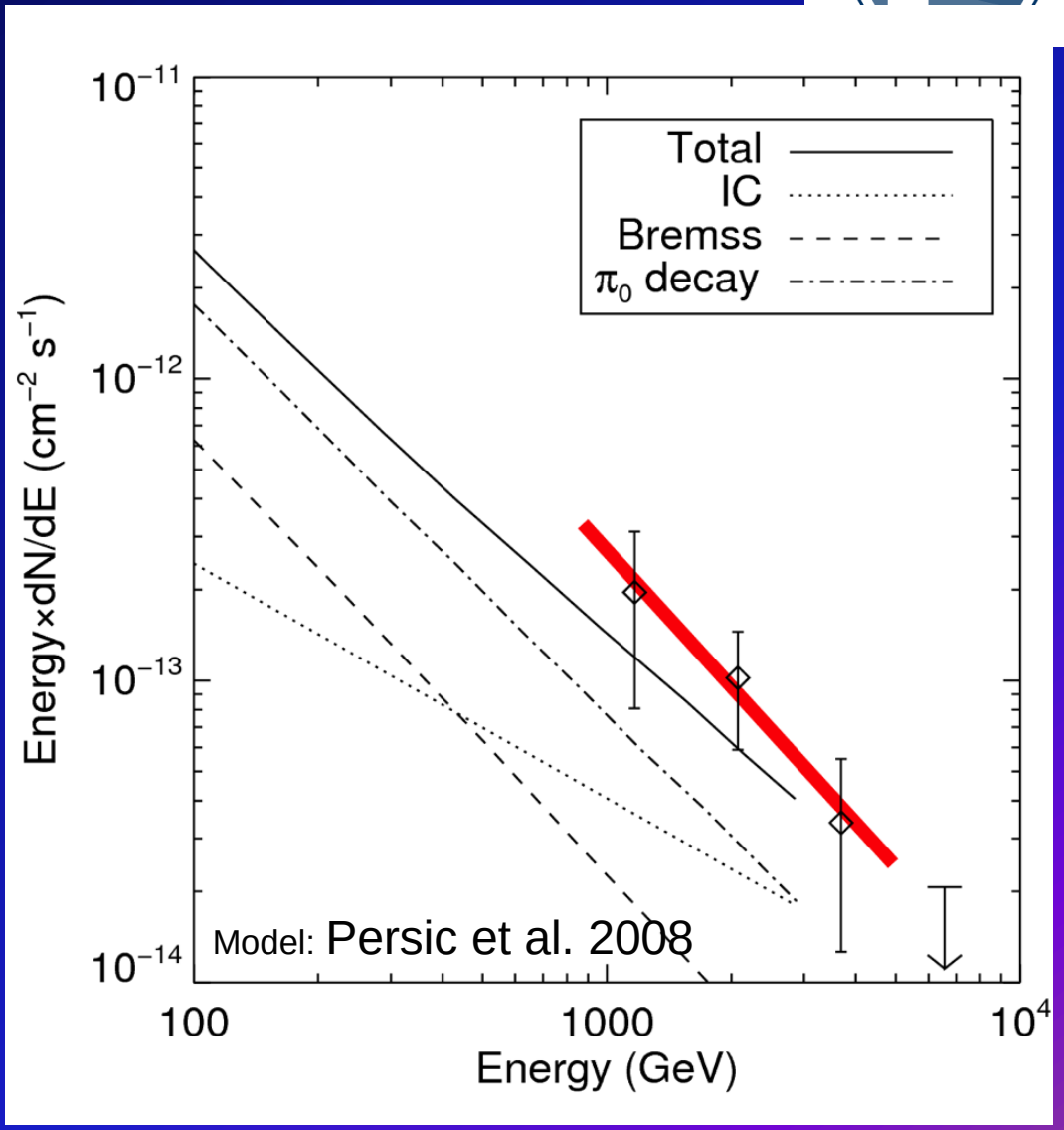
# Systematic Checks

- All hardware operating normally, no moonlight data, dark field
- "Hard cuts": Enormous images (>200 PE); bright star effects mitigated; very low background (S/N ~ 1/3)
- Result verified (5.2σ) by independent calib/analysis/simulation package(s)
- Alternate background estimation: Ring method → 5.1σ on-source
  - Also ~5σ using a binned maximum-likelihood method
  - Reflected-region BG method always has 11 off-source regions
  - Significance distribution is Gaussian (mean 0, σ = 1)
- No bias in long data set: Stack extragalactic non-blazar data
  - With the same analysis: Combined excess of -4 events (-0.2σ) in ~121 h of live-time (no moonlight data)
- Not due to brightness of M 82 (V=9.3, or 8.2 integrated over full extent)
- Two V < 9 stars in FOV: Excesses of 1.1σ & 0.8σ at their locations (>0.7º from M 82)
- Not due to dodgy behavior in a telescope: Signal still present when each tel. is individually excluded



# The VHE Gamma-Ray Spectrum

- Fit Range: 875 GeV to ~5 TeV
  - Fit to $dN/dE \sim (E / TeV)^{-\Gamma}$
  - $\chi^2/ndf = 0.1/1$ (70%)
- $\Gamma = 2.5 \pm 0.6$
- 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



# Some Quick Interpretation

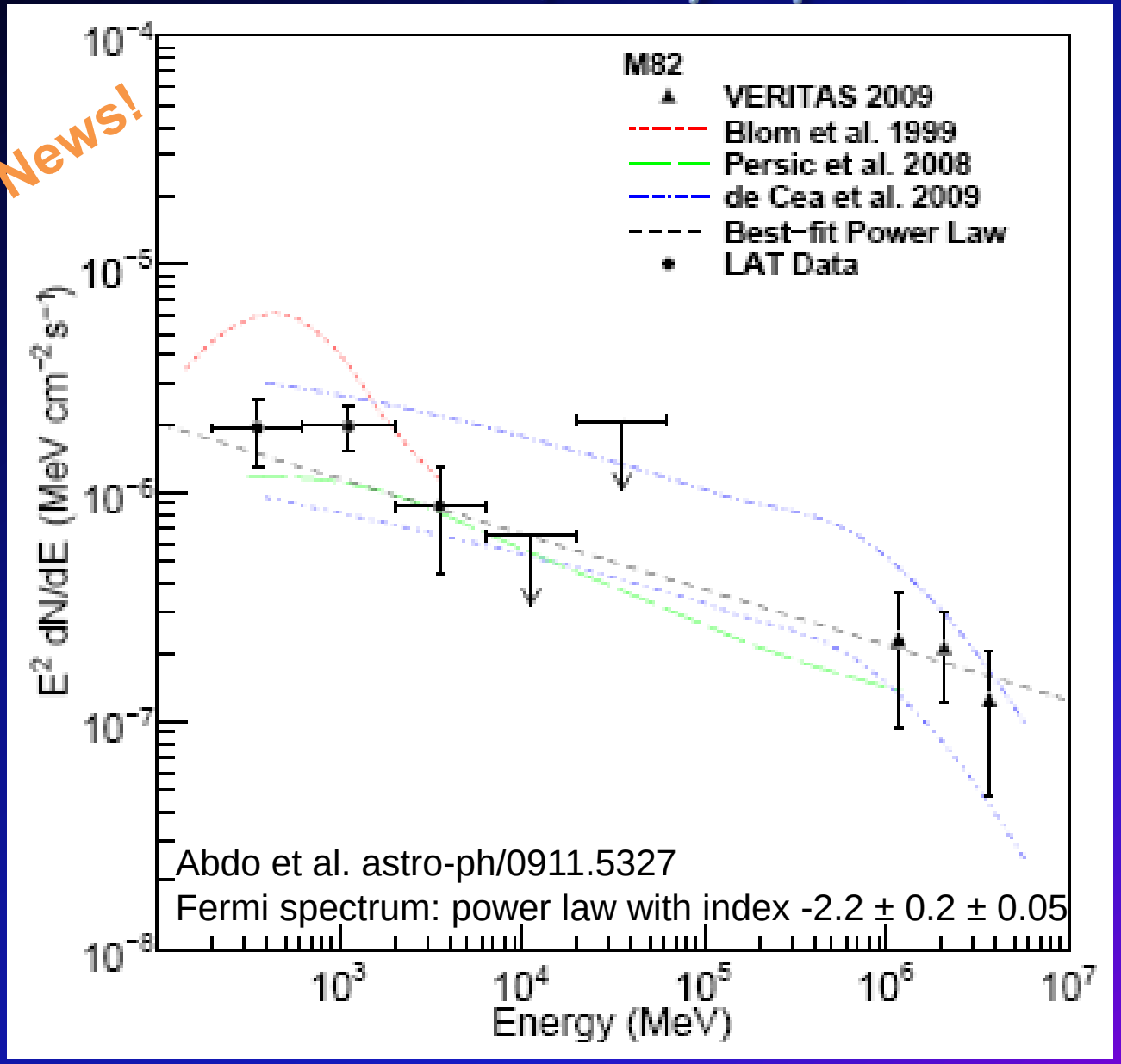
- Leptons or hadrons? We can't say, yet....
- Hadronic channel: Protons + Matter → Pions → γ-rays; but also → Pions → Secondary Electrons
  - Use radio emission from secondary electrons to limit γ-ray flux from CR hadrons @ 20 GeV
  - Extrapolate VERITAS spectrum downwards: $\Gamma = 2.5 \rightarrow$ Flux $\sim 2 \times$ higher; $\Gamma = 2.3 \rightarrow$ OK
  - Either the true gamma-ray spectrum from 10 GeV to 1 TeV is "harder" than the VERITAS measurement, or the VHE flux is not predominantly from CR hadrons

# Some Quick Interpretation

- Leptons or hadrons? We can't say, yet....
- Leptonic channel: CR electrons + ambient photons => X-rays & γ-rays via IC scattering
  - Use non-thermal X-ray flux => limit number of electrons @ 1 GeV, but need 10 TeV electrons for VHE
  - Theory & comparison to CR-induced X-ray flux to VHE flux => IC spectrum: $\Gamma \sim 2$ from 100 keV to 100 GeV
    - Electron energy losses (IC & synchrotron) => Steepening + cut-off in IC spectrum above some energy
  - If Fermi + VERITAS shows a cut-off, the particles responsible for VHE γ-rays could be identified

# Broad-band γ-ray spectrum

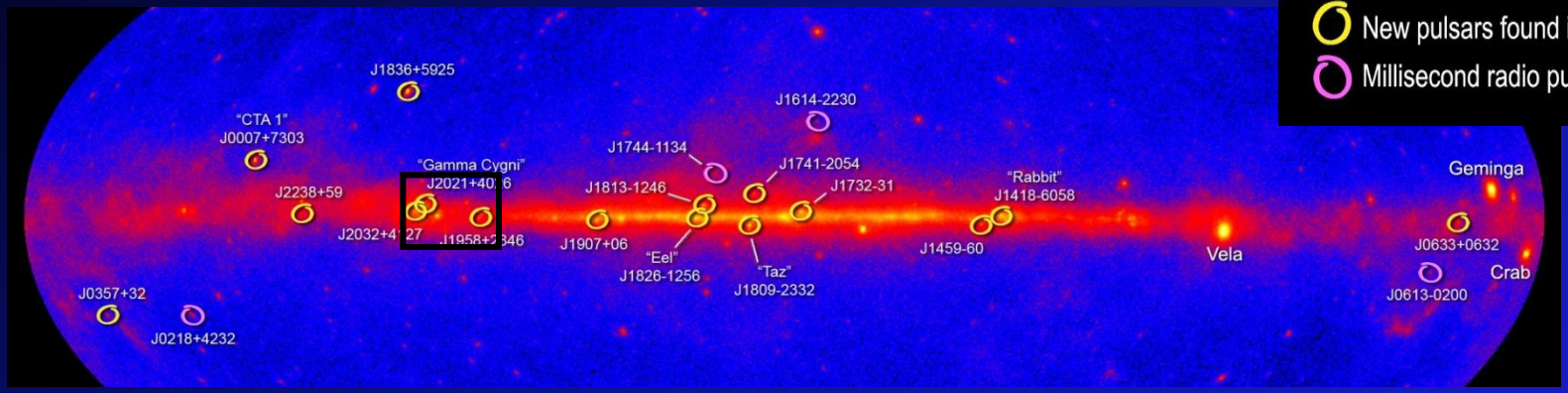
Breaking News!



# SKY SURVEY

# Motivation and Context

- Efficient method of searching for new sources over a large region




- *Un-biased* indication of source population

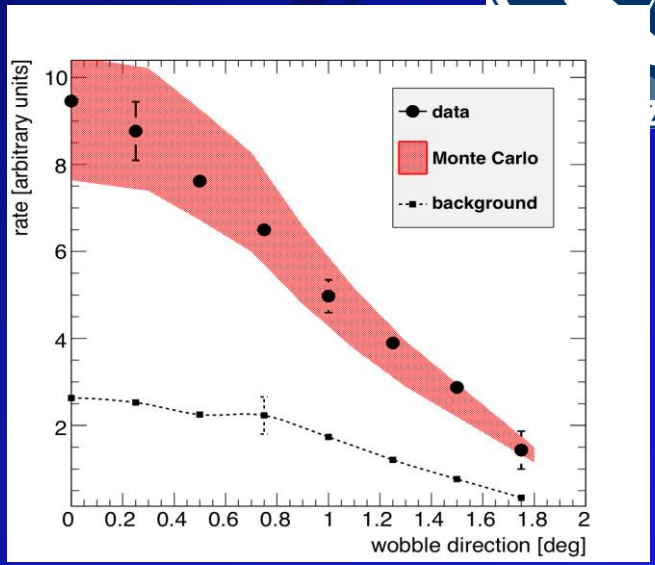
- Southern hemisphere well-surveyed
  - HESS Galactic plane survey, ~14 sources in initial survey
- Best limits in northern hemisphere sky : HEGRA's Galactic plane survey
  - $-2^\circ < l < 85^\circ$, flux upper limits: 15% Crab to several Crab

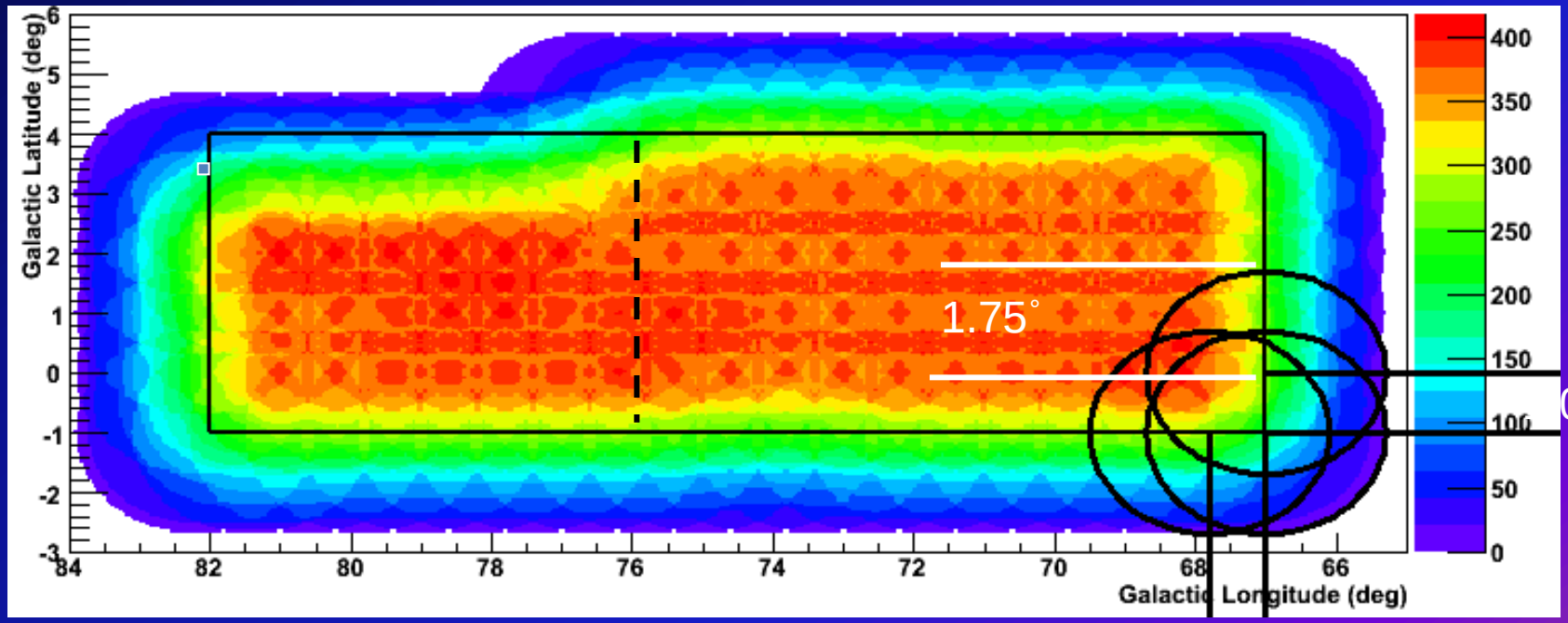
- Size and choice of region based on
  - VERITAS sensitivity and FOV
  - Material distribution, density of potential TeV γ-ray emitters (SNR, PWN, high E-dot pulsars, EGRET unidentified sources..)

# Survey Observation Strategy

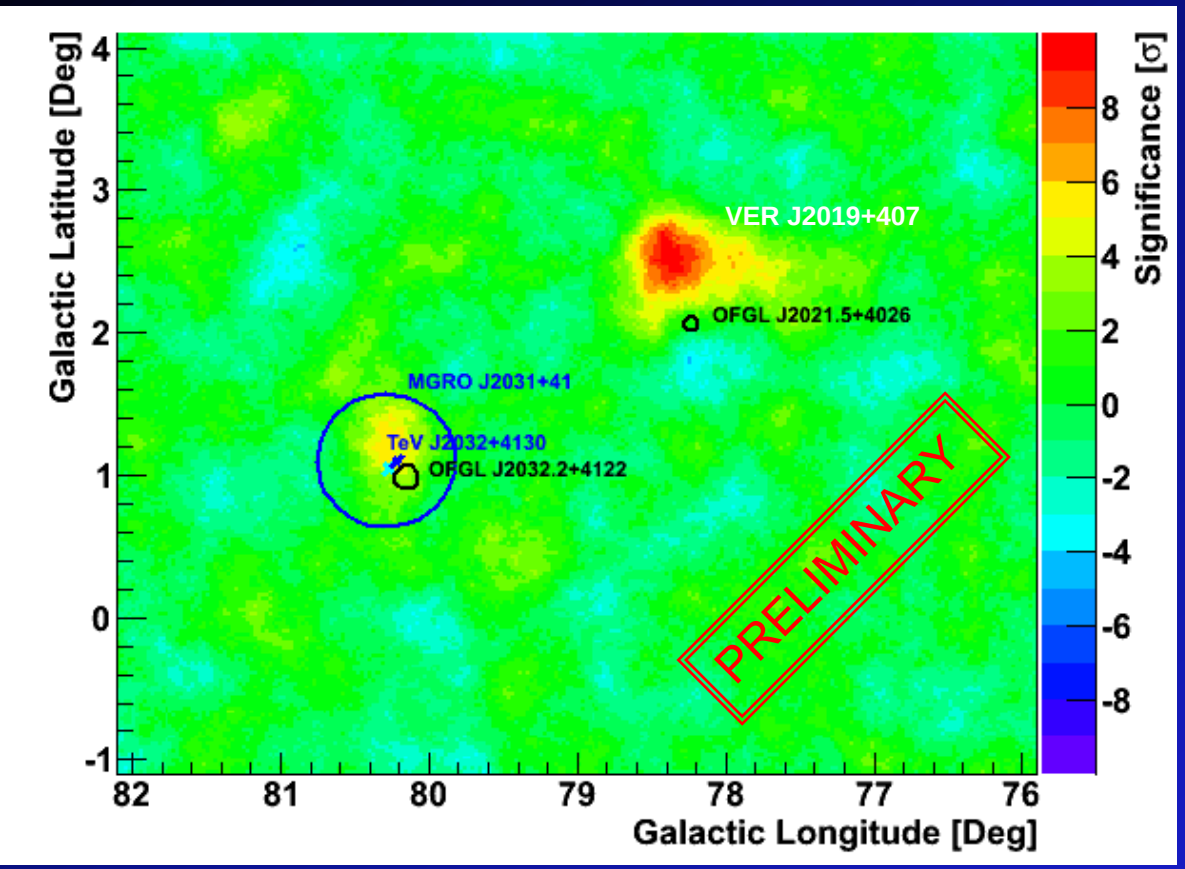
Made possible by good VERITAS off-axis sensitivity

- Survey covers region 67˚ < l < 82˚, -1˚ < b < 4˚
- Available observing period: April-June, Sep.-Nov.
- ~6 hrs effective exposure before followup.
- ~112 hours in base survey, ~56 hours followup.



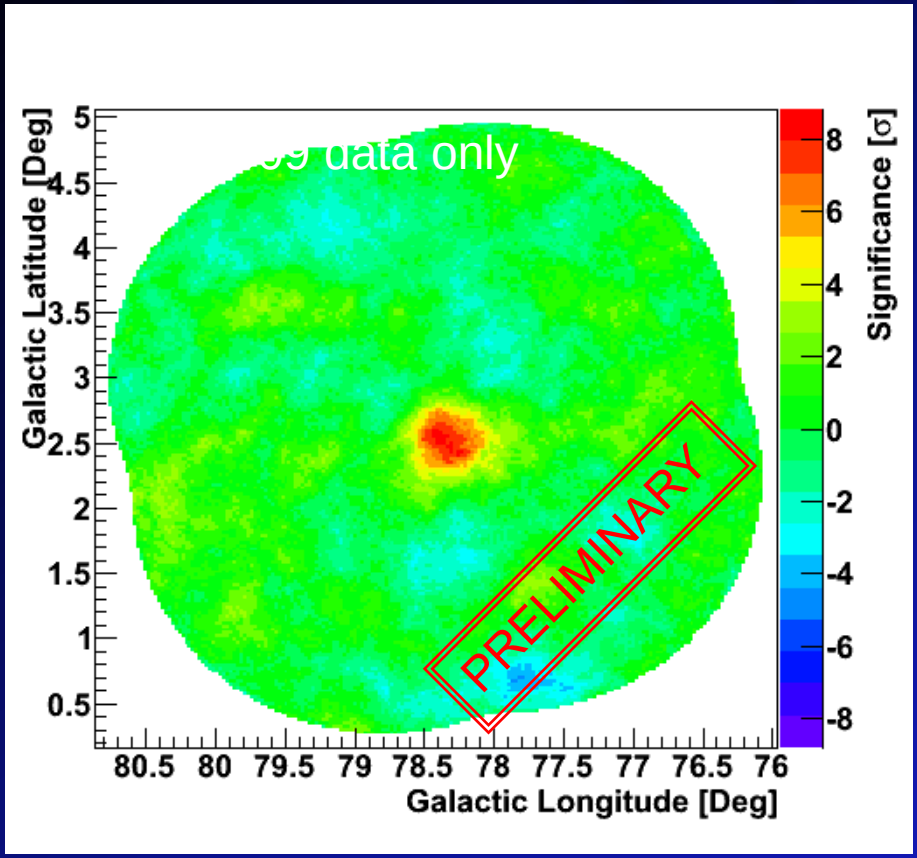
# One Interesting Region




- VER J2019+407
  - New VERITAS source
- TeV J2032+4130
  - known source, first detected by HEGRA
  - Likely associated: MGRO J2031+41, 0FGL J2032.2+4122 (LAT pulsar)
  - Detection: >5σ at nominal position (no trials)

- Partial survey map, generated with standard threshold extended source analysis
- Includes all data in survey region taken to this point
- Exposure uneven due to followup (more intensive followup around VER J2019+407 than around TeV J2032+4130)

# VER J2019+407

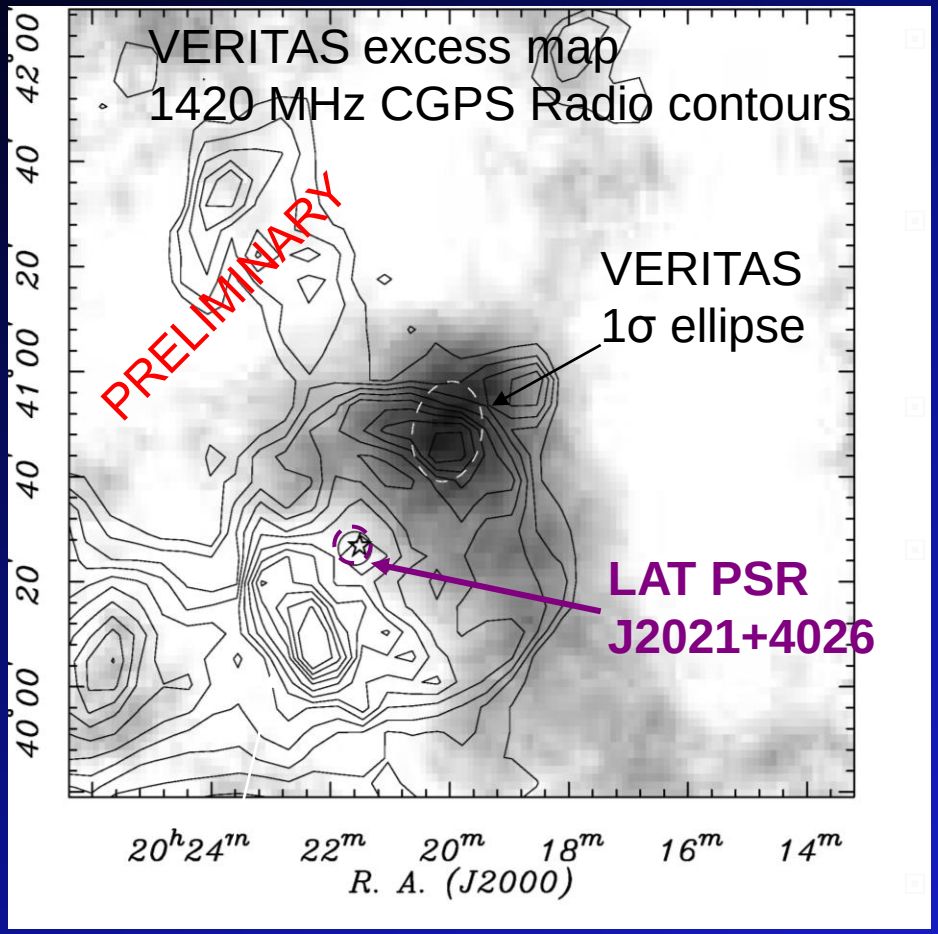



- Early follow-up candidate
- Recent (last 2 months) follow-up treated as an independent search
  - 0.25˚ radius search region
  - 0.6˚ wobble, position indicated by earlier data
- 8.5σ (~7.5σ) pre- (post-) trials in Fall 2009 data alone

Preliminary position: RA: 304.97˚ 0.017˚(stat), Dec: 40.79˚ 0.023˚(stat)
Preliminary extension: 0.16˚ 0.028˚ (0.11˚ 0.027˚) for the major (minor) axis

- Derived from 2-d Gaussian (convolved with VERITAS PSF) fit to uncorrelated excess map (Fall 2009 data only)
- Flux ~ 2-5% Crab

# VER J2019+407 in context




No visible γ-ray emission to the southeast

In northwest region of Gamma Cygni SNR (G78.2+2.1)

- What exactly is it?

PWN?

- core ~0.5˚ away from Fermi pulsar
- Association seems unlikely

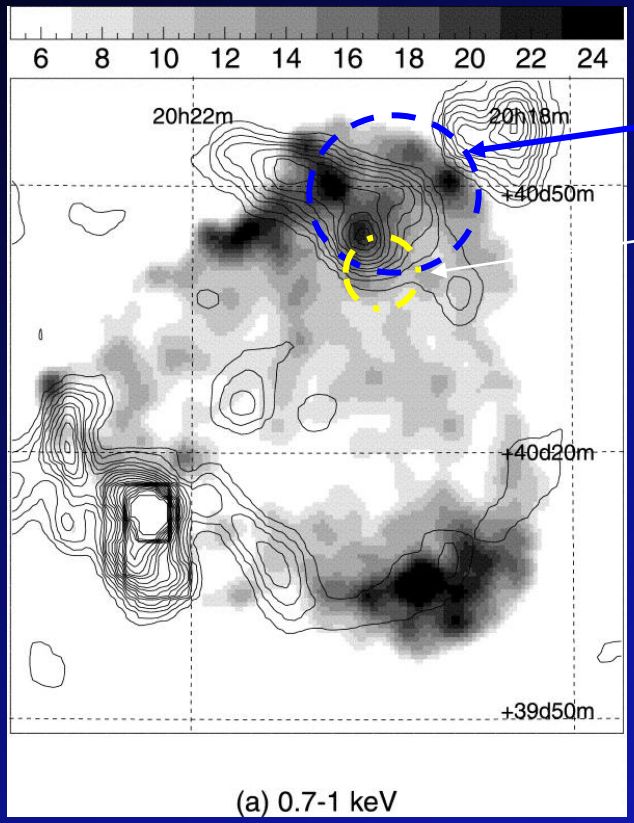
VERITAS emission *does* overlap well with radio contours in northwest

Shock-cloud interaction?

- Plenty of CO in southeast, not much in northwest
- Two partial shells in HI, one in northwest (Ladouceur and Pineault 2008, A&A 490, 197)
- Cloudlets? Enough mass in HI?

Scenario: SNR was expanding in bubble blown by progenitor star; now hitting dense material in ISM.

# VER J2019+407 in context




ASCA X-ray map
4.85 GHz radio contours

Core of VERITAS excess

In 4-10 keV band, pair of faint hard X-ray sources under core (part of C2, Uchiyama et al.)

- Uchiyama et. al. ApJ, 571:866-875, 2002
  - Soft X-ray emission belt (1-3 keV) from north to southeast
    - shock interacting with cavity wall of ambient clouds?
  - Suggests hard sources in north are shocked dense cloudlets
    - Nonthermal bremsstrahlung of GeV electrons

# Cygnus Region: Broad Limits

- No hotspots above 5σ post-trials in *base* survey
- Much stronger limits than available in the past from HEGRA
- Preliminary Flux Limits (99% CL, all points in survey below 3σ)
  - <3% Crab above 200 GeV (point source)
  - <8.5% Crab above 200 GeV (0.2˚ radius extended source)
- Possible indication that source population in Cygnus region differs from inner galaxy
  - HESS survey: out of 14 sources in -30˚<l< 30˚, saw 12 sources with fluxes ≥ 5% Crab above 200 GeV ⇒ expect ~2-3 in this survey

# Survey Summary

- Detection of 2 sources with VERITAS survey technique and followup observations
  - Discovery:  VER J2019+407
  - TeV J2032
- Further followup observations in survey region ongoing.
- Prospects for future:
  - Spectra and energy-dependent morphology studies (VER J2019+407, TeV J2032).
  - Joint analysis (morphology, cross-correlation studies) with Fermi data in the region.

# SUPERNOVA REMNANTS AND PULSAR WIND NEBULAE

IC 443

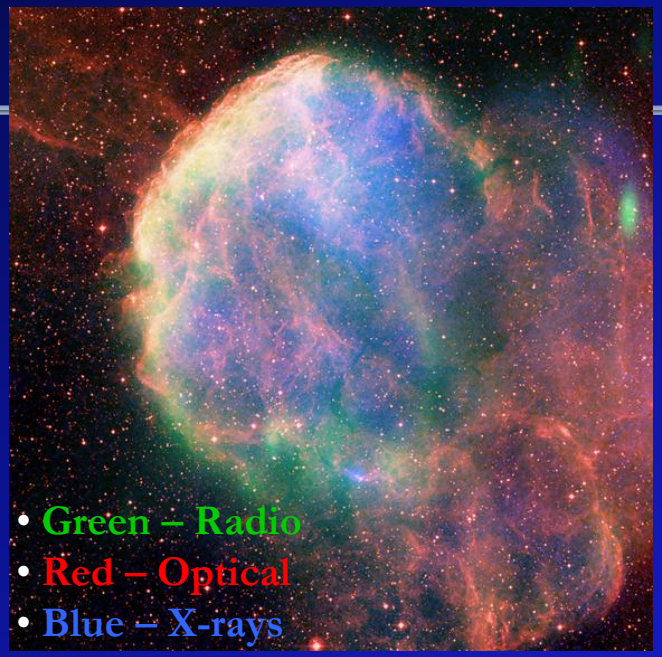
SNR G106.3+2.7 / Boomerang

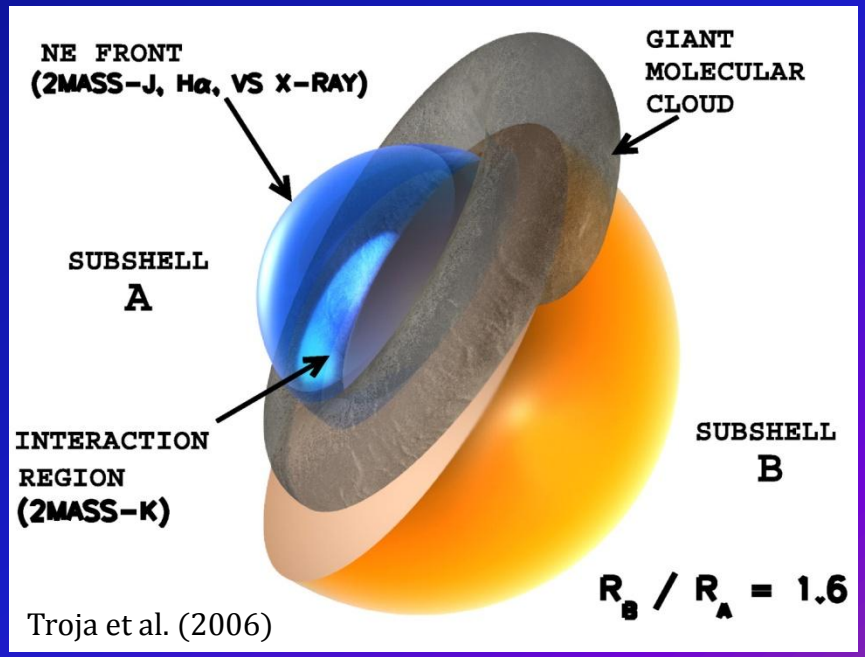
SNR G54.1+0.3 / PSR J1930+1852

Cassiopeia A

# IC 443

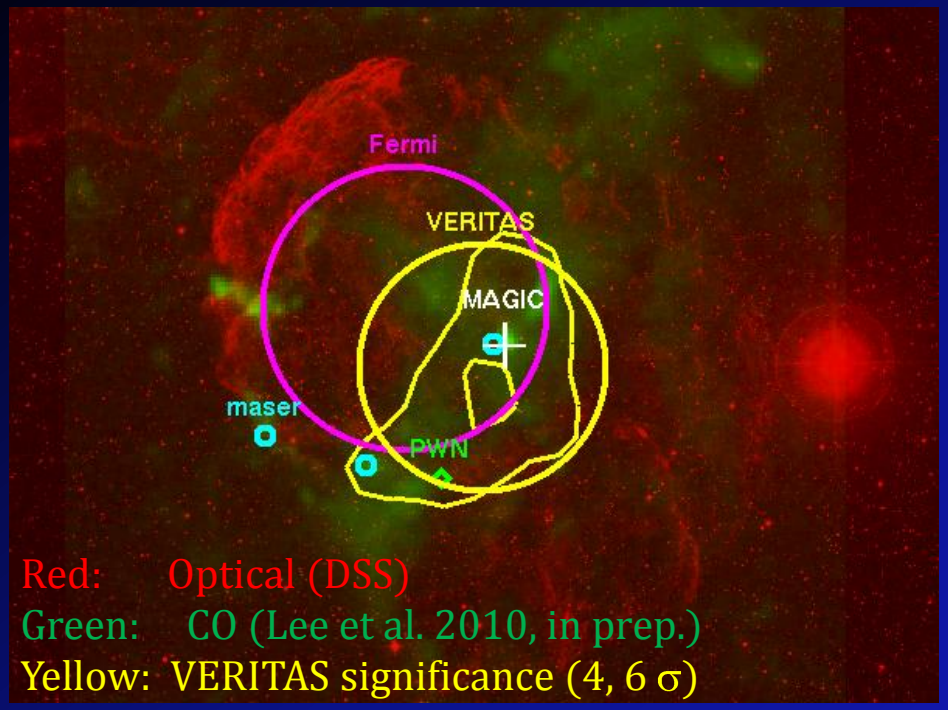
- Shell interacting with massive cloud
- Age ~20-30 kyr, 0.75° diameter
- PWN at southern edge of shell
- Discovered in GeV by EGRET
  - Now AGILE, Fermi
- Discovered in TeV in 2007
  - by MAGIC (5.7 σ in 29 hrs)
  - by VERITAS (7.1/6.0 σ pre/post-trials in 15.9 hrs)



Troja et al. (2006)

# IC 443




- Total live time: 37.9 hrs.
- 8.3 σ peak significance pre-trials
- Power-law fit 0.3 – 2 TeV:
  - Index: $2.99 \pm 0.38_{stat} \pm 0.3_{sys}$
  - Flux (> 300 GeV) ~ 3.2% Crab

*2-D Gaussian profile fit:*

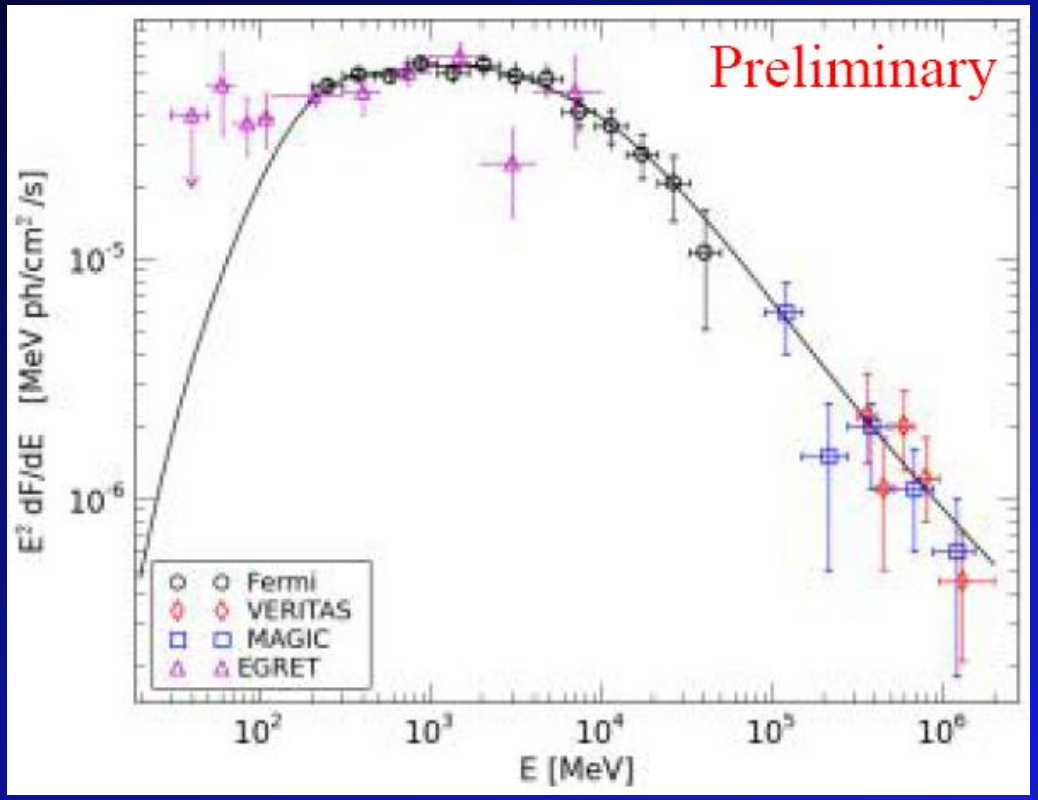
*Centroid: 06 16.9 +22 32.4* $\pm 0.03^{o}_{stat} \pm 0.07^{o}_{sys}$

*Extension:* $\sigma \sim 0.16^{o} \pm 0.03^{o}_{stat} \pm 0.04^{o}_{sys}$

- 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? (both extended)
  - Broad-band morphological evolution distinguishes between scenarios (not all PWN)
  - Window into propagation / diffusion of Cosmic Rays in interstellar medium

*Acciari et al. 2009, ApJ 698 L133*

# IC 443

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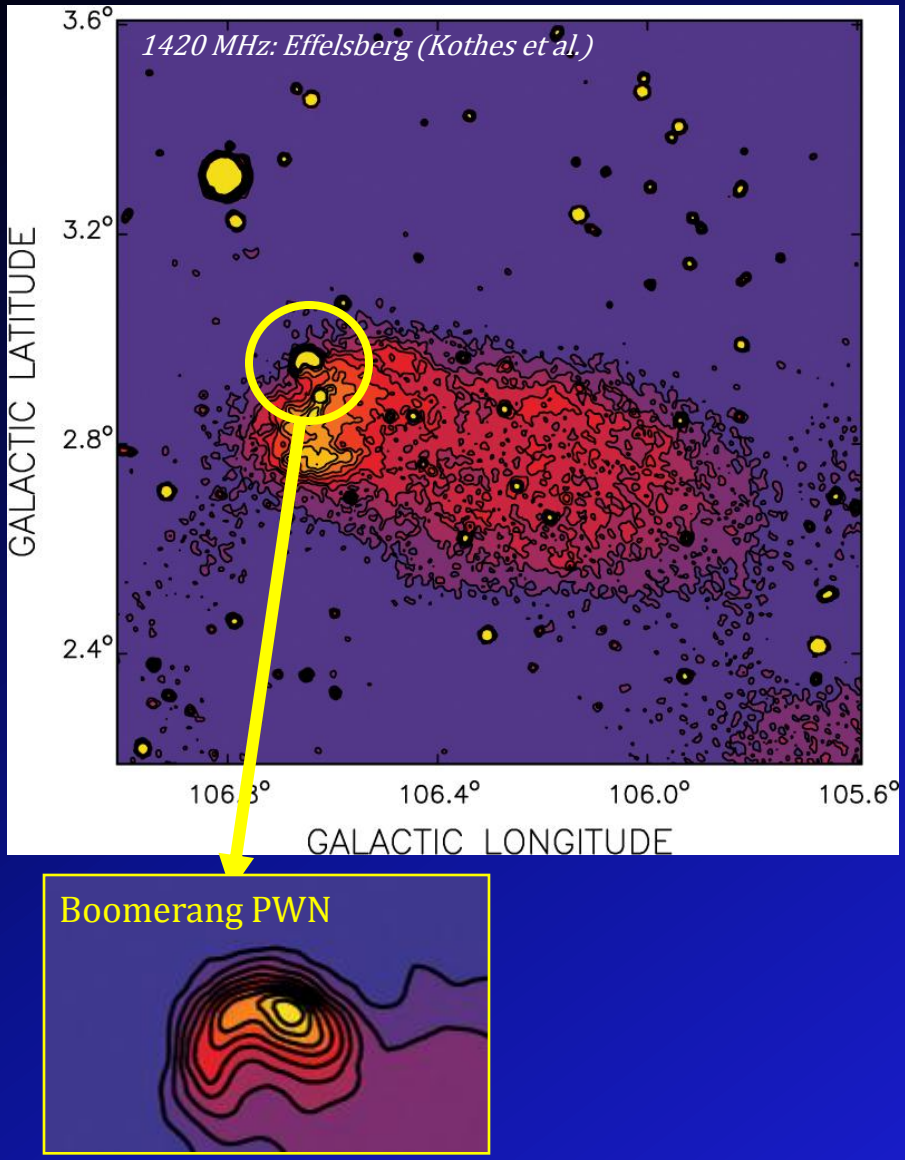
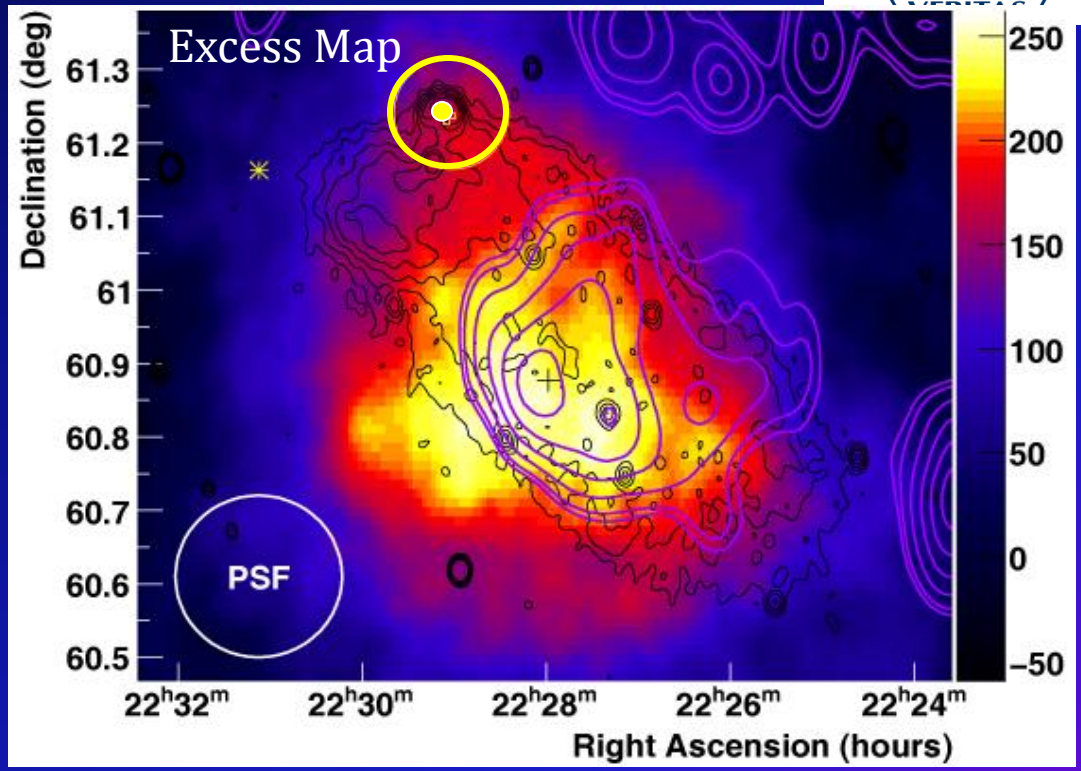
# SNR G106.3+2.7 / PSR J2229+6114




- Energetic pulsar + wind nebula discovered in the error box of source 3EG J2227+6122.
  - Age ~ 10,000 years
  - E-dot = $2.2 \times 10^{37}$ erg/s
  - Likely part of the larger SNR G106.3+2.7
  - Distance ~ 800 pc (Kothes et al)
- On Fermi/LAT Bright Source List
- MILAGRO: Extended emission at ~35 TeV

# SNR G106.3+2.7 / PSR J2229+6114

- Observations made in 2008 resolve TeV emission overlapping the radio shell of G106.3+2.7
  - 7.3 σ detection in 33 hours (6.0 σ post-trials)
- TeV emission is extended
  - Spans a 0.4 0.6 region
  - Peak is 0.4 away from PSR
  - Overlaps with region of high CO density

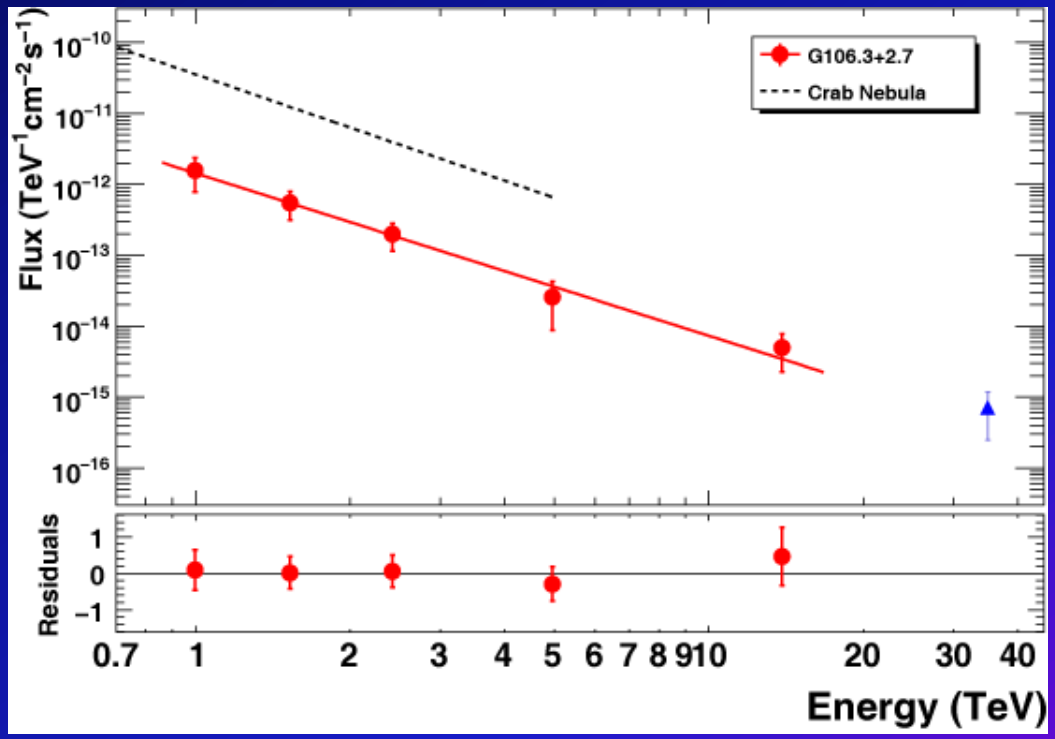



Black – Radio (DRAO)
Circle – FGST Error Box
Dot – Pulsar Position
Purple - $^{12}$CO Emission (FCRAO)
Yellow star – 1AGL J2231+6109

*Acciari et al. 2009, ApJ 703 L6.*

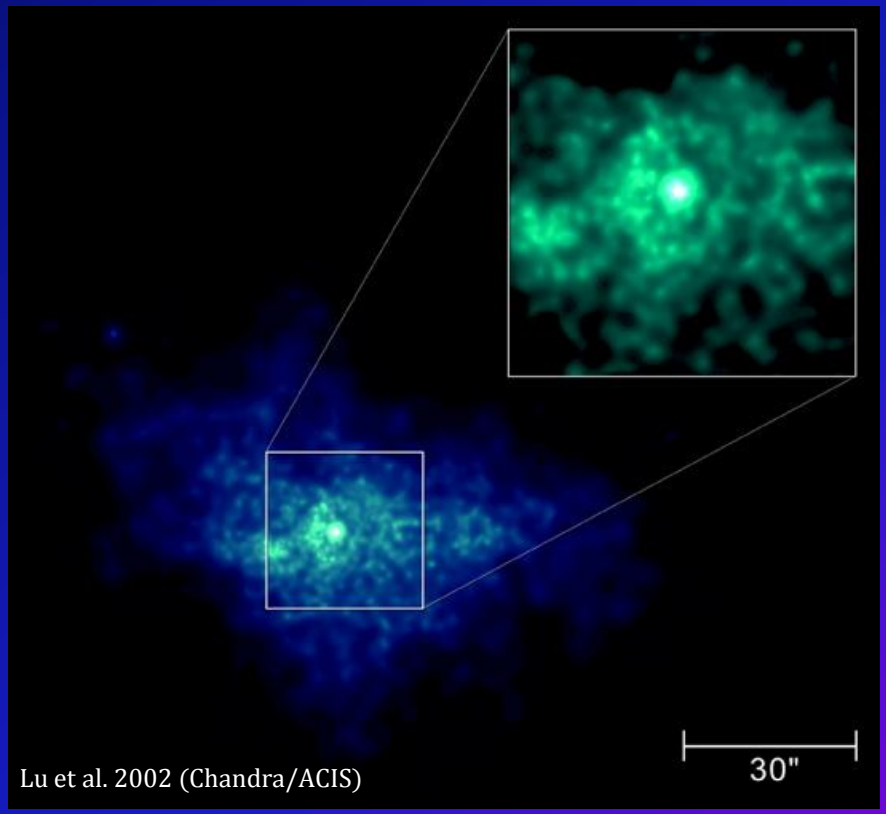
# SNR G106.3+2.7 / PSR J2229+6114

- Energy Spectrum
  - Integrate over 0.32 radius centered on emission peak
  - Well fit by a pure power law
  - Index: $2.3 \pm 0.3_{stat} \pm 0.3_{sys}$
  - Flux ($> 1$ TeV) ~ 5% Crab
- Extension of spectrum is consistent within errors with Milagro point at 35 TeV
- Spectrum may favor hadronic origin?



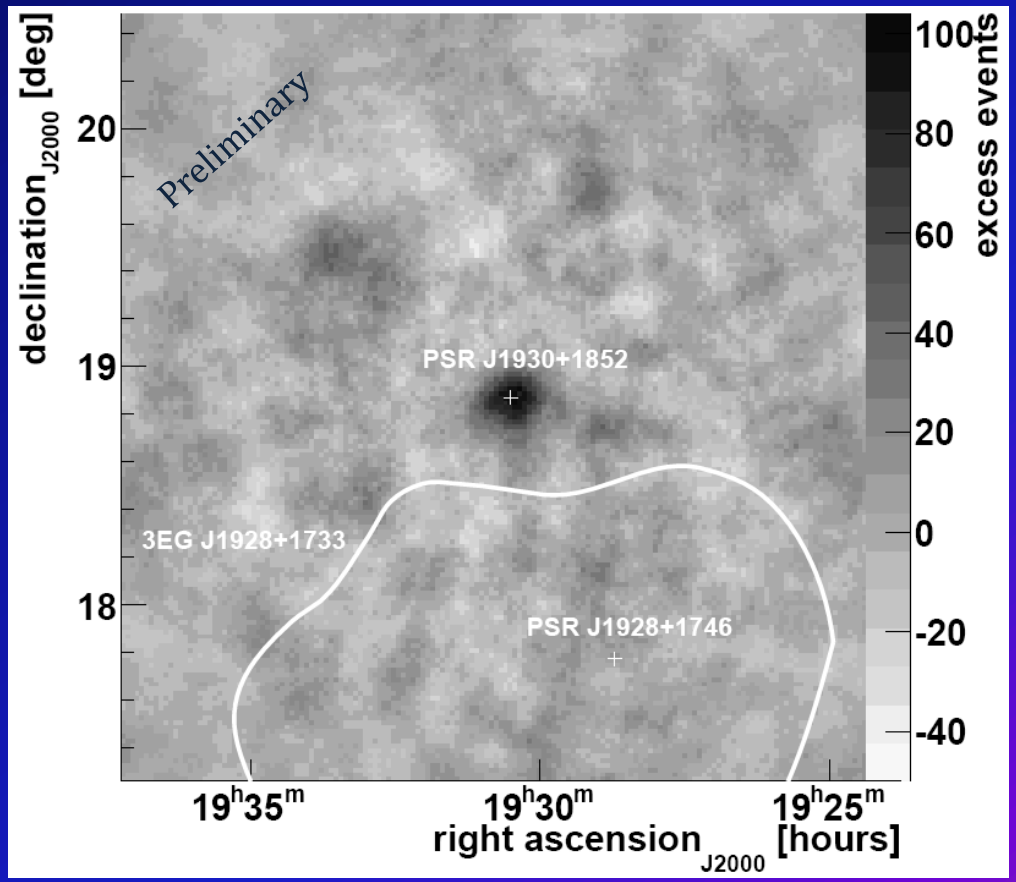
# SNR G54.1+0.3 / PSR J1930+1852

- "Cousin of the Crab"
  - X-ray jet/torus, no thermal shell
  - Age ~ 2900 years
  - E-dot = $1.2 \times 10^{37}$ erg/s
  - Distance ~ 6.2 kpc



# SNR G54.1+0.3 / PSR J1930+1852

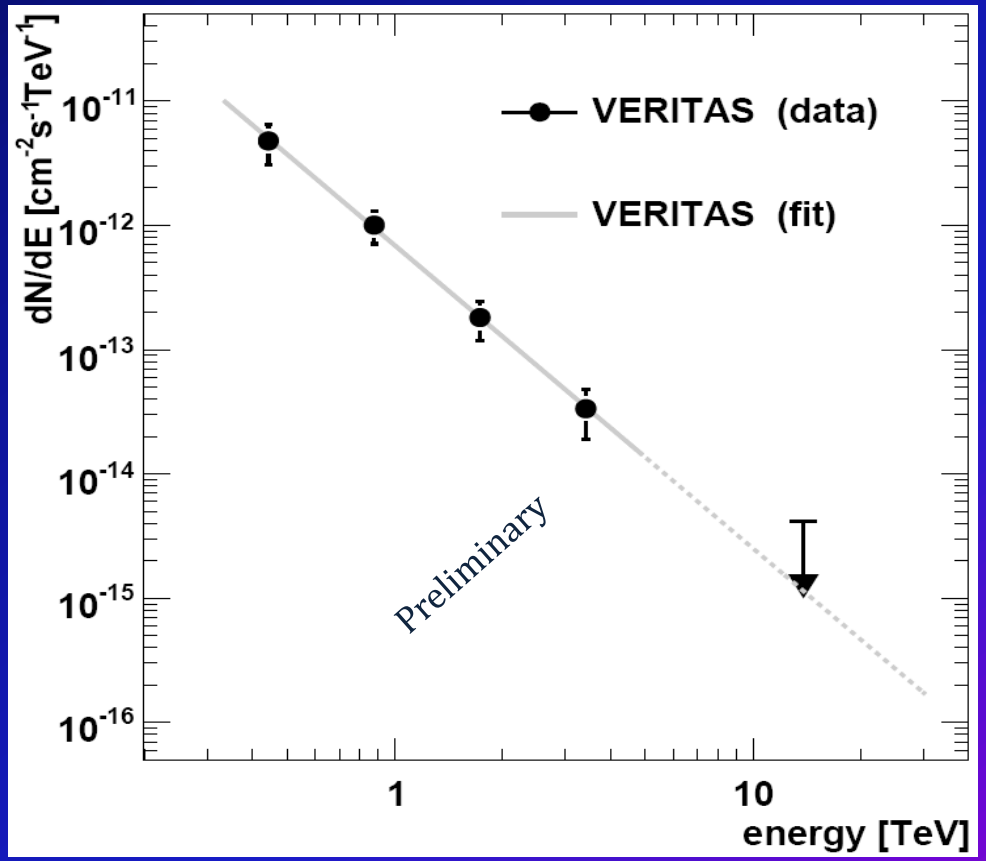
- Hint of signal in 2007 moonlight data.
- 2008/09 follow-up yields a 7-σ detection in 31 hours
- Location compatible with pulsar
- Consistent with point source.




*Acciari et al. (2009), in prep.*

# SNR G54.1+0.3 / PSR J1930+1852

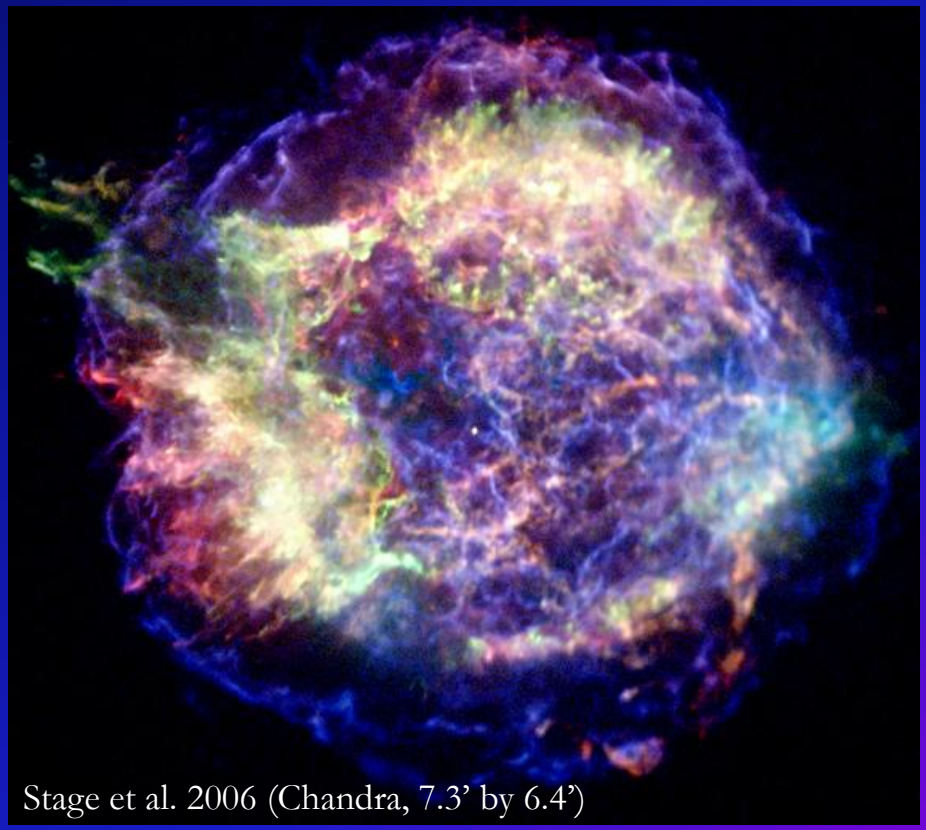
- Power-law spectrum:
  - Index: $2.40 \pm 0.24_{stat} \pm 0.3_{sys}$
  - Flux ($> 1$ TeV) ~ 2.5% Crab
- Lγ / E-dot ~ 0.15%
  - Similar to other young TeV PWNe, eg G0.9+0.1, Kes 75
  - VHE γ-rays from freshly injected electrons




*Acciari et al. (2009), in prep.*

# Cassiopeia A

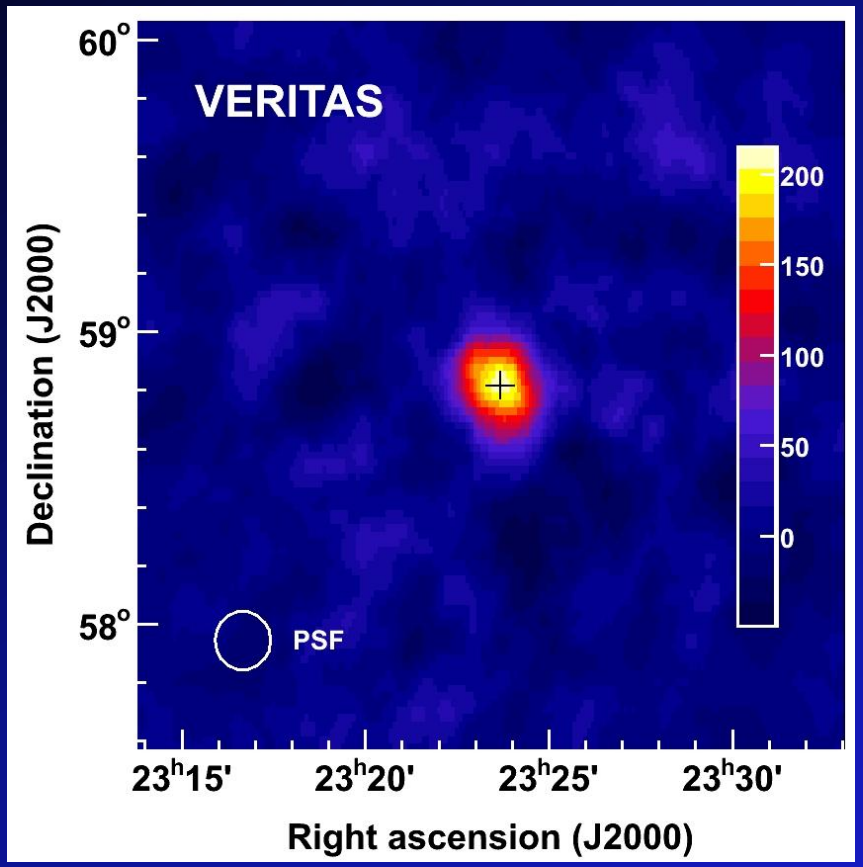
- Young (~330 yr), well studied shell-type SNR
  - Distance ~3.4 kpc
- 5-arcmin diameter
  - Comparable to TeV PSF
- Discovered in TeV by HEGRA (232 hrs, 5 σ), confirmed by MAGIC (47 hrs, 5.3 σ)

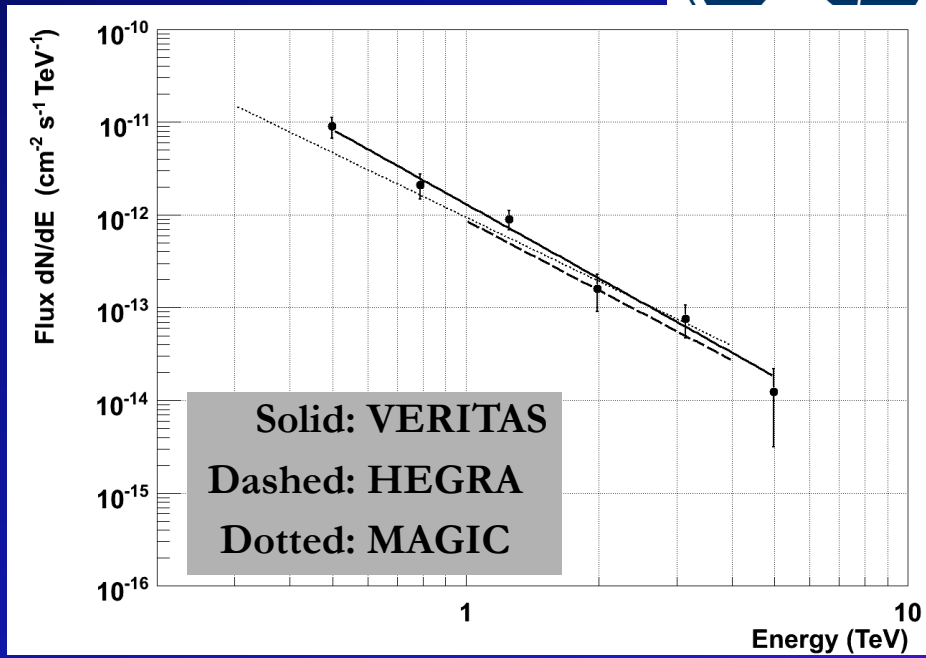


Stage et al. 2006 (Chandra, 7.3' by 6.4')

# Cassiopeia A

- VERITAS: 22 hr data in 2007, 8.3 σ
- Consistent with point source




- Index: $2.61 \pm 0.24_{stat} \pm 0.2_{sys}$
- Flux (> 1 TeV) ~3.5% Crab
- No sign of a cut-off at high energy.
  - Fermi spectrum connects at lower energy
- Electrons or hadrons?

*Acciari et al. 2009, submitted*

# THE FUTURE OF GAMMA-RAY ASTRONOMY

# 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 ← accomplished
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

# 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.

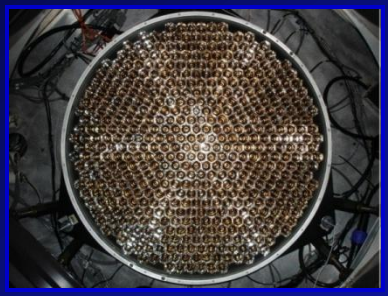
Increase photon collection by ~35%.

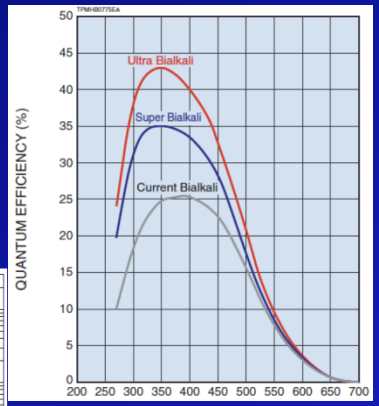
Improves background rejection, $E_{th}$, sensitivity.

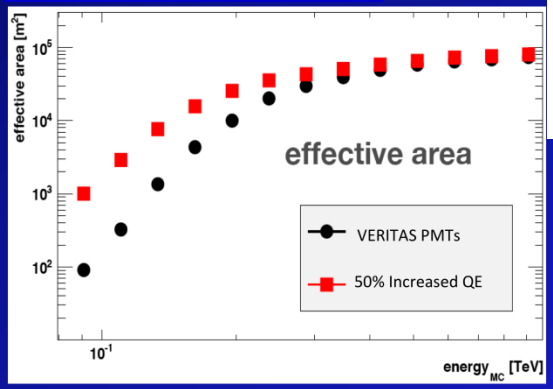
**TRIGGER Upgrade**

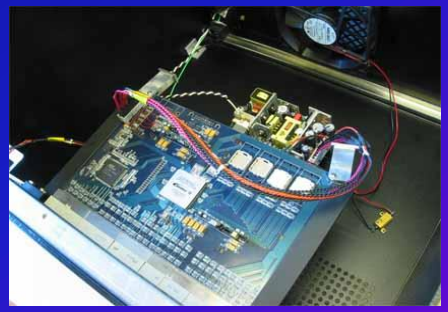
Smaller coincidence window
Topological Trigger

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

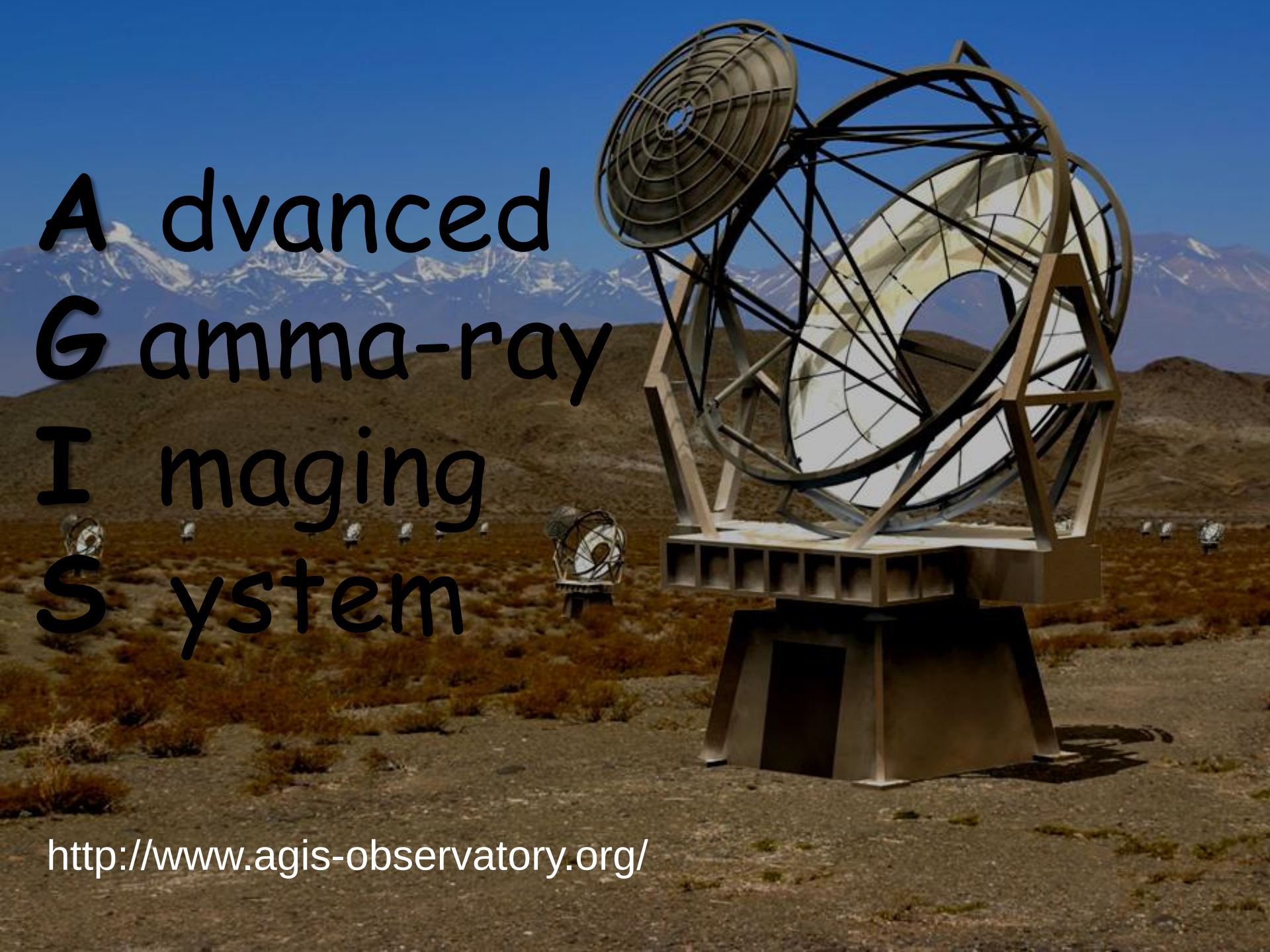




Prototype Trigger Systems

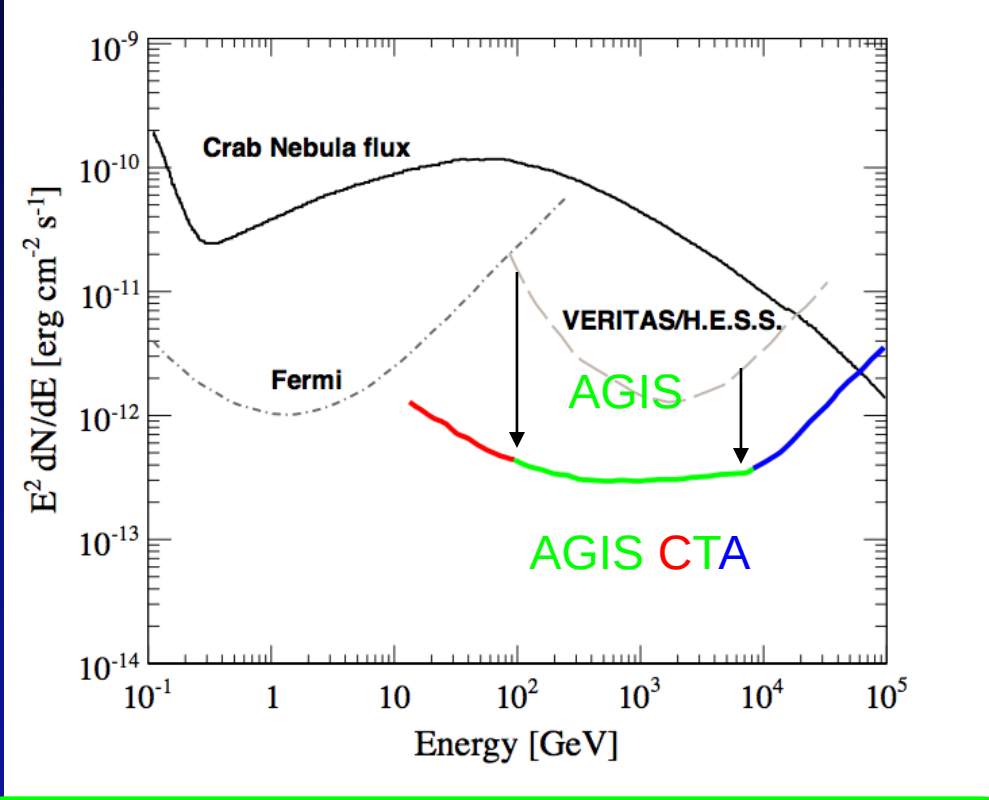

A dvanced
G amma-ray
I maging
S ystem
http://www.agis-observatory.org/

# The promise of a next-generation instrument


- Increased sensitivity:
  - Detailed spectral studies of starburst galaxies (M 82, NGC 253)
  - Discovery of weaker sources ⟶ population studies of starbursts, SNRs, PWNe, …
- Lower energy threshold, larger high-energy effective area
  - Spectra over broader energy range → search for features, cutoffs
- Excellent angular resolution:
  - Morphology studies of pulsar wind nebulae, supernova remnants
  - Improved localizations → better MWL associations
  - Resolve emission from young SNRs (Cassiopeia A)

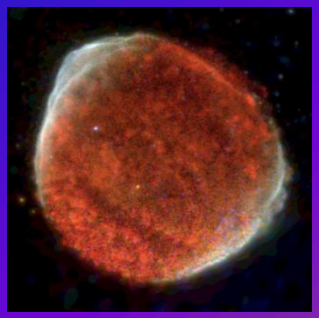
# Science Goals → Instrument Design

- z > 0.5 blazars GRBs
- pulsars
- Fermi sources



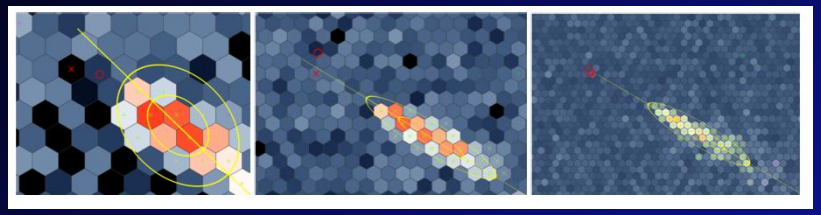

high energy cutoffs of cosmic accelerators

- high resolution imaging
- morphology of galactic cosmic accelerators
- mapping large diffuse emission regions
- survey capabilities
- best point source sensitivity in HE-VHE $\gamma$-rays



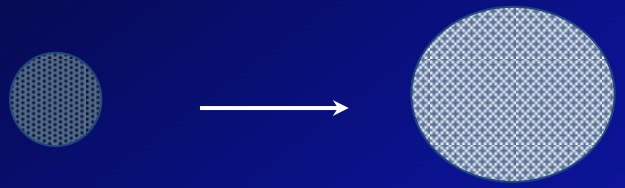
# Instrument design

Pixelation



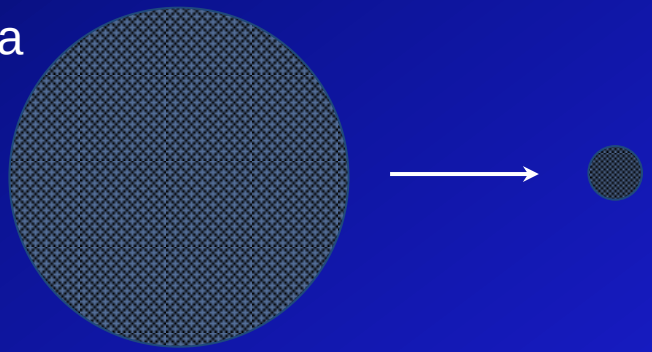
0.28º 0.20º 0.07º

FOV

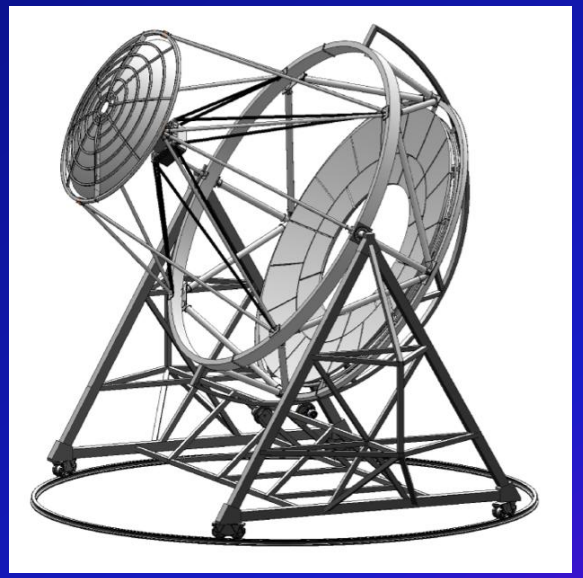


3.5 deg. 8 deg.

Camera Size:



AGIS Element:
Schwarzschild-Couder optics



Telescope with short f/D
& compact high resolution

36 telescope array with 100-200 m spacing will provide a ~1 km$^2$ effective area @ 1 TeV with 0.02-0.05° angular resolution

# 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.**
    - **New information on origins of cosmic rays.**
  - **Stringent limits from Galactic plane survey.**
  - **Detection of new TeV source near γCygni SNR, VER J2019+407**
  - **Detection of 2 new PWN/SNR: G106.3+2.7, G54.1+0.3.**
  - **Detailed studies of SNRs: IC 443 and Cas-A.**
- VERITAS Upgrade will significantly improve sensitivity.

  ⇒T1 Relocation already has!
- Broad-band studies (GeV – TeV) underway – much more to come.