TeV Gamma-Ray Astrophysics with VERITAS

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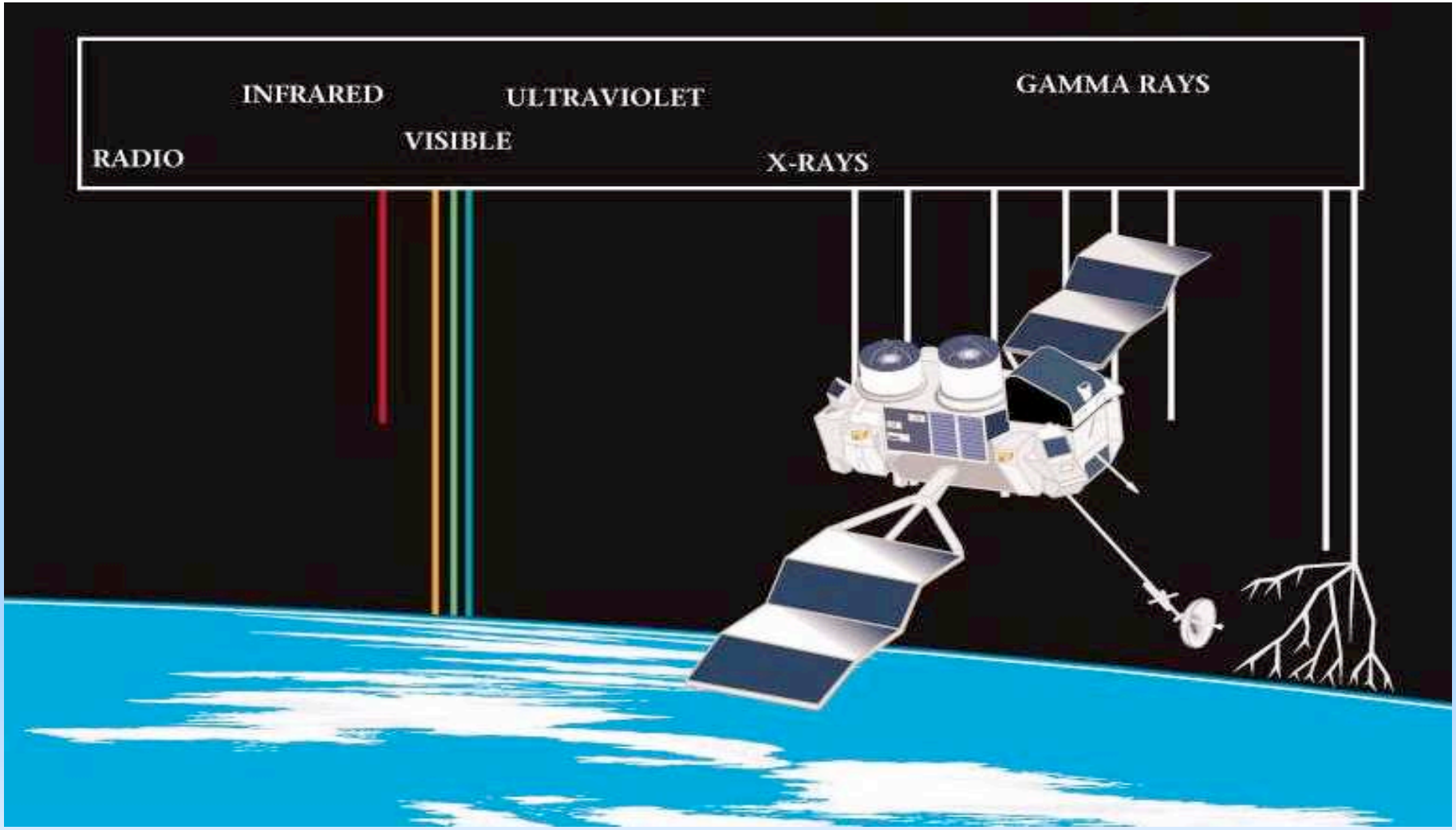
Overview

- Ground-based Gamma-ray astronomy
- VERITAS
- Status
  - Some Highlights
  - Auger Follow-up observations
- Future plans



radio	mm	IR	Visible	UV	X-rays →	Gamma-rays →				
$1x10^{-6}$	$1x10^{-3}$		1		$1x10^{3}$	$1x10^{6}$	$1x10^{9}$	$1x10^{12}$	$1x10^{15}$	E (eV)
1	$1x10^{-3}$		$1x10^{-6}$		$1x10^{-9}$	$1x10^{-12}$	$1x10^{-15}$	$1x10^{-18}$	$1x10^{-18}$	λ (m)
$2x10^{8}$	$2x10^{11}$		$2x10^{14}$		$2x10^{17}$	$2x10^{20}$	$2x10^{23}$	$2x10^{26}$	$1x10^{29}$	ν (Hz)

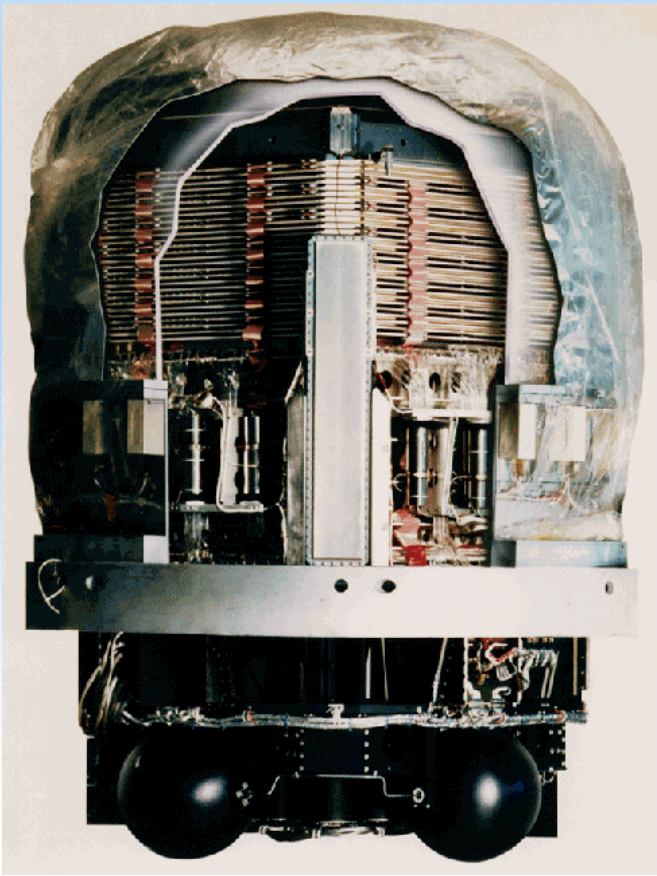
What are Gamma-Rays?

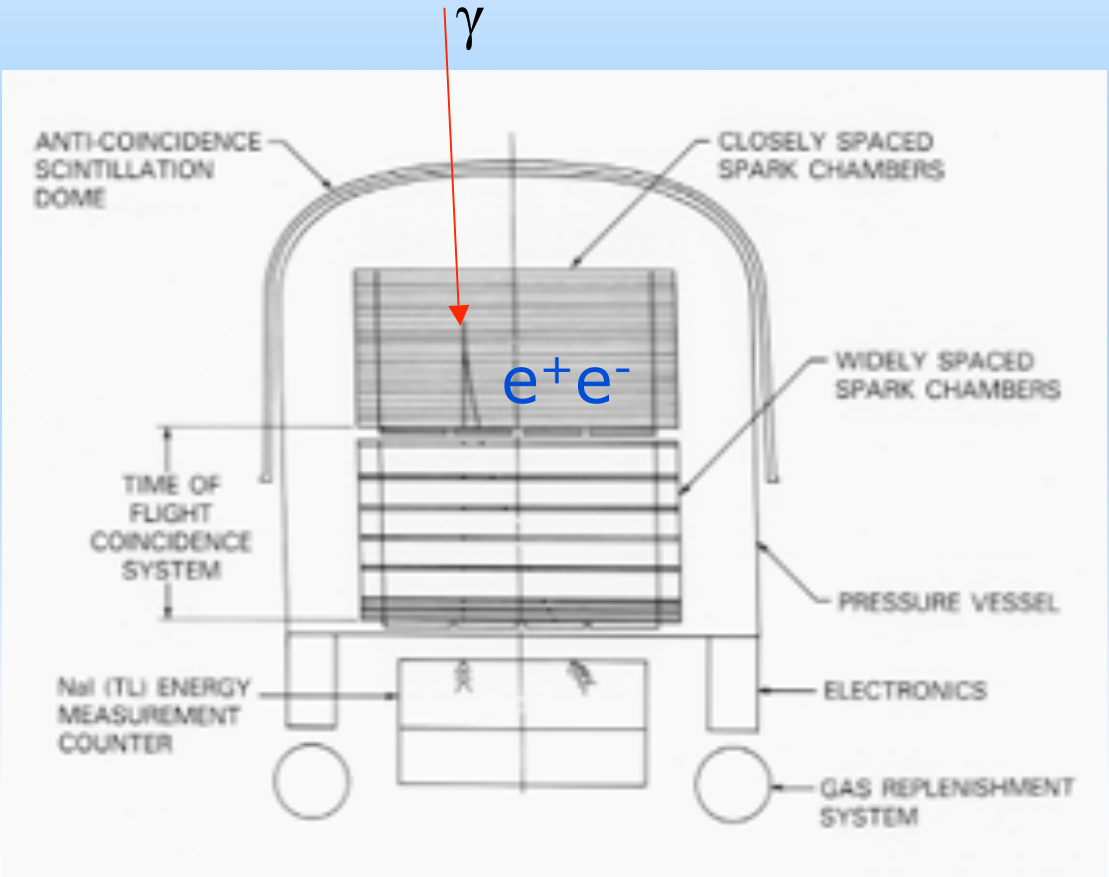
- Loose definition
  - Lower limit sometimes defined as >0.511 MeV
  - No upper limit!
  - <30 MeV =Low Energy Gamma rays
  - 30 MeV - 30 GeV = High Energy Gamma rays
  - 30 GeV - 30 TeV = Very High Energy Gamma Rays
  - 30 TeV - 30 PeV = Ultra High Energy Gamma Rays
  - >30 PeV = Extremely High Energy Gamma Rays

How do we detect them?

- The atmosphere is opaque to gamma-rays
- But they can be detected directly via $e^+ e^-$ pair production using satellite-borne particle trackers

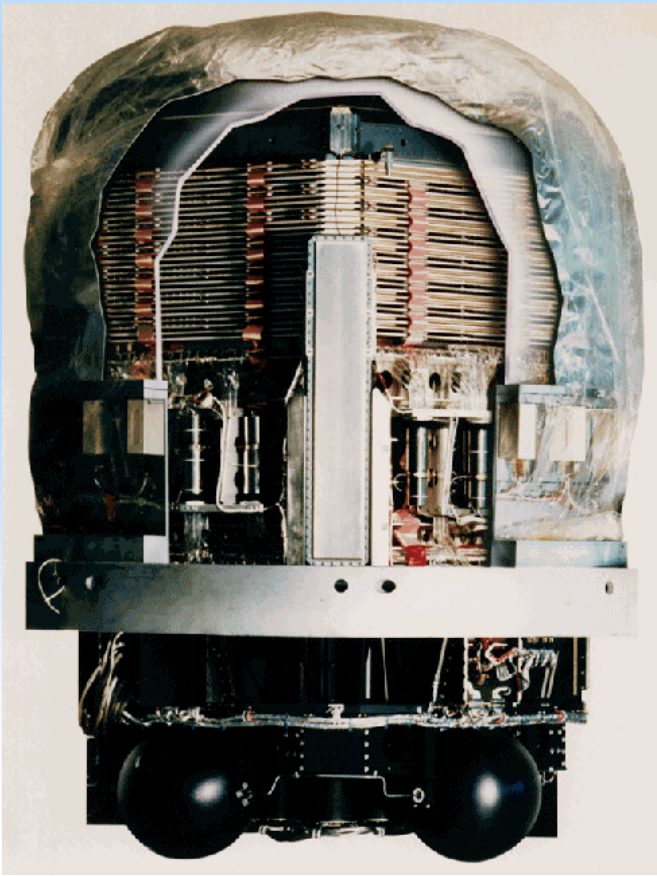
EGRET

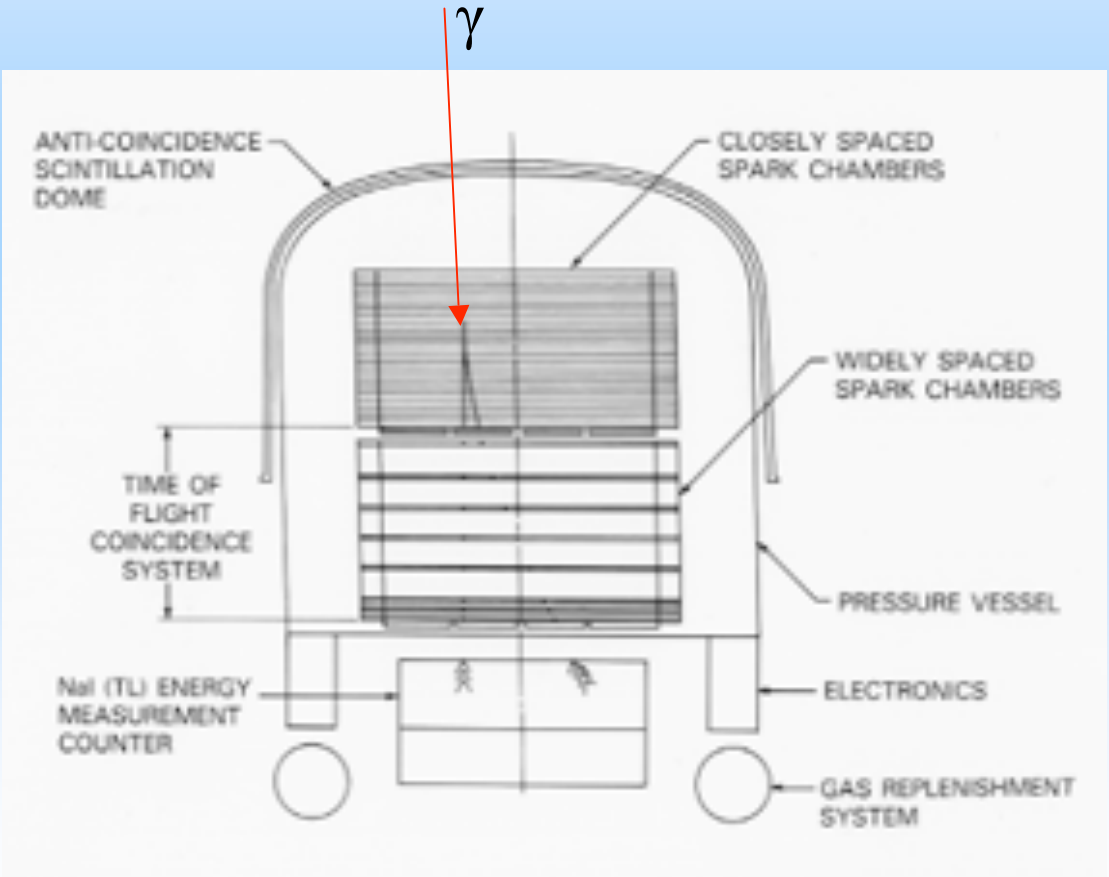




- This works well, but what about higher energies?
- Satellite effective area < $1m^2$
- e.g. Crab Nebula, Integral flux >1TeV = $6/m^2$/year
- Need to increase the effective area...

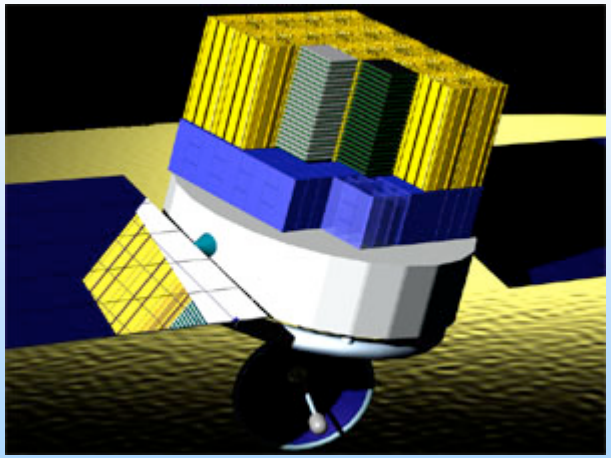
EGRET

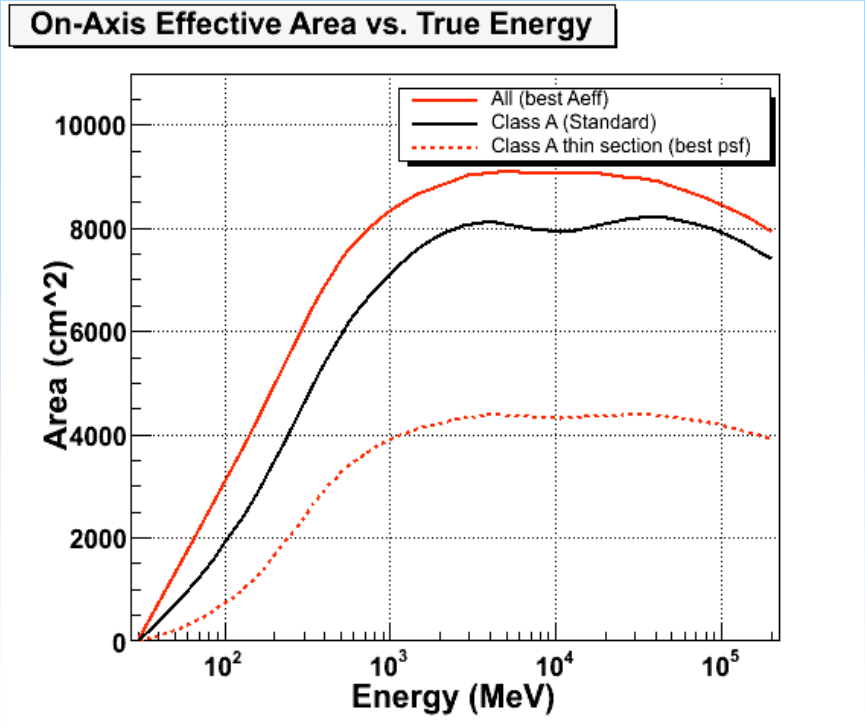


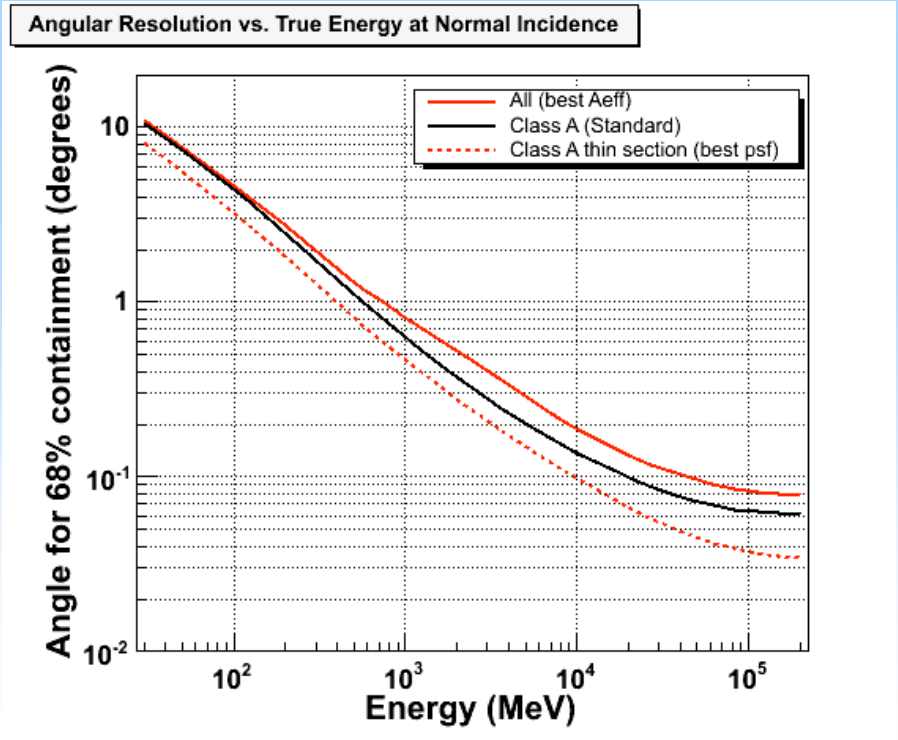


Build a bigger satellite?

- Satellites are heavy!
- Fermi launched in 2008
- But still not really big enough...
- Also - small detector means poor angular resolution



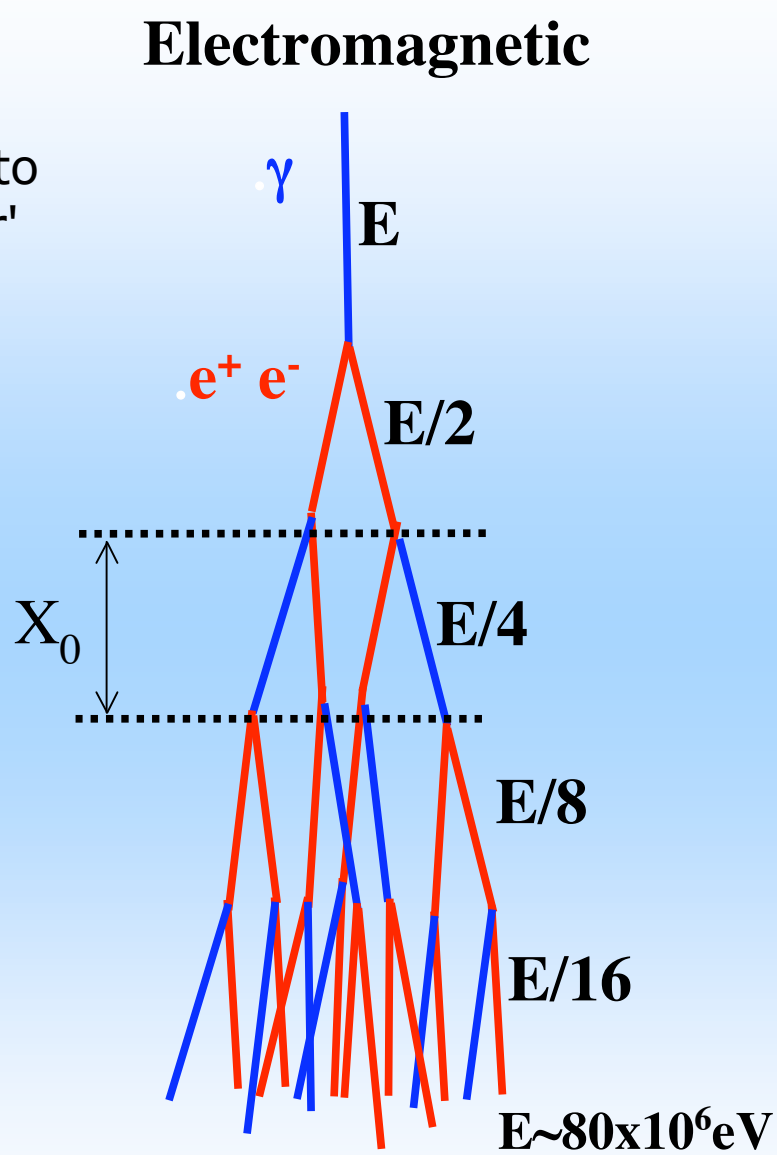




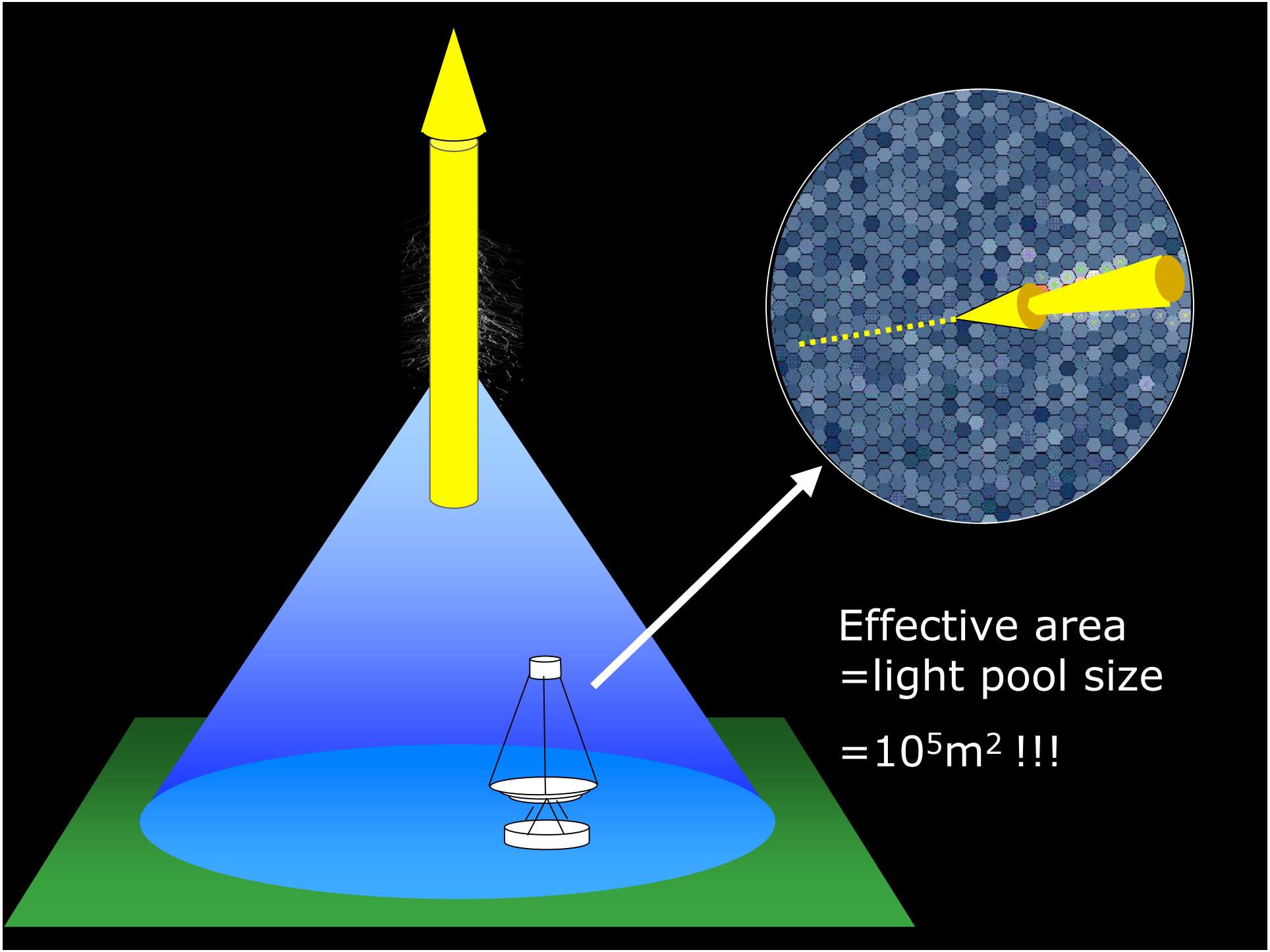
What happens when a very high energy gamma-ray enters the atmosphere?

- Pair production and Bremsstrahlung lead to an electromagnetic cascade or 'air shower'

Direct detection of particles is possible, but only at high energies and high altitude, with poor sampling



1 atmosphere ~ 28 X_0


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

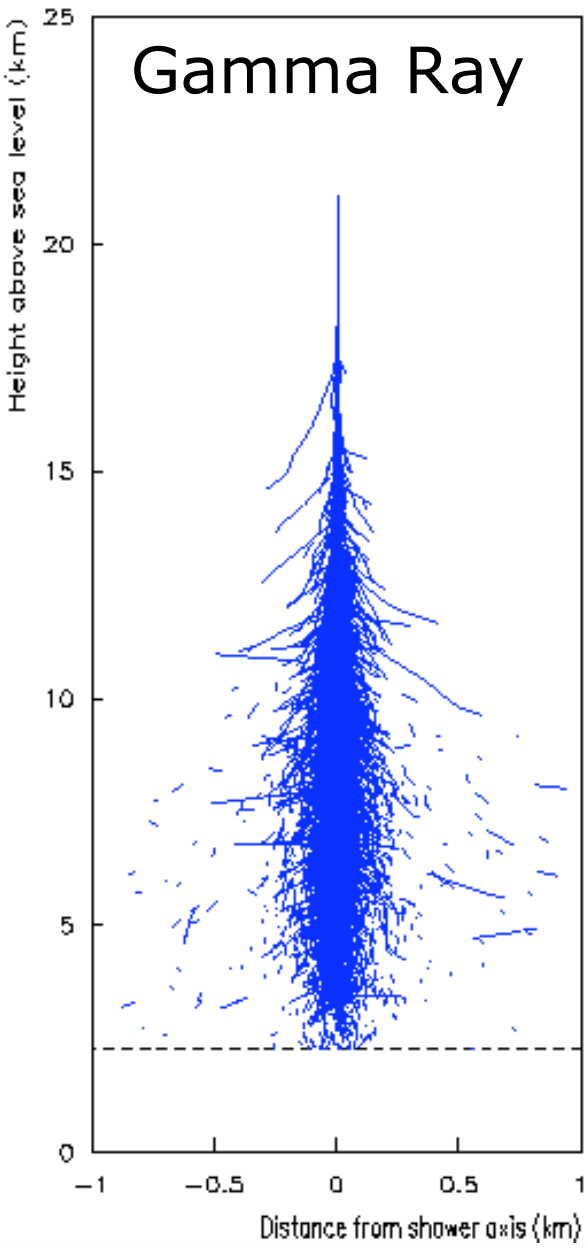
What is a Cherenkov Telescope?

The Jelley & Galbraith light bucket (1952)

Very simple device:

- Mirror
- Photon detector (PMT)
- Oscilloscope

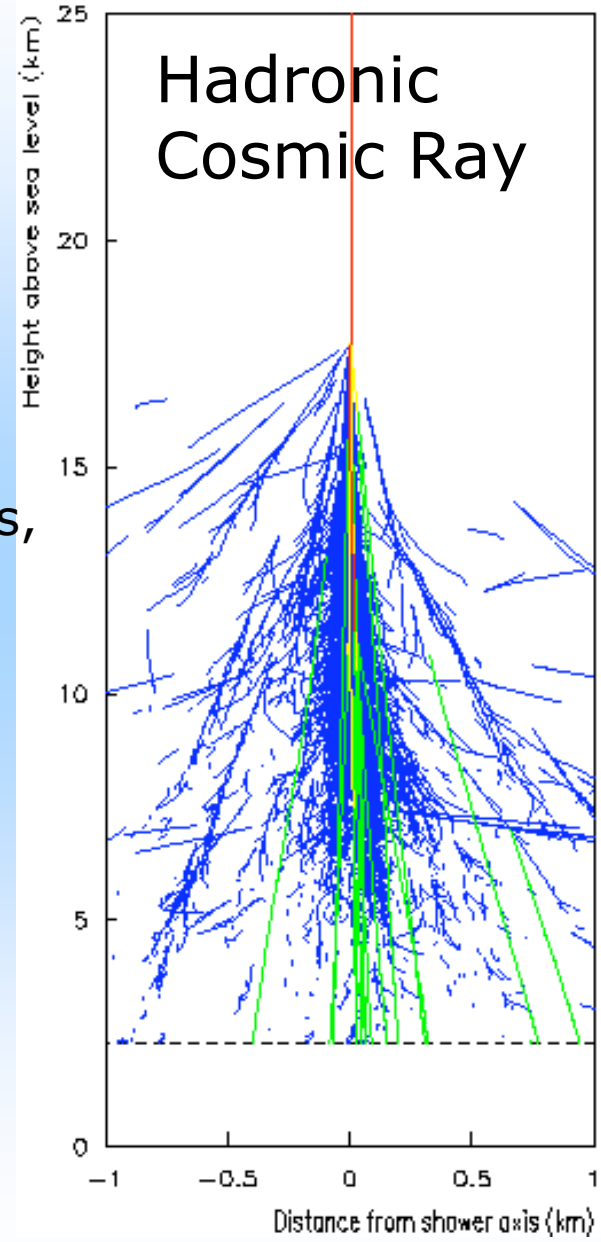
What about the background?



For each gamma shower , there are >1000 times as many hadronic cosmic ray showers.

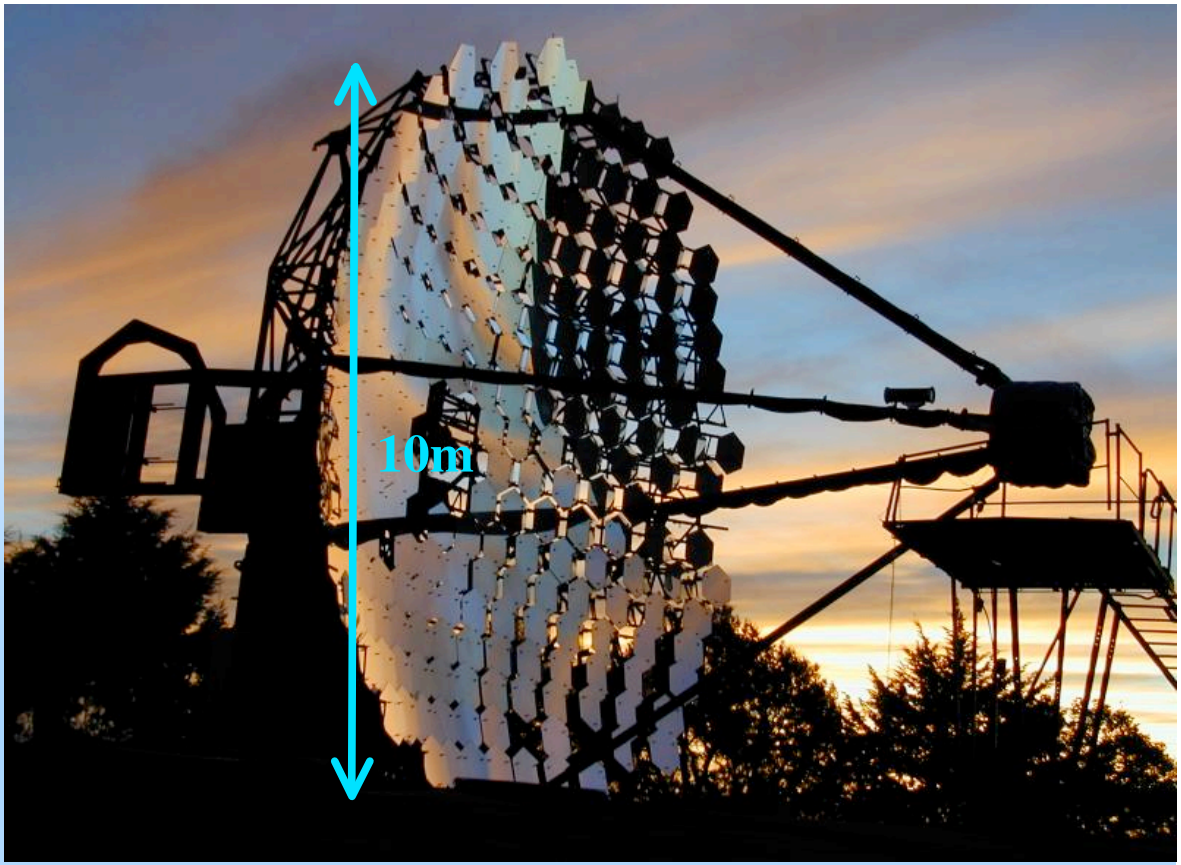
They are more ragged, and wider than gamma showers (transverse pion subshowers, penetrating muons)

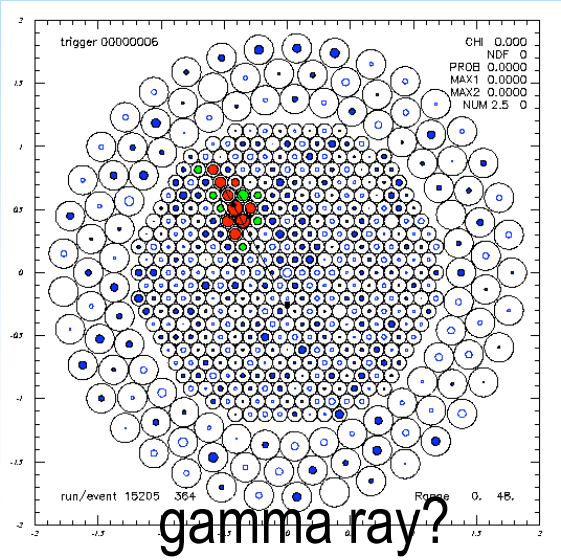
They are isotropic - their images do not point back to the source



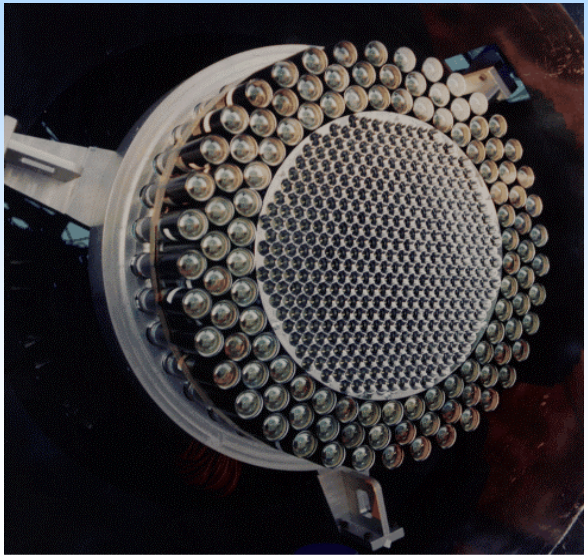
A More Advanced Cherenkov Telescope

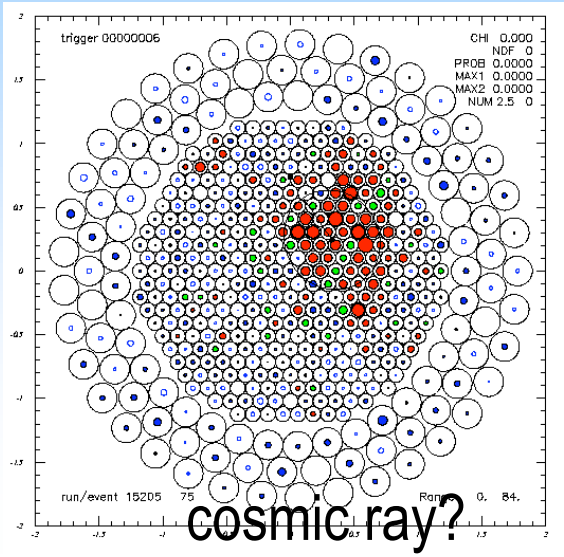
- The Whipple 10m (1968-)
- Added Tracking and an Imaging Camera
- Increased the mirror area to ~100m^2





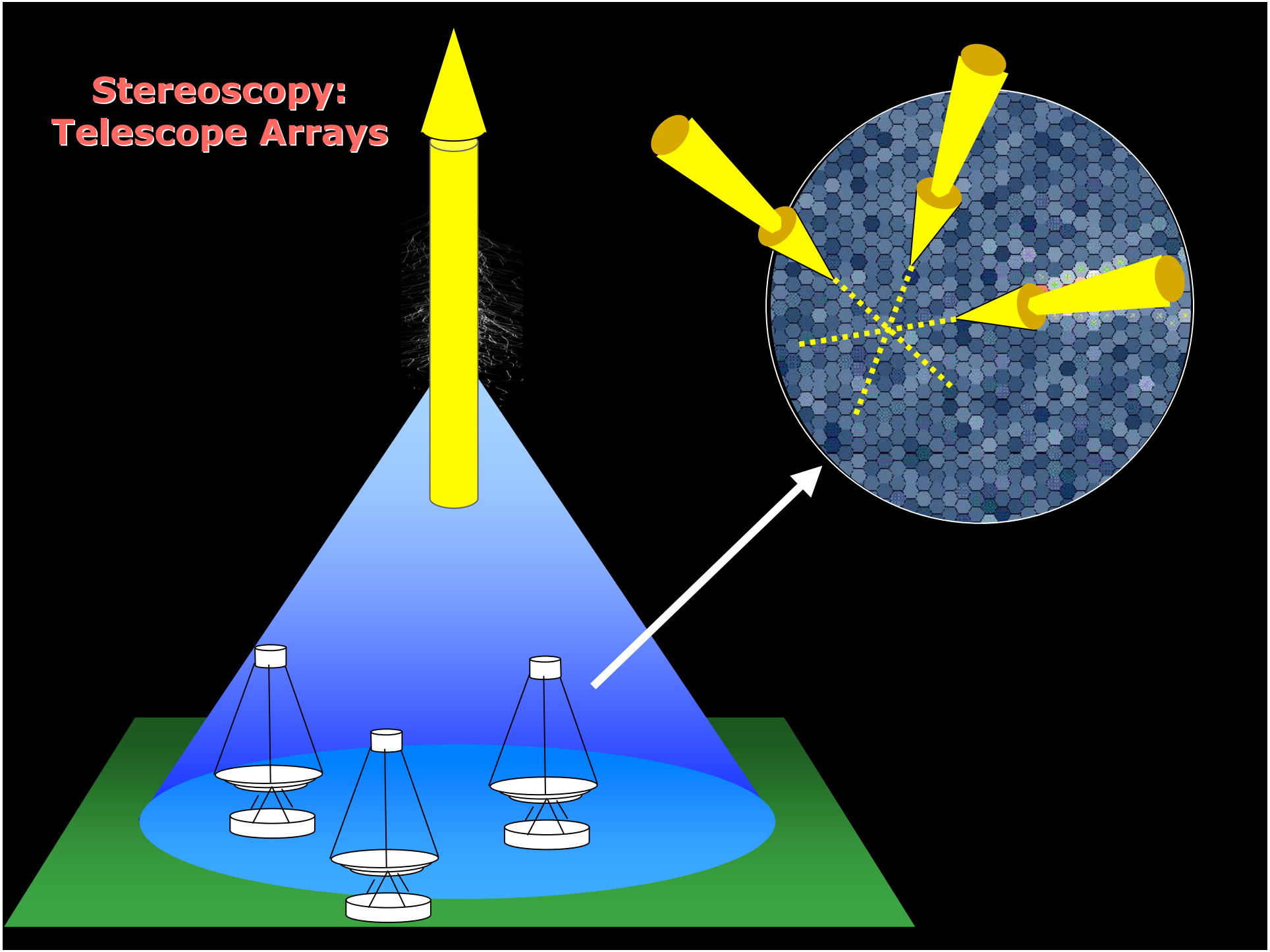
gamma ray?





cosmic ray?

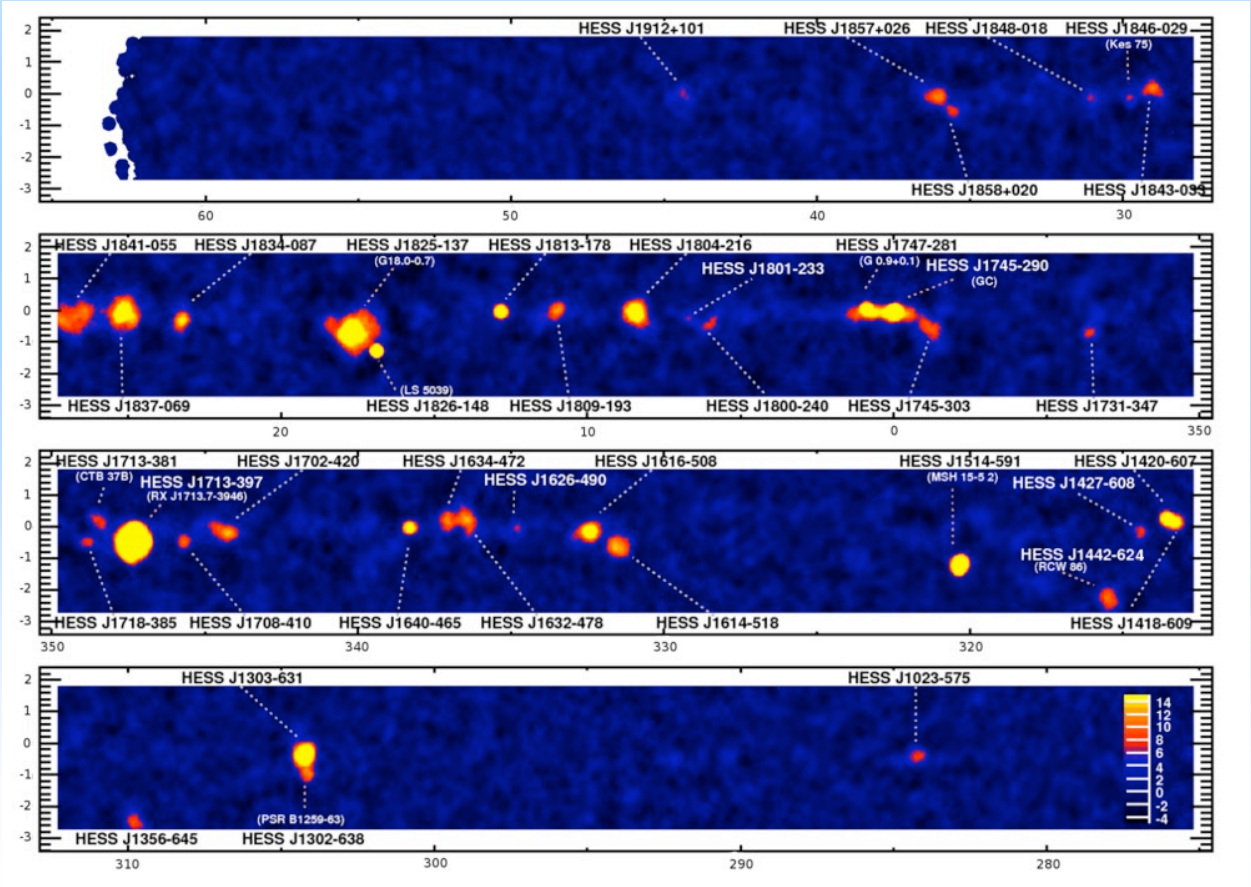
Stereoscopy: Telescope Arrays



VERITAS
MAGIC
H.E.S.S.
CANGAROO III

What is there to look at?

- Whipple detected the first source in 1989: Crab Nebula
- Also detected AGN, but still <10 sources
- New Arrays have seen >70 sources



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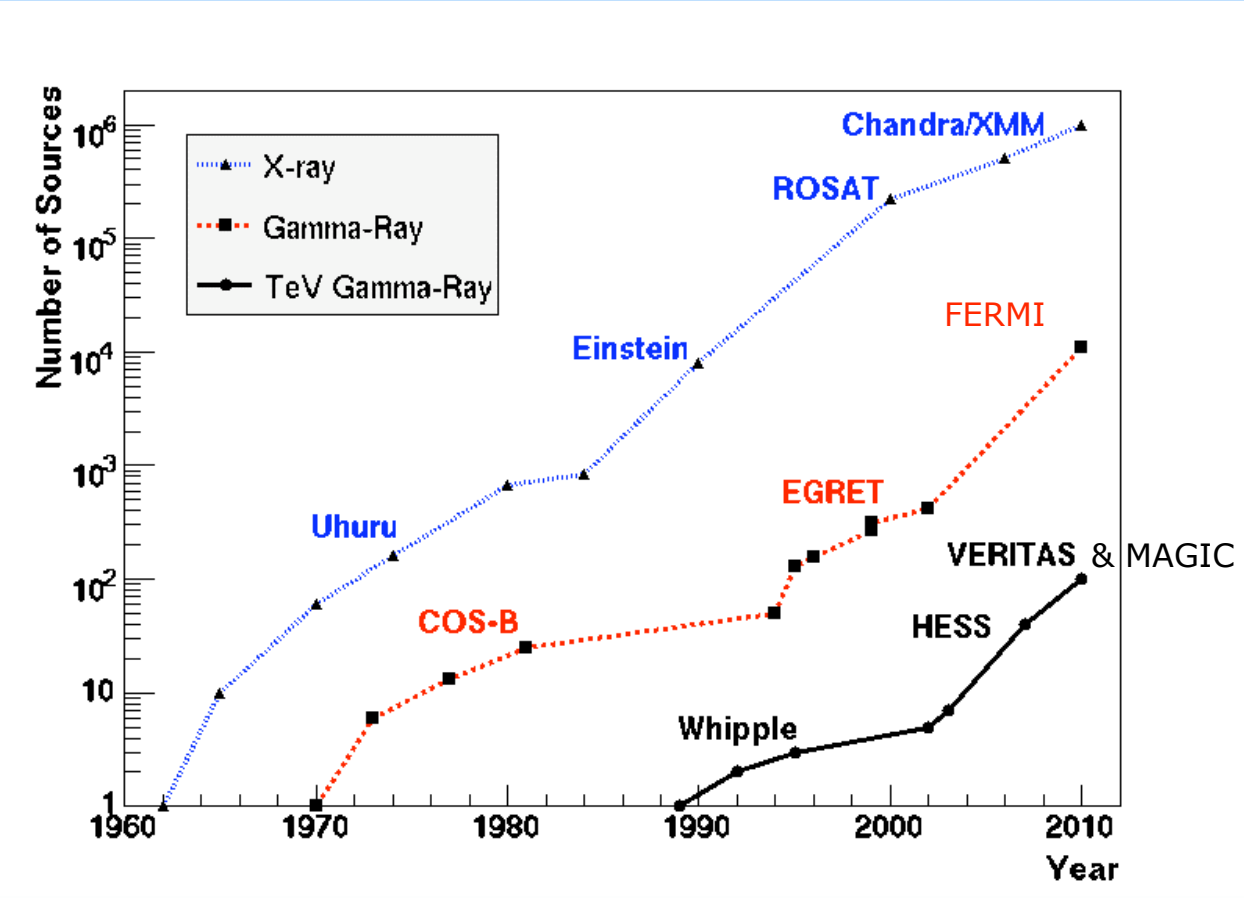
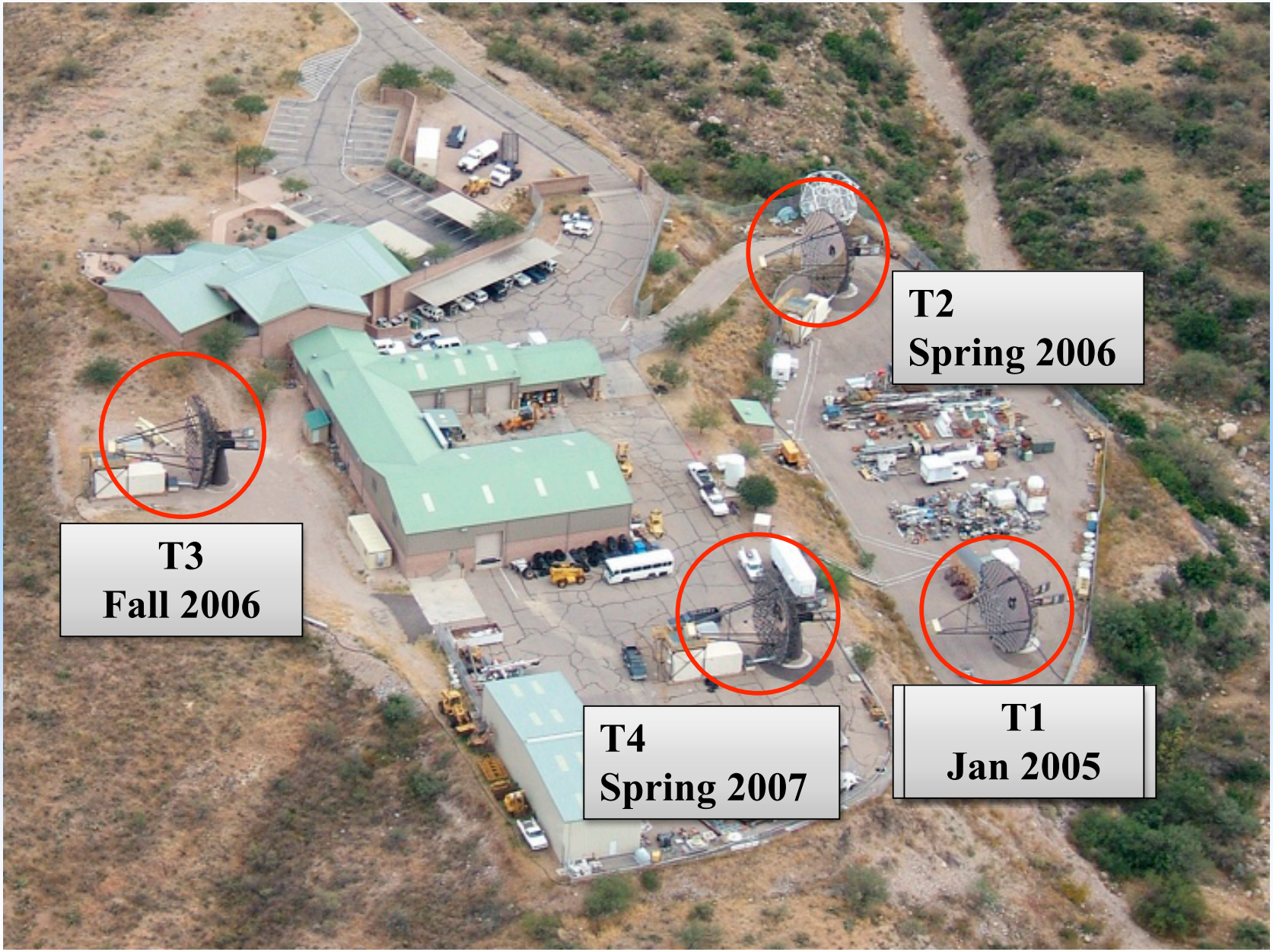


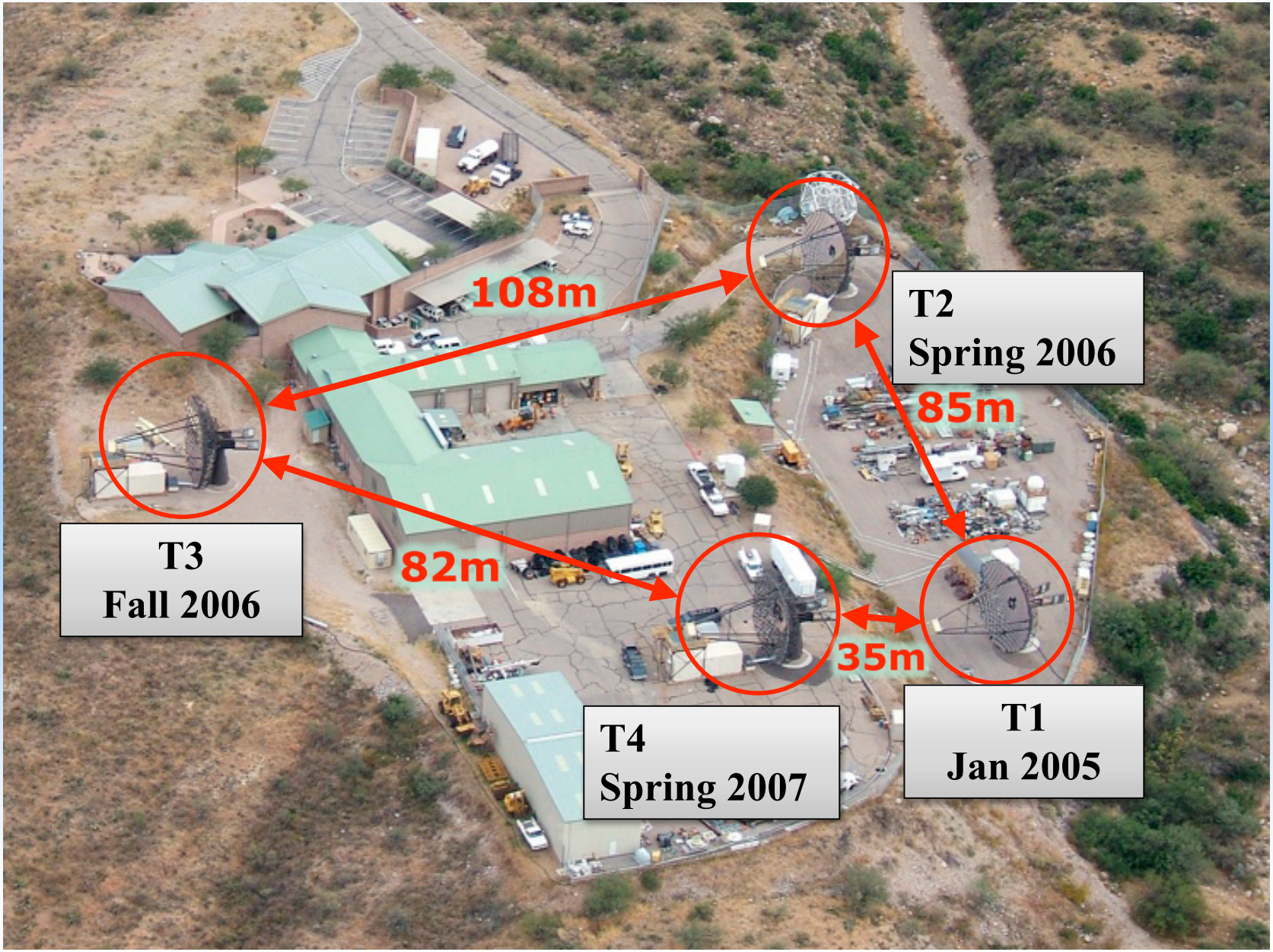
VERITAS Status: Complete!

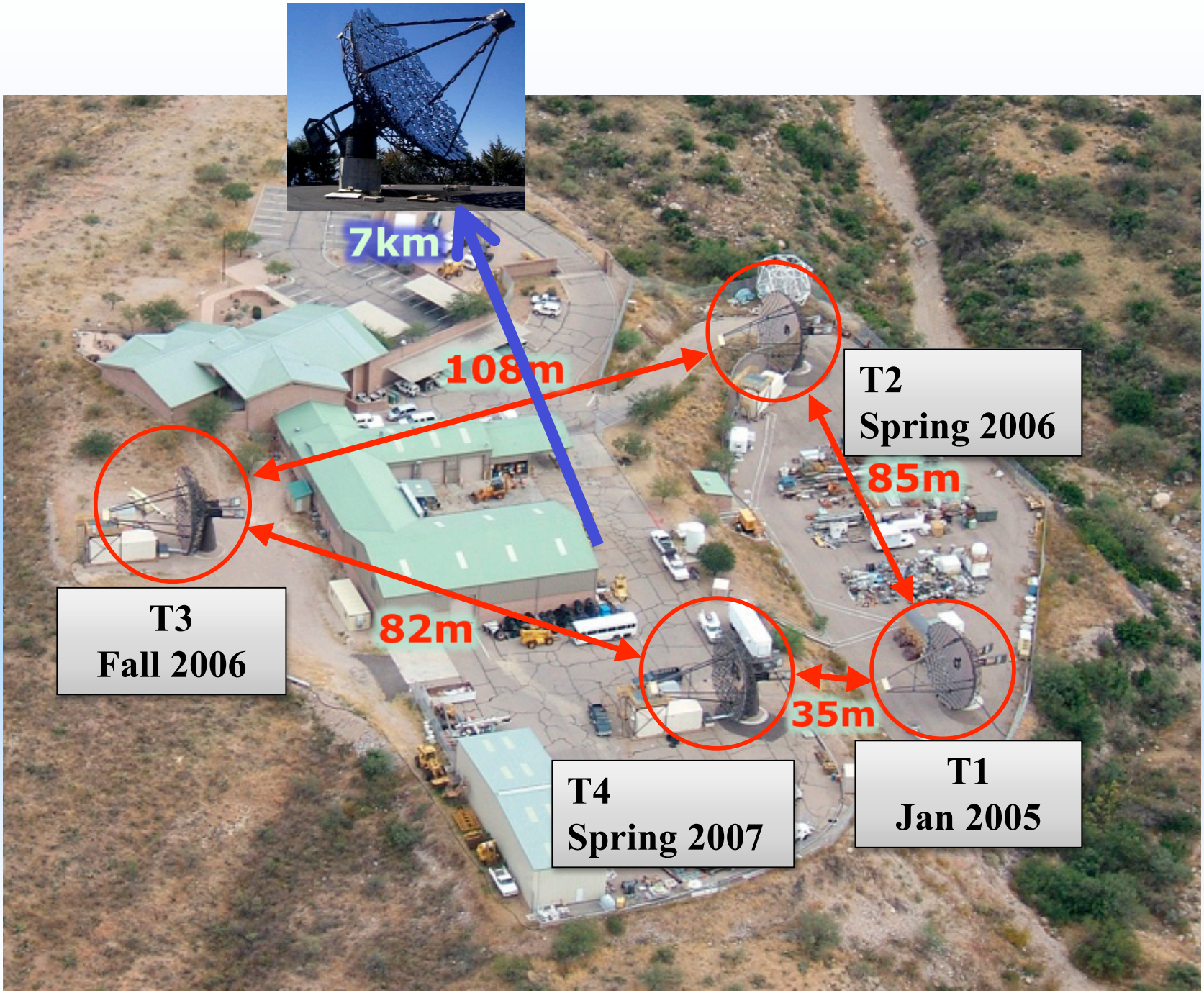
- Smithsonian Astrophysical Observatory
- Purdue University
- Iowa State University
- Washington University in St. Louis
- University of Chicago
- University of Utah
- University of California, Los Angeles
- McGill University, Montreal
- University College Dublin
- University of Leeds
- Adler Planetarium
- Argonne National Laboratory
- Barnard College
- DePauw University
- Bartol Research Institute/ University of Delaware
- Grinnell College
- University of California, Santa Cruz
- University of Iowa
- University of Massachusetts
- Cork Institute of Technology
- Galway Mayo Institute of Technology
- National University of Ireland Galway

- ~25 Associate Members

Construction Timeline




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


7km
108m
T2
Spring 2006
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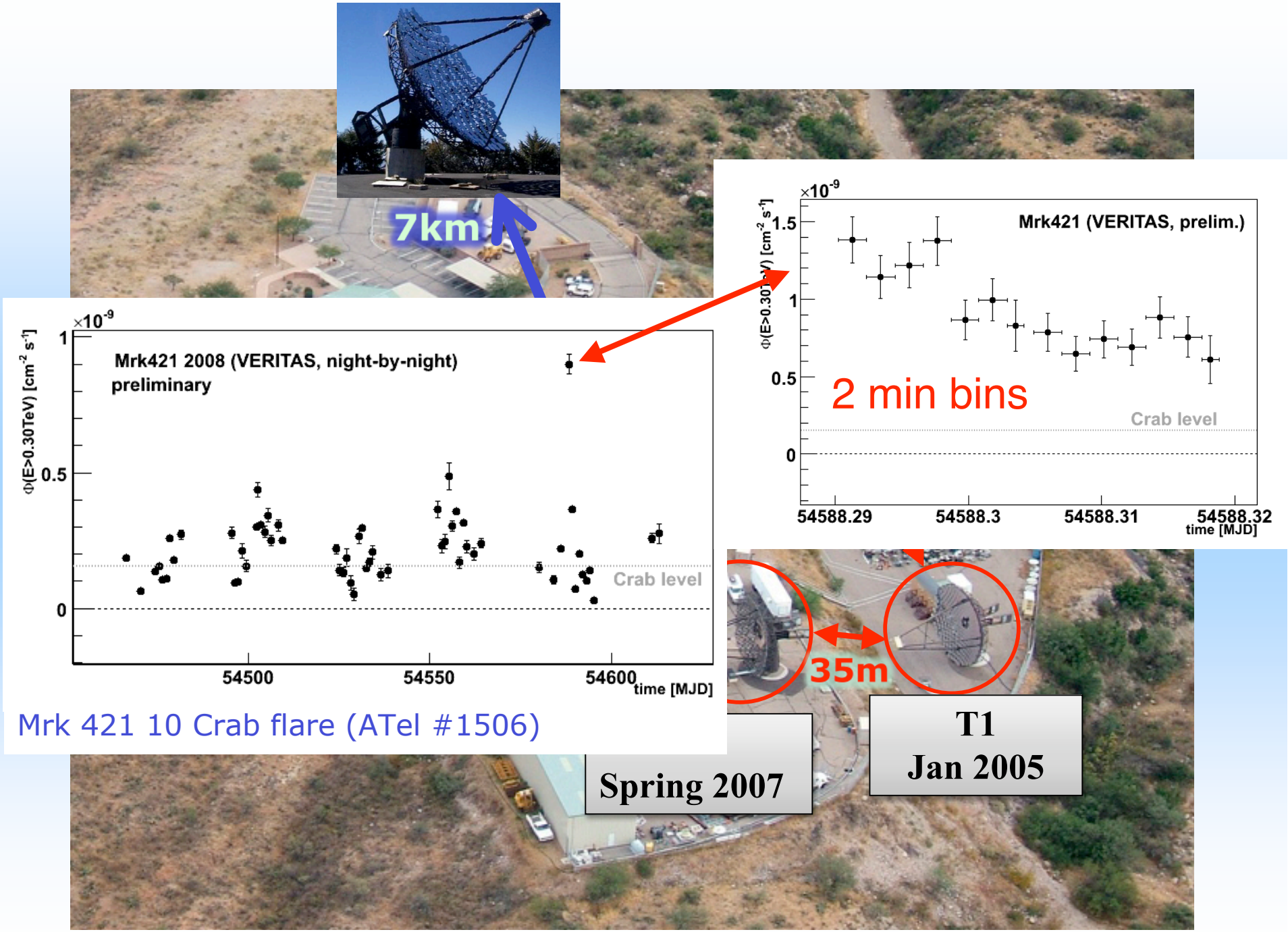
T3
Fall 2006
82m
35m
T4
Spring 2007
T1
Jan 2005

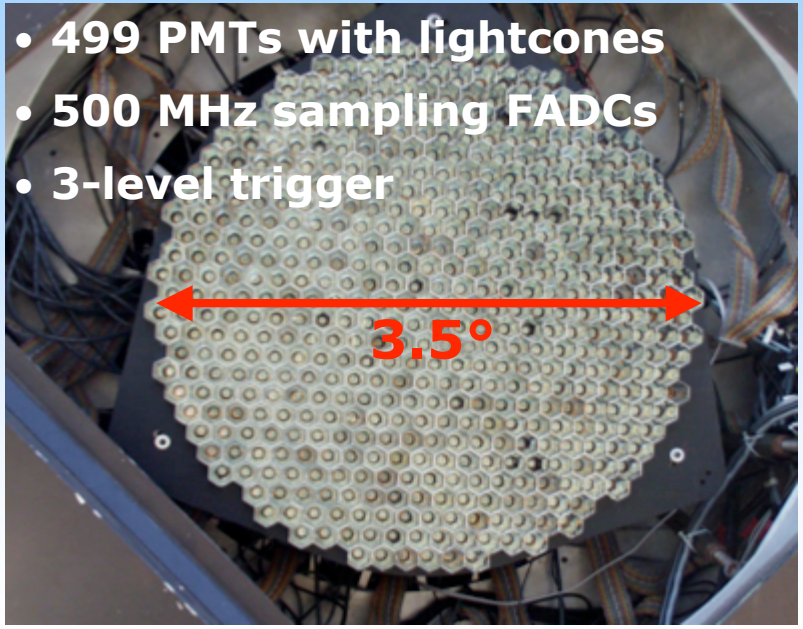


Mrk 421 10 Crab flare (ATel #1506)

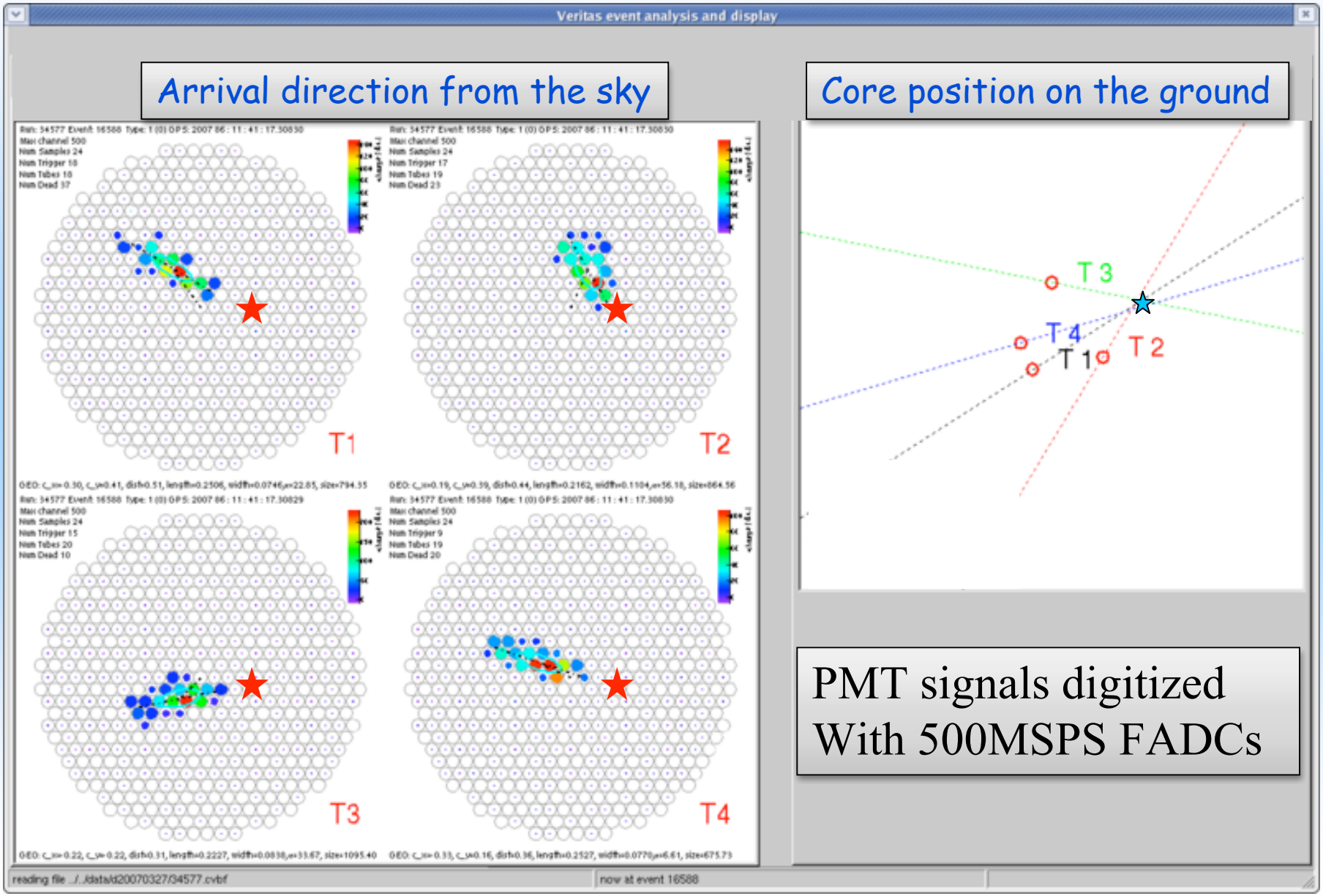
VERITAS

• Situated at 1250m altitude at the Whipple Observatory near Tucson

• 111m² tessellated mirror
• Recoated every ~2 years
12m

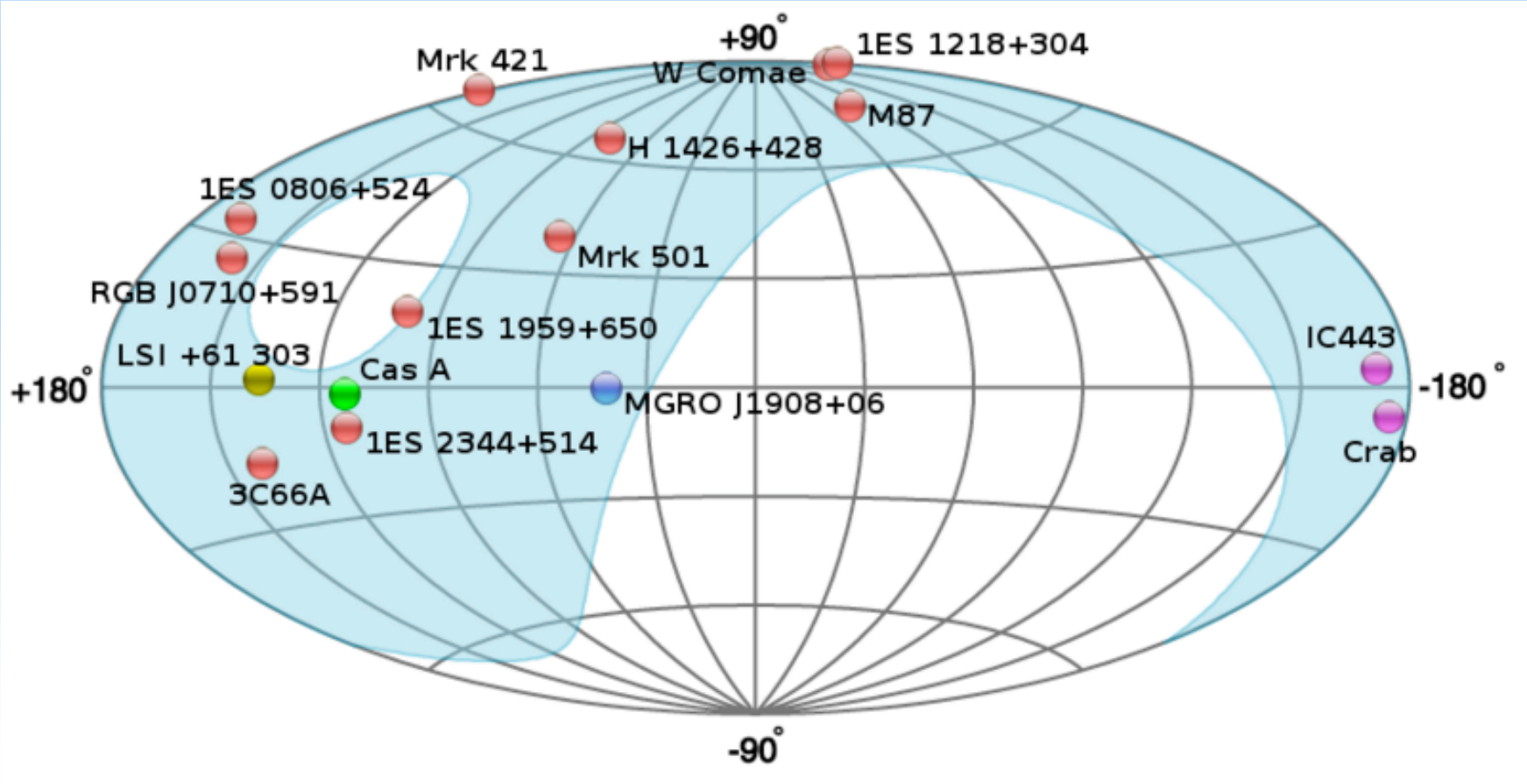

• 499 PMTs with lightcones
• 500 MHz sampling FADCs
• 3-level trigger
3.5°

Data


Veritas event analysis and display
Arrival direction from the sky
Core position on the ground
T1
T2
T3
T4
T 3
T 4
T 1
T 2
PMT signals digitized
With 500MSPS FADCs

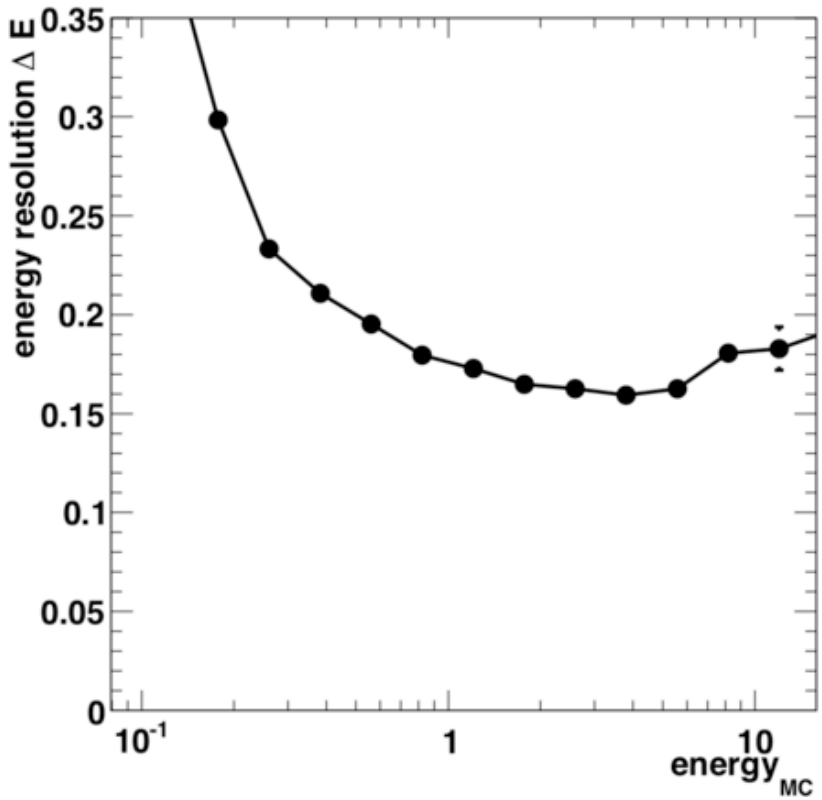
VERITAS Source Catalogue

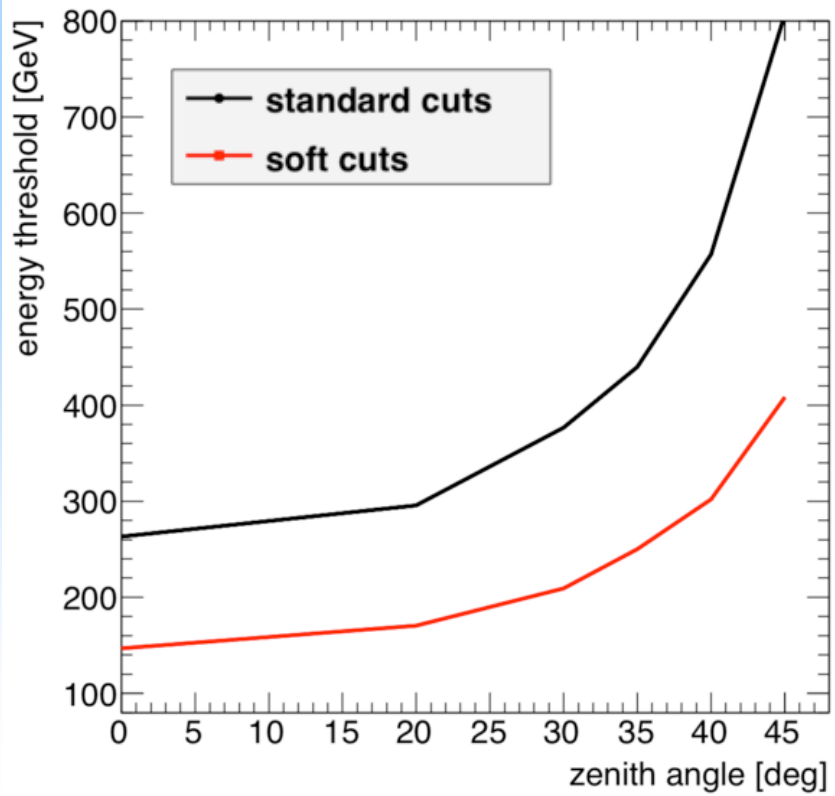
- 2007-8: 707 hours under clear skies, plus 89 hours moonlight
- 2008-9: 548 hours under clear skies, plus 132 hours moonlight (so far)
- >95% Taken with all four telescopes operating.
- 16 detected and published sources – more on the way!
- Many upper limits, published and in prep.



VERITAS Technical Performance

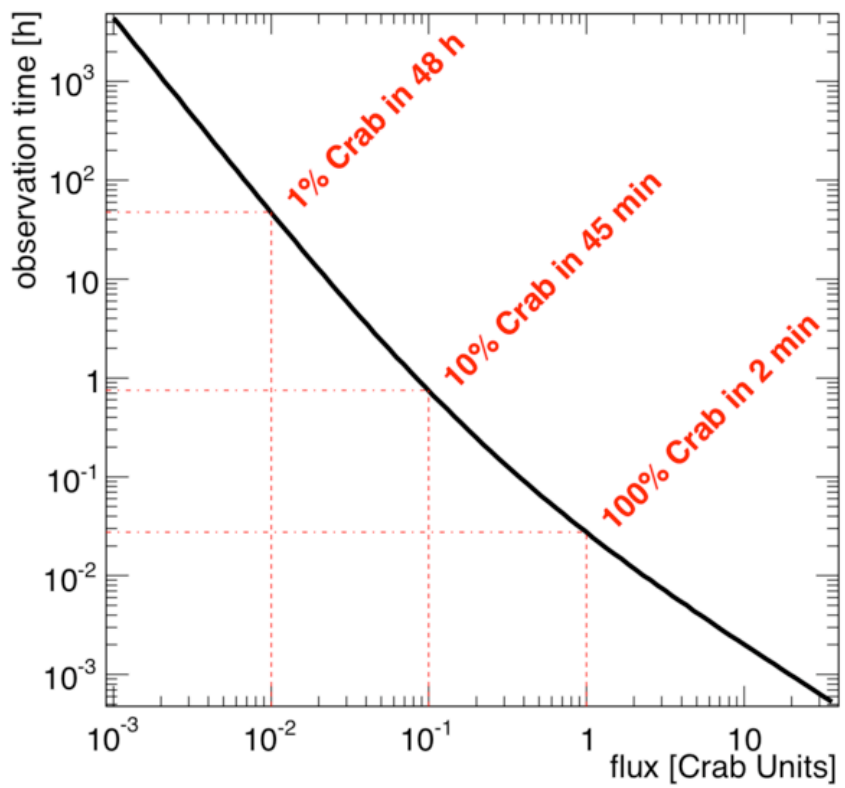
- Energy resolution ~15-20% >300GeV
- Energy threshold ~150 GeV with 'soft' cuts

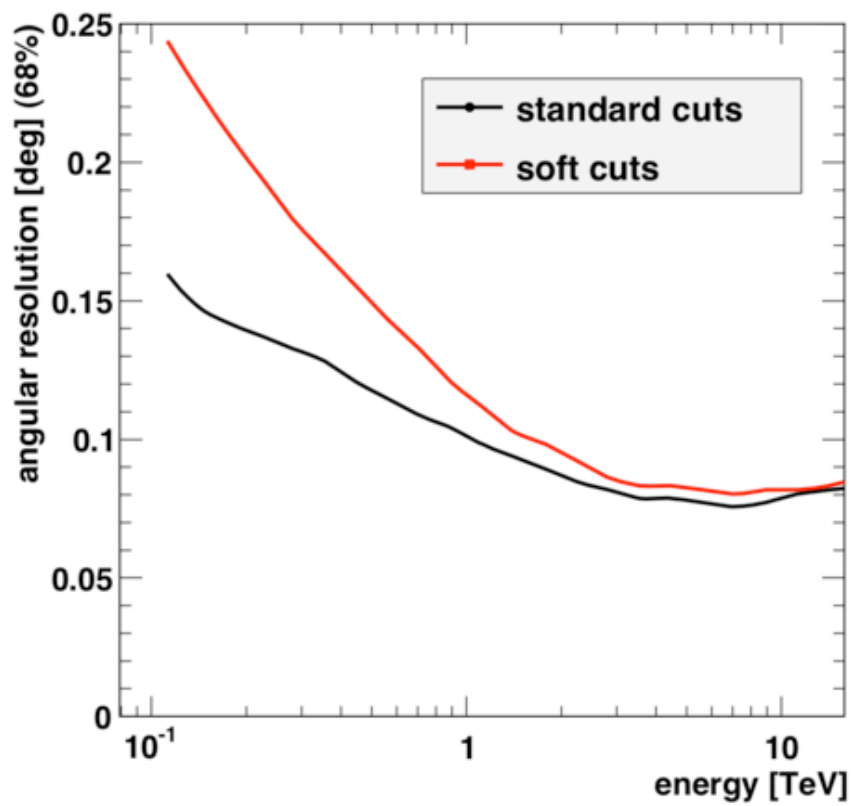




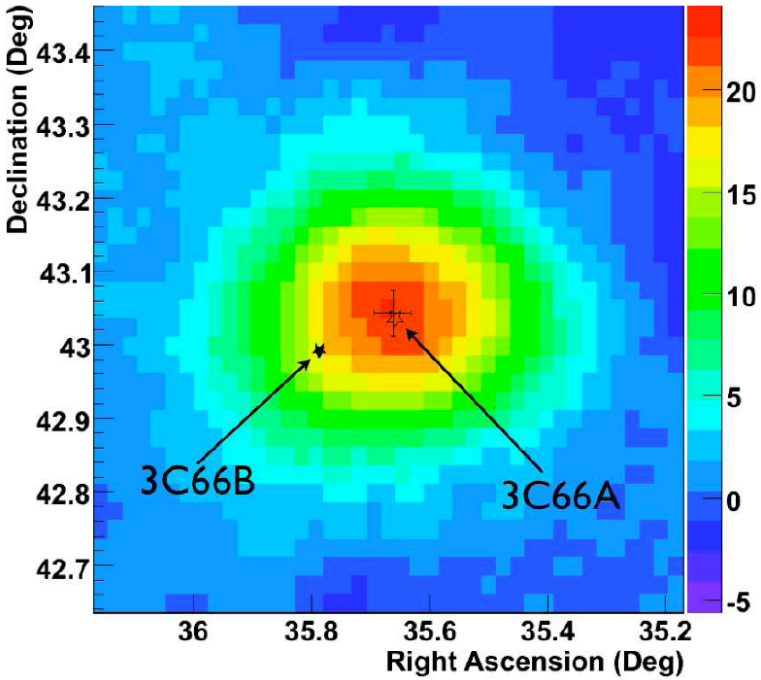
VERITAS Technical Performance

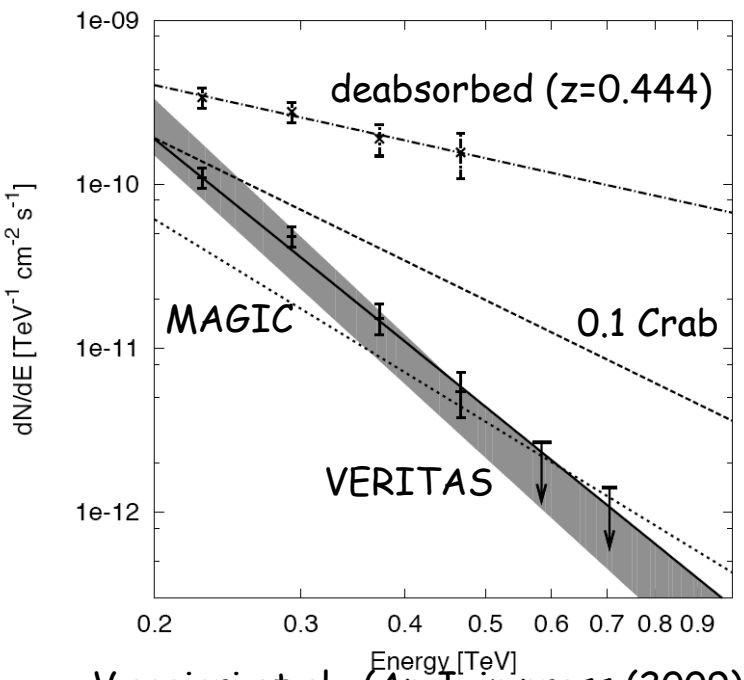
- Conservative sensitivity of 1% Crab in <50 hours
- MAGIC ~1.6% Crab in 50 hours,
- H.E.S.S., originally 1% Crab in 25 hours, currently significantly degraded due to poor mirror reflectivity
- Angular resolution ~0.1° (68% containment)





Angular resolution is important! resolving 3C66A/B



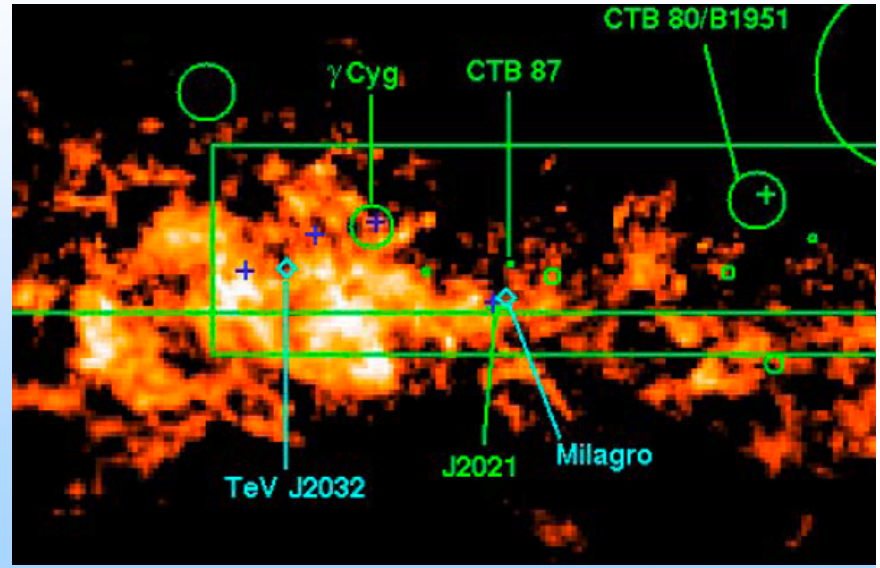


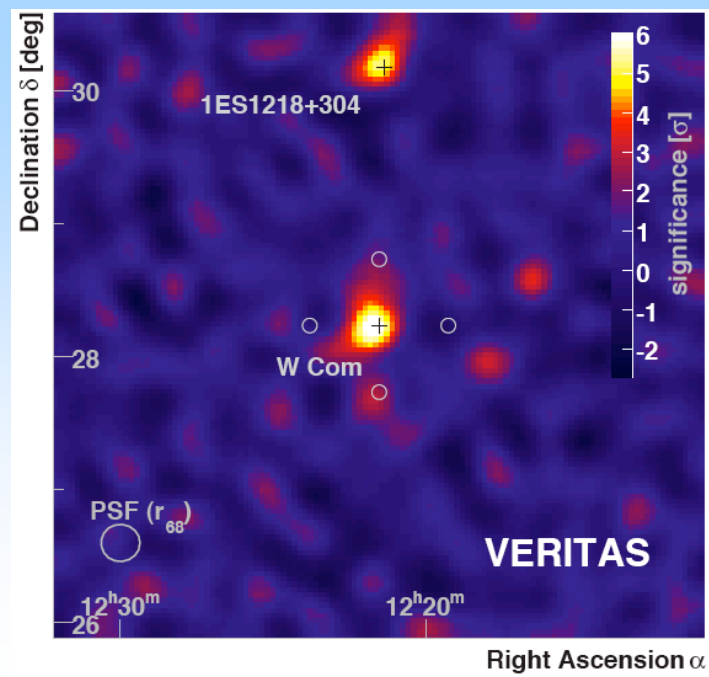
V.acciari et al. (Ap.J. in press (2009))

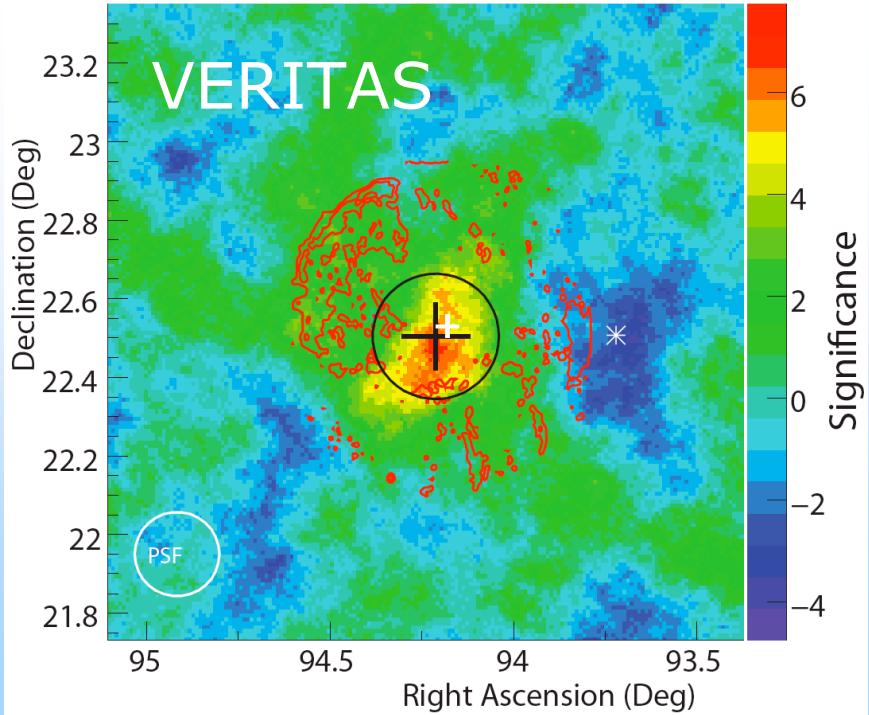
- 3C66A (IBL) / 3C66B (Radio Galaxy)
- MAGIC 5.4σ, 54 hrs in 2007
  - 2.7% Crab, $\Gamma=3.1\pm0.3$
  - Favour 3C66B (85% Confidence)
- VERITAS 21σ, 33 hrs mostly in 2008
  - variable, average ~6% Crab
  - $\Gamma=4.1\pm0.4_{stat}\pm0.6_{syst}$
  - Favour point source at 3C66A (4.3σ)
- No evidence of γ-rays from 3C66B (extrapolating MAGIC flux would expect 700 at 3C66B, see 300, consistent with spillover)
- Either 3C66A all along, or both are variable, and varied in opposite directions.
- Redshift of 3C66A very uncertain (z=0.444 based on one line)

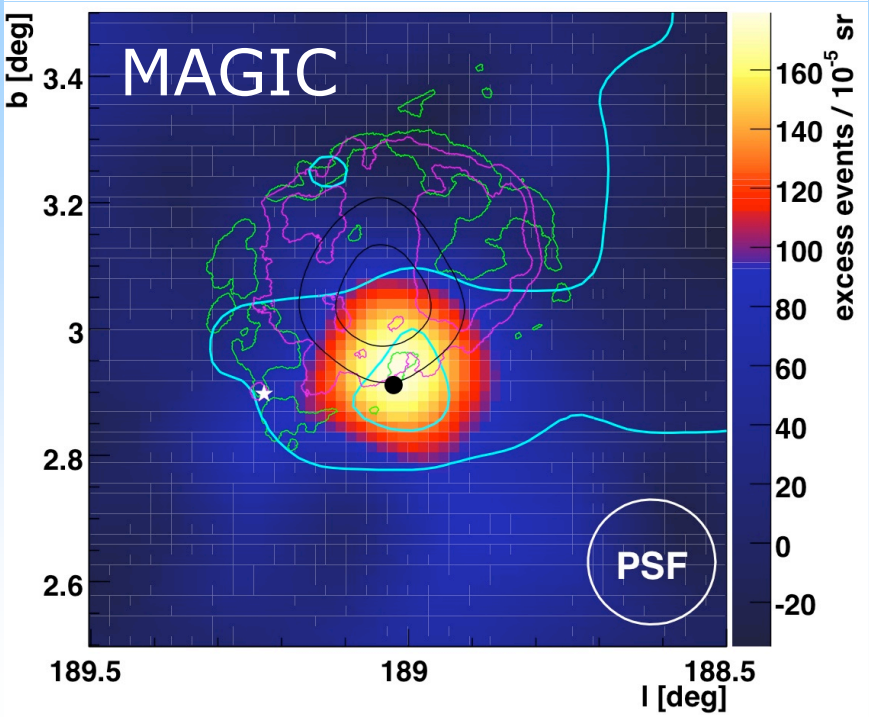
Some Other Key VERITAS Achievements

- 4 new detections: 1ES0806+524, RGB J0710+591, WComae, 3C66A
- Extended extragalactic TeV source classes (both WComae and 3C66A are *IBLs*)
- Ongoing contributions to *EBL density* studies (with 1ES1218+304)
- Unparalleled morphological and spectral studies of *IC443*, *Cas A*
- First evidence of TeV emission associated with activity at the ***core*** of M87
- Completed a 120 hour *survey* of the Cygnus region
- Bright *flare* studies of Mrk421, 1ES2344+514, WComae, 3C66A
- Detailed time-resolved studies of the gamma-ray binary *LSI+61°303*
- GRB observations with 2-3 minute response
- Excellent coordination with RXTE, Swift, Fermi, HESS, MAGIC and numerous optical/radio observatories.





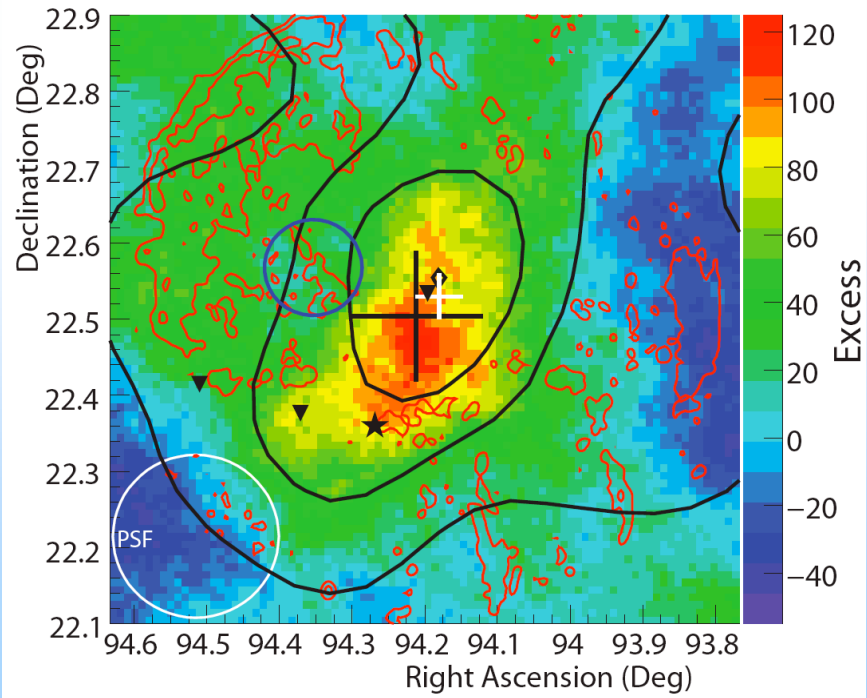


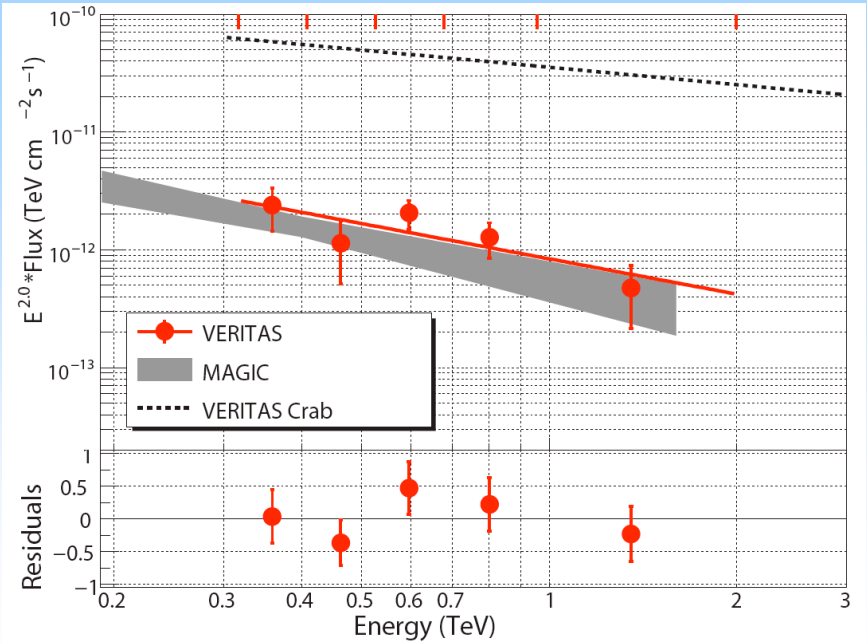


A Highlight: IC443

- IC443: an SNR interacting with molecular clouds.
- Distance 1.5 kpc
- age uncertain (3-30 kyr)
- Angular size 45′
- Best candidate for an EGRET SNR association
- Whipple 10m placed limits

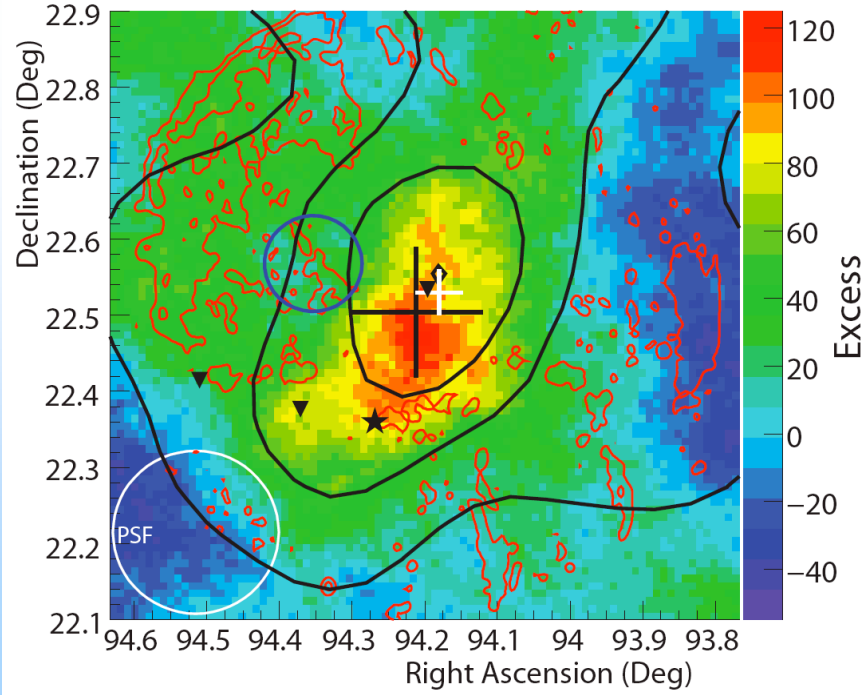
- TeV source detected in 2007 by MAGIC and VERITAS
- MAGIC source (MAGIC J0616+2236) is unresolved, with a soft spectrum (-3.1)
- VERITAS observed for 37 hours,
- 8.3σ result.



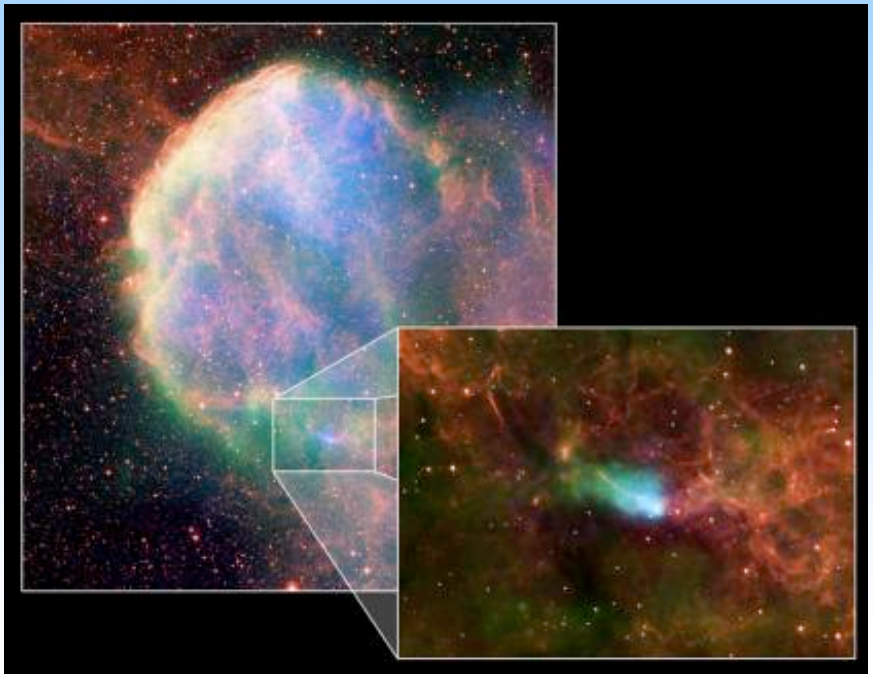


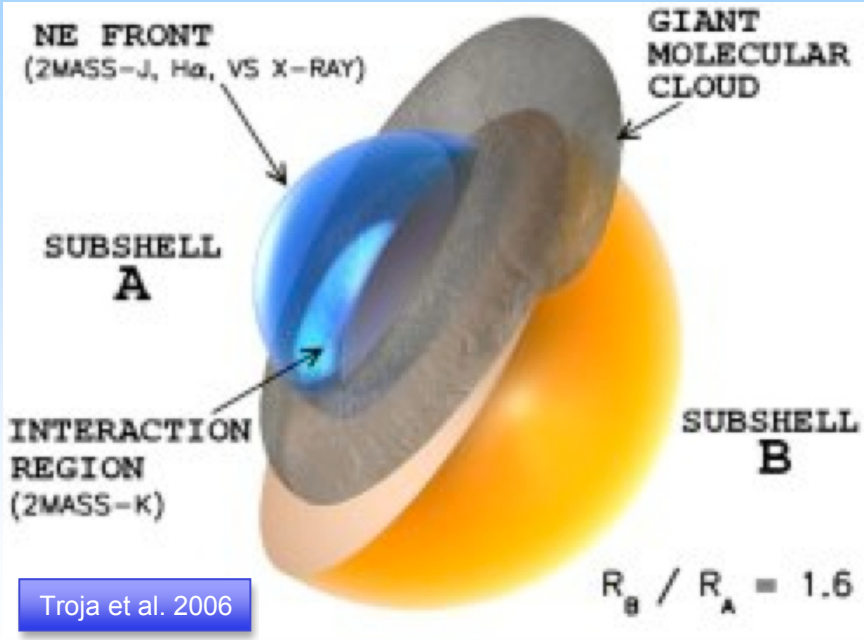
IC443

- VERITAS resolves the source
- 0.16° extent
- MAGIC/VERITAS spectra consistent
- Fermi source 0FGL J0617.4+2234 is displaced, but not significantly (yet!)



- 2 interpretations:
  - inverse Compton scattering off electrons associated with a PWNe (e.g. Bartko & Bednarek, 2007)
  - hadronic cosmic rays accelerated in the SNR interact with the foreground molecular cloud (e.g. Torres et al., 2008)
- Energy dependent Fermi-VERITAS morphology studies should allow us to discriminate between the two

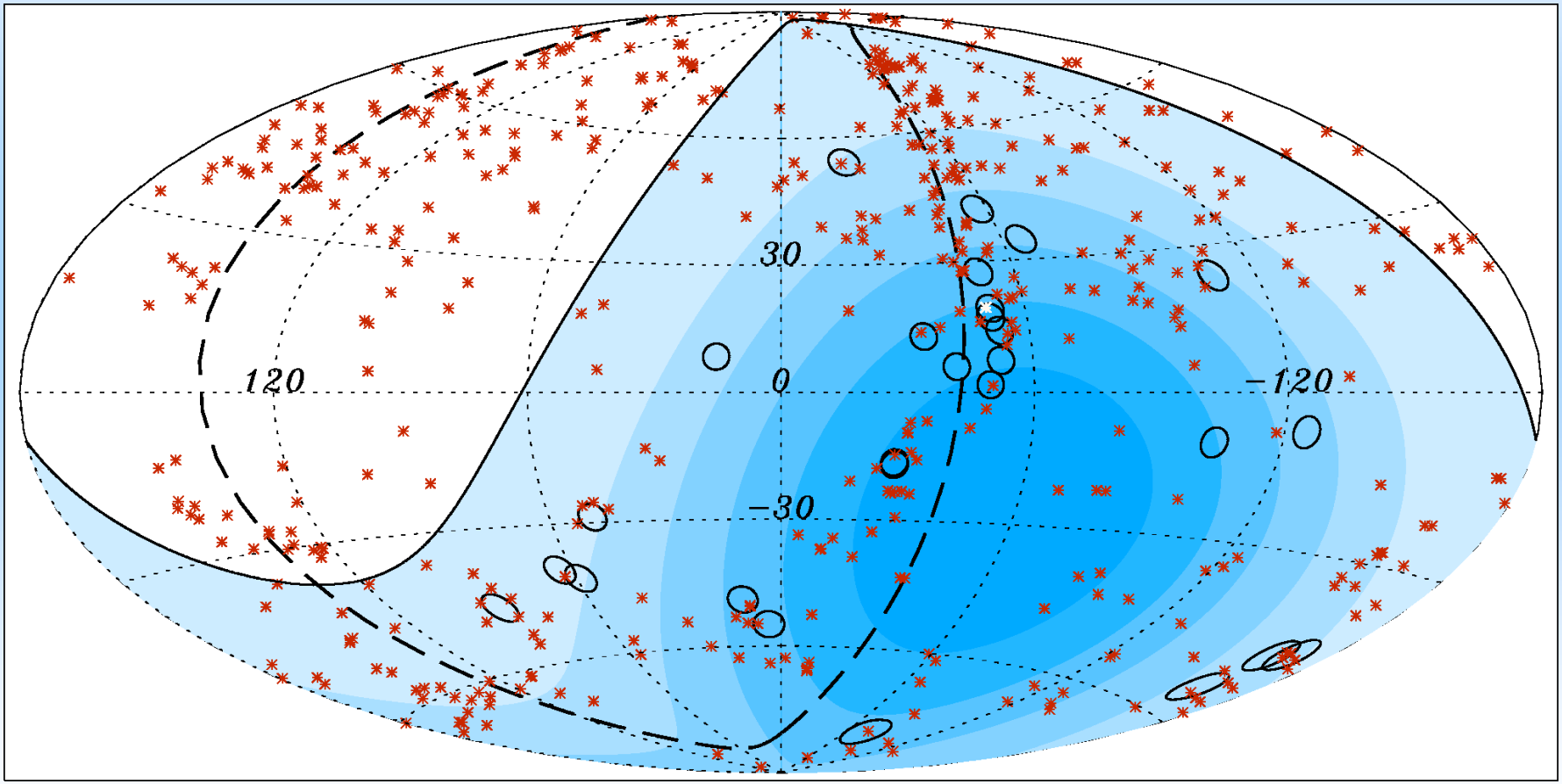




Troja et al. 2006

What about Auger?

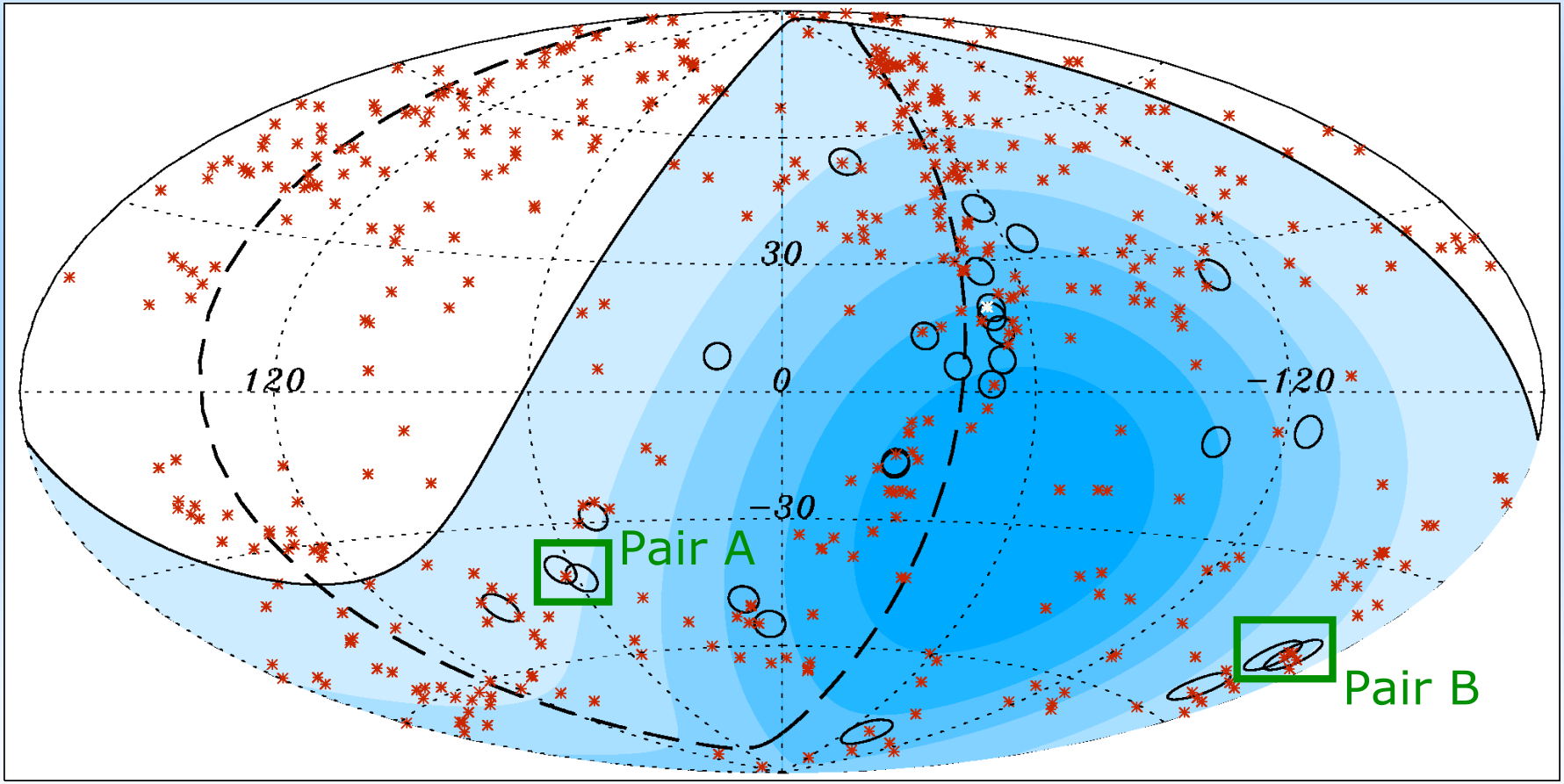
- The Auger Collaboration measured a significant correlation between the arrival directions of UHE cosmic rays and a catalog of close AGN (Veron-Cetty & Veron, 12th Ed).



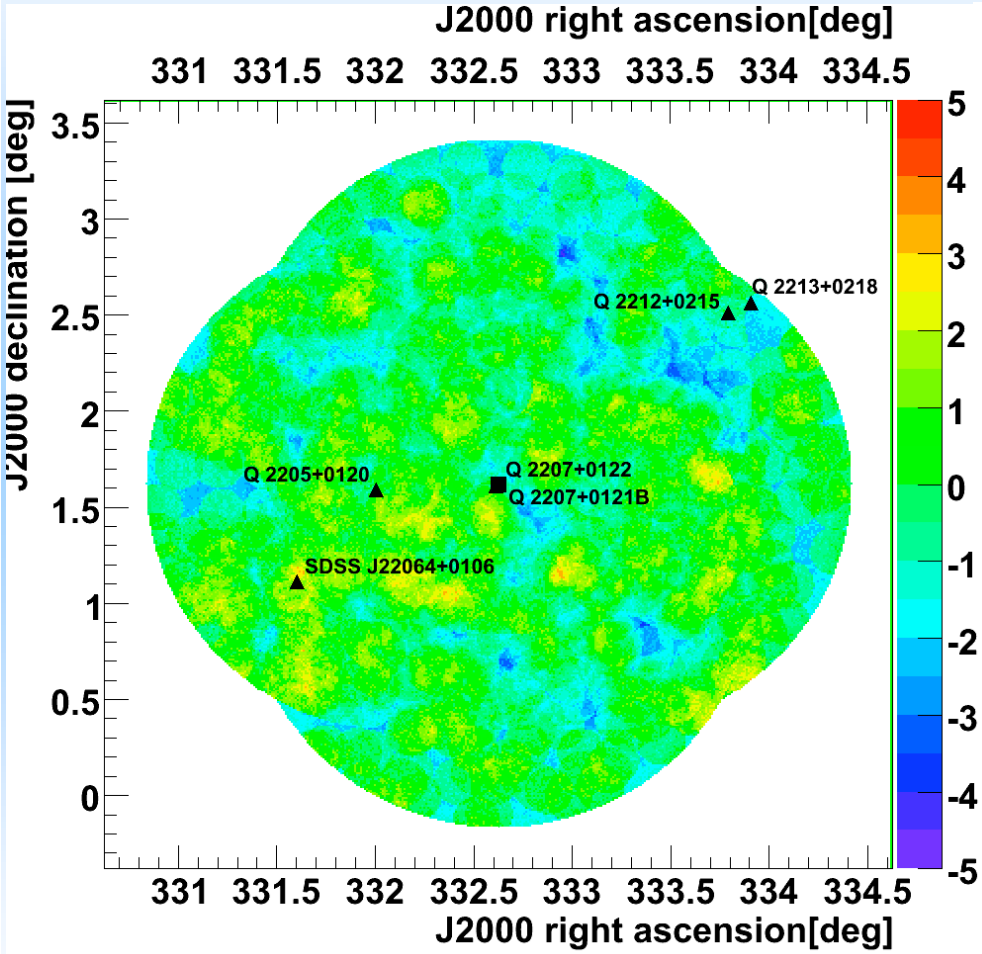
How was it done?

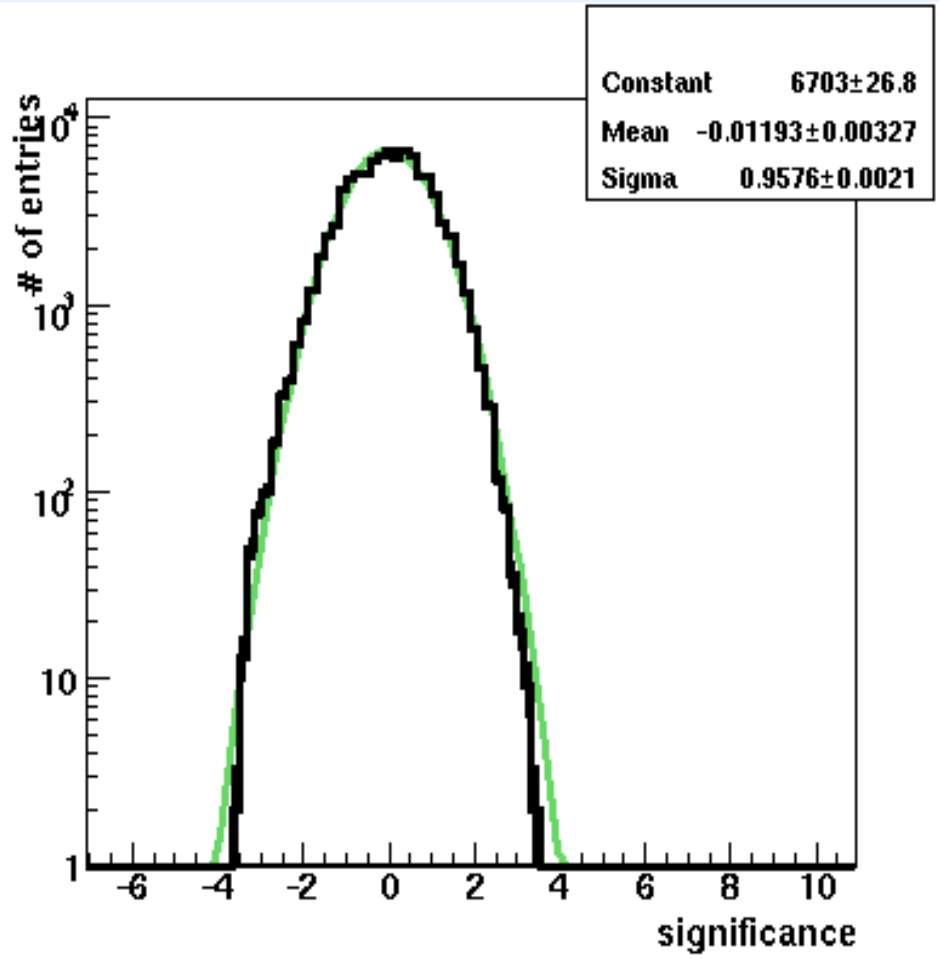
- With an initial dataset, they optimized the significance of the correlation by varying:
  - ψ = angular separation between CR arrival direction and source = 3.1°
  - z_{max}=maximum source redshift = 0.018 = 75Mpc
  - E_{th} = minimum energy of CR events = 57 EeV
  - 15 events in this dataset remain after cuts
- They then applied these cuts *a priori* to a new dataset, and measured a correlation (13 events, 8 correlate within 3.1°, expect 2.7, Probability of chance occurrence=1.7×10^{-3})

- ~50% of the Auger sky is at declination >-10°
- Of the final 27 event dataset, 7 events have declination> -10°
- 4 of these overlap in two pairs:

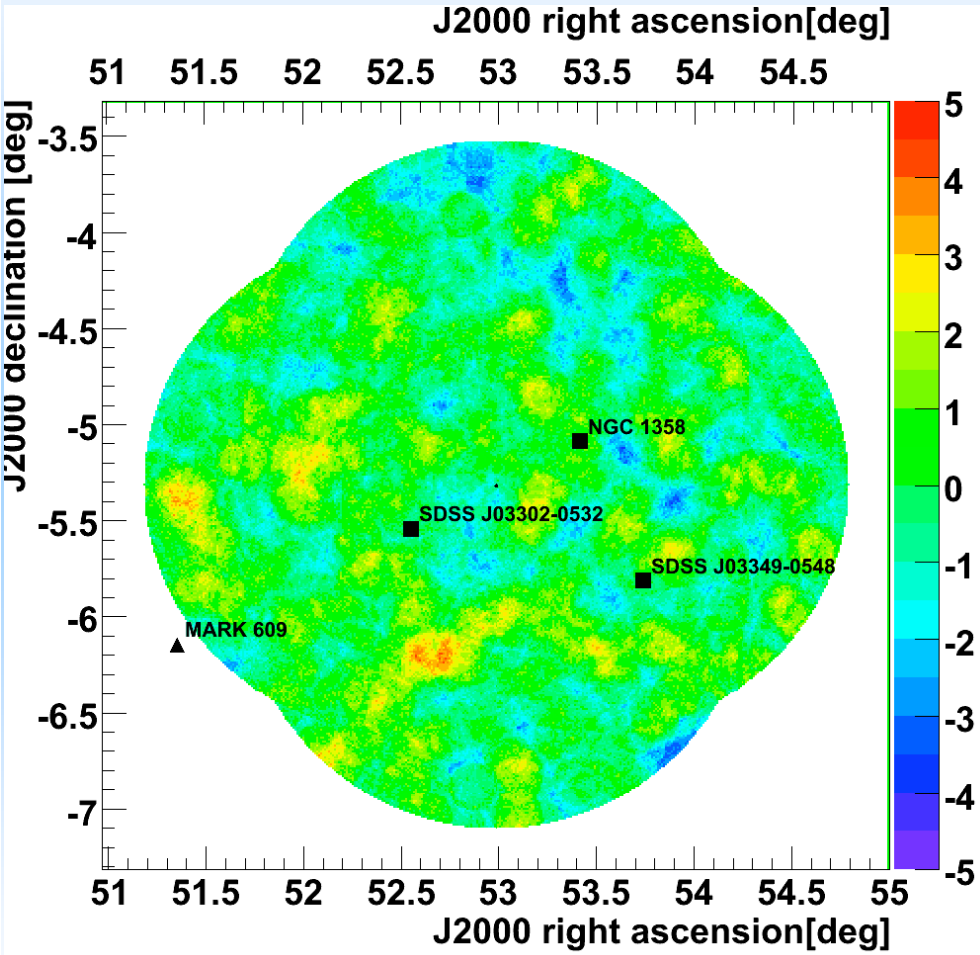


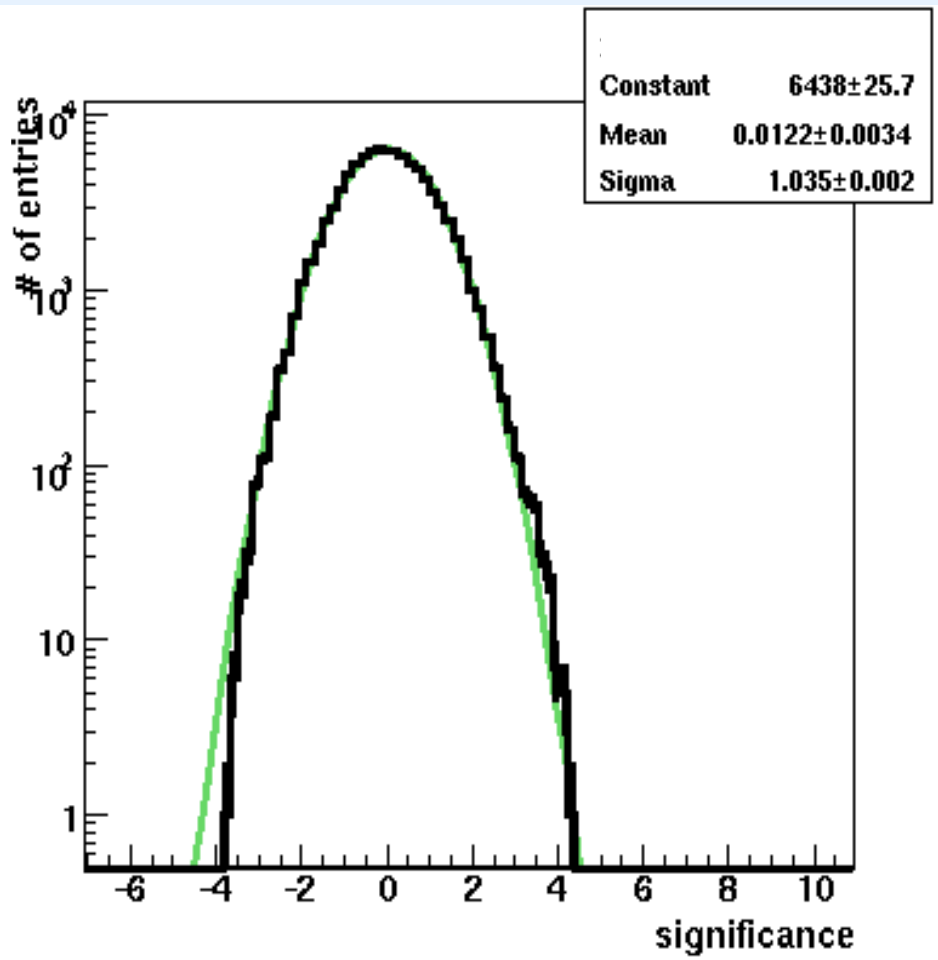
Results: Pair A (3 hours)





Results: Pair B (10 hours)





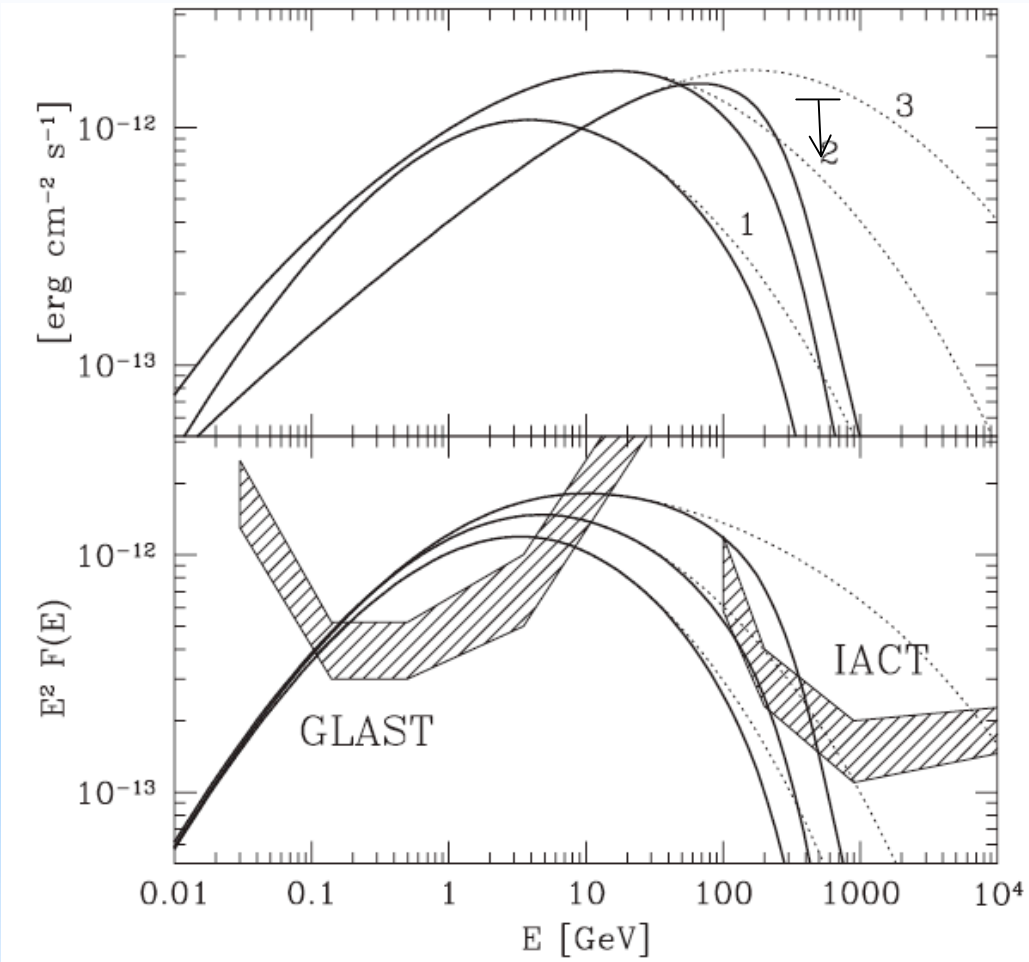
Results

Source Name	*ON-source* (events)	*OFF-source* (events)	Background Normalization	99% confidence upper limits (events)	(ph m^{-2} s^{-1} > 500 GeV)
Q 2207+0122	4	78	0.10	4.6	8.6×10^{-9}
Q 2207+0121B	4	78	0.10	4.6	9.6×10^{-9}
Q 2205+0120	7	73	0.10	9.5	2.3×10^{-8}
SDSS J22064+0106	7	34	0.10	13.4	4.9×10^{-8}
Q 2212+0215	3	35	0.10	7.0	3.9×10^{-8}
Q 2213+0218	0	10	0.10	3.8	3.8×10^{-8}
NGC 1358	26	179	0.10	19.1	1.4×10^{-8}
SDSS J03302-0532	13	170	0.10	6.1	4.9×10^{-9}
SDSS J03349-0548	13	137	0.10	10.8	8.3×10^{-9}

99% Confidence ULs at a few percent Crab flux

(Holder et al, Heidelberg Gamma Ray Symposium)

Gabici & Aharonian, 2005



- Most optimistic scenario:
- IGMF>1nG
- synchrotron photons directly from electrons produced after first UHECR interactions

Figure 4. Figure taken from [30]. Spectra for a source located at a distance of 100Mpc. The luminosity in UHECRs is 2 10^{44}erg/s, with a spectral index of $\delta = 2$. TOP: $B_{IGMF} = 0.5$(curve 1), 5 (2), 50nG(3), $E_{cut} = 10^{21}$eV. BOTTOM: $E_{cut} = 5\,10^{20}$, 10^{21}, $5\,10^{21}$eV, $B_{IGMF} = 1$nG. Dotted: intrinsic spectra. Solid: spectra after absorption. The VERITAS limit is indicated by the arrow.

Implications

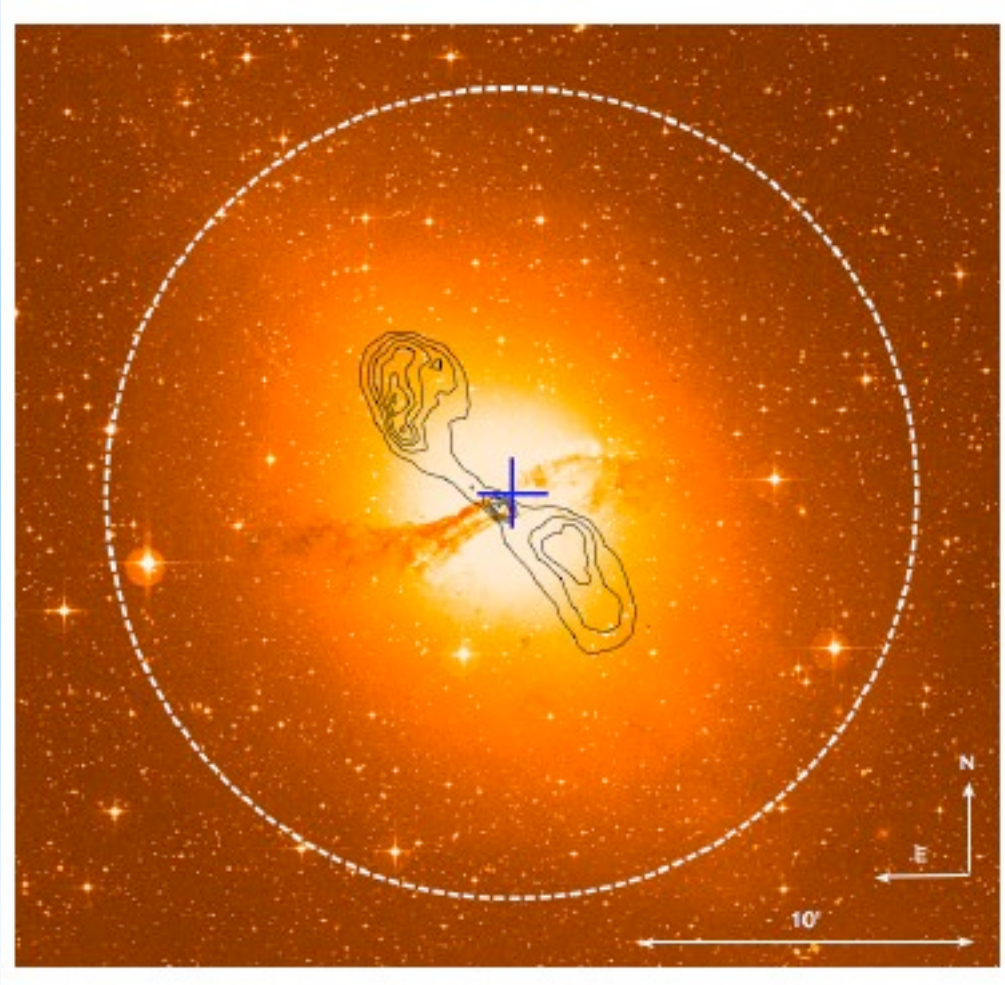
- Not very constraining at present.
- Reasons we might miss a gamma-ray flux:
  - Flux is below our sensitivity
  - The source is outside of our field of view
  - The source is very extended
    - depends on unknown IGMF
  - The source is time variable

Implications

- 'Speculative' observations - but a positive result could
  - Clearly identify the origin of the UHECRs
  - Allow to probe the strength and structure of the IGMF
- Future Auger results will hopefully identify interesting regions more clearly
- With their high sensitivity and excellent angular resolution, ground-based TeV observatories *may* provide the definitive measurements to identify the sources of the highest energy cosmic rays.
- Next competitive VERITAS TAC round this summer – collaborators welcome – need a good case!

Stop Press!

- H.E.S.S. detection of Centaurus A
- Aharonian et al., 2009
- Closest AGN (3Mpc)
- 115 hours, 5σ, 0.8% Crab Flux
- Consistent with a realistic UHECR related flux
- many other possible astrophysical scenarios … but promising!



What next? The Competition:

First Light "end of 2008+"
(K. Kosack, SLAC 08/08)
… soon!

Taking engineering data – trigger rate 300-600Hz.
Serious stereo observations begin in ~1 month
(Teshima, April 09)

Plans for a VERITAS Upgrade

- Overall goals: reduce energy threshold and improve sensitivity.
- These goals impact essentially all science programs

- Relocate Telescope 1 (funded and approved)
- Increase the photon collection efficiency
- Upgrade the trigger
- Automatic facet alignment
- Build an extra telescope

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- Relocate Telescope 1 (funded and approved)
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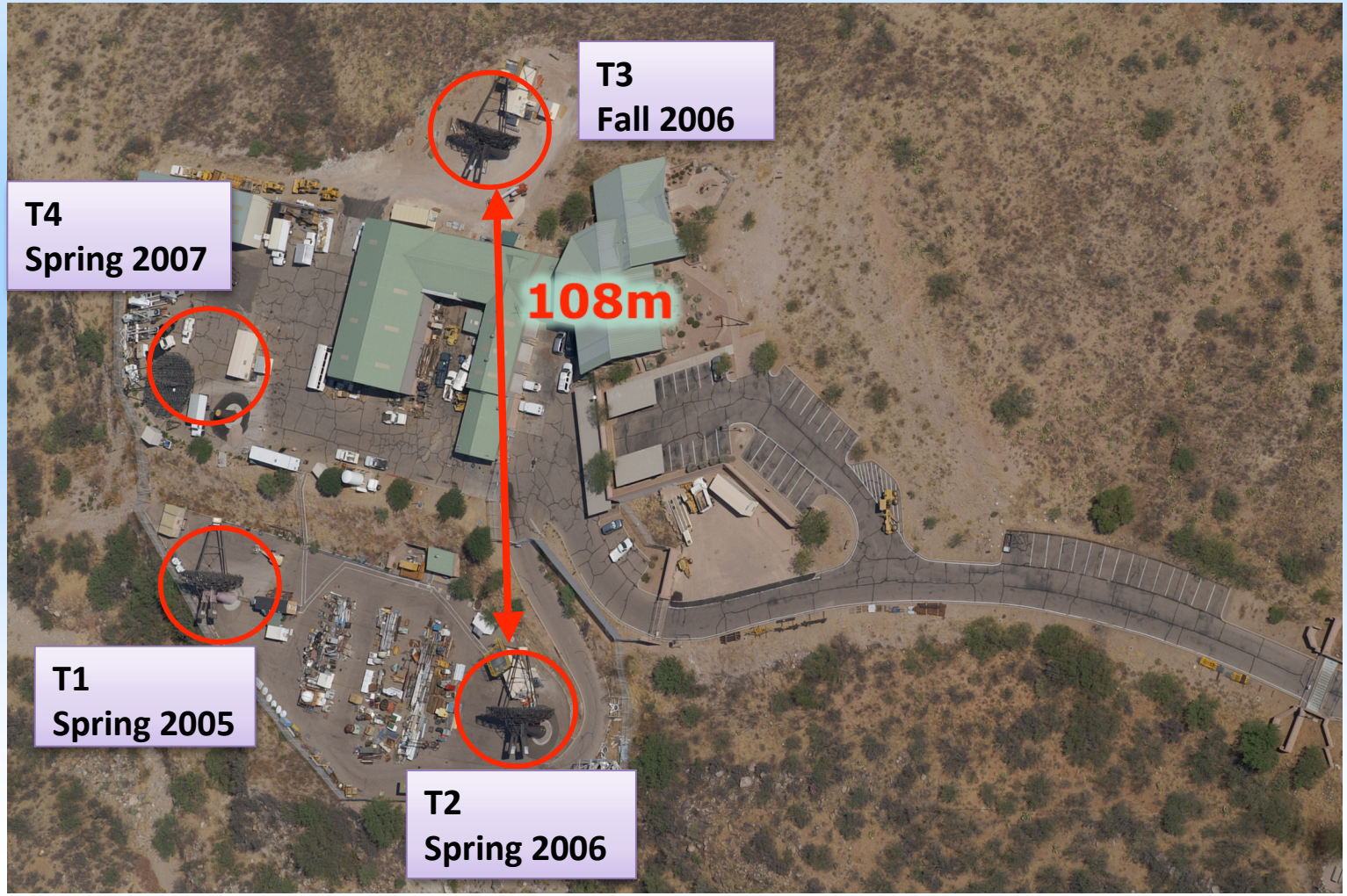
Baseline Upgrade 1: Relocate T1

- Fully funded and approved
- Will start next month (May, 2009)



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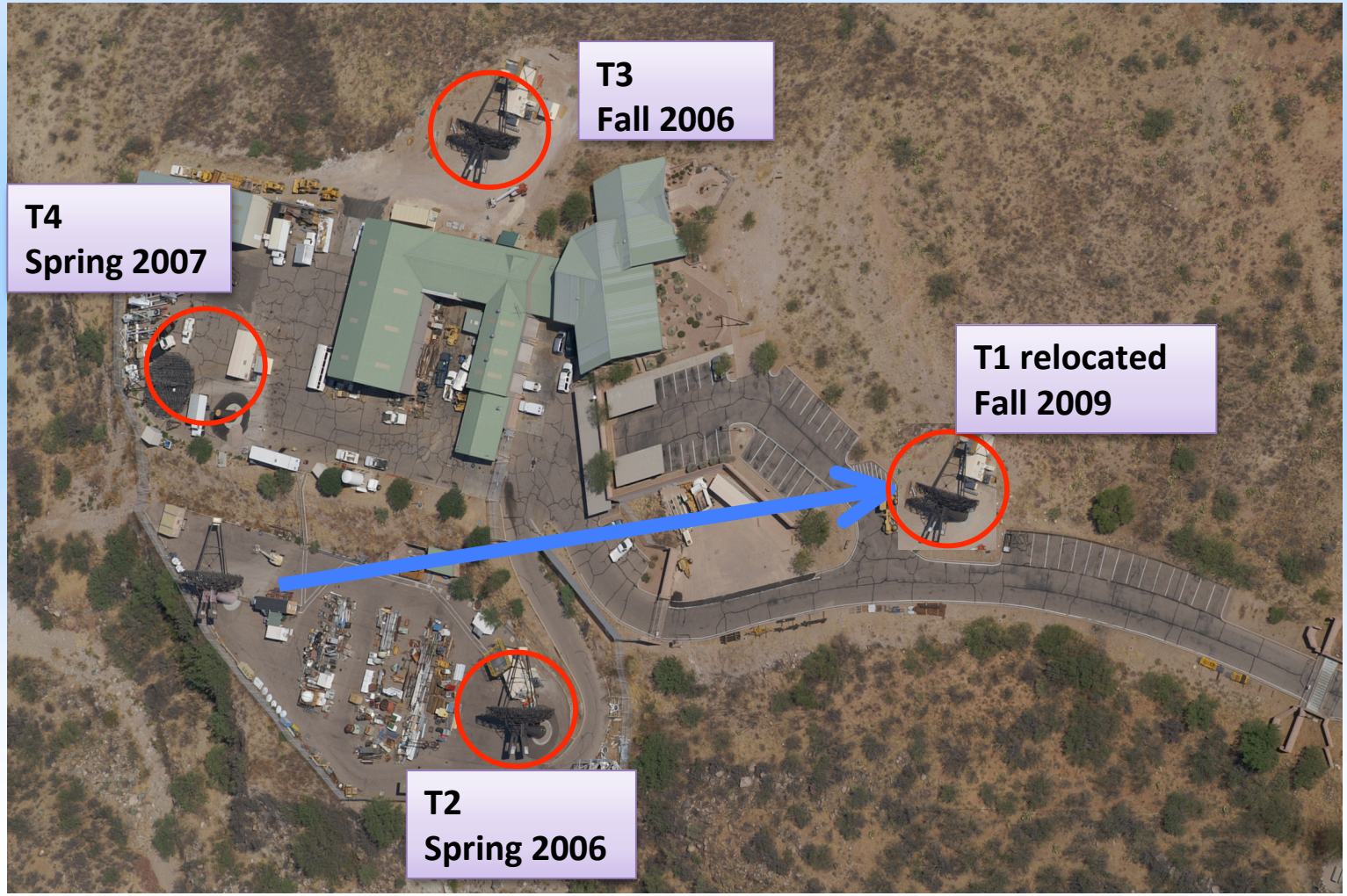
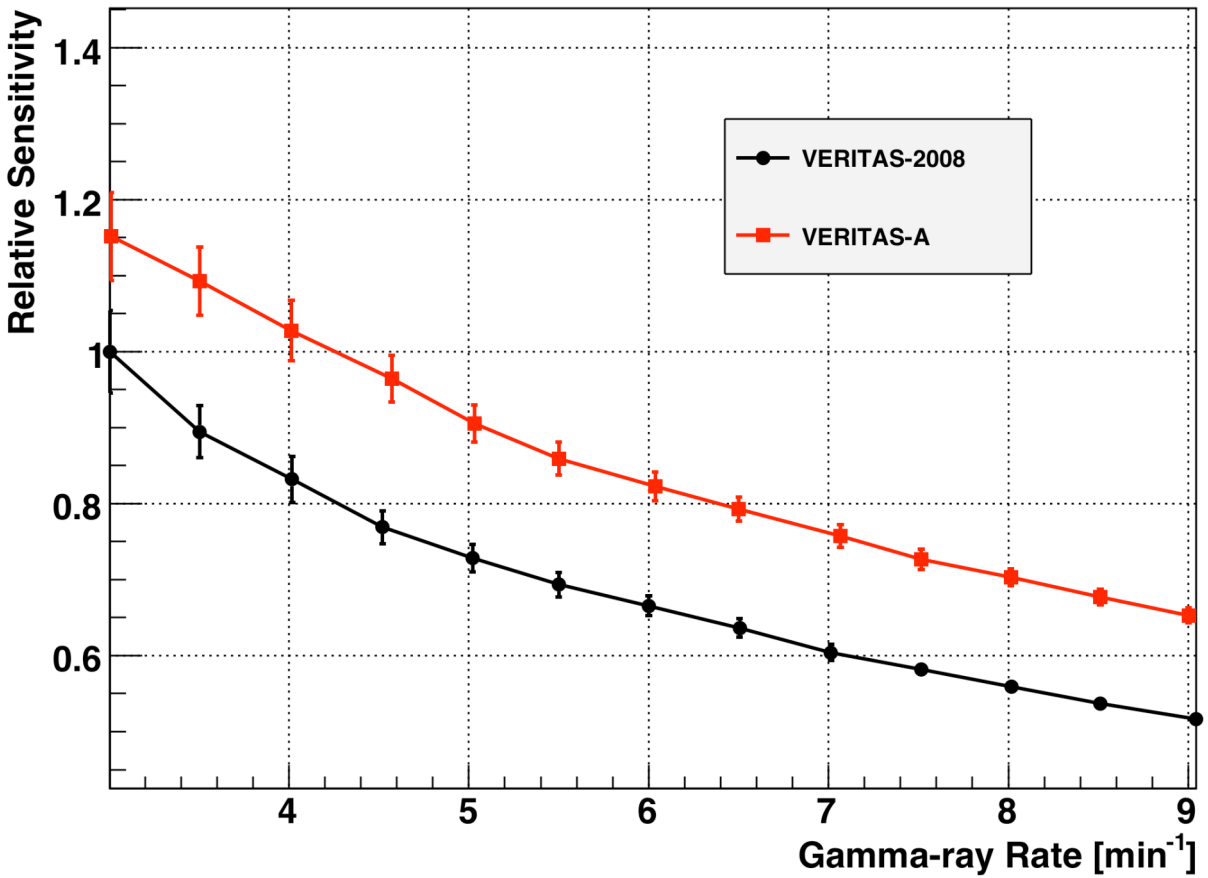


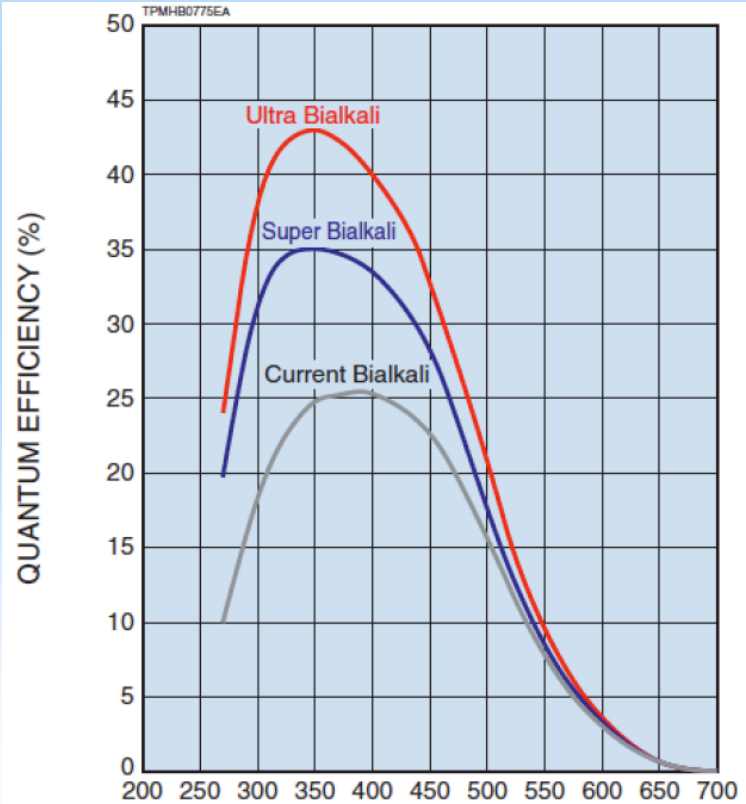
Baseline Upgrade 1: Relocate T1

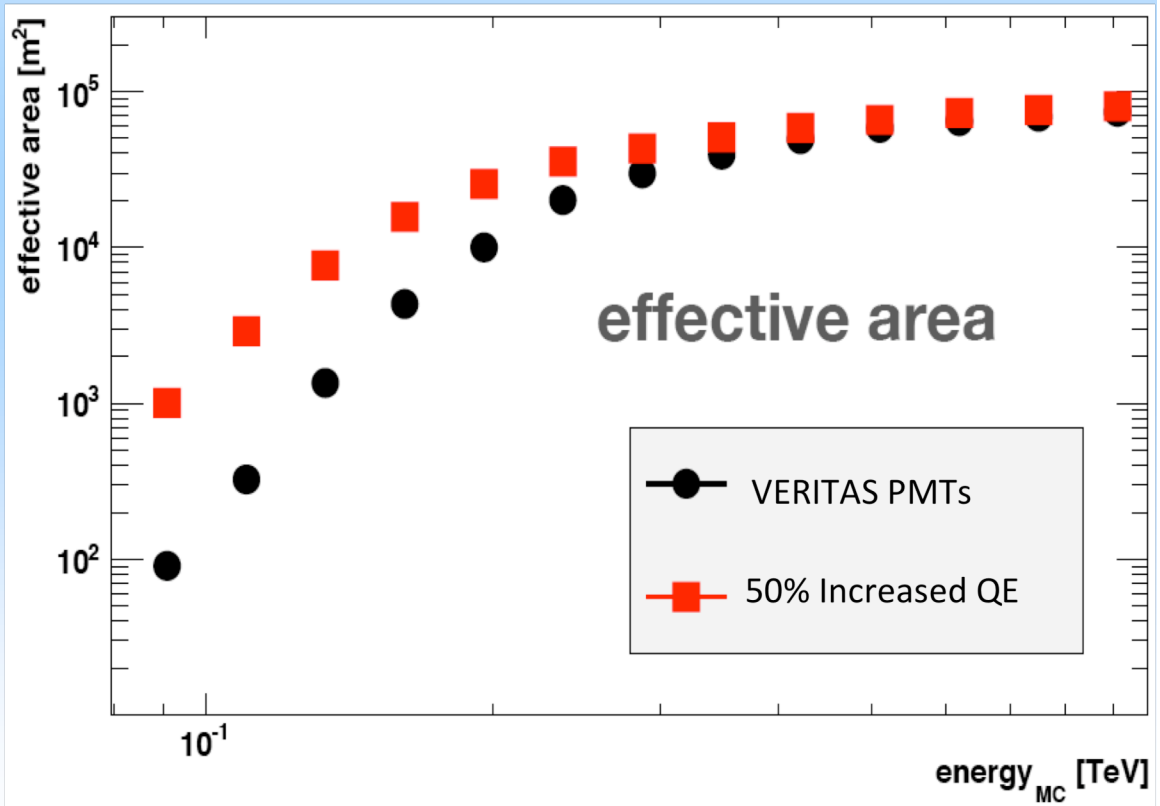
- ~20% increase in sensitivity
- ~30% decrease in weak source observing time
- ~15% increase in effective area >300 GeV
- Simulations did not account for lowered CFD threshold



Baseline Upgrade 2: High QE PMTs

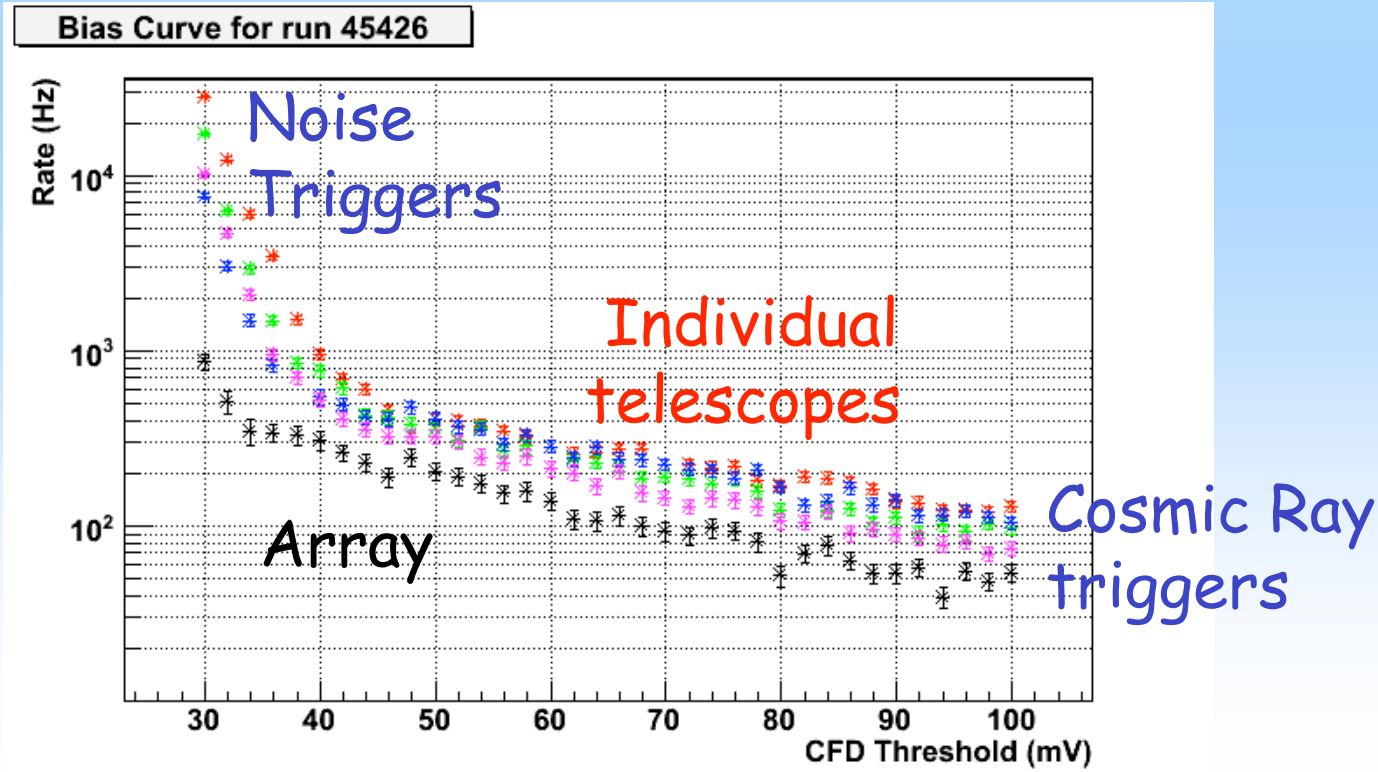
- ~17% sensitivity improvement (~27% in observing time)
- Dramatic increase in effective area at low energies





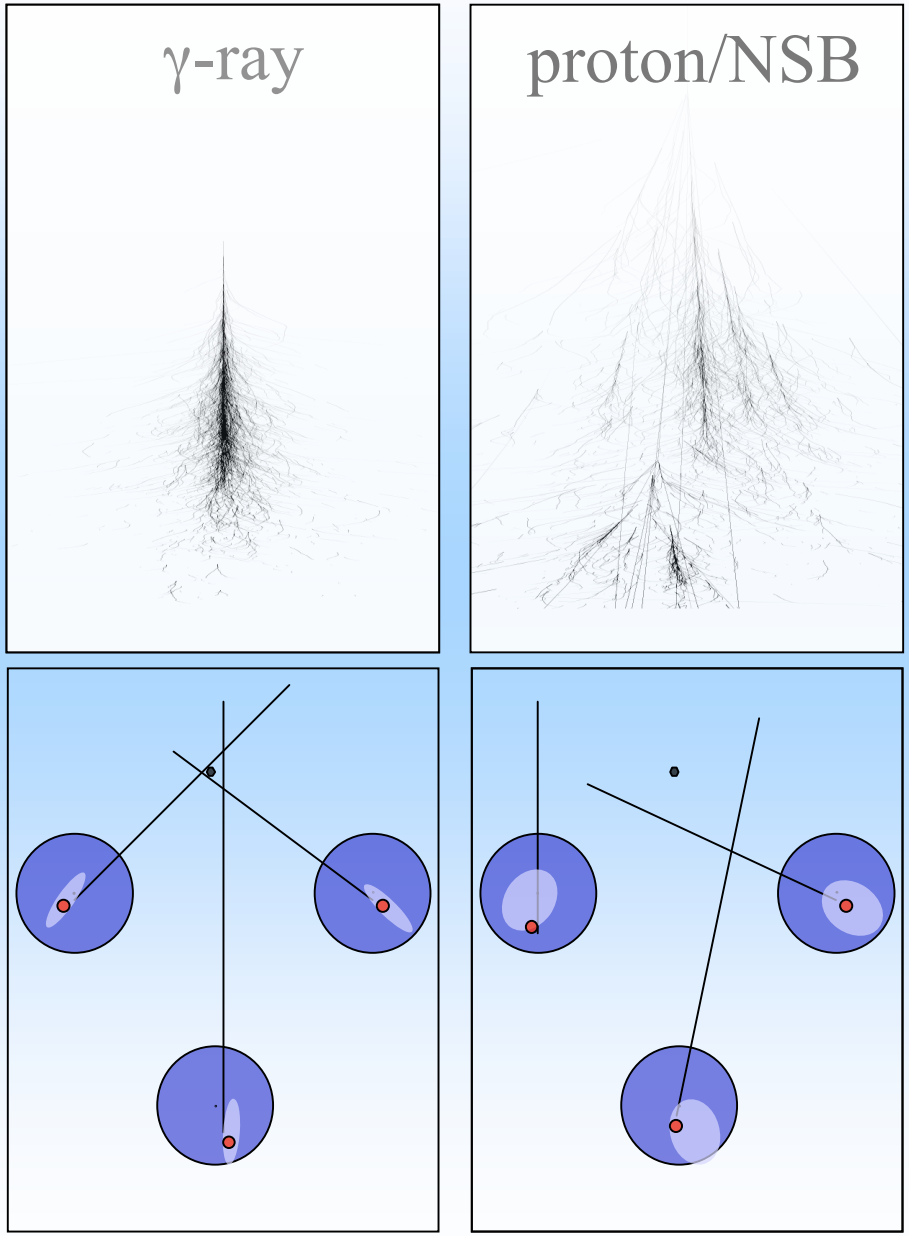
Baseline Upgrade 3: Trigger Upgrade

- Each PMT signal channel has programmable Discriminators (CFDs)
- CFD output sent to programmable pattern selection trigger (L2)
  - any 3 adjacent PMTs in a camera within ~7ns
- A valid trigger is transmitted to a central array trigger (L3), which corrects for path length and triggers on telescope coincidence
  - any 2 out of 4 telescopes within 100ns
- Trigger rate ~ 250 Hz



Baseline Upgrade 3: Trigger Upgrade

- Current L2 system is CAMAC-based, uses RAM memory lookup tables to check for valid patterns (e.g. any 3 adjacent pixels)
- Wash U and Iowa State/Argonne have developed and field-tested **FPGA** based L2 trigger systems
- These systems allow a **fast parameterization** of 'hit' pixels
- This information can be transmitted to a central location, where a **geometrical array trigger** provides gamma-hadron discrimination at the hardware level (e.g. with *parallaxwidth* parameter)
- Should reduce energy threshold by 40%



The Further Future

A dvanced

G amma ray

I maging

S ystem

"Ground-Based Gamma Ray Astronomy, Towards the future", Oct. 20-21 2005, Malibu, CA (UCLA)

"Ground-Based Gamma Ray Astronomy, Towards the future", May 11-12 2006, Santa Fe, NM (LANL)

"Future of Very High Energy Gamma Ray Astronomy, Towards the future", May 13-14 2007, Chicago, IL, (UofChicago) - Formation of AGIS R&D group

Collaboration meeting, June 27-28 2008, UCLA, Formation of AGIS collaboration

Collaboration meeting, April 2009, ANL.

Institutions:

ADLER	SAO
ANL	Stanford
Barnard	UNAM
Delaware	UCLA
IAFE	UCSC
Iowa State	U. Chicago
LANL	U. Iowa
McGill	Utah
Penn State	Yale
Purdue	Washington U.

Executive Group:

J. Buckley

S. Funk

H. Krawzcynski

F. Krennrich (SP)

V. Vassiliev

AGIS Specifications

- AGIS is envisioned as a stand-alone, 50-telescope array, or a 36-telescope array if we merge with the European CTA project

Specifications for the AGIS 36 Telescope Array	Target
Telescope Spacing[a]	120 - 150 m
Effective Mirror Area per Telescope[b]	100 m^2
Field of View (FOV)	8 deg.
Pixelation	0.05 - 0.10 deg.
Effective Collection Area	1 km^2
Energy Threshold[c]	100 GeV
Angular Resolution	0.02 - 0.05 deg.

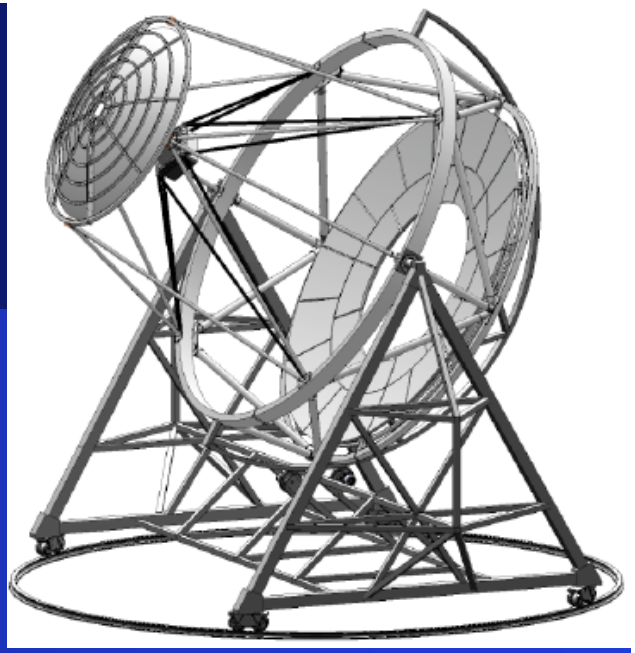
[a] final value is subject to further Monte Carlo simulations.

[b] Takes into the improved coverage of the photosensitive material in the focal plane with MAPMTs.

[c] Energy Threshold is the energy at which the γ-ray rate for a Crab Nebula like spectrum peaks.

[b] Accounts for improved coverage of the photosensitive material in the focal plane due to MAPMTs.

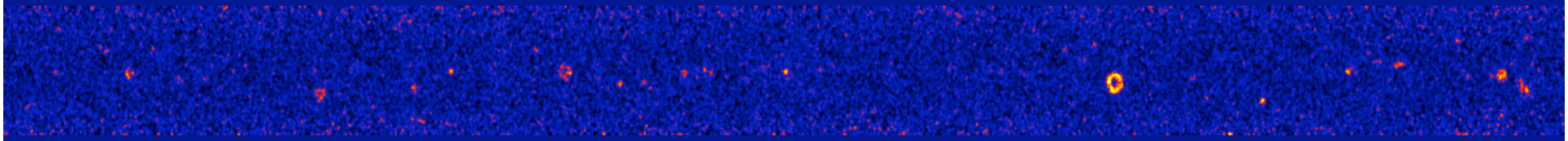
AGIS R&D



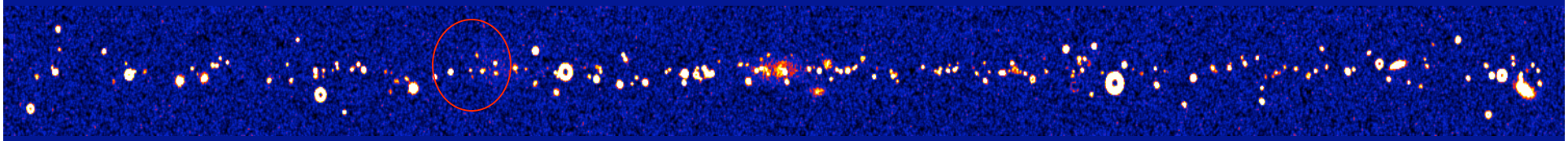
- R&D Work is underway
  - Topological trigger: Iowa
  - Data Acquisition: U Chicago, SLAC
  - Camera Design: Wash U
  - Photo-detectors: ANL, Barnard, UCSC
  - telescope design: UCLA, ANL
- Key design feature is the Schwarzchild-Couder optical design
  - provides small focal plate scale and reduces aberrations
  - wide field of view for a small camera
- Next step is a prototype telescope

To See more

HESS Simulation (real exposure)



AGIS/CTA Simulation (flat exposure)

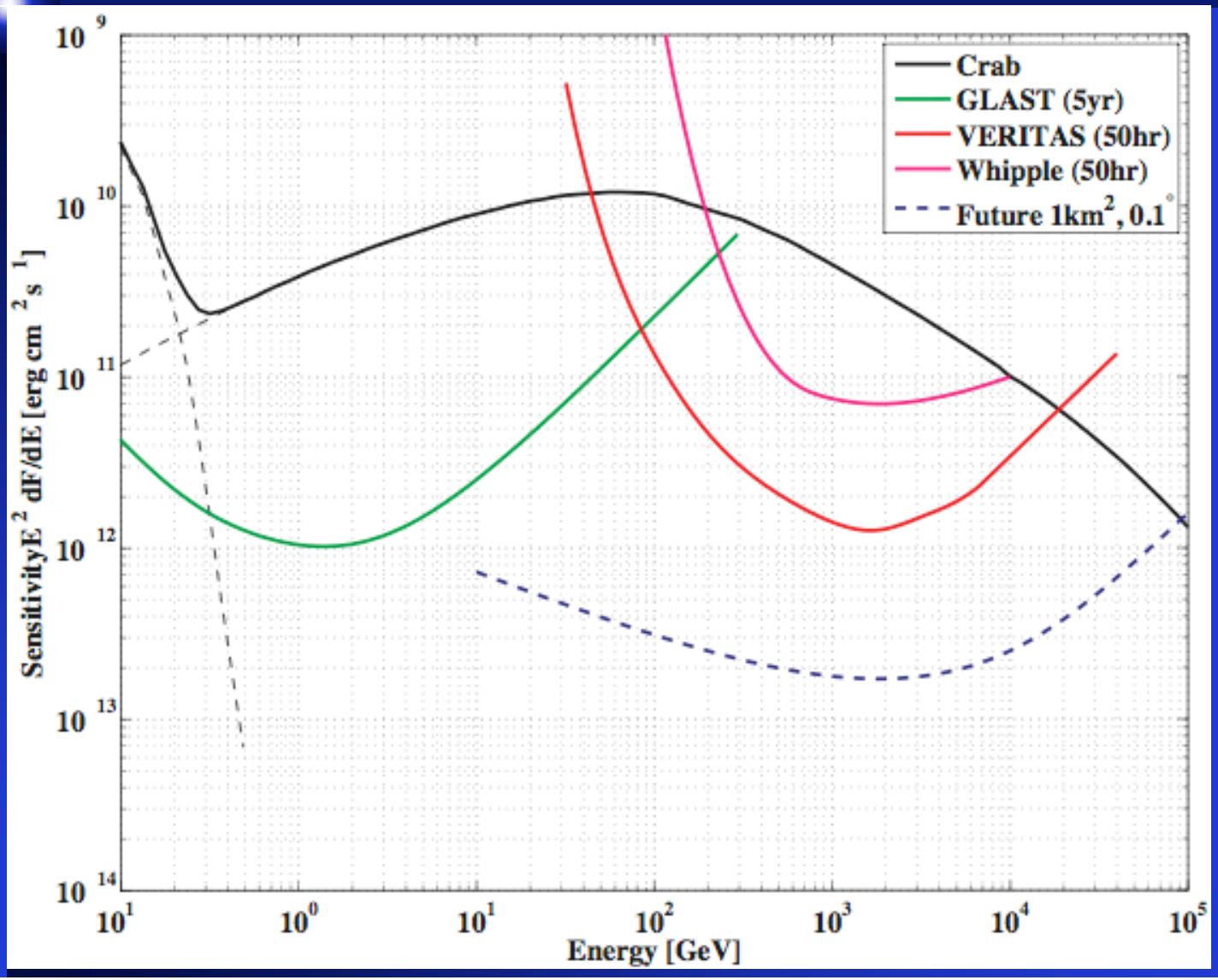


8° FOV

Digel & Funk 2008

10 x better sensitivity

Sensitivity



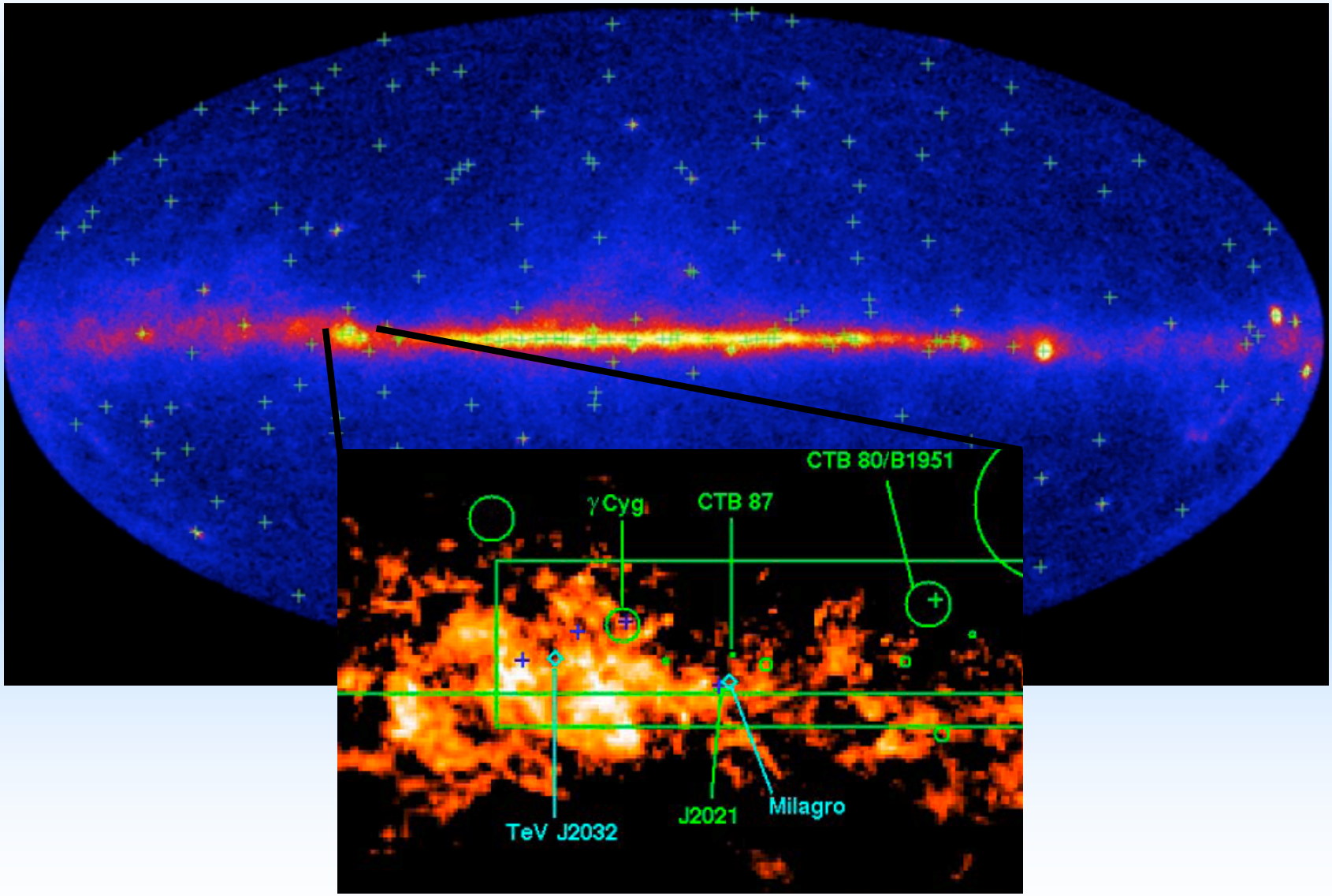
Summary

- Ground-based gamma-ray astronomy is now a true astronomical discipline
  - Many sources
  - Many different classes
  - Detailed spectral and morphological studies.
- The VERITAS Observatory has been operating smoothly for almost 2 years.
- Results so far are promising – many more publications in the pipeline

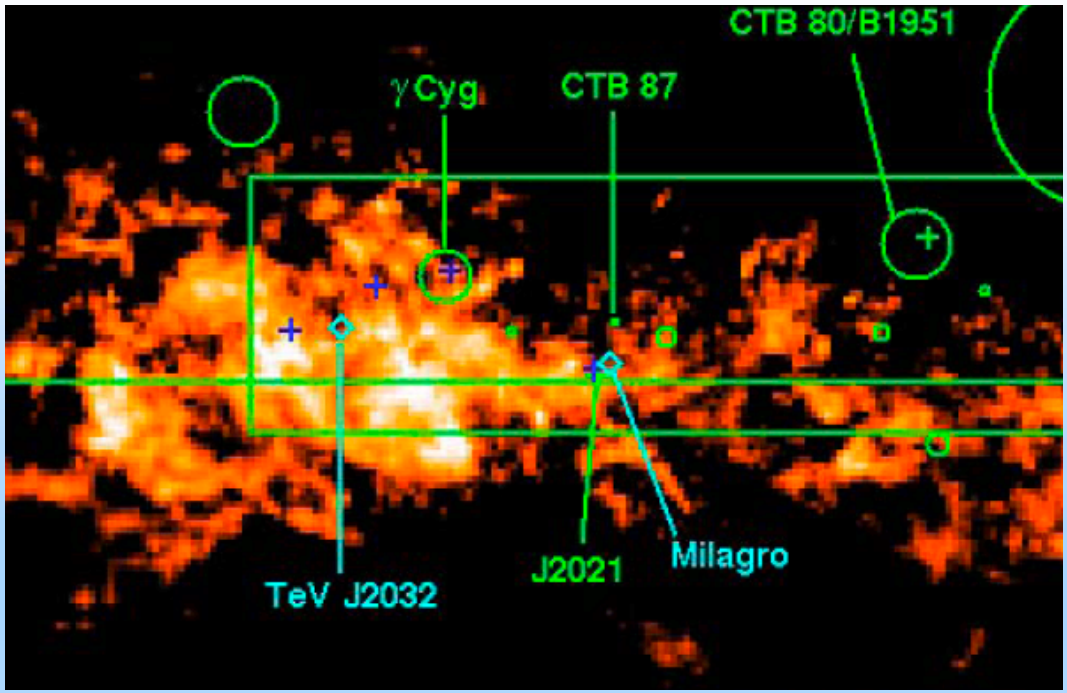
- A few simple VERITAS upgrades promise significant improvement in the short-term

- The AGIS Collaboration is now aggressively planning a future installation
- Significant R&D is already underway
- Collaborators welcome!

VERITAS: Survey



VERITAS: Survey



- VERITAS Sky Survey: Deep, unbiased observations of the Cygnus region of the galactic plan
- Ambitious effort, Initial program (l~80° to 65°, b -1° to +4°)
- ~ 120 hour exposure completed fall 2008(~6 hour acceptance corrected exposure at each point)
- Region contains many high and low-mass XRBs, OB associations, colliding wind binaries etc.
- Analysis ongoing; results soon.

Implications

- Production mechanisms for a gamma-ray flux :
  - (I) efficient particle acceleration associated with the same central engine - i.e. "bright" CR AGN are bright gamma -ray sources.

Implications

- Production mechanisms for a gamma-ray flux :
  - (I) efficient particle acceleration associated with the same central engine - i.e. "bright" CR AGN are bright gamma -ray sources.
  - …but none of the AGN targeted here are good standard TeV candidates

- (II) electromagnetic cascades initiated by proton-photon interactions of the UHECRs on the CMBR.

$$p + \gamma_{CMB} \rightarrow p + \pi^0 \rightarrow p + \gamma_{EeV} + \gamma_{EeV}$$

- Flux estimate and source angular extent depends strongly on the IGMF strength, which is essentially unknown.
- Discussion based on Gabici & Aharonian (2005)

- (II) electromagnetic cascades initiated by proton-photon interactions of the UHECRs on the CMBR.

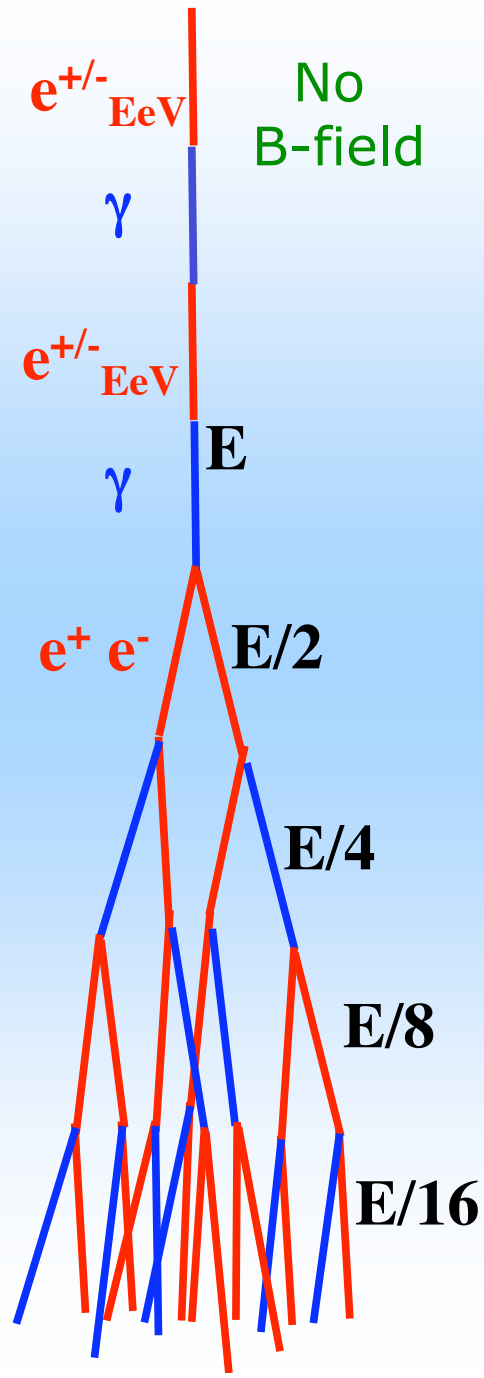
$$p + \gamma_{CMB} \rightarrow p + \pi^0 \rightarrow p + \gamma_{EeV} + \gamma_{EeV}$$

- Flux estimate and source angular extent depends strongly on the IGMF strength, which is essentially unknown.
  - A) low IGMF (< 10^{-12} G) = point-like source. TeV photons from cascade.
- Cascade develops through pair production and Inverse Compton, initially in the extreme Klein-Nishina regime

$$\gamma_{EeV} + \gamma_{CMB} \rightarrow e^-_{EeV} + e^+$$

$$e^-_{EeV} + \gamma_{CMB} \rightarrow e^- + \gamma_{EeV}$$

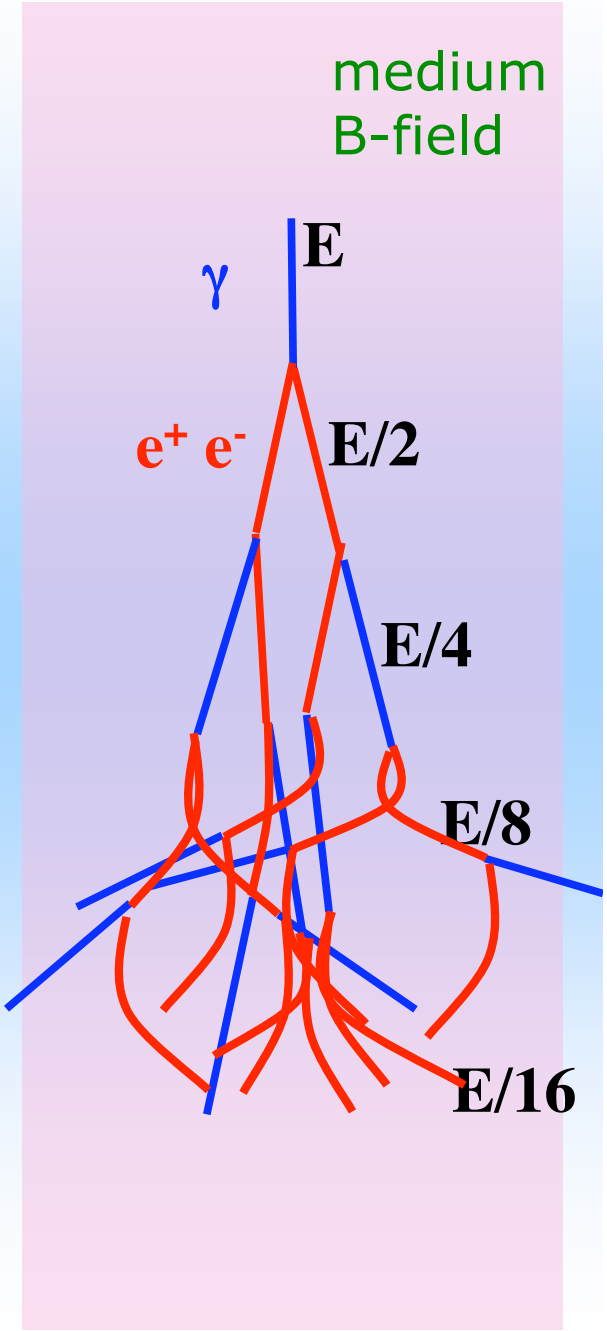
- i.e "oscillates" from photon to electron, losing energy until $\Gamma<1$, when particle multiplication phase begins



- (II) electromagnetic cascades initiated by proton-photon interactions of the UHECRs on the CMBR.

$$p + \gamma_{CMB} \rightarrow p + \pi^0 \rightarrow p + \gamma_{EeV} + \gamma_{EeV}$$

- Flux estimate and source angular extent depends strongly on the IGMF strength, which is essentially unknown.
  - B) medium IGMF (10^{-12} to 10^{-9} G) = extended source. TeV photons from cascade.
- Cascade develops through pair production but electrons are deflected and isotropized
- Leads to an "extended pair halo" 10° - 20° in extent
- Extremely difficult to detect or put limits on
- Milagro limits might be interesting..



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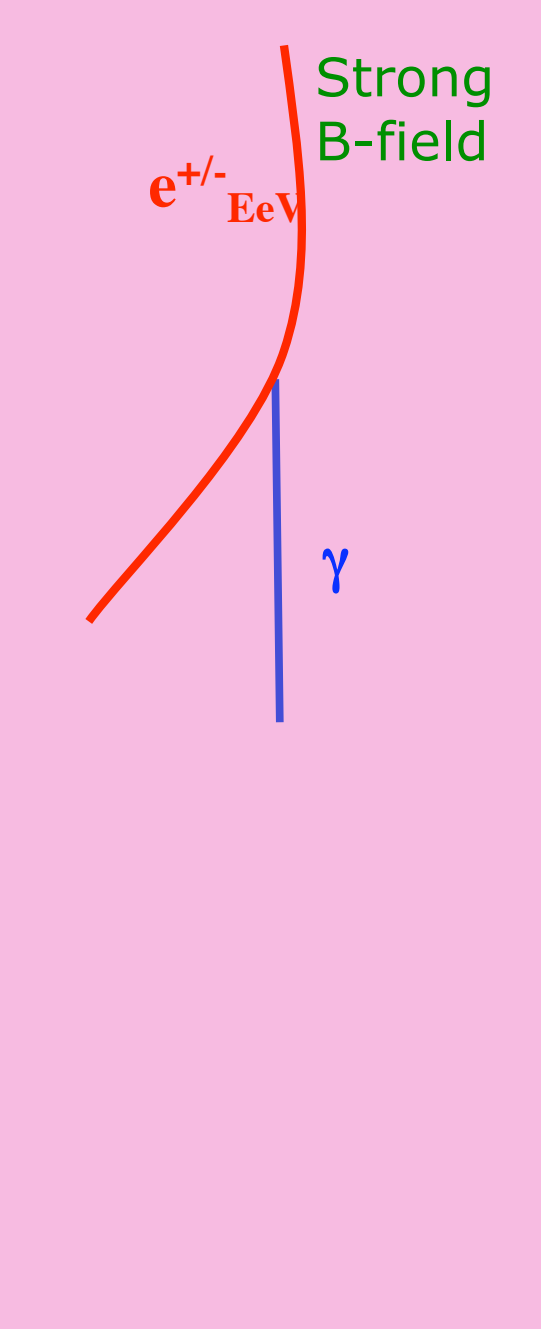
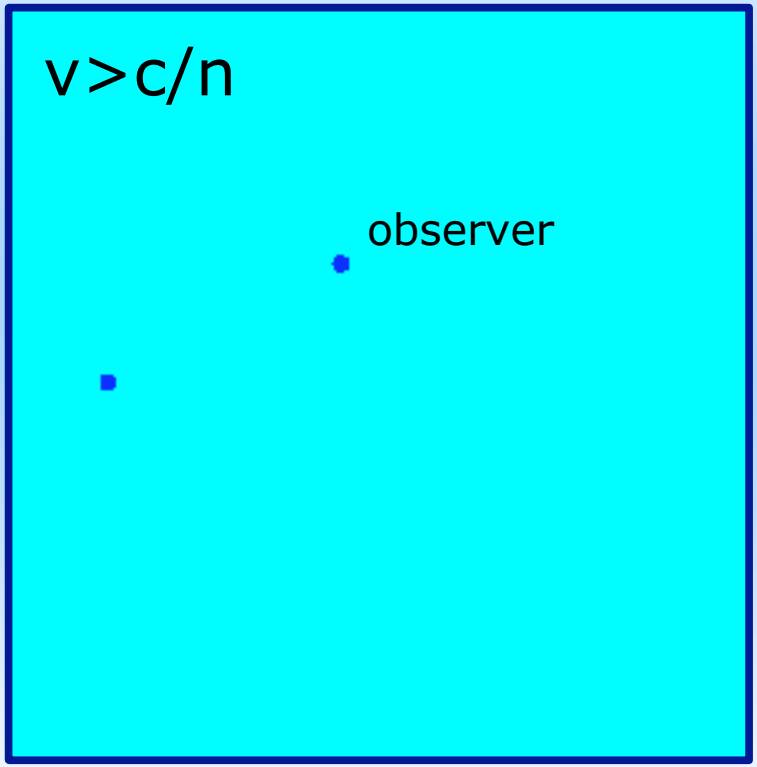
$$p + \gamma_{CMB} \rightarrow p + \pi^0 \rightarrow p + \gamma_{EeV} + \gamma_{EeV}$$

- Flux estimate and source angular extent depends strongly on the IGMF strength, which is essentially unknown.
  - C) strong IGMF (> 10^{-9} G) = slightly extended source. Synchrotron TeV photons.
- Electromagnetic cascade suppressed by synchrotron losses, but synchrotron photons are in the GeV - TeV range
- Angular size of the emission region for 300 GeV photons is dominated by deflections of the path of the UHECR by the IGMF during the first interaction length.
- a source at a distance of 50 Mpc would have an angular extent of ~0.16°, for B=10^{-9} G



Cherenkov radiation

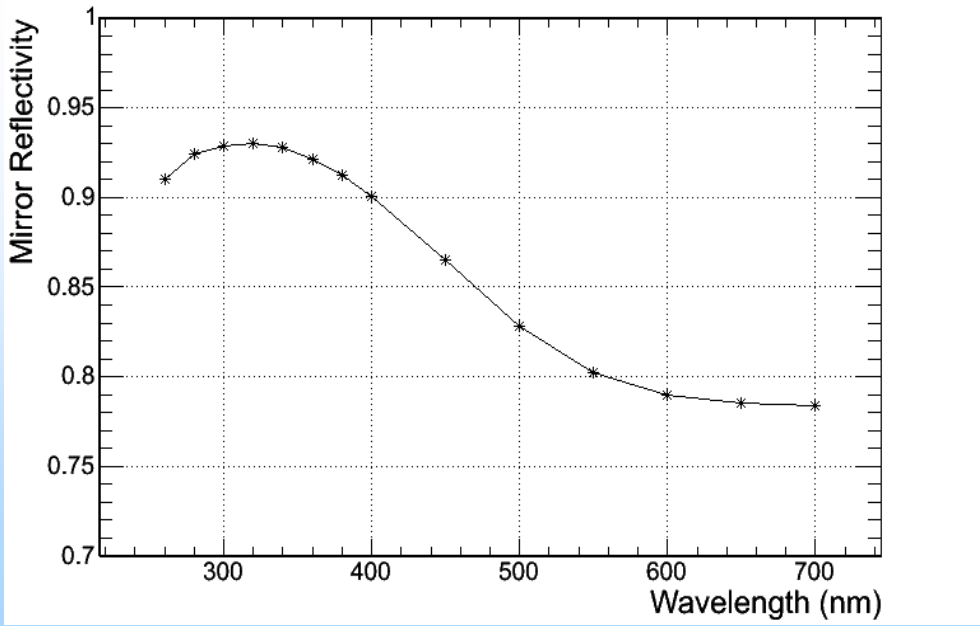
- The charged particles in the shower are moving faster than the speed of light in air (=c/n)
- A moving charge causes atoms in the atmosphere to become polarised and emit light

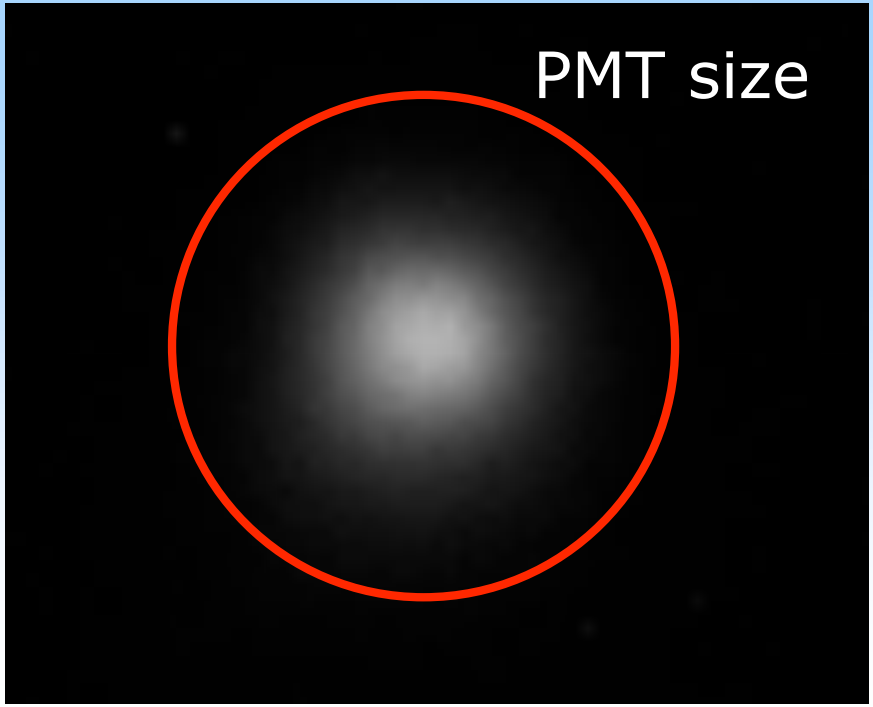


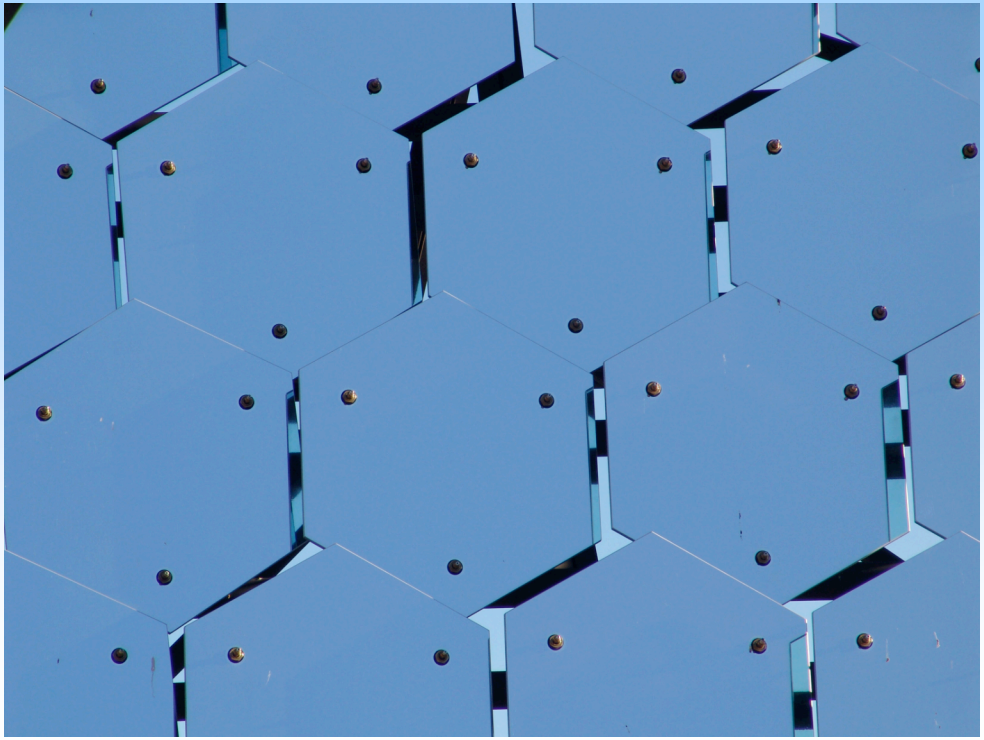
A fast particle causes a cone shaped "shock wave" - The emission forms a coherent wavefront at the Cherenkov angle $\cos\theta = 1/\beta n$ (~1.3° in air)

Optical Performance

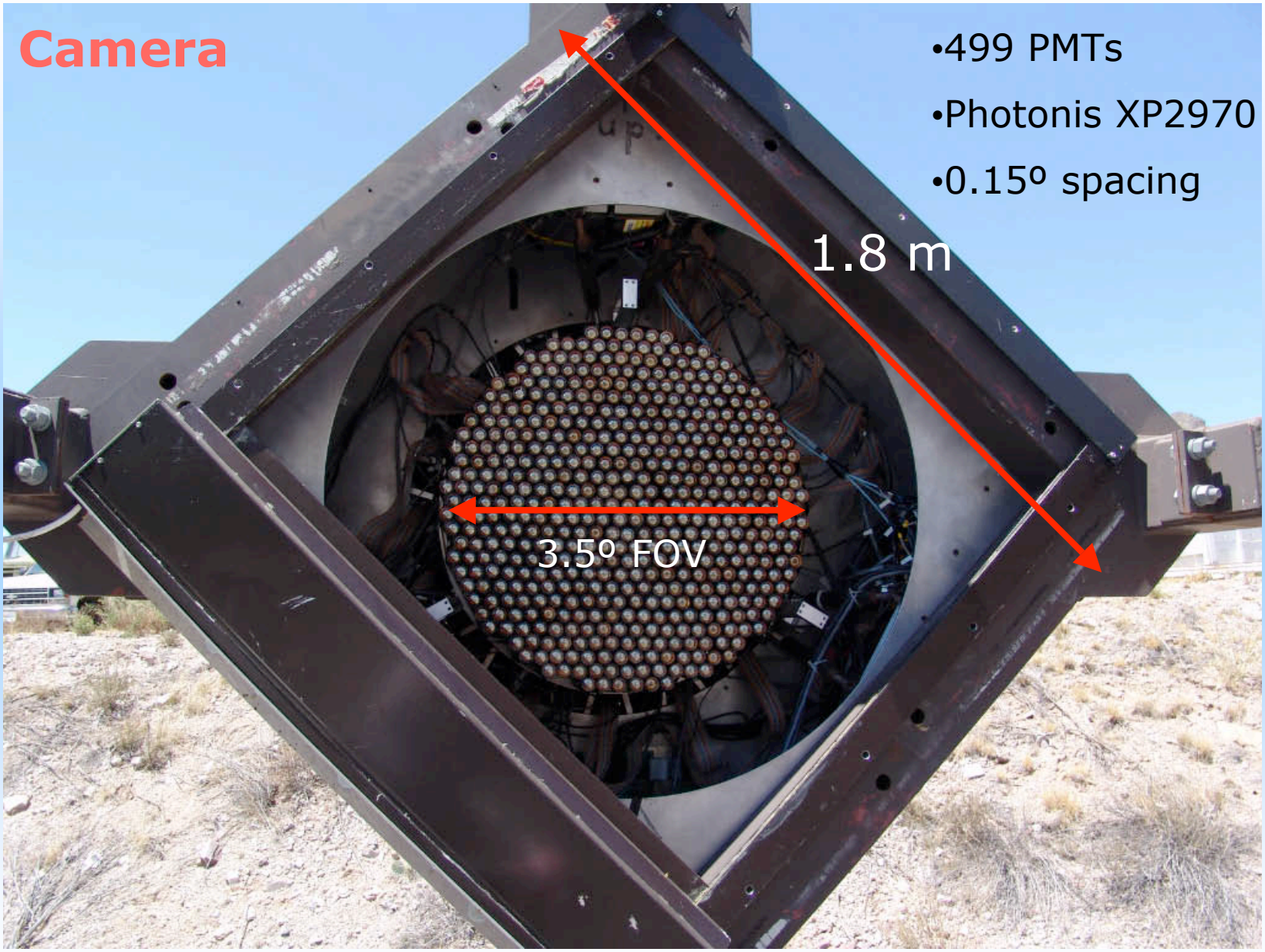
- 350 mirror facets
  - glass
  - aluminium coated on-site
- reflectivity >90% at 320nm
- PSF
  - 0.06º







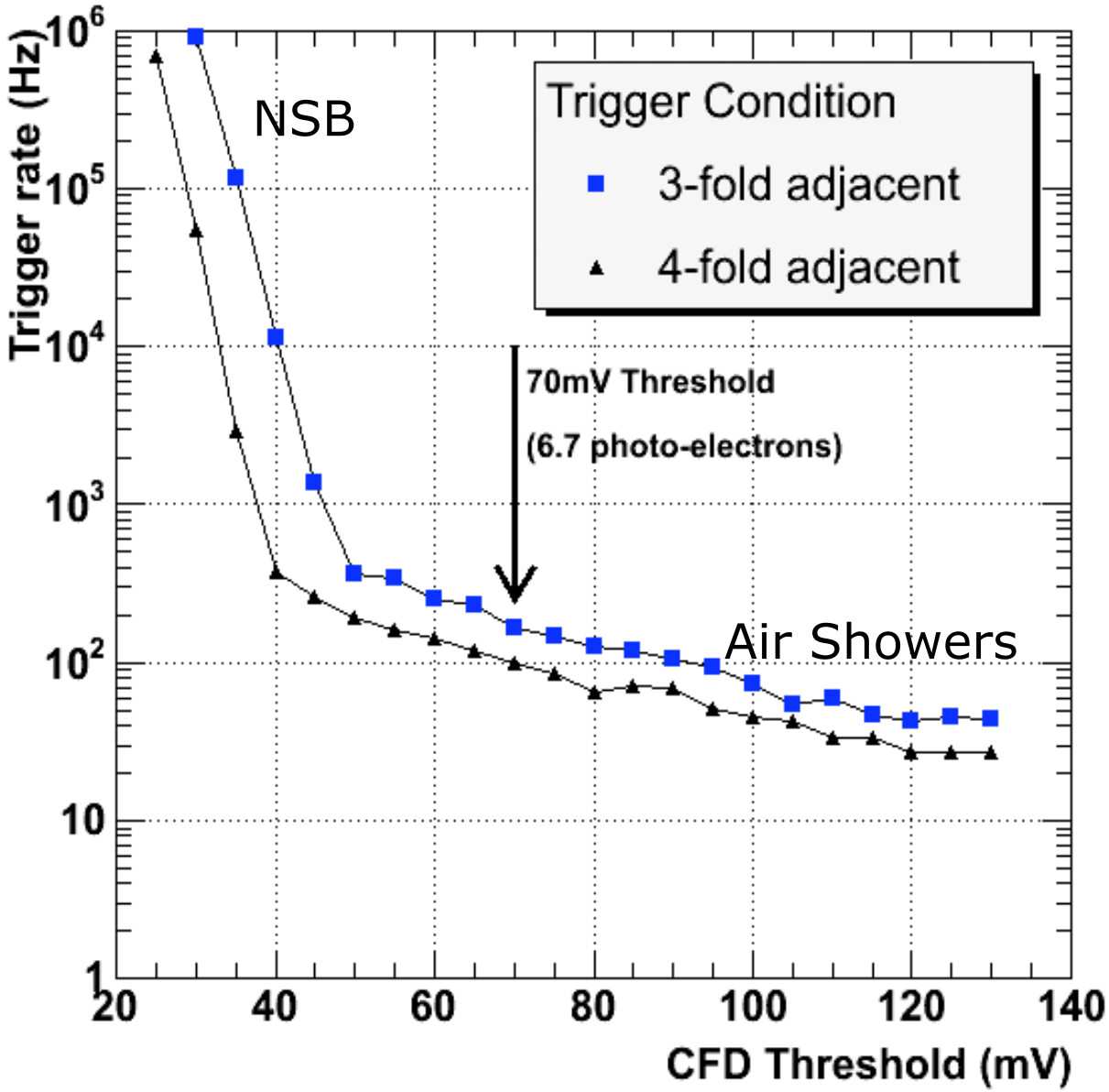
Camera



- 499 PMTs
- Photonis XP2970
- 0.15º spacing

3-Level Trigger

- Each channel has programmable CFDs
- CFD output sent to programmable pattern selection trigger
  - any 3 adjacent PMTs within ~5ns gives a telescope trigger
- telescope triggers sent over fibre-optic to an array trigger system which corrects path lengths
  - any 2 telescopes within 100ns
- Trigger rate ~ 220 Hz



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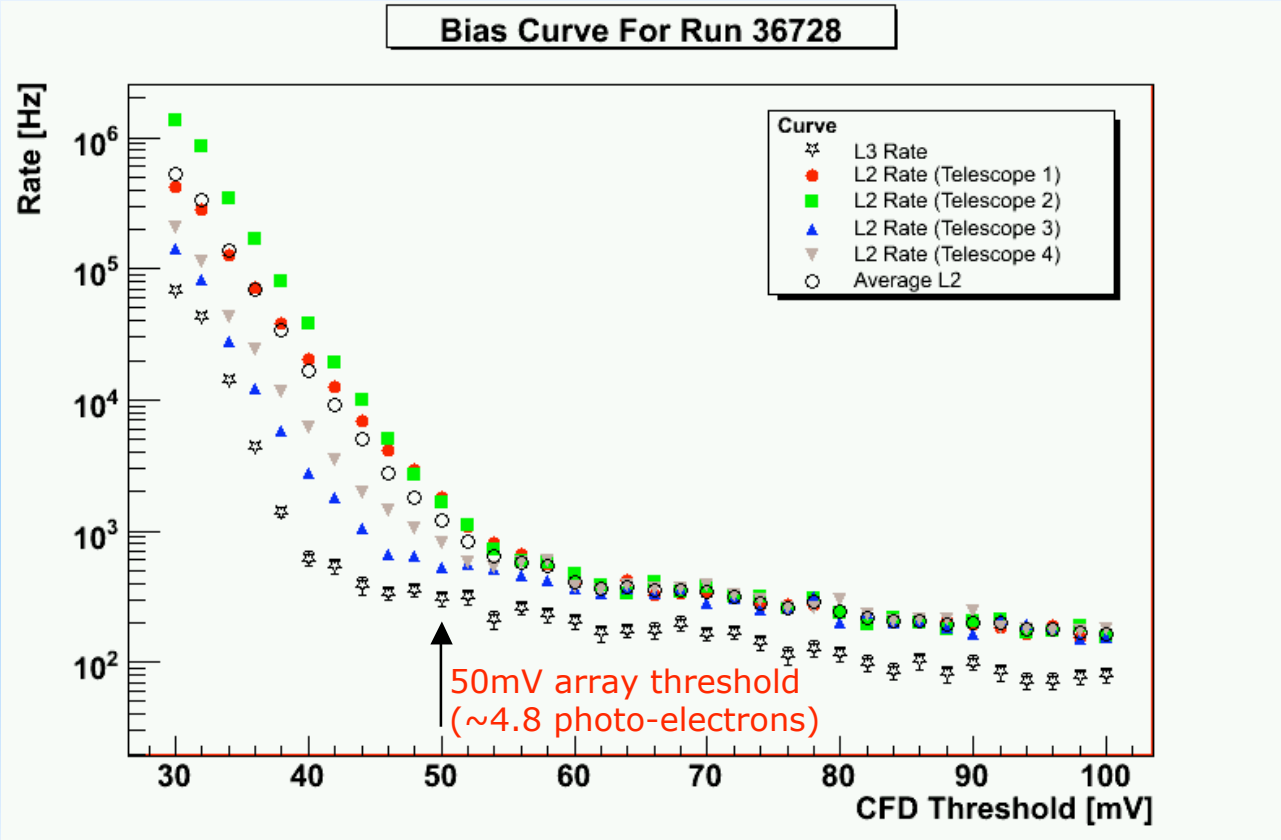
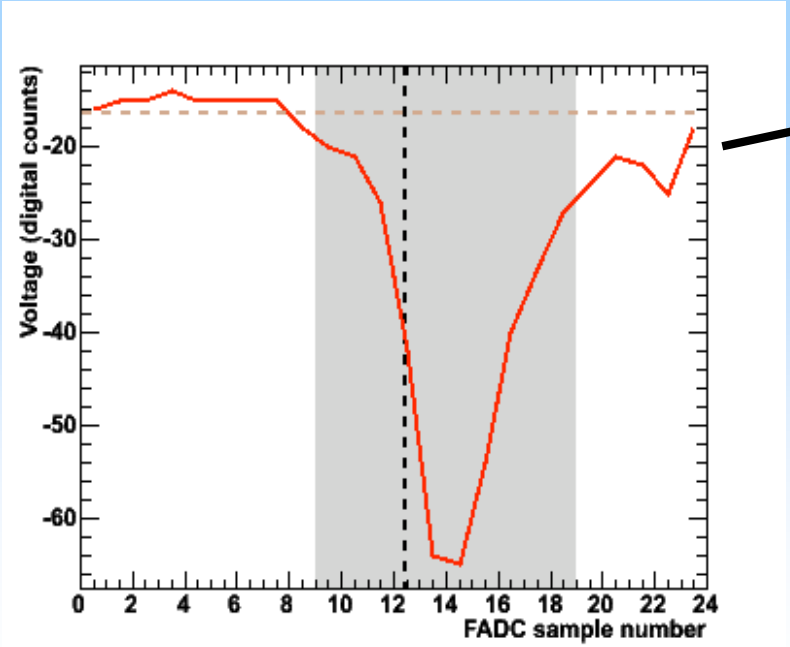
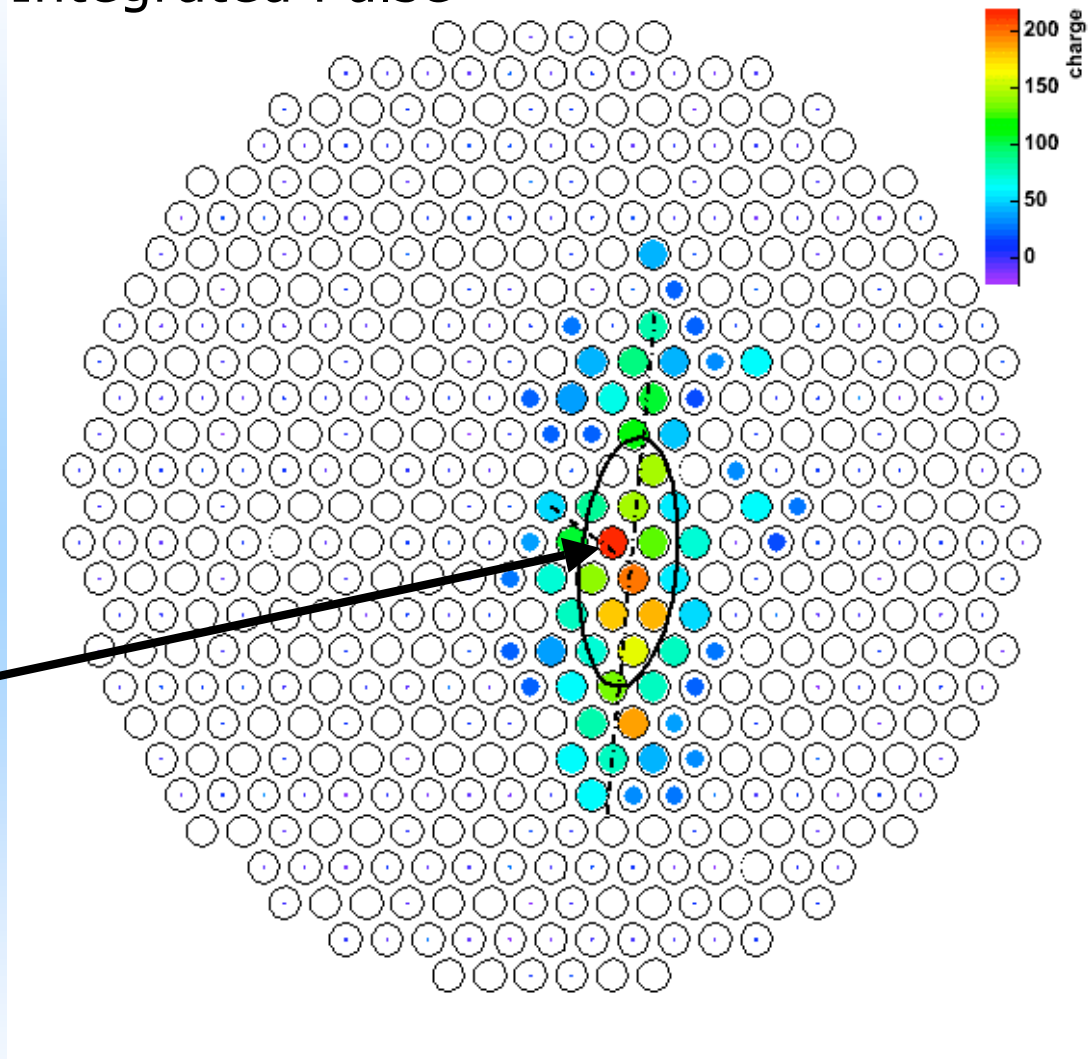


Data Acquisition

- PMT signals digitised with 500MHz sampling FADCs
- Data rates
  - 24 samples/channel
  - 13.5 kb/event/Tel @ 250 Hz
  - **15 Gb/hour !**
  - 15 Tb/year

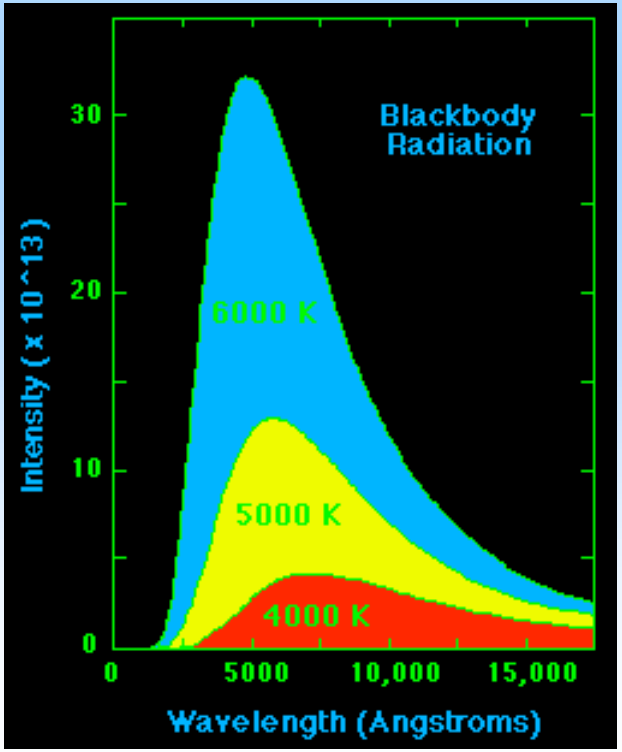


Integrated Pulse



How are they produced?

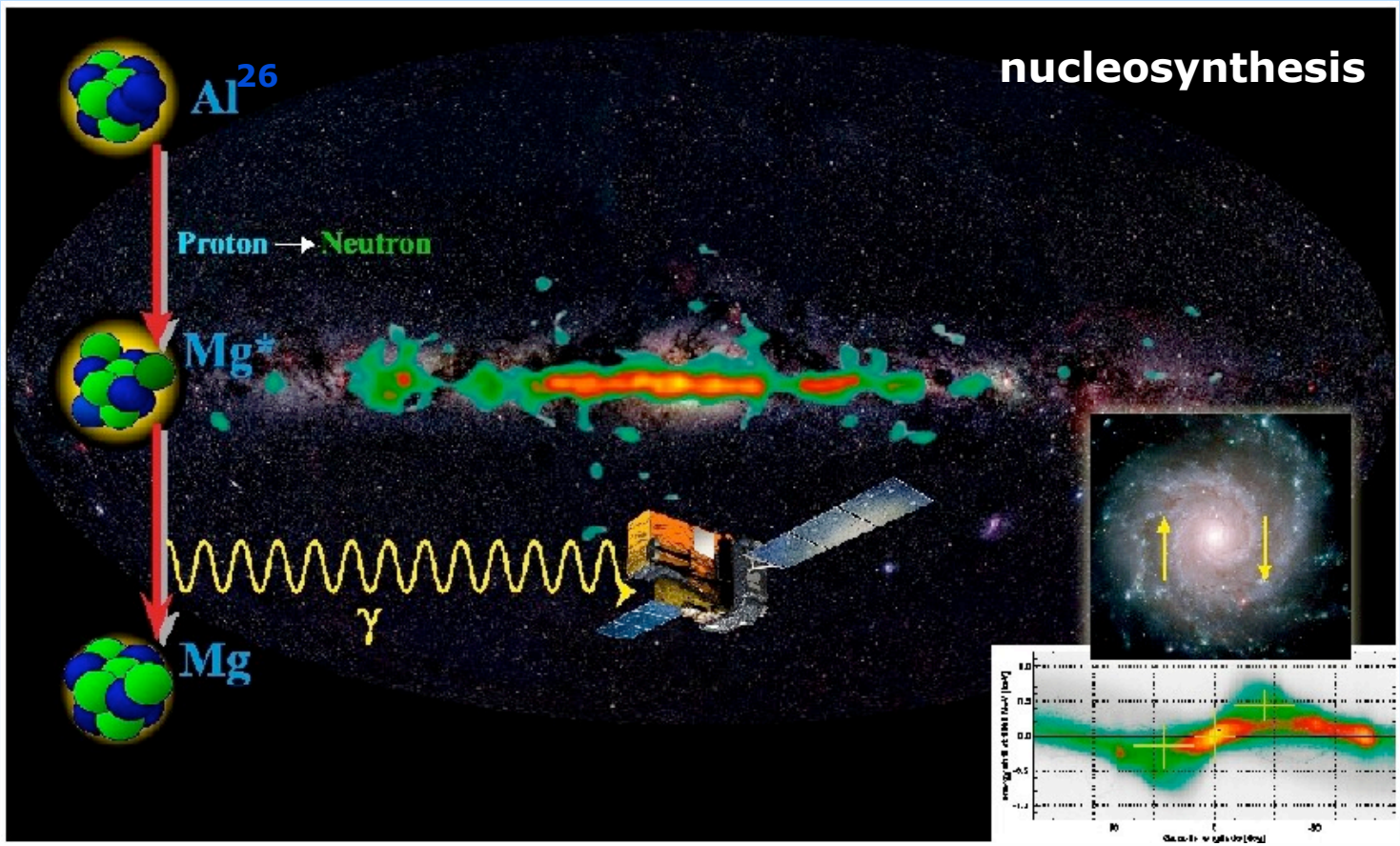
- More usefully:
  - Thermal emission (black-body) accounts for the majority of observed photons from microwave to X-rays
  - Gamma-rays are produced by non-thermal mechanisms



$$\lambda_{\max} = \frac{2.898 \times 10^{-3}}{T}$$

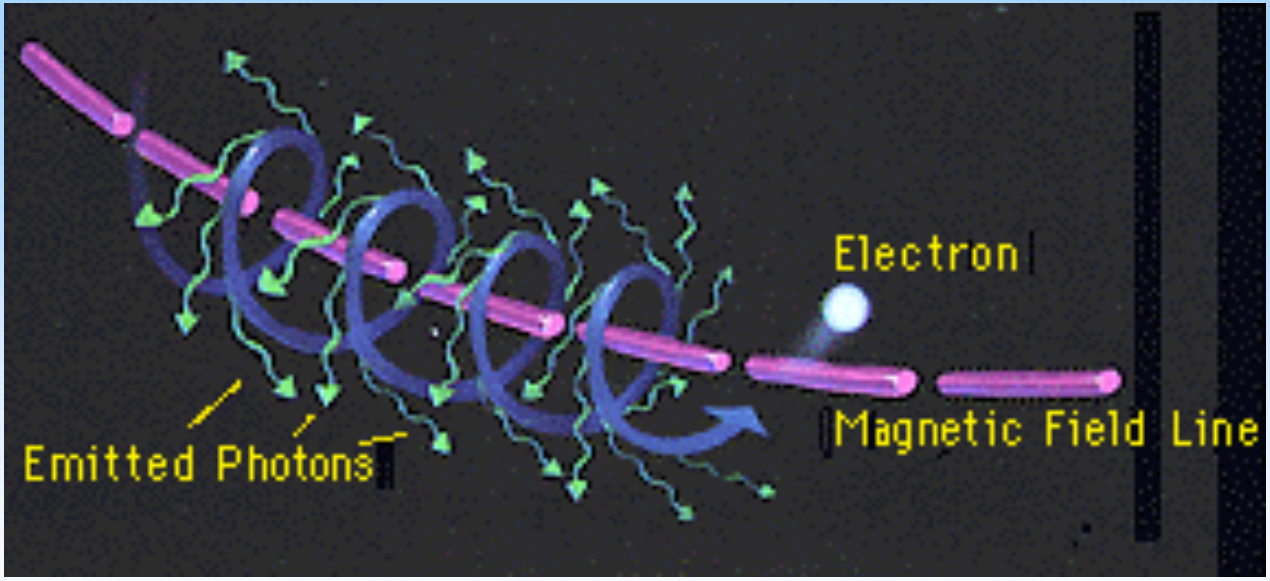
Non-thermal emission mechanisms

- Radioactive decay
  - Produces line emission
  - Relatively low energies (<few MeV)



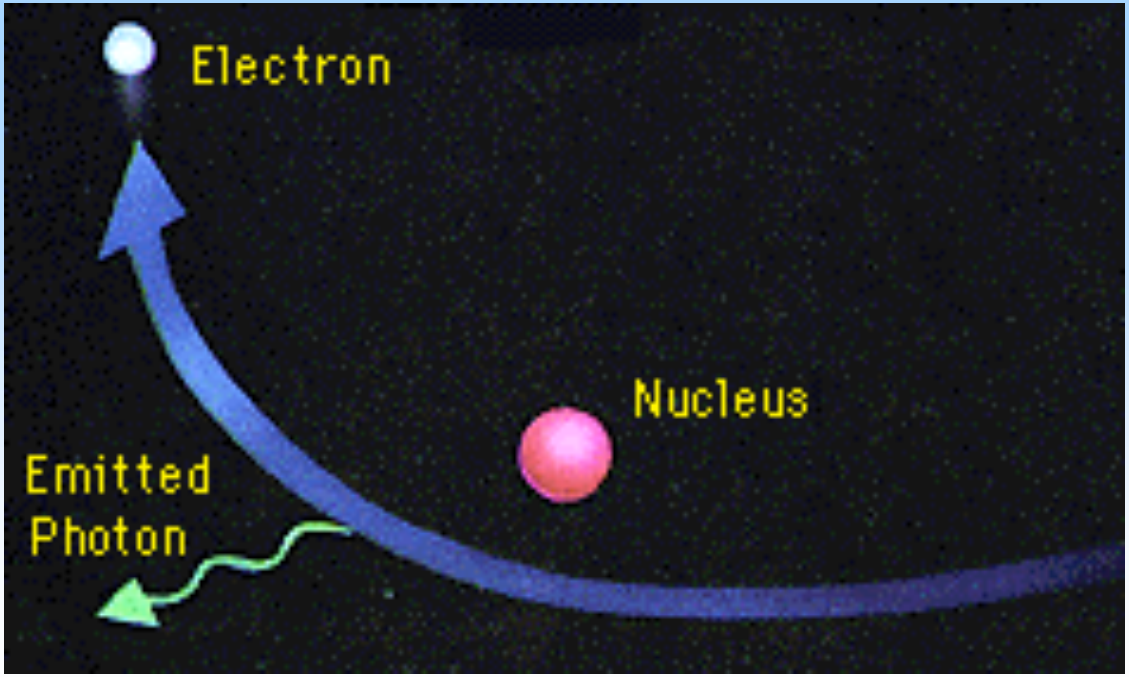
Non-thermal emission mechanisms

- Synchrotron Radiation
  - Produced by relativistic electrons spiralling around magnetic field lines
  - Synchrotron radiated power $\propto E^4$
  - Synchrotron photon energies << electron energies



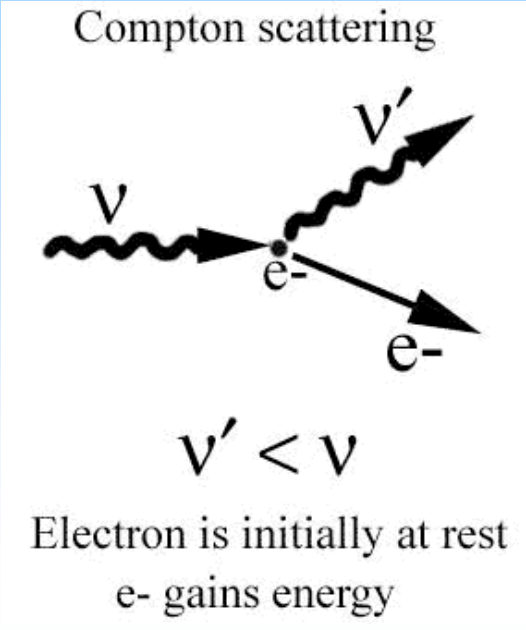
Non-thermal emission mechanisms

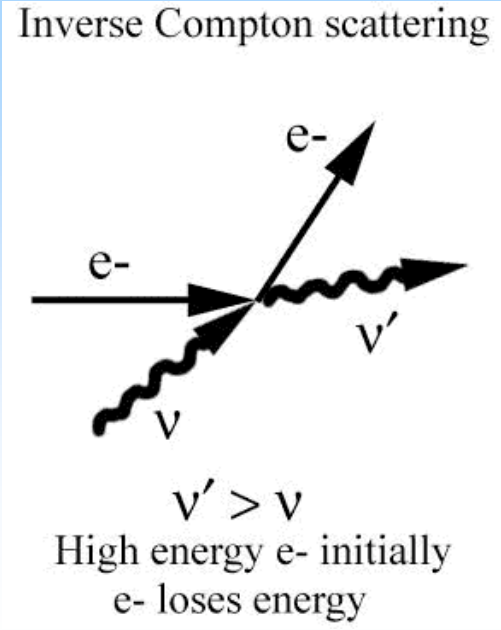
- Bremsstrahlung Radiation
  - Interaction of a high energy (relativistic) electron in the electrostatic field of a nucleus
  - Accelerated charged particle emits radiation
  - $E_{radiation} \sim 1/3\ E_{particle}$



Non-thermal emission mechanisms

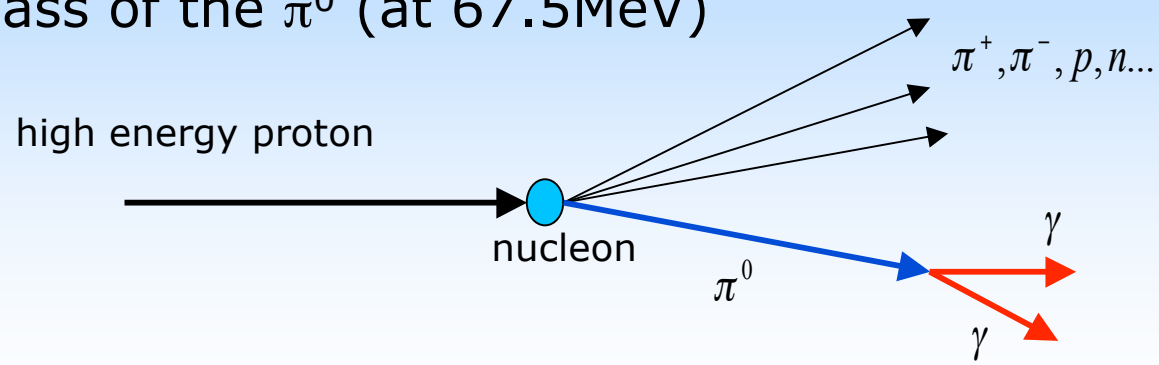
- Inverse Compton Emission
  - In Compton scattering, electron is boosted to higher energy by interaction with a photon
  - in Inverse Compton processes, the photon is boosted to higher energy by collision with a relativistic electron
  - final photon energy $E \sim \gamma^2 E_0$
  - electron Lorentz factor γ can be 100 - 1000





Non-thermal emission mechanisms

- Elementary particle decay
  - relativistic protons collide with nucleons in some target material (e.g. ambient gas)
  - neutral pions (π^0) are produced, which rapidly decay (after 8.10^{-17} seconds) into two gamma rays
  - efficient mechanism to convert proton kinetic energy into gamma rays above 280MeV.
  - Produces gamma-ray spectrum which reflects the proton energy spectrum, but with a "bump" at half the rest mass of the π^0 (at 67.5MeV)



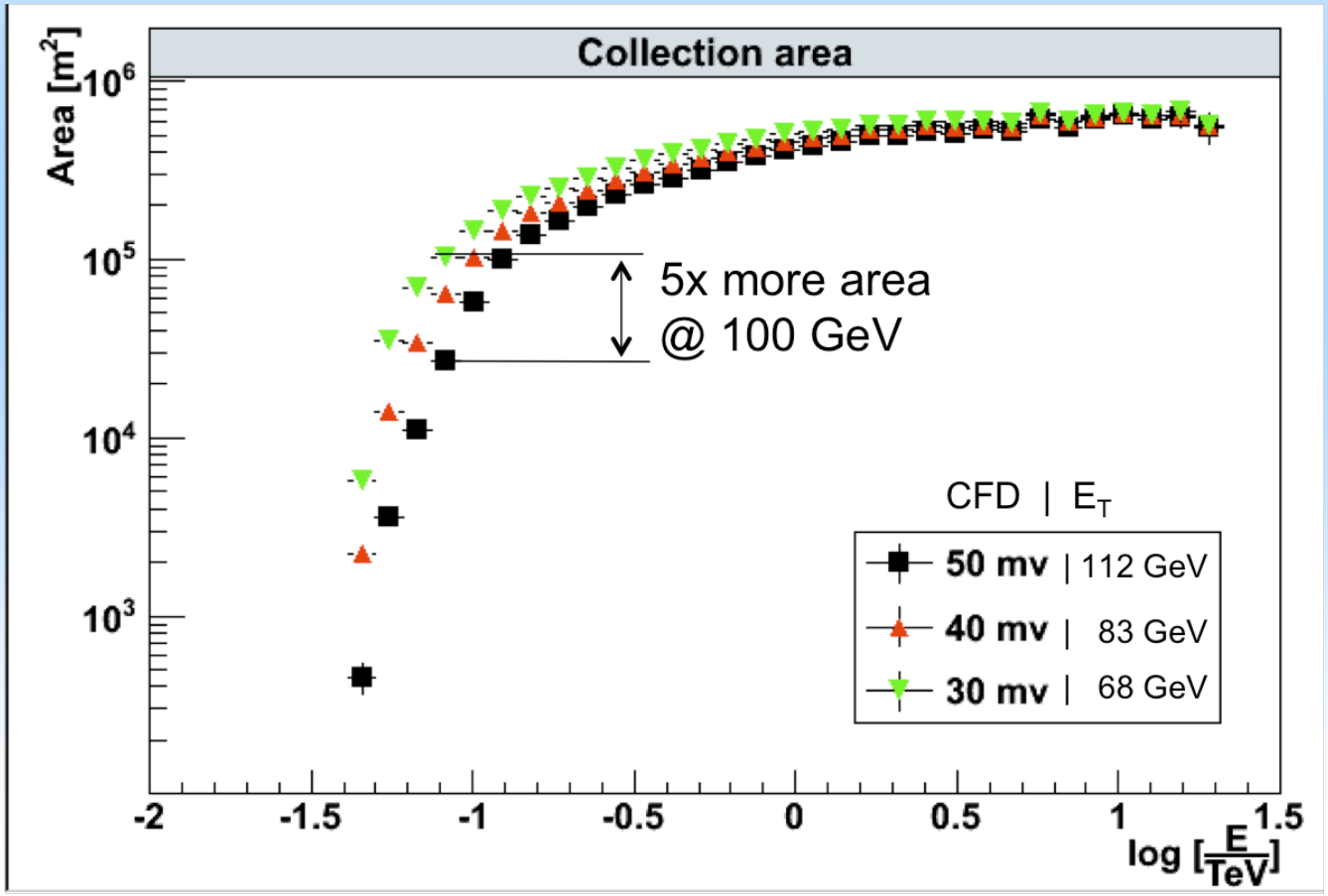
- What this is not:
  - Clear identification of close AGNs as the sources of the highest energy cosmic rays, with a measured maximum distance of 75Mpc and a measured IGMF deflection of 3.1°
- What this is:
  - Statistical evidence for a correlation between the CR arrival directions and a source population with a similar distribution to that of close AGNs
- GZK absorption allows for sources out to ~200Mpc – and the distribution of distances of the source population is unknown
- Significant correlation is seen for ψ up to 6°. The magnitude of the deflection is expected to vary across the sky (e.g galactic B-fields).
- Starting from the best guess cosmic ray arrival directions, gamma-rays can be used as tracers to identify the true sources.

Baseline Upgrade 2: High QE PMTs

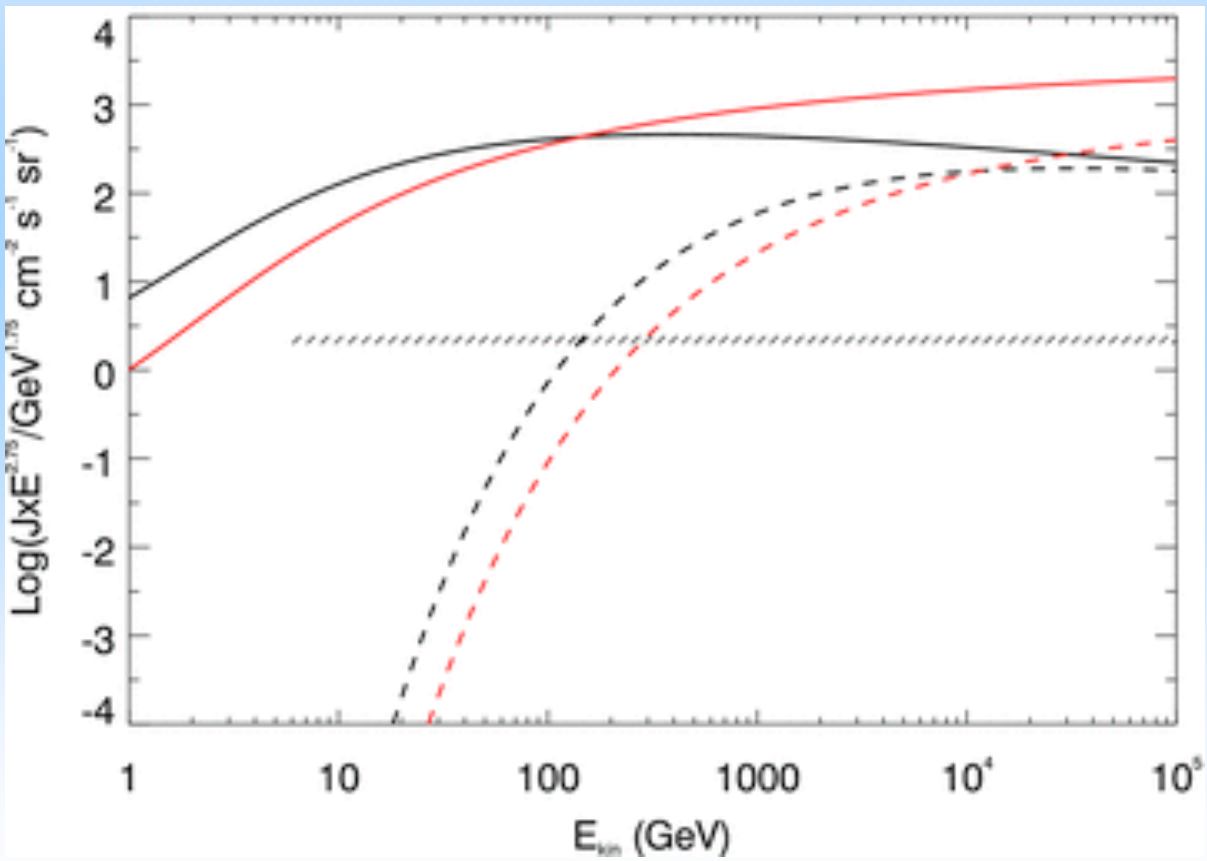
- Questions:
  - Can we acquire a suitable PMT?
  - Can we retrofit the cameras?
- Requirements:
  - Identify a PMT
  - Lab/field tests
  - Simulations with new array layout & QE curve

Baseline Upgrade 3: Trigger Upgrade

- Questions:
  - We have proof of principle of FPGA based L2 systems
  - Can the data acquisition support an increased trigger rate?
  - What is the effect on threshold of the geometrical array trigger?

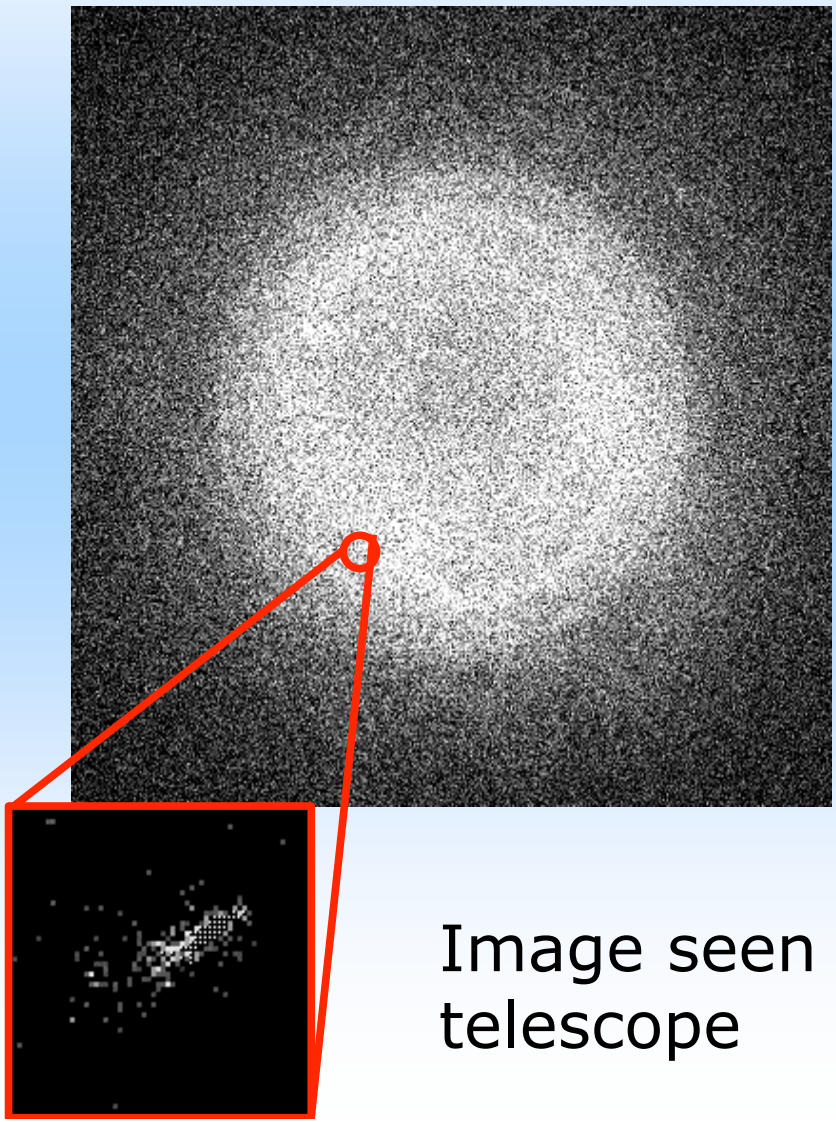


- Figure 1. Current CR spectrum generated by IC 443 at two different distances, 10 (solid curve) and 30 (dashed curve) pc, at the age of the SNR. Two types of accelerators are considered, one providing a continuous injection (black) and the other providing a more impulsive injection of CRs (red). The horizontal line marks the CR spectrum near the Earth. The y-axis units have been chosen to emphasize the excess of CRs in the SNR environment.



Photon distributions on the ground

Gamma ray



400m

Hadronic Cosmic Ray

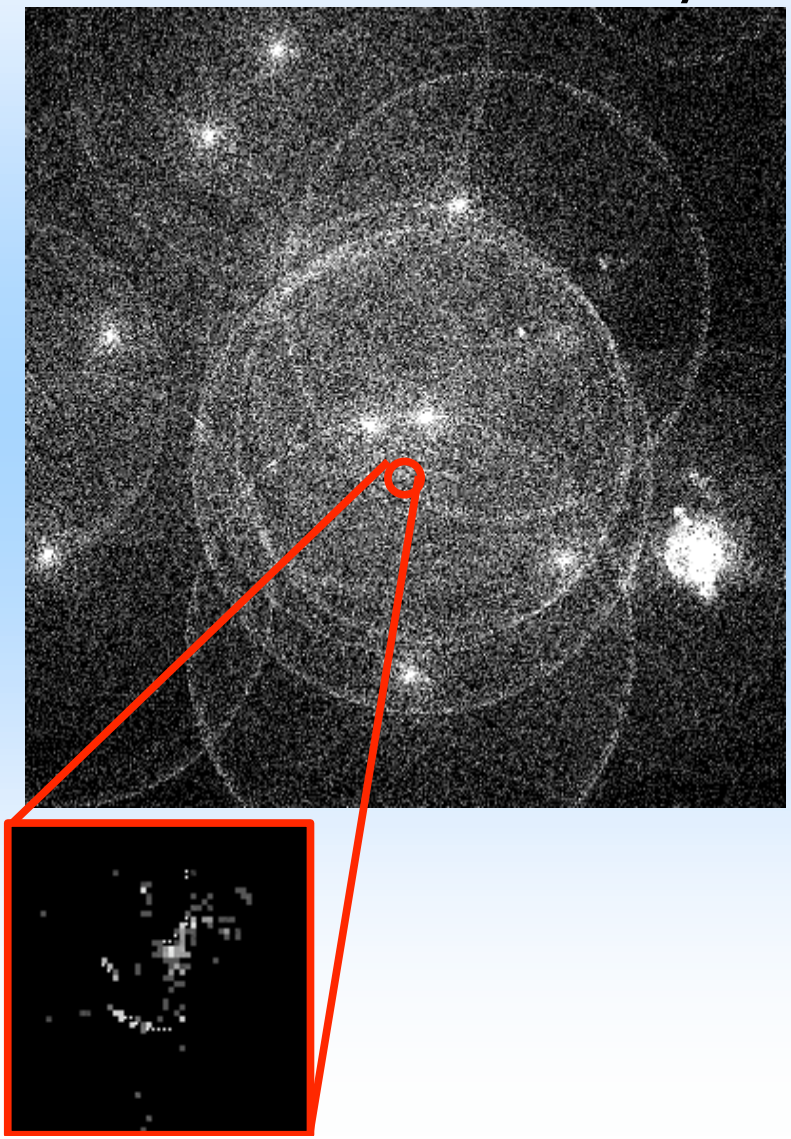


Image seen by a telescope