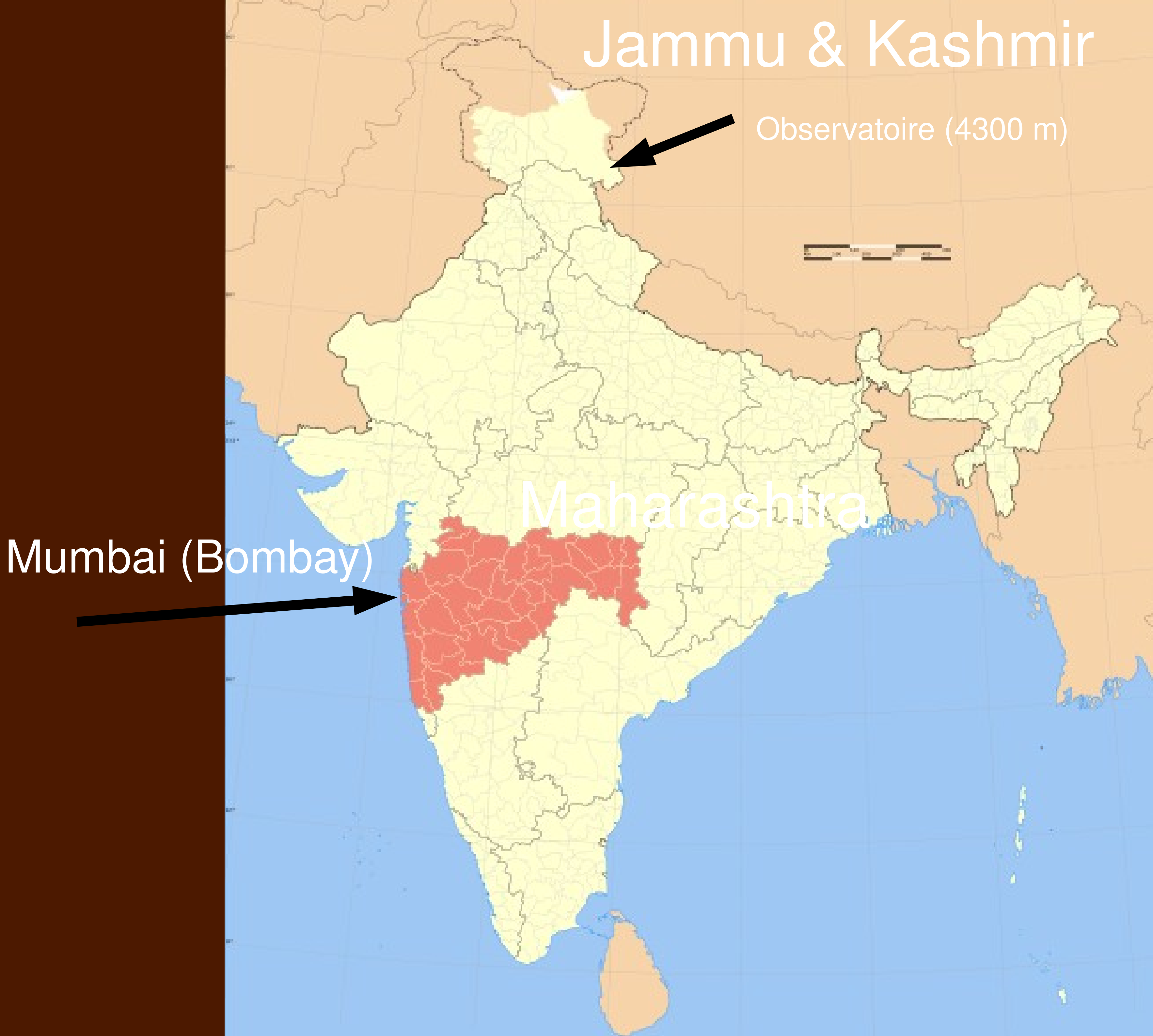
Gamma-Ray Source Observations with the HAGAR telescope System at Hanle in the Himalayas

Richard J. Britto

Department of High Energy Physics
Tata Institute of Fundamental Research
Mumbai, India

LPNHE, Paris, 25/06/2009

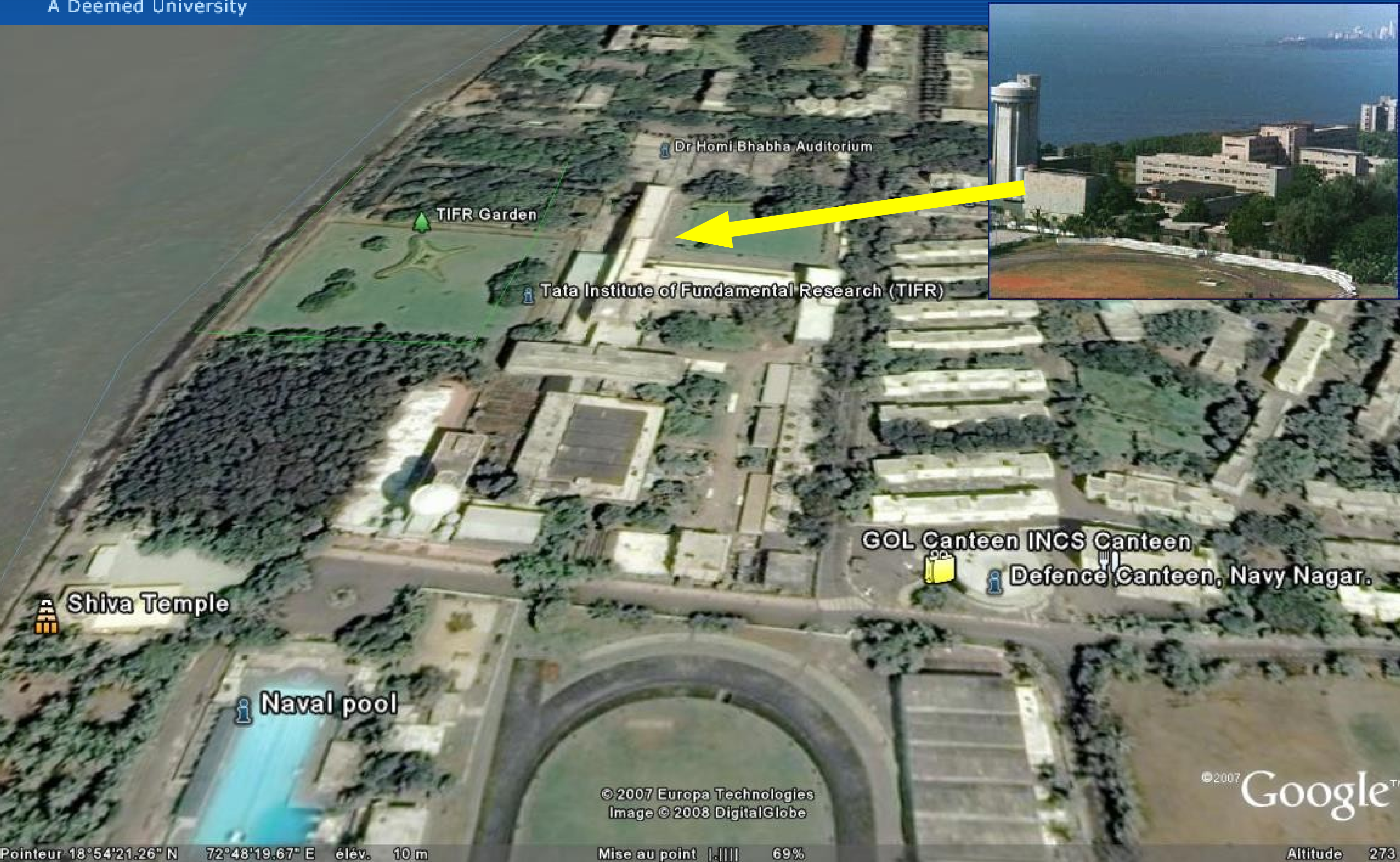

Jammu & Kashmir
Observatoire (4300 m)
Maharashtra
Mumbai (Bombay)


TIFR
© 2007 Europa Technologies
Image © 2008 DigitalGlobe
©2007 Google™
Pointeur 18°53'59.42" N 72°48'45.90" E élév. 5 m
Mise au point 100%
Altitude 1.14 km

टाटा मूलभूत अनुसंधान संस्थान

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

TIFR
A Deemed University



Plan

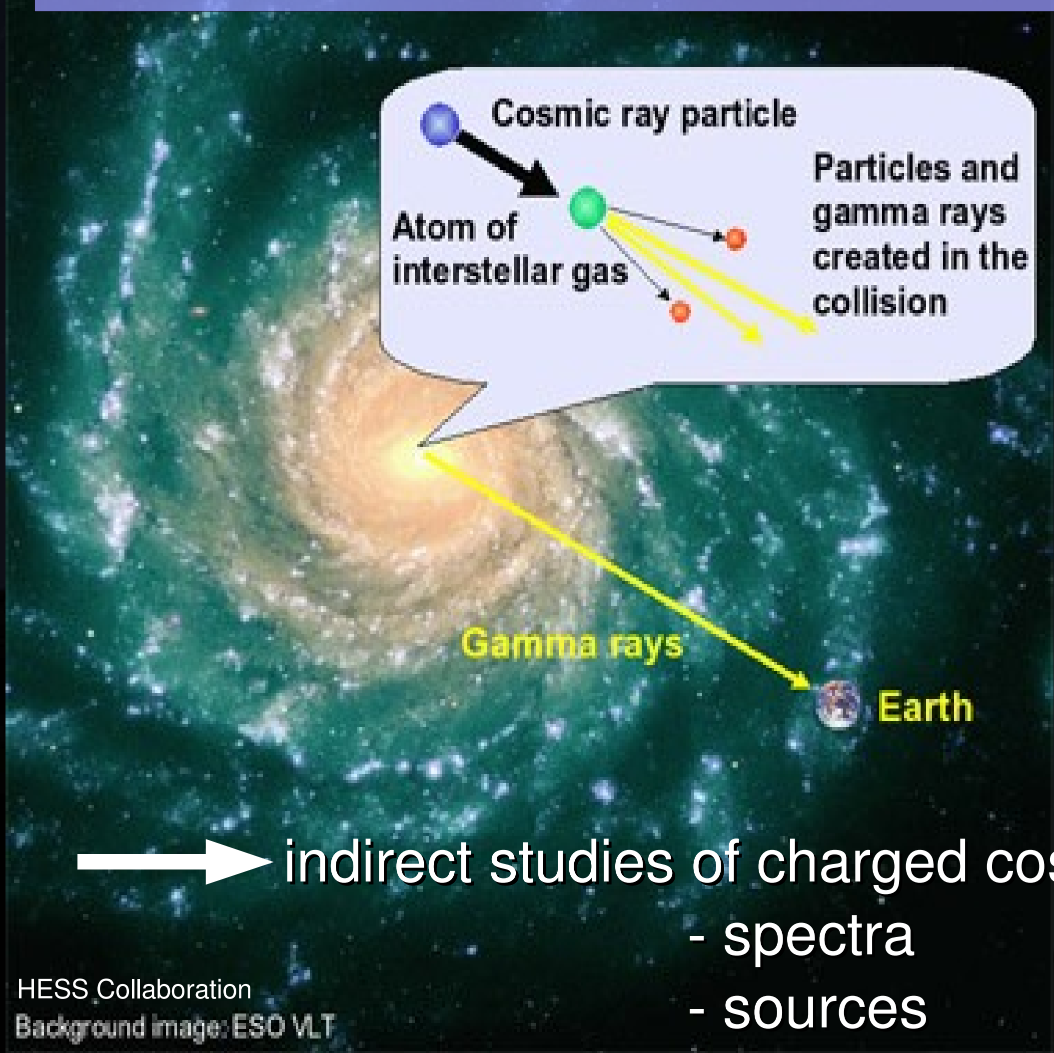
- Introduction to gamma-ray astronomy
- Gamma-ray astronomy in India
- HAGAR experiment
- Calibration & simulations
- Analysis method
- Data selection
- Preliminary results
- Perspectives

Gamma-ray astronomy (1/2)

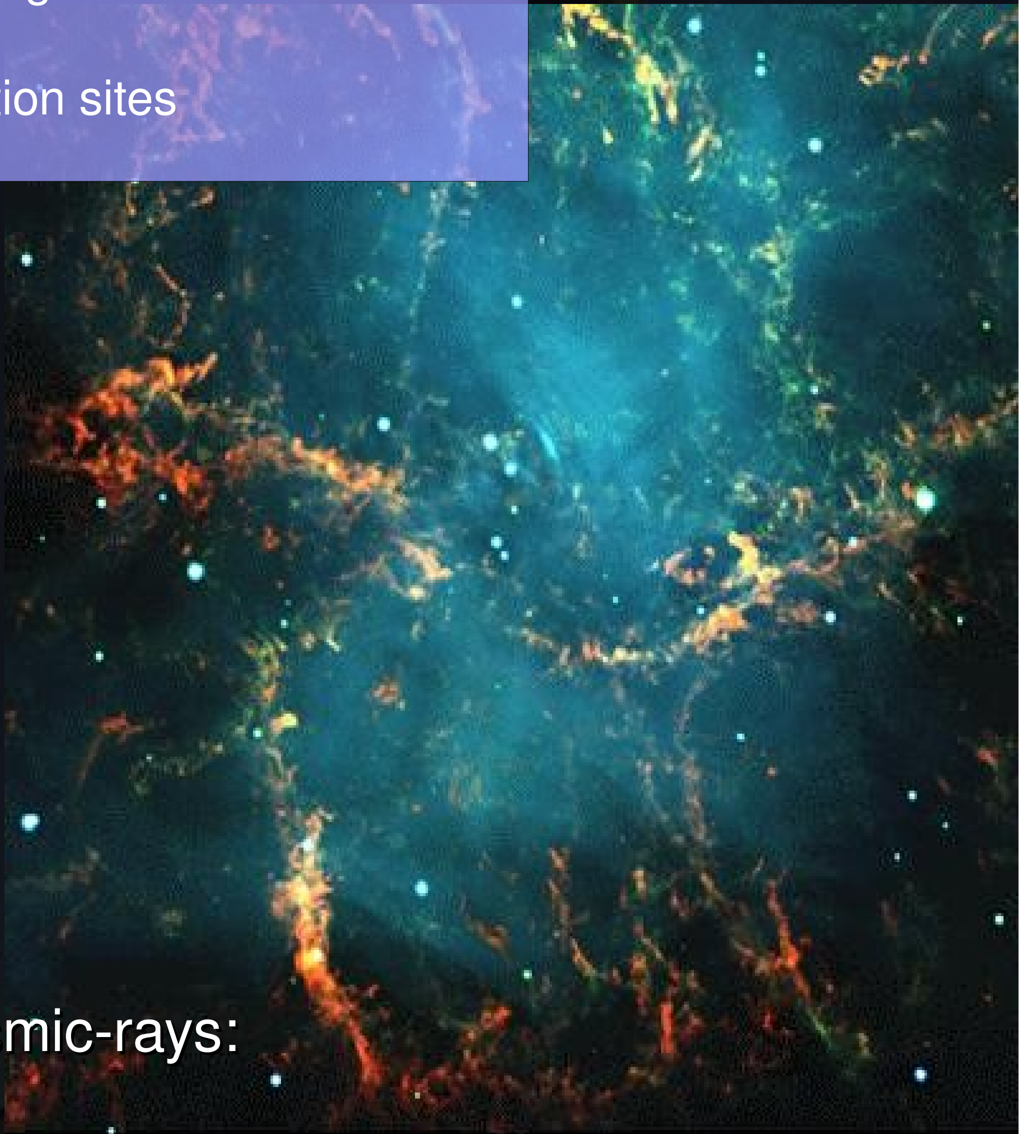
- scattering of charged particules by Galactic magnetic field

BUT:

- propagation of gamma-rays from their production sites



HESS Collaboration
Background image: ESO VLT



The Crab Nebula in Taurus (centre) (VLT KUEYEN + FORS2)

ESO PR Photo 40g/99 (17 November 1999)

→ indirect studies of charged cosmic-rays:

- spectra
- sources

Gamma-ray astronomy (2/2)

Gamma-ray astronomy allows study of:

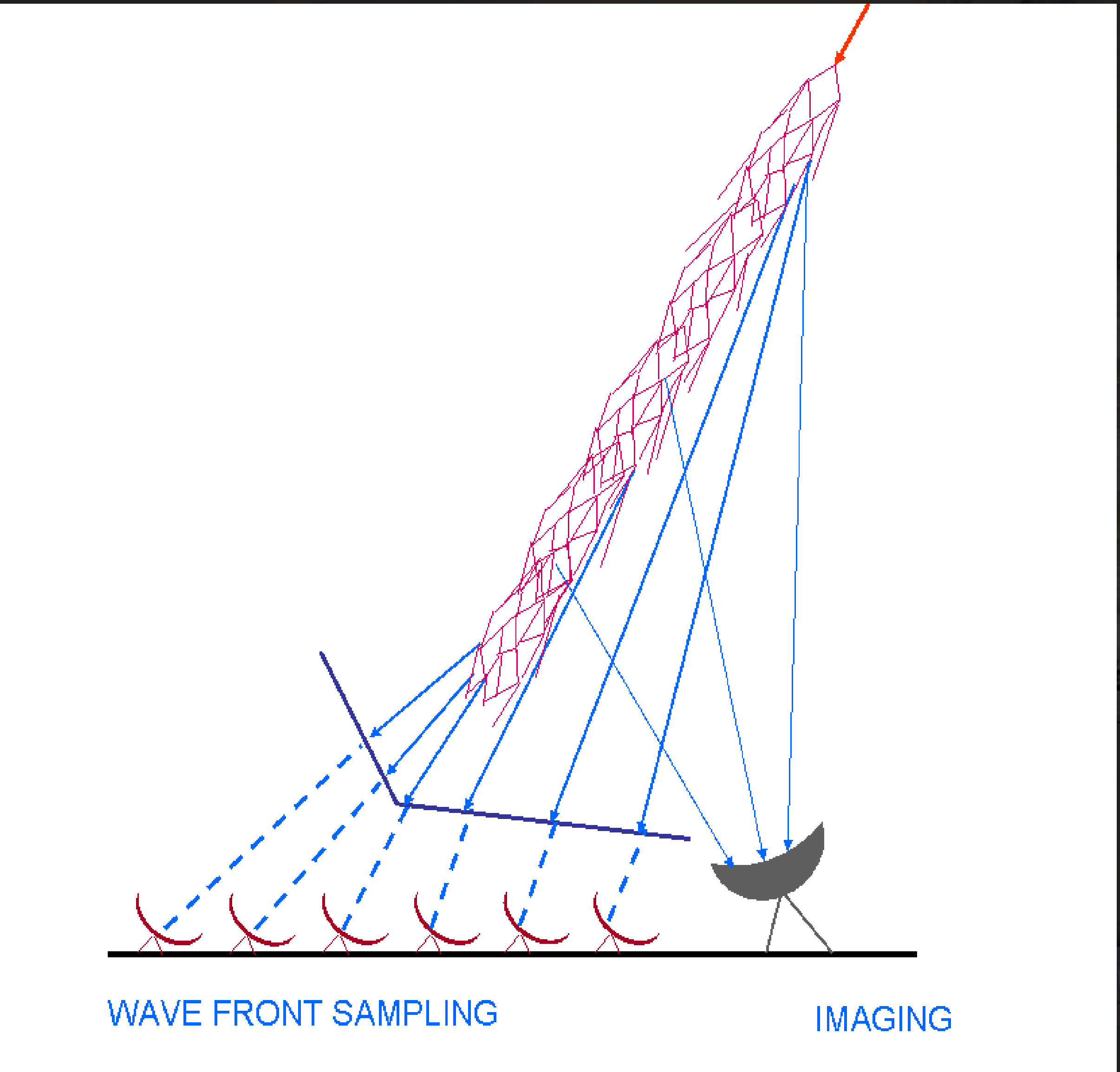
- Supernova remnants (SNRs)
- Pulsars
- Microquasars
- Active Galactic Nuclei (AGNs)
- Gamma-Ray Burst (GRBs)

- Diffuse Gamma-rays:

  - Galactic: from interaction of charged cosmic-rays with the interstellar medium and radiation fields + Galactic dark matter?
  - Extragalactic: non resolved sources (blazars)

+ dark matter?

Imaging and Wavefront Sampling Technique



Imaging : Whipple, CAT, TACTIC, MAGIC, etc.

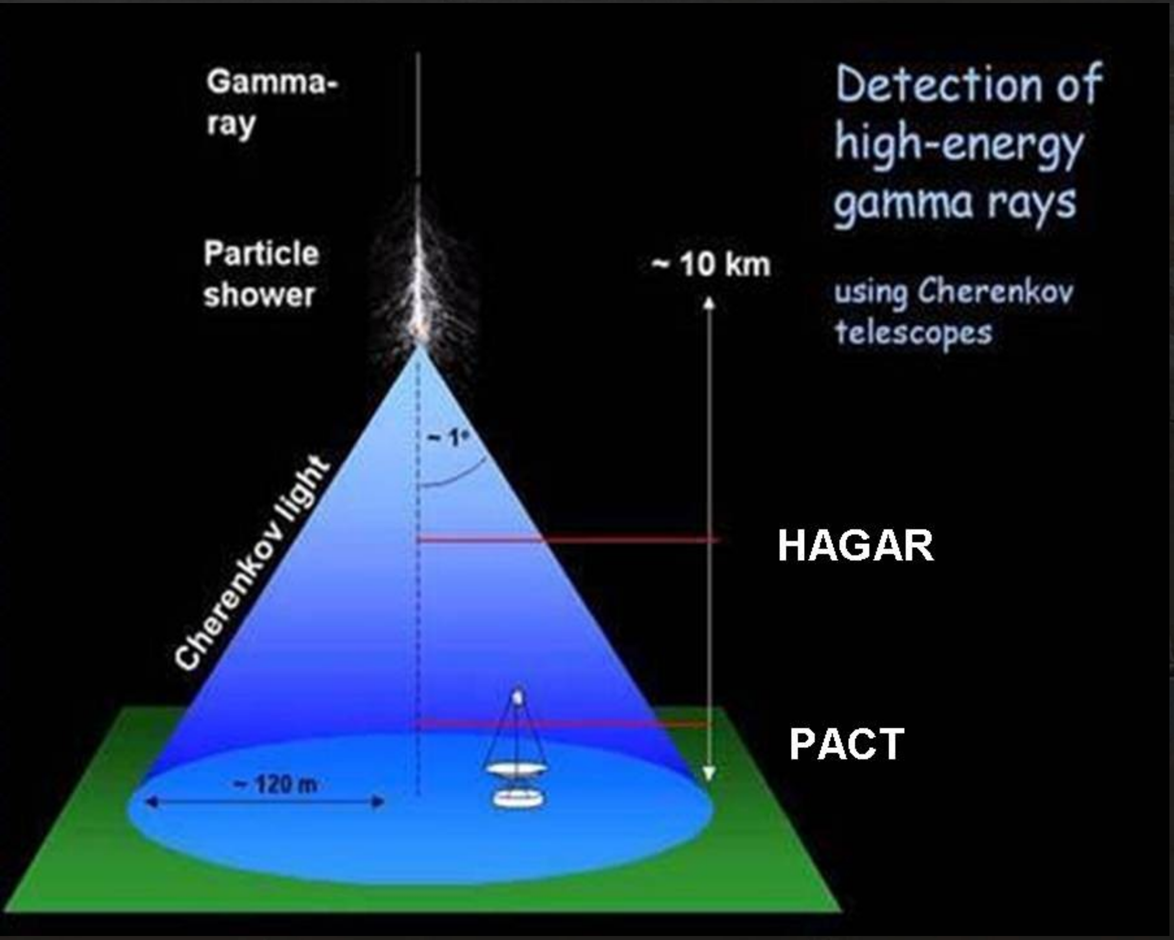
Wavefront sampling : STACEE, CELESTE, PACT, HAGAR etc

Stereoscopic imaging : HEGRA, HESS, VERITAS, CANGAROO-III, etc

Methods of lowering energy thresholds of atmospheric Cherenkov experiments

1. Larger mirror areas : expensive

2. Experiments at higher altitudes : cost effective

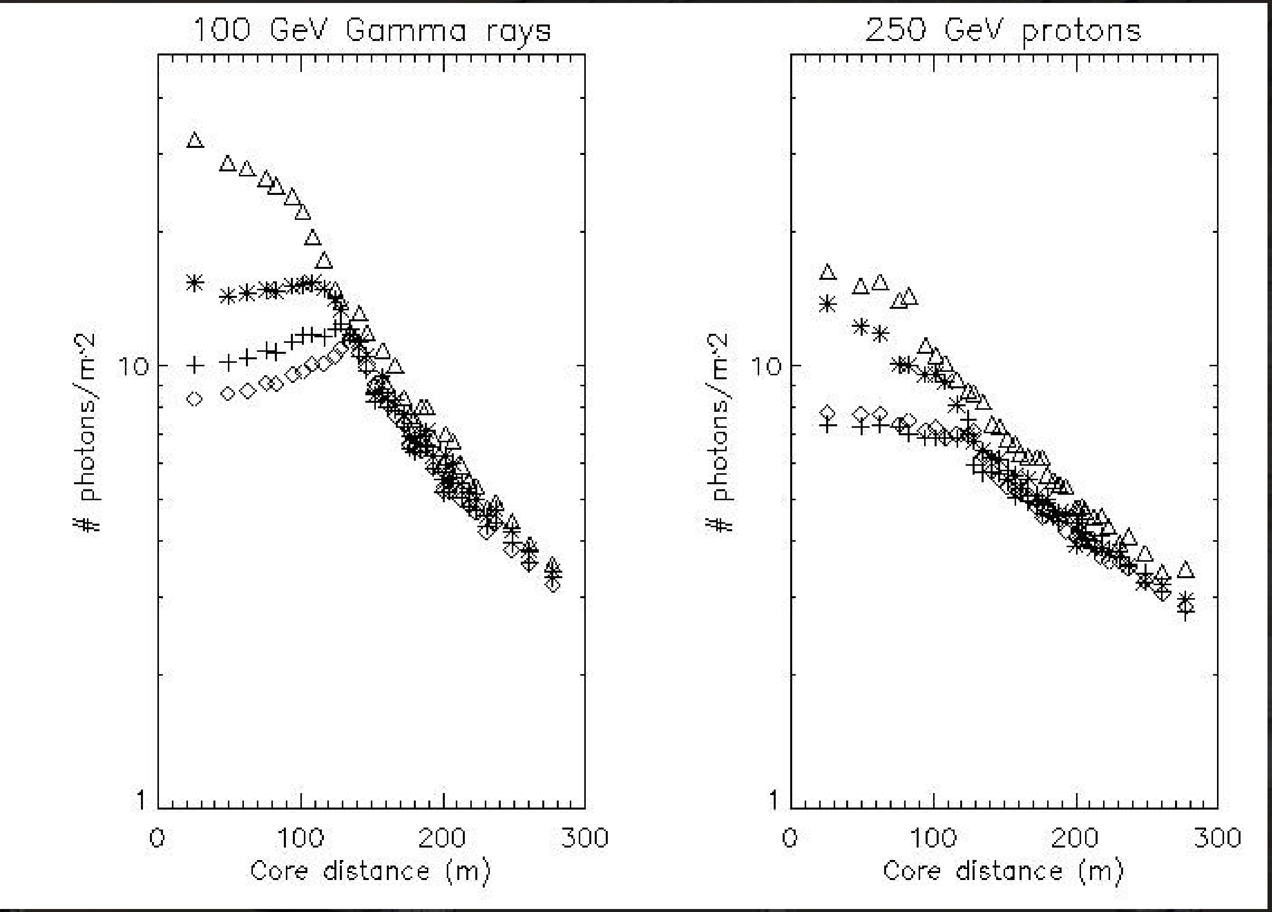


Higher Cherenkov photon density at higher altitude

Lower atmospheric attenuation of Cherenkov photons

--> Significant reduction in energy threshold at higher altitudes

Lateral Distribution of Cherenkov Photons from Extensive Air Showers at Different Altitudes



- Near shower core Cherenkov photon density is 4-5 times higher at Hanle compared to sea level.
- Atmospheric attenuation : @Hanle : 14% @sea level : 50%

L'Astronomie Gamma en Inde

- Dès 1969 à Ooty par le TIFR
- PACT (Pachmarhi, centre de l'Inde, depuis 1986)
- TACTIC (Mont Abu, Rajasthan, depuis 2000)
- HAGAR (Himalaya) 2005 -->
- MACE (Himalaya) 2012 -->
- GRAPES III (particle detector)

Compact Array à Ooty

The first atmospheric Cherenkov telescope consisted of two parabolic mirrors and the activity continued with a progressively increasing sensitivity. The collection area of mirrors were progressively increased to 6.4 m2 (using 10 mirrors of 0.9 m diameter) in 1977 to 20 m2 in 1979, by adding 8 more mirrors of 1.5 m diameter.

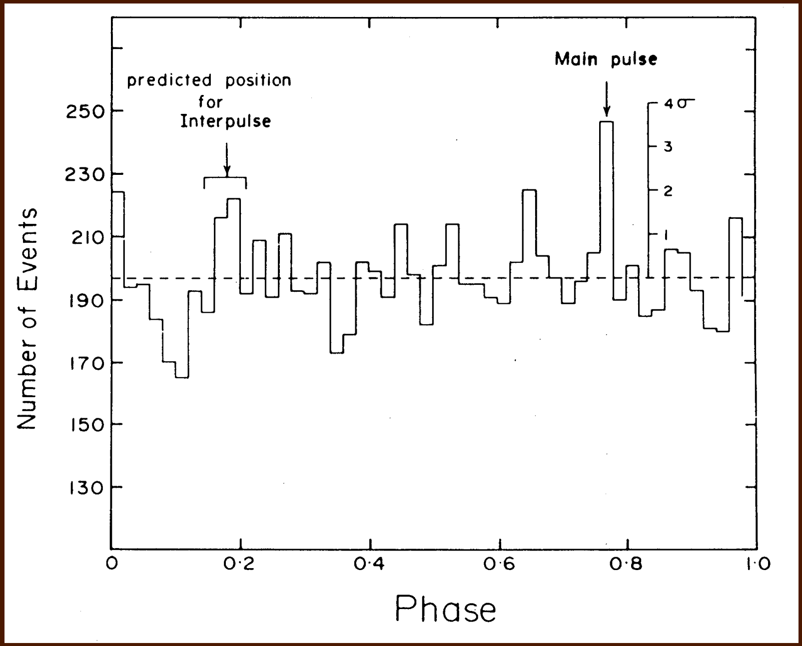
11°N
2 300 m asl
Sud de l'Inde

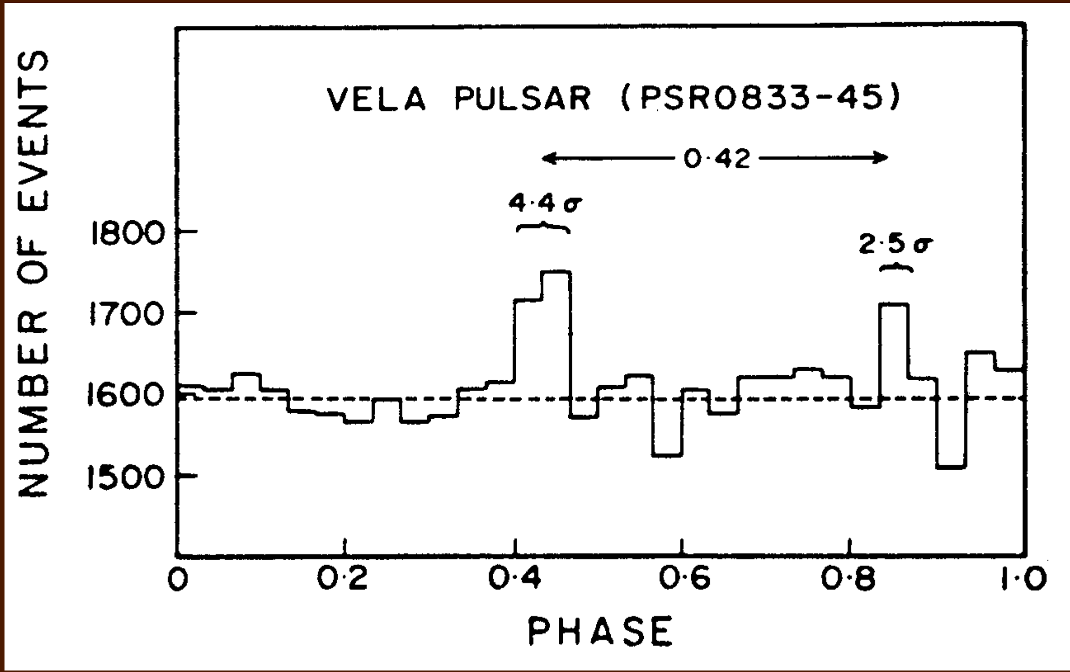
Installation déménagée
à Pachmarhy en 1986

Compact Array à Pachmarhy

Crab pulsar > 4,5 TeV
Avec 10 miroirs de 90 cm
27 h d'observation

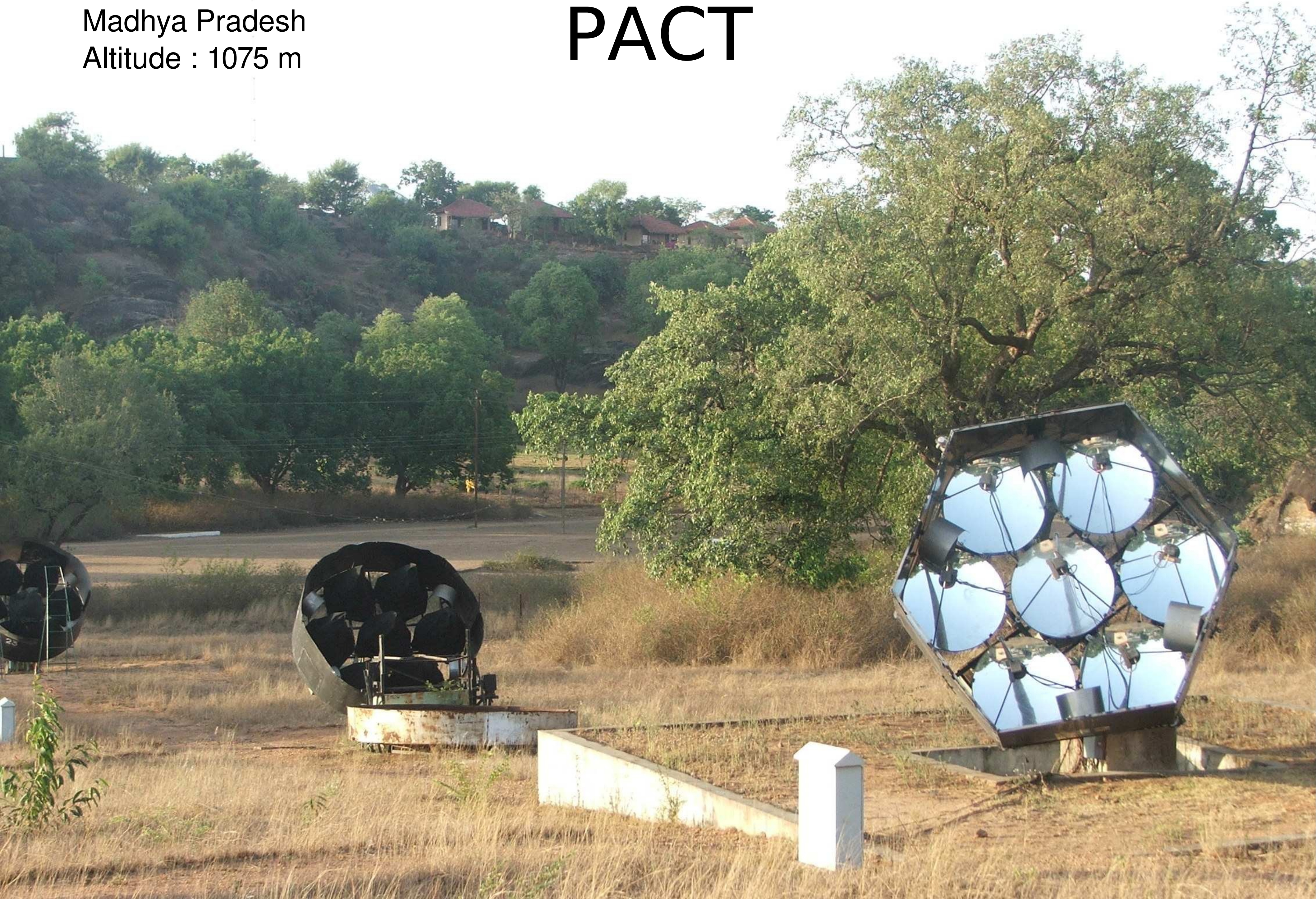
Saison 1976-1977

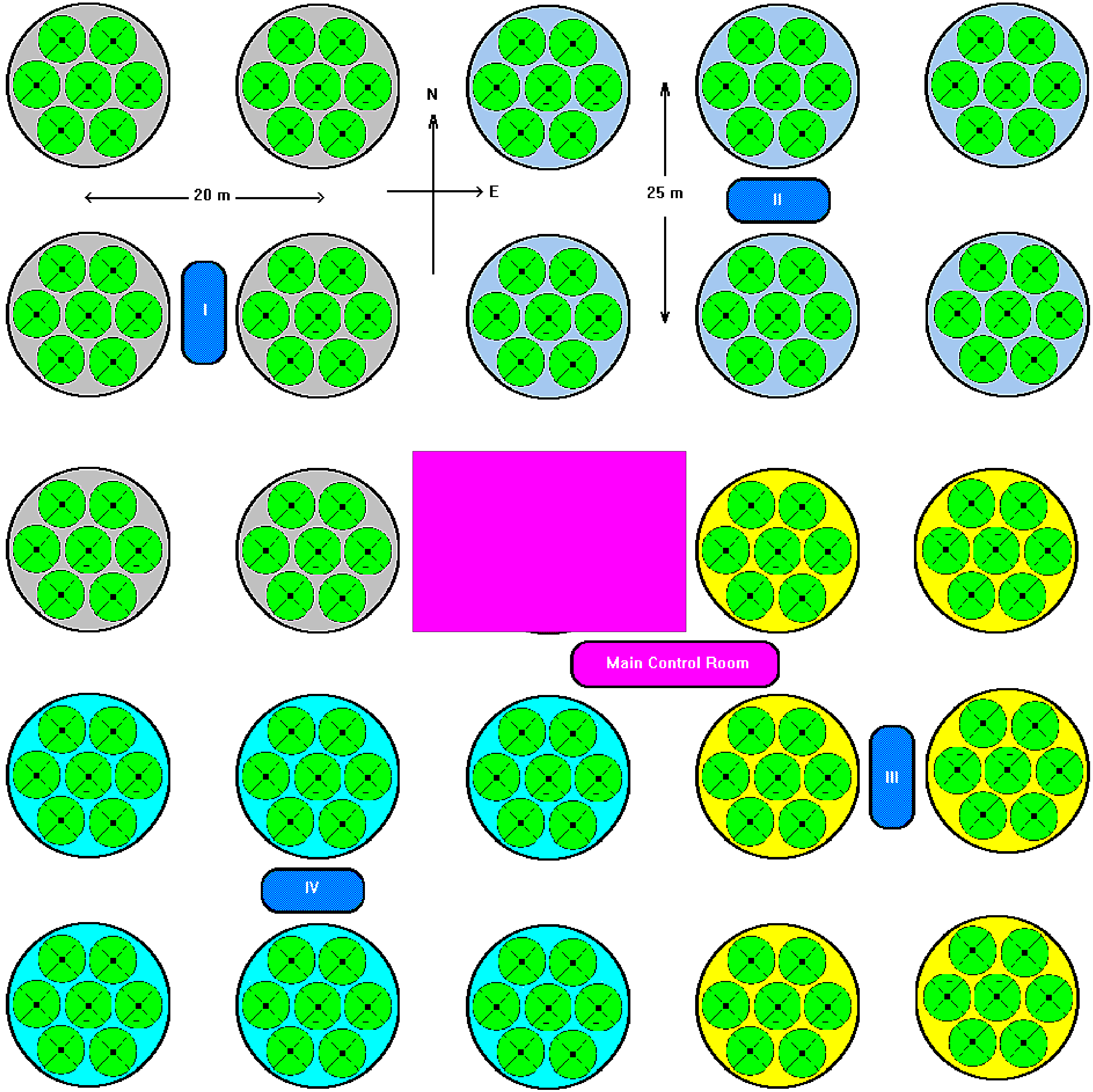




Pachmarhi
Madhya Pradesh
Altitude : 1075 m

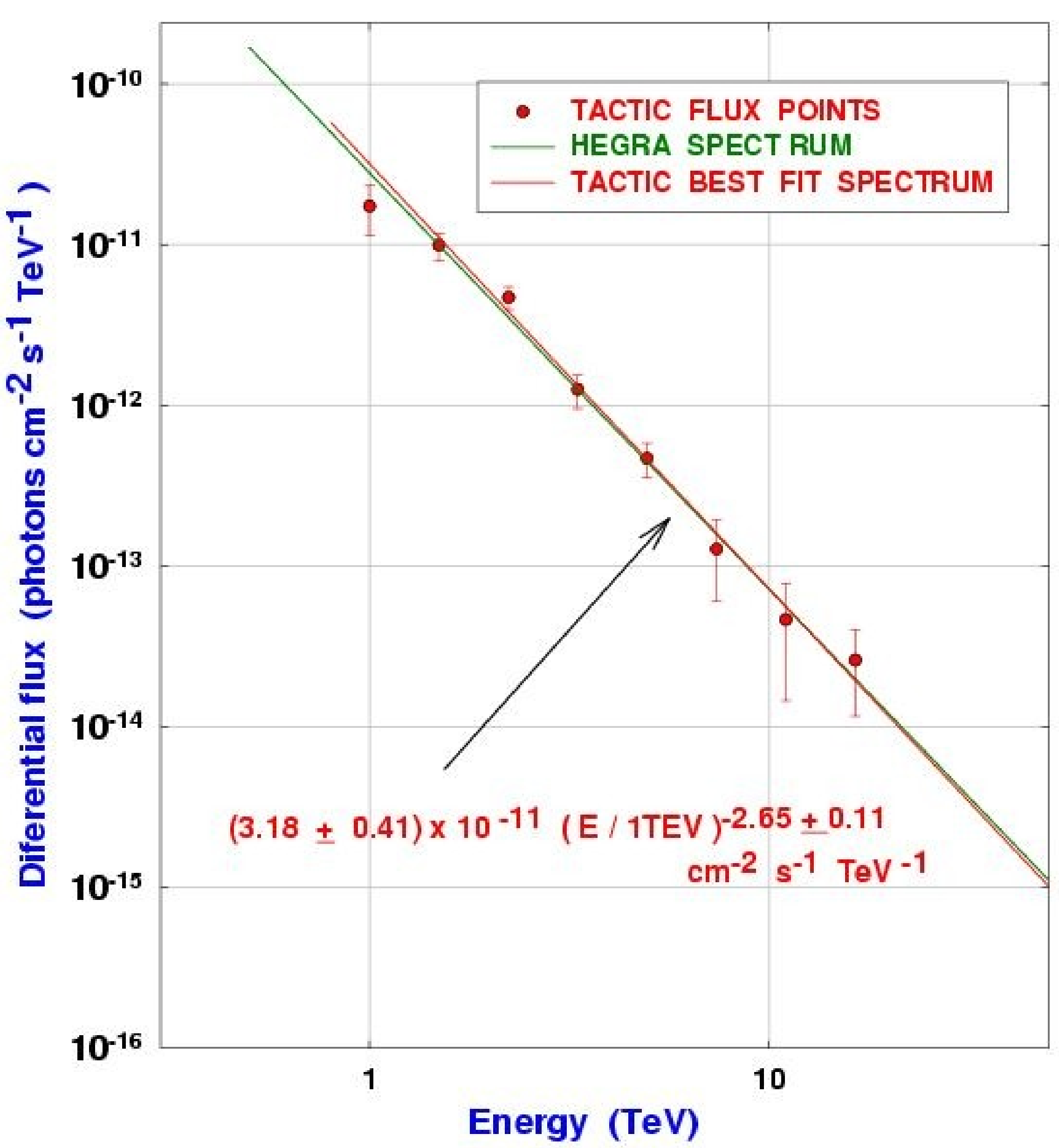
PACT





N
E
20 m
25 m
I
II
III
IV
Main Control Room

TACTIC

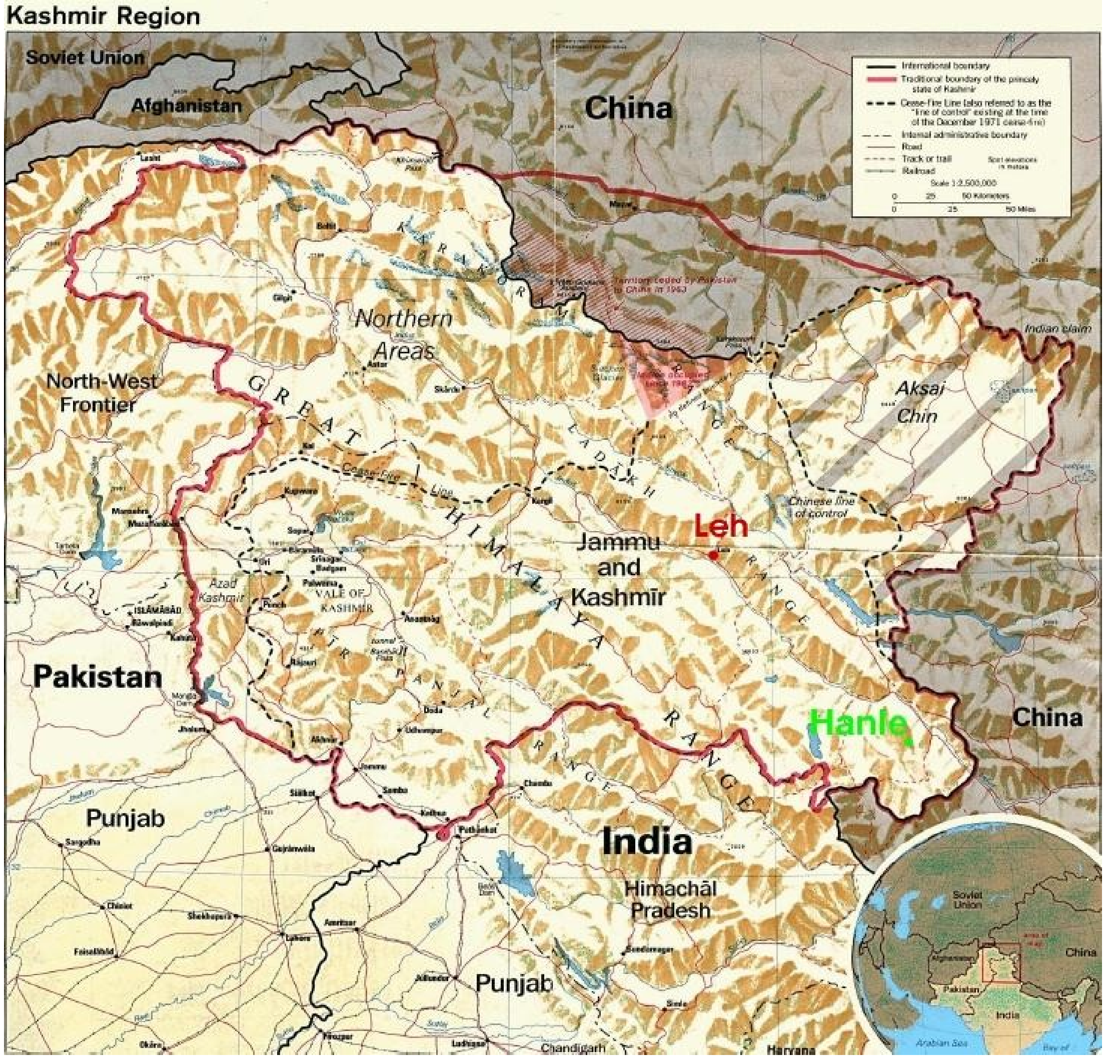


TACTIC FLUX POINTS
HEGRA SPECTRUM
TACTIC BEST FIT SPECTRUM
Diferential flux (photons cm-2 s-1 TeV-1)
Energy (TeV)
(3.18 ± 0.41) x 10 -11 (E / 1TEV)-2.65 ± 0.11
cm-2 s-1 TeV -1

Details of Hanle site

Location :

- Latitude : 32° 46′ 46″ N
- Longitude : 78° 57′ 51″ E
- Altitude : 4300 *m*



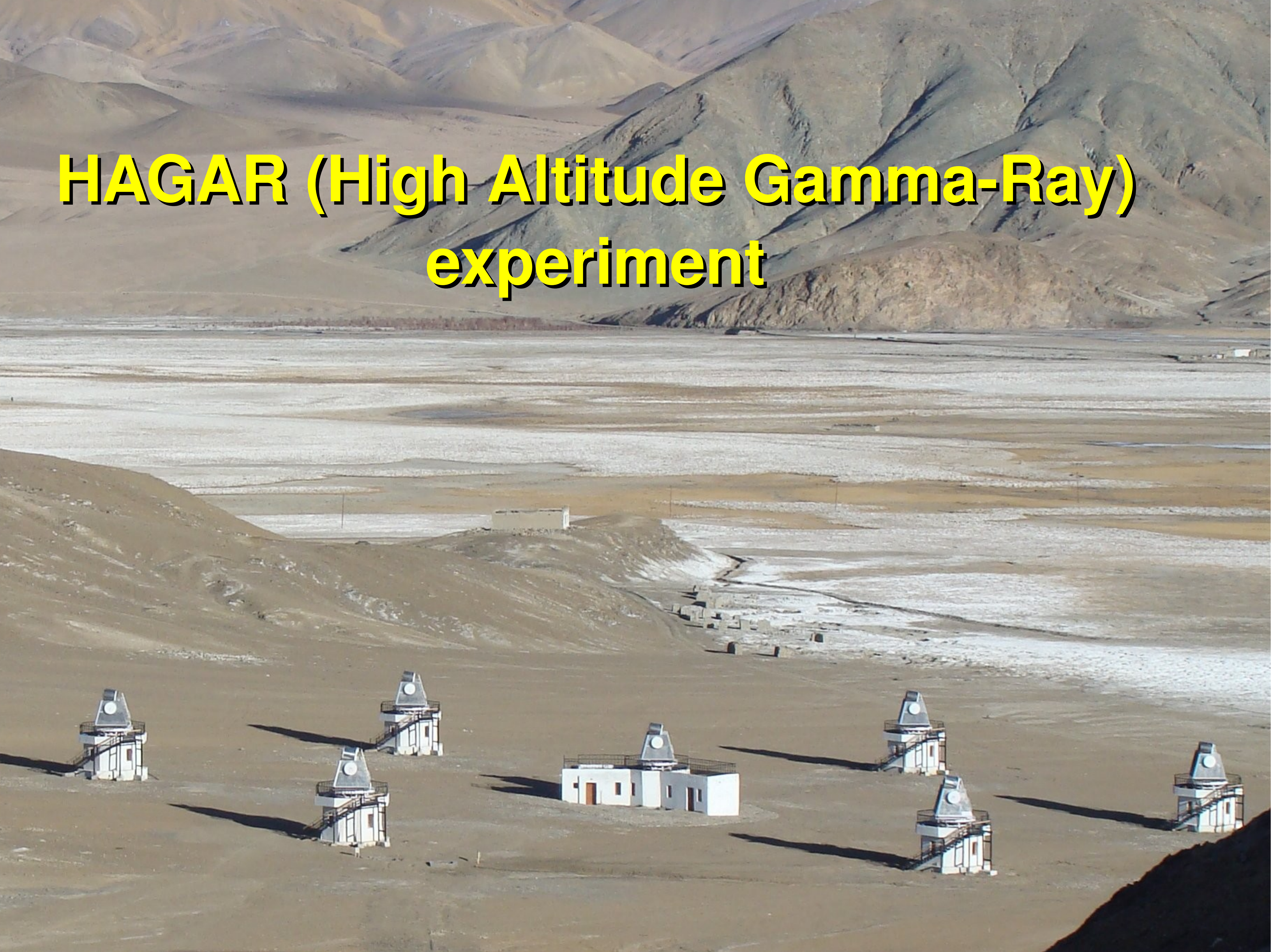
Site Characteristics :

- Low sky brightness
- Low humidity
- Easy accessibility
- Observations throughout the year


INDIAN ASTRONOMICAL OBSERVATORY
Mt Saraswati
Indian Institute of Astrophysics
Digpa Ratsa Ri - Hanle-Ladakh
This foundation stone was laid by
H.E. General K.V.Krishna Rao, PVSM (Retd)
Governor of Jammu & Kashmir
on October 16, 1997

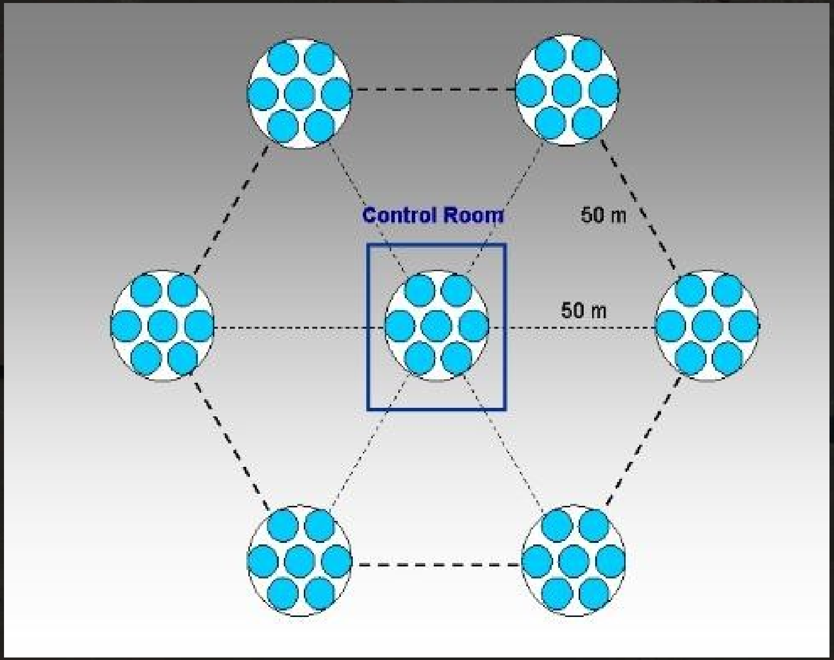
http://www-dapnia.cea.fr/Images/astImg/2200_1.jpg

HAGAR (High Altitude Gamma-Ray) experiment



High Altitude GAmma Ray (HAGAR) Experiment

- Experiment based on wavefront sampling technique
- Located at Hanle base camp at altitude of 4300 m
- Started as a collaboration between IIA and TIFR, but now part of a larger collaboration : Himalayan Gamma Ray Observatory (HiGRO) between BARC, IIA and TIFR (+SINP ….)
- Completely indigenously designed and assembled
  Civil and mechanical : IIA, Optics and DAQ : TIFR



→ 7 telescopes consisting of 7 para-axially mounted parabolic mirrors of diameter 0.9 m

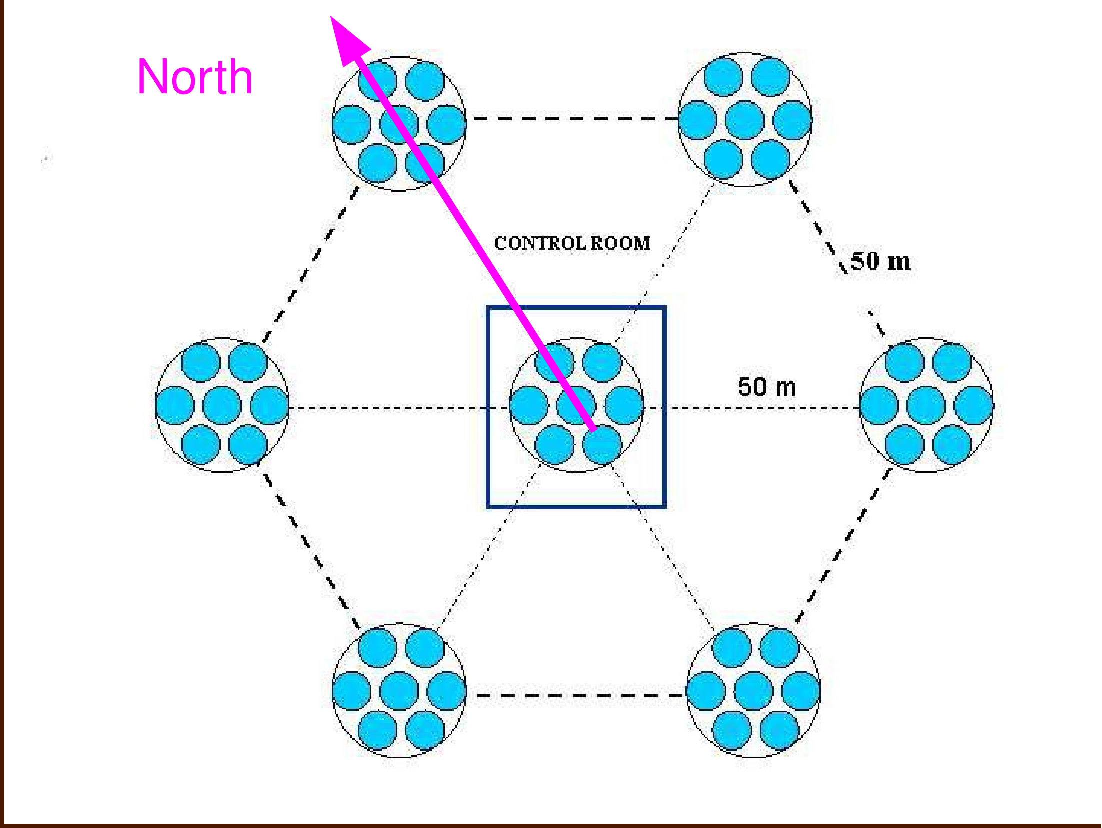
→ f/D ~ 1

→ Photonis UV sensitive phototube (XP2268B) at the focus of each mirror

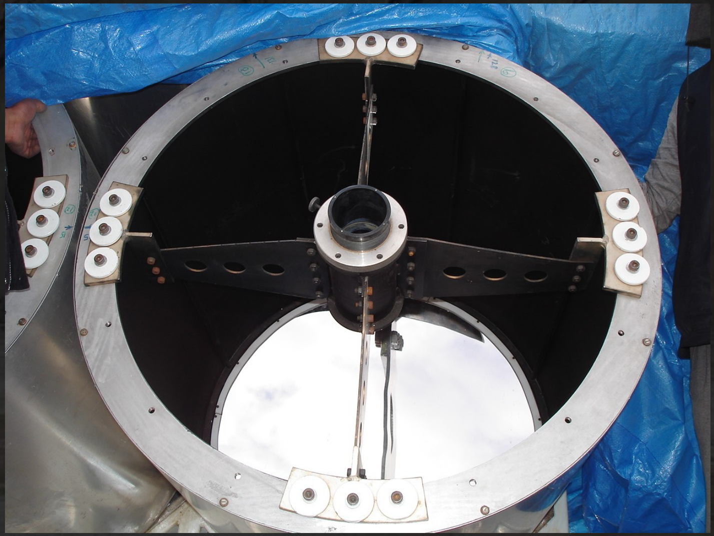
- 31 m^2 seulement de surface collectrice

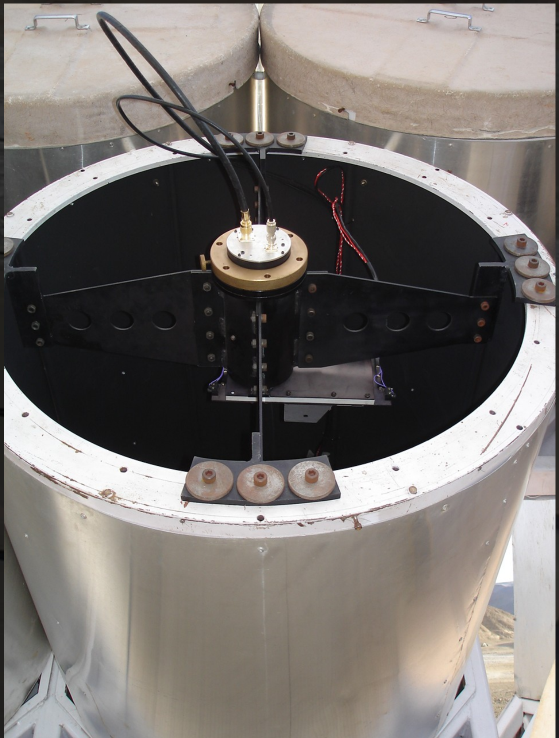
MAIS :

- 1ère exploitation de la technique Tcherenkov atmosphérique à très haute altitude (4300 m)



HAGAR Telescope





Tracking System

- Based on indigenously developed ACTOS for PACT
- Alt-azimuth mount, each axis driven by separate steppar motor
- Maximum zenith angle coverage upto 85°
- Steady state pointing accuracy of servo is ± 10 arc sec
- Maximum slew rate : 30°/min

Motion Control Interface Unit

Data Acquisition System (before Flash-ADCs)

- High voltages given to individual PMTs are controlled through CAEN controller model (SY1527)

- PMT pulses are brought to control room through coaxial cables of type LMR-ultraflex-400 and RG213

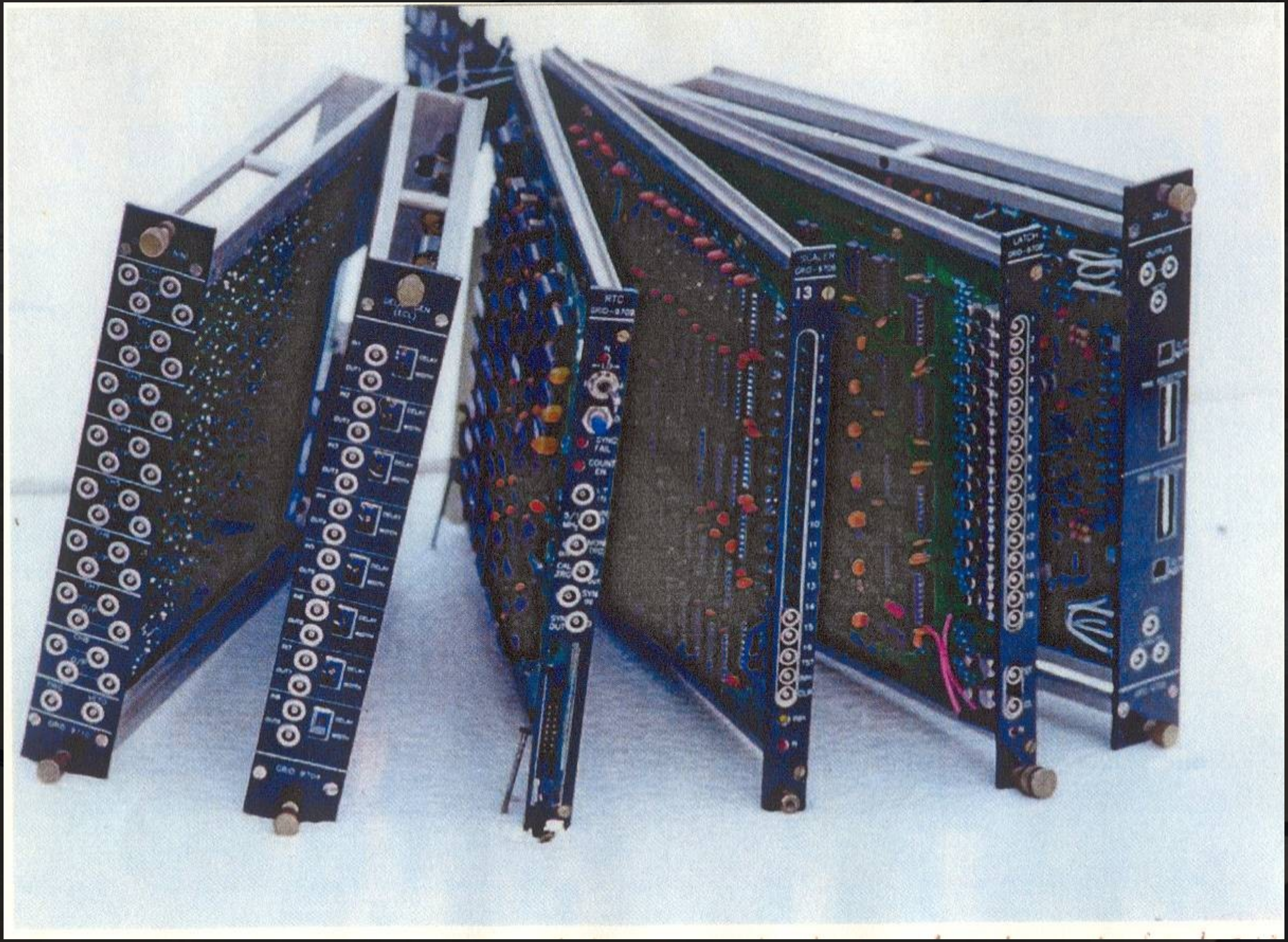
- Data acquisition through CAMAC based instrumentation

- Event generated on coincidence of at least 4 telescope pulses

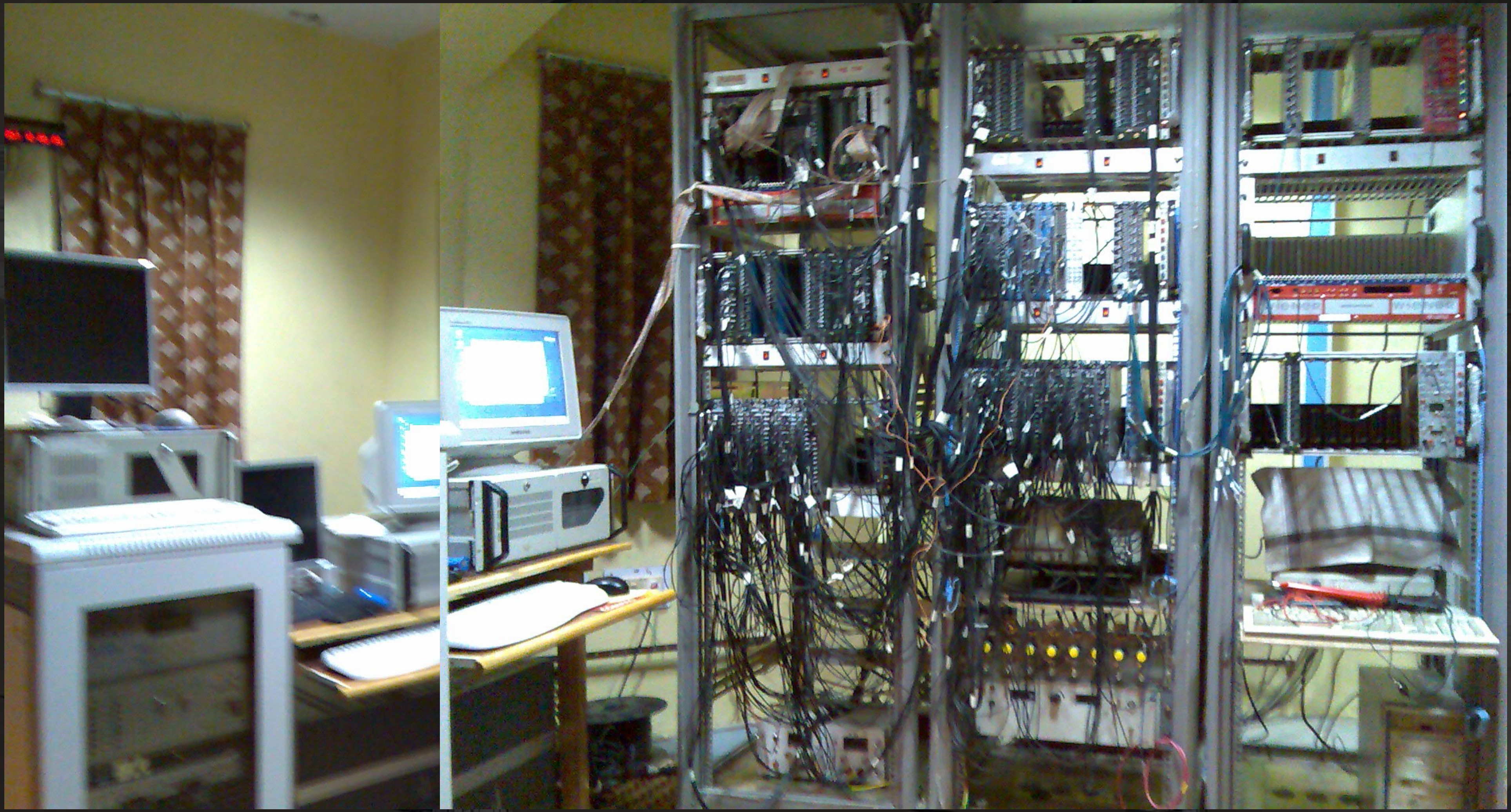
- Data recorded for each event:
  relative arrival time of shower front at each mirror
  accurate to 0.25ns using TDCs
  pulse height at each mirror using 12 bit ADC (QDCs)
  absolute event arrival time accurate to micro-sec

- Various count rates recorded every second for monitoring purpose

Electronics Modules Developed In-house



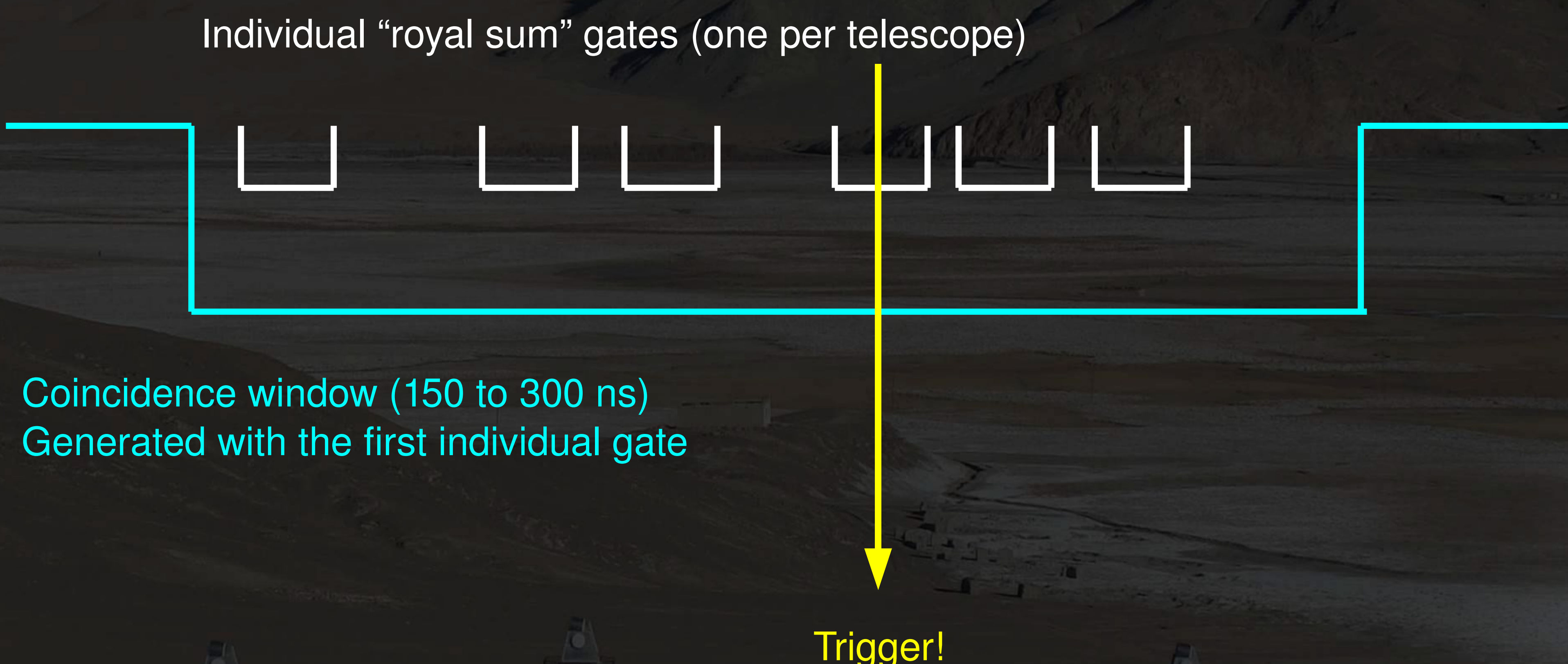
Data Acquisition and Telescope Control



Current status of TDCs/QDCs

- 7 telescopes with 7 mirrors ---> 49 PMTs
- 49 individual + 7 “royal sum” TDC channels
- 7 QDC “royal sum” channels (module for the 49 individual QDC channels are installed)
- Now, only the 7 royal sum TDC channels are used for signal extraction.

Trigger


Individual “royal sum” gates (one per telescope)
Coincidence window (150 to 300 ns)
Generated with the first individual gate
Trigger!

Present Status of HAGAR

All 7 telescopes commissioned

Regular source data since september 2008

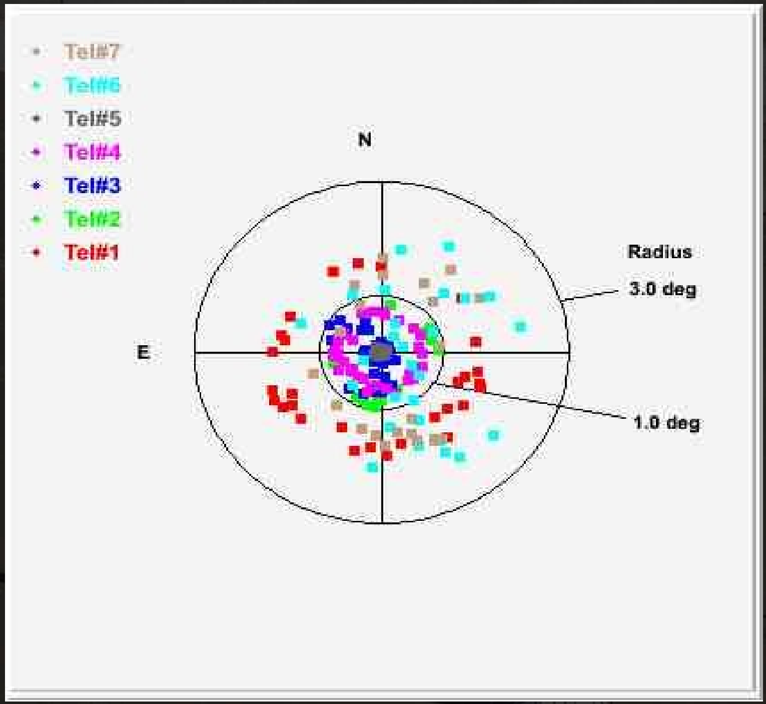
Telescope alignment

Telescope pointing

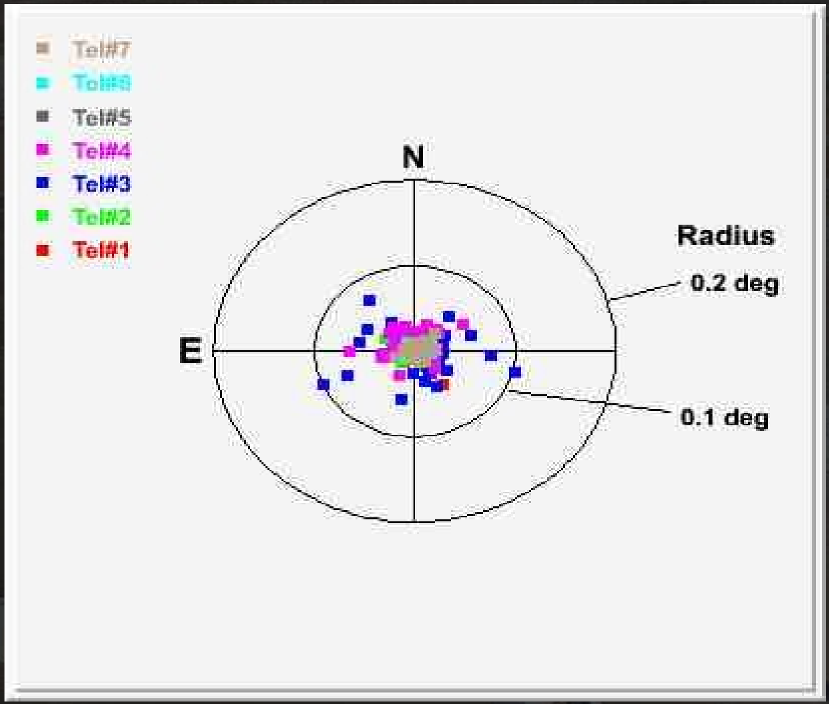
For each telescope pointing model is worked out sighting large no. of stars

Pointing accuracy ~ few arc-min

Star offsets relative to telescope axis



Before pointing model



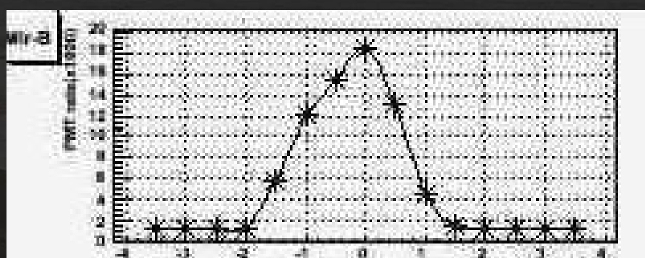
After application of pointing model

Telescope alignment

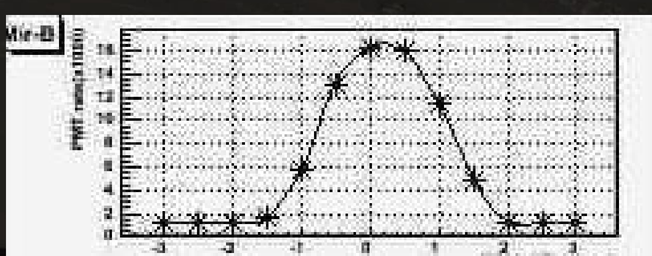
Mirror alignment

To ensure co-alignment of mirror axes with telescope axis, RA-DEC scans are performed around bright stars

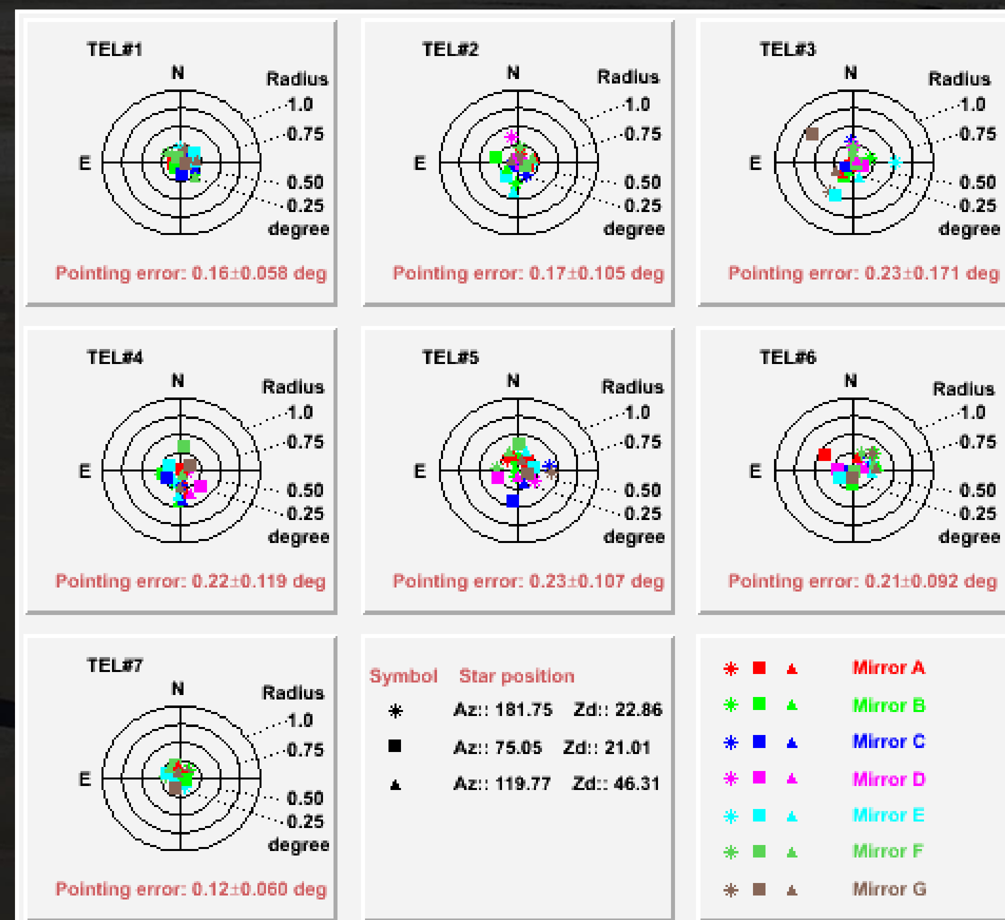
RA scan



DEC scan



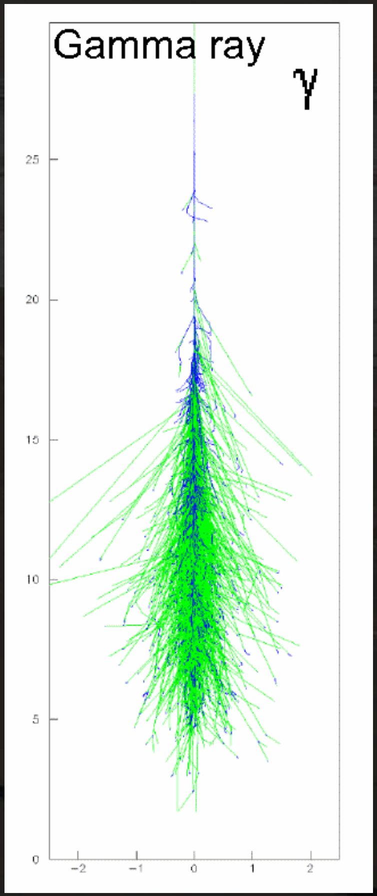
After pointing model & mirror alignment

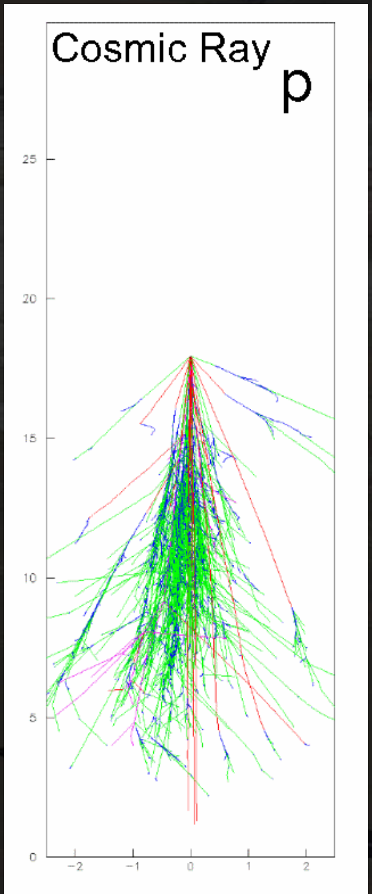


Overall pointing accuracy Including mirror alignment : 0.2°± 0.1°

Extensive Air Shower Simulations

CORSIKA package used for simulations of extensive air showers initiated by gamma-rays and cosmic ray particles





gamma e^+ / e^- muons hadrons

- CORSIKA simulates interactions and decays of hadrons, air nuclei, muons, electrons and photons in atmosphere
- Tracks down all the particles and photons in the shower to observation level
- Simulates Cherenkov emission by relativistic charged particles in shower

CORSIKA

Inputs :

- Primary type and energy
- Arrival angle of primary
  - gamma-rays : vertical
  - Cosmic rays : within 3° around vertical
- Impact parameter : 0-200 *m*
- Altitude of observation level and geomagnetic field
  - Hanle altitude : 4.3 *kms*
- Telescope array geometry
- Wavelength range : 270-650 *nm*

Output :

Arrival time, direction and position of Cherenkov photons hitting telescopes

Detector Simulation

Site and instrument related parameters

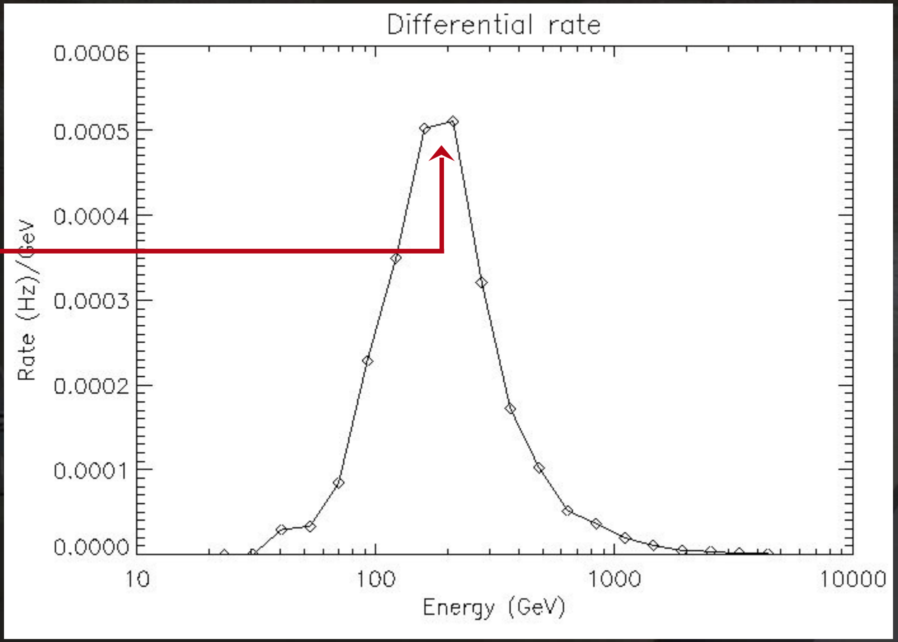
- Atmospheric attenuation of Cherenkov photons
- Night sky background : 1.5×10^{8} ph cm^{-2} s^{-1} sr^{-1}
- Field of view : 3° FWHM
- Reflectivity of mirrors : ~ 80%
- Phototube response :
  Gain = 2.2×10^{6}, Quantum efficiency : peak = 24% at 400 nm
  Pulse shape : Gaussian with rise time 2 ns and width 3.3 ns
- Attenuation of pulse in coaxial cables :
  30 m LMR-Ultraflex-400, 55m RG213
- Pulse amplification : factor of 10
- Discriminator thresholds : ~180 mV for telescope pulses
- Trigger generation criteria : at least 4 telescope pulses
  out of 7 crossing threshold

Performance Parameters

- Trigger rate : Pr 9.9 Hz, nuclei 3.6 Hz,
  electrons 0.16 Hz
  Total = 13.7 Hz

- Energy threshold :

  E_{th} = 185 GeV

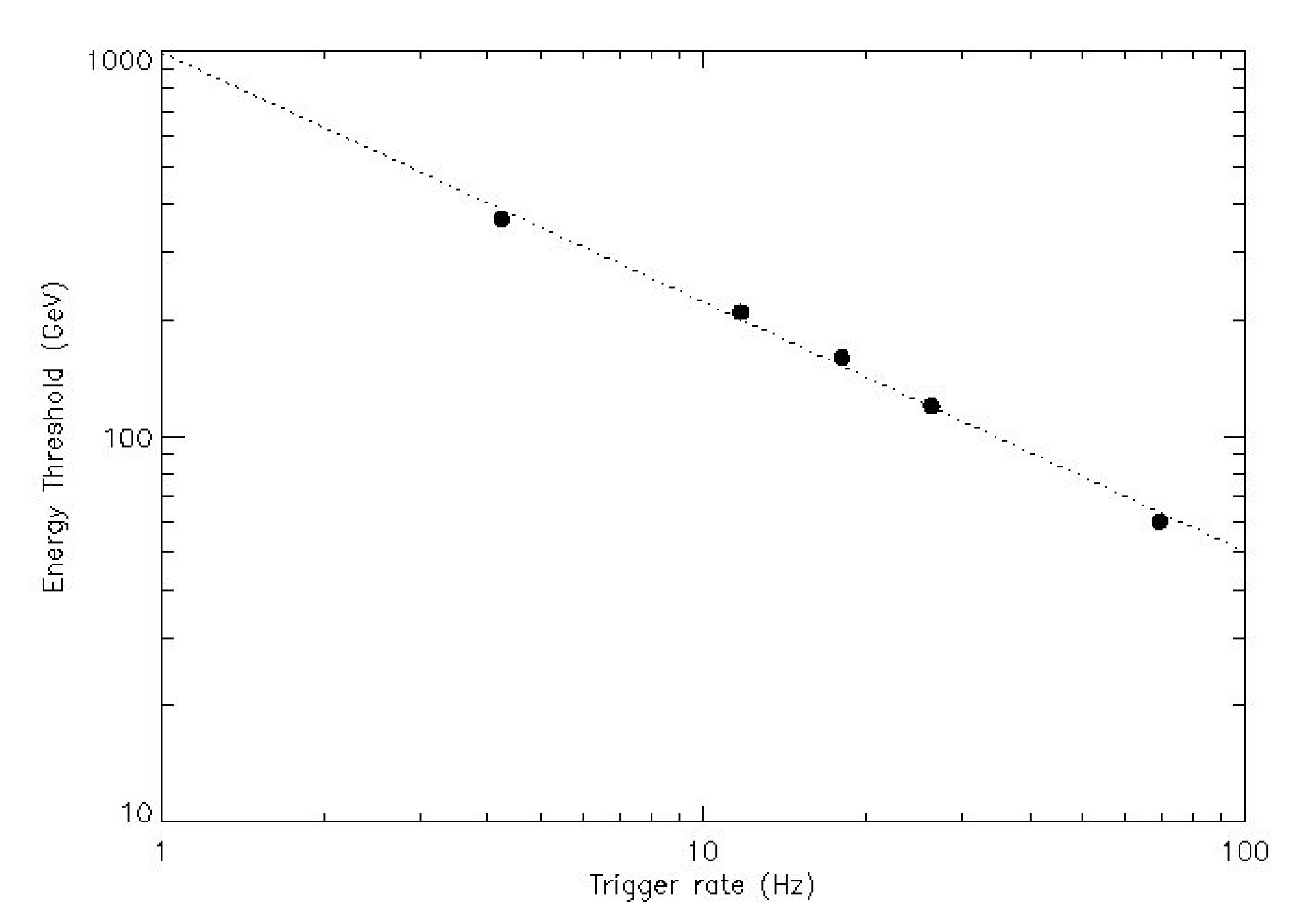


- Expected gamma-ray rate from Crab
  Nebula ~ 9.6 counts /min

- Collection area = 4×10^4 m^2

HAGAR Energy Threshold

HAGAR energy threshold vs trigger rate

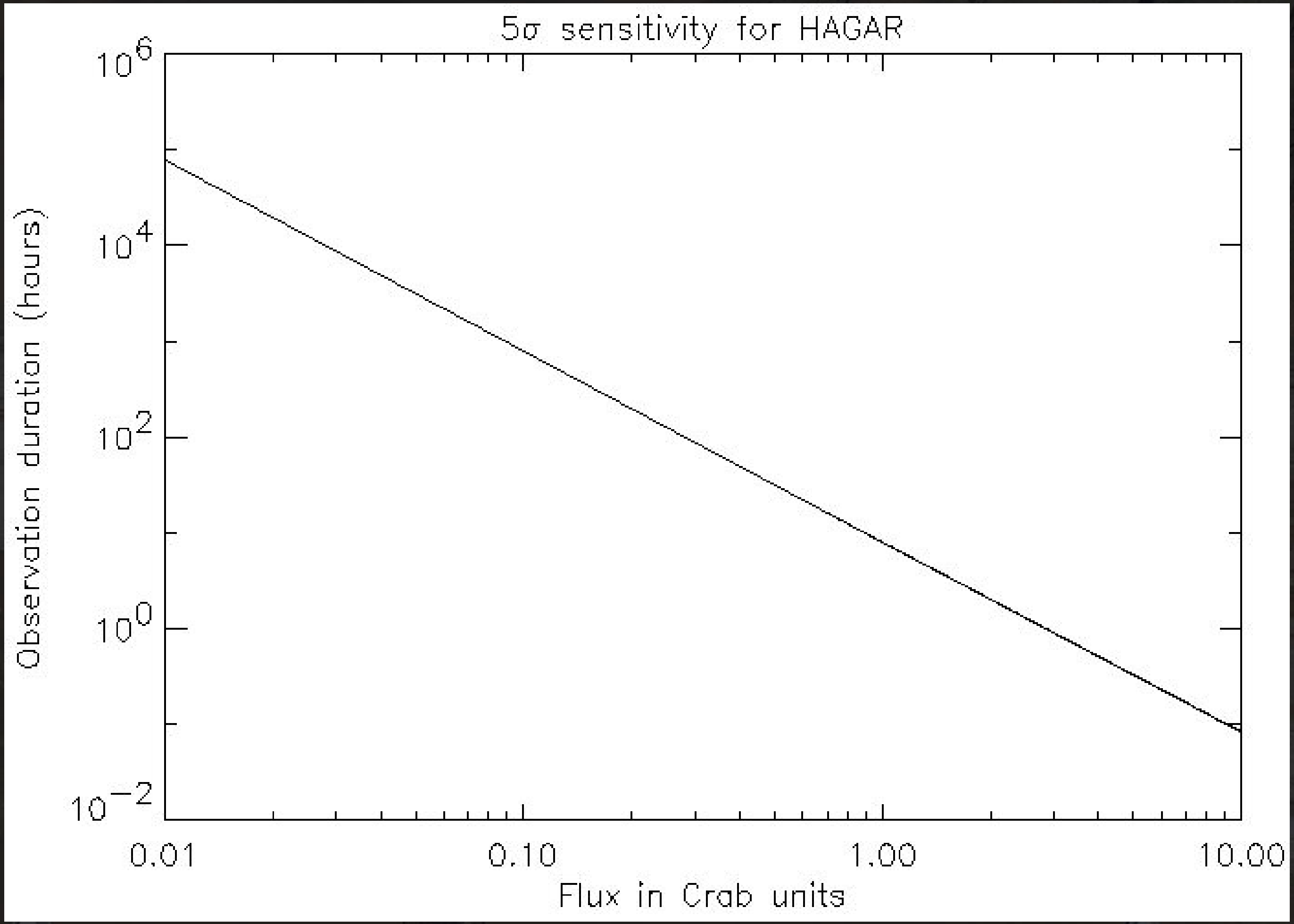


- Fine tuning of mirror alignment
- Cleanliness of mirrors
- Operation at higher PMT gain

--> Lower energy threshold possible

PMT gain : $1 \times 10^6 - 5 \times 10^6$

Sensitivity of HAGAR

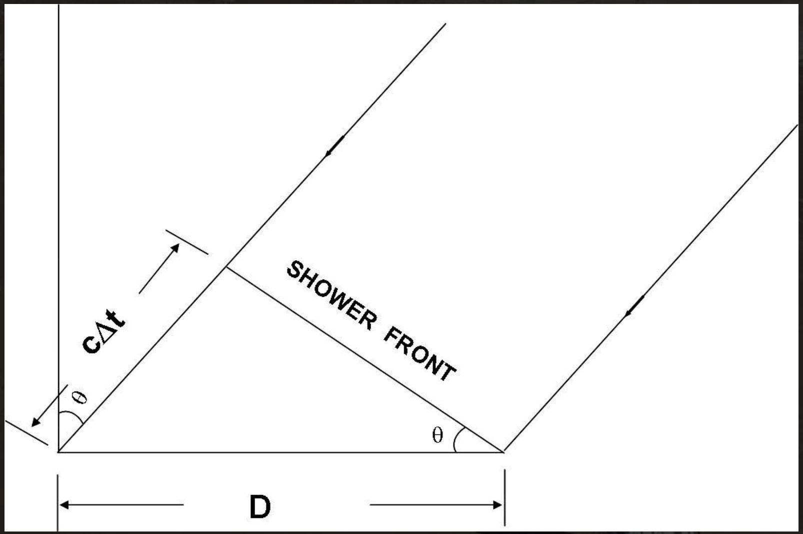


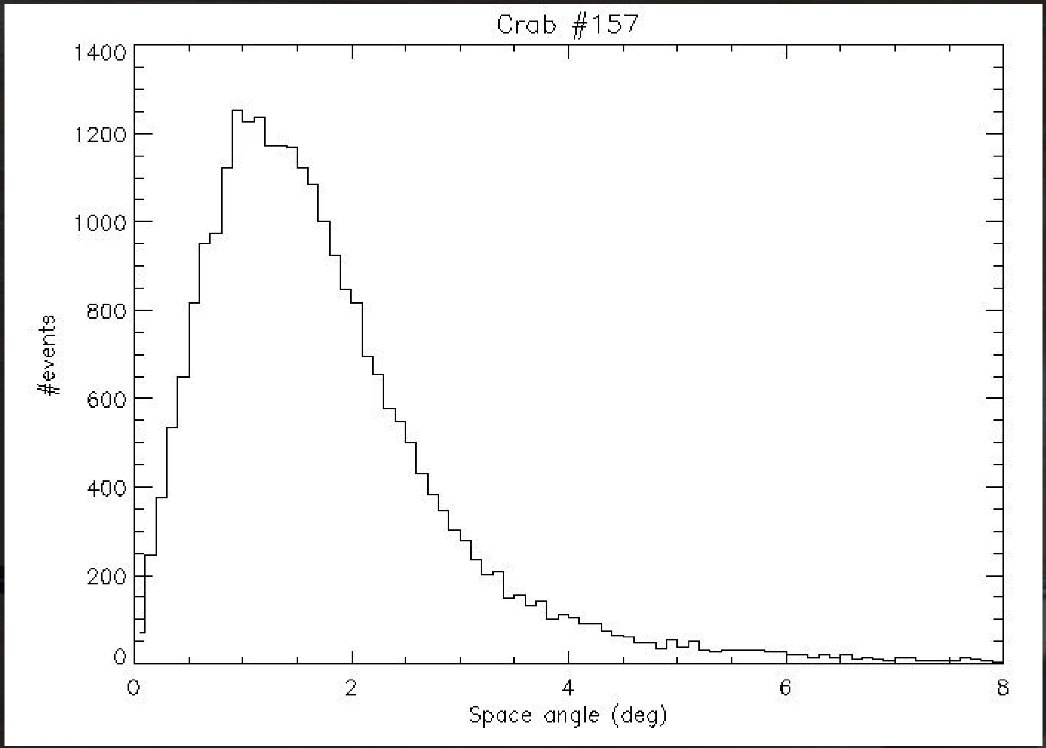
Raw sensitivity of HAGAR : 1.8 sigma/√hr for Crab like sources

Improvement in sensitivity : Off-axis rejection
Gamma-Hadron Separation parameters

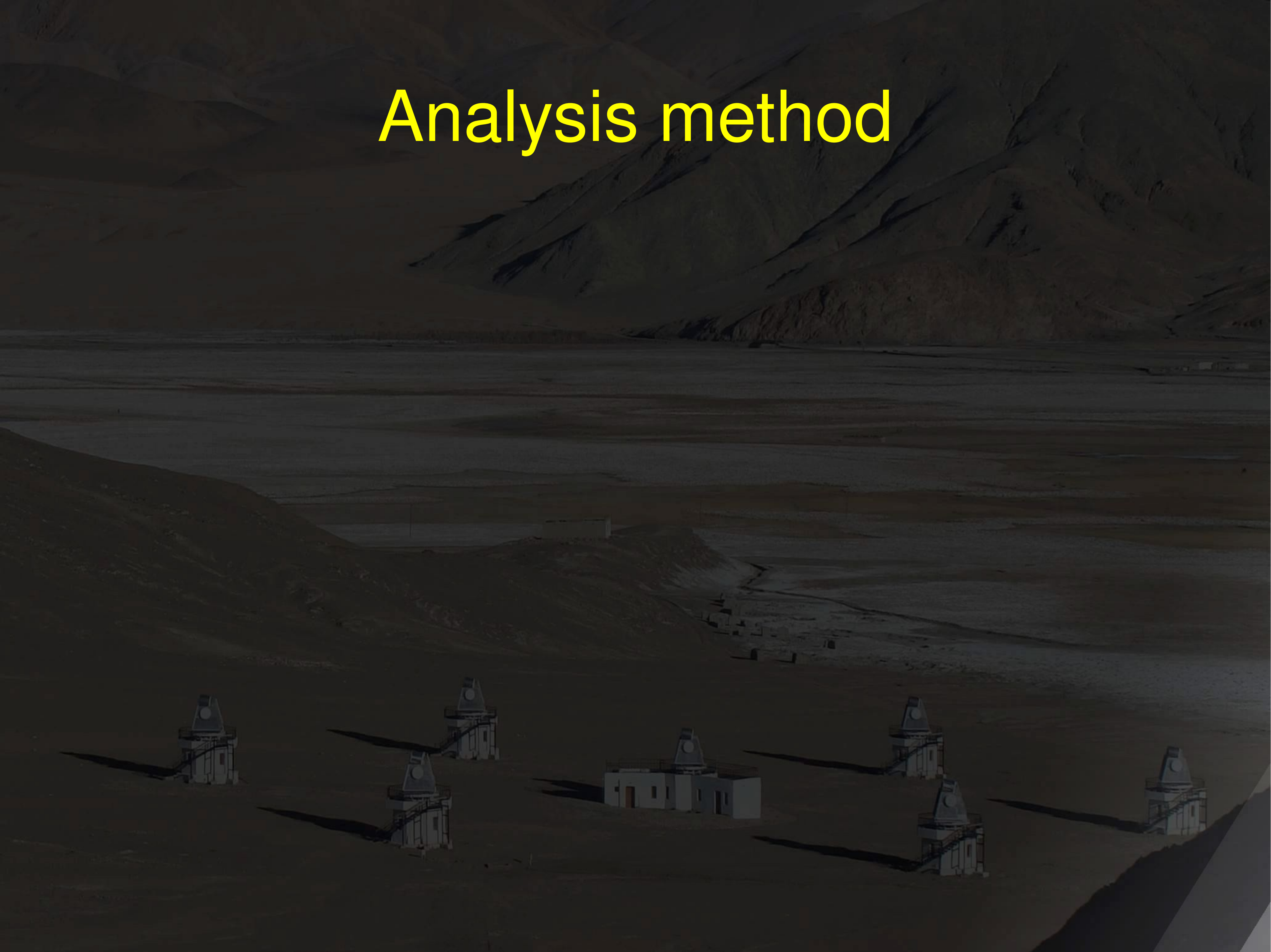
Analysis Method

- Selection cuts applied based on data quality, stability of rates etc
- Arrival direction of a shower is determined by reconstructing the shower front using arrival time of Cherenkov shower front at each telescope
- Plane front approximation to Cherenkov shower front
- Space angle : angle between normal to the plane front and source direction



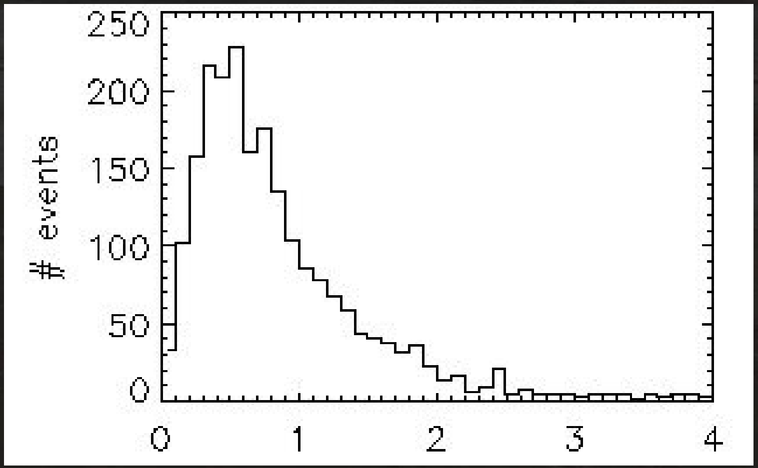


Analysis method



Angular Resolution of HAGAR

- Space angle between two independent estimates of shower direction obtained using different sets of mirrors



Distribution of space angles between directions given by mirrors ‘D’ and ‘G’ for ndf ≥ 4

- Angular resolution = 0.3°± 0.1°

→ Ten times smaller than FOV diameter, this angular resolution is reachable if spherical/parabolic wavefront fit, And using information on all TDCs

Analysis Method

- Space angle distributions generated for source and background runs taken on same night covering same hour angle range

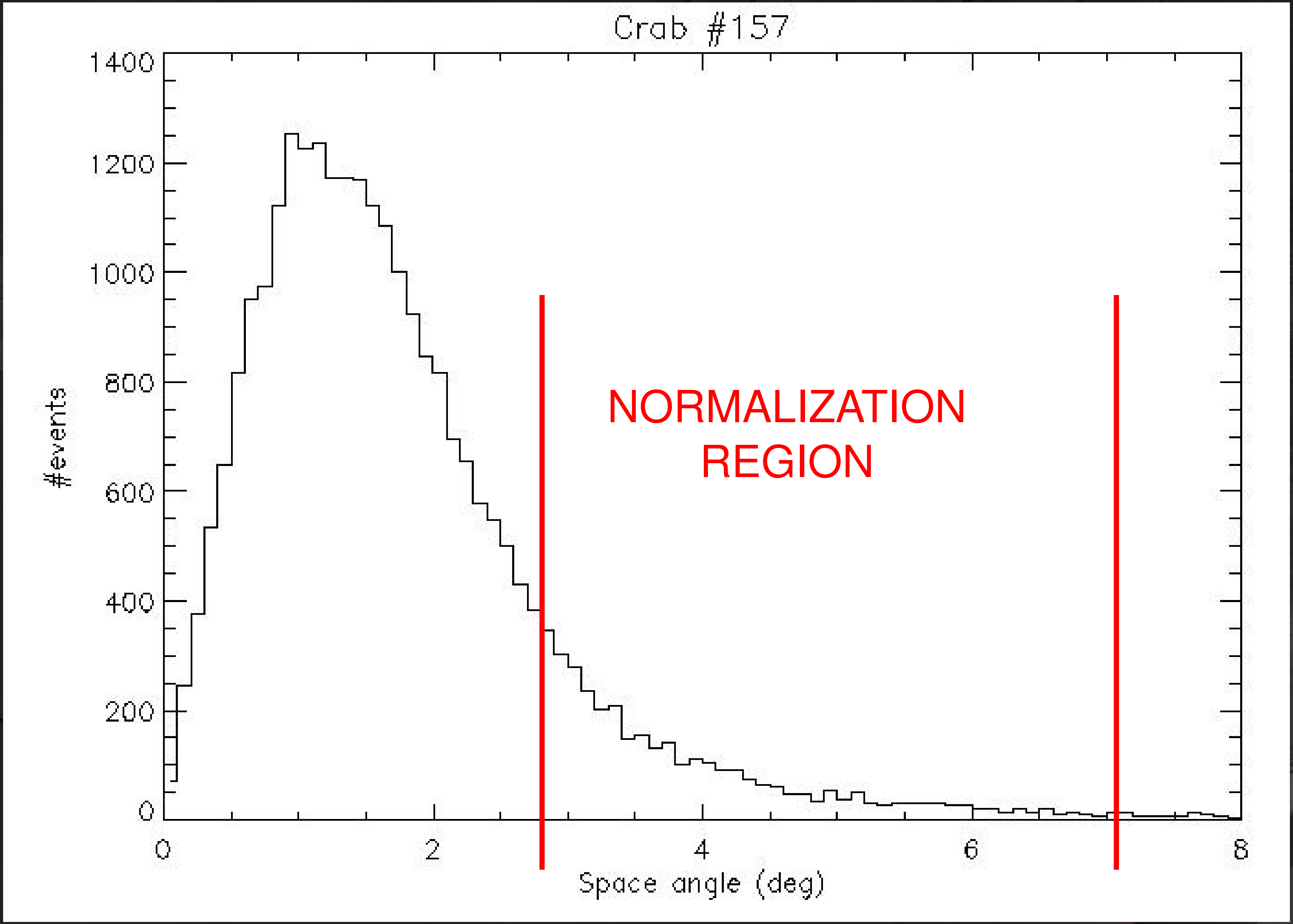
- Background space angle distributions are normalized w.r.t. source distributions by comparing shape in “85 % cut” to 7˚ window

- gamma-ray signal obtained as excess of source events over background events in 0˚ to “85 % cut” region as

$$\text{Excess} = \text{ON} - \text{C} \times \text{OFF}$$

where C is normalization constant, C = ON (tail) / OFF (tail)

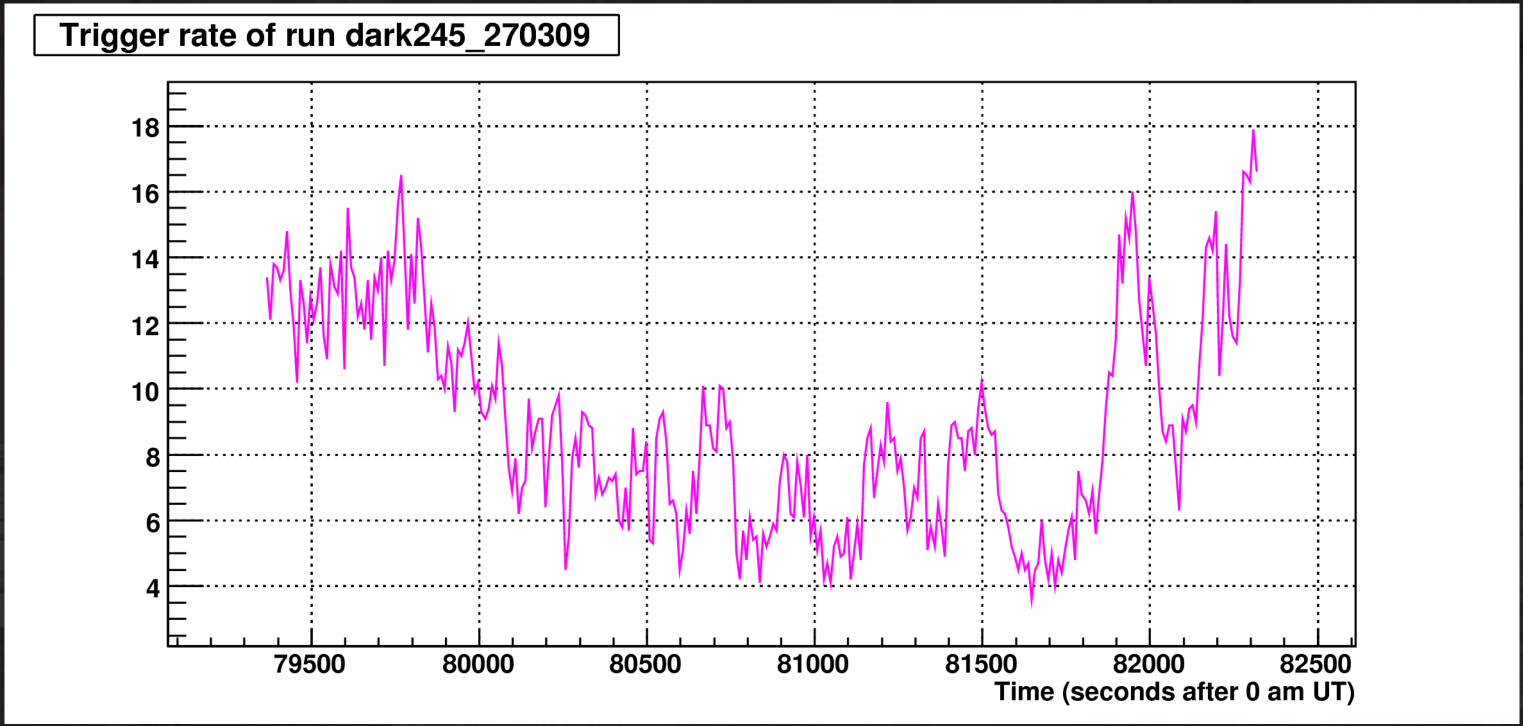
Analysis Method



Data selection

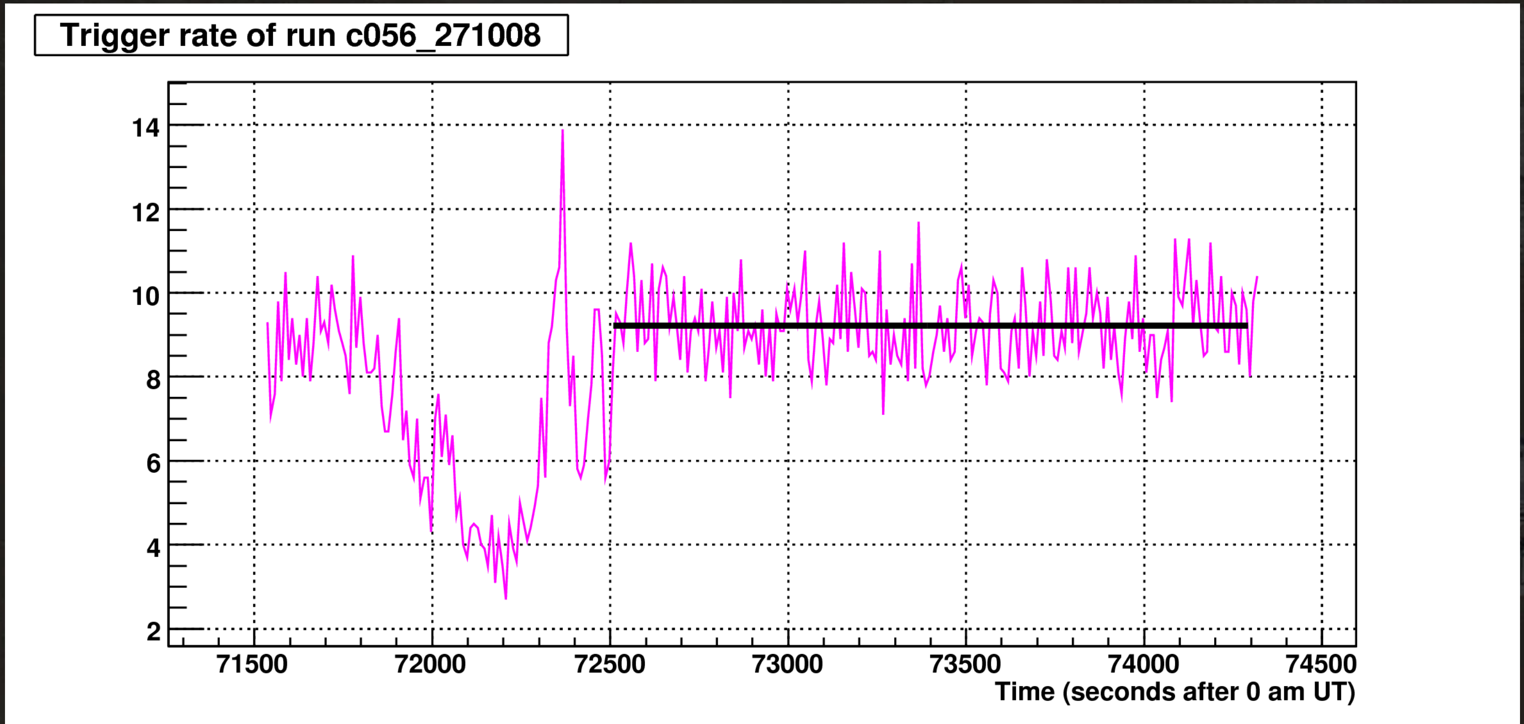
- Run selection:
  - Trigger rate stability (raw data & after sp. angle computing)
- Pair selection
  - Differences in trigger rates (raw & after sp. Ang.)
  - ON/OFF ratio per telescope
  - Differences in parameters of the space angle distribution shape
  - Value of the normalization constant C
  - Differences in coincidence window rate (Crab)
  - Differences in NSB rates (dark regions 2nd season)

Raw trigger rates



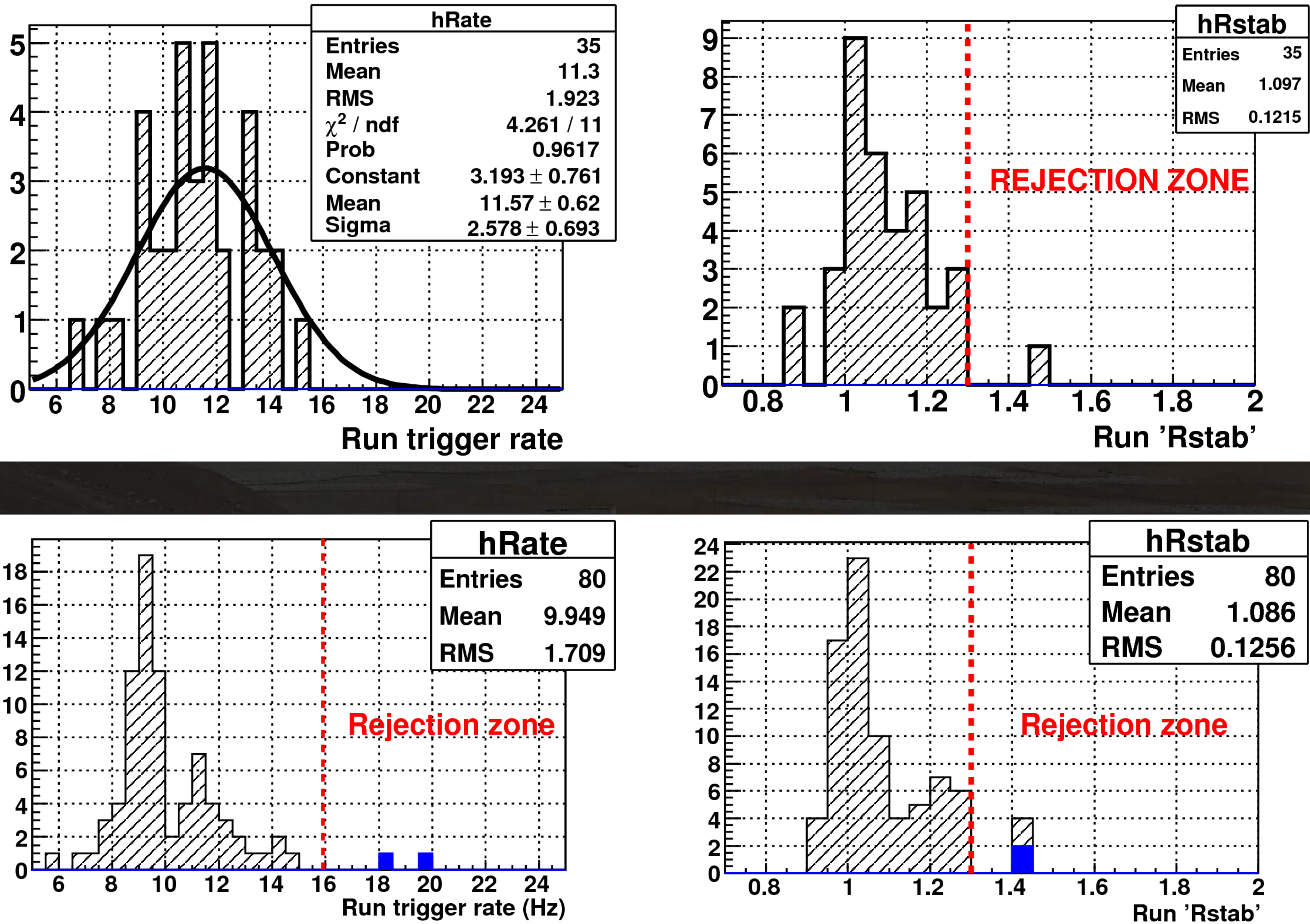
R_stab > 1.25

R_stab is the relative RMS of the 10 sec bins



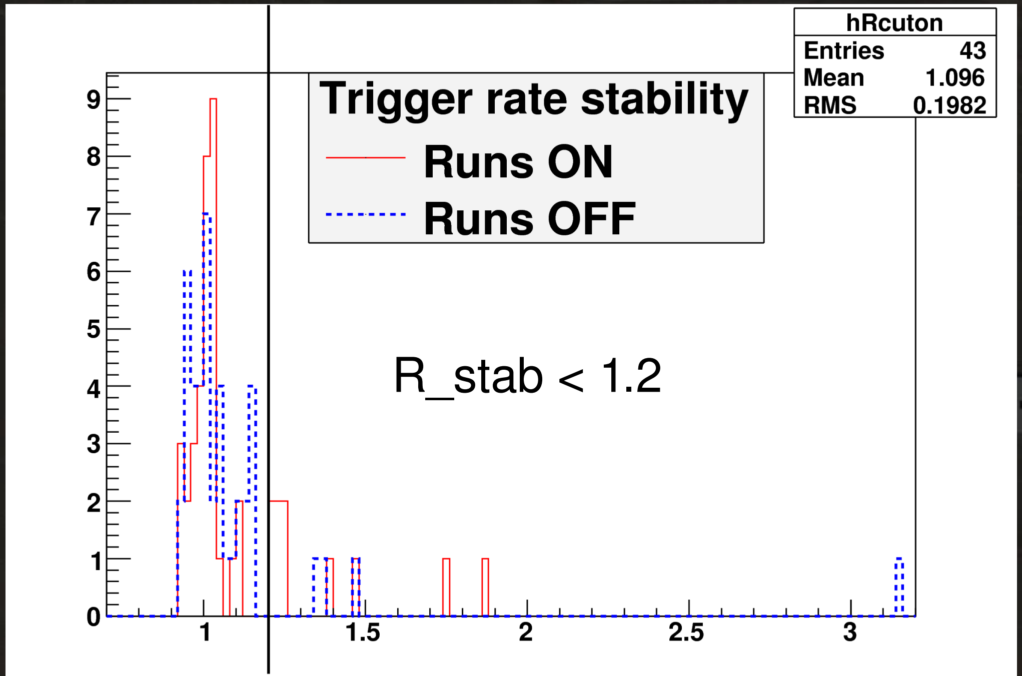
R_stab < 1.25
(cut run)

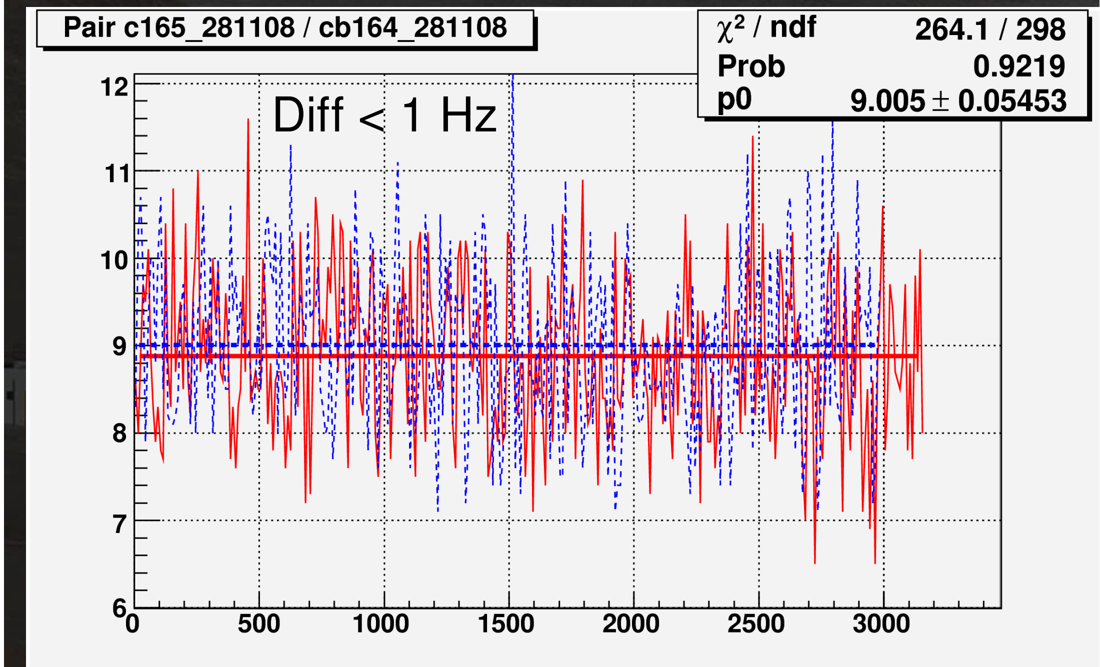
ON/OFF diif
Required to be
Within 2 Hz


hRate
Entries 35
Mean 11.3
RMS 1.923
χ² / ndf 4.261 / 11
Prob 0.9617
Constant 3.193 ± 0.761
Mean 11.57 ± 0.62
Sigma 2.578 ± 0.693
Run trigger rate
hRstab
Entries 35
Mean 1.097
RMS 0.1215
REJECTION ZONE
Run 'Rstab'
hRate
Entries 80
Mean 9.949
RMS 1.709
Rejection zone
Run trigger rate (Hz)
hRstab
Entries 80
Mean 1.086
RMS 0.1256
Rejection zone
Run 'Rstab'

Trigger rate of selected events

- Events are rejected if
  - TDC values out of range
  - Large chi ² in plane front fitting
- Trigger rate parameter computed again to check no biais due to analysis procedure





New event selection:

* Common hour angle

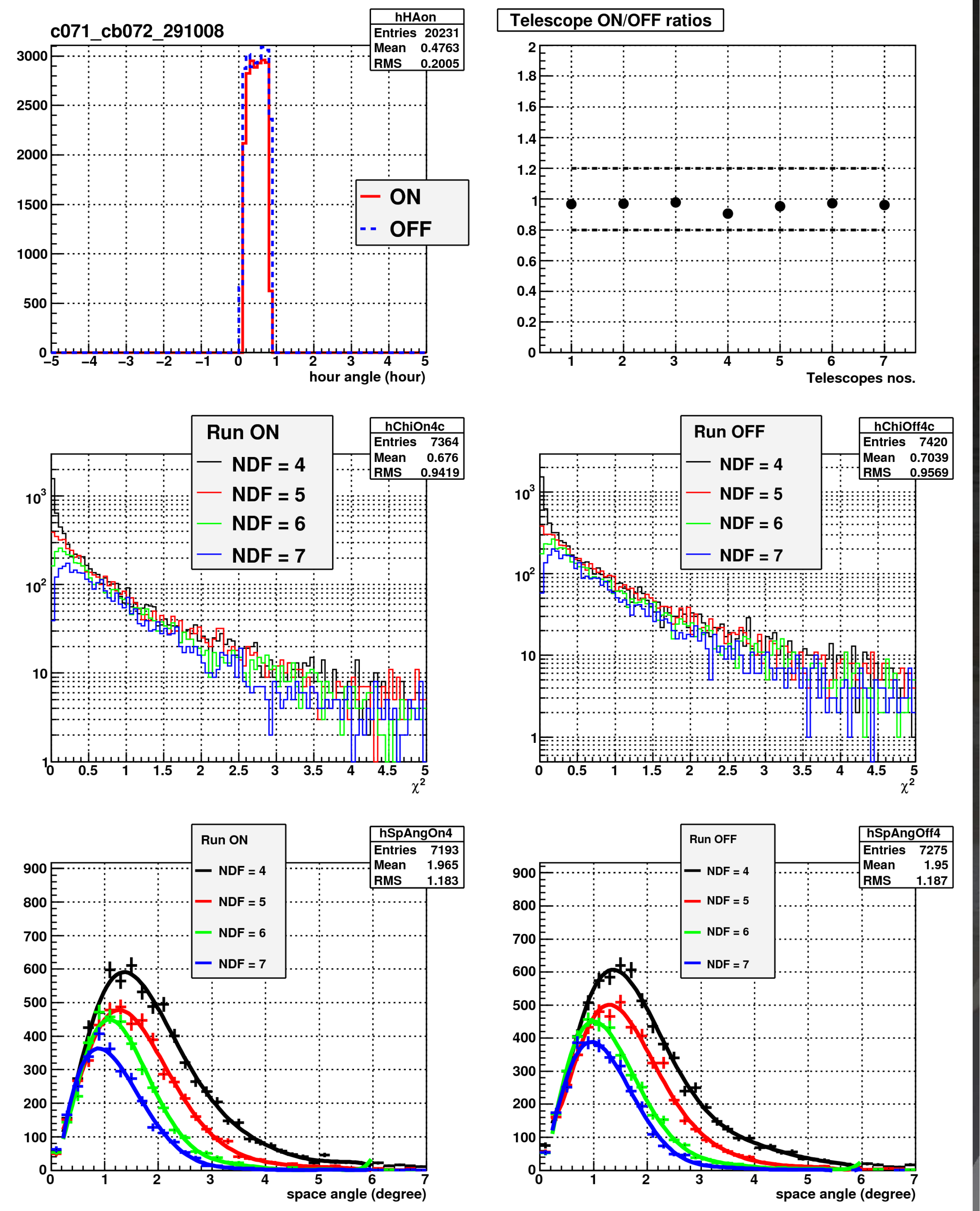
* Chi ² < mean + 1 sigma

Pair selection:

* ON/OFF ratio per tel
  at 1.0 +/- 0.2

* Space angle distribution
  parameters:
  - 85 % cut
  - peak value
  - FWHM

Differences < 0.15°



New event selection:

* Common hour angle

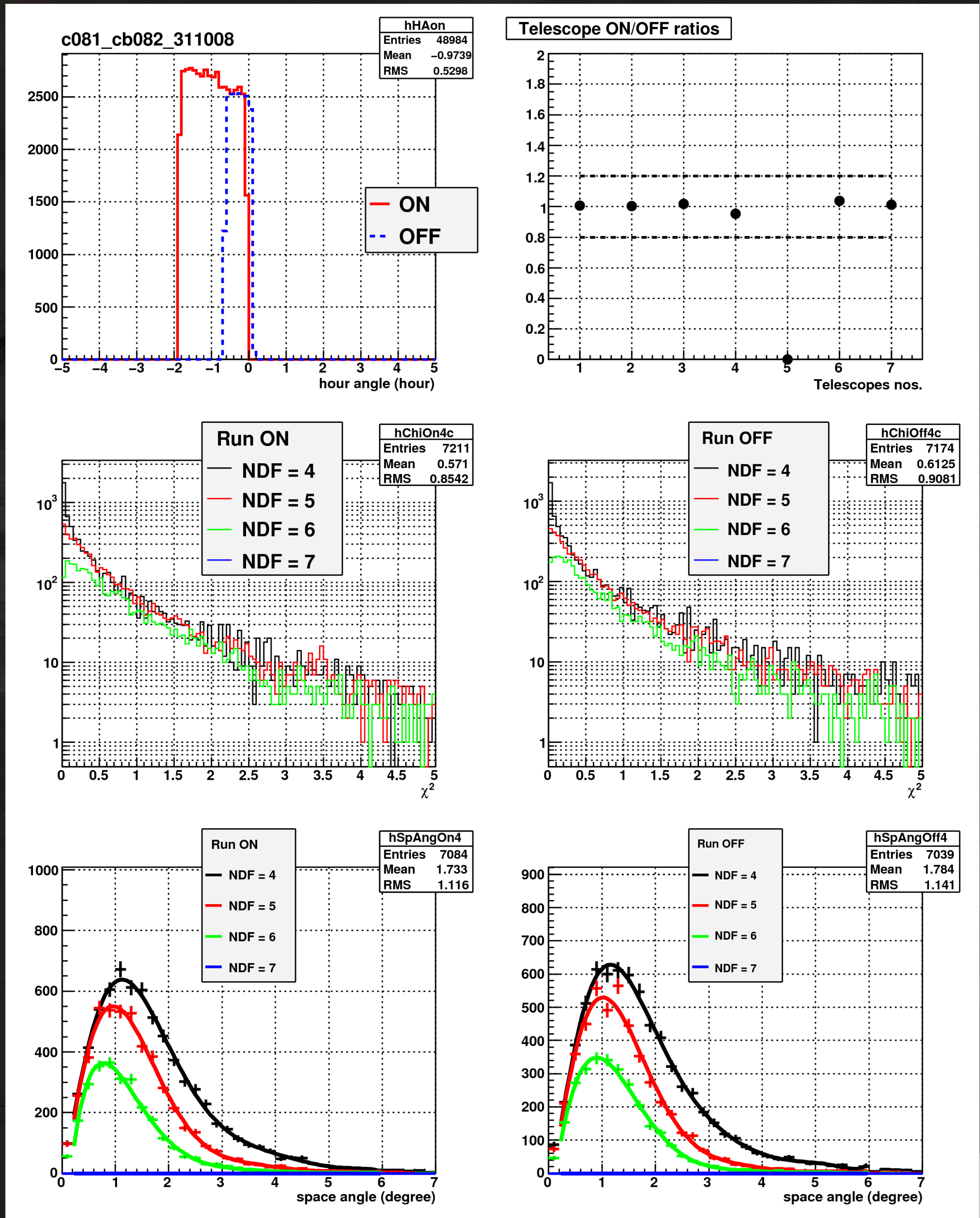
* Chi ^{2} < mean + 1 sigma

Pair selection:

* ON/OFF ratio per tel
  at 1.0 +/- 0.2

* Space angle distribution
  parameters:
    - 85 % cut
    - peak value
    - FWHM

Differences < 0.15°



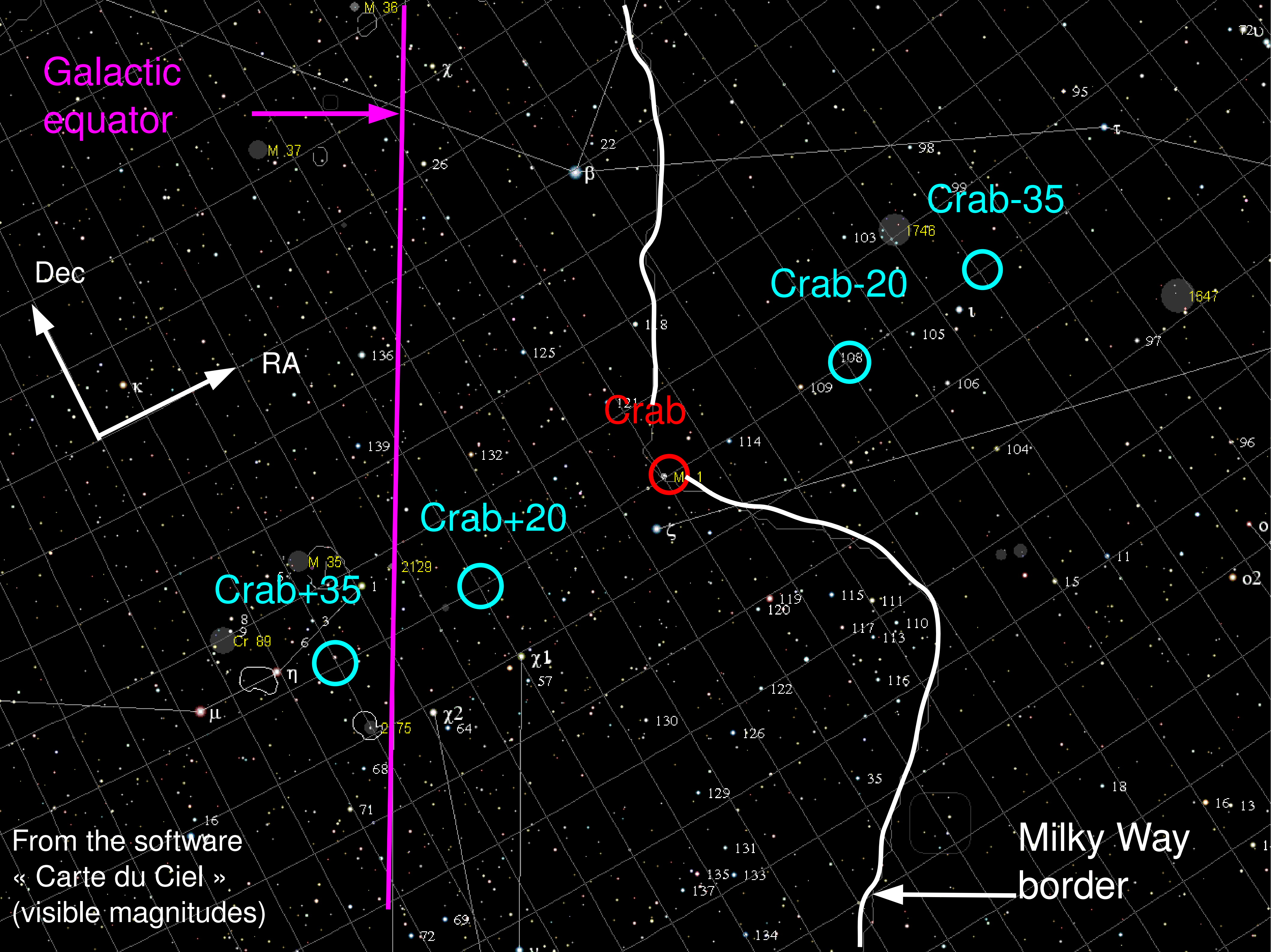
Dark regions and Crab data

- **Crab nebula:** standard candle of gamma-ray astronomy (steady flux): use for calibration purpose and to define analysis strategies

- **Dark regions:** OFF-sources to estimate/reduce systematic effects in the ON-OFF analysis,

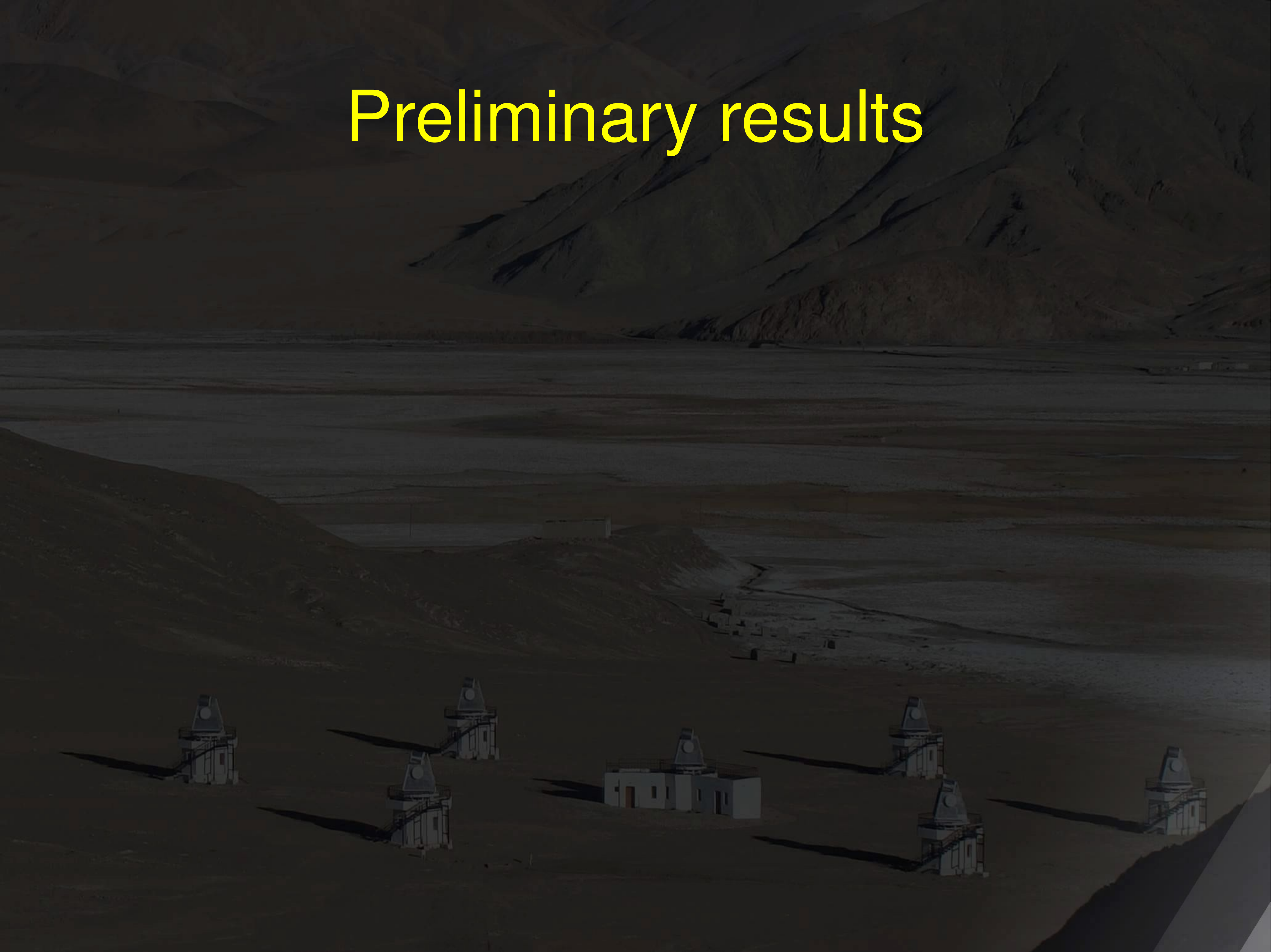
  by an OFF-OFF analysis (background fluctuations)

  ---> d22mw_15xx to d22mw_1939



Galactic equator
Dec
RA
Crab
Crab-35
Crab-20
Crab+20
Crab+35
Milky Way border
From the software « Carte du Ciel » (visible magnitudes)

Preliminary results



Significance N_σ

Quantify signal detection

Formulated from the numbers of events N_{ON} and N_{OFF}

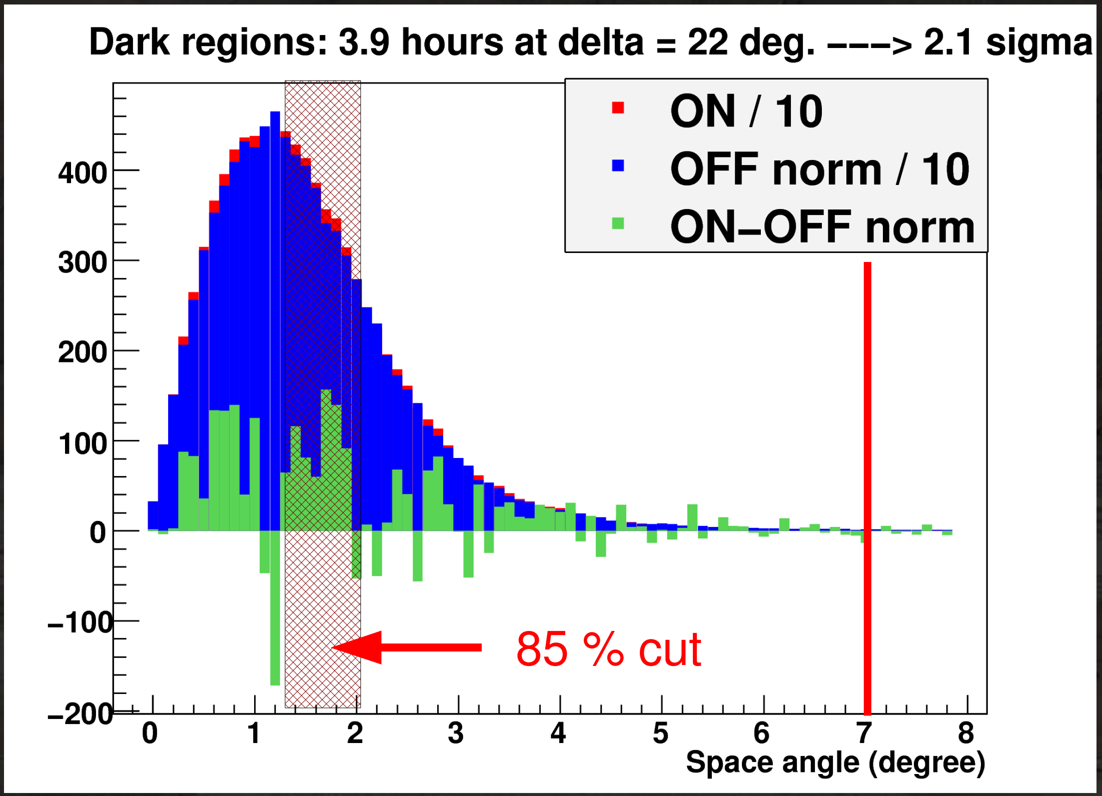
$$N_\sigma = \frac{N_{ON} - N_{OFF}}{\sqrt{N_{ON} + N_{OFF}}}$$

is the number of standard deviations from $N_{ON} - N_{OFF}$ to zero

< 3 sigma: upper limit
3 – 5 sigma: maybe a signal
5 sigma: we confirm! (if systematics are evaluated)

Dark regions:

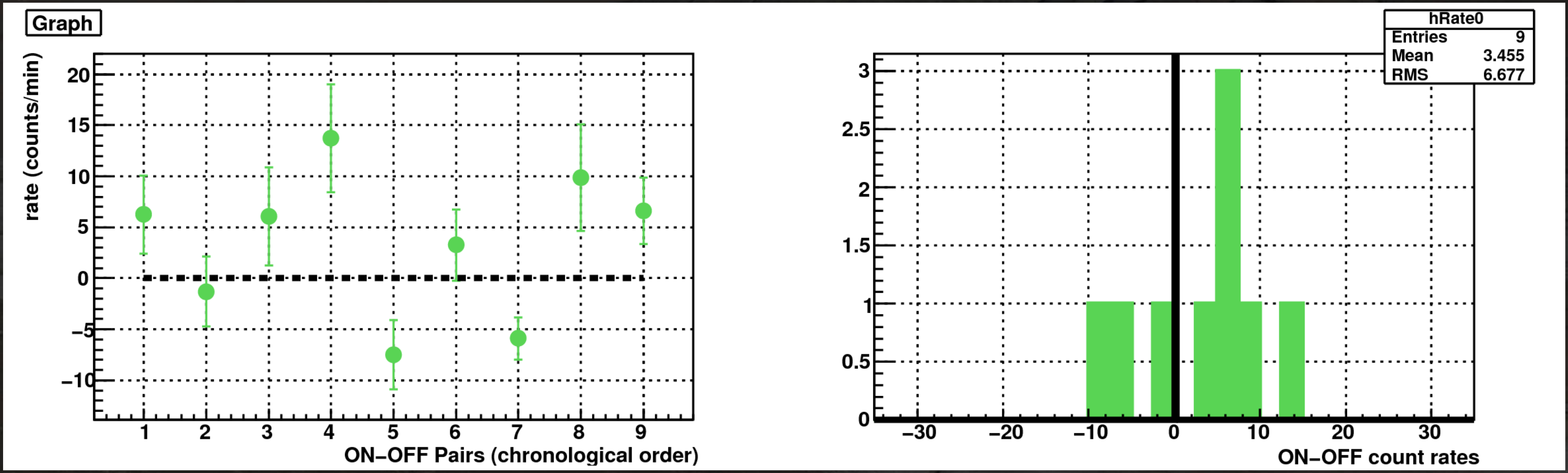
All NDF together



ON: 46643 events
OFF: 47294 events
ON – C x OFF = 642.8 events

Dark regions:

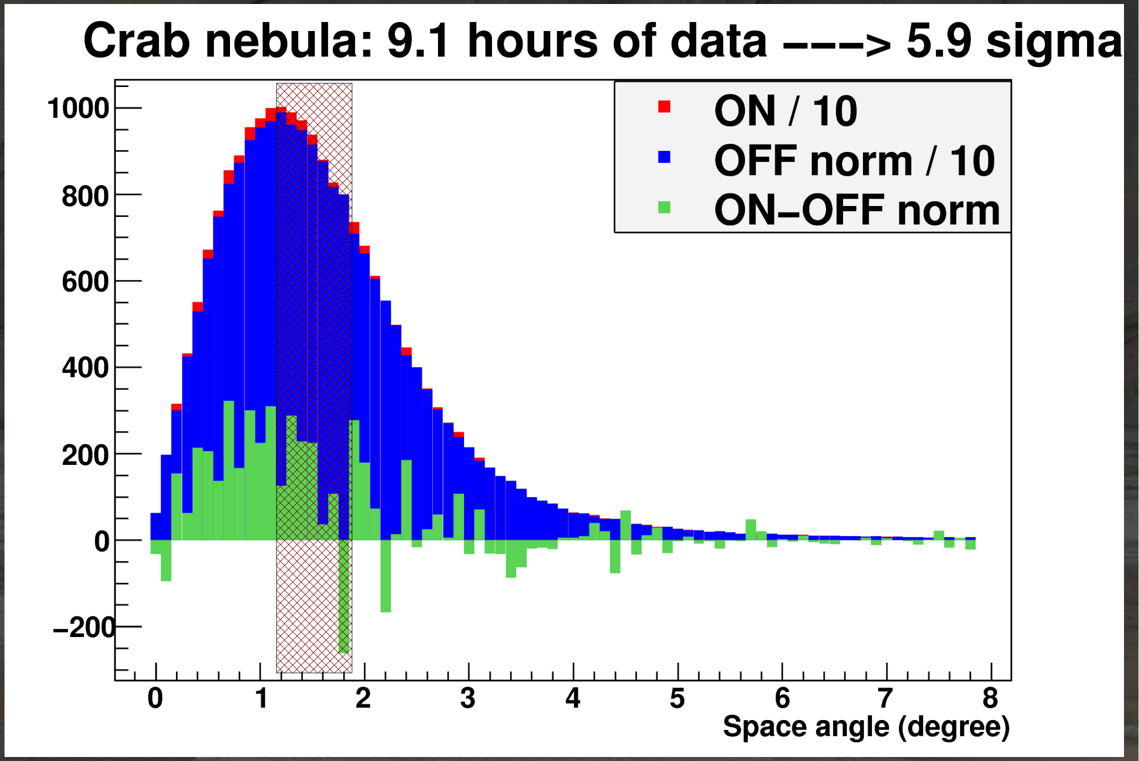
All NDF together



→ 9 pairs - No signal

Crab nebula

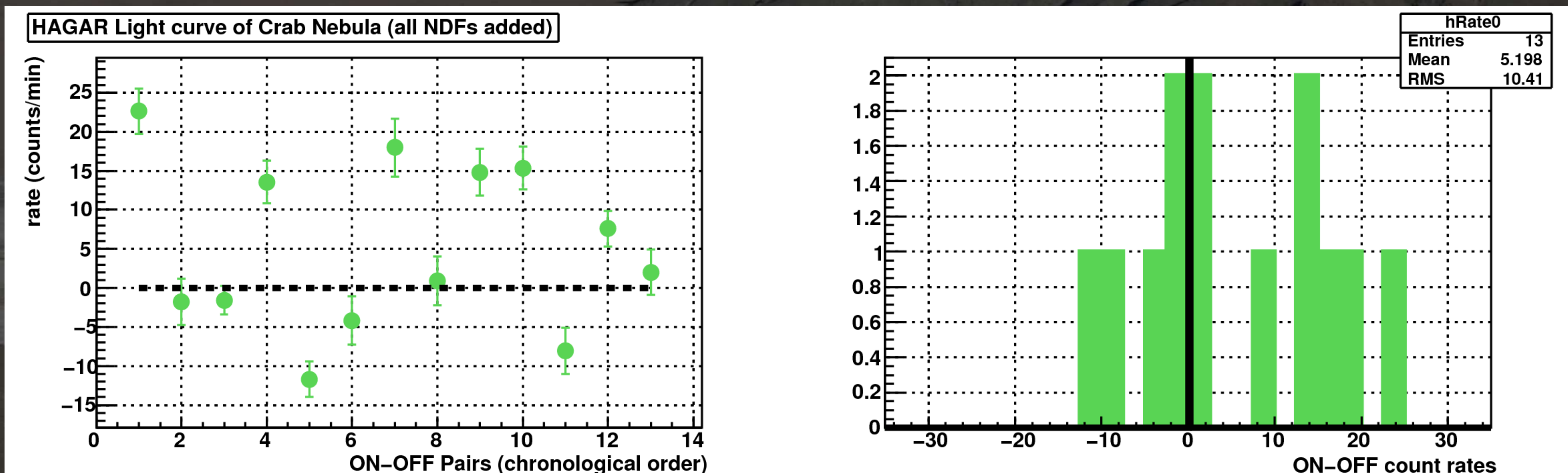
All NDF together



ON: 99000 events
OFF: 100430 events
ON – C x OFF = 2604.5 events

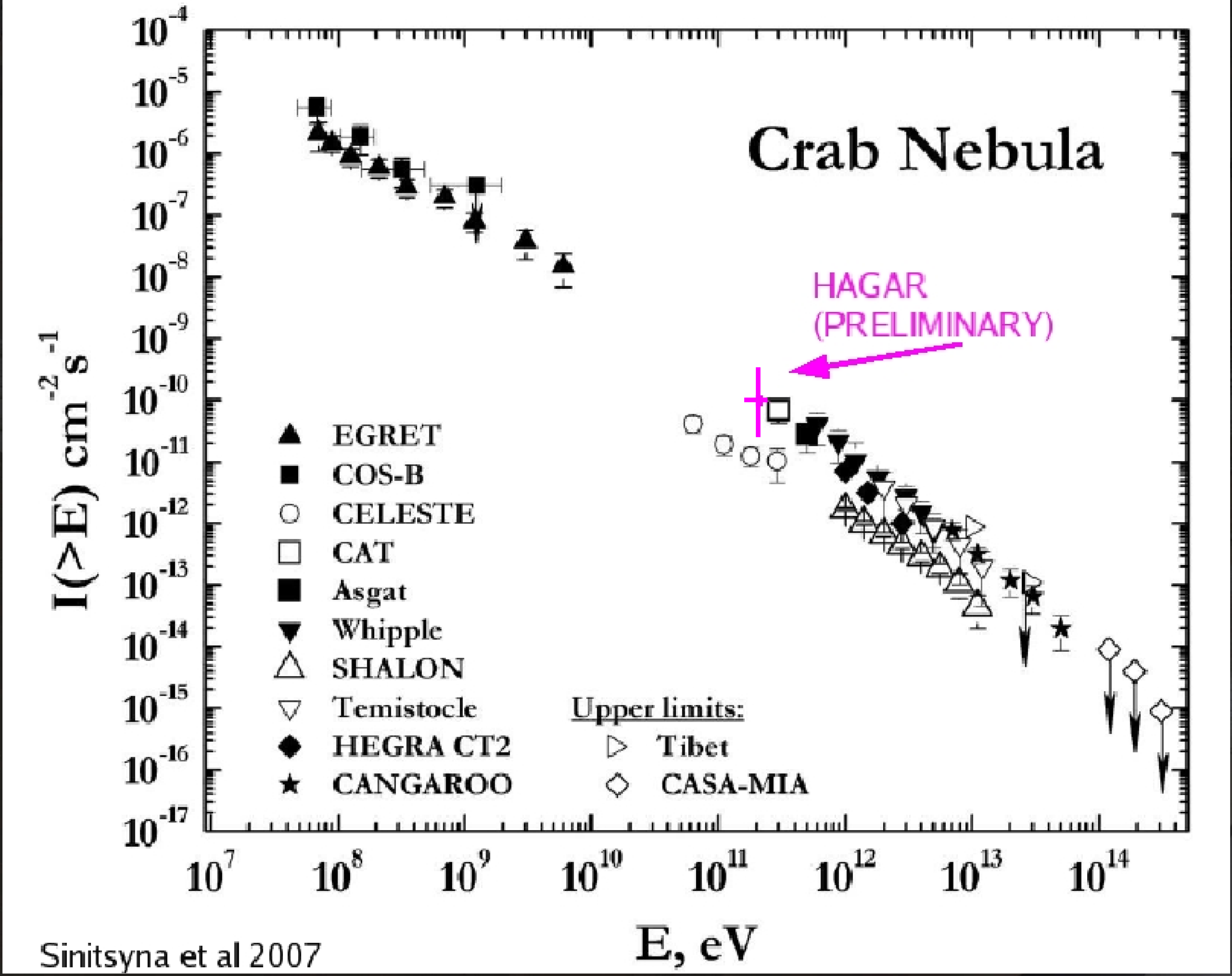
Crab nebula

All NDF together



13 pairs
9.1 hours
5.9 sigma
4.1 +/- 0.7 gamma/min

4.1 / 5 x 10^10 => Flux = 8.2 x 10^-11 /m2/s


Crab Nebula
HAGAR
(PRELIMINARY)
I(>E) cm^-2 s^-1
E, eV
EGRET
COS-B
CELESTE
CAT
Asgat
Whipple
SHALON
Temistocle
HEGRA CT2
CANGAROO
Upper limits:
Tibet
CASA-MIA
Sinitsyna et al 2007

On going work & perspectives

Gamma/hadrons discrimination

Standard analysis cuts

separate cuts on variables to maximise hadronic rejection

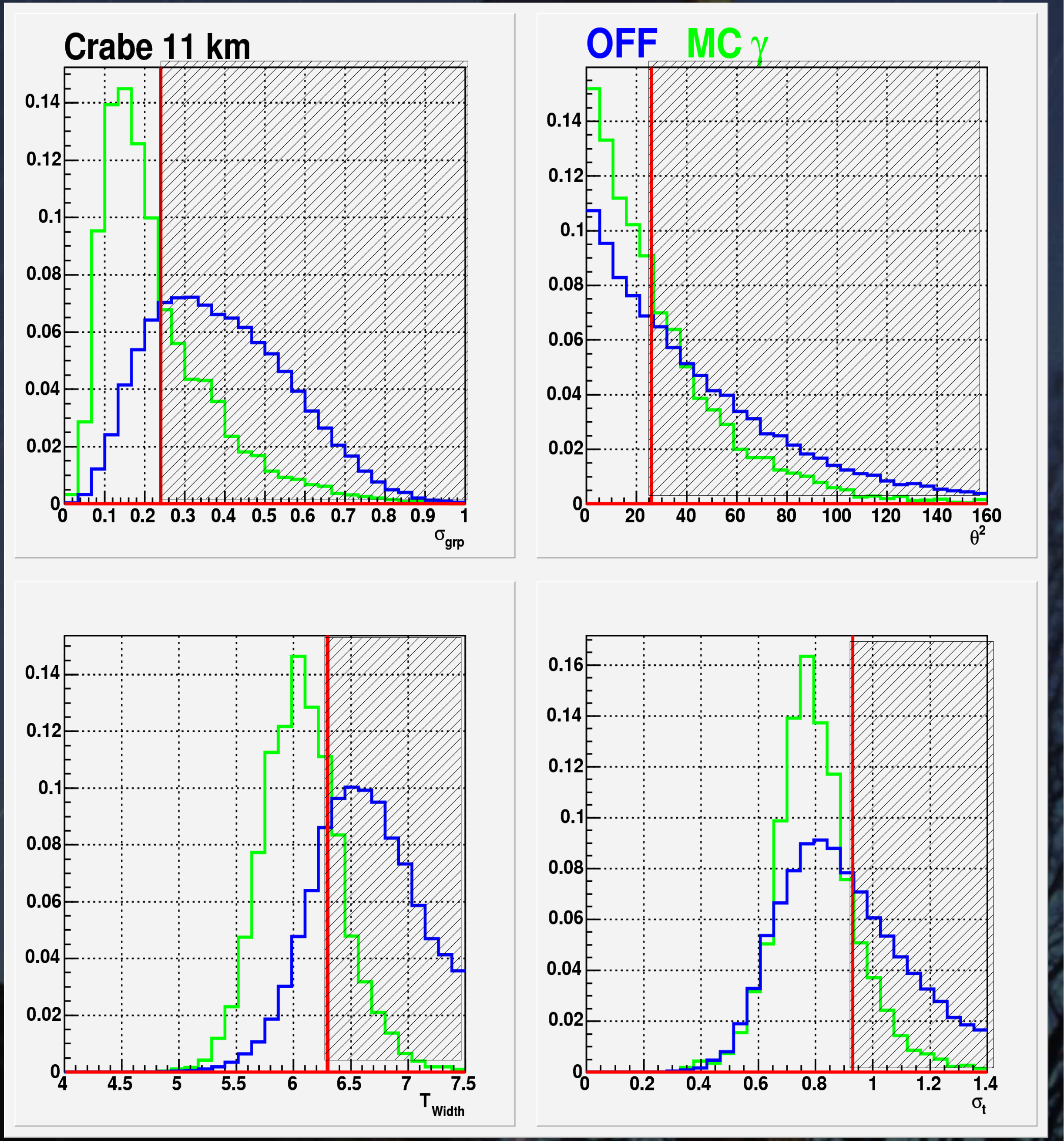
Example of Crab data with 11 km SP:

- γ MC
- OFF (mostly hadronic events)

Gamma/hadrons discrimination

Standard analysis cuts

separate cuts on variables to maximise hadronic rejection



Example of Crab data with 11 km SP:

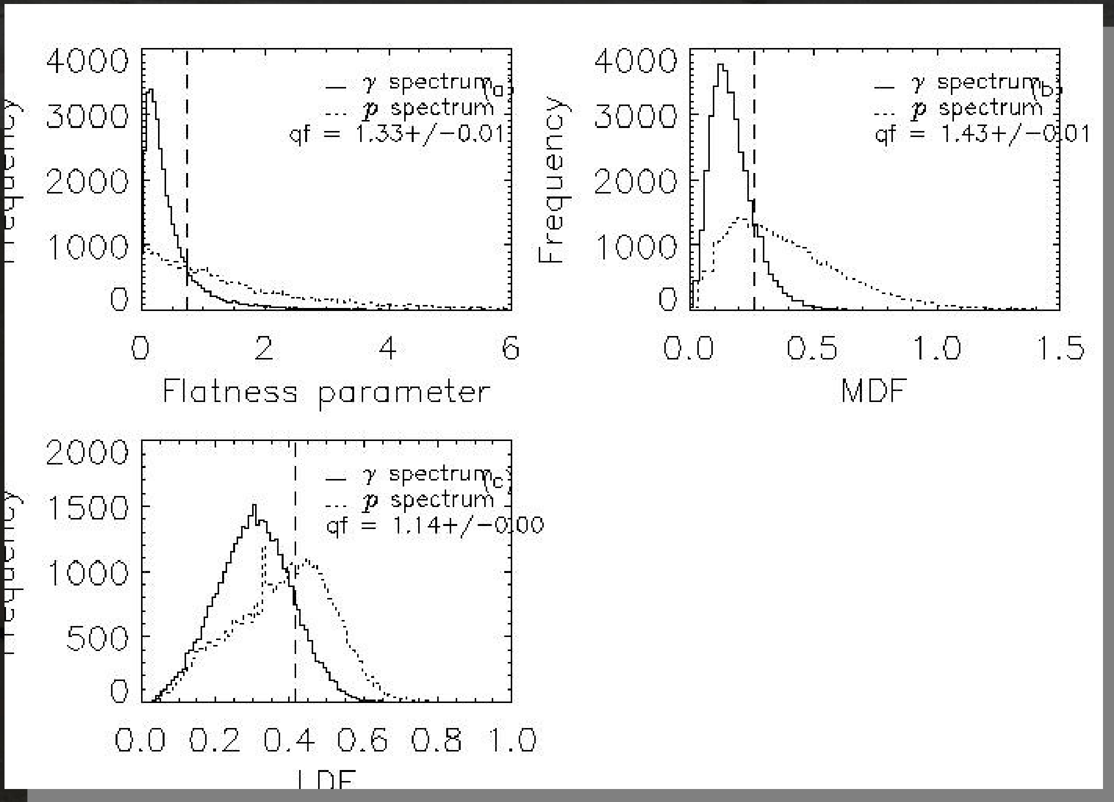
- γ MC
- OFF (mostly hadronic events)

Possible GHS Parameters

- **Parameters based on density information :**
  LDF, MDF and Flatness Parameter

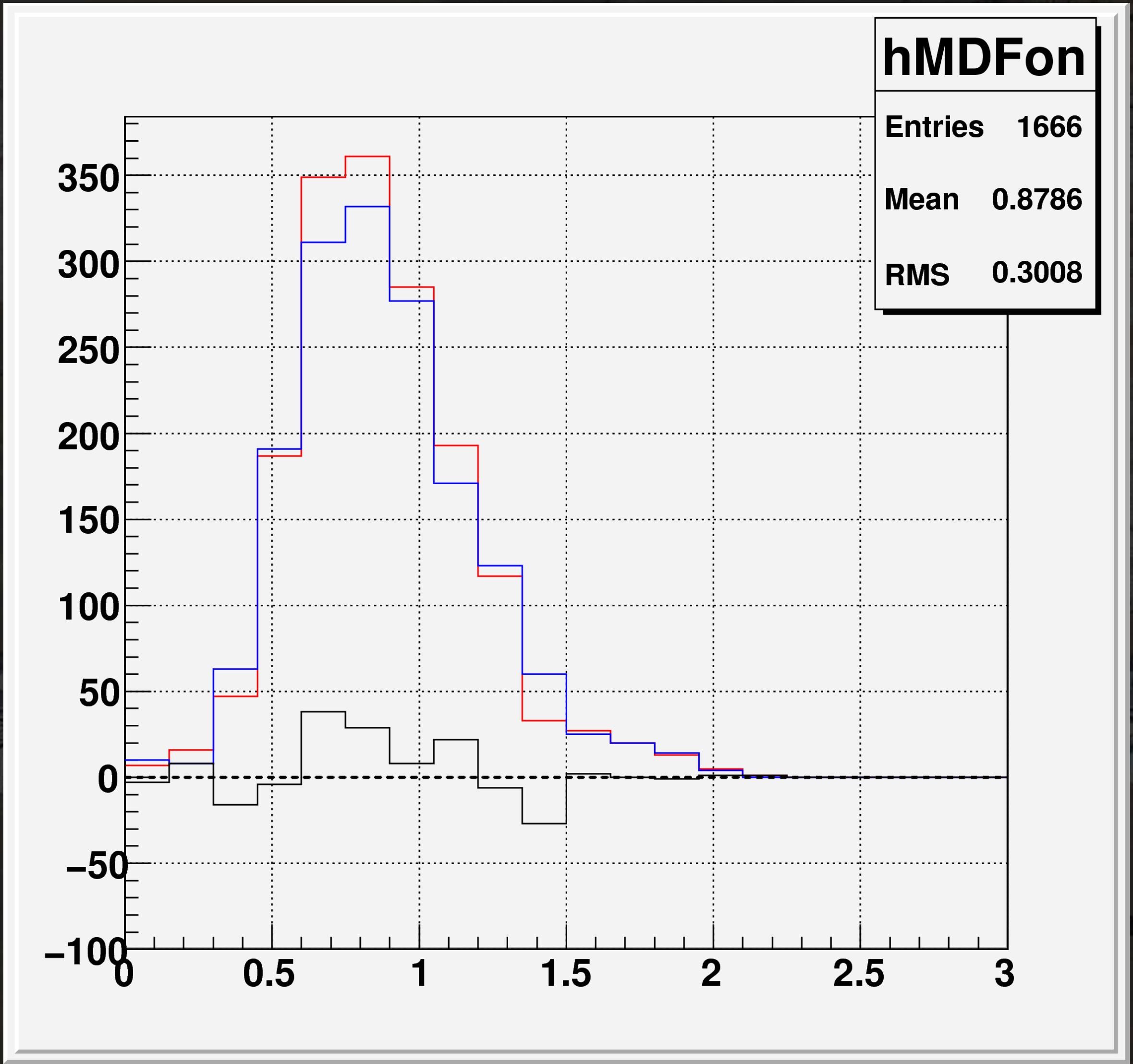
Based on CORSIKA simulations for PACT

(*Chitnis & Bhat, Exp. Astronomy, 13, 77, 2002)*



- **LDF : Local density fluctuations**
- **MDF : Medium range density fluctuations**
  → **similar to grp parameter used for CELESTE**
- **Flatness parameter**

➔ **Efficacy of these parameters to be checked for HAGAR**

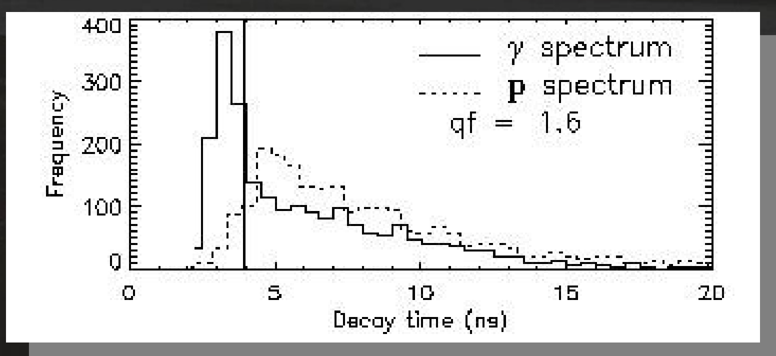

hMDFon
Entries 1666
Mean 0.8786
RMS 0.3008
350
300
250
200
150
100
50
0
−50
−100
0
0.5
1
1.5
2
2.5
3

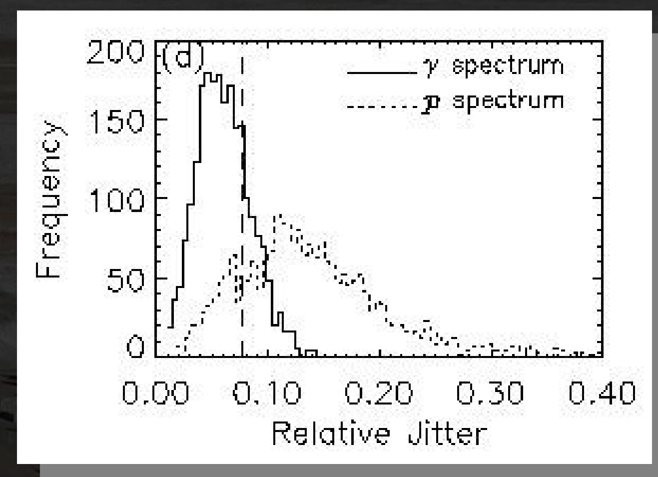
Possible GHS Parameters

- **Parameters based on timing information : Timing jitter and Pulse shape**

Based on CORSIKA simulations for PACT

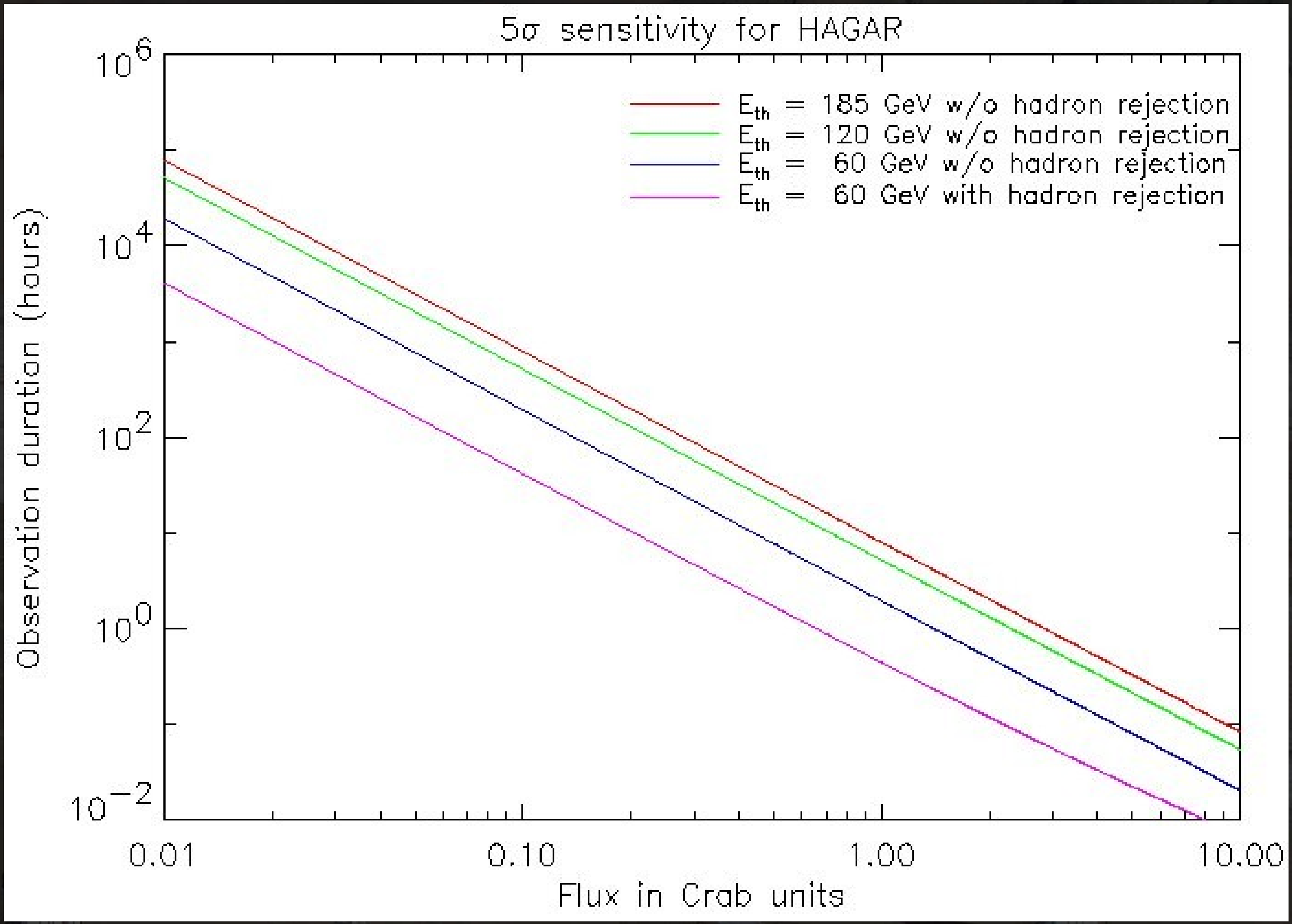
(Chitnis & Bhat, Astroparticle Physics, 15, 29, 2001)





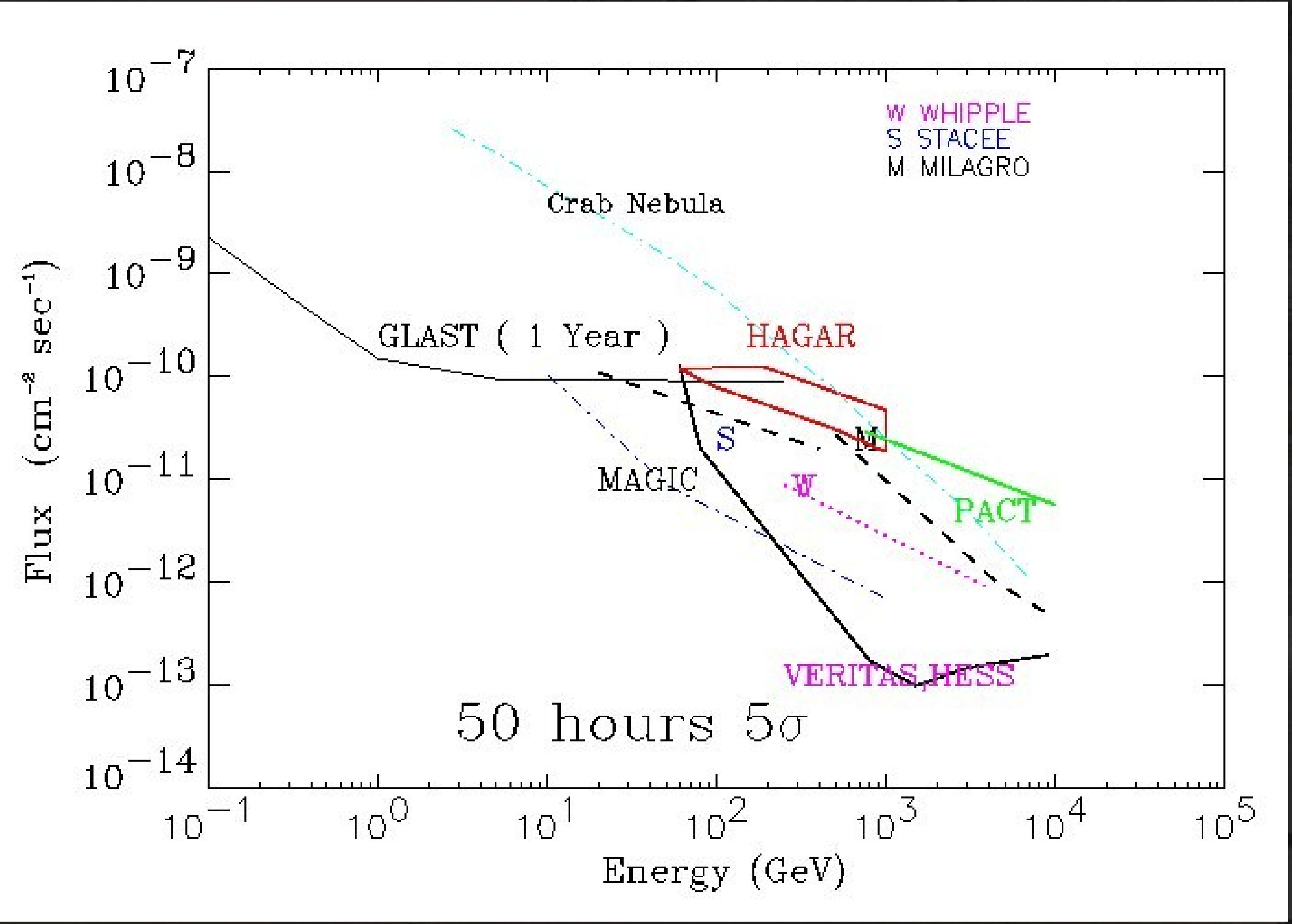
➔ **Efficacy of these parameters to be checked for HAGAR**

Sensitivity of HAGAR



Assuming 98% rejection for cosmic ray showers and 35% acceptance for γ -rays, sensitivity for energy threshold of 60 GeV ~ 7.6σ /√hour for Crab

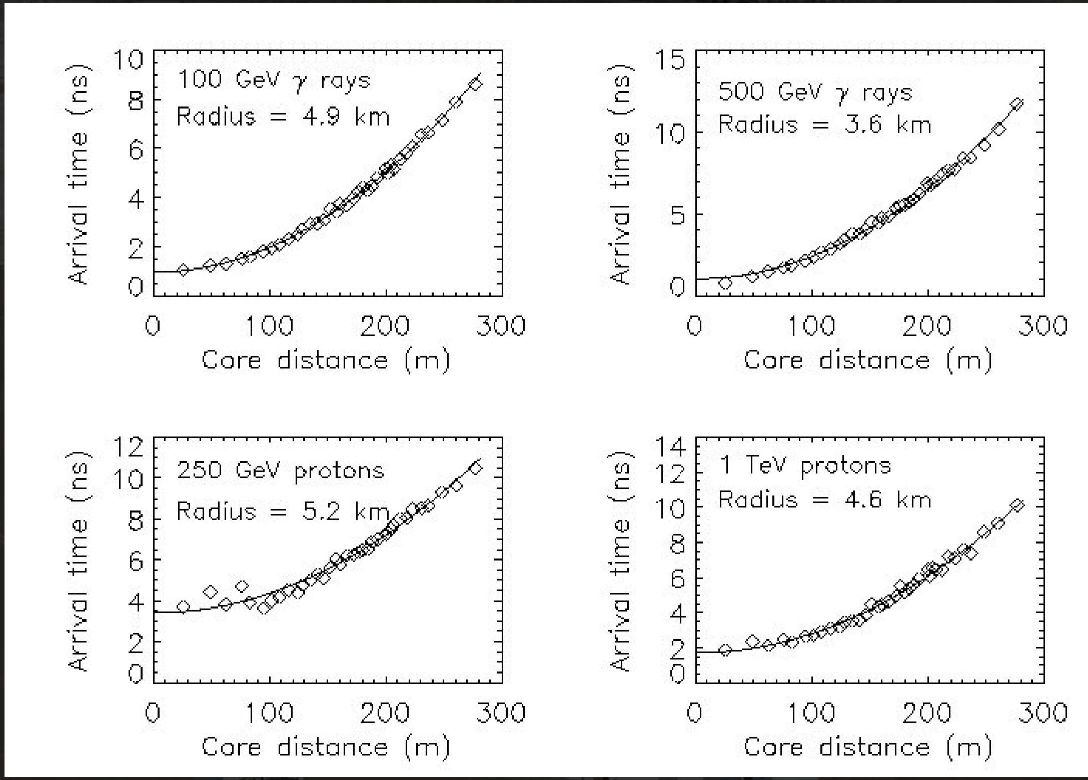
Sensitivity of Various gamma-ray Experiments



Improvements in Analysis

1. Spherical front fitting

- Cherenkov shower front at observation level is spherical
- Plane front approximation introduces core distance dependent error in estimate of shower axis direction



- Necessary to find robust algorithm for spherical front fitting
- This will allow efficient background rejection by eliminating off-axis cosmic ray showers to large extent

Improvements in Analysis

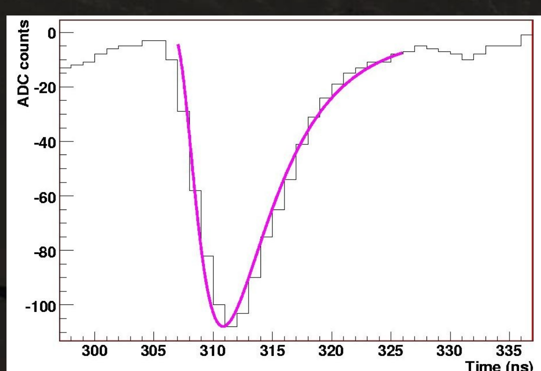
2. Use of GHS parameters

- Efficacy of GHS parameters based on density fluctuations, arrival time fluctuations and pulse shape to be checked for HAGAR

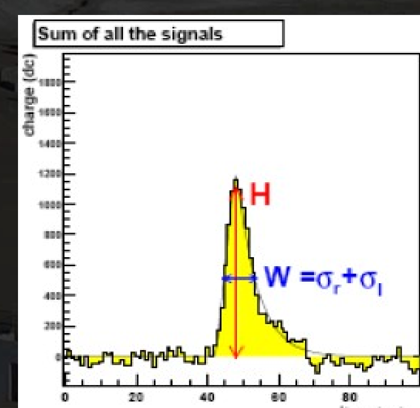
- CELESTE has used parameter $sigma_{grp}$ based on density fluctuations to achieve moderate rejection

- Flash-ADCs or waveform digitizers (model : acqiris DC271A) with sampling rate of 1 GS/s have been incorporated in HAGAR DAQ recently

FADC pulse shape



GHS parameter used by CELESTE



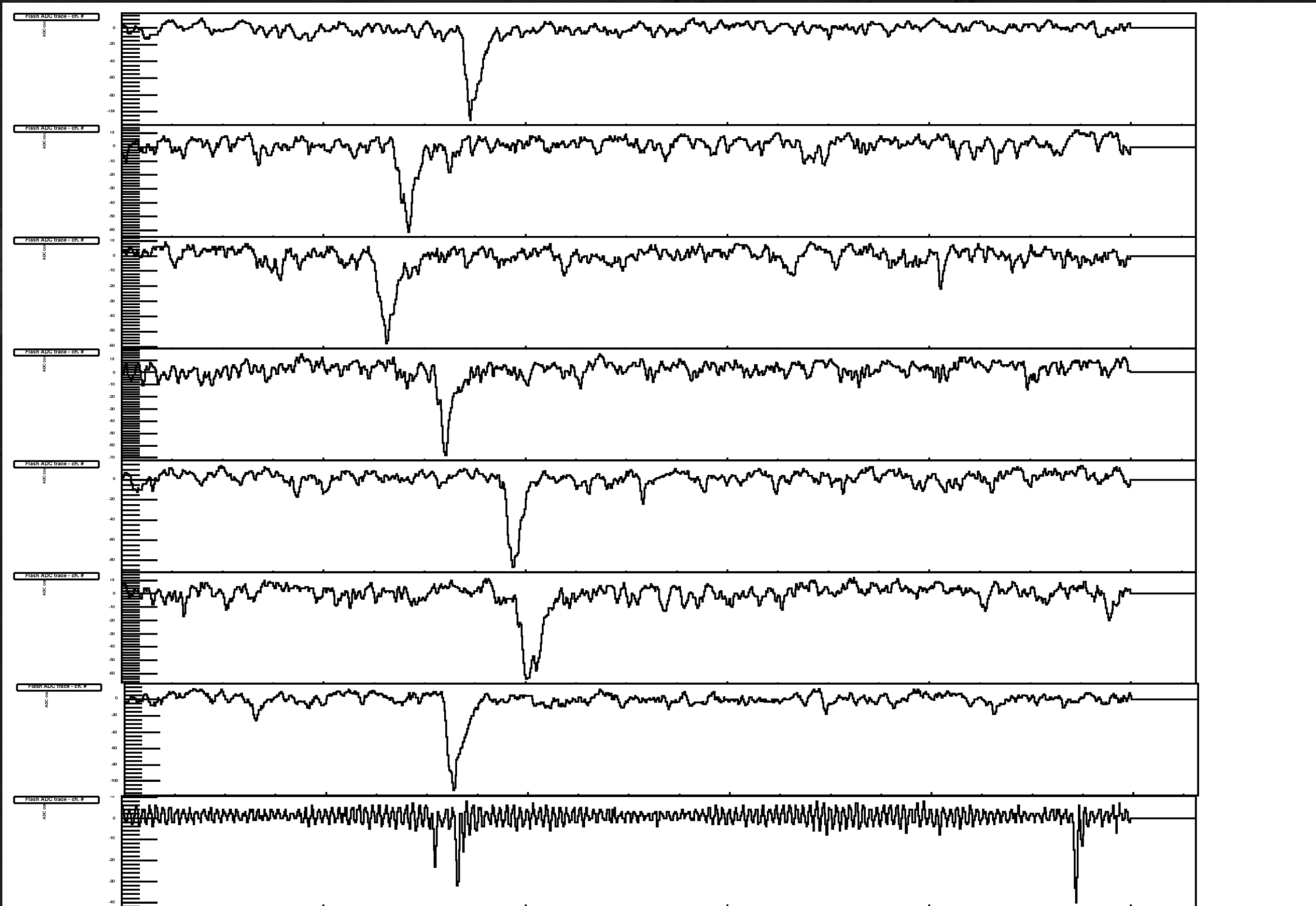
- Advantages of FADC : Suppression of Night sky background contribution by narrowing down window, use of W/H and pulse shape for GHS

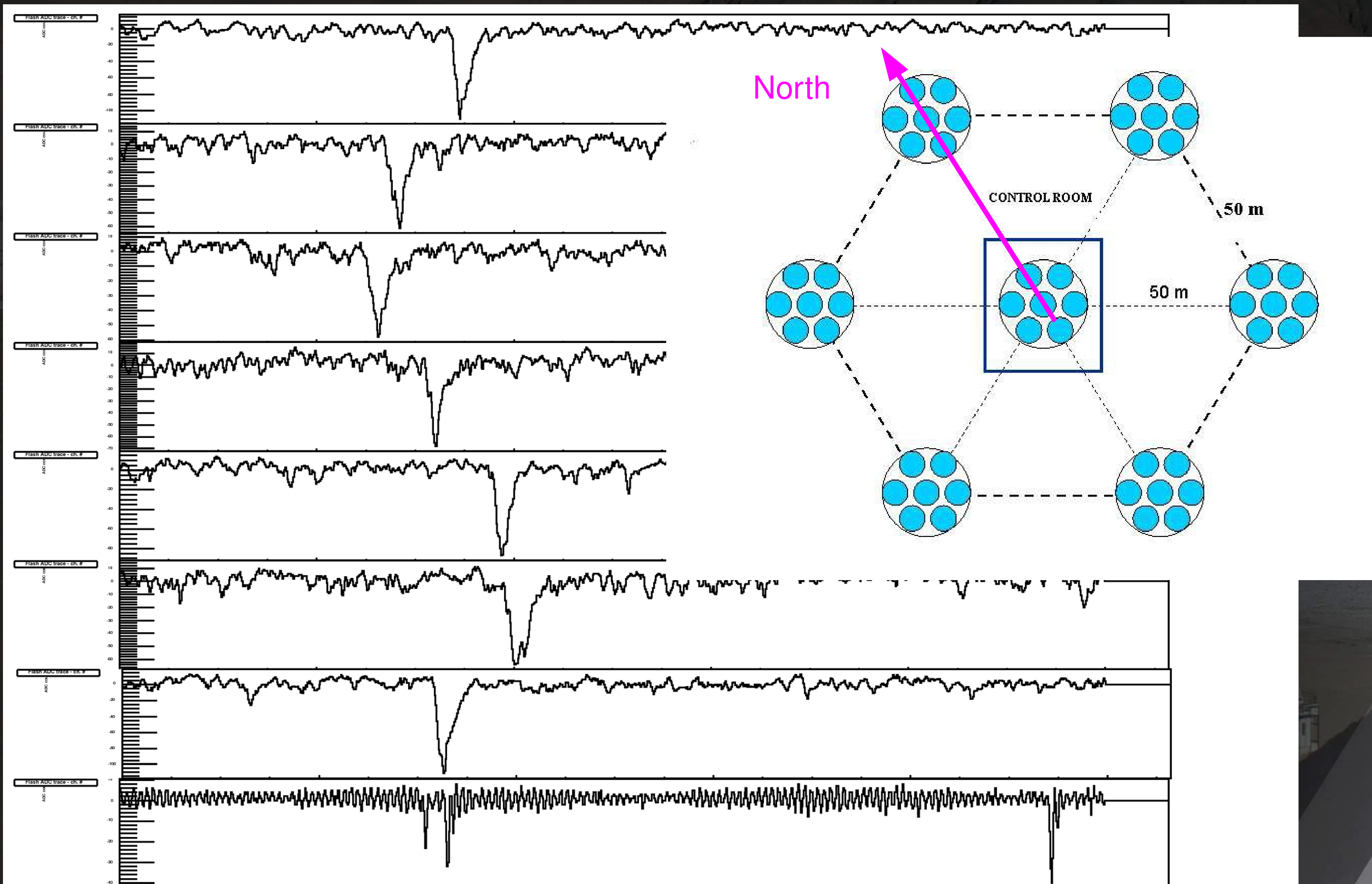
Improvements in Analysis

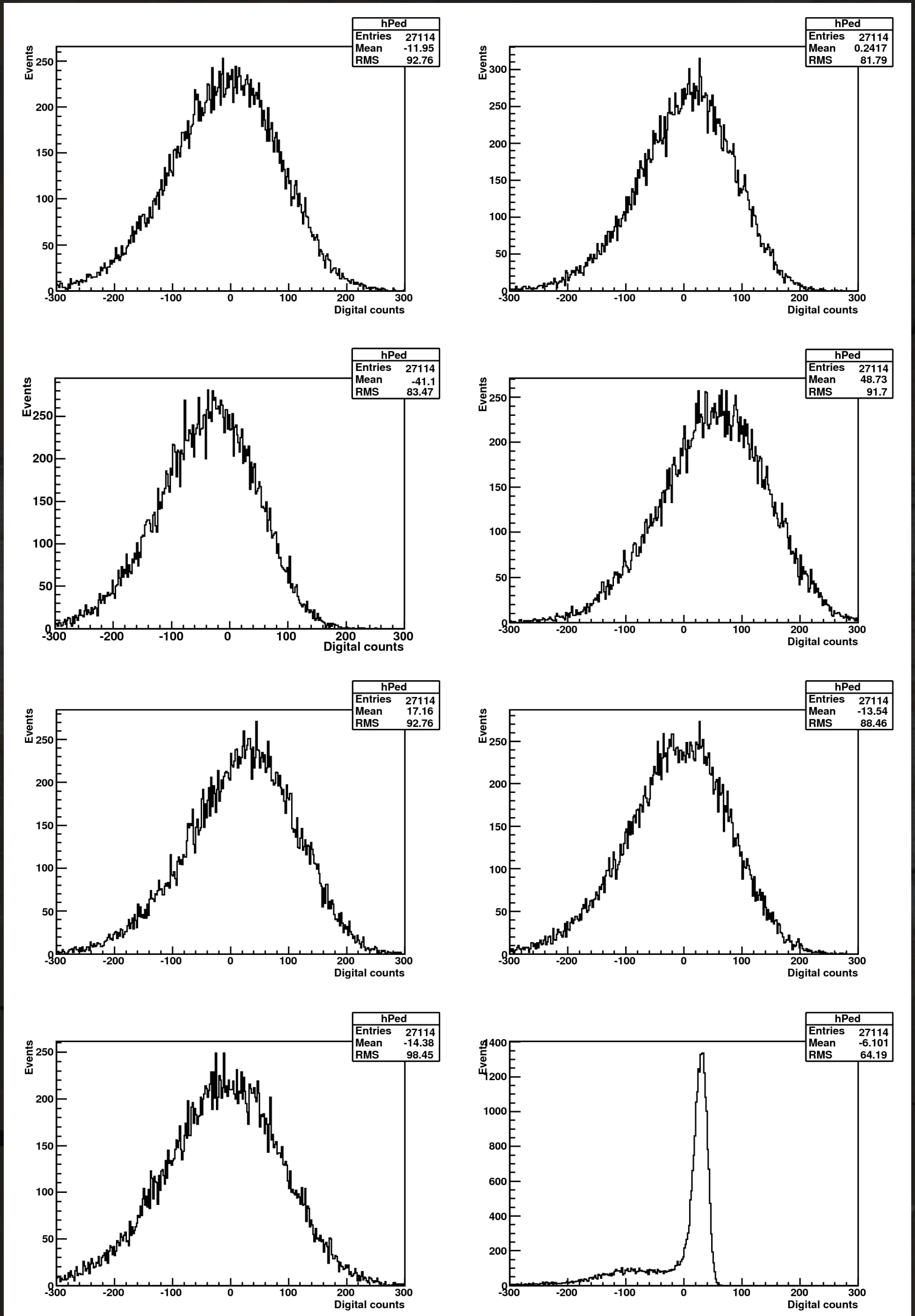
3. Other improvements

* Software padding for balancing NSB in ON and OFF regions
* FADC expected to improve energy estimate of primary

Flash ADCs


Flash ADC trace - ch. #
Flash ADC trace - ch. #
Flash ADC trace - ch. #
Flash ADC trace - ch. #
Flash ADC trace - ch. #
Flash ADC trace - ch. #
Flash ADC trace - ch. #
Flash ADC trace - ch. #


North
CONTROL ROOM
50 m
50 m


hPed
Entries 27114
Mean -11.95
RMS 92.76
hPed
Entries 27114
Mean 0.2417
RMS 81.79
hPed
Entries 27114
Mean -41.1
RMS 83.47
hPed
Entries 27114
Mean 48.73
RMS 91.7
hPed
Entries 27114
Mean 17.16
RMS 92.76
hPed
Entries 27114
Mean -13.54
RMS 88.46
hPed
Entries 27114
Mean -14.38
RMS 98.45
hPed
Entries 27114
Mean -6.101
RMS 64.19
Events
Digital counts

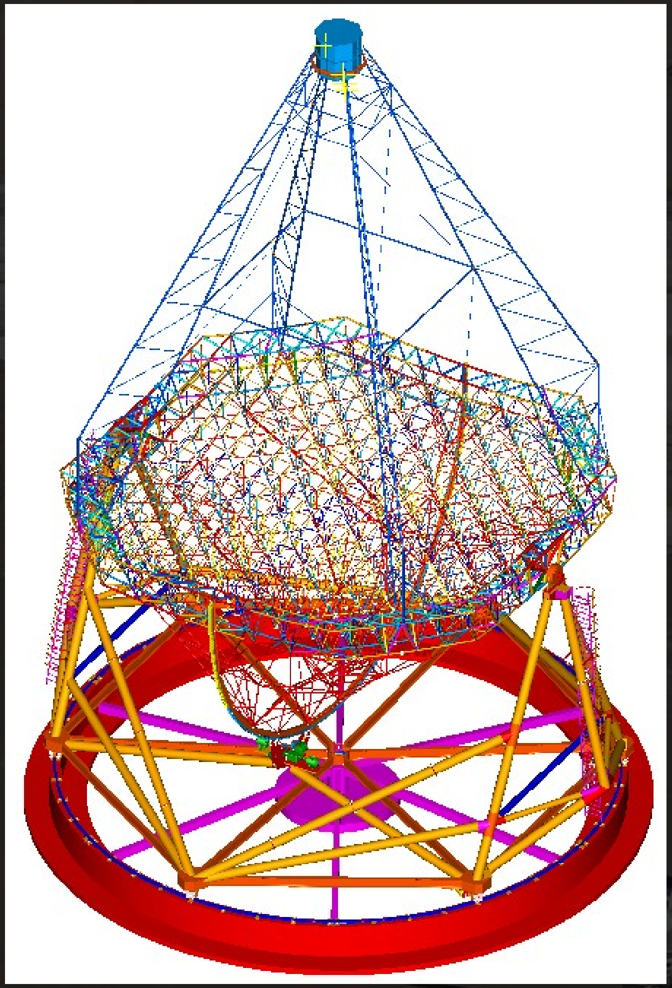
Summary

- Preliminary results on Crab Nebula
- Systematics to be understood (NSB, simulations and more test runs)
- Hadronic rejection to be implemented
- Flash ADCs analysis is starting

---> Confident for interesting results on various sources

Future Prospects at HIGRO

Major Atmospheric Cherenkov Experiment (MACE)



- Second stage of HIGRO collaboration (IIA, BARC and TIFR)
- Initially single imaging telescope of dia 21 m
  - ➔ cluster of 1408 PMTs with pixel resolution of 0.1° covering FOV of 4° × 4° at the focus
  - ➔ lower energy threshold of 20 GeV
  - ➔ Sensitivity : 5 sigma Crab in 13 min > 200 GeV
    43 min > 55 GeV
  - ➔ located near HAGAR : common events
  - ➔ first light expected in 2012
- Will be augmented by one more similar element by 2014 to enable stereoscopic operations

B. S. Acharya	TIFR
P. Battercharjee	SINP
R. J. Britto	TIFR
V. R. Chitnis	TIFR
R. Cowsik	IIA
N. Dorji	TIFR
K. S. Gothe	TIFR
P. U. Kamath	IIA
P. K. Mahesh	IIA
B. K. Nagesh	TIFR
A. Naidu	TIFR
N. K. Parmar	TIFR
T. P. Prabhu	IIA
L. Saha	SINP
F. Saleem	IIA
Sandeep Kumar	TIFR
A. K. Saxena	IIA
S. K. Rao	TIFR
S. K. Sharma	TIFR
A. Shukla	IIA
B. B. Singh	TIFR
R. Srinivasan	IIA
G. Srinivasulu	IIA
P. V. Sudersanan	TIFR
S. S. Upadhya	TIFR
P. R. Vishwanath	IIA

S. Nazma Islam
(Visiting Graduate Student in TIFR)


5 3 2009

Back up slides

Details of Spectral Shapes Used for Simulations

- **For γ -rays :** ***(20 GeV – 5 TeV)***

$$J(E) = 3.2 \times 10^{-7} (E_{TeV})^{-2.49}\ m^{-2}\ s^{-1}\ TeV^{-1}$$

- **For protons :** ***(50 GeV – 5 TeV)***

$$J(E) = 0.0867 (E_{TeV})^{-2.7}\ m^{-2}\ s^{-1}\ sr^{-1}\ TeV^{-1}$$

- **For α particles :** ***(100 GeV – 10TeV)***

$$J(E) = 0.0595 (E_{TeV})^{-2.7}\ m^{-2}\ s^{-1}\ sr^{-1}\ TeV^{-1}$$

- **For electrons :** ***(50 GeV – 5 TeV)***

$$J(E) = 638.97 (E_{GeV})^{-3.3}\ m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}$$

Reconstruction of Arrival Direction

If the x_i, y_i, z_i, are the co-ordinates of the ith telescope, l, m, n, the direction cosines of shower axis and t_i is the arrival time of photons at this telescope then equation relating them

$$lx_i + my_i + nz_i + c\left(t_i - t_0\right) = 0$$

Where t_0 is the time at which the shower front passes through the origin of the co-ordinate system. Then the arrival direction can be estimated by χ^2 minimization

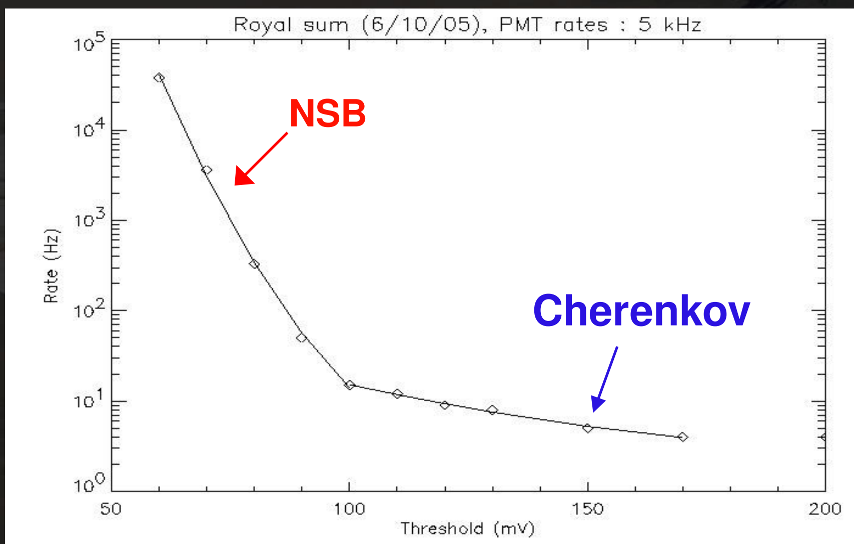
$$\chi^2 = \sum_{i=0}^{n} \omega_i \left(lx_i + my_i + nz_i + c\left(t_i - t_0\right)\right)^2$$

The value of l, m, n, and t_0 are calculated using following eqns

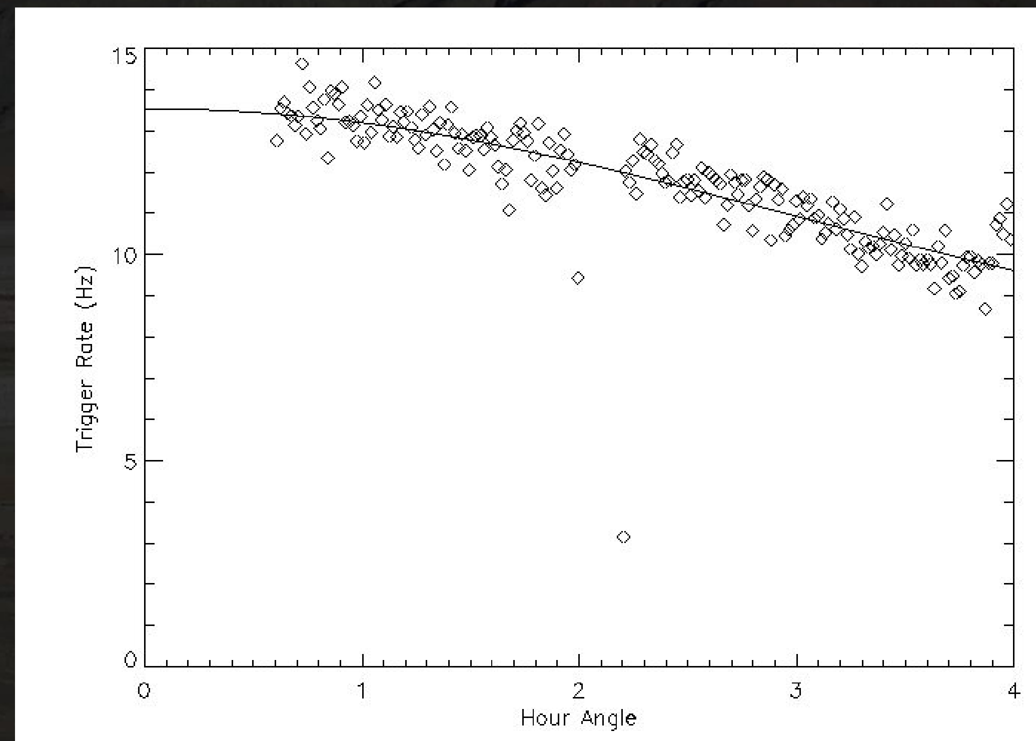
$$\frac{\partial \chi^2}{\partial l} = 0, \qquad \frac{\partial \chi^2}{\partial m} = 0, \qquad \frac{\partial \chi^2}{\partial t_0} = 0, \qquad l^2 + m^2 + n^2 = 1$$

Preliminary Tests

Rate-bias curve



Dark region tracking



PMT rate stability, fixed angle runs etc

HAGAR RESULTS ON d22mw

* Excess for NDF >= 4
* Excess for NDF = 4
* Excess for NDF = 5
* Ecxess for NDF = 6
* Excess for NDF = 7

NDF >=4: 9 pairs = 3.9 h
3.18 +/– 1.20 γ / min --> 2.12 σ

NDF = 4: 5 pairs = 2.1 h
–0.55 +/– 1.20 γ / min --> –0.46σ

NDF = 5: 7 pairs = 3.1 h
–1.74 +/– 0.85 γ / min --> –2.06σ

NDF = 6: 8 pairs = 3.4 h
1.14 +/– 0.68 γ / min --> 1.67 σ

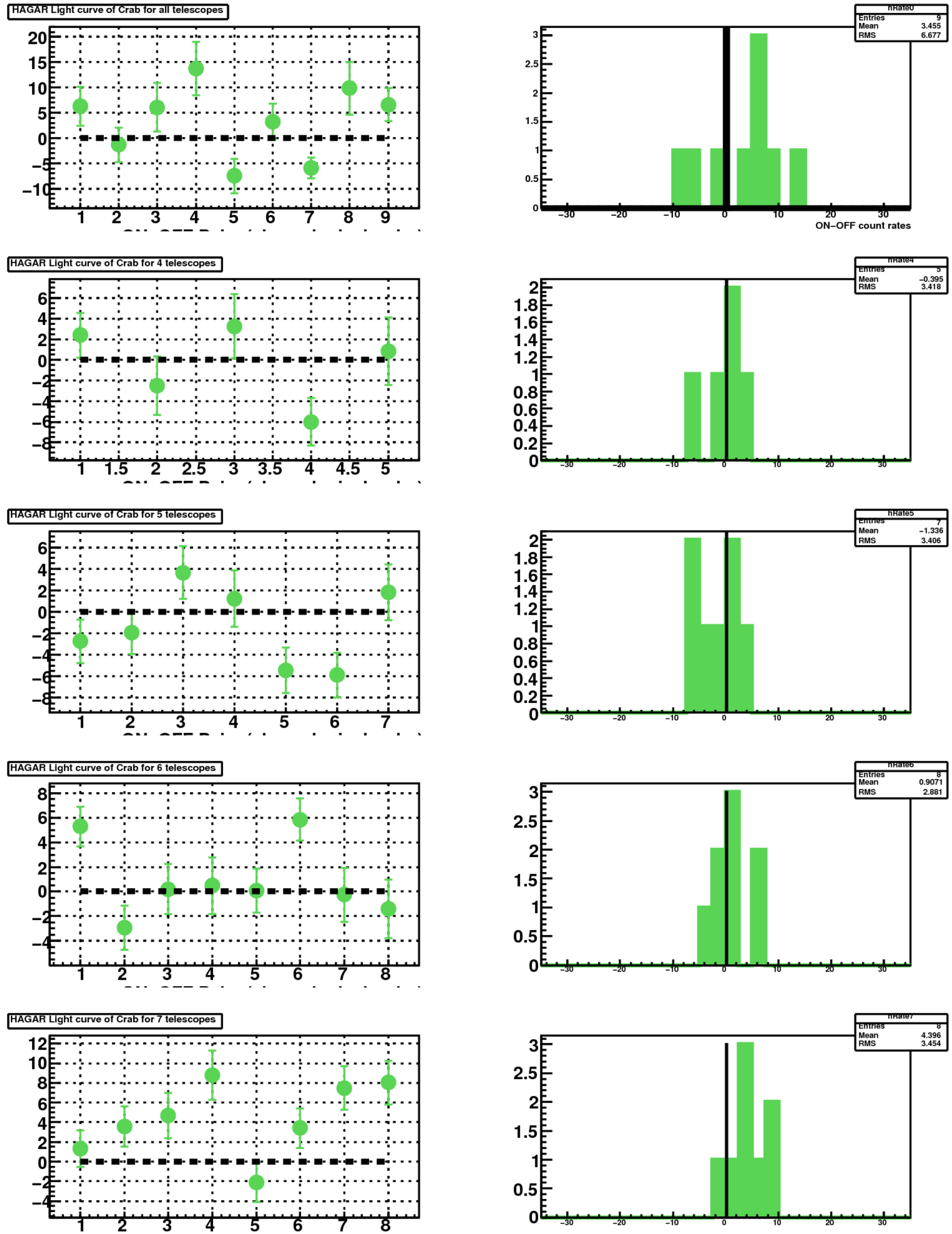
NDF = 7: 8 pairs = 3.4 h
3.91 +/– 0.75 γ / min --> 5.23 σ

RUN/PAIR SELECTION:

* | Diff Trigger rate | < 1.0 Hz
* Rcut (rate stab.) < 0.00
* 0.8 < Tel Ratios (1 to 7) < 1.2
* | Diff Space Angle Cut | < 0.0
* | Diff Space Angle Peak | < 0.0
* | Diff Space Angle FWHM | < 0.0
* 0.85 < norm Const (85 %) < 1.15

MAIN ANALYSIS CUTS:

* TDC ranges
* common hour angle
* χ^2 on plane front fitting
* Space Angle Cut = 85 %



HAGAR RESULTS ON CRAB NEBULA

* Excess for NDF >= 4
* Excess for NDF = 4
* Excess for NDF = 5
* Ecxess for NDF = 6
* Excess for NDF = 7

NDF >=4: 13 pairs = 9.1 h
4.12 +/– 0.70 γ / min –––> 5.95 σ

NDF = 4: 9 pairs = 6.5 h
3.72 +/– 0.63 γ / min –––> 5.91 σ

NDF = 5: 12 pairs = 8.6 h
0.88 +/– 0.46 γ / min –––> 1.93 σ

NDF = 6: 10 pairs = 7.5 h
–0.53 +/– 0.43 γ / min –––> –1.23 σ

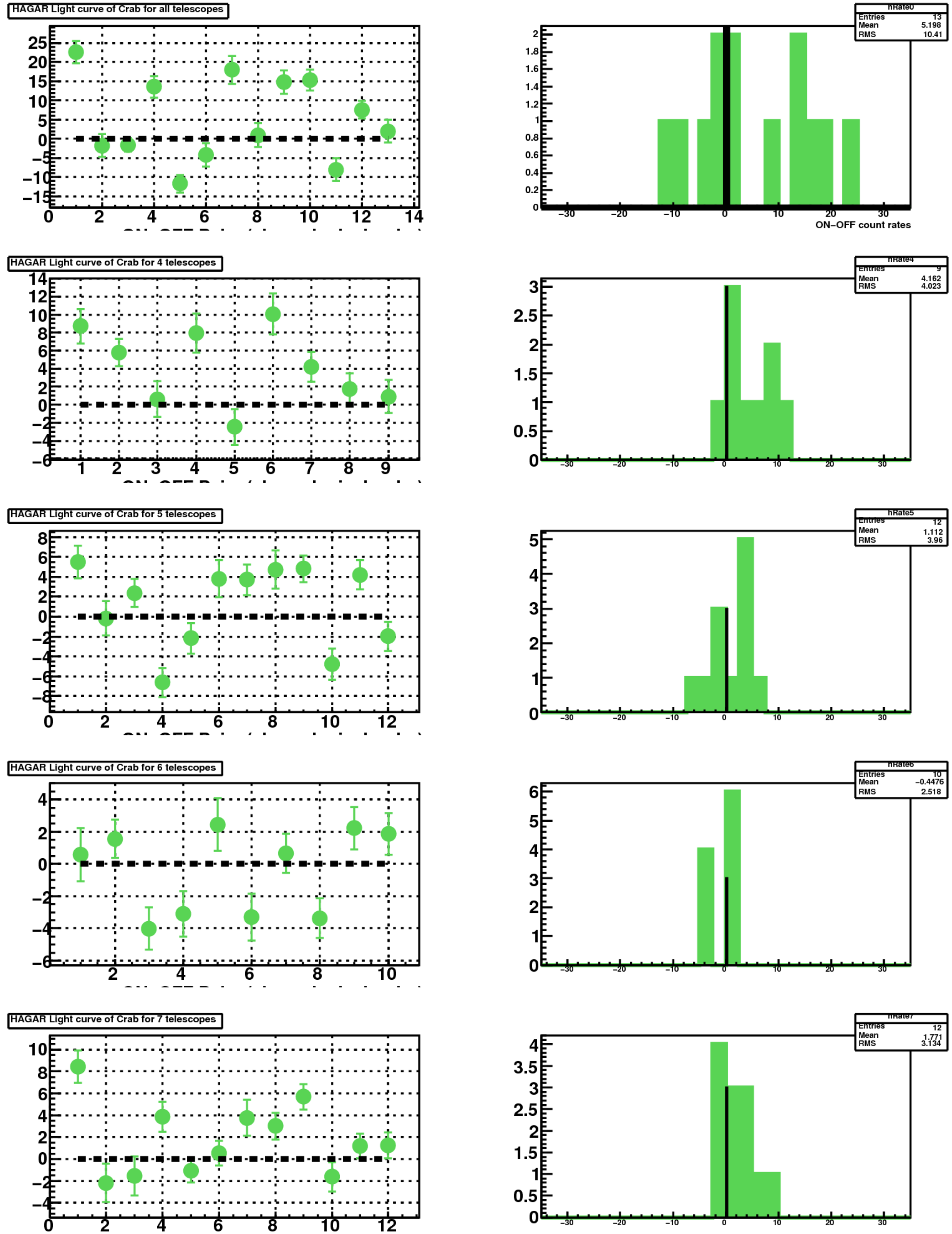
NDF = 7: 12 pairs = 8.5 h
1.81 +/– 0.38 γ / min –––> 4.76 σ

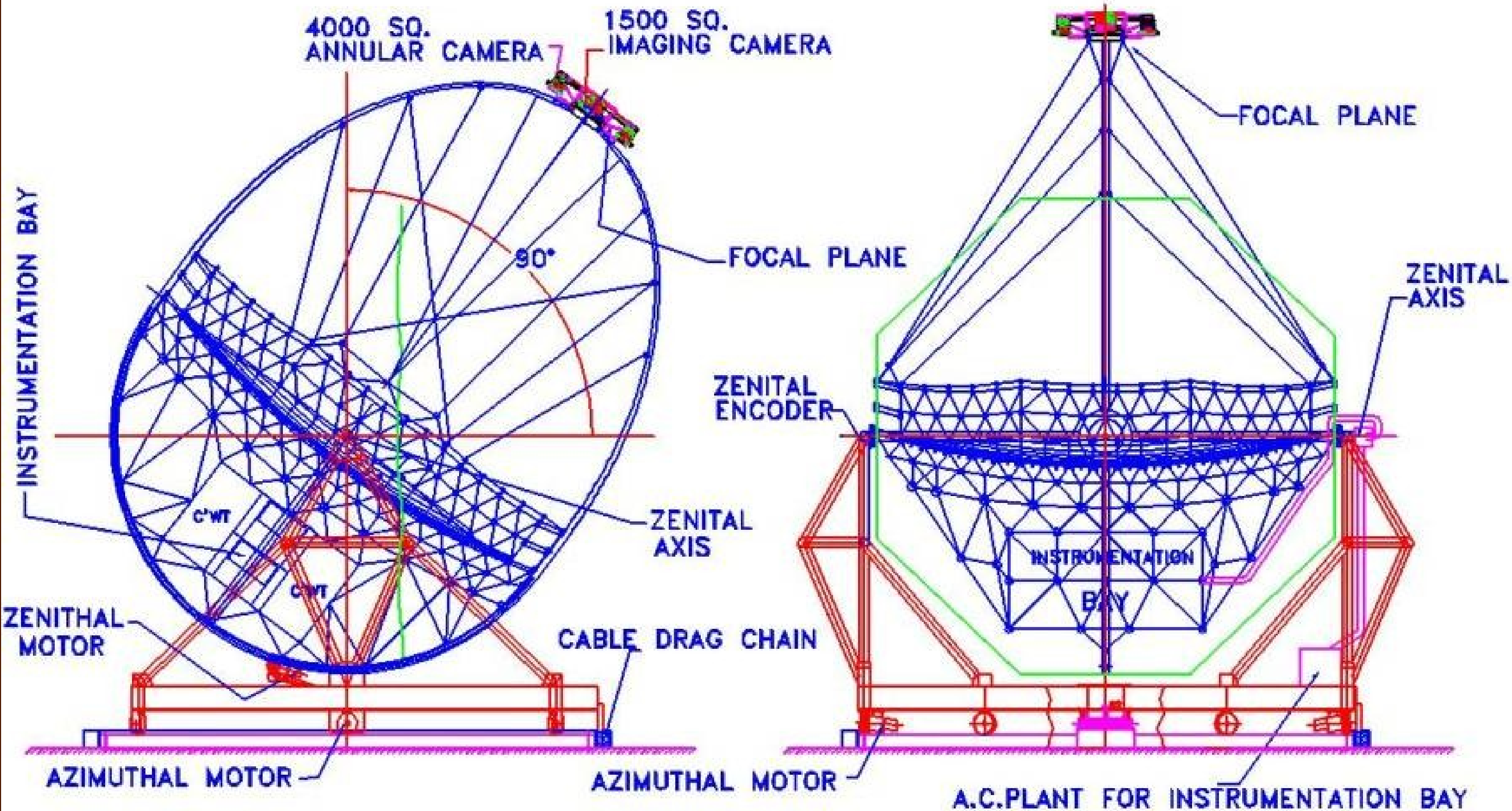
RUN/PAIR SELECTION:

* | Diff Trigger rate | < 1.0 Hz
* Rcut (rate stab.) < 0.00
* 0.8 < Tel Ratios (1 to 7) < 1.2
* | Diff Space Angle Cut | < 0.0
* | Diff Space Angle Peak | < 0.0
* | Diff Space Angle FWHM | < 0.0
* 0.85 < norm Const (85 %) < 1.15

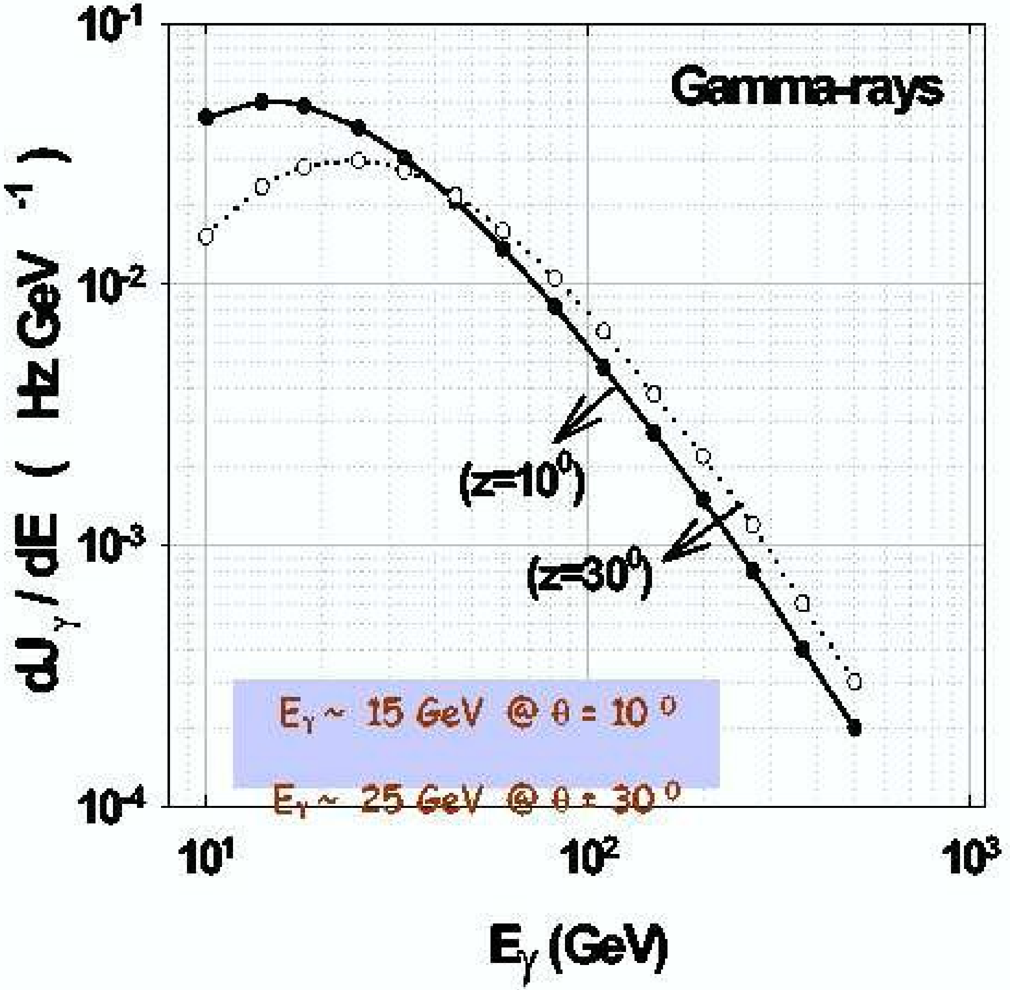
MAIN ANALYSIS CUTS:

* TDC ranges
* common hour angle
* χ^2 on plane front fitting
* Space Angle Cut = 85 %

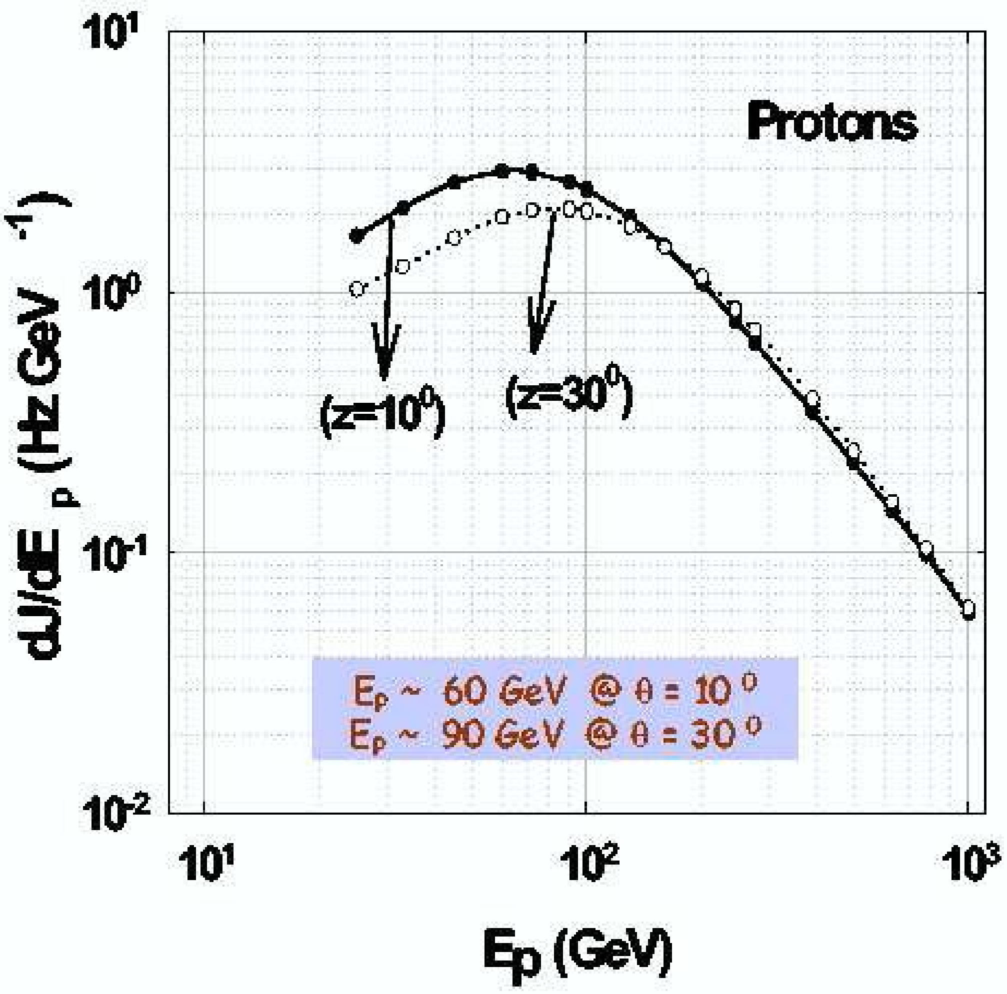




4000 SQ.
ANNULAR CAMERA
1500 SQ.
IMAGING CAMERA
INSTRUMENTATION BAY
90°
FOCAL PLANE
C'WT
C'WT
ZENITAL
AXIS
ZENITHAL
MOTOR
CABLE DRAG CHAIN
AZIMUTHAL MOTOR
FOCAL PLANE
ZENITAL
AXIS
ZENITAL
ENCODER
INSTRUMENTATION
BAY
AZIMUTHAL MOTOR
A.C.PLANT FOR INSTRUMENTATION BAY



Gamma-rays
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{1}
10^{2}
10^{3}
dJ_γ / dE (Hz GeV^{-1})
E_γ (GeV)
(z=10^0)
(z=30^0)
E_γ ~ 15 GeV @ θ = 10^0
E_γ ~ 25 GeV @ θ = 30^0



Protons
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{1}
10^{2}
10^{3}
dJ/dE_p (Hz GeV^{-1})
Ep (GeV)
(z=10^0)
(z=30^0)
E_p ~ 60 GeV @ θ = 10^0
E_p ~ 90 GeV @ θ = 30^0