# VHE measurements of the Crab nebula by HAGAR Telescopes

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for
HAGAR Collaboration

Introduction : The Crab Nebula

- Remnant of supernova explosion occurred in 1054 and one of the best studied non-thermal astrophysical source

- Pulsar at the center of the nebula injecting relativistic electrons to the nebula

- Emission predominantly by non-thermal processes covering from radio to TeV energies

- First TeV source detected by the Whipple telescope (1989)

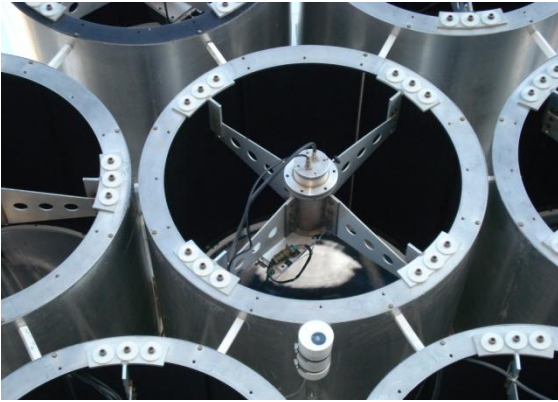- Very strong and stable at TeV energy (standard candle)

X-RAY   OPTICAL

INFRARED   RADIO

Normal   Flare State
April 2011

Crab Nebula

Geminga pulsar
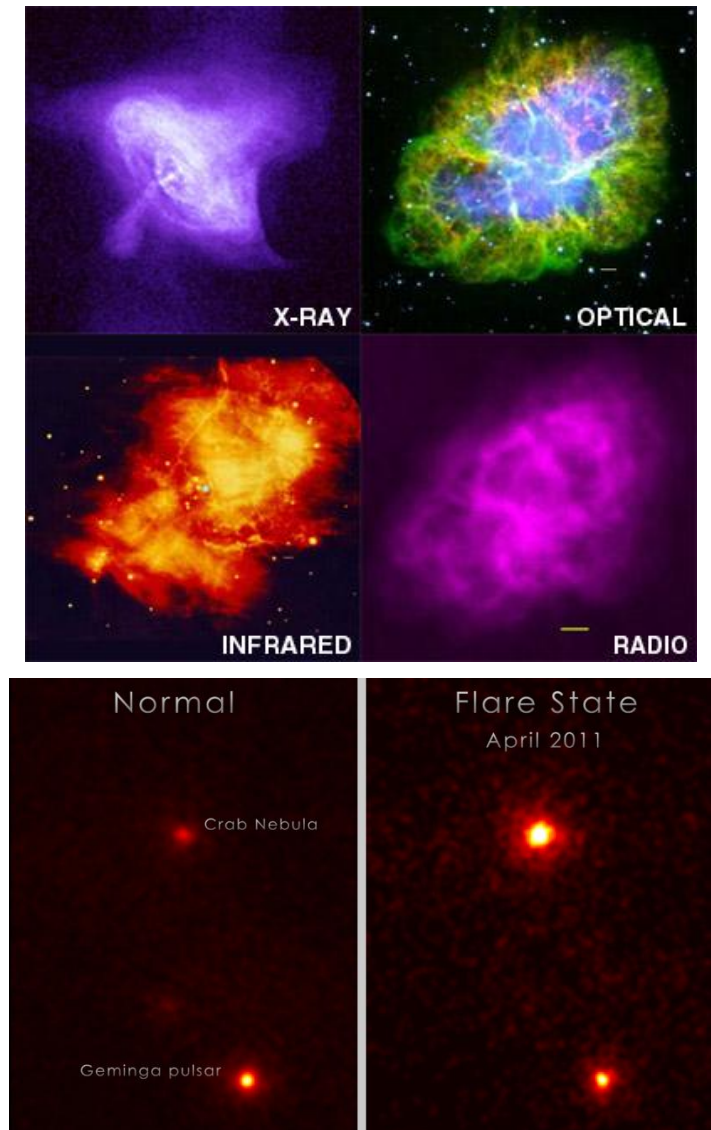
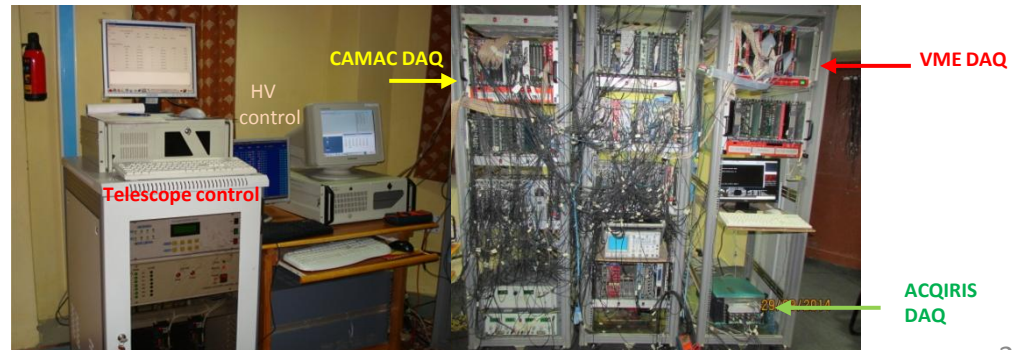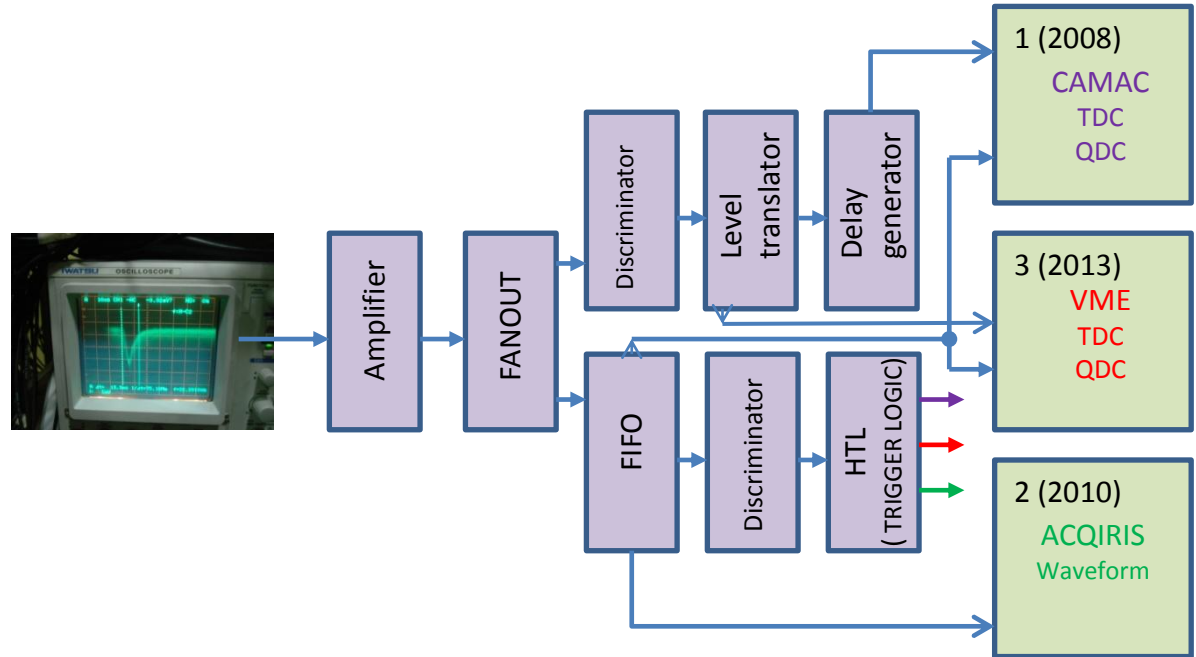Fermi-LAT flare of April 2011
(Credit: NASA/DOE/Fermi LAT/R. Buehler)

HAGAR : High Altitude Gamma Ray Observatory

(Array of 7 Atmospheric Cherenkov Telescopes)

07-05-2018

HAGAR : Crab nebula observations

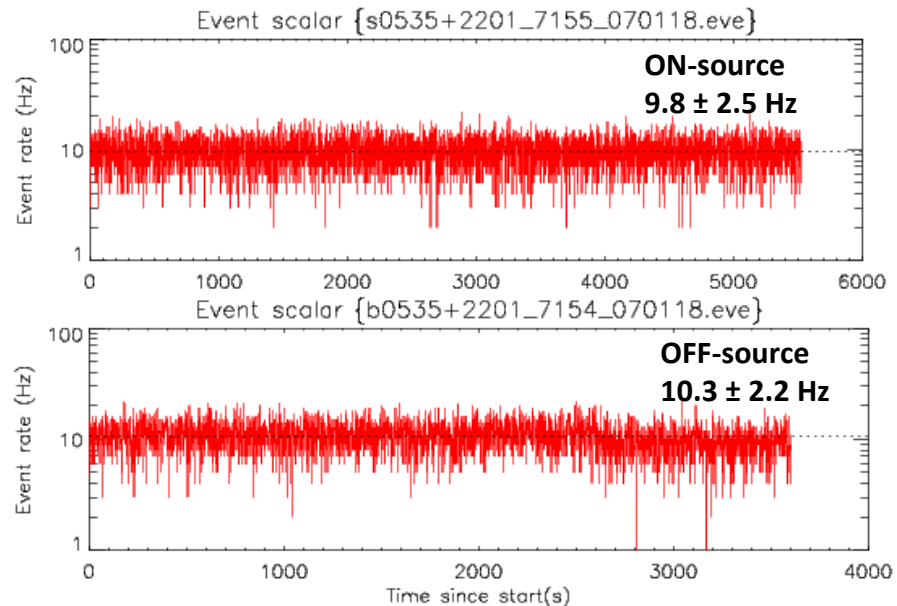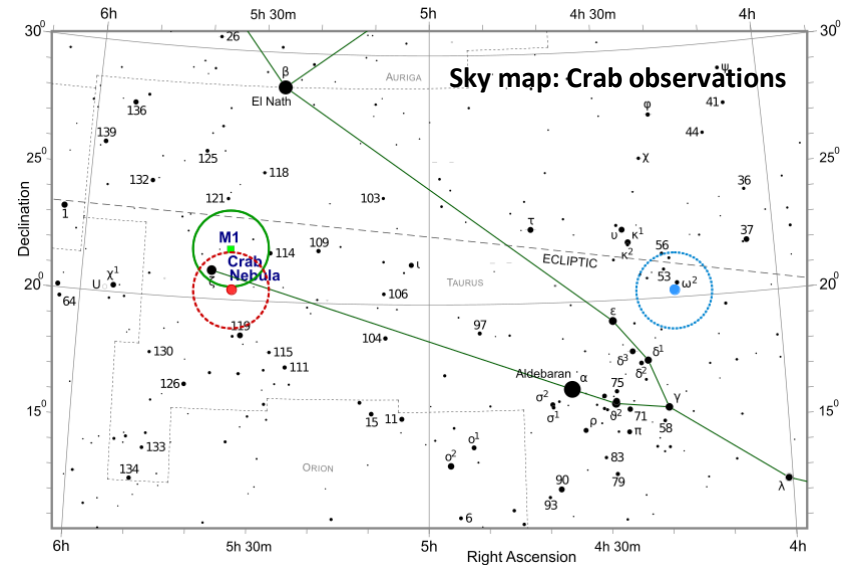Observations : ON-OFF mode (source followed by its background or vice versa)

Signal : Comparison of cosmic-ray events from a gamma ray source region with similar cosmic-ray background region.

Observation log
(2008 – 2017)

Source	Number of ON/OFF run pairs	Duration (hours)
Crab nebula	241	219.0
Dark region	108	97.5
Fixed angle	98	46.1
Bright sky region	26	24.8

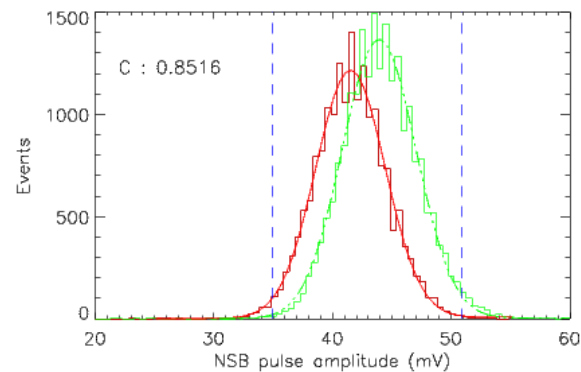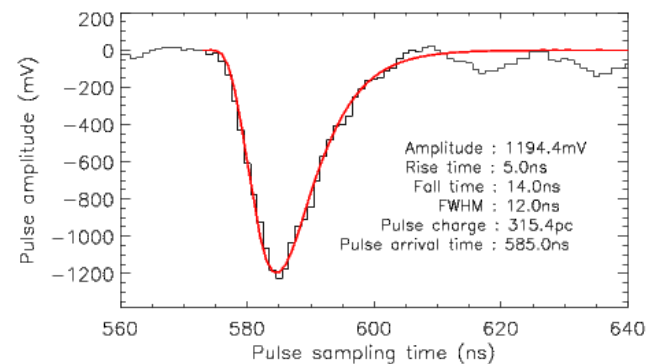$$Signal = \frac{N_{on-source} - C * N_{off-source}}{duration}$$
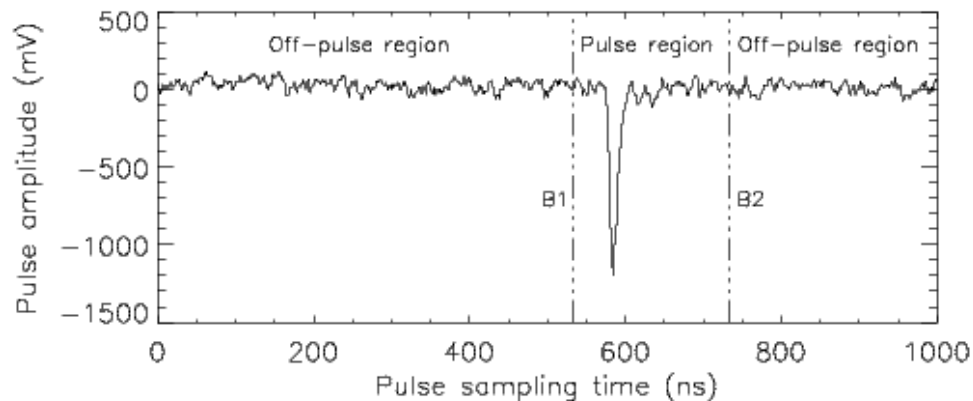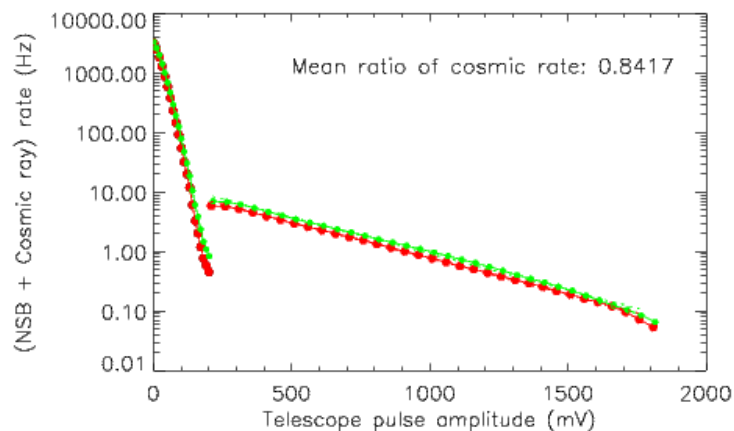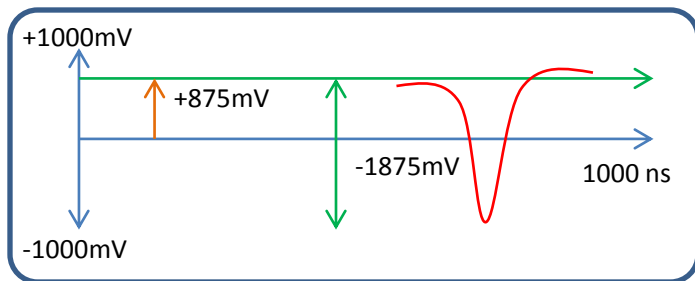
$$Significance\ (\sigma) = \frac{N_{on-source} - C * N_{off-source}}{\sqrt{N_{on-source} + C^2 * N_{off-source}}}$$
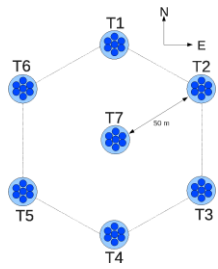

Sky map: Crab observations

Event scalar {s0535+2201_7155_070118.eve}

ON-source
9.8 ± 2.5 Hz

Event scalar {b0535+2201_7154_070118.eve}

OFF-source
10.3 ± 2.2 Hz

HAGAR : Event/waveform analysis

Acqiris : 8bit waveform digitizer

Parameter	Configuration
Full scale (8bit)	2000 mV
Voffset	+875 mV
Pre-trigger delay	800 ns
Sampling period	1ns
Samples	1000

+1000mV

+875mV

-1875mV

1000 ns

-1000mV

Mean ratio of cosmic rate: 0.8417

Off-pulse region   Pulse region   Off-pulse region

B1   B2

Amplitude : 1194.4mV
Rise time : 5.0ns
Fall time : 14.0ns
FWHM : 12.0ns
Pulse charge : 315.4pc
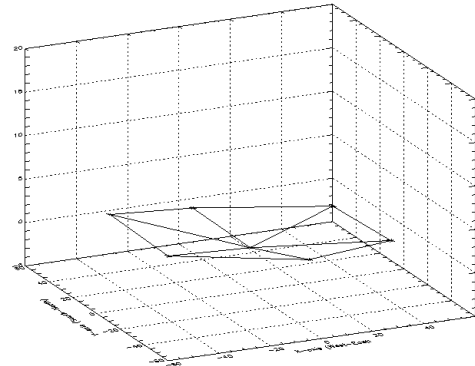Pulse arrival time : 585.0ns

C : 0.8516

HAGAR : Event direction measurement

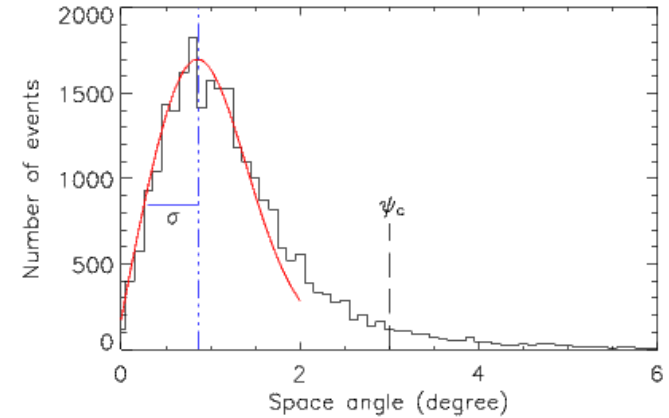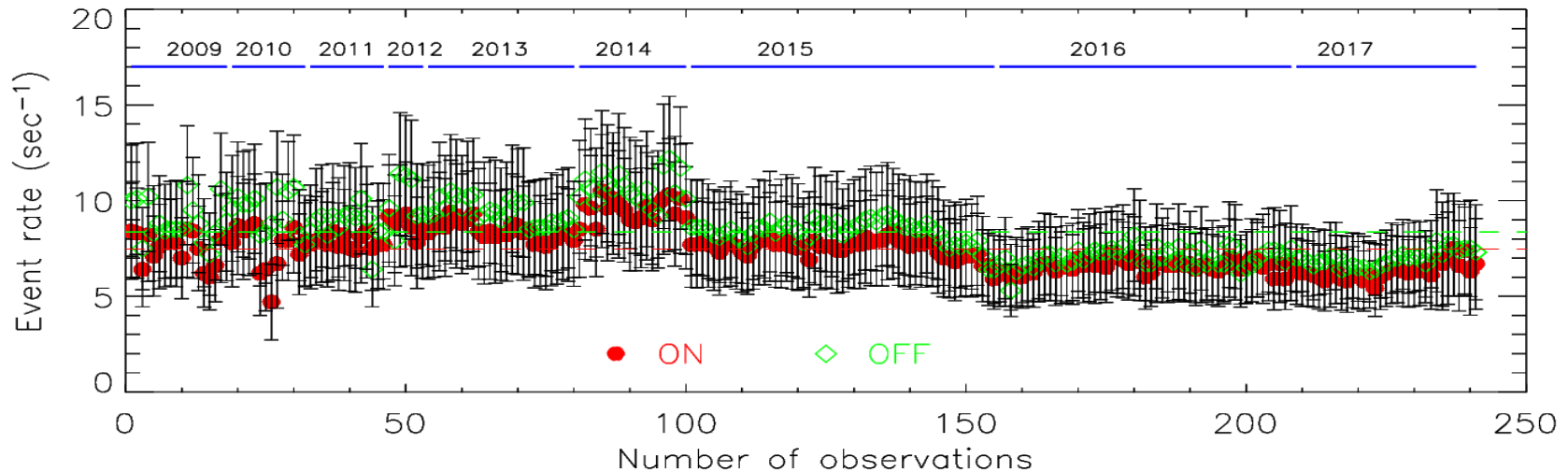Cherenkov shower plane
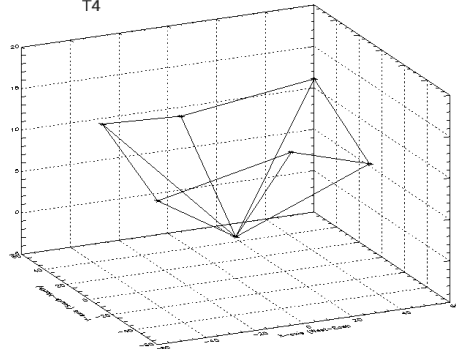
original   Tzero corrected
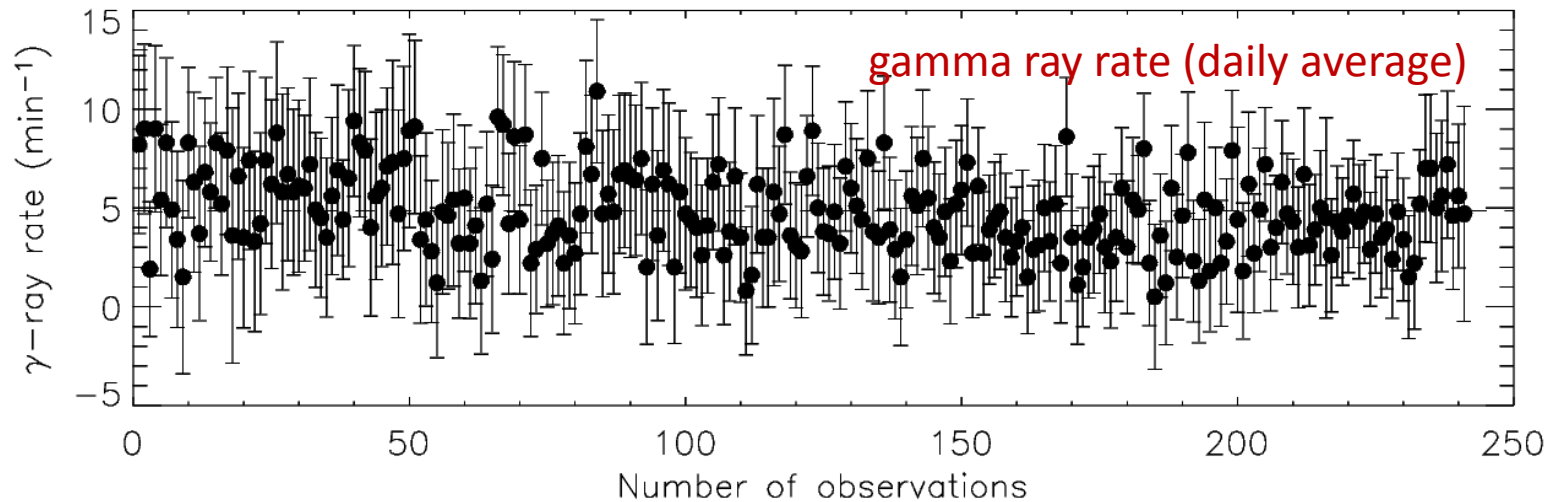
$$\chi^2 = \sum w_{ij}(T0_i - T0_j - C_{ij})^2$$
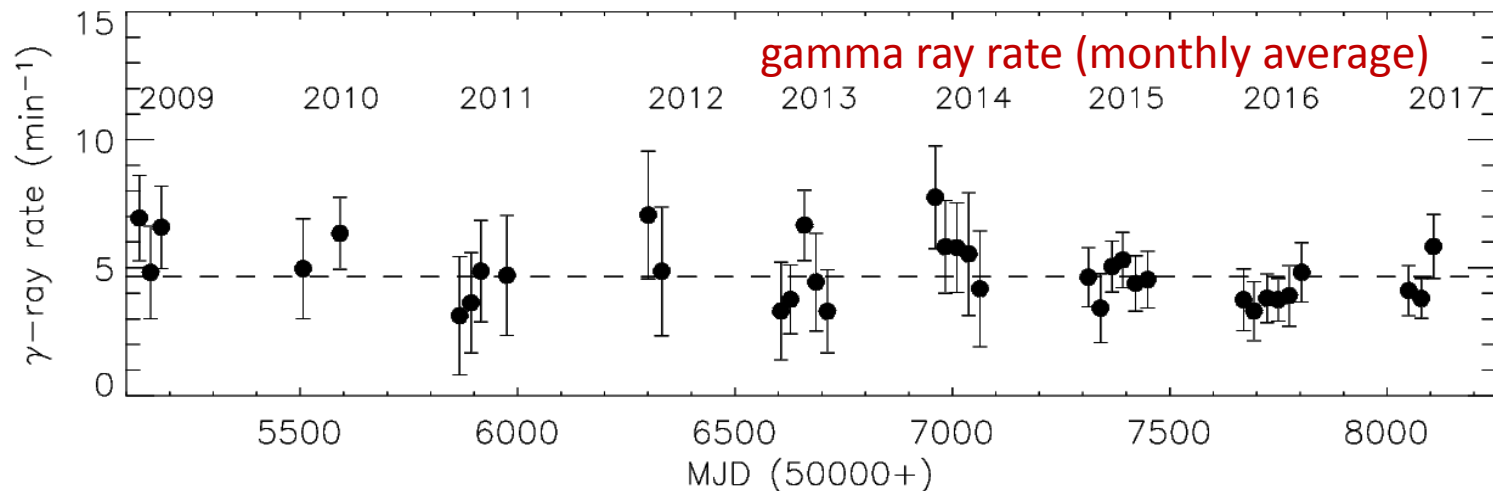
$$\chi^2 = \sum w_i (lx_i + my_i + nz_i + c(t_i - t_0))^2$$

$$\cos\psi = l_1 \cdot l_2 + m_1 \cdot m_2 + n_1 \cdot n_2$$

ON   OFF

HAGAR : gamma ray rate from Crab nebula direction

gamma ray rate (daily average)

Average gamma rate $_{(>230\,GeV)}$ = $(4.64 \pm 0.23_{sta} \pm 0.13_{sys})$ min^{-1}

gamma ray rate (monthly average)

HAGAR : Total signal from Crab nebula direction

Year	MJD	Runs	Duration (hours)	Average Event rate (Hz) ON-source	Average Event rate (Hz) OFF-source	γ-rate min^{-1}	Significance N_σ	$\frac{\sigma}{\sqrt{T}}$
2009	55127 - 55188	18	11.2	7.54 ± 0.80	8.92 ± 1.04	6.13 ± 0.98	6.26	1.63
2010	55500 - 55596	14	9.3	7.55 ± 1.18	9.40 ± 1.02	5.83 ± 1.14	5.09	1.63
2011	55861 - 55976	14	9.2	7.85 ± 0.39	8.75 ± 0.84	4.09 ± 1.07	3.85	1.49
2012	56299 - 56332	7	4.6	8.77 ± 0.53	9.97 ± 1.32	6.08 ± 1.78	3.41	1.76
2013	56599 - 56714	27	26.6	8.41 ± 0.48	9.38 ± 0.62	4.45 ± 0.71	6.28	1.52
2014	56956 - 57064	20	19.5	9.52 ± 0.57	10.66 ± 0.78	5.86 ± 0.89	6.55	1.44
2015	57306 - 57456	55	55.7	7.54 ± 0.45	8.35 ± 0.61	4.64 ± 0.46	10.20	1.43
2016	57663 - 57811	53	51.8	6.55 ± 0.31	7.03 ± 0.48	3.86 ± 0.43	8.97	1.19
2017	58043 - 58112	33	31.1	6.74 ± 1.15	7.21 ± 1.80	4.43 ± 0.56	7.91	1.37
Average	All data	241	219.0	7.47 ± 1.08	8.35 ± 1.36	4.64 ± 0.23	20.30	1.24

$$significance = 1.24\sigma\sqrt{T}$$
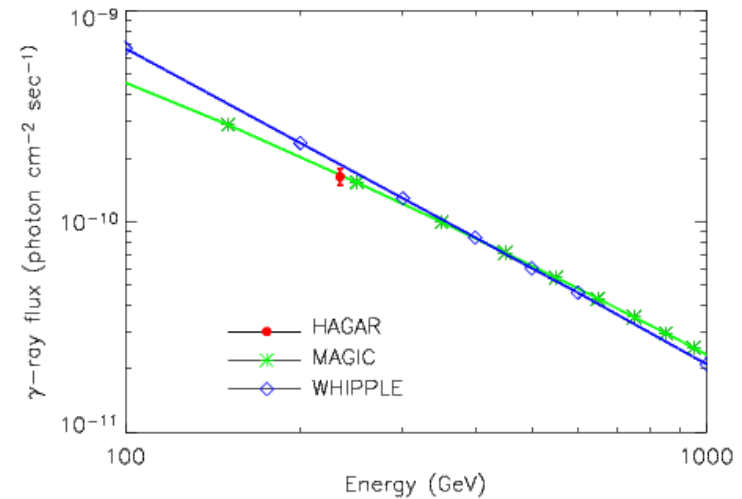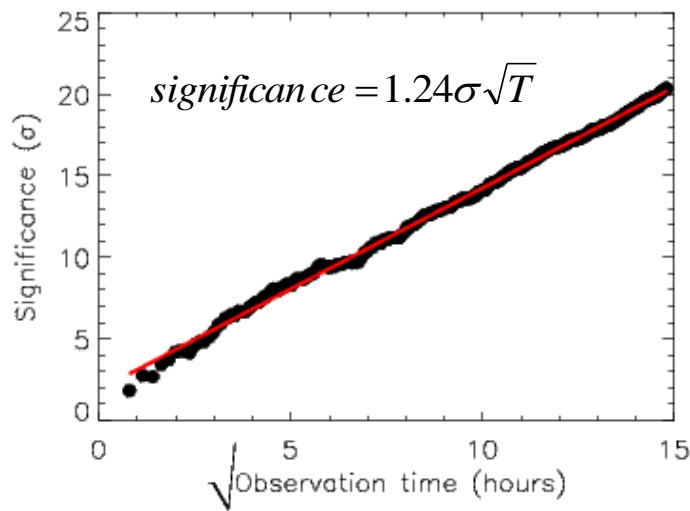
flux(>230 GeV) = (1.64 ± 0.09) x 10^{-10} photons cm^{-2} sec^{-1}

HAGAR : systematic measurement

Dark region : Tracking sky

Fixed angle : Transiting sky
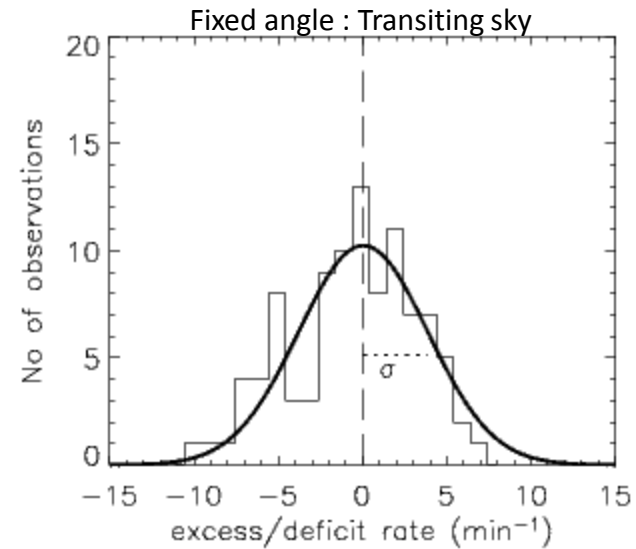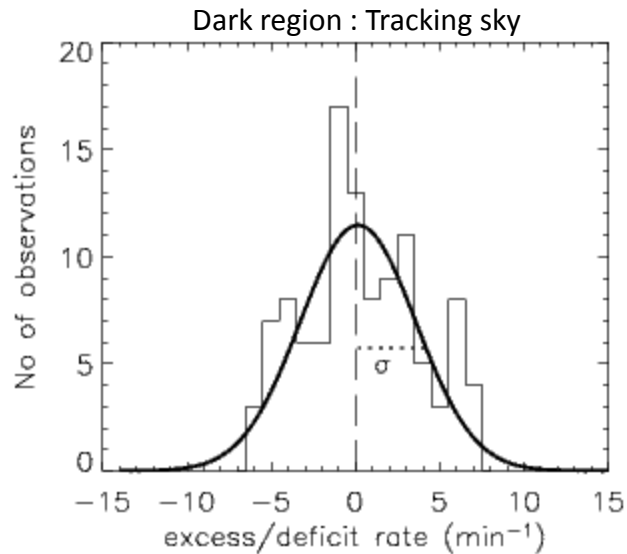
	Dark region	Fixed angle
Runs (N)	108	98
Average Event rate (Hz)	7.99±1.31	9.49±2.17
Excess/deficit rate (minute^{-1})	0.01±0.37	-0.02±0.62
σ	3.43	3.84
Error on mean ($\frac{\sigma}{\sqrt{N}}$)	0.33	0.39

Crab nebula

Zeta tauri

Excess/deficit signal from zeta-tauri runs

NTT=>4
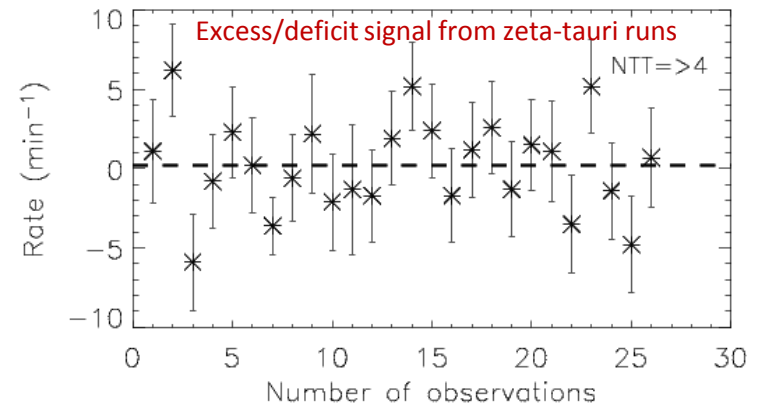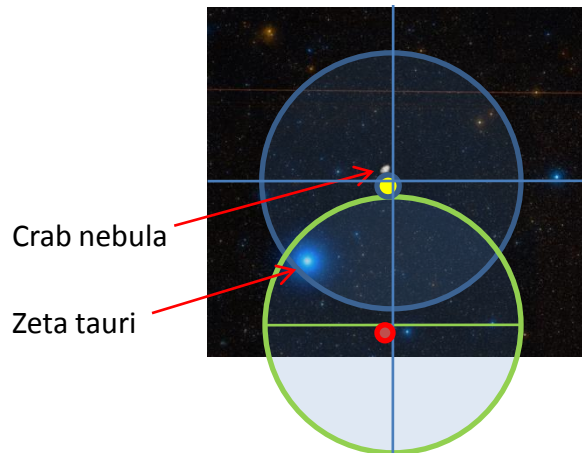
HAGAR : Crab nebula measurement

- VHE photons of energies greater than 230 GeV from the Crab nebula was detected by the HAGAR telescopes.

- Statistical significance of 20σ over the observation period of 219 hours spanning nine years.

- The measured flux agree with MAGIC and Whipple telescopes.

- The systematic error in the estimated gamma ray rate is less than 3%.

- Measurement from the dark regions devoid of any known gamma ray source indicate that normalization can efficiently equalize cosmic ray events in the ON-OFF run pairs.

Thanks