Recent Results from VERITAS (VHE γ-rays and CR's)

Rene A. Ong (UCLA)

for the VERITAS Collaboration

COSPAR 2012 (Mysore, India) – V. HESS Centennial Anniversary

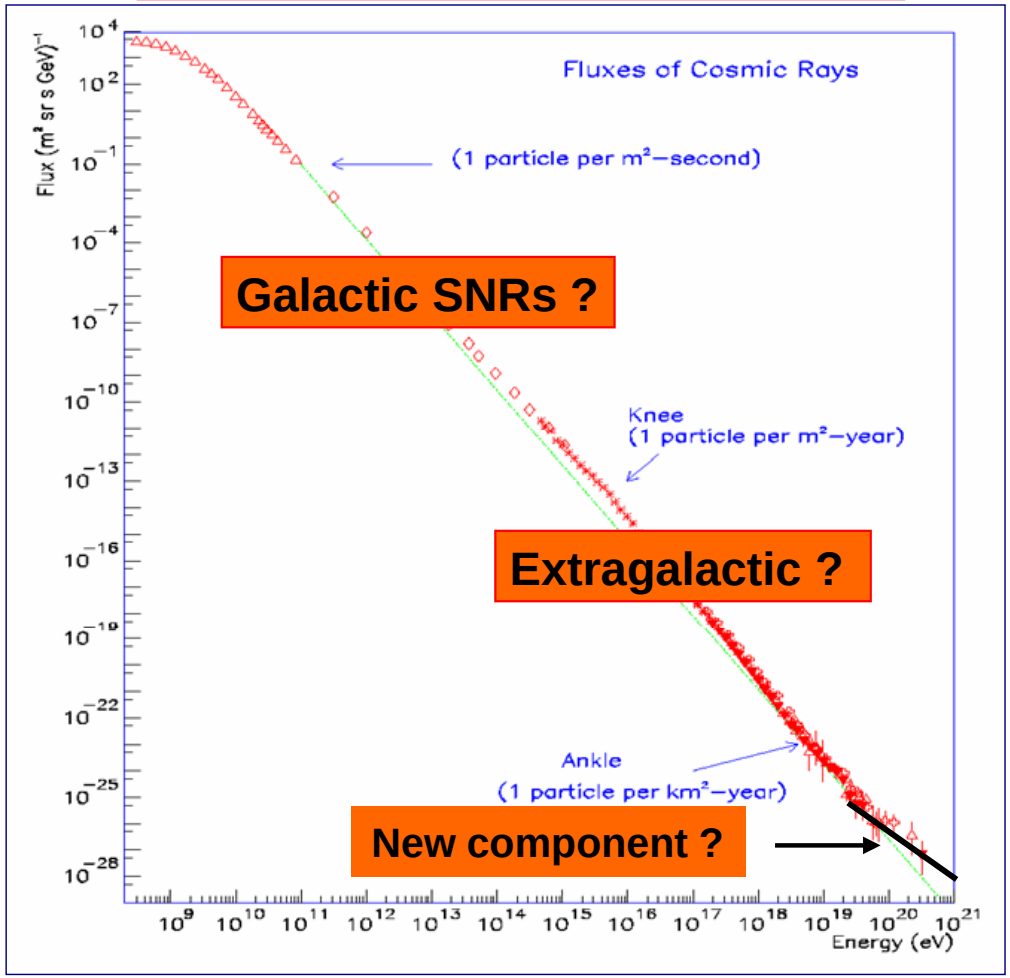
OUTLINE

- VHE γ-rays as probes to understand CR origin
- The VERITAS Observatory
- Snapshot of new VERITAS results
  Concentrate here on Galactic sources:
  - Supernova Remnants (SNRs): Tycho
    Pulsar Wind Nebulae (PWN): CTA1
  - Binary Systems: HESS J0632 +057
  - Un-identifieds: Cygnus Region (Gal Center in questions)
  - Crab Pulsar

  (No time to show a lot of other nice results, including
  AGN, Starburst galaxies, M87, and dark matter studies).
- VERITAS Upgrade & Future

Origin of Cosmic Rays

Diffuse, all particle spectrum



S. Swordy

100 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.

(VHE = Very High Energy E > 100 GeV)

Rich Variety of VHE Sources → CR's

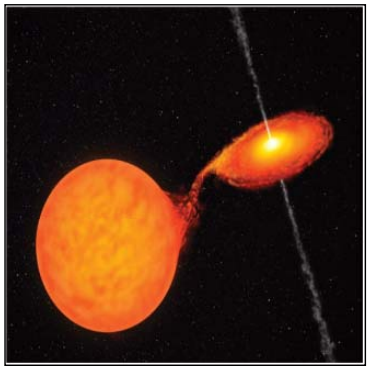
Pulsars
Pulsar Wind Nebulae

NS dynamo
Winds

Supernova Remnants

Shocks
Fermi mechanism
Origin of CRs ?

Binary systems



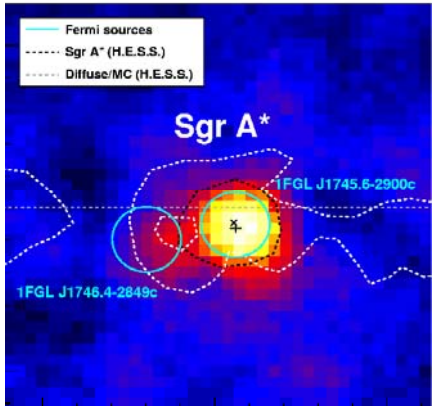
Accretion-powered jets,
Colliding winds, or …?

Star Forming Regions

OB Assoc., WR stars,
molecular clouds, etc.

& Extragalactic sources
(AGN, starbursts)

Un-Identifieds



???

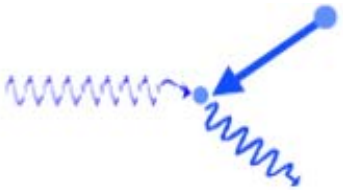
VHE γ-rays as Tracers of CRs

VHE γ-rays:

- are *Not Deflected* by interstellar magnetic fields.
- *are Tracers* of parent particle populations – those particles accelerated by shocks.
- do not have a large Galactic diffuse γ-ray background.

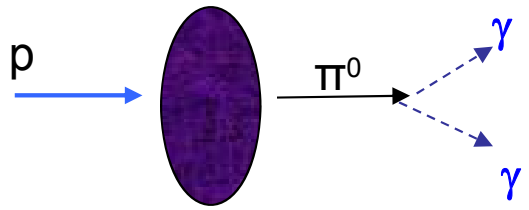
But both electrons and protons to produce γ-rays.

Accelerated electrons
→ VHE γ-rays
Up-scattering of soft photons



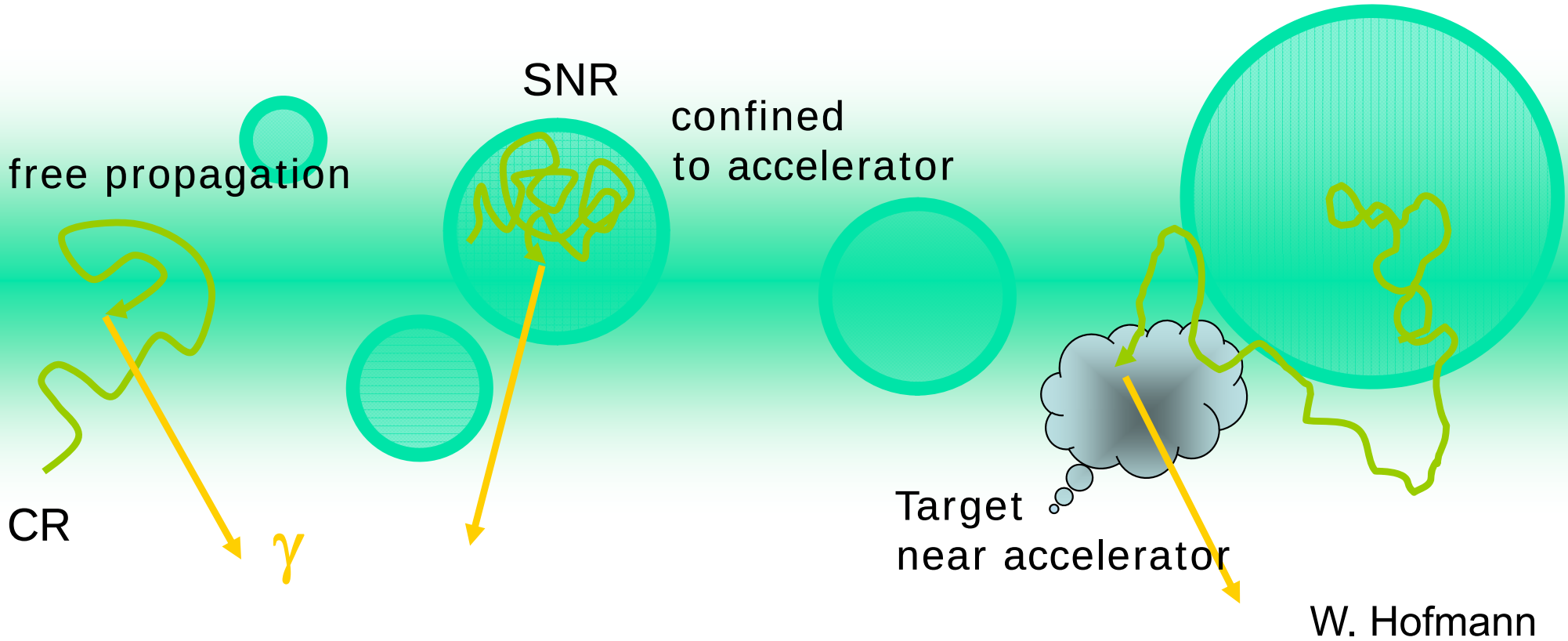
Inverse Compton Scattering

Accelerated protons
→ VHE γ-rays
Target interaction, π^0 decay



π^o and target material

Tracing the HE Particles



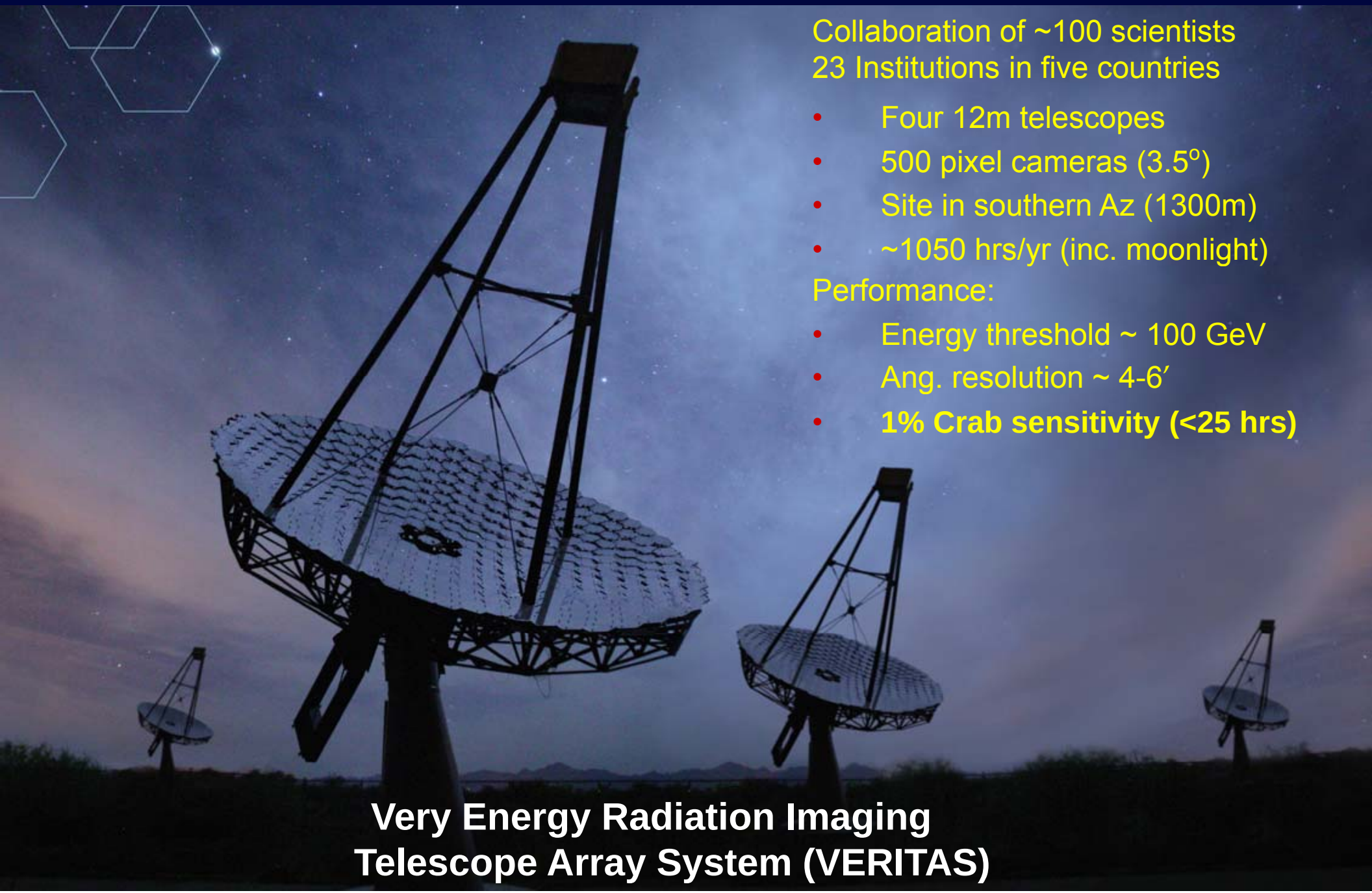
VHE γ-rays come from secondary interactions:

- p: π^o production and decay
- e: Inverse Compton scattering and Bremsstrahlung

Trace beam density x target density

Need to disentangle e, p components → MWL observations are crucial.

VERITAS



Collaboration of ~100 scientists
23 Institutions in five countries

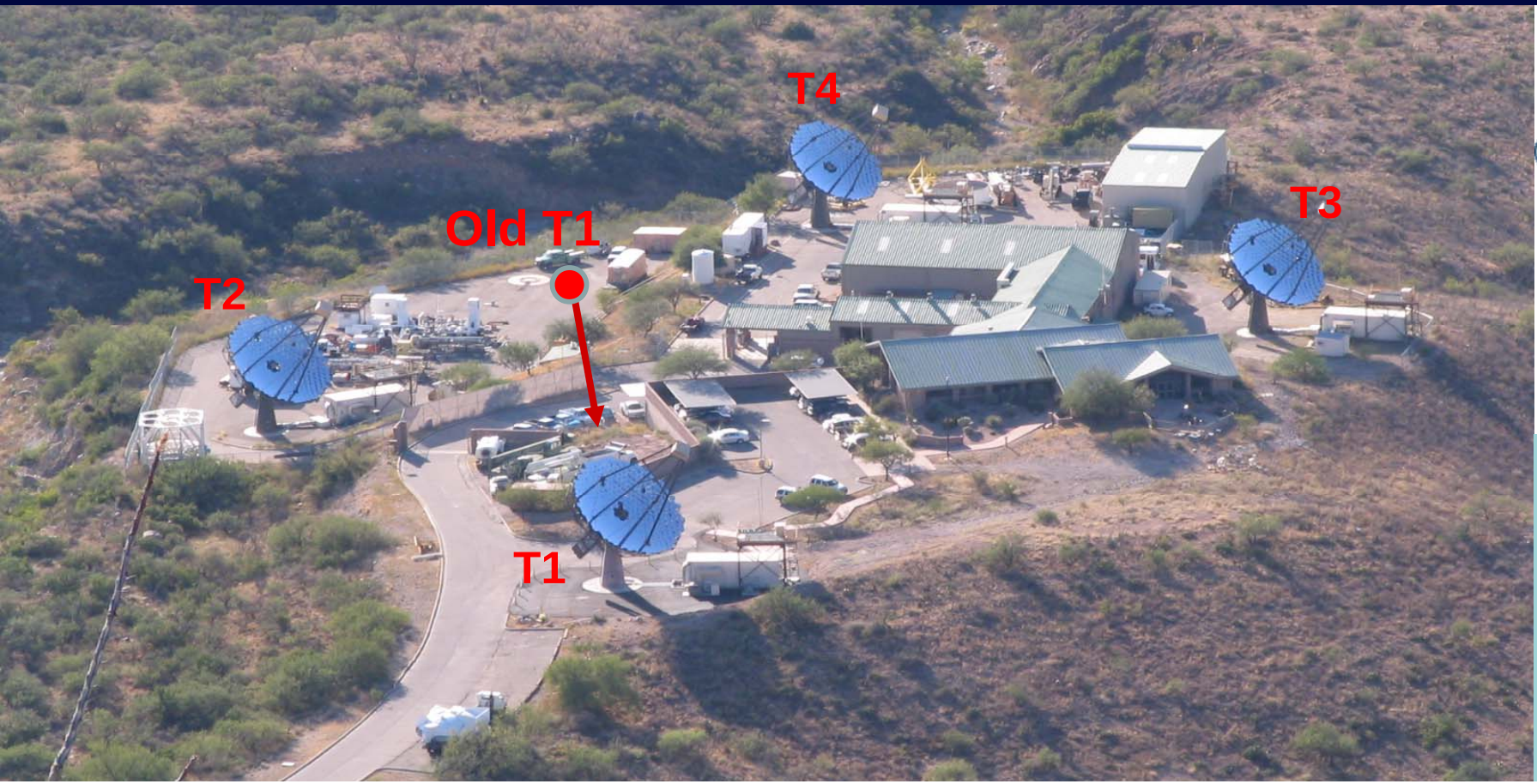
- Four 12m telescopes
- 500 pixel cameras (3.5^{o})
- Site in southern Az (1300m)
- ~1050 hrs/yr (inc. moonlight)

Performance:

- Energy threshold ~ 100 GeV
- Ang. resolution ~ 4-6′
- **1% Crab sensitivity (<25 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
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DePauw Univ.
Grinnell College
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U. of Iowa
U, of Minnesota
U. of Utah
Washington U.

Canada
McGill Univ.

U.K.
Leeds Univ.

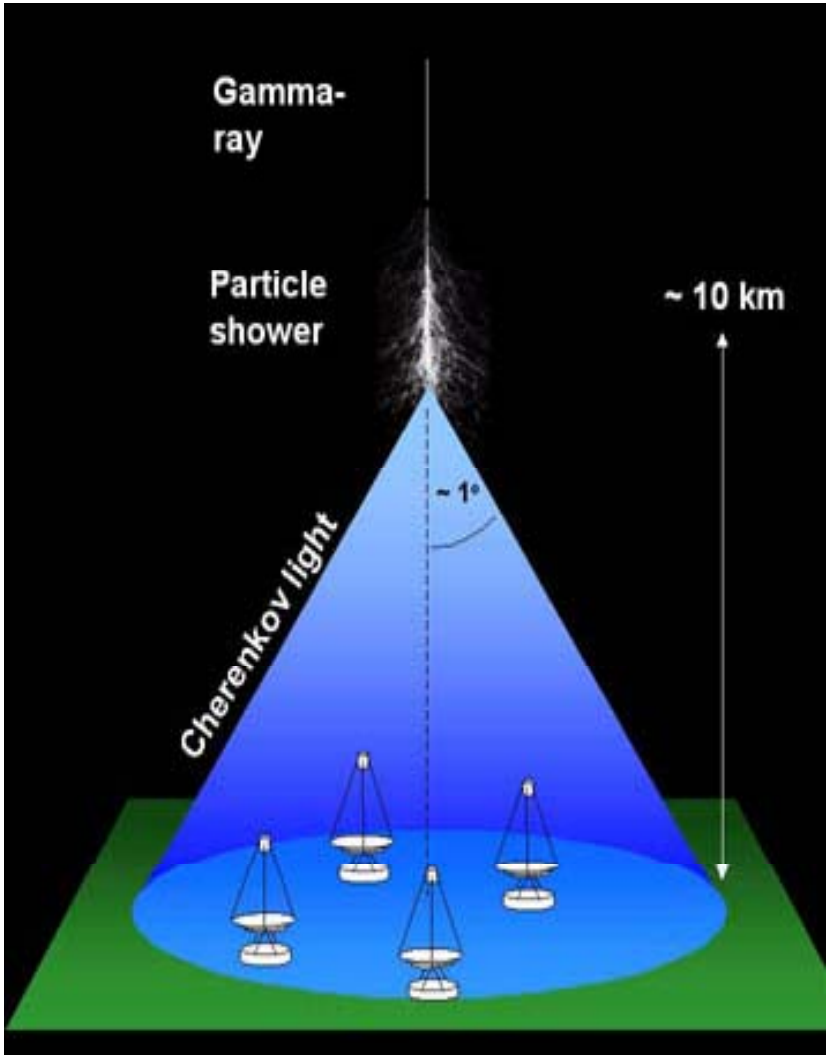
Ireland
Cork Inst. Tech.
N.U.I. Galway
Galway-Mayo Inst.
Univ. College Dublin

Non-Affiliated Members
Anderson Univ.
Cal Poly, SLO
De Pauw U.
DESY/Potsdam
Georgia Tech
Grinnell College
Penn State

MWL Partnerships:
35 Associate Members (IceCube, Fermi, Swift, etc.)
MOU's with Fermi-LAT, IceCube

New: VERITAS-Fermi GI Program (2013)

Atmospheric Cherenkov Technique



Reconstruct IMAGE in camera of each telescope:

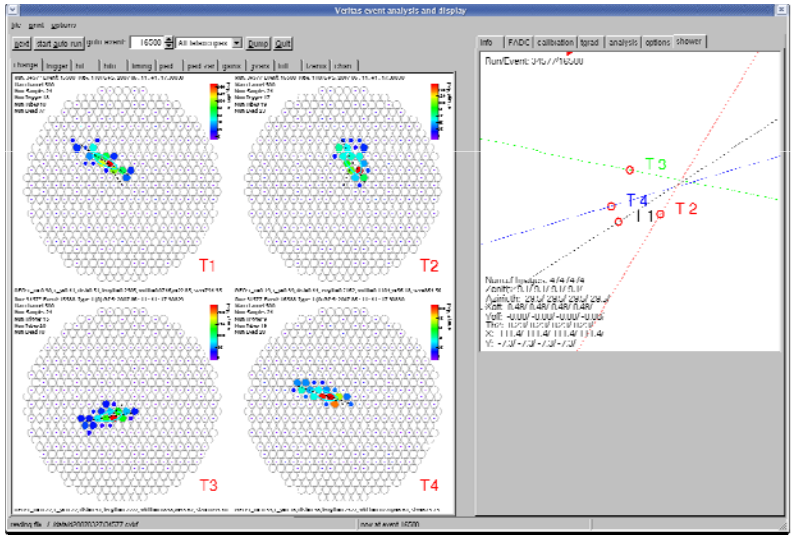


Image axis → **γ-ray direction**

Intensity → **γ-ray energy**

Image shape → **particle type**

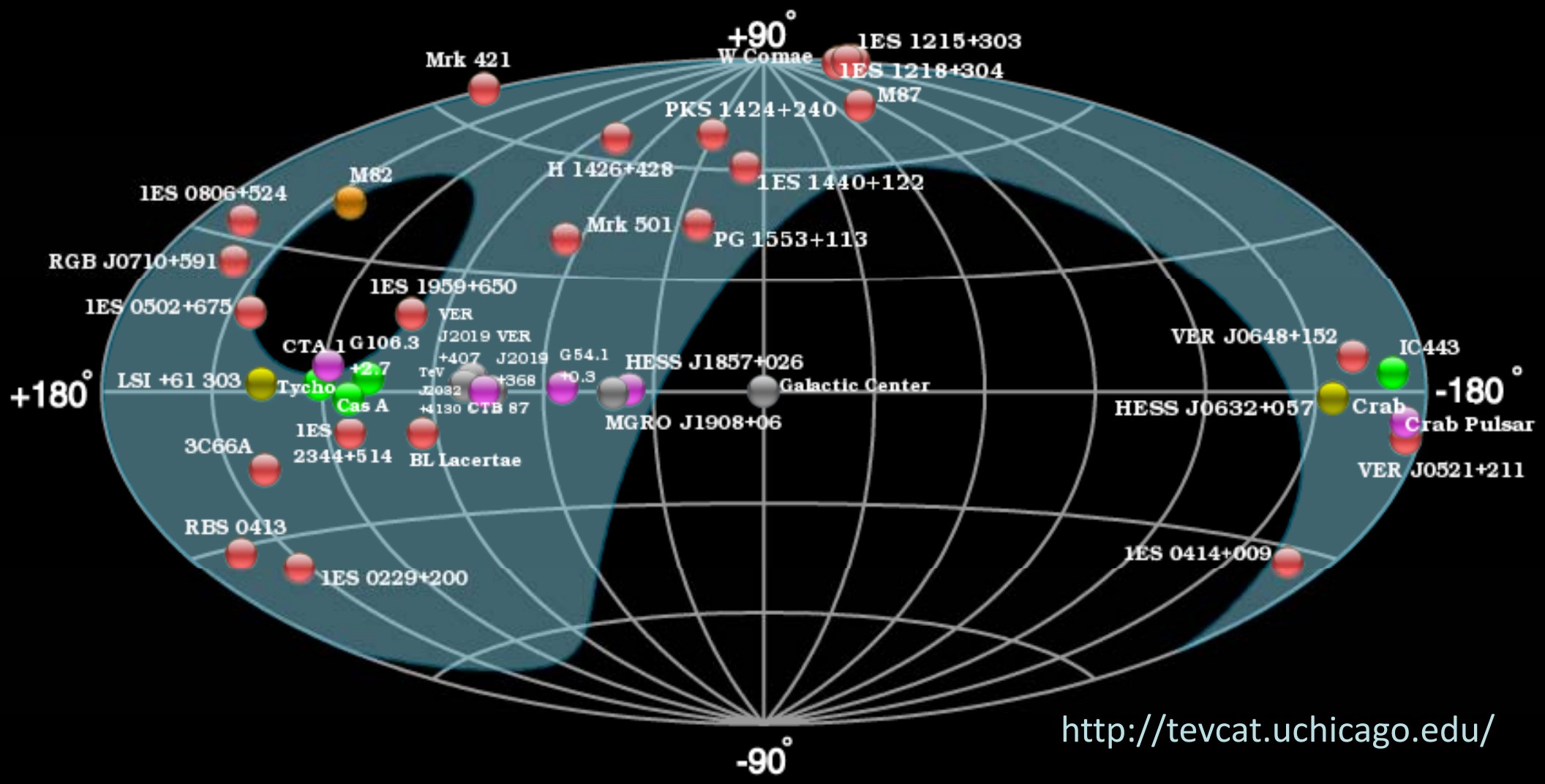
Stereoscopy gives greatly improved

ang. resolution, E resolution,

γ / had separation, SENSITIVITY

VERITAS Sky Map (2012)

>40 sources (>5σ post trials) covering 8 source classes
At least 17 sources are Galactic (SNRs, PWNe, Binaries, UnIds, Pulsars)



http://tevcat.uchicago.edu/

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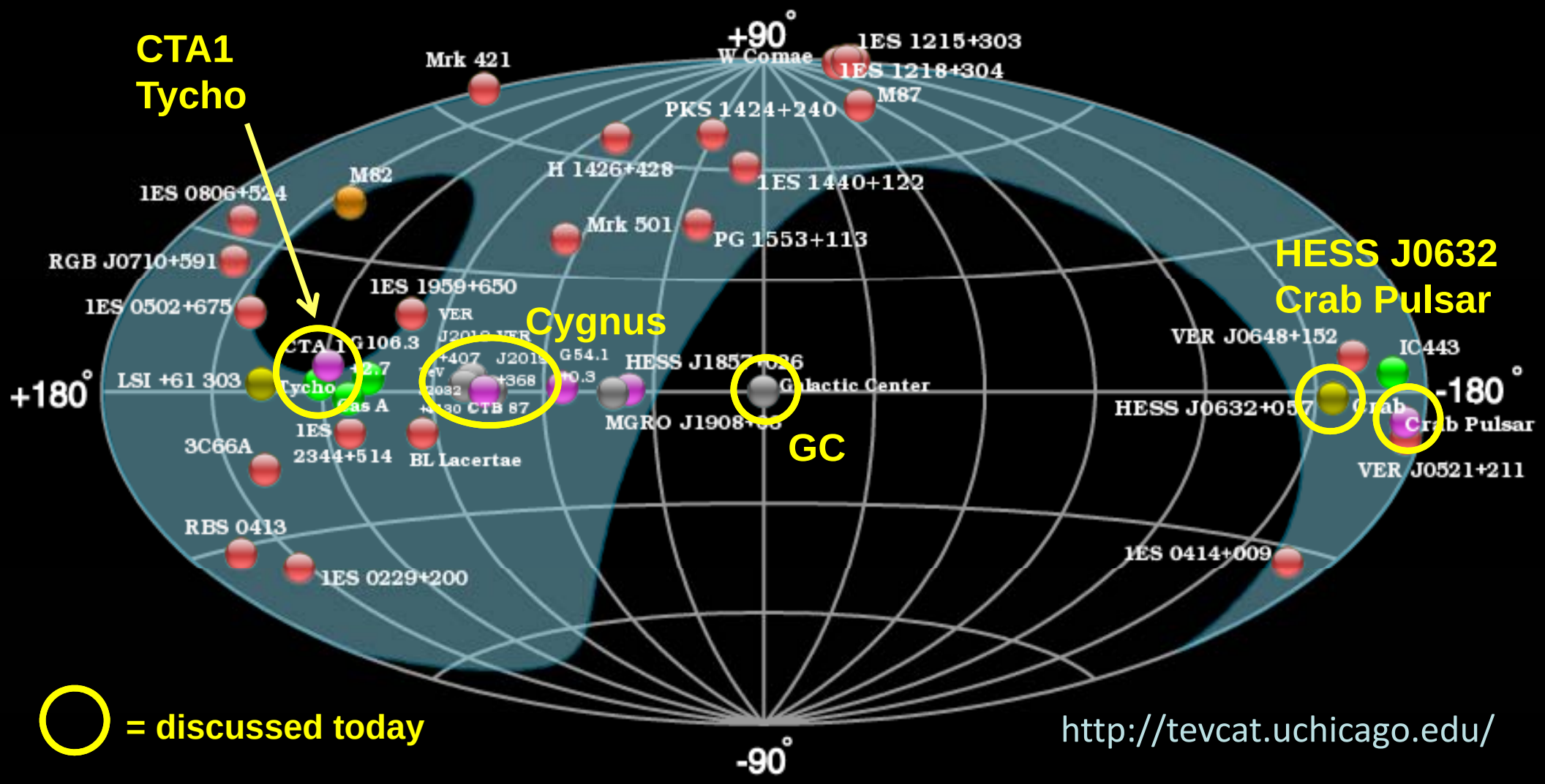
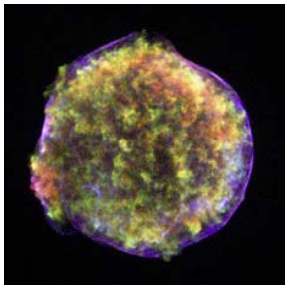


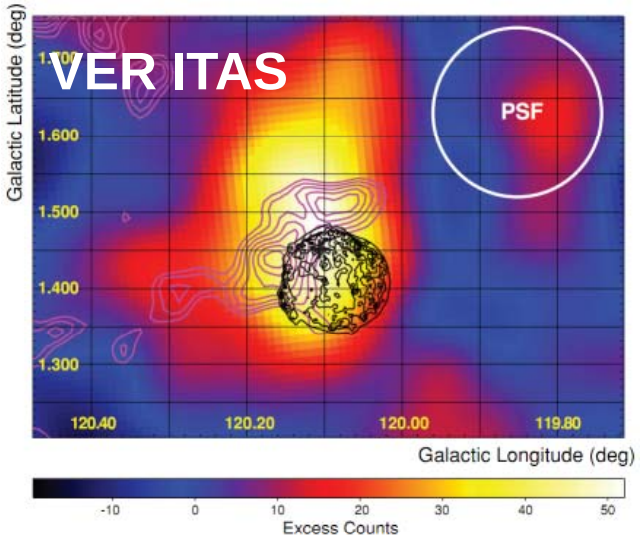
○ = discussed today

http://tevcat.uchicago.edu/

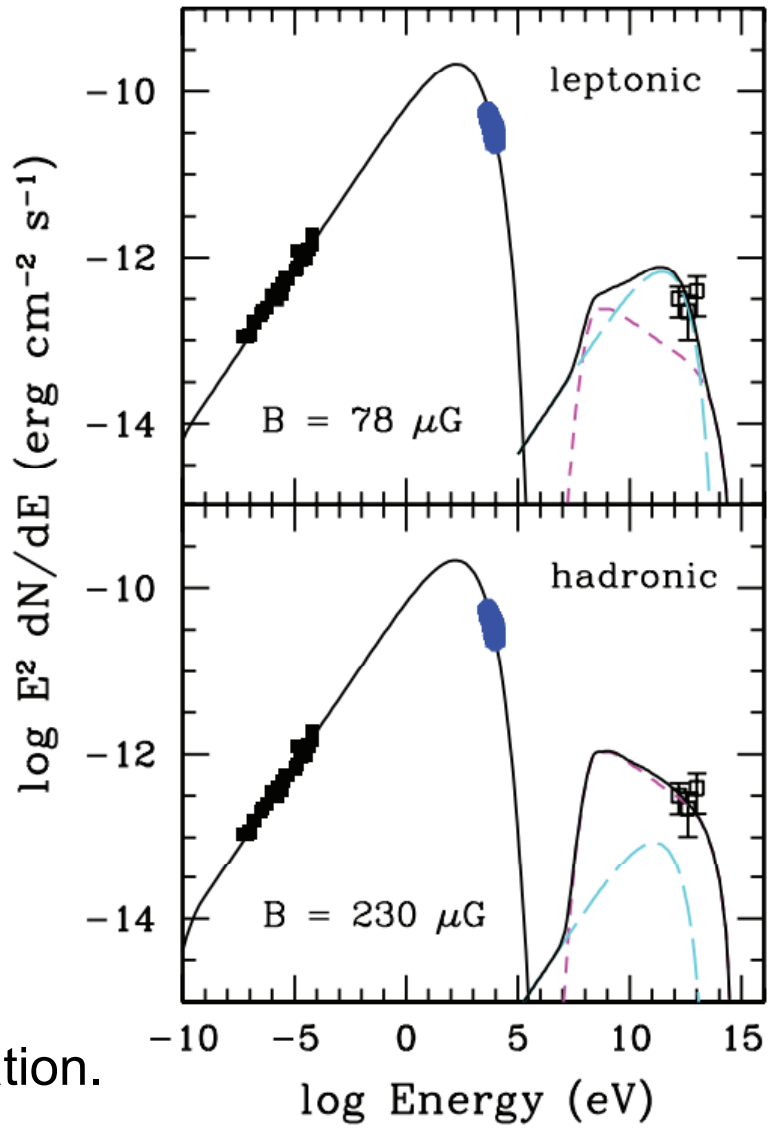
Selection of Recent VERITAS Results

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.
- Weak source (0.9% Crab) with hard spectrum $\Gamma = 1.95 \pm 0.51 \pm 0.30$.
- Consistent with leptonic and hadronic acceleration.

Tycho with Fermi-LAT, Hadrons ?

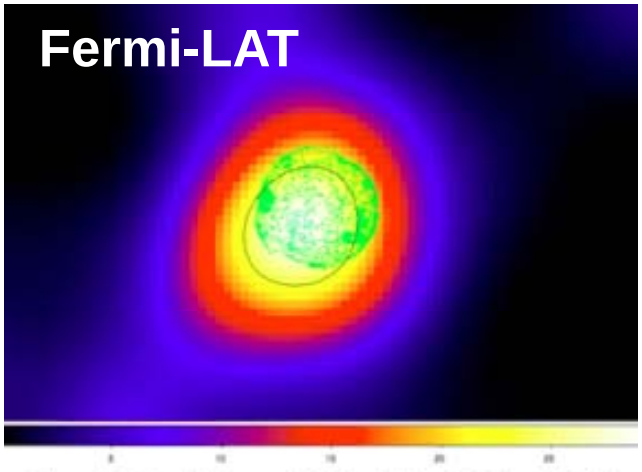
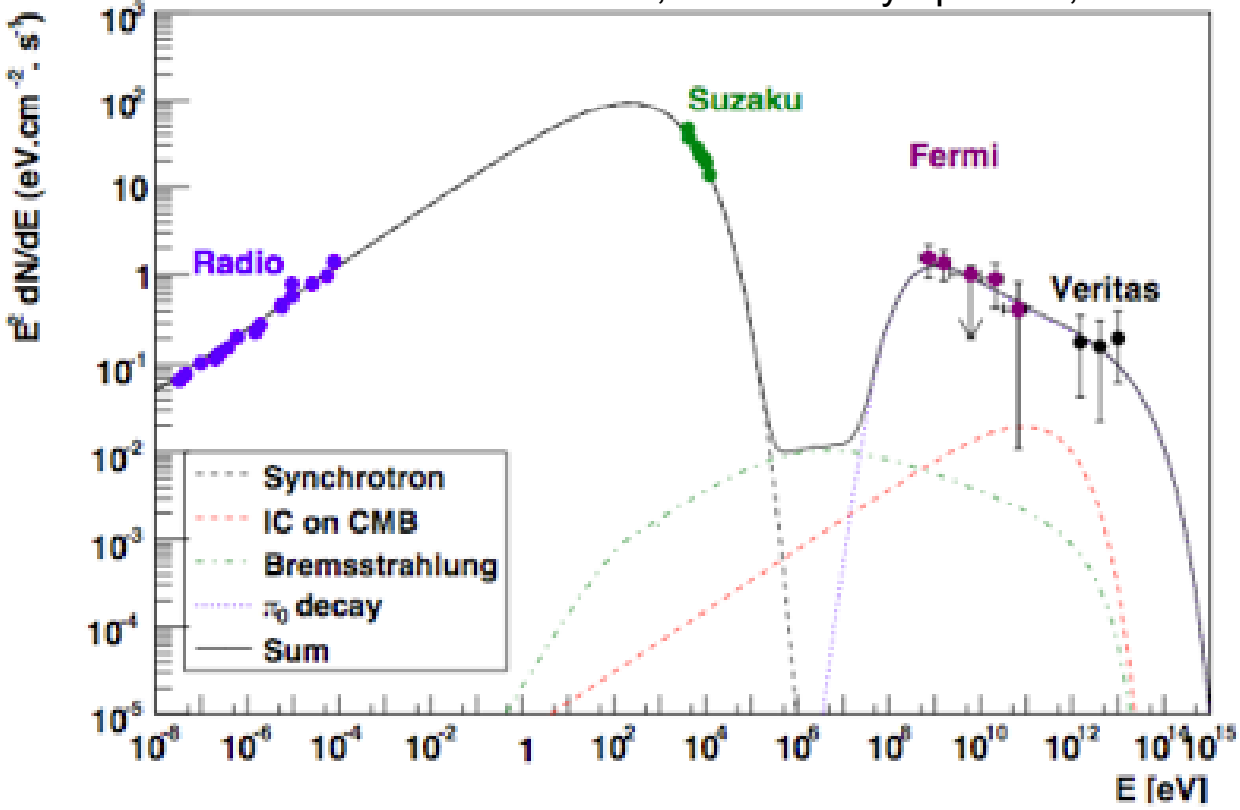


Figure 2: *Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.*

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



Fermi-LAT & VERITAS:

- Fermi-LAT detection.
- Photon index of 2.3 ± 0.1 and shape of SED favor hadronic origin.
- 6-8% of E_{sn} transferred to CR acceleration (D~2.8kpc).

Good evidence for hadronic acceleration (perhaps also in Cas A)

CTA 1: First Blind-Search Fermi Pulsar

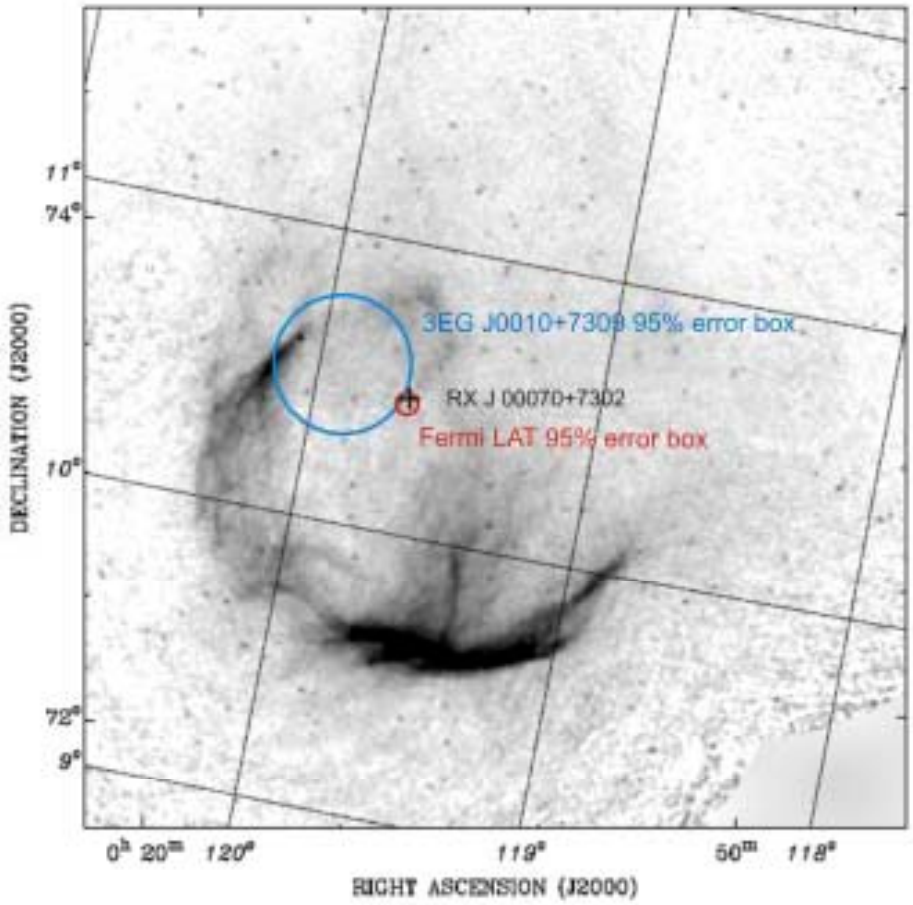
CTA 1:

- 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 (first blind search) – 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)



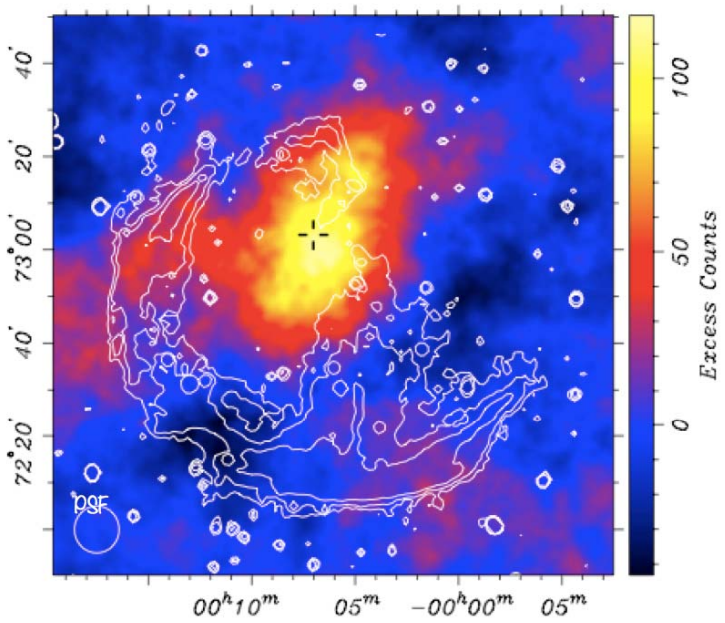
Fermi-LAT source (red), X-ray PWN, EGRET source (blue) and radio contours.

CTA 1: VERITAS VHE Discovery

VERITAS Discovery: VER J0006+729

- Data: ~40 hrs, Oct 2010-Dec 2011.
- F (> 1 TeV) ~ 4 x 10^{-12} erg/cm^2/s
  ~ 0.2% spin-down luminosity.

Color: VERITAS excess map
White: Radio 1420 MHz (Pineault et al. 1997)
Cross: Fermi-LAT pulsar (Abdo et al. 2008)



E. Aliu et al. 2012

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- Data: ~40 hrs, Oct 2010-Dec 2011.
- F (> 1 TeV) ~ 4 x 10^{-12} erg/cm^2/s
  ~ 0.2% spin-down luminosity.
- Broadband SED: TeV emission consistent with synchrotron IC.
- **Typical PWN near pulsar of age < 100 ky.**

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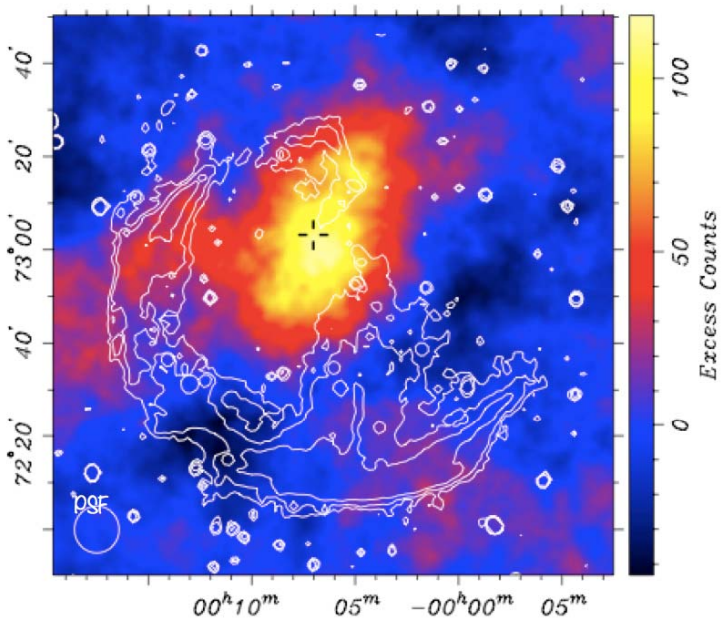
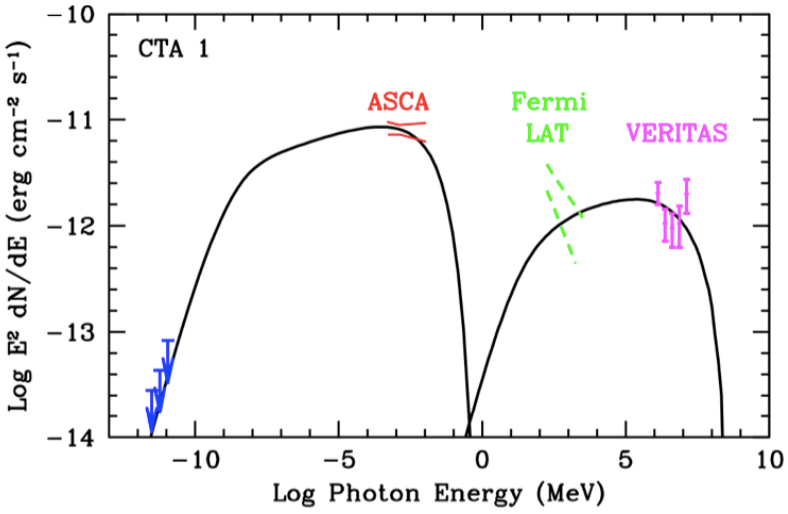
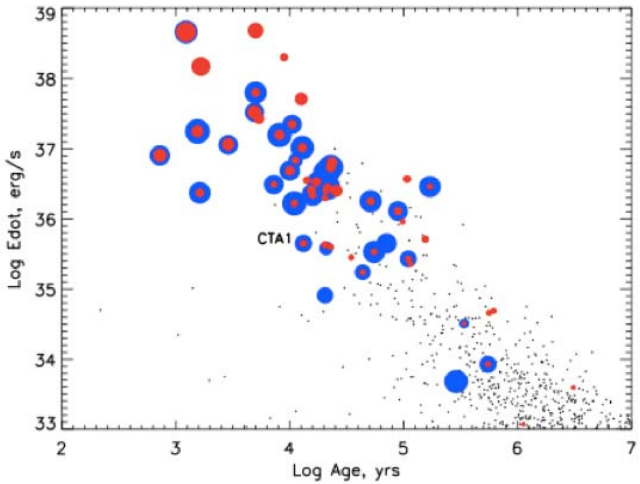






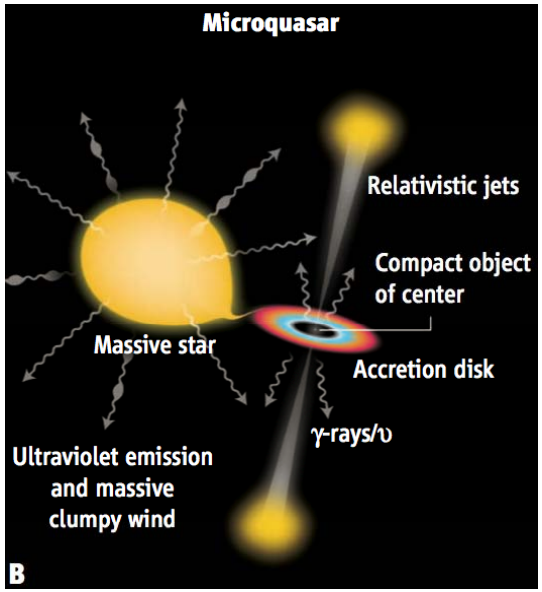
E. Aliu et al. 2012

Binary Sytems

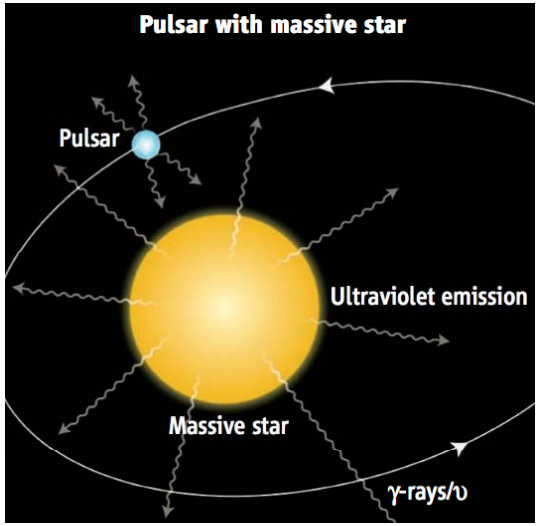
Currently 7 binary systems known at HE and VHE

- Fascinating, but complicated, systems.
- Emission can involve a jet, stellar wind, stellar disk, pulsar …
- Complicated by many unknown factors: geometry, nature of wind or disk, unknown compact object, etc.

Name	GeV	TeV
PSR B1259-63	✔	✔
LS 5039	✔	✔
LS I +61 303	✔	✔
LS VI +05 11(HESS J0632+057)	✘	✔
Cygnus X-1	✔	?
Cygnus X-3	✔	✘
1FGL J1018.8-5856	✔	✘



Mirabel (2012)

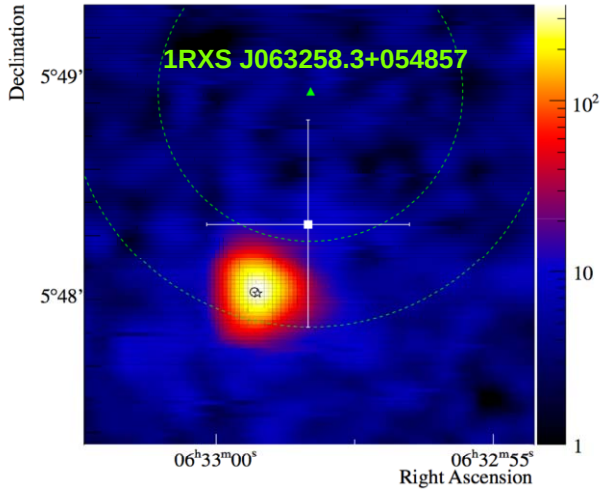


LS VI +05 11 (HESS J0632) – A New Binary

HESS J0632+057

- 2004: Discovery (HESS).
  Near MWC 148 (B0pe star) in Monoceros loop.
- 2009: Evidence for variability (VERITAS).
- 2010: Detection (VERITAS).
- 2011: X-ray (Swift) detection of period ~ 321 d.

White marker w. errors (Hinton et al. 2009)
Color/small circle: XMM, star: MWC 148



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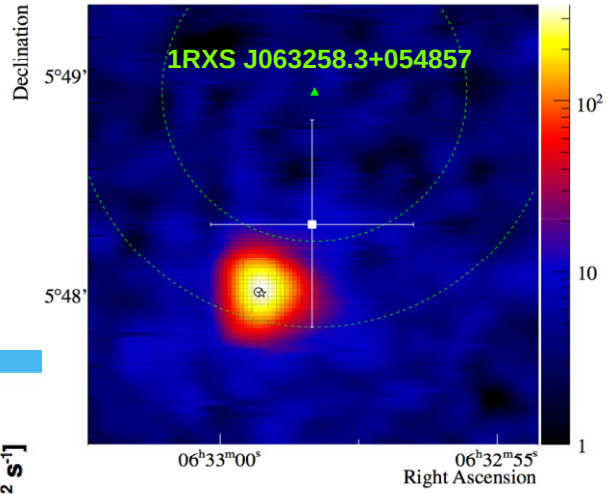
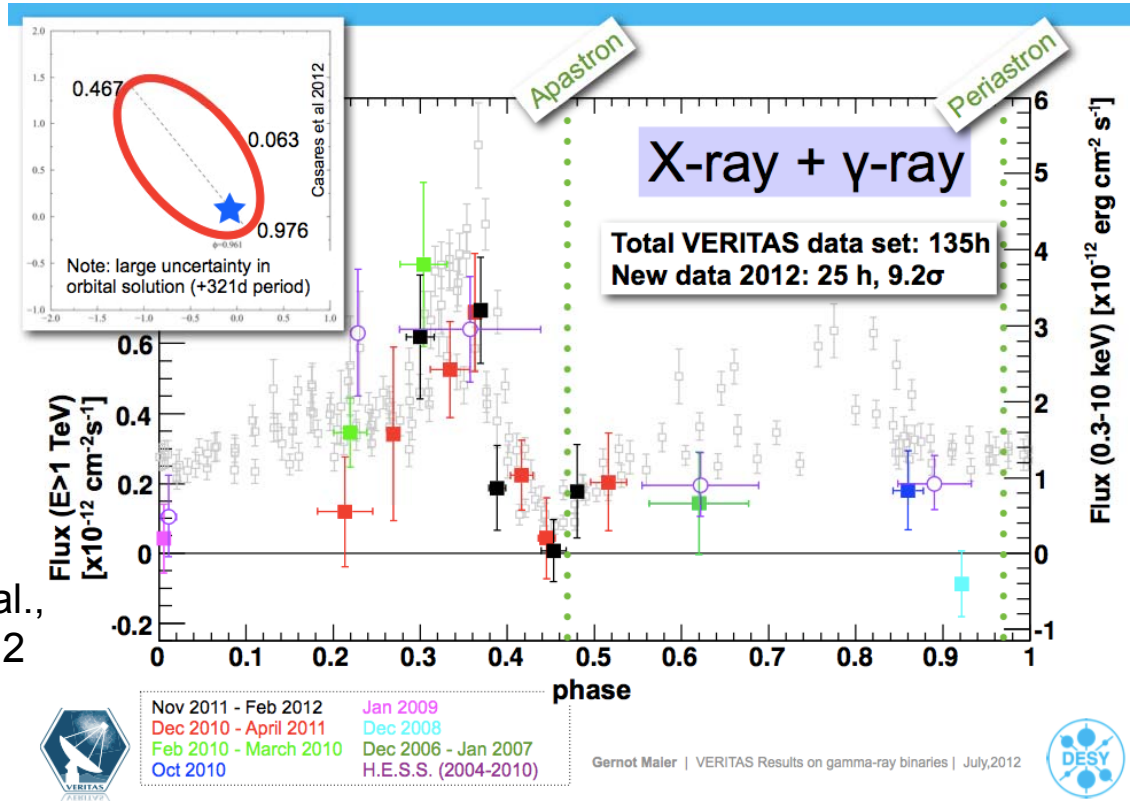




G. Maier et al., Gamma 2012

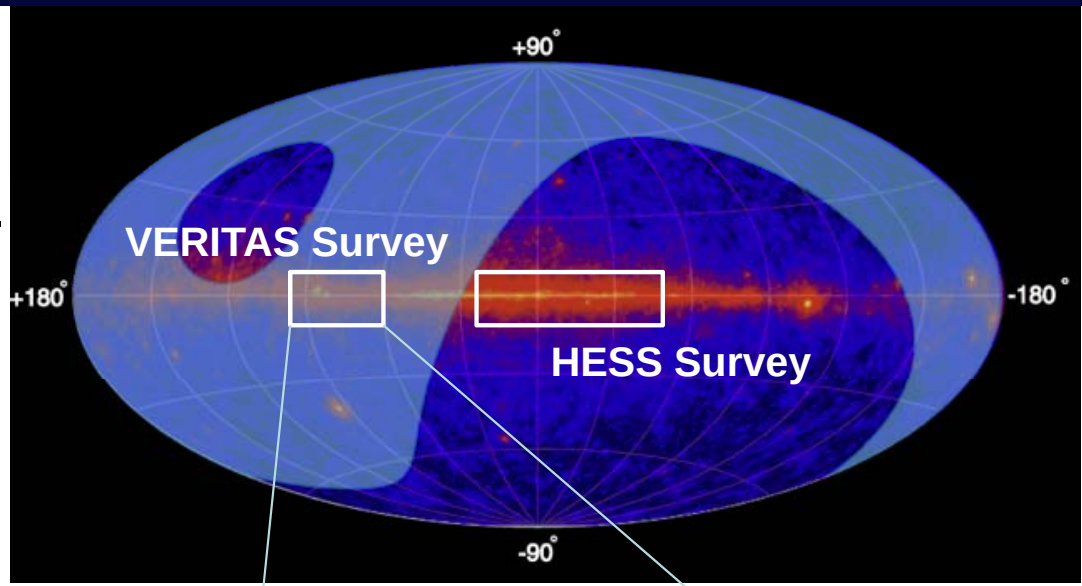
- 2011-12: Detections by VERITAS and HESS, clearly periodic/

First Binary detected by VHE observations.

VERITAS Cygnus Sky Survey

VHE Sky Surveys:

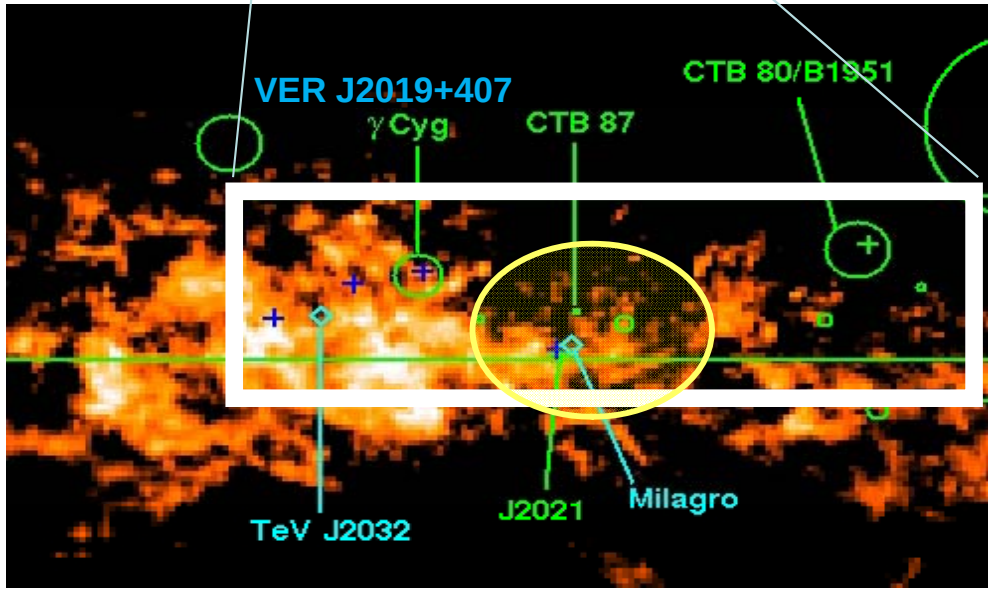
- **HEGRA (97-02):** North, ~25% Crab.
- **HESS (03-04):** South, ~3% Crab. and extended (05-08).
- **Milagro (01-07):** North, ~35% Crab at E > 10 TeV.



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.

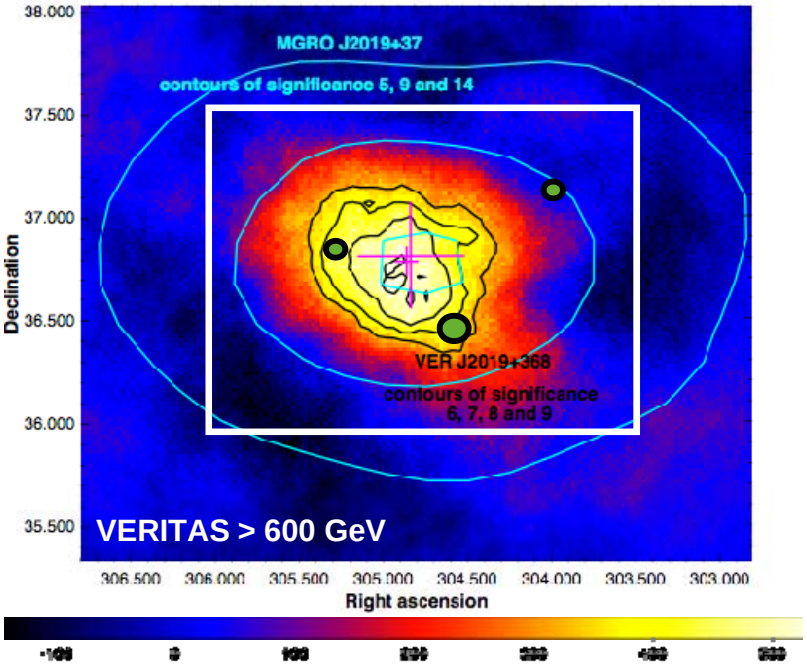
Note: strong Milagro source MGRO J2019+37



VERITAS Observations of Cygnus OB1

Observations and Analysis:

- 75h, May-Dec 2010
- E_{th} ~ 600 GeV.
- Strong VERITAS excess, consistent with large Milagro source.



E. Aliu et al., Gamma 2012

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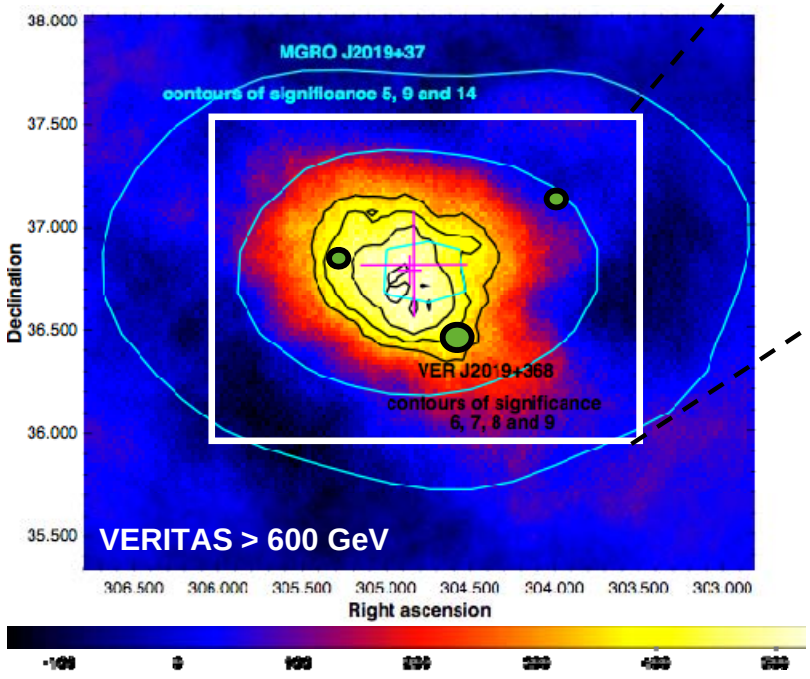

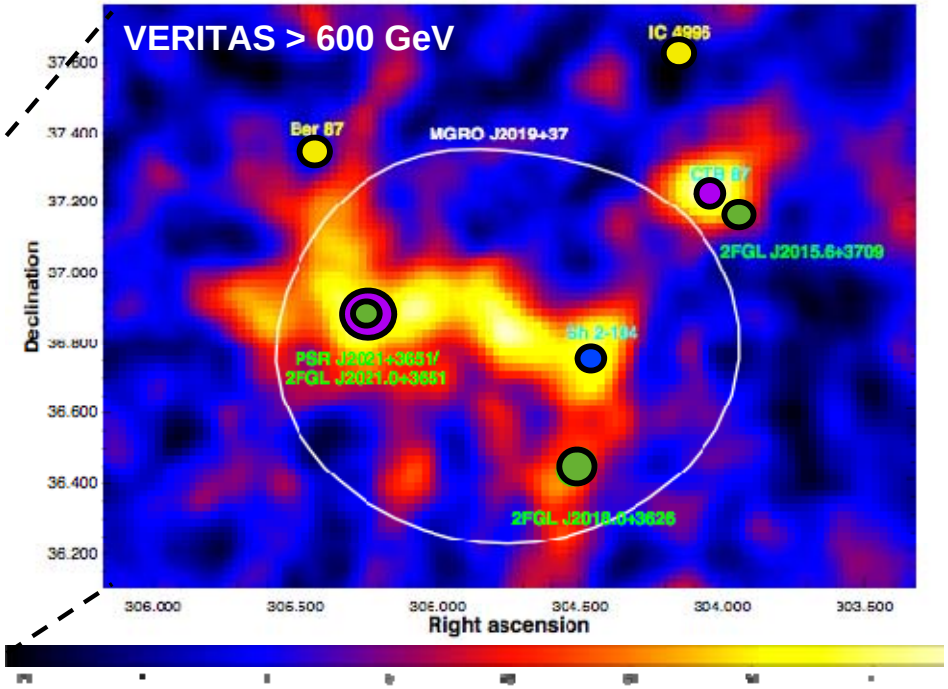

VERITAS Map:

- Separates into point source (CTB 87) and complex central region (extended emission).

E. Aliu et al., Gamma 2012

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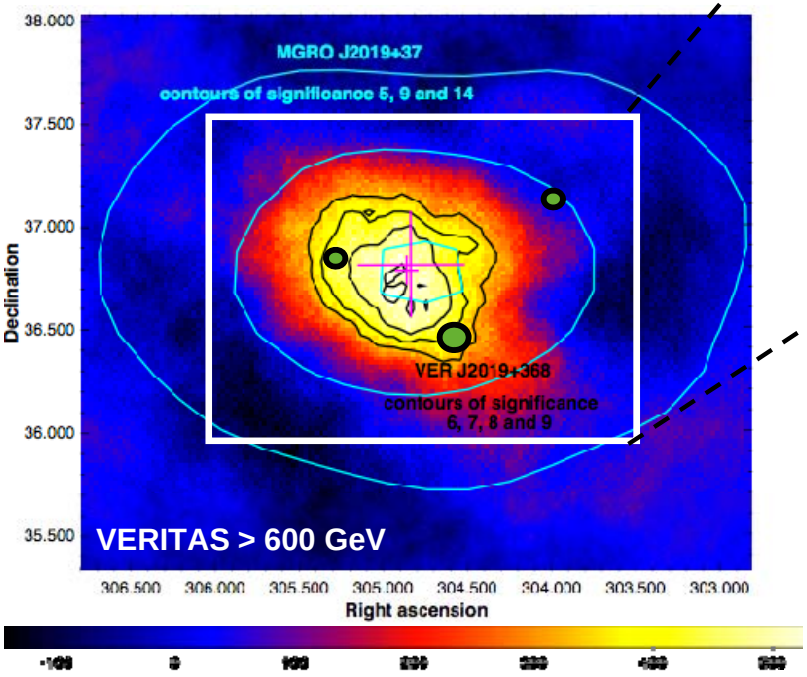
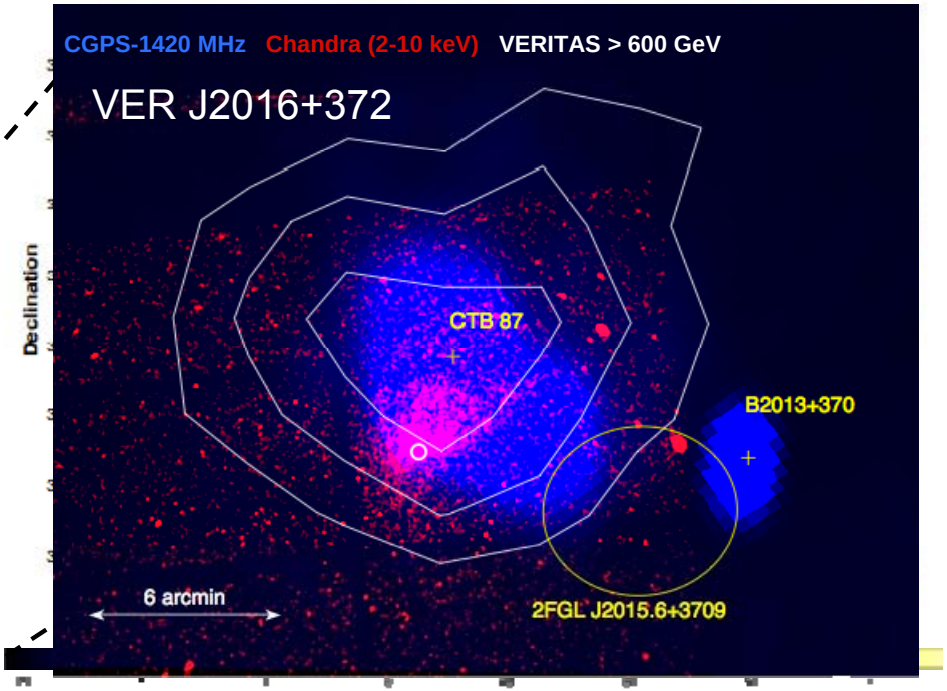




VERITAS Map:

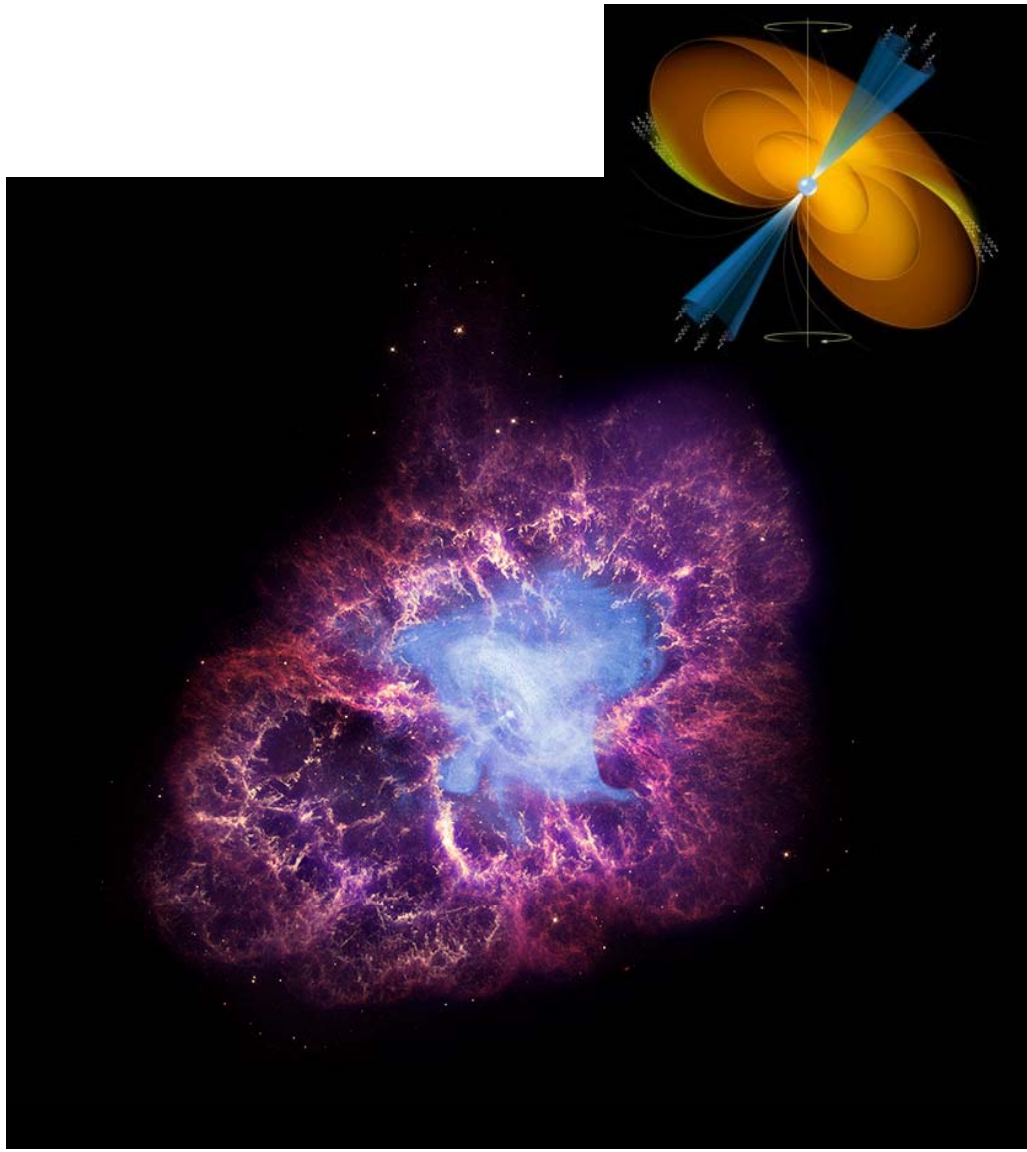
- Separates into point source (CTB 87) and complex central region (extended emission).
- CTB 87 – very likely a pulsar wind nebula.
- Central region likely has multiple extended sources → **CR acceleration** ? (supported by very hard $E^{-1.8}$ spectrum).

E. Aliu et al., Gamma 2012

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.



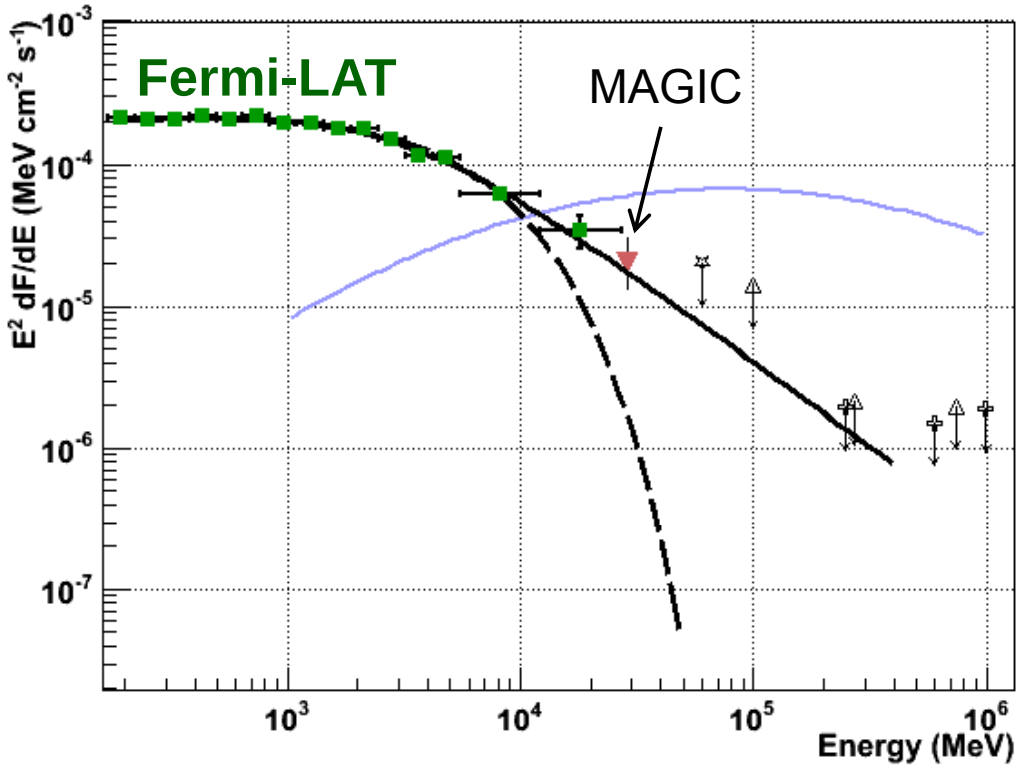
γ-ray Observations of the Pulsar

- **Fermi-LAT (first EGRET):** exquisite measurements around spectral break near few GeV.
- **MAGIC:** detection at 25 GeV (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)

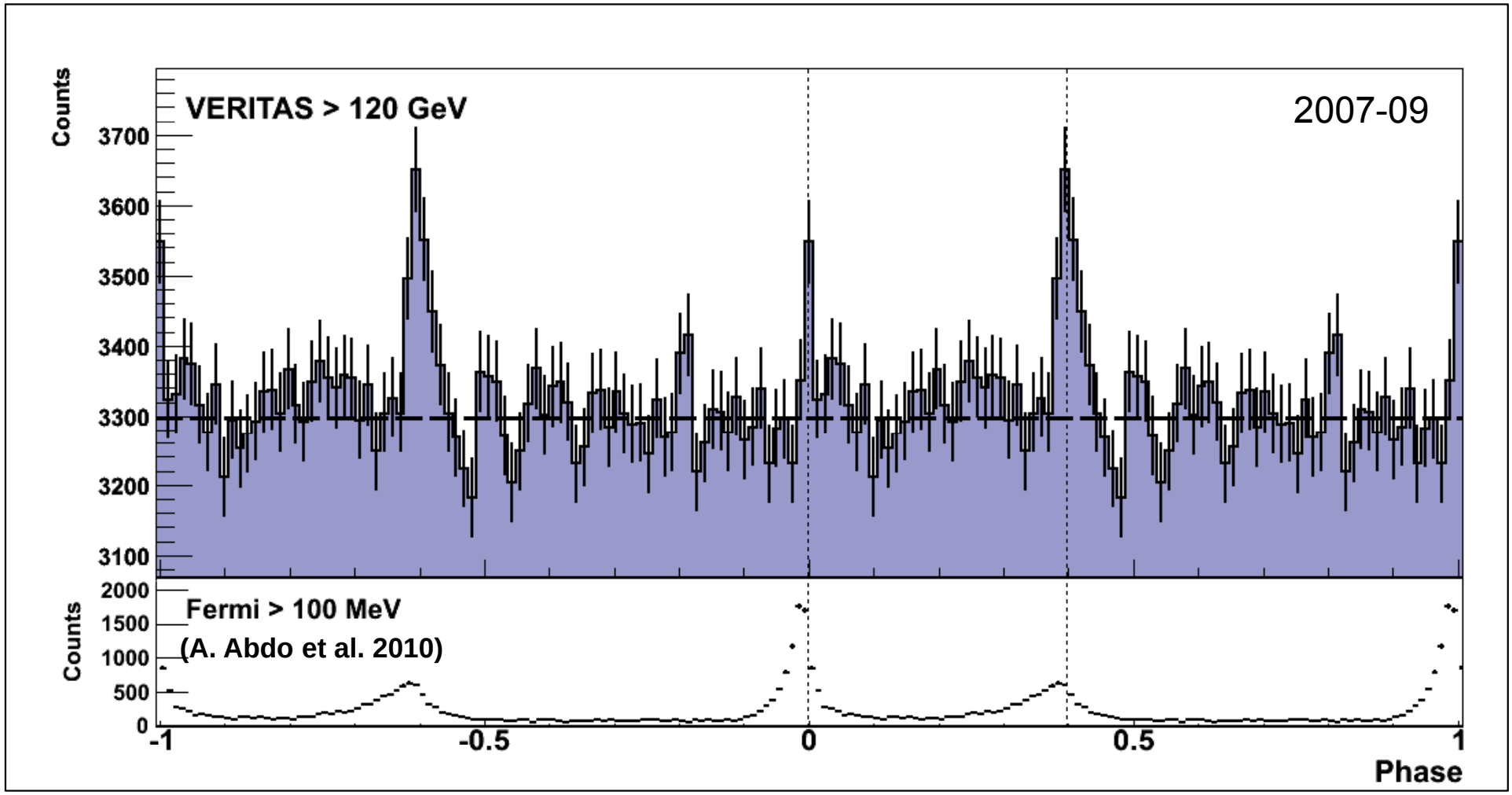
- Special trigger to lower E_{th}.
- Similar pulse profile to EGRET.
- Exponential E_{cutoff} ~ 18 GeV.
- Rule out polar cap model.



Conventional view:

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

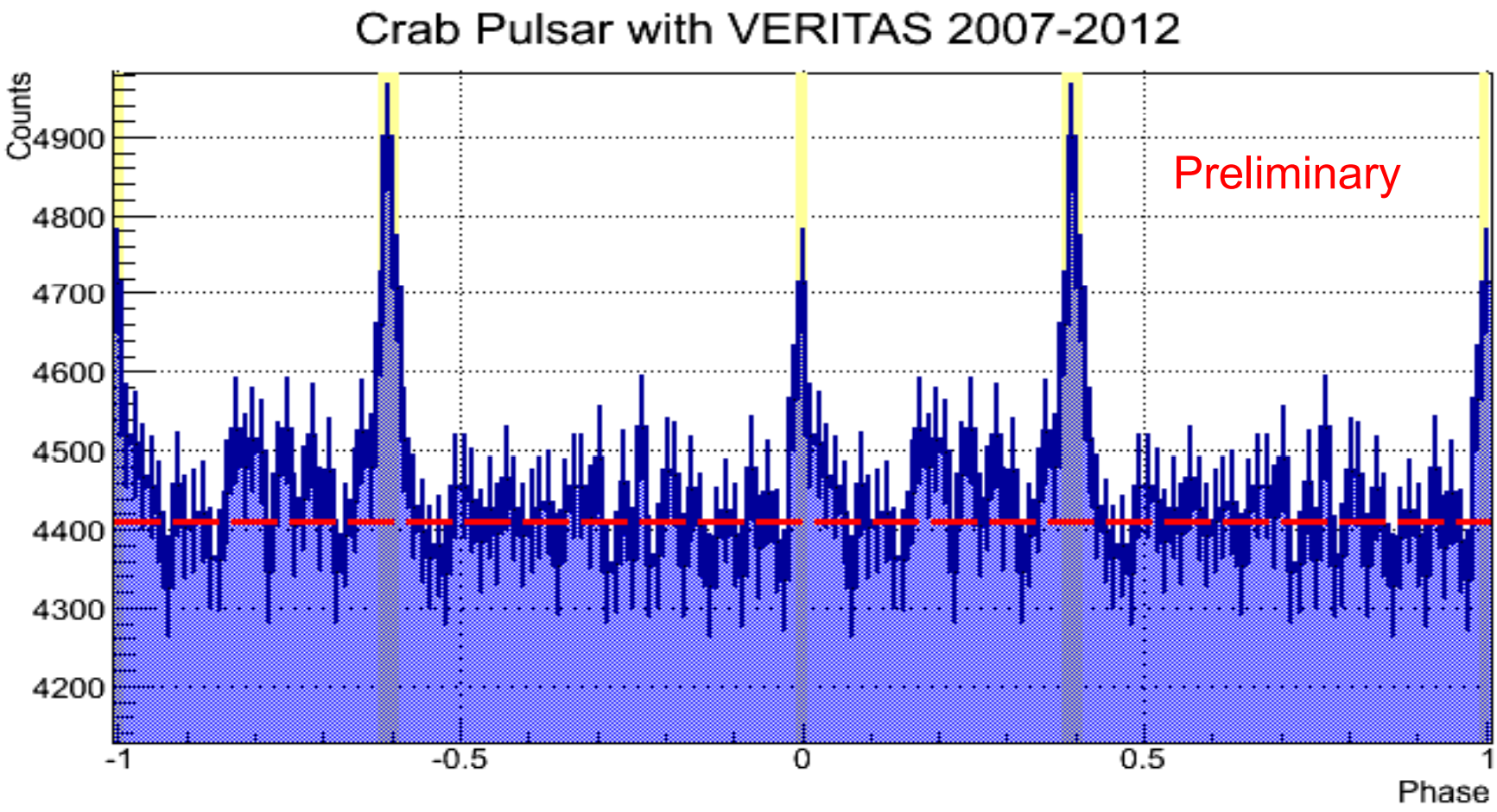
The VERITAS Detection



- 2007-09: 107h → clear two-peak pulsed signal.

E. Aliu et al.,
Science 334, 69 (2011)

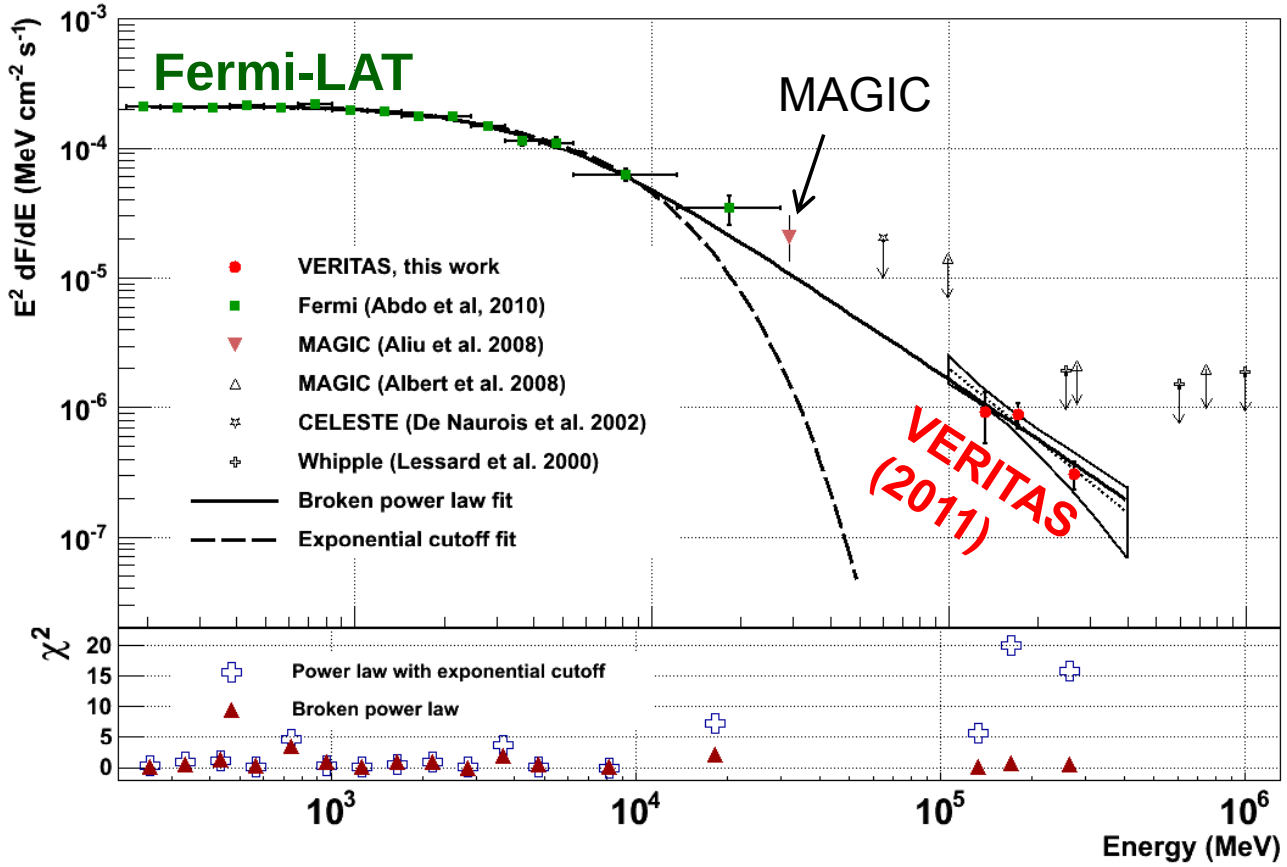
The VERITAS Detection



- 2007-09: 107h → clear two-peak pulsed signal.
- 2007-12, combined data: 130h, 10.7σ.
- 1514 ±145 total pulsed excess events.

E. Aliu et al.,
Science 334, 69 (2011)

The First VHE (E>100 GeV) Pulsar



- VERITAS detection @ 280 GeV → emission region > 10 stellar radii.
- Detection above 100 GeV → curvature radiation not likely dominant .
- Narrowing of pulses → tapered acceleration region ?
- Interesting limits on Lorentz invariance violation.

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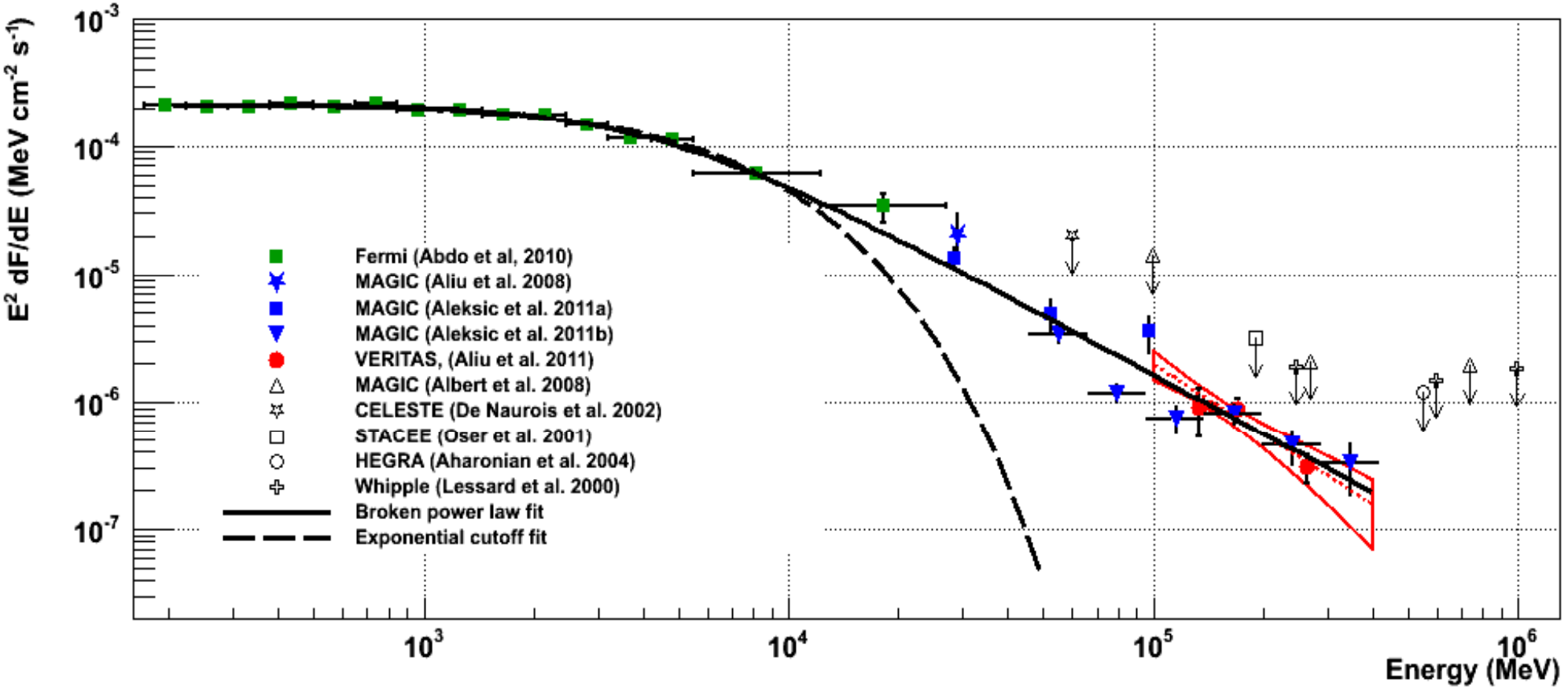


- VERITAS detection @ 280 GeV → emission region > 10 stellar radii.
- Detection above 100 GeV → curvature radiation not likely dominant.
- Narrowing of pulses → tapered acceleration region ?
- Interesting limits on Lorentz invariance violation.
- VERITAS VHE discovery now confirmed by MAGIC.

VERITAS Upgrade 2009-2012

VERITAS began full operations in Fall 2007.
In 2009, process of upgrading VERITAS started.

VERITAS Upgrade Schedule:

Year	Item	Status
2009	Relocation of Telescope 1	Complete
2010	Network Upgrade	Complete
2011	Trigger Upgrade: faster, more flexible telescope trigger.	Complete
2012	**Camera Upgrade: replacement of all 2,000 PMTs with high-QE devices.**	**In Progress Completion: 8/2012**

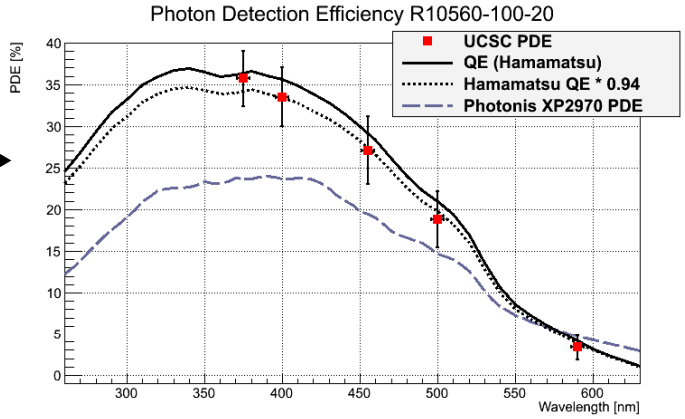
September 2012: Expected start of operations of VERITAS II

VERITAS Camera Upgrade

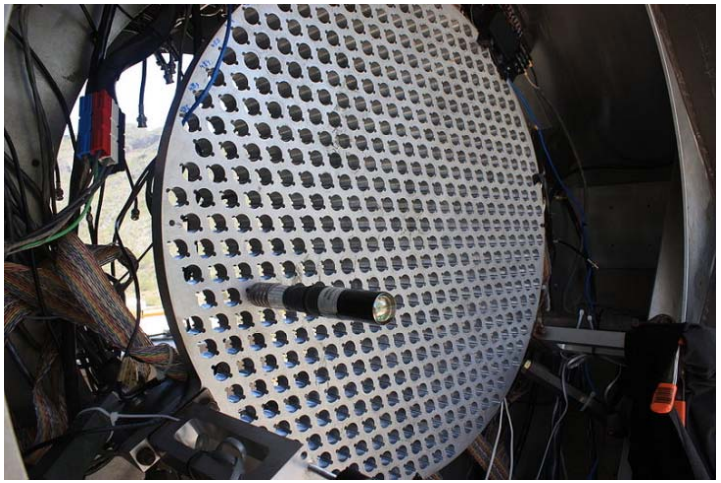
Camera upgrade (2010-2012):

- Replace all pixels with HQE PMTs (Hamamatsu R10560-100 SBA).
- Improved sensitivity and lower E threshold (120 GeV→ 80 GeV) .
- Operational in September 2012.

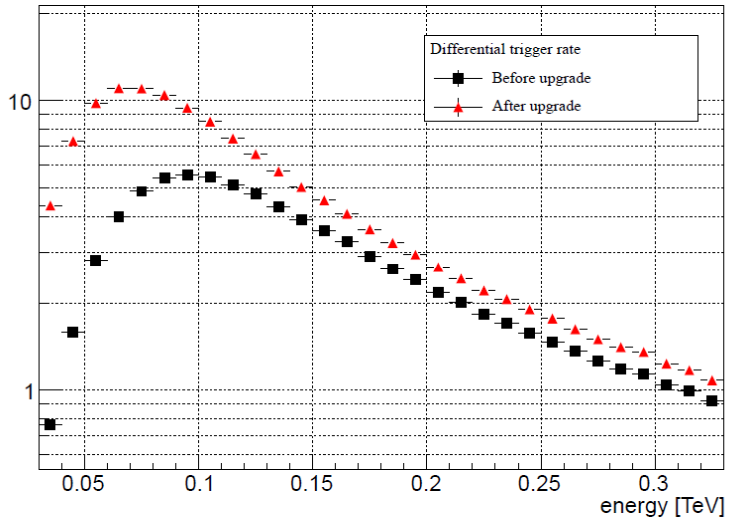
Measured QE/PDE ⟶ (40% increase)



PMT sorting (June 2012)



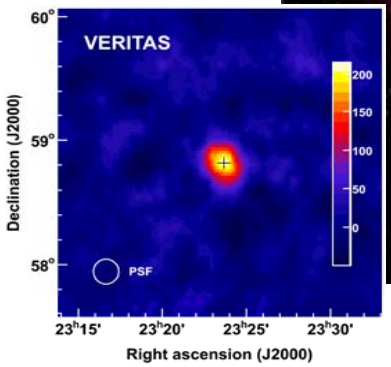
Empty VERITAS camera ! (5 July 2012)

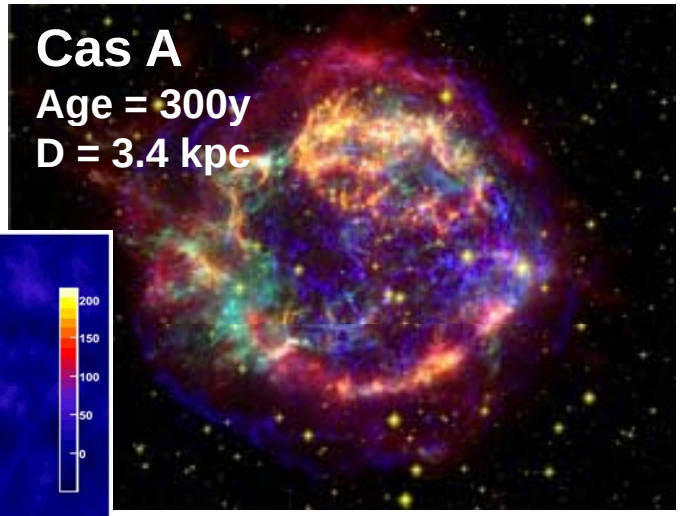


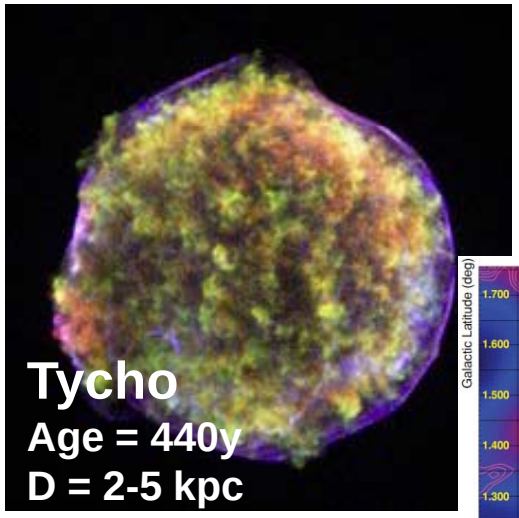
Expected improvement in collection area

Some of the VERITAS SNRs

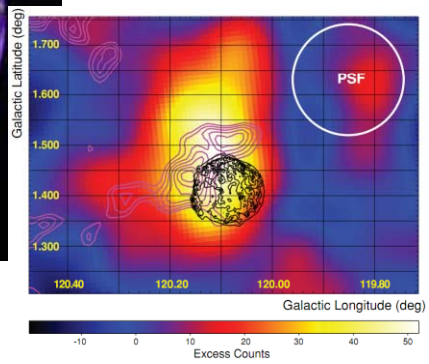
Cas A
~3% Crab

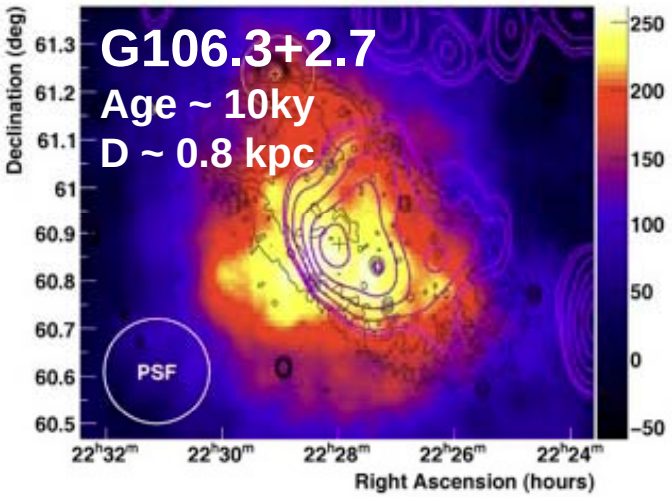






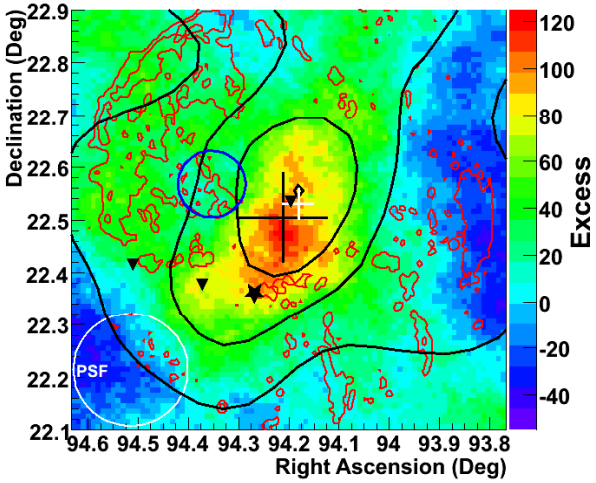
Tycho
~1% Crab

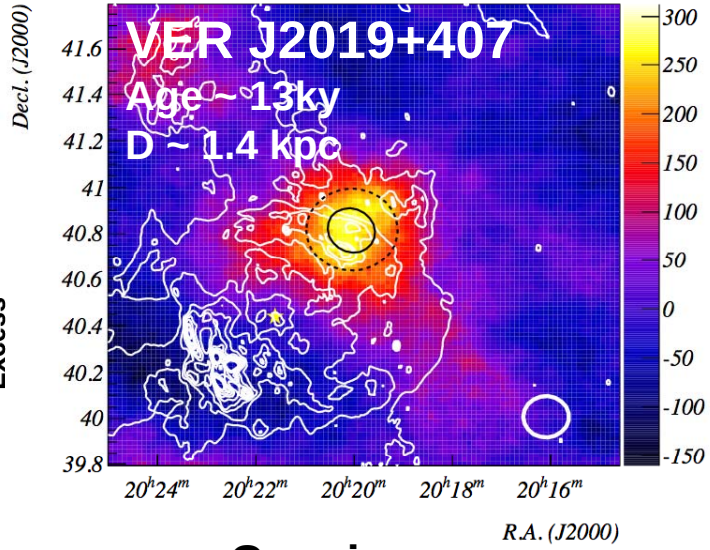




Boomerang

IC 443
Age ~ 30ky
D ~ 0.8kpc





γ-Cygni

Summary

VERITAS: many good results, some have strong bearing on understanding CR origin.

- **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**: new VHE discovery by VERITAS; indicates a likely PWN.
- **LS VI +5 11**: first binary system discovered by VHE observations.
- Cygnus Region: new sources: **VER J2019+407** (γ-cygni) and **VER J2016+372** (CTB 87) neither seen yet by Fermi-LAT. **MGRO J2019** is complex object likely containing multiple sources.
- **Crab Pulsar**: first pulsar detected >100 GeV. Pulse profile is different than lower energies – new understanding of pulsars needed !
- **Upgraded VERITAS II** will lead to a lot more science and more discoveries !