High-energy astrophysics with VERITAS

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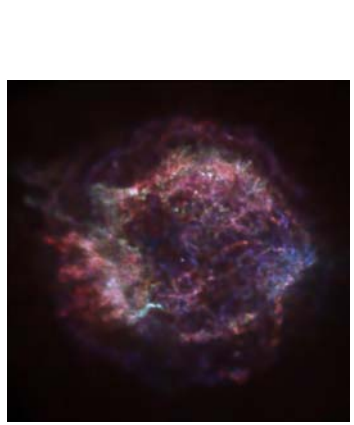
Outline

- Very high-energy (VHE) gamma-ray astrophysics
- Ground-based observations with Cherenkov arrays
- VERITAS & Instrument performance
- Recent science results
  - Extragalactic sources: AGN, Starburst Galaxy
  - Galactic sources: binary systems, SNR
  - Astroparticle physics: dark matter searches
- Upgrade & Outlook
- Conclusions

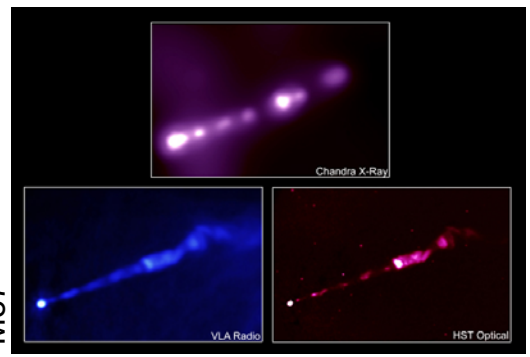
Very high-energy gamma-ray astrophysics

- At E> 50 GeV, several classes of sources known…
  - Galactic:
    - Supernova Remnants
    - Pulsar Wind Nebulae
    - Binary systems
  - Extragalactic:
    - Active Galactic Nuclei
    - Starburst galaxies
- …or expected:
    - Gamma-Ray Bursts
    - Dark matter annihilation

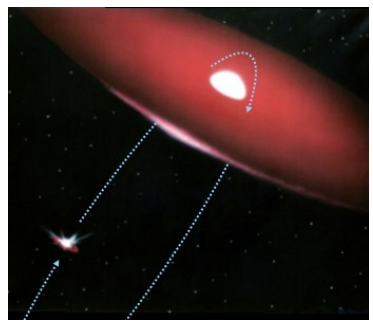


Cas A – XMM Newton

Crab: HST + Chandra



M87



PSR B1259

Connection to (astro) particle physics

- Instrumentation and techniques
- Origin of cosmic rays
  - Where are the accelerators?
  - How do they work? To what energies?

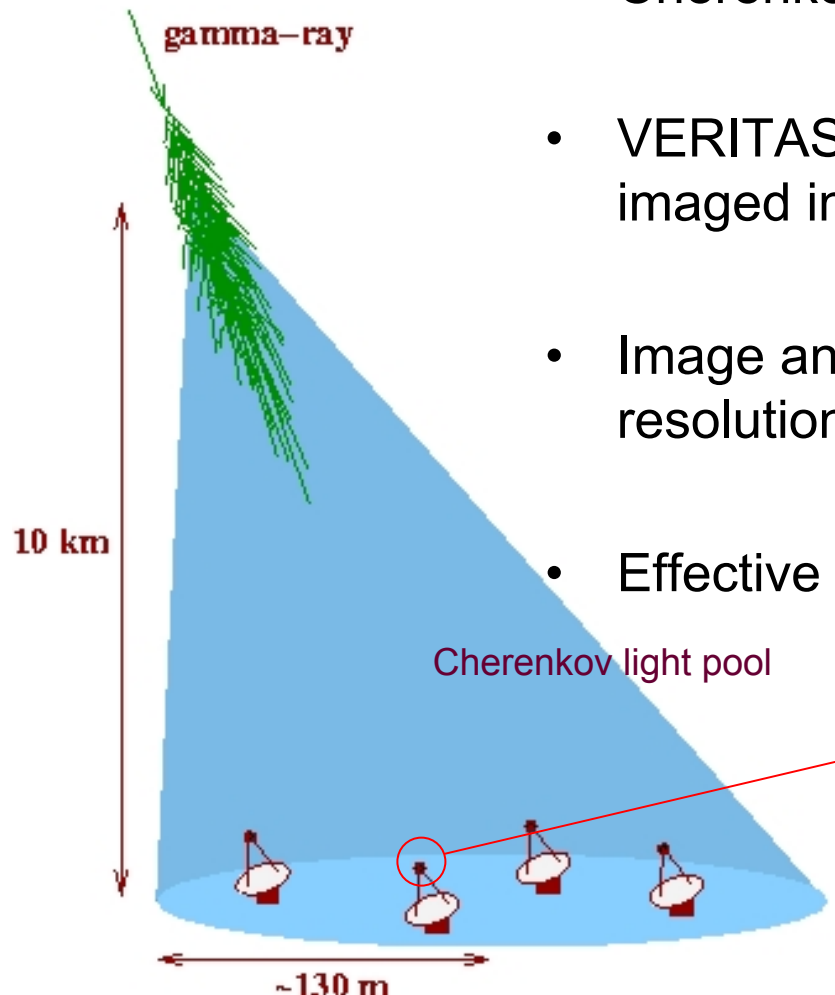
    (relevant to Auger, HiRes, etc)
- Understanding the nature of particle accelerators
  - What is being accelerated? (electrons, protons?)

    (relevant to IceCube, Antares, etc)
- Astrophysical sources for fundamental physics
  - Eg. can use AGN flares to look for effects of quantum gravity if start times are well understood
- Discovery space for new physics
  - Eg. Large mass reach for WIMPs

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 sources have power law ($E^{-\gamma}$) spectra 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
- Multi-wavelength, multi-particle studies to disentangle production issues
- Fundamental particle physics issues:
  - Dark matter annihilation?
  - Primordial black holes?
  - Energy-dependent *c* ?

Ground-based observations



- Now on third generation instruments using the Air Cherenkov technique pioneered by Whipple
- 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 ~ 10^5 m^2

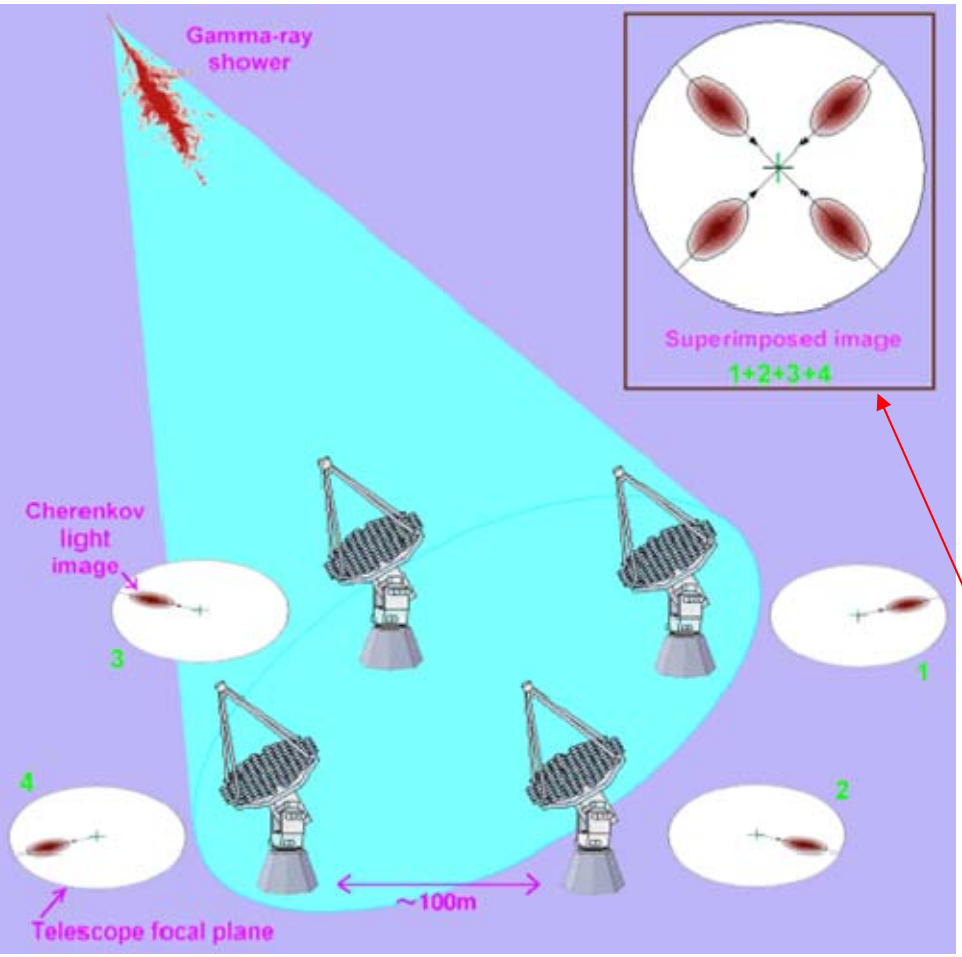
Cherenkov light pool

Multi-PMT camera

Cherenkov telescopes come full circle over 45 years…

1967

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 (1300 m a.s.l.) near Tucson, Az
- International collaboration: US, Canadian, UK, Irish groups; ~ 80 collaborators at 20 institutions
- Science observations started in 2006; fully operational since 2007

- 80 GeV to 50 TeV energy range
- Currently most sensitive VHE gamma array in the world

VERITAS - site

- 800 hrs/yr dark time
- 200 hrs/yr partial moonlight
- Summer shutdown (monsoon)

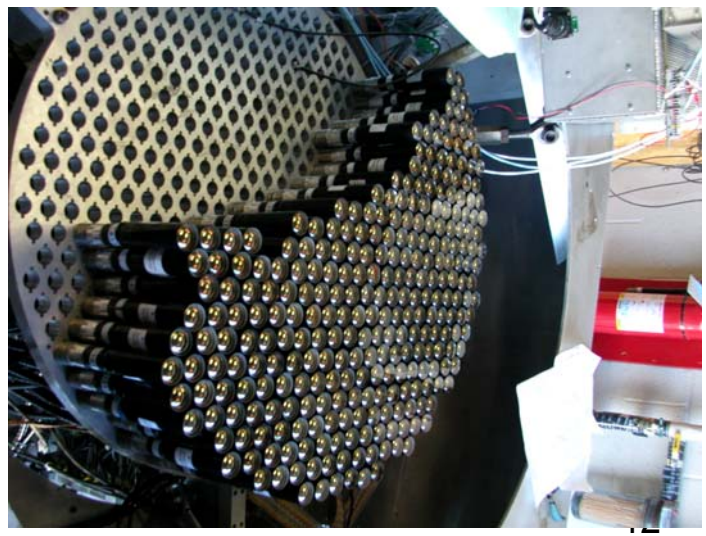
Fred Lawrence Whipple Observatory (FLWO) basecamp

VERITAS - site

- Move of T1 led to ~15% increase in sensitivity

VERITAS – telescopes & cameras

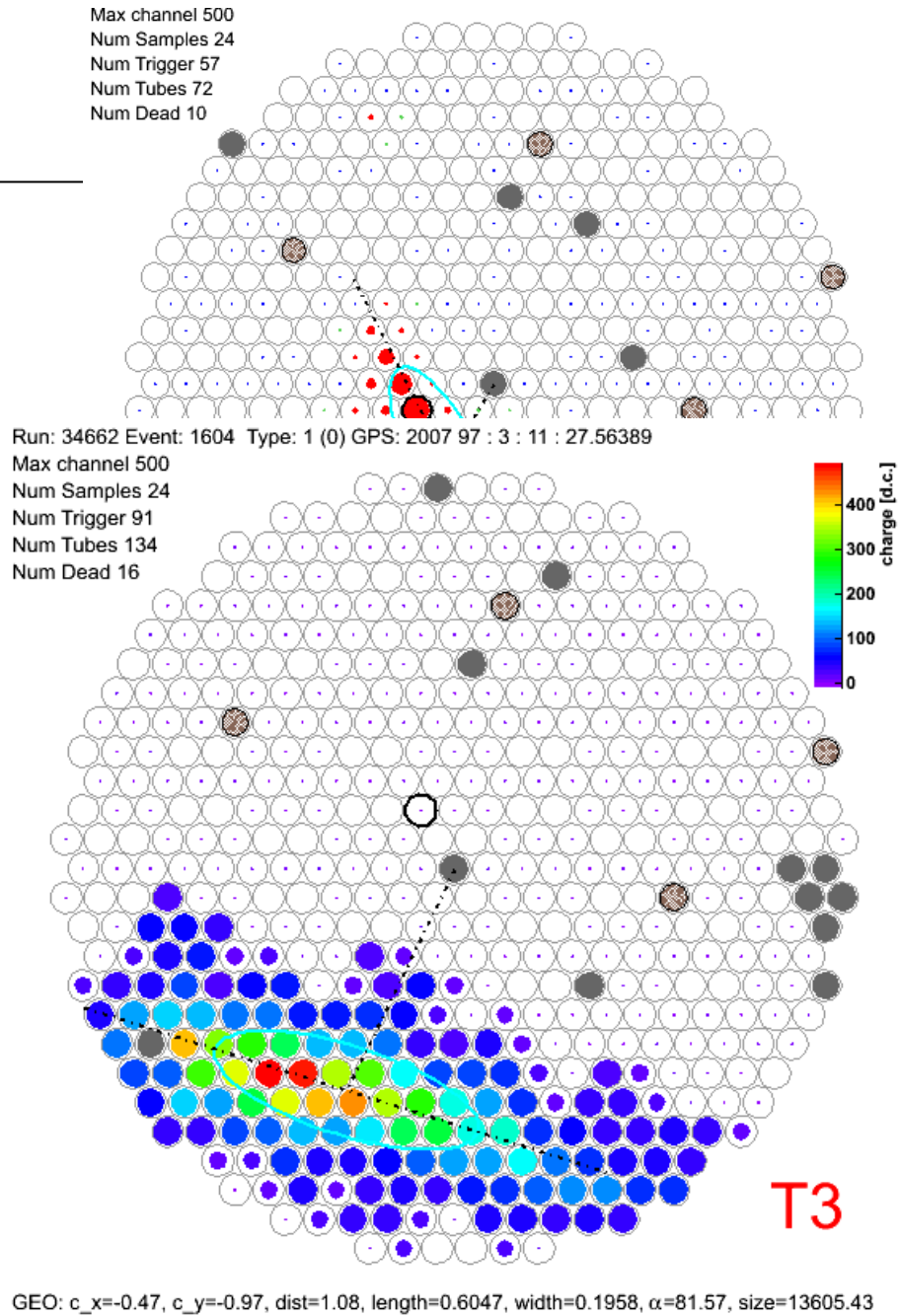
- Each 12-m f/1 telescope: tesselated mirror, 350 facets; total mirror area 109 m^2
- Each camera: 499 29mm PMTs
- Each PMT: 0.15^o f.o.v. (2.6 mrad); overall f.o.v = 3.5^o



Partially assembled camera

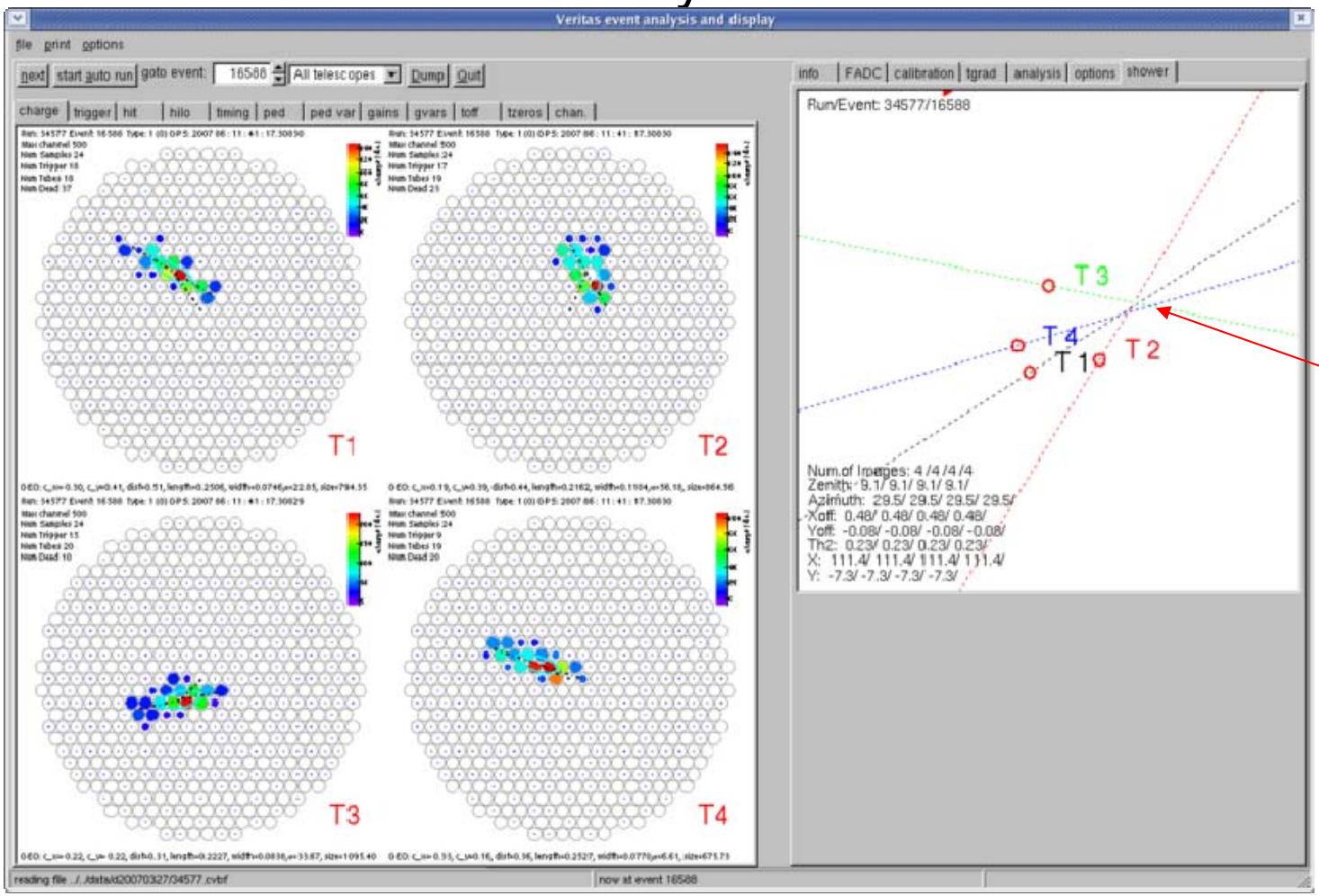
VERITAS – electronics

- 3-level trigger:
  - constant fraction discriminator on each PMT
  - telescope pattern trigger requires adjacent pixels
  - multi-telescope (array) coincidence
- Each PMT read out by 500 MSample/s FADC (2 ns sampling)
- Typical event rate: 300 Hz (10% deadtime)



Instrument Performance

- ‘Effective area’ of array ~ 10^5 m^2



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: 50 mCrab @ 5σ in under one hour

  energy resolution: ~15%

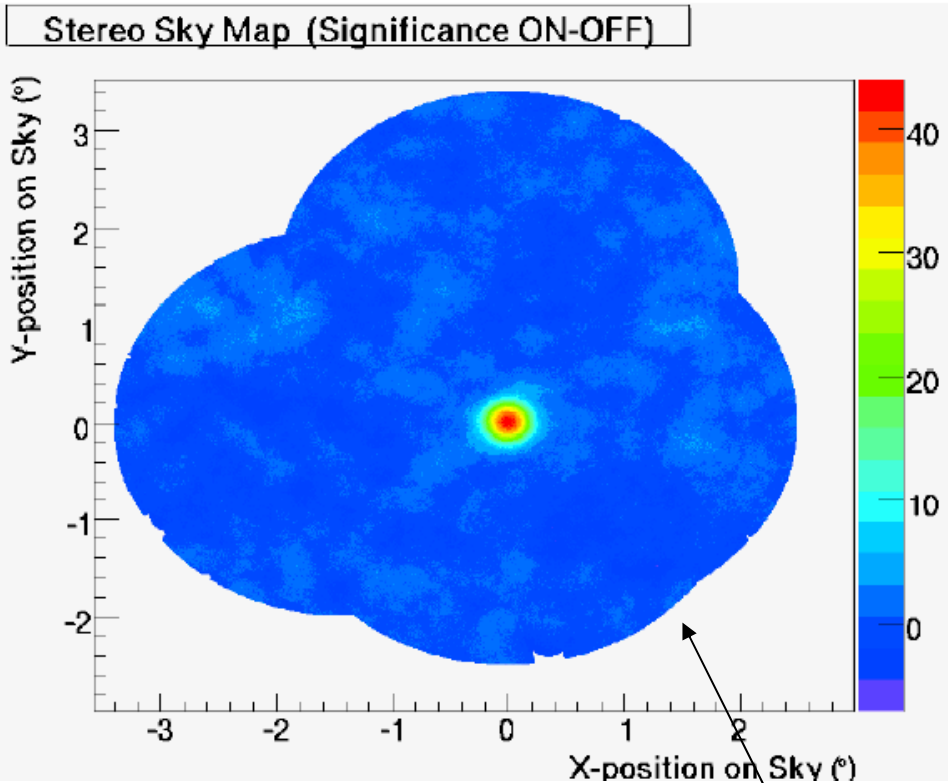
  core reconstruction: <25 m out to 180m from array centre

  spectral reconstruction above ~150 GeV

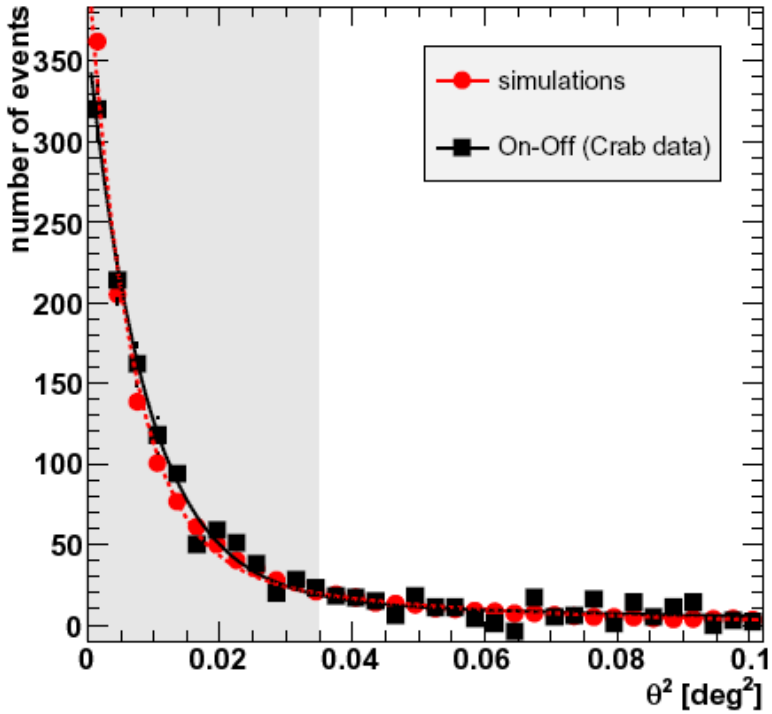
- Crab (standard candle) data used to measure pointing, sensitivity

Instrument Performance

PSF: ~0.06° – 0.10°



Angle between γ-arrival direction and known source position

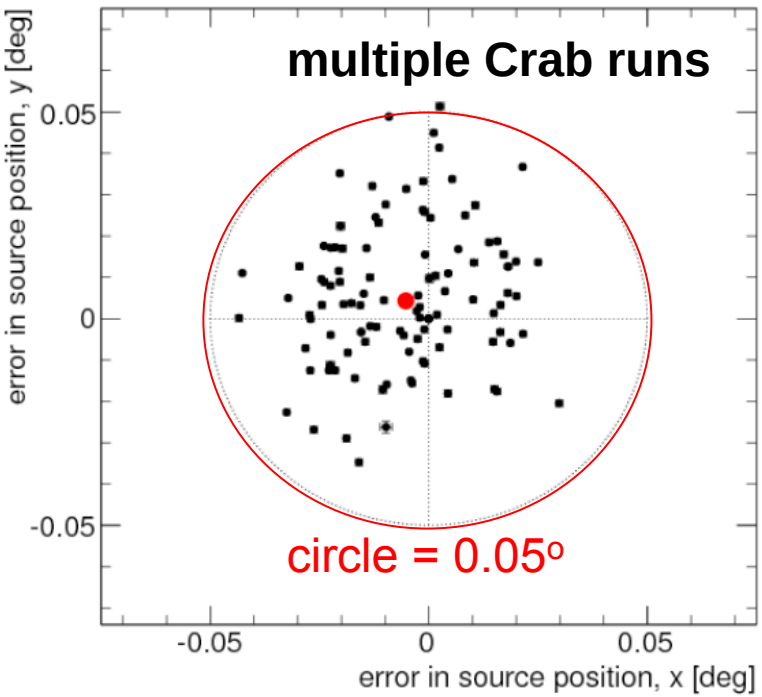


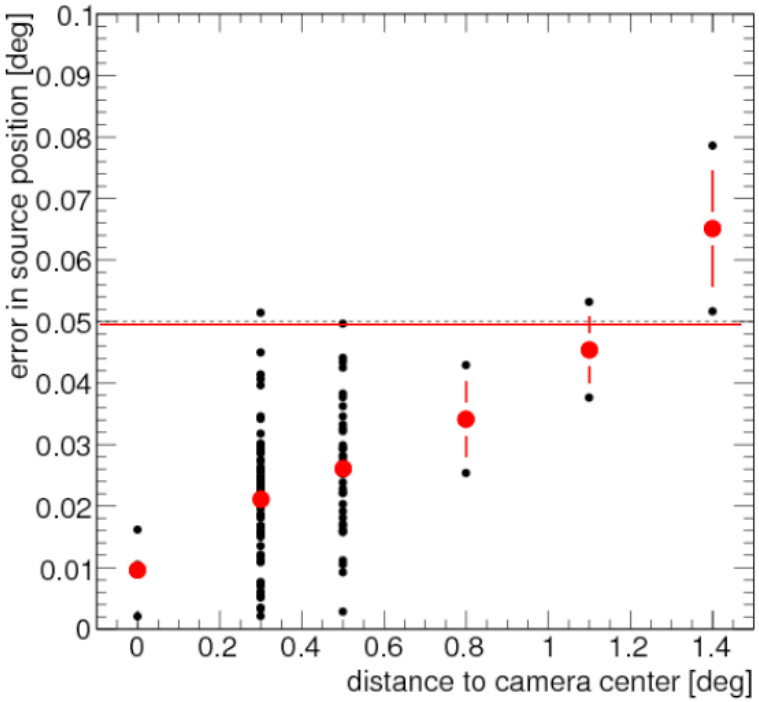
3-telescope Crab data

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

Instrument Performance

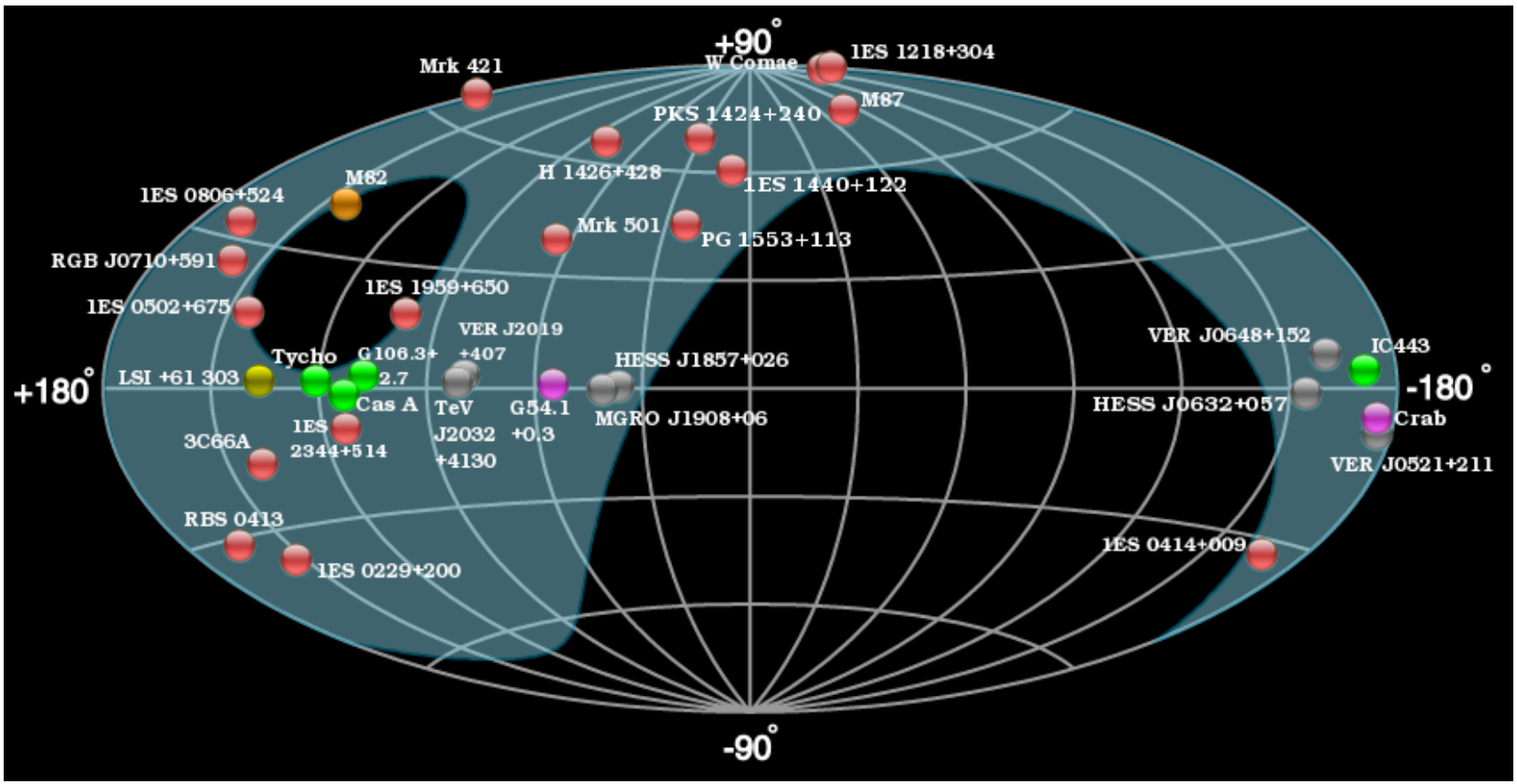
pointing accuracy: few arc-minutes (depends on location in camera)





Recent VERITAS Science Results

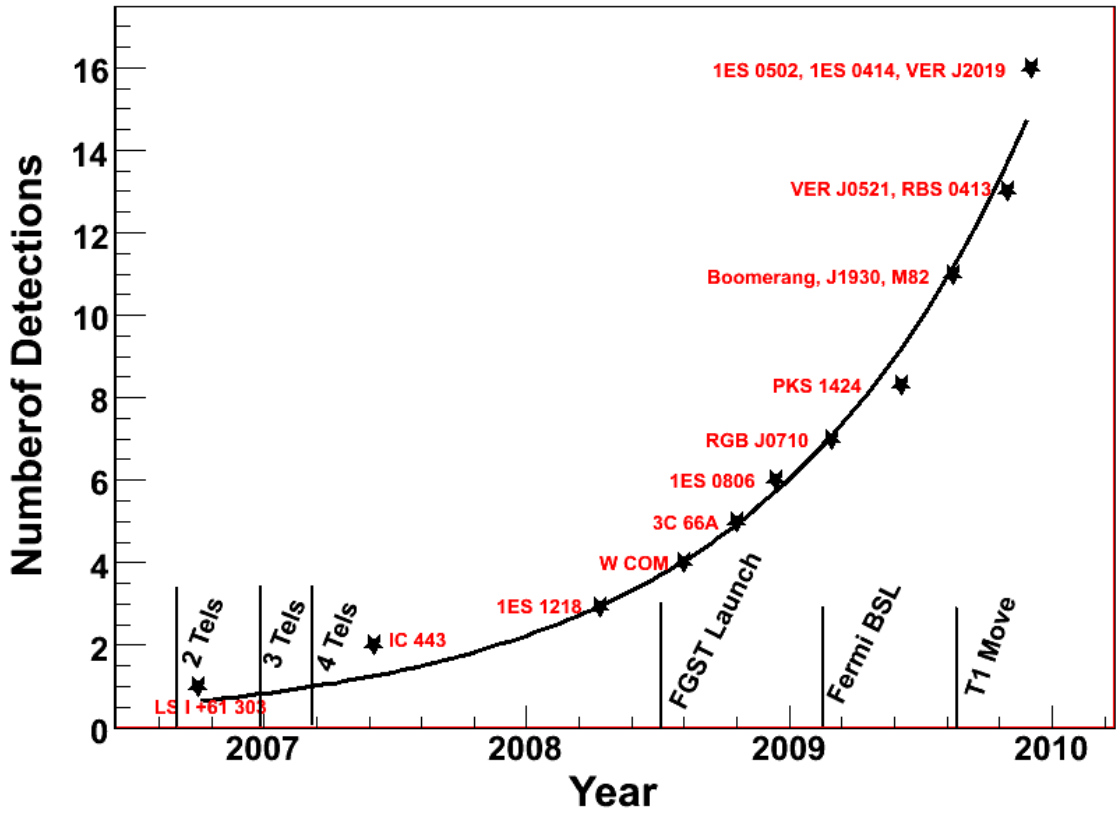
- 33 source detections in 7 source classes:
  - blazars, radio galaxy, starburst galaxy, PWN, SNR, XRB, UnID



From TeVcat: tevcat.uchicago.edu

Recent VERITAS Science Results

- 16 discoveries:
  - 7 AGN, 3 SNR/PWN, 1 starburst galaxy, 5 other



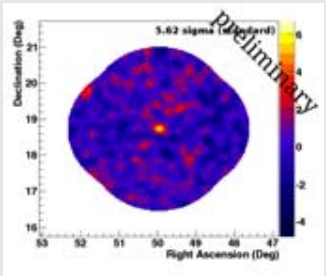
Extragalactic observations

- AGNs are most common TeV source type
- Aim: understand jet production by supermassive black holes and the physics behind gamma-ray production
  - leptonic?
  - hadronic?
- Multiwavelength campaigns important
- One goal: measure the extragalactic background light (EBL) through its effect on blazar spectra

$$\gamma_{TeV}\,\gamma_{EBL} \rightarrow e^+e^-$$

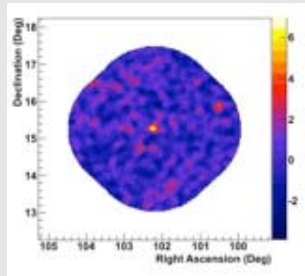
Extragalactic: AGN discoveries

RBS 0413



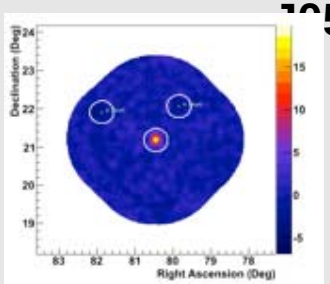
- ~5.5σ in 25 h
- 1.6% Crab
- X-ray bright HBL @ z=0.19
- brightest LAT extrapolation
- ATEL #2272 with Fermi

RX J0648.7+1516



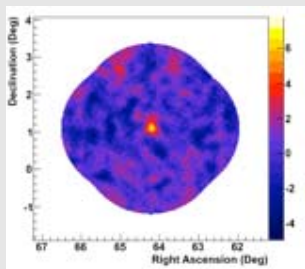
- ~5.2σ in 18 h
- 2% Crab
- Keck: Blazar
- z=0.179 (Lick 3m)
- ATEL #2486

VER J0521+211 (RGB J0521.8+2112)



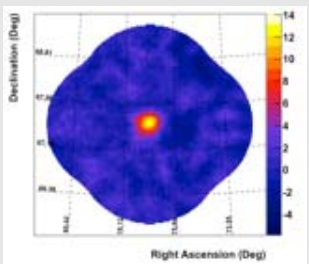
- ~8σ in 15h
- 4% Crab
- z=? (unsuccessful MMT, MDM, IR efforts)
- bright flare (>20% Crab)
- ATELs #2260 & #2309

1ES 0414+009



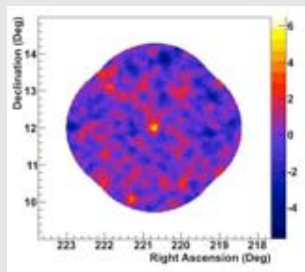
- ~7σ in 45 h; 2% Crab
- among X-ray brightest HBL
- z=0.287
- EBL! high-z Mkn 421
- H.E.S.S. detection

1ES 0502+675



- ~12σ in 30 h
- 5% Crab
- z≠0.341? (1h MMT exposure – no features, no redshift)
- ATEL #2301

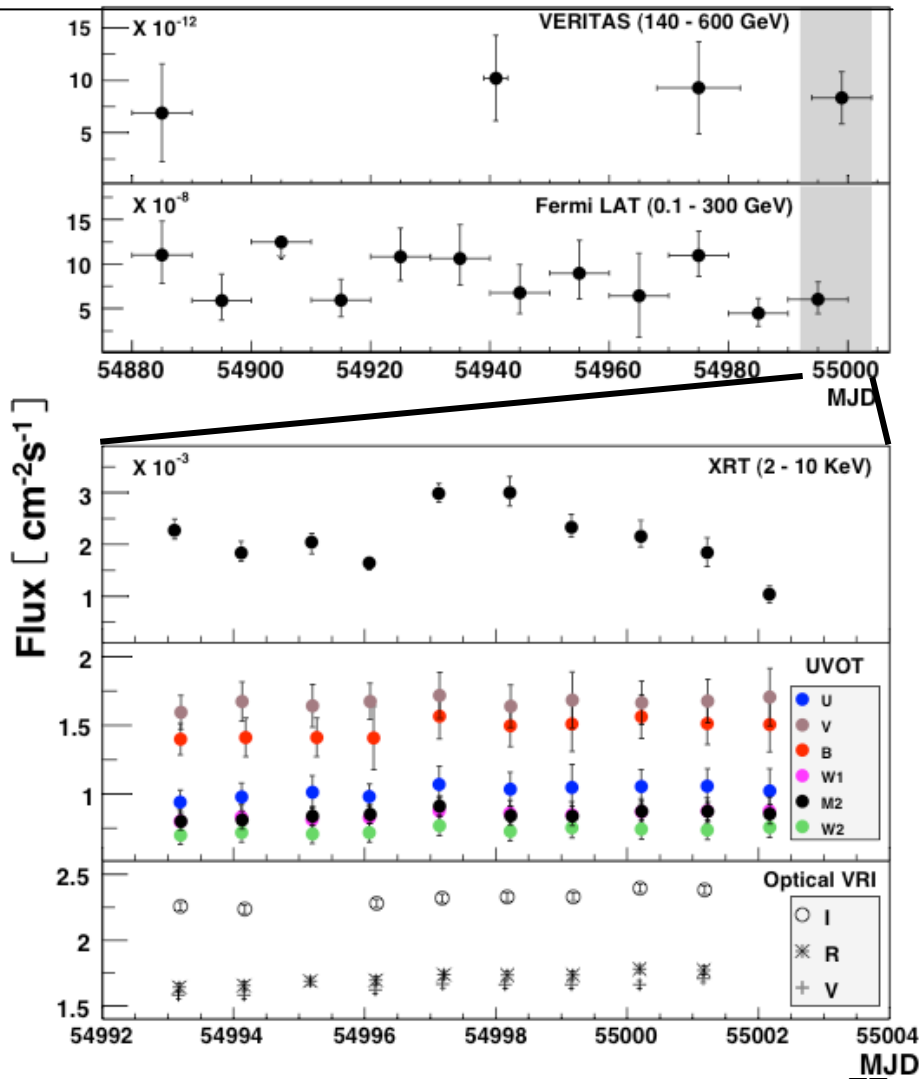
1ES 1440+122



- ~5.2σ in 50 h
- <1% Crab
- hard-spectrum IBL (LAT)
- z=0.162
- ATEL #2786

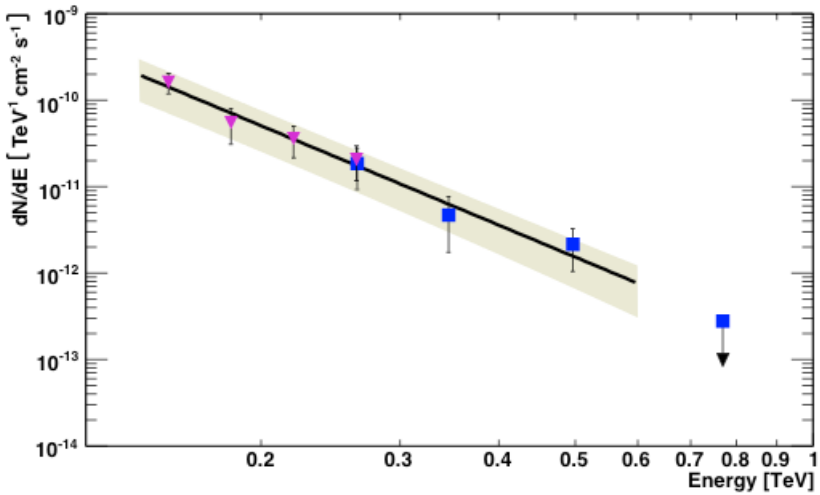
Extragalactic: PKS 1424+240

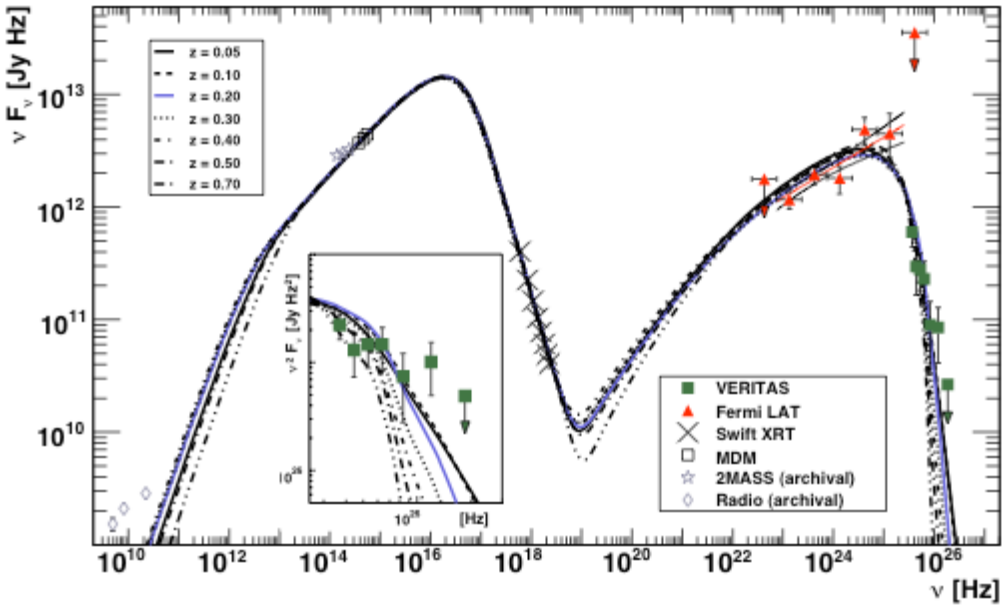
- IBL/HBL
- unknown redshift
- Detected by Fermi-LAT (100 MeV–300 GeV)
- First VHE source discovered as a LAT follow-up
- Discovery triggered observations at other wavelengths



ApJL 708, L100 (2010)

Extragalactic: PKS 1424+240





- Fermi power law: $\Gamma = 1.73 \pm 0.07_{stat} \pm 0.05_{sys}$
- Steep VERITAS power law: $\Gamma = 3.8 \pm 0.5_{stat} \pm 0.3_{sys}$
- z < 0.66, else EBL would make spectrum softer still
- Flux at ~5% of Crab value

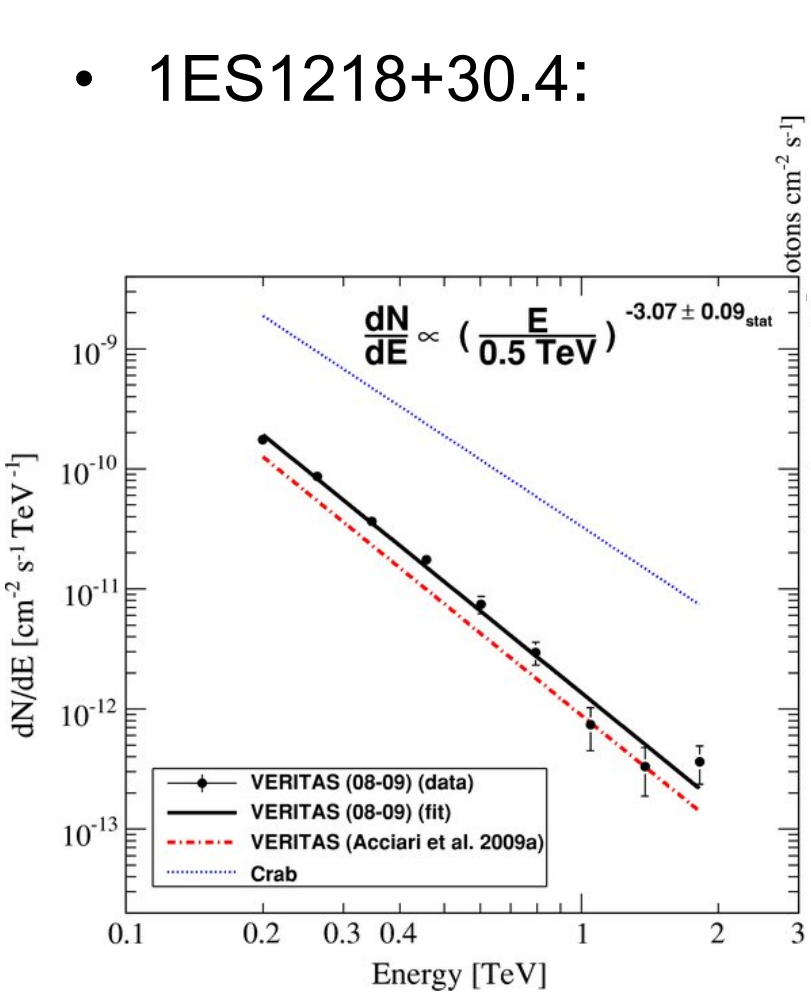
Extragalactic: 1ES1218+30.4

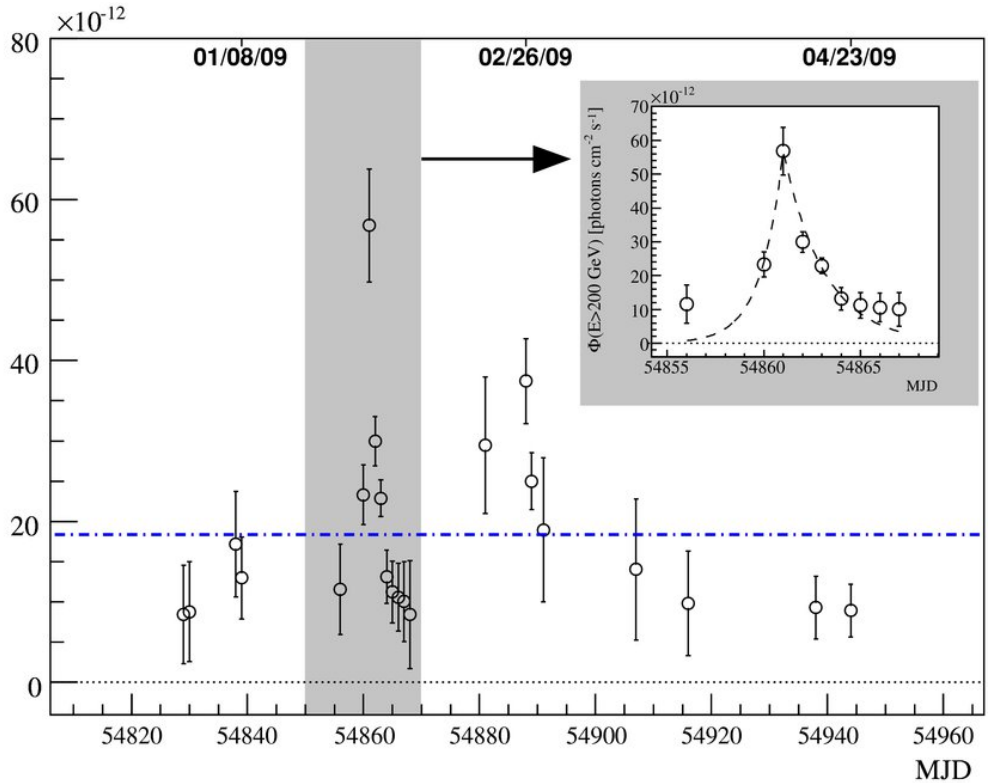
- 1ES1218+30.4:
  - Active Galactic Nucleus, Blazar Class
  - X-ray bright; EGRET source; detected by MAGIC at VHE
  - z=0.182
  - Hard intrinsic spectrum given this relatively large redshift

- Flare Jan 25 – Feb 5, 2009: 7% Crab to 20% Crab
  - ~1 day variability time scale challenges kiloparsec jet model of hard-spectrum emission (Boettcher et al. 2008)

Extragalactic: 1ES1218+30.4

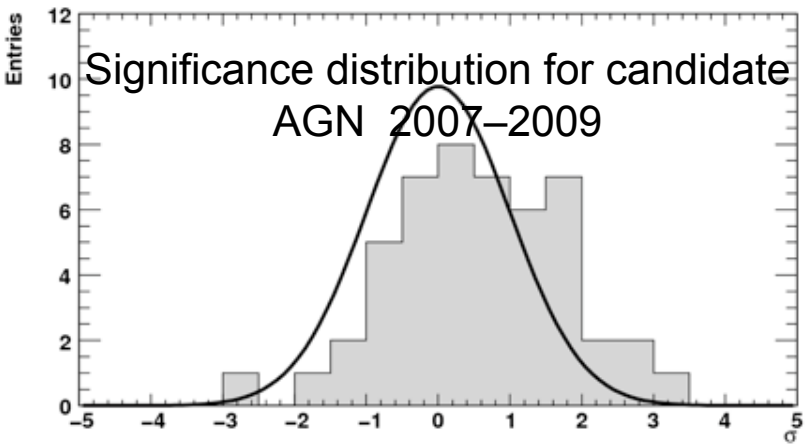
- 1ES1218+30.4:

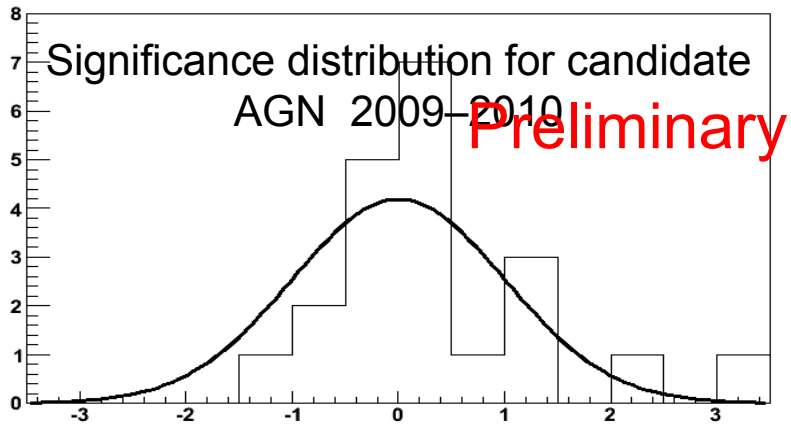




Extragalactic: Stacked AGN observations

- 2007–2009
  - Exposures on 80% of good X-ray sel. candidates
  - Non-detections: 5σ "stacked" excess (49 AGN, ~6 h each)
  - Most upper limits are best ever: ~2% Crab
- 2009–2010
  - Exposures on 21 Fermi-LAT motivated candidates
  - Upper limits in preparation
  - Will be compared to extrapolated Fermi-LAT flux





Extragalactic: Starburst Galaxy M82

- First observation of VHE gamma rays from a starburst galaxy (SG)

- VERITAS result establishes starburst galaxies as a new class of VHE source

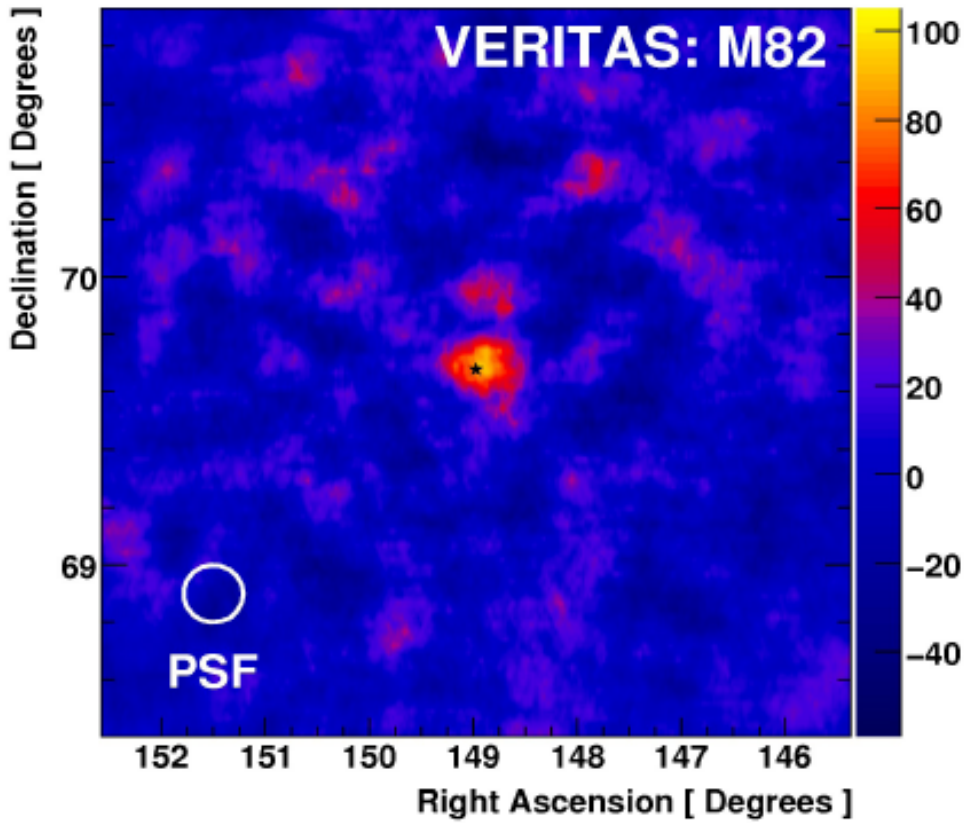
- Starburst galaxies have high rates of star birth and death:
  - many supernovae and stellar winds
  - copious cosmic-ray production
  - gamma-ray production from CR collisions

Nature 472 770-772 (2009)

Extragalactic: Starburst Galaxy M82

•140 h over 2 years to detect;
5 sigma (post trials) for
E > 700 GeV; 0.9% Crab

• Detection supports idea of SNRs as source of cosmic rays



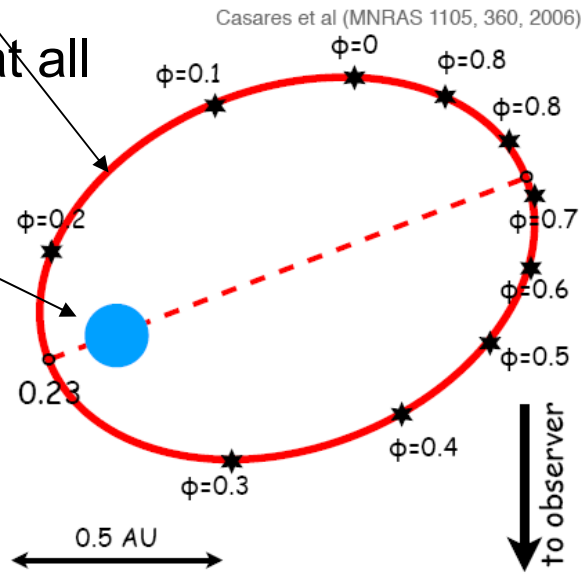
Galactic observations

- Several galactic source types:
  - Supernova remnants (SNR)
  - Pulsar wind nebula (PWN)
  - Binary systems

- VERITAS has extensive targeted observations as well as a Sky Survey of the Cygnus region

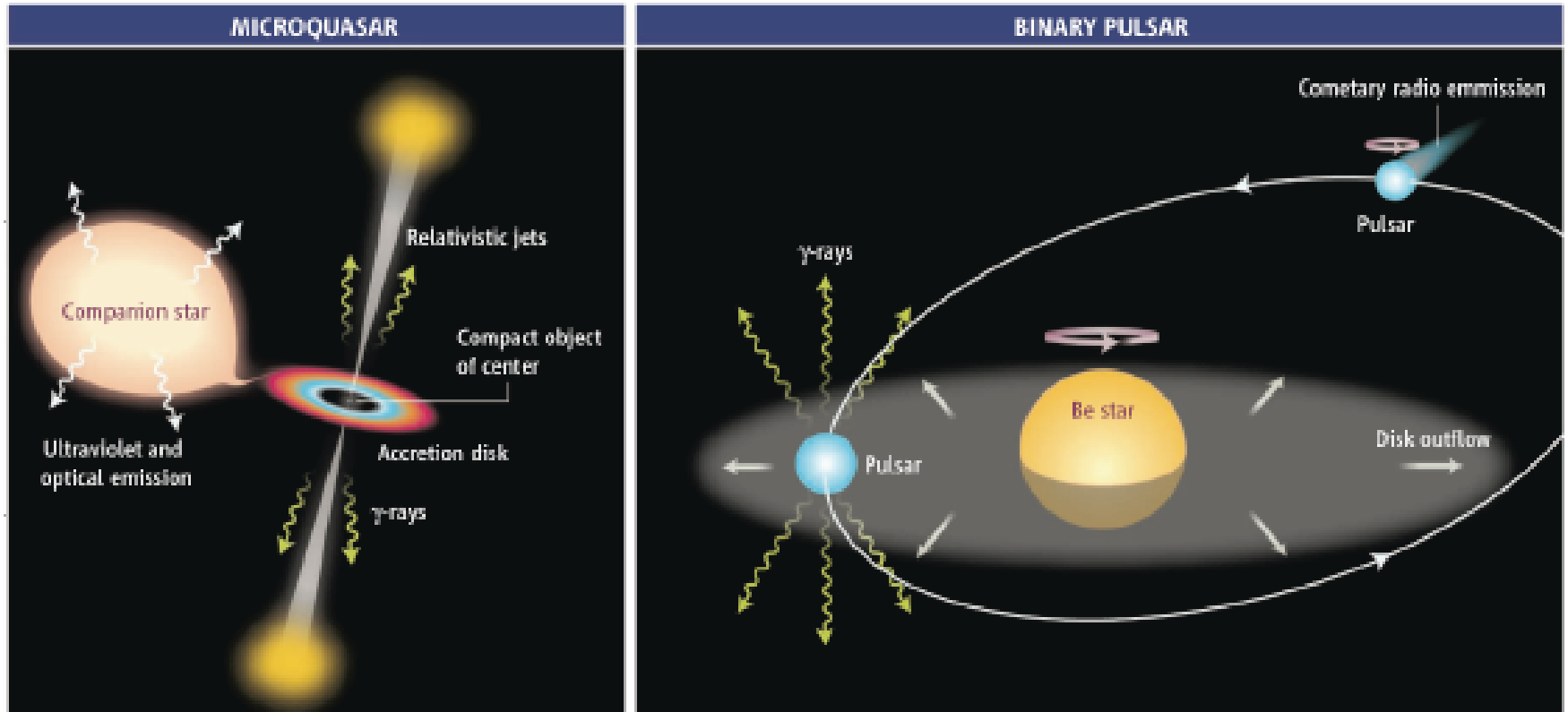
Galactic: LSI +61 303

- LSI +61 303:
  - high-mass X-ray binary (period: 26.5 days)
  - massive Be star with compact companion (NS, BH) in tight orbit, and circumstellar disk
  - variable (phase-dependent) emission seen at all wavelengths



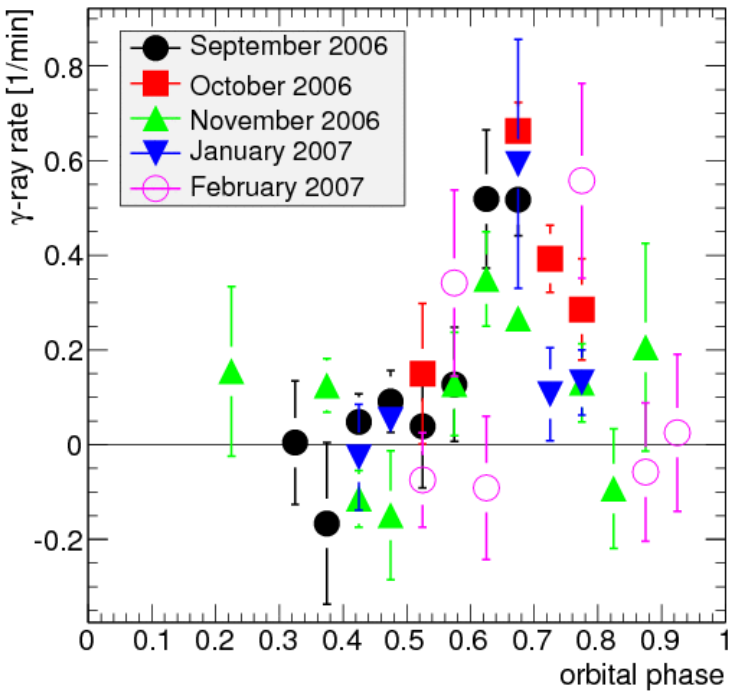
Galactic: LSI +61 303

- At least two models for VHE emission in system:
  - relativistic jet powered by accretion (“microquasar”)
  - acceleration in collision of relativistic pulsar wind with companion wind
  - in both models, VHE γ emission believed to be inverse Compton



Galactic: LSI +61 303

- Initial observations during 5 orbital cycles:
  - 2-telescope data: Sep – Dec ’06: 32 hours
  - 3-telescope data: Jan – Feb ’07: 12 hours
- VERITAS clearly observed variable emission @ 8.8σ

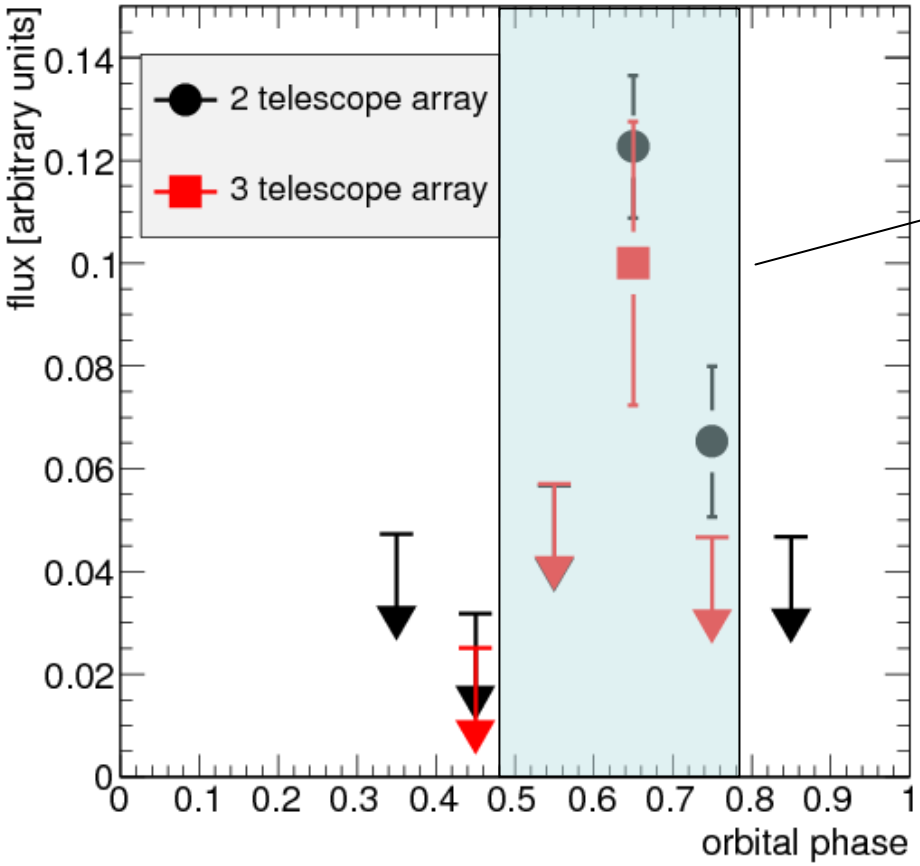


raw rates, binned *vs* binary phase

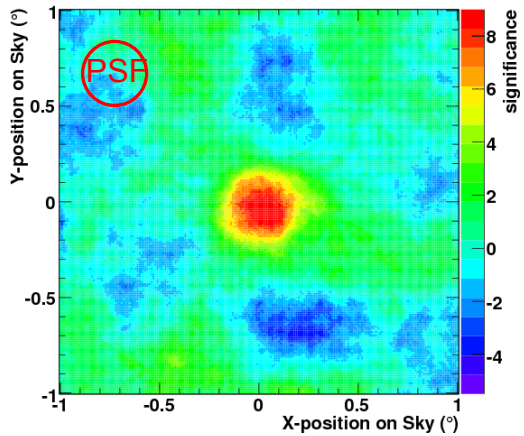
Because period is close to lunar period, no data in [0.95, 0.20]

Galactic: LSI +61 303

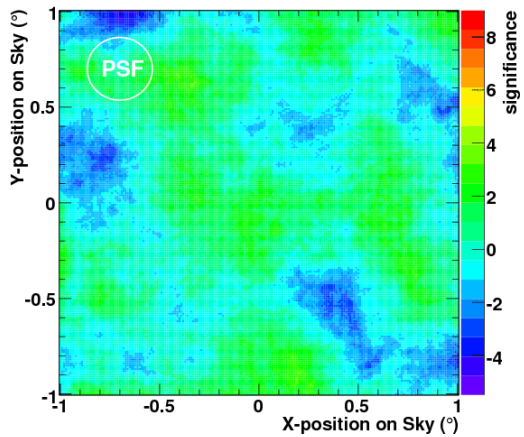
- emission observed near apastron (phase 0.73): flux > 0.10 Crab
- flux < 0.03 Crab outside in other observed phase bins
- 26.5 day period has 99.94% probability



0.5<ϕ<0.8
25 hours

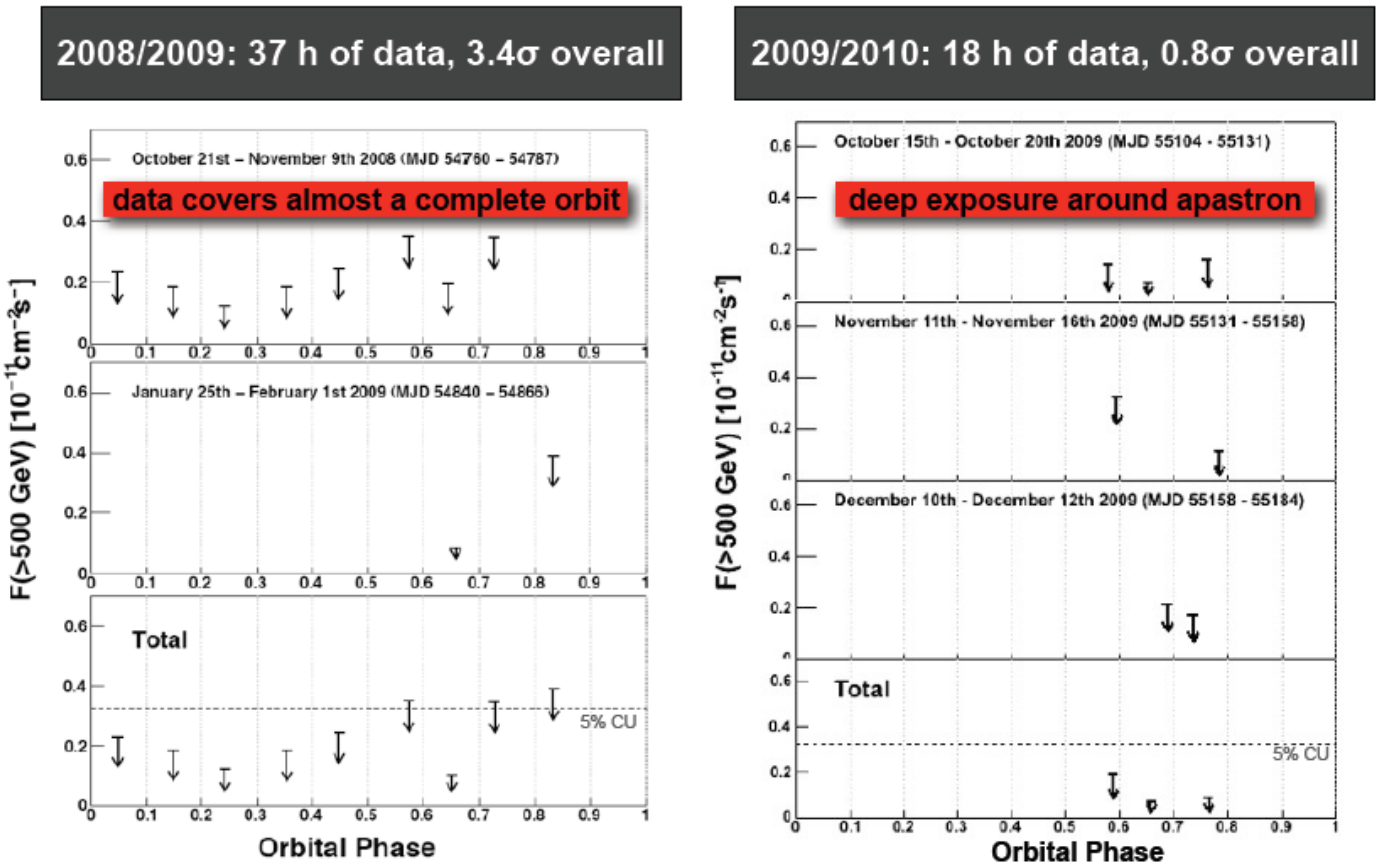


0.8<ϕ<0.5
19 hours



Galactic: LSI +61 303

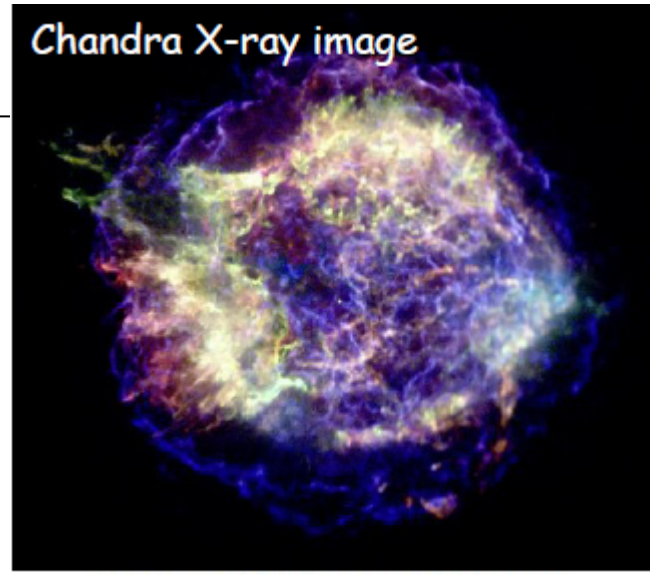
- Newer data: less clear to interpret!
- 55 hours of data since Fermi launch, Sept 2008 – early 2010

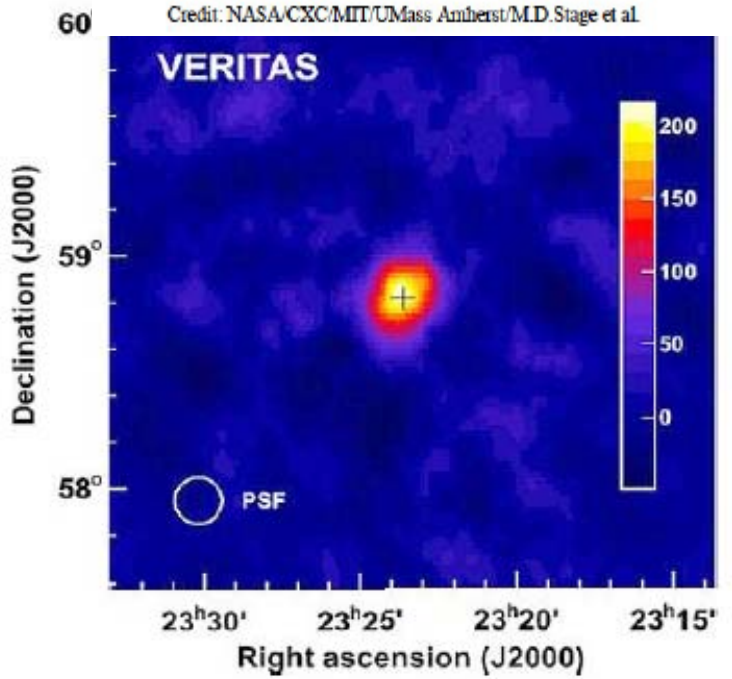


Galactic: Cassiopeia A (Cas A)

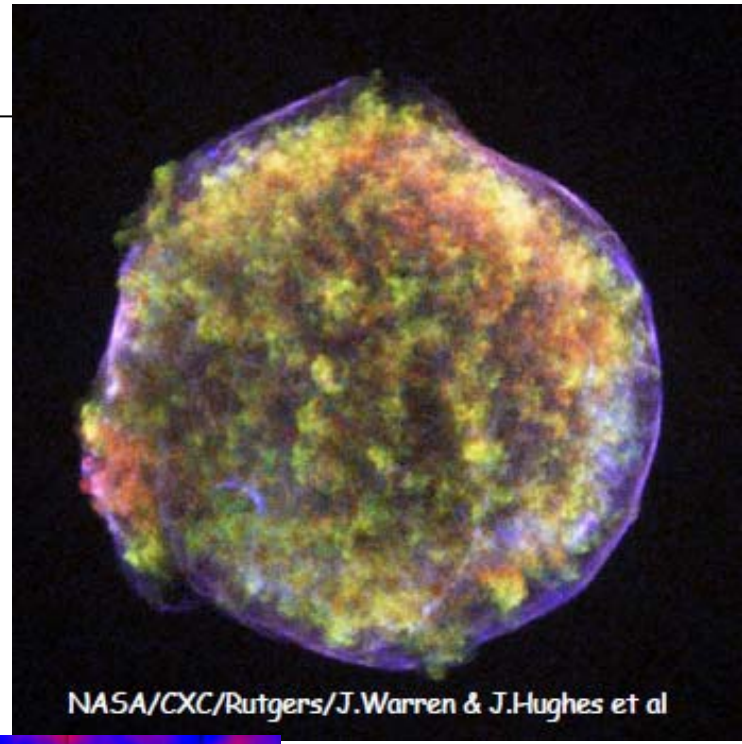
- young (~300 year) supernova remnant
- no (apparent) interactions with nearby material

- VERITAS: 22 hours of data in 07-08 season, 8.3σ
- consistent with point source, at ~3.5% of Crab flux
- modeling uses Fermi-LAT and VERITAS data:
  - prefers hadronic models, but electronic models can be made to work too

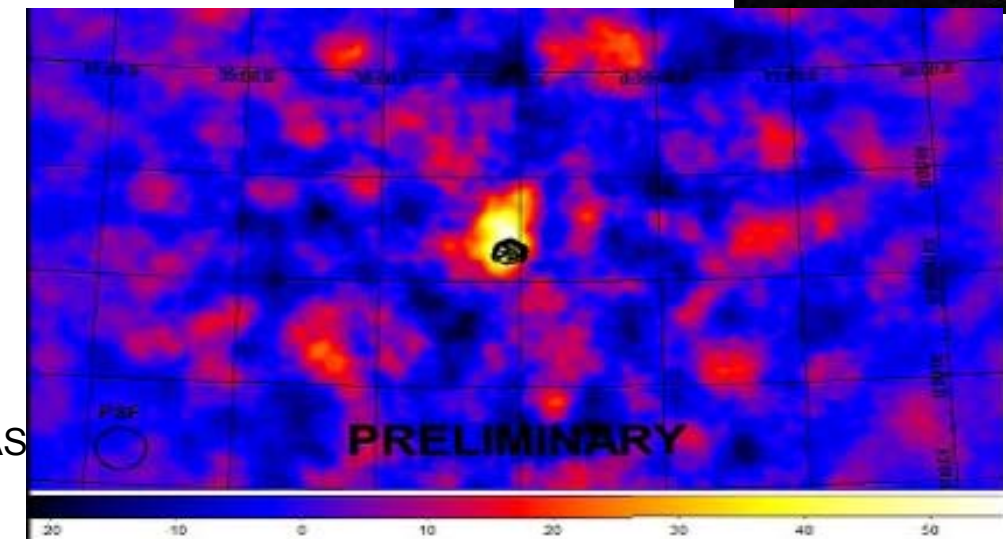




Galactic: Tycho (G120.1+1.4)

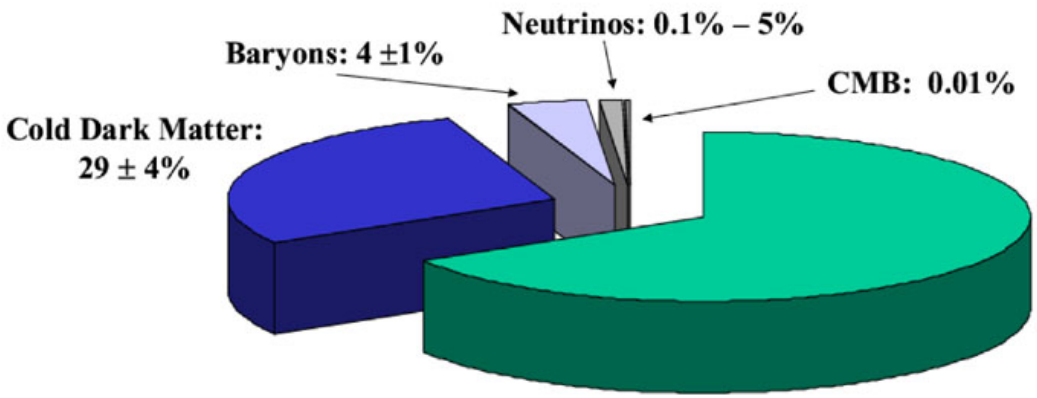


- supernova remnant discovered by Tycho Brahe (1572)
- X-rays (blue data) indicate electrons up to 10 TeV
- VERITAS: 67 hours of data (2008, 2010), 5σ, ~1% Crab
- Peak significance close to where molecular cloud is interacting with SNR



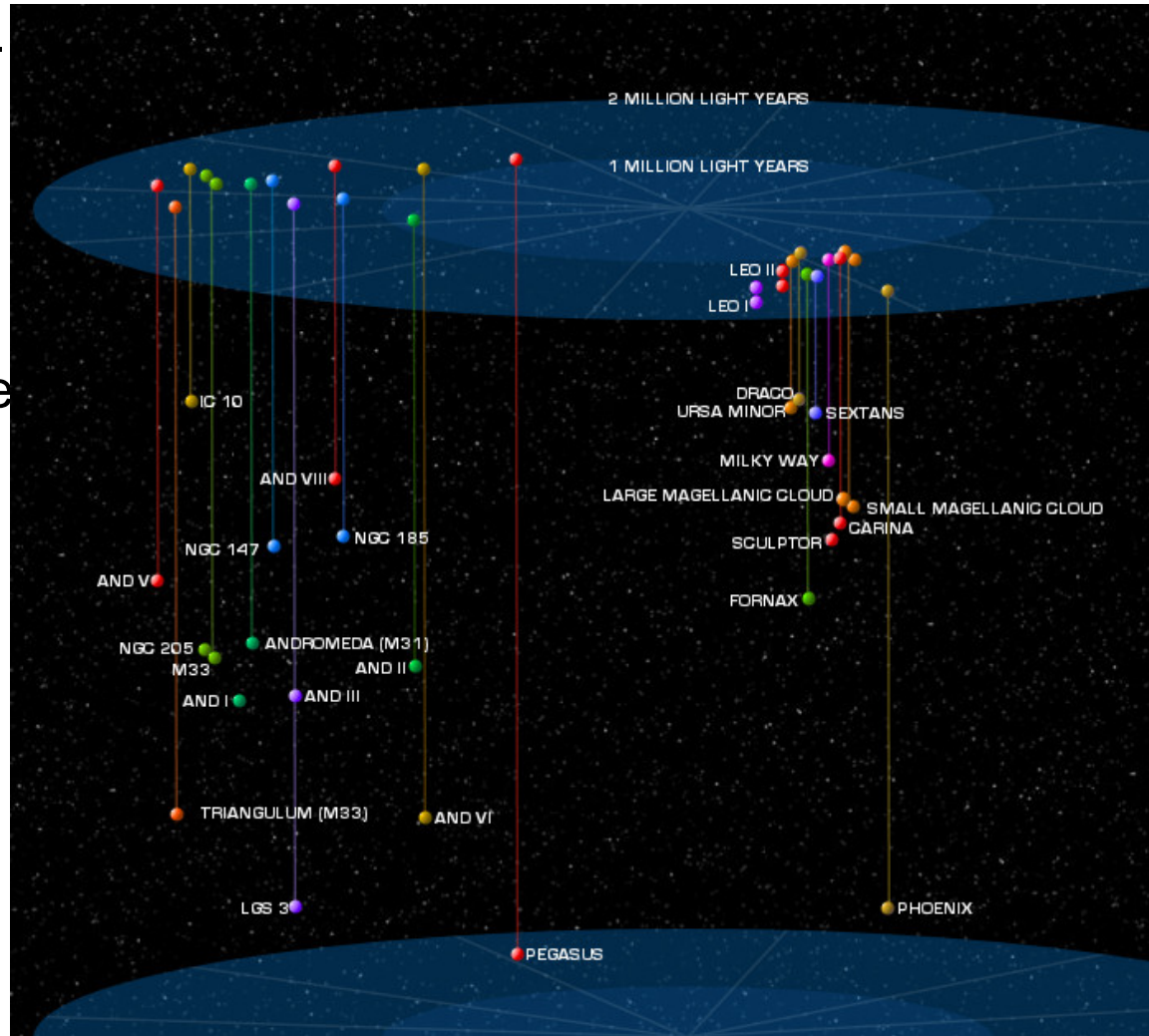
Astroparticle: Dark Matter Searches

- Dark matter ~25% of energy density of Universe
- Must be non-baryonic, cold, heavy, gravitationally bound
- WIMPs (eg. neutralino) in 50 GeV – 10 TeV range are well-motivated candidates
- Self-annihilation could lead to GeV/TeV gamma signal
- Cherenkov arrays well-suited for this search



Astroparticle: Dark Matter Searches

- Good targets are nearby galaxies with high mass-to-light ratios:
- Local group: M32, M23
- Dwarf Sphericals:Ursa Minor, Draco, Willman I, Bootes I, Coma Berenice
- Globular Clusters: M5



Astroparticle: Dark Matter Searches

- Dwarf Sphericals are probably best: high mass-to-light ratio (DM dominated), close-by

- Low astrophysical background

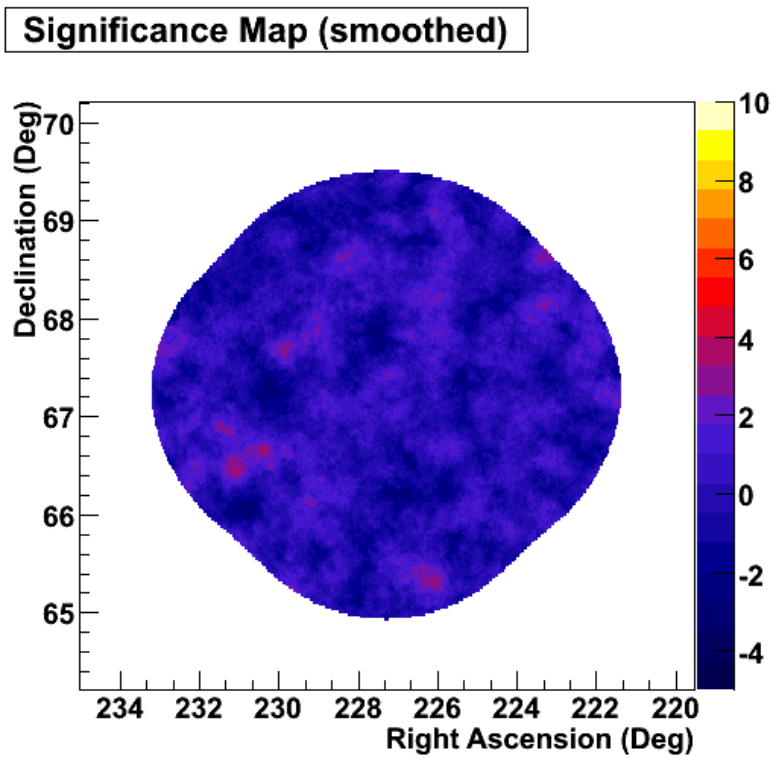
eg: Ursa Minor

~20 hrs data

No detection

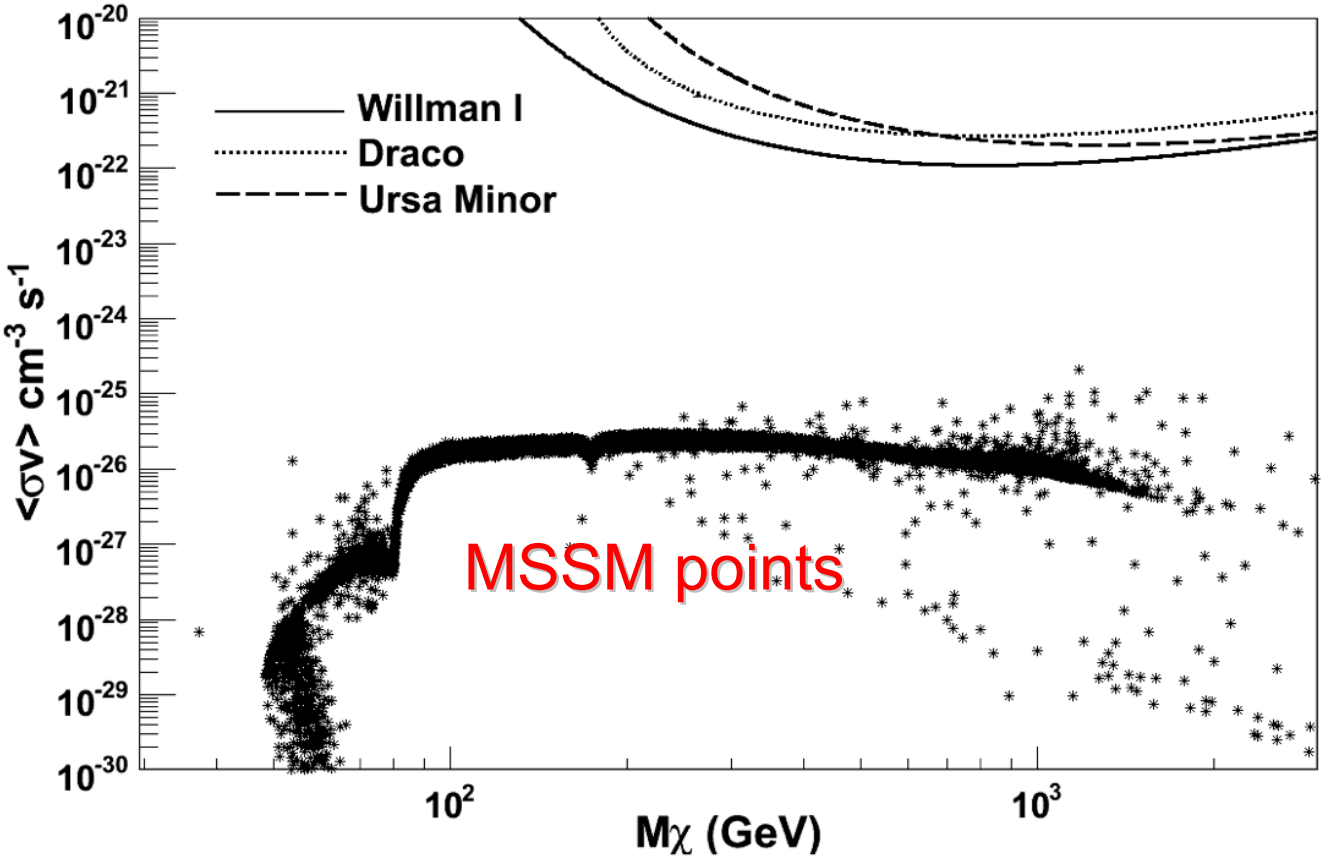
95% CL u.l. @ 1-2% Crab Nebula flux

ApJ 720, 1174 (2010)



Astroparticle: Dark Matter Searches

- Need significant astrophysical boost factor to constrain models

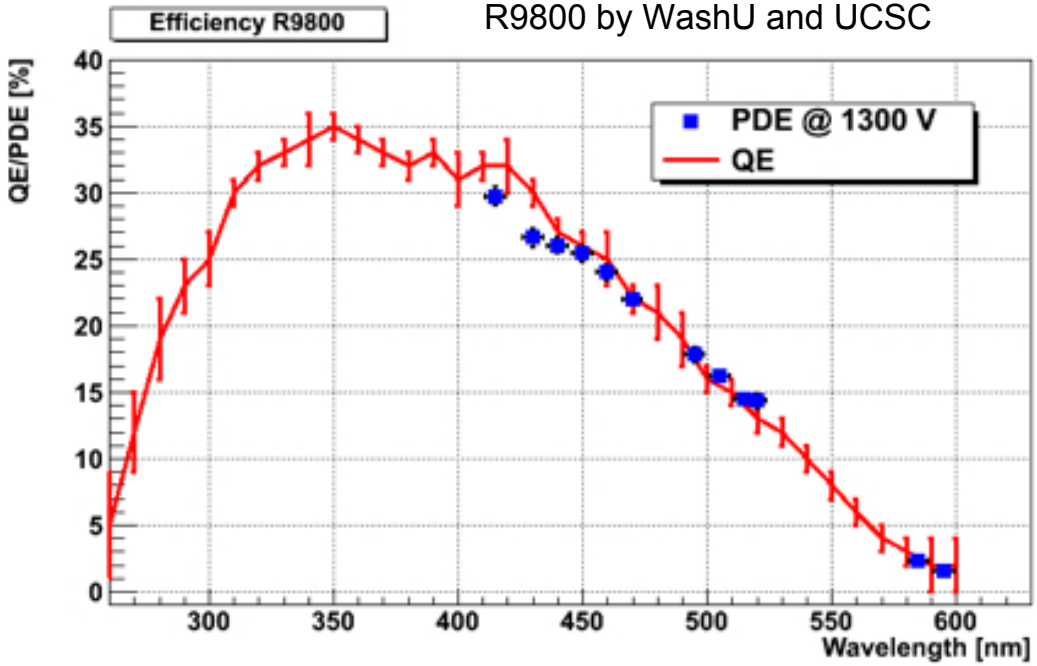


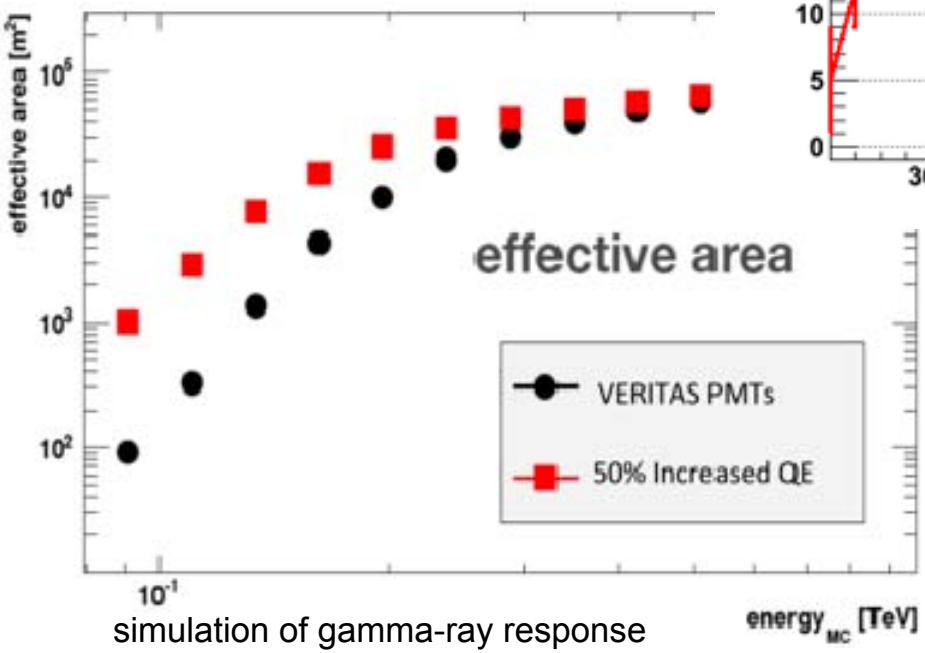
The future: VERITAS Upgrades

- PMT replacement with high efficiency PMTs (summer 2012, funded)
  - Super-bialkali: ~50% increase in QE over current tubes
  - lower energy threshold (trigger threshold from 120 → 80 GeV)
  - improved sensitivity
- FPGA-based Trigger upgrade (installed, now commissioning)
  - lower energy threshold and improved CR event rejection
- Improved atmospheric monitoring with LIDAR System (2011, funded)
- Drive update (study phase)
  - shorter response time to GRBs, etc.

VERITAS Upgrade

QE and PDE measurement of Hamamatsu R9800 by WashU and UCSC





simulation of gamma-ray response

Outlook

- Typical year is 800-1000 hours of observing
- First two years: Four Key Science Projects (50% of time)
  - Dark matter, AGN, SNR, Sky Survey
- Remainder of time: competitive observations (40%) decided by TAC (time allocation committee), and discretionary (10%)
- Now: observing by competitive proposals (TAC), typically oversubscribed by ~2x
- Upgrade will improve sensitivity; moonlight running will increase duty cycle
- Likely > 4-5 years of stable operation ahead of us

Conclusions

- Four-telescope VERITAS array is now in full operation
- Most sensitive Cherenkov array in the world
- A healthy observing program with many detections & discoveries: galactic, extragalactic, astroparticle, GRB
- Active collaboration with other VHE instruments, Fermi/LAT and instruments at other wavelengths
- Upgrade underway w/several years of stable operation following