VERITAS: exploring the high energy Universe

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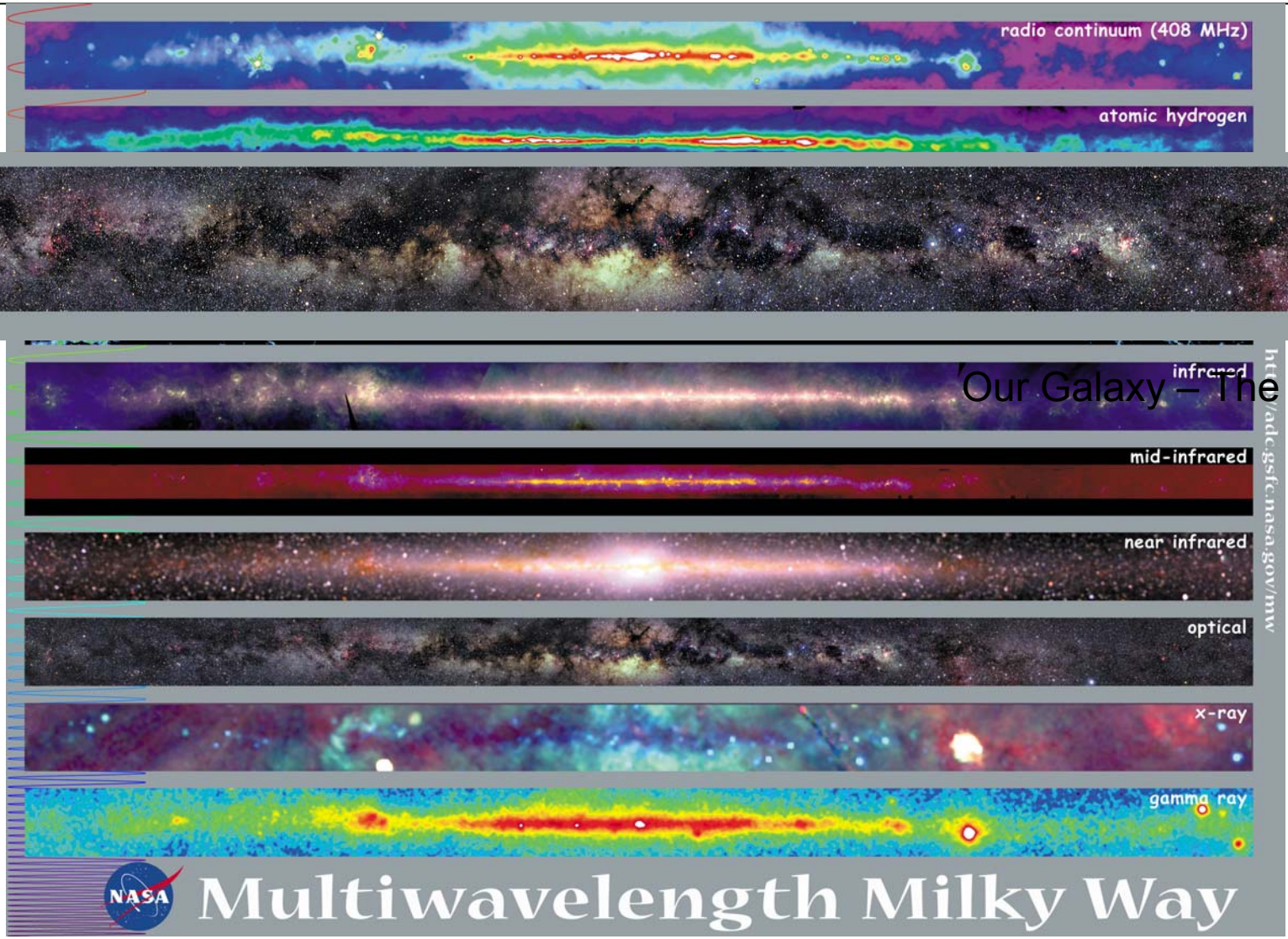
Outline

- Beyond the optical
- Very high-energy (VHE) gamma-ray astrophysics
- Ground-based observations – Cherenkov arrays
- VERITAS
- Instrument performance
- First science results
- Observing plan
- Outlook

Astronomy beyond the optical …

- Information about cosmos comes from EM waves
  (and more recently, particles) (and soon, gravitational waves?)
- Historically, for >99% of history, this has meant optical light.
- Not surprising that new information brings new insights!
- Very High-Energy (VHE) gamma-rays are produced in (and carry information about) some of the most energetic processes known.

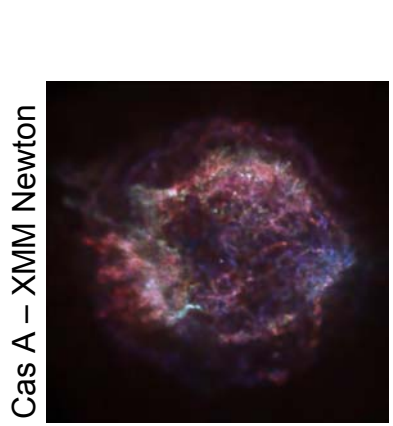
The Universe looks different at different wavelengths!



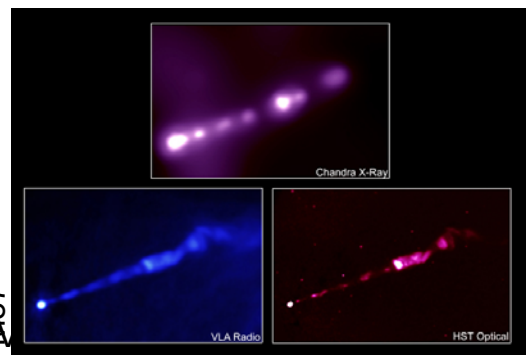
Our Galaxy – The Milky Way

Very high-energy gamma-ray astrophysics

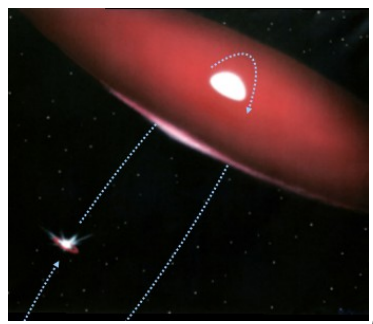
- VHE gamma rays are produced in some of the most violent astrophysical environments!
- At E> 50 GeV, several classes of sources known…
  - Supernova Remnants
  - Pulsar Wind Nebulae
  - Active Galactic Nuclei
  - Binary stars
- …or expected:
  - Gamma-Ray Bursts
  - Dark matter annihilation


Cas A – XMM Newton


Crab: HST + Chandra



M87

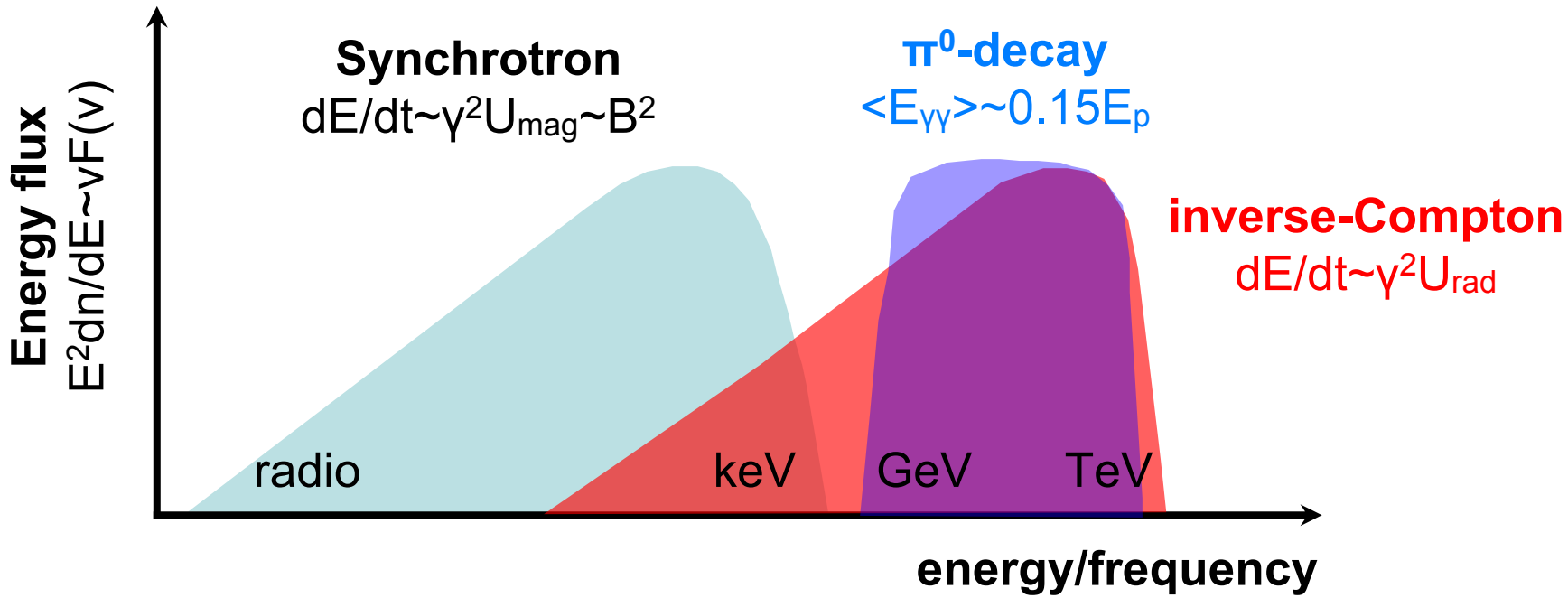

PSR B1259

VHE gamma-ray sources

- Crab (nebula) is most constant source in sky;
  flux (E> 1 Tev) ~ 2 x 10^{-7} $\gamma/m^2/s$
- All known sources have power law ($E^{-\gamma}$) spectra in GeV-TeV regime, to >multi TeV
- Multi TeV γ ➔ source populations (p, e) at higher energy
  - What is the source population?
  - How do they get accelerated to these energies?
- Dominant production processes believed to be:
  - Inverse Compton scattering (of lower energy photon population)
  - π^0 production & decay
- Fundamental physics questions can be addressed:
  - Dark matter annihilation
  - Energy-dependent *c* ?

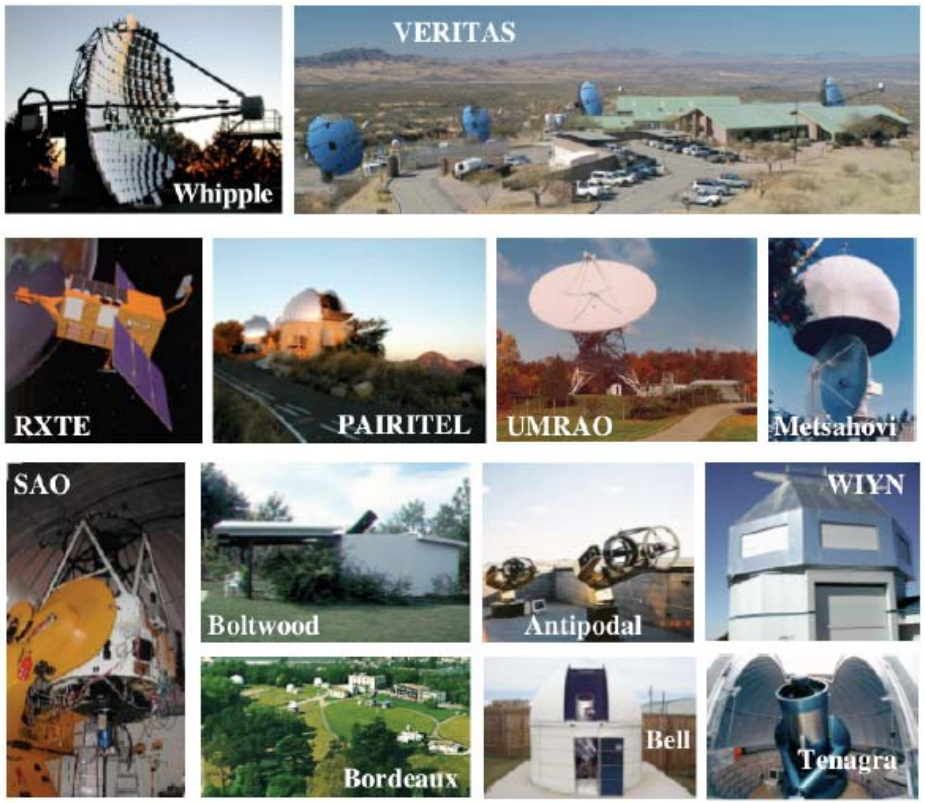
Spectral energy distributions of VHE sources

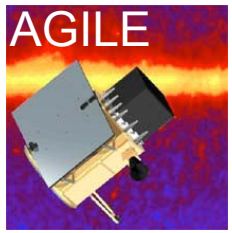
Assume γ-ray flux connected to population of high-energy charged particles



Observables: correlation, flux variability, time lags

Multi-wavelength studies are critical…



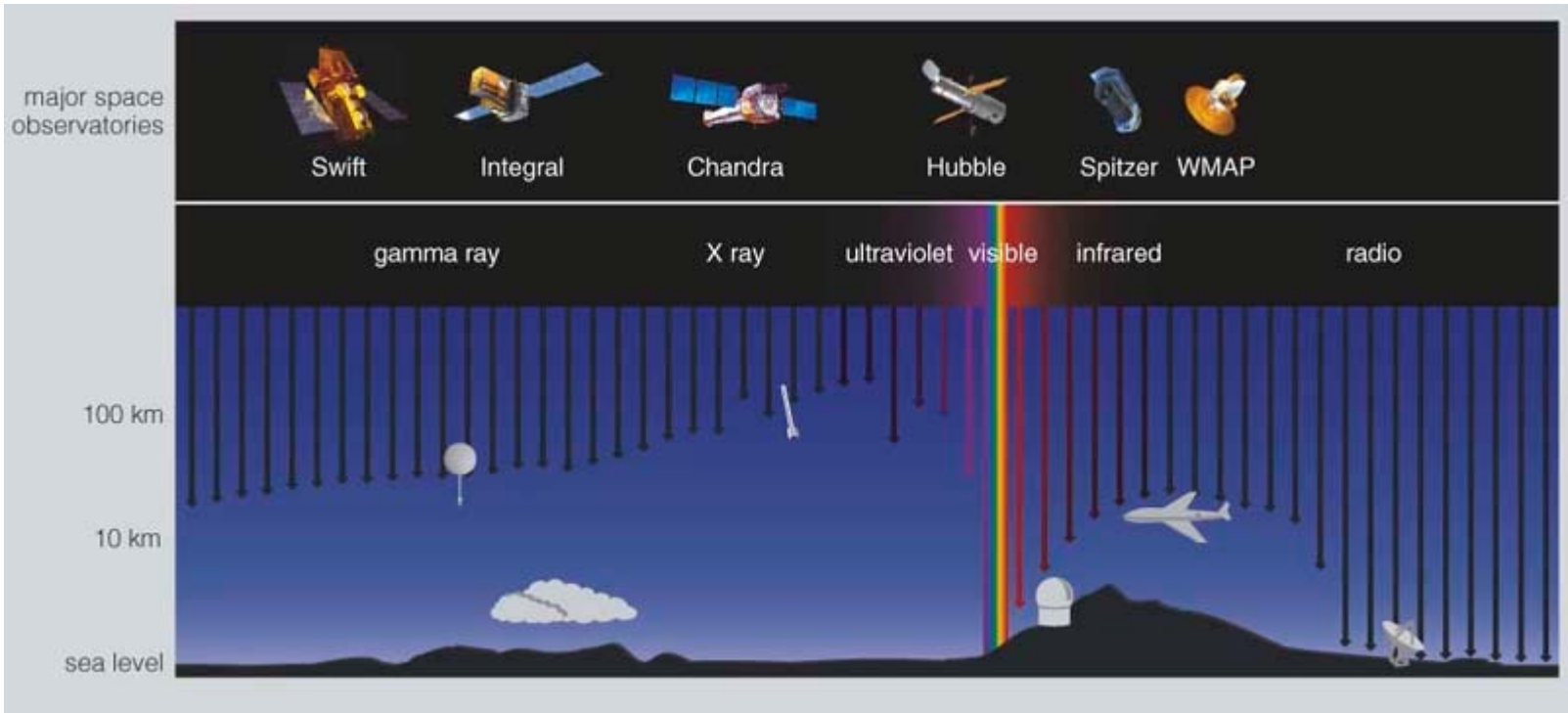


Multi-wavelength Program

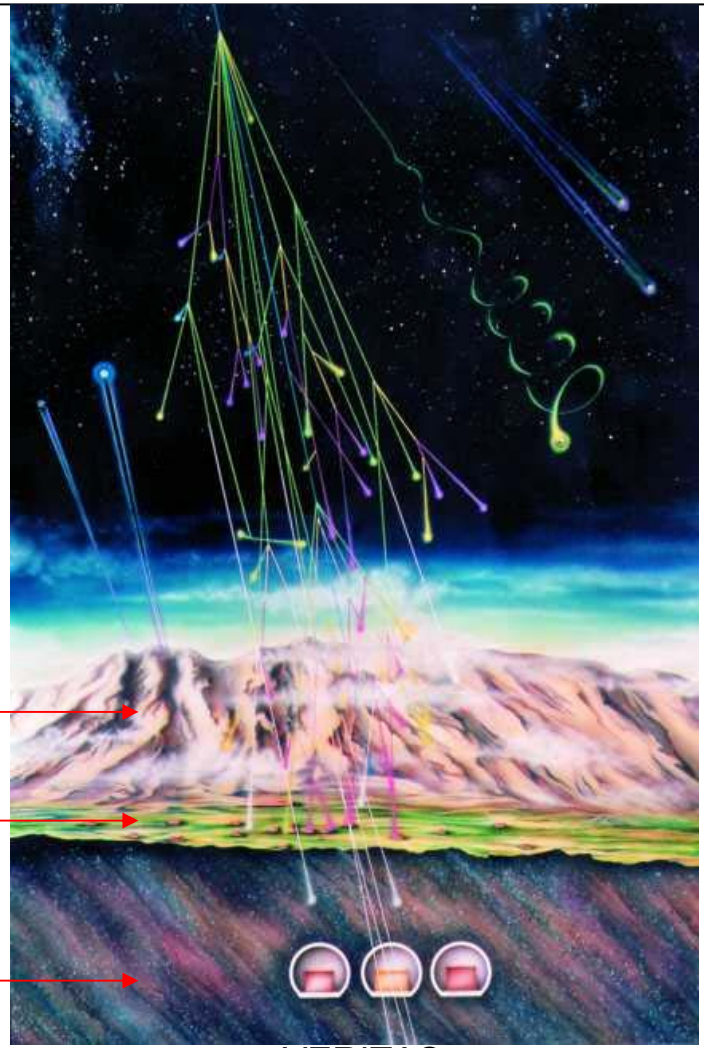
Some of our Partners

Ground-based γ-ray astrophysics

Atmosphere is (thankfully) absorbent…



Use the atmosphere to our advantage…

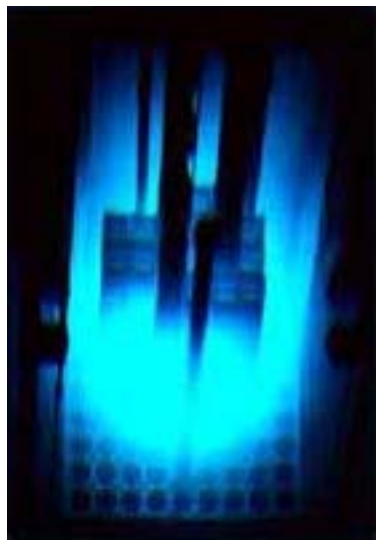


Use “shower” of charged particles produced in atmosphere:
Secondary particles are ultra-relativistic and radiate Cherenkov light

High-altitude cosmic-ray research

Ground-based cosmic-ray detectors for highest energies

Underground detectors for neutrinos



Cherenkov light in water

… with the air Cherenkov technique

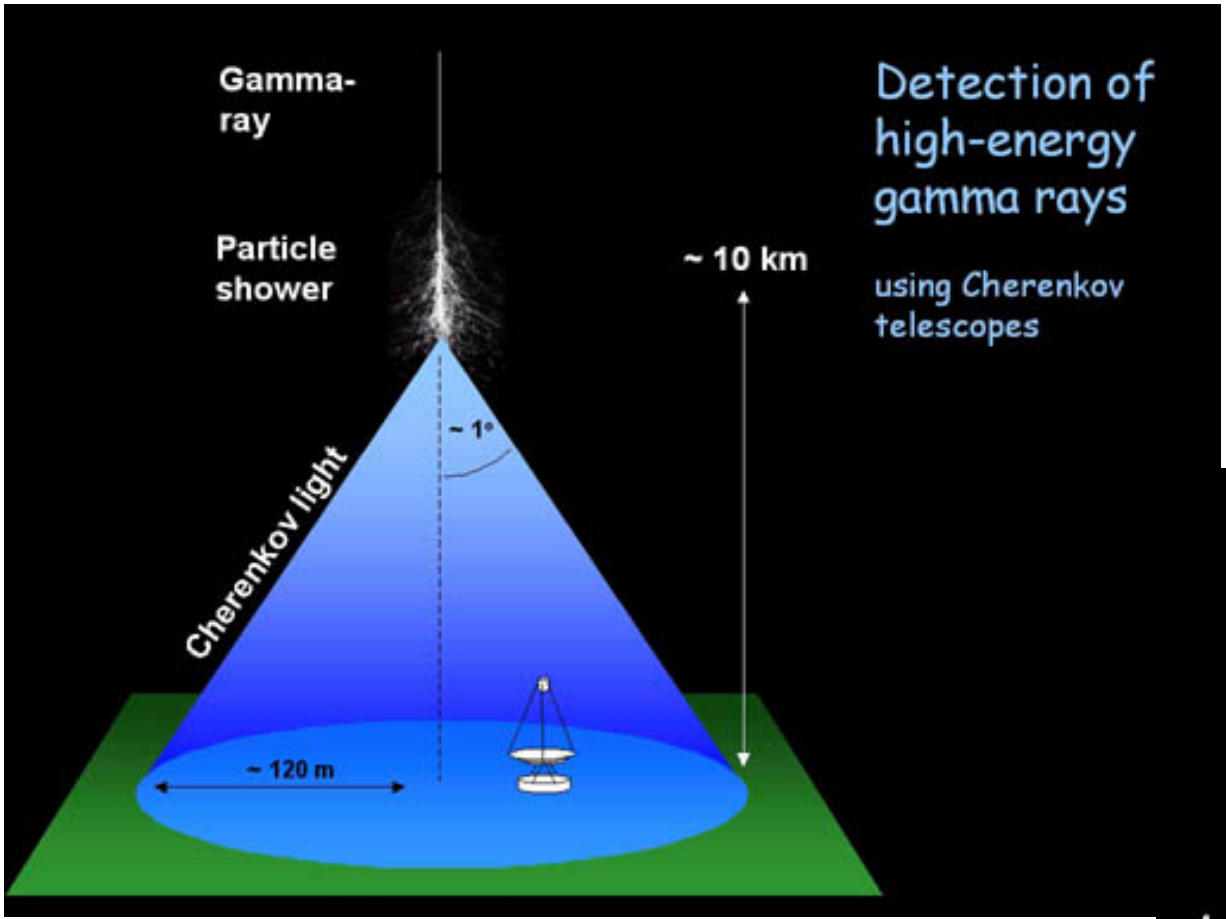
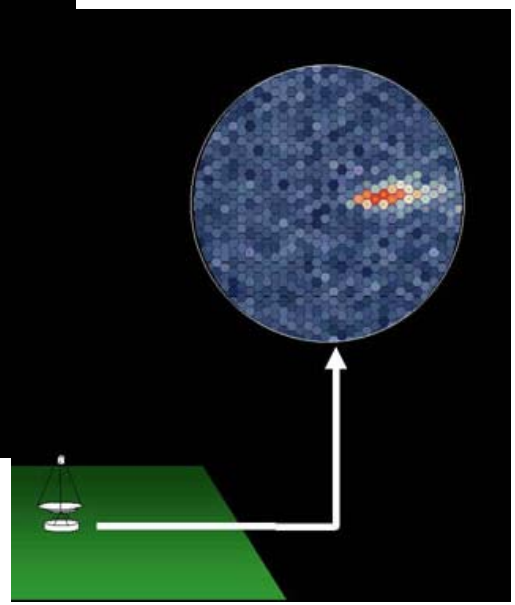
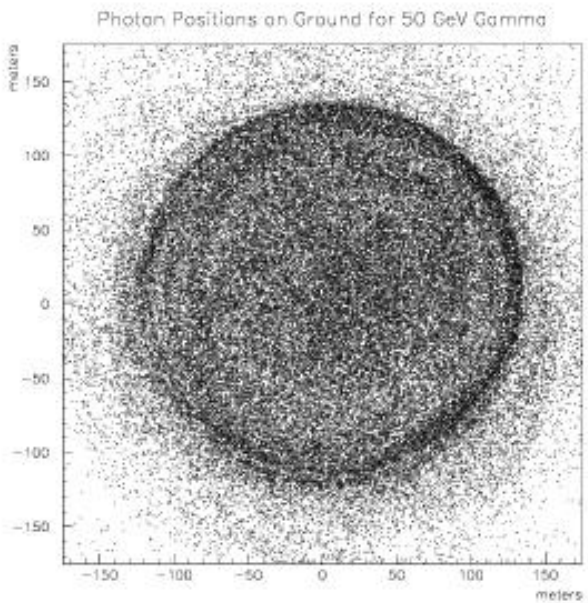
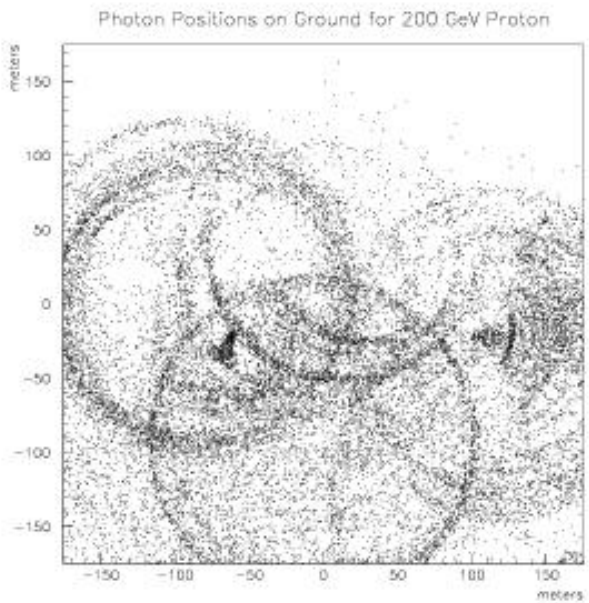


Image the Cherenkov light from the shower in focal plane of telescope



Cherenkov light pools on ground

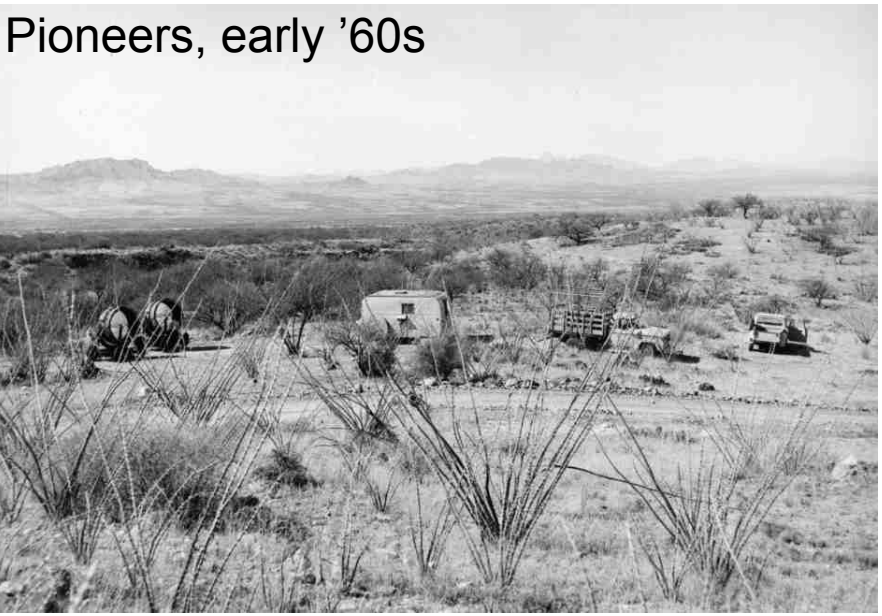




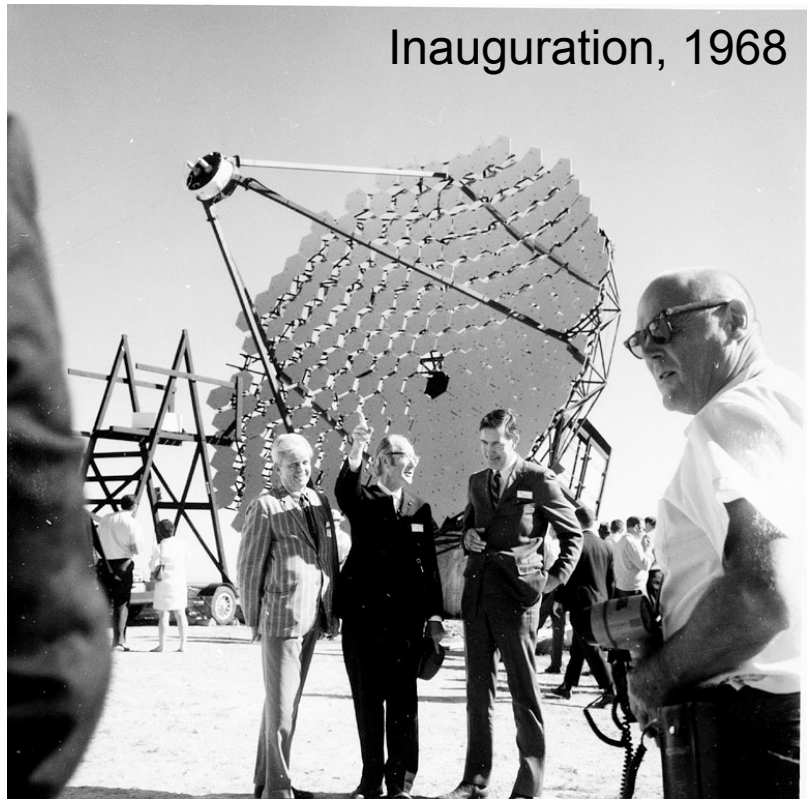
Signal vs Background

Whipple: The Ol' GrandDaddy of 'em all…

Pioneers, early '60s

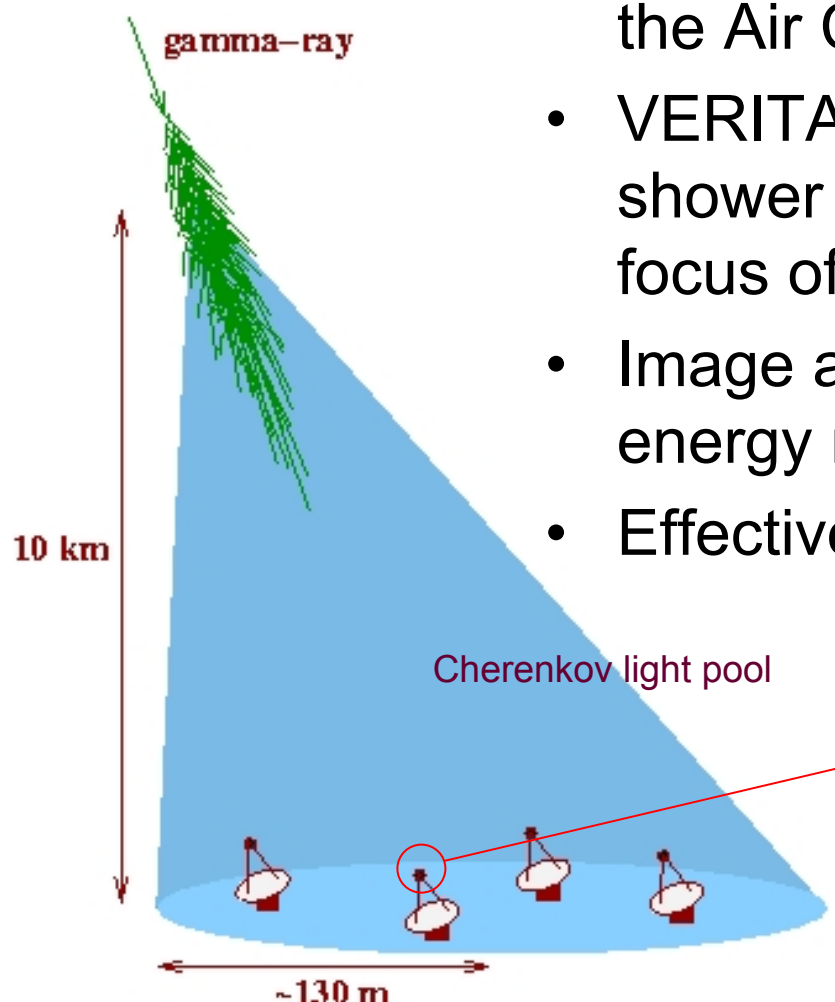


Inauguration, 1968



Built in '60s
First detected Crab (nebula) in 1989
Still operating today!

Ground-based observations

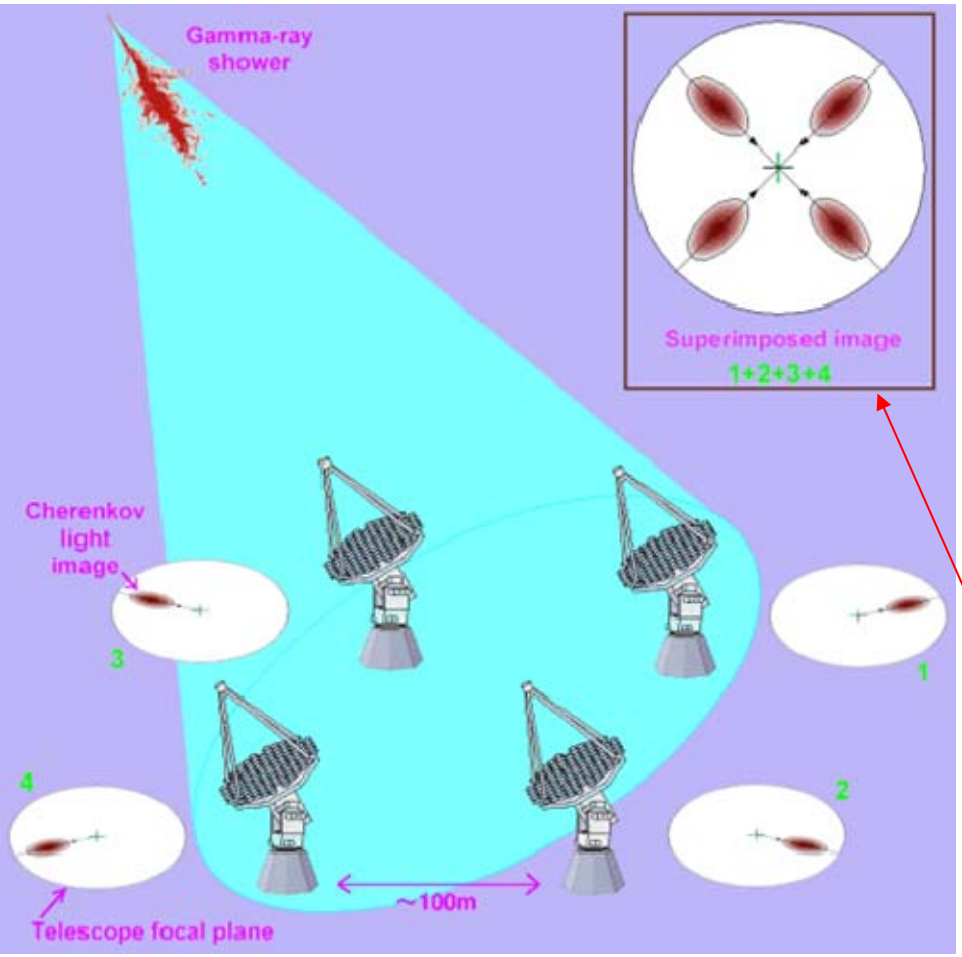


- Now on third generation instruments using the Air Cherenkov technique
- VERITAS uses the *imaging technique:* shower is imaged in multi-PMT camera at focus of telescope
- Image analysis allows good angular and energy resolution
- Effective area ~ size of light pool ~ 10^4 m^2

Cherenkov light pool

Multi-PMT camera

Ground-based observations - arrays



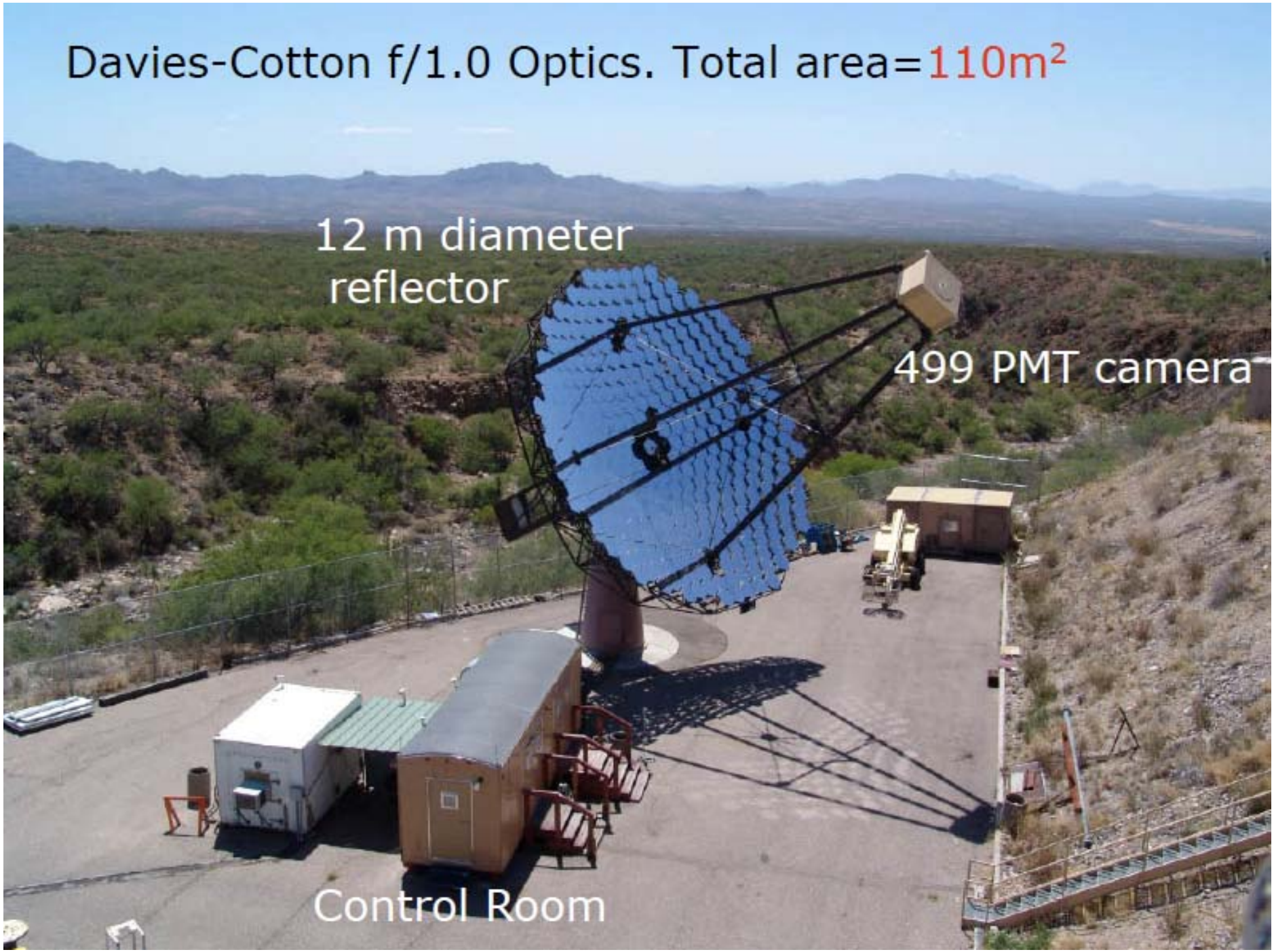
- Imaging *arrays* (multiple views of same shower) dramatically improve resolution & sensitivity
- Angular resolution << 1^{o} possible
- Energy resolution ~15%

Multiple views allow reconstruction of gamma-ray origin

VERITAS

- An array of four 12-m imaging air Cherenkov telescopes
- Sited at Whipple Observatory basecamp near Tucson, Az
- International collaboration: Canadian, US, UK, Irish groups; ~ 80 collaborators at 20 institutions
- Science observations started in 2006

- 100 GeV to > 10 TeV energy range
- Camera of each telescope composed of 499 PMTs
- Readout of PMTs by 500 MSamples/s (2 ns) FADCs
- Three-level trigger system including array trigger


Davies-Cotton f/1.0 Optics. Total area=110m²
12 m diameter reflector
499 PMT camera
Control Room

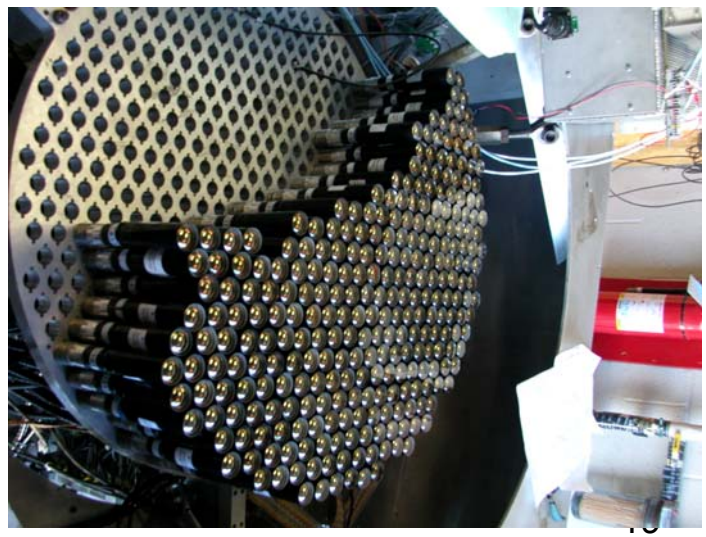
VERITAS - site

T1, 2009
~15% sensitivity improvement

Fred Lawrence Whipple Observatory (FLWO) basecamp

VERITAS – telescopes & cameras

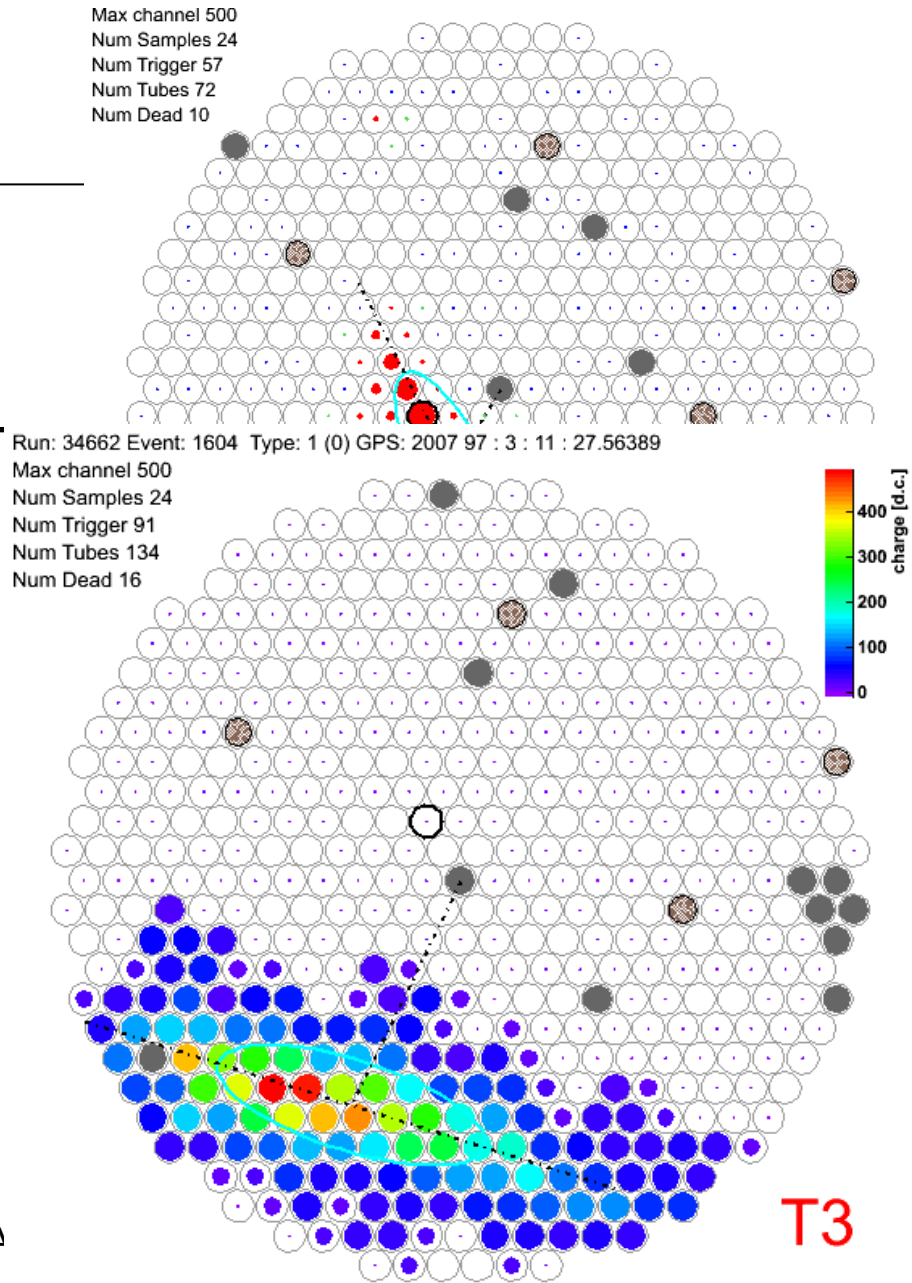
- Each 12-m f/1 telescope: tesselated mirror, 350 facets; total mirror area 109 m^2
- Each camera: 499 29mm PMTs
- Each PMT: 0.15^o f.o.v. (2.6 mrad); overall f.o.v = 3.5^o



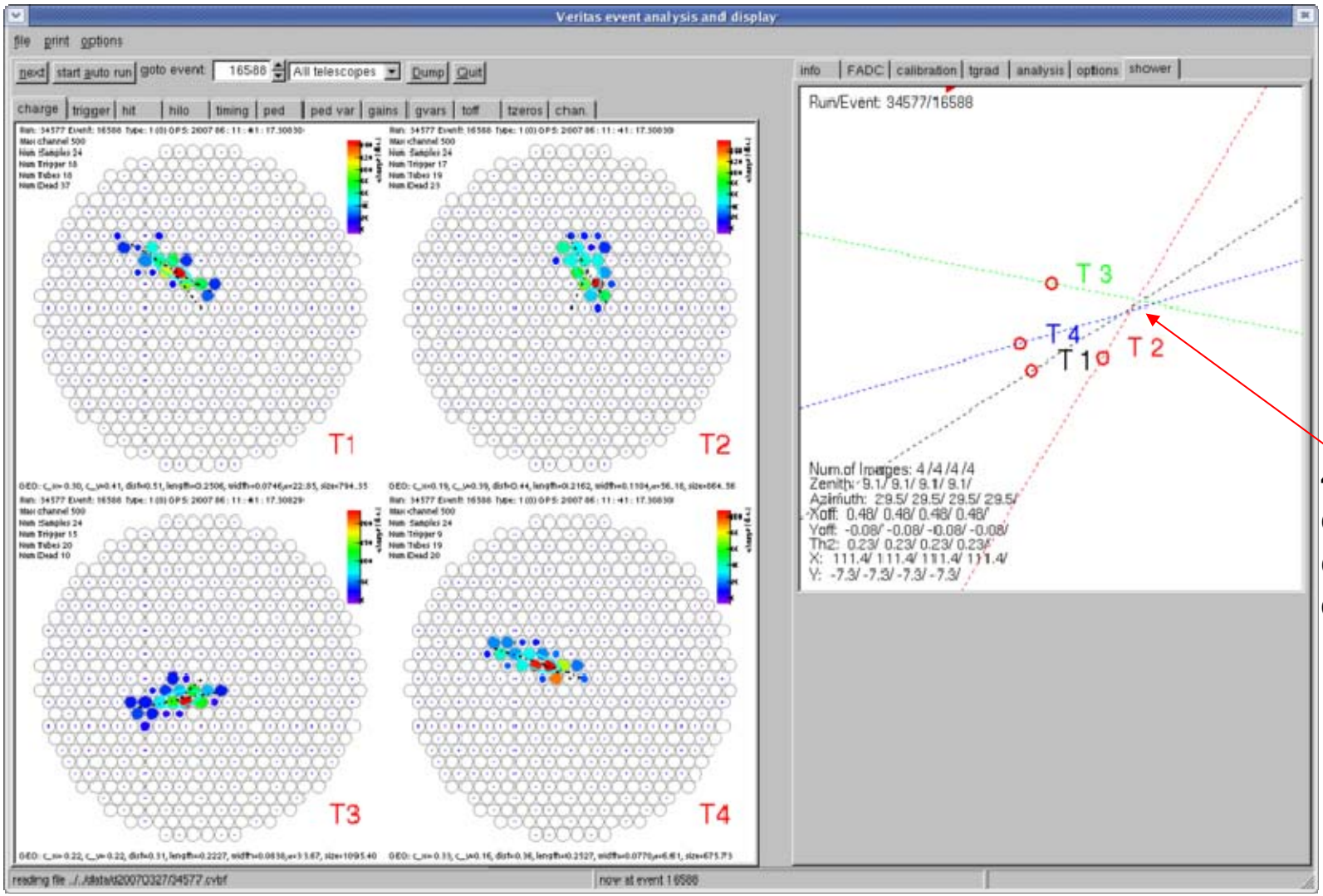
Partially assembled camera

VERITAS – electronics

- 3-level trigger:
  - constant fraction discriminator on each PM
  - telescope pattern trigger requires adjacent pixels
  - multi-telescope (array) coincidence
- Each PMT read out by 500 MSamples/s FADC (2 ns sampling)



Typical Event



4-telescope event;
core position outside array

Instrument Performance

- Performance achieved:

  PSF: ~0.06^{o} – 0.10^{o}

  pointing accuracy: few arc-minutes (depends on location in camera)

  sensitivity: 100 mCrab @ 5σ in << 1 hour

  10 mCrab in under 50 hours

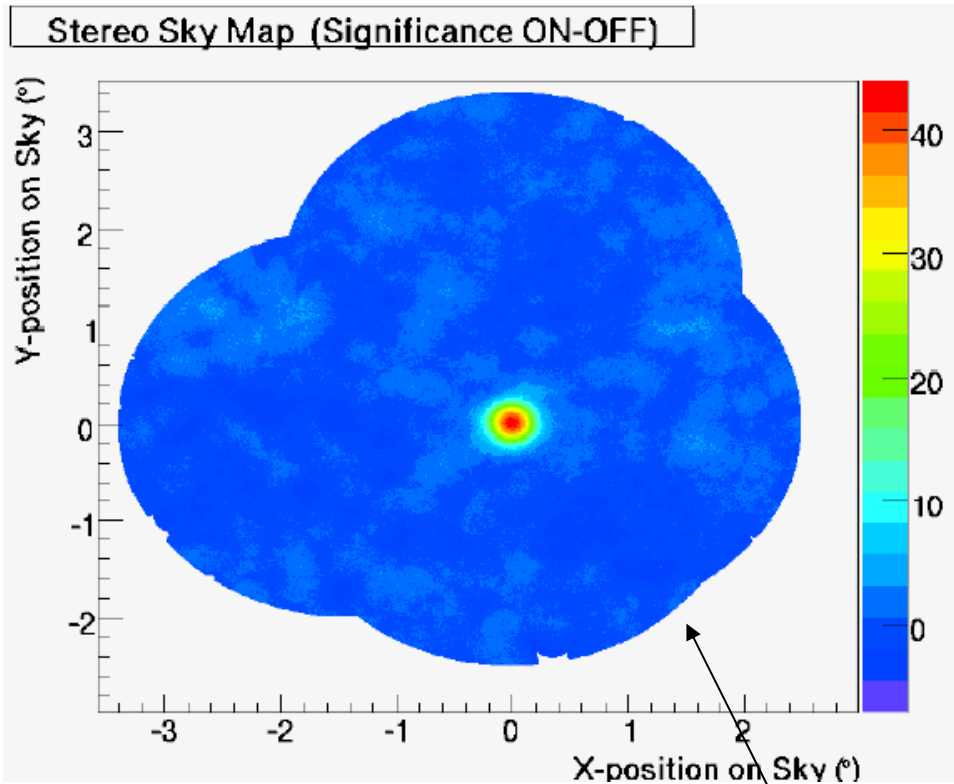
  energy resolution: 15%

  core reconstruction: <25 m out to 180m from array centre

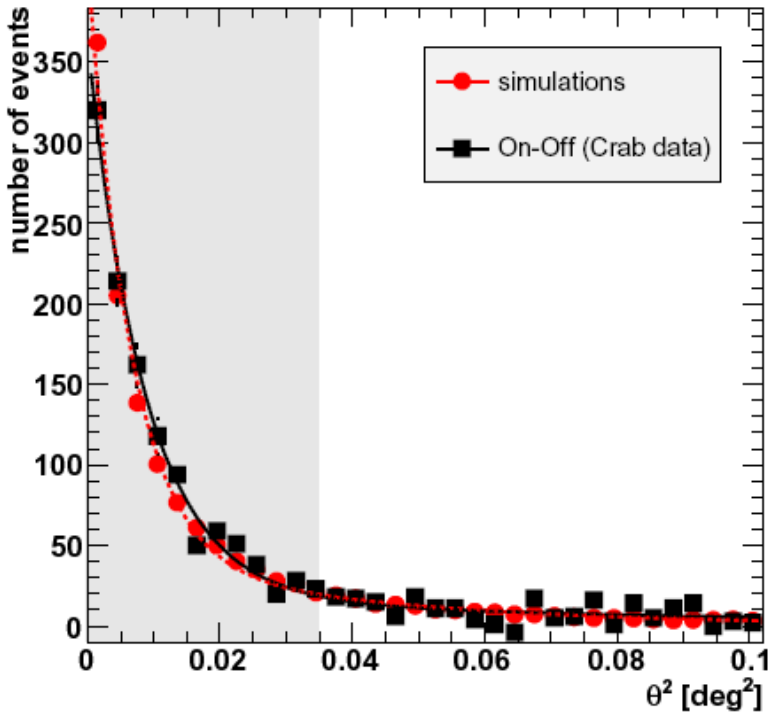
- Crab (standard candle) data used to measure pointing, sensitivity

Instrument Performance

PSF: ~0.06^o – 0.10^o



Angle between γ-arrival direction and known source position

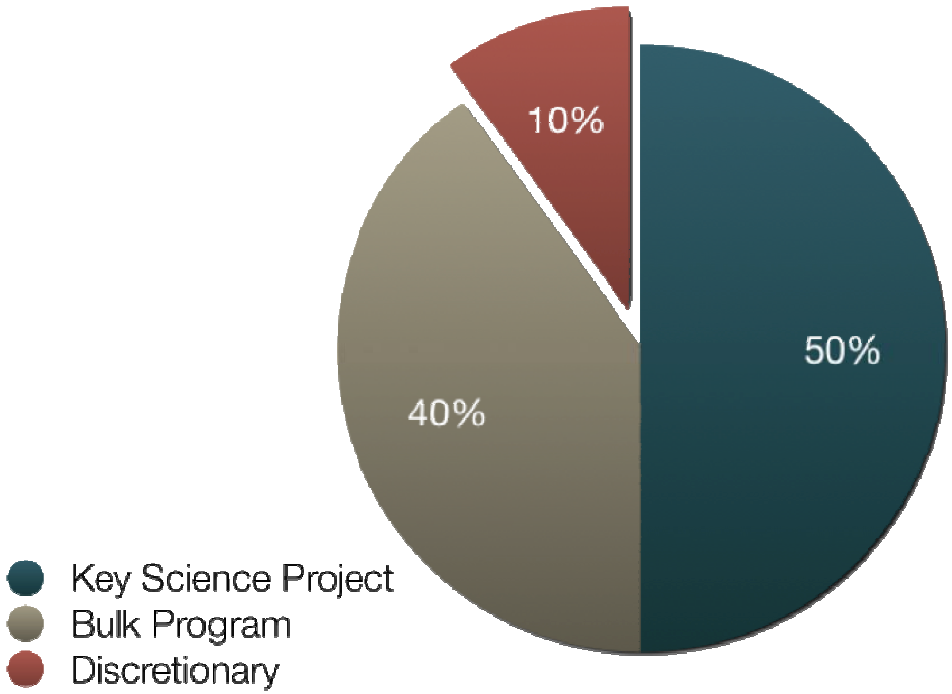


3-telescope Crab data

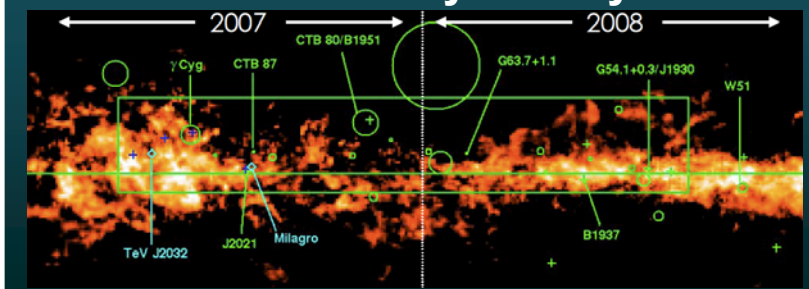
funky shape from “wobble” data – source offset from centre of field-of-view

VERITAS Science Program

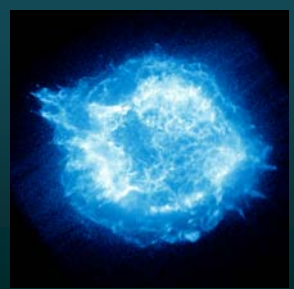
Observations:
~800 h / year
+ >200 h / year
(moon light)



Galactic Sky Survey

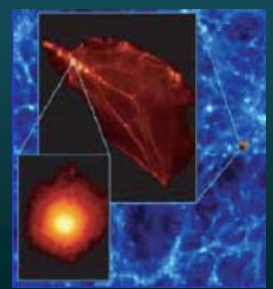


SNR

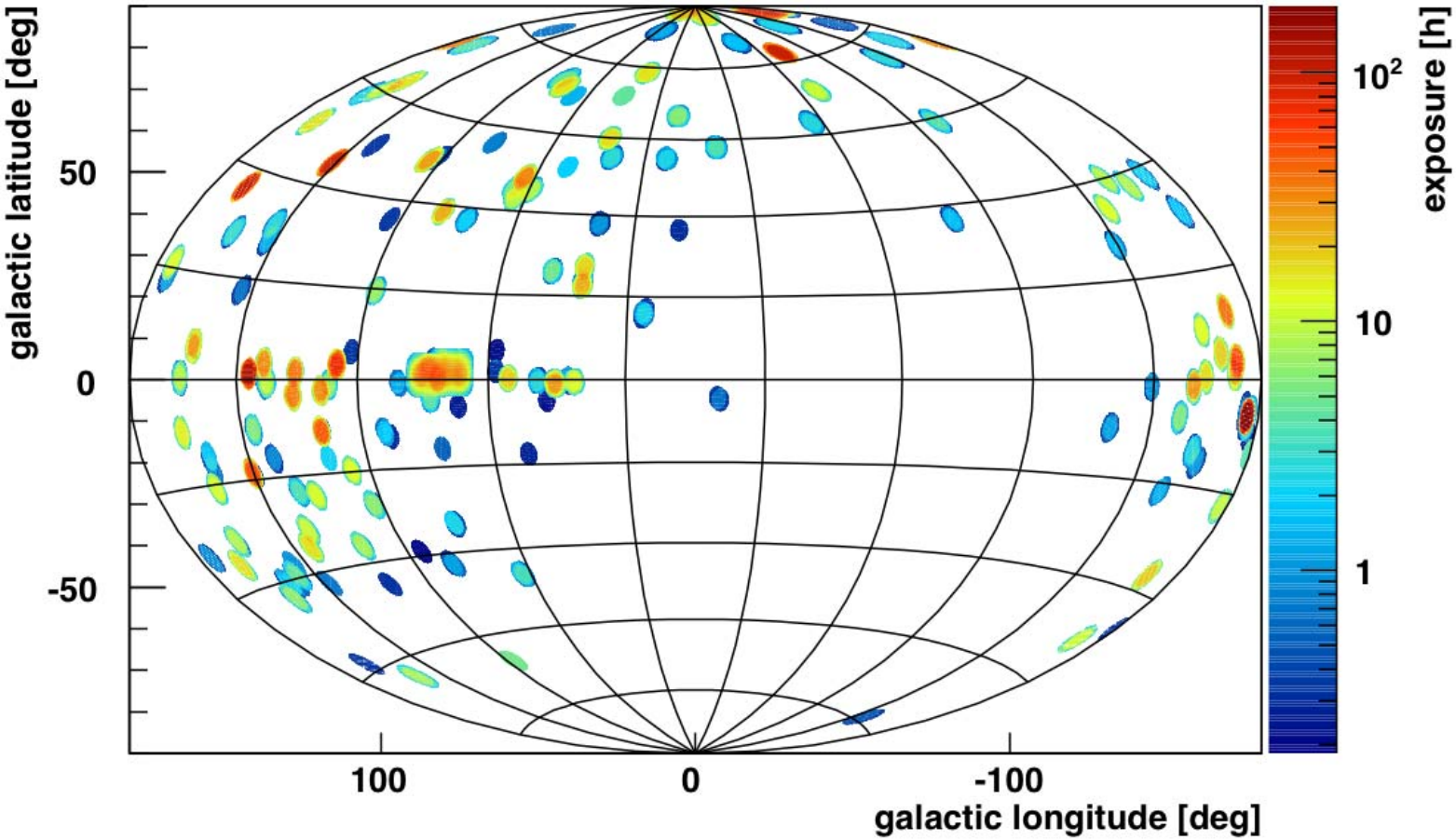


Blazars

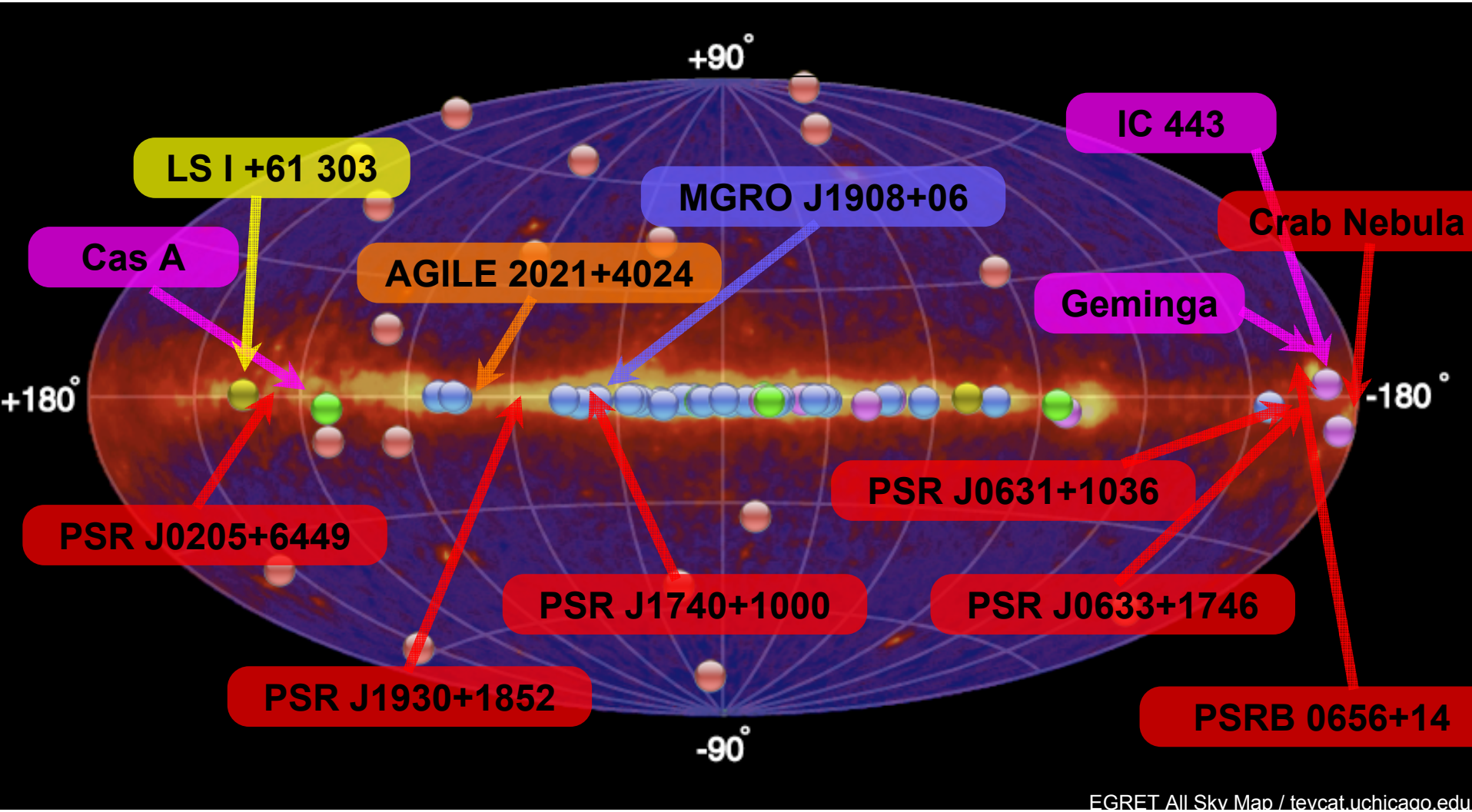
Dark Matter



VERITAS sky exposure 2006-2008

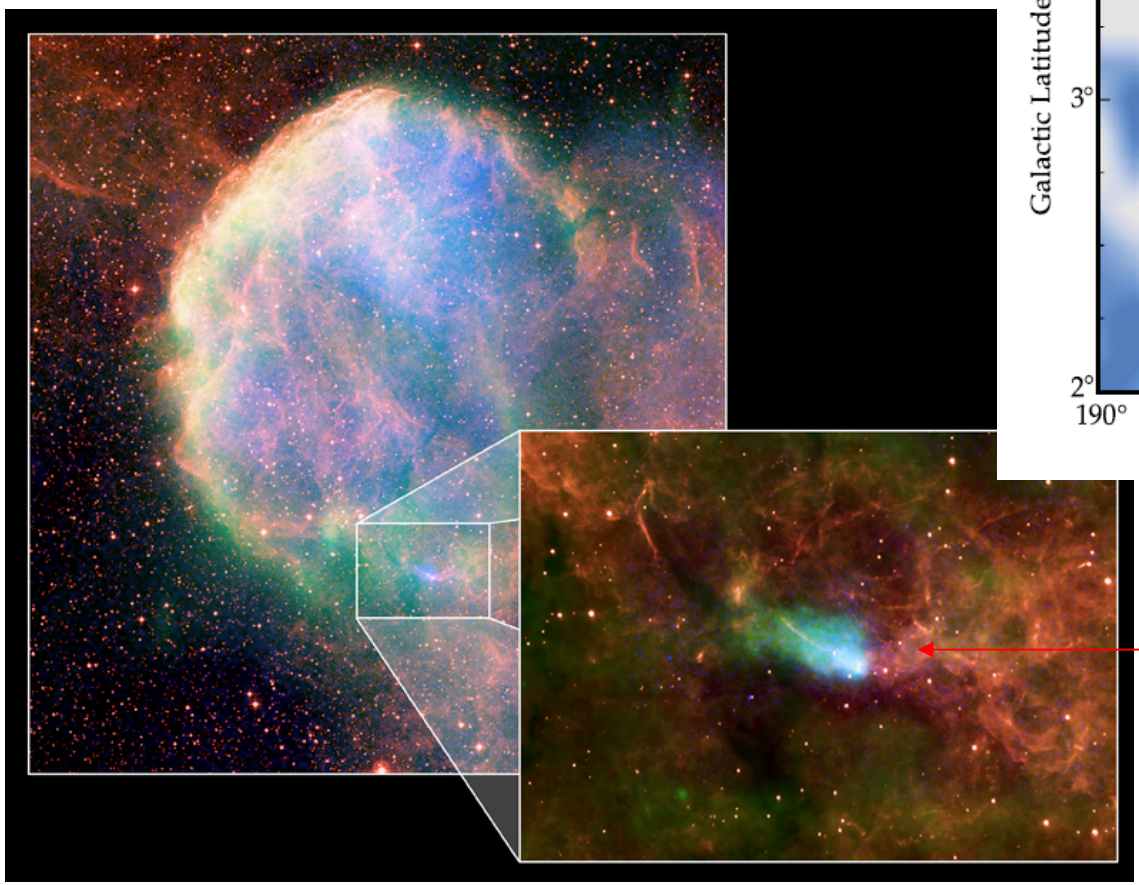


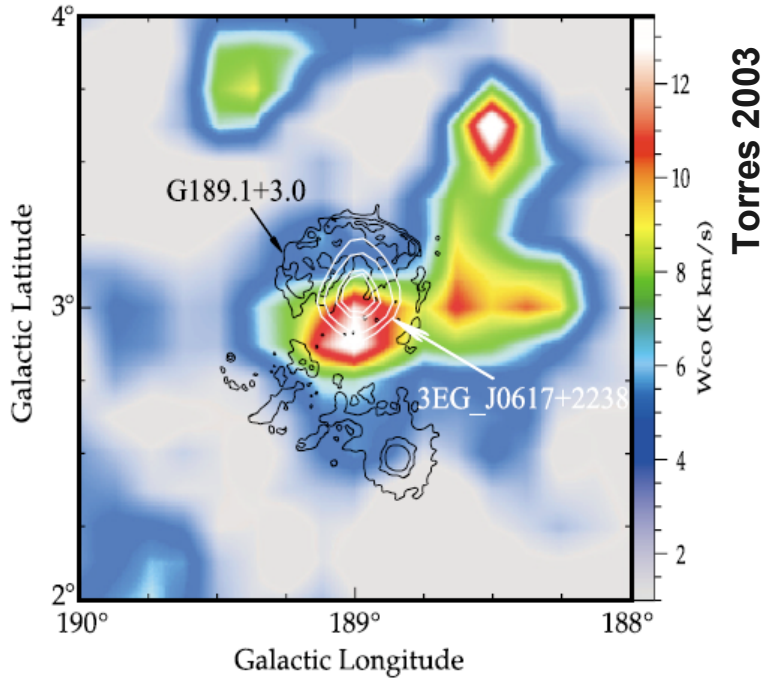
Galactic Sources



SNR IC 443

Distance 1.5 kpc
Middle-aged SNR: 3×10^3 to 3×10^4 yrs
Shell size 45’





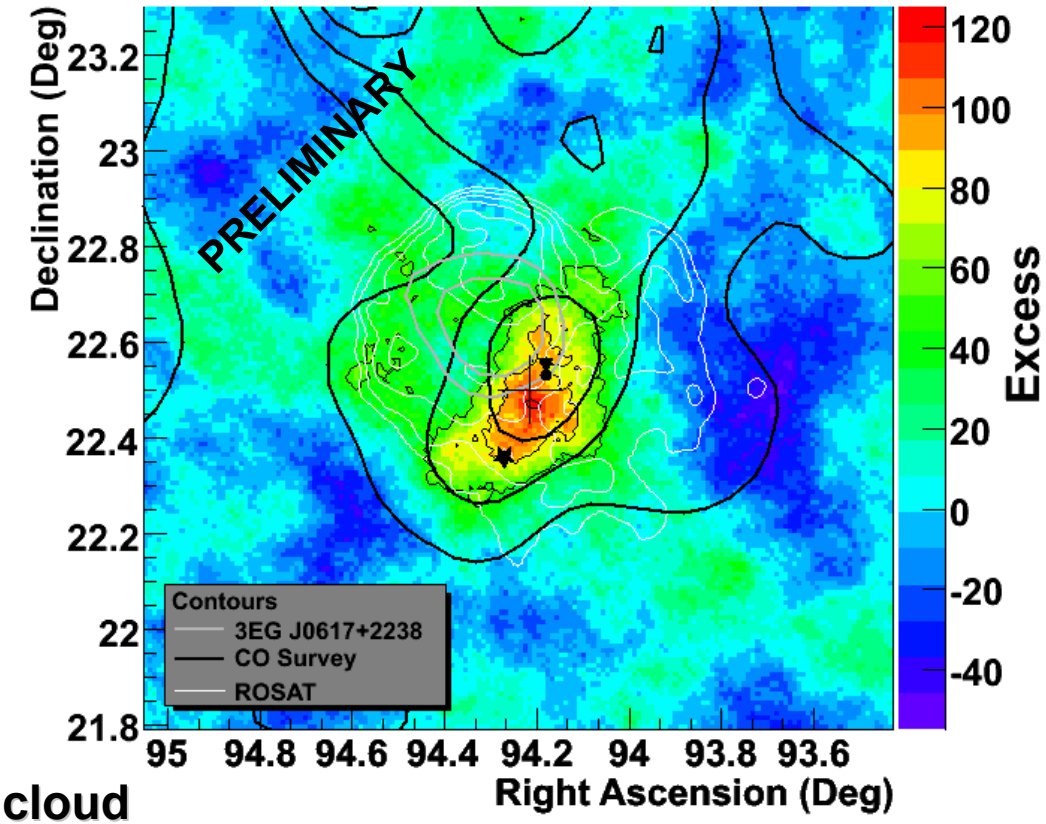
- SNR/molecular cloud interaction
- pulsar wind nebula

SNR IC 443

Co-discovered 2007 by VERITAS (7.1σ/6.0σ pre/post, 16h) & MAGIC (5.7σ, 29h)

- Extended TeV emission 0.17º±0.02º
- TeV emission not consistent with optical emission (to NE); elongated along cloud direction
- SNR shock interacting with cloud?
- steep energy spectrum: Γ~-3

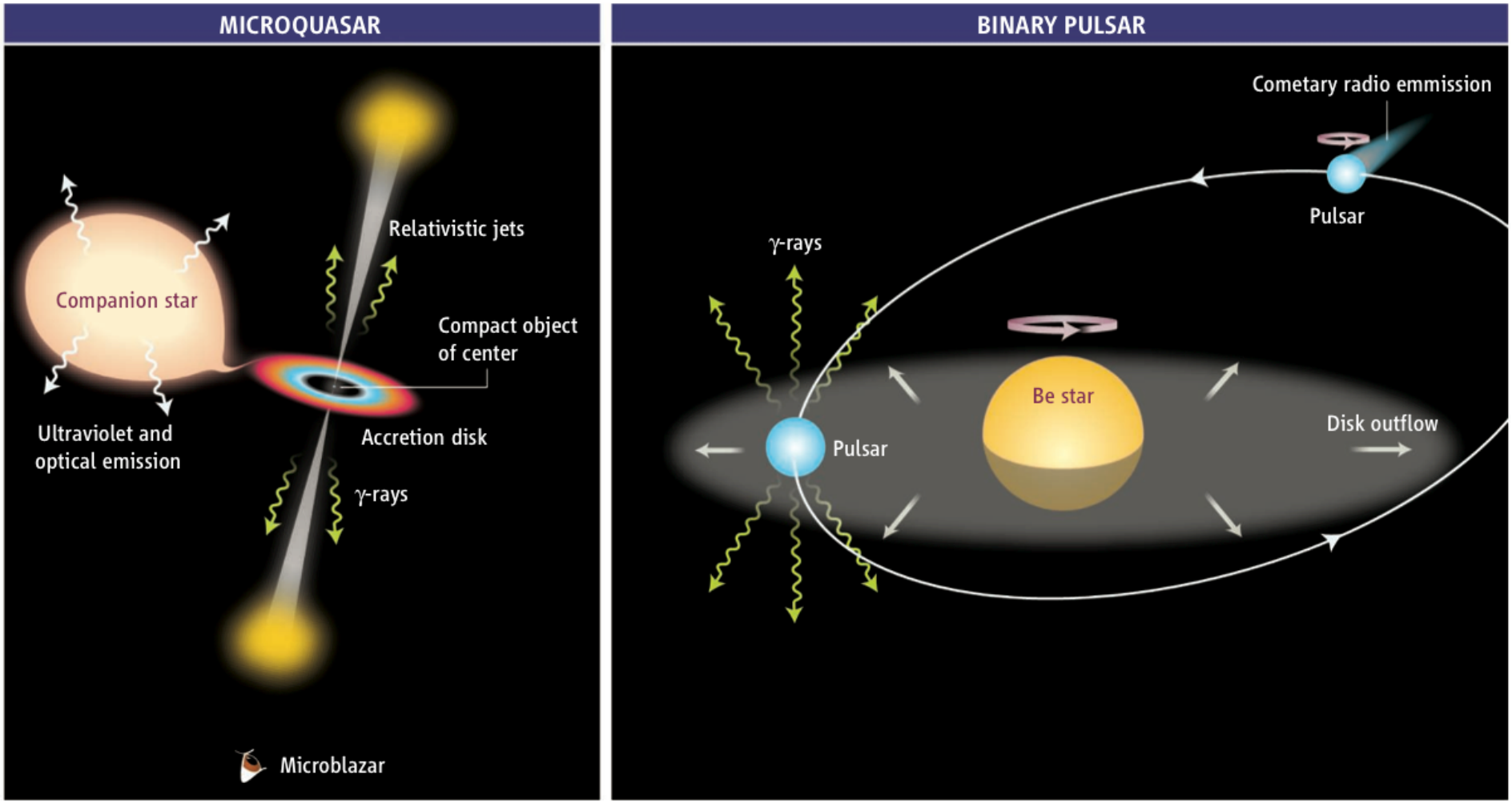
Smoothed Excess Map (radius 0.115º)

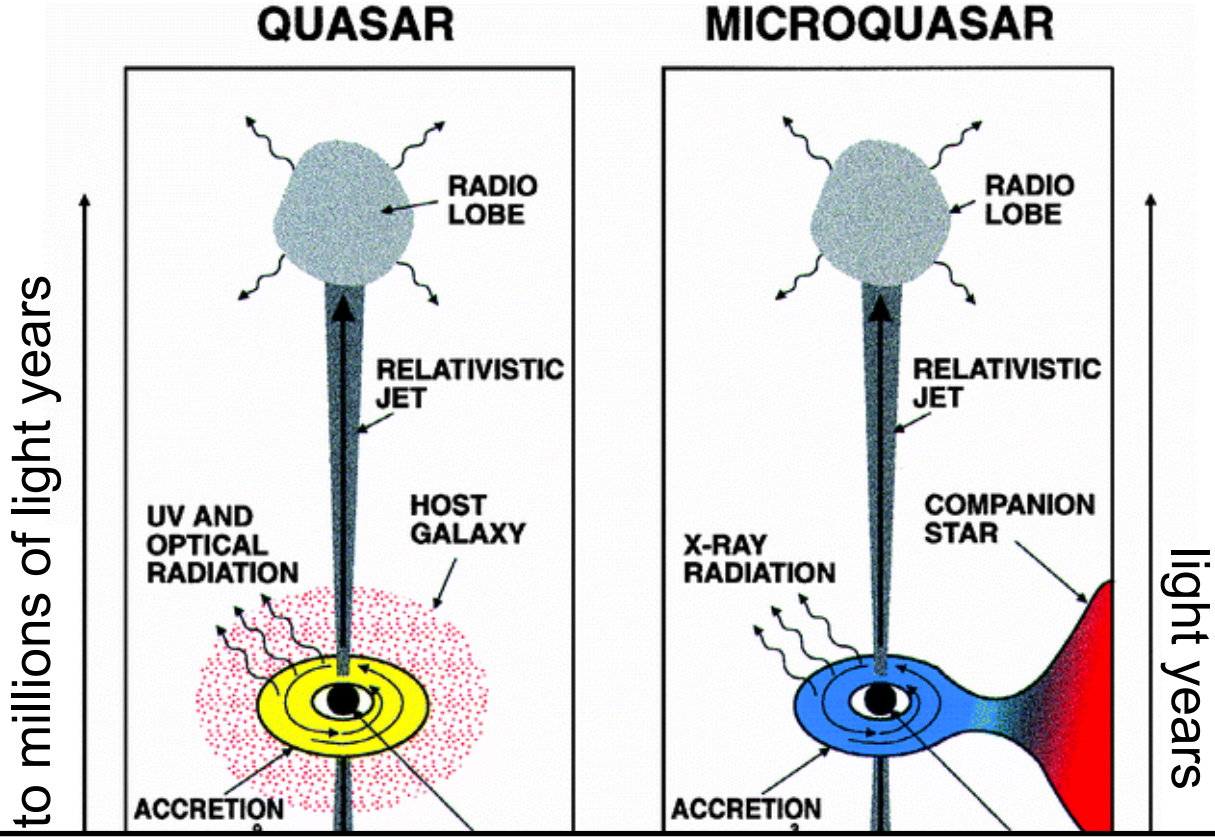


TeV emission could be

- **CR-induced pion production in cloud**
- **associated with the pulsar wind nebula to the south (relic electrons?)**

Binary systems/microquasars

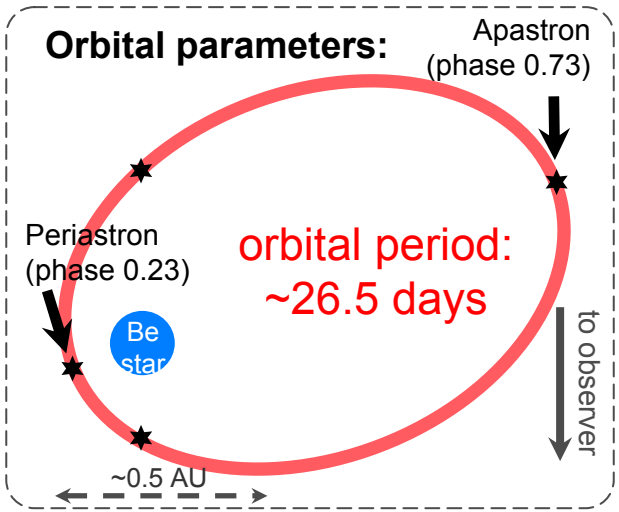




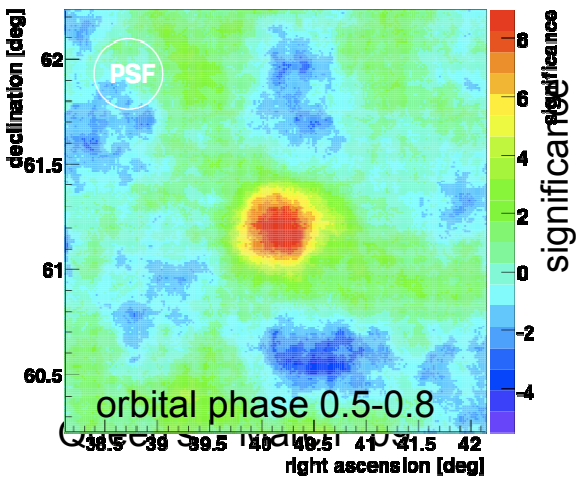
Object	AGN	μ–quasars	H–H	GRB
Size [pc]	$\sim 10^5$	$\lesssim 10$	< a few	$\sim 10^{-5} - 10^{-1}$
Luminosity [$L_\odot$]	$10^7 - 10^{19}$	$< 10^5$	$10^1 - 10^4$	10^{21}
Central mass [$M_\odot$]	$10^6 - 10^9$	$1 - 10$	< 10	$1 - 10$
Lorentz factor [Γ]	$10 - 10^3$	> 10	$\lesssim 1.0000005$	$100 - 300$
Magnetic field [G]	~ 100	~ 100	< 200	$\sim 10^{16}$

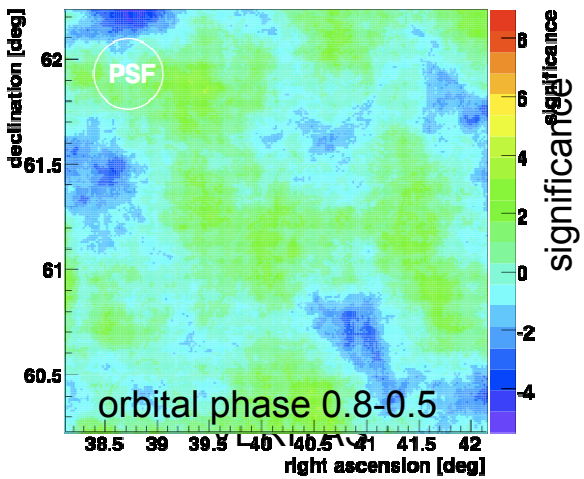
Huarte-Espinosa & Mendoza (2006)

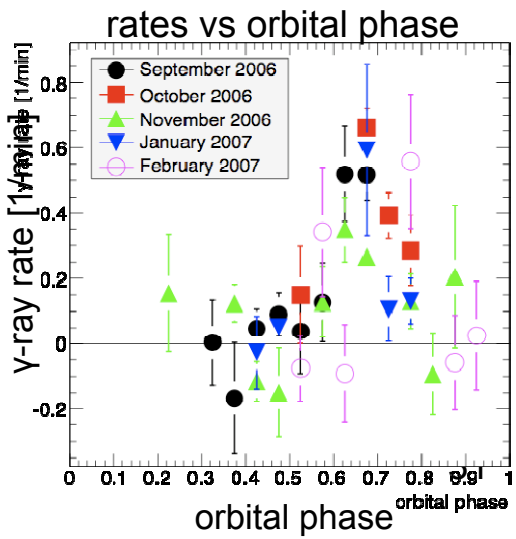
LS I +61 303: γ-rays from a binary system



- about 44 h of 2 and 3 telescope data (during construction phase, 2006-2007)
- observation during 5 orbital cycles covering phases 0.3-0.95
- total detection significance: 8.8 σ
- highly variable in rate, maximum at apastron
- 2007-2008: no detection during periastron



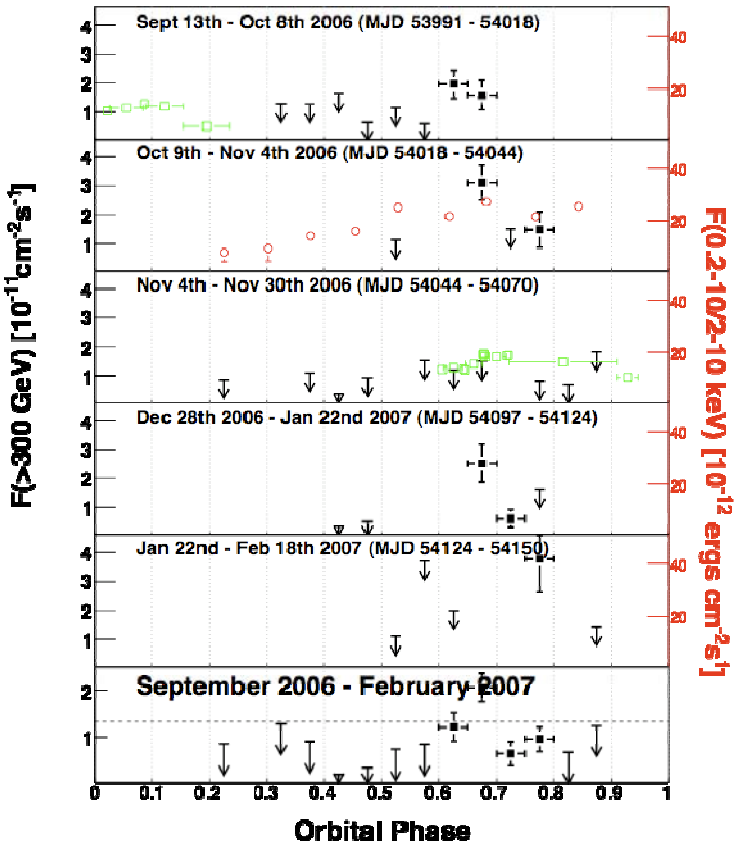




LS I +61 303: Two years of VERITAS observations

2006-2007

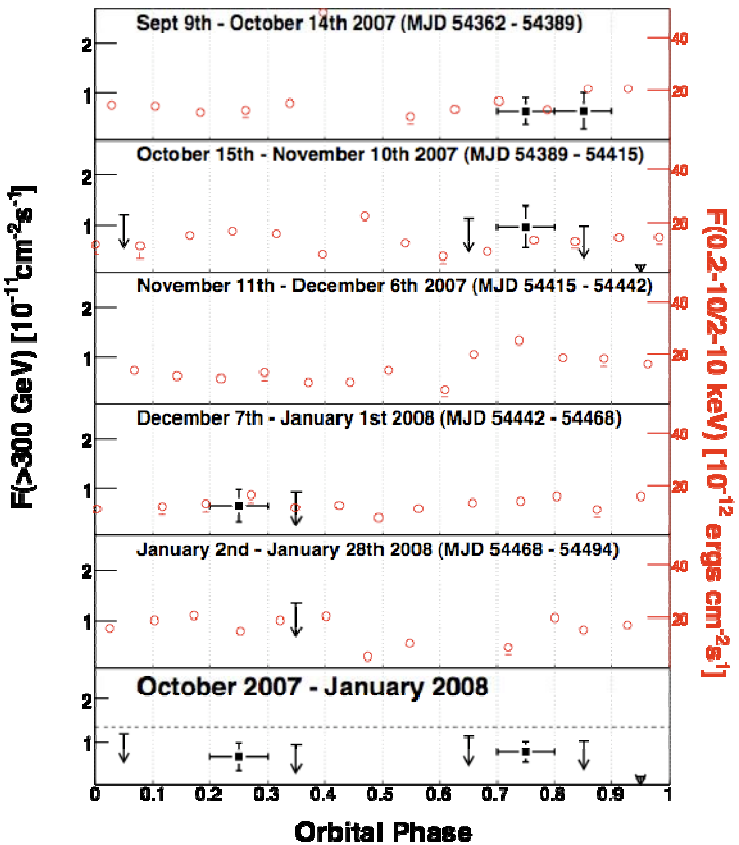
45 h of 2/3-telescope data



2007-2008

12 h of 4-telescope data

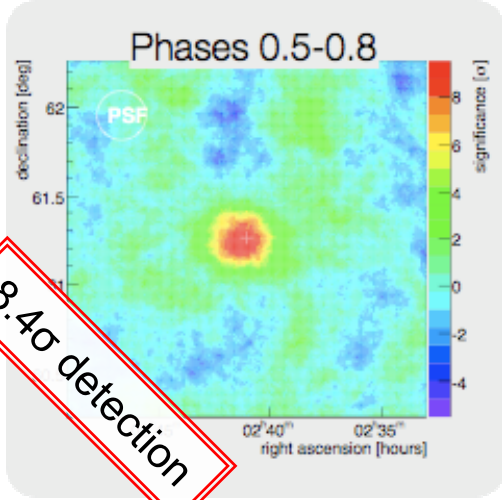
(analysis of data taken in moonlight conditions still ongoing)



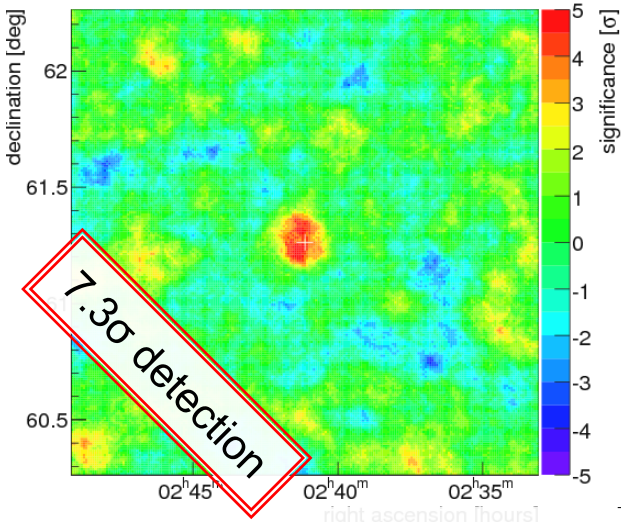
LSI 61+303

2006-2007 | 2007-2008 | 2008-2009

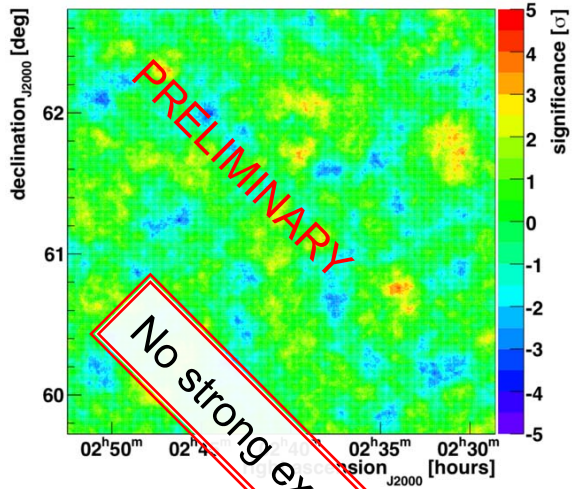
apastron



8.4σ detection

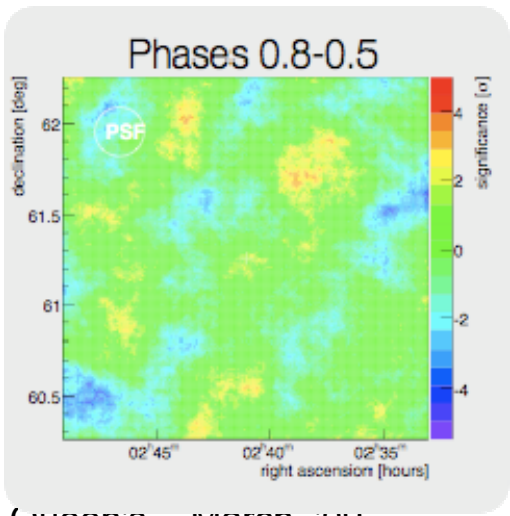


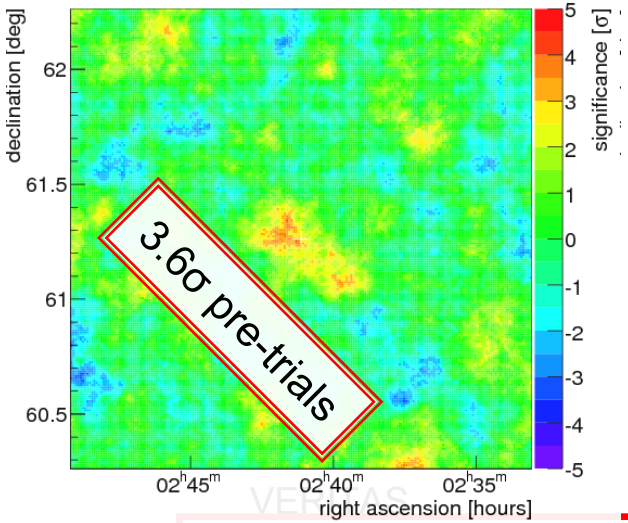
7.3σ detection



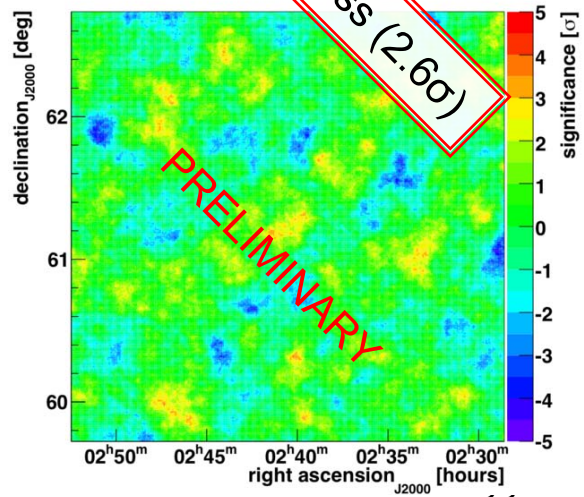
No strong excess (2.6σ)

periastron



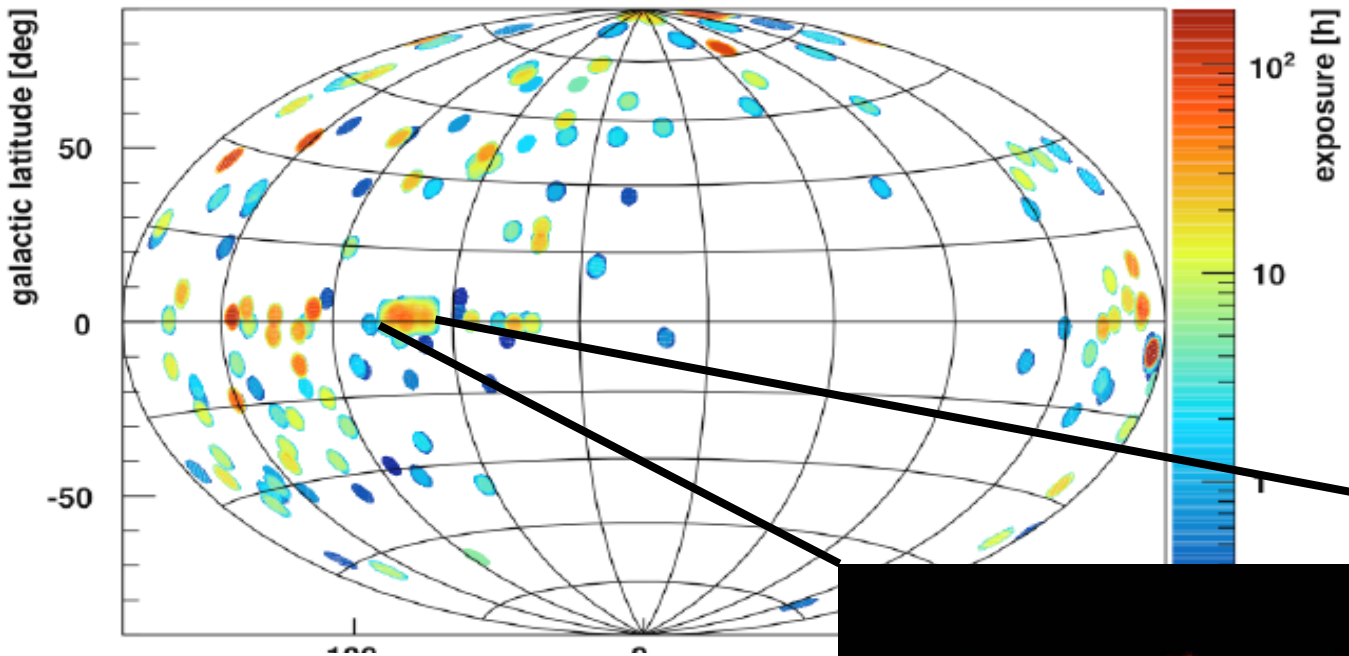


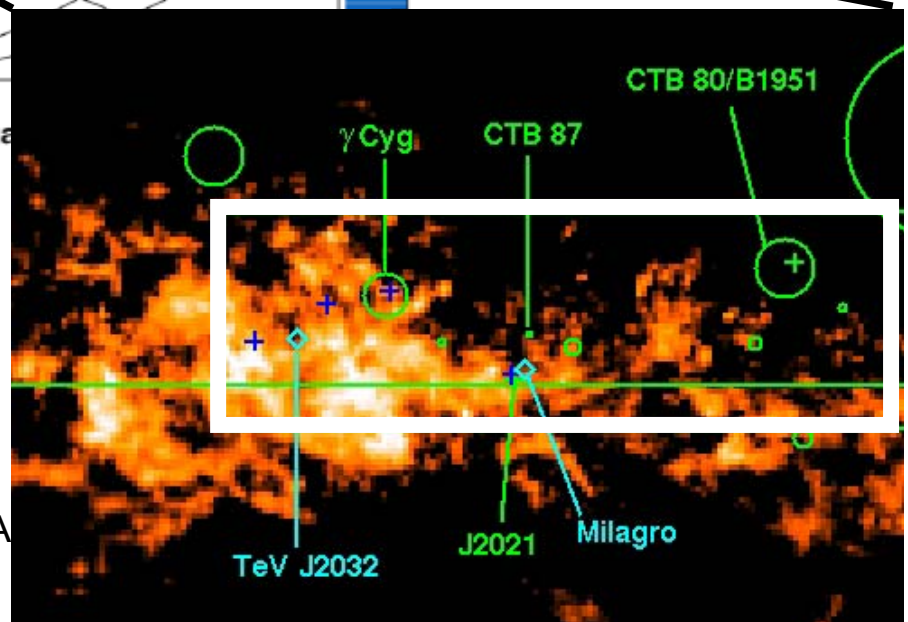
3.6σ pre-trials



Strong indication of orbit-to-orbit variability

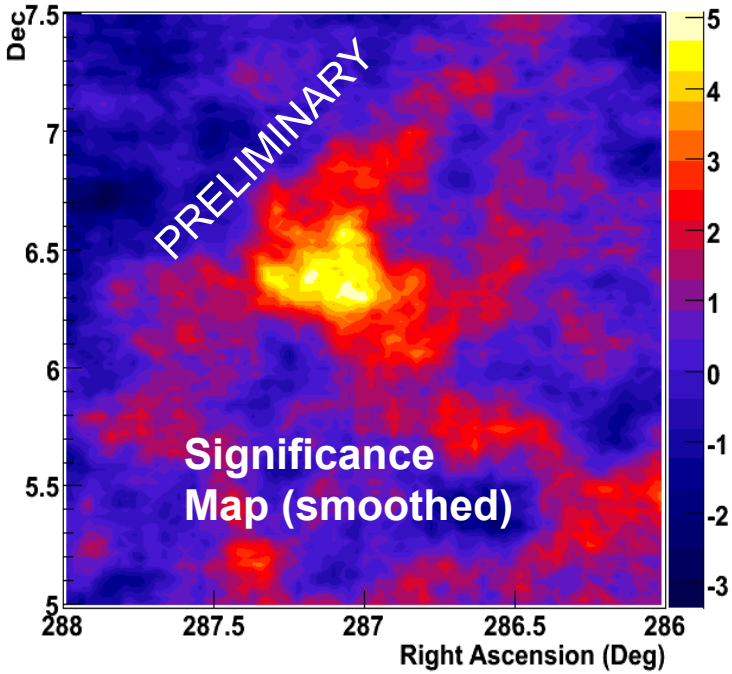
VERITAS Sky Survey





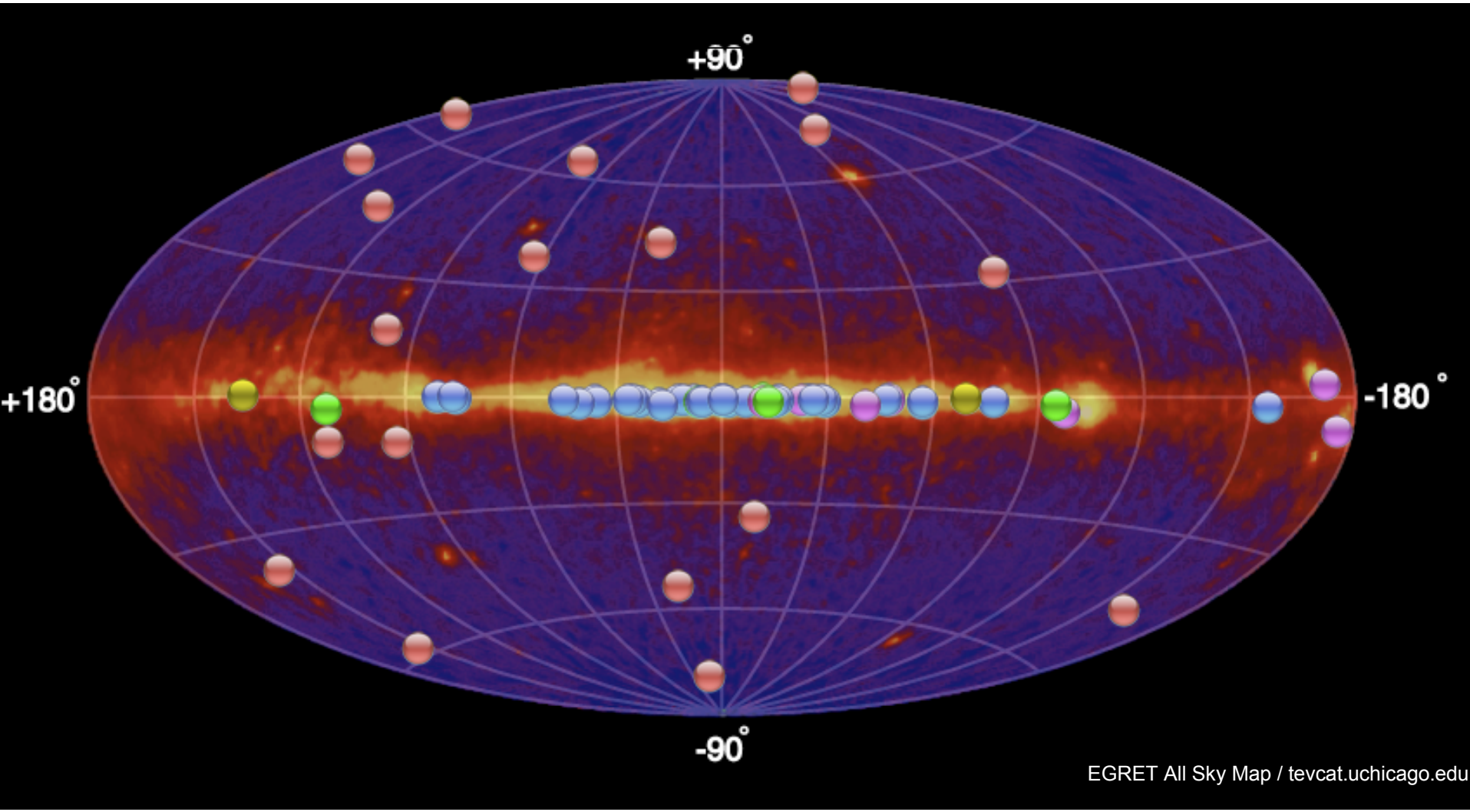
- Partial survey of Cygnus region
  - -1 < b < 4 and 67 < l < 82
- Completed this fall (along with a small/moderate amount of followup)
  - >6 hrs acceptance-corrected exposure at each point
  - Survey analysis ongoing

MGROJ1908+06 / HESS J1908+063



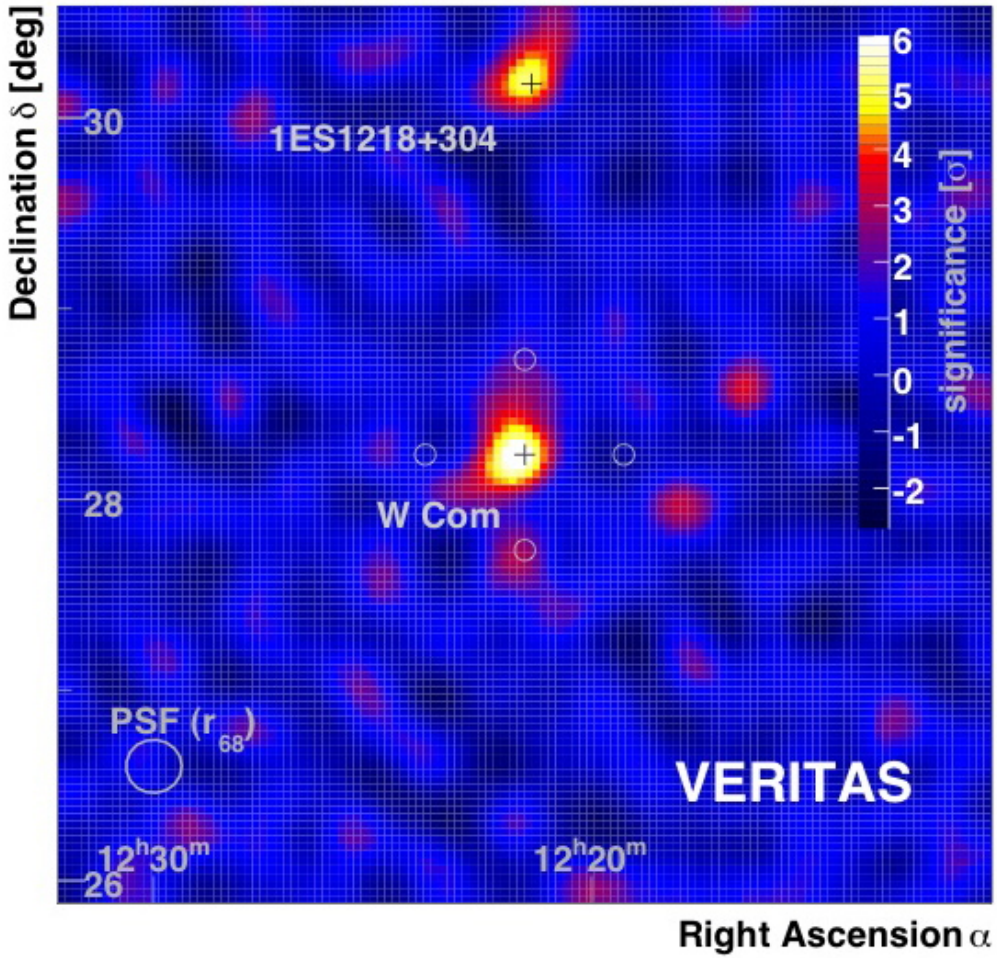
- Test case for Sky Survey extended sources
  - Chose MGRO J1908+06/HESS J1908+063
    - MGRO unidentified source
    - Detected in H.E.S.S. galactic plane survey (~80% of Crab Nebula Flux, <2.6° extension at 20 TeV)
- VERITAS:
  - ~22h of 4-telescope data
  - 4.85σ detection
  - ~0.2° extension
  - position in agreement with HESS J1908+063

Extragalactic Sources



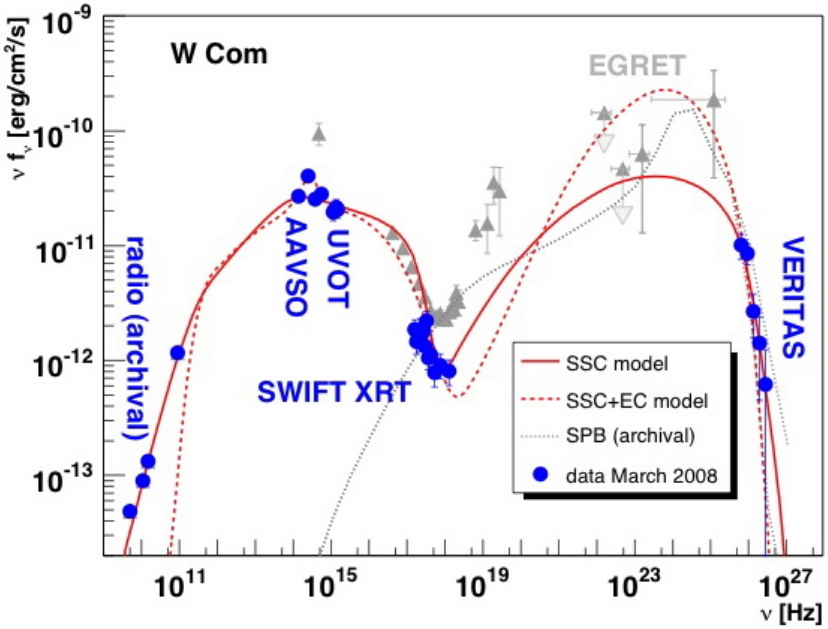
W Comae – a VERITAS discovery

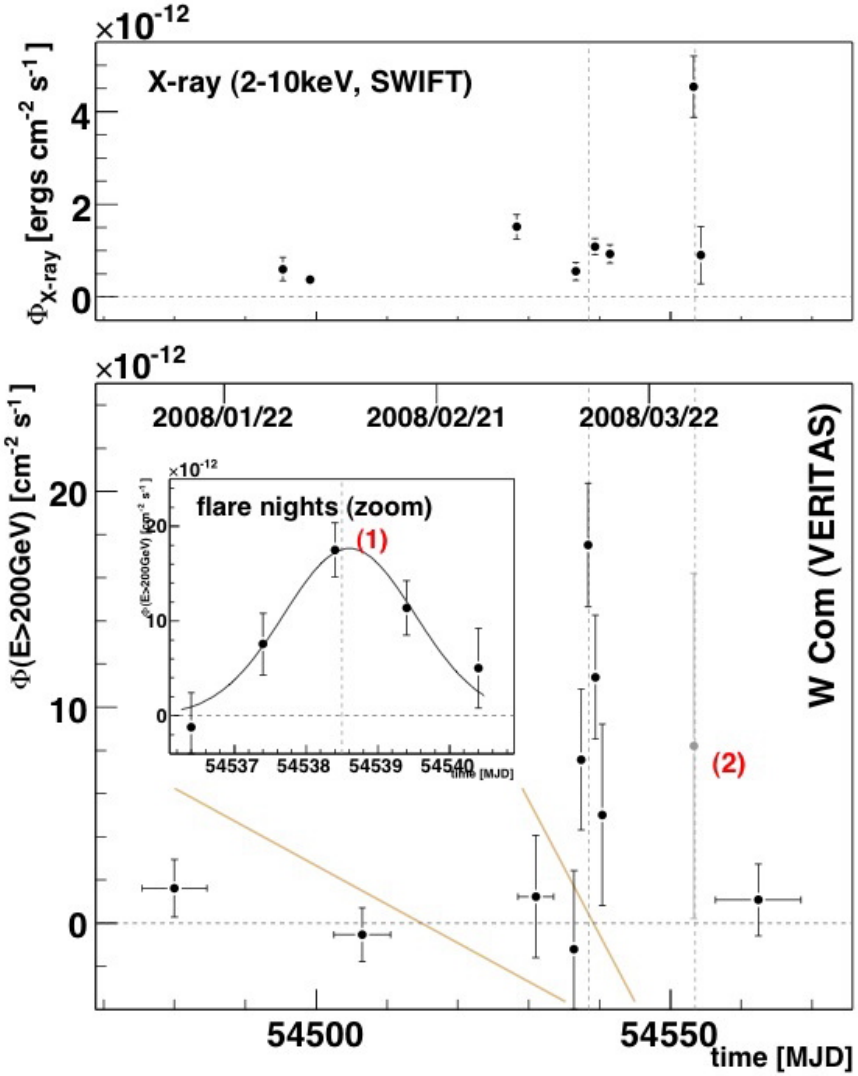
- IBL of redshift z=0.102
- 39.5 h observation; 4.9σ excess
- First observation of two AGNs in one field of view… !



W Comae – a VERITAS discovery

- Strong flare observed (March ’08)



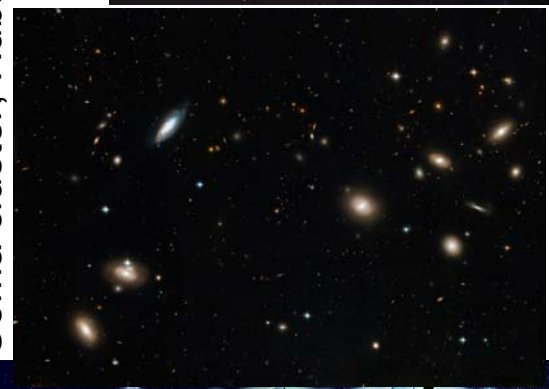


Possible new source classes

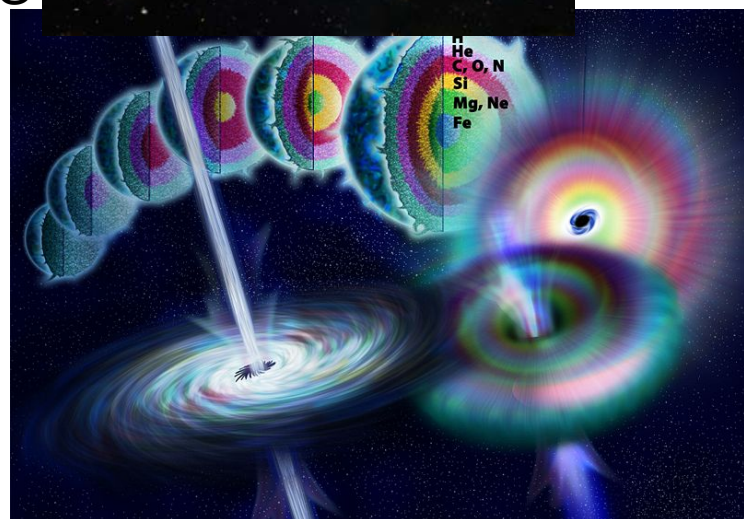
- Several classes of objects are mooted as potential gamma-ray sources:
  - Starburst galaxies (SN-rich… CR rich?)
  - Galaxy clusters, dwarf galaxies, globular clusters (dark matter rich…)
  - GRBs (believed to be inspiralling compact objects)

VERITAS has an active program of exploration on these (and other) classes.

Starburst M82



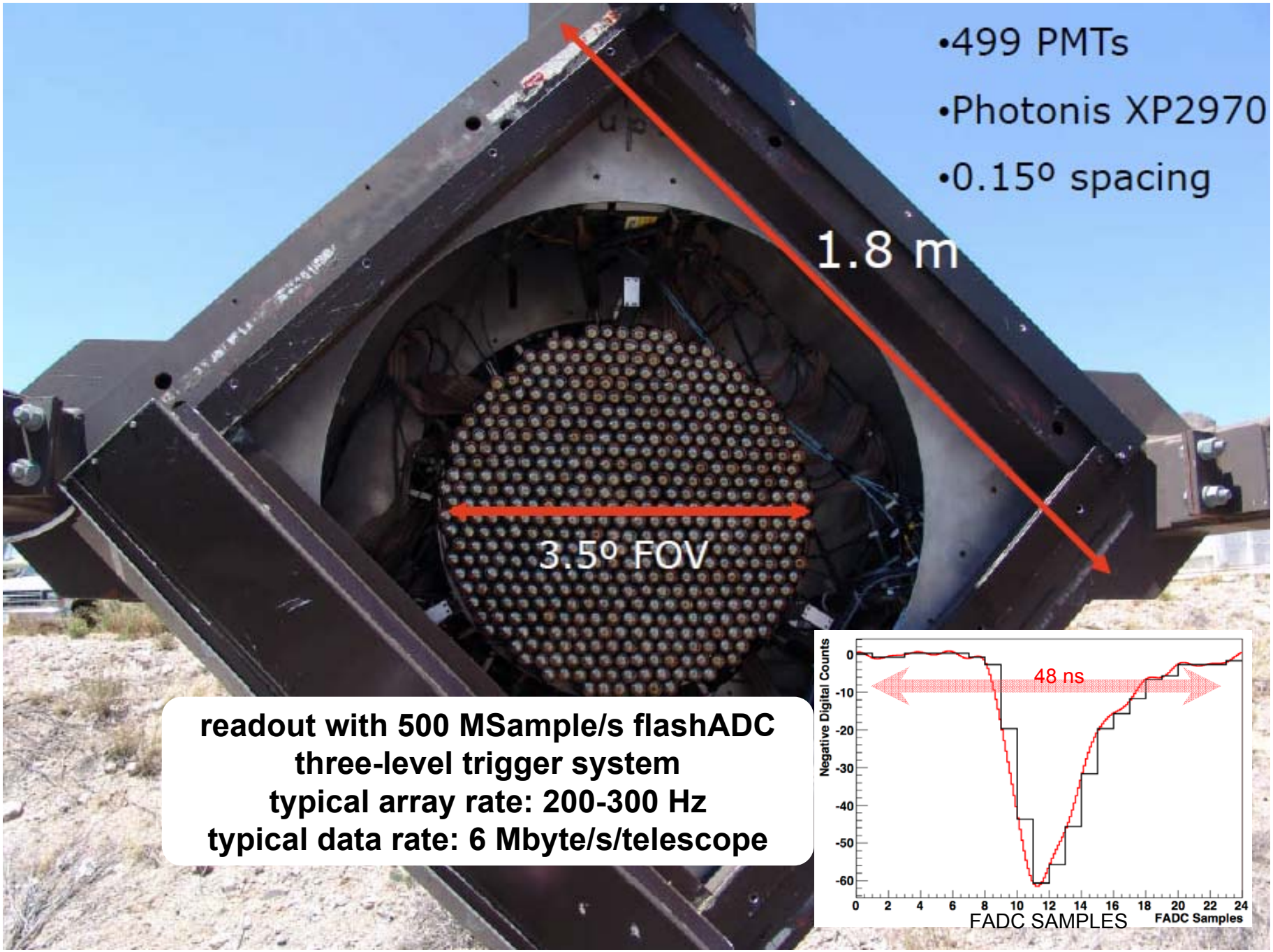
Coma cluster, Hubble



Conclusions & Outlook

- Four-telescope VERITAS array is now in full operation – the most sensitive Cherenkov telescope in the world
- Productive science programme now underway with four Key Science Projects + competitive time
- The γ-ray sky is getting curiouser and curiouser!

Backup slides


•499 PMTs
•Photonis XP2970
•0.15º spacing
1.8 m
3.5º FOV
readout with 500 MSample/s flashADC
three-level trigger system
typical array rate: 200-300 Hz
typical data rate: 6 Mbyte/s/telescope
48 ns
Negative Digital Counts
0
-10
-20
-30
-40
-50
-60
0 2 4 6 8 10 12 14 16 18 20 22 24
FADC Samples
FADC SAMPLES

Trigger system

Level 1 (Pixel) Trigger:

Constant fraction discriminators (typical threshold at 50 mV or ~4-5 photoelectrons)

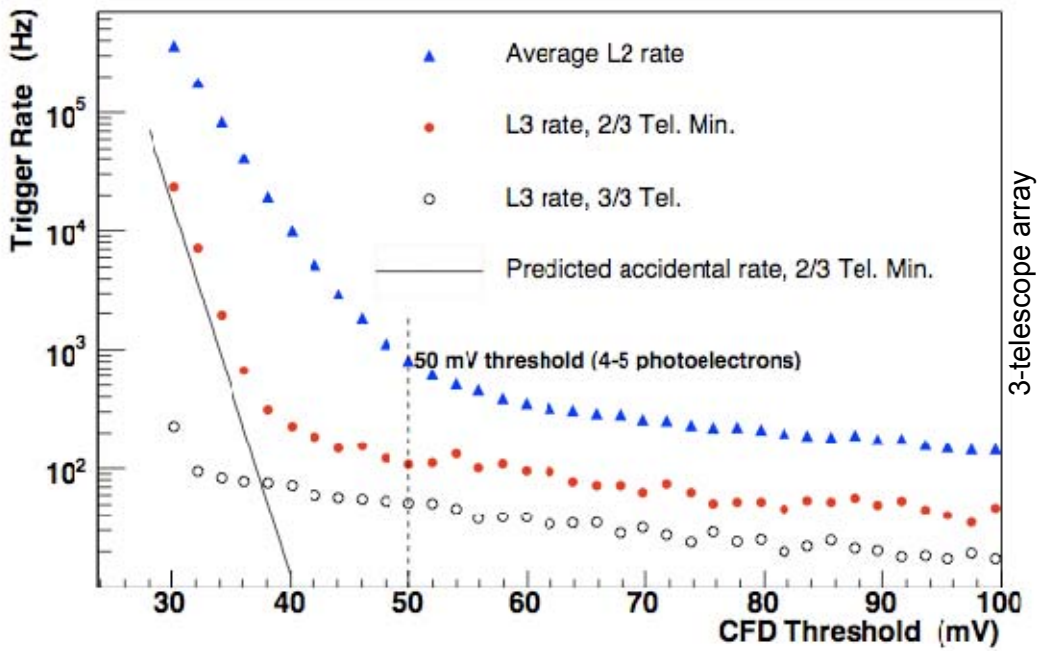
Level 2 (Pattern) Trigger:

Recognize patterns of trigger pixel in the camera (standard is three adjacent pixels in a time window of 6 ns)

Level 3 (Array) Trigger:

Telescope coincidence trigger (i.e. in a time window of ~100 ns)

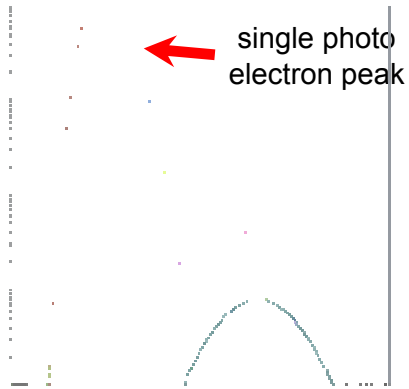
Dependance of the array trigger (L3) and pattern trigger rates (L2) on CFD thresholds



Typical array rate: 200-300 Hz (dead time ~10%)

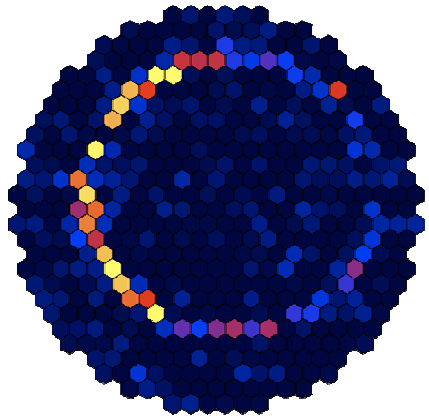
Calibration

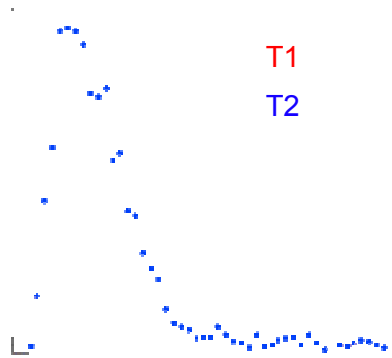
single photoelectrons



digital counts

muon rings



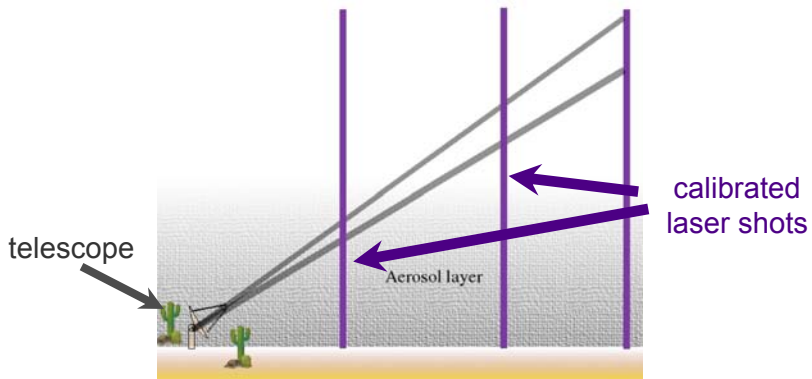


charge/degree

pointing monitor

measurement of absolute pointing and position of focus box (->source location better than 100'' -> will be ~20'')

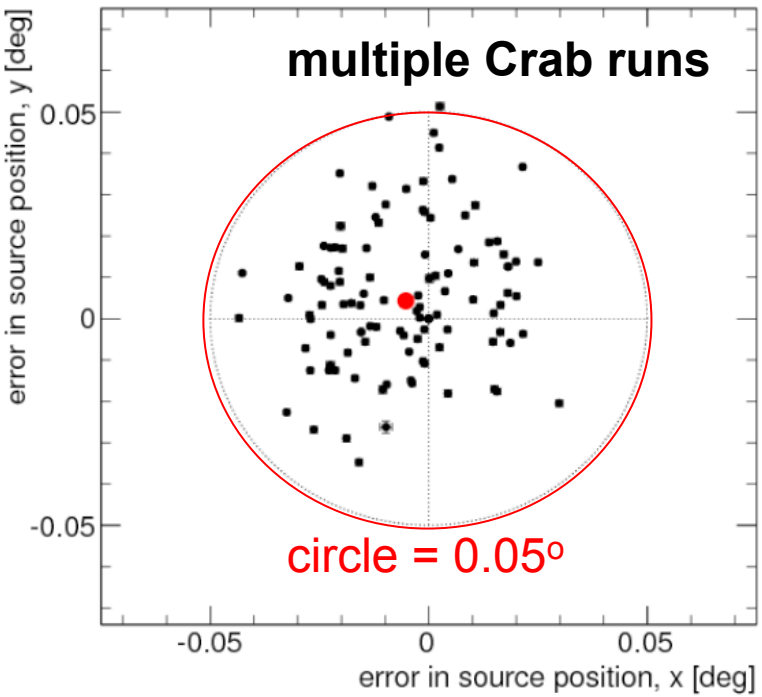
atmospheric studies

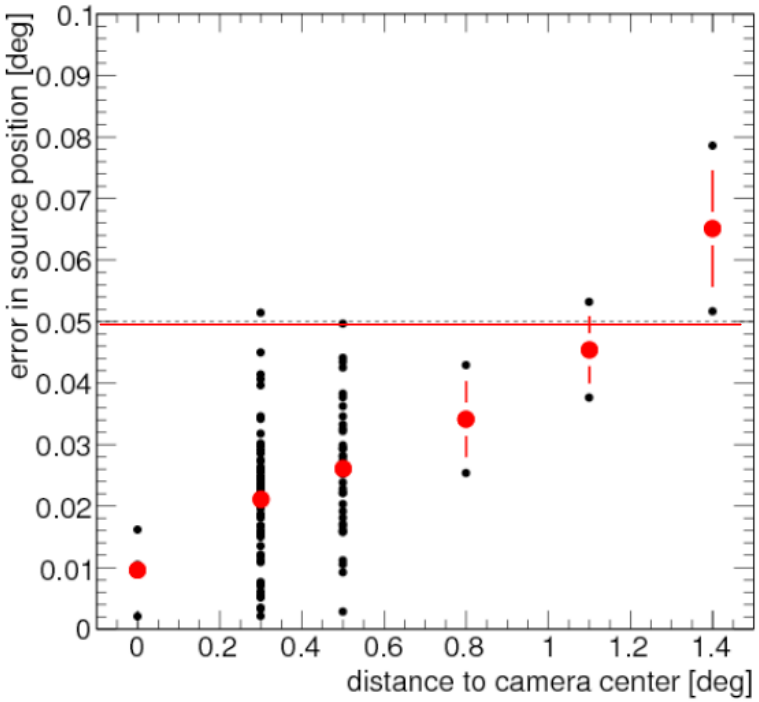


measurement of Rayleigh scattering with calibrated laser source

Instrument Performance

pointing accuracy: few arc-minutes (depends on location in camera)



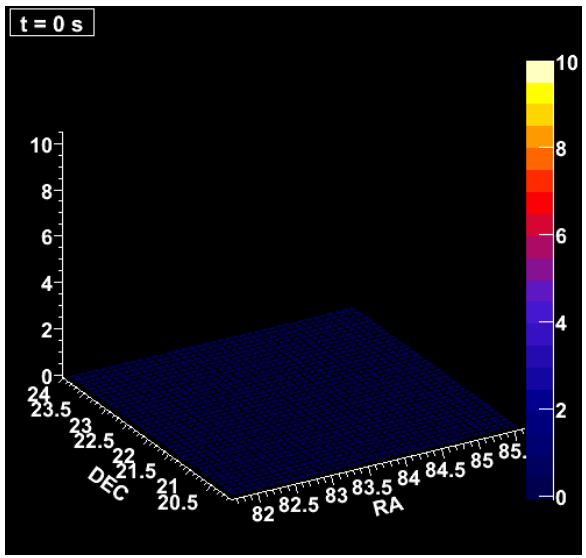


Instrument Performance

- Crab (standard candle) rate:

  ~30 $\sigma/\sqrt{\text{hour}}$ (cf STACEE: ~2$\sigma/\sqrt{\text{hour}}$)

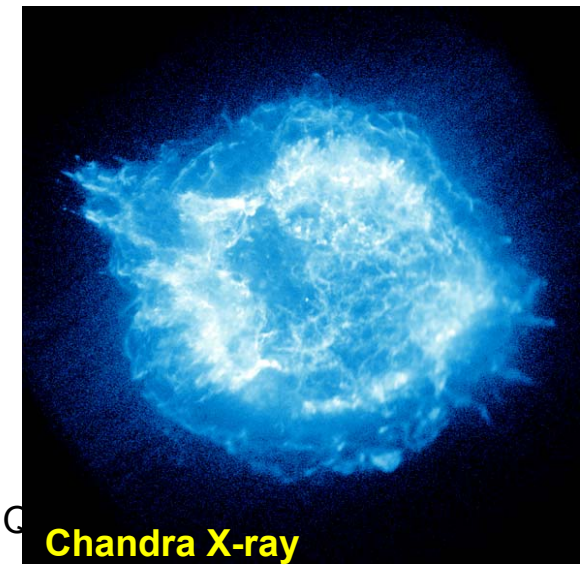
- 100 mCrab sensitivity @ 5σ in < 1 hour

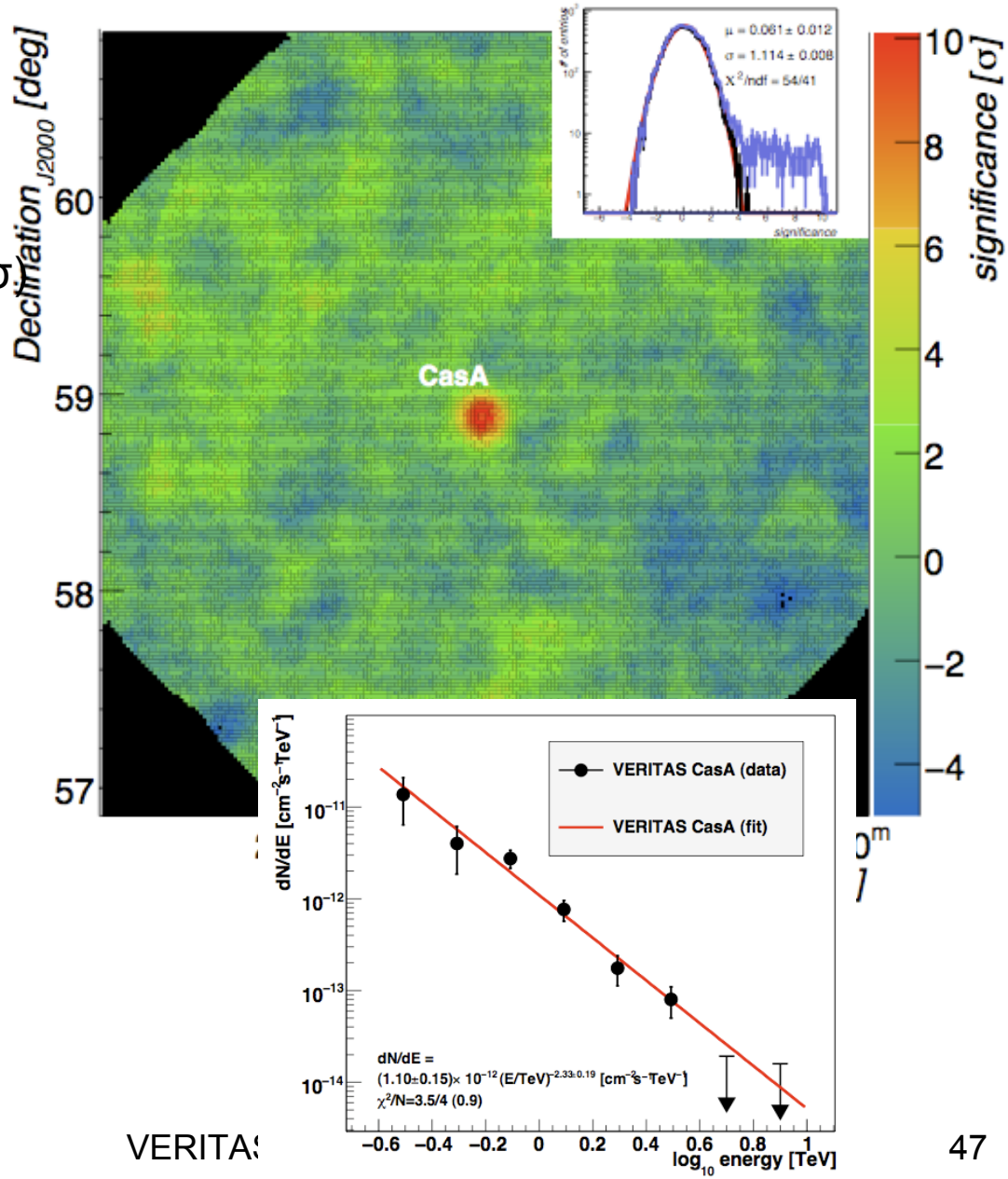


Crab signal emerging…
in real-time!

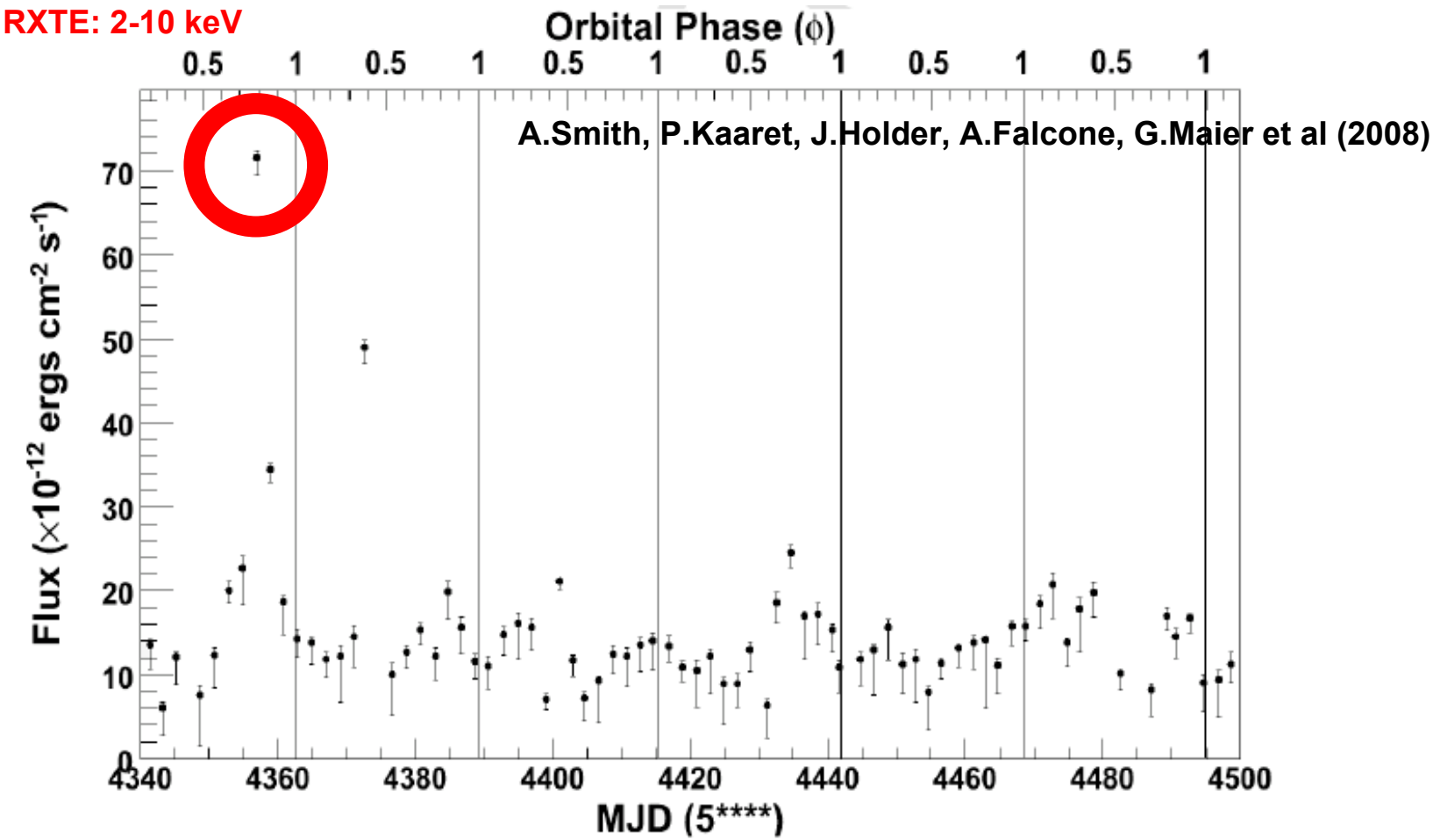
Cas A

- young (330 years) SNR
- small extension (5 arcmin)
- HEGRA discovery (232 h, 5σ) (MAGIC, 47 h, 5.3σ)
- Oct/Nov 2007: 20.3 h, 9.8σ
- Flux: 3% of Crab
- consistent with point source





LS I +61 303: X-ray flares



Does LS I +61 303 host a young, highly magnetized pulsar?
(Dubus, Giebels (ATel #1715), Bednarek (2009))