Status of VERITAS:

Crab Observations
&
Latest Results

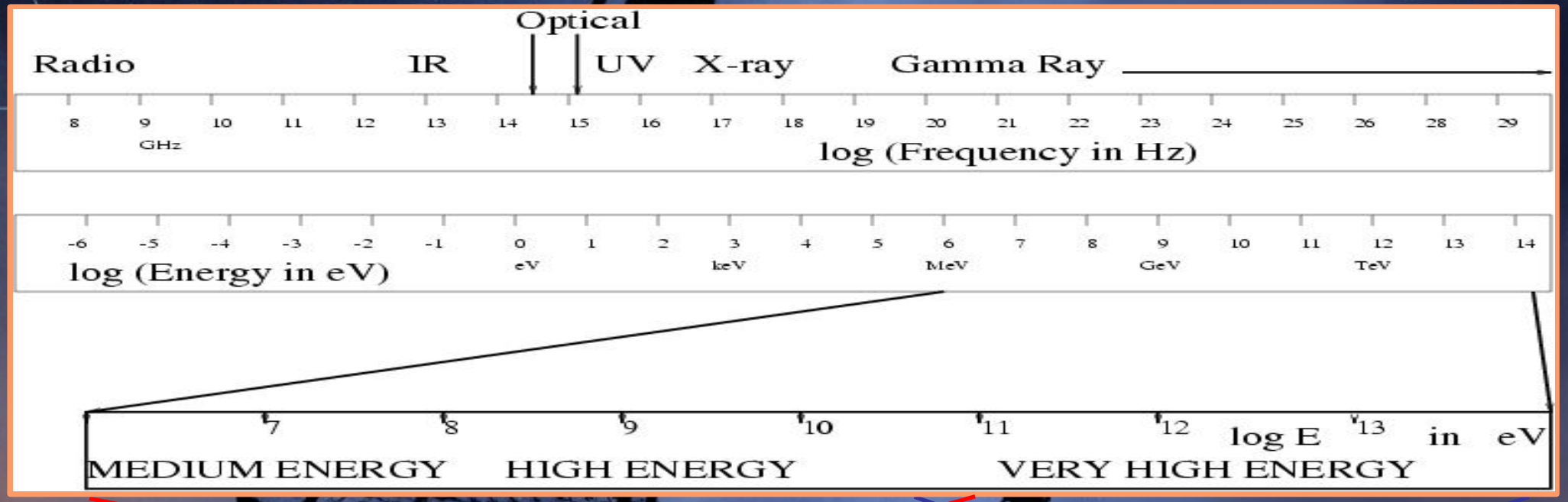
Ozlem Celik, UCLA

UC Santa Cruz, 9/4/2007

Outline

- Science Introduction
- Instrument
- Technique
- Latest Results
- Crab Observations
- Future Plans

VHE Astronomy

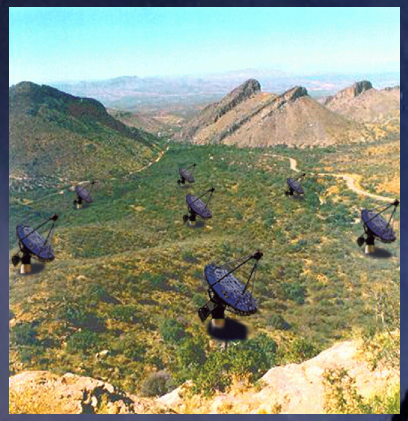


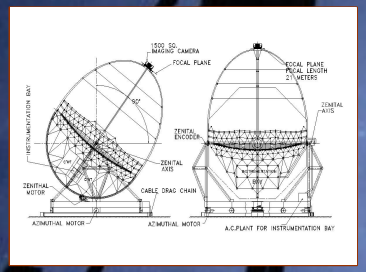
GLAST
Satellite
All-sky survey
Broad energy range

VERITAS, CANGAROO,
HESS, MAGIC
Ground-based
Highest energies

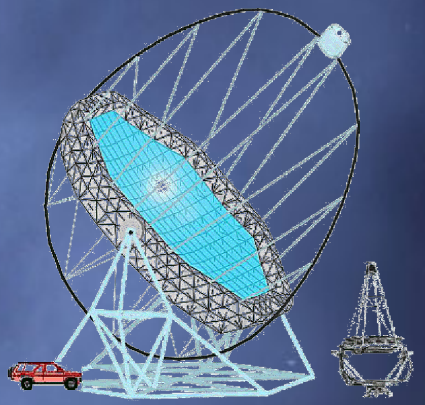
VHE Regime: astrophysical particle accelerators and (potentially) exotic physics (dark matter, massive relics)

Major IACT Observatories





MACE
(India)
2 tel. 2008



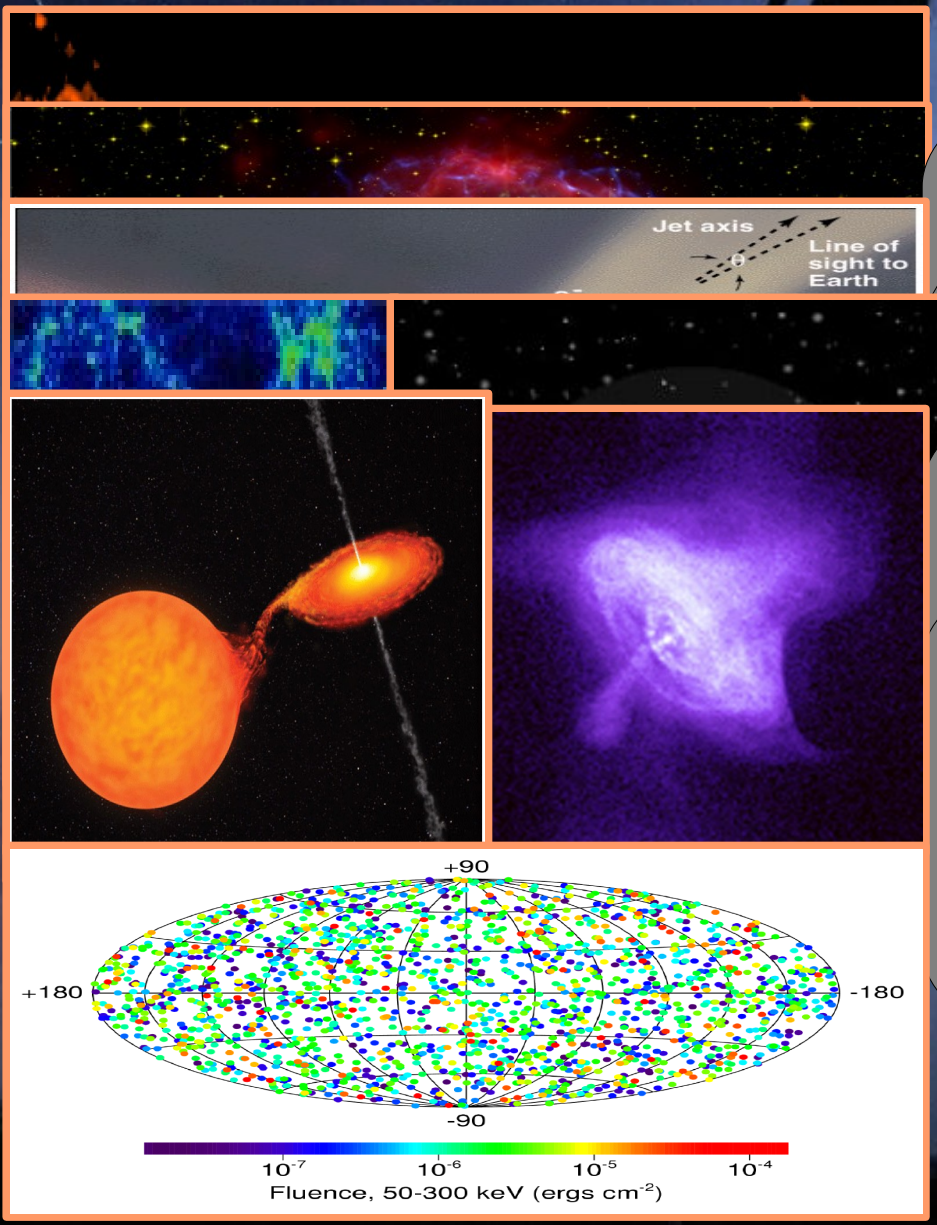
VERITAS, (Arizona)
4 tel. 2007
7 tel. 2008?

MAGIC (La Palma),
1 tel., 2004
2 tel., 2008

HESS, (Namibia) 4 tel., 2003
5 tel., 2007

CANGAROO III, 4 tel., 2006
(Australia)

VHE Science



SKY SURVEY

Supernova Remnants and Pulsar Wind Nebula

VHE BLAZARS

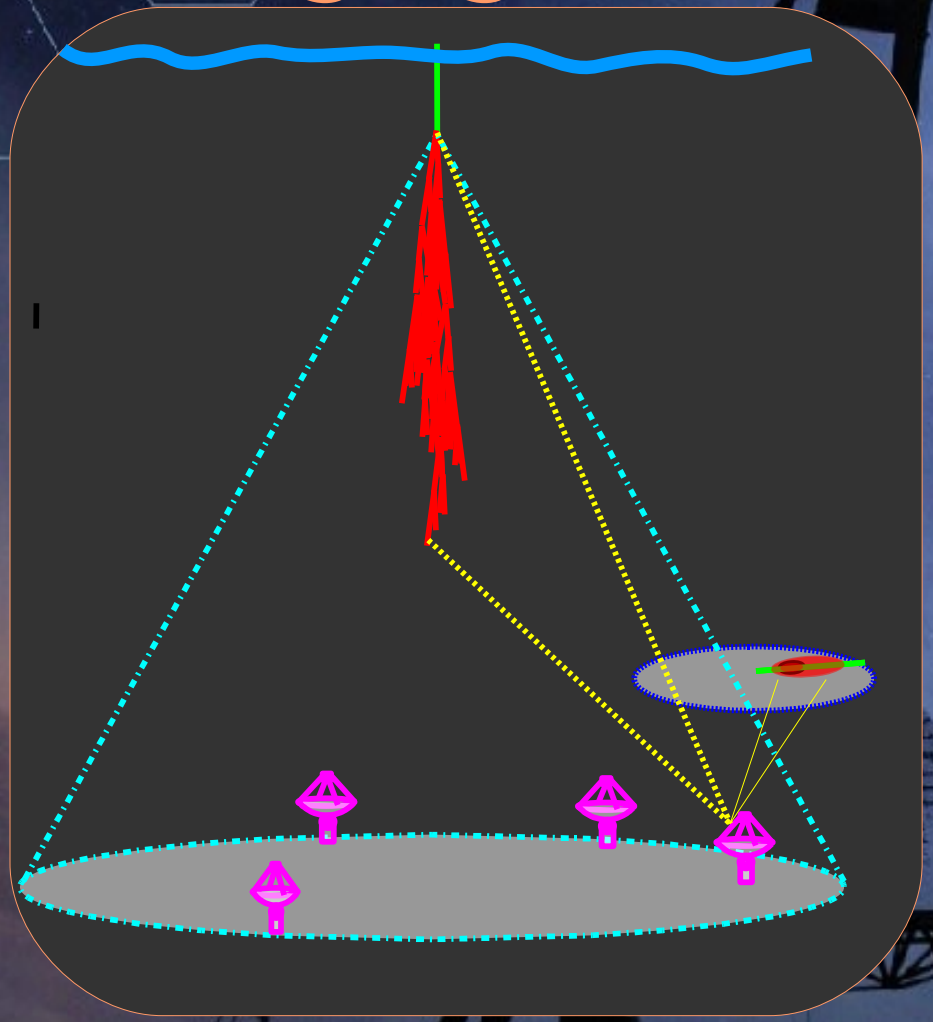
Dark Mattter

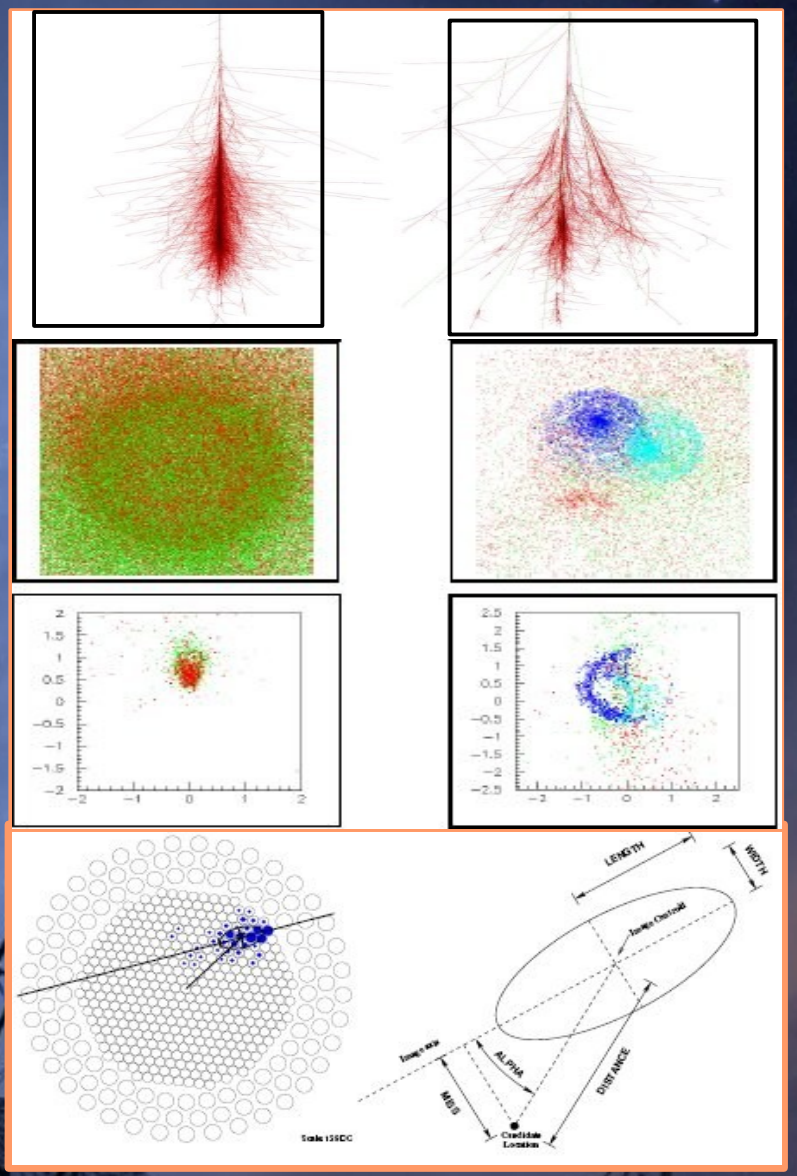
Microquasars

Pulsars

GRBs

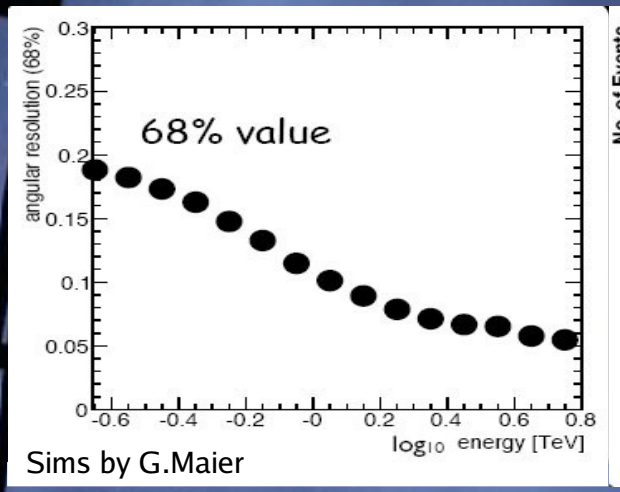
Imaging Technique



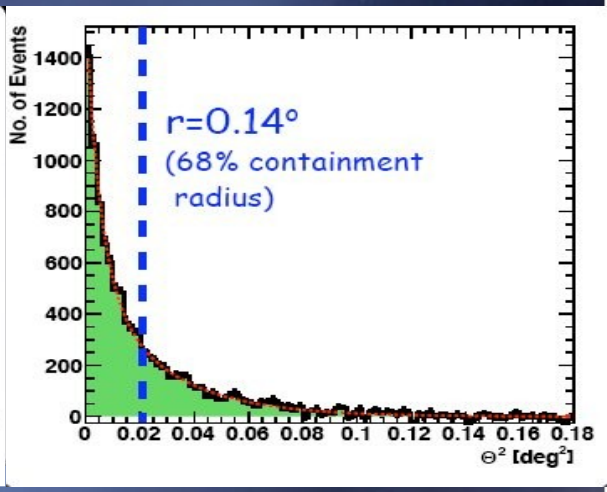


- Distinguish compact images of gamma-ray showers from more irregular images of hadron showers.
- Additional rejection from knowledge of source position for point sources.

Stereo Observation Advantages

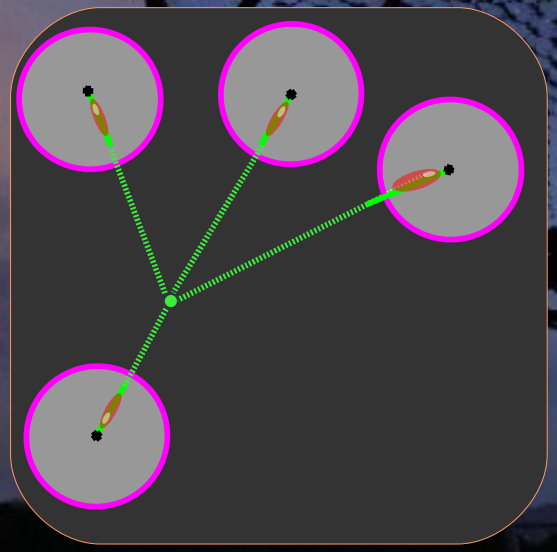


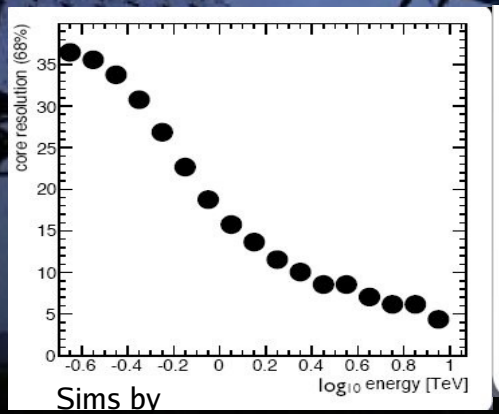
Sims by G.Maier



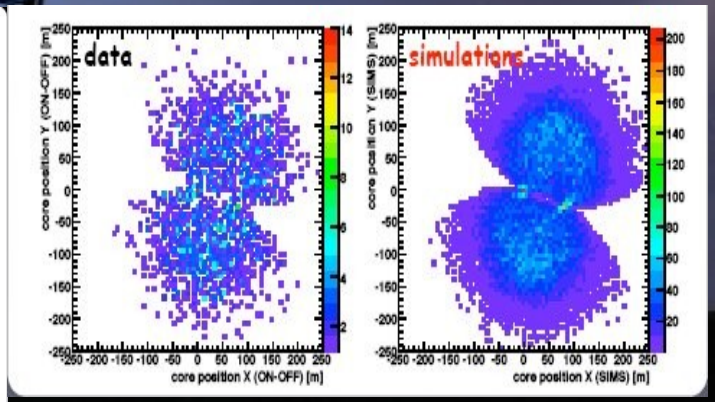
Stereo Angular Resolution ~ 0.1 – 0.2°

- Core Reconstruction Resolution: ~ 5-30 m

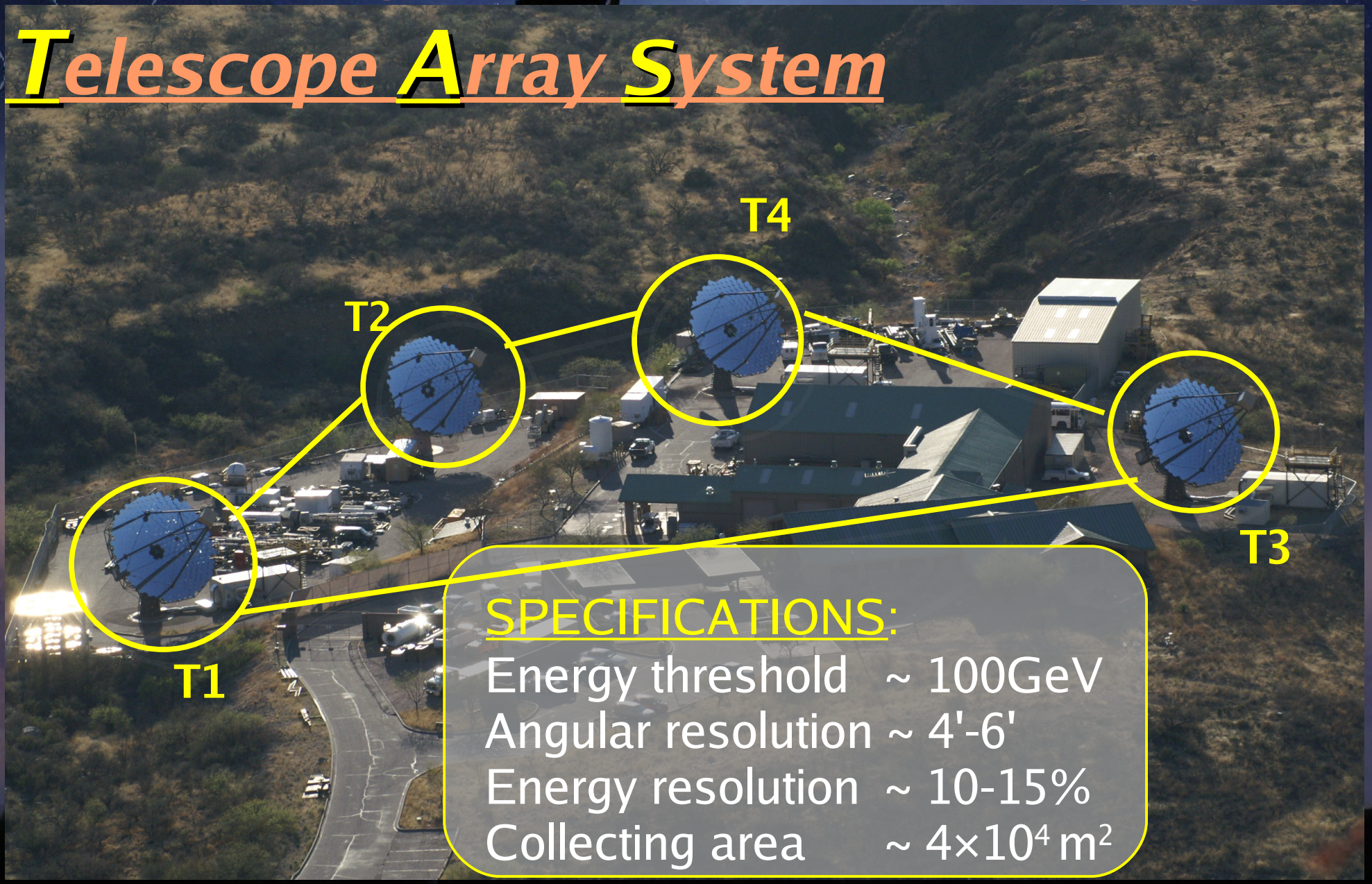




Sims by



Very Energetic Radiation Imaging Telescope Array System

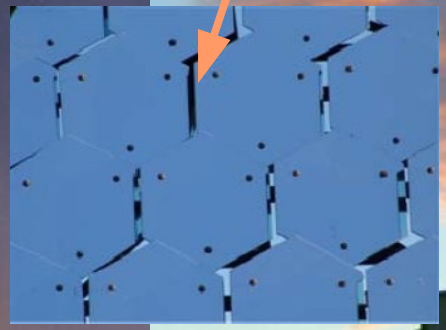


SPECIFICATIONS:

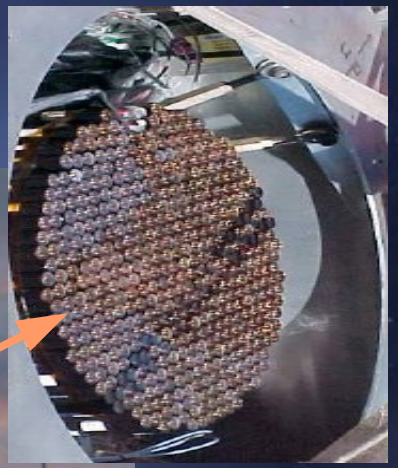
Energy threshold ~ 100GeV
Angular resolution ~ 4'-6'
Energy resolution ~ 10-15%
Collecting area ~ 4×10^4 m^2

Telescope Design

12 m diameter/focal length
350 mirror facets -> 110 m^2
PSF - FWHM ~ 0.06°



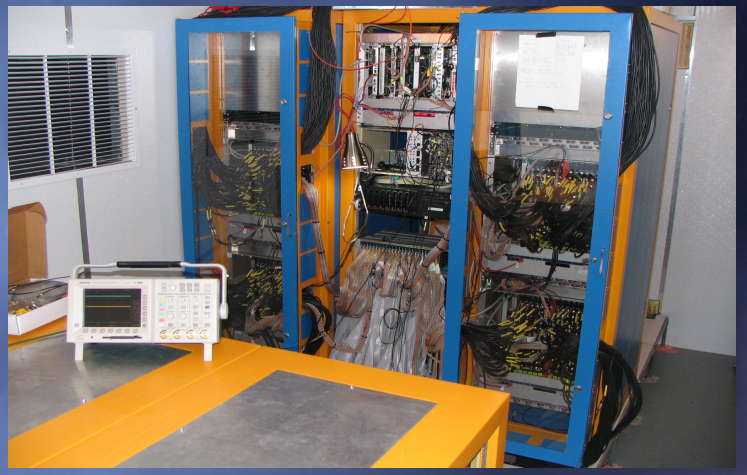
499 pixels
0.15° spacing
FoV ~ 3.5°

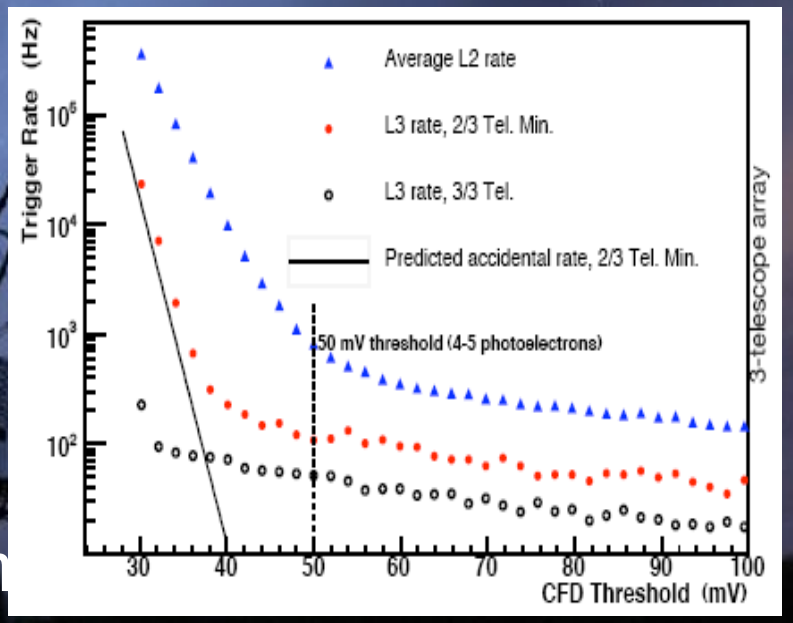


500 MHz FADC's
3-Level Trigger

Veritas Trigger System

- Level 1 (Pixel) Trigger:
  Constant Fraction Discriminators
  Th ~4-5 pe.
- Level 2 (Telescope) Trigger:
  Coincident triggers of Pixel Patterns : 3NN
- Level 3 (Array) Trigger
  Coincident triggers of multiple telescopes: 2/4
  Event time/number tagging.
  Command for recording of event
  Interface to Array Control, Trackin
  Telescope DAQ, DB, Data Harvester.





4 Telescope Observations

Last telescope commissioned in March.
4 Telescope array started observations on April 2007.

A 4-Telescope Event !

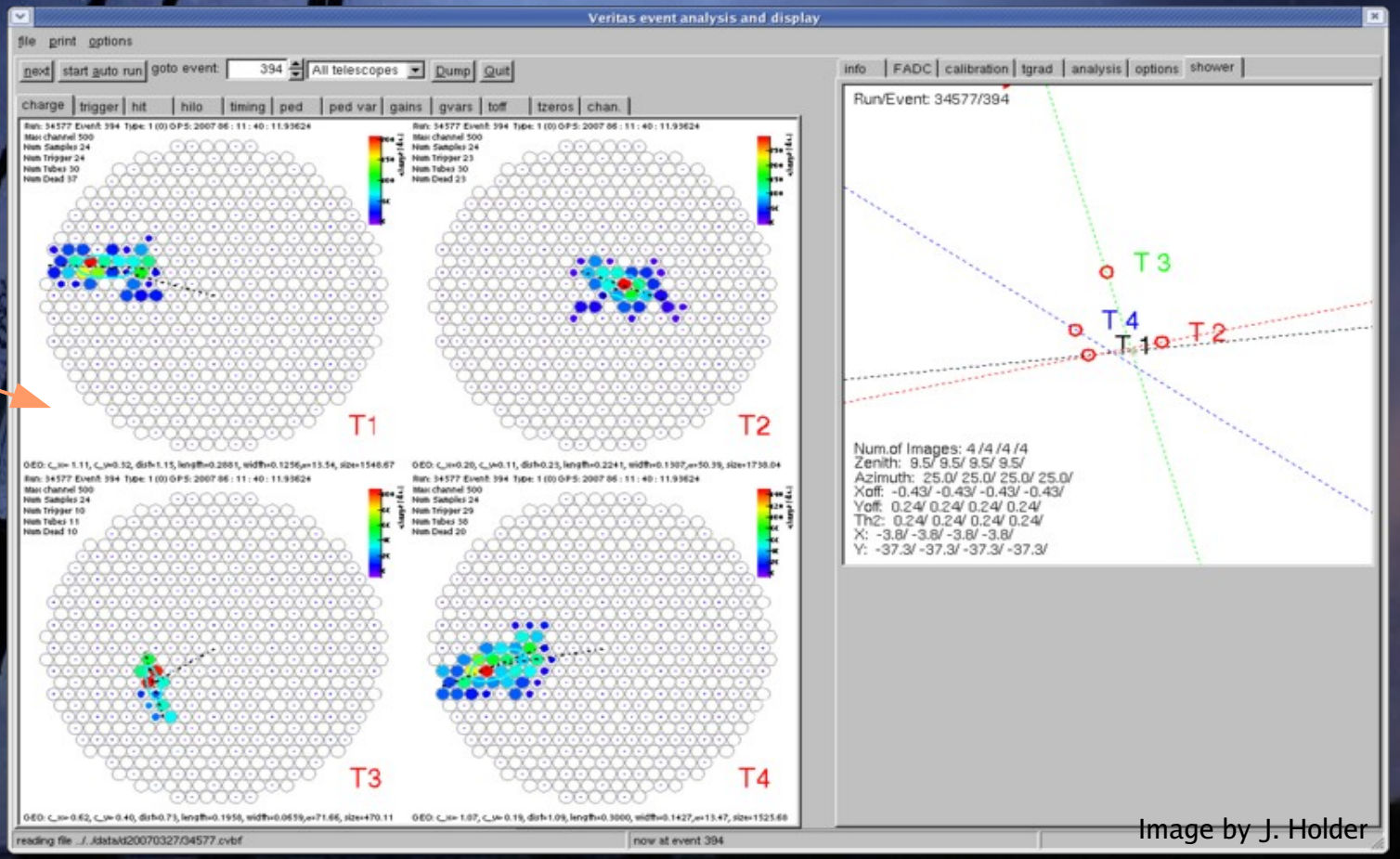
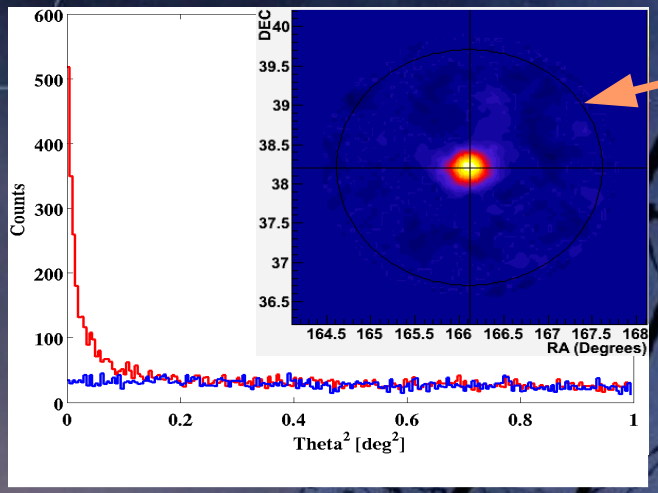


Image by J. Holder

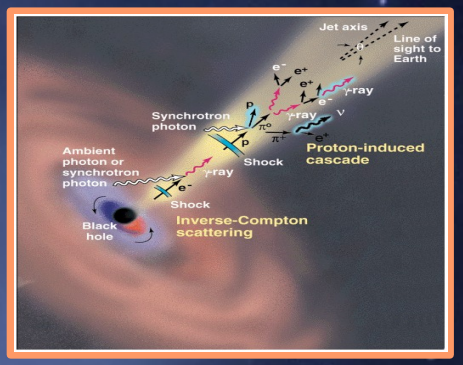
Summary of Latest Results

- AGN's
- Binary System
- SNRs
- GRBs
- Others

AGN Observations



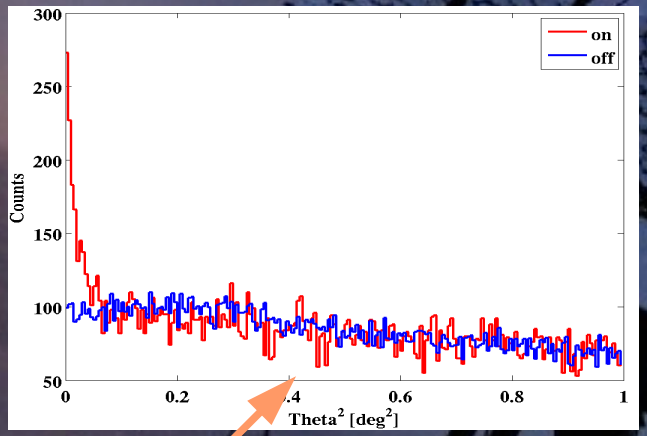
Mrk 421: Observed for > 7 hrs
35 σ - 5.6 gamma/min



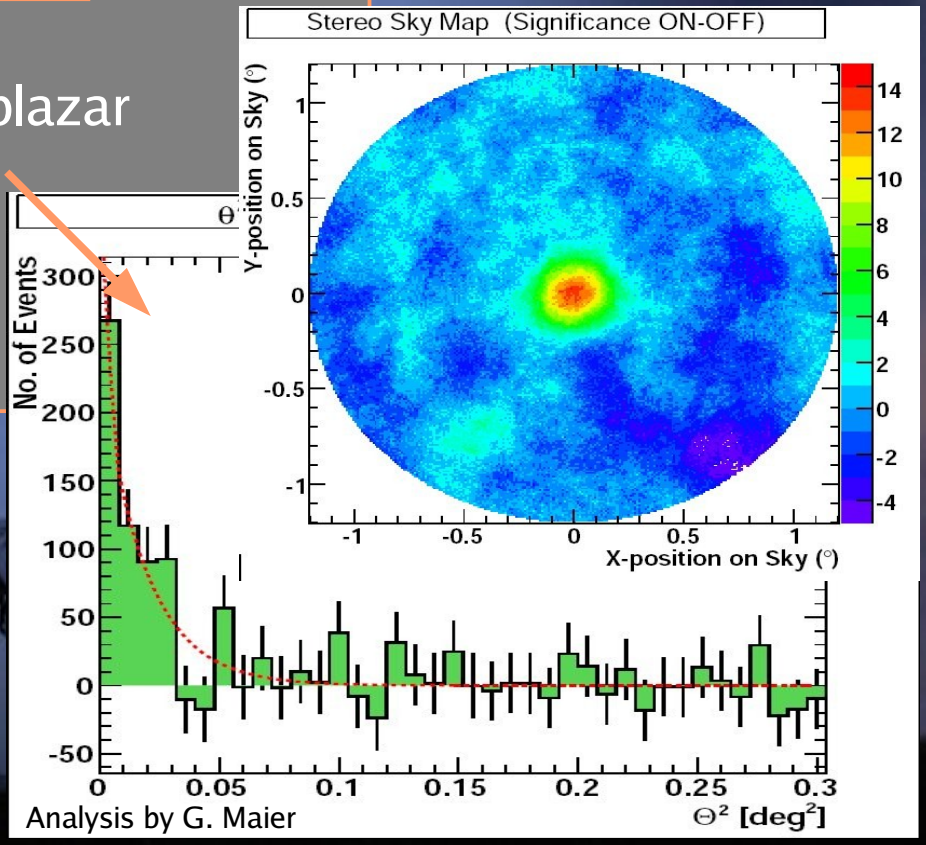
1ES1218+304

z=0.182 =>
2nd farthest VHE blazar

~ 18 hrs of data
σ = 9.0
R = 0.23 γ /min

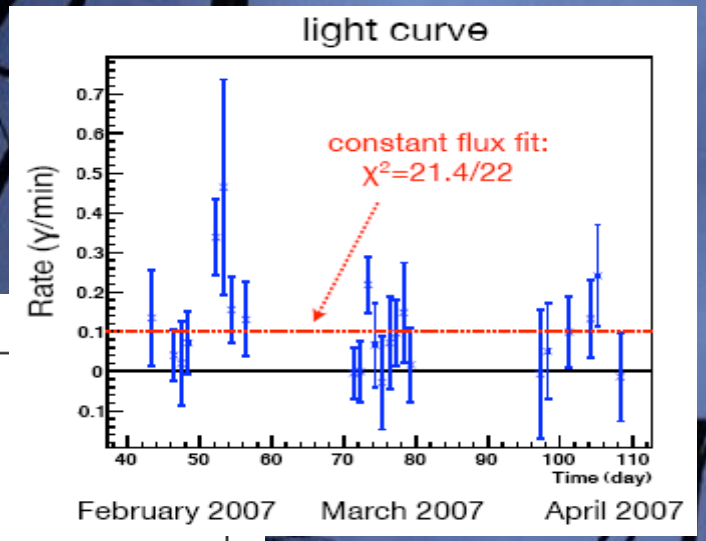


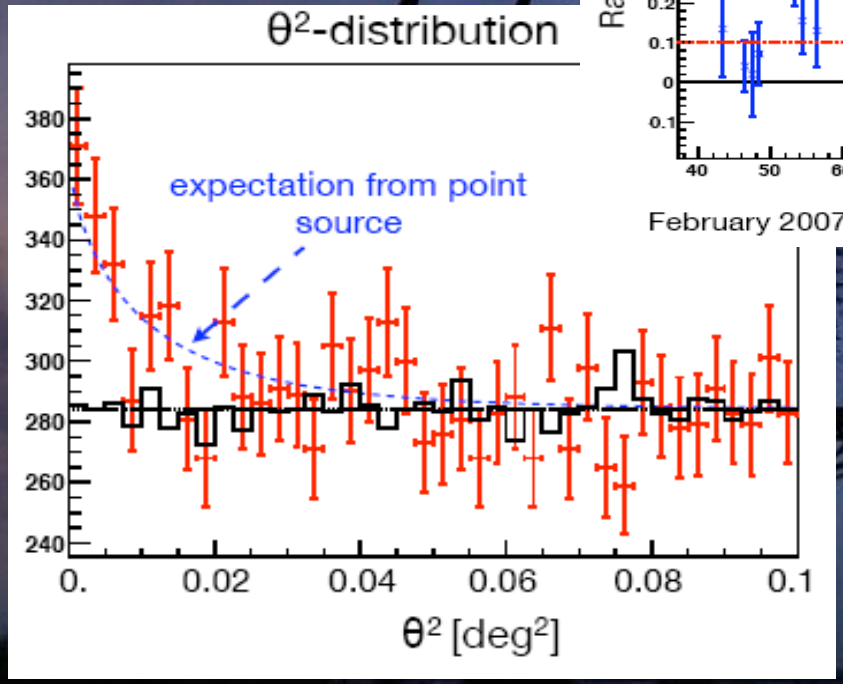
M rk 501: Observed > 11.4 hrs
16 σ - 0.8 gamma/min



AGN Observations - 2

M87: Non-Blazar extra-galactic source:
A giant Radio Galaxy





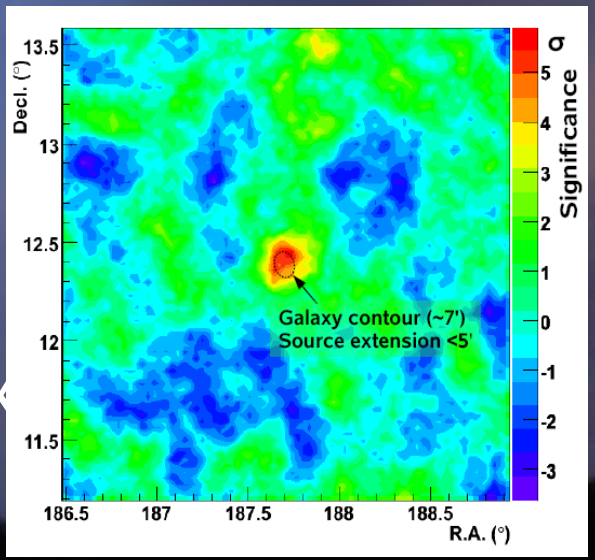
Detected: 5.1 σ
R= ~0.1 γ/min
~1.7% Crab Flux

Upper Limits on:
- 1ES0647+250
- 1ES0806+524
- H1426+428
- 1ES1011+496
- RXJ1211.9+2242

HBL

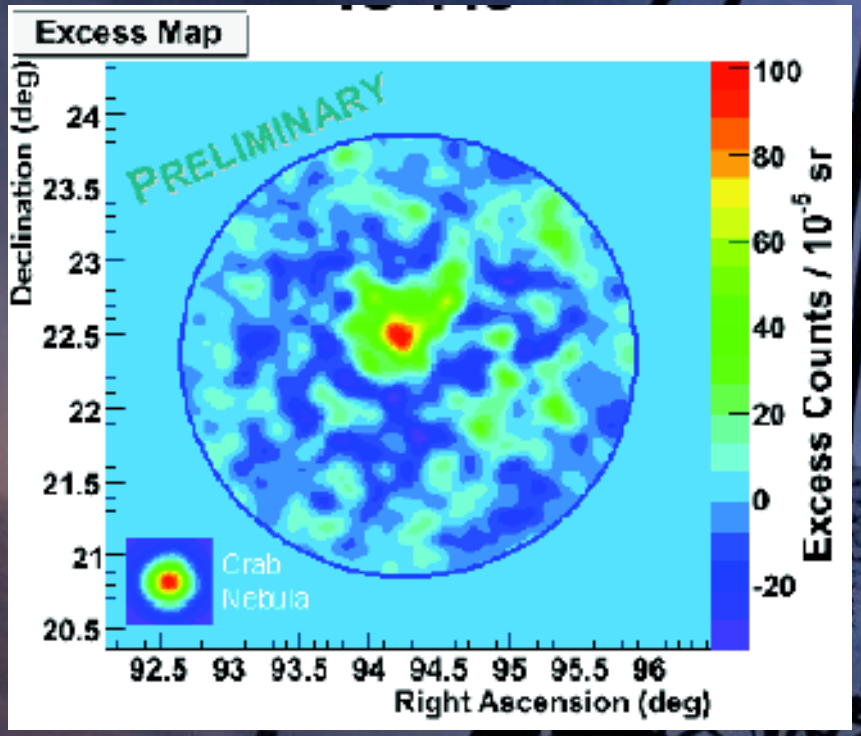
- RGBJ1413+436
- 1ES1627+402
- 3C279

FSRQ



SuperNovae Remnant & PWNe

IC443: SNR Interacting with molecular Cloud

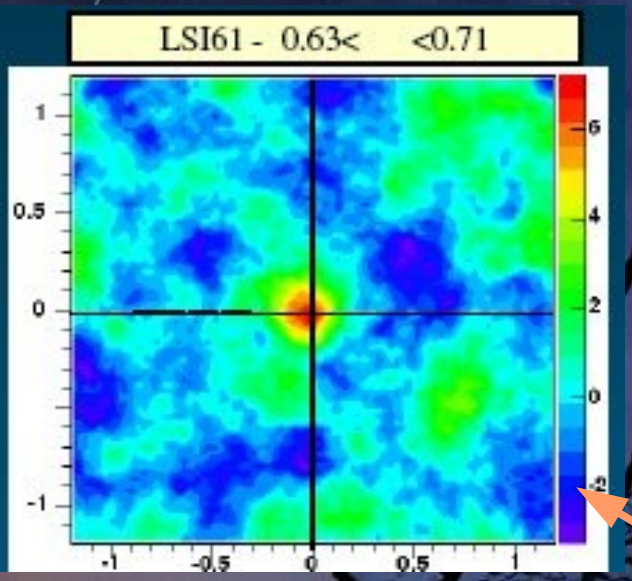


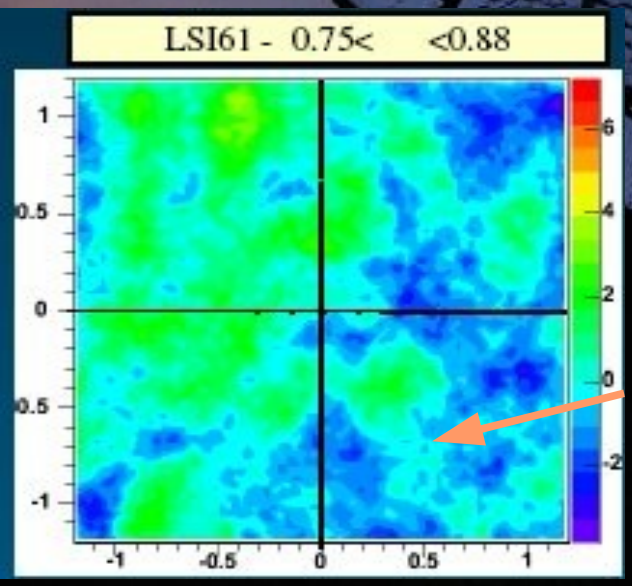
- 16 hrs of 3-Telescope Obs.
- 6 σ Detection at 0.24 γ/min
- F(E>200 GeV) ~ 4% Crab Flux.

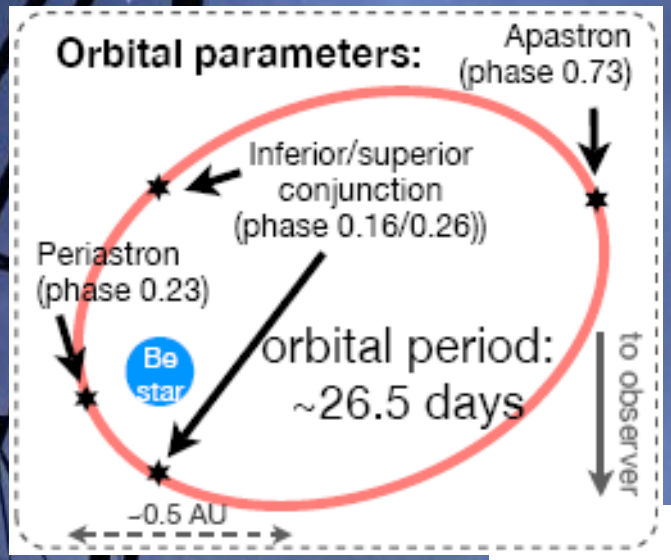
PWNe Upper Limits:

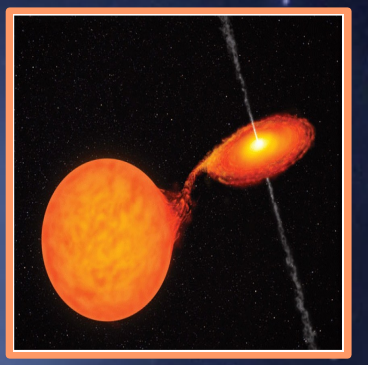
- J2021+3651: F_{UL} = 4.6% Crab
- J2229+6114: F_{UL} = 2.7% Crab
- J0205+6449 (3C58): F_{UL} = 2.4% Crab
- MGRO J2019: F_{UL} = 3.0% Crab

Binary Systems: LSI+61 303



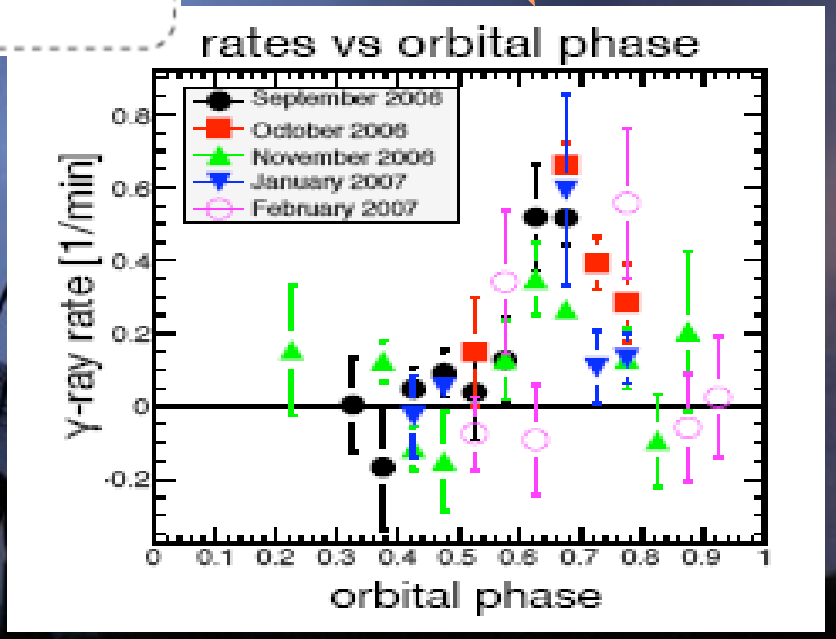






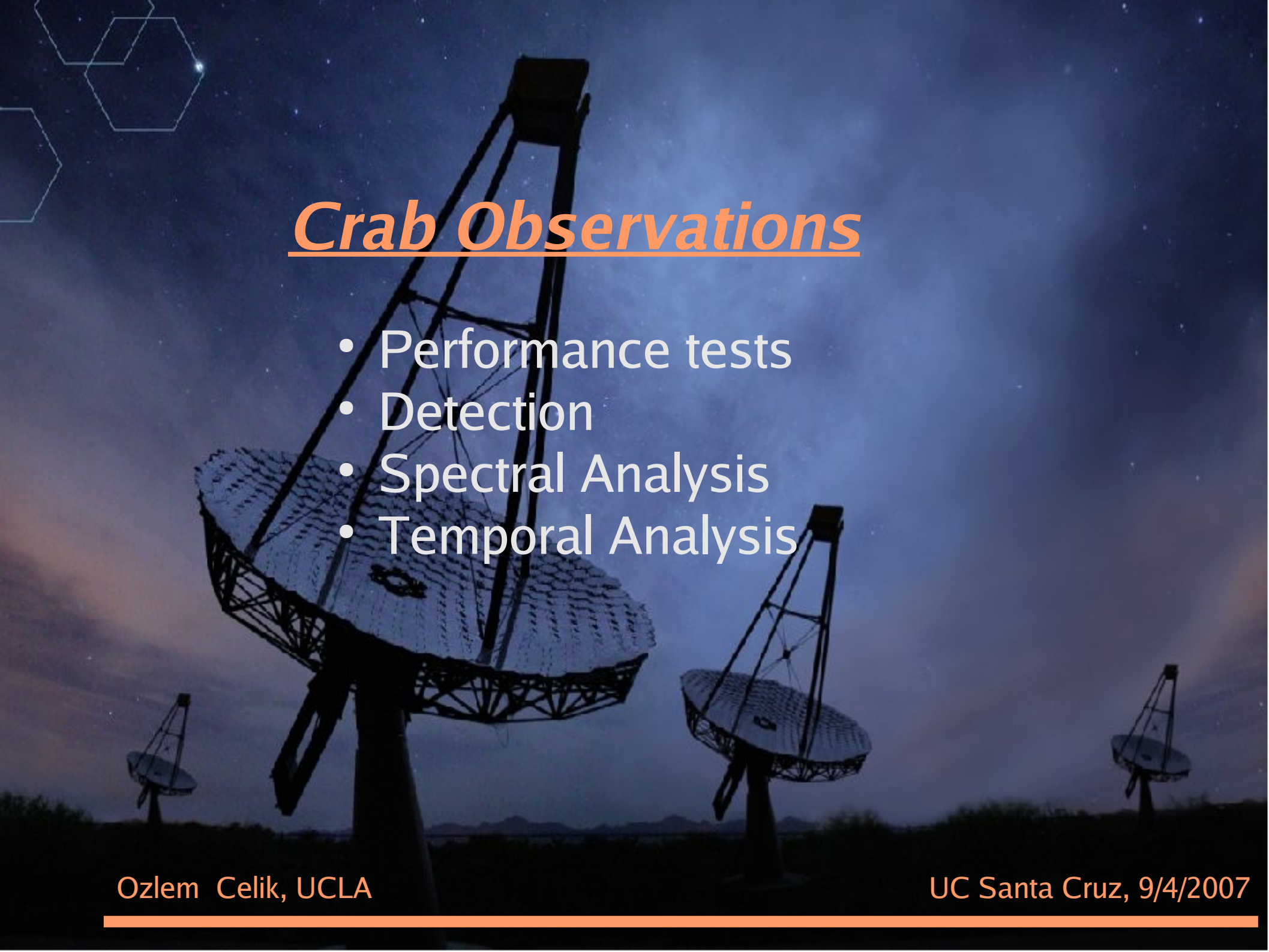
Observations of
5 orbital cycles,
phases 0.3-0.95

8.5 hrs of data
σ = 7.1
R = 0.33 γ/min
7 hrs of data
σ = 0.24
R = 0.013 γ /min



More Observations

- Upper limits on GRBs:
  - 070311: F_{UL} = 2.6% Crab, (T+44 mins)
  - 070521: F_{UL} = 2.1% Crab, (T+18 mins)
  - 070612b: F_{UL} = 1.5% Crab, (T+12 mins)
- Sky Survey: In Progress....



Crab Observations

- Performance tests
- Detection
- Spectral Analysis
- Temporal Analysis

Crab Nebula

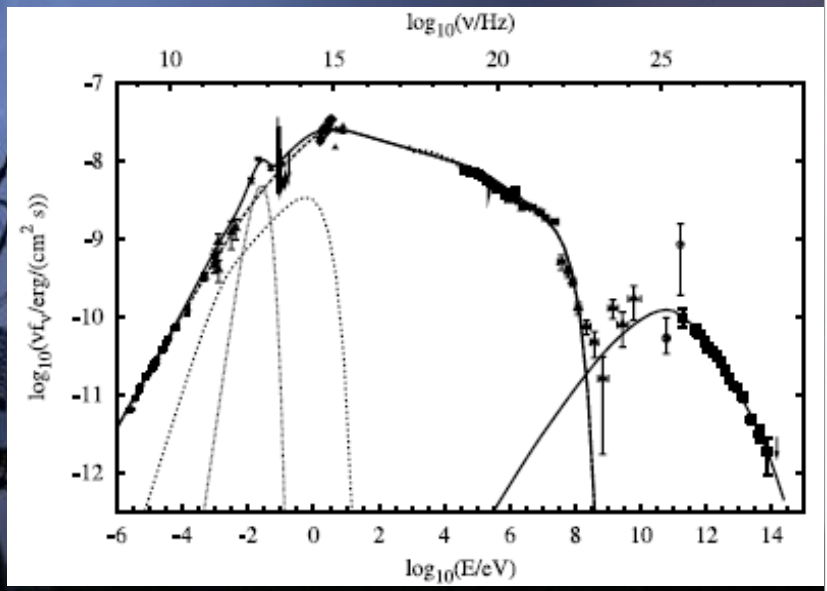
- Prototypical center filled SNR – plerion.
- "Standard Candle" of TeV astronomy.
- Pulsar: P=33 ms, L= 5 x 10^{38}erg s^{-1}.
- Polarization ⇒ Non-thermal radiation.

- Rotational Energy -> Pulsar wind -> Termination shock-> e acceleration up to PeV energies.
- Strong B fields: Synchrotron photons up to ~100 MeV.
- Accelerated e's interact with their own syncrotron photons:

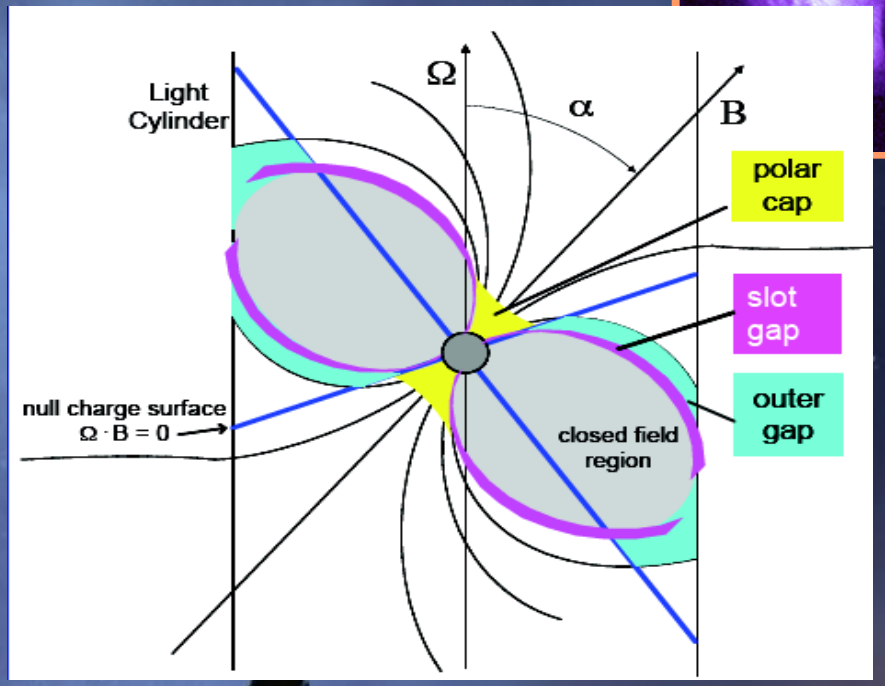
Inverse Compton Process

⇓

VHE γ-rays ~GeV to TeV.



Crab Pulsar



Polar Gap Models:

- HE GR's mainly from synchro-curvature radiation of e^- and e^+.
- Close to the surface of the pulsar. High B.
- Sharp cutoff at a few GeV.

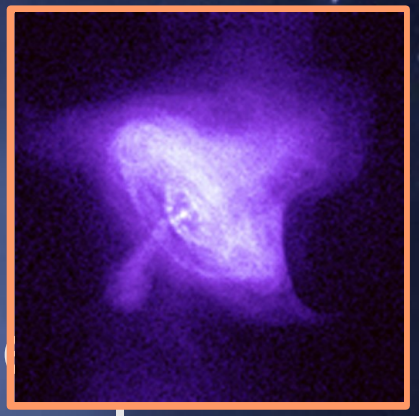
Outer Gap Models:

- Via synchro-curvature radiation from accelerated pairs.
- Additional IC component from upscattered low E (IR, Opt, X-ray) photons by accelerated pairs.
- Acceleration region is at the outer magnetosphere, less B.
- Gentler cutoffs than the polar cap models.

Hybrid Models:

Slot Gap Model:e acceleration along the edge of the open field region from the neutron star surface to near the light cylinder

The Data Set



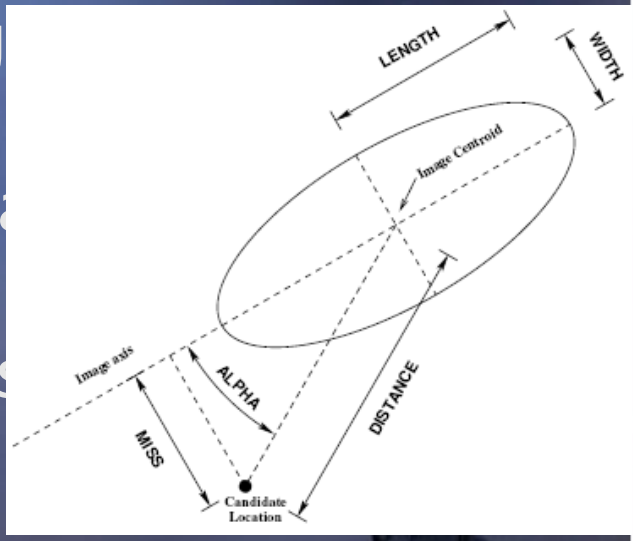
- Data taken with the optimum hardware/obs configuration is used for detection and spectral analysis.

- Run Quality Selection:
  - Event trigger rates.
  - Instrument response to CRs.
  - The deadtime of the system.

- 2-Telescope data set - 15.7 hrs (47 runs).
- 3-Telescope - 3.7 hrs (11 runs).
- 2/2 and 2/3 trigger mode.

Offline Analysis

- Calculation of Calibration Parameters:
  - Pedestal, Relative Gain, Timing params.
  - DB access: Tracking, Array Info, Pixel Status
  - Run Info construction.
- Application of Calibration
  - Bad pixel removel, FADC Trace Integ
  - Calibrated Event Reconstruction
- Padding - Cleaning – Hillas Parameteriz
- Stereo reconstruction
  - Geometrical recons – Shower Params
- Event Selection
- Background Estimation:
  - Reflected region model, Ring background model
- Gamma/Hadron Seperation – Spectral Analysis



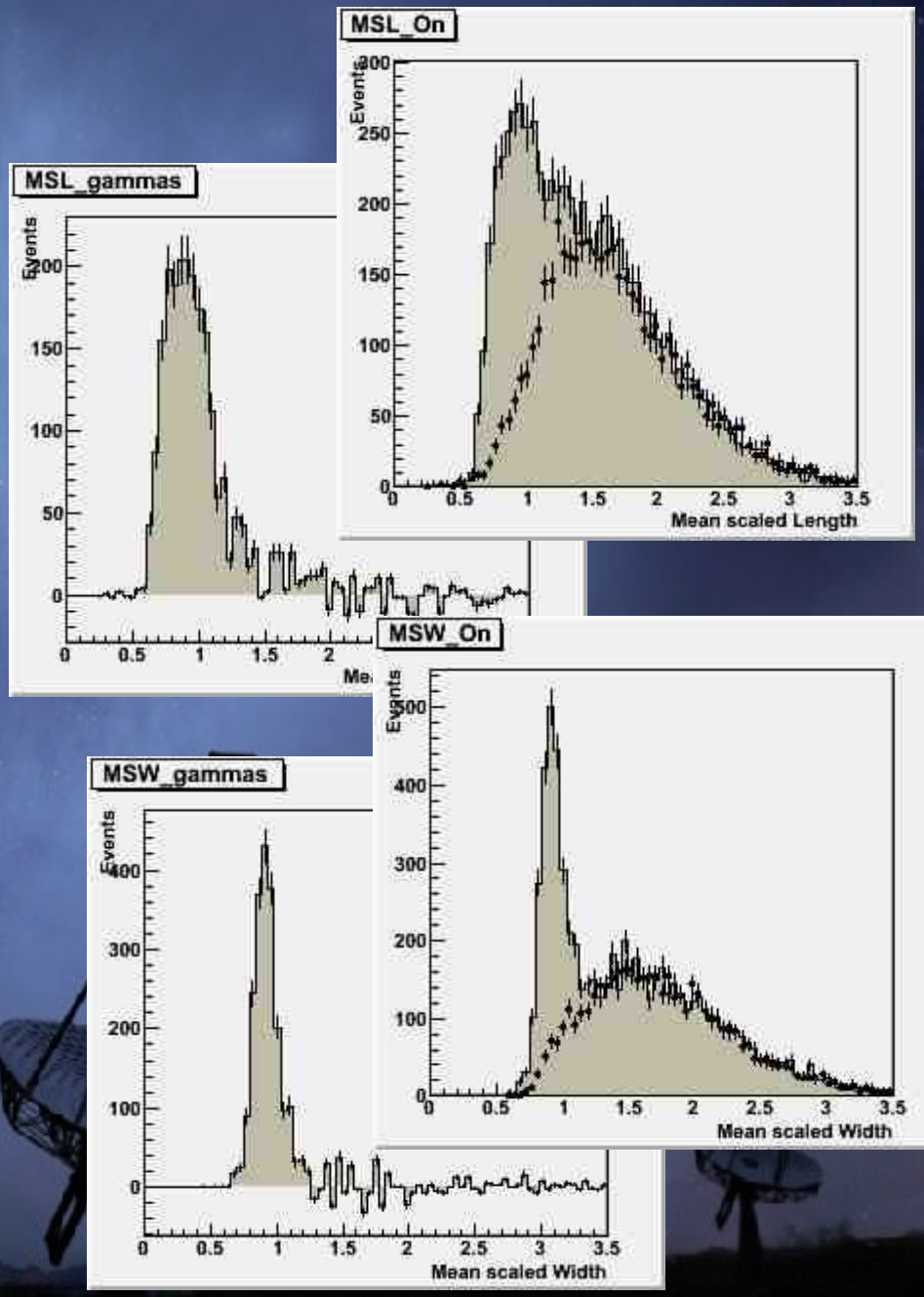
Analysis Cuts

- Selection Cuts

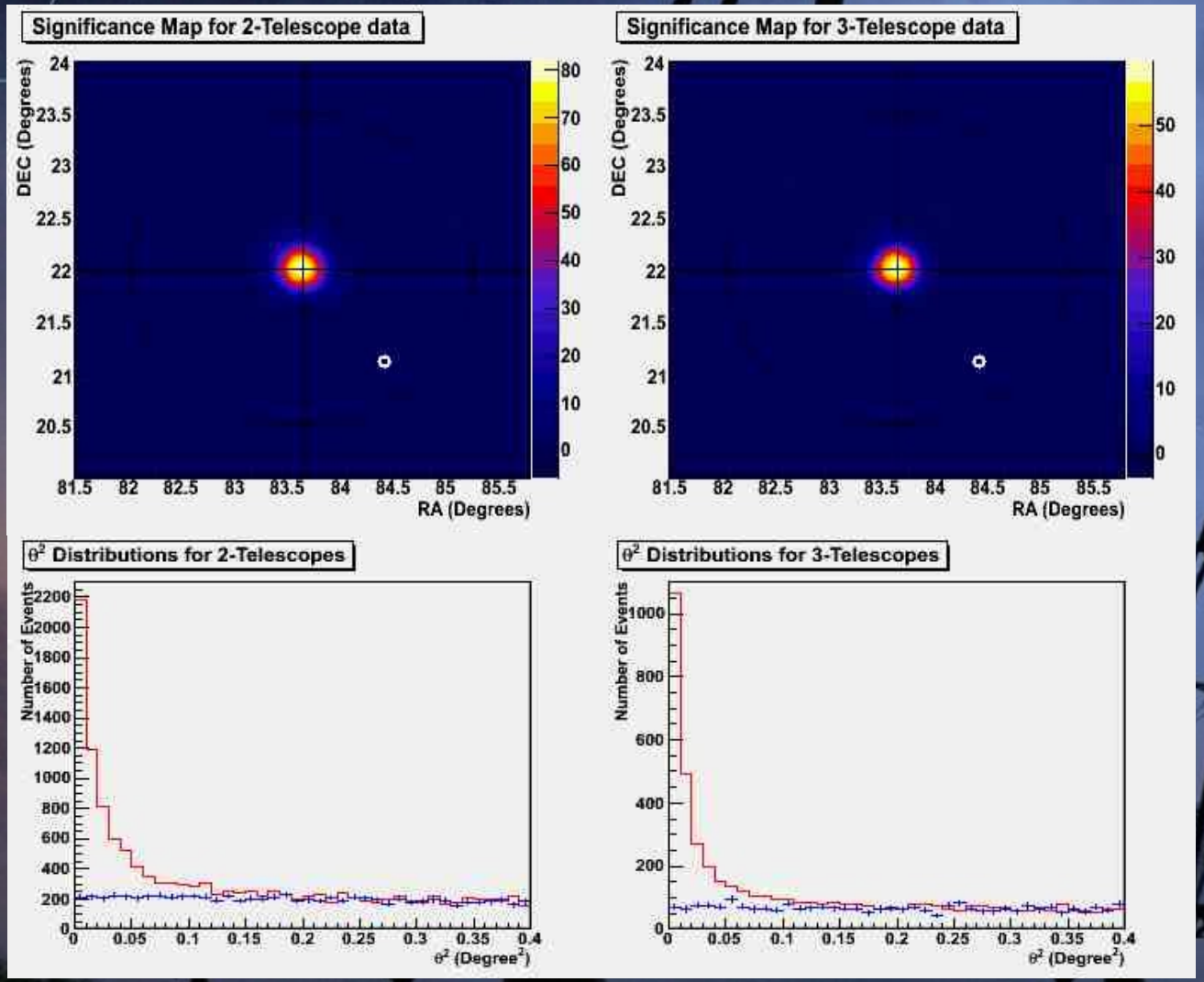
Event Selection
Size > 400 d.c.
# of Pixels > 5
0.05 < Distance < 1.3°

- Gamma/Hadron Seperation Cuts

Gamma/Hadron Separation
0.05 < MSW < 1.02
0.05 < MSL < 1.15
$\theta^2 < 0.025$



Detection of Crab Nebula



2-Telescope:

$\sigma = 81.88$

$\sigma / \sqrt{hr} = 20.64$

γ-Rate = 3.51 γ/min

$Rate_{Bg}$ = 0.64 bg/min

3-Telescope:

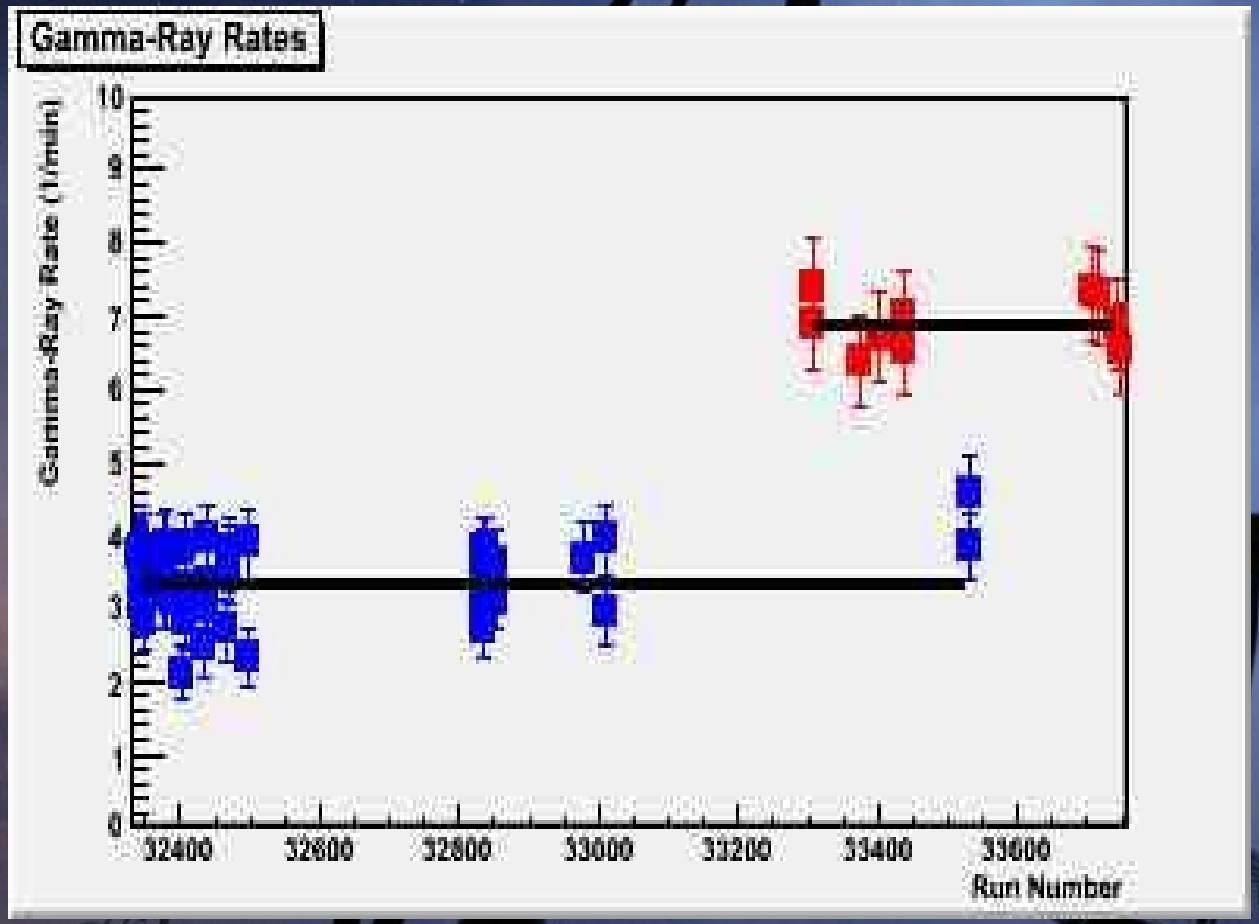
$\sigma = 59.80$

$\sigma / \sqrt{hr} = 31.29$

γ-Rate = 7.02 γ/min

$Rate_{Bg}$ = 0.94 bg/min

Stability of the Gamma-Ray Rates



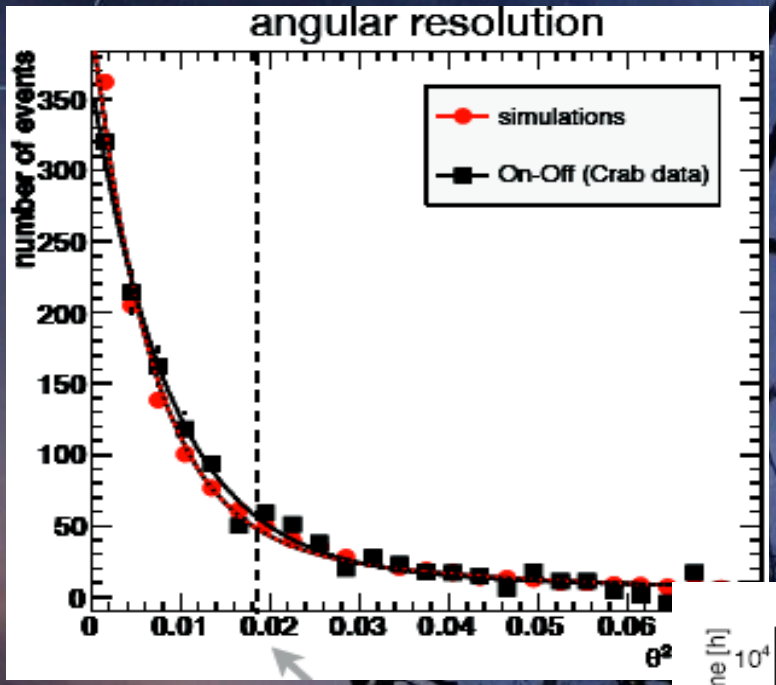
2-Telescope (blue):

Mean Rate= 3.5 γ/min

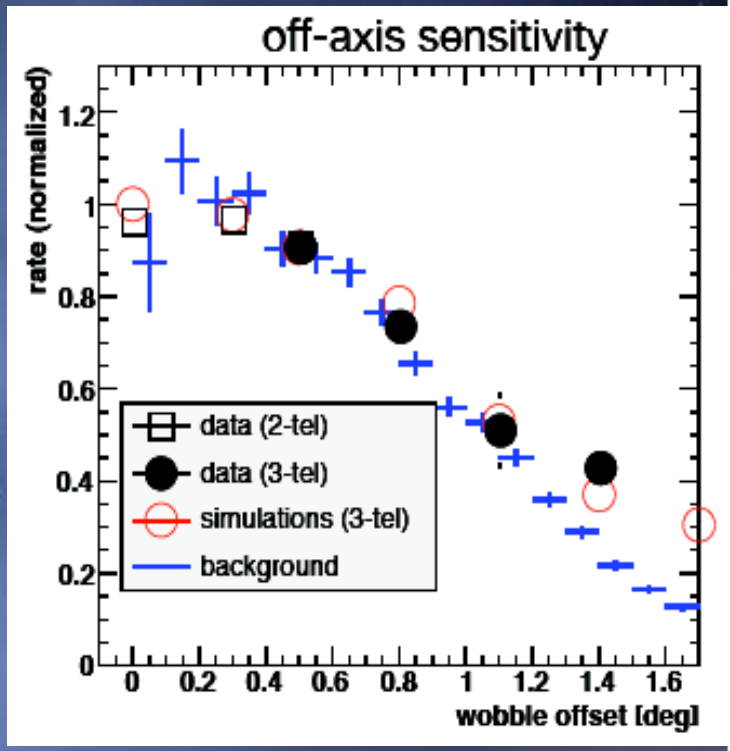
3-Telescope (red):

Mean Rate = 7.0 γ/min

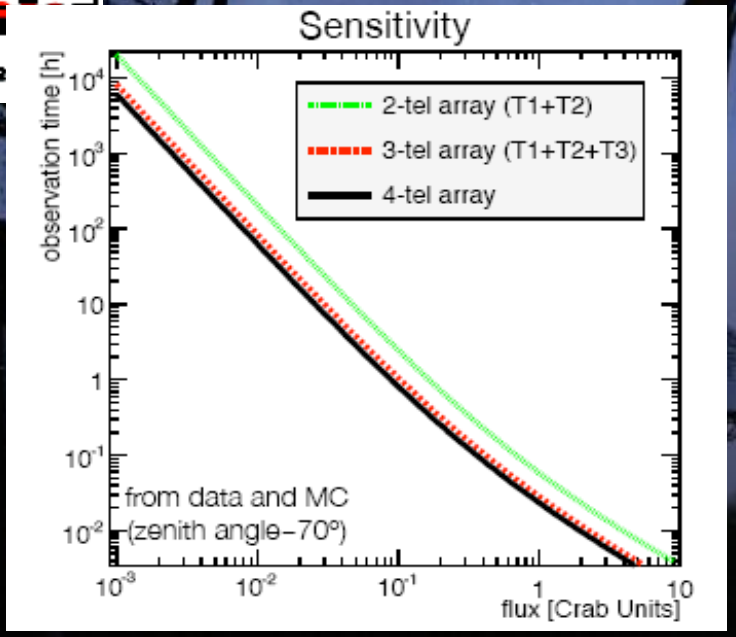
Veritas Performance



Off-axis sensitivity better than 65% for source offsets < 1°

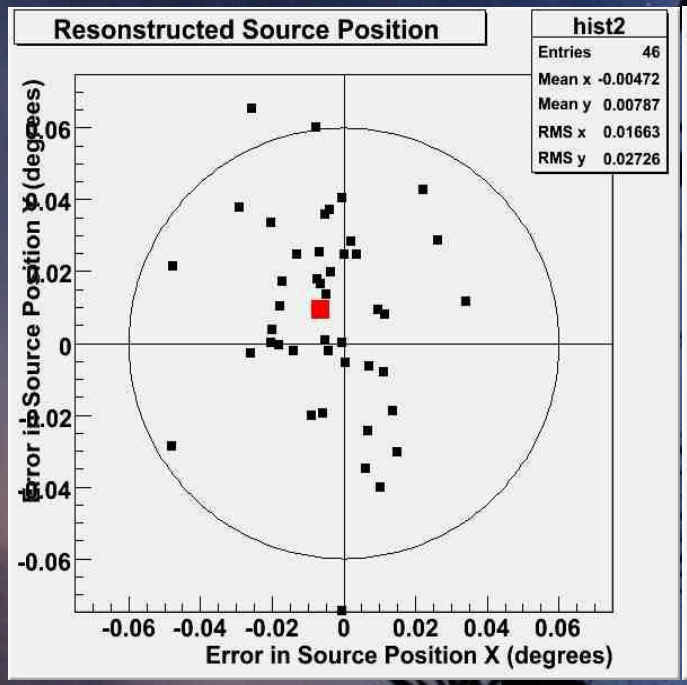


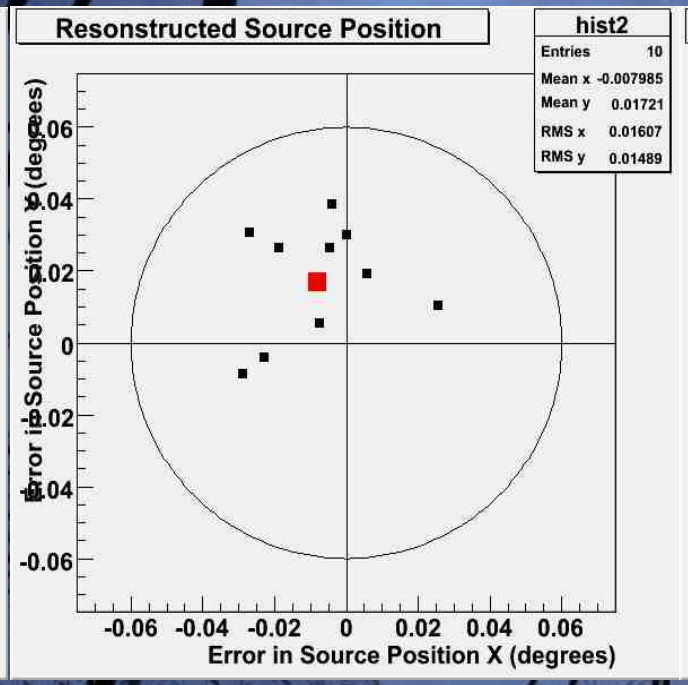
Angular resolution is better than 0.14° event by event

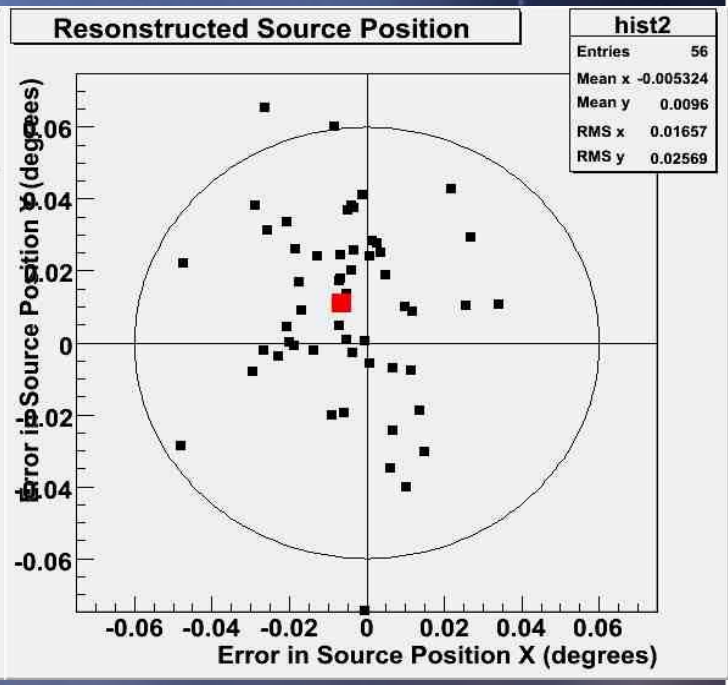


Sensitivity for 10% of Crab Nebula flux: (5σ detection):
2-telescopes: 3.3 h
3-telescopes: 1.2 h
4-telescopes: < 1h

Source Position Reconstruction

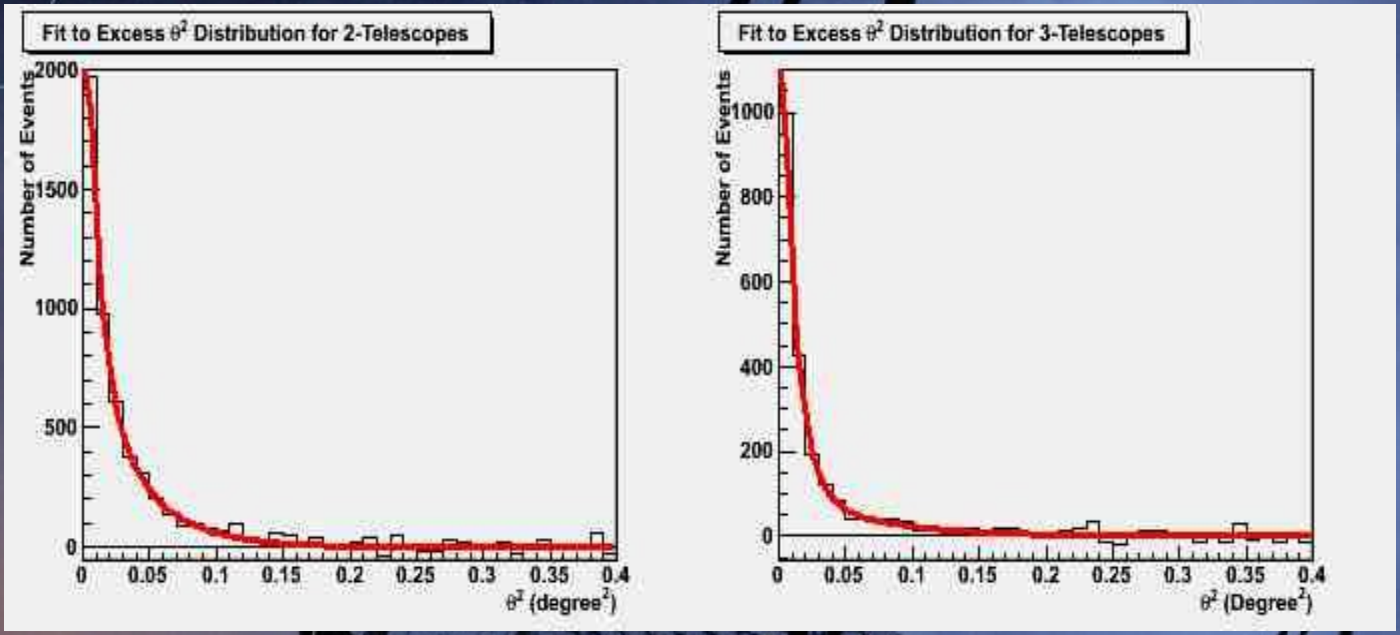






2-Telescope Mean Error in Source Position: 0.012°
3-Telescope Mean Error in Source Position: 0.019°
2-3 Telescope Mean Error in Source Position: 0.013°

Fit to θ^2 Distributions



$$Fit = A[\exp(-\frac{\theta^2}{2\sigma_1^2}) + A_{rel}\exp(-\frac{\theta^2}{2\sigma_2^2})]$$

2-Telescope:

A_{Rel} = 0.429

σ_1 = 0.068

σ_2 = 0.137

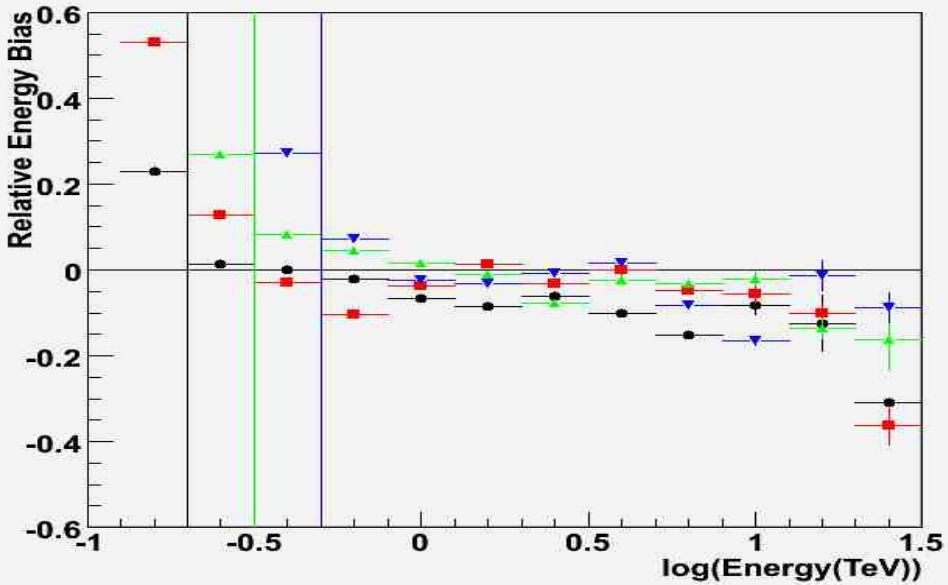
3-Telescope:

A_{Rel} = 0.089

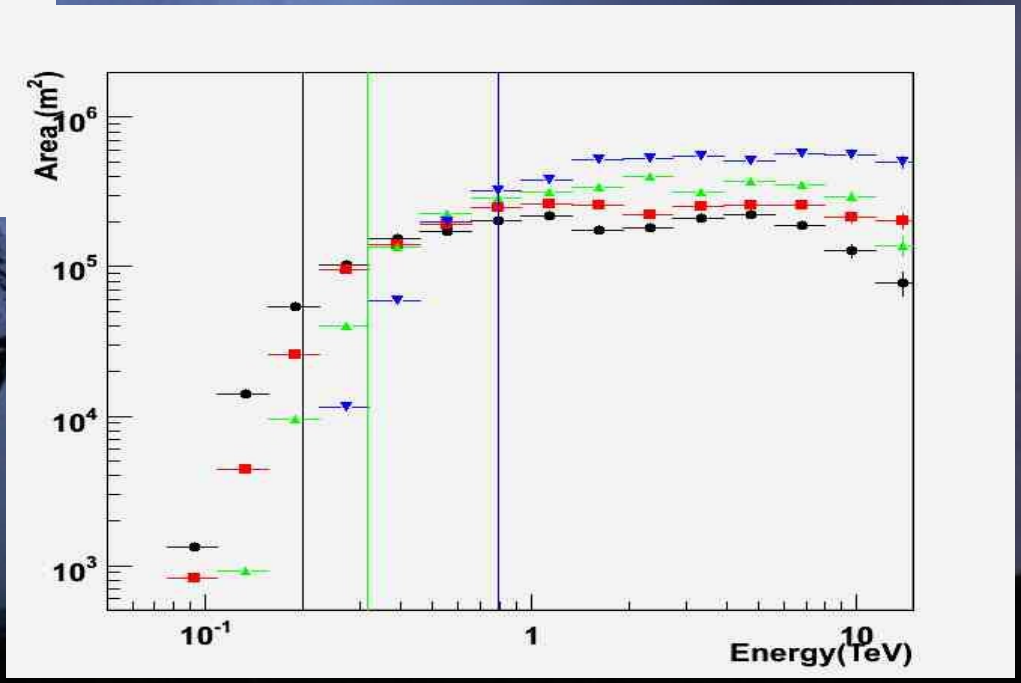
σ_1 = 0.070

σ_2 = 0.168

Energy Reconstruction - Effective Area



Spectrum Cuts
0.05 < MSW < 1.2
0.05 < MSL < 1.4
$\theta^2 < 0.1$

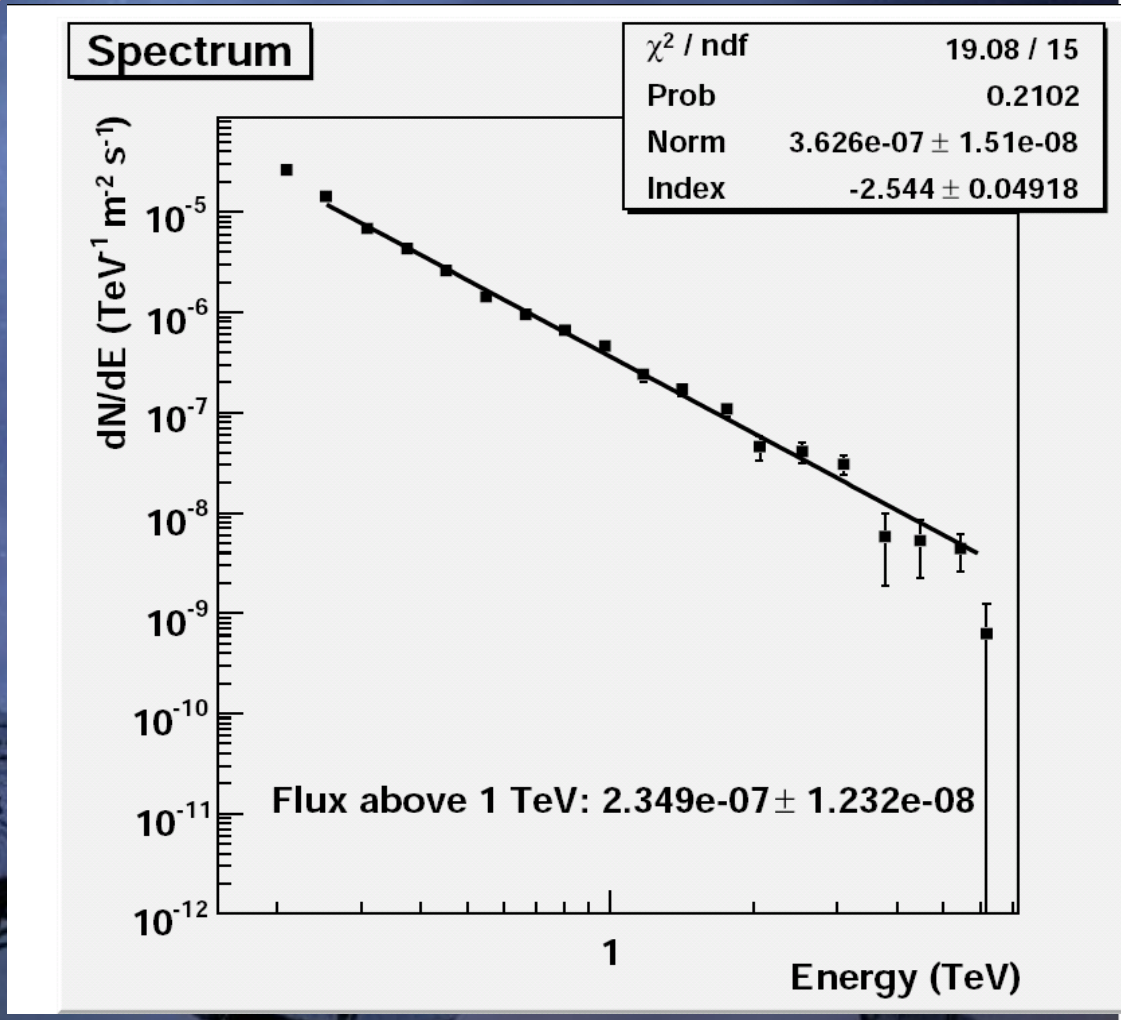


Black = Zenith Angle 0°
Red = Zenith Angle 20°
Green = Zenith Angle 30°
Blue = Zenith Angle 40°

Vertical lines : %10 Energy Bias

Energy Spectrum

- The 3 Telescope data set is used.
- Looser cuts are applied to data.
- Fit includes:
  - Energy bins with < 10% energy bias
  - Energy bins with >2 σ

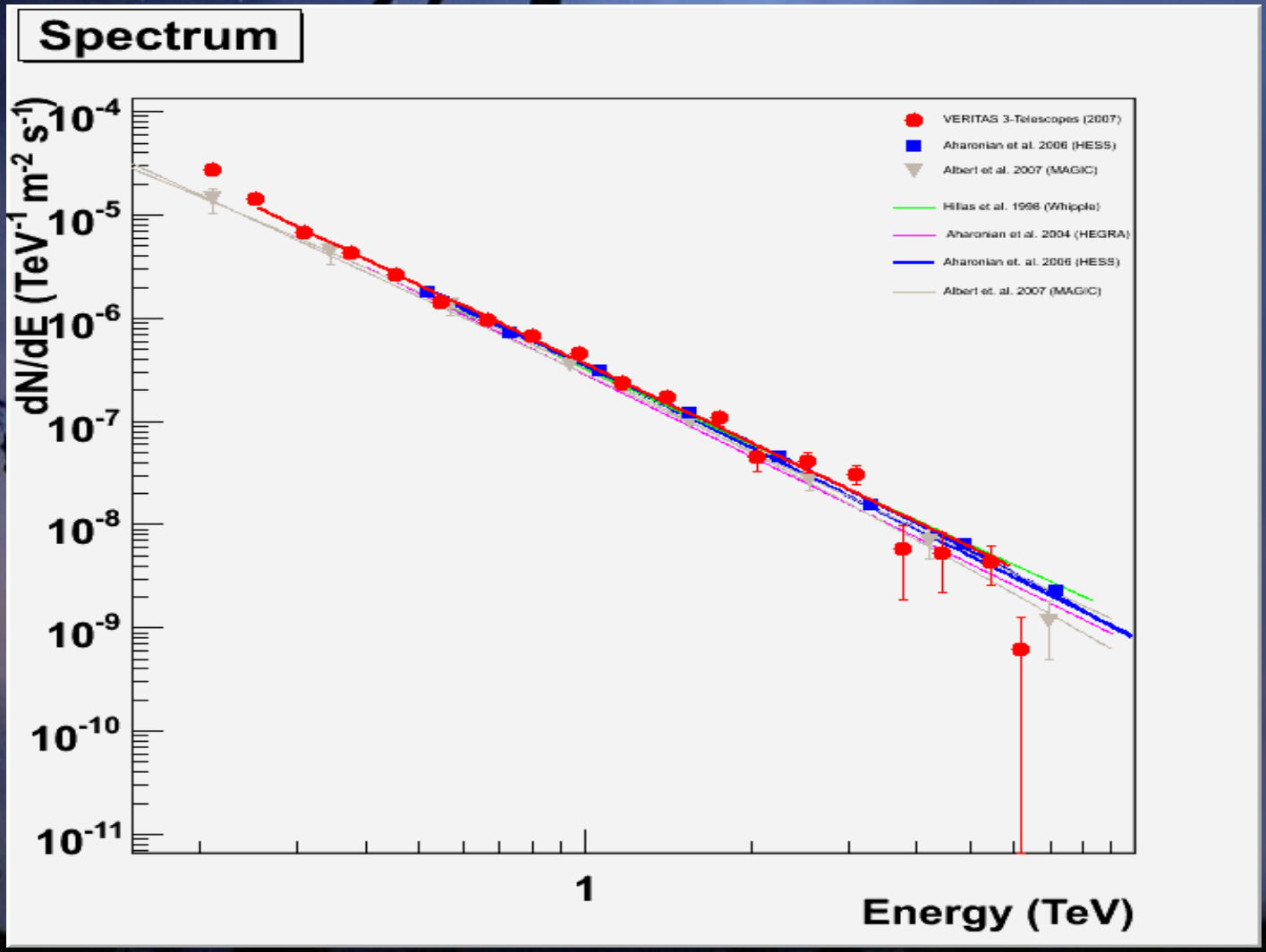


Fit Result:

$\Gamma = 2.54 \pm 0.05$

$I_0(1\ \text{TeV}) = (3.63 \pm 0.15) \times 10^{-7}\ \text{TeV}^{-1}\ \text{m}^{-2}\ \text{s}^{-1}$.

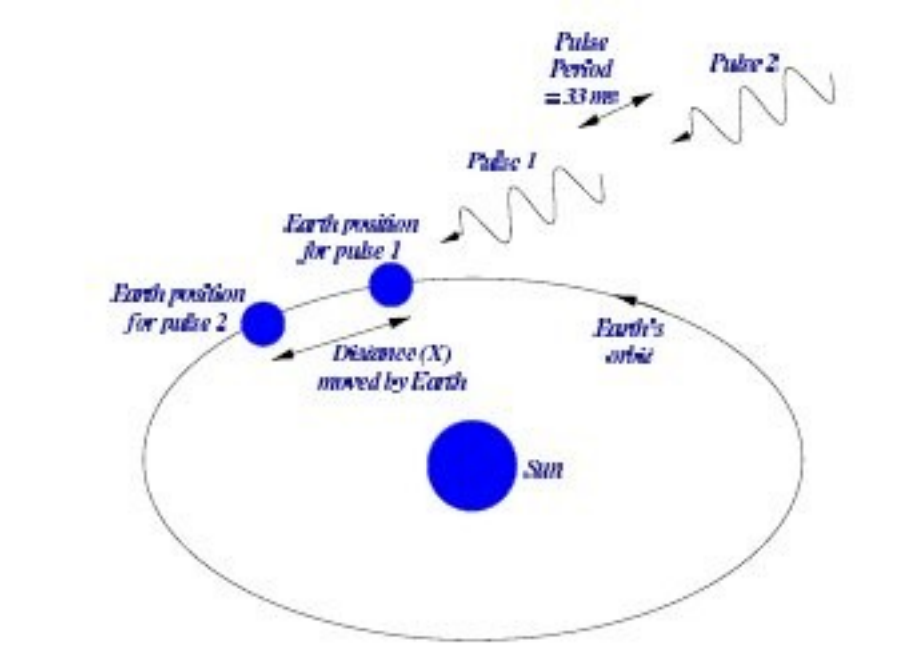
Comparison with Other Results



Temporal Analysis: Barycentering

Search pulsed emission:
Event arrival times -->
Phase of the pulsar star in an intertial frame

$$\phi(T) = \phi(T_0) + f(T_0)(T - T_0) + \frac{1}{2}\dot{f}(T_0)(T - T_0)^2$$



UTC: Universal Coordinated Time
TAI : International Atomic Time
TDT: Terrestial Dynamical Time
TDB: Barycentric Dynamical Time
Time Of Flight Corrections:

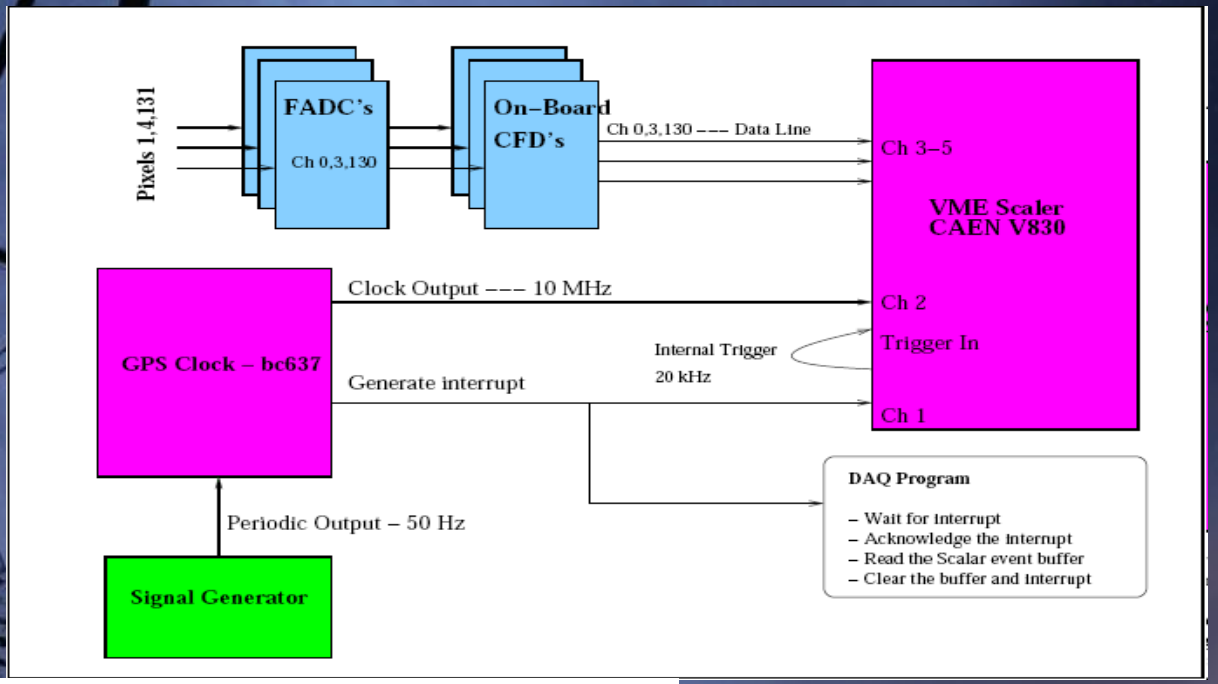
- From Earth center to Solar System Barycenter
- From Observatory to Earth center

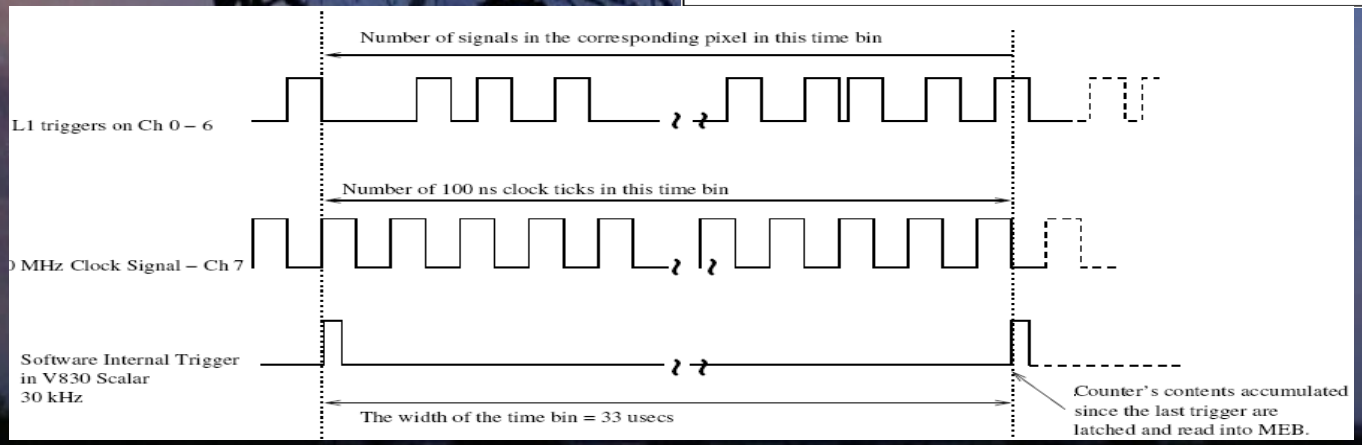
$$t_b = t_{\rm UTC} + \Delta_{\rm TAI-UTC} + \Delta_{\rm TDT-TAI} + \Delta_{\rm TDB-TDT} + \Delta_{\rm Earth\to SSB} + \Delta_{Observatory\to Earth}$$

Optical Pulsar Set-Up: Hardware

Event rate:
20 kHz (50 usecs)

Absolute time tagging rate:
50 Hz (20 msecs)

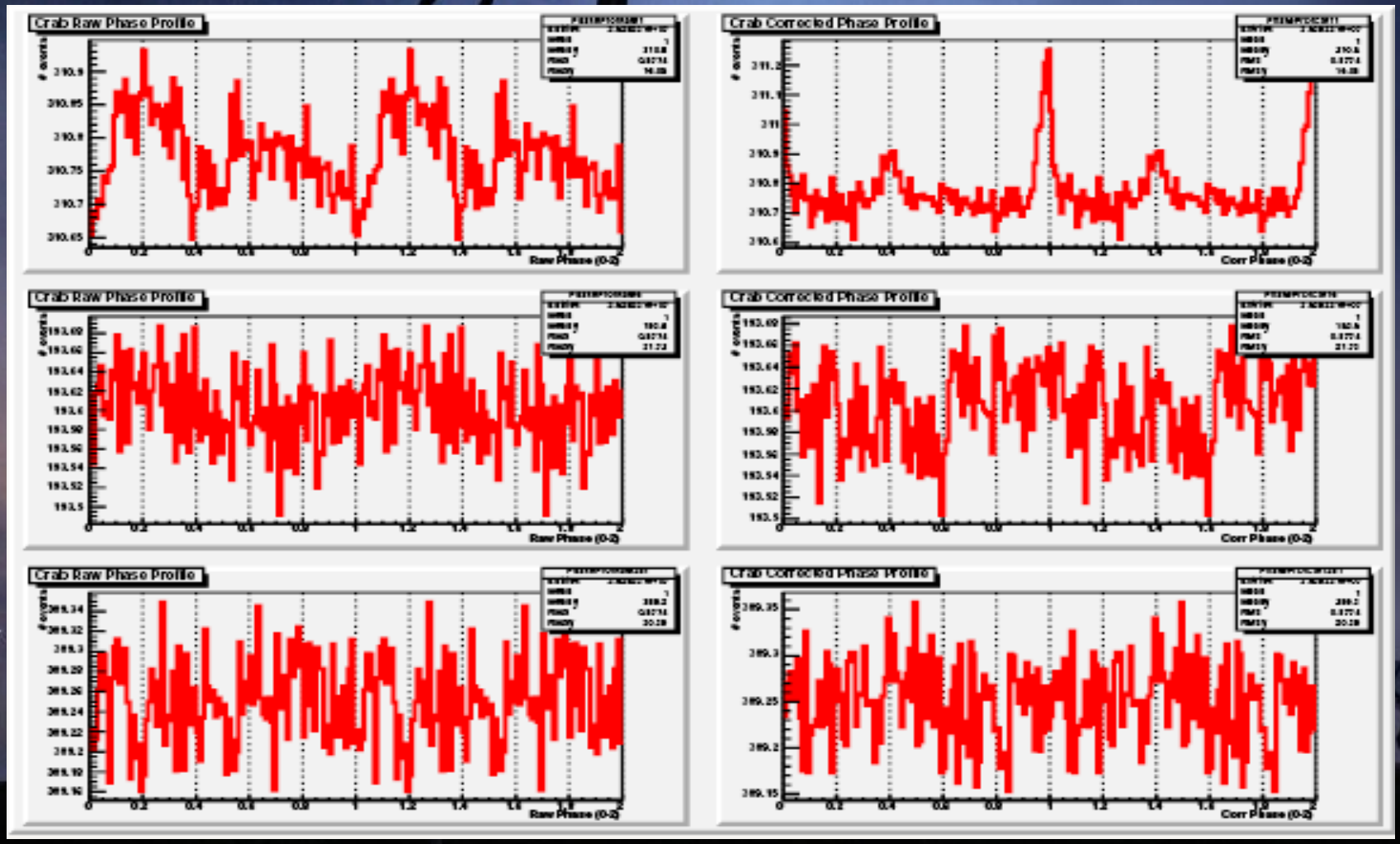




Interpolate time to each event trigger

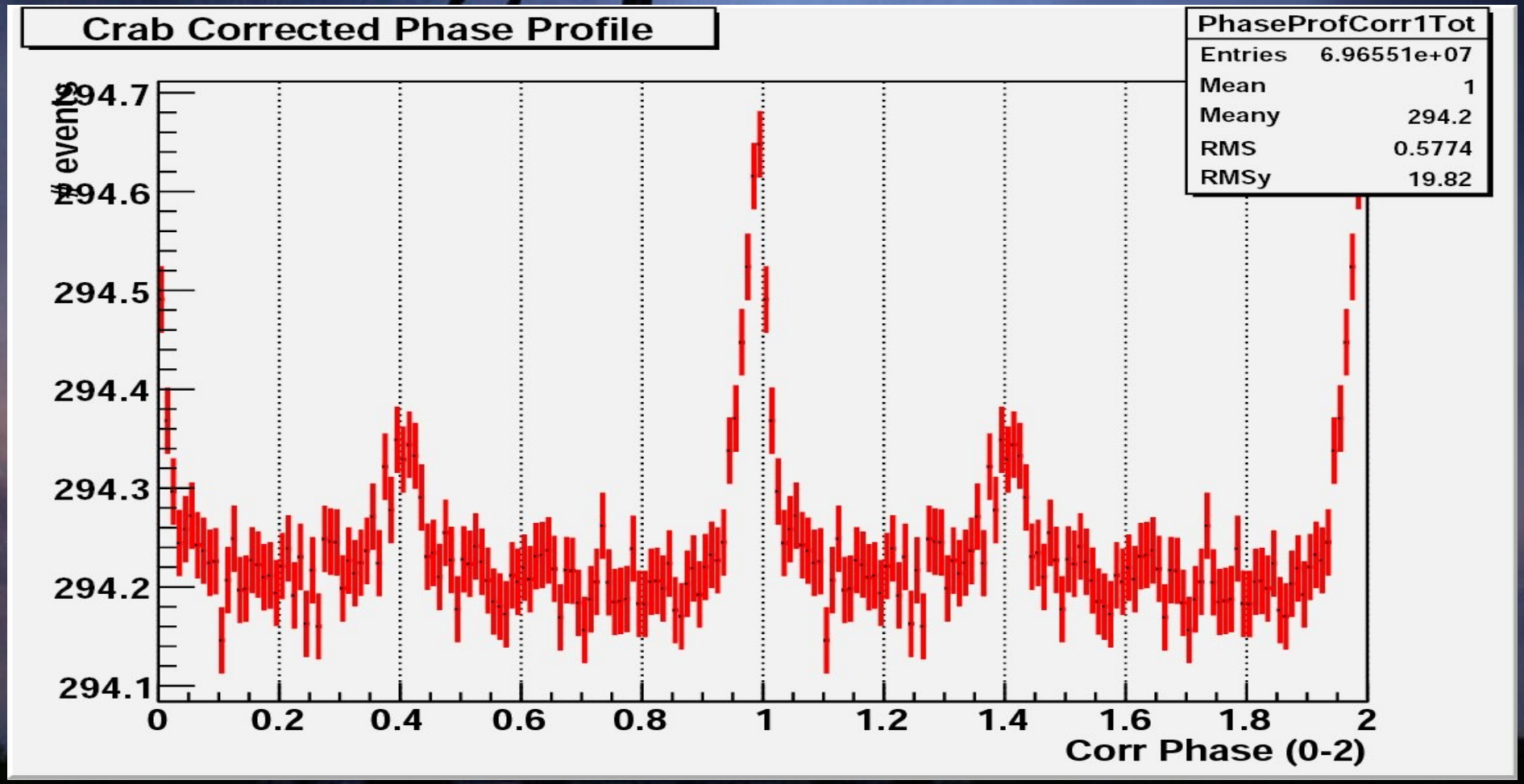
Optical Pulsar Result - I

Run taken on 061222. Duration 12 mins. CFD Th=15 mV, Width = 6 ns, Gains nominal.
Central Pixel (1) - A first ring pixel (4) – A pixel on the outer camera (131) .



Optical Pulsar Result - II

Plots of 4 runs over the span of 3 days combined. Total time 33 mins.

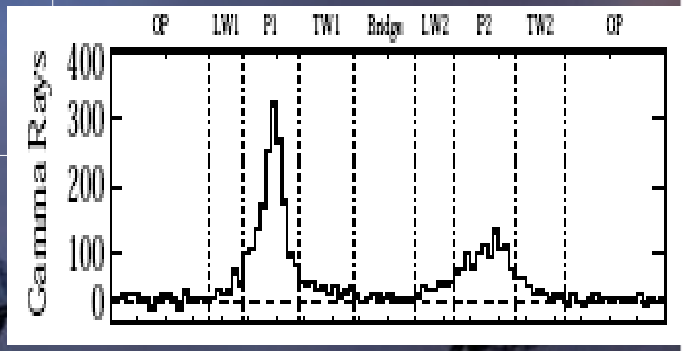


Temporal Analysis: Gamma-Rays

- Preliminary Results.
- The cuts are NOT Optimized for low energies yet.
- Loose cuts are used to increase the candidate gamma-ray events at low energies.

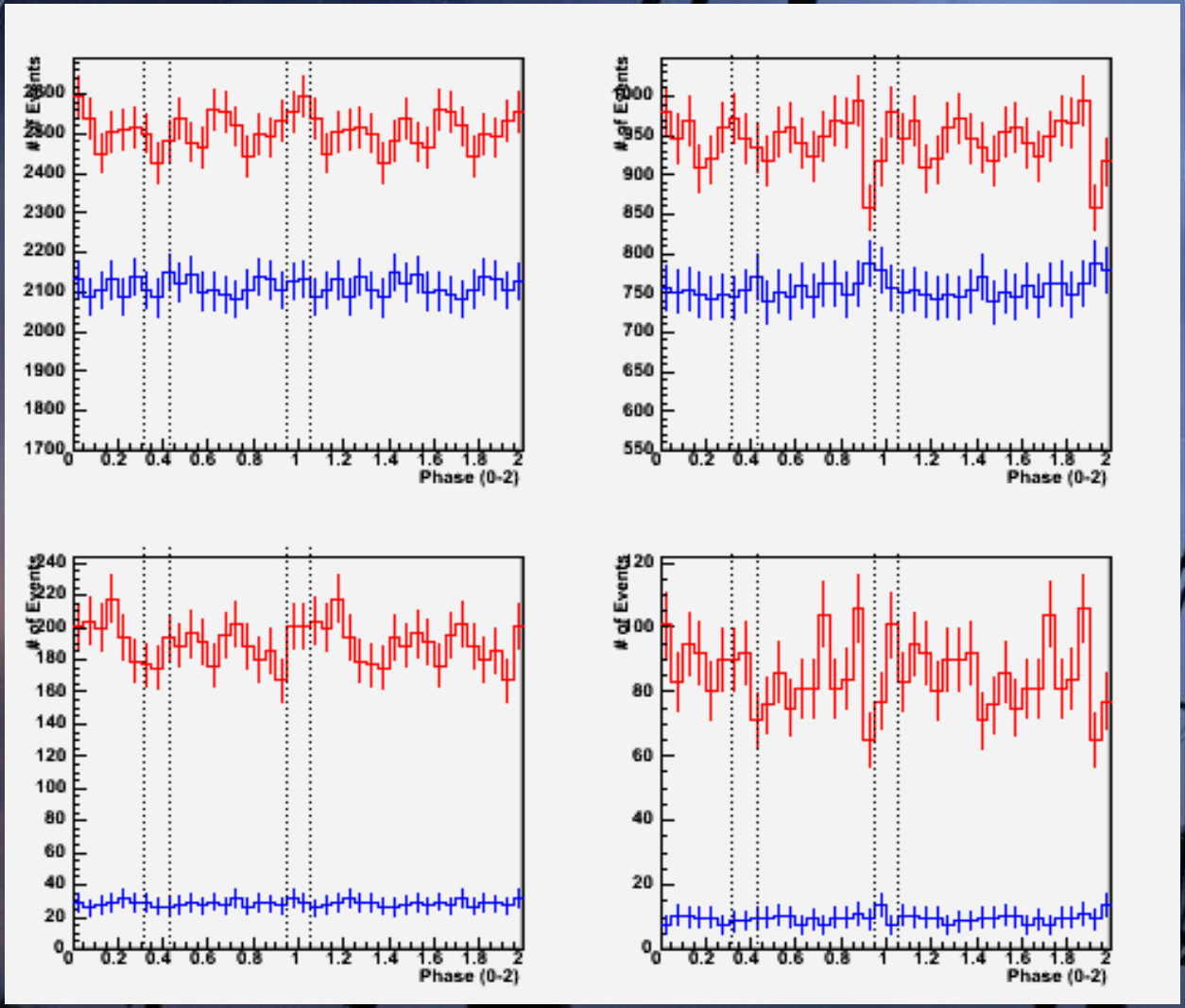
Event Selection
Size > 0 d.c.
# of Pixels > 5
0.05 < Distance < 1.3°

Temporal Analysis Loose Cuts
0 < MSW
0 < MSL
$\theta^2 < 0.04$



- EGRET pulse shape is used to define the pulsed emission phase regions.

Temporal Analysis Preliminary Results



Loose Cuts:

2T: $\sigma = 0.49$

3T: $\sigma = 0.38$

Standard Cuts:

2T: $\sigma = 0.15$

$F_{UL}(>240\ GeV) = 3.5 \times 10^{-12}\ cm^{-2}\ s^{-1}$.

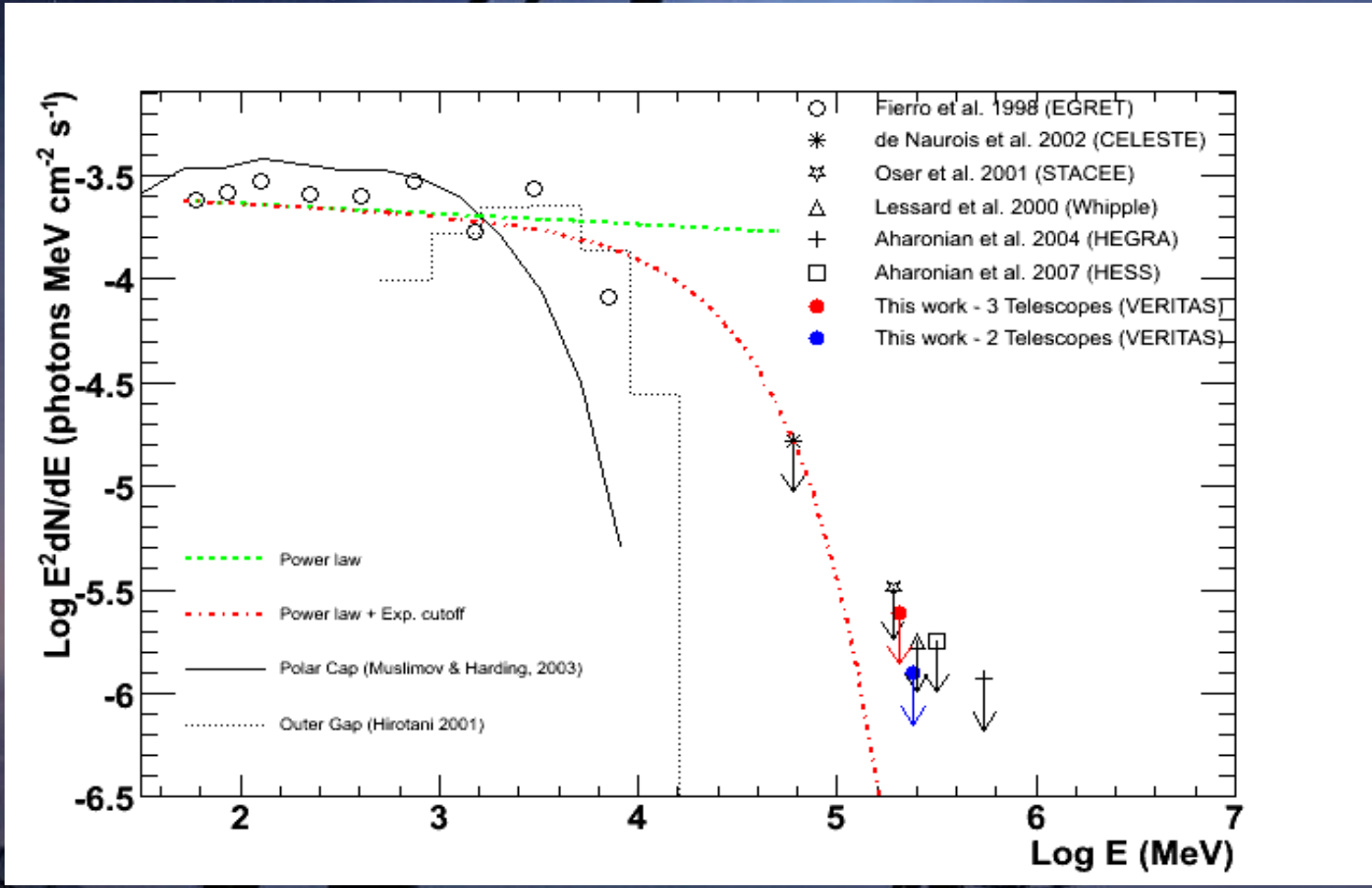
$E_{cutoff} = 54\ GeV$

3T: $\sigma = 0.35$

$F_{UL}(>200\ GeV) = 8.17 \times 10^{-12}\ cm^{-2}\ s^{-1}$.

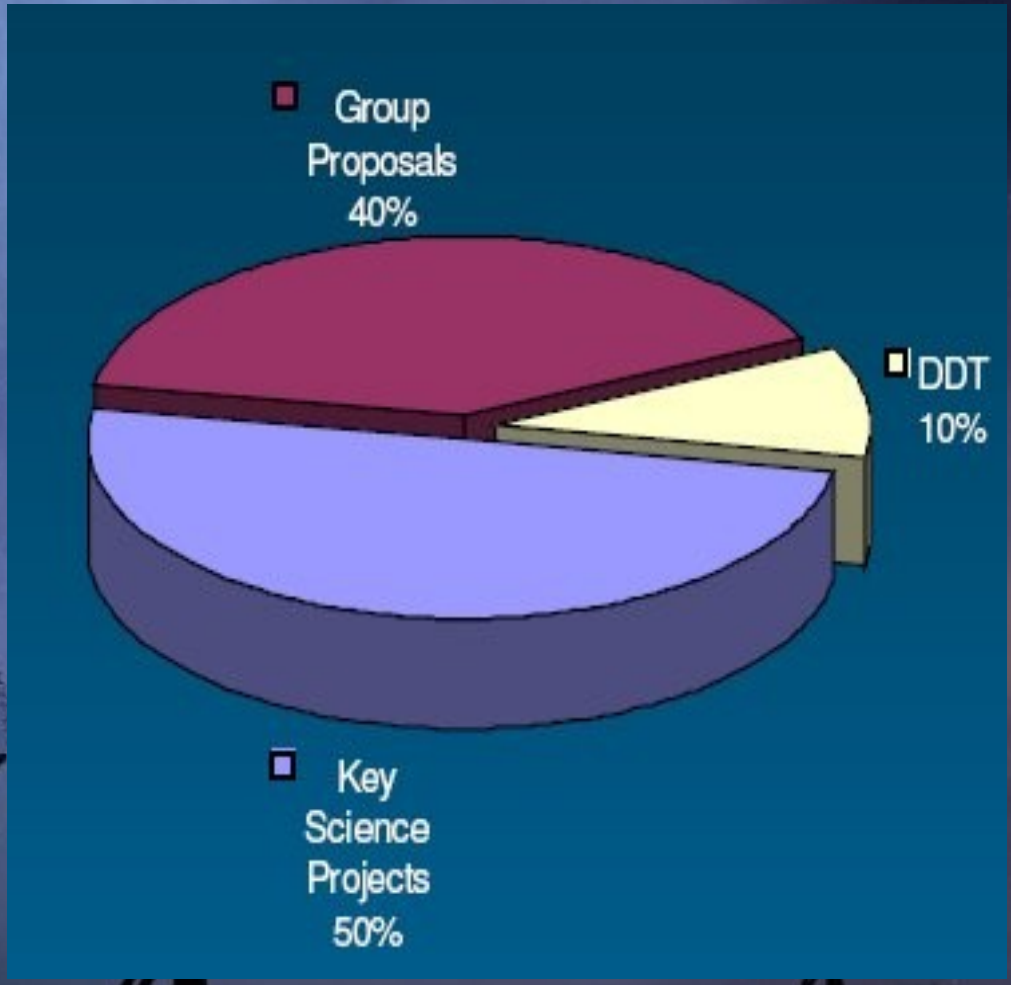
$E_{cutoff} = 52\ GeV$

Comparison with Other Results



VERITAS Observing Plan

- Key Science projects:
  - Galactic Plane Survey
  - Dark Matter
  - Supernova Remnants
  - Blazars
- Group Proposals:
  - Science Groups
  - TAC allocates time
- Director's Discretionary Time:
  - Target Of Opportunities



Summary - I

- The Crab Nebula spectrum for 3-telescope array is measured. It is in agreement of previous measurements.

I_0 (1 TeV) = (3.63 ± 0.15)x10^{-7} TeV^{-1} m^{-2} s^{1}.

Γ = -2.54 ± 0.05.

F(>1TeV) = (2.35 ± 0.12) x10^{-7} m^{-2} s^{-1}.

- The pulsed emission is searched from the Crab Pulsar with no detection.
- The integral flux upper limit for the emission is calculated using the method of Helene.
- F_{UL}(>200 GeV)= 8.17 x 10^{-12} cm^{-2} s^{-1}.
- Work is in progress to optimize cuts for low energy events

Summary - II

- 4 Telescopes are operational since March'07.
- 2-year science program began at temporary site @ Tucson, AZ.
- Latest Detections:
  - Mrk 421, Mrk501, Crab Nebula
  - 1 ES 1218, M87 – AGNs
  - IC443 - SNR
  - LSI +61 303 -- A μ-quasar
  - Various upper limits
- Observing Program emphasizing Key Science Projects.

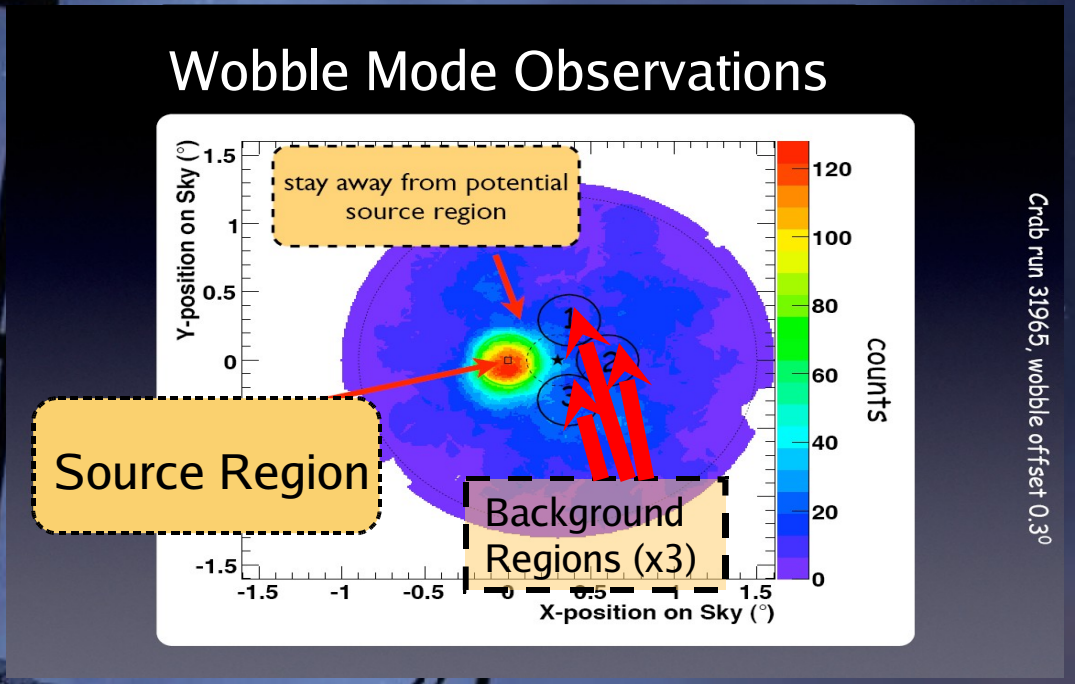
Backup Slides

VERITAS Collaboration

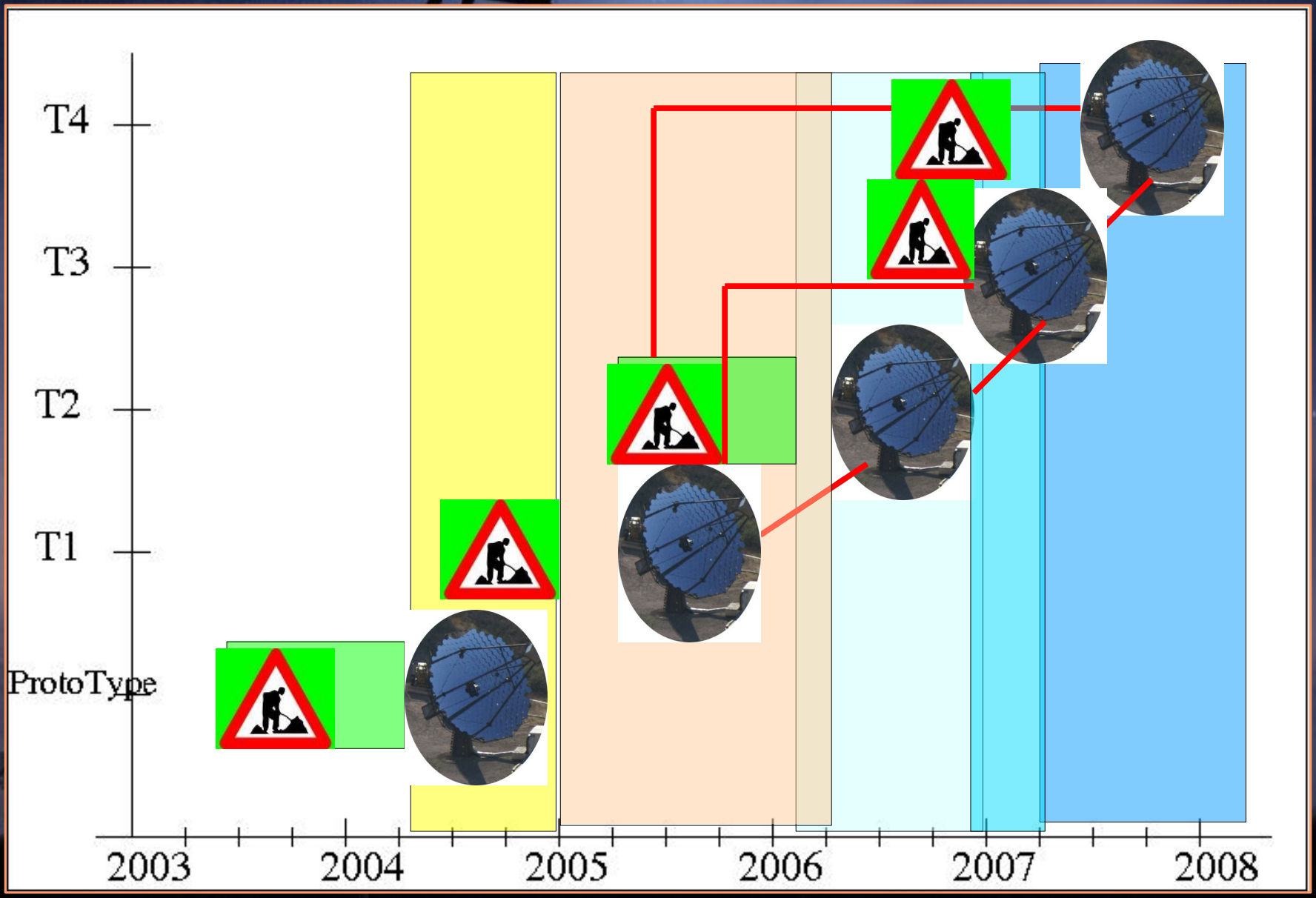
- Smithsonian Astrophysical Observatory *
- Adler Planetarium
- Purdue University *
- Barnard College, NY
- Iowa State University *
- DePauw University, IN
- Washington University, St. Louis *
- Grinnell College, IA
- University of Chicago *
- University of California, Santa Cruz
- University of Utah *
- University of Massachussetts
- University of California, Los Angeles *
- Cork Institute of Technology
- McGill University, Montreal *
- Galway-Mayo Institute of Technology
- National University of Ireland, Dublin *
- National University of Ireland, Galway
- University of Leeds *
- Argonne National Lab
- Associate Members

Stereo Observation Advantages

- No Off-region observations!



VERITAS History

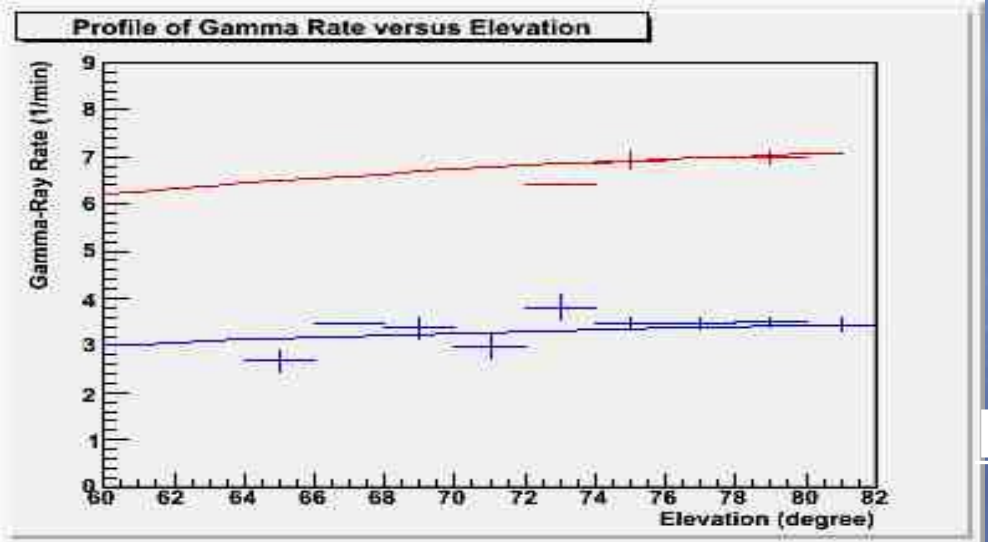


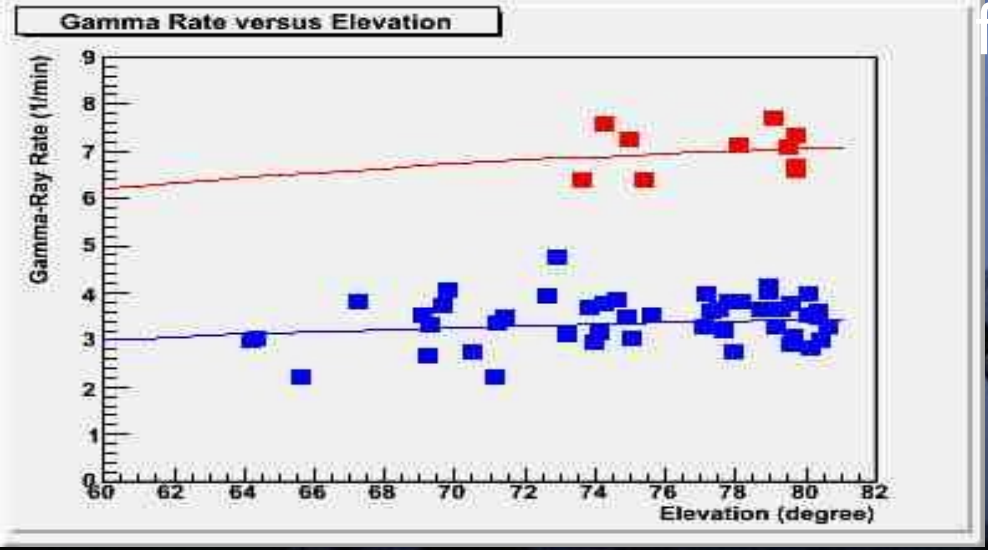
Summary of VERITAS3b Sensitivity

Sensitivity = 27.8 $\sigma/hr^{1/2}$
Gamma Ray Rate = 7.6 γ /min
Background Rate = 0.9 evt/min

Source Flux (Crab units)	Time Req.(hrs)
1	0.024
0.2	0.34
0.1	1.12
0.05	4.00
0.03	10.55
0.02	23.07
0.01	89.62

Gamma-Ray Rate vs. Elevation

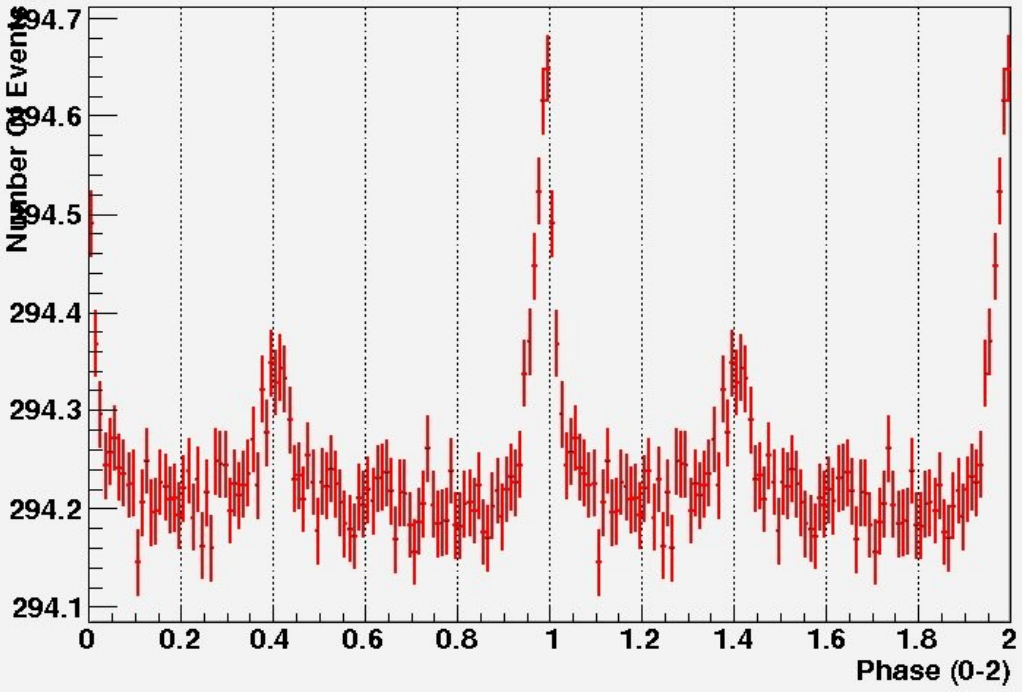




Fit Function:

$f(El.Ang.) = N * Cos(90^{o} - El.Ang.)$

Optical Pulsar



Event times are transformed to solar barycenter to correct for motion of Earth.

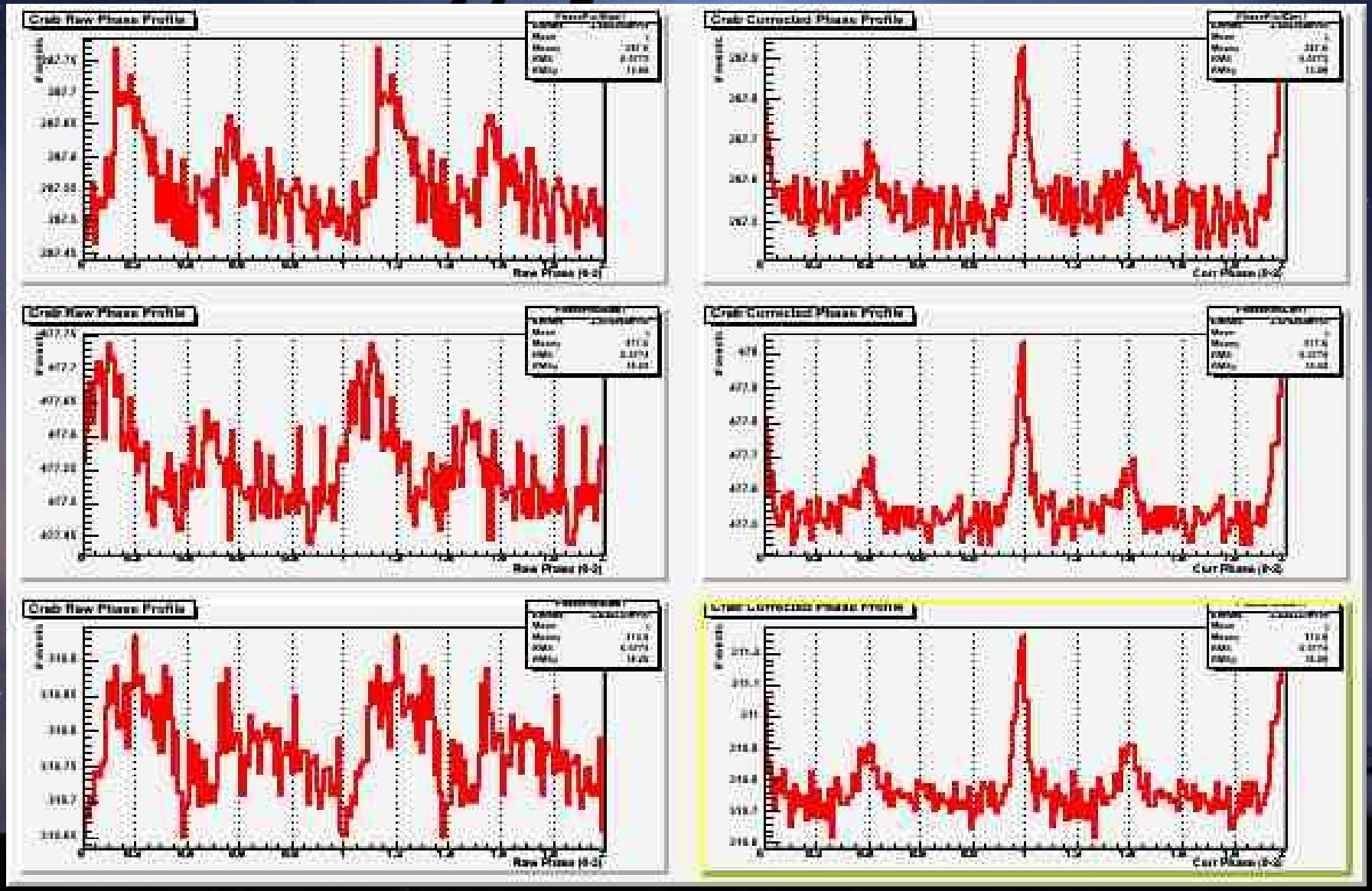
Relative phaseof pulsar rotation for each event is calculated.

Temporal analysis is made using 3 independent barycentering libraries.

Difference in the corrected phase of each event < 1-2 / 100th of the phase.

3 runs from 2 different nights. Total of 30 mins.
Event Rate= 20 kHz. (50 μs)
GPS time-stamping rate = 50 Hz. (20 ms)
Histogram bin size = 330 μs (1/100th phase)

Optical Pulsar Result - II



Optical Pulsar – DAQ Configuration

- Data rate – (Integration time of the scaler):
  20 kHz (50 usecs)
- Absolute time taging rate: 50 Hz (20 msecs)
- Histogram bins/phase (width): 200 (165 usecs)
- CFD output widths: 6 ns – 13 ns
- CFD Thresholds/Gain factors: 10 mV / nominal
  18 mV / 2 x nom.
  25-30 mV / 3 x nom.
- 10 min run has ~12 M events.
- Analysis:
  - Extrapolate the absolute time stamps
  - Barycenter and calculate the phase of each event (Thanks to Pascal's Barycentering libraries)