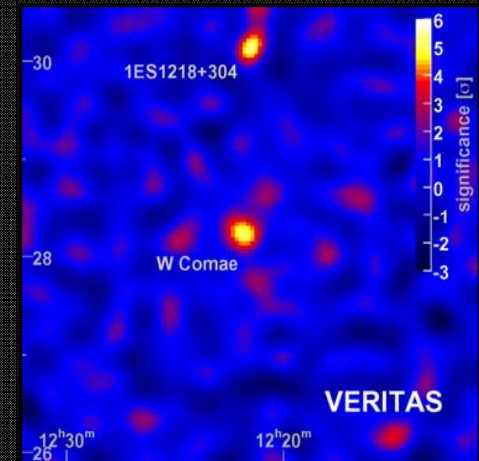
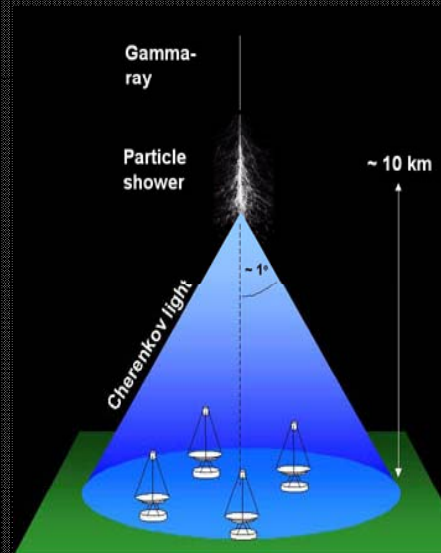
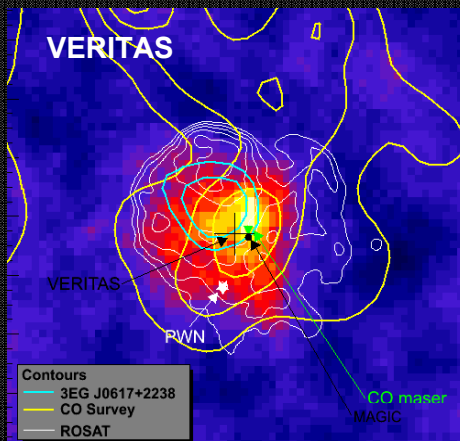


# VERITAS Explores the TeV $\gamma$ -ray Sky

## VERITAS (Mt. Hopkins, AZ)



# Outline

---

## Scientific Motivation

- A “New Astronomy”
- Physicist’s Viewpoint
  - *Astrophysical TeV accelerators*  
(1 TeV =  $10^{12}$  eV)
  - *Origin of Cosmic Rays, understanding black holes ...*
  - *Probes of new physics*

## Experimental Technique

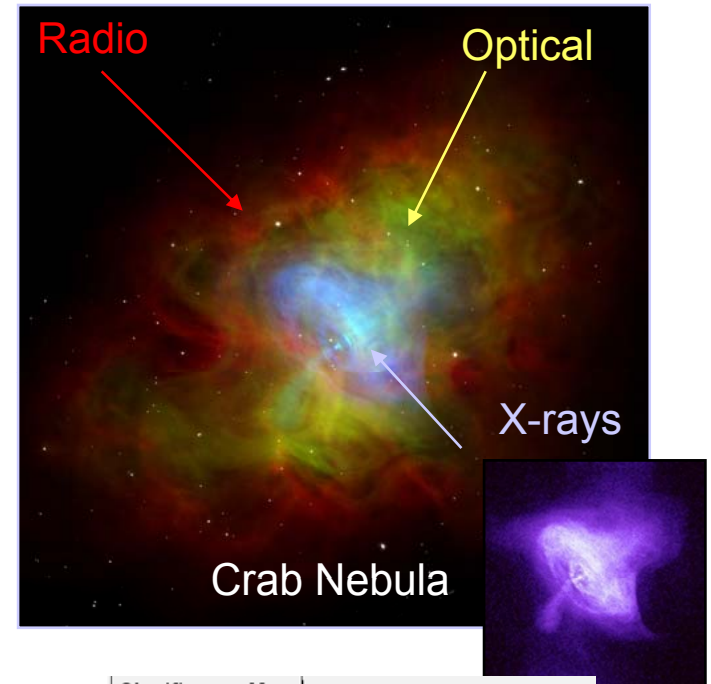
## The VERITAS Project

- Description, performance, operations
- Science Highlights – some brand new results !
- (Fermi Gamma-ray Space telescope)

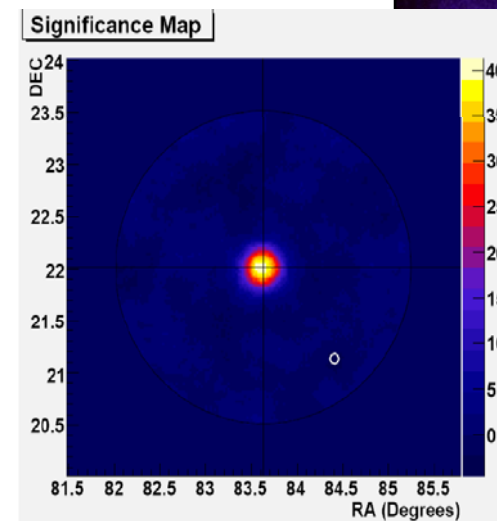
## Future

# A New Astronomy

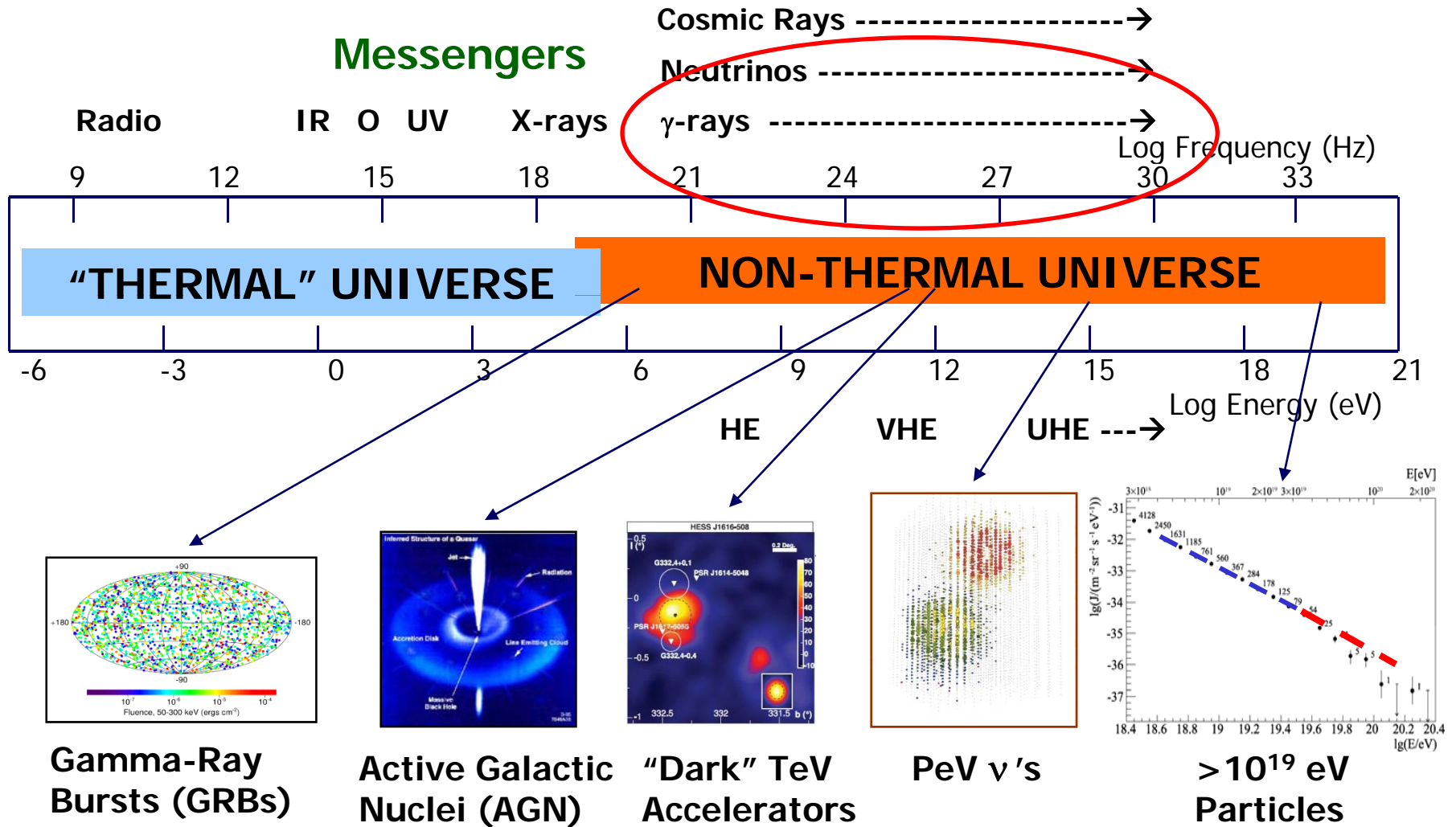
- Before 1940's – Astronomy only used visible light.
- New wavebands (radio, IR, X-ray,  $\gamma$ -ray) change our picture of the universe
  - Different spatial scales
  - Different time scales
  - Different emission processes
  - ▶ New physics
- Other messengers (cosmic rays, neutrinos, grav. waves)



TeV  $\gamma$ -rays

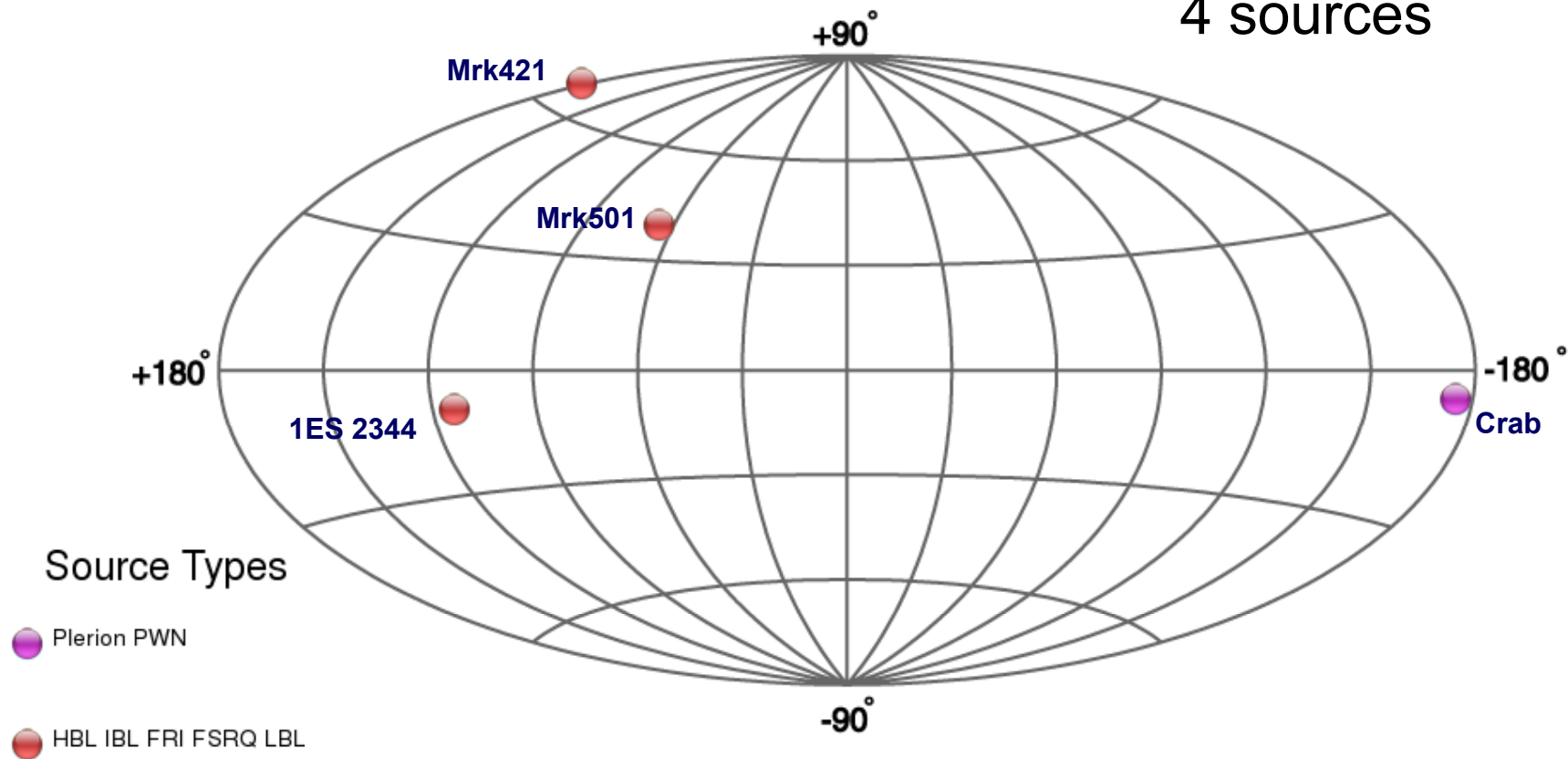


# New Windows & New Messengers



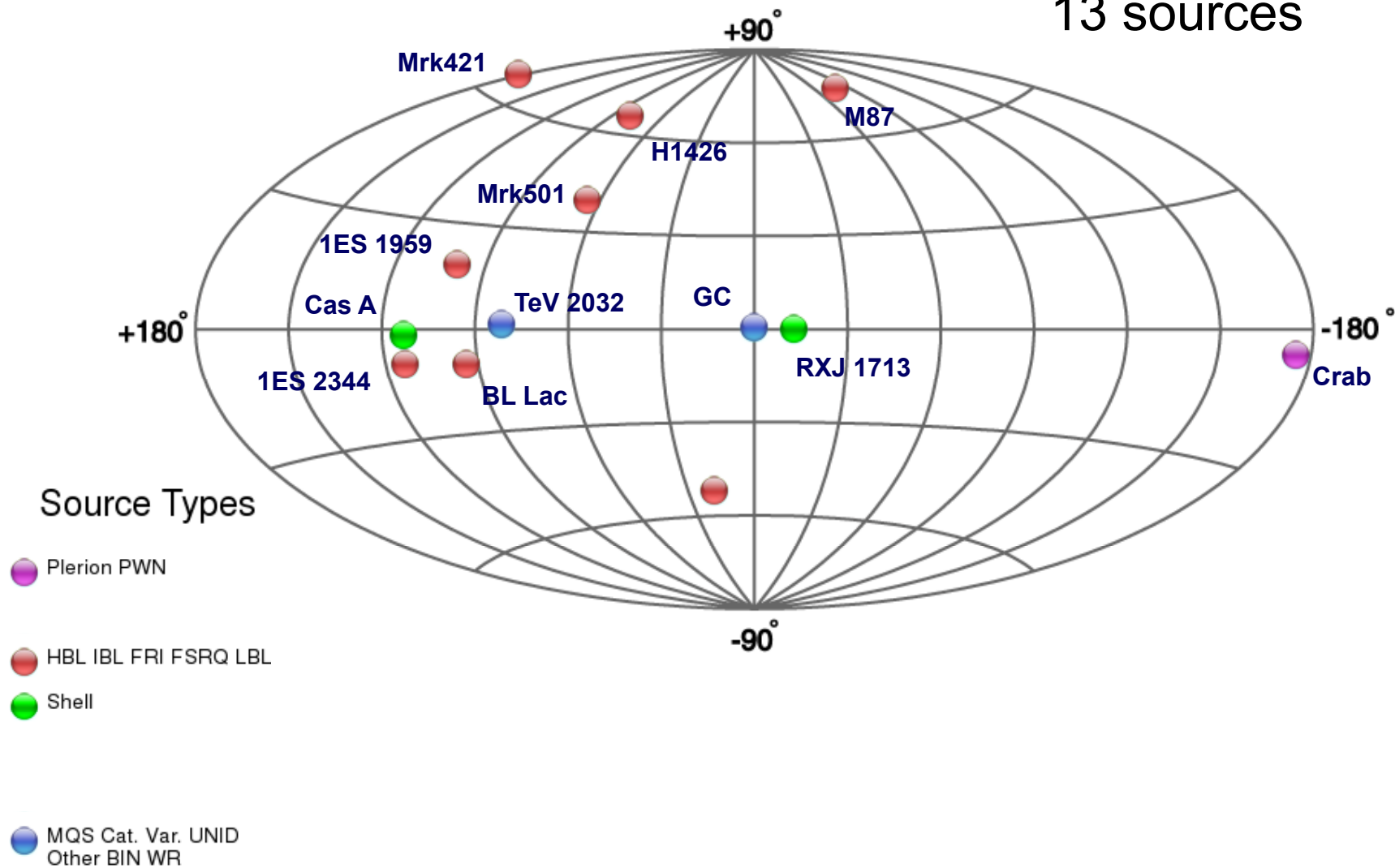
# The TeV $\gamma$ -ray Sky - 1999

4 sources



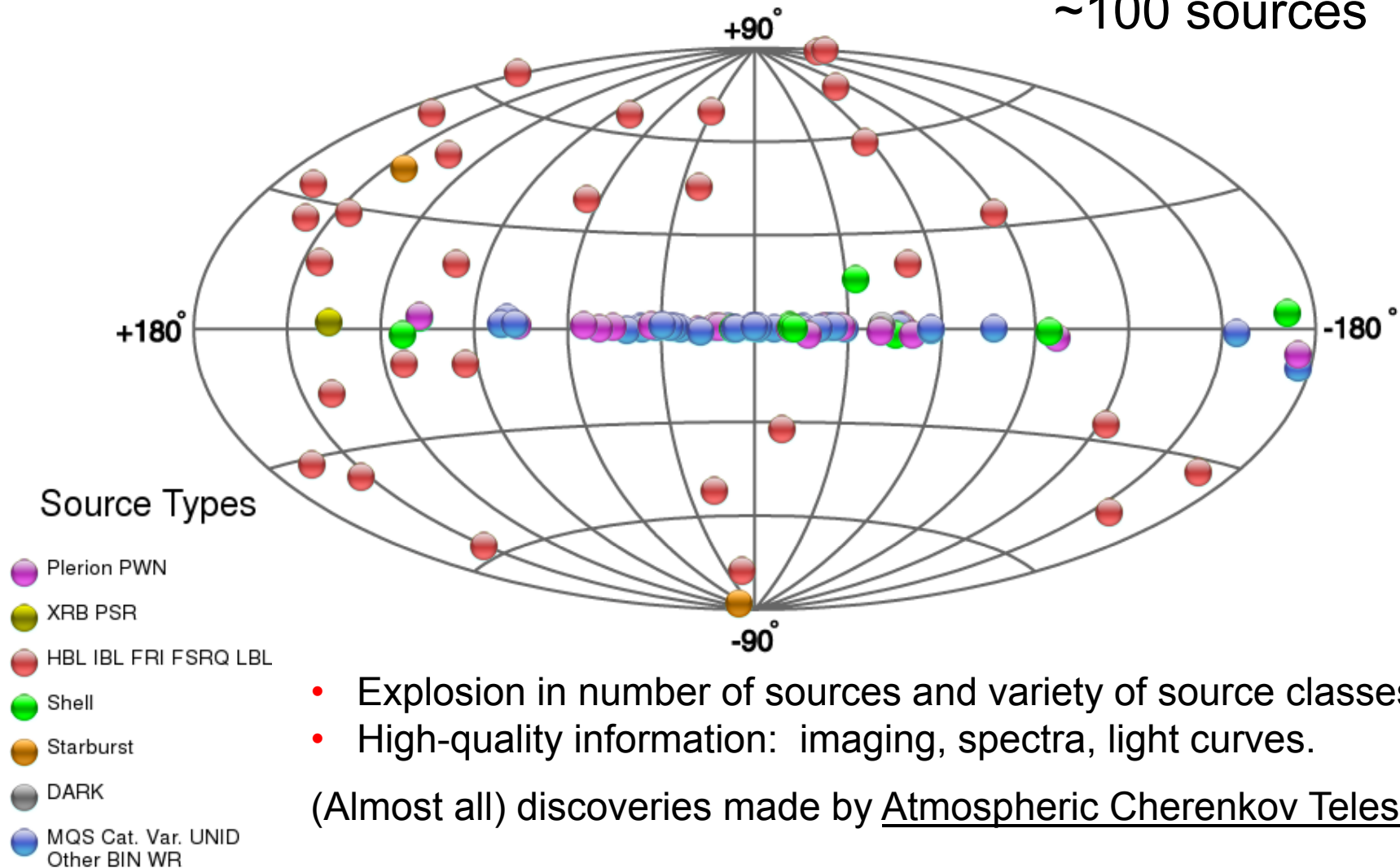
# The TeV $\gamma$ -ray Sky - 2004

13 sources



# The TeV $\gamma$ -ray Sky - 2009

~100 sources

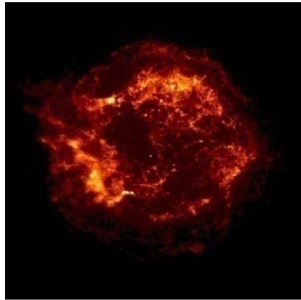


- Explosion in number of sources and variety of source classes.
- High-quality information: imaging, spectra, light curves.

(Almost all) discoveries made by Atmospheric Cherenkov Telescopes

# A Wide Variety of Sources ...

## Supernova Remnants



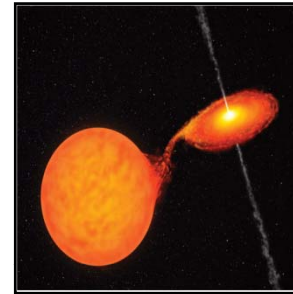
Shocks  
Fermi mechanism

## Pulsars/PWN



NS dynamo  
Winds

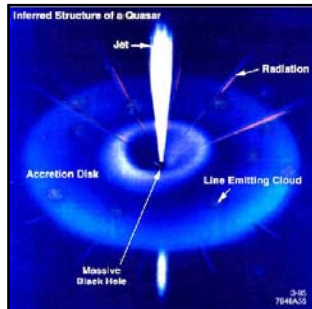
## HMXBs (microquasars)



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

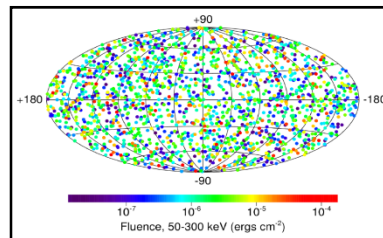
GALACTIC

## Active Galactic Nuclei



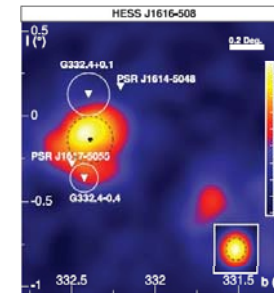
SMassive BH  
Jets

## Gamma-Ray Bursts



Massive star collapse  
Relativistic shocks

## Dark accelerators...



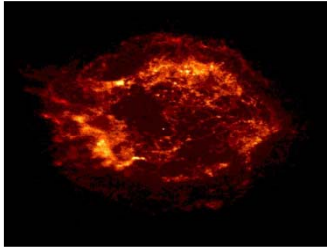
???

EXTRA-GALACTIC

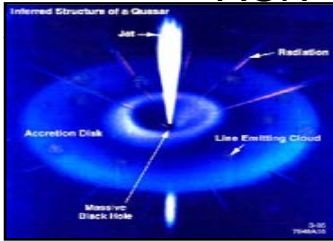


# Key Physics Issues

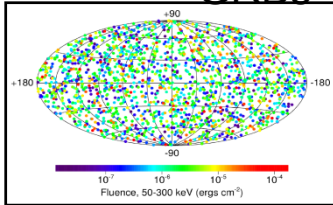
SNR



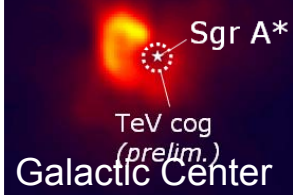
AGN



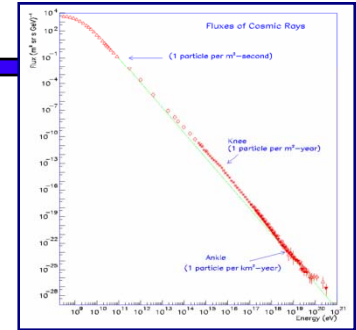
GRBs



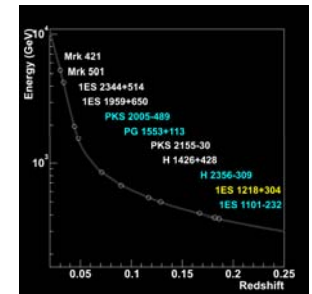
Sgr A East  
SNR



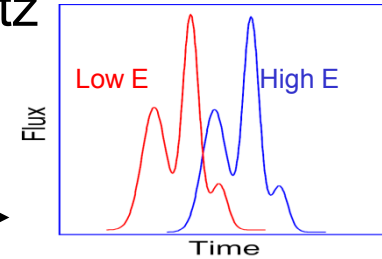
Origin of  
cosmic rays



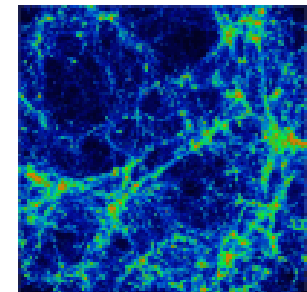
Cosmological  
 $\gamma$ -ray horizon



Tests of Lorentz  
invariance



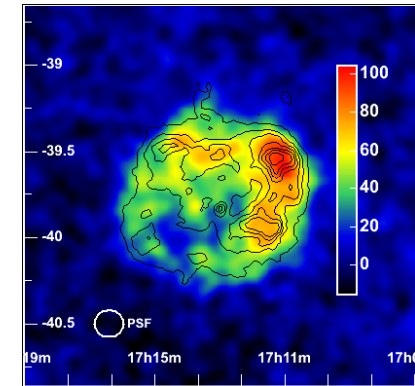
Cold dark matter  
(WIMP) searches



# Origin of Cosmic Rays = SNRs ?

Why (VHE) gamma rays?

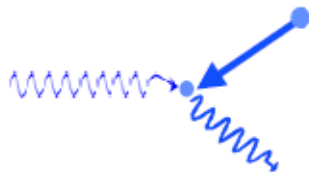
- Unlike cosmic rays, *not deflected* by interstellar magnetic fields.
- *Tracers* of parent particle populations – those particles accelerated by shocks.



SNR Image (RXJ 1713-3946)

**Accelerated electrons**  
→ **VHE  $\gamma$ -rays**

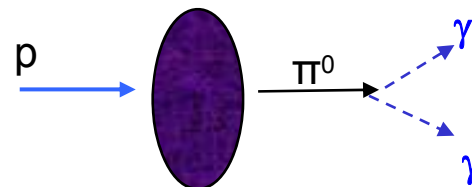
Up-scattering of soft photons



Inverse Compton Scattering

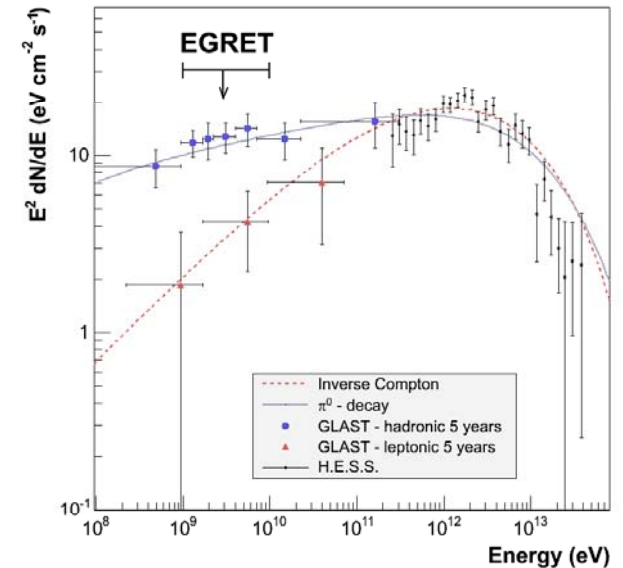
**Accelerated protons**  
→ **VHE  $\gamma$ -rays**

Target interaction,  $\pi^0$  decay



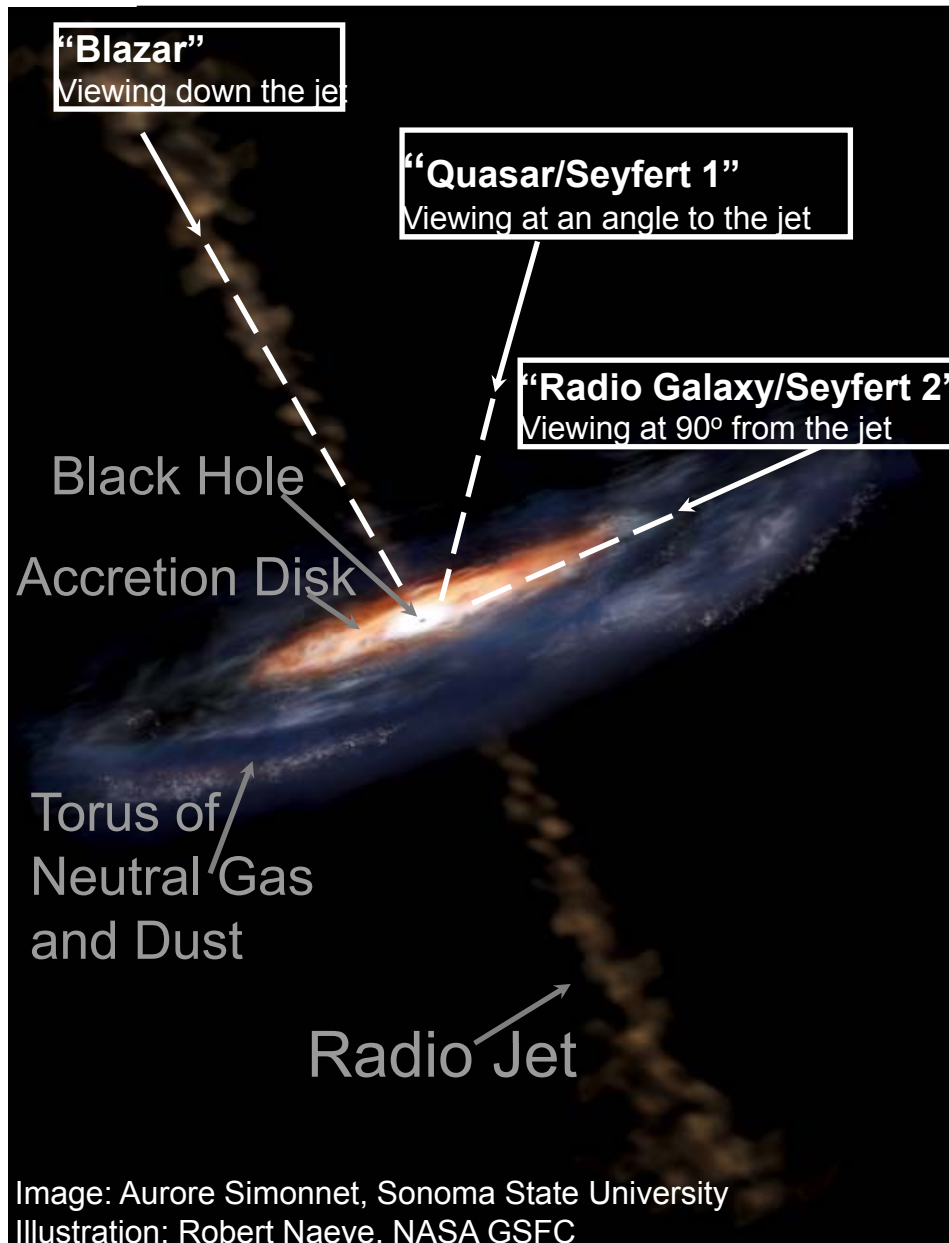
Target material

There is good evidence for SNR acceleration of CRs, but the case is far from settled.



Spectral Energy Distribution

# Active Galaxies



## Active Galactic Nuclei (AGN)

- High-luminosity extragalactic objects
  - Probe properties of the universe at large distances
- Highly variable !
- Jets powered by accretion on to supermassive BH

So far, AGN are generally:

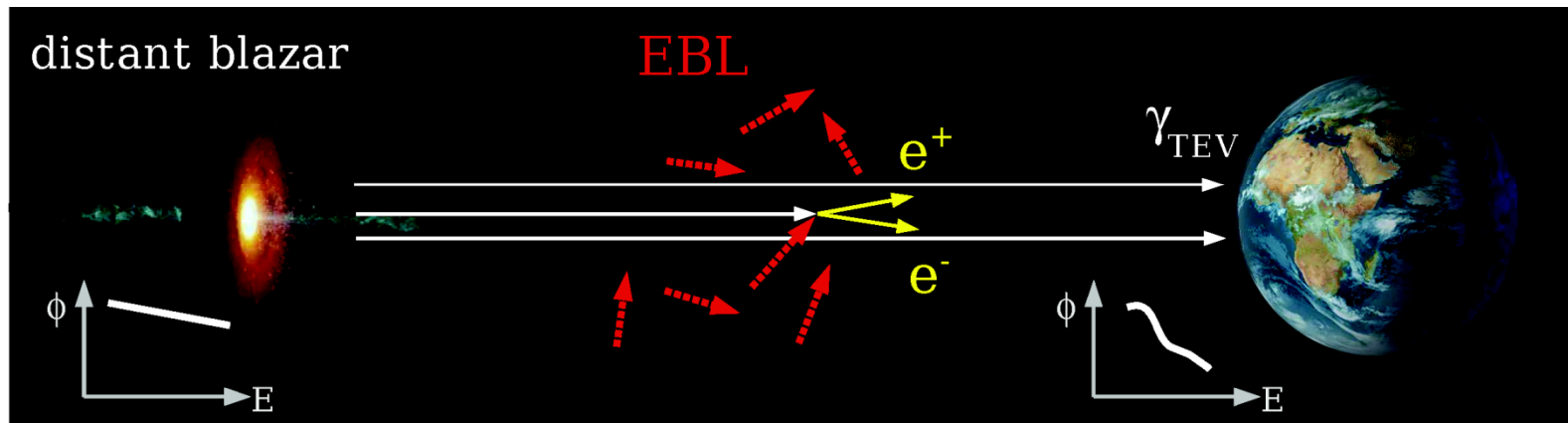
- Blazars
  - Jets aligned with line of sight

But also radio galaxies (e.g M87)

- Jet viewed from the side

What are the relevant acceleration, emission, propagation mechanisms ?

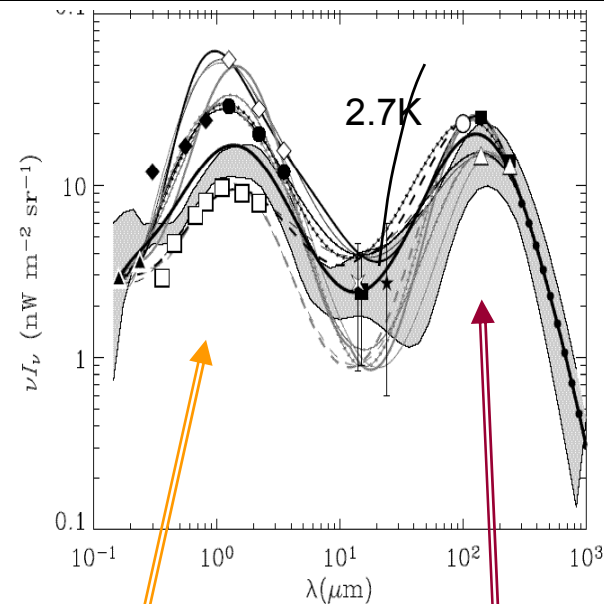
# Extragalactic Background Light (EBL)



Diffuse extragalactic background light (how much light since recombination?)

- Complements direct measurement in Optical, IR: *difficult*.
- Absorption signature in 50-1000 GeV band for distant sources.

VHE  $\gamma$ -ray measurements provide important constraints on the cosmological radiation fields.



Red shifted  
stellar light

Red shifted  
dust light

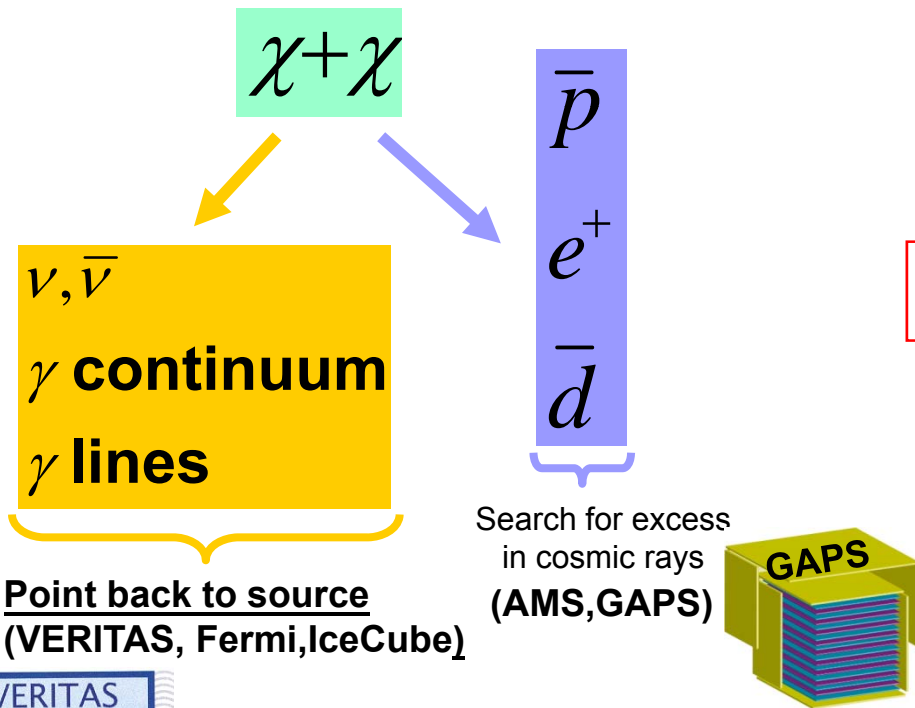
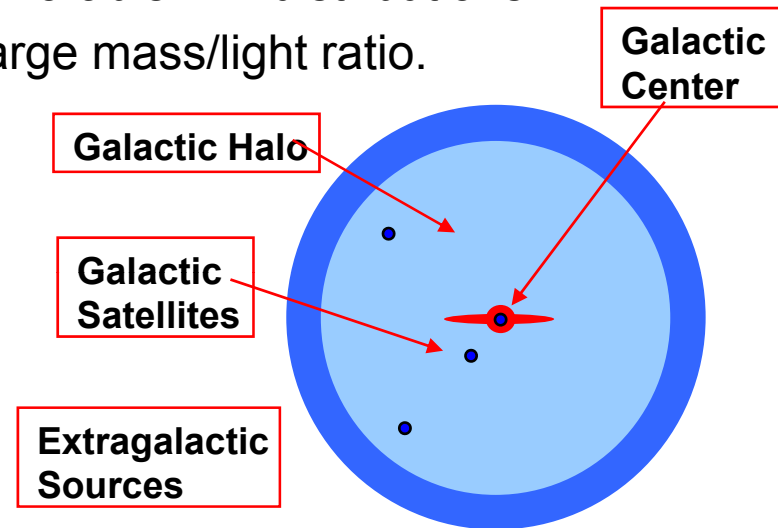
# Search for Cold Dark Matter

Hypothesis: DM = WIMPs

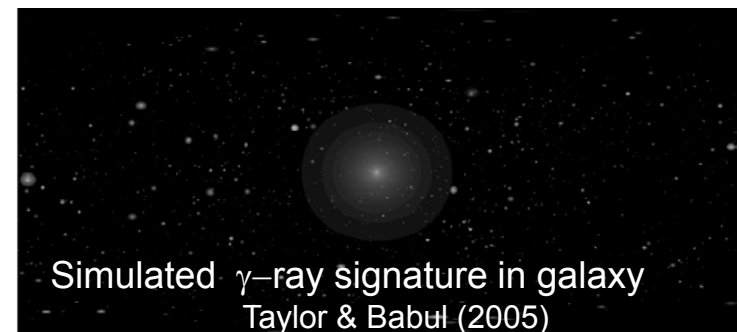
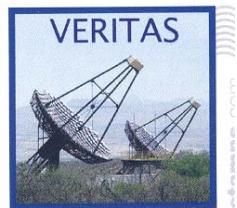
- Indirect detection of WIMP annihilation  $\rightarrow \gamma, \nu$  etc.

Target regions with:

- Favorable DM distributions.
- Large mass/light ratio.



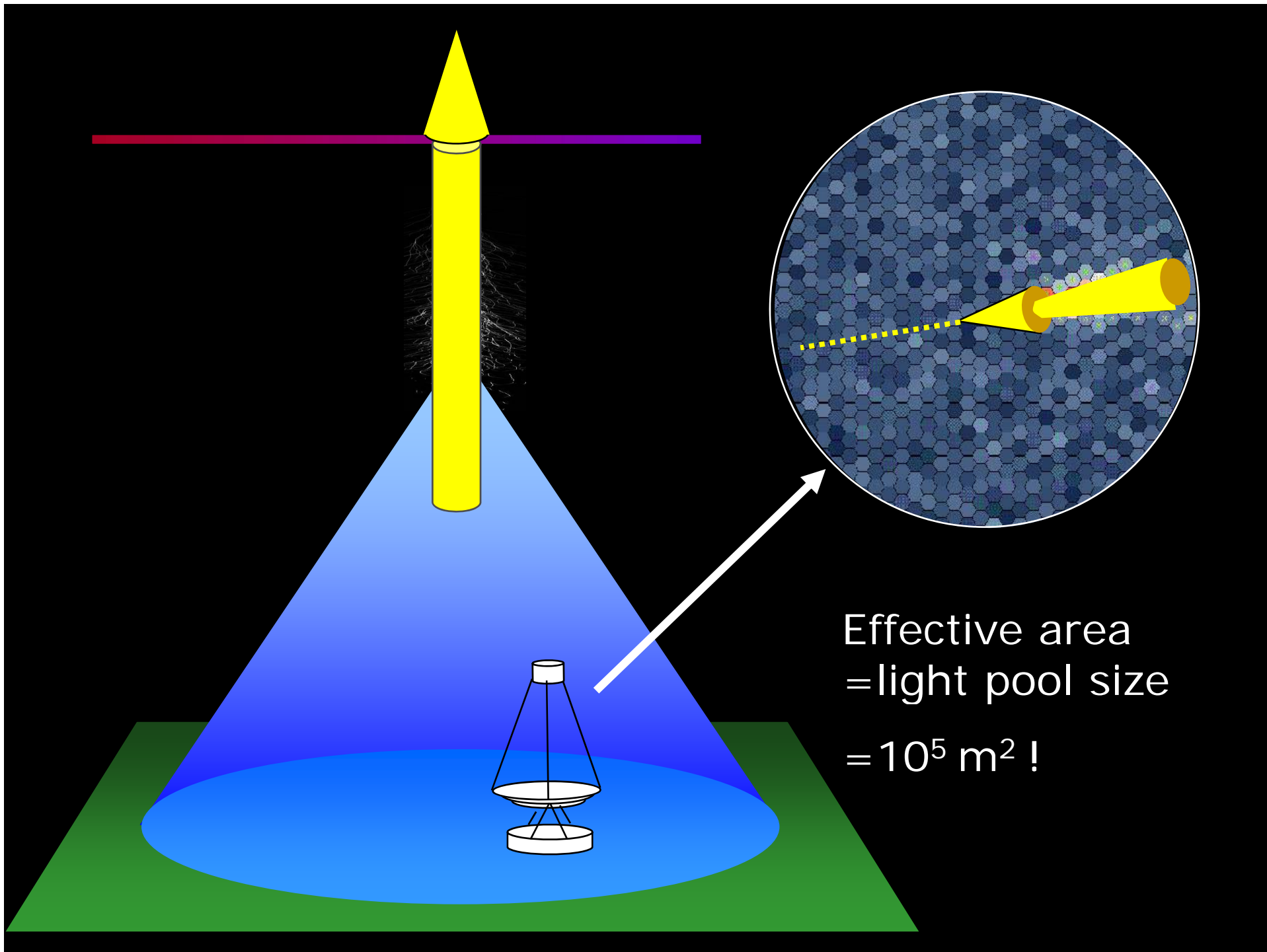
Point back to source  
(VERITAS, Fermi, IceCube)



**Complementary approach to direct detection & LHC  
Eventual goal is to do DM astronomy !**



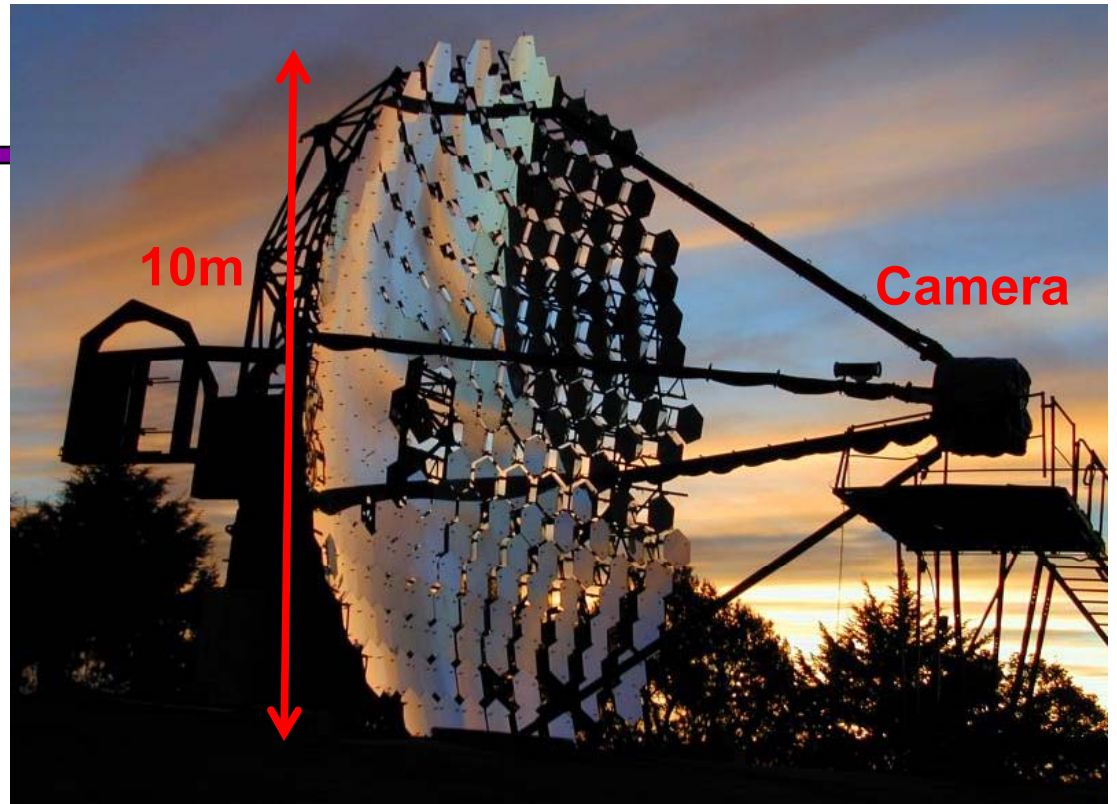
# **Experimental Technique**



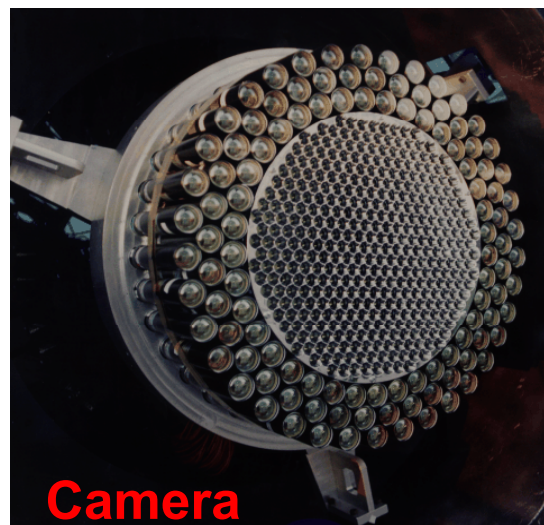
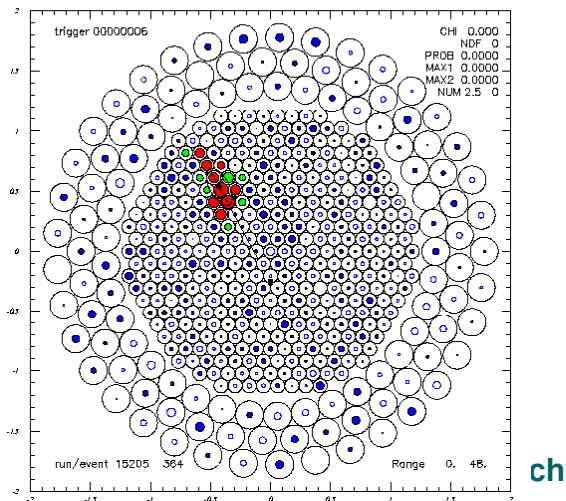
Effective area  
= light pool size  
=  $10^5 \text{ m}^2$  !

# Whipple 10m $\gamma$ -ray Telescope

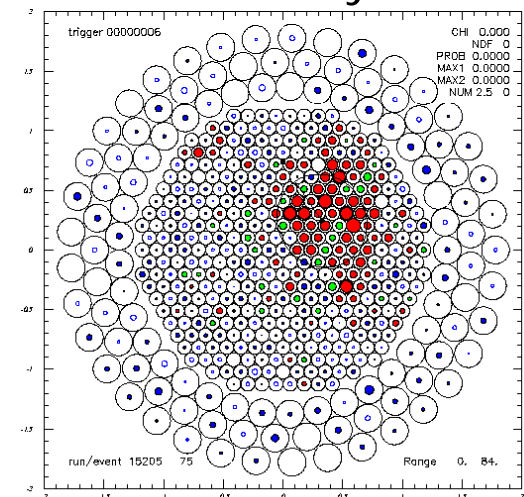
- The Whipple 10m (1968 - )
- Pioneered use of Imaging.  
(T. Weekes et al.)
- Made first source detections.  
(Crab Nebula in ~90 hours)



gamma ray?

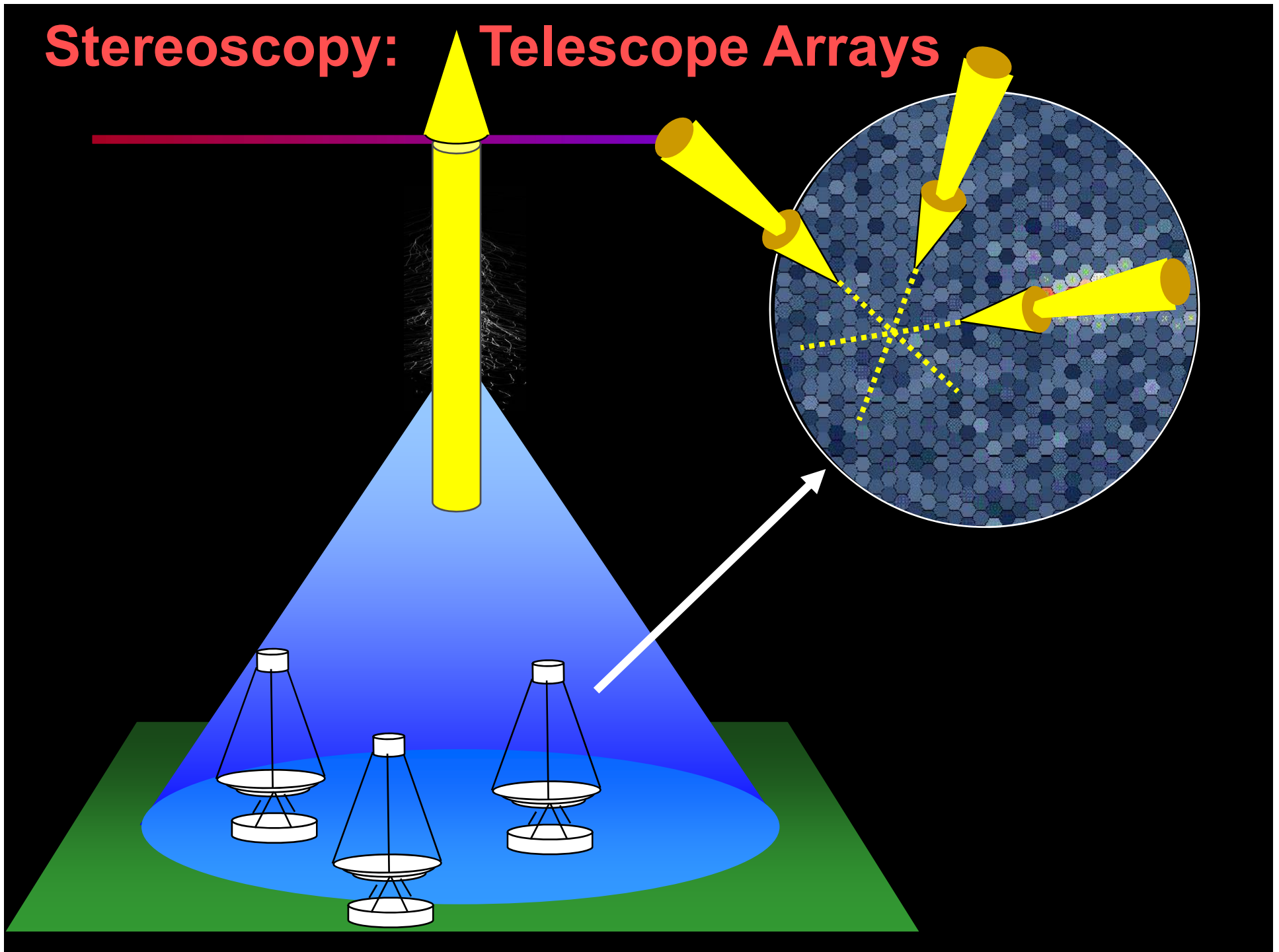


cosmic ray?

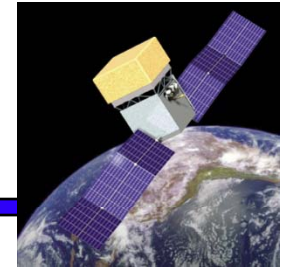




# Stereoscopy: Telescope Arrays

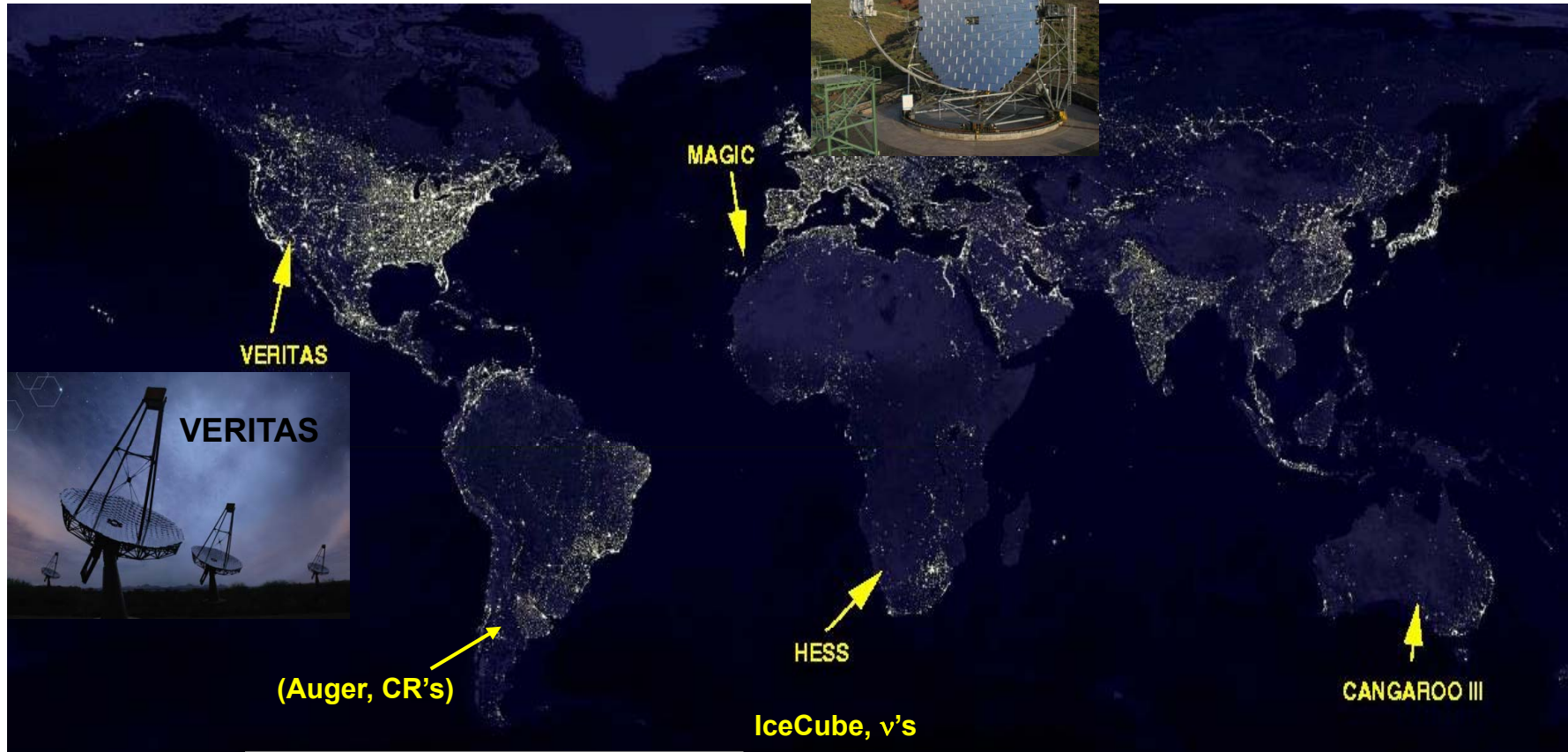


# Major VHE Telescopes



Fermi

Multi-messenger Astronomy



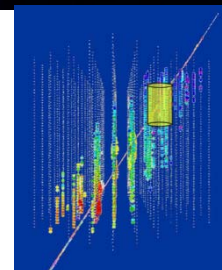
VERITAS



MAGIC



HESS



IceCube



CANGAROO

# VERITAS



Collaboration of ~100 scientists.  
24 Institutions in four countries.

## Detector Design:

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

## Performance:

- Energy threshold ~ 100 GeV.
- Ang. resolution ~ 4-6'.
- Pointing accuracy < 50".
- **Detect Crab Nebula in ~40s.**

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

# VERITAS: Mt. Hopkins, AZ



In 2007



## **U.S.:**

Adler Planetarium  
Argonne National Lab  
Barnard College  
DePauw Univ.  
Grinnell College  
Iowa State Univ.  
Purdue Univ.  
Smithsonian

Univ. of California, Los Angeles  
Univ. of California, Santa Cruz  
Univ. of Chicago  
Univ. of Delaware  
Univ. of Iowa  
Univ. of Massachusetts  
Univ. of Utah  
Washington Univ., St. Louis

## **Canada:**

McGill Univ.

## **U.K.:**

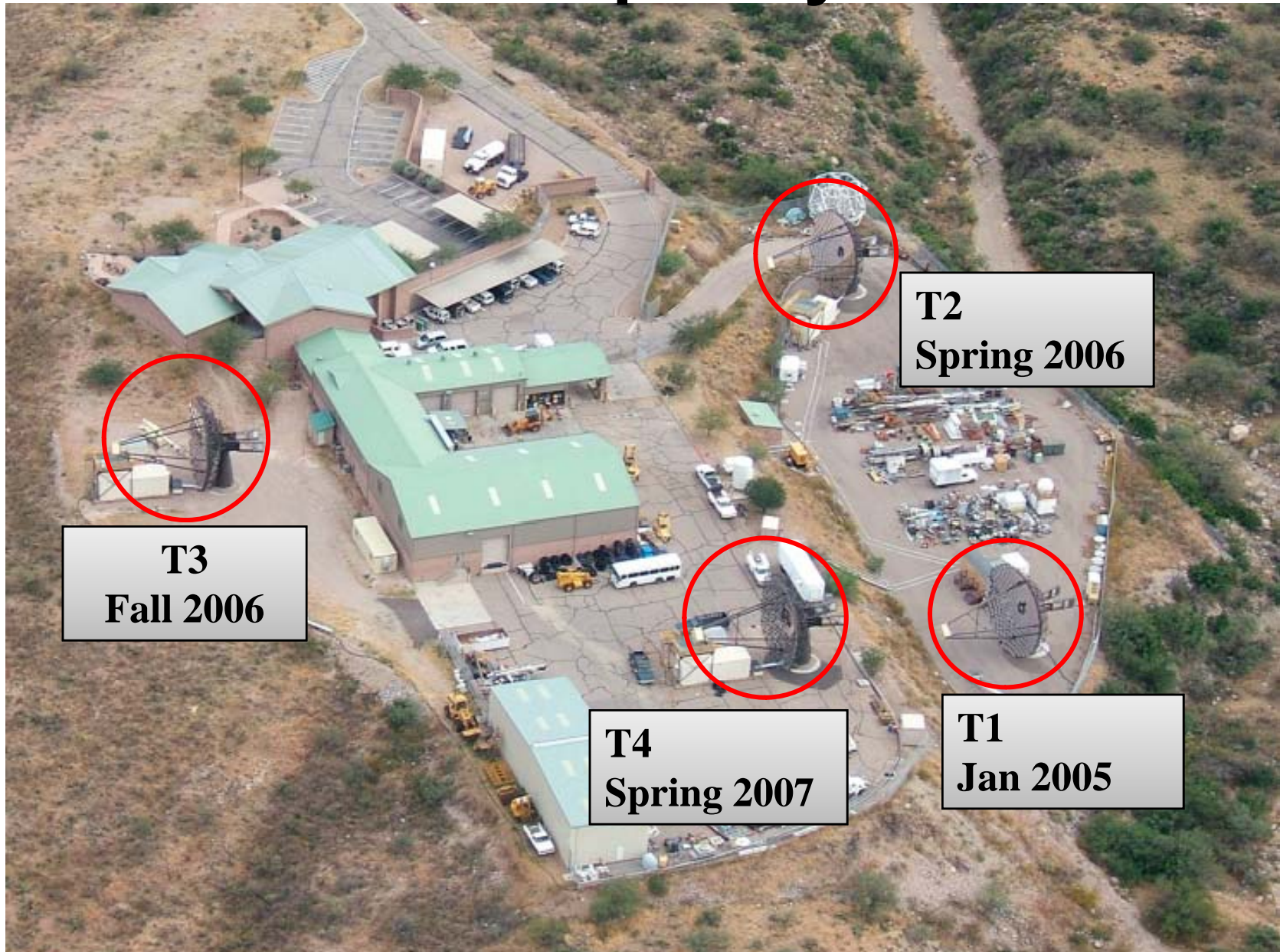
Leeds Univ.

## **Ireland:**

Cork Inst. Tech.  
Galway-Mayo Inst. Tech.  
Nat. Univ. Ireland, Galway  
Univ. College Dublin

**+ ~25 Associate Members**

# Telescope Layout

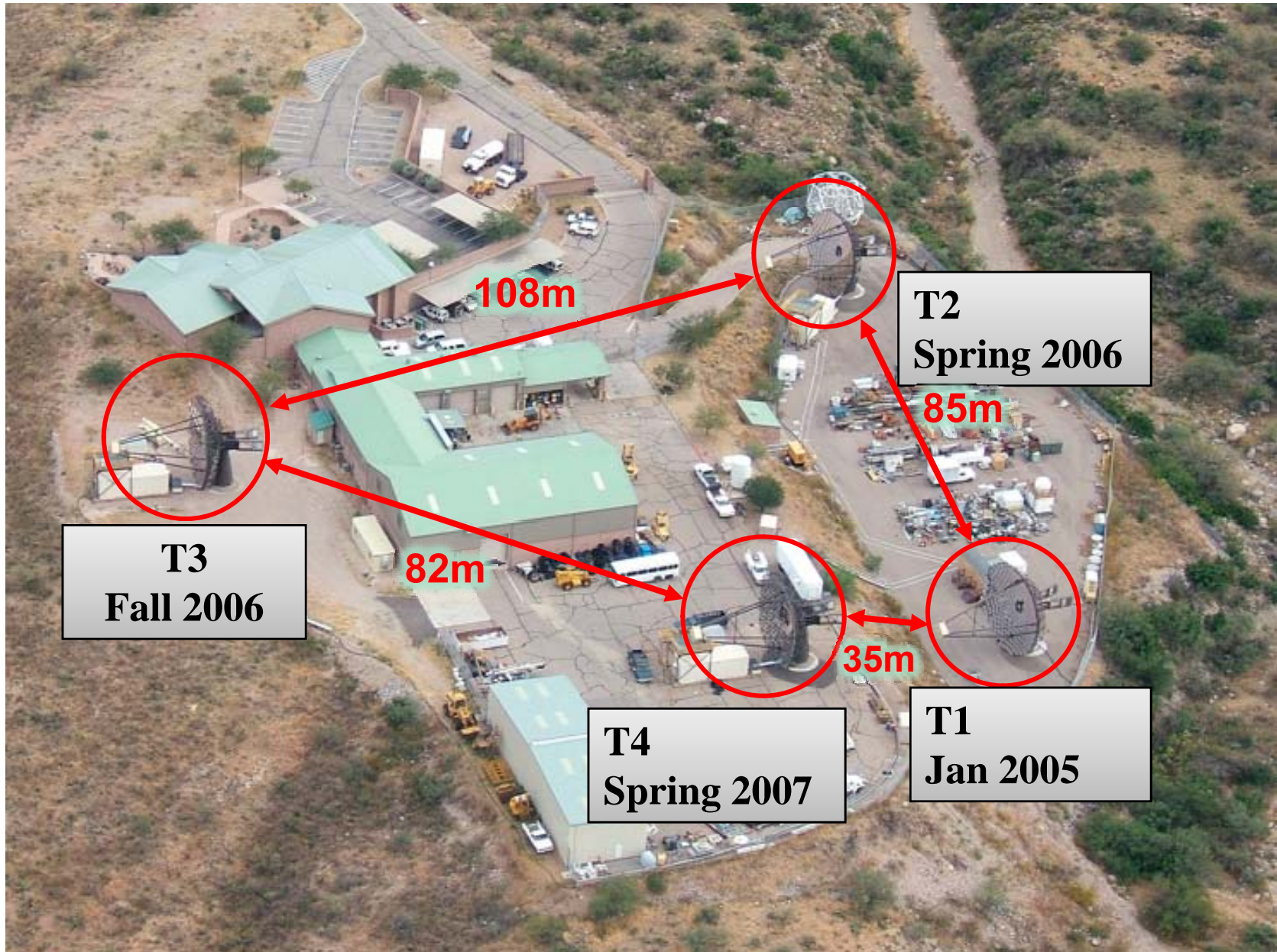


**T3**  
**Fall 2006**

**T2**  
**Spring 2006**

**T4**  
**Spring 2007**

**T1**  
**Jan 2005**

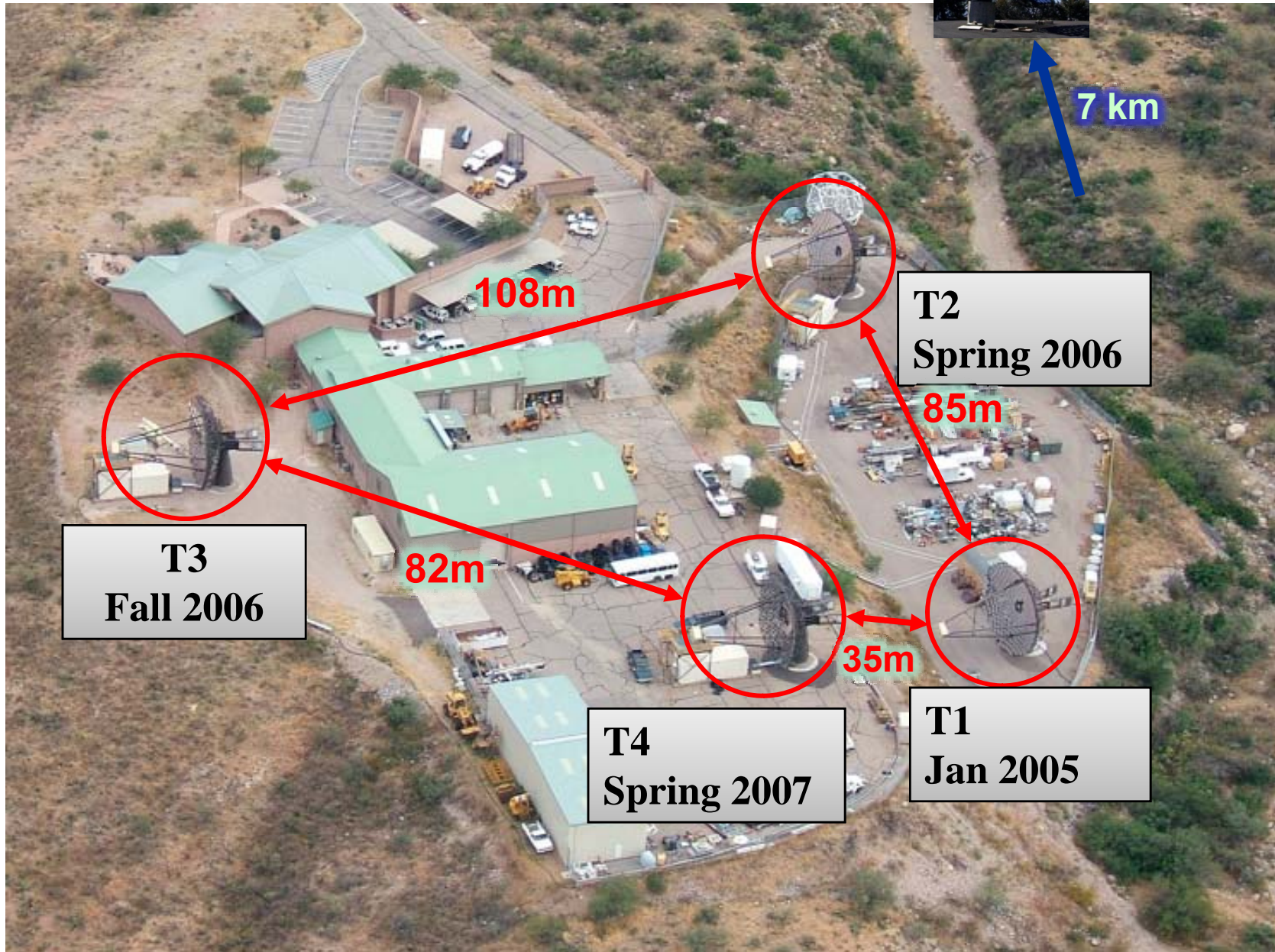


**T3**  
**Fall 2006**

**T2**  
**Spring 2006**

**T4**  
**Spring 2007**

**T1**  
**Jan 2005**



**T3**  
**Fall 2006**

**T2**  
**Spring 2006**

**T4**  
**Spring 2007**

**T1**  
**Jan 2005**

108m

85m

82m

35m

7 km

# T1 Relocated

T1  
Sep 2009



95m



T2  
Spring 2006

85m



T3  
Fall 2006

108m

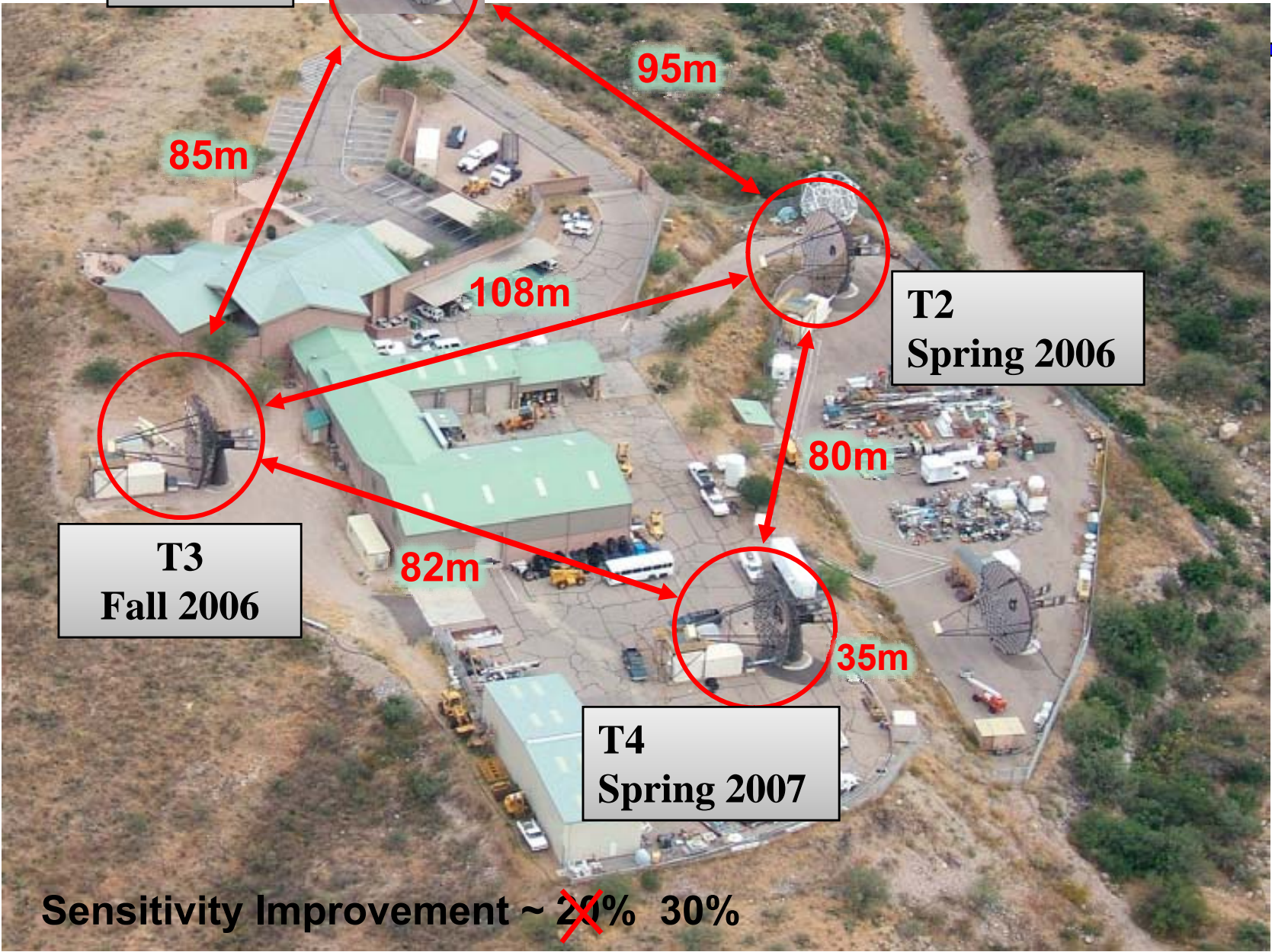
82m

T4  
Spring 2007

80m

35m

Sensitivity Improvement ~ ~~20%~~ 30%





# VERITAS (2010)



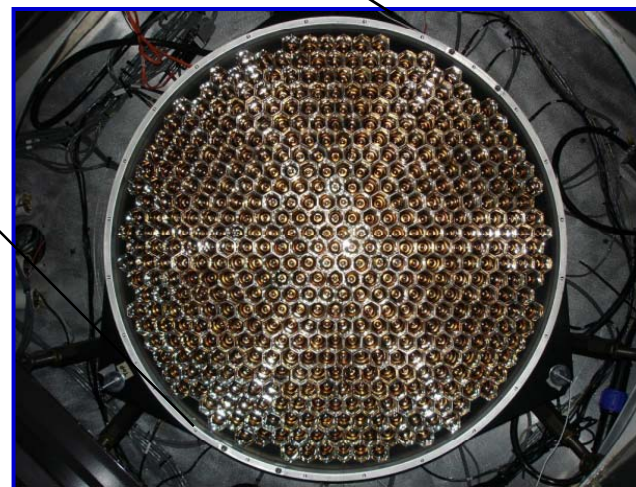
# A VERITAS Telescope



12m reflector, f1.0 optics



350 Mirror Facets

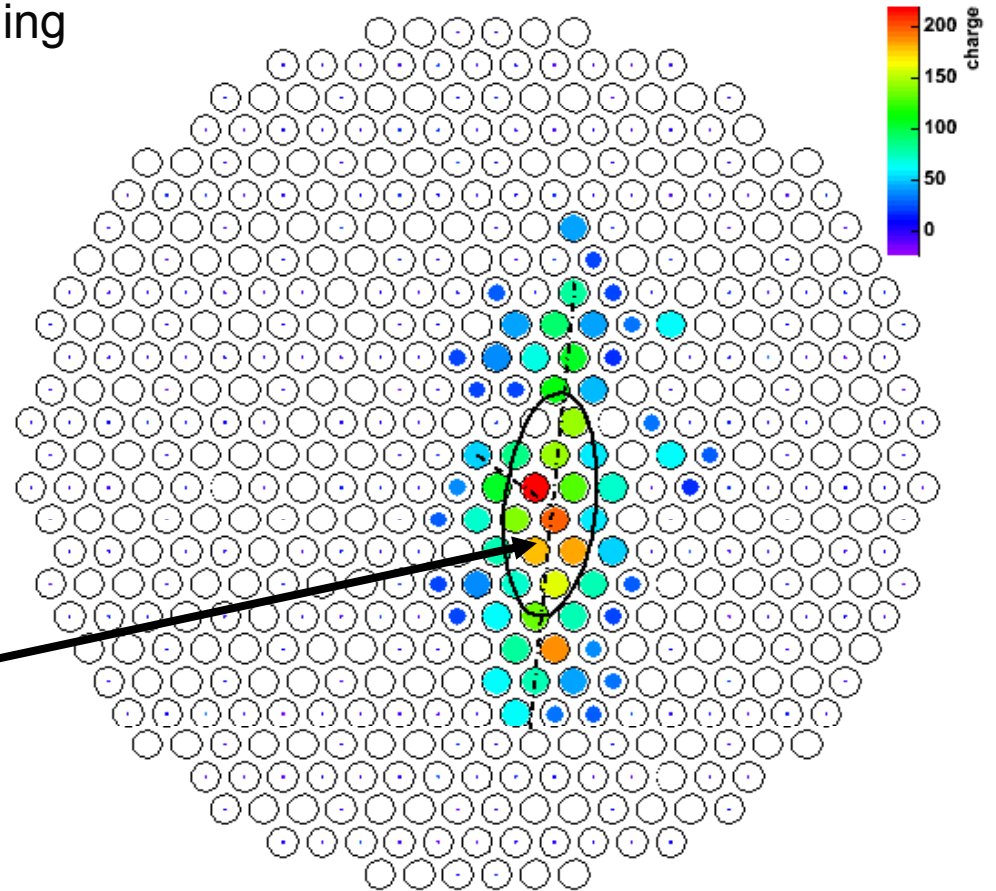
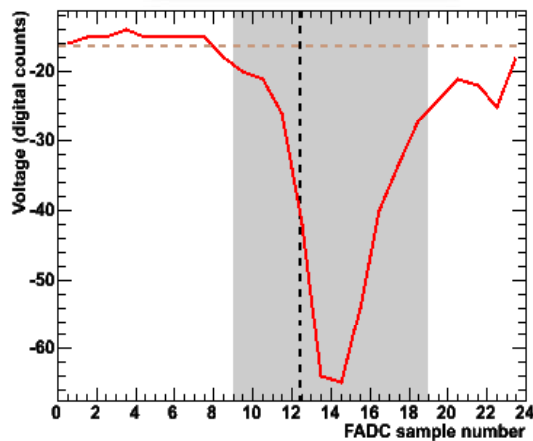


500 pixel Camera

# VERITAS Data Acquisition

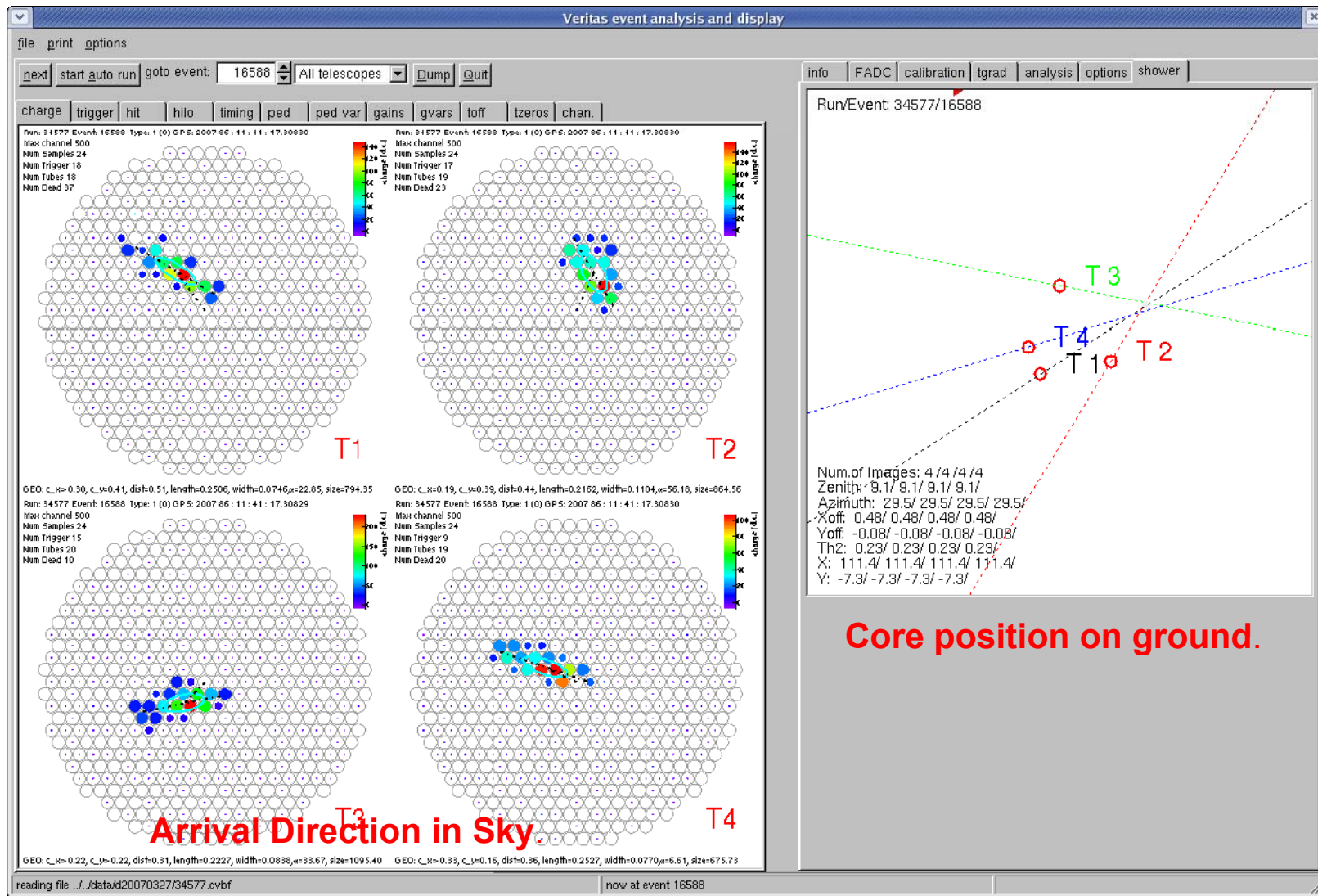


- PMTs digitized with 500 MHz sampling FADCs
  - 20 samples/channel.
  - <10% deadtime @ 250 Hz.



Timing & Amplitude on all channels.

# Four-Telescope Event





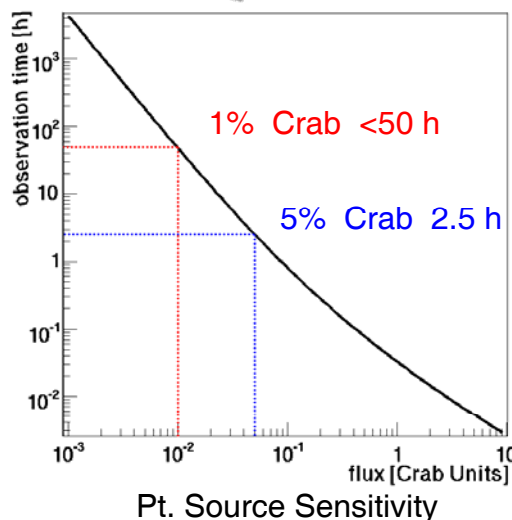
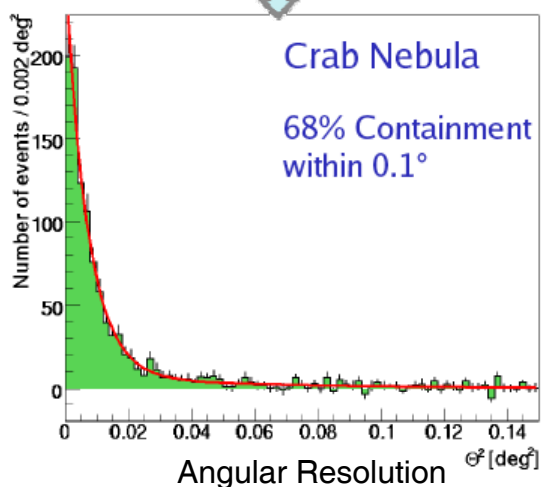
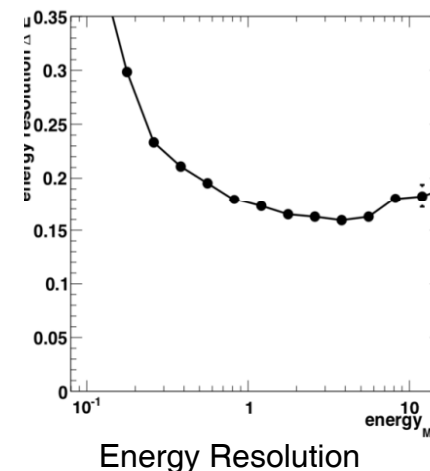
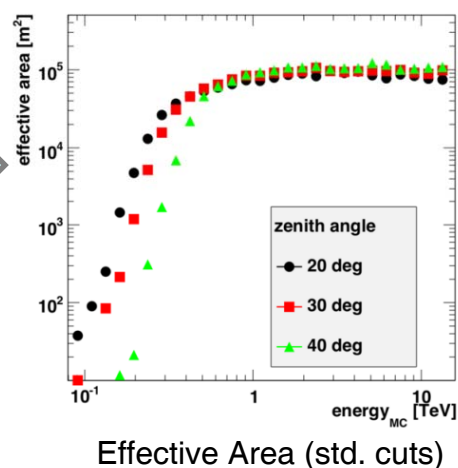
# VERITAS Performance

## Canonical Performance Values:

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

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

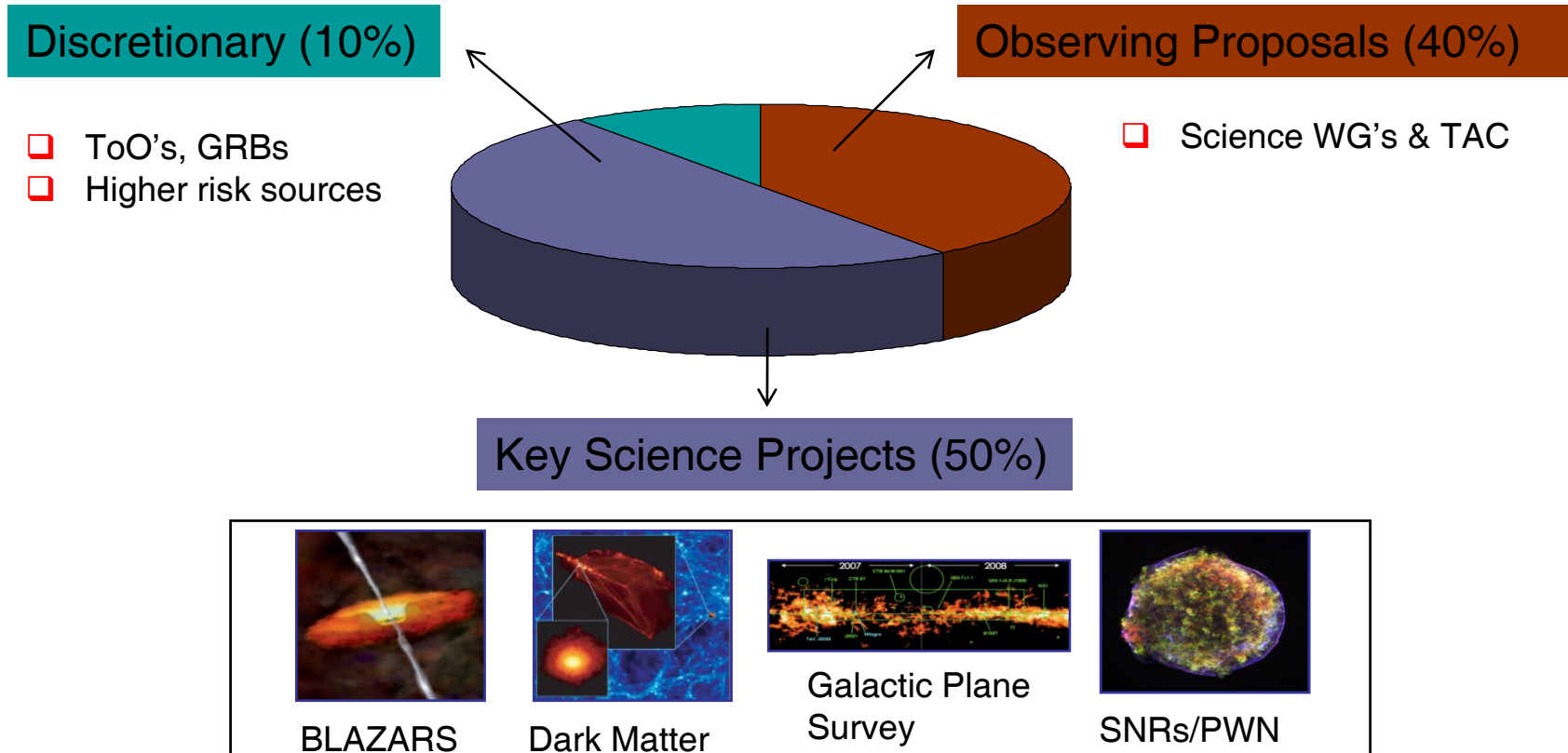
- Angular Resolution:  $r_{68} < 0.1^\circ$
- Pointing Accuracy: < 50''



## Operational & Analysis Improvements:

- “Hard” and “Soft” cuts permit improved E range, sensitivity.
- Enhanced reconstruction techniques give better sensitivity: **1% Crab ~ 40 h.**
- Future improvement: better PSF & new array configuration.

# Observation Strategy 2007-09



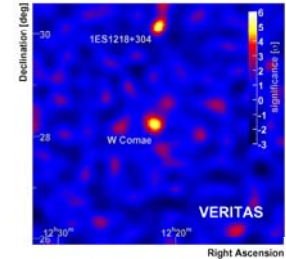
- ❑ **800 hours/year Dark Time + 25% Moonlight (= 1000 hours total).**
- ❑ **> 95% Data taken with all four telescopes operational.**

# VERITAS Science Highlights (so far)



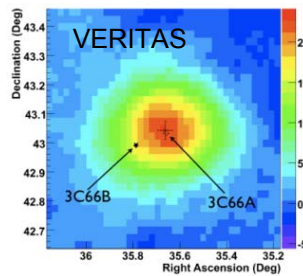
## 2007:

- ❑ **Detection of SNR IC 443 (w. MAGIC).**
- ❑ Detection binary LS I +61 303, confirming variability.
- ❑ Detection of blazar 1ES 1218+304 and radio galaxy M87.

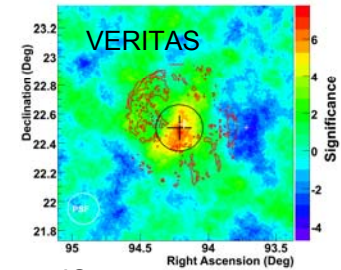


## 2008:

- ❑ Detection of blazar 1ES 2344+514, correlated TeV flare with X-ray.
- ❑ **Discovery of blazar 1ES 0806+524 (ATEL #1415).**
- ❑ **Discovery of blazar W Comae (ATEL #1422), a new LBL.**
- ❑ Detection of SNR Cas-A.
- ❑ **Discovery of blazar 3C 66A (ATEL #1753), the first IBL.**



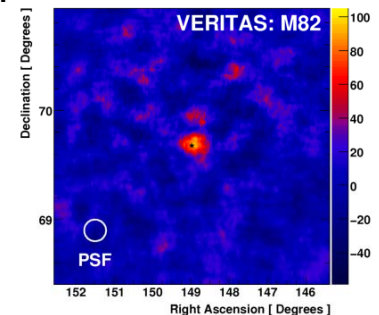
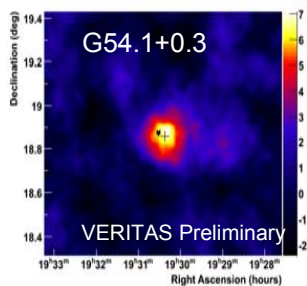
W Comae & 1ES 1218+304



IC 443

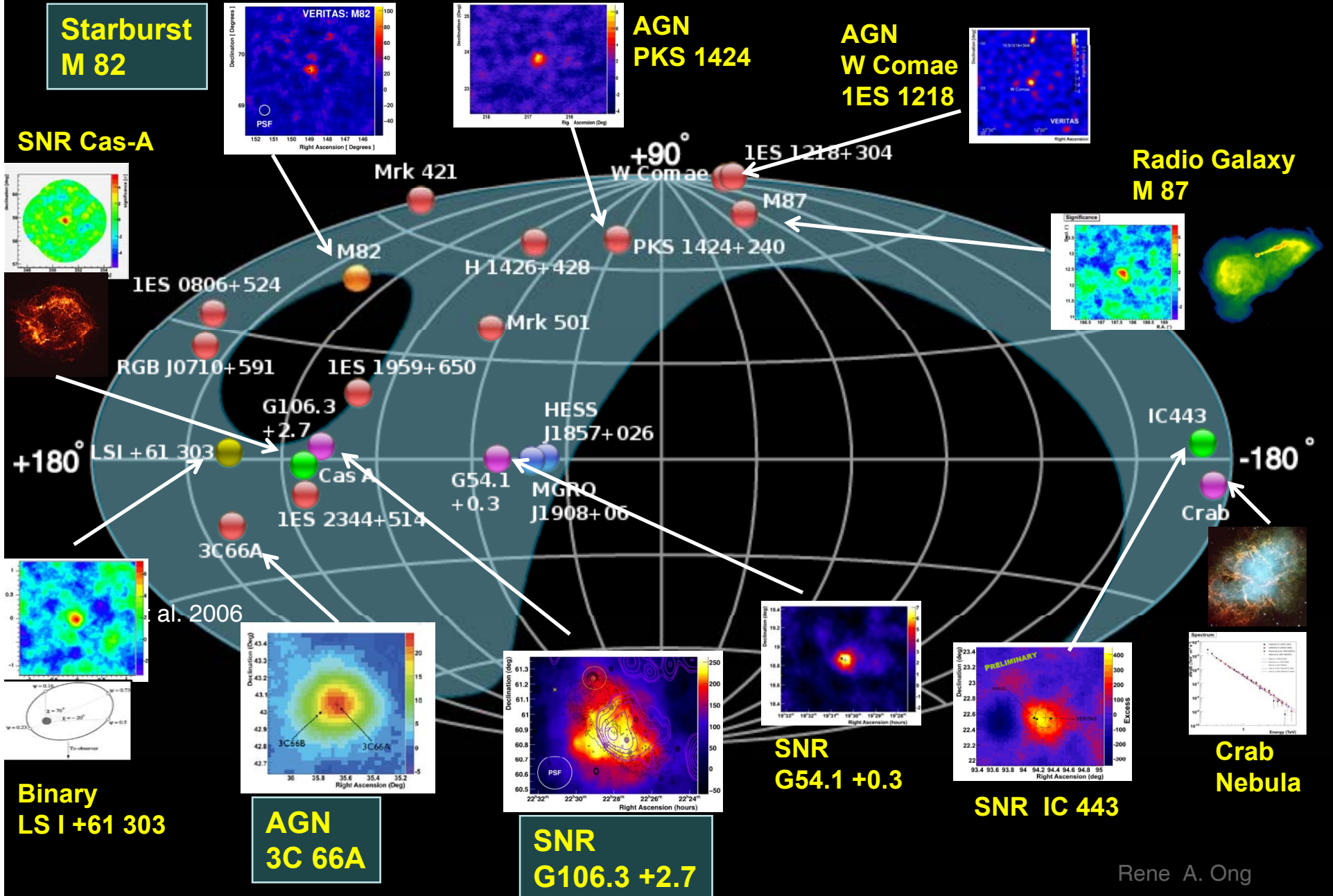
## 2009:

- ❑ Measurement of source extent of SNR IC 443.
- ❑ Simultaneous MWL observations of Mrk 421 reported (w. MAGIC).
- ❑ **Discovery of blazar RGB 0710 (ATEL #1941).**
- ❑ MWL observations of LS I +61 303 (w. Swift, RXTE).
- ❑ **Radio imaging of TeV emission region of M87 (w. MAGIC, HESS, VLBA).**
- ❑ Evidence for variability in HESS J0632+057.
- ❑ **July 09 (ICRC): 5 New Sources**
- ❑ **Discovery of M82 – starburst galaxy**
- ❑ **Discovery of 2 new Galactic sources and 2 new AGN.**



- ❑ **2010: First results from Sky Survey**
  - ❑ **Discovery of 5 new sources (2 AGN, 3 unidentified)**

# The VERITAS SKY (Oct 09)





# Recent High Profile Results



Science Magazine  
NEWS SCIENCE JOURNALS CAREERS BLOGS & COMMUNITIES MULTIMEDIA COLLECTIONS JOIN US/Subscribe

### Radio Imaging of the Very-High-Energy T-Ray Emission Region in the Central Engine of a Radio Galaxy

The VERITAS Collaboration, the VLBA 42 GHz NET Monitoring Team, the H.E.S.S. Collaboration, the MAGIC Collaboration

The activities of matter onto a massive black hole is believed to fuel the relativistic plasma jets found in many active galactic nuclei (AGN). Although some AGN accelerate particles to energies exceeding  $10^7$  electron volts and emit bright sources of very-high-energy (VHE) T-ray emission, it is not known where the VHE emission originates. Here we report on radio and VHE observations of the radio galaxy Messier 87, revealing a patch of extremely strong VHE T-ray flares accompanied by a strong increase of the radio flux from the nucleus. These results imply that charged particles are accelerated to very high energies in the immediate vicinity of the black hole.

M 87

Research.gov  
POWERING KNOWLEDGE AND INNOVATION

### VERITAS Discovers Very High Energy Gamma Rays from the Starburst Galaxy M82

Agency: NSF  
Date: November 02, 2009

The VERITAS (Very Energetic Radiation Imaging Telescope Array System) collaboration, an international team of astronomers from the United States, Canada, United Kingdom and Ireland, has discovered very high energy (VHE) gamma rays emitted by the starburst galaxy M82 (the Cigar Galaxy). The observed gamma rays have energies more than a billion times higher than the energy of visible light, and are the highest energy photons ever detected from a galaxy undergoing rapid star formation. This discovery was made from observations taken in less than one hour of observing time.

This is the first example of a very-high-energy gamma ray source associated with a starburst galaxy, and its discovery provides fundamental insight into the origin of cosmic rays. "and Rene Ong, a professor of physics at the University of California, Los Angeles, and the spokesperson for the VERITAS collaboration. "Our program has been supporting studies of VHE gamma rays and cosmic rays in separate and very different experiments for over a decade." said Jim Whitcomb, principal investigator for particle and nuclear astrophysics in NSF's Division of Physics. "This significant VERITAS discovery provides an immediate connection between the activities of these two types of very energetic particles and enhances our understanding of the early universe."

Cosmic rays are particles striking the Earth's atmosphere and are produced in violent processes in our own Milky Way galaxy and beyond. Although the Earth is constantly bombarded by cosmic rays, their origin remains a mystery nearly 100 years after their discovery. The VERITAS would provide critical evidence to help scientists understand the origin of cosmic rays by simply being the discovery of the Messier 82 starburst with the acceleration of cosmic rays.

The VERITAS observations strongly support the long held theory that supernovae and massive star winds are the dominant accelerators of cosmic ray particles. Observations with high levels of star formation such as M82 have high numbers of supernovae and massive stars. These "nucleus" galaxies would then be expected to have a higher number of cosmic rays per unit volume.

The VERITAS discovery indicates that the cosmic-ray density in M82 is approximately 500 times the average density in our Galaxy, the Milky Way.

M 82

nature  
International weekly journal of science

### A connection between star formation activity and cosmic rays in the starburst galaxy M82

The VERITAS Collaboration

1. Department of Physics and Astronomy, University of California, Los Angeles, Irvine, CA 92697, USA  
2. Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada  
3. Department of Physics and Astronomy, University of Alberta, Edmonton, Alberta, Canada  
4. Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada  
5. Department of Physics and Astronomy, University of Western Ontario, London, Ontario, Canada  
6. Department of Physics and Astronomy, University of Toronto, Toronto, Ontario, Canada  
7. Department of Physics and Astronomy, University of New Brunswick, Saint John, New Brunswick, Canada  
8. Department of Physics and Astronomy, University of Regina, Regina, Saskatchewan, Canada  
9. Department of Physics and Astronomy, University of Saskatchewan, Saskatoon, Saskatchewan, Canada  
10. Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, Canada  
11. Department of Physics and Astronomy, University of Ottawa, Ottawa, Ontario, Canada  
12. Department of Physics and Astronomy, University of Guelph, Guelph, Ontario, Canada  
13. Department of Physics and Astronomy, University of Windsor, Windsor, Ontario, Canada  
14. Department of Physics and Astronomy, University of Northern Iowa, Cedar Rapids, Iowa, USA  
15. Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA  
16. Department of Physics and Astronomy, University of New Hampshire, Durham, New Hampshire, USA  
17. Department of Physics and Astronomy, University of Mississippi, Oxford, Mississippi, USA  
18. Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina, USA  
19. Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina, USA  
20. Department of Physics and Astronomy, University of Texas at Dallas, Dallas, Texas, USA  
21. Department of Physics and Astronomy, University of Texas at Austin, Austin, Texas, USA  
22. Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, Texas, USA  
23. Department of Physics and Astronomy, University of Texas at El Paso, El Paso, Texas, USA  
24. Department of Physics and Astronomy, University of Texas at Permian Basin, Amarillo, Texas, USA  
25. Department of Physics and Astronomy, University of Texas at Tyler, Tyler, Texas, USA  
26. Department of Physics and Astronomy, University of Texas at Brownsville, Brownsville, Texas, USA  
27. Department of Physics and Astronomy, University of Texas at San Marcos, San Marcos, Texas, USA  
28. Department of Physics and Astronomy, University of Texas at El Paso, El Paso, Texas, USA  
29. Department of Physics and Astronomy, University of Texas at Dallas, Dallas, Texas, USA  
30. Department of Physics and Astronomy, University of Texas at Austin, Austin, Texas, USA

NewScientist  
Space

### Transparent universe reveals hidden galaxies

10 December 2009 | New Scientist | Mozilla Firefox

The universe is far more transparent to high-energy light than we thought. The discovery, based on sightings of ultraviolet light from the Lyman-alpha forest, the first galaxies, has implications for our understanding of the galaxies we look and work.

Blue light travels through the cosmic voids. But photons with very high energy of more than 100 gigaelectronvolts can collide with ionized hydrogen light. The Lyman-alpha forest, the first galaxies, has implications for our understanding of the galaxies we look and work. Blue light travels through the cosmic voids. But photons with very high energy of more than 100 gigaelectronvolts can collide with ionized hydrogen light. The Lyman-alpha forest, the first galaxies, has implications for our understanding of the galaxies we look and work. Blue light travels through the cosmic voids. But photons with very high energy of more than 100 gigaelectronvolts can collide with ionized hydrogen light. The Lyman-alpha forest, the first galaxies, has implications for our understanding of the galaxies we look and work.

1ES 0502+675  
Rene A. Ong

physicstoday  
Physics Update

### Seeing cosmic-ray sources

At 200 GeV or more, cosmic rays are thought to be produced by supernovae. But the evidence has been inconclusive. Observations made in 2008 with the VERITAS observatory have revealed that the diffuse gamma-ray emission from the Milky Way disk is attributed largely to each particle from a field of 100 supernovae. But to determine whether the disk glow is due to the galaxy, 10 supernovae were observed. And observations of first galaxies have found 10 supernovae to produce 100 gamma rays. These observations have been reported in the journal Science.

The new VERITAS gamma-ray results have opened the first glimpse of first galaxies and the cosmic-ray emission from the Milky Way. The new VERITAS gamma-ray results have opened the first glimpse of first galaxies and the cosmic-ray emission from the Milky Way. The new VERITAS gamma-ray results have opened the first glimpse of first galaxies and the cosmic-ray emission from the Milky Way.

# NEW: Starburst Galaxy M 82

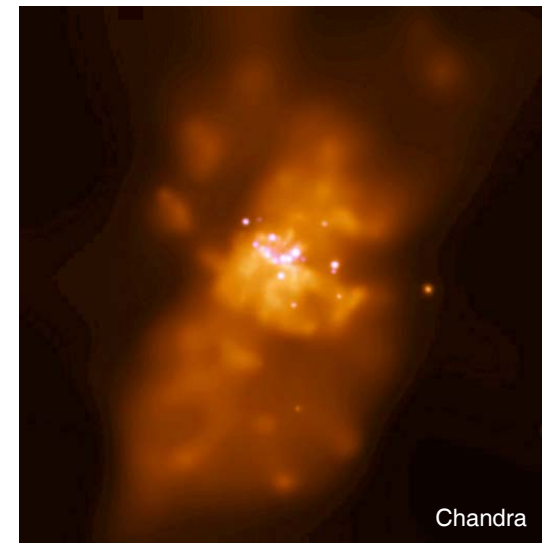
---

## ❑ M82: Prototype starburst galaxy

- Interacting with group of galaxies over ~300 Myrs.
- Tidal forces → active starburst region (HST shows > 200 massive star clusters).
- SMBH <  $3 \times 10^7 M_{\text{sun}}$ , but no AGN activity.

## ❑ Starburst Region

- High star formation and SNR rate.
- High CR density (from radio emission).
- High gas density  $\sim 150 /\text{cm}^3$ .
- $\gamma$ -rays from cosmic rays interacting with gas and photon fields.  
Gives insight onto origin of CR's.
- Previous limits < 10% Crab (HEGRA, Whipple).



# NEW: Starburst Galaxy M 82

## ❑ VERITAS Data & Analysis

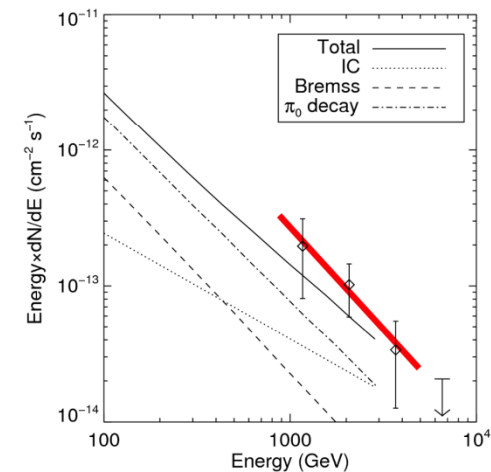
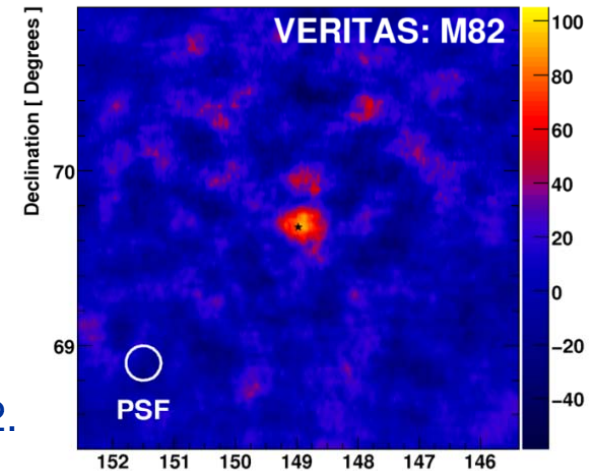
- 2007-09: 137 h live time.  
Extremely long exposure.

## ❑ Detection !

- Small signal, but consistent with point source at M82.
- Many systematic checks.
- Among weakest VHE sources  $\sim 0.8\%$  Crab.
- Fermi (GeV) subsequently announced M82 detection.

## ❑ Interpretation

- **First detection of extragalactic VHE source not clearly associated with AGN activity.**
- Consistent with predictions, general nature of CR interactions. In principle, a whole new set of extragalactic sources now accessible.

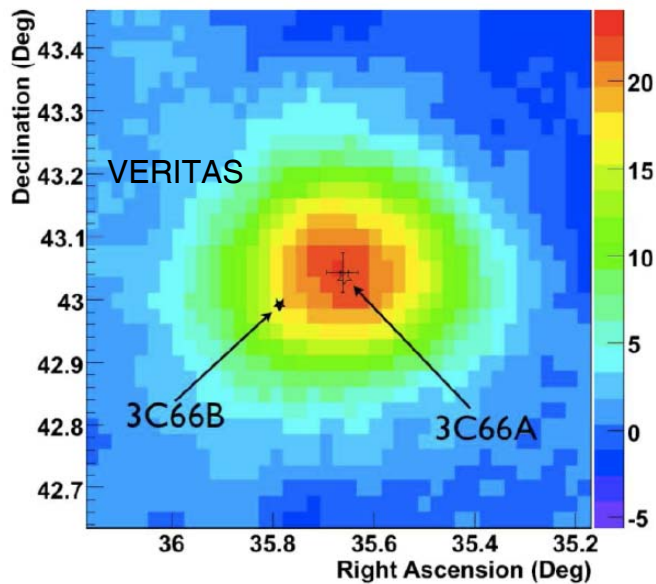


“A Connection between Star Forming Activity and Cosmic Rays in the Starburst Galaxy M 82,” V. Acciari et al., Nature, 02 November 2009.

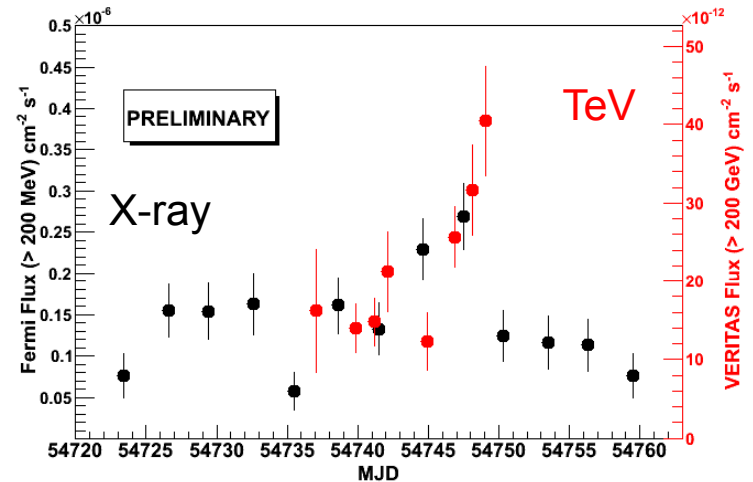
# 3C 66A: A Typical VERITAS Blazar

## 3C 66A

- Int. BL Lac at nominal  $z=0.44$ .
- **VERITAS discovery  $21\sigma$ , 33h, Flare !**  
ATEL #1753, V.A. Acciari et al., ApJ 693, L104 (2009)
- Soft spectrum:  $\Gamma = 4.1 \pm 0.4_{\text{stat}} \pm 0.6_{\text{sys}}$   
(due to absorption ?) .

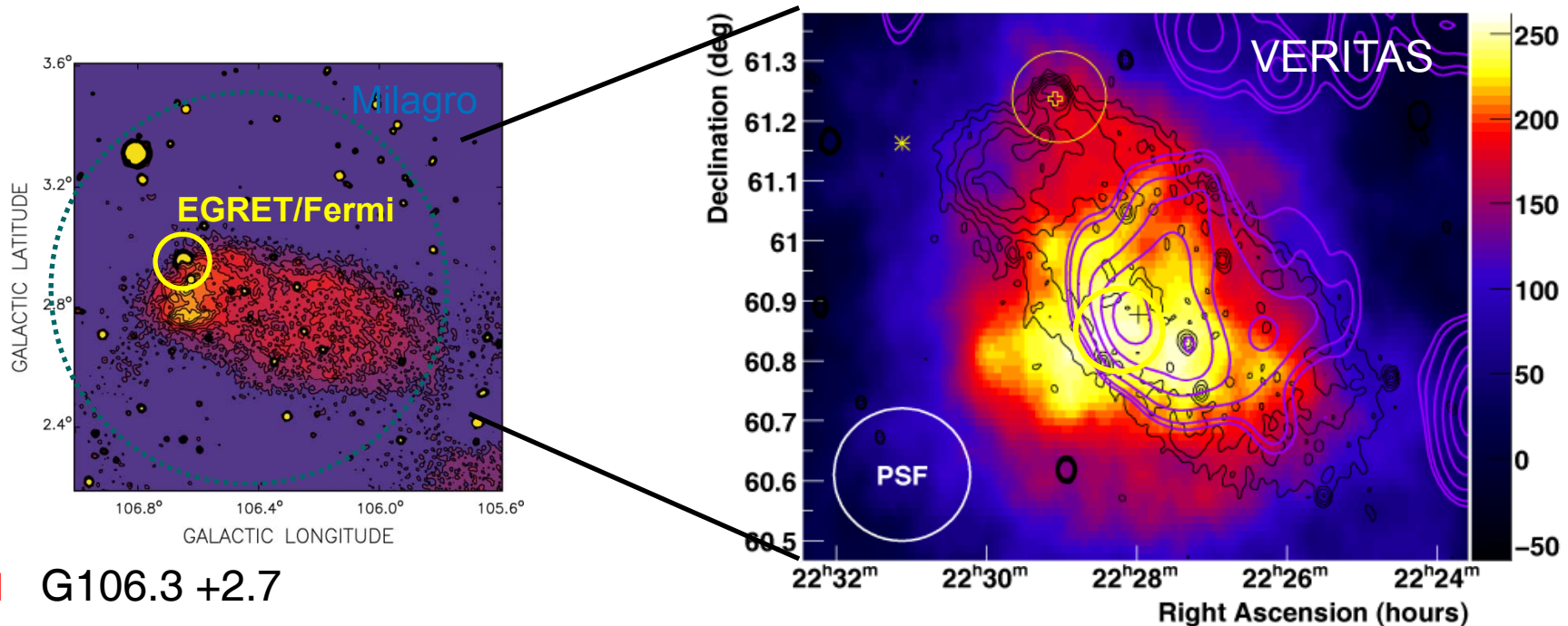


## TeV $\gamma$ -ray flare Correlated with X-rays, also Fermi



- ❑ MAGIC reports 3C66B  $0.12^\circ$  away.  
 $5.4\sigma$  in 54 h from 2007 data.
- ❑ VERITAS data excludes 3C66B at  $4.3\sigma$ .
- ❑ **VERITAS clearly detects this very distant object; this has clear implications for understanding the EBL.**  
(Paper in works with Fermi-LAT).

# NEW: SNR G106.3 +2.7 (“Boomerang”)



## □ G106.3 +2.7

- Energetic pulsar PSR and SNR  
E-dot  $\sim 2 \times 10^{37}$  erg/s, age  $\sim 10$  ky.
- EGRET error ellipse  
Fermi-LAT pulsar J2229.0+6114.
- Milagro reports  $> 10$  TeV emission from region.

## □ VERITAS Results

V. A. Acciari et al., ApJ 703, L6 (2009).

- 33 h data, solid detection, flux  $\sim 5\%$  Crab.
- Clearly extended, peak overlaps CO.
- $\Gamma = 2.3 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$ ,  
hard power-law spectrum.

Points towards Hadronic Origin

Rene A. Ong

# Dark Matter Searches



## ❑ VERITAS DM Program

- Comprehensive program, ~ 7% of observing time, variety of objects:

Dwarf Galaxies (Draco, Willman I)

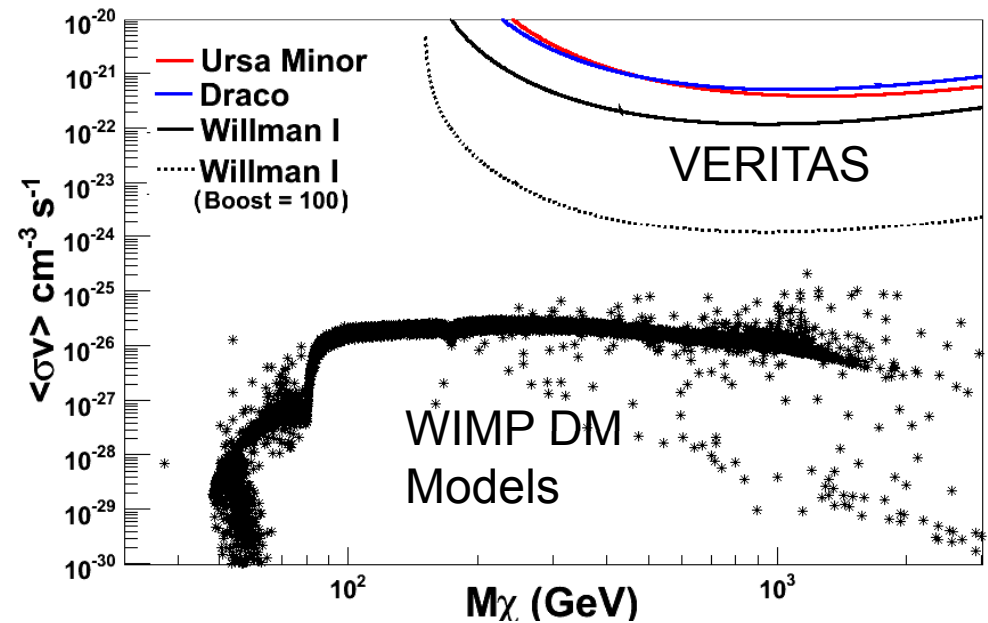
Local Galaxies (M32, M33)

Globular Clusters (M5)

Galaxy Clusters (Coma)

- **So far, no Detections**  
→ **Limits on 7 candidate sources**  
**Observations to continue, now including Galactic center.**

VERITAS limits on dwarf galaxies



# What's next for VERITAS ?

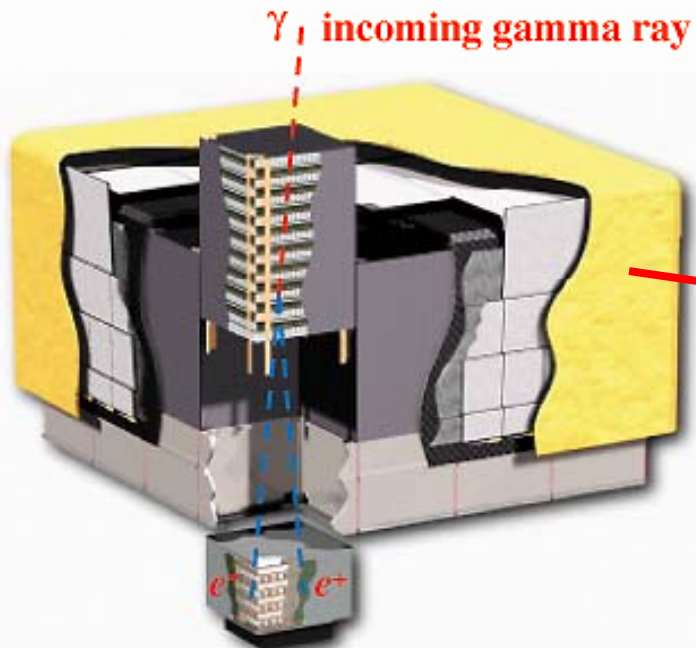
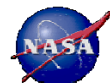
---

Many Things !

- New Results: 6 new sources in last six weeks.
- Observing: completed 2 years of >5 year program.
- Fermi Gamma-Ray Space Telescope: important overlap.
- Spectra and modelling: → source mechanisms.
- MWL studies: radio, optical, X-ray,  $\gamma$ -ray.
- Upgrade: new cameras, topological trigger.
- ...

# Fermi GST

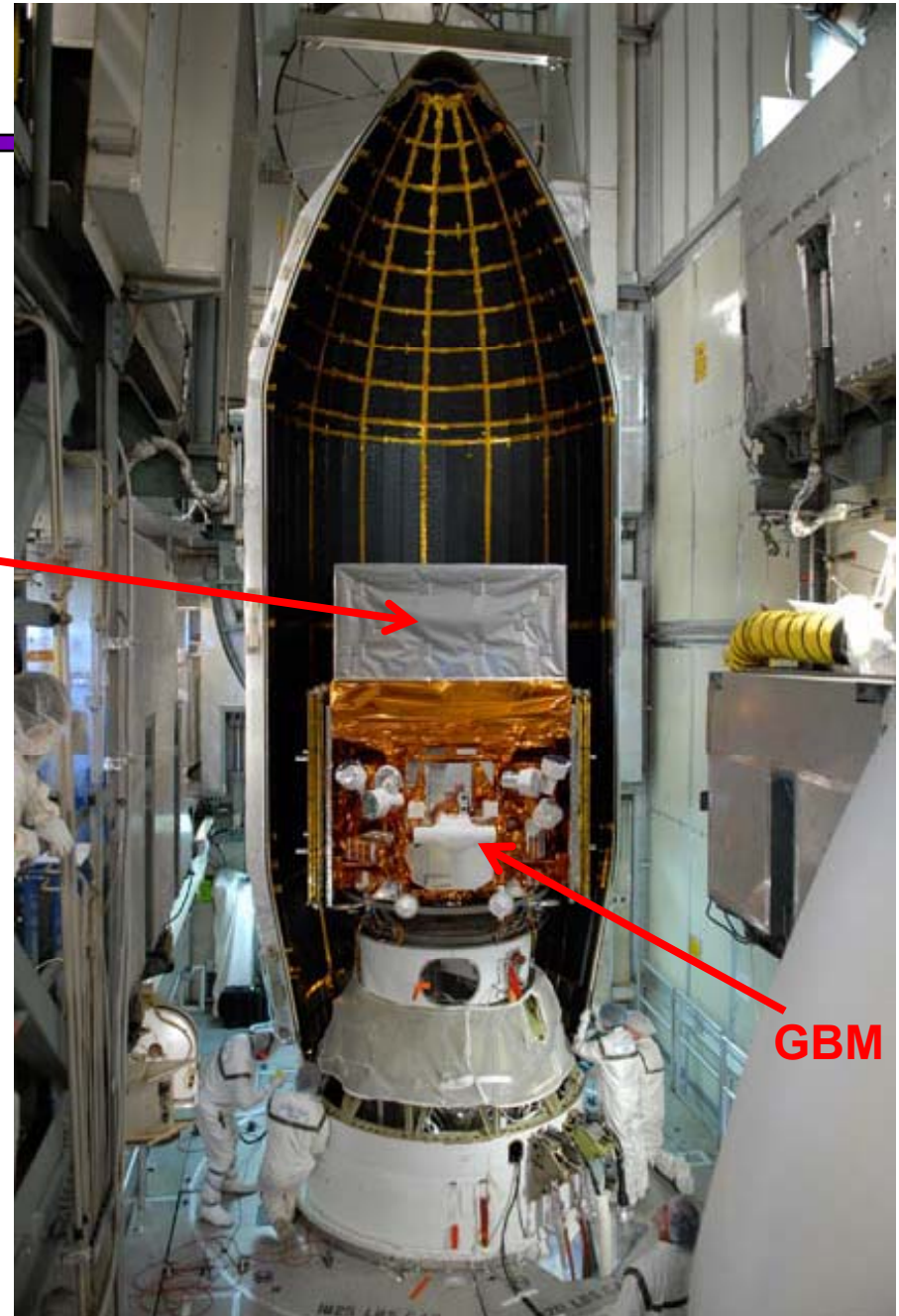
## Large Area Telescope (LAT)



electron-positron pair

$\gamma$ -ray converts in LAT to an electron and a positron ; tracking these give us the direction and energy of the photon.

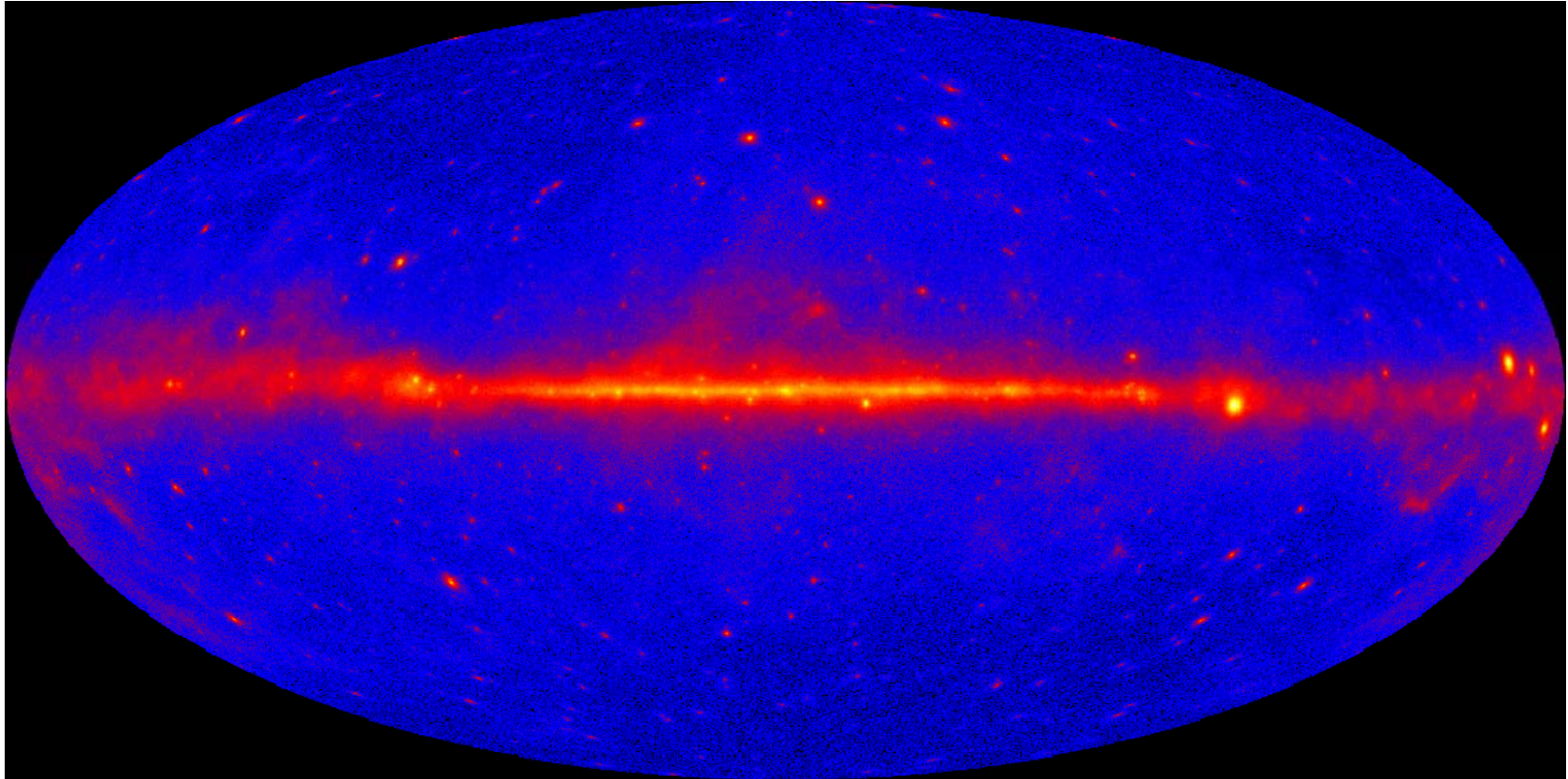
Launched from Cape Canaveral  
11 June 2008





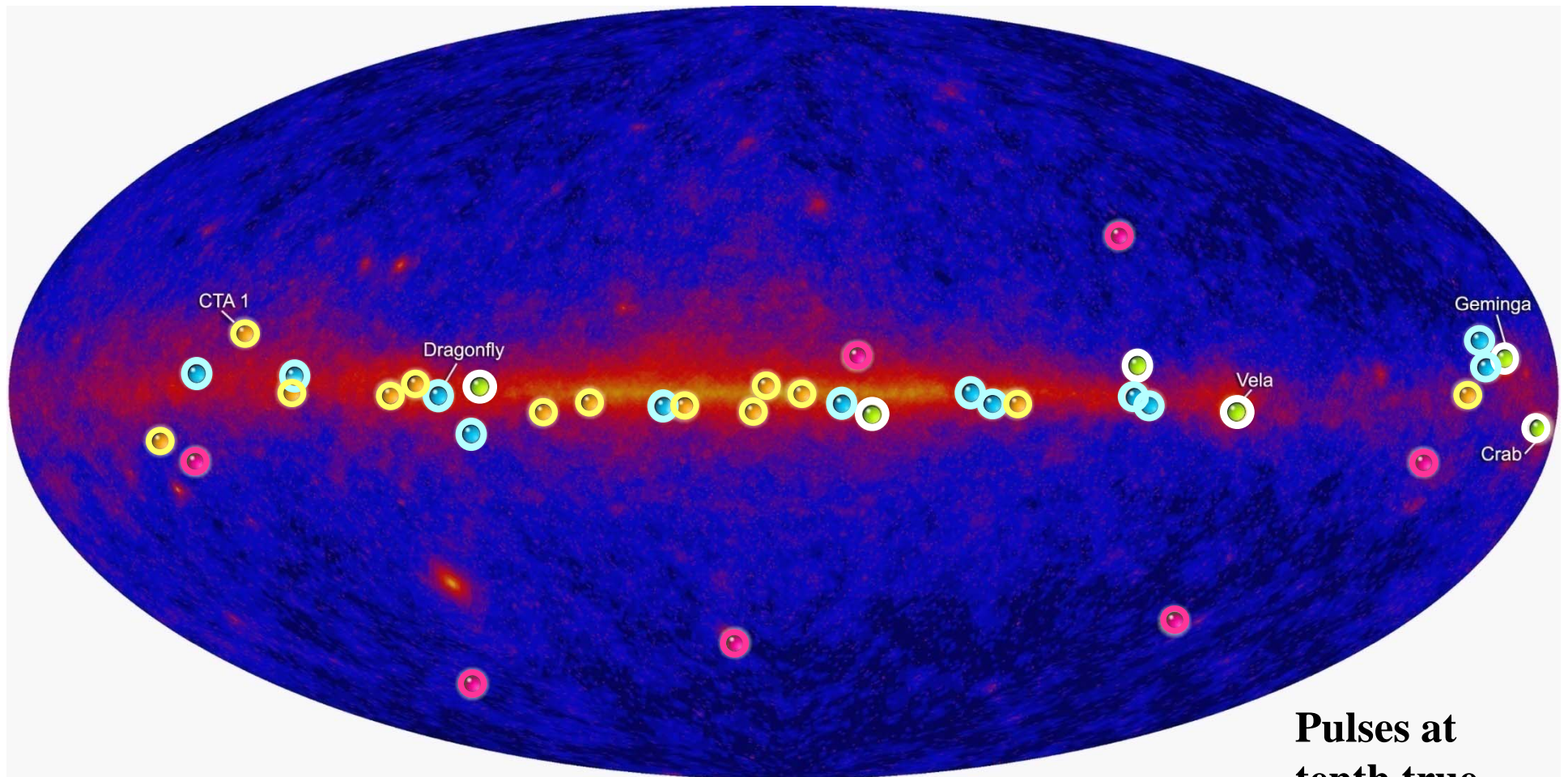
# Fermi $\gamma$ -ray Sky after 1 year

---



Fermi basically sees the same types of sources as TeV telescopes.  
(main exceptions: diffuse emission, pulsars and GRBs).

# $\gamma$ -ray Pulsars Detected by Fermi



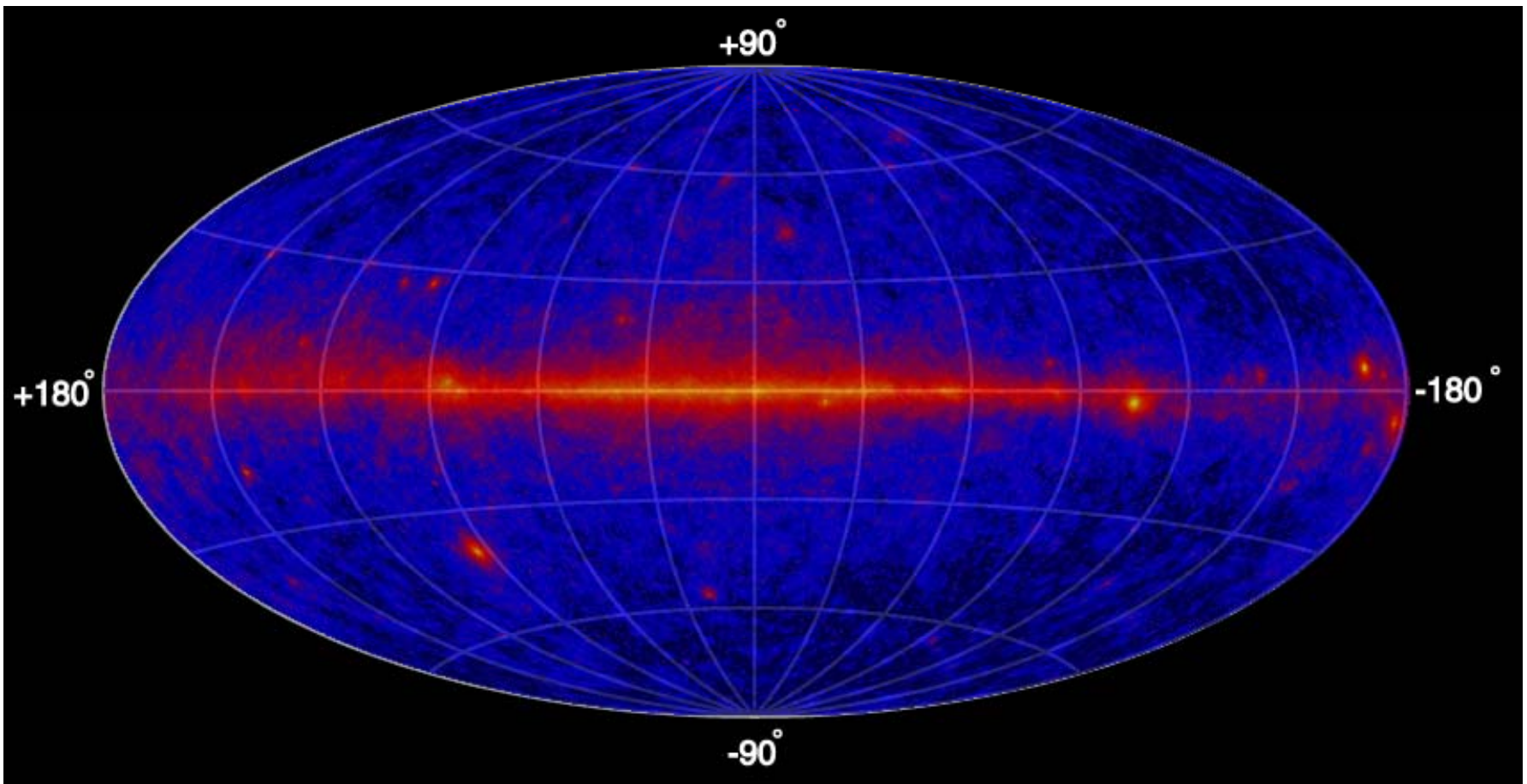
Fermi Pulsar Detections

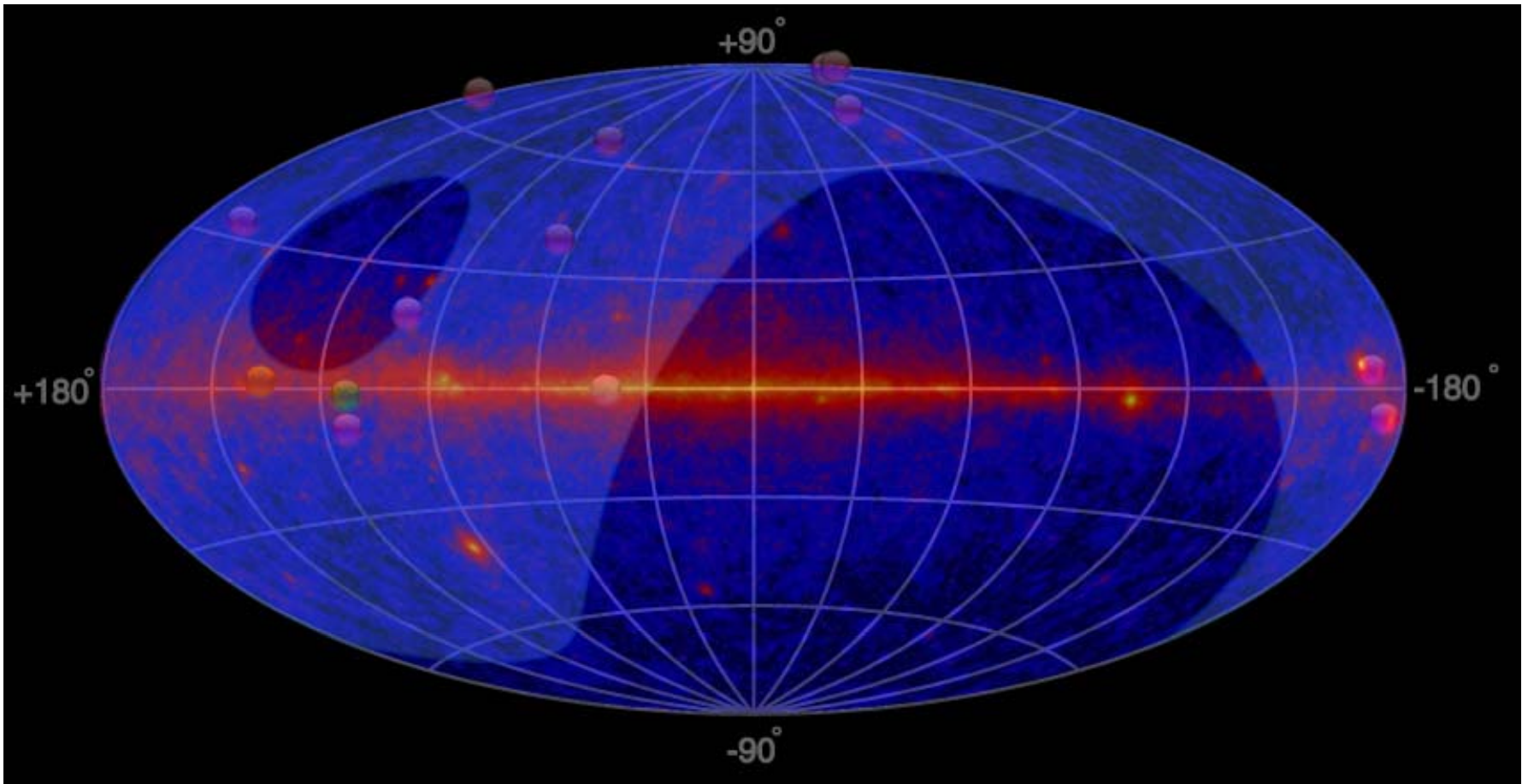
- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Confirmed pulsars seen by Compton Observatory EGRET instrument

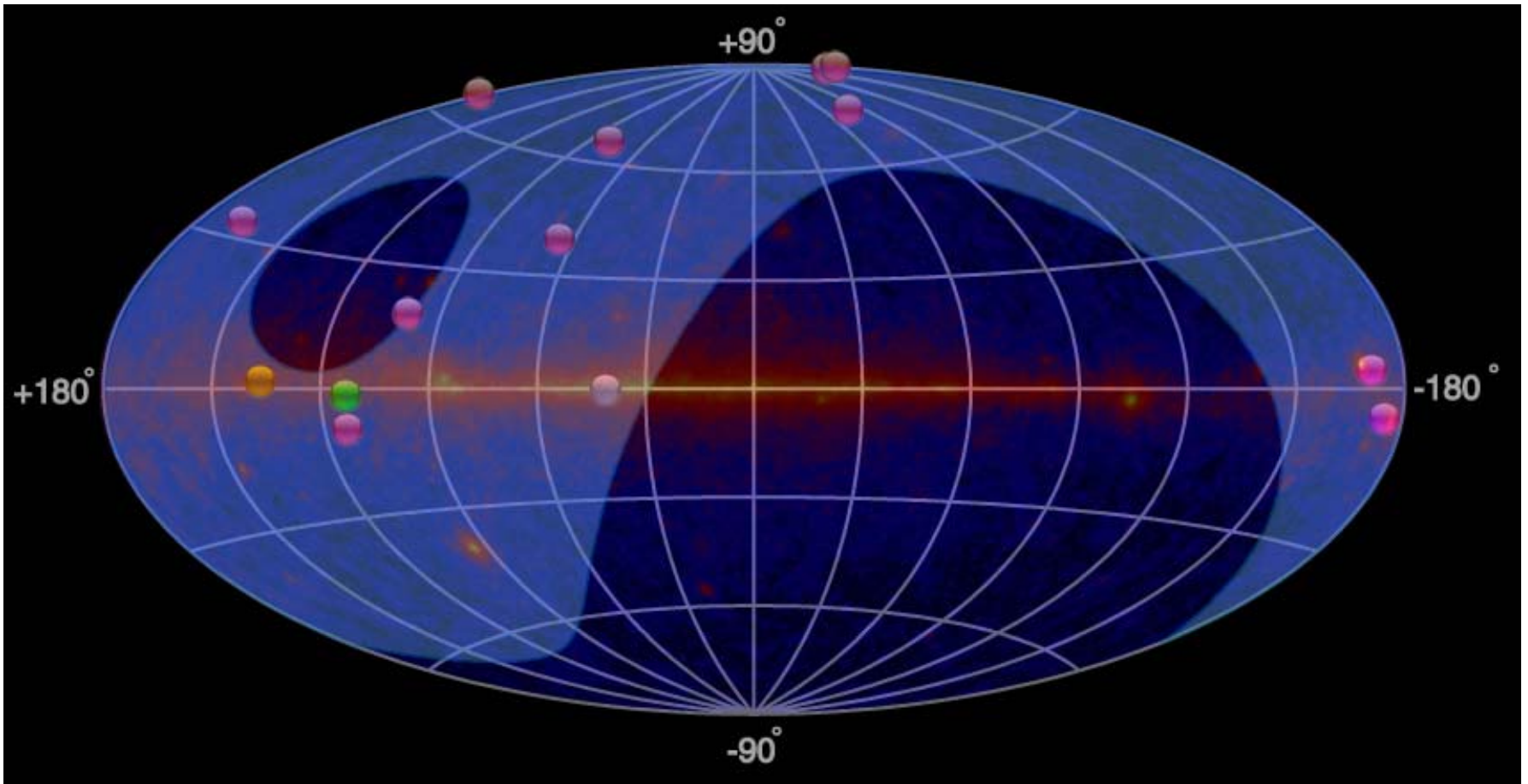
**Pulses at  
tenth true  
rate**

# The Fermi (GeV) Sky

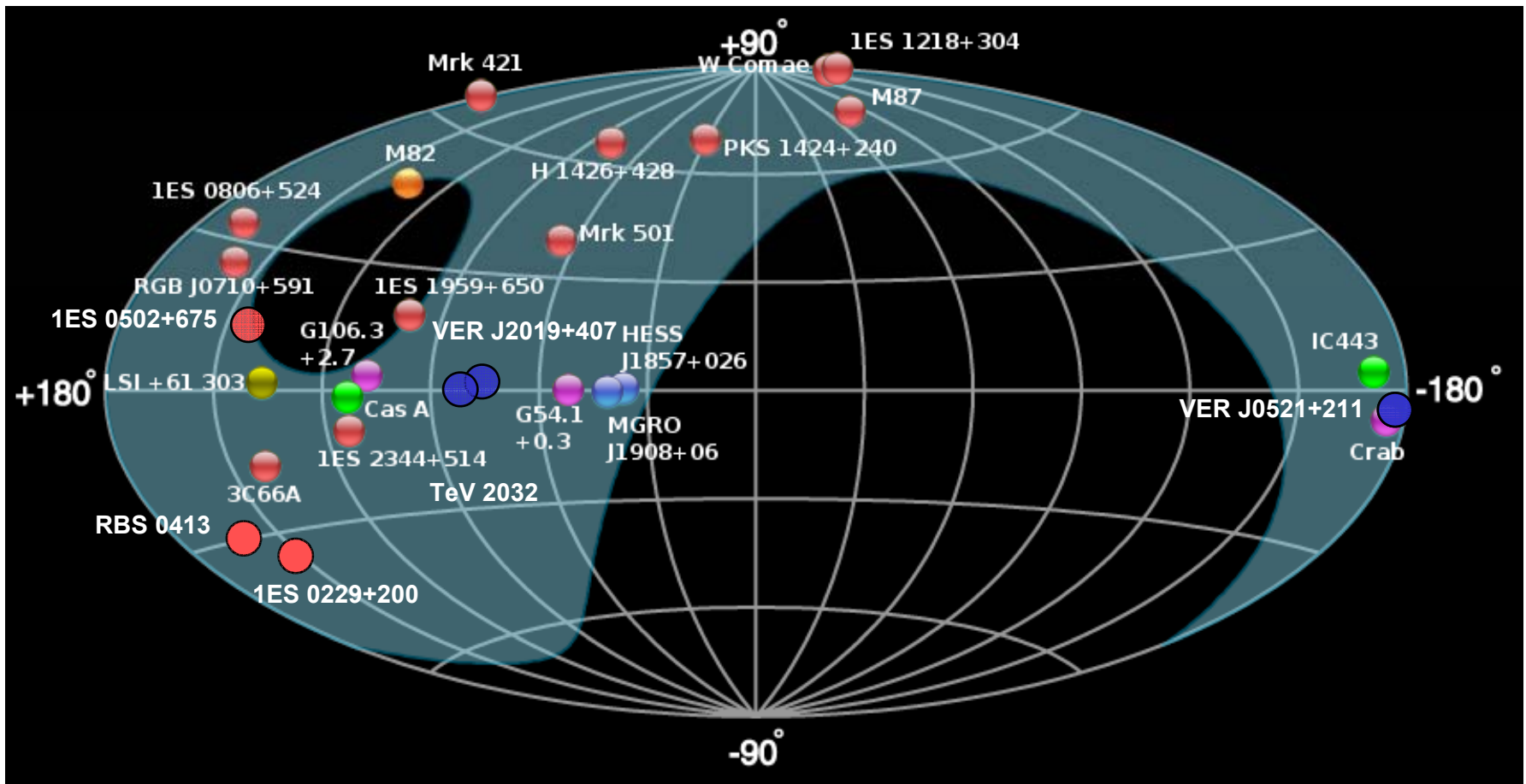
---







# The VERITAS Sky (2010)



# The VERITAS Sky (2010)

---

1ES 0502+675



VER J2019+407



VER J0521+211



RBS 0413



TeV 2032



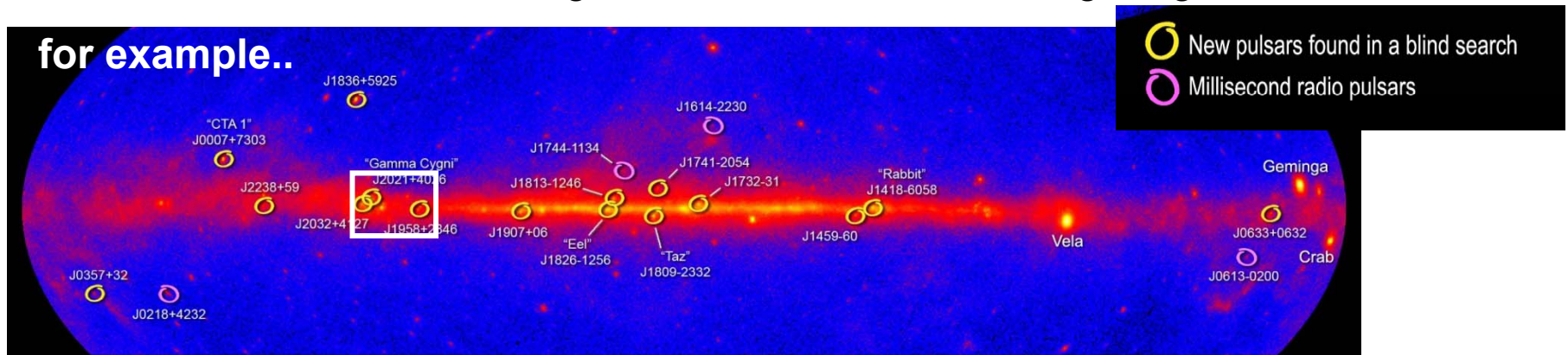
1ES 0229+200





# VERITAS Sky Survey: Motivation

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



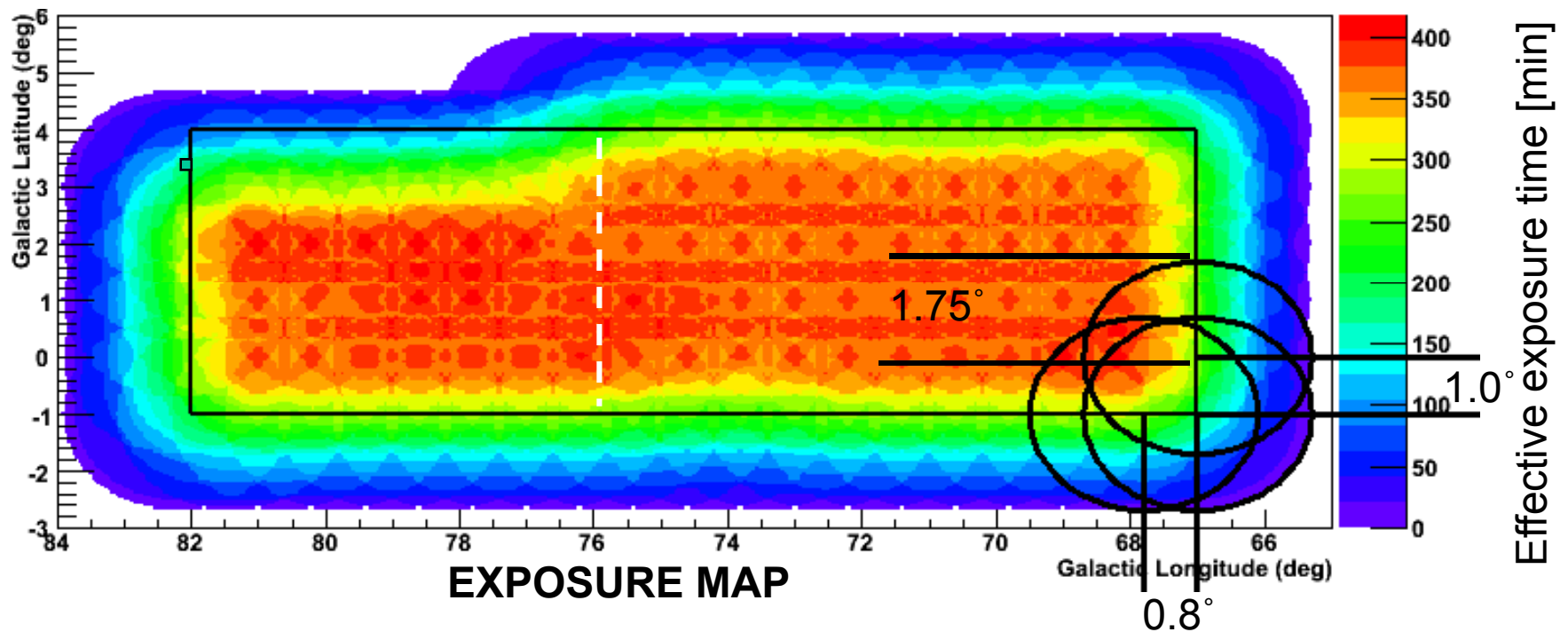
- *Un-biased* indication of source population
- Southern hemisphere well-surveyed
  - HESS Galactic plane survey, ~14 sources in initial survey
- Best limits in northern hemisphere sky : HEGRA's Galactic plane survey
  - $-2^\circ < l < 85^\circ$ , flux upper limits: 15% Crab to several Crab
- Size and choice of region based on
  - VERITAS sensitivity and FOV
  - Material distribution, density of potential TeV  $\gamma$ -ray emitters (SNR, PWN, high  $E\cdot\dot{E}$  pulsars, EGRET unidentified sources..)

# VERITAS Sky Survey: Strategy

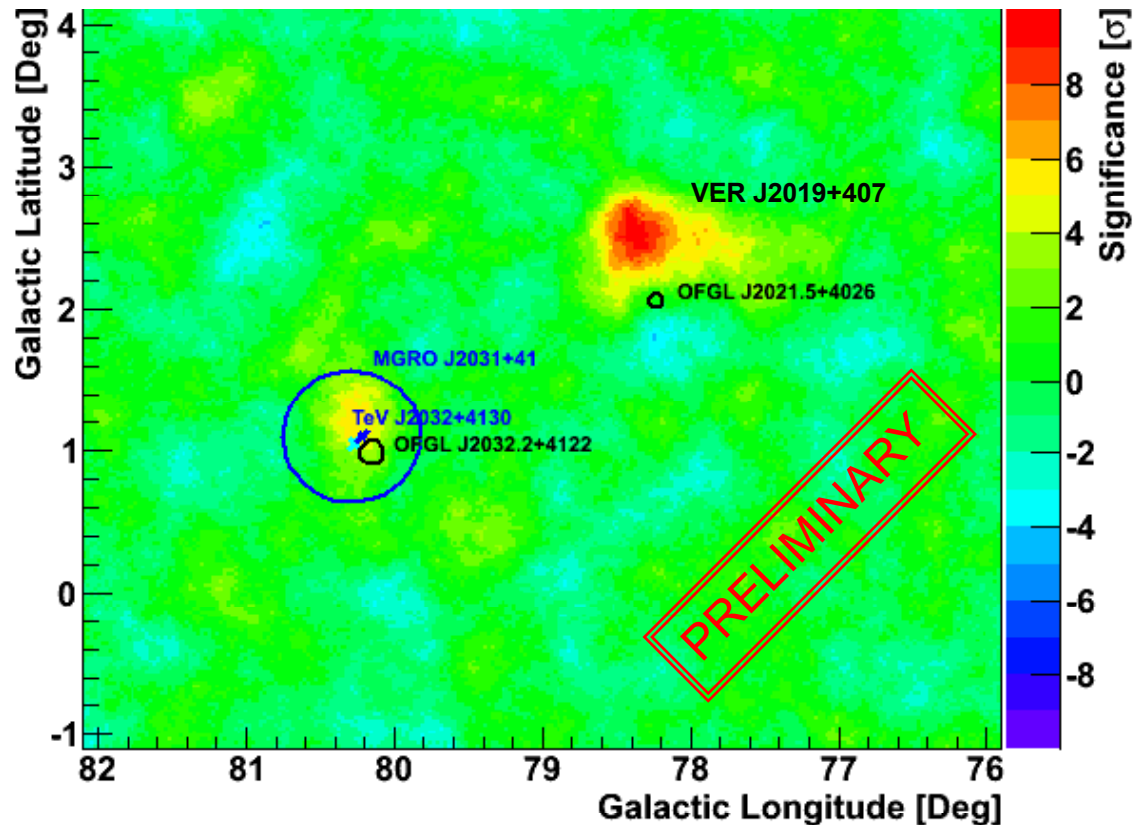
**Most sensitive survey of the Galactic plane in N. Hemisphere at TeV  $\gamma$ -ray energies.**

Made possible by good VERITAS off-axis sensitivity

- Survey covers region  $67^\circ < l < 82^\circ$ ,  $-1^\circ < b < 4^\circ$
- $\sim 6$  hrs effective exposure at every location (before follow-up).
- $\sim 112$  hours in base survey,  $\sim 56$  hours follow-up.



# One Interesting Region



- VER J2019+407
  - New VERITAS source**
  
- TeV J2032+4130
  - known source, first detected by HEGRA
  - Likely associated: MGRO J2031+41, OFGL J2032.2+4122 (LAT pulsar)
  - Detection:  $>5\sigma$  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)

# FUTURE

---

Next 5-10 years will be very exciting for this field.

VERITAS will survey the VHE  $\gamma$ -ray sky with great sensitivity, complementing:

Fermi-LAT (GeV  $\gamma$ -rays, in space)

IceCube ( $\nu$ , South Pole)

Auger (UHECR, S. Hemisphere)

In the future:

- HAWC: 1 TeV air shower array (proposed, Mexico).
- Large 1 km<sup>2</sup> array of atm. Cherenkov telescopes.

**CTA = Cherenkov Telescope Array**



# VERITAS Upgrade (2010-2012)

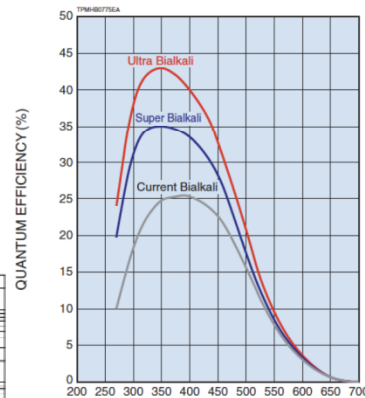
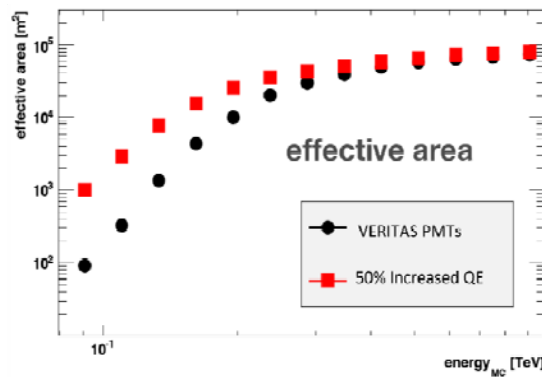
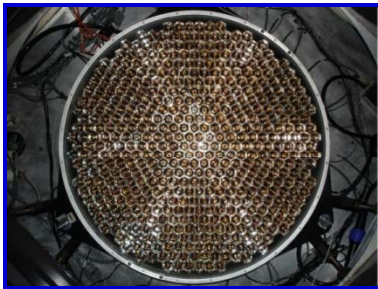
- We plan to replace the PMT cameras and L2 trigger system to significantly improve the sensitivity and energy threshold.

## CAMERA Upgrade

PMT replacement with high efficiency PMTs.

Increase photon collection by ~35%.

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

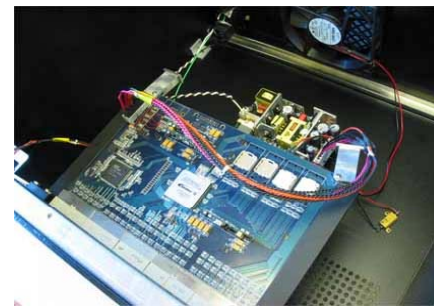
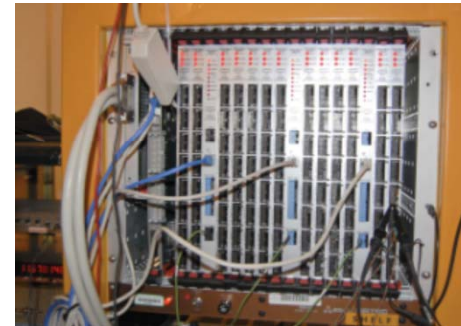


## TRIGGER Upgrade

Smaller coincidence window

Topological Trigger

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

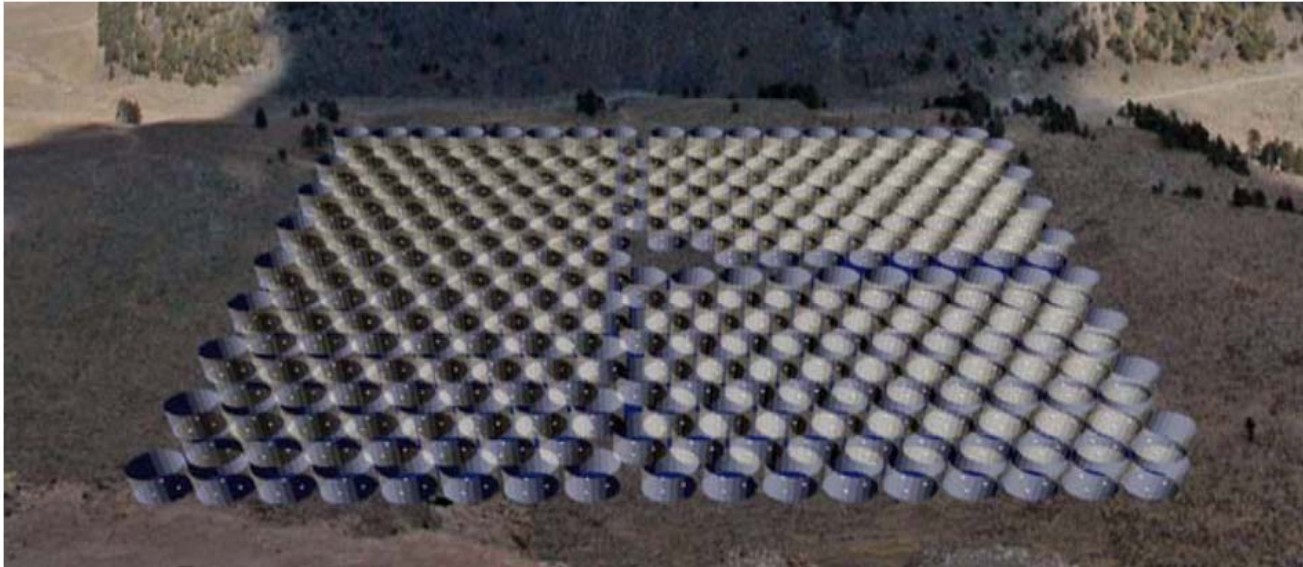


Prototype  
Trigger  
Systems

Upgrade now funded through NSF MRI R2

# HAWC

---



HAWC array of water tanks at high altitude  
(operational by 2014 ?)



Prototype tank

## ❑ HAWC Design

- Measures the air shower particles that reach ground level.
- Main advantages: high-duty cycle, wide field-of-view.
- Higher E threshold (TeV), not as sensitive as atm-Cherenkov.

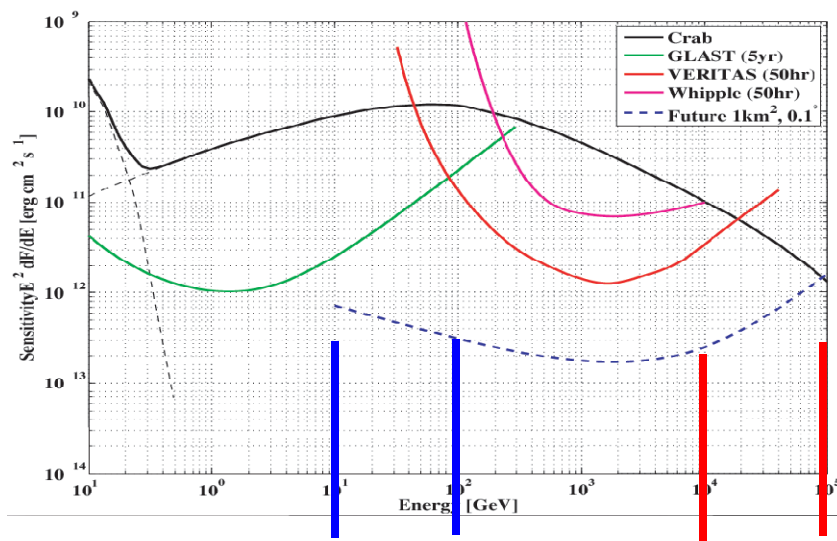
# 1 km<sup>2</sup> Atm. Cherenkov Array

Large (1 km<sup>2</sup>) array.

- 50+ telescopes, aperture 8-20m.
- \$300-400M class observatory, 2 sites.

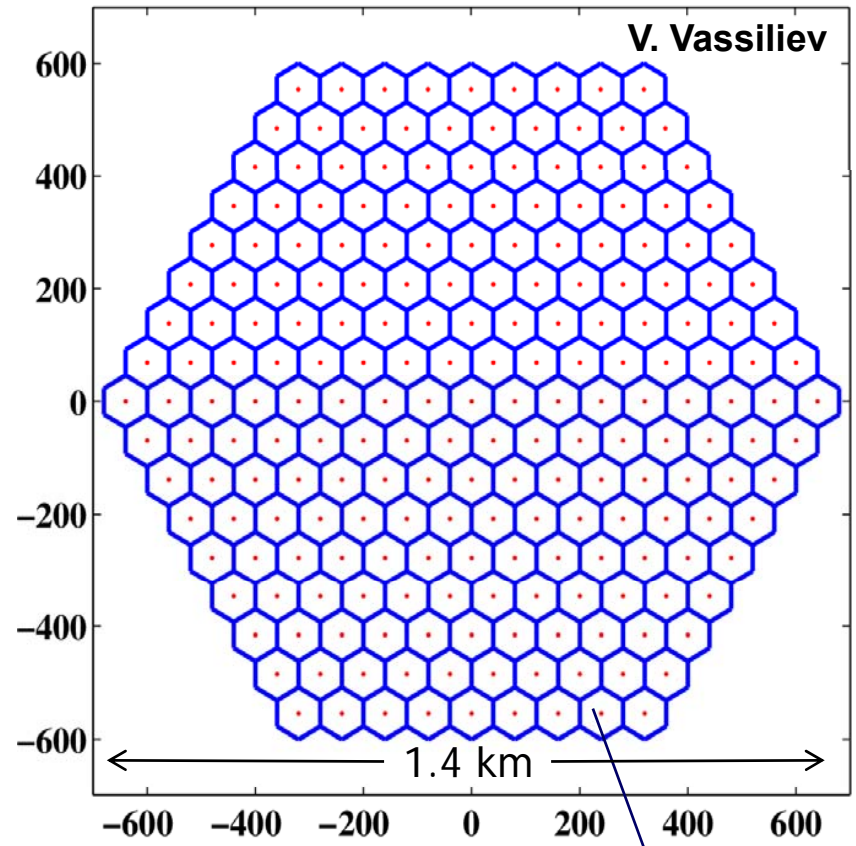
Factor of >10 more sensitive than VERITAS.

**AGIS (U.S.) & CTA (Europe) in Design Phase.**



Transition to Fermi Regime (GRBs, etc.)

Spectral cutoffs (acceleration mechanisms)



10-12m telescope  
Wide-field  
8-10° FoV



# AGIS (2019)

## Advanced Gamma Imaging System



### Institutions:

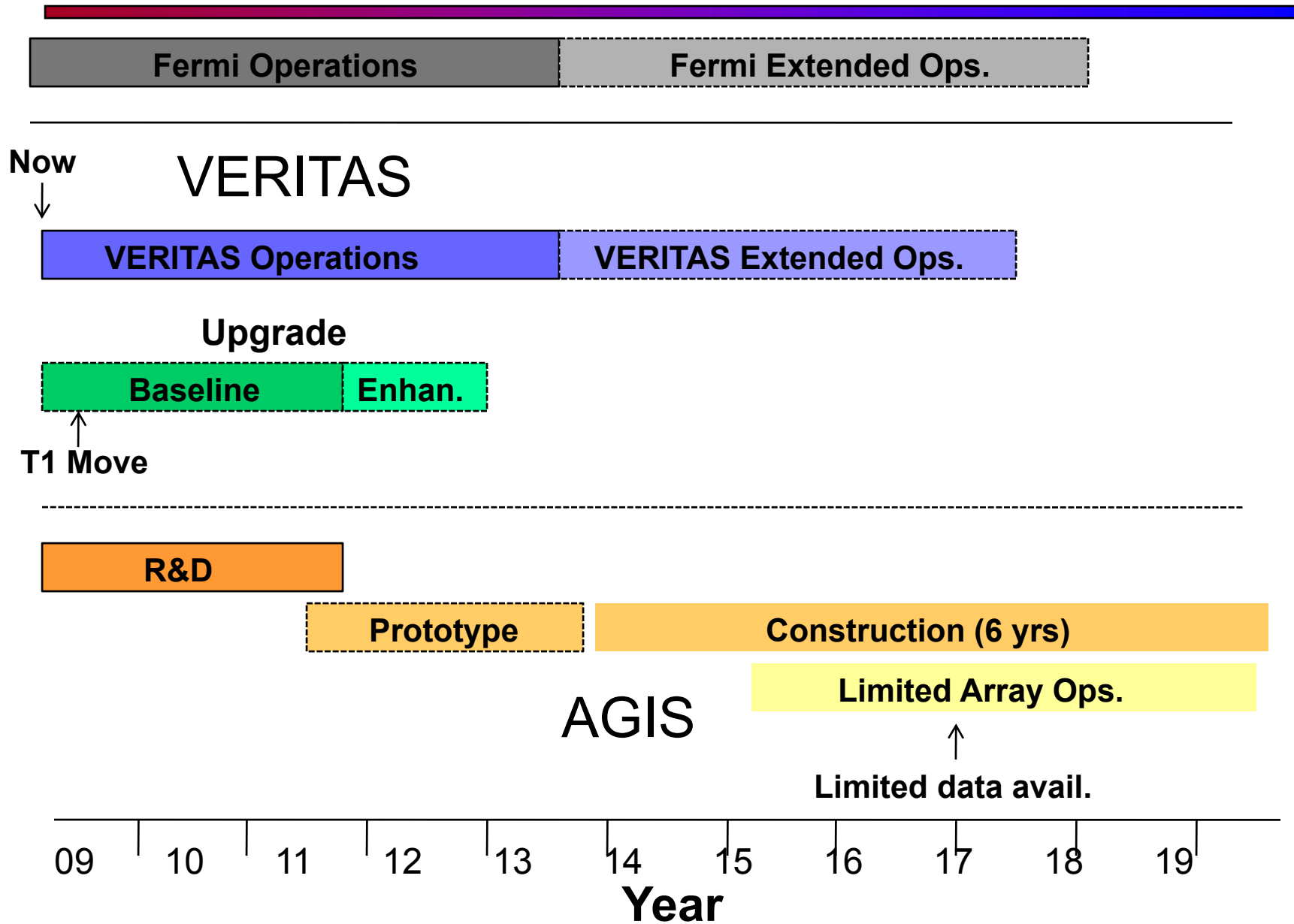
ADLER  
ANL  
Barnard  
Delaware  
IAFE  
Iowa State  
LANL  
McGill  
Penn State  
Purdue

SAO  
Stanford/SLAC  
UNAM  
UC, Los Angeles  
UC, Santa Cruz  
U. Chicago  
U. Iowa  
Utah  
Yale  
Washington U.

Wide-Field  
Schwarzschild-Couder Telescope



# Timeline for Future



# Summary

---

- VHE  $\gamma$ -rays probe astrophysics of extreme physical conditions, as yet not well explored. There is also discovery potential for physics beyond our standard model.
- Exciting discoveries of many, unexpected sources of VHE  $\gamma$ -rays. But still, most of the sky remains unexplored.
  - **VERITAS and Fermi are now both operational and getting exciting results.**
- New Astronomy of TeV  $\gamma$ -rays (and neutrinos, grav. waves) should reveal many surprises over the next 10 years.

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

**Marcel Proust (1871-1922)**

