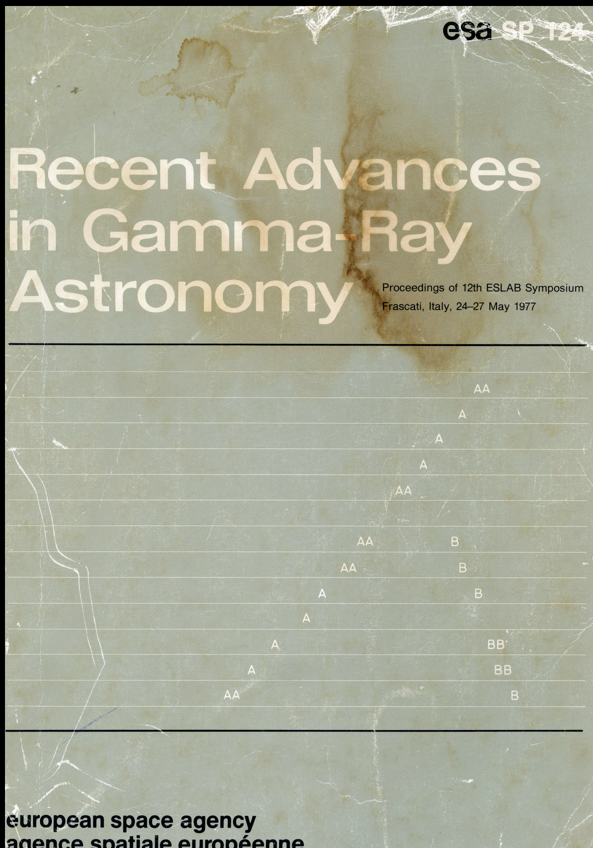
Michael Hillas

and the Whipple TeV Gamma-ray collaboration.

19th ICRC La Jolla, 1985
Michael Hillas, Ken Gibbs, Peter Gorham, Vic Stenger, Dave Liebing, A.Gregory (visitor), Dick Lamb, Trevor Weekes & David Fegan

1977 Gamma-ray Astronomy … a prescient paper.



GAMMA-RAY ASTRONOMY FROM 10-100 GeV: A NEW APPROACH

T.C. Weekes

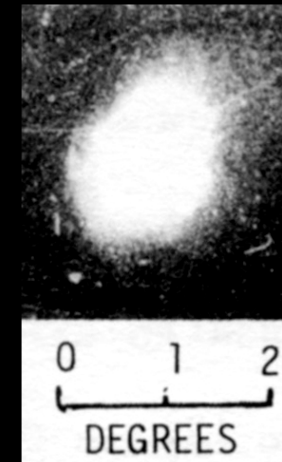
Mt. Hopkins Observatory, Center for Astrophysics, Amado, USA

K.E. Turver

University of Durham, UK

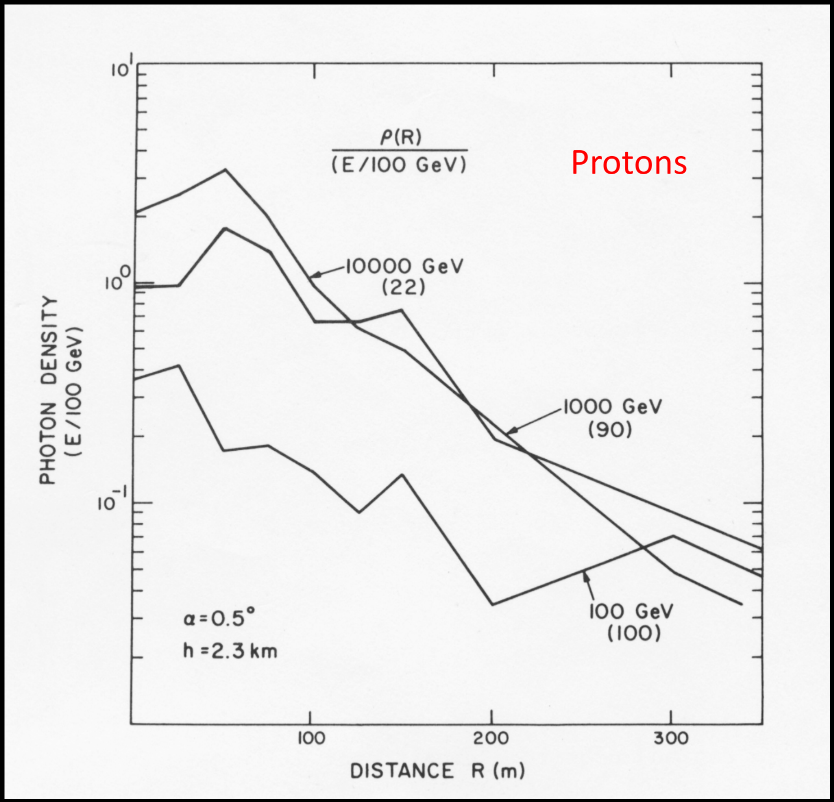
ABSTRACT

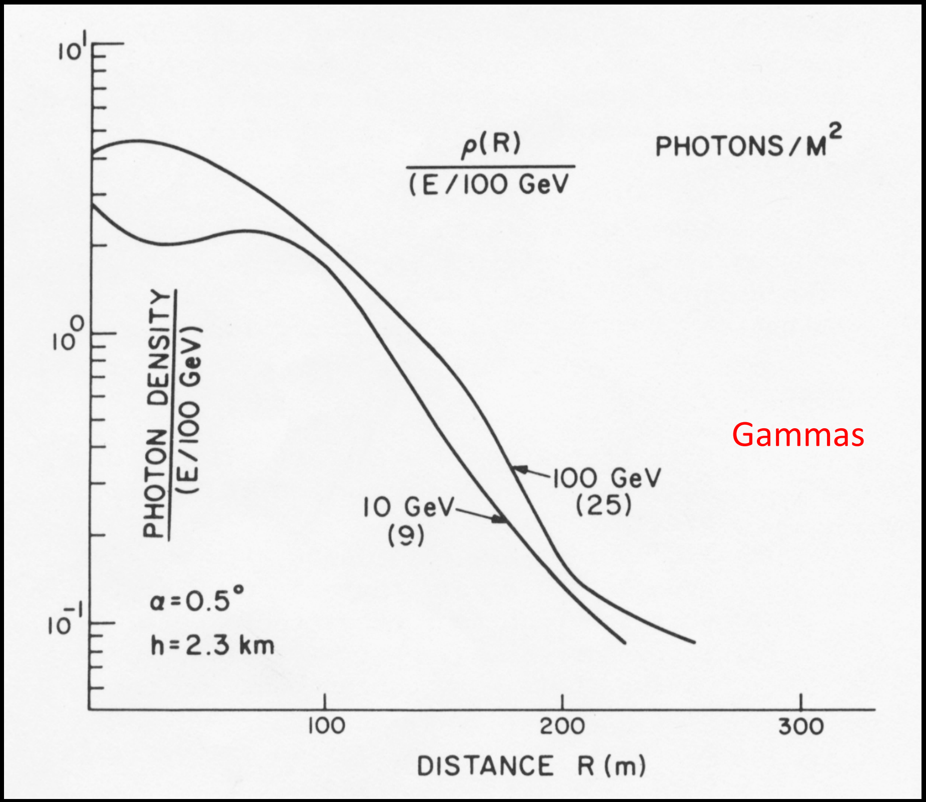
Recent advances in gamma ray astronomy at satellite energies suggest a new look at the experimental technique at high energies. The suggestion by the University of Durham group that proton induced showers of energy 100 GeV are deficient in Cerenkov light compared with gamma ray showers indicates that gamma ray experiments in the range 10-100 GeV would be extremely fruitful. Results of the computer simulations are presented and a qualitative description is given of an experiment which would exploit this feature; this would involve the use of two parallel large reflectors each equipped with multiple detector channels to provide two "images" of the shower in Cerenkov light.



Gamma-ray Astronomy from 10 – 100 GeV: A new approach.
Weekes, T.C. & Turver, K.E. Proc. 12th ESLAB Symp. Frascati, Italy, ESA SP-124 July 1977.

SEPARATION of signal from background.



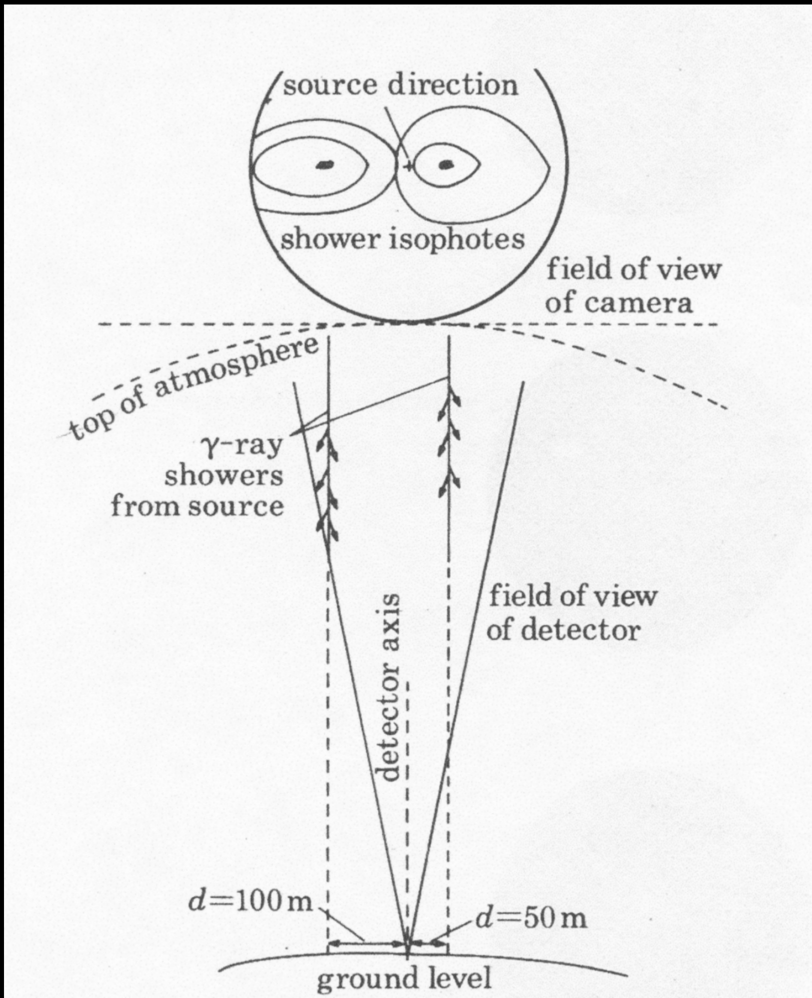


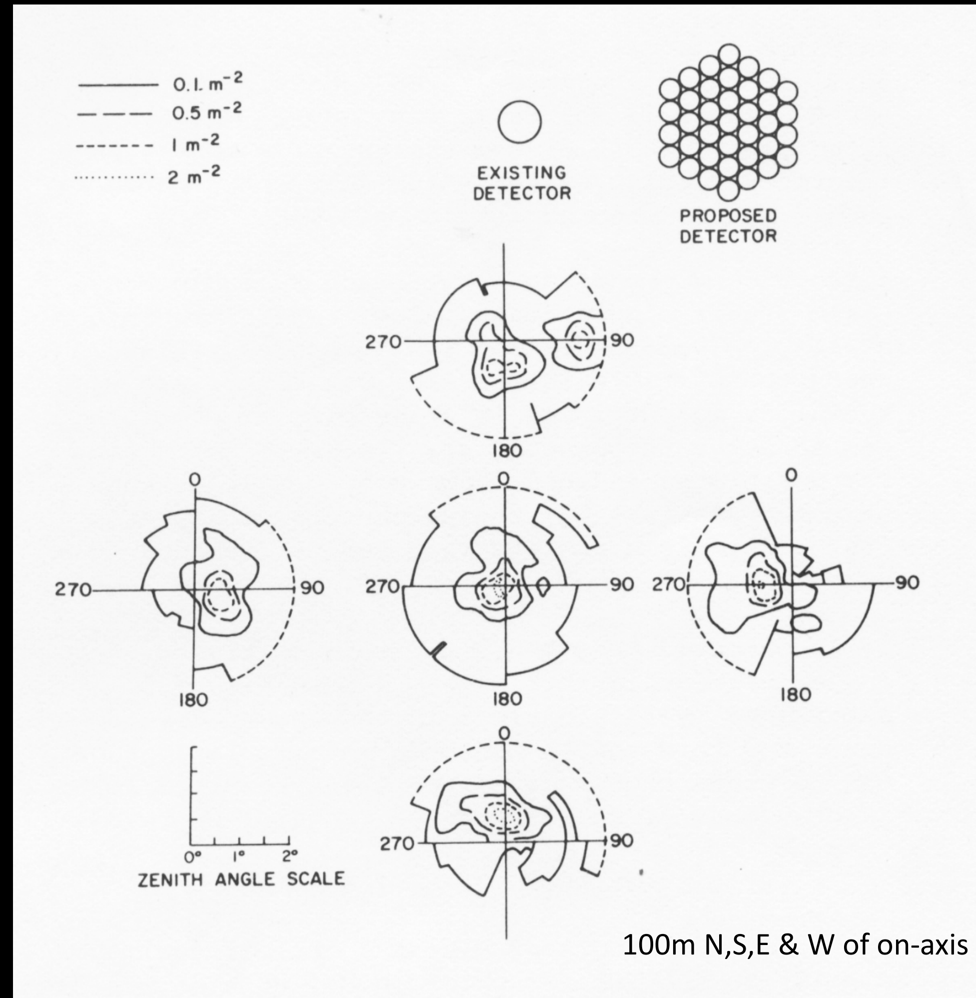
Averaged Lateral Distributions of light based on Monte Carlo simulations.

Browning and Turver 1975 – protons
Gough and Turver 1977- gamma rays

Two alternatives:-
Fast timing of shower front,
or,
2D imaging of shower light spots

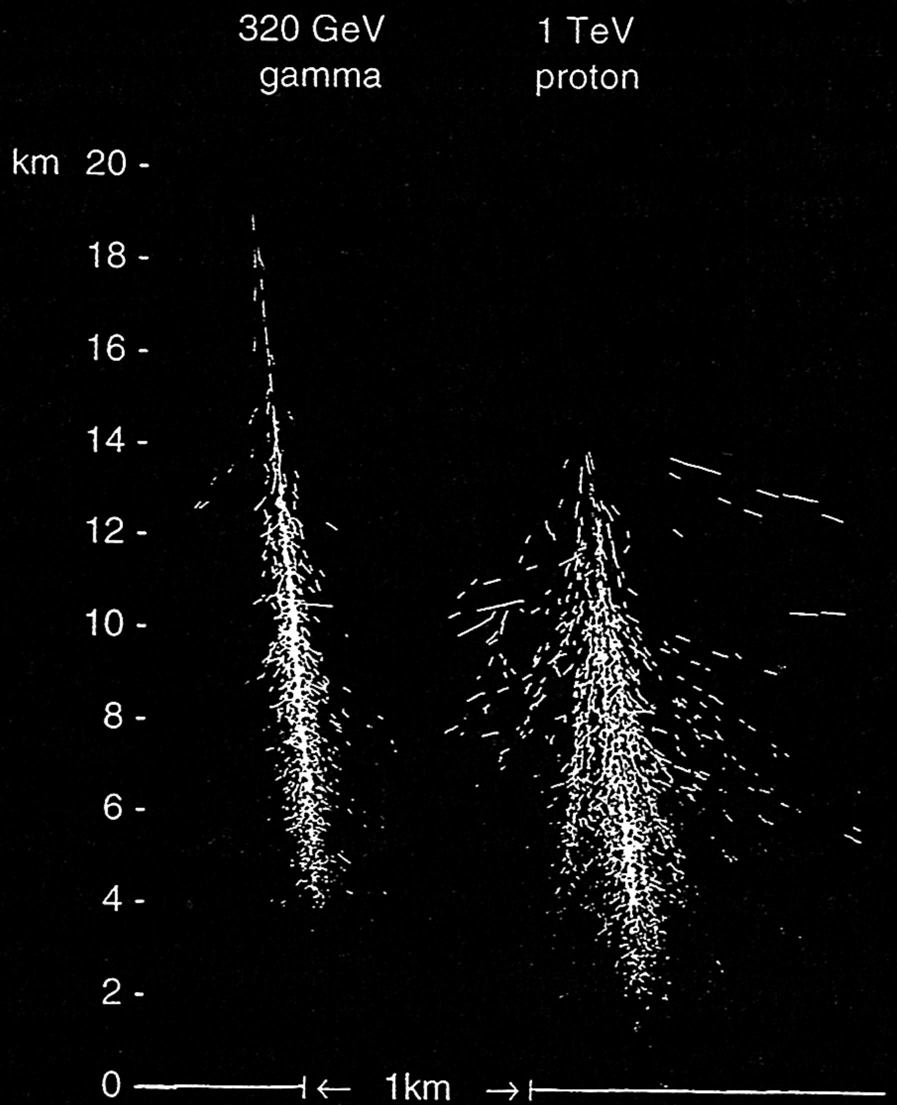
TeV point-source searching – based on IMAGING

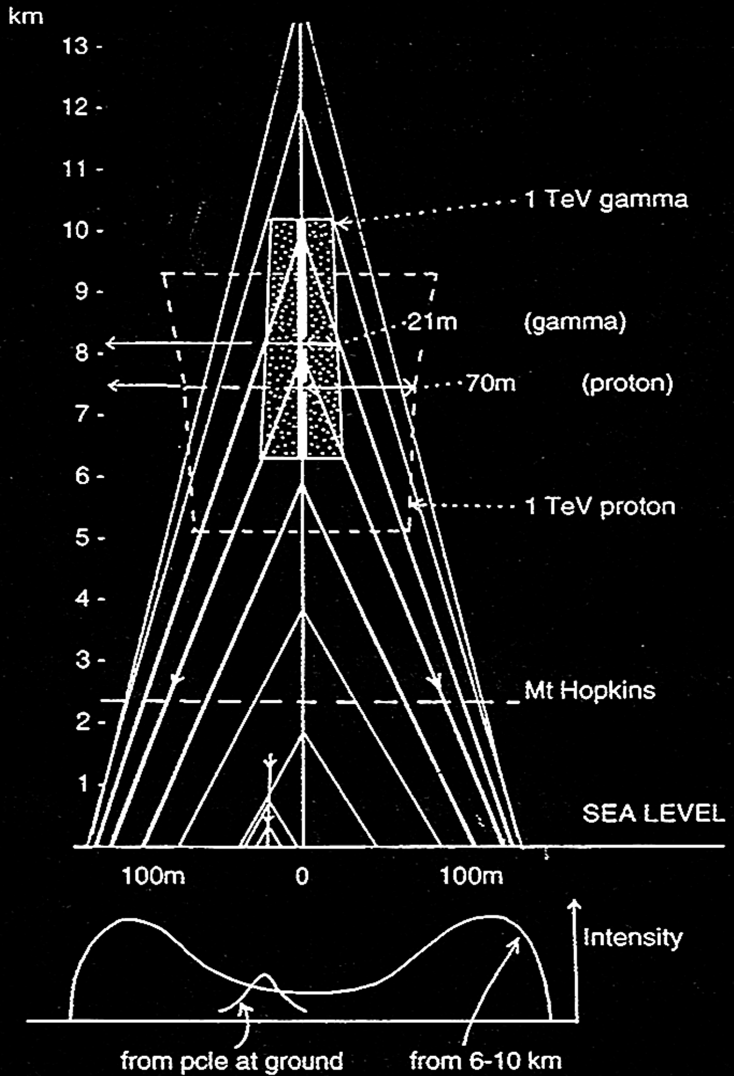




5 views: 100 GeV Gamma-ray light isophotes

Atmospheric shower development





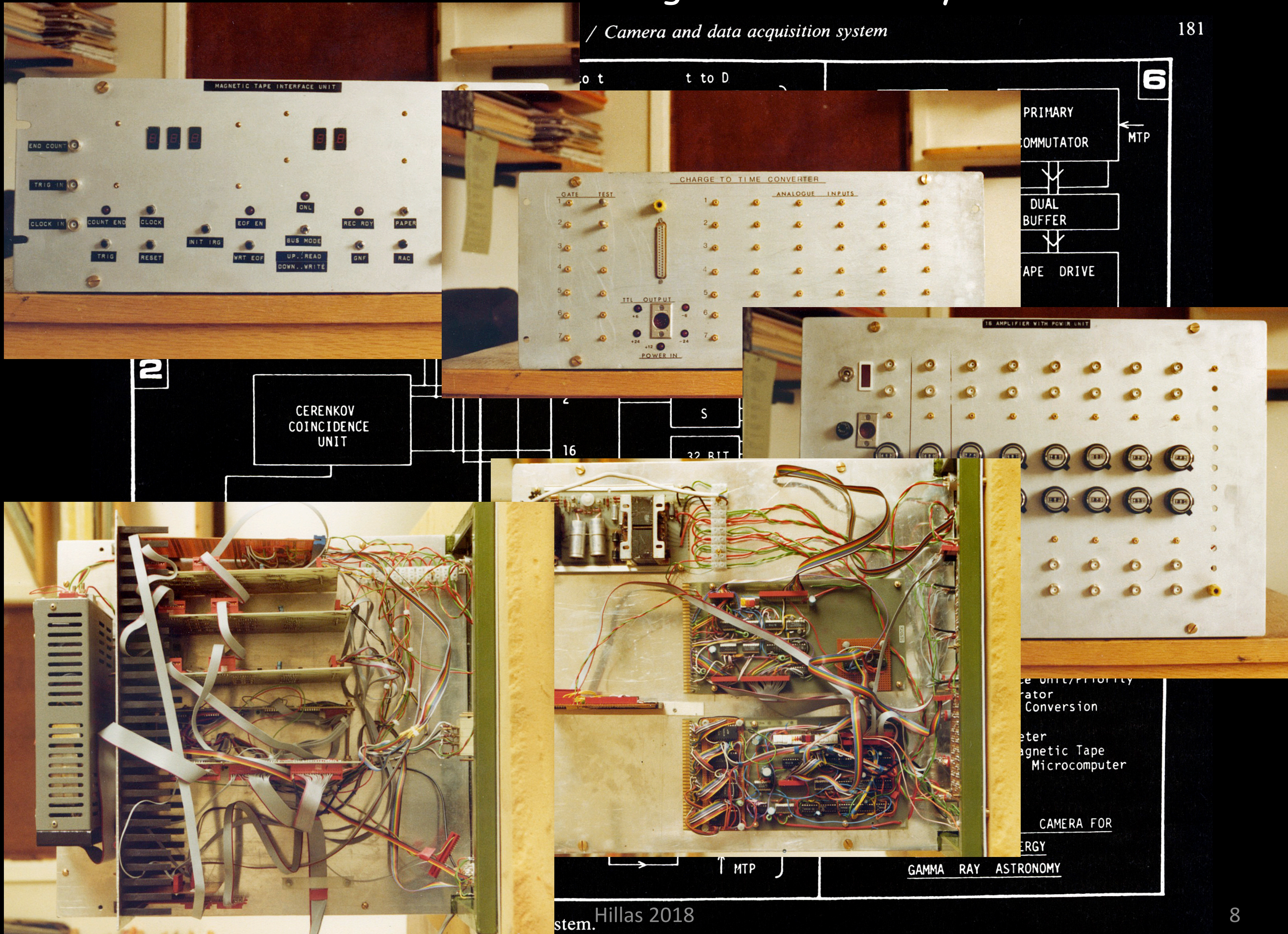
Diagrams after Michael Hillas

1978 … Meeting at University College Dublin (UCD) Neil Porter, David Fegan and Trevor Weekes – exploratory discussions about the technical possibility of imaging.

Optimistically thinking about a prototype 19 or 37 pixel PMT imaging camera for evaluation observations.

1980 & 1982 first funding (Ireland) … hardware design and prototype

1980-1982 … first imager electronic system.



However ... disturbing communication Trevor Weekes to Neil Porter

Feb 1981

SMITHSONIAN INSTITUTION
ASTROPHYSICAL OBSERVATORY

TELEPHONE: (602) 398-2432
(602) 792-6741
(FTS) 762-6741

MT. HOPKINS OBSERVATORY
P. O. BOX 97 AMADO, ARIZONA 85640

February 11, 1981

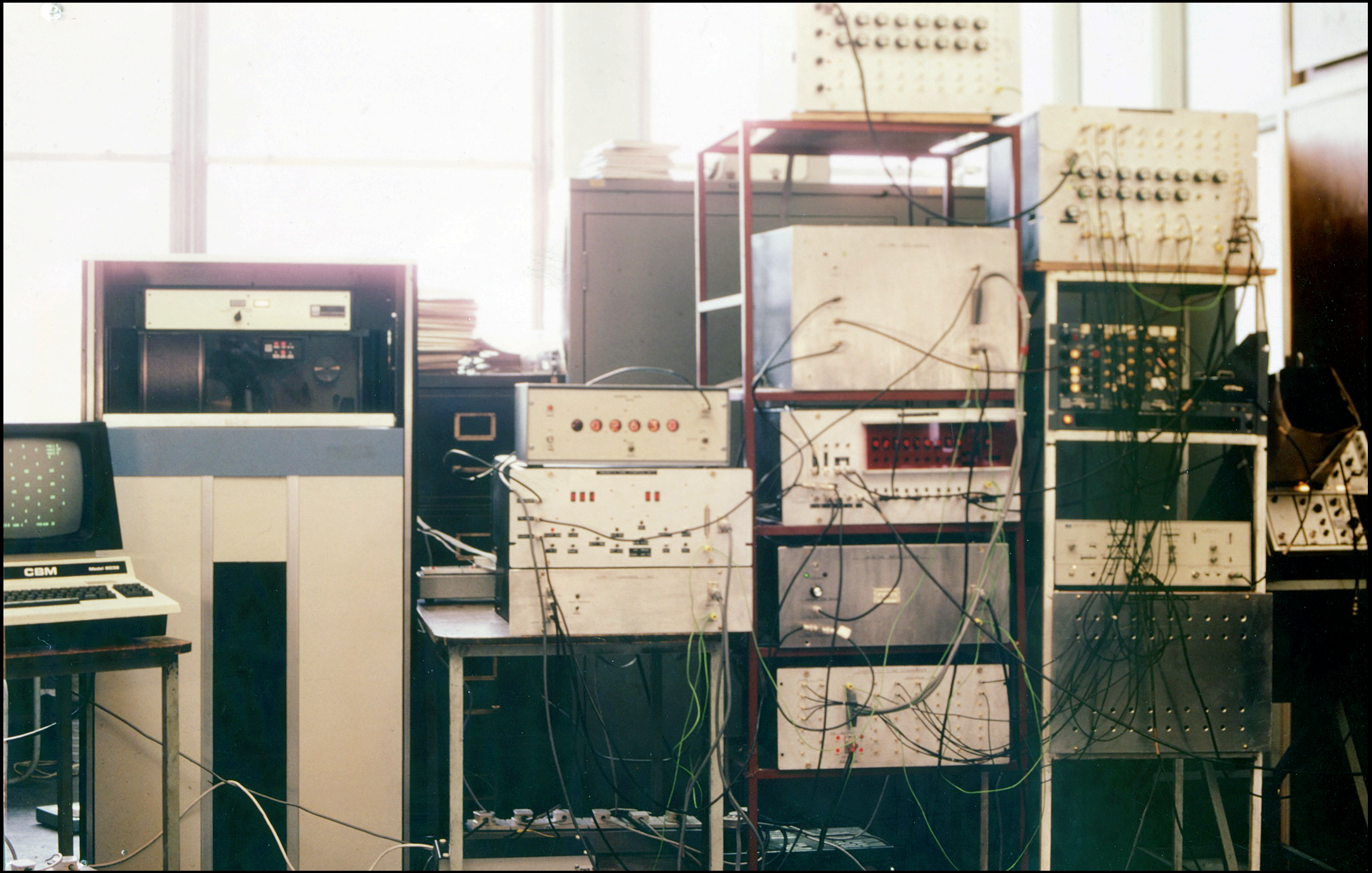
Prof. N.A. Porter
Physics Department
University College
Belfield, Dublin 4
Ireland

Dear Neil,

The news from here is not too good but you should know it as it must effect our future observing plans. As you will have gathered, the new President is not well disposed towards scientific research and is, in fact, cutting back on all agencies (except the military). It is not clear yet how this will affect the Smithsonian but it is sure to have some fairly serious repercussions. We already have a ban on new hiring (I have funds for a data aide but cannot use them!), severe cuts on travel etc., and it is expected that the overall budgets will also be reduced.

The most serious cut has been at NASA and I have heard that the Gamma Ray Observatory has got the axe. Since we were hoping to ride on its coat tails, as it were, this is a bad blow.

1982 completed expandable prototype [19,37,61 tubes].



D.J.Fegan, D.McLaughlin, J.Clear, M.F.Cawley and N.A.Porter.
Nuclear Instruments and Methods 211, p179-191, 1983.

1982 Tucson, Az – Formation of the Whipple collaboration.

ICRC Bangalore Sept 1983

XG 4-10

118

Application of Two Dimensional Imaging of Atmospheric Cerenkov Light to Very High Energy Gamma Ray Astronomy.

M.F. Cawley[1,3], J. Clear[1,3], D.J. Fegan[3], K. Gibbs[1], P. Gorham[5], R.C. Lamb[2], I. MacRae[4], P.K. MacKeown[1,2,6], N.A. Porter[3], V.S. Stenger[5], K.E. Turver[4], T.C. Weekes[1].

(1) Harvard-Smithsonian Center for Astrophysics, (2) Iowa State University, (3) University College, Dublin (4) University of Durham, (5) University of Hawaii, (6) University of Hong Kong.

1. Introduction

The history of the use of two dimensional imaging to record the Cerenkov light images from small air showers has recently been reviewed by Porter (1982). The possibility of using arrays of small phototubes in the focal plane of large reflectors to improve the angular resolution of the atmospheric Cerenkov technique was first suggested by Weekes and Turver (1977). The preliminary design and expected performance of a camera based on the 10m Optical Reflector on Mount Hopkins was described by Weekes (1981).

Proc 18th ICRC Bangalore, 1, 118, 1983.

1982-1984 incremental progress … many teething problems.

" During the 1982-83 observational season (using 19 PMTs), many difficulties had to be surmounted. In practical terms, only a limited amount of useful observational data were acquired, some of it 'engineering' in nature, the rest punctuated by breaks in observational schedules for technical reasons. A disastrous experience was a lightning strike, giving rise to weeks of mid-winter downtime, preventing Crab observations."

"The task of delivering an Imaging Atmospheric Cherenkov Telescope (IACT) was proving to be much more challenging than anticipated at the outset. The second year of operation, 1983-84 was somewhat more encouraging, since the camera had been upgraded to 37 tubes during autumn 1983. However, there were many, many unresolved issues some of which were interdependent".

Among the many unresolved issues -

1. Reliable operational procedures and protocols required establishment.

2. Calibration and image preparation / cleaning … by trial/error.

3. Sky brightness variations / viewing conditions … hidden systematics ?

4. Optics issues: mirror alignment/focussing/reflectivity.

5. Simulations. Greater numbers of consistent & trustworthy shower simulations were urgently required, but from where?

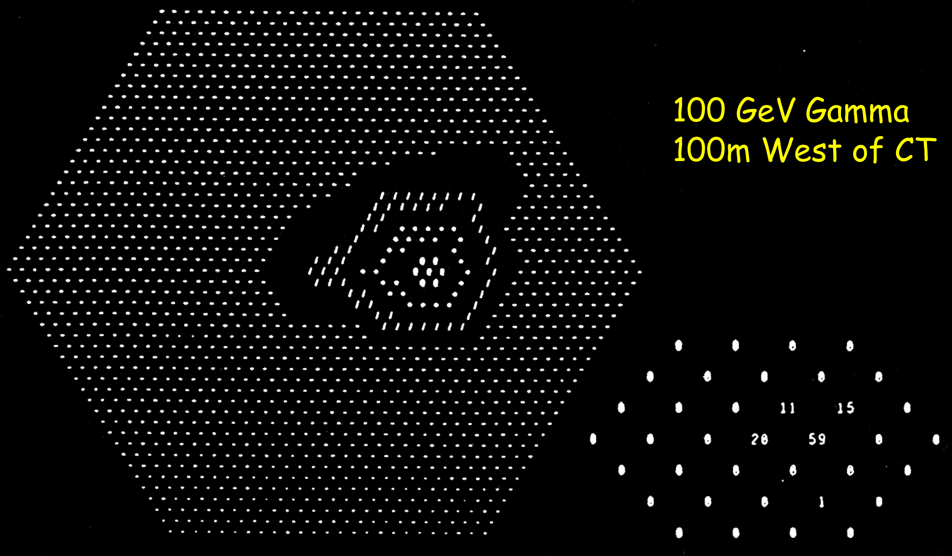
6. Background rejection algorithms then in use, largely based on intuition.

7. Funding sources urgently needed - to cover logistics of operation, software development & post-doc support.

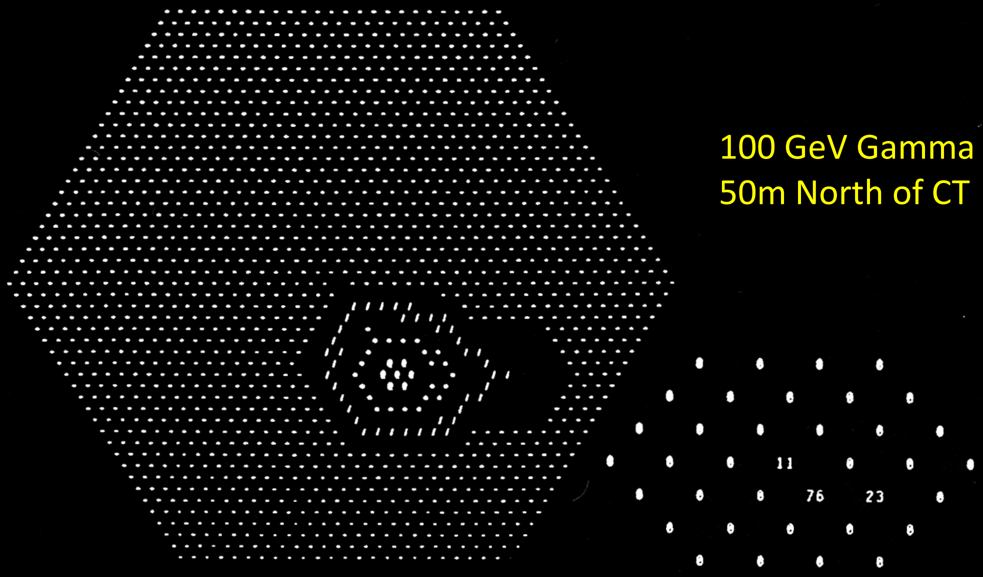
8. Very small team – required expansion to stand any chance of achieving a successful outcome.

Ellipses – crude fitting and linear interpolation - *beermats*

$\theta_{\frac{1}{2}} = \sqrt{2\sigma_x\sigma_y Ln2}$	50% light containment angle
$3_i = \mu_{30}$	Third moment: Asymmetry
$f = 1 - \frac{\sigma_x}{\sigma_y}$	Ellipse: flattening



100 GeV Gamma
100m West of CT



100 GeV Gamma
50m North of CT

Simulations, limited in number & fluctuation-dominated in the angular distribution of light.

Poor alignment of shower major-axis with arrival direction.

1984 - a serendipitous event ….

AAS invitation to Michel Hillas to visit Tucson (invite initiated by Trevor Weekes).

Presentation at Steward Observatory on Cygnus X-3 (non-Whipple related).

Sometime before the visit, Hillas had been busy simulating Cherenkov light from 10^{16} to 10^{17} eV hadronic showers.

While in Tucson, and following some quick estimations, he made a brief informal presentation to Whipple on Cherenkov light from 10^{11} to 10^{12} eV showers.

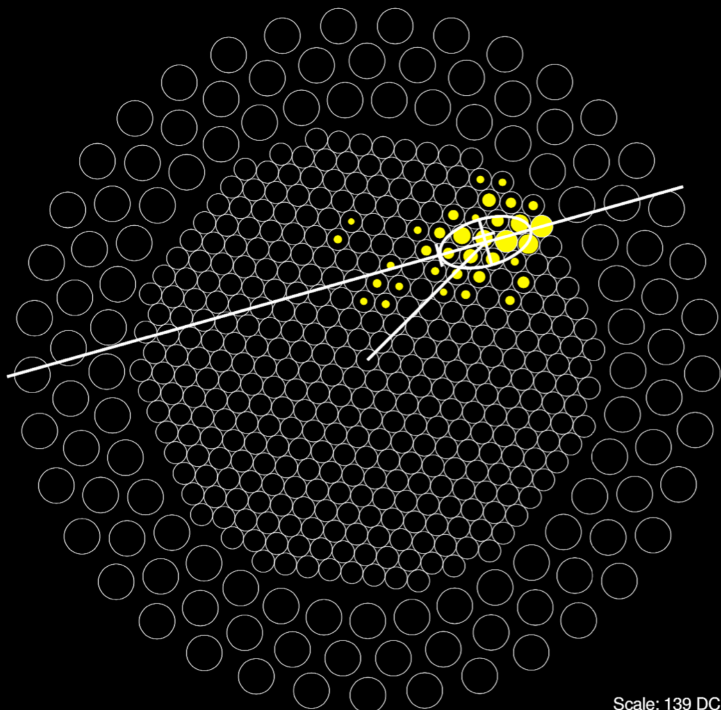
Back-of-envelope treatment demonstrated vividly shower pointing & narrowness as properties almost certainly of value as gamma-ray selection parameters.

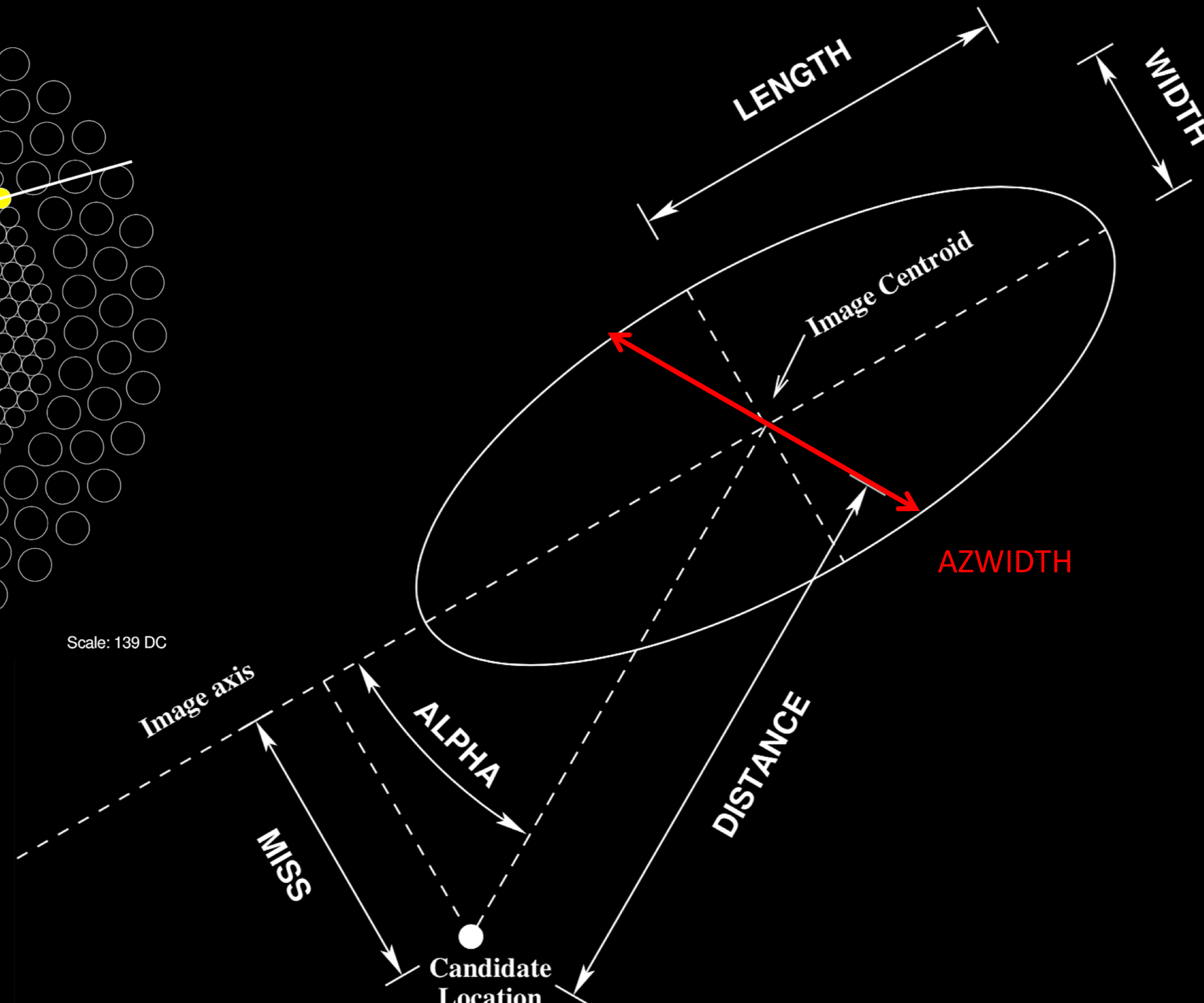
The *Hillas shower TeV simulations* (noise-free) demonstrated clarity and elegance & elicited enthusiastic responses from the Whipple group.

Very encouraging indeed, given the complex set of interdependent technical issues & conflicting sets of simulations compromising Whipple progress at that time.

So, intrigued …

Michael Hillas returned to Leeds and began informally to simulate Gamma and Proton showers [10^{11} to 10^{12} eV]





Assumptions underpinning the Hillas simulations :-

1. Hadron cascades: at TeV energies, a scaling model is sufficient.

2. Electron-photon cascades: follows particles down to 0.05 MeV, thin- sampling employed for particles below 1/4000th of the primary energy.

3. Light detected by 37 tubes in focal plane – Zones 0,1,2,3. [1, 6, 12, 18 tubes]

4. Finite mirror diameter accounted for - 10m, in that rays from a particular radiating track falling on different parts of the mirror, not considered parallel. However, bundles of rays within +/- 0.03 deg are grouped together.

5. Mirror focus – paraboloid, all incident rays from common direction reach a common point in the focal plane. PSF of 0.05 deg, ignored as too small to matter.

6. Geomagnetic field 0.50 gauss, dip angle 59 deg, altitude of observatory 2308m, with Poissonian fluctuations assumed in conversion to photoelectrons.

1984 [May 8th] Photon simulations, C-light Prog EMHCMH

Copy of Letter also enclosed in 2nd package, which has the 300 GeV simulations AMH.

THE UNIVERSITY OF LEEDS

Leeds
LS2 9JT , England.
Telephone (0532) 431751

From the Department of Physics

8 May 1984. 8-May 84

Dear Neil,

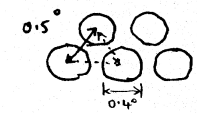
I enclose some maps of Cerenkov light patterns from simulated showers (1 TeV and 0·3 TeV). I apologise for the weight of paper: this is so large because maps are plotted for 19 observing positions in each simulated shower. Light intensities are plotted on a $\frac{1}{4}° \times \frac{1}{4}°$ square grid superimposed on the sky surrounding the source direction.

I just send these for your comment, to see whether they are useful, and whether a useful degree of resolution is employed. More showers can easily be run off, with modifications to the display if required. (I could get several TeV and many 300 GeV showers in an overnight job at any time.)

1984 [May 30th] C-light - 37pixel Gamma-ray light patterns.

A.M. Hillas — Cerenkov light patterns in focal plane of mirror.

Grid of 37 photomultiplier tubes placed with centres 0.5° apart, and diameter 0.4°



At each mirror position, 3 patterns (①..③) are printed

The most important one → * ① Mirror aimed at source: source in centre of field.

② Mirror displaced so that source appears on photomultiplier displaced 0.5° ↙ from centre (to allow longer view of some patterns)

③ A different displacement, quoted in degrees →↑ in the caption (not "grid units" but degrees) (perhaps unnecessary, but shows what pattern is like when source does not fall exactly on a photomultiplier)

Signals in special rings of photomultipliers

Numbers of photoelectrons printed

mirror diameter

R: Radial distance from shower axis (in shower plane)

```
MIRROR  0  (diam.  10.0m)   X,Y,R..  (  0.0m,   0.0m,   0.0m)  -  Cerenkov density  1.4711E+02 (  1315
 Third pattern has centre displaced by (x)  0.65,  (y)  0.26 grid units
```

→ ↑ grid units ✗

①	②	③
0 0 10 0	2 0 C 0	6 5 0 1
43 9 1 0 0	0 0 8 0 0	0 39 73 35 13
52 51 75 14 0 0	29 14 2 0 C 0	0 0 37 28 270 0
0 28 15 $\boxed{436}$ 33 26 C	69 53 69 12 0 1 0	0 0 0 3 74 22 0
0 4 32 16 0 0	25 14 $\boxed{448}$ 38 32 0	0 14 0 0 24 1
0 0 21 23 0	1 28 21 0 0	0 0 0 0 22
0 0 0 34	0 17 33 0	0 0 0 0

γ-ray source

γ-ray source

γ-ray Source

Method of calculating no. of photoelectrons:
Assume (peak photocathode quantum efficiency) × (mirror reflection efficiency) = 0·12

R:

```
MIRROR  1  (diam.  10.0m)   X,Y,R..  ( 40.0m,   0.0m,  40.0m)  -  Cerenkov density  1.0022E+02 (  1265
 Third pattern has centre displaced by (x)  0.21,  (y)  0.17 grid units
```

degrees ✗

①	②	③
0 0 0 0	0 0 0 0	0 0 0 0
0 0 0 0 0	0 0 0 0 0	0 0 0 0 0
10 6 0 0 0 0	0 0 0 0 0 0	23 8 2 0 0 0
19 15 174 $\boxed{0}$ 0 0 0	12 3 0 0 0 0 0	9 17 160 88 1 0 0
116 152 33 0 1 0	10 136 0 C 0 0	148 64 28 1 0 0
8 5 0 0 0	143 19 3 0 0	28 1 0 0 0
0 5 0 0	7 0 0 0	3 0 0 0

① 928 photoelec
② 916 photoelec
③ 667 photoelec

of expectation $147{\cdot}1 \times \pi \times 5^2 \times 0{\cdot}12 \times 58\%$

$= 804$

(but dense spot may hit or miss!)

If checking again total light reaching mirror, note that 42% of the light falls in gap between the phototubes.

See note opposite

This is just a displaced ~~x~~ version of ①, and numbers differ only because the Poissonian sampling from "expected" numbers is done afresh.

1985 [Feb 27th] Simulating background

Protons & Nuclei

Physics Department,
University of Leeds,
Leeds LS2 9JT

27 Feb 1985

27 Feb '85

Professor N. A. Porter,
Physics Department,
University College,
Belfield,
Stillorgan Road,
Dublin 4
Eire

Dear Neil,

Thank you for your letter, preprints, and large set of shower data. As I am writing to let you know what I am doing about the Cerenkov showers at present, and as I have some important questions about selection of the data, I will not try to make any observations on the nuclearites paper, as I have not yet digested the different treatments.

Just after I rang you about obtaining typical background shower data, I received another set of showers which had been brought over from Dublin by Dick Lamb while I was away, and I have done some work already with those. Notable differences between the two sets of data prompt me to ask some questions relevant to my attempts to provide calculated parameters for comparison.

I am accumulating a set of simulated background showers: protons and nuclei arriving in random positions and with a natural spectrum of energies are simulated, to obtain a scatter diagram of "image width" versus "image length" as seen for such background showers on the actual array of 37 photomultipliers. (I only use events in which the largest signal is in one of the central 7 tubes, so as not to risk a drastic curtailment of the image.) This is well under way, and should be done in another week.

ditto ....

I am not sure whether I am getting quite the right image dimensions, but they are in the right general region. I wonder whether there is some noise in the data (at any rate in the "1 digit = 4 photoelectron"set), so that some of the "1" counts are spurious. Any knowledge of spurious rates? I can probably deduce the rate of spurious signals with reasonable approximation from outlying parts of small events.

Are you proposing to make a large contribution to Stephens's workshop at La Jolla in August?

Finally, In reply to your suggestion of a visit to discuss simulations, some time during the Easter vacation (March 25th to April 18th) or some Monday or Wednesday (with few exceptions, such as April 29th*), would very probably be suitable, if you would like to make a suggestion.

* and March 20.

Yours sincerely,

Michael.

A. M. Hillas

1985 [March 30th] Simulations and Parameter investigations

PROGRESS REPORT ON CERENKOV IMAGE SIMULATIONS

A. M. Hillas

Physics Department, University of Leeds,
Leeds LS2 9JT, England

A full report will be prepared for publication, but this brief summary is being circulated to interested parties involved in the experiment at the Whipple observatory.

Main Points

1. If the results of the Monte Carlo simulations of Cerenkov images of showers are correct, the images of gamma-ray showers have notably different characteristics from proton or nuclear showers, at any rate in the TeV energy range. The present 37-photomultiplier detector system on Mt.Hopkins should be capable of distinguishing individual showers of the two types in most cases.

2. The predictions of the gross image characteristics studied so far do appear to be correct in the case of the random background of proton showers. The predicted characteristics of gamma-ray showers are therefore likely to be correct, although, being of smaller angular extent, they may possibly be more affected by optical imperfections of some type not yet taken into account.

3. The success of specific strategies for classifying individual shower images as being due to gamma-rays (emitted by a source in the centre of the field of view) or not has been examined, using simulated showers.

4. The high-energy particles from Cygnus X-3 have not been shown to be gammas, although they must be uncharged: the Kiel and Soudan experiments detected a high flux of associated muons, suggesting a hadronic nature. The Cerenkov image shapes should be capable of distinguishing between gamma and hadronic showers.

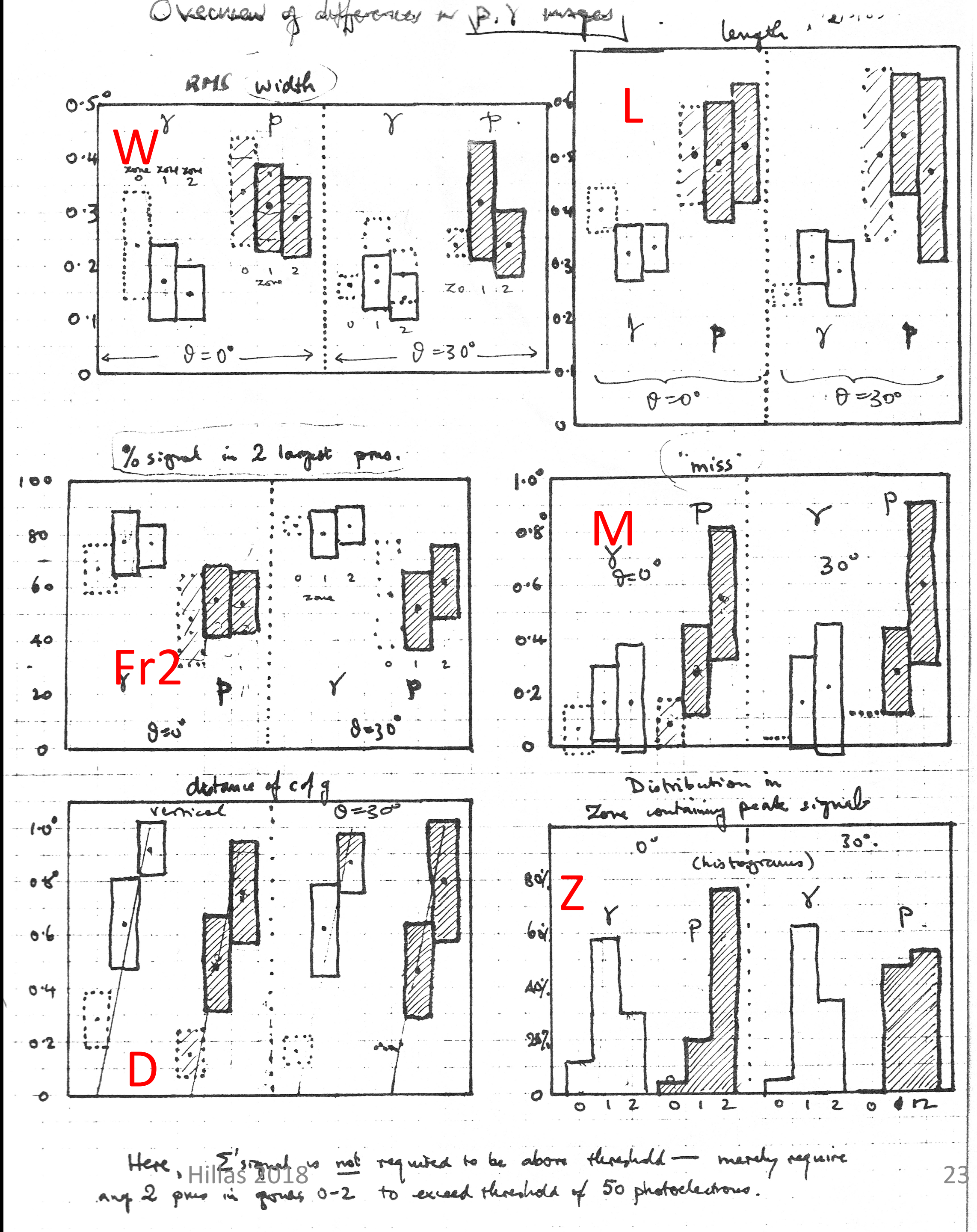
1985 [March 30th] …

Rough overview sketch of Gamma and Proton image simulations.

Vertical and 30 deg, shower incidence.
Zones 0, 1, 2

For each parameter, boxes show +/- 1 sigma range around mean.

W Width
L Length
Fr2 % sig in 2 largest pmts
M Miss
D Distance cog (centroid) from center of fov (degs).
Z Distribution in zone containing peak signals.



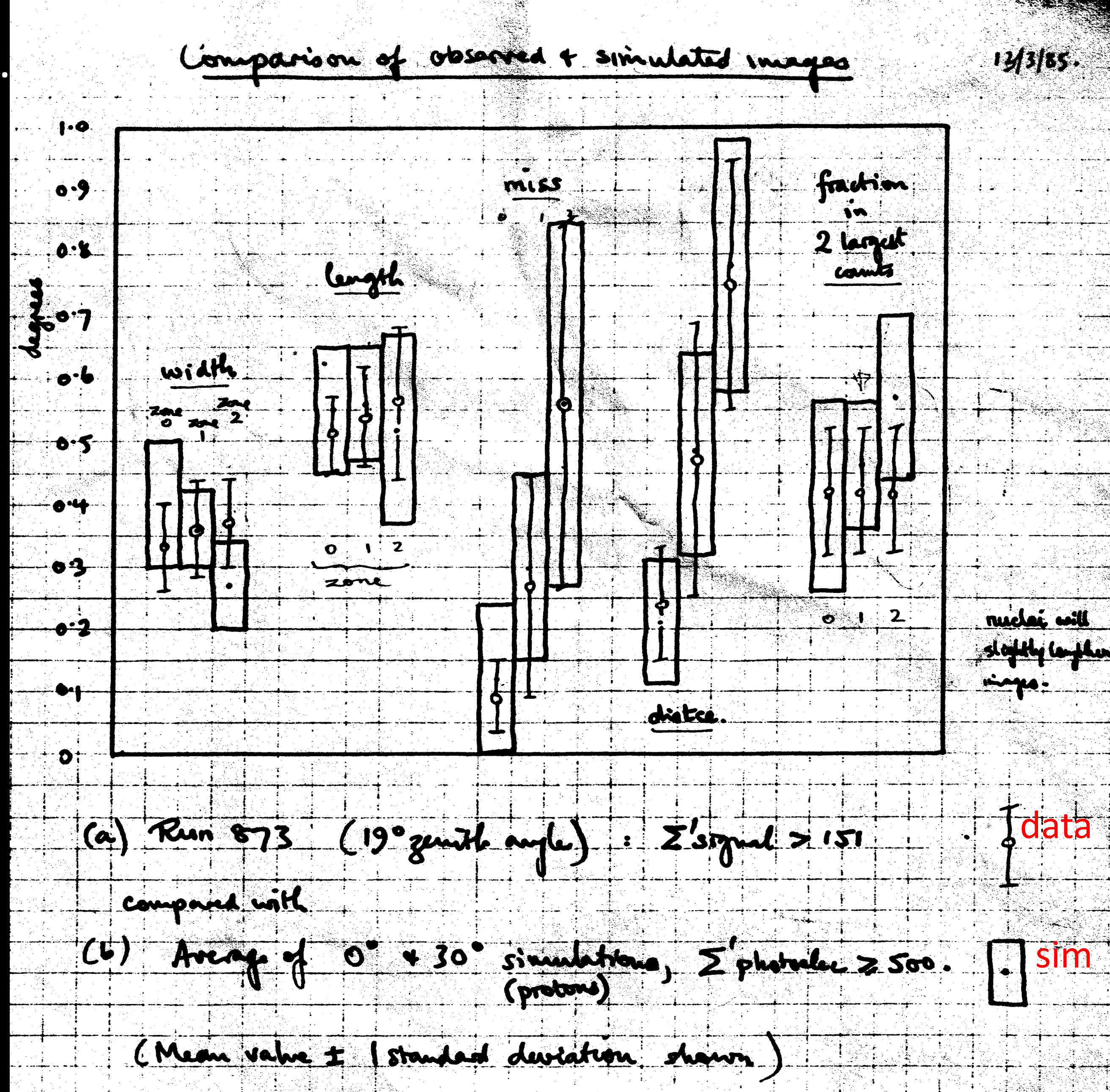
1985 [March 30th] .

Comparison of simulated background proton images
with parameters from observational Run 873

+/- 1 sigma distributions about mean are plotted.

Michael Hillas notes –

Until a sample of showers enriched in gammas can be obtained, this is the best evidence in support of the simulations reproducing the physics of the real situation, hence providing confidence in selection.



1985 [May 11th] Software improvisation & flagging trouble.

(copy ~~sent to~~ N.A.P.)

~~TREVOR~~

THE UNIVERSITY OF LEEDS

Leeds
LS2 9JT
Telephone (0532) 431751

9

(4)

Copy, for information. AMH.

From the Department of Physics

11th May 1985

Dr. D. J. Fegan,
Physics Department,
University College,
Dublin 4.

Dear David,

Thank you again for the tape of shower data. There was no problem in reading the files from tape, although I had some problems in reading and manipulating some of the files because (a) I could not persuade the system to give me more working disk space and often found I could not hold more than one on disk, (b) the Fortran programs kept giving failure messages (probably sorted out now -- connected with record lengths) and I had to write simple Pascal reading and normalising programs (but I have now checked that they give the same eventual image patterns as STEVE1 FORTRAN), and (c) I had assorted problems associated with record lengths. However, I am pretty sure that the patterns I produced were correct. (I can post compressed lists if necessary.)

The results are disturbing. Evidently there are more factors affecting images that remain to be sorted out.

1985 [May 11th]

ZONE 2

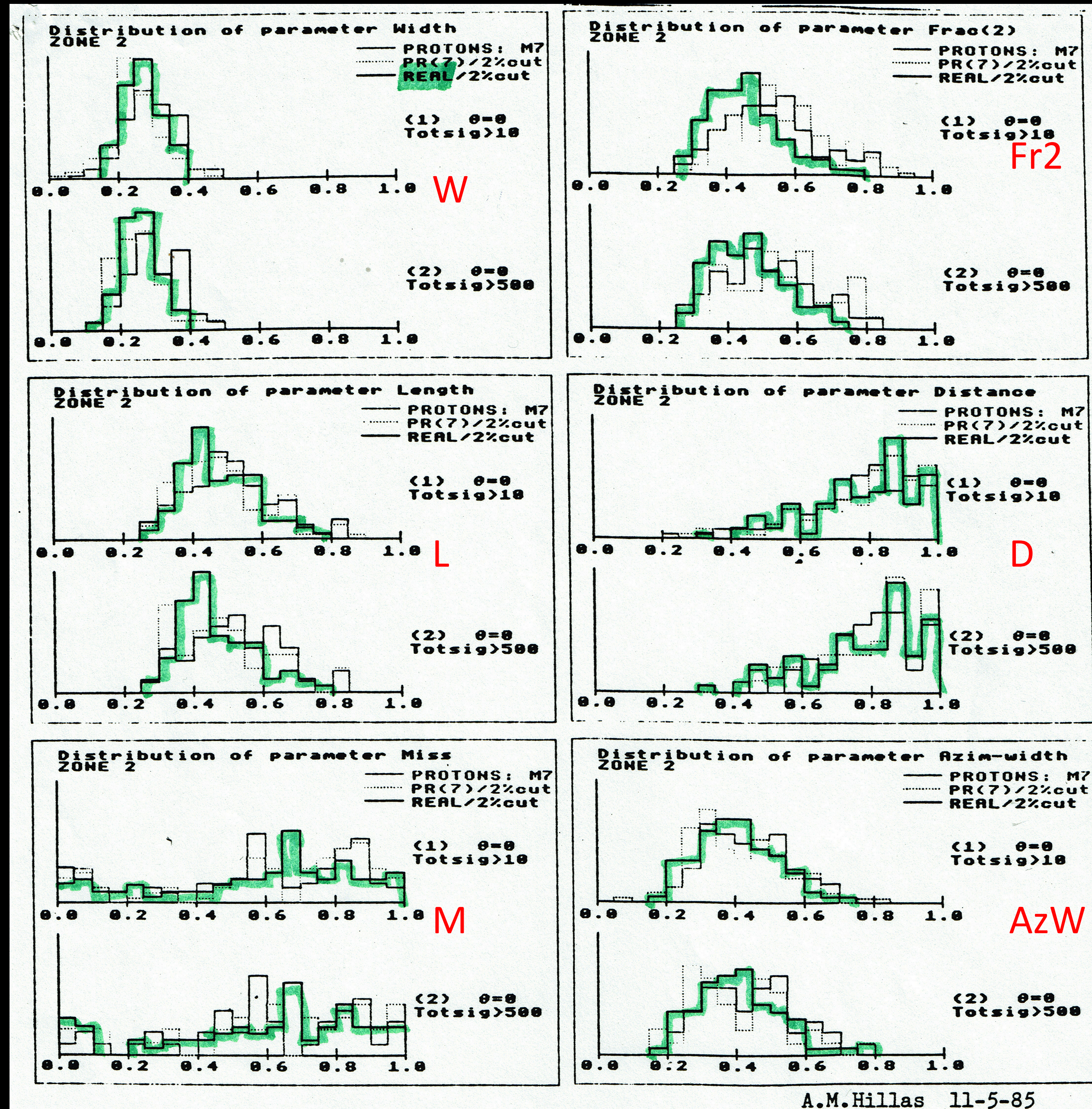
Comparison of REAL data images with simulated proton images - Vertical

SHOWER SEL.
At least 2/19 > 40 pe
TOP: Total sig > 10 pe
BOT: Total sig > 500 pe

TUBE REJ. < 2% of raw total signal eliminated.

Michael Hillas notes –

Concentrated images - (large values Frac(2)) less prominent in REAL than in simulations – tube noise spread ?



1985 [May 11th]

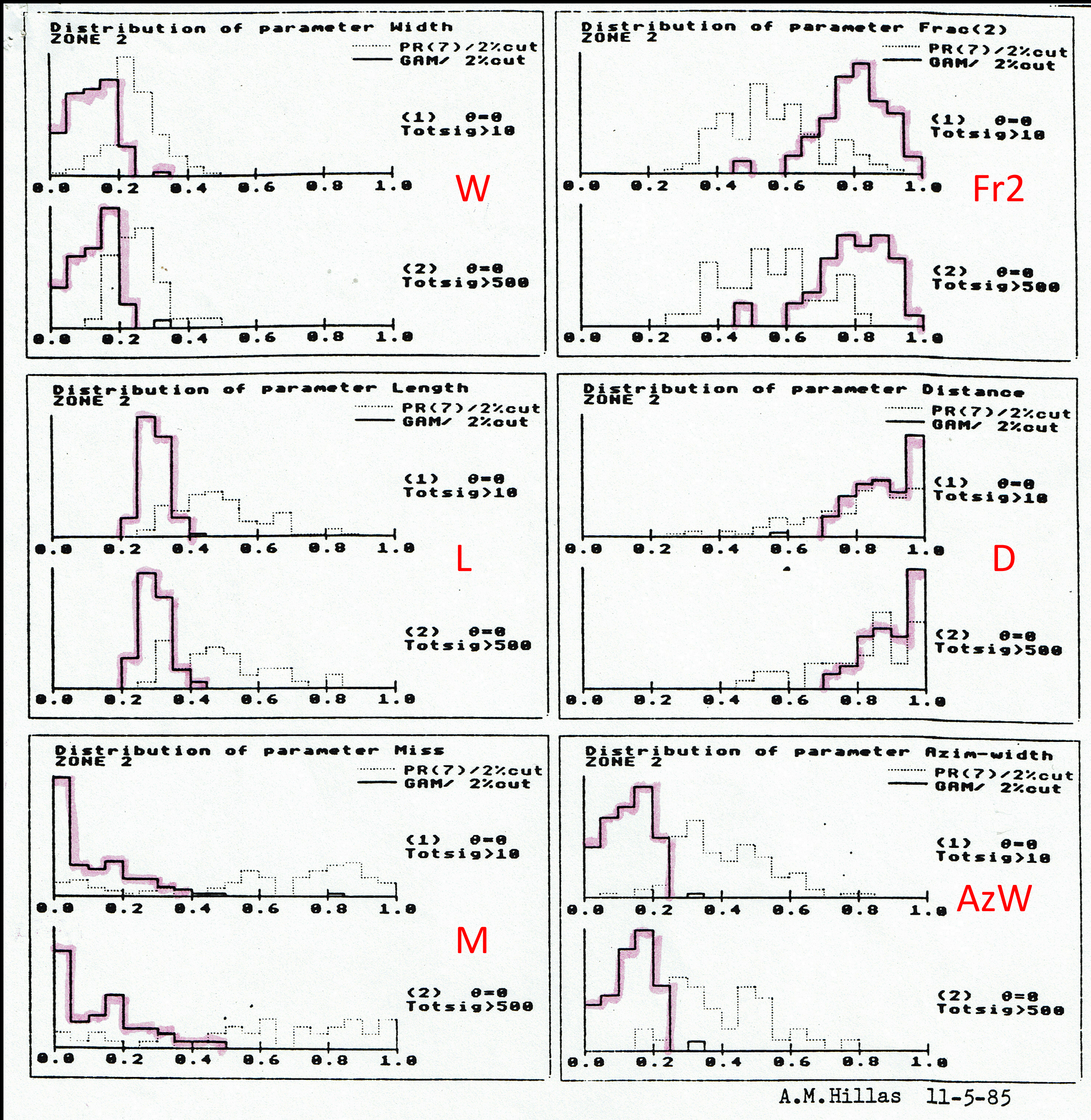
ZONE 2

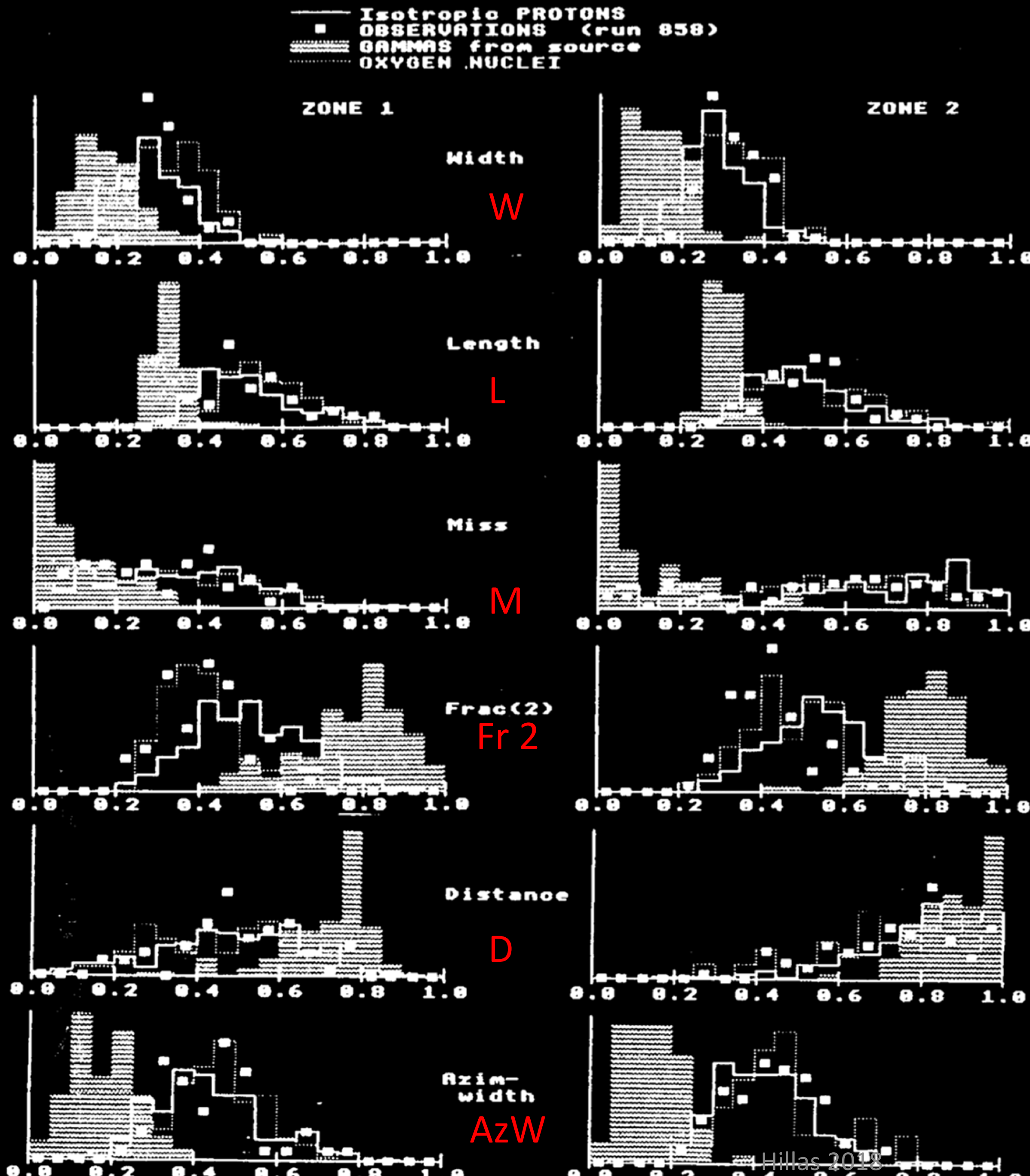
Comparison of SIMULATED GAMMA images with SIMULATED proton images - Vertical

SHOWER SEL.
At least 2/19 > 40 pe
TOP: Total sig > 10 pe
BOT: Total sig > 500 pe

TUBE REJ. < 2% of raw total signal eliminated.

As Michael Hillas happily noted –LARGE separation in image characteristics between simulated protons [$E^{-2.65}$ dE] and center of fov simulated gammas, [$E^{-2.25}$ dE]

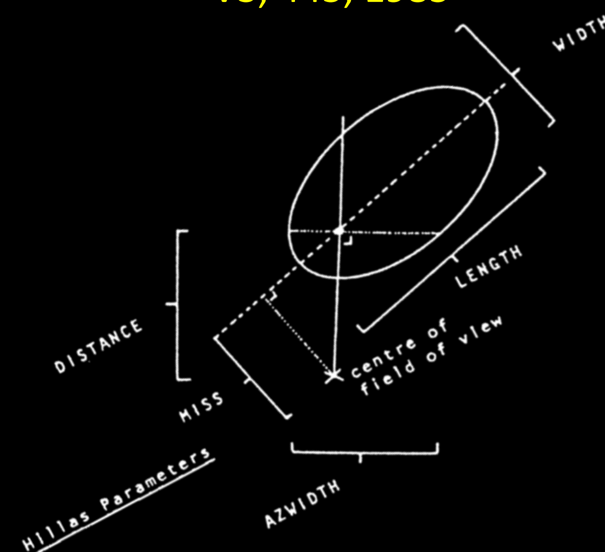




CANONICAL IMAGING PUBLICATION OF Michael Hillas -

"CHERENKOV LIGHT IMAGES OF EAS PRODUCED BY PRIMARY GAMMA RAYS AND BY NUCLEI."

Proc. 19th ICRC, La Jolla V3, 445, 1985



WHIPPLE 1983-1985: Scientific accomplishments - modest.

250 hrs total of high quality exposure. Main sources monitored were Crab Nebula (43 hrs); Cygnus X-3 (101 hrs); Her X-1 (30 hrs); M31 (16 hrs).

Orientation cuts were un-productive, but a simple shape cut was promising.
Frac(2) = $(P_1 + P_2)$ / (Sum over 37) > 0.75

Table 6.2: Crab Nebula [1983-85] observations made with a compactness cut, Frac(2), at a trigger threshold energy of $E_t > 4 \times 10^{11}$ eV.

Exposure	Raw ON	Raw OFF	σ	Cut ON	Cut OFF	σ	Flux ph cm^{-2} s^{-1}
34 hrs	329,169	328,236	+1.1	8415	7709	+5.6	6×10^{-11}

706 excess cut events in 2032 min; ~ 1 event every 3 min

OBSERVATIONS OF THE CRAB NEBULA AT ENERGIES > 4.10^{11}

M.F. Cawley[1], D.J. Fegan[1], K. Gibbs[2], P.W. Gorham[3], R.C. Lamb[4], D.F. Liebing[4], P.K. MacKeown[5], N.A. Porter[1], V.J. Stenger[3], and T.C. Weekes[2].

Proc. 19th ICRC, La Jolla 1985, V1, 131, 1985

WHIPPLE 1983-1985 data … formal Hillas-based analysis

Crab Nebula - Whipple 1983-1985 data. Hillas parameter analysis classifications [A], [B], [C] and [D]. The raw data event populations were [ON] 332,953 and [OFF] 333,671 events respectively. Image parameters calculated factoring in zone and zenith angle dependencies. [After Ken Gibbs.]

SELECTION	[A]	[B]	[C]	[D]
ON source cut event count total	630	766	1183	394
OFF source cut event count total	504	650	1057	314
Count differences (2343 min. obs.)	126	116	126	80
Significance(σ)	3.74	3.08	2.66	3.01

[A] Four or more of *Length, Width, Miss, Distance, Azwidth, Frac(2);*
[B] Two or more of *Length, Frac(2), Azwidth;*
[C] Two or more of *Length, Width, Azwidth;*
[D] Four or more of *Length, Width, Miss, Frac(2) or Azwidth.*

Showers satisfying the Frac(2) selection criteria alone, produced a greater statistical significance of $4.56\,\sigma$ a full $1.0\,\sigma$ less than the detection level significance published at the La Lolla meeting which was also based on the Frac(2) parameter cut, but subjected to different image cleaning and preparation.

Very discouraging

A HILLAS
joining Whipple
To: David Fegan,
Reply-To: A HILLAS

2nd July 2014

Dear David,

....

I am still unclear about the main reason for it taking so long to get a positive gamma signal from the Crab, based on these parameters (i.e. in Ken Gibbs's work).
(After a year or two Trevor despatched Dick Lamb to Leeds, to find what was wrong with my programs. He did not locate a problem there, and I remember Neil Porter at a Durham meeting saying we should assume they were right.)
One suggestion made some years later was that things went right when we changed to commercial pulse-handling circuits, but Trevor disagreed.

Regards,

Michael Hillas

1983-1987 data

Hillas Parameterisation of Whipple Crab data with 37 pixel camera.

Eventually, based on a combination of 183 data scan pairs, both shape & orientation were successfully employed in the establishment of a 7.59 sigma effect.

91 hours exposure on Nebula, E = 0.6 TeV with a detection rate of 6.4 gammas hr^{-1}

7 years after construction of the Whipple imager commenced.

Table 1: Hillas parameterization of ON/OFF data - Whipple observations (by individual season and combined) of Crab Nebula, November 1983 to November 1987.

EPOCH	Winters '83 to '85	Winter '86-'87	Oct&Nov '87	Σ
No. of run pairs	70	53	60	183
Raw [ON]	255711	220530	220023	696264
Raw [OFF]	255310	220690	219627	695627
Difference	401	-160	396	637
Significance(σ)	0.56	-0.24	0.60	0.54
Excess % of [ON]	0.16	-0.07	0.18	0.09
Frac(2) [ON]	1468	4323	5764	11555
Frac(2) [OFF]	1231	4109	5452	10792
Difference	237	214	312	763
Significance(σ)	4.56	2.33	2.95	5.10
Excess % of [ON]	16.14	4.95	5.41	6.60
Azwidth [ON]	896	2477	3469	6842
Azwidth [OFF]	797	2235	3008	6040
Difference	99	242	461	802
Significance (σ)	2.41	3.53	5.73	7.07
Excess % of [ON]	11.05	9.77	13.29	11.72
Combination 4/5 [ON]	394	1169	1728	3291
Combination 4/5 [OFF]	314	1010	1379	2703
Difference	80	159	349	588
Significance(σ)	3.01	3.41	6.26	7.59
Excess % of [ON]	20.3	13.6	20.2	17.87

Table 2: Crab Nebula : Combined datasets for the 1983-85, 1986-1987 and October/November 1987 observations. Significances for raw data, five individual parameters and a combination of any 4 from 5 of the parameters

Raw	Width	Length	Azwidth	Frac-2	Miss	Combination [4/5]
0.54σ	4.30σ	3.16σ	7.07σ	5.10σ	3.33σ	7.59σ

Finally, in 1989

CANONICAL Crab Nebula detection

– with the 37 pixel camera a 9 sigma detection of the Crab Nebula was achieved, based on Azwidth cut, with $E_0 > 0.7$ TeV.

175 ON/OFF data pairs taken exclusively during 1986-1988 with a very stable camera setup - Hillas parameterisation resulted in an 8.91 standard deviation. 14.2 excess events hr^{-1}
$F = 1.8 \times 10^{-11}$ ph cm^{-2} s^{-1}

Azwidth (Zones 1&2) rejects > 98% of background signal content.

Excess candidate Gamma-ray events in the ON source data of order 15% of total OFF source cut data.

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. Weekes,[1] M. F. Cawley,[2] D. J. Fegan,[3] K. G. Gibbs,[1] A. M. Hillas,[4] P. W. Kwok,[1] R. C. Lamb,[5] D. A. Lewis,[5] D. Macomb,[5] N. A. Porter,[3] P. T. Reynolds,[1,3] and G. Vacanti[5]

Received 1988 August 1; accepted 1988 December 9

Ap J 342. 379, July 1, 1989

Table 8.1: Crab Nebula [1986-1988] image selection based on Azwidth cut discrimination, Weekes et al., [202]

Epoch	ON	OFF	All(%)	Diff.	OFF(%)	Significance (σ)
No Selection (Raw or All)						
1986-1988	652,974	651,801	100.0	+1173	0.2	+1.03
Azwidth Selection						
1986-1988	9092	7929	1.2	+1163	14.7	+8.91

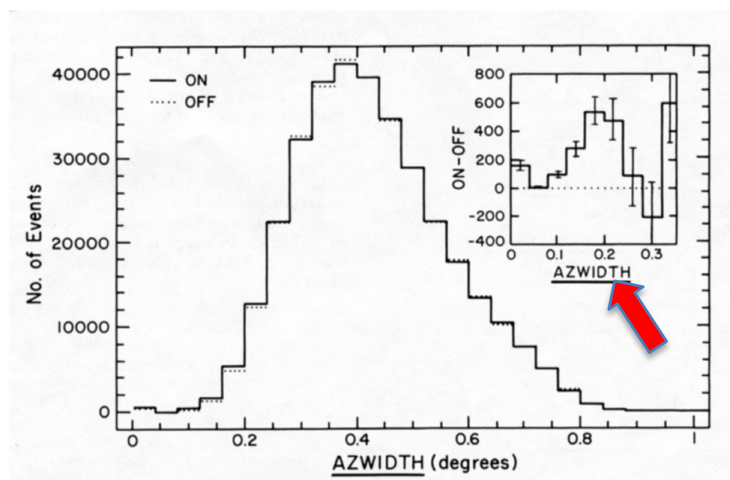


Figure 8.7: Crab Nebula: Distribution of "all or raw" ON and OFF Azwidth parameters ($\theta_z < 30°$) for image zones 1 and 2 combined, with the numeric differences between the two γ-ray Azwidth distributions shown in the inset, after Weekes et al., [202].

1989 … COLLABORATION MEETING, MAYNOOTH, IRELAND

BACKTRACKING …

1986 - INHERENT high resolution attainable with a 10m reflector, Hillas & Patterson

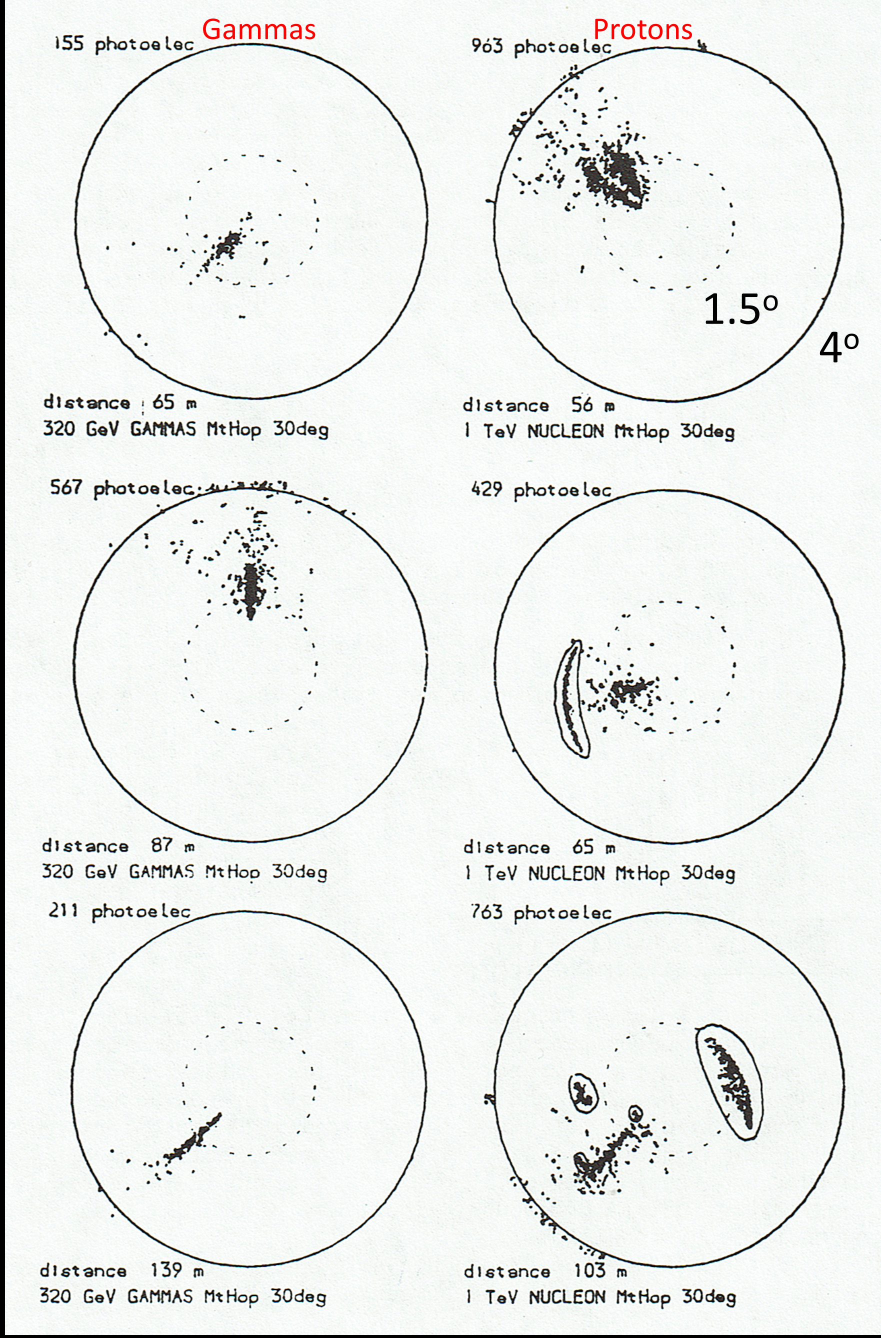
NATO DURHAM WS p243 - [Editor K.E.Turver]

Making the case for camera configurations of finer pixel density, despite the cost implications – 37, 61, 91, 127, 169, 217 …. Photon and Proton simulations in 4° fov, 10m displaying every photoelectron. Light from muons ringed.

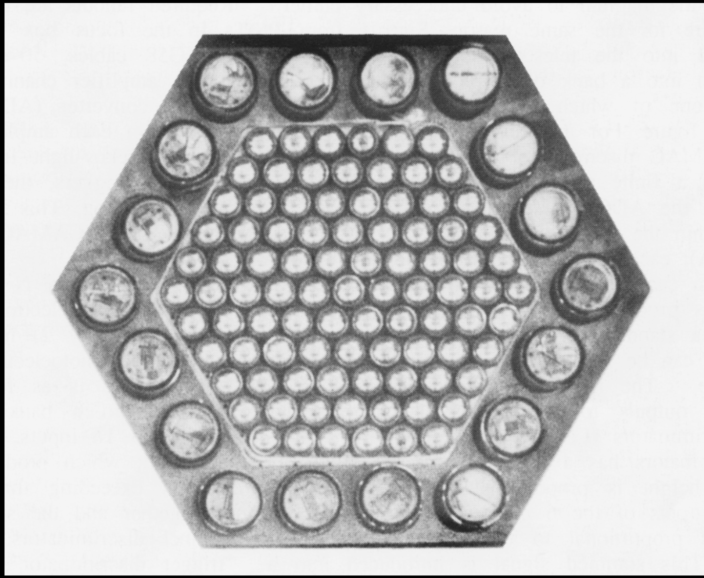
1986 HERCULES – A new instrument for TeV Astronomy, Weekes, Lamb & Hillas

NATO DURHAM WS p235 - [Editor K.E.Turver]

Improving sensitivity of Whipple's existing 10m instrument through construction of a 2nd 10m class reflector … 193 pixel cameras [inner 169 tubes with with separation of 0.25 degrees] with camera fov 4.75 deg.].



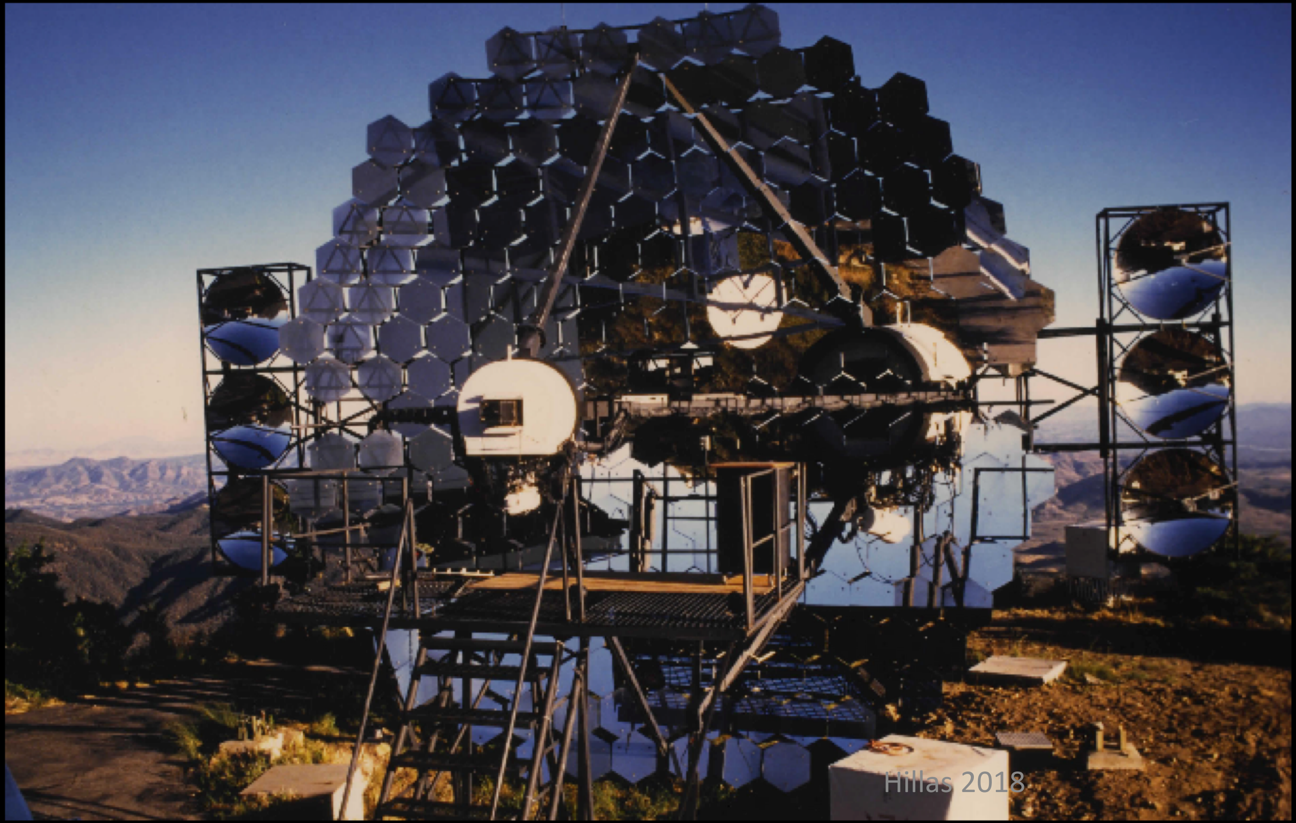
1988 - Whipple upgraded to a 109 pixel camera based on detailed analysis of noise in the PMTs by Michael Hillas.



Inner core of 91 x 29 mm tubes set in 2.5 degrees hexagonal close packed array, outer 18 tubes of 50 mm.

To infill the complete 3.5 degree fov with 271 tubes, was an obvious aspiration, but was unrealistic in terms of cost.

Out-riders … 6 x 1.5 m mirrors – an independent trigger.



Whipple's
High Resolution Camera
(HRC)
inaugural operation
April 1988

1988–1989 & 1989-1990 : HRC Crab Nebula observations.

New Gamma-ray domains evaluated for the HRC by Michael Hillas from his Simulations.

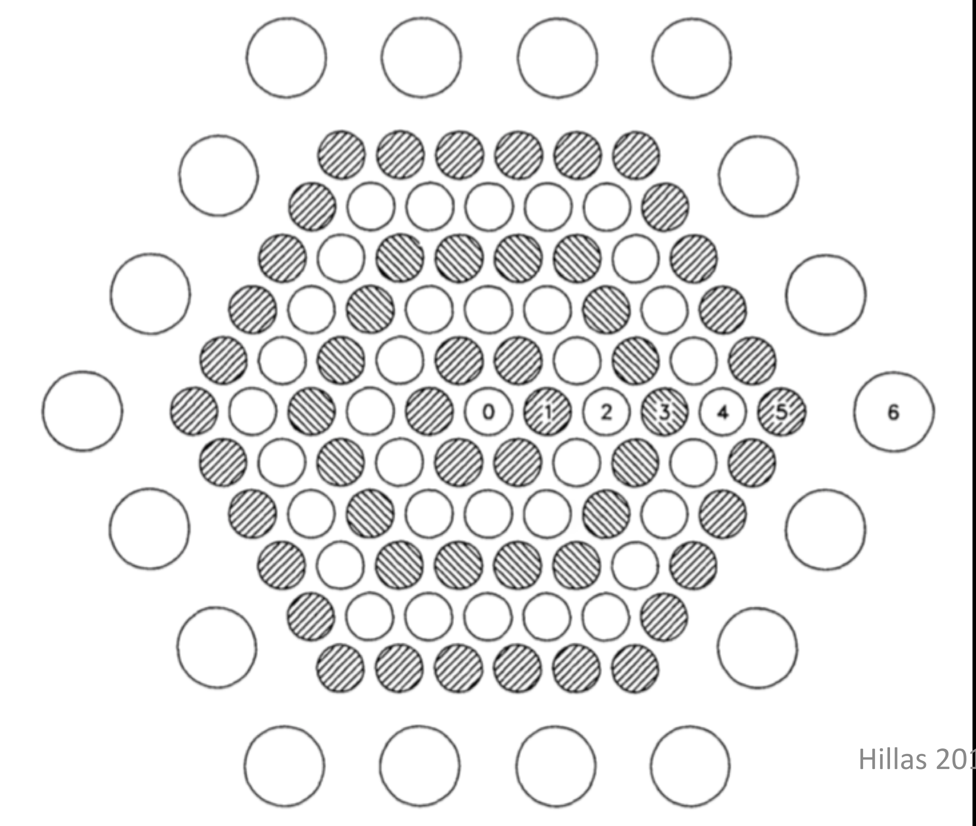
FILTERING PERCENTAGES

Test	Filter Criterion	Percentage Removed
Trigger:	2 pixels not greater than 40 p.e.	1.0
Size:	Total signal < 1 p.e.	1.1
Center:	Zone 0 and 1 omitted	7.0
Outside:	Zone 6 omitted	13.2
Cosmic ray:	Conc = 1.0	1.2
Total removed by filtering		23.5

PARAMETER CUTOFFS

Zone	1	2	3	4	5	Factor, k
Width	<0.26	0.16	0.15	0.15	0.18	0.18
Length	<0.36	0.35	0.34	0.34	0.34	0.13
Miss	<0.08	0.08	0.08	0.08	0.08	0.00
Conc	>0.42	0.41	0.42	0.45	0.48	1.00
Azwidth	<0.22	0.19	0.17	0.15	0.15	0.13

NOTE.—$P(z) = P(0) - [k(\sec(z) - 1)]$, where z = zenith angle.



K-factors for Zenith angle scaling of Hillas parameters, Zones 1 through 5

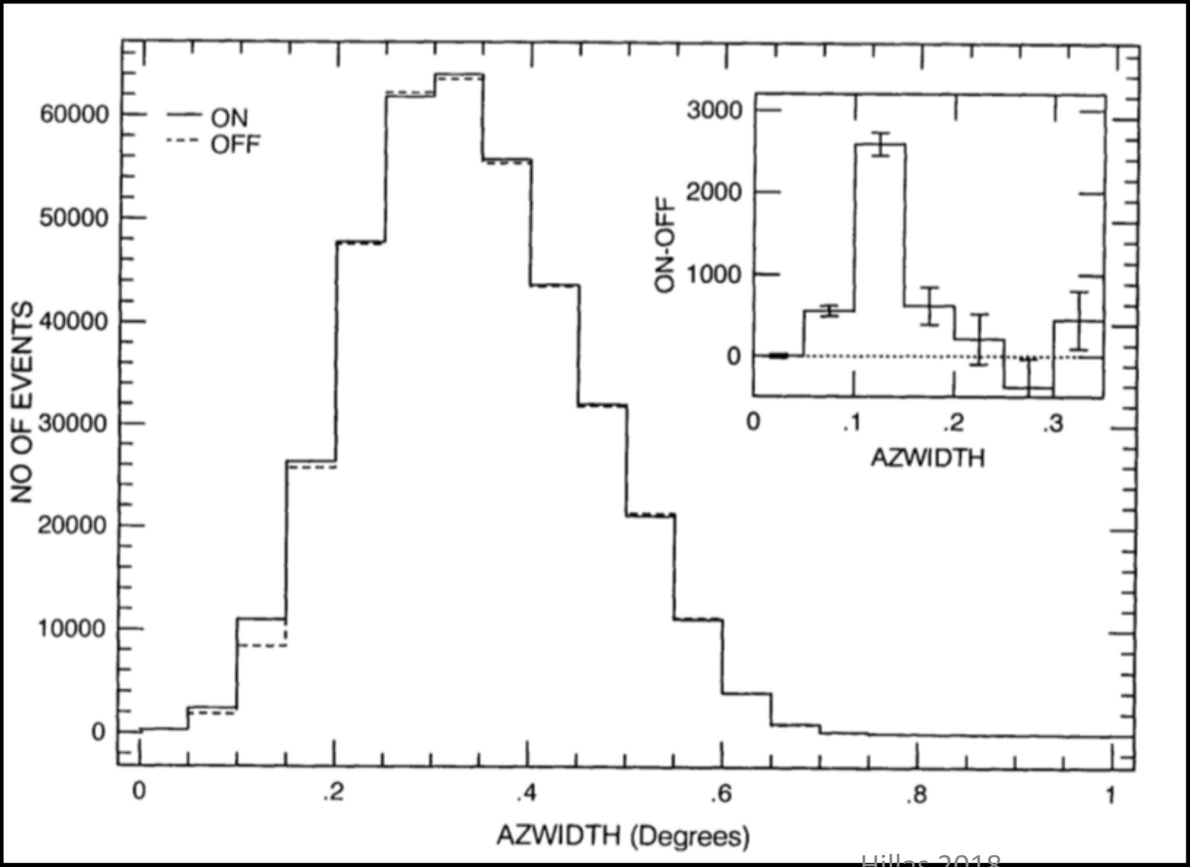
New Gamma-ray selection algorithms applicable only in Zones 2,3,4,& 5 i.e. max tube signal for each image must be in one of these zones.

THE ASTROPHYSICAL JOURNAL, 377:467–479, 1991 August 20

GAMMA-RAY OBSERVATIONS OF THE CRAB NEBULA AT TeV ENERGIES

G. VACANTI,[1,2] M. F. CAWLEY,[3] E. COLOMBO,[4,5] D. J. FEGAN,[6] A. M. HILLAS,[7] P. W. KWOK,[4,8] M. J. LANG,[4,6] R. C. LAMB,[1] D. A. LEWIS,[1] D. J. MACOMB,[1,9] K. S. O'FLAHERTY,[6] P. T. REYNOLDS,[1,4,6,10] AND T. C. WEEKES[4,10]

Received 1990 December 7; accepted 1991 March 1



5.1 sigma Raw data excess

20.0 sigma Azwidth based detection

107 excess events hr^{-1}

Flux 7.0×10^{-11} ph cm^{-2} s^{-1} from within the Nebula

No evidence of 33 ms Pulsar periodicity.

On-axis source angular resolution demonstrated to be +/- 0.1 degrees

Observed Excesses as a Function of Parameter and Zone

Parameter	Zone 2	Zone 3	Zone 4	Zone 5	Zone 2–5
Width					
ON	7098	9152	12224	24996	53470
OFF	6602	7801	11025	24497	49925
Diff.	+496	+1351	+1199	+499	+3545
Sigma	+4.2	+10.4	+7.9	+2.2	+11.0
Length					
ON	13108	22272	32687	36790	104857
OFF	12384	20714	31623	36584	101305
Diff.	+724	+1558	+1064	+206	+3552
Sigma	+4.5	+7.5	+4.2	+0.8	+7.8
Miss					
ON	5670	6586	6108	5918	24282
OFF	5286	5845	5539	5698	22368
Diff.	+384	+741	+569	+220	+1914
Sigma	+3.7	+6.6	+5.3	+2.0	+8.9
Conc					
ON	5918	9614	12642	19253	47427
OFF	5407	8316	11552	18514	43789
Diff.	511	1298	1090	739	3638
Sigma	+4.8	+9.7	+7.0	+3.8	+12.0
Azwidth					
ON	4040	4901	3599	2082	14622
OFF	3478	3475	2588	1848	11389
Diff.	+562	+1426	+1011	+234	+3233
Sigma	+6.5	+15.6	+12.9	+3.7	+20.0

Spectacular response

109 pixel camera

Exposure time
1808 min
65 x 28 m scans

107 excess
gammas hr^{-1}

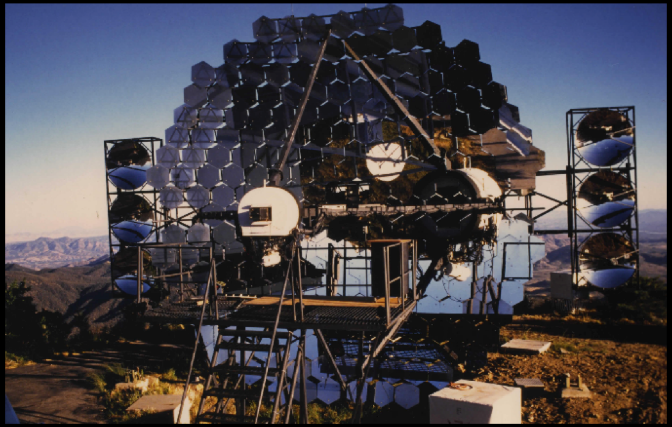
Coll Area
4.2×10^8 cm^2

S/N improvement
of 3 to 4 over
37 pixel camera

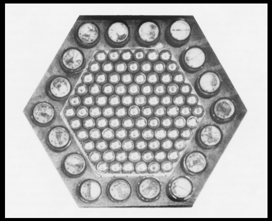
0.4 to 4.0 TeV
Energy range

Independent & 2/91 tube Trigger Modes: Crab Nebula, 1989-1990

	Independent Trigger		2/91 HRC Trigger		Sum Total	
	Raw	Azwidth	Raw	Azwidth	Raw	Azwidth
On	125,665	930	100,968	6,784	226,633	7,714
Off	125,607	702	99,608	5,858	225,215	6,560
Diff.	+58	+228	+1,360	+926	+1,418	+1,154
σ	+0.12	+5.64	+3.04	+8.24	+ 2.11	+9.66



IT requires – 3/4 > threshold in coincidence.
singles rates 1 kHz.
Integrates light across full fov and is biased towards BROAD showers.



10 m trigger, 2f pixel coincidence - trigger bias towards NARROW showers that Azwidth picks out at analysis stage.

Consistency check on 38 data pairs.

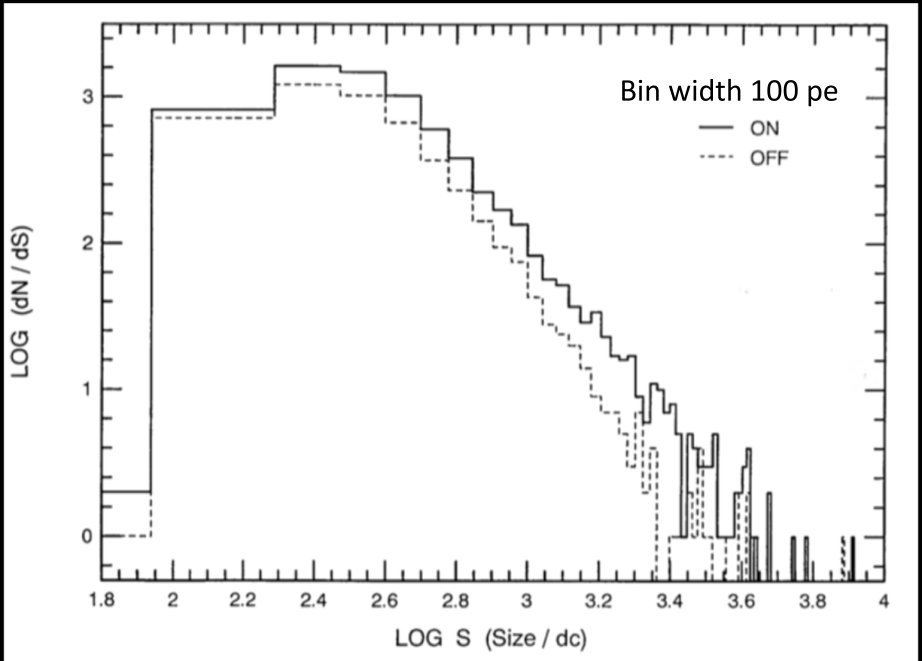
IT trigger vetos HRC, so no double-triggers

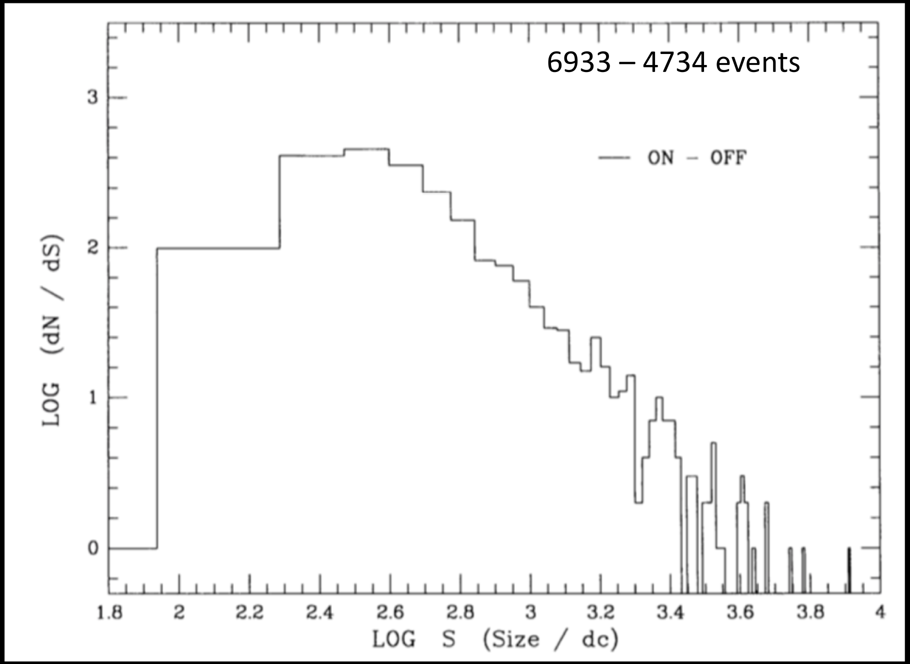
No bias in 2/91 trigger system since 5.64 sigma signal observed in Azwidth selected IT trigger data.

So, gradually … REAL SCIENCE BEGAN TO EMERGE -

Hillas MCS employed - linking integrated image event sizes (photoelectron summation) with a primary Gamma-ray spectrum.

Events constrained to Azwidth < 0.16 deg and Distance values between 0.68 and 0.95 deg. Usefull dynamic range of energy spans 0.4 to 4 TeV. [Diff index -2.4 +/- 0.1].



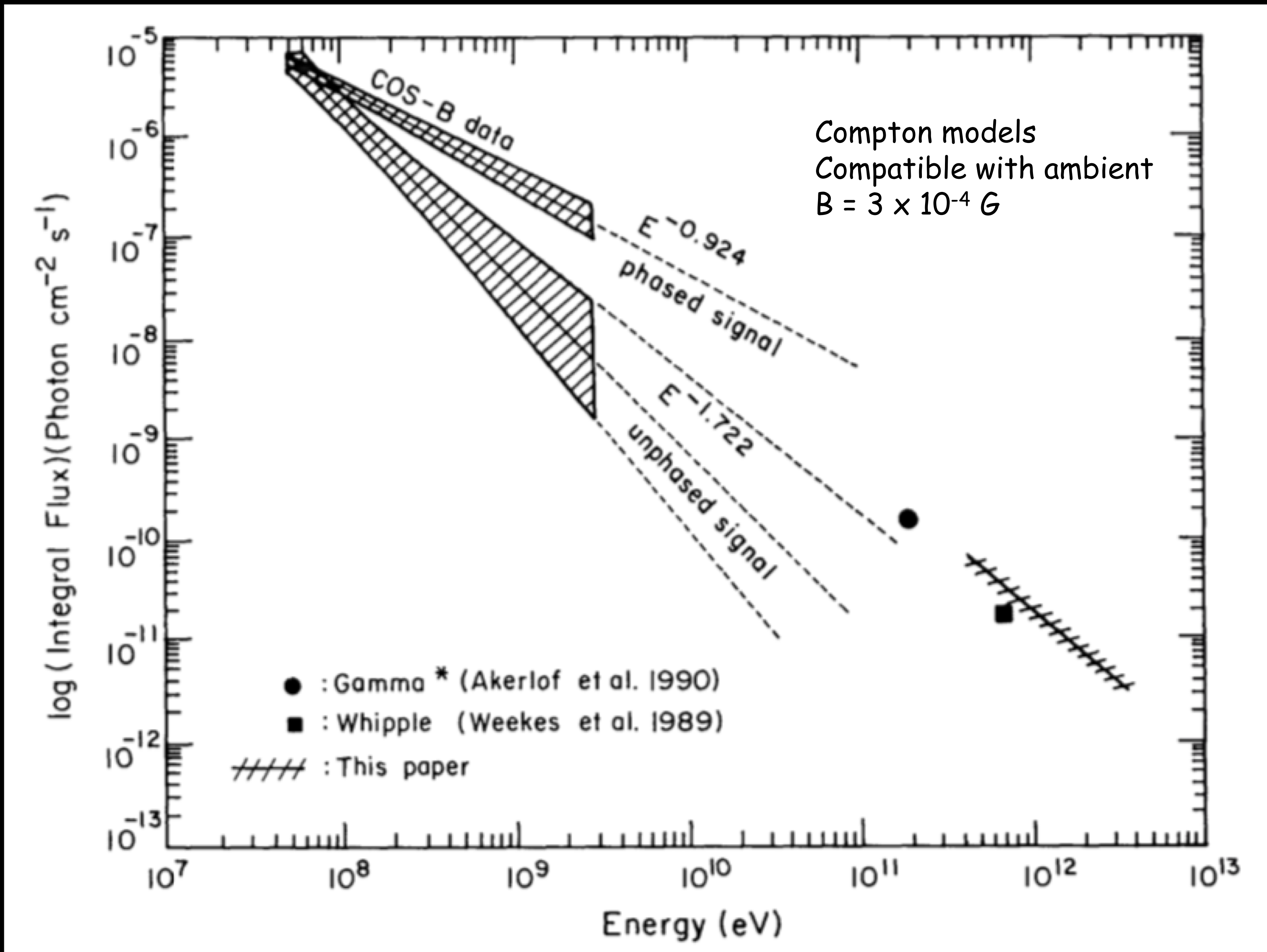


(ON-OFF) difference clearly flatter than OFF distribution in size. [Diff index of background -2.7].

Best estimate of source spectrum: $N(E) \times dE = 2.5 \times 10^{-10} (E/0.4\ \text{TeV})^{-2.4+/-0.3}$ ph $cm^{-2}\ s^{-1}\ TeV^{-1}$
… above 2 TeV excess is 8 sigma significance; above 4 TeV excess is 3.2 sigma.

Compton model best fit to the quoted spectrum?

EXPERIMENTAL integral photon flux Crab Nebula and pulsar, c 1990.



THE ASTROPHYSICAL JOURNAL, 503:744–759, 1998 August 20

THE SPECTRUM OF TeV GAMMA RAYS FROM THE CRAB NEBULA

A. M. HILLAS,[1] C. W. AKERLOF,[2] S. D. BILLER,[1,3] J. H. BUCKLEY,[4,15] D. A. CARTER-LEWIS,[5] M. CATANESE,[5] M. F. CAWLEY,[6] D. J. FEGAN,[7] J. P. FINLEY,[8] J. A. GAIDOS,[8] F. KRENNRICH,[5] R. C. LAMB,[9] M. J. LANG,[12] G. MOHANTY,[5,13] M. PUNCH,[7,10] P. T. REYNOLDS,[4,10] A. J. RODGERS,[1] H. J. ROSE,[1] A. C. ROVERO,[14] M. S. SCHUBNELL,[2] G. H. SEMBROSKI,[8] G. VACANTI,[4,11] T. C. WEEKES,[4] M. WEST,[1] AND J. ZWEERINK[5]

Received 1997 July 10; accepted 1998 March 26

ABSTRACT

The spectrum of gamma rays from the Crab Nebula has been measured in the energy range 500 GeV–8 TeV at the Whipple Observatory by the atmospheric Cerenkov technique. Two methods of analysis that were used to derive spectra, in order to reduce the chance of calibration errors, gave good agreement, as did analysis of observations made with changed equipment several years apart. It is concluded that stable and reliable energy spectra can now be made in the TeV range. The spectrum can be represented in this energy range by the power-law fit, $J = (3.20 \pm 0.17 \pm 0.6) \times 10^{-7} \times (E/1\ \mathrm{TeV})^{-2.49 \pm 0.06 \pm 0.04}\ \mathrm{m^{-2}\ s^{-1}\ TeV^{-1}}$, or by the following form, which extends much better to the GeV domain: $J = (3.25 \pm 0.14 \pm 0.6) \times 10^{-7} E^{-2.44 \pm 0.06 \pm 0.04 - 0.151 \log_{10} E}\ \mathrm{m^{-2}\ s^{-1}\ TeV^{-1}}$ (E in TeV). The integral flux above 1 TeV is $(2.1 \pm 0.2 \pm 0.3) \times 10^{-7}\ \mathrm{m^{-2}\ s^{-1}}$. Using the complete spectrum of the Crab Nebula, the spectrum of relativistic electrons is deduced, and the spectrum of the inverse Compton emission that they would generate is in good agreement with the observed gamma-ray flux from 1 GeV to many TeV, if the magnetic field in the region where these scattered photons originate (essentially the X-ray–emitting region, around 0.4 pc from the pulsar) is $\sim$16 nT (160 μG), in reasonable agreement with the field deduced by Aharonian & Atoyan. If the same field strength were present throughout the nebula, there would be no clear need for an additional radiation source in the GeV domain such as has recently been suggested; the results give an indication that the magnetic field is well below the often-assumed equipartition strength (35–60 nT). Further accurate gamma-ray spectral measurements over the range from 1 GeV to tens of TeV have the potential to probe the growth in the magnetic field in the inner region of the nebula.

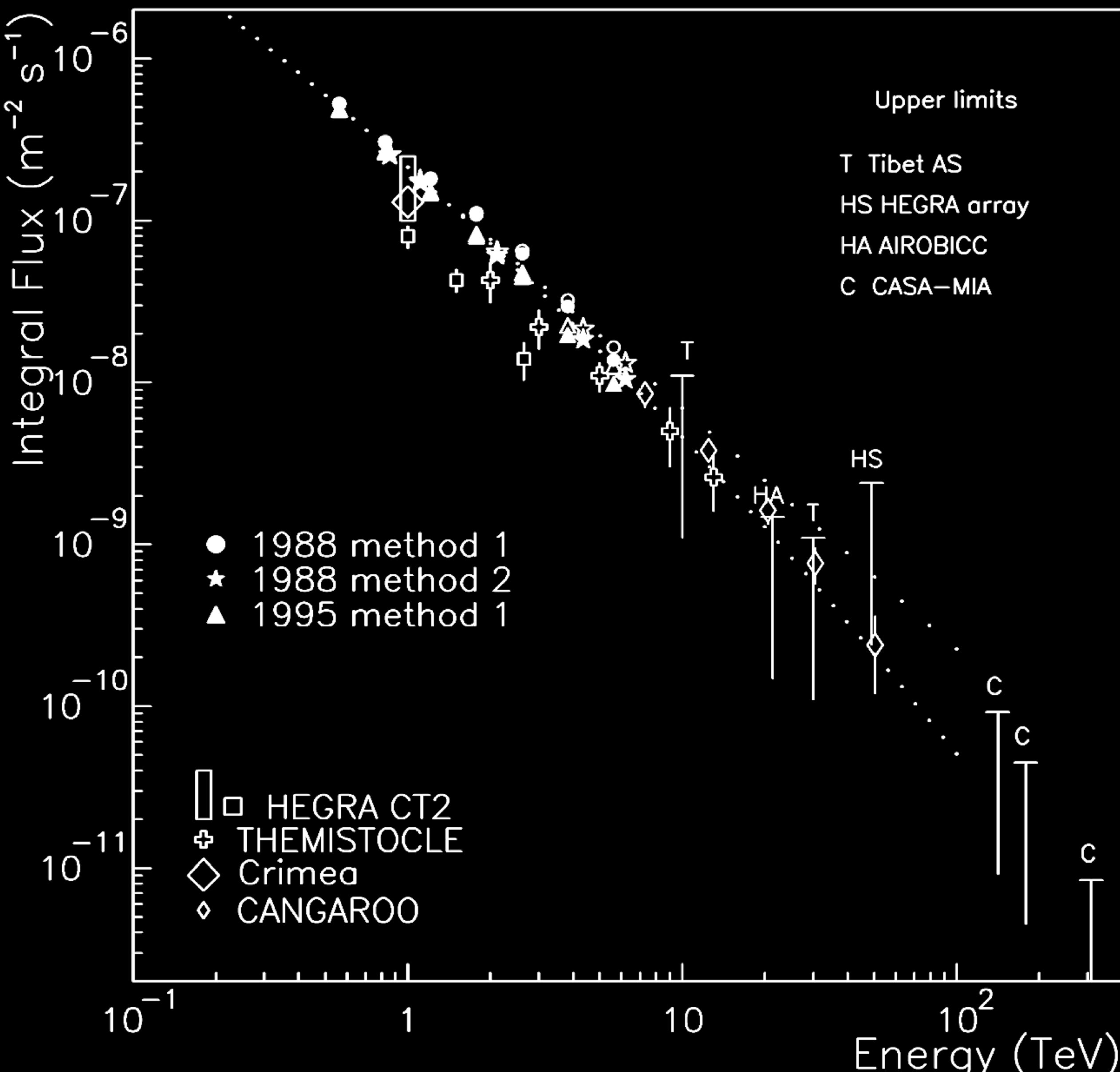
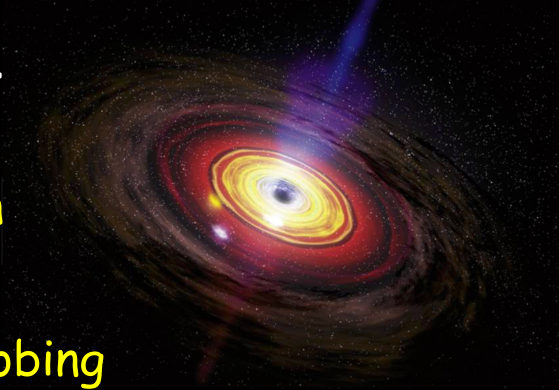


FIG. 2.—Integral flux of photons from Crab Nebula obtained by various workers. *Upper dotted line:* Power-law fit to the Whipple points [i.e., log (flux) is linear in log *E*]; *lower dotted line:* quadratic fit in log *E.*

Leeds, sometime in late 1990's, Dick Lamb's retirement.

TeV LEGACY – some of the stuff of this meeting.



Hundreds of galactic and extra-galactic sources populate an amazingly bright and diverse Cosmos at TeV energies.

Ground based techniques contributing to investigation & probing of particle acceleration mechanisms in violent astrophysical environments.

A rich observational source harvest, stimulating theorists to explain acceleration mechanisms and source dynamics.

Few contributors have been as influential in both the experimental and theoretical aspects of the TeV discipline as has Michael Hillas. His style is beautifully epitomised in his 2013 review of the early days, written in a most self-effacing manner by the master whom we celebrate here.

Evolution of ground-based gamma-ray astronomy from the early days to the Cherenkov telescope arrays

A.M. Hillas

School of Physics and Astronomy, University of Leeds, Leeds LS2 9JK, UK

What a collaborator, thank you Michael.