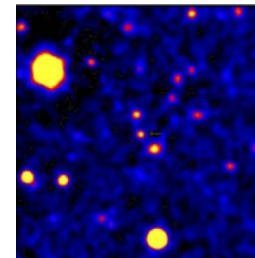
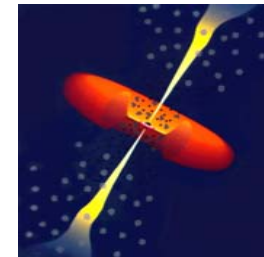
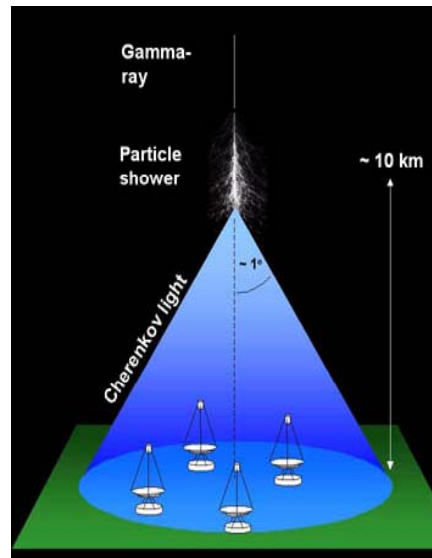
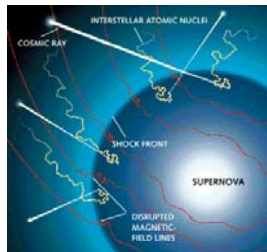
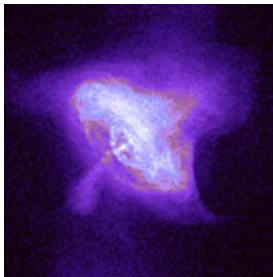


# The Very High-Energy Universe



Rene A. Ong

UCSD Colloquium

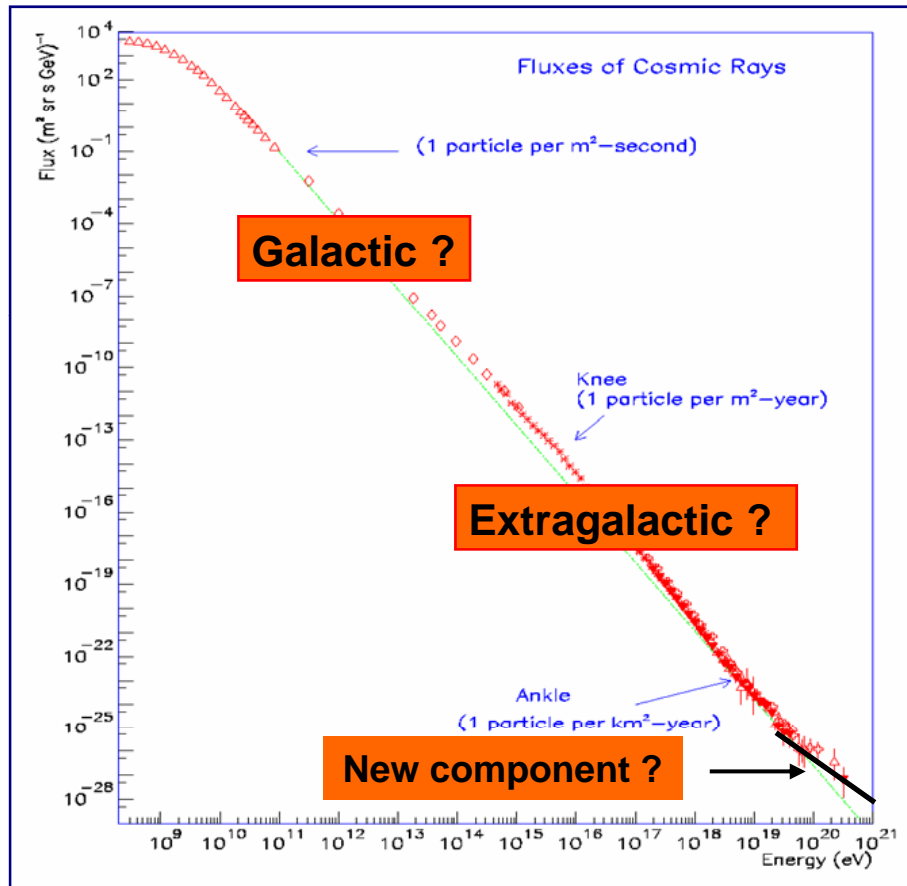
24 May 2007

# Outline

---

- **Scientific Motivation**
  - Origin of cosmic rays
  - A New Astronomy
  - Observational picture
  - Beyond the Standard Models
- **Atmospheric Cherenkov Telescopes**
- **The VERITAS project**
  - Description & operation
  - First results
  - Science Program
- **Summary**

# Origin of Cosmic Rays



**Diffuse, all particle spectrum**

90 year old mystery !

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

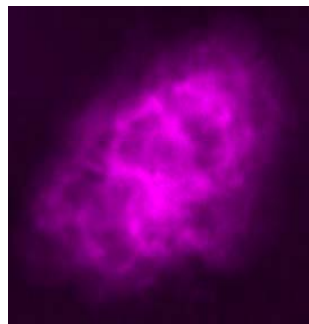
**Neutral messengers**

$\gamma, \nu$   
required to directly observe  
cosmic accelerators.

# A New Astronomy

- Before 1940's – Astronomy only used visible light.
- Since then – Other wavebands (radio, IR, X-ray,  $\gamma$ -ray ... )  
Other particles (CR's,  $\nu$ 's ... )
- And ... **New Wavebands = New Physics**

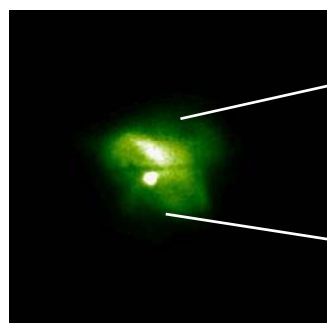
## The Crab Nebula and Pulsar



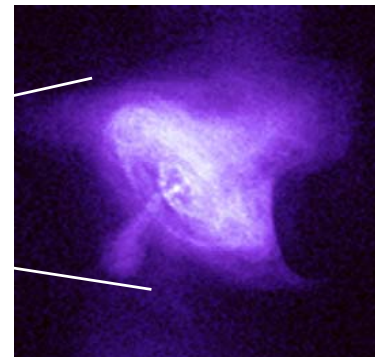
Radio



Visible

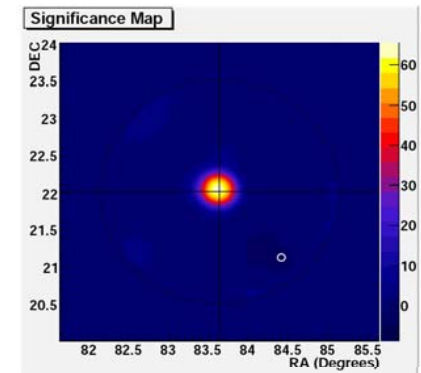


X-ray



Crab Pulsar

X-ray



Crab Nebula

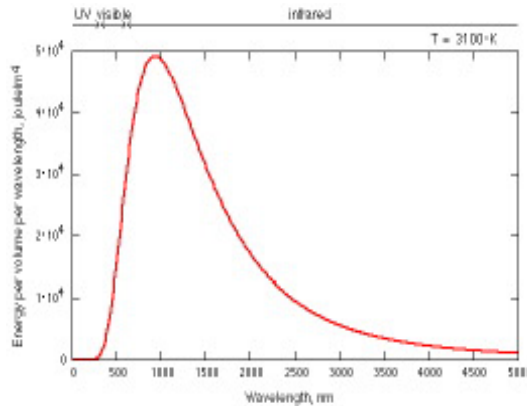
TeV  $\gamma$ -ray

# Producing & Detecting $\gamma$ -rays

## 1. How do we even produce such extreme energies ?

Thermal Universe  $E < 10$  KeV

Non-thermal Universe  $E > 10$  KeV



Blackbody  
Spectrum

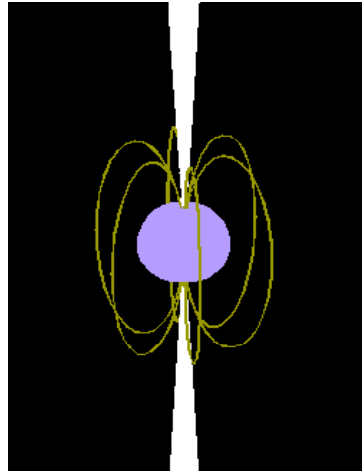


Accelerator  
or  
New Physics

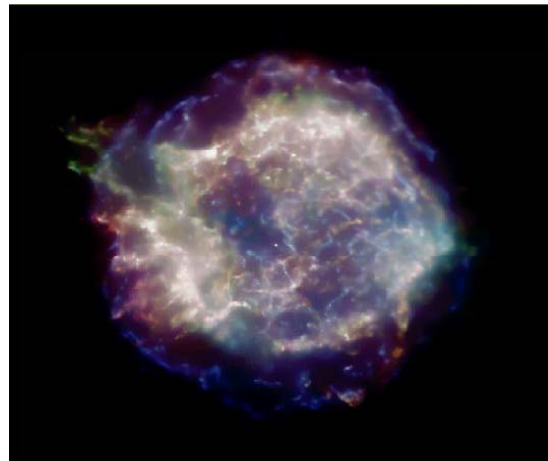
## 2. How do we even detect such extreme energies ?

Answer: Can only detect by total absorption.

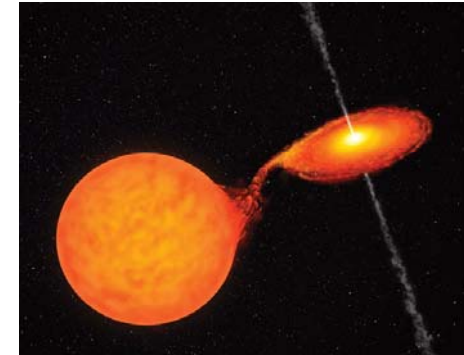
# Galactic Sources



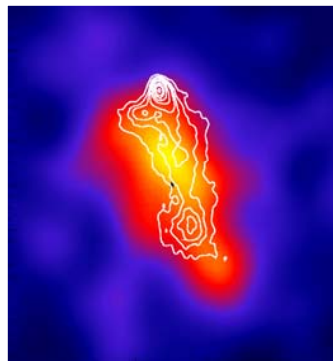
**Pulsars**



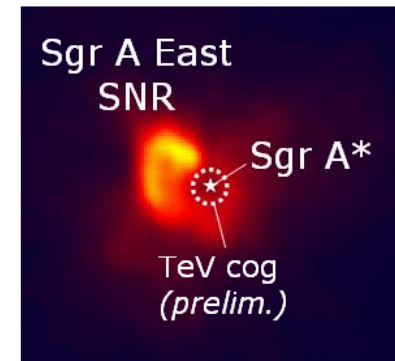
**Supernova Remnants (SNRs)**



**Microquasars**



**Pulsar Nebulae**

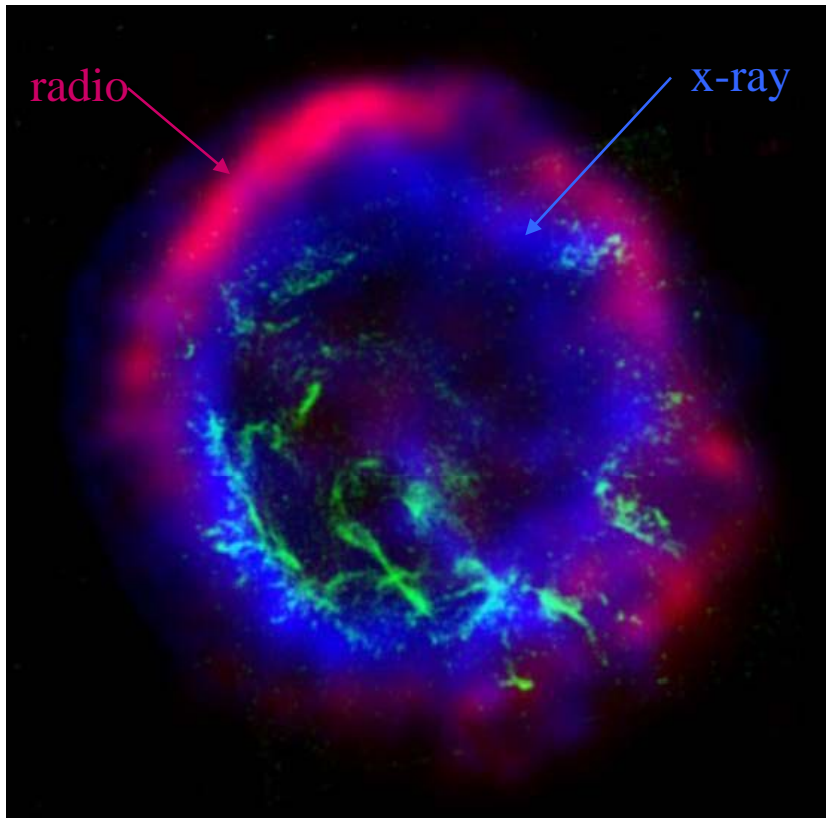


**Galactic Center**

**All these are now known  
HE  $\gamma$ -ray sources.**

# Supernova Remnants (SNRs)

---



SNR E102

- Collapse of massive star.
- Shell expands and shock front forms as it sweeps up material from ISM.
- Acceleration of particles via canonical Fermi process.
- In  $\sim 10^4$  yrs, blast wave begins to decelerate and slowly dissipate.

SNRs are thought to produce the bulk of the cosmic rays.  
Clear confirmation still missing.

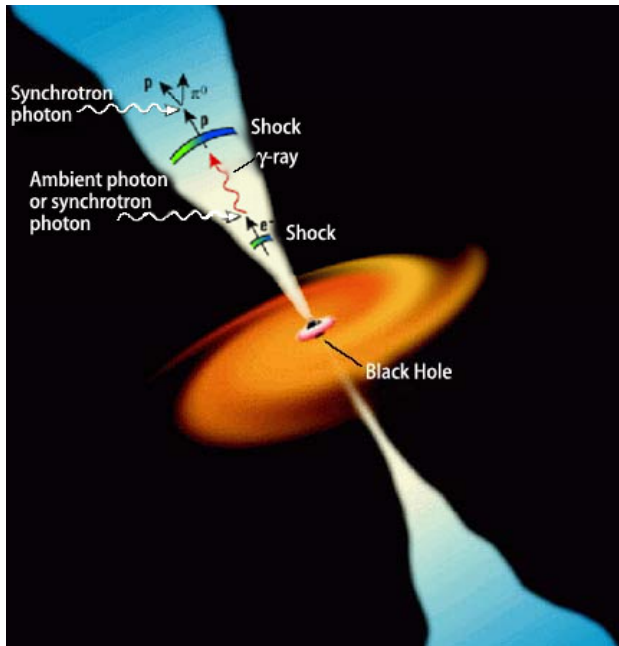
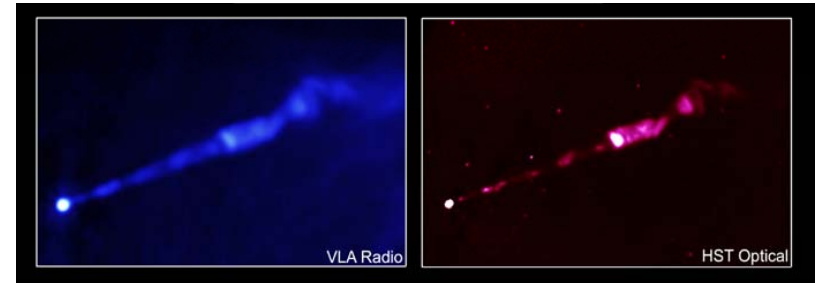


# Extragalactic Sources

New view of the Universe → Many Surprises

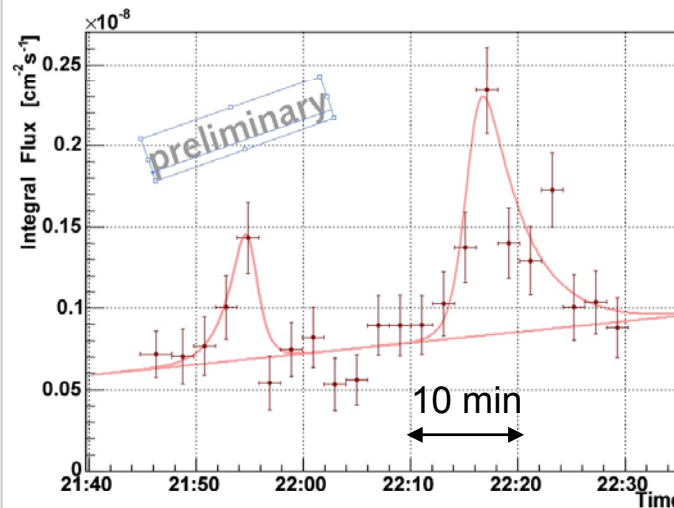
**M87 Jet**

Example: Active Galactic Nuclei (AGN)



**Supermassive BHs  
Jets beamed towards us**

Markarian 501 Flares



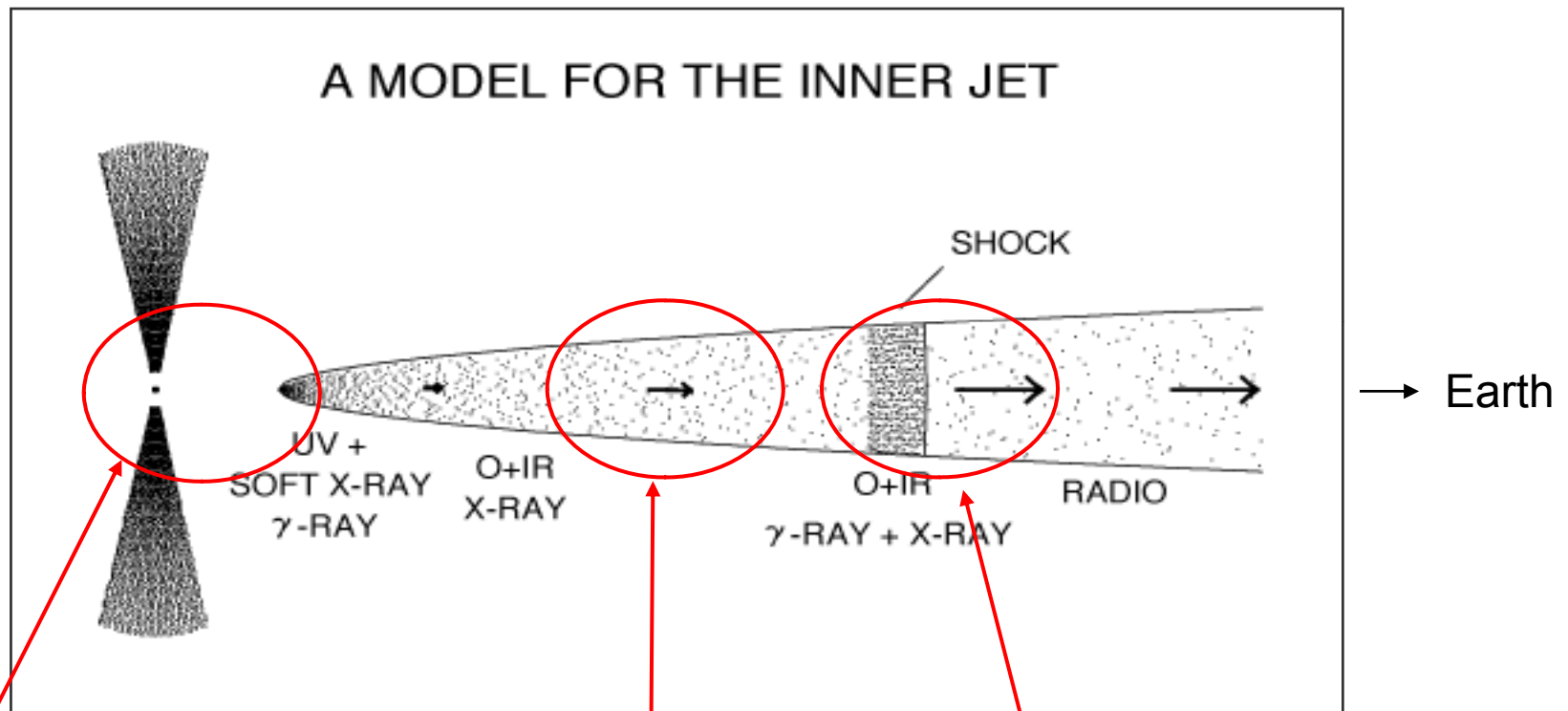
**Remarkable variability**



**Central BH**



# Understanding AGN



How do Jets form  
& what powers them?

Nature of beam:  
energetics  $\Gamma$   
particle type: e or p  
field strengths  $B, \gamma$

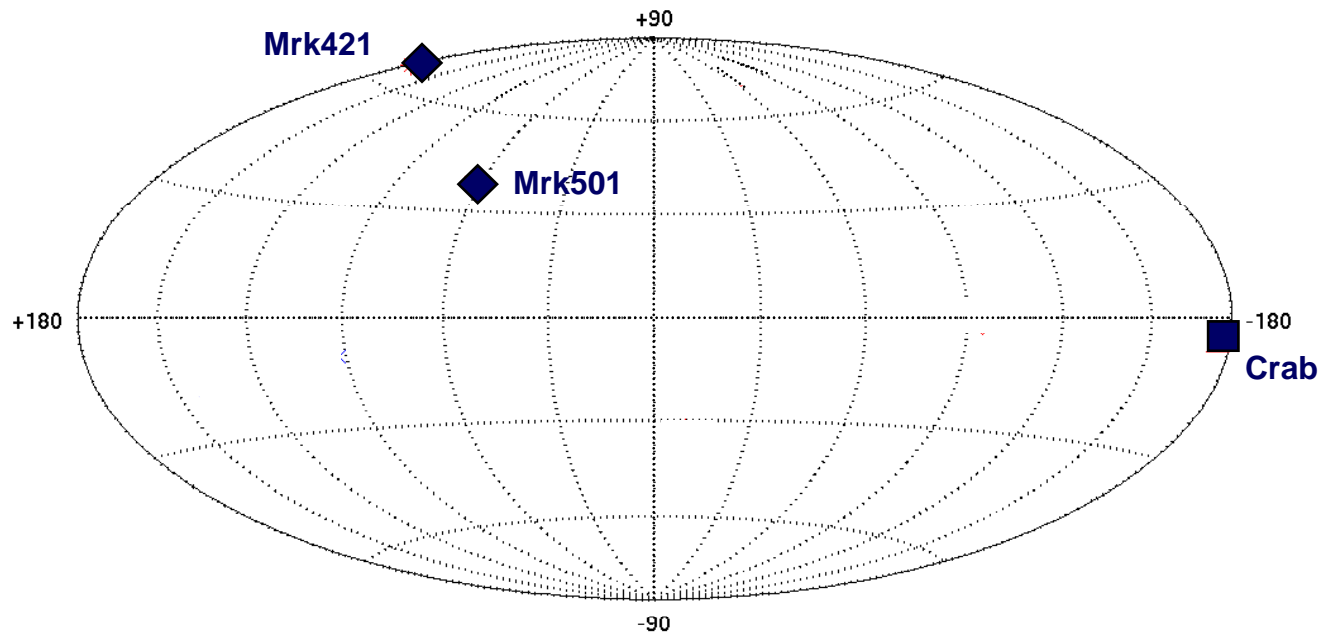
Geometry & External:  
emission zones  
source of soft photons

---

# OBSERVATIONAL PICTURE

# The VHE Sky - 1995

3 sources



■ Pulsar Nebula

◆ AGN

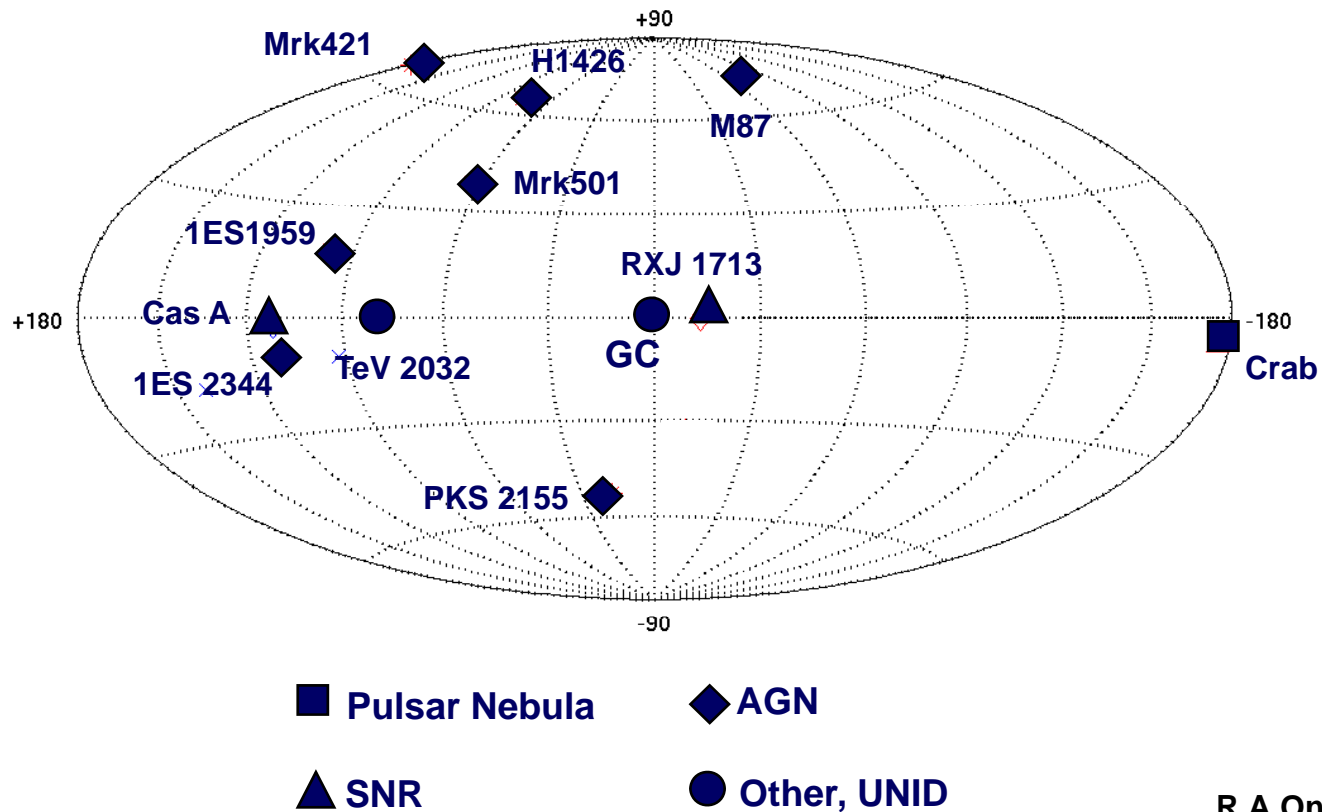
▲ SNR

● Other, UNID

R.A.Ong  
Sep 2005

# The VHE Sky - 2003

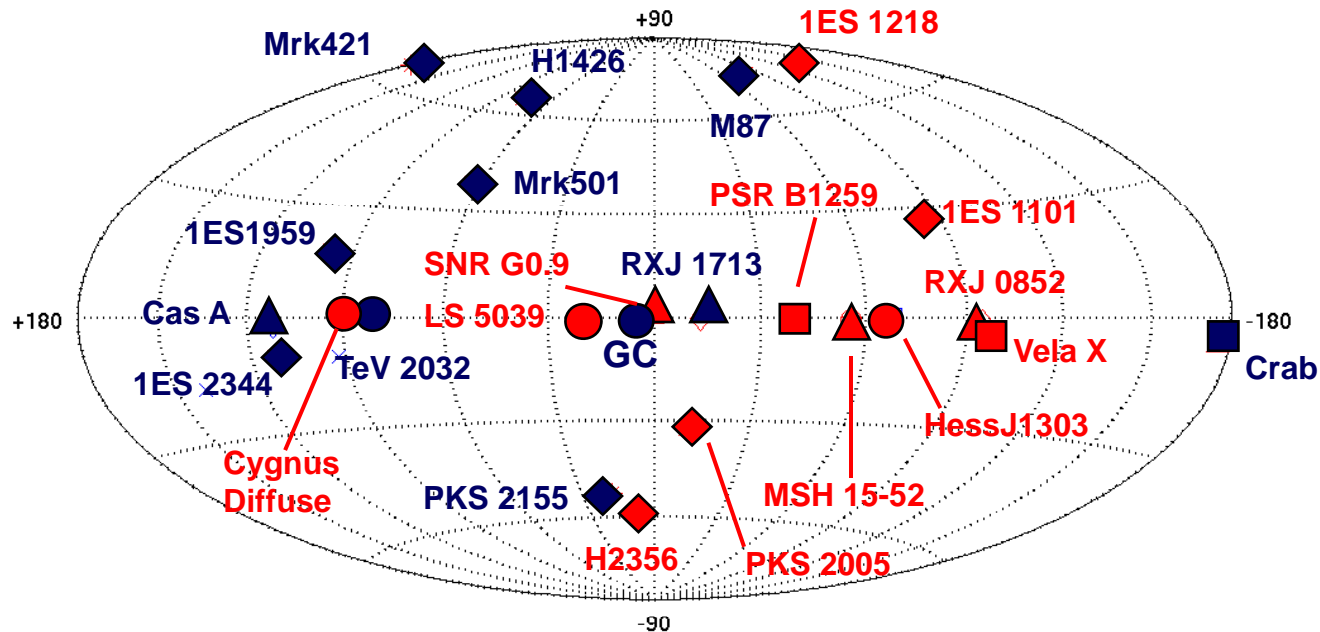
12 sources



R.A.Ong  
Sep 2005

# The VHE Sky - 2006

30+ sources  
and counting ...

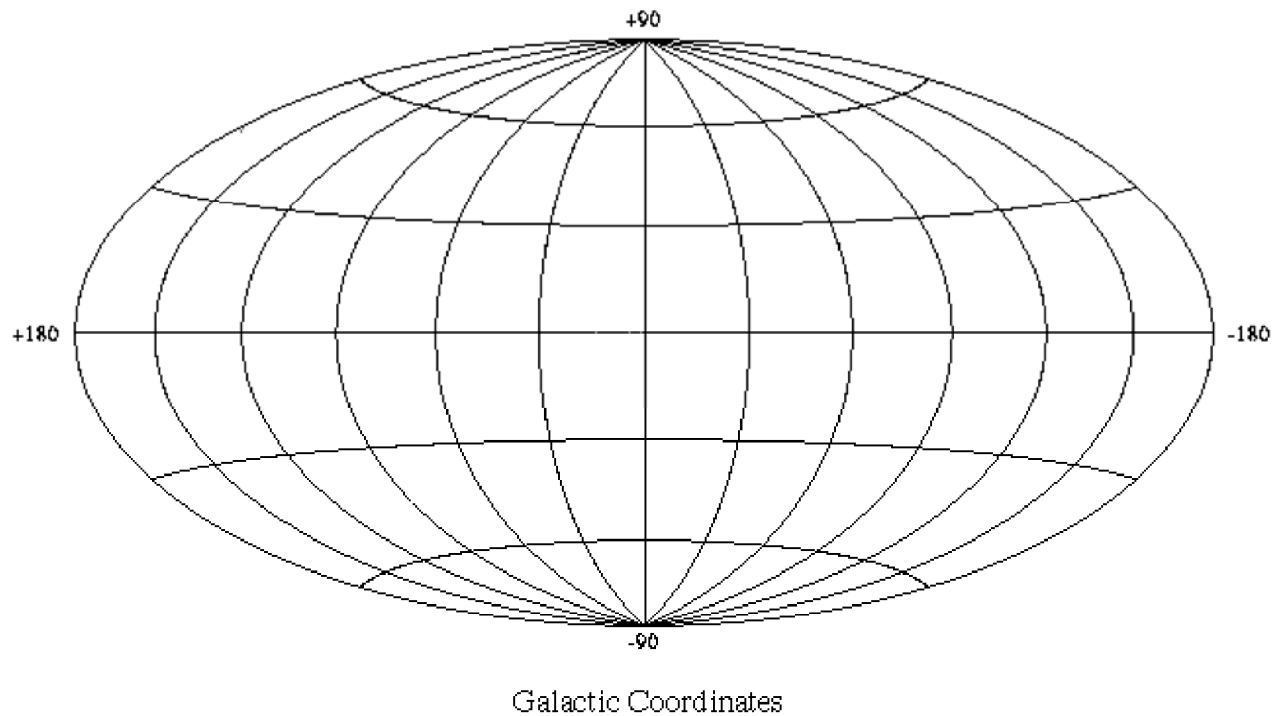


- Pulsar Nebula
- ◆ AGN
- ▲ SNR
- Other, UNID

R.A.Ong  
Sep 2005

# High-Energy Neutrino Sky

---



- No sources yet.

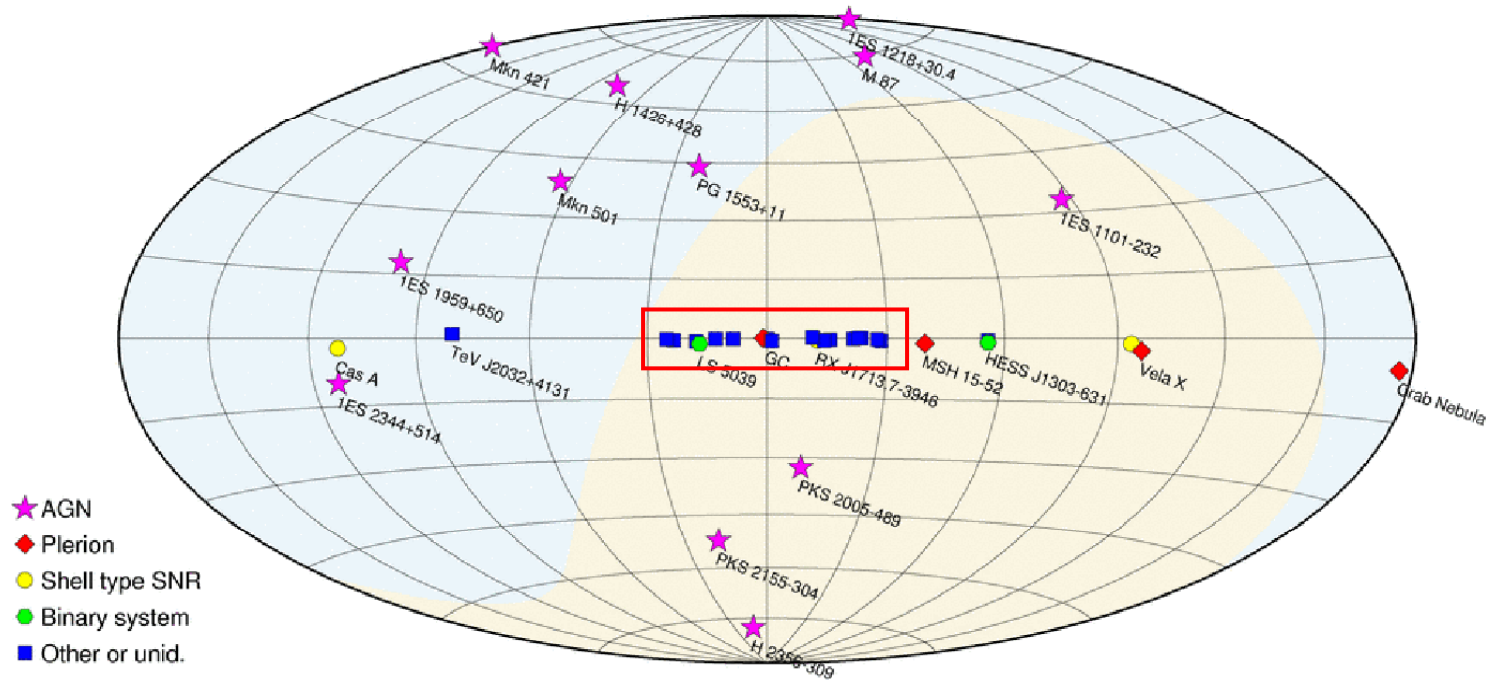
# The VHE Sky - 2006

## TeV Gamma-Ray sky in 2006

39 sources ( $E > 100$  GeV)

(Galactic coordinates)

29 discovered since 2003  
27 are Galactic



Background colours indicating northern / southern sky

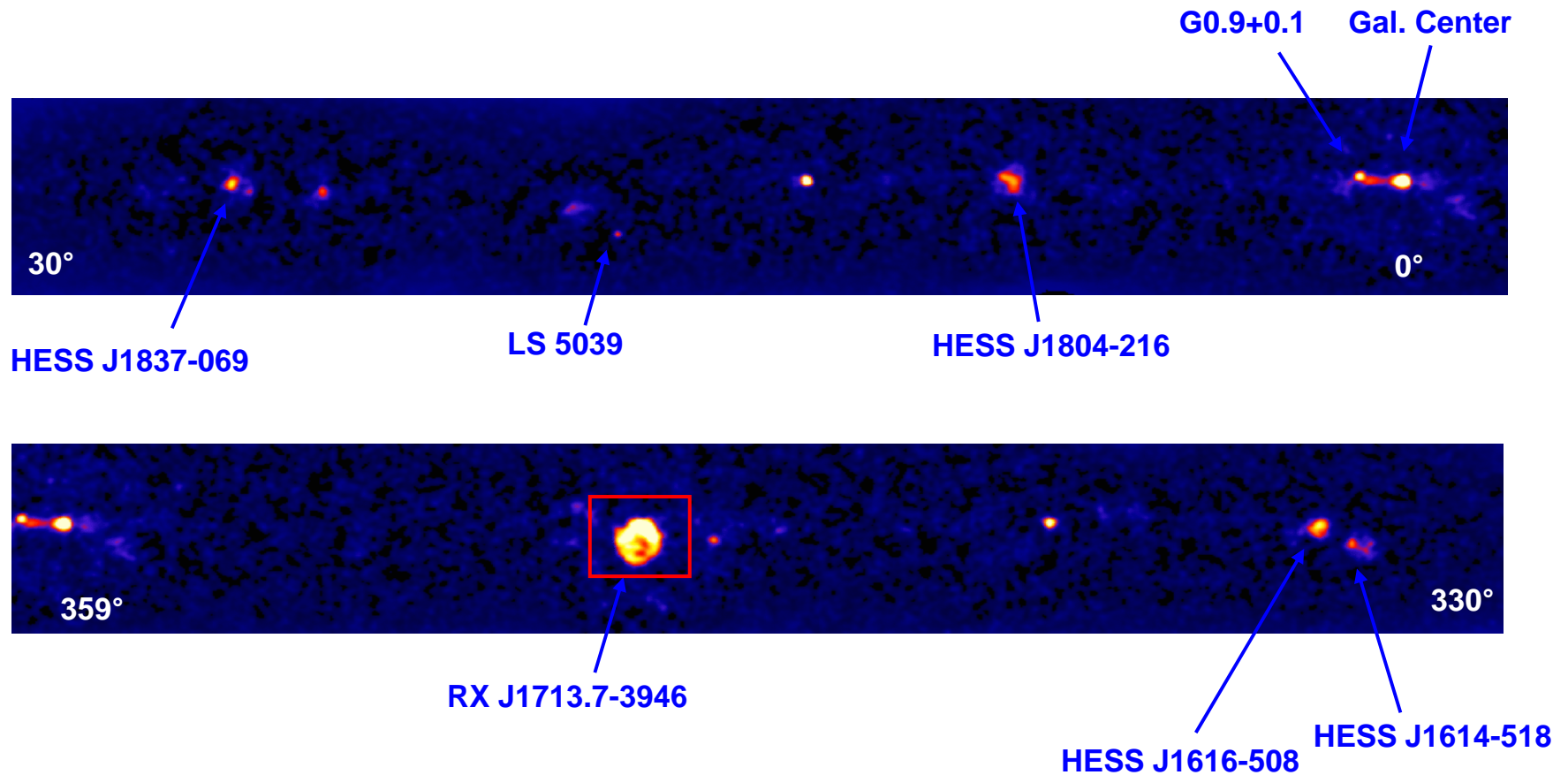
(Hermann 2006)



# HESS Galactic Plane Survey

HESS Telescope (Namibia) 2003-2005

> 25 new sources discovered – many unidentified !



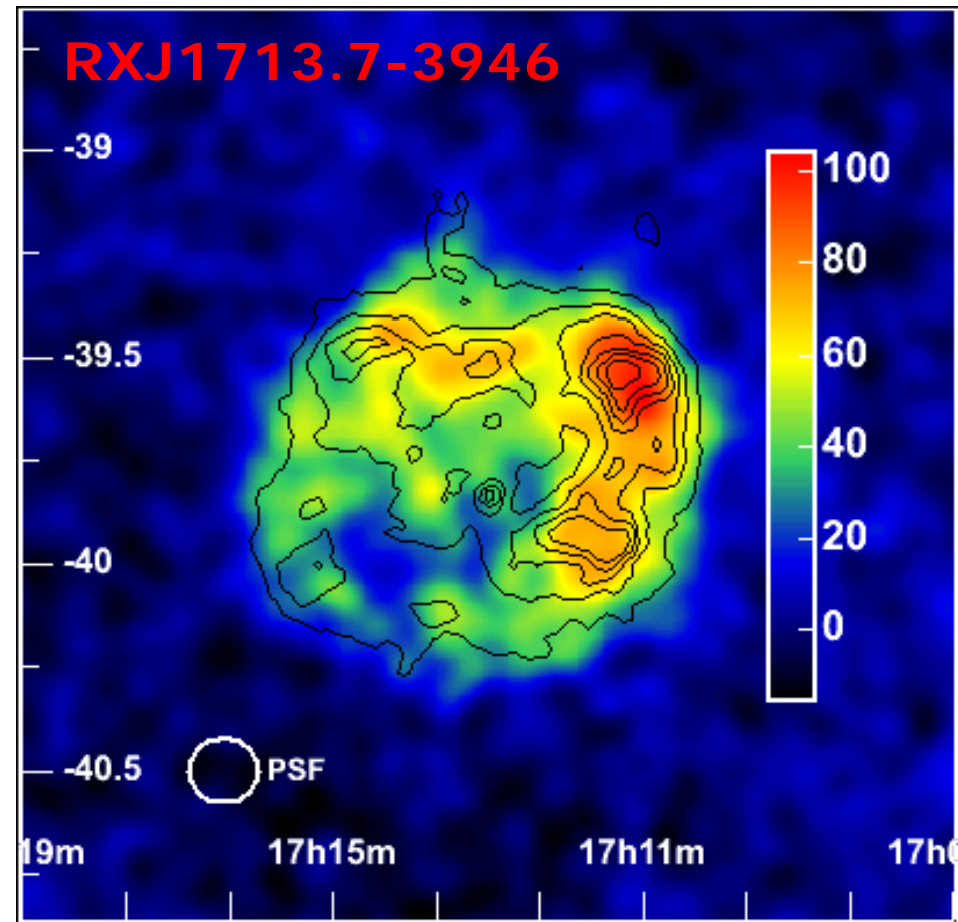
# SNR RXJ 1713-3946

## HESS Observations

- Very Extended source
- Spectrally resolved image
- Good correlation with X-rays.

This and other detections support picture of CR acceleration.

... but... not fully established.  
VERITAS will study SNRs in northern hemisphere.



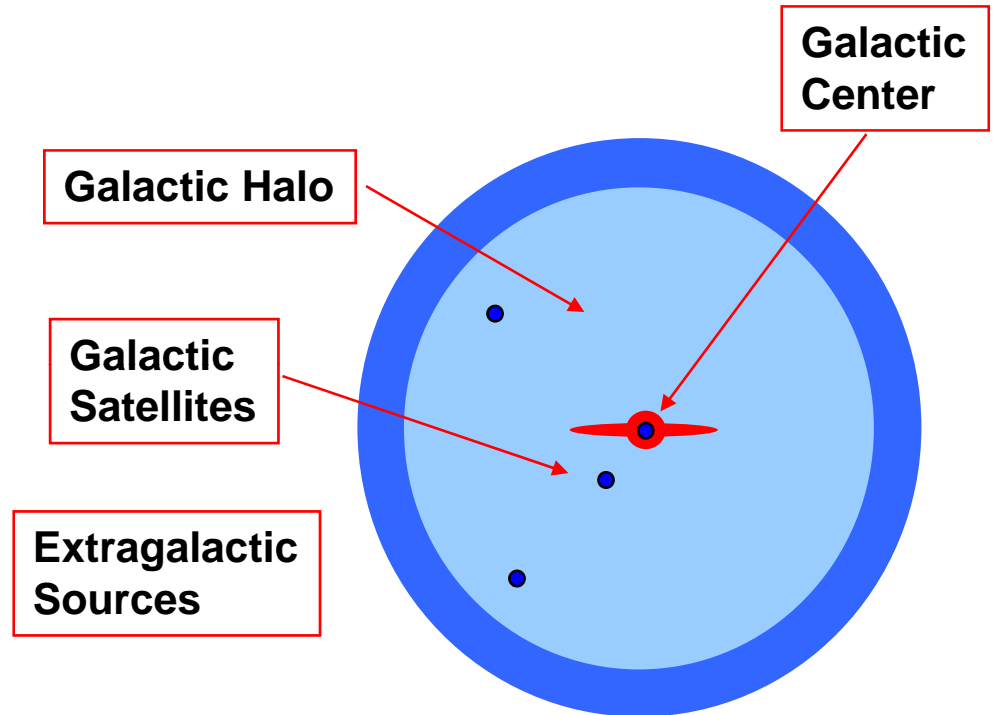
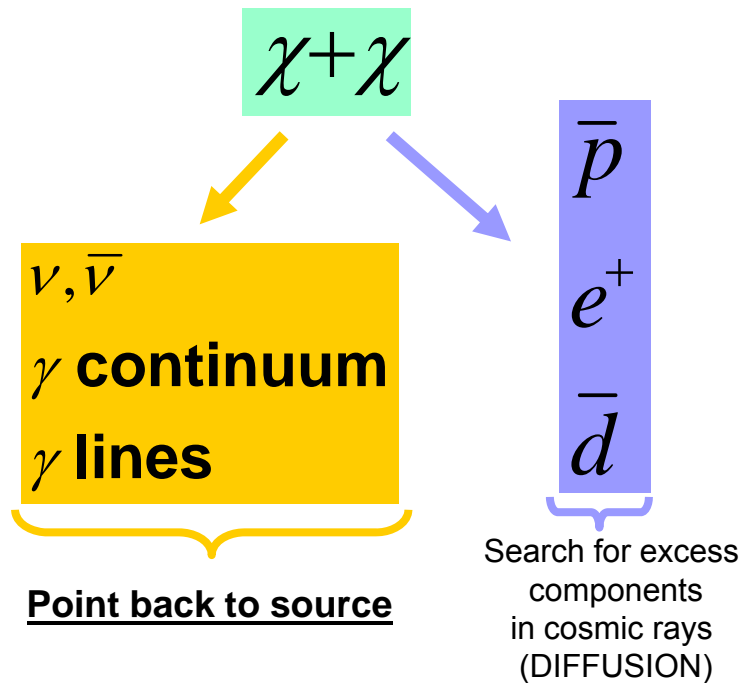
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# Beyond the Standard Models

# Dark Matter & SUSY

Hypothesis: DM = WIMPs

- High WIMP density in certain locations.
- WIMP annihilation  $\rightarrow \gamma, \nu$  etc.



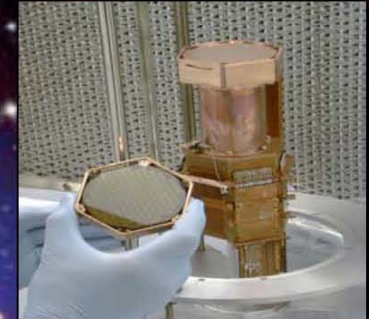
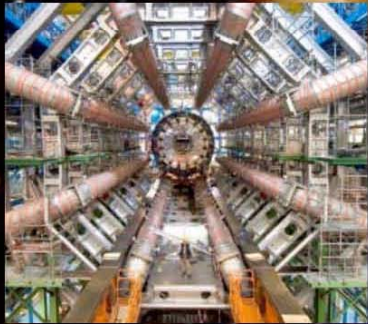
**Complementary approach to direct detection & LHC.  
(e.g. Baltz et al., Hooper et al., Baer & Profumo ...)**



# The Hunt for Dark Matter

## A Symposium on Collider, Direct and Indirect Searches

Fermilab May 10-12, 2007



Registration

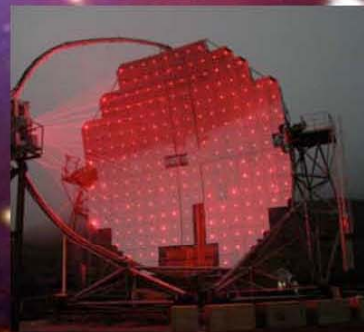
Program

Plenary speakers

Organizers

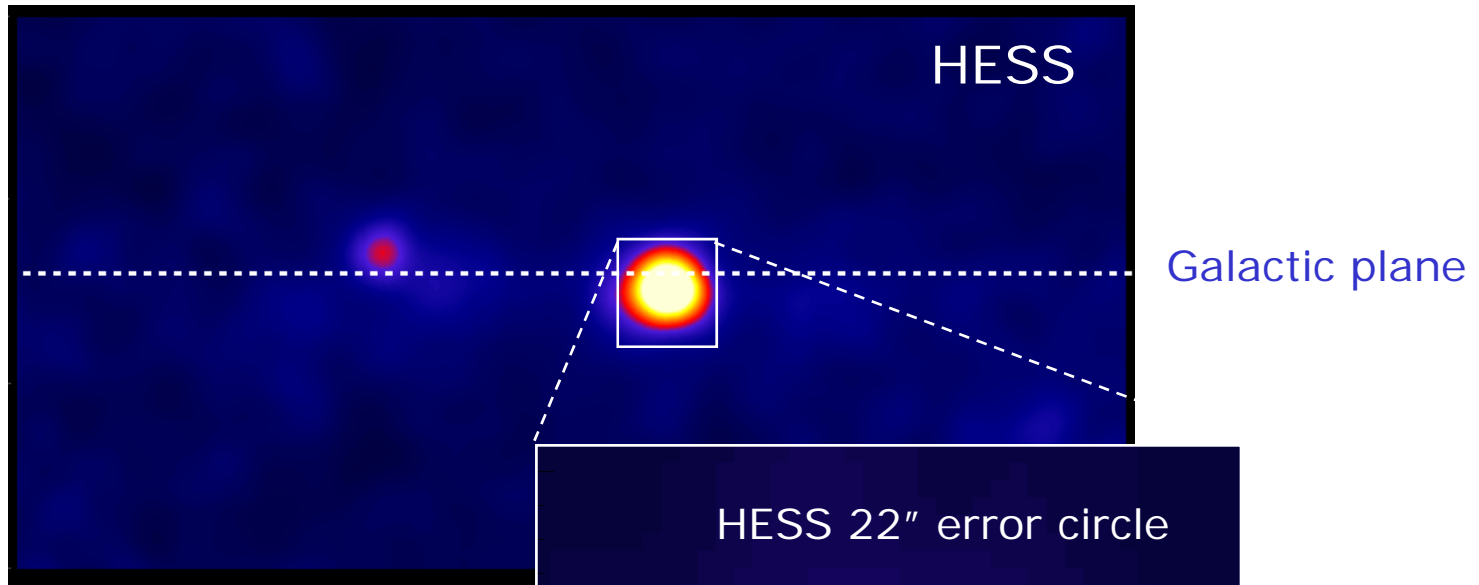
Sponsors

Participants



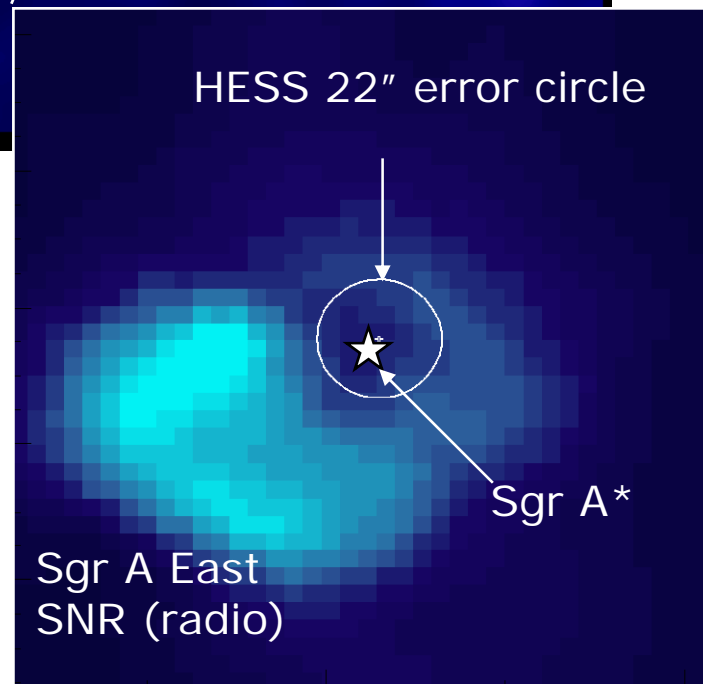
Hosted by the Fermilab Center for Particle-Astrophysics

# The Galactic Center



Galactic Center is a strong source of TeV  $\gamma$ -rays ...

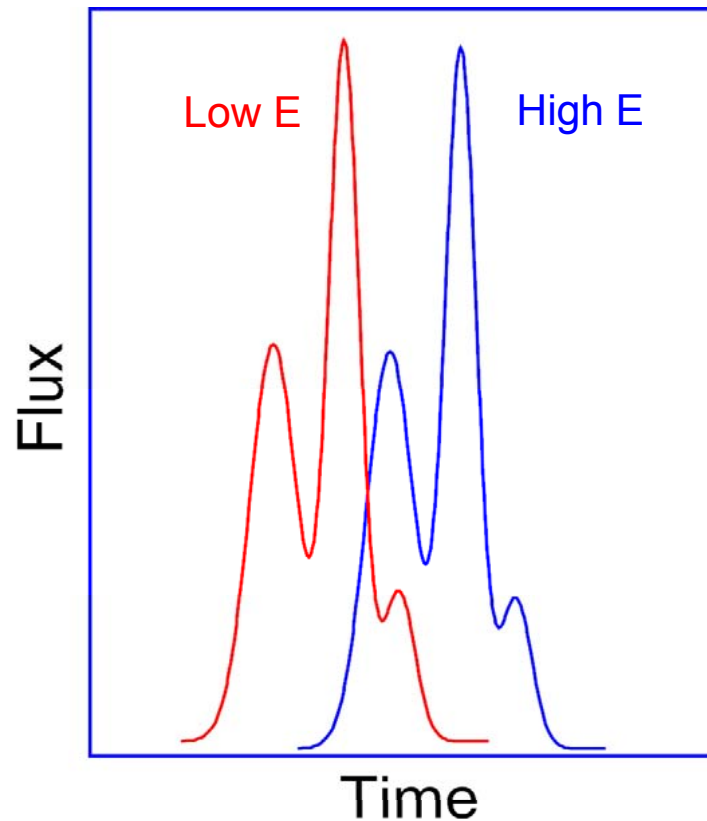
**is it dark matter ?**



# Fundamental Physics

---

## Lorentz invariance violation



Quantum gravity “foam” of space time.

- Variation in  $c$ .
- Requires long distances and high energies.

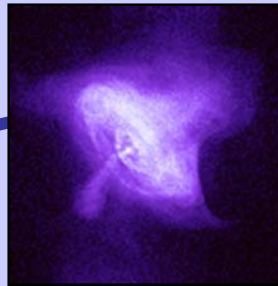
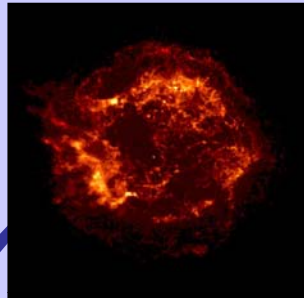
**See article by Lee Smolin  
in Nov 2006 Physics Today.**



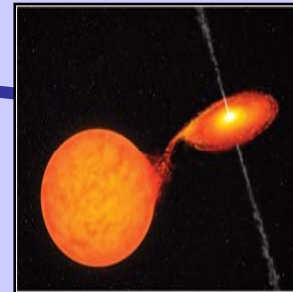
# VHE $\gamma$ -ray Science

Origin of Cosmic Rays

SNRs

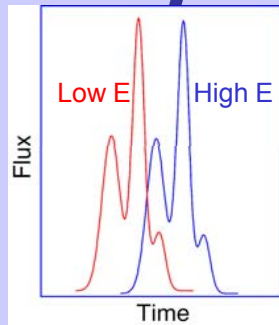
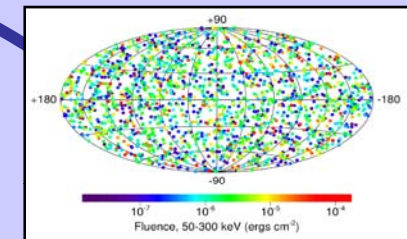


Pulsars

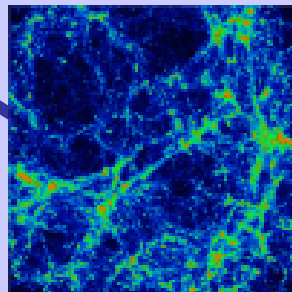


Microquasars

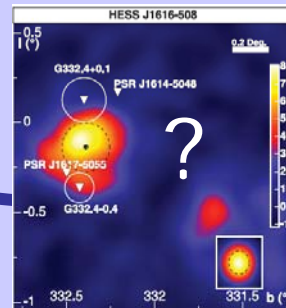
Gamma-Ray Bursts



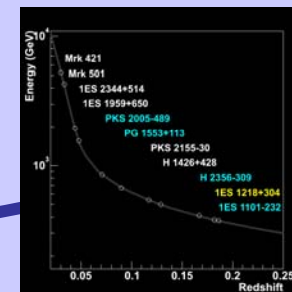
Testing Lorentz Invariance



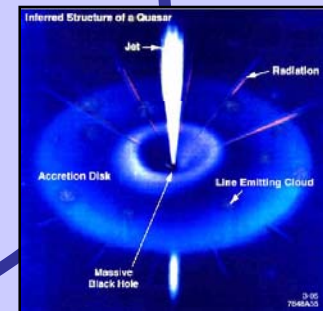
Cold Dark Matter



Something New !



cosmological  $\gamma$ -Ray Horizon



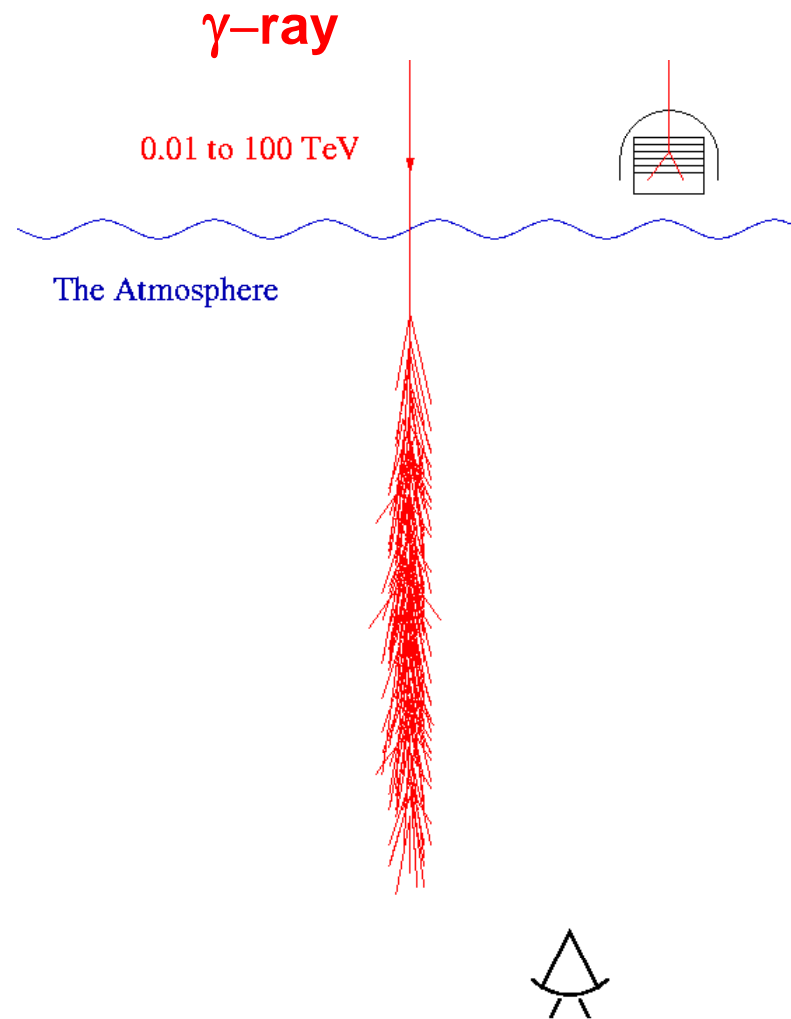
AGN

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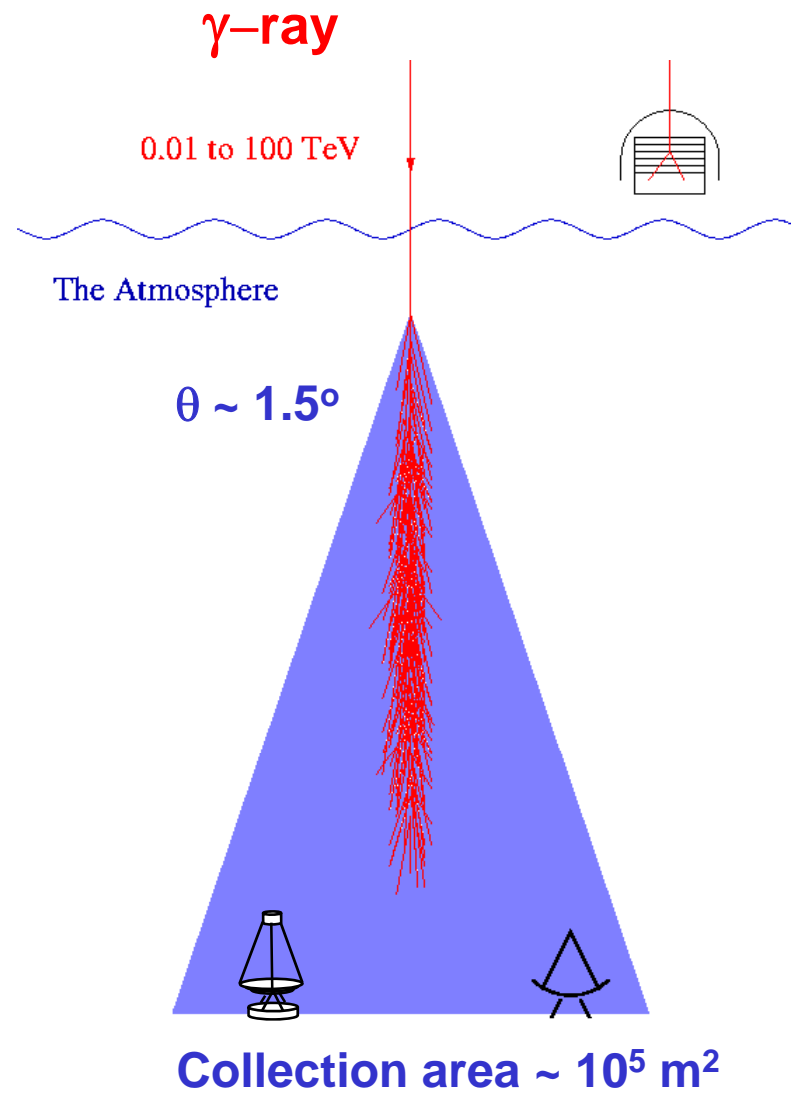
# Experimental Technique

# Air Showers

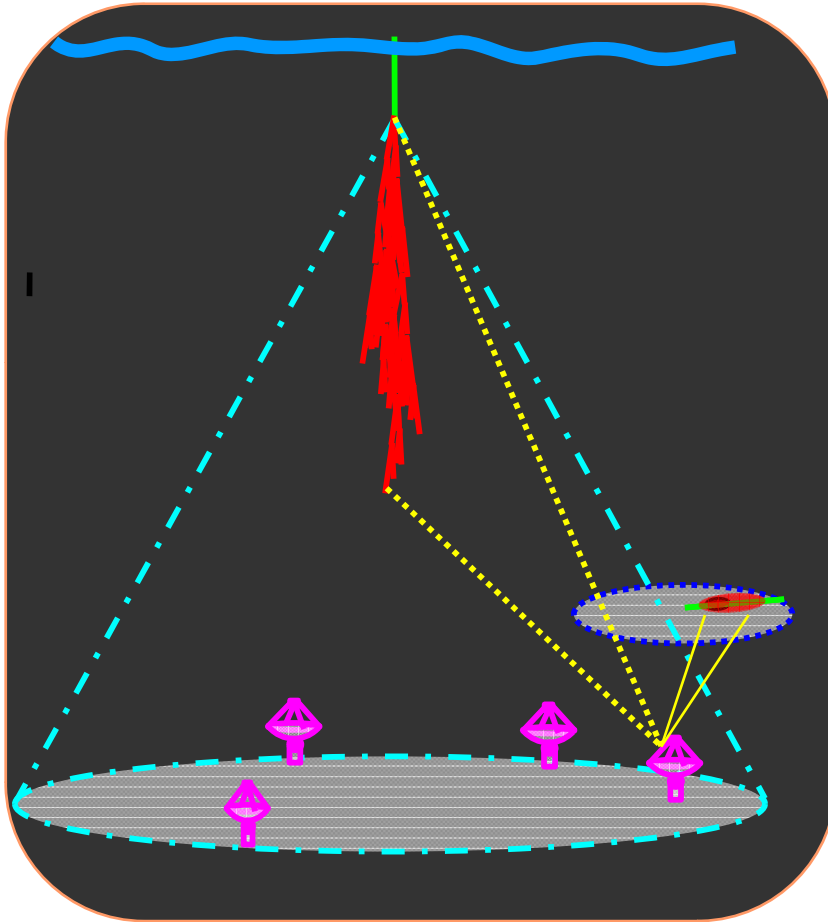
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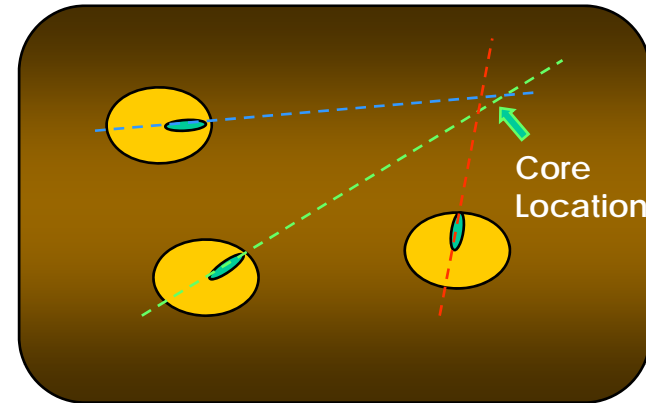
# Cherenkov Telescopes



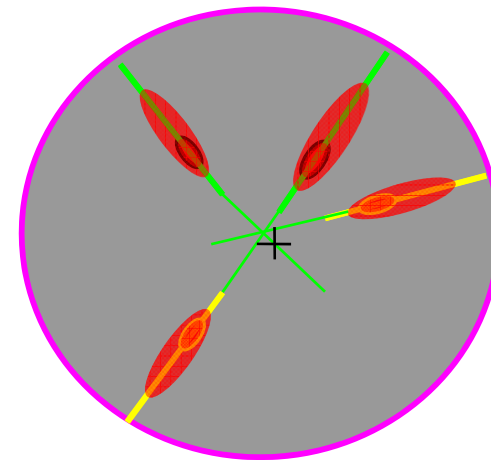
# Cherenkov Telescope Arrays



Very large collection area ( $>10^4 \text{ m}^2$ )  
Stereoscopic viewing



Core Reconstruction ( $< 15\text{m}$ )



Direction Reconstruction ( $< 0.1^\circ$ )

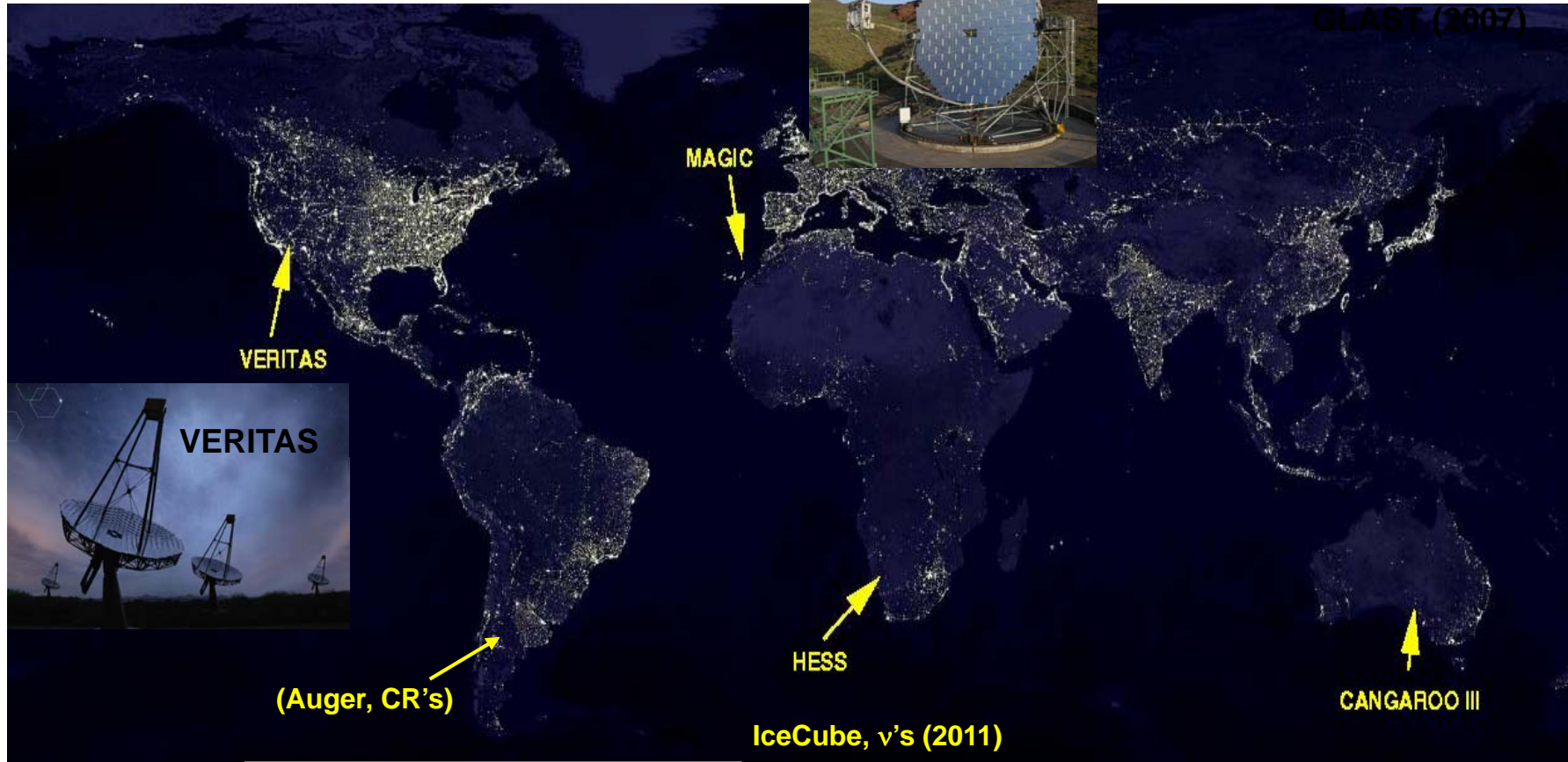
# Major New VHE Telescopes



GLAST (2007)



MAGIC



VERITAS

MAGIC

HESS

CANGAROO III

IceCube, v's (2011)

(Auger, CR's)



VERITAS



HESS



CANGAROO



# GLAST Satellite Telescope

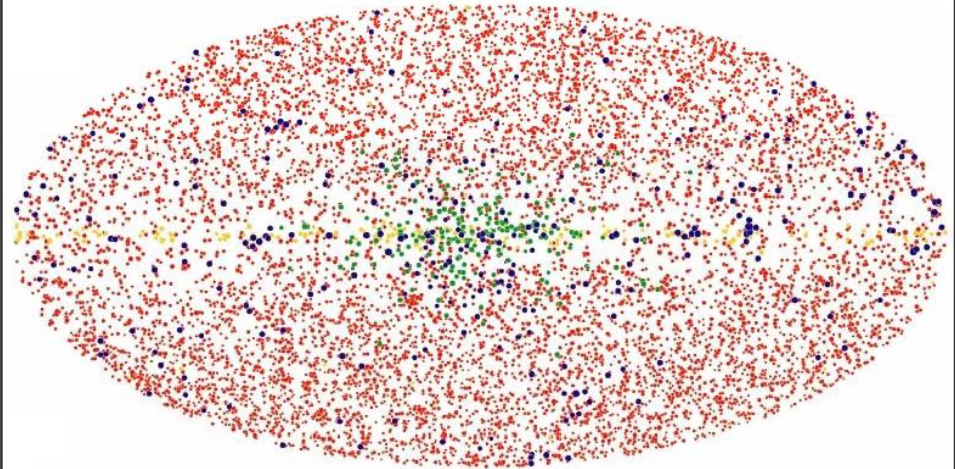


## GLAST LAT Instrument:

- Si-strip tracker
- CsI calorimeter
- Anti-coincidence veto

## Extensive LAT Catalog

$5\sigma$  Sources from Simulated  
One Year All-sky Survey



Results of one-year  
all-sky survey.  
(Total: 9900 sources)

● AGN  
● 3EG Catalog

● Galactic Halo  
● Galactic Plane

**Simulated sky map from 1 year survey.**

**Launch in late 2007.**

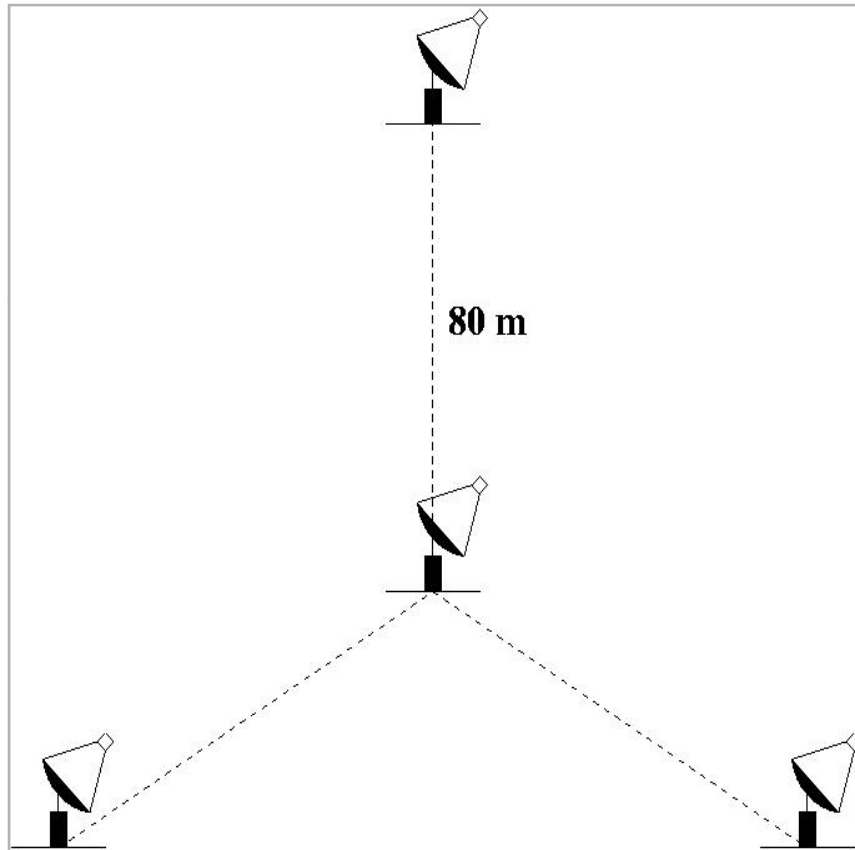


# VERITAS



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

# VERITAS Design



## Detector Design:

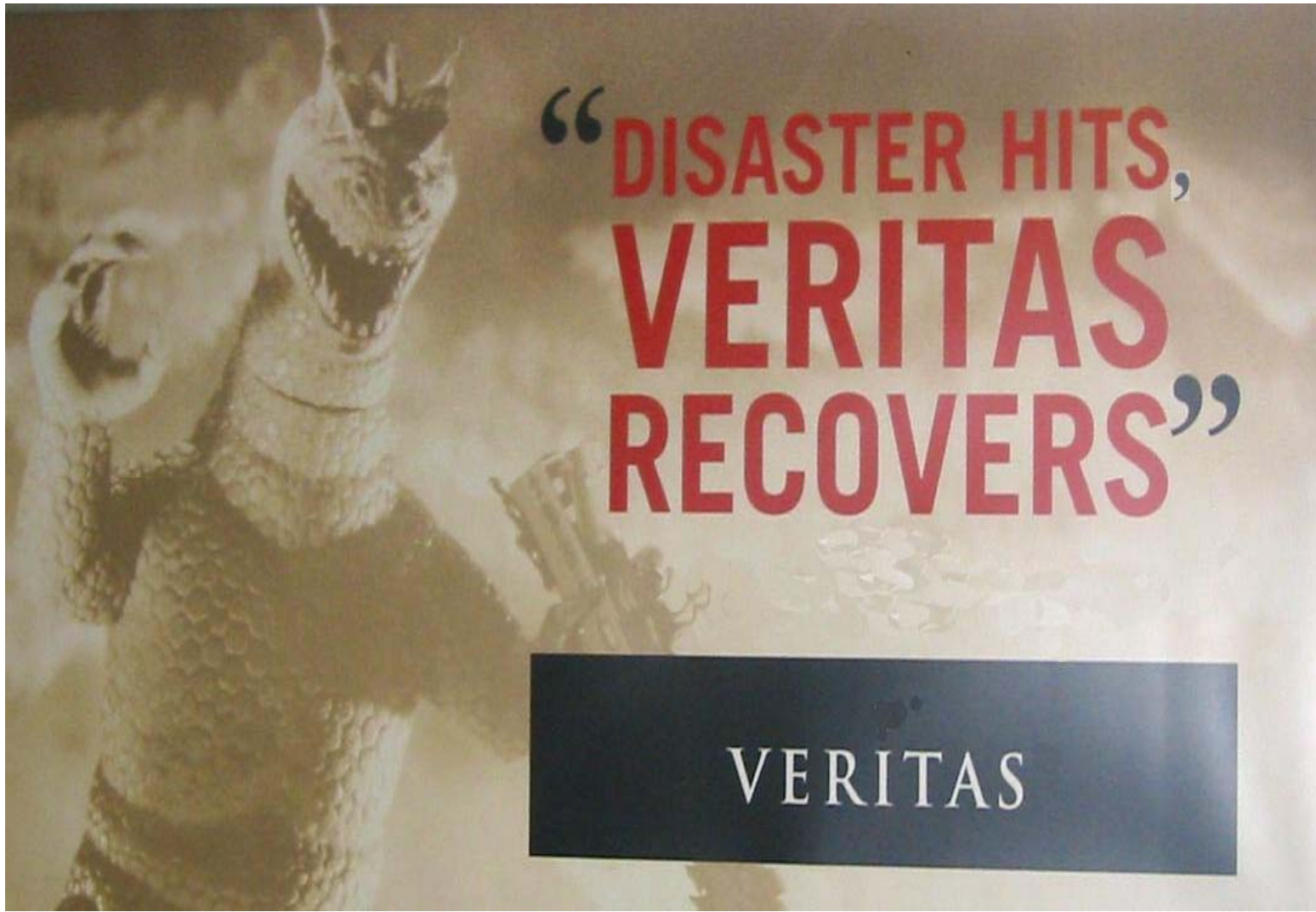
- Four 12m telescopes.
- 500 pixel cameras ( $3.5^\circ$ ).
- Site in southern Az (1300m)
- Fully operational in 2007.

## Performance:

- Energy threshold  $\sim 100$  GeV.
- Ang. resolution  $\sim 4\text{-}6'$ .
- Detect Crab Nebula in  $<60$  s.

# Bumps in the Road

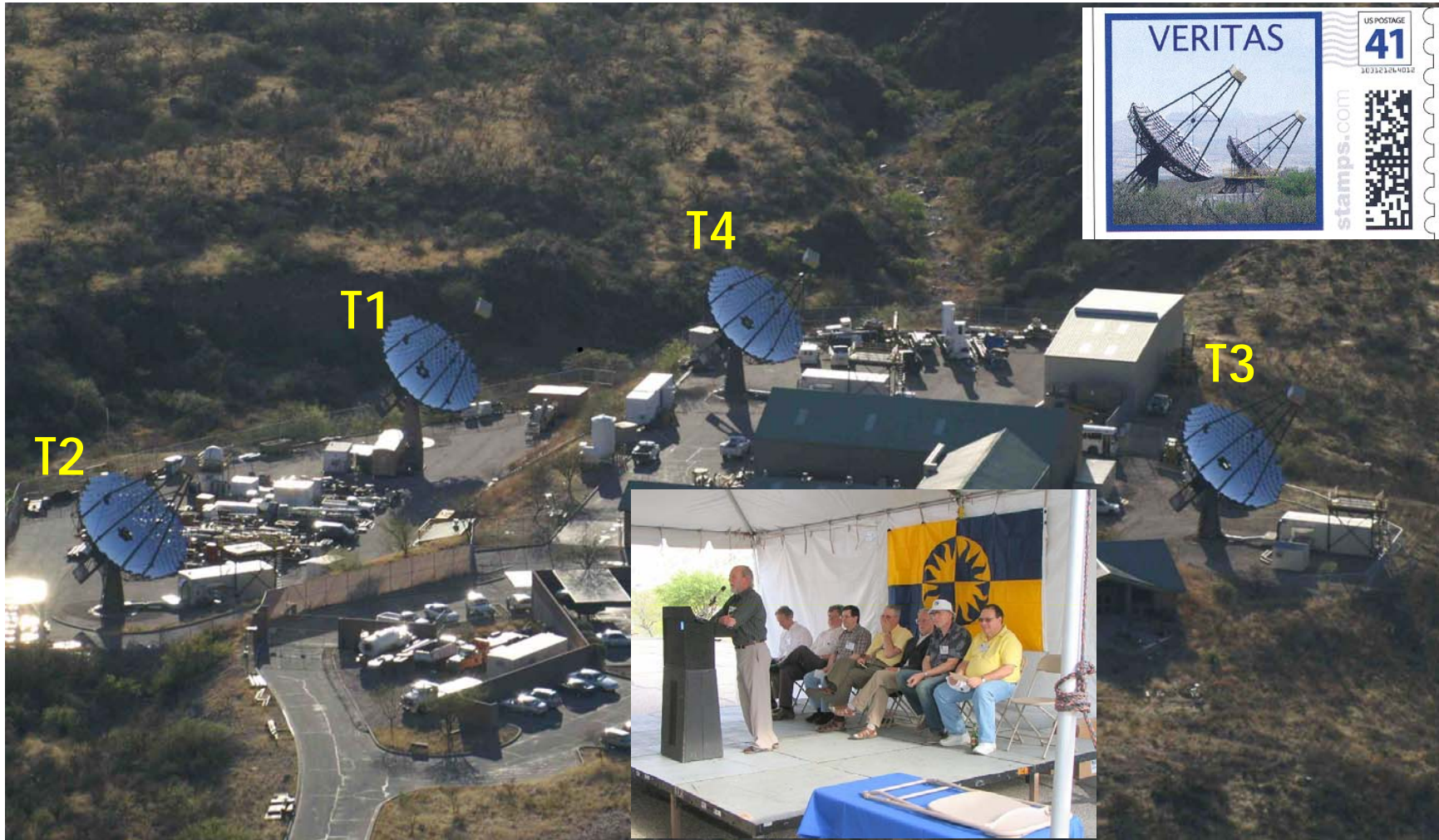
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# VERITAS – April 2007

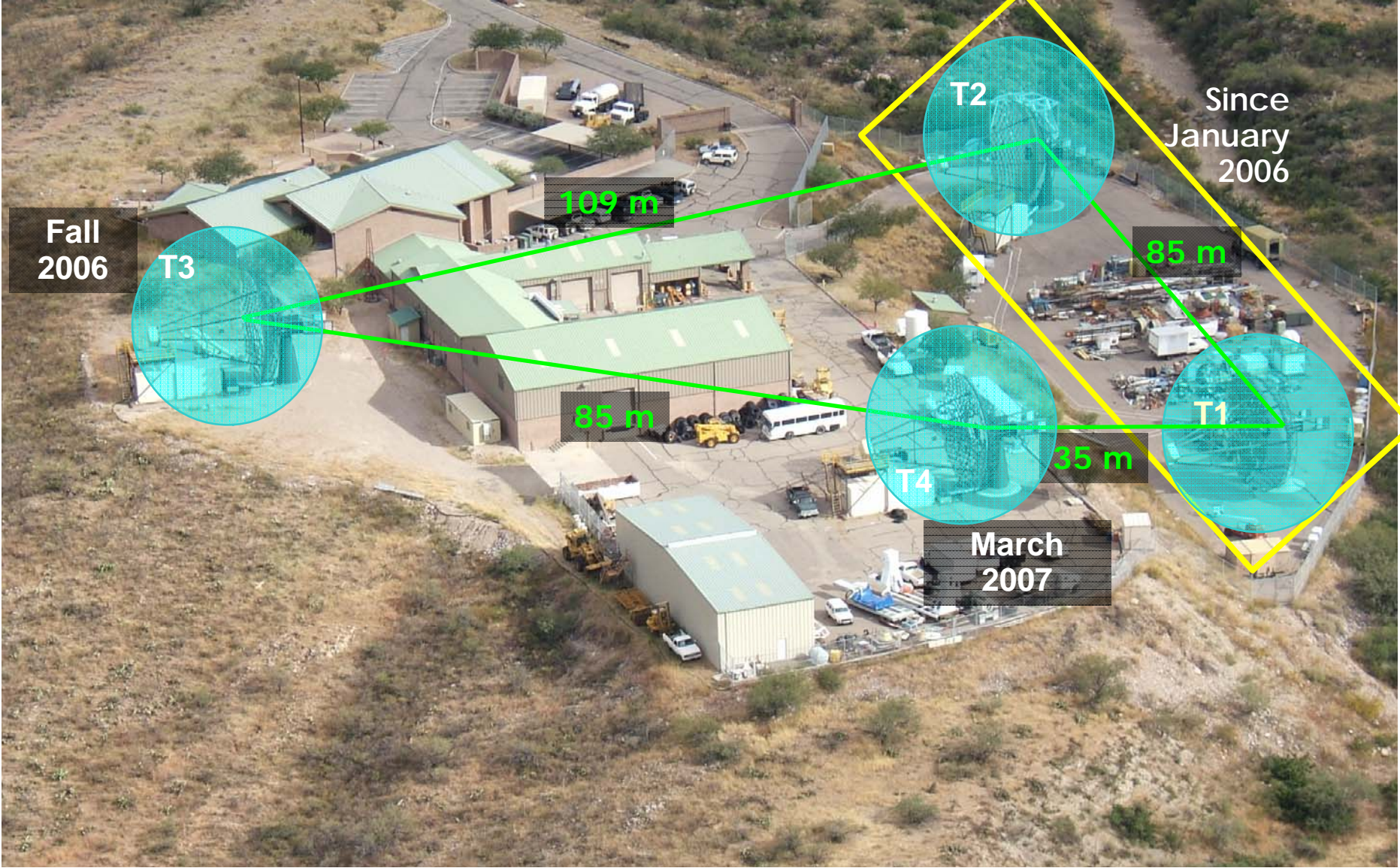
F.L. Whipple Basecamp Mt. Hopkins, AZ (1300m a.s.l.)



First Light Celebration, 04/28/07



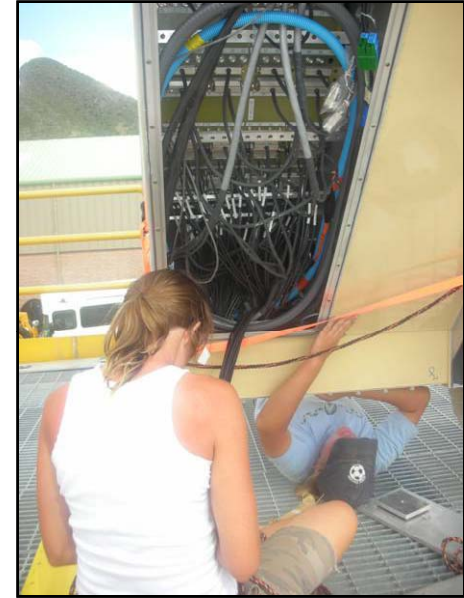
# Telescope Layout





# Construction 2004-2007

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# Telescope and Camera



12m reflector, f1.0 optics



500 pixel Camera



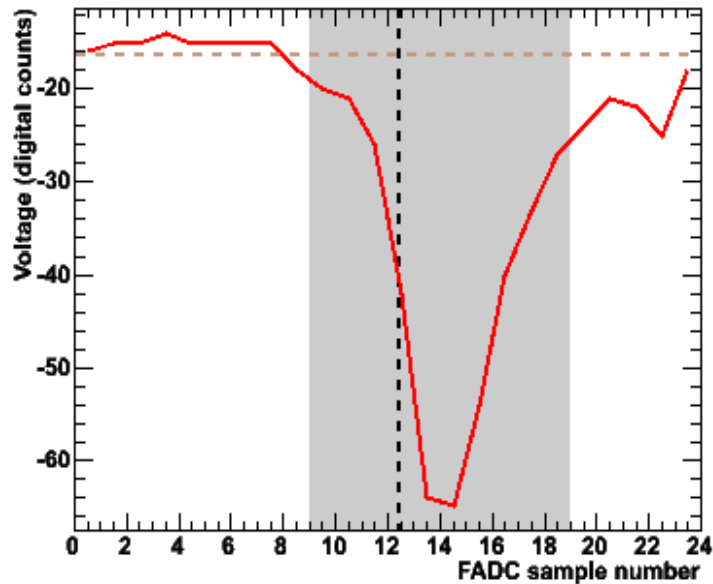
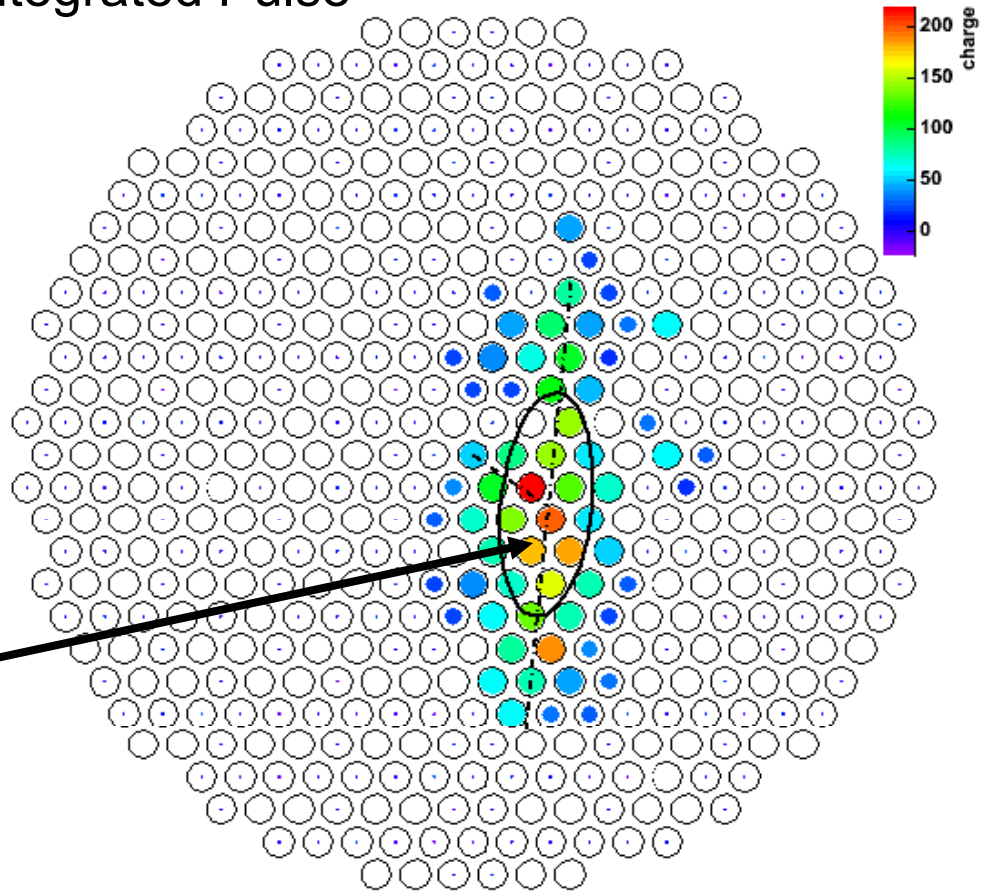
# VERITAS Data Acquisition



Integrated Pulse

mp|

lity.



Telescopes meet all specifications.

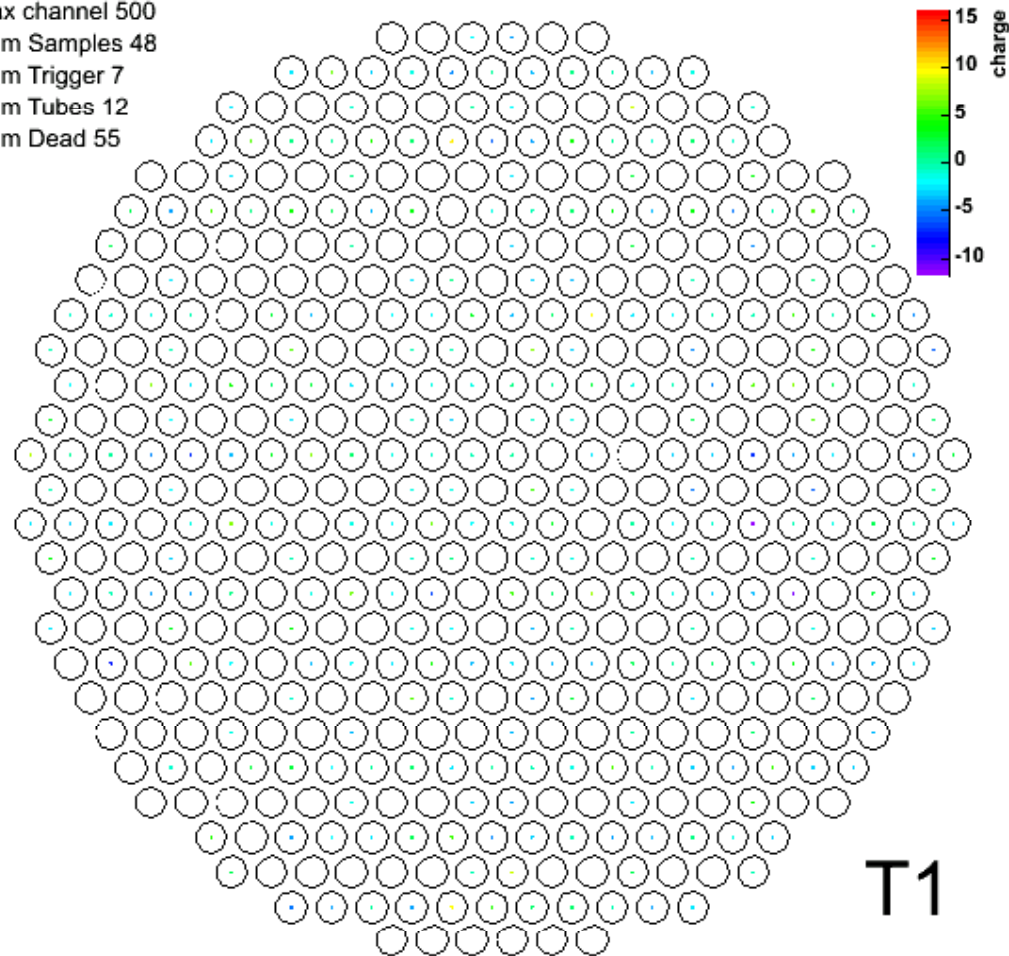


# Telescope 1 Movies



Run: 574 Event: 897 GPS: 63 : 3 : 56 : 57.94600  
Max channel 500  
Num Samples 48  
Num Trigger 7  
Num Tubes 12  
Num Dead 55

$\gamma$ -ray



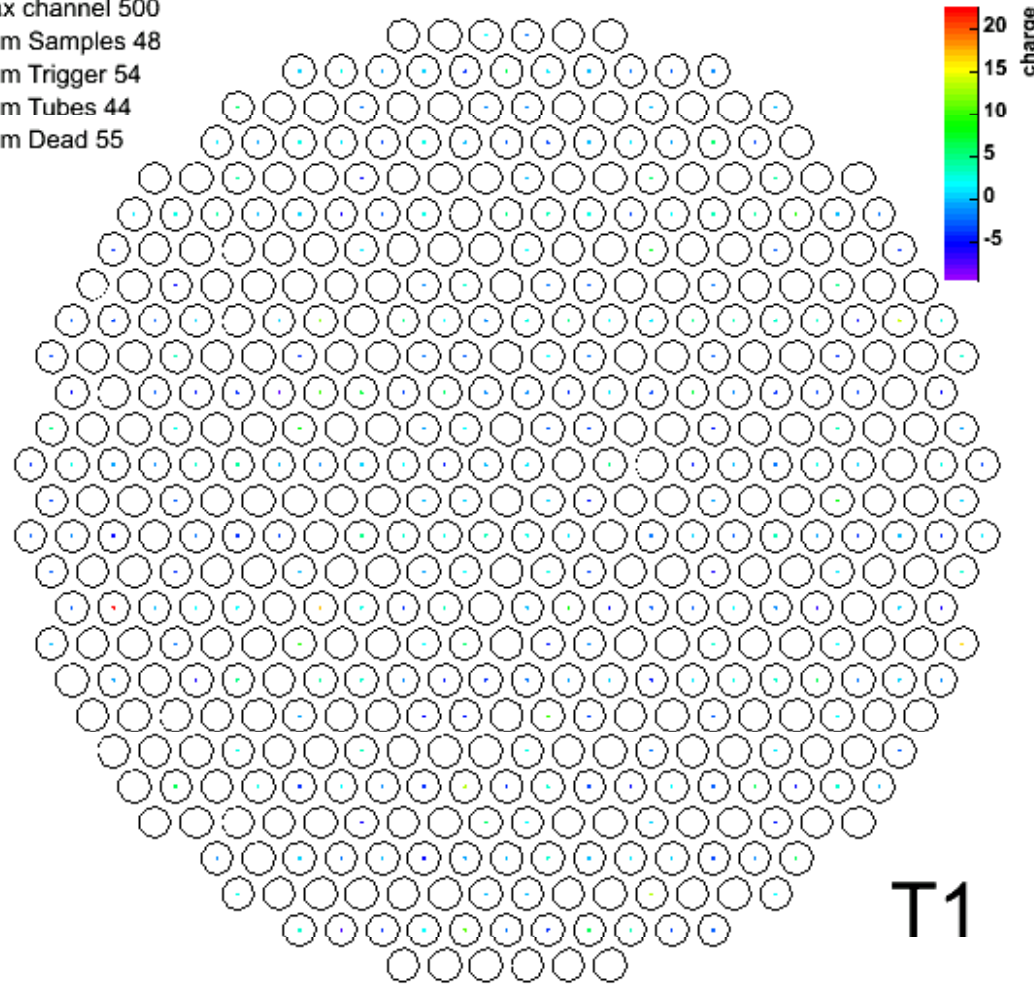
GEO: c\_x=0.27, c\_y=-0.58, dist=0.63, length=0.1599, width=0.0763,  $\alpha$ =2.98, size=811.76

# Telescope 1 Movies



Run: 574 Event: 34 GPS: 63 : 3 : 56 : 45.59971  
Max channel 500  
Num Samples 48  
Num Trigger 54  
Num Tubes 44  
Num Dead 55

Cosmic  
Ray



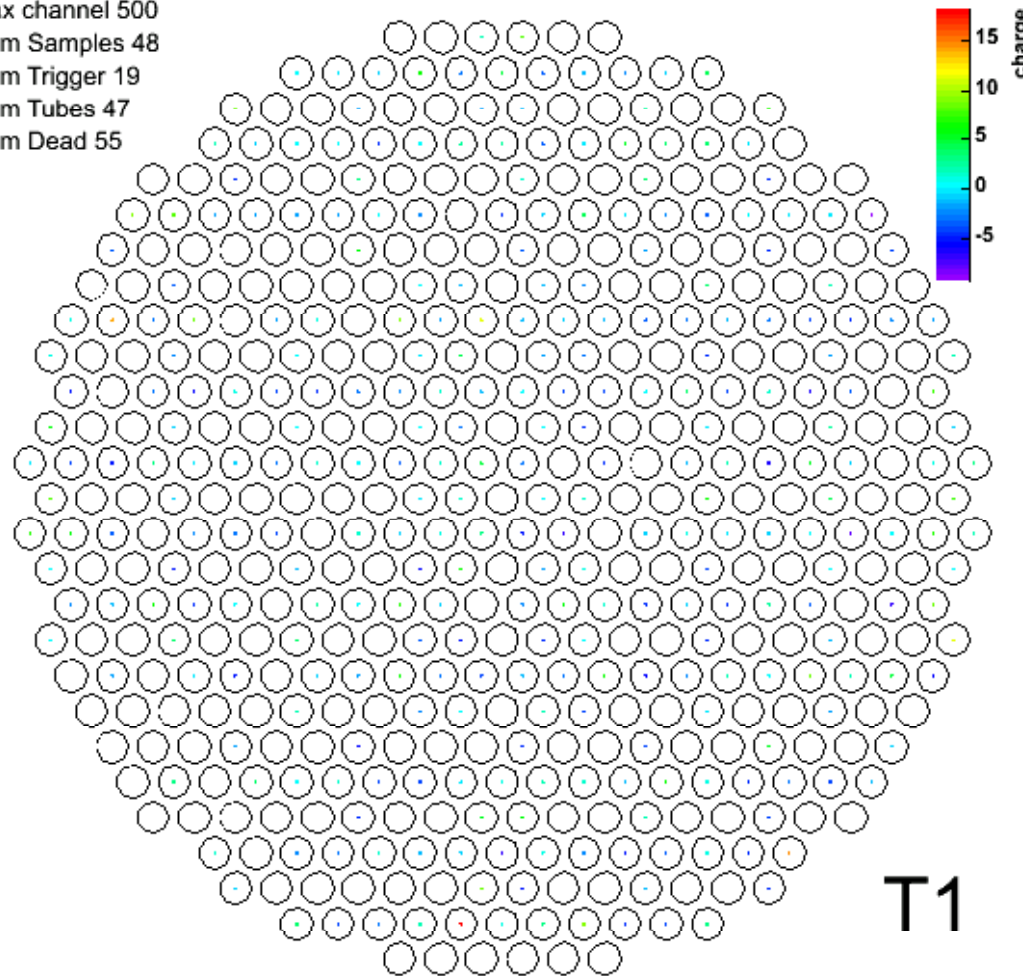
GEO:  $c_x=0.07$ ,  $c_y=-0.00$ ,  $dist=0.07$ ,  $length=0.9564$ ,  $width=0.3997$ ,  $\alpha=33.97$ ,  $size=2189.19$

# Telescope 1 Movies



Run: 574 Event: 305 GPS: 63 : 3 : 56 : 51.08530  
Max channel 500  
Num Samples 48  
Num Trigger 19  
Num Tubes 47  
Num Dead 55

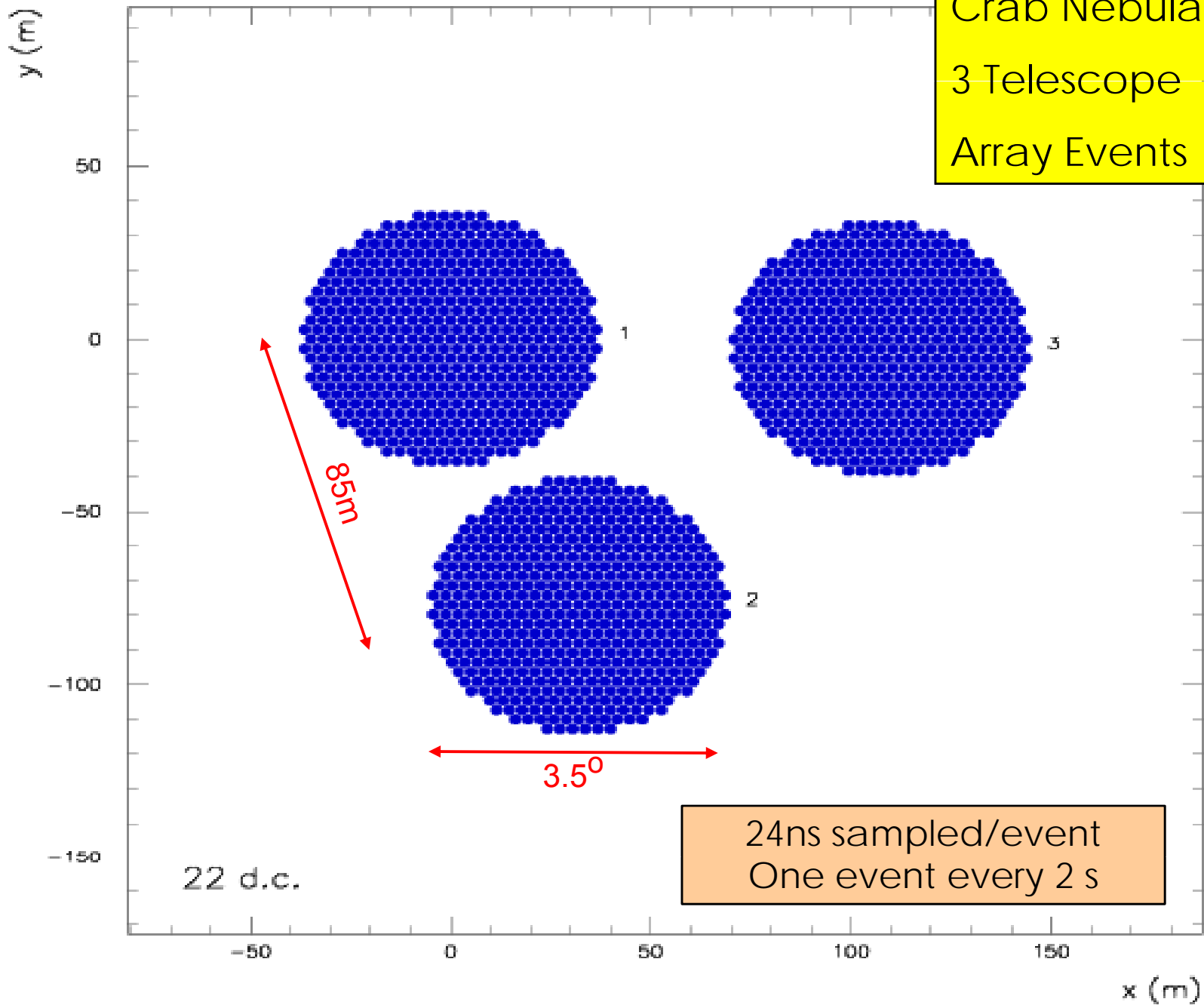
Muon  
Ring



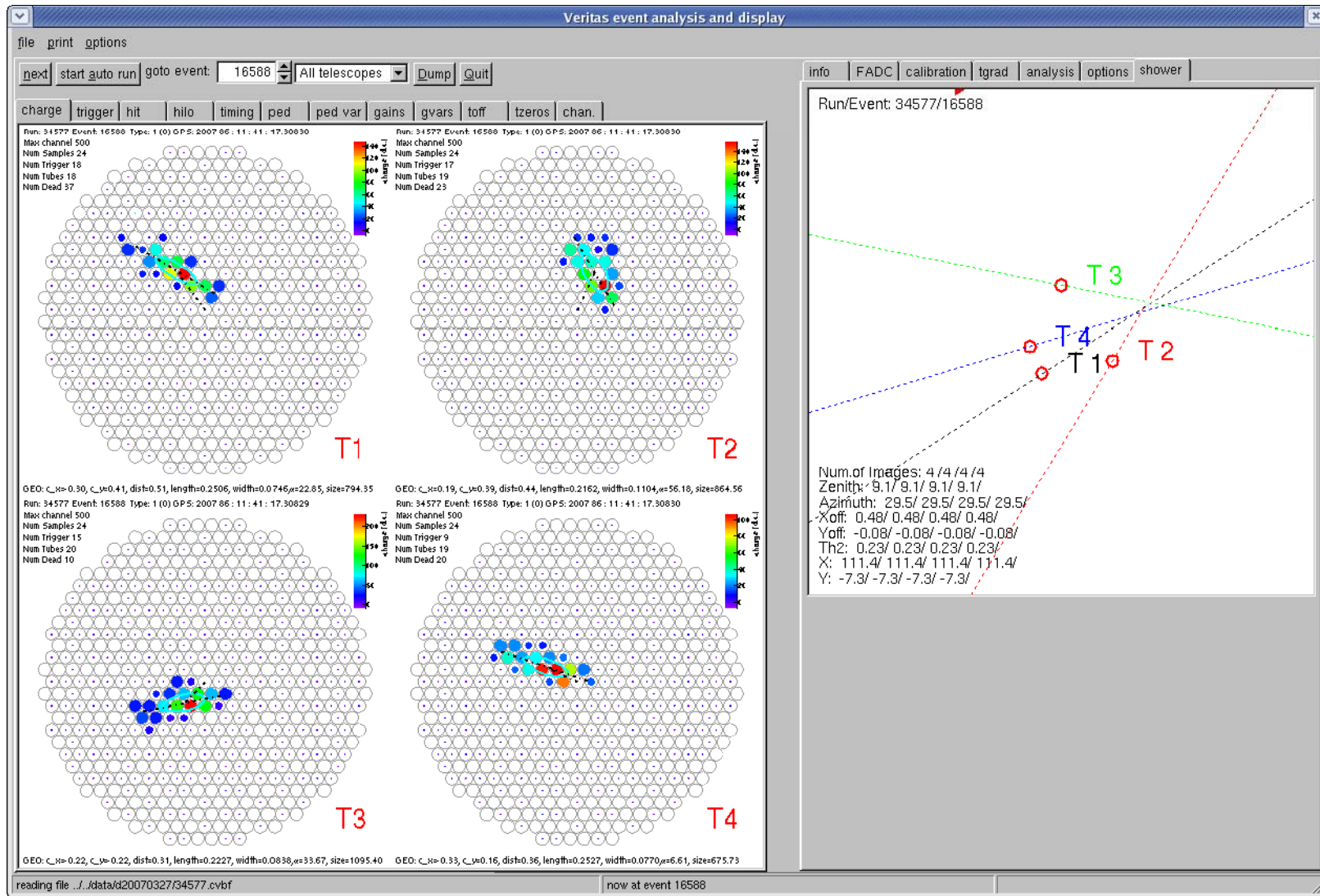
GEO: c\_x=0.73, c\_y=0.07, dist=0.73, length=0.6909, width=0.5157,  $\alpha=75.47$ , size=2350.66

# Event : 1026

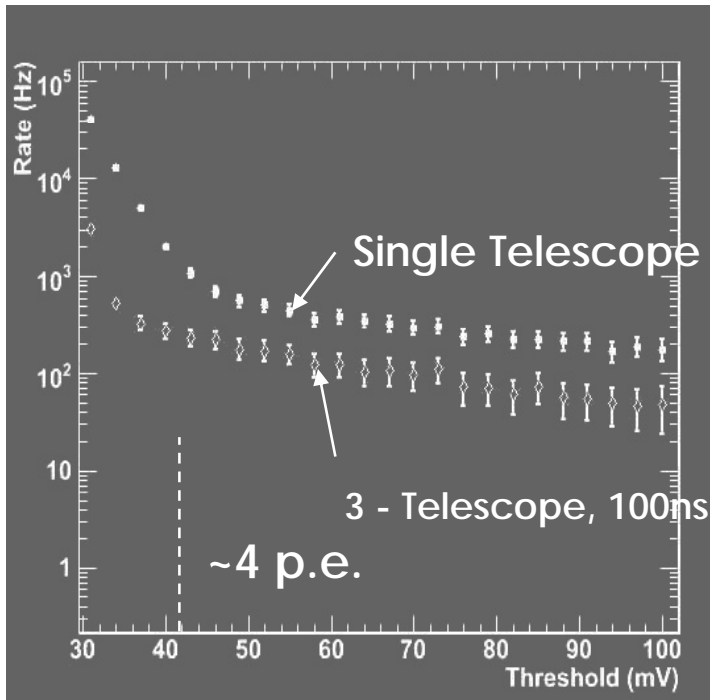
Crab Nebula  
3 Telescope  
Array Events



# Typical 4 Telescope Event

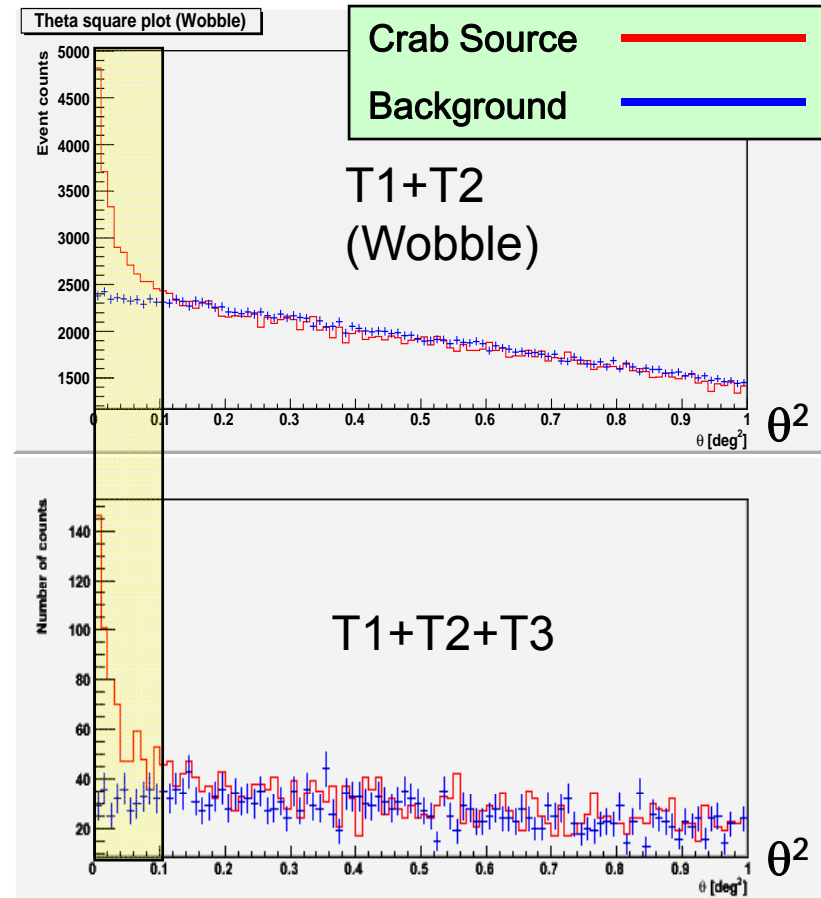


# VERITAS Performance I



## Three Level Trigger

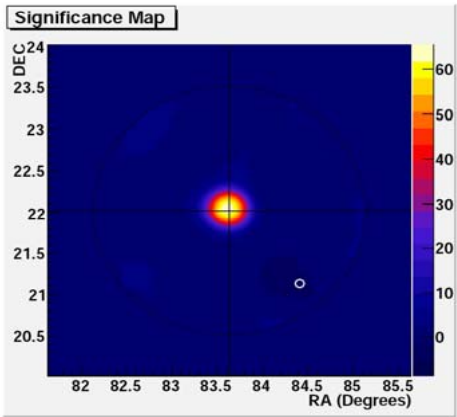
- L1 – CFD (4 p.e.)
- L2 – Telescope (pattern)
- L3 – Array (~ 150 Hz)



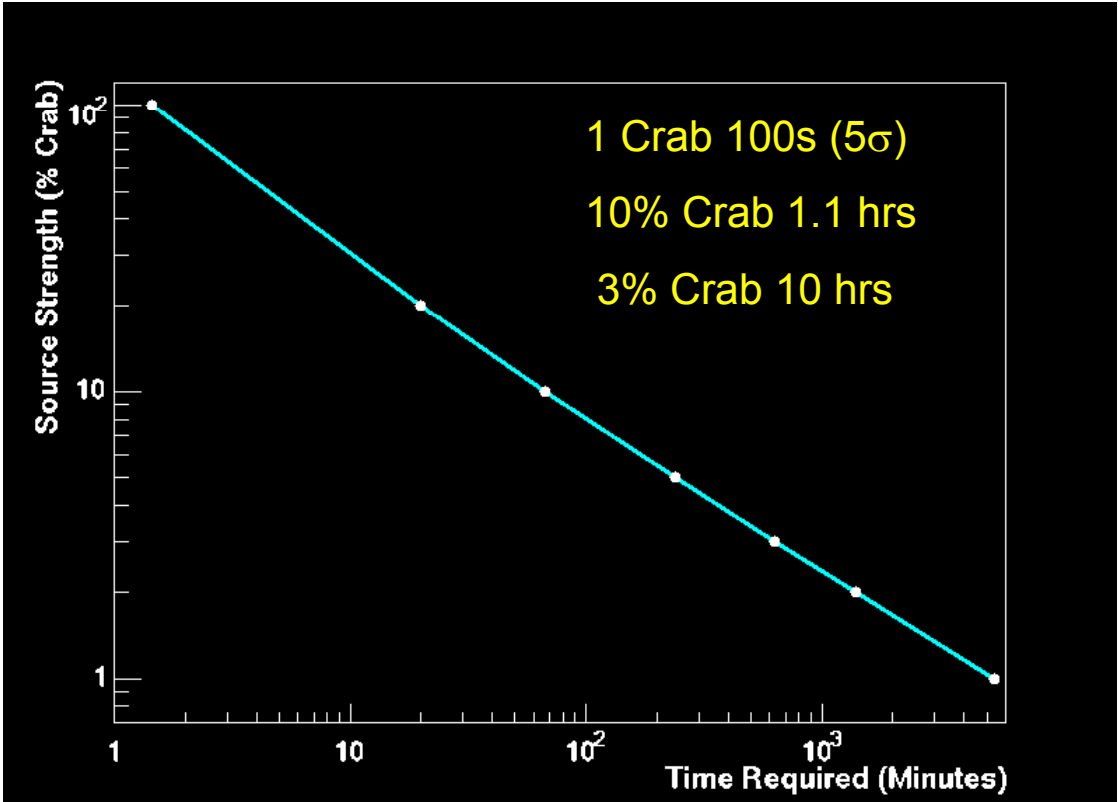
## Angular Resolution

- 2, 3 Telescope Crab Data
- Single  $\gamma$  resolution  $< 0.1^\circ$

# VERITAS Performance II



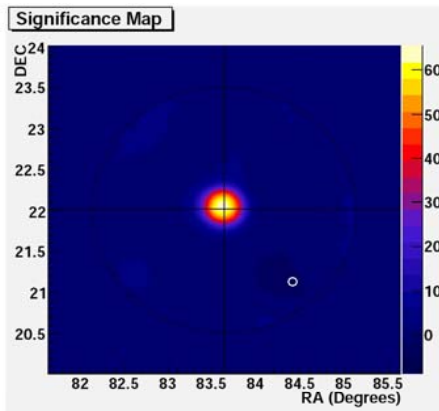
Crab Signal  
3 Telescopes  
3.6 hrs,  $58\sigma$



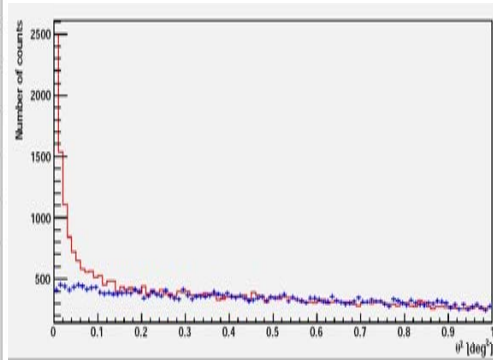
3 Telescope Sensitivity  
Crab Nebula data  
Will improve with 4 telescopes



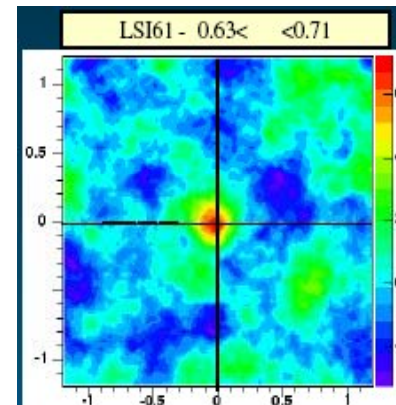
# VERITAS Detections (so far)



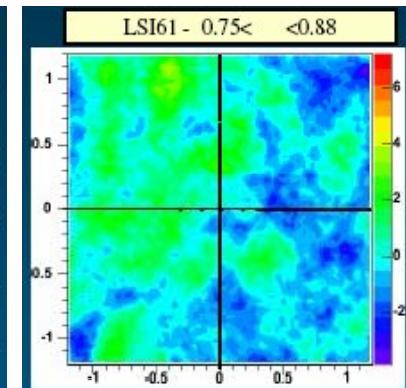
Crab Nebula,  
5 $\sigma$  in <2 mins



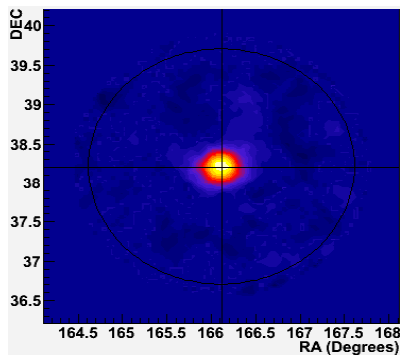
Crab Nebula,  
 $\theta^2$  plot, 12.6  $\gamma$ /min



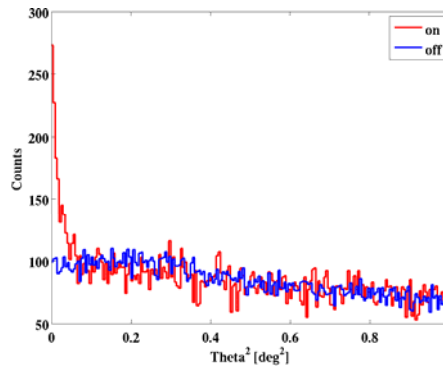
$\mu$ Quasar LSI+61 303  
Phase 0.63-0.71



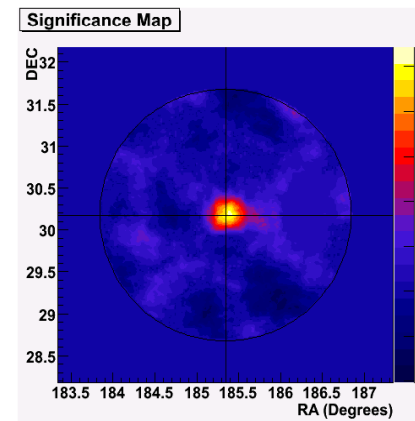
$\mu$ Quasar LSI+61 303  
Phase 0.75-0.88



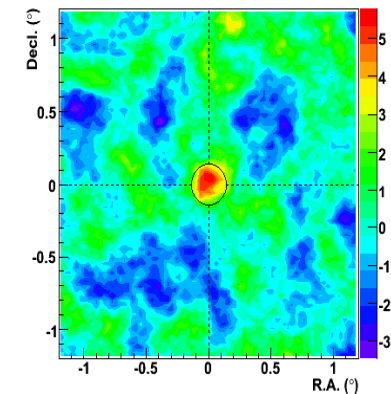
Blazar Mrk 421  
z=0.03



Blazar Mrk 501  
z=0.03

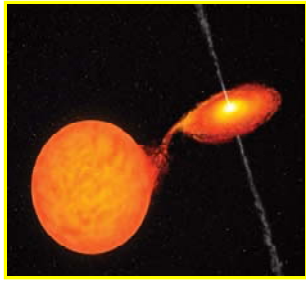


Blazar 1ES1218+30  
z=0.182  
2<sup>nd</sup> most distant blazar

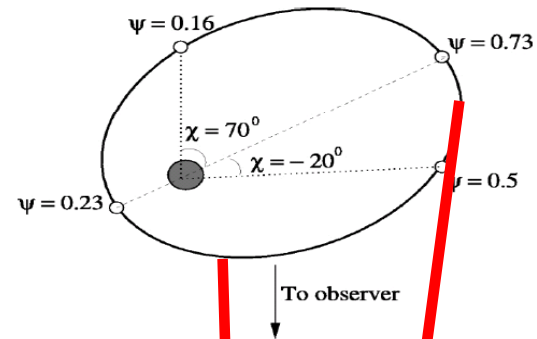


Radio Galaxy M87  
15 hrs, 6.1 $\sigma$ ,  
0.02 Crab

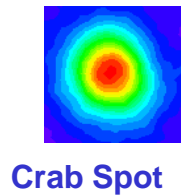
# Microquasar LSI +61 303



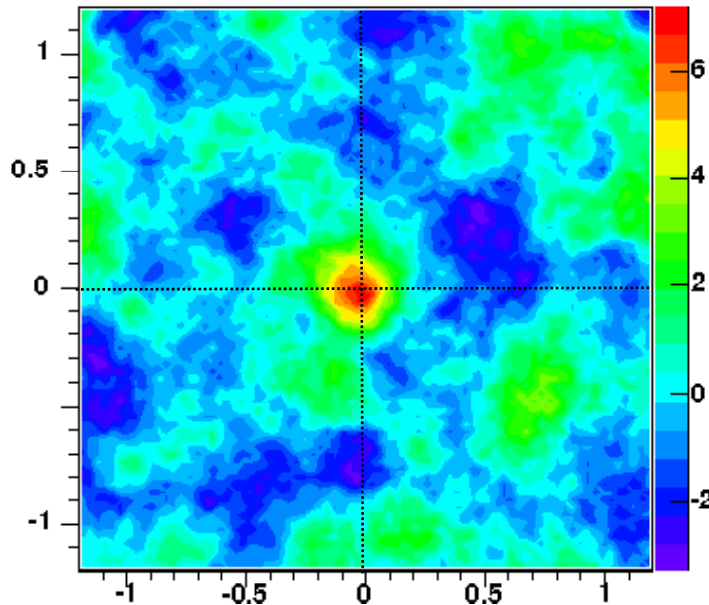
- HMXB located at 2 kpc distance
- Be Star coupled with NS
- 26.5 day orbital cycle



LSI61 -  $0.63 < \Psi < 0.71$

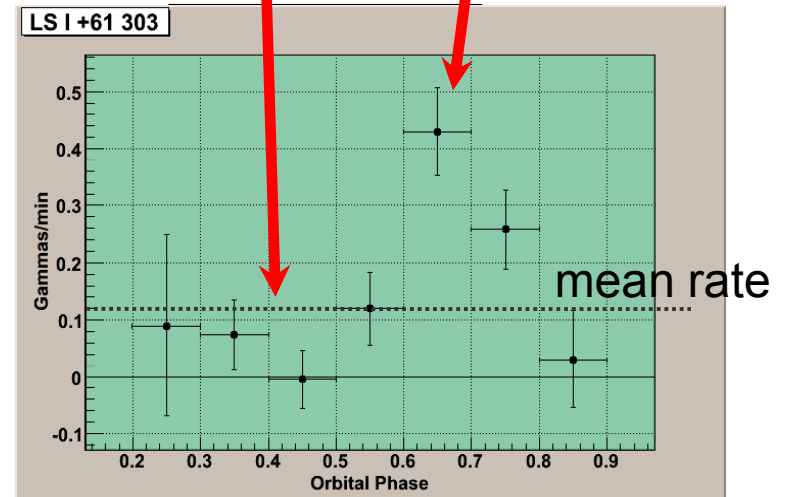


Crab Spot



VERITAS 3 Telescopes

8.3 hrs,  $7.1\sigma$ , 7% Crab



VERITAS

Rate versus orbital phase.

# AGN 1ES1218



## 1ES1218+30.4:

One of most distant blazars discovered at TeV  $\gamma$ -rays (MAGIC, Albert et al. 2006)

Redshift: 0.182

## VERITAS Observations:

Dec. 2006 - March 2007 (~ 29 hrs)

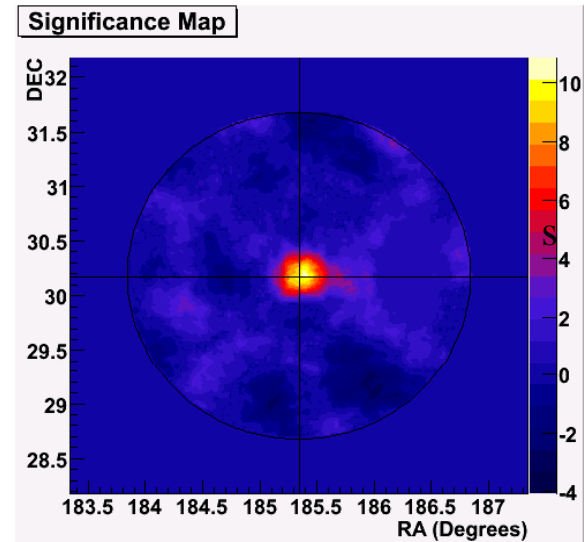
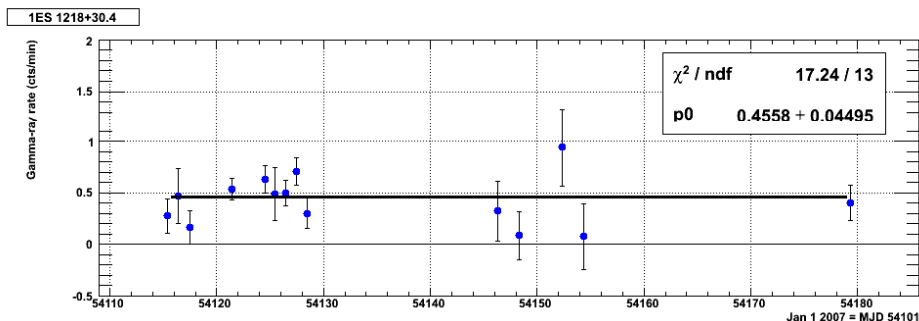
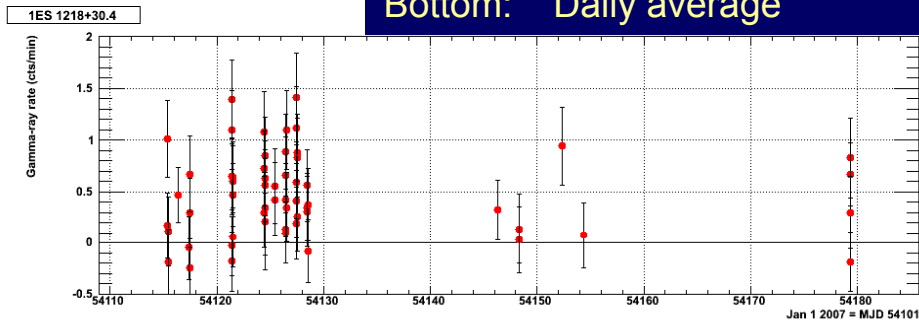
Excess: 13.2  $\sigma$

Flux: ~5% Crab.

Lightcurves:

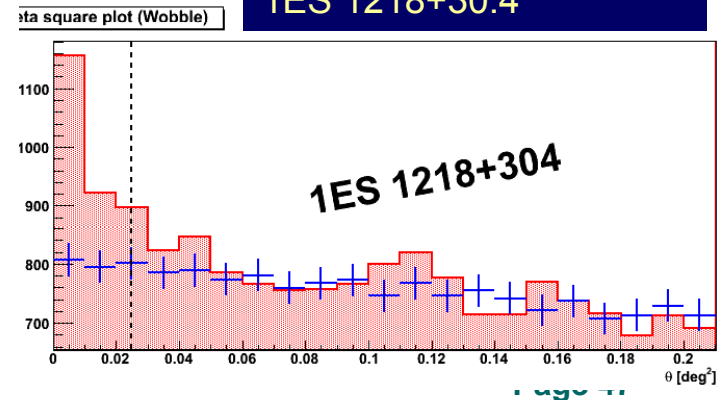
Top: Run-by-Run averages

Bottom: Daily average



Map of excess significance.

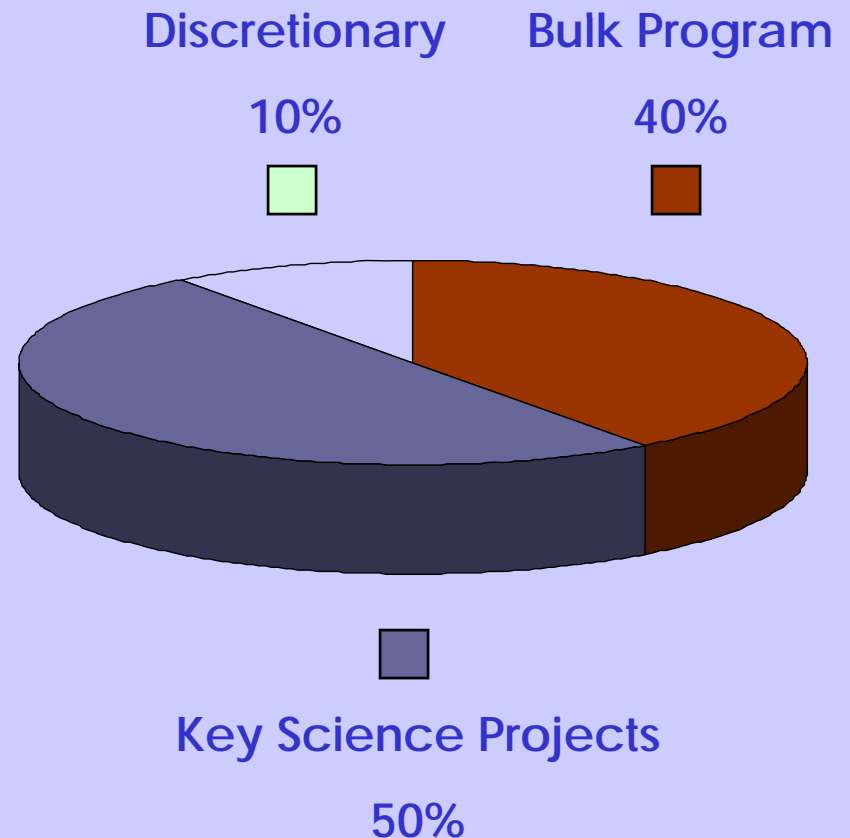
## Theta-sq distribution of 1ES 1218+30.4



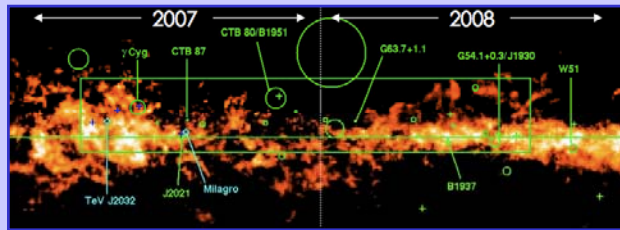
# VERITAS Science Program



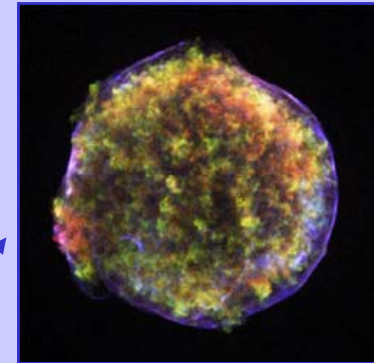
- Key Science Projects:
  - **Four highlight science topics.**
- Bulk Science Program
  - **All possible topics.**
  - **Determined by TAC selection.**
- Discretionary Time
  - **ToO's, unique topics, engineering.**
  - **Determined by Spokesperson.**



# Key Science Projects



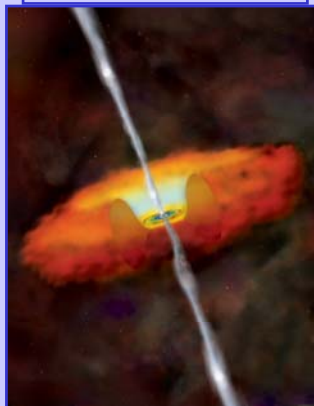
SKY SURVEY



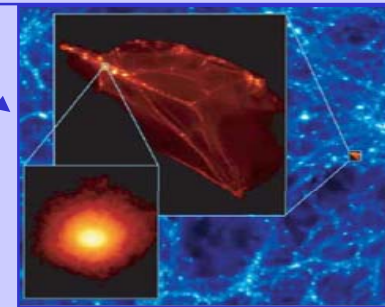
SNRs/PWN



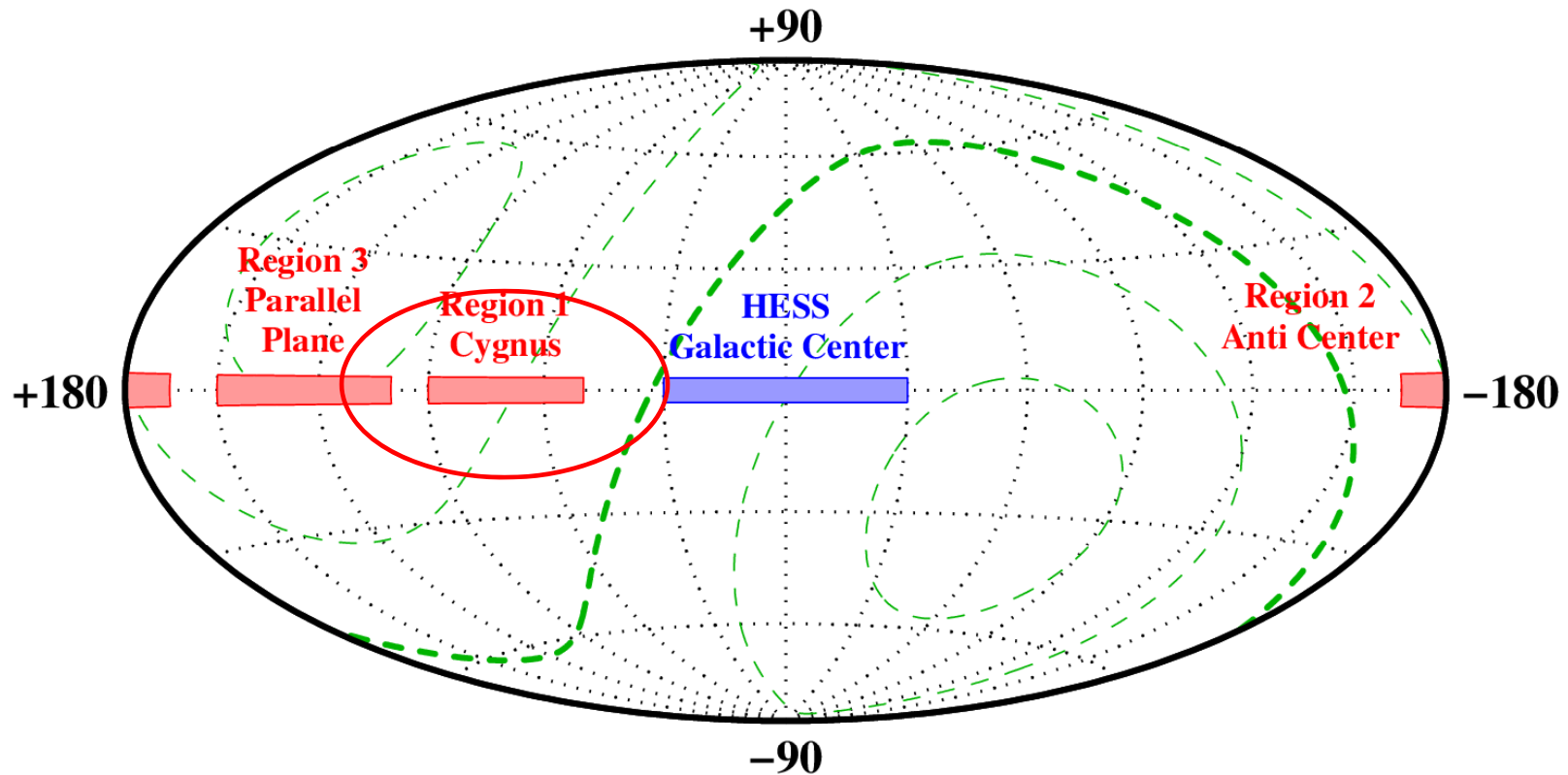
BLAZARS



DARK MATTER



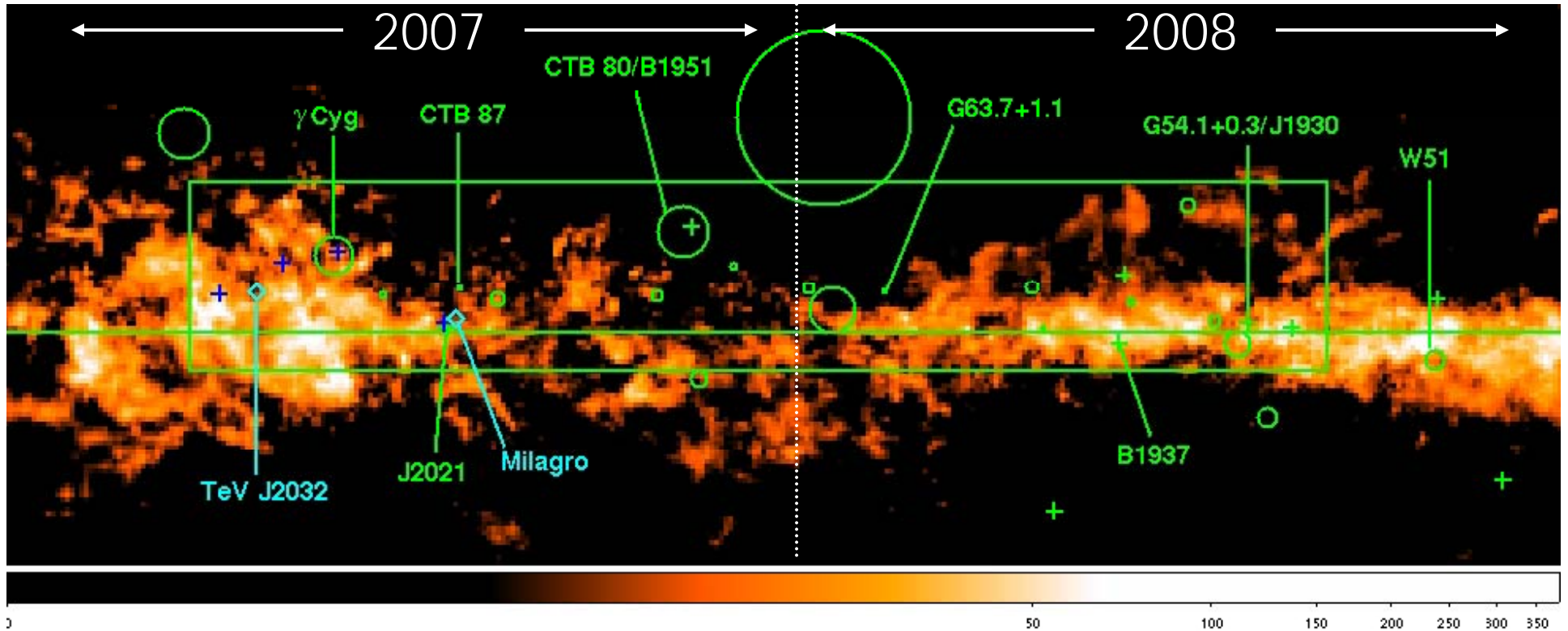
# VERITAS Survey Regions



- 3 regions of Galactic Plane, start with Region 1.
- Sensitivity of ~5% of Crab.
- Two years, ~200 hrs of observation.



# Cygnus Arm



CO map, with circles=SNRs, blue pluses=EGRET GeV, green pluses=pulsars.

Most obvious targets:

SNRs, PWN, EGRET sources, X-ray binaries, VHE sources.



# Summary

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- VHE particles provide unique tests of the limits of physical laws. Probe astrophysics in regimes not yet explored. Possibility for discovery of physics beyond our standard models.
- Exciting discoveries of many, unexpected sources of VHE gamma-rays. But still, most of the sky remains unexplored.  
**→ VERITAS is now operational and getting exciting results.**
- New Astronomy of TeV  $\gamma$ -rays and neutrinos should reveal many surprises over the next 5-10 years.

**“The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes.”**

**Marcel Proust (1871-1922)**