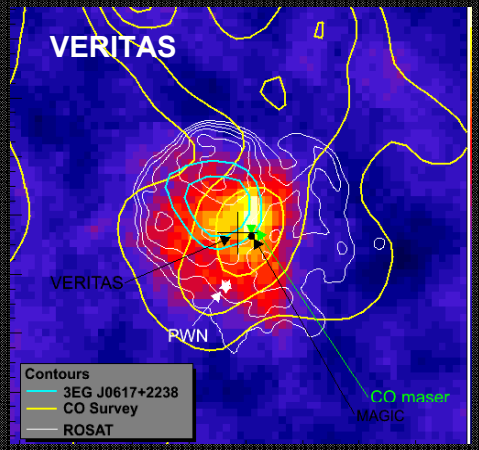
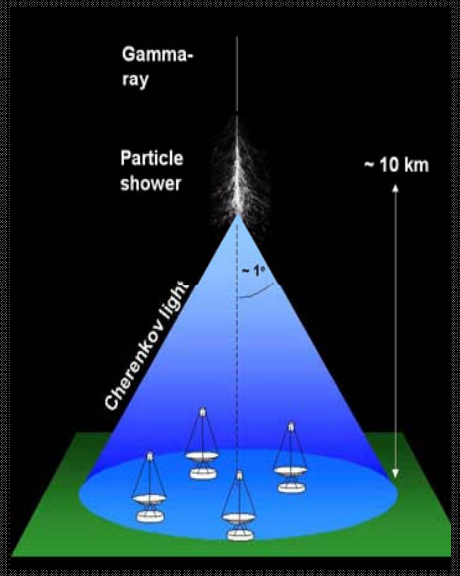
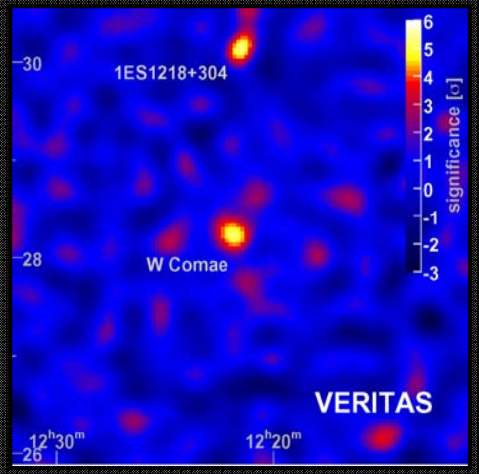
The Very High Energy Universe







Rene A. Ong Colloquium @ U. Wisconsin 04 Dec 2009

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

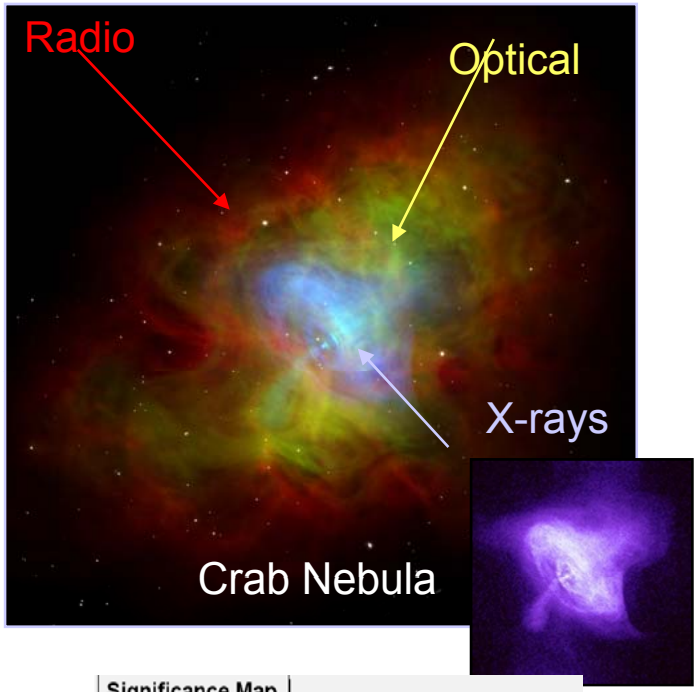
The VERITAS Project

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

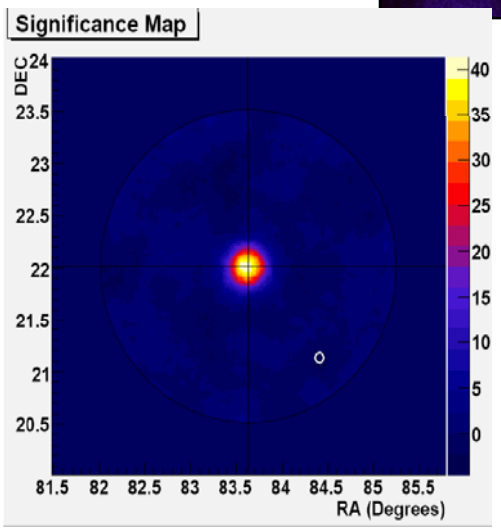
Future

A New Astronomy

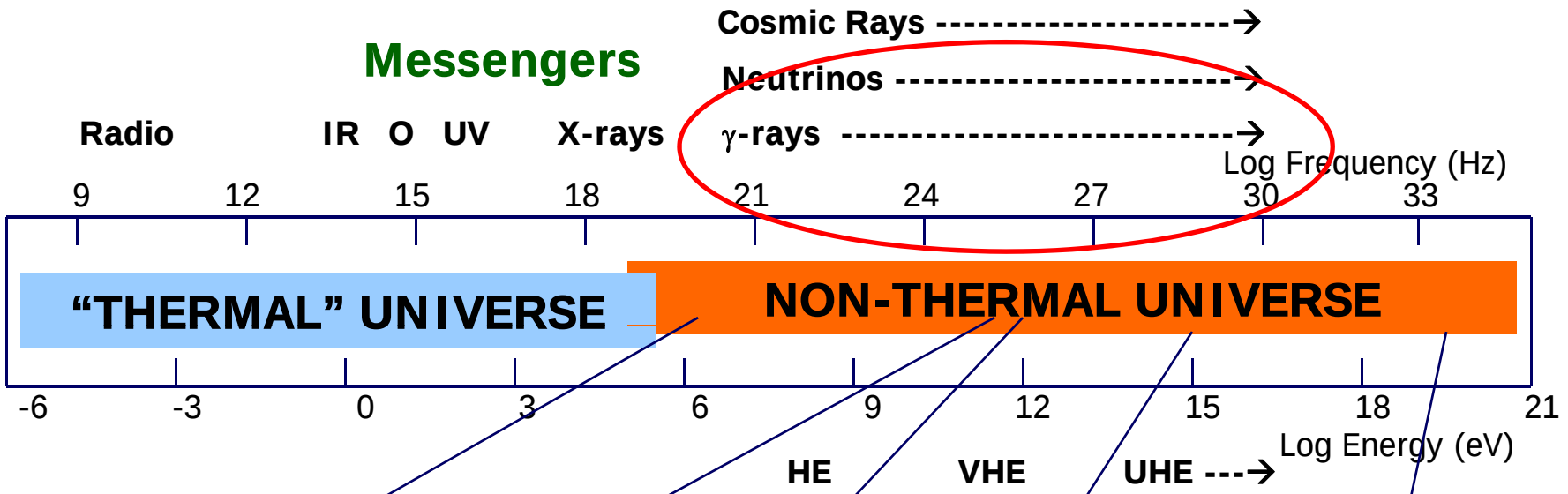
- Before 1940's – Astronomy only used visible light.
- New wavebands (radio, IR, X-ray, γ-ray) change our picture of the universe
  - Different spatial scales
  - Different time scales
  - Different emission processes
  - New physics
- Other messengers (cosmic rays, neutrinos, grav. waves)

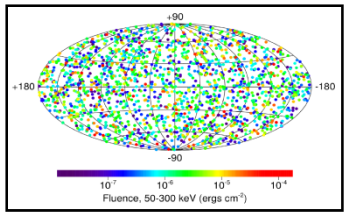


TeV γ-rays

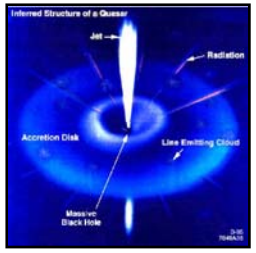


New Windows & New Messengers

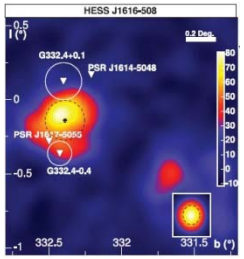




Gamma-Ray Bursts (GRBs)

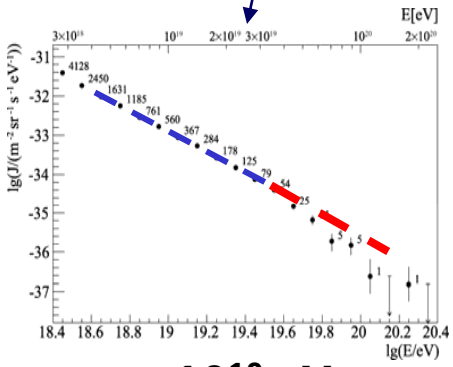


Active Galactic Nuclei (AGN)



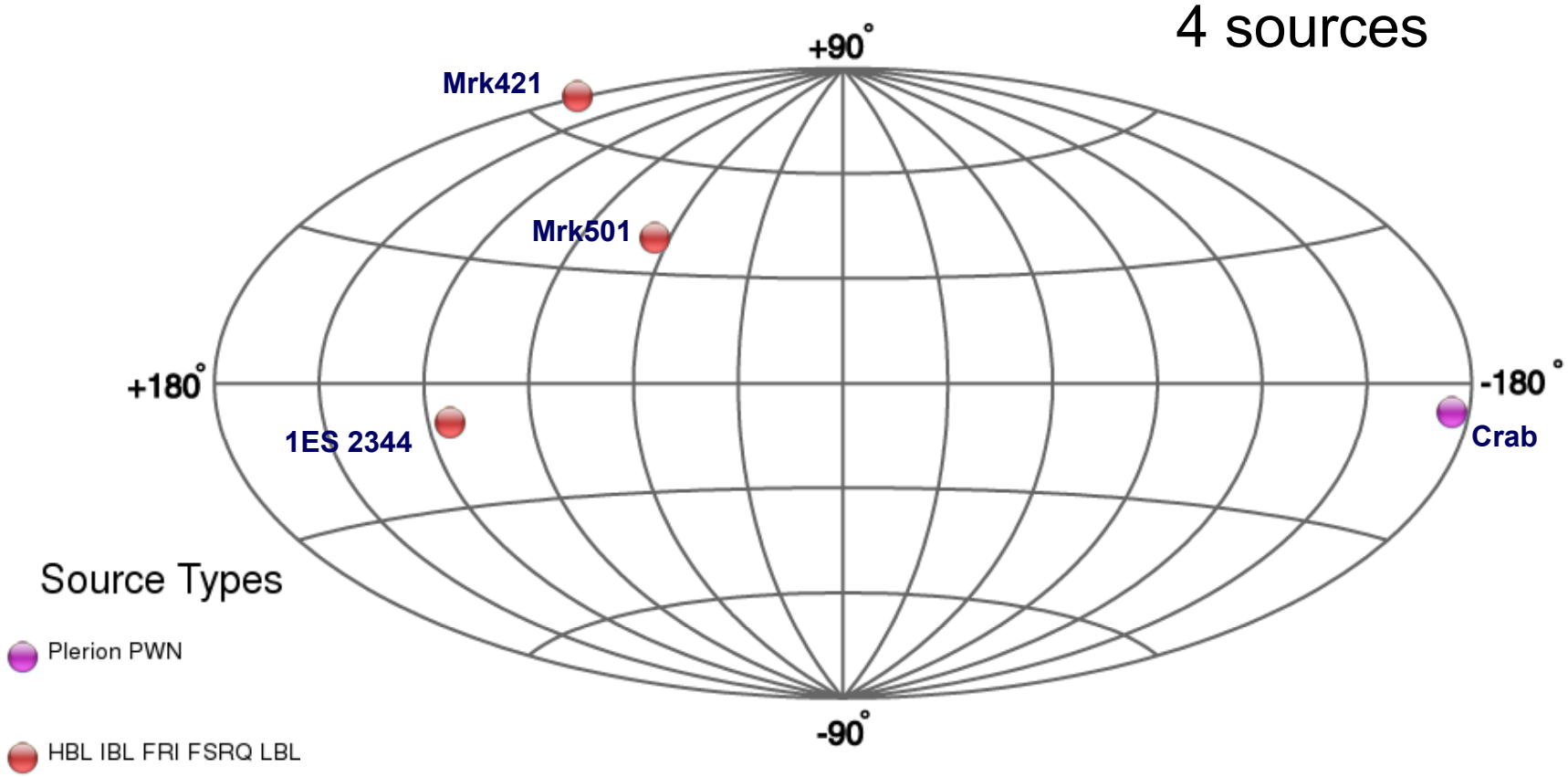
"Dark" TeV Accelerators

PeV ν's

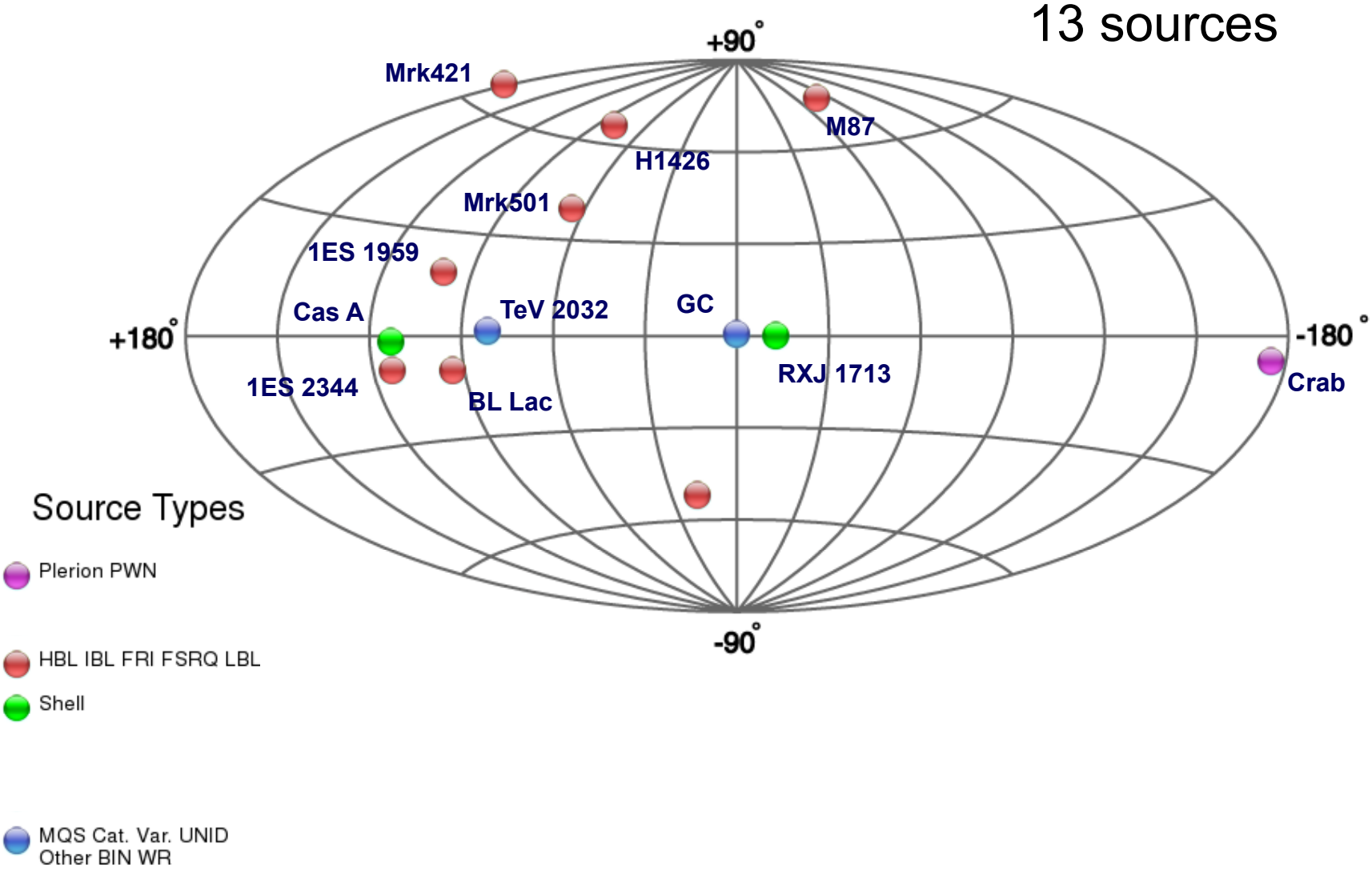


>10^{19} eV Particles

The TeV γ-ray Sky - 1999

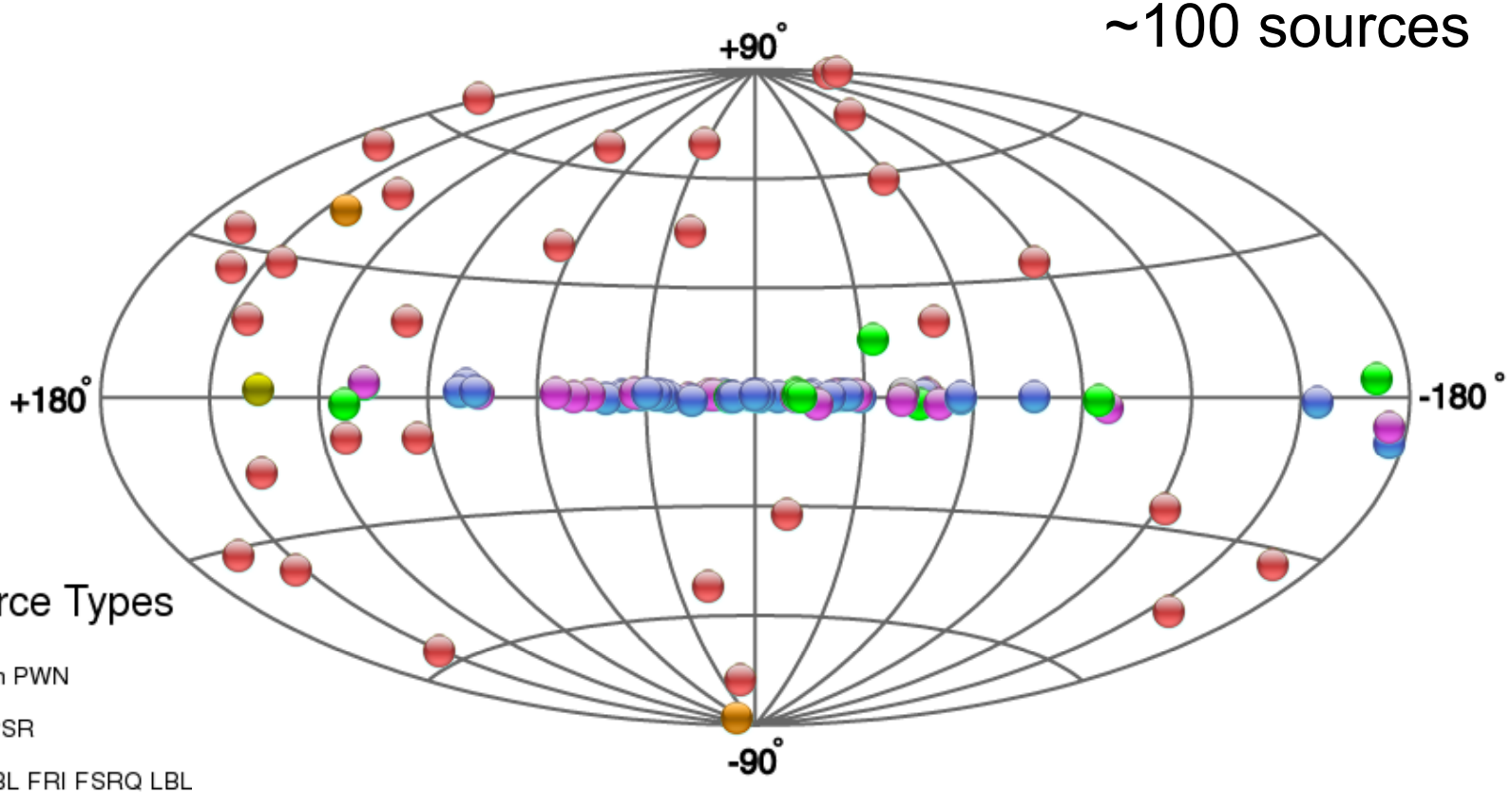


The TeV γ-ray Sky - 2004



The TeV γ-ray Sky - 2009

~100 sources



Source Types

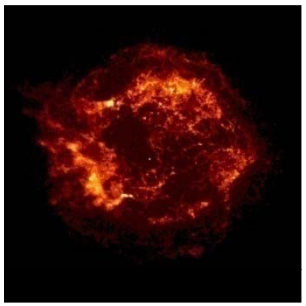
- Plerion PWN
- XRB PSR
- HBL IBL FRI FSRQ LBL
- Shell
- Starburst
- DARK
- MQS Cat. Var. UNID Other BIN WR

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

(Almost all) discoveries made by Atmospheric Cherenkov Telescopes

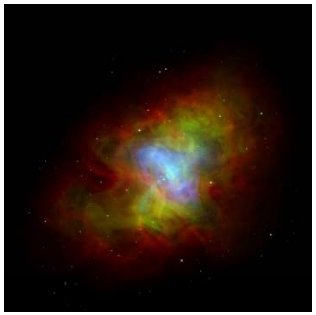
A Wide Variety of Sources …

Supernova Remnants



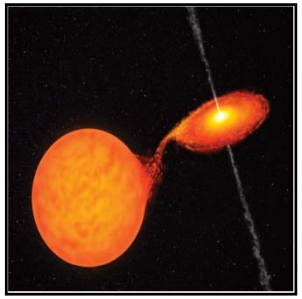
Shocks
Fermi mechanism

Pulsars/PWN



NS dynamo
Winds

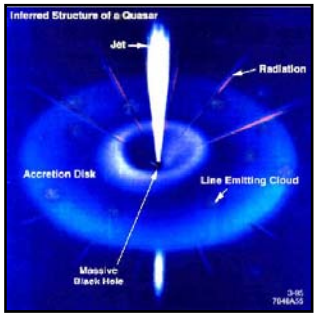
HMXBs (microquasars)



Accretion-powered jets,
Colliding winds, or …?

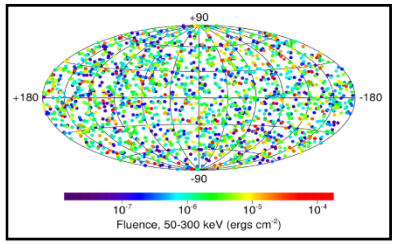
GALACTIC

Active Galactic Nuclei



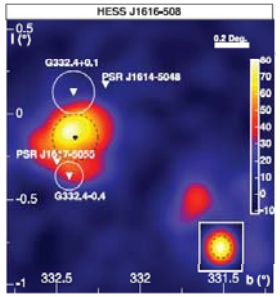
SMassive BH
Jets

Gamma-Ray Bursts



Massive star collapse
Relativistic shocks

Dark accelerators…

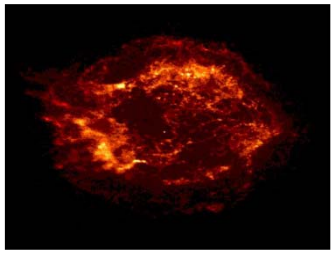


???

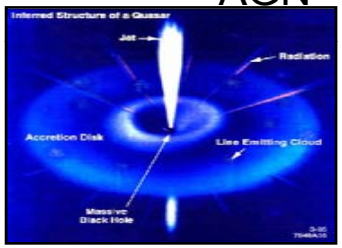
EXTRA-GALACTIC

Key Physics Issues

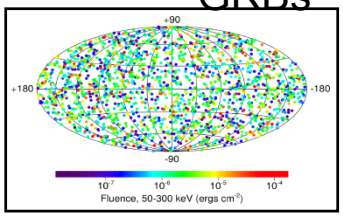
SNR

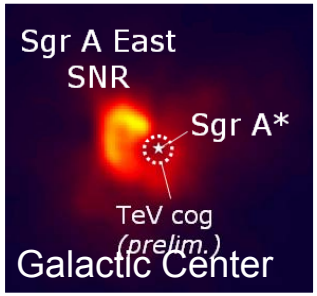


AGN

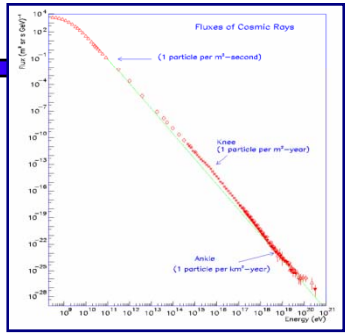


GRBs



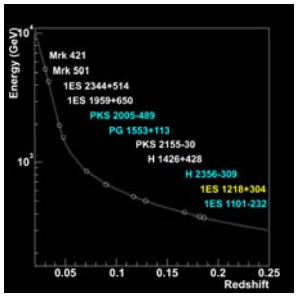


Origin of cosmic rays

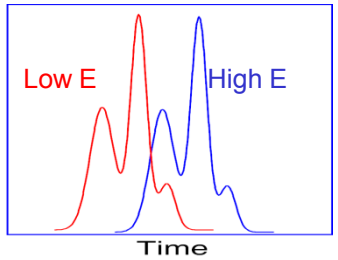


?

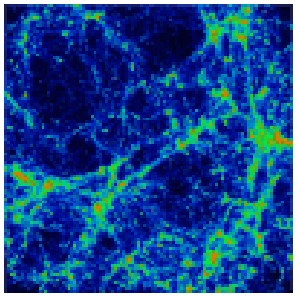
Cosmological γ-ray horizon



Tests of Lorentz invariance



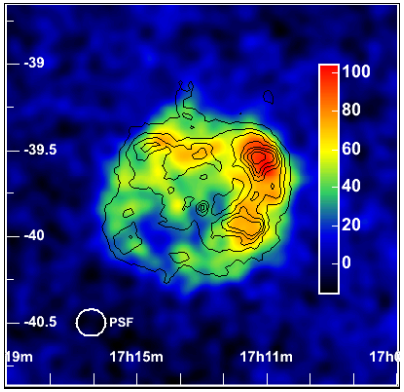
Cold dark matter (WIMP) searches



Origin of Cosmic Rays = SNRs ?

Why (VHE) gamma rays?

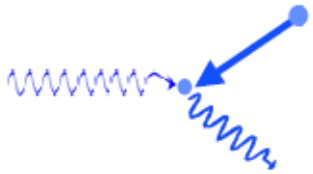
- Unlike cosmic rays, *not deflected* by interstellar magnetic fields.
- *Tracers* of parent particle populations – those particles accelerated by shocks.



SNR Image (RXJ 1713-3946)

Accelerated electrons → VHE γ-rays

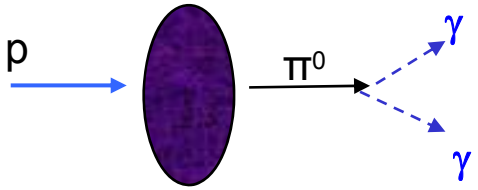
Up-scattering of soft photons



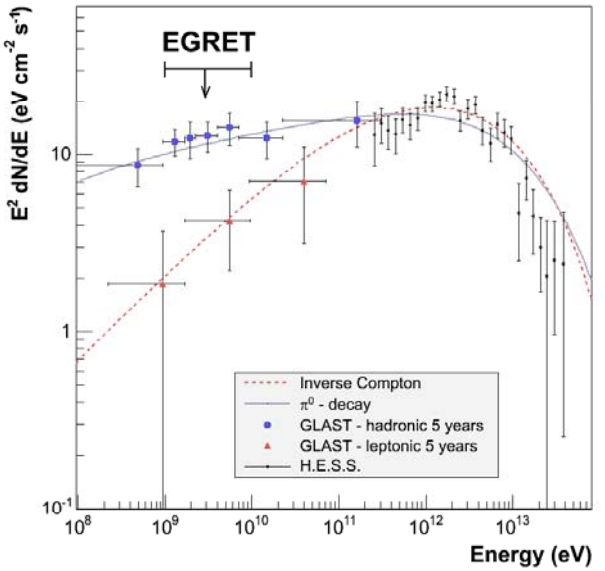
Inverse Compton Scattering

Accelerated protons → VHE γ-rays

Target interaction, π^0 decay



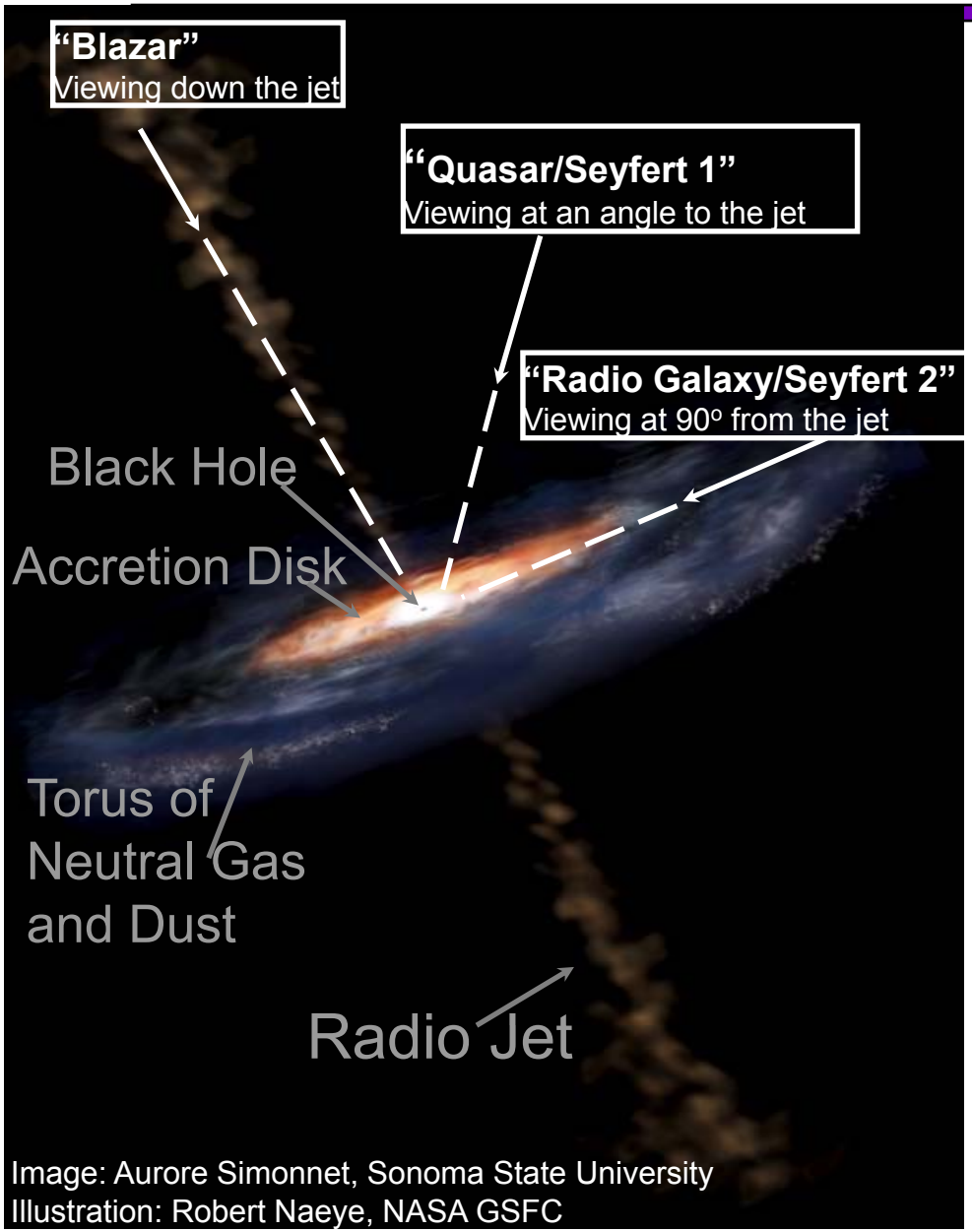
Target material



Spectral Energy Distribution

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

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

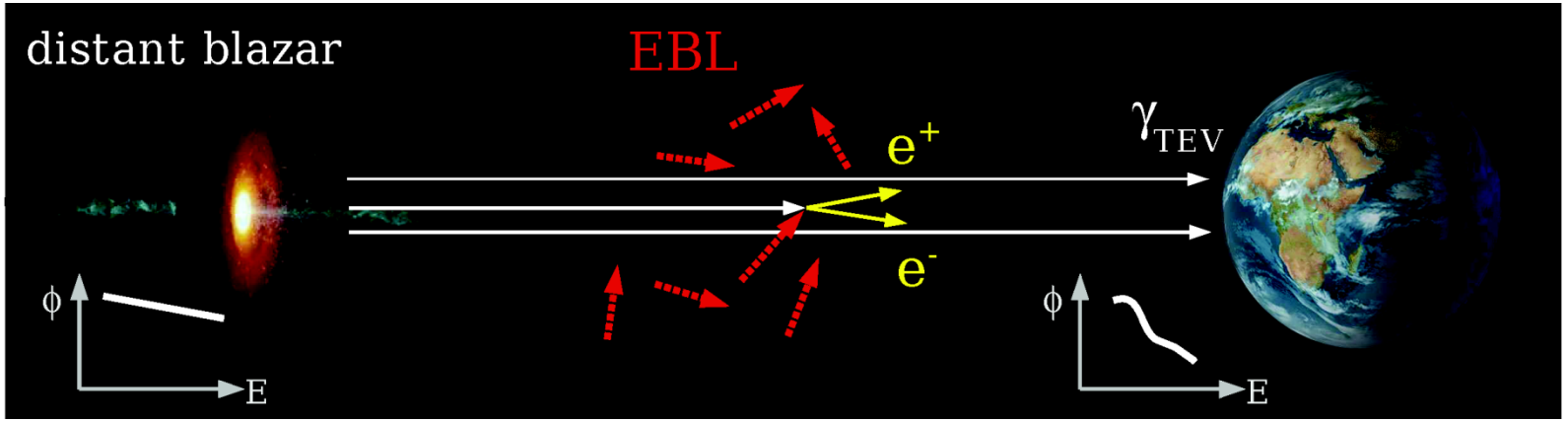
So far, AGN are generally:

- Blazars
  - ➔ Jets aligned with line of sight

But also radio galaxies (e.g M87)

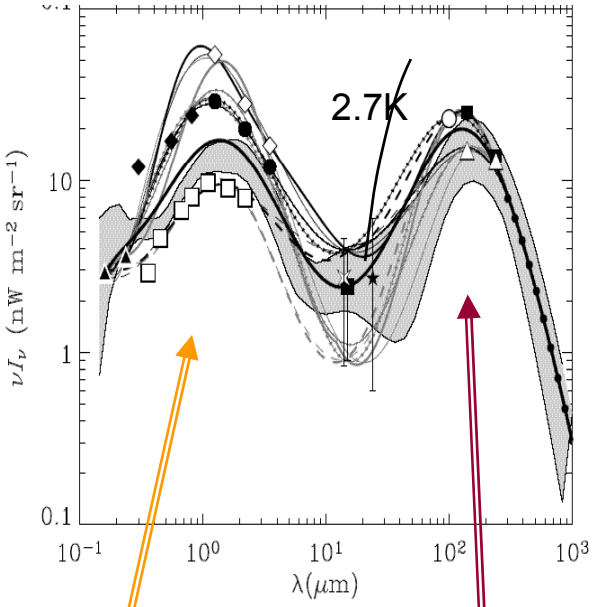
- ➔ Jet viewed from the side

Extragalactic Background Light (EBL)



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

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



Red shifted stellar light

Red shifted dust light

Search for Cold Dark Matter

Hypothesis: DM = WIMPs

- Indirect detection of WIMP annihilation → γ, ν etc.

$\chi + \chi$

$\nu, \bar{\nu}$

γ **continuum**

γ **lines**

Point back to source

$\bar{p}$

e^+

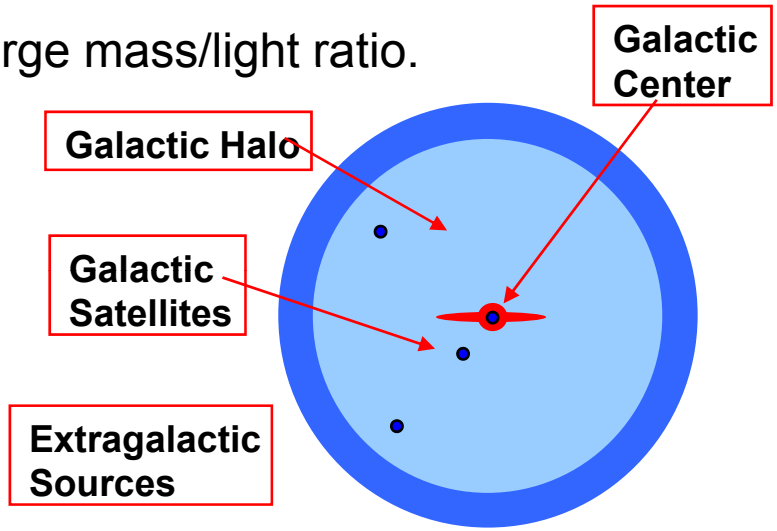
$\bar{d}$

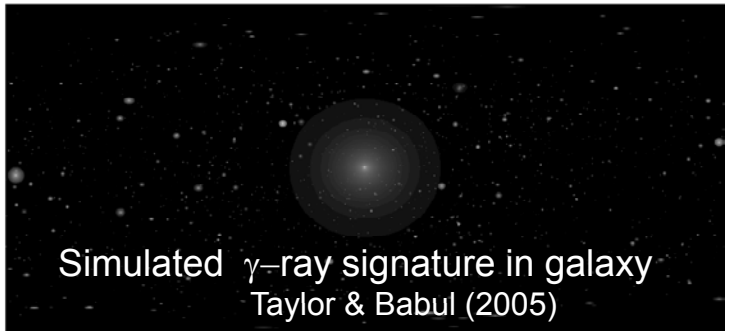
Search for excess components in cosmic rays (Diffusion)

(PAMELA,AMS,GAPS)

Target regions with:

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

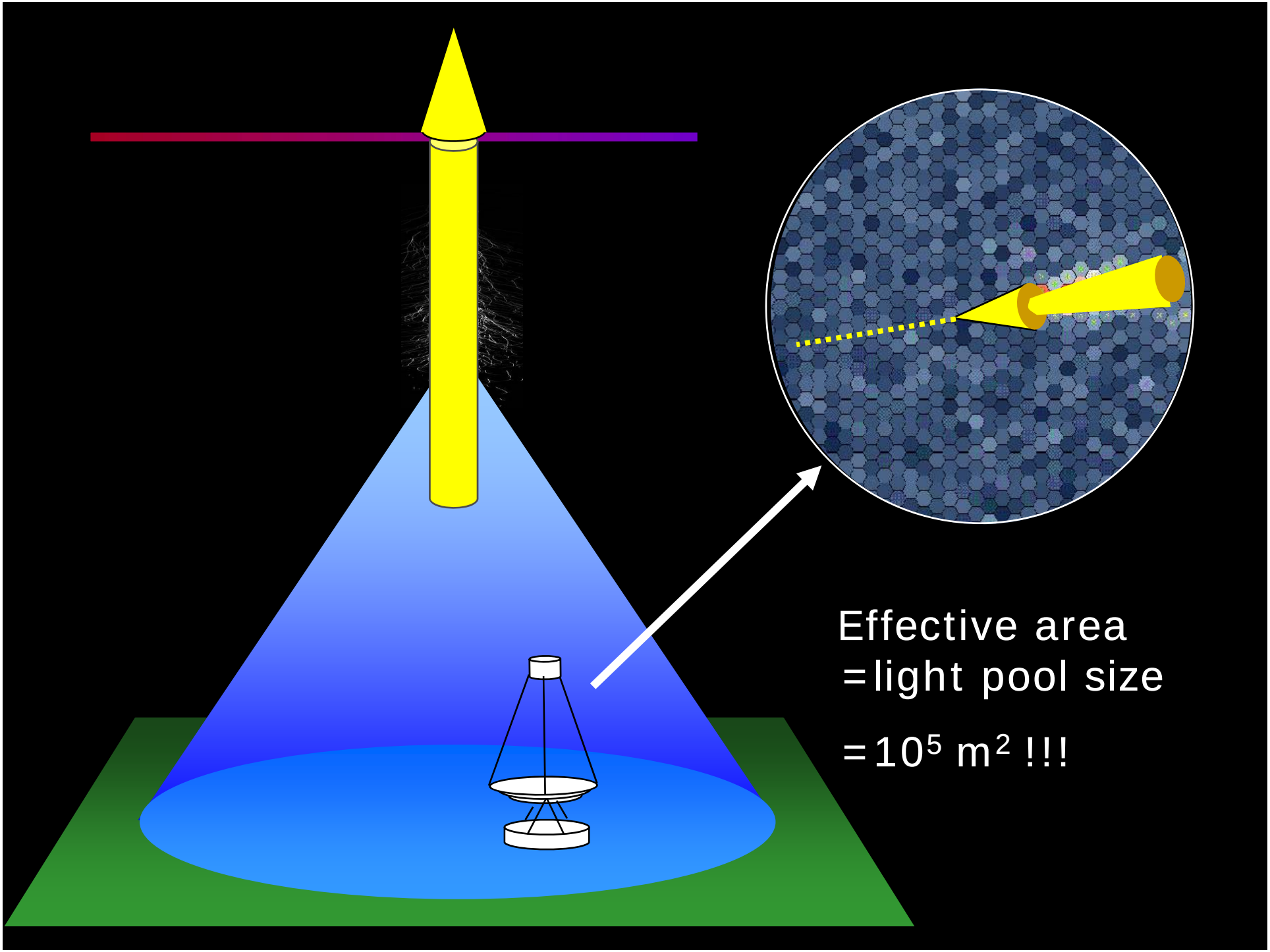




Complementary approach to direct detection & LHC

Goal is to do DM astronomy !

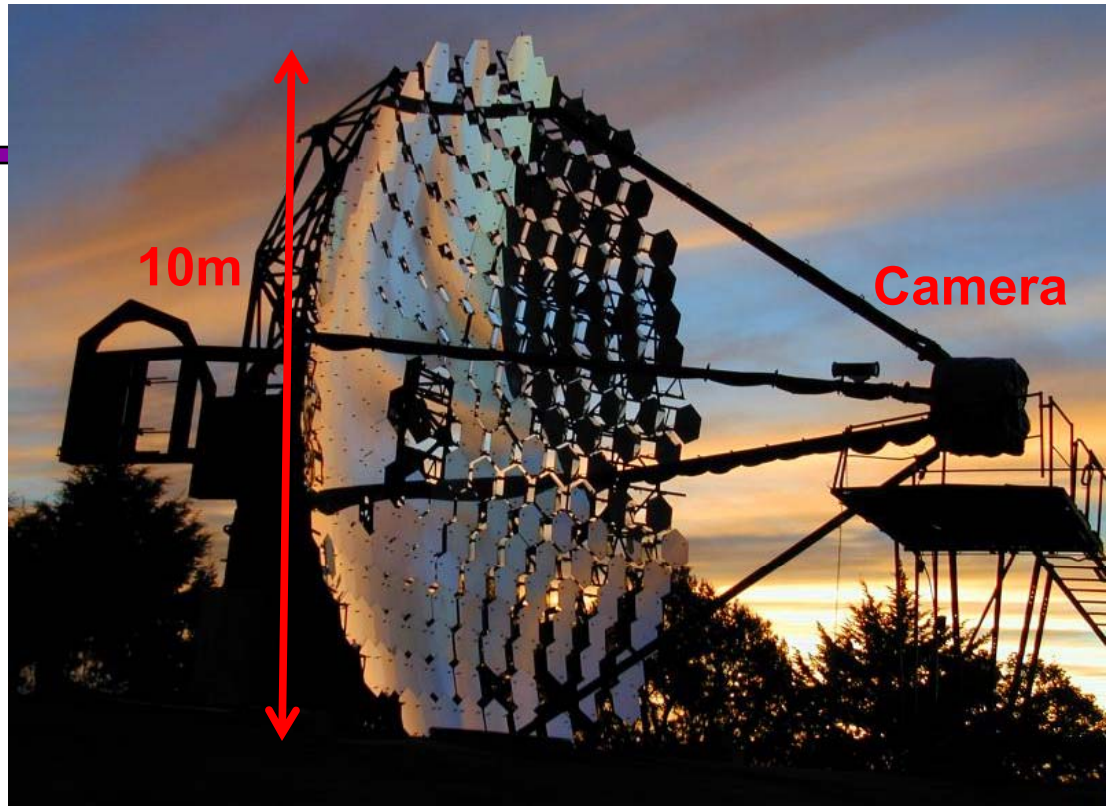
Experimental Technique


Effective area
=light pool size
=10^5 m^2 !!!

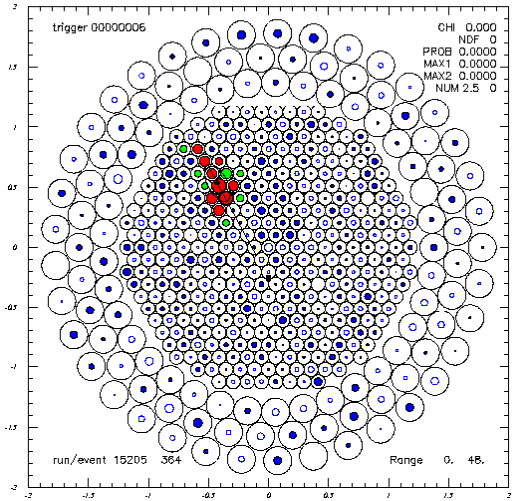
Whipple 10m
γ-ray Telescope

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

Wisconsin involvement in Haleakela.



gamma ray?



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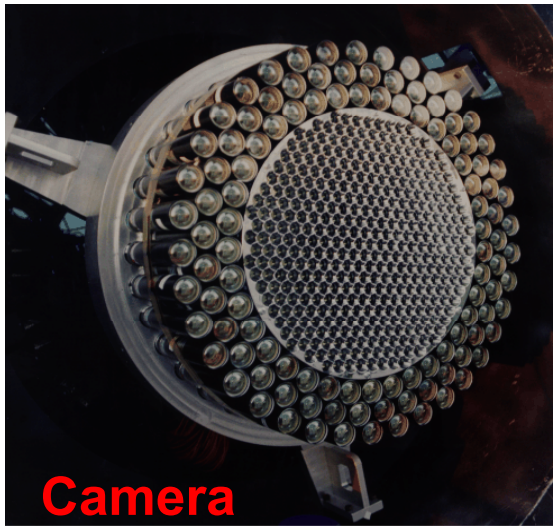
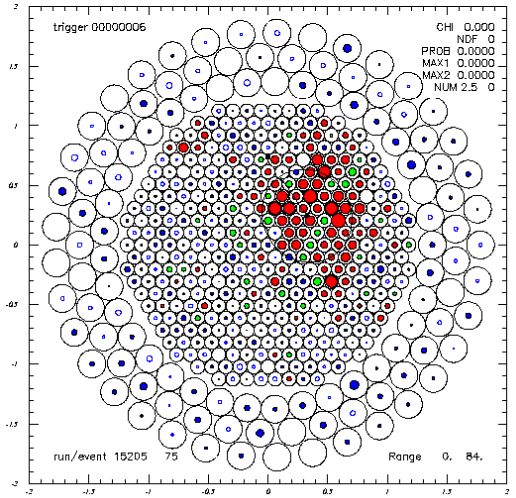
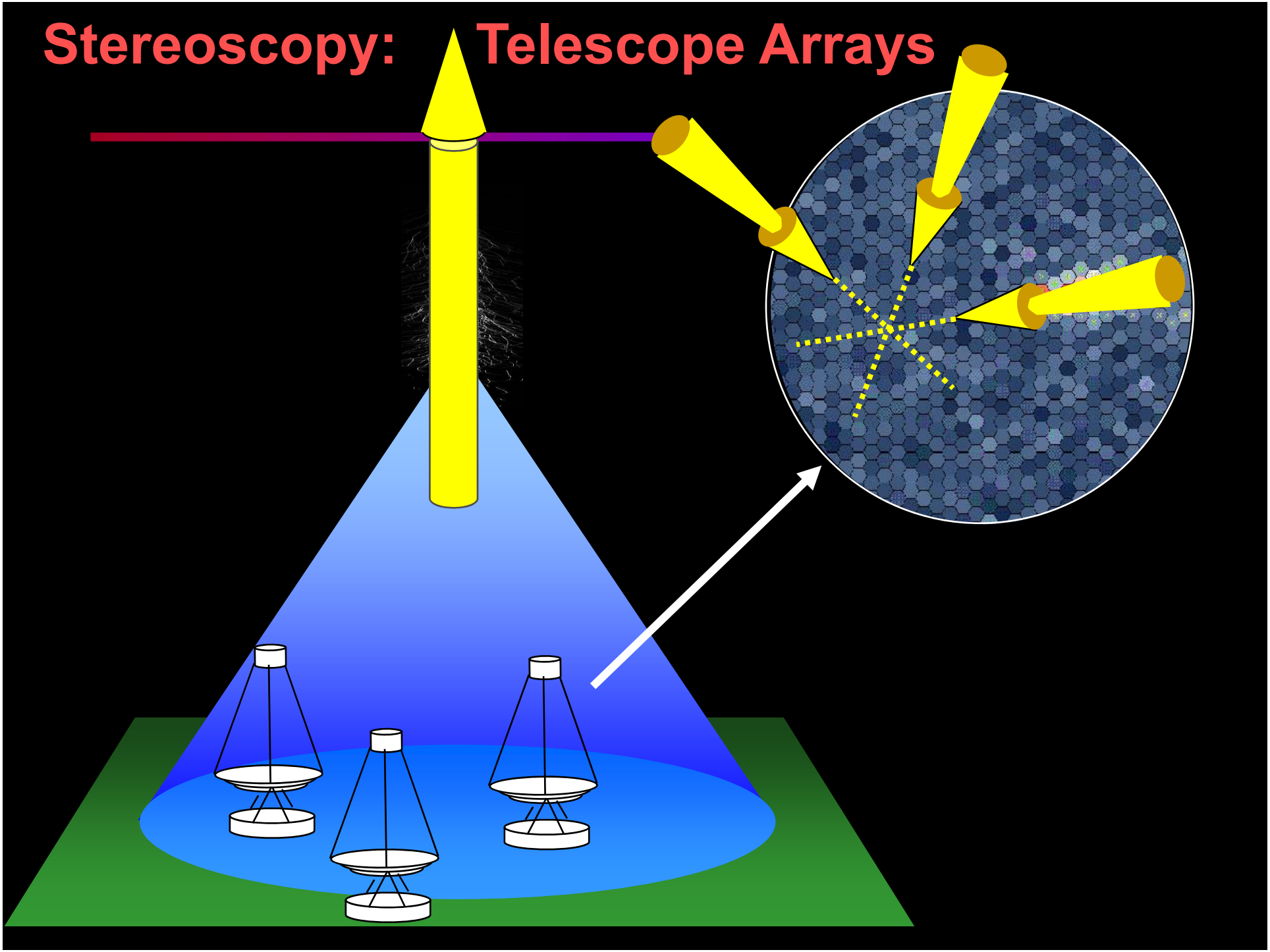


cosmic ray?



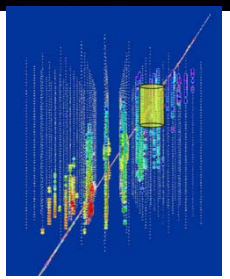
Stereoscopy: Telescope Arrays



Major VHE Telescopes

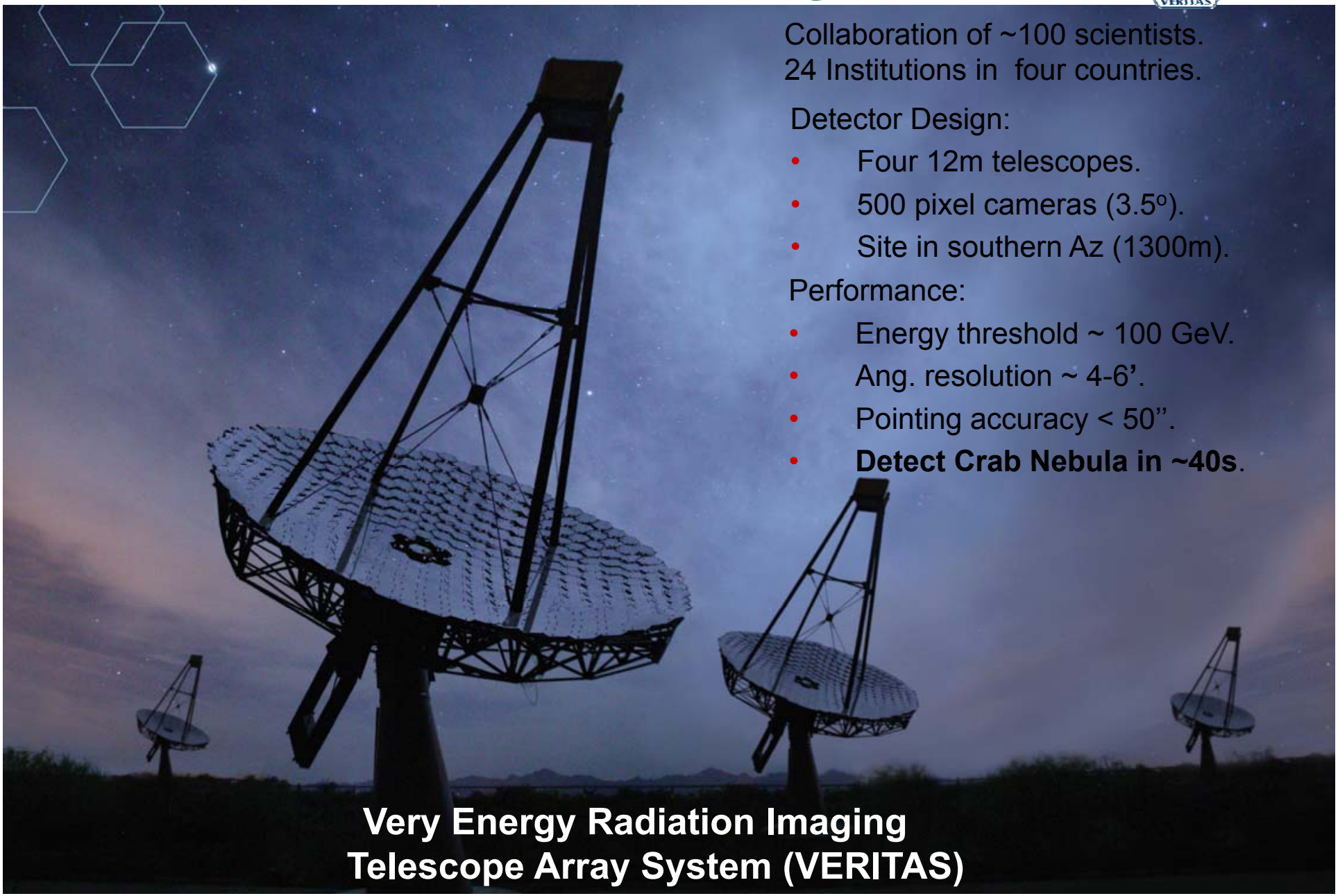
Fermi

Multi-messenger Astronomy



IceCube

VERITAS



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

Detector Design:

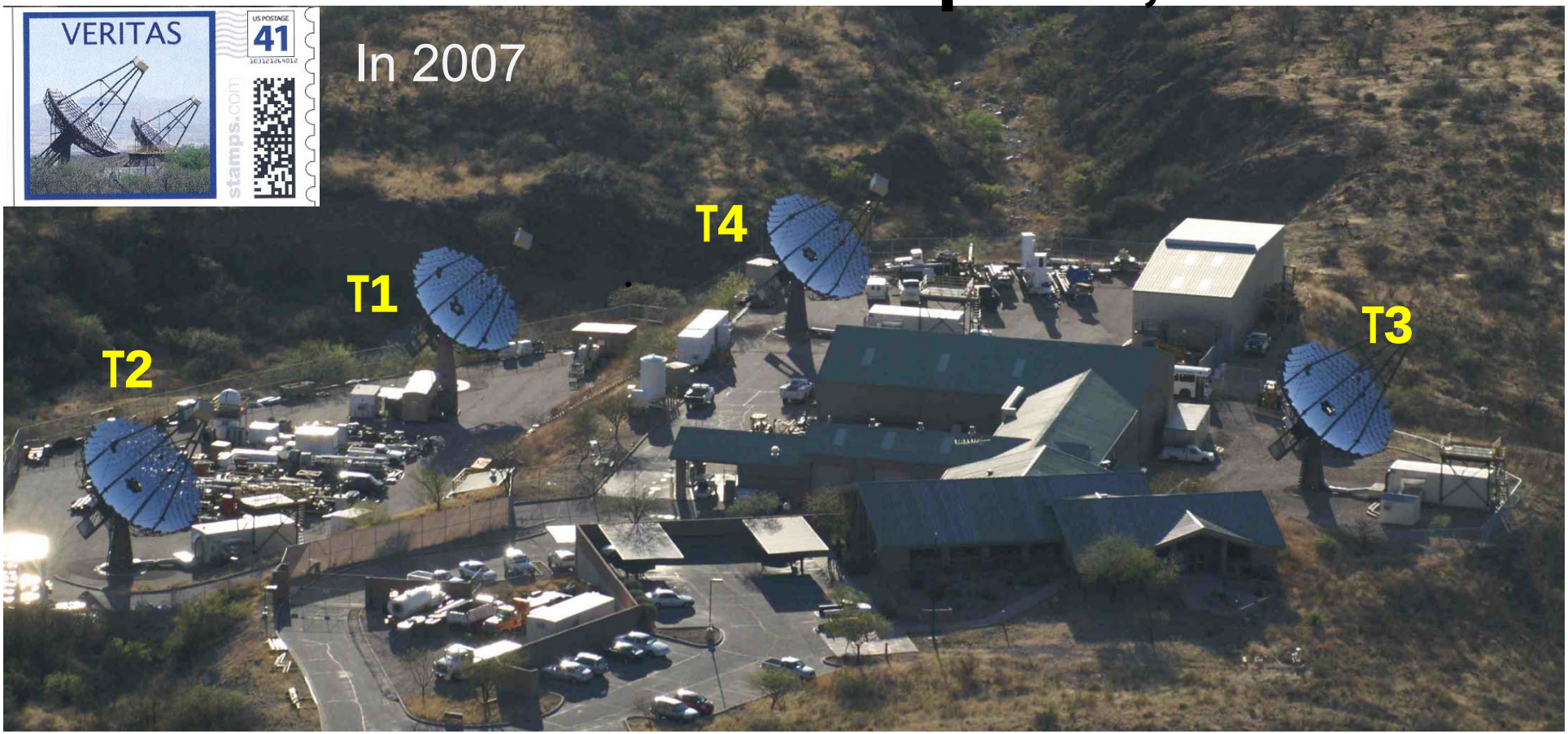
- Four 12m telescopes.
- 500 pixel cameras (3.5º).
- Site in southern Az (1300m).

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



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.:

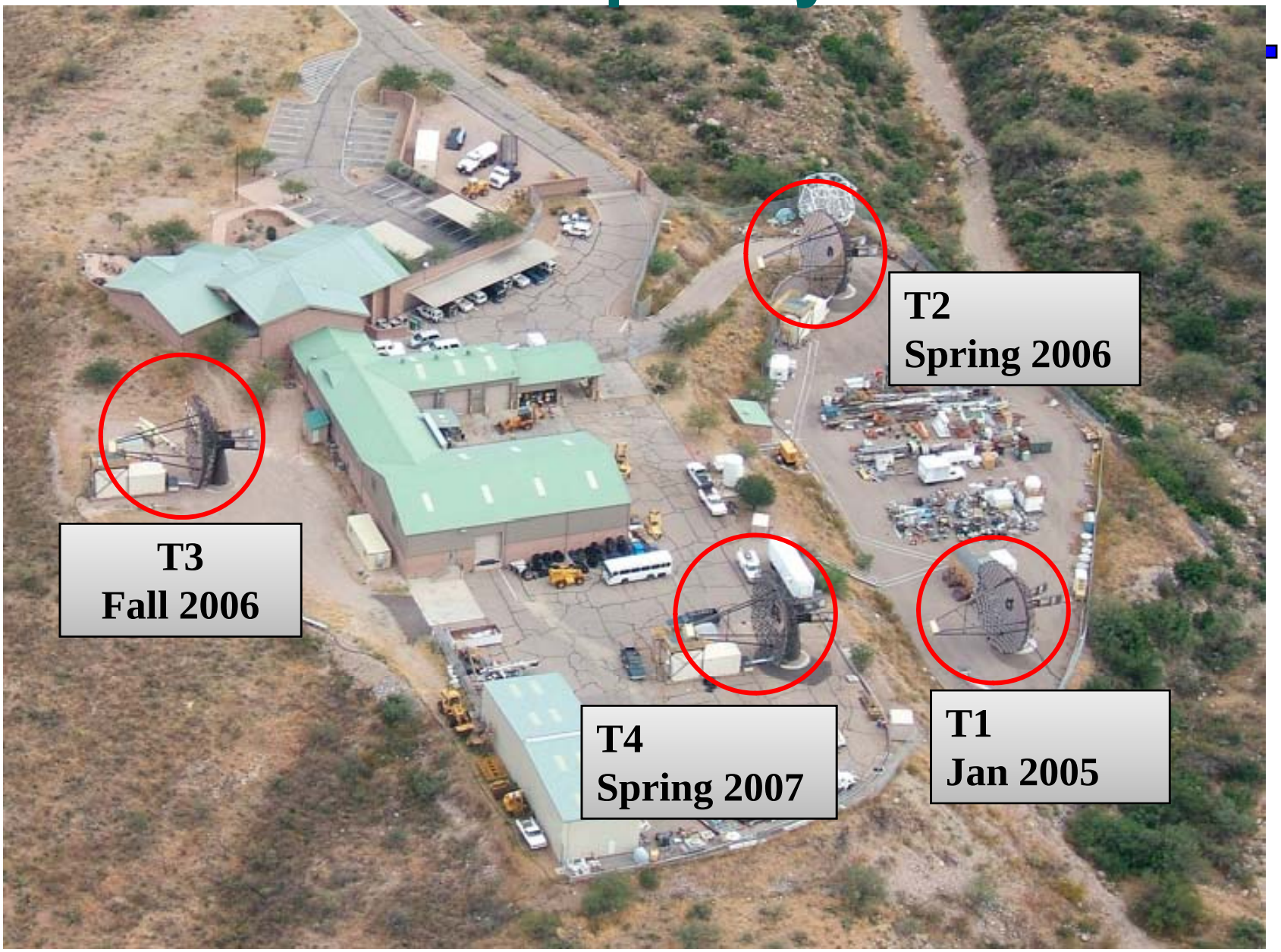
Leeds Univ.

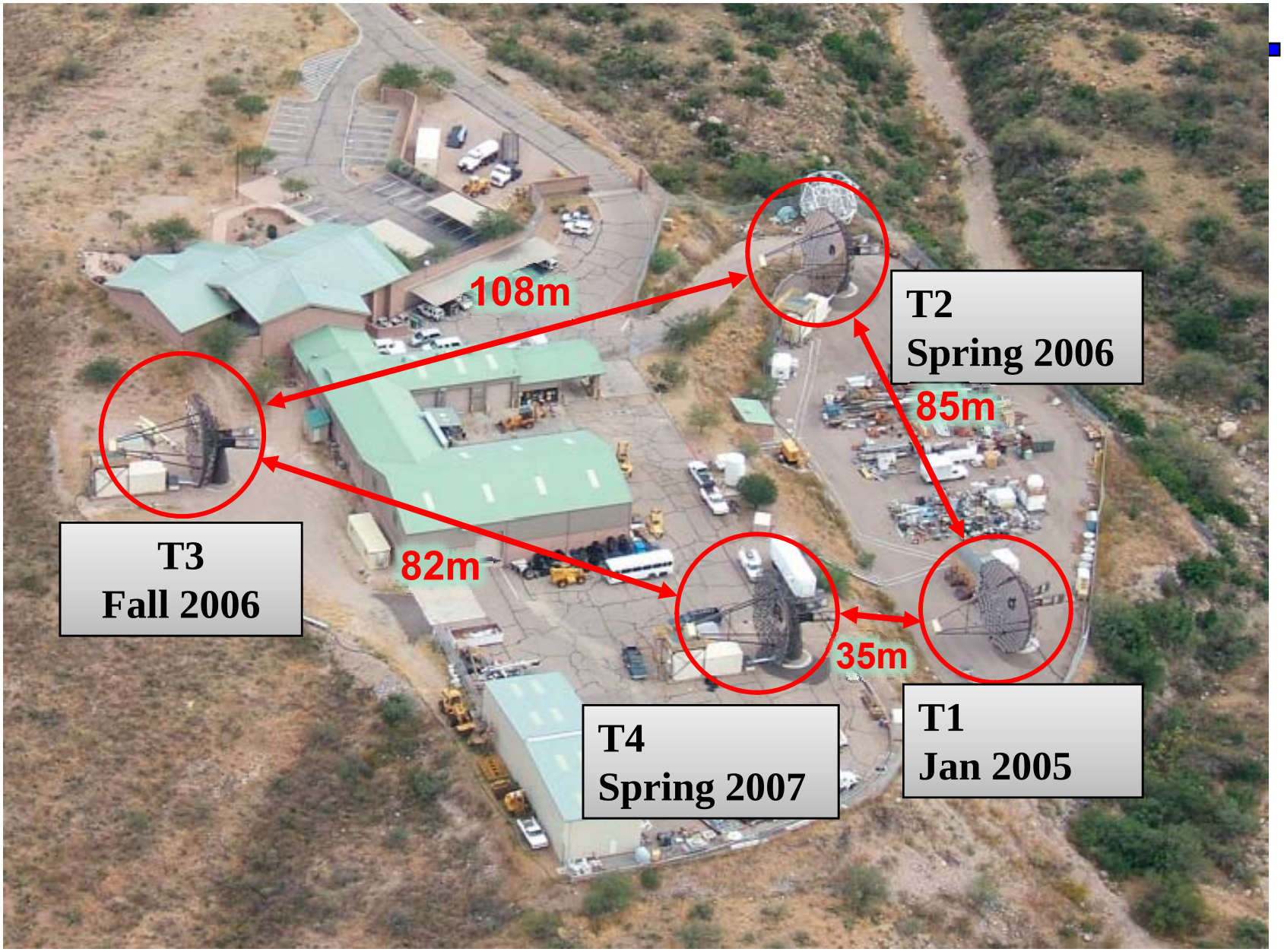
Ireland:

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

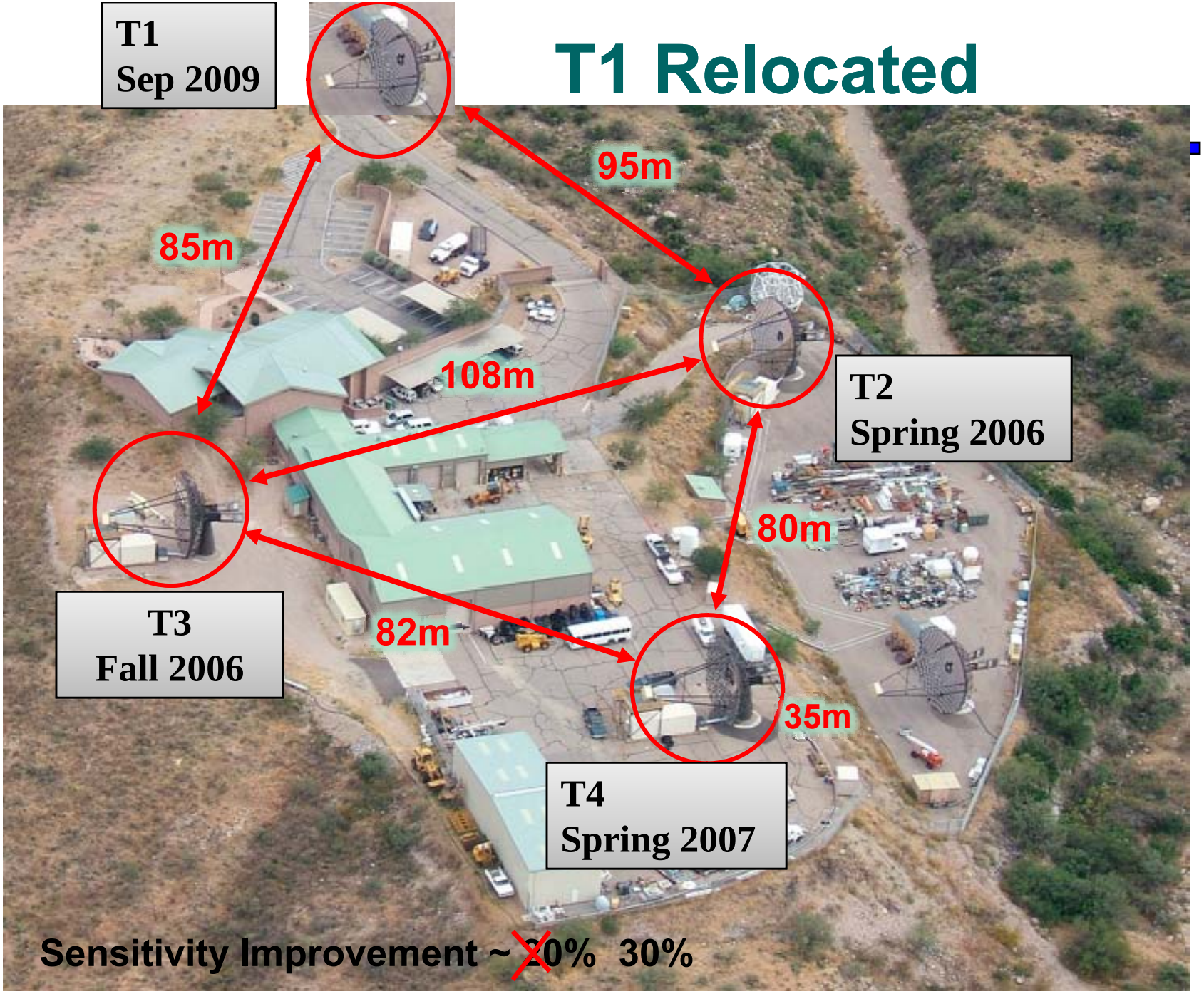
+ ~25 Associate Members

Telescope Layout




108m
T2
Spring 2006
85m
T3
Fall 2006
82m
35m
T4
Spring 2007
T1
Jan 2005

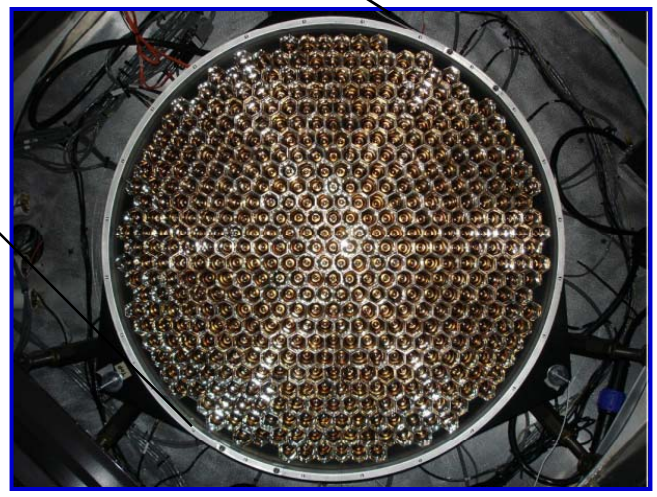
T1 Relocated



A VERITAS Telescope

12m reflector, f1.0 optics

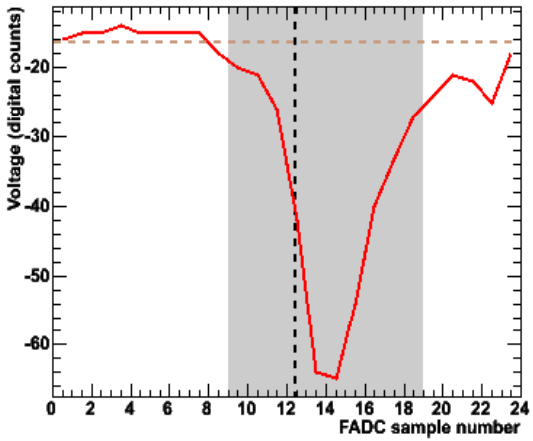
350 Mirror Facets

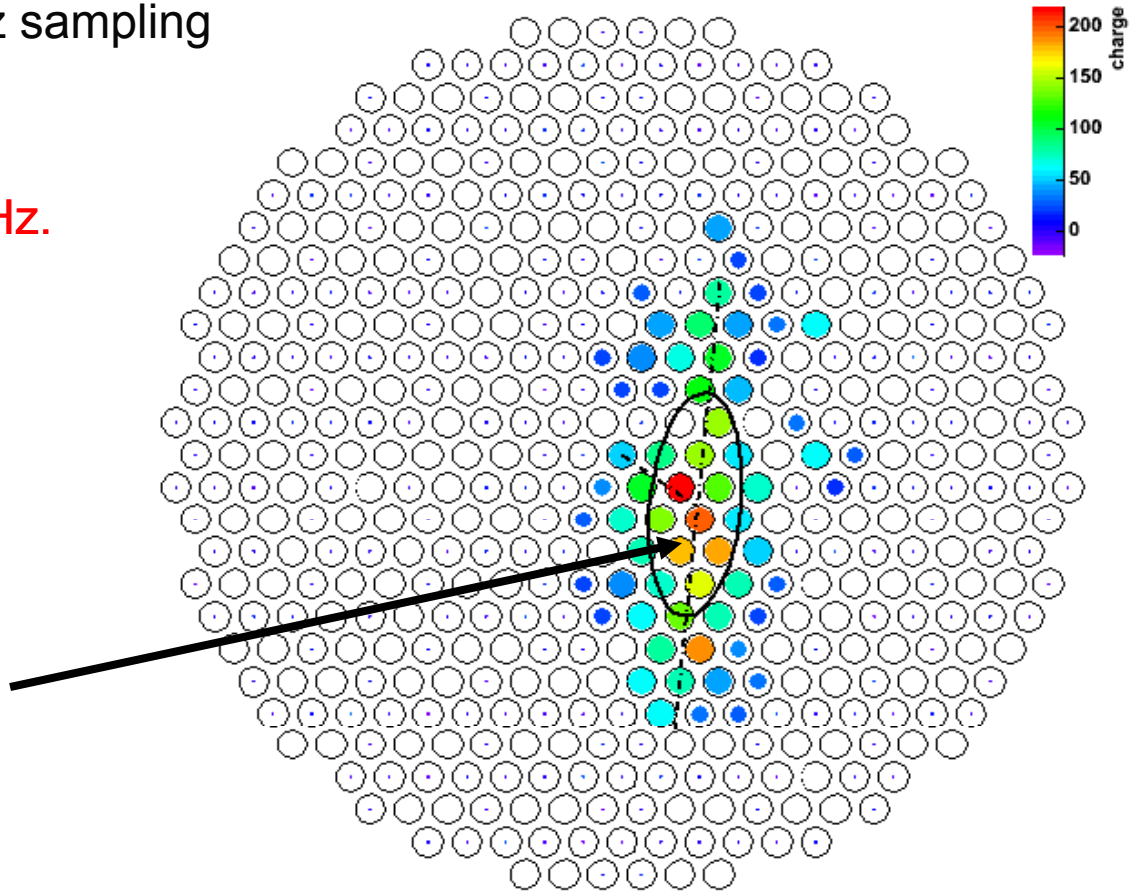


500 pixel Camera

VERITAS Data Acquisition

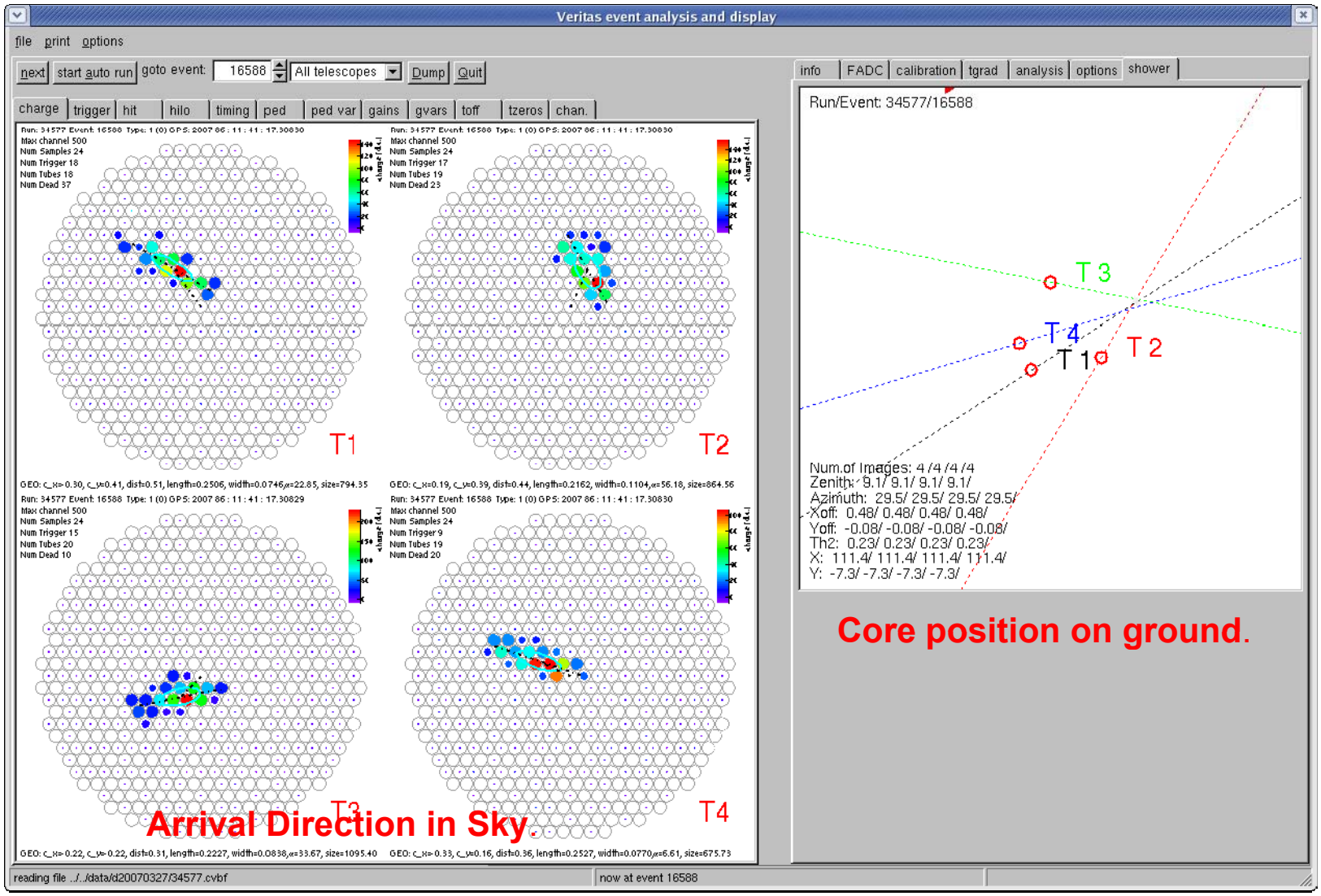
- PMTs digitized with 500 MHz sampling FADCs
  - 20 samples/channel.
  - <10% deadtime @ 250 Hz.





Timing & Amplitude on all channels.

Four-Telescope Event



Arrival Direction in Sky.

Core position on ground.

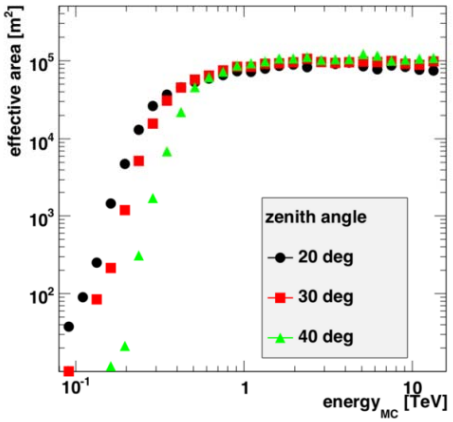
VERITAS Performance

Canonical Performance Values:

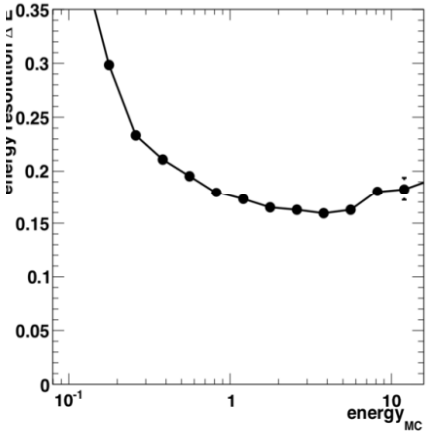
- Energy Range: 100 GeV – 30 TeV (spectra >150 GeV)
- Energy Resolution: 15% – 20%

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

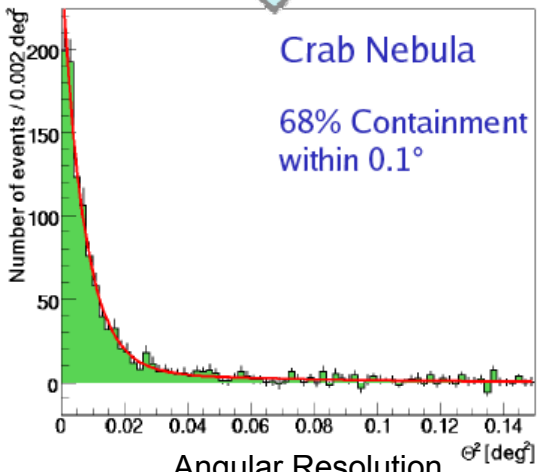
- Angular Resolution: r_{68} < 0.1°
- Pointing Accuracy: < 50″



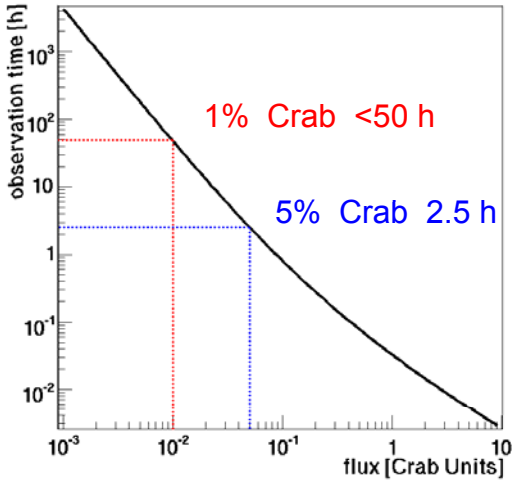
Effective Area (std. cuts)



Energy Resolution



Angular Resolution



Pt. Source Sensitivity

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.

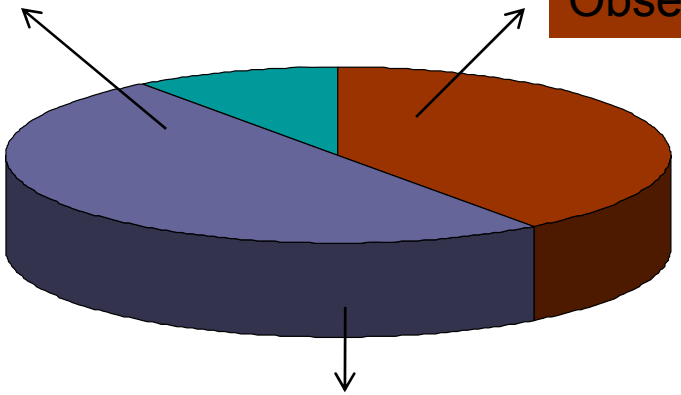
Observation Strategy 2007-09

Discretionary (10%)

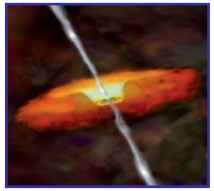
- ToO's, GRBs
- Higher risk sources

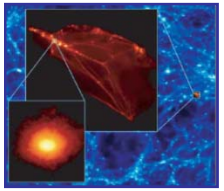
Observing Proposals (40%)

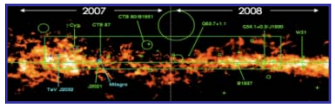
- Science WG's & TAC



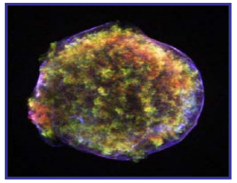
Key Science Projects (50%)


BLAZARS


Dark Matter



Galactic Plane Survey

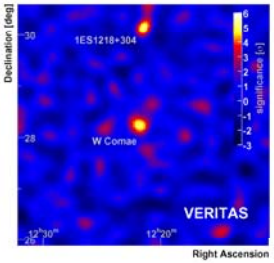

SNRs/PWN

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

VERITAS Science Highlights (so far)

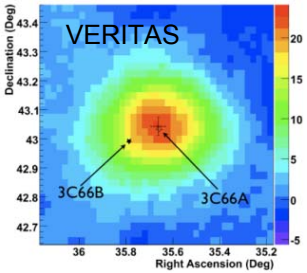
2007:

- **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.



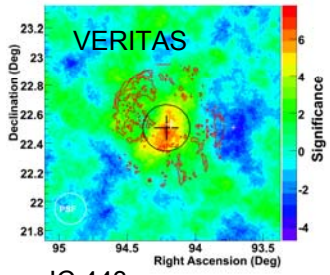
W Comae & 1ES 1218+304

2008:



3C 66A

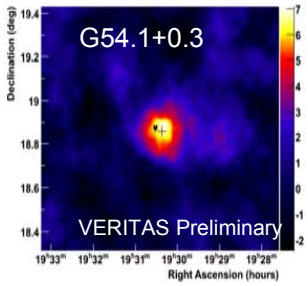
- Detection of blazar 1ES 2344+514, correlated TeV flare with X-ray.
- **Discovery of blazar 1ES 0806+524 (ATEL #1415).**
- **Discovery of blazar W Comae (ATEL #1422), a new LBL.**
- Detection of SNR Cas-A.
- **Discovery of blazar 3C 66A (ATEL #1753), the first IBL.**

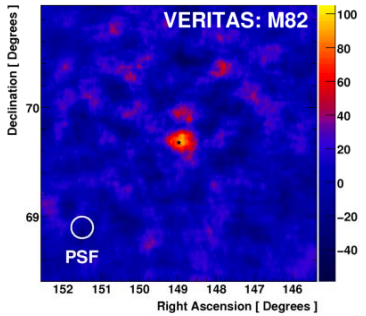


IC 443

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.

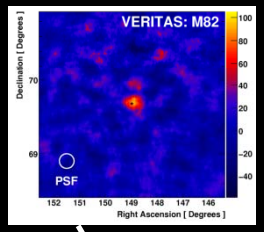




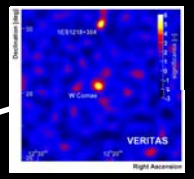
- **Nov 09: First results from Sky Survey**
  Discovery of 4 new sources (2 AGN, 2 unidentified)

The VERITAS SKY (Sep 09)

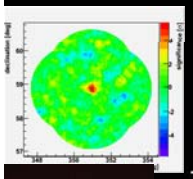
Starburst
M 82

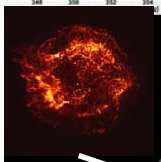


AGN
W Comae



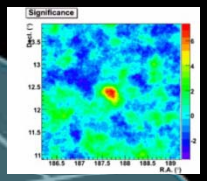
SNR Cas-A

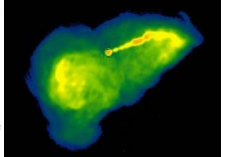


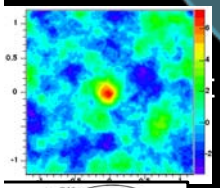


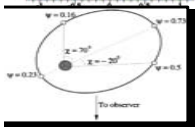
Mrk 421
+90°
W Comae
1ES 1218+304
M87
M82
H 1426+428
PKS 1424+240
1ES 0806+524
Mrk 501
RGB J0710+591
1ES 1959+650
G106.3
+2.7
HESS
J1857+026
IC443
+180°
LSI +61 303
Cas A
G54.1
+0.3
MGRO
J1908+06
-180°
1ES 2344+514
Crab
3C66A

Radio Galaxy
M 87



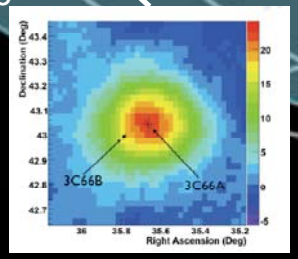




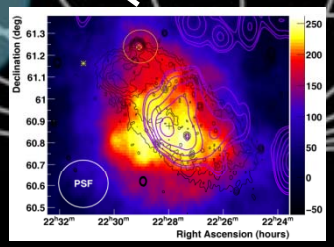


al. 2006

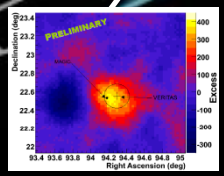
Binary
LS I +61 303



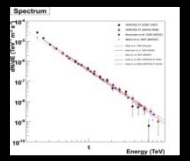
AGN
3C 66A



SNR
G106.3 +2.7



SNR IC 443



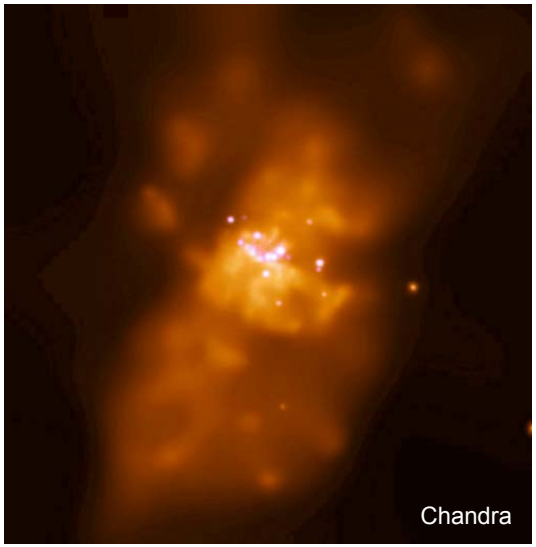
Crab
Nebula

/tevcat.uchicago.edu/

NEW: Starburst Galaxy M 82

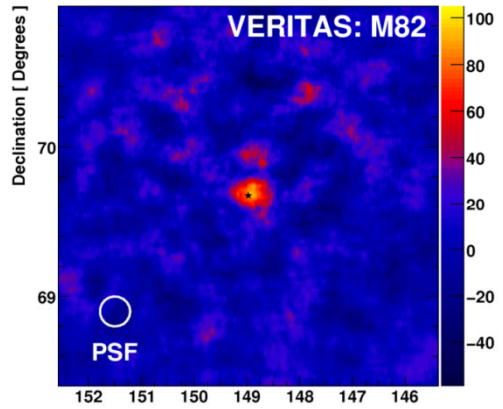
- **M82: Prototype starburst galaxy**
  - Interacting with group of galaxies over ~300 Myrs.
  - Tidal forces → active starburst region (HST shows > 200 massive star clusters.
  - SMBH < 3 x 10^7 M_{sun}, but no AGN activity.

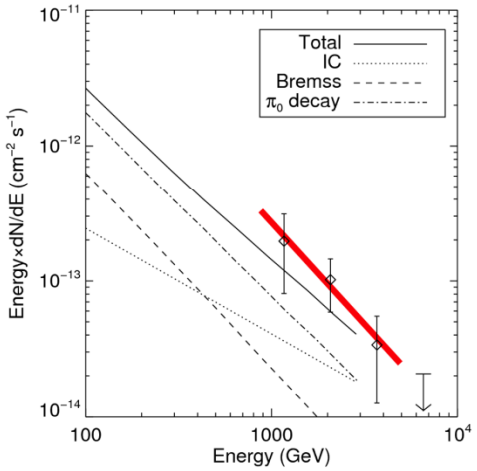
- **Starburst Region**
  - High star formation and SNR rate.
  - High CR density (from radio emission).
  - High gas density ~ 150 /cm^3.
  - γ-rays from cosmic rays interacting with gas and photon fields. Insight onto origin of CR's.
  - Previous limits < 10% Crab (HEGRA, Whipple).



NEW: Starburst Galaxy M 82

- **VERITAS Data & Analysis**
  - 2007-09: 137 h live time.
    Extremely long exposure.
- **Detection !**
  - ~5σ excess
    Consistent with point source at M82.
  - Many systematic checks done,
  - Among weakest VHE sources ~0.8% Crab.
- **Interpretation**
  - **First detection of extragalactic VHE source not clearly associated with AGN activity.**
  - Consistent with predictions, general nature of CR interactions.



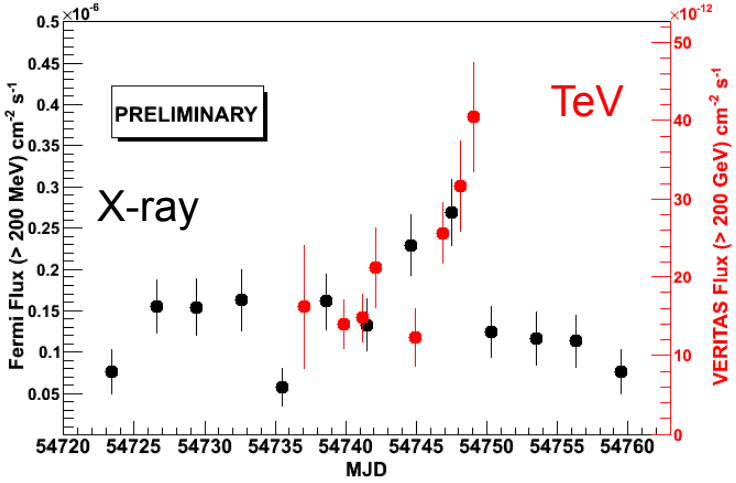


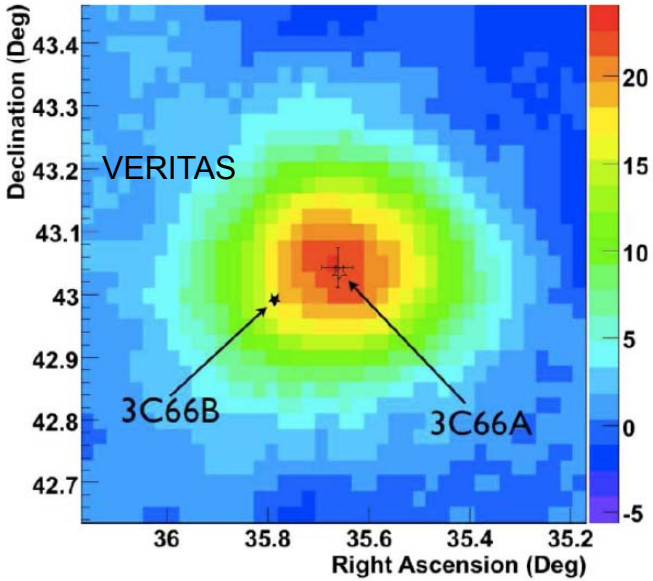
"A Connection between Star Forming Activity and Cosmic Rays in the Starburst Galaxy M 82," V. Acciari et al., Nature, 02 November 2009.

3C 66A: A Typical VERITAS Blazar

- 3C 66A
  - Int. BL Lac at nominal z=0.44.
  - **VERITAS discovery 21σ, 33h, Flare !**
    ATEL #1753, V.A. Acciari et al., ApJ 693, L104 (2009).
  - Soft spectrum: $\Gamma = 4.1 \pm 0.4_{stat} \pm 0.6_{sys}$ (due to absorption ?) .

TeV γ-ray flare

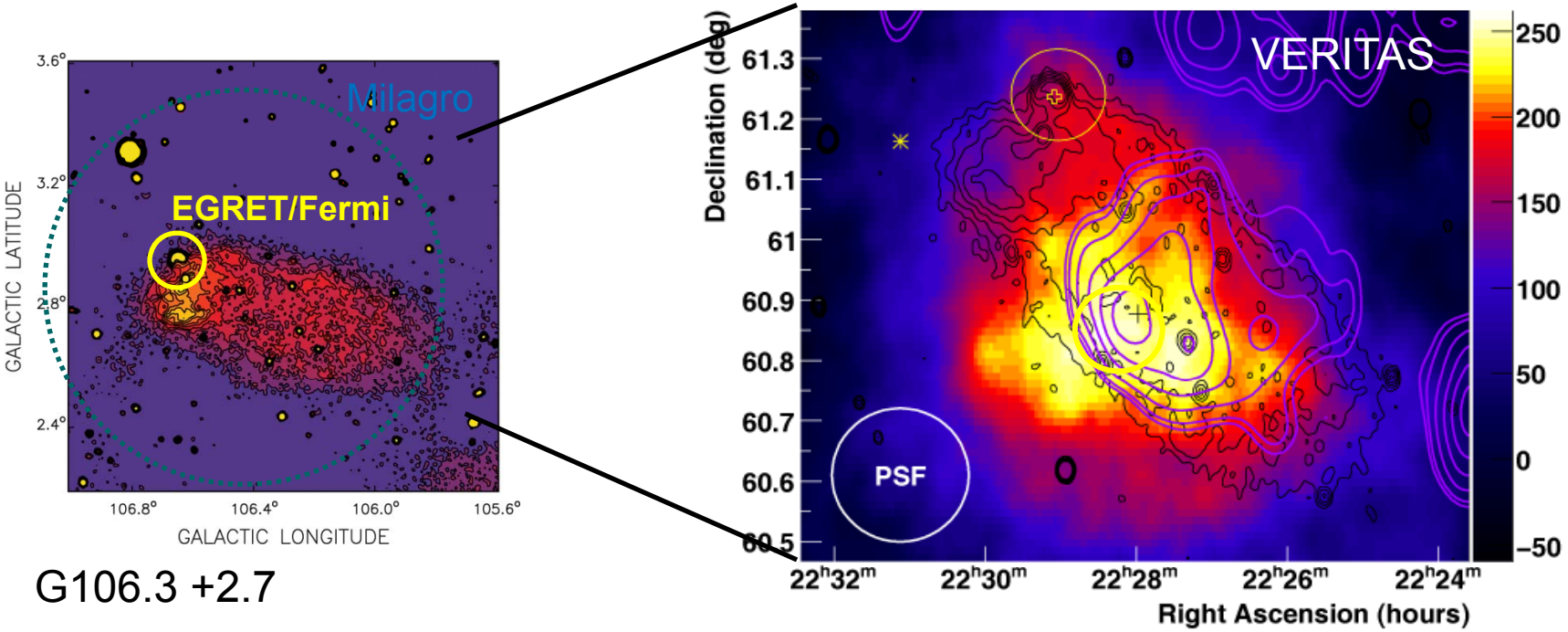




- MAGIC reports 3C66B 0.12° away. 5.4σ in 54 h from 2007 data.
- VERITAS data excludes 3C66B at 4.3σ.

VERITAS clearly detects 3C 66 A !

NEW: SNR G106.3 +2.7 (“Boomerang”)



- G106.3 +2.7
  - Energetic pulsar PSR and SNR
    E-dot ~ 2 x 10^{37} erg/s, age ~ 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 ~5% Crab.
  - Clearly extended, peak overlaps CO.
  - Γ = 2.3 ± 0.3stat ± 0.3sys,
    hard power-law spectrum.

    Hadronic Origin ?

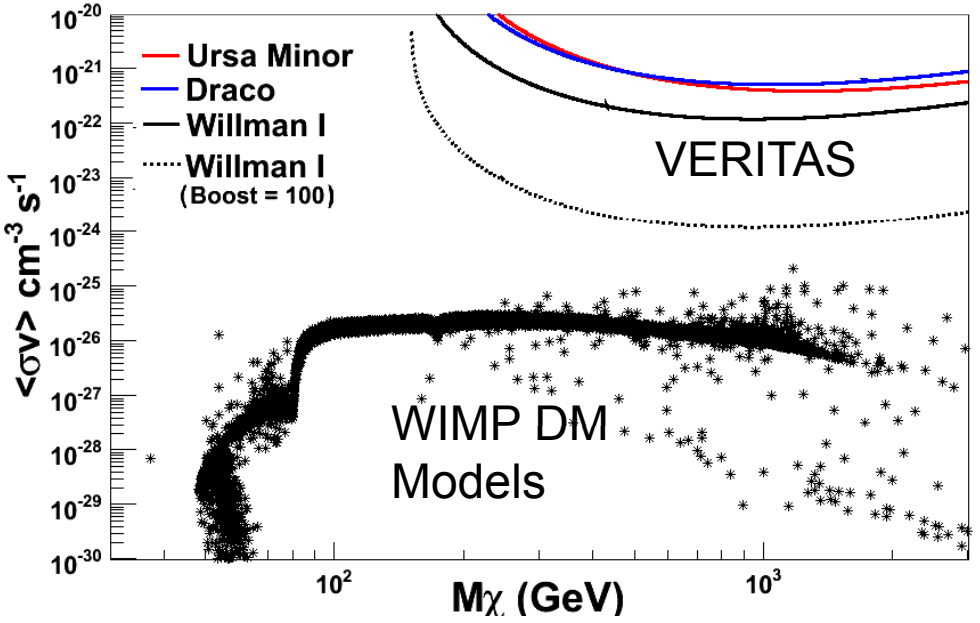
Dark Matter Searches

- VERITAS DM Program

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

  Dwarf Galaxies (e.g. Draco…)
  Local Galaxies (e.g. M32, M33)
  Globular Clusters (e.g. M5)
  Galaxy Clusters (e.g. Coma)

VERITAS limits on dwarf galaxies



- **So far, no Detections**
  → Limits on 7 candidate sources

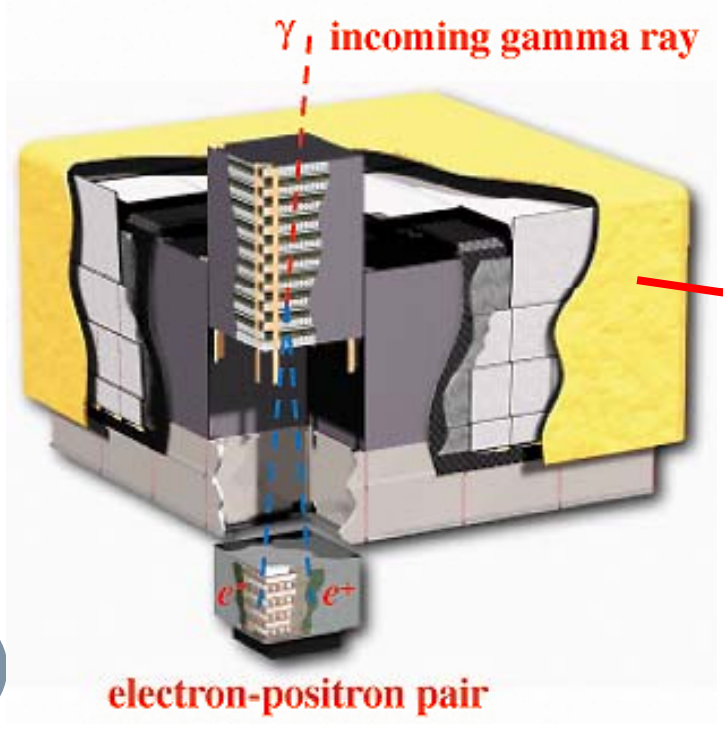
What's next for VERITAS ?

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, γ-ray.
- Upgrade: new cameras, toplogical trigger.
- …

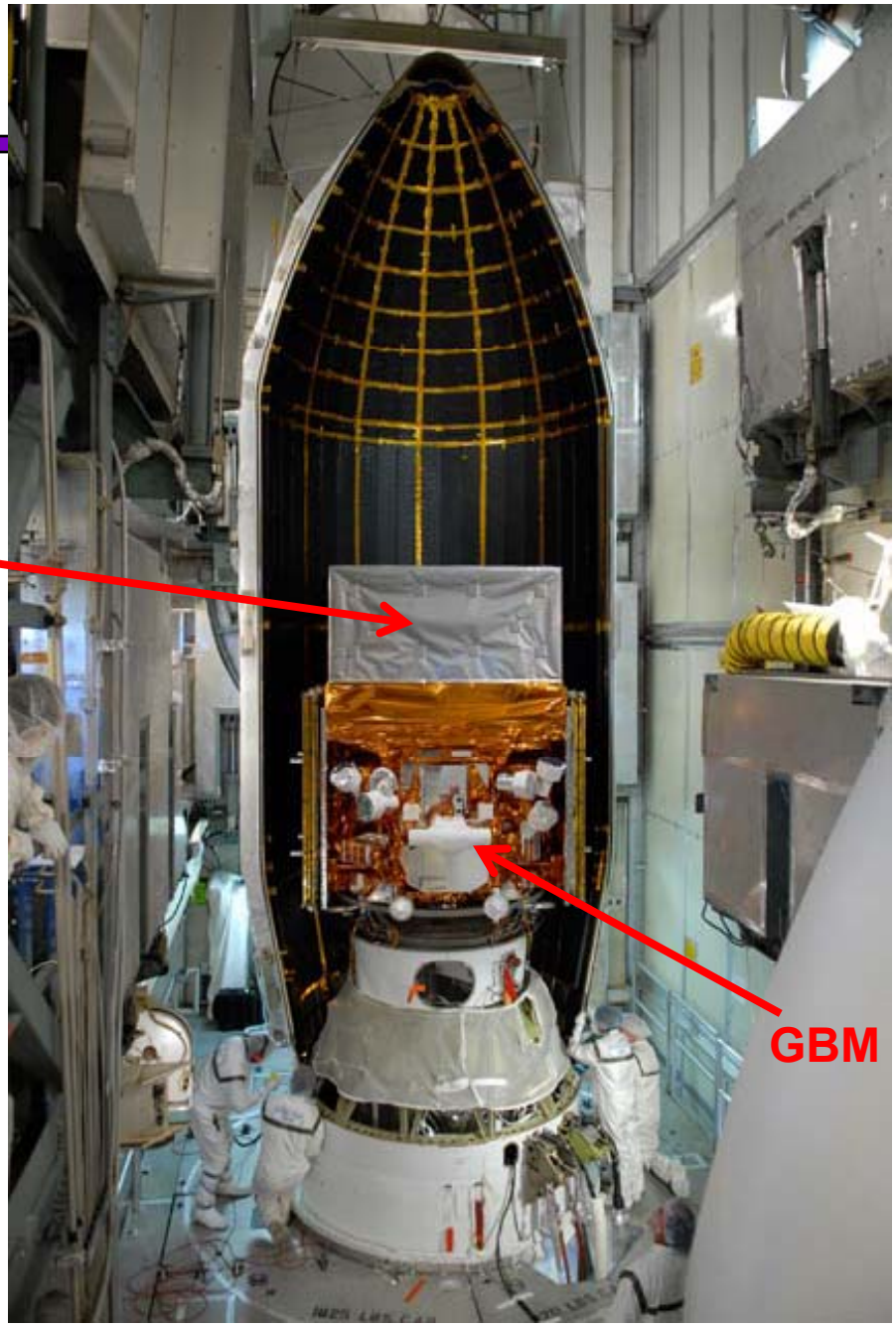
Fermi GST

Large Area Telescope (LAT)

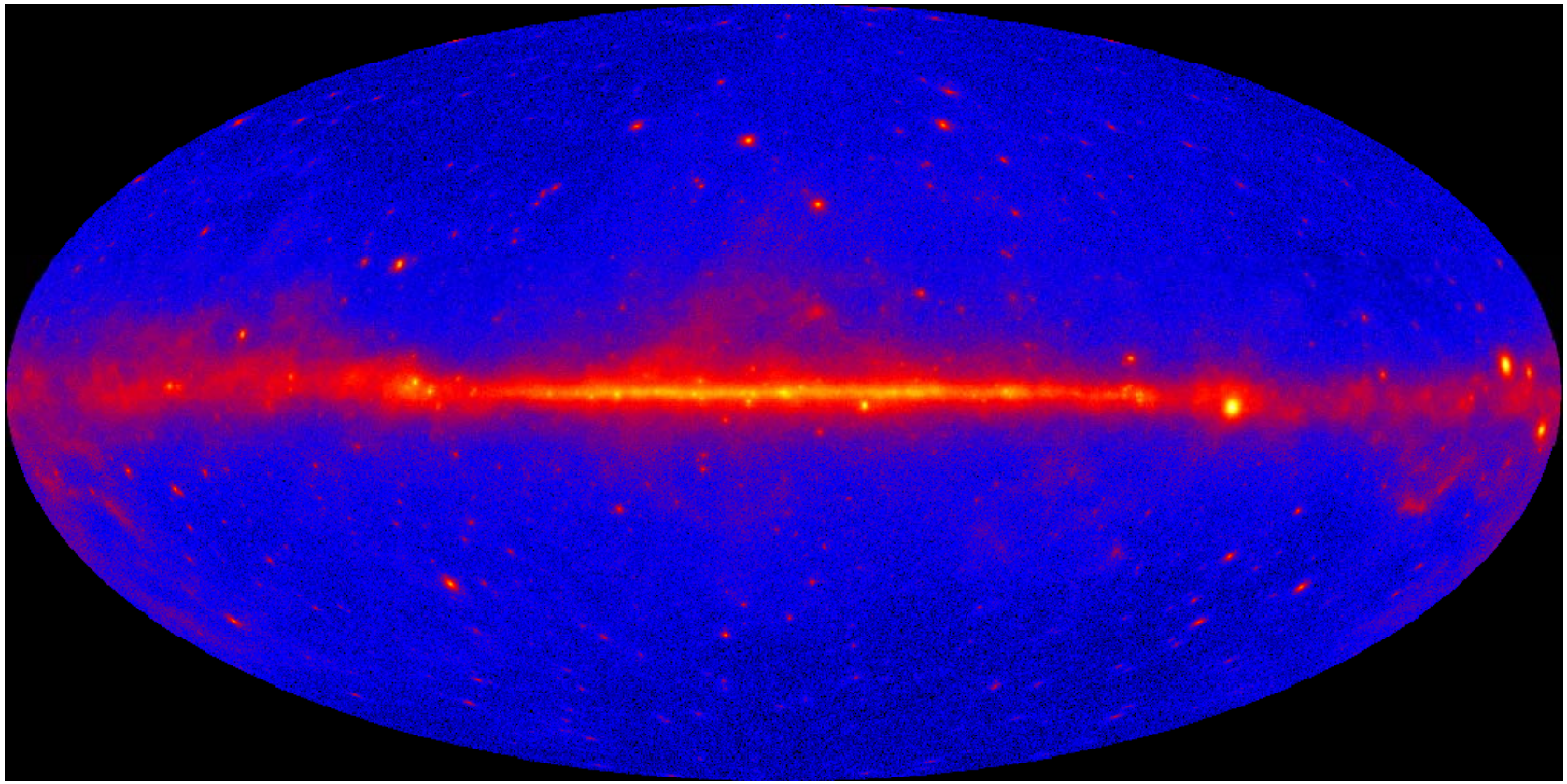


γ-ray converts in LAT to an electron and a positron ; tracking these give us the direction and energy of the photon.

Launched from Cape Canaveral
11 June 2008



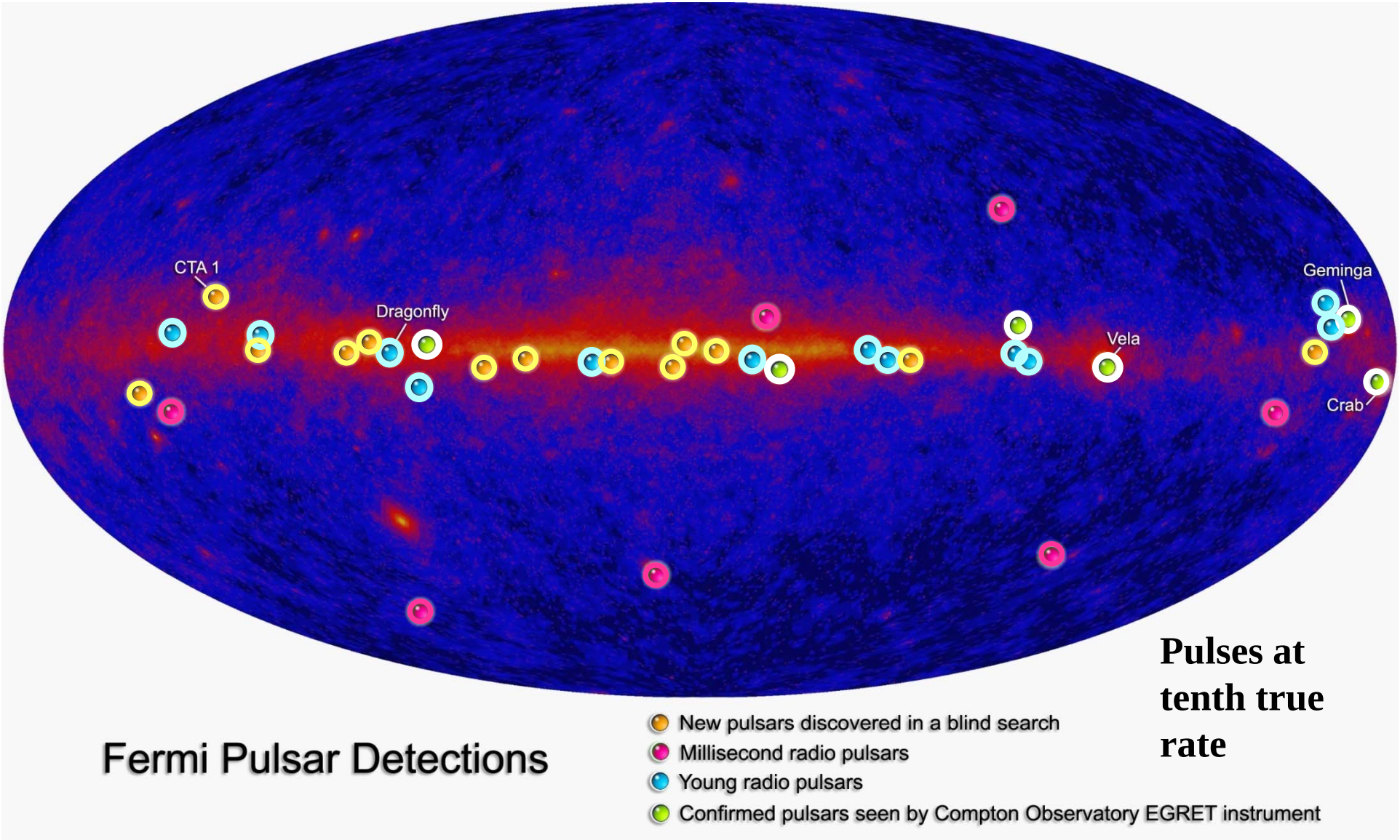
Fermi γ-ray Sky after 1 year



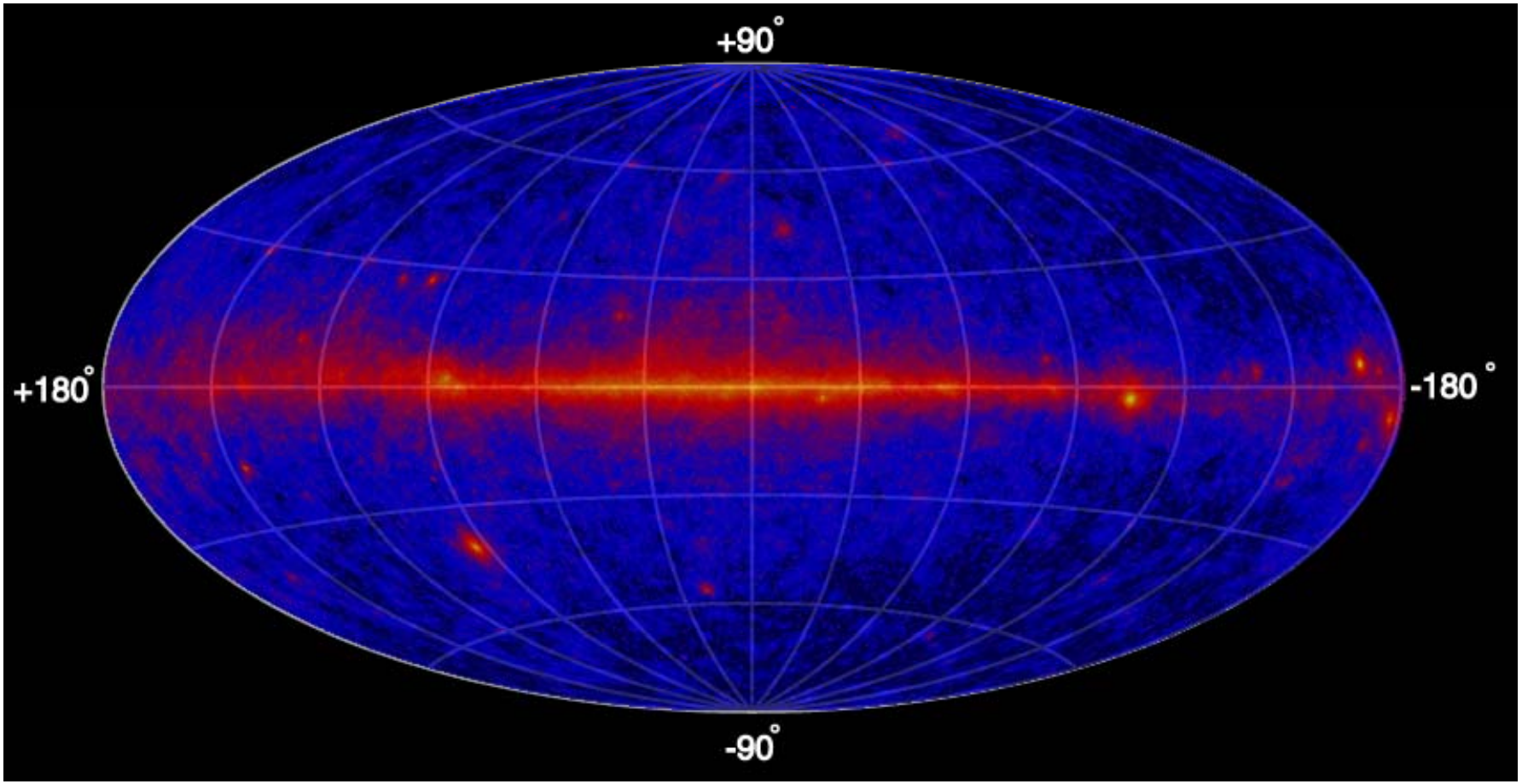
Fermi basically sees the same types of sources as TeV telescopes.

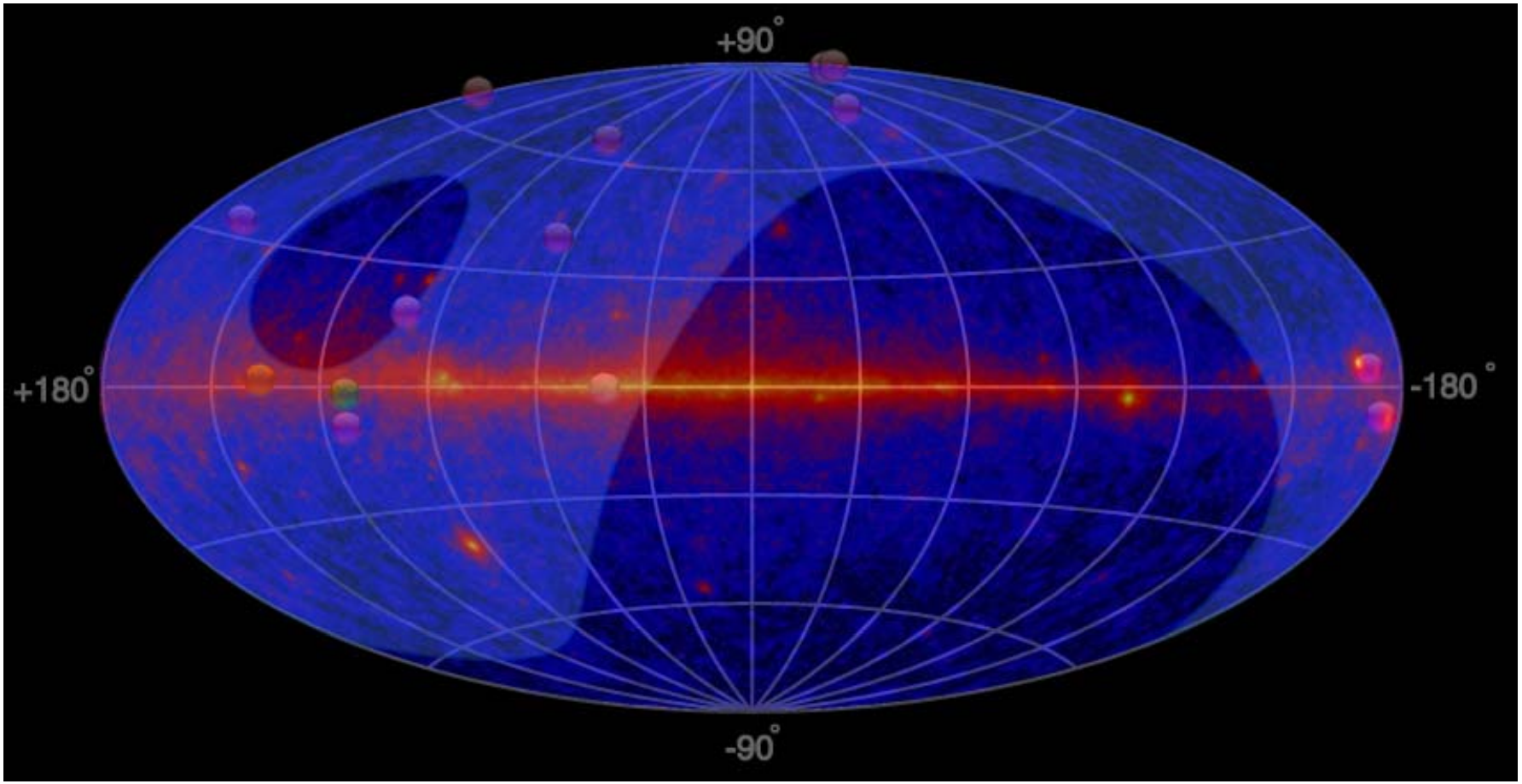
(main exceptions: diffuse emission, pulsars and GRBs).

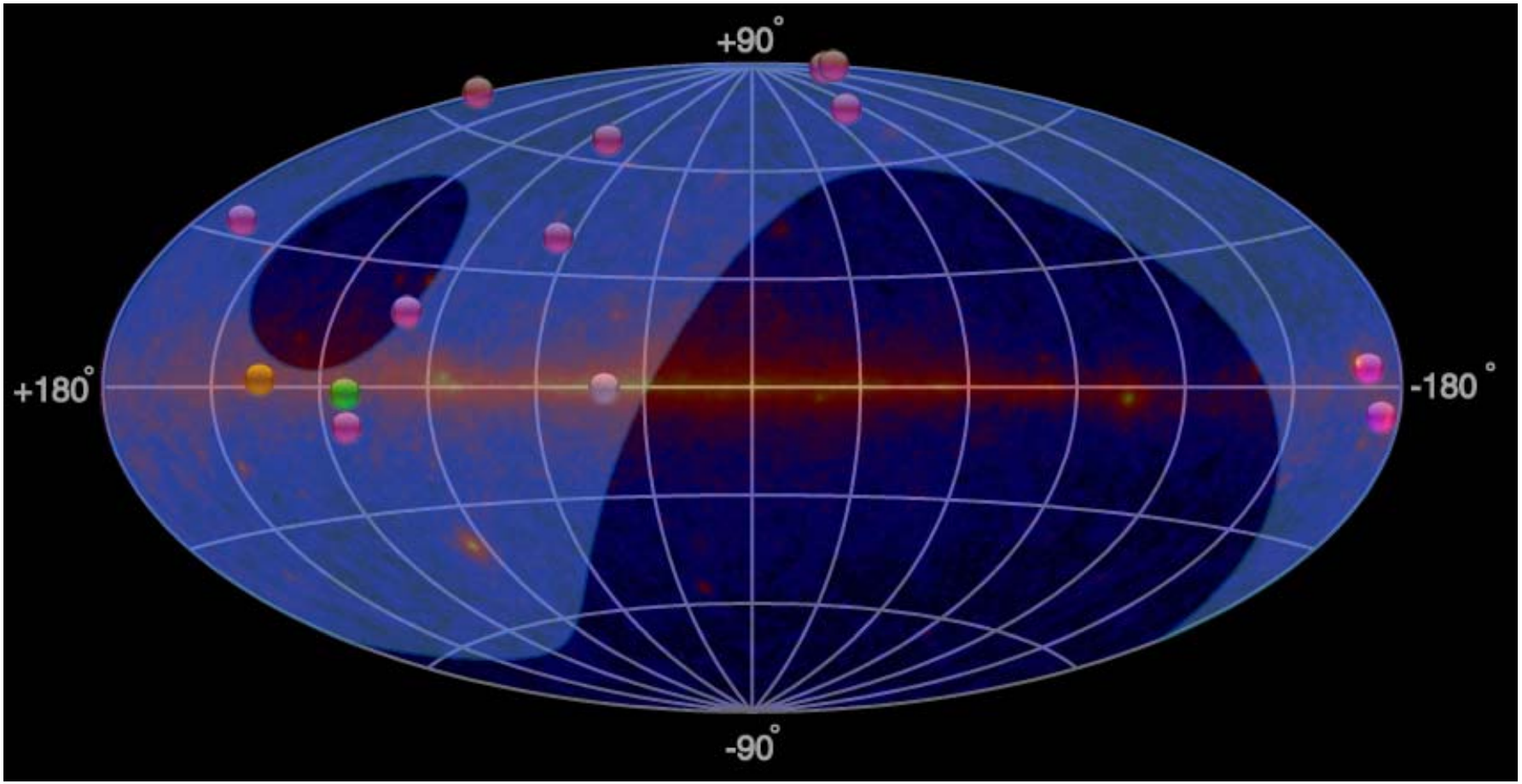
γ-ray Pulsars Detected by Fermi



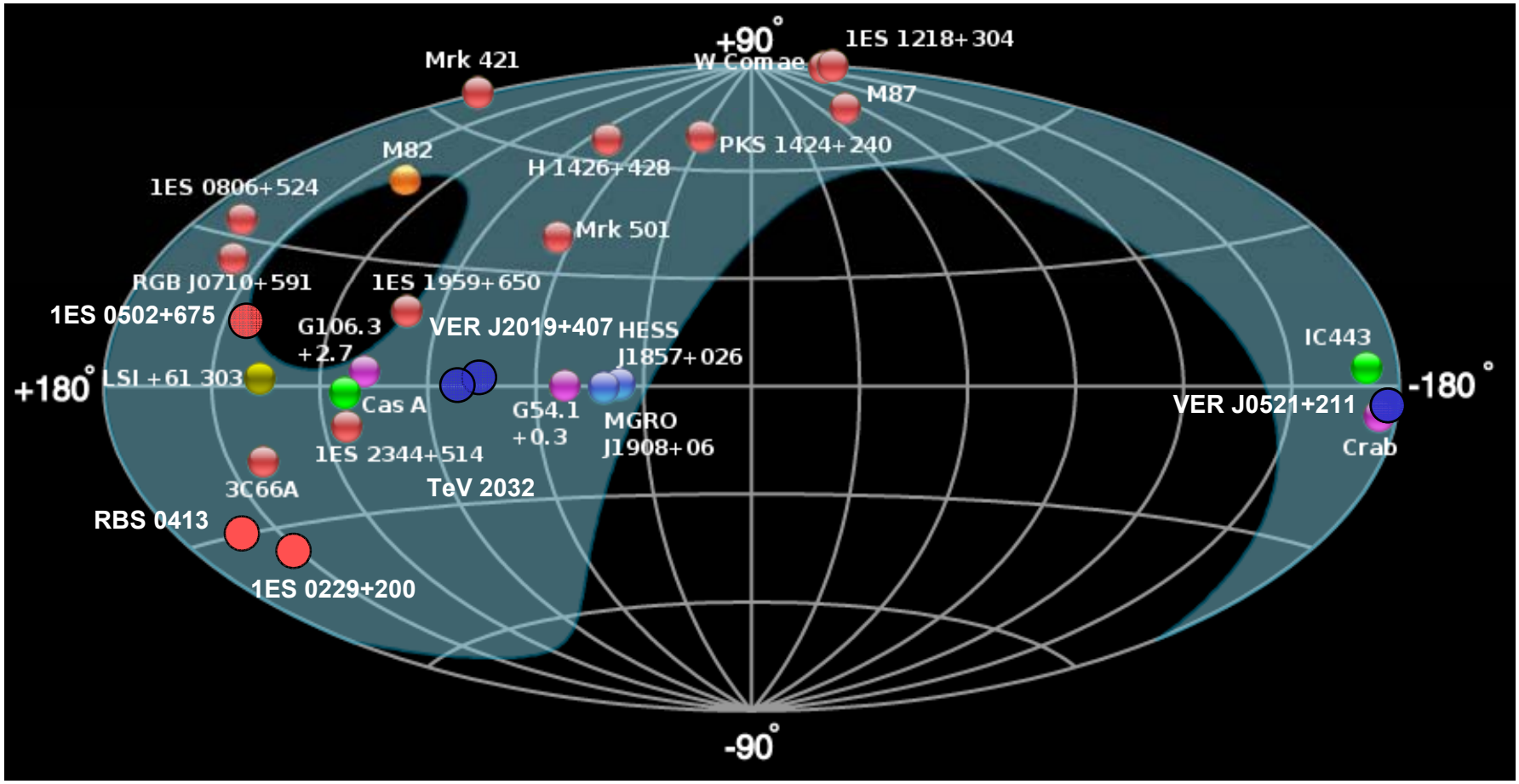
The Fermi (GeV) Sky




+90°
+180°
-180°
-90°

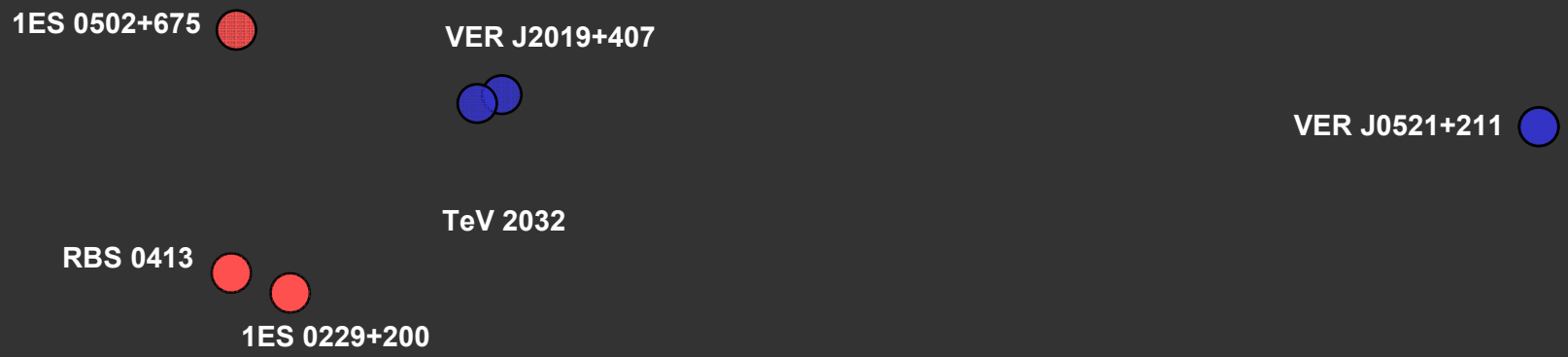

+90°
+180°
-180°
-90°

The VERITAS Sky (Oct 2009)



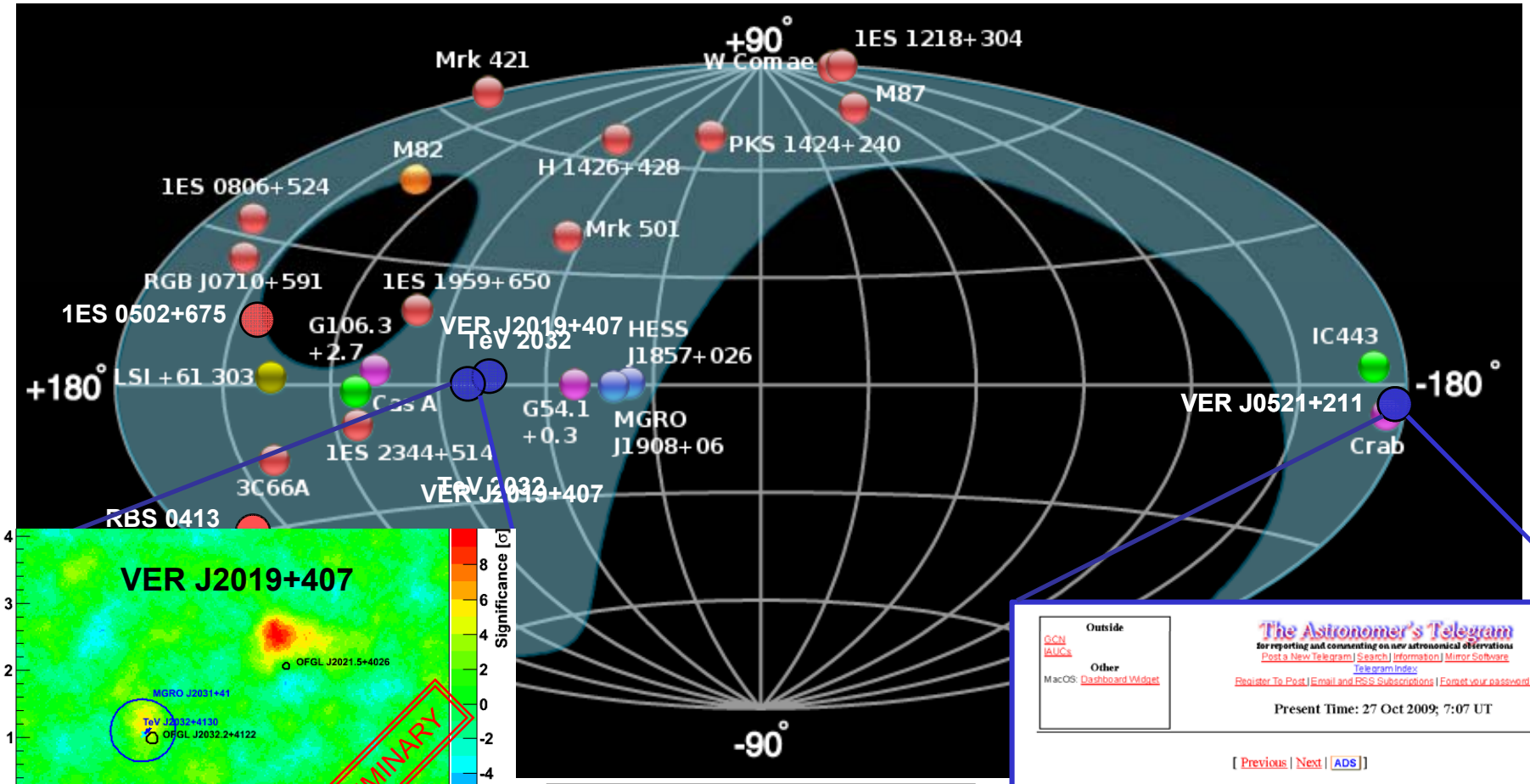
New sources in last 6 weeks !

The VERITAS Sky (Oct 2009)



New sources in last 6 weeks !

The VERITAS Sky (Oct 2009)



? ? ?

So far,
27 sources detected
6 source categories

New AGN ?

FUTURE

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

VERITAS will survey the VHE γ-ray sky with great sensitivity, complementing:

Fermi-LAT (GeV γ-rays, in space)

IceCube (ν, South Pole)

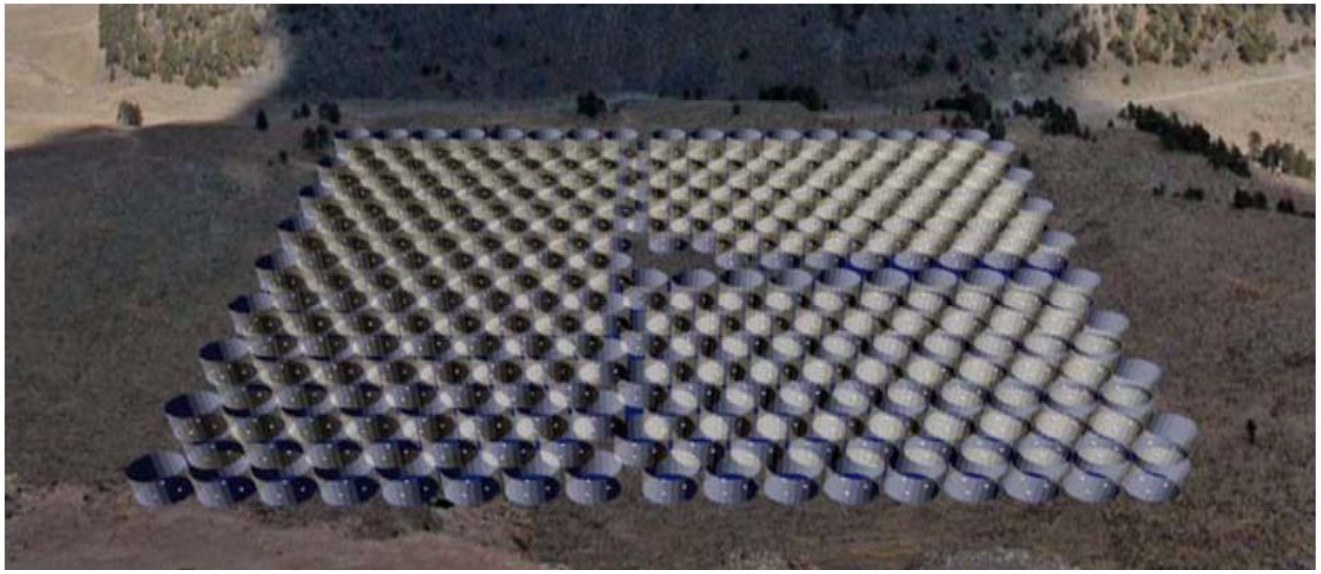
Auger (UHECR, S. Hemisphere)

(HAWC, TeV γ-rays, Mexico, proposed)

Farther in the future:

- Large 1 km^2 atm. Cherenkov telescope array.

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.

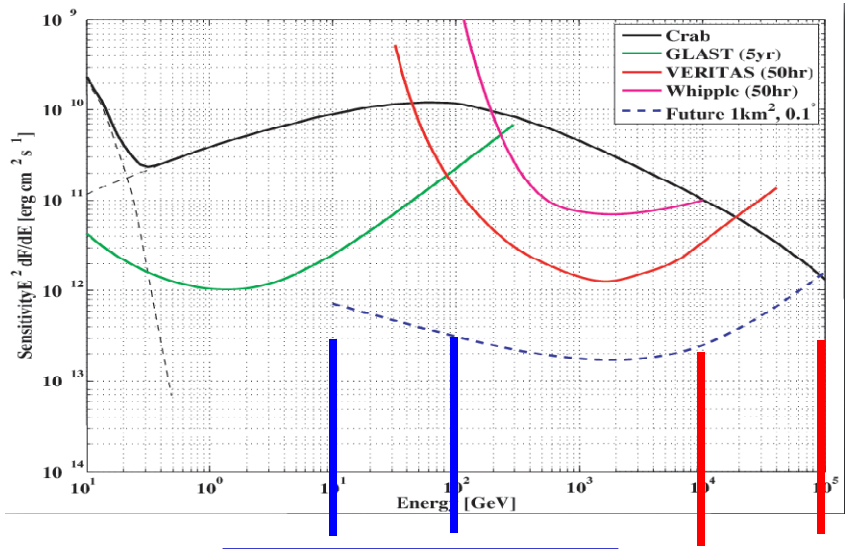
Km² Atm. Cherenkov Array

Large (1 km²) array.

- 50+ telescopes, aperture 8-20m.
- $200-300M class observatory.

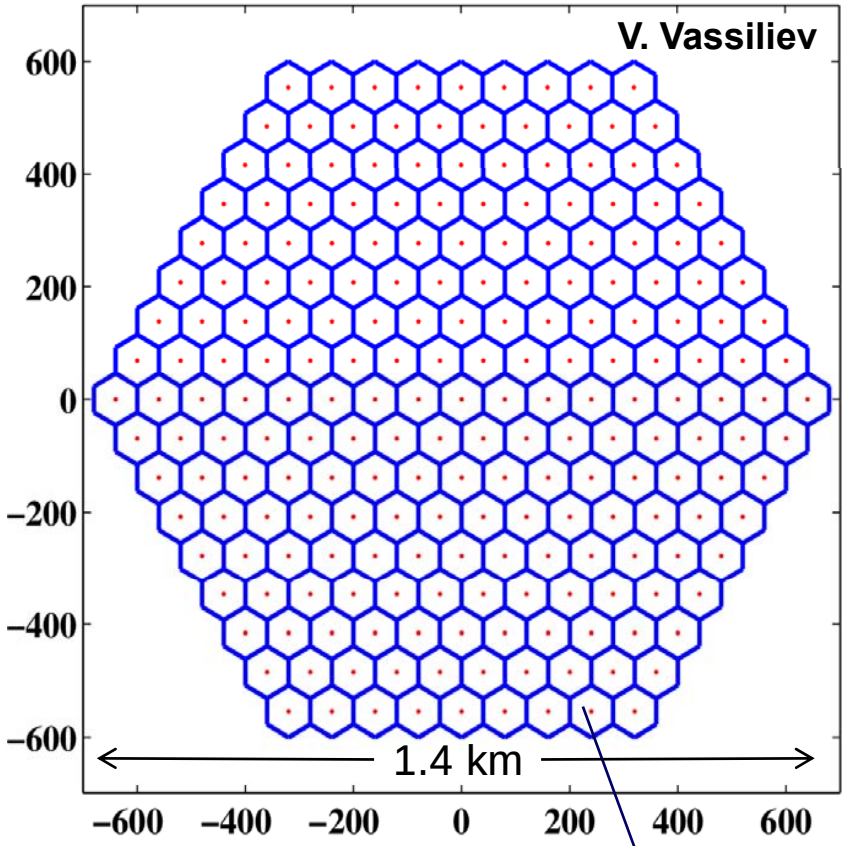
Order of mag. more sensitive than VERITAS.

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



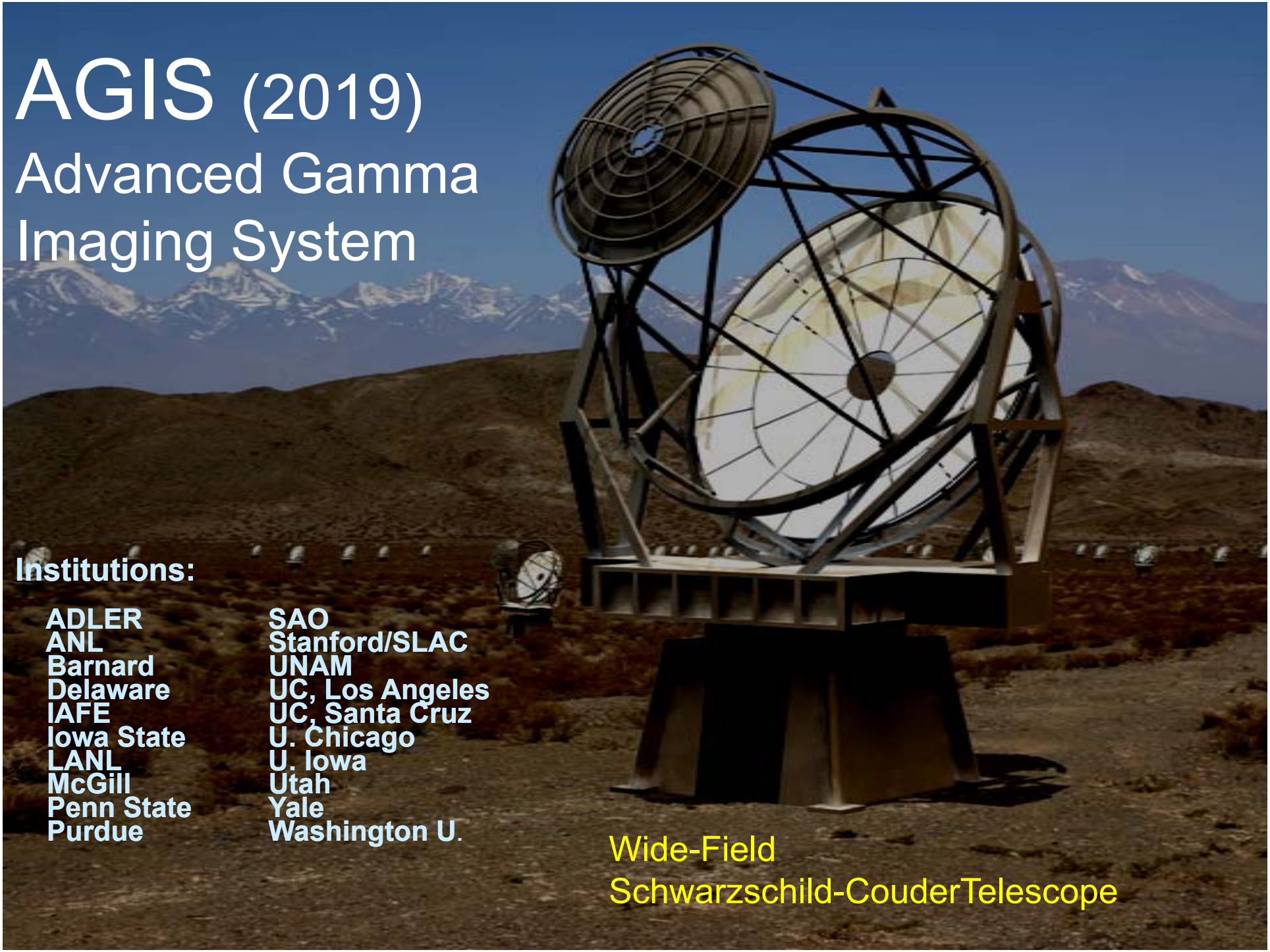
Transition to Fermi Regime (GRBs, etc.)

Spectral cutoffs (acceleration mechanisms)



9-12m telescope
Wide-field
8-10°

AGIS (2019)
Advanced Gamma Imaging System



Institutions:

ADLER	SAO
ANL	Stanford/SLAC
Barnard	UNAM
Delaware	UC, Los Angeles
IAFE	UC, Santa Cruz
Iowa State	U. Chicago
LANL	U. Iowa
McGill	Utah
Penn State	Yale
Purdue	Washington U.

Wide-Field
Schwarzschild-CouderTelescope

Summary

- VHE γ-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 γ-rays. But still, most of the sky remains unexplored.

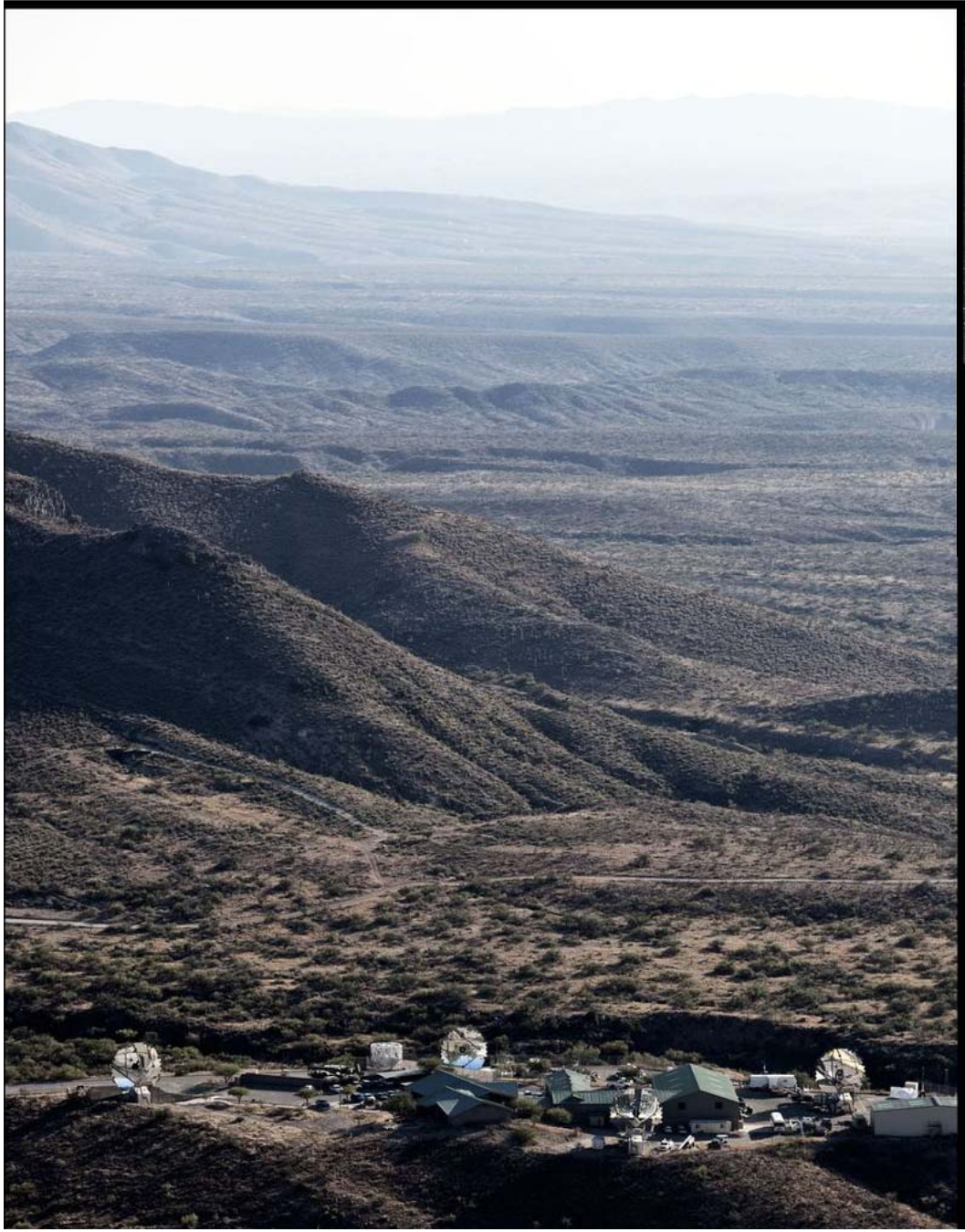
  → **VERITAS and Fermi are now both operational and getting exciting results**.

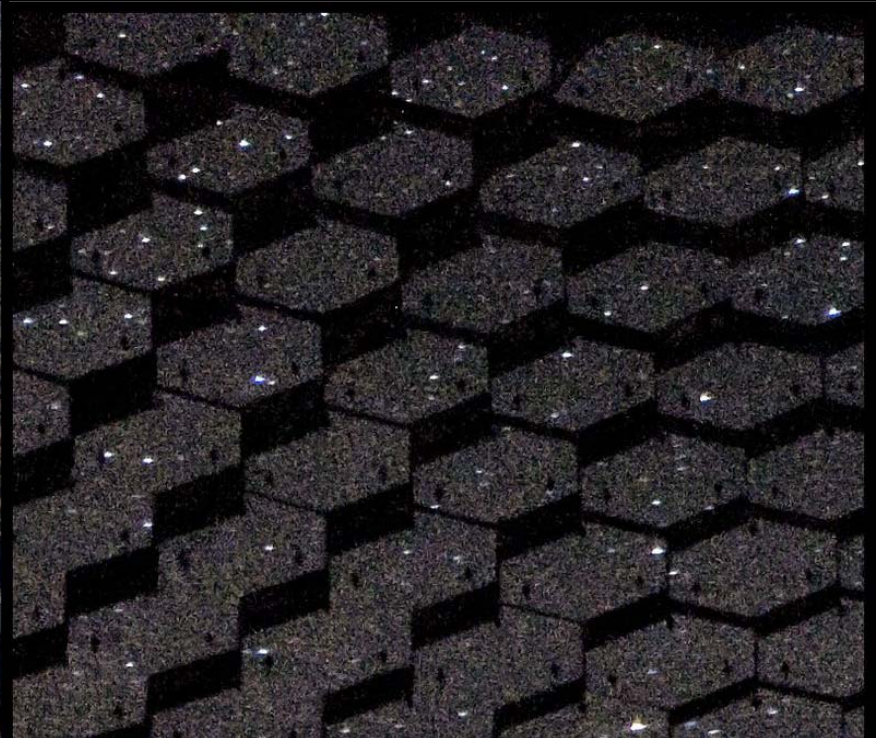
- New Astronomy of TeV γ-rays (and neutrinos, grav. waves) should reveal many surprises over the next 10 years.

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

Marcel Proust (1871-1922)

Fezziwig Press & Photography (http://stujenks.typepad.com)





EXTRA