Michael Hillas

Particle physics and cosmic rays

Thanks to Alan Watson for helping me recall the past
Thanks to Jim Hinton for organizing this meeting

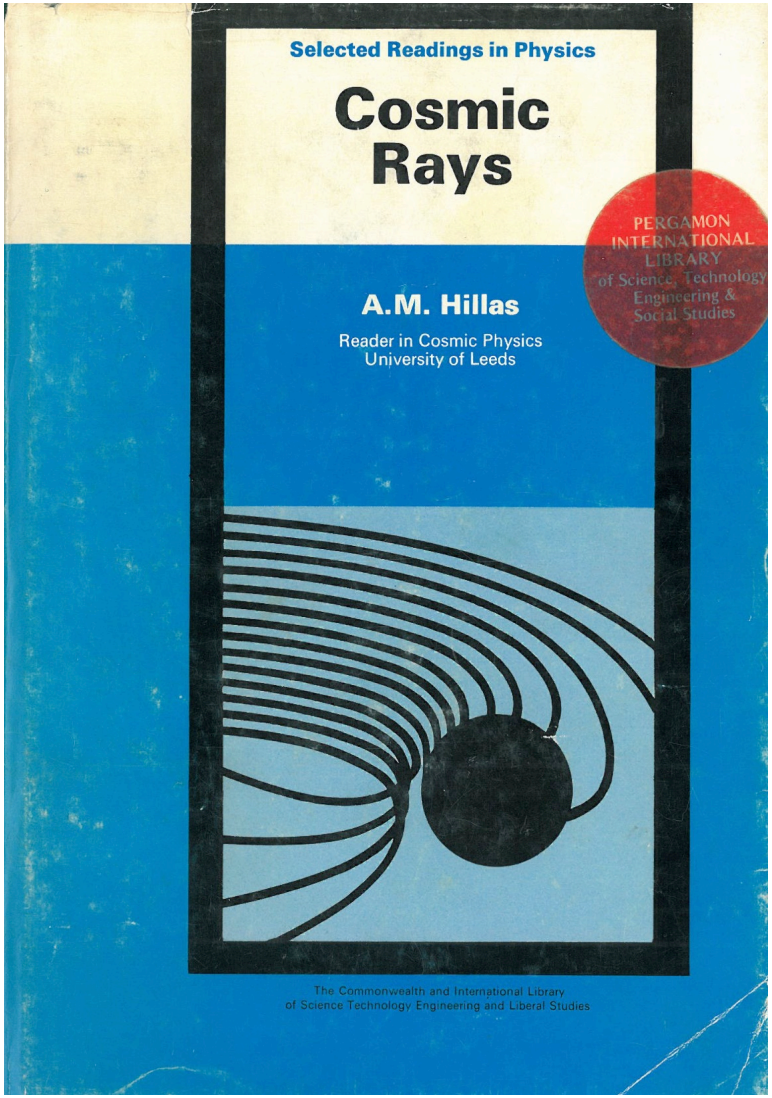
Outline

- *Cosmic Rays,* A.M.H., Pergamon Press, 1972
- 1976-78: Leeds/Bartol I
- 1981: Hillas splitting algorithm
- 1985-1990: Leeds/Bartol II
- 2005: Second Galactic population
- 2016: Last meeting with AMH

1972

Cosmic Rays

- 9 chapters in 132 pages
  - A concise overview of all aspects
- Includes reprints of 16 foundational papers, e.g.
  - Clay, E-W effect
  - Auger, EAS
  - Lattes et al., π discovery
  - Fermi, 1949 acceleration
  - Parker, solar modulation



1972

Average shower profile from cuts at constant intensity (B.F.T.)*

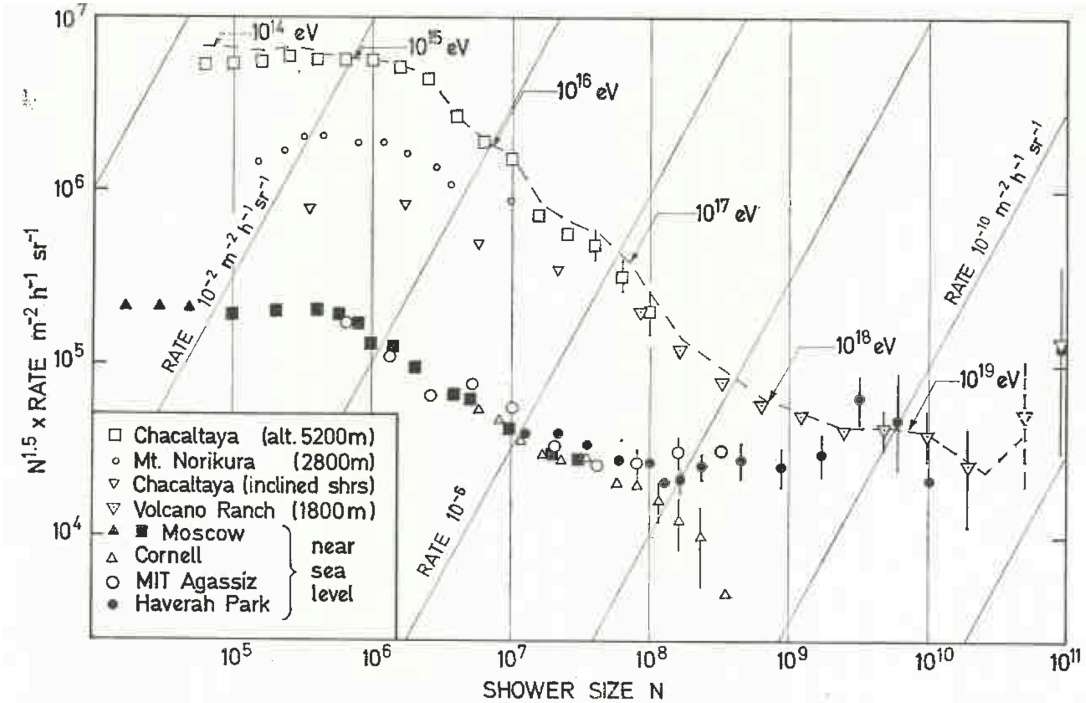


FIG. 24. Rate of observing near-vertical air showers of more than N particler near sea level, and at high altitudes. The dashed line represents the envelope of all such curves. The "inclined" Chacaltaya showess shown have passed through the same amount of air as the vertical showers at Volcano Ranch.

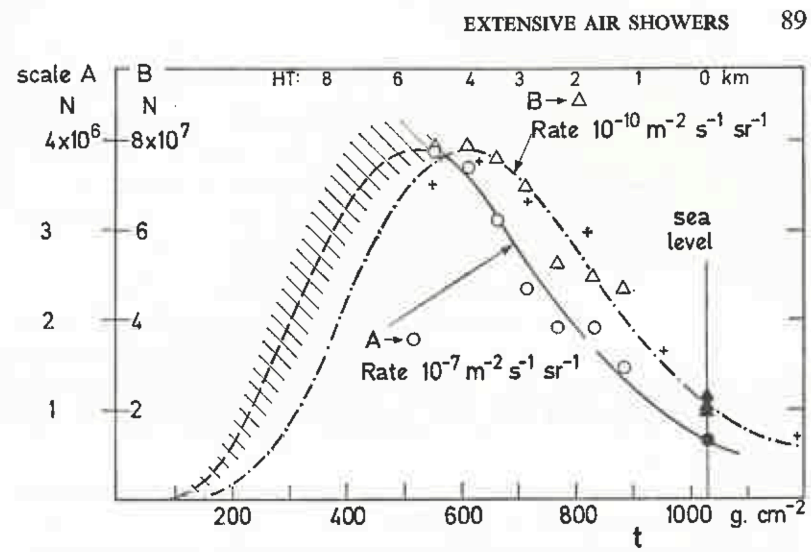


FIG. 23. Number of particles N in showers which are detected at a fixed rate (A or B) under different thicknesses t of air, from inclined showers at Chacaltaya, and from sea-level laboratories. $N(t)$ is believed to show approximately the growth and decay of showers of a particular energy. One relies on theory to continue the curve in the upper half of the atmosphere. (The crosses are obtained by scaling down data from a later Chacaltaya publication.)

A.M.H. book, pp 89, 92.

*Before Fluorescence Telescopes

Obtain energy for each intensity by integrating energy loss × N(t)

1974

Fit assuming scaling, and primary Fe

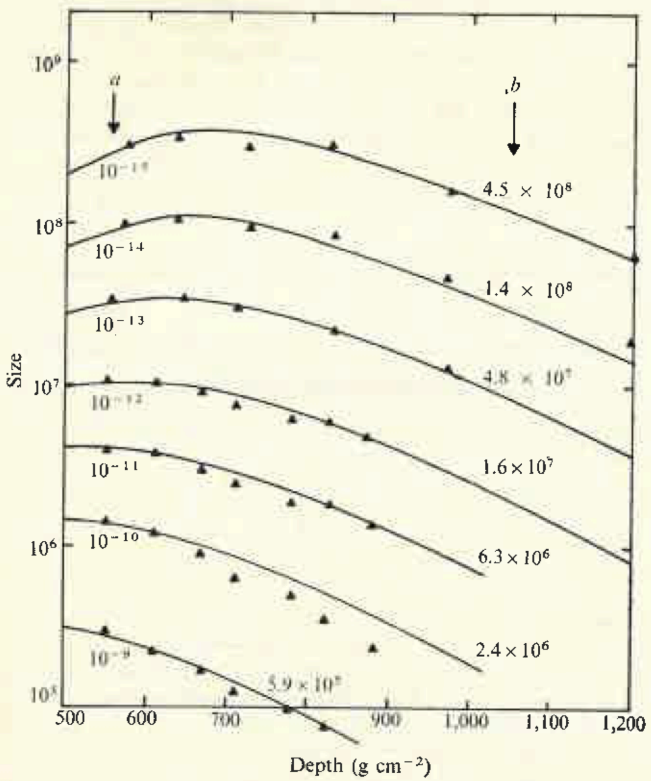


FIG. 1 Comparison between data and calculations of shower size against depth. Each calculated curve is normalised at one depth only (600 g cm^{-2}) to the data. *a*, Intensity (cm^{-2} s^{-1} sr^{-1}); *b*, corresponding total primary energy per nucleus, E_0 (GeV). ▲, refs 4 and 5.

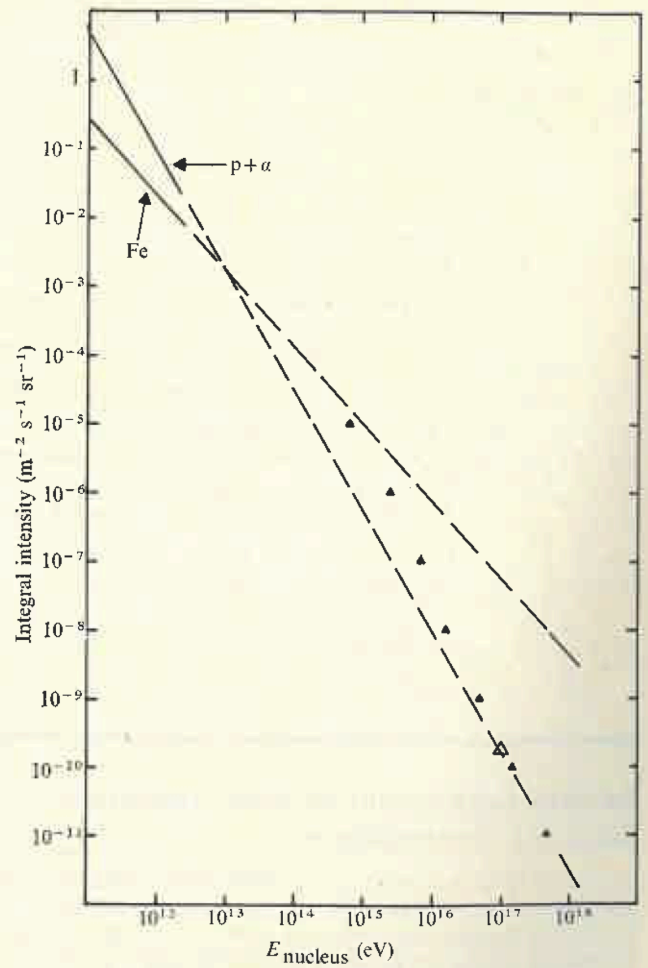
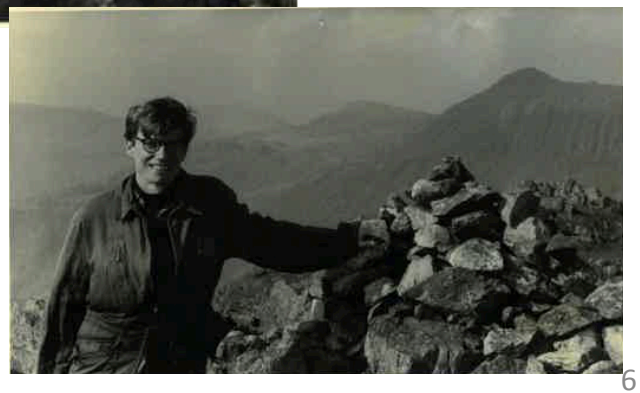


FIG. 2 Data points represent the primary integral energy spectrum obtained from Fig. 1 as described in the text. The normalisation obtained at 10^{17} eV from the EAS calibration of refs 4 and 5 is also shown as a △. – – –, Extrapolations of Fe and $p + \alpha$ spectra measured at lower energies in balloon experiments (refs 10 and 11).

Figures from TG, Nature 24 (1974) pp 122-24

Working (and walking) with Michael Leeds, Aug-Sept 1976

Crinkle Crags, Cumbria
(after negotiating the “Bad Step”)



1976

I. Problem: Understand the physics of EAS atmospheric cascades (1976-1981)

- Shower development is too fast 10^{15}–10^{18} eV
  - Chacaltaya, Tien Shan, Volcano Ranch
  - Strong violation of Feynman scaling?
  - Dominance of heavy primaries?
- Before fluorescence detectors (Auger, TA)
  - Shower profiles from constant intensity cuts
  - Fluctuations, including mixed composition, obscure the analysis
  - Hillas' suggestion: use a simple formula to analyze the procedure of making constant intensity cuts

1976

The G-H formula

TG & Hillas, ICRC Plovdiv vol. 8, 373, 1977

$$S_1(E,t) = S_o \frac{E}{\varepsilon} \exp[t_{max}] \, (t/t_{max})^{t_{max}} \, e^{-t} \quad , \qquad (1)$$

with $t_{max} = .51 \, \ln(E/\varepsilon) - 1$, $S_o = 0.045$, and $\varepsilon = 0.074$ GeV.

Convolve this formula with the distribution of starting points to study the method of constant intensity cuts:

$$\psi(>N|E,t_o) = H(E - \frac{N}{S_o}\varepsilon) \int_o^{t_o} \frac{dt}{\lambda_F} e^{-t/\lambda_F} H(t-t_1)H(t_2-t) \qquad (2)$$

(Where H(x) is a step function)

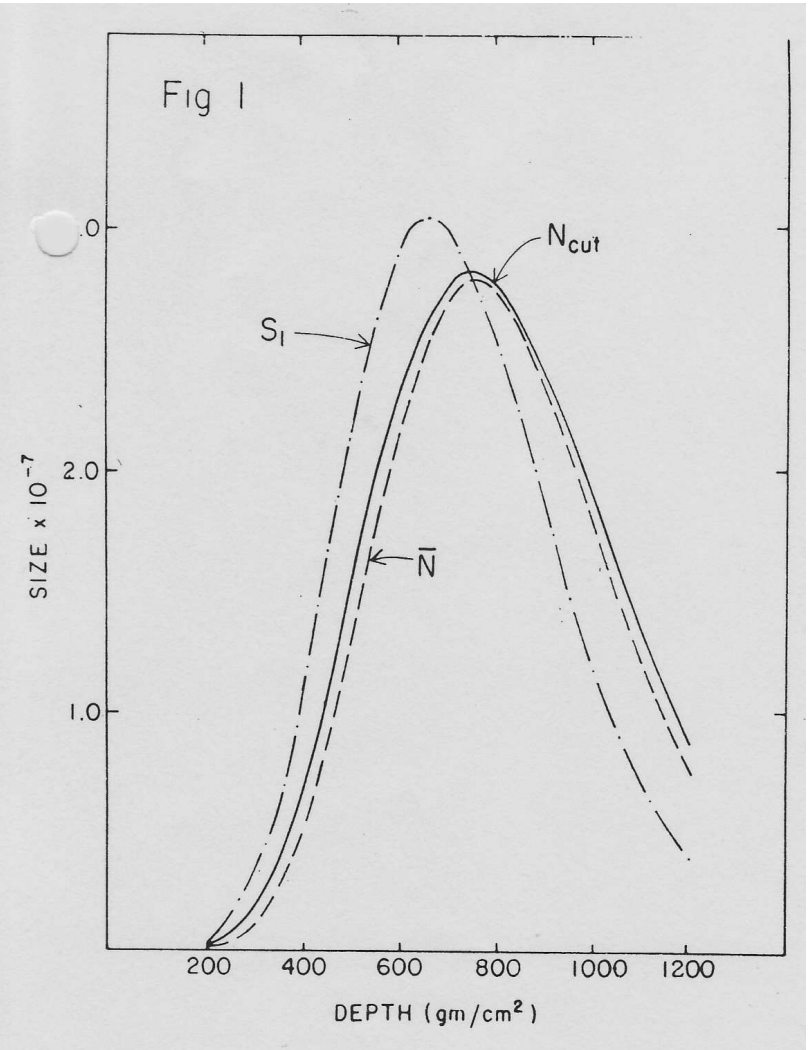
In Eq. (2), $\frac{N}{S_o}\varepsilon$ is the minimum energy required to produce a shower with N particles at its maximum of development. To give a shower with size >N at t_o the cascade must be initiated at slant depth t between t_1 and t_2 ($0 \leq t_1 \leq t_2$) where t_1 and t_2 are roots of

$$N = S_o \frac{E}{\varepsilon} \exp[t_{max}] \left(\frac{t_o - t}{t_{max}}\right)^{t_{max}} e^{-(t_o - t)} \quad .$$

1977

Comparison

- S_1: Single profile
- $\overline{N}$: Average of many
- N_{cut}: Result of constant intensity cut procedure

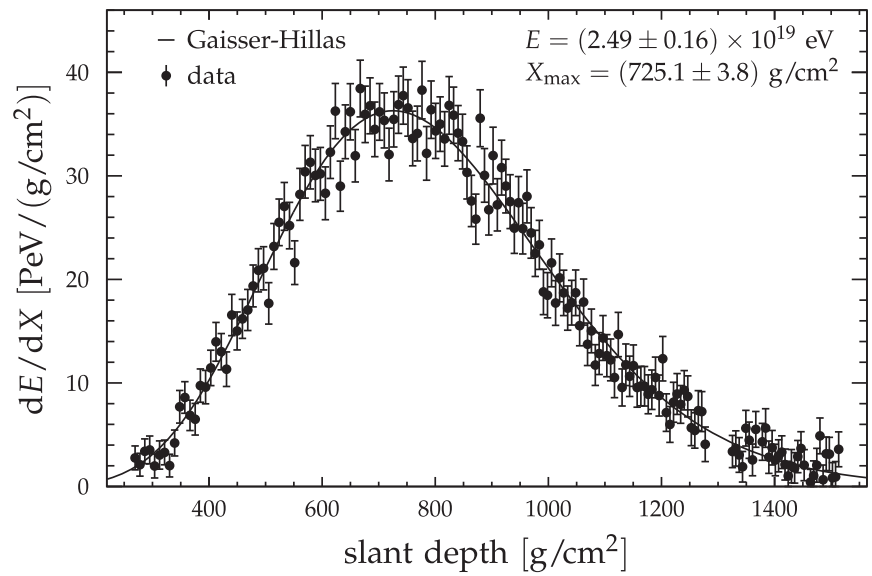


1977

Nachleben of the G-H function

$$N(X) = N_{\max}\left(\frac{X - X_1}{X_{\max} - X_1}\right)^{(X_{\max}-X_1)/\Lambda} \exp\left(-\frac{X - X_{\max}}{\Lambda}\right)$$

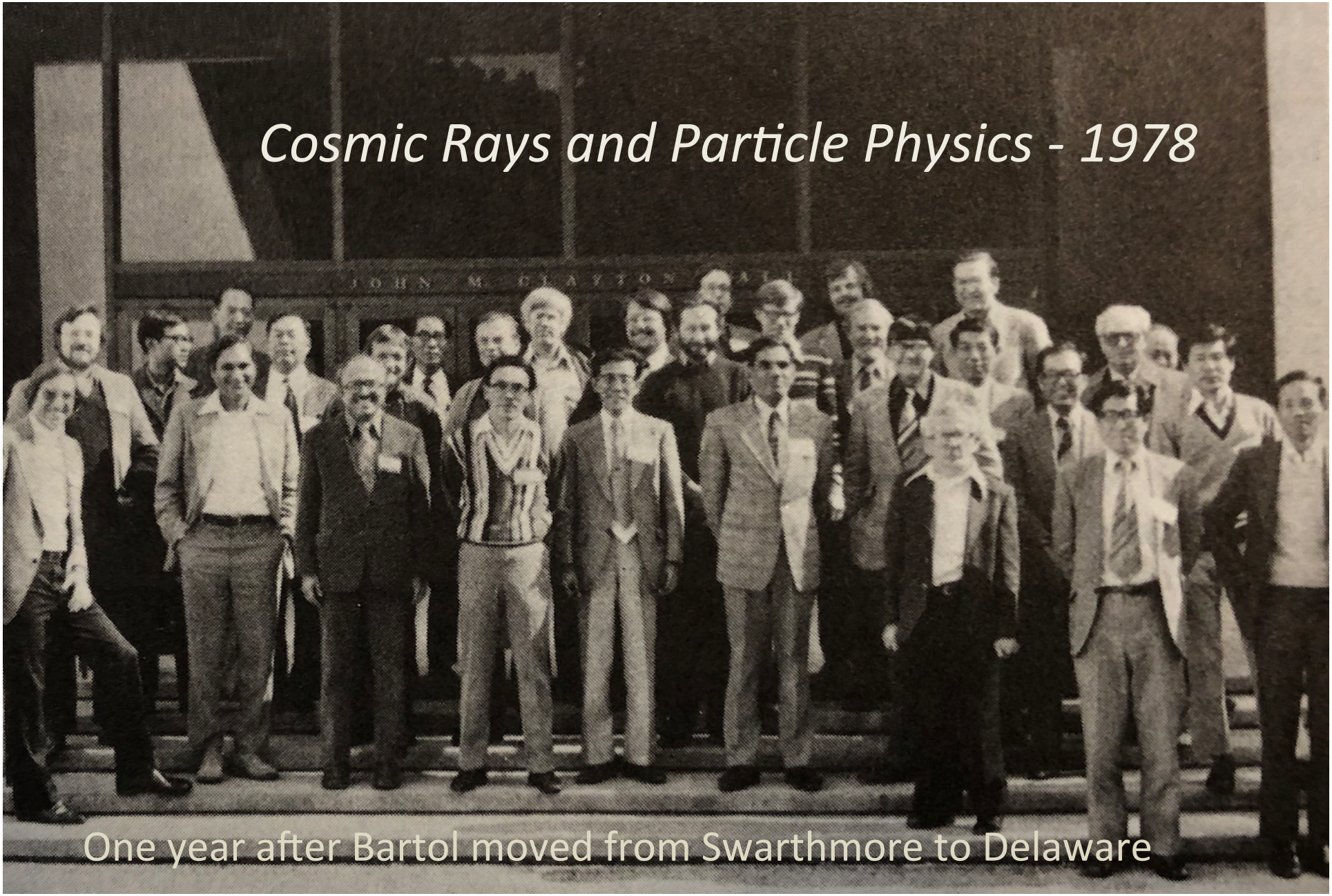
- Formula in terms of
  - Slant depth X (g/cm^2)
  - Starting depth X_1
  - Attenuation length Λ
- Used to fit profiles by Auger, TA
- However, X_1 is a free parameter
  - Usually negative !!!



(d) Longitudinal profile (dots) and Gaisser-Hillas function (line).

Fit to a 25 EeV shower in Auger

(Auger Collab., PR D90 (2014) 122005


Cosmic Rays and Particle Physics - 1978
One year after Bartol moved from Swarthmore to Delaware

The Bartol Conference 1978

- October 1978
  - Hillas gave a major presentation, “High energy cosmic rays, particle physics and astrophysics”
  - Maintain scaling with
    - Increasing σ
    - Nuclear primaries
  - Addresses other data
    - Direct measurements at lower energy
    - Inclusive lepton spectra for intermediate energies
    - Muons in EAS

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J. Phys. G: Nucl. Phys., Vol. 4, No. 2, 1978. Printed in Great Britain. © 1978

LETTER TO THE EDITOR

Does Feynman scaling remain valid at ultra-high energies?

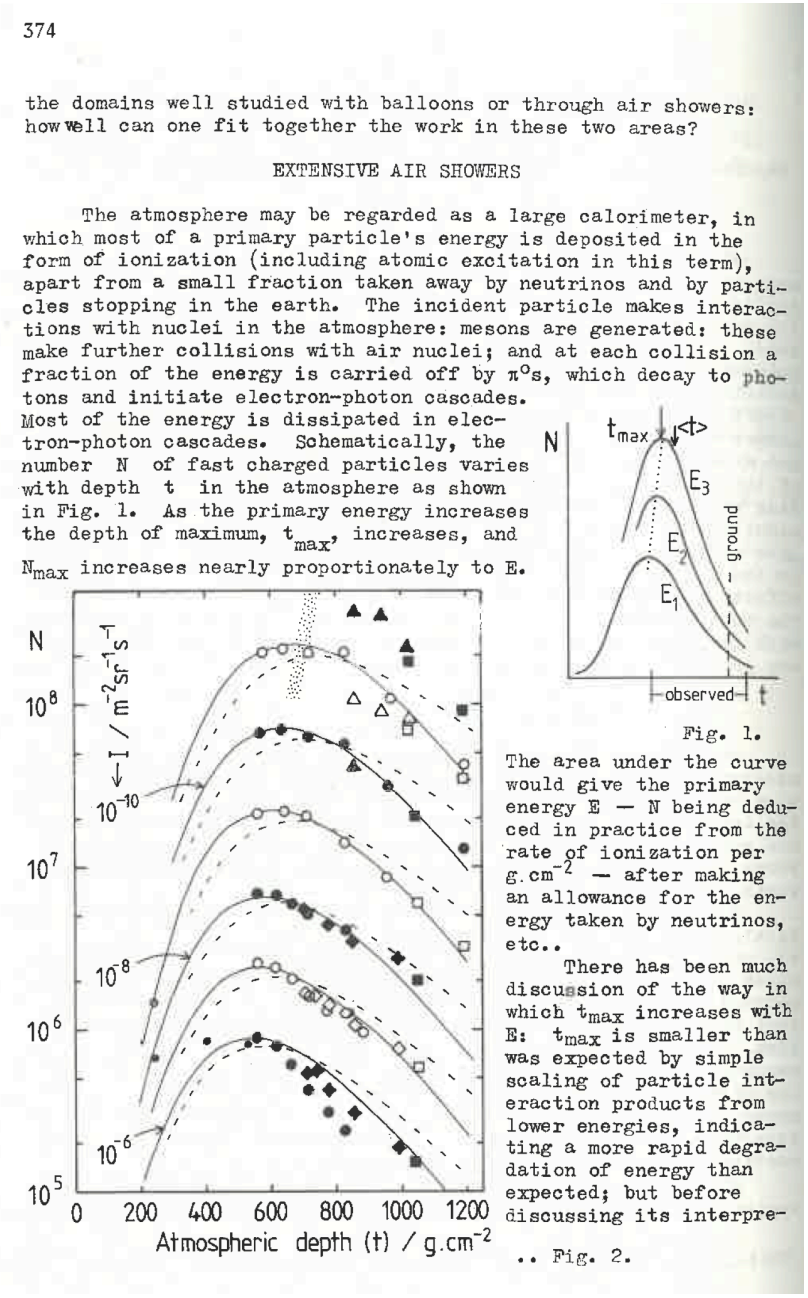
M Ouldridge† and A M Hillas
Physics Department, University of Leeds, Leeds LS2 9JT, UK

Received 22 November 1977

1978

Shower profiles to be fitted

- Solid lines in Fig. 2:
  - “scaling” with
  - Energy-dependent σ
  - Mixed composition
  - Energy-loss integrals give primary energy for each point of a spectrum
- Dashed lines
  - Pure scaling
  - Constant cross sections



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the domains well studied with balloons or through air showers: how well can one fit together the work in these two areas?

EXTENSIVE AIR SHOWERS

The atmosphere may be regarded as a large calorimeter, in which most of a primary particle's energy is deposited in the form of ionization (including atomic excitation in this term), apart from a small fraction taken away by neutrinos and by particles stopping in the earth. The incident particle makes interactions with nuclei in the atmosphere: mesons are generated: these make further collisions with air nuclei; and at each collision a fraction of the energy is carried off by π^0s, which decay to photons and initiate electron-photon cascades. Most of the energy is dissipated in electron-photon cascades. Schematically, the number N of fast charged particles varies with depth t in the atmosphere as shown in Fig. 1. As the primary energy increases the depth of maximum, t_{max}, increases, and N_{max} increases nearly proportionately to E.

Fig. 1.

The area under the curve would give the primary energy E — N being deduced in practice from the rate of ionization per $g.cm^{-2}$ — after making an allowance for the energy taken by neutrinos, etc..

There has been much discussion of the way in which t_{max} increases with E: t_{max} is smaller than was expected by simple scaling of particle interaction products from lower energies, indicating a more rapid degradation of energy than expected; but before discussing its interpre-

.. Fig. 2.

1978

Composite spectrum

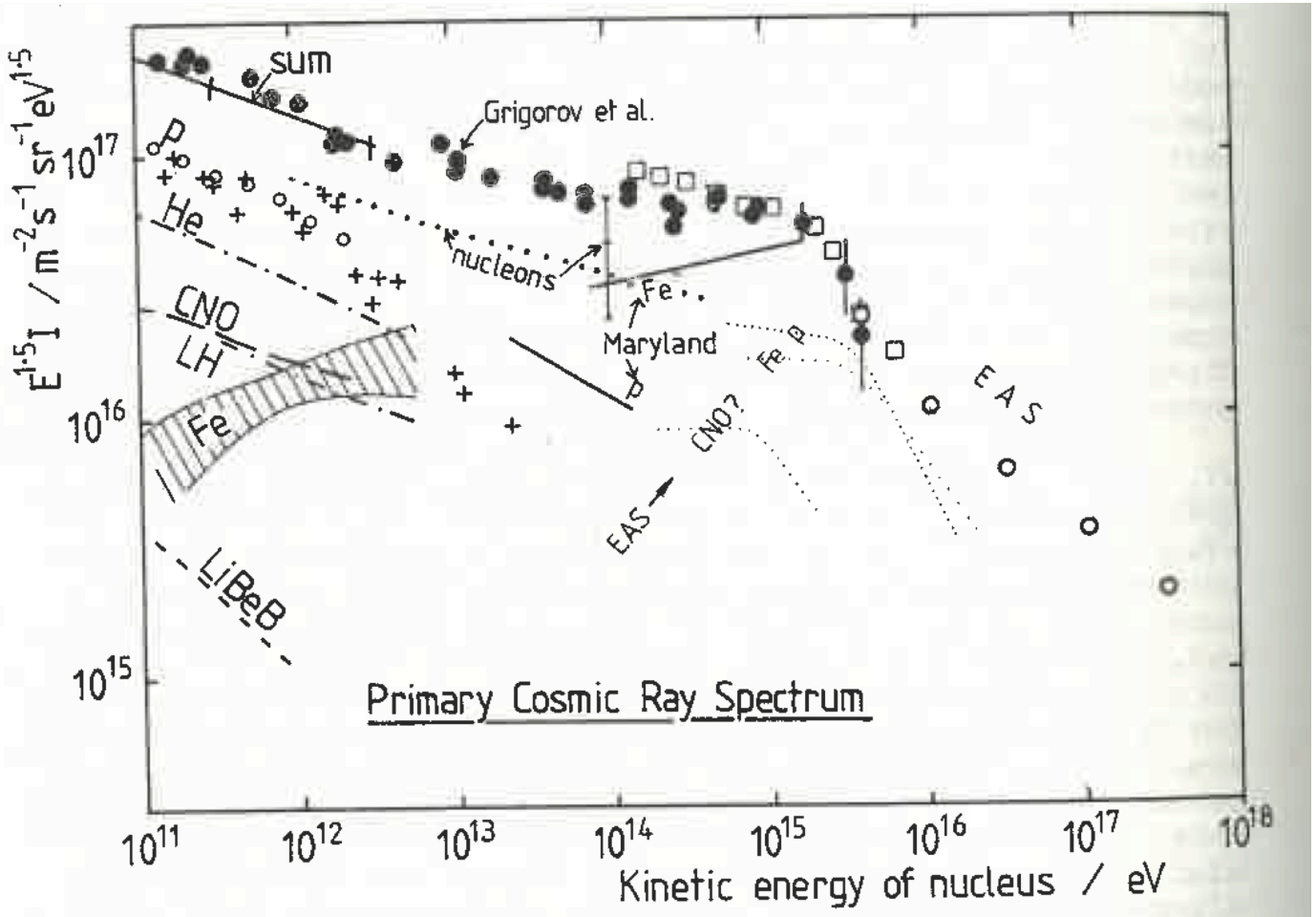

Fig. 6

1978

Rising cross section

this rather odd formula having been used by previous workers, to represent hadron attenuation in the atmosphere[13], and to calculate muon production (though this is actually insensitive to λ_N)[14]. Mean free paths of pions and kaons were assumed to have this same energy dependence. Fig. 4 shows this assumed λ_N as a function of energy, and the right-hand scale shows the equivalent inelastic proton-proton cross-section. For comparison, the p-p cross sections measured at the CERN ISR are also plotted, including the high-energy values deduced by Amaldi et al.[15] using dispersion relations applied to measurements of forward scattering amplitudes. (Their total cross-sections have been multiplied by 0.825 to give estimated inelastic cross-sections.) The true rise in cross section is evidently very much like that assumed, at least to ~10^{14} eV. By 10^{17} eV, σ_{pp} would have tripled, and $\sigma_{p\text{-}air}$ doubled.

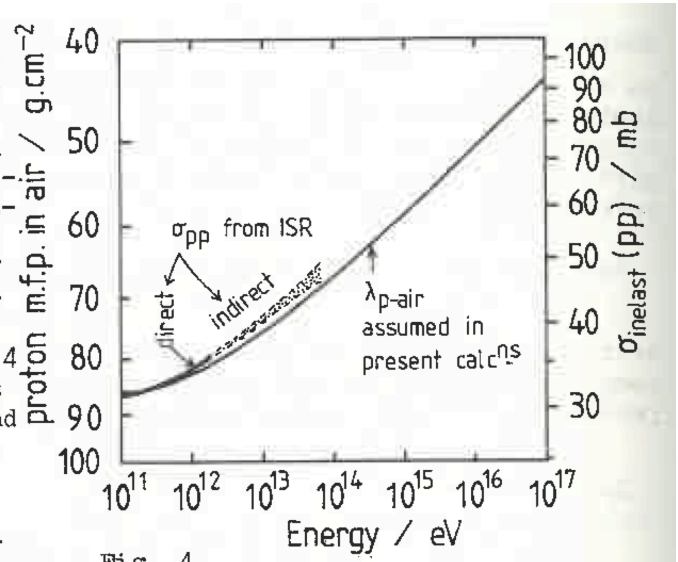

Fig. 4

1978

Rising cross section

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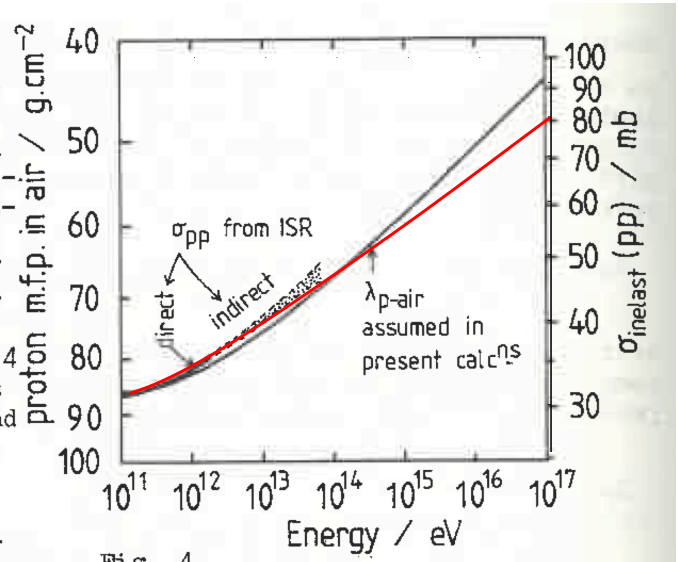


Fig. 4

1978

Muons in EAS

- Measurements of Vernov et al
  - Factor 10 above their calculation with p and pure scaling
- Hillas uses
  - Mixed composition
  - "scaling" with increasing σ

Surprisingly, the choice between the radically different solutions (a) and (b) has not yet been convincingly decided in the air shower domain, as both have their advocates. I believe that some of the objections to scaling are not valid. For example Vernov et al.[3] have argued that the number of muons in showers is almost an order of magnitude greater than expected from scaling. Fig. 5 shows their measurements of the average number N_μ of muons above 10 GeV in showers containing N_e electrons — see the points in the diagram — and the line represents the prediction from their scaling model. (N_μ/N_e can be low in a scaling model for two reasons: t_{max} is large, and hence N_e can be high at sea level, as compared with a high-multiplicity model; and in order for pions to have the energy — tens of GeV — at which decay competes well with interaction, many successive steps of cascading are needed in a low-multiplicity model, and the energy losses to π^0s leaves little energy for μs.) In principle, the ratio is sensitive to the multiplicity in π-air collisions. However, it turns out that one has to be careful

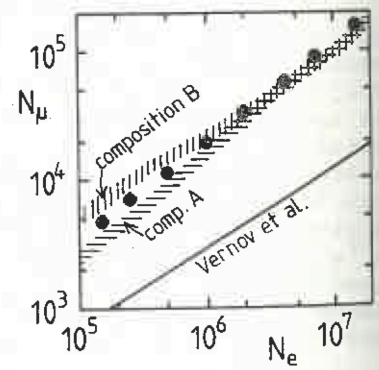


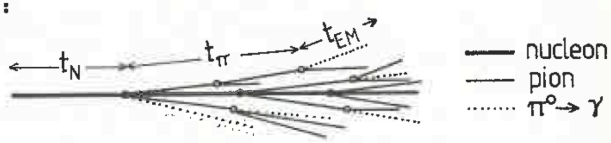
Fig. 5

1978

Calculation of energy deposition

as ionization:

Fig. 3:



This parcel travels a distance t, carried first by a nucleon, then by a pion, say, and finally in the electromagnetic cascade, so

that $t = t_N + t_\pi + t_{EM}$,

adding the distances travelled in each form. Averaging over all the parcels of energy in the primary particle, and over many primaries, one has for the mean depth of energy deposition,

$$\langle t \rangle = \langle t_N \rangle + \langle t_\pi \rangle + \langle t_{EM} \rangle .$$

In crude terms, all of the energy travels with the nucleon to its first collision, then a fraction $(1-K)$, where K is the inelasticity, travels along a further path with the nucleon, etc., so that if the mean free path of the nucleon is λ_N,

$$\langle t_N \rangle = \lambda_N + (1-K)\lambda_N + (1-K)^2 \lambda_N + \ldots$$
$$= \lambda_N / K \approx 2.\lambda_N .$$

Then, 2/3 of the energy travels along the first flight path of the

$\sum E_{\pi^o}$

over all π^os in the cascade. For a scaling model, apart from complications due to π-μ decay (which breaks strict energy scaling features), $E_{\pi^o typ}$ increases in proportion to E_{prim}.

So $\langle t \rangle = \langle t_N \rangle + \langle t_\pi \rangle + \langle t_{EM} \rangle$.

This increases by 80 g cm^{-2} for each decade increase in $E_{\pi^o typ}$.

SCALING : this corresponds to one decade increase in E_{prim}. (Not quite accurate when π-μ decay takes away appreciable energy.)

HIGH MULTIPLICITY model : this corresponds to >2 decades increase in E_{prim}.

constant if λ_N, inelasticity constant.

only change is that due to π-μ decay if λ_π constant (shorter at low E_{prim}).

But do λ_N, λ_π change?

- Analogous to the Matthews-Heitler model

1981

Hillas' splitting for hadronic interactions: (Paris ICRC 1981)

1) Split the total available energy randomly into two parts, A and B
2) Assign A as the energy of the leading nucleon;
3) Further subdivide the remaining energy B randomly into $J = 2^N$ parts, with $N = 2$;
4) Split each of the $J = 4$ pieces of energy randomly into two parts, A' and B';
5) Assign A' as the energy of a pion;
6) Subdivide B' again and assign one piece as another pion;
7) Continue in this way until the energy remaining is less than some preassigned threshold value. The energy threshold can depend on the problem at hand, but must be at least as large as m_π.

The analytic form for the pion energy fraction is

$$\frac{\mathrm{d}n_\pi}{\mathrm{d}x_\pi} = 2^N \left\{ \frac{1}{x_\pi} - \sum_{n=0}^{N} \frac{(\ln \frac{1}{x_\pi})^n}{n!} \right\}$$

Hillas splitting algorithm-extended

Note: the highest energy is scaled up by one unit on the plots

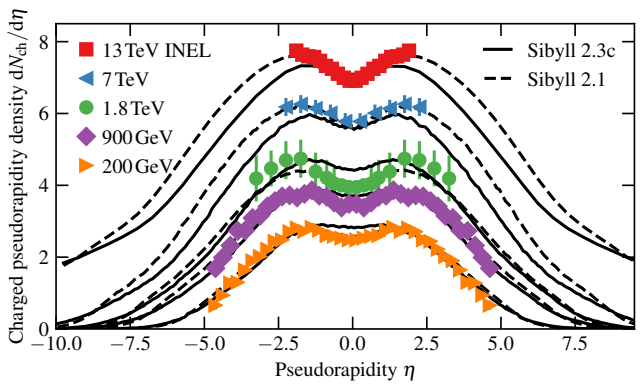
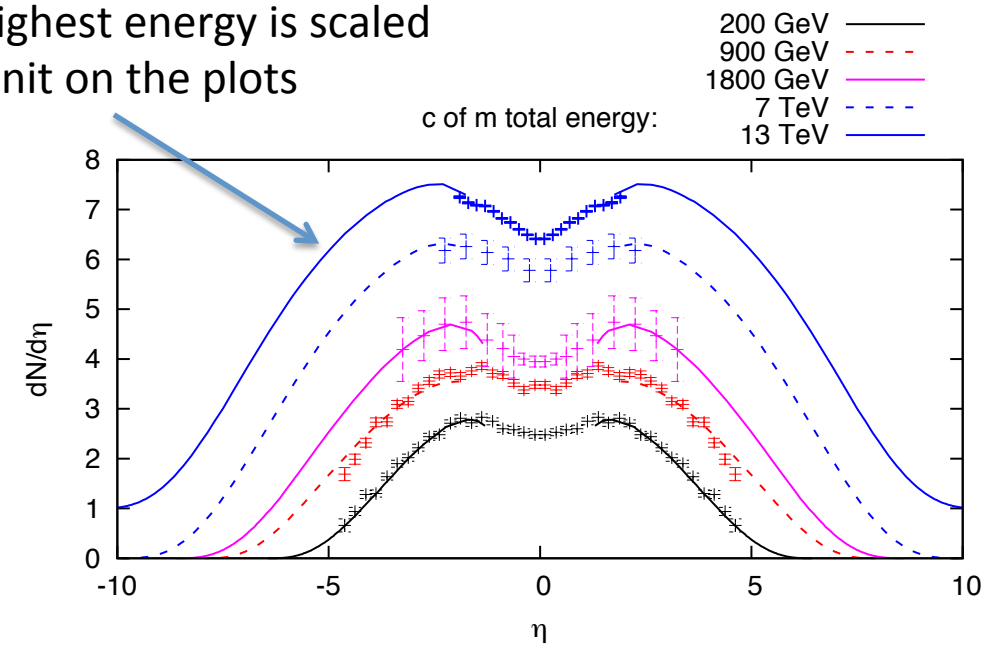


FIG. 2.3. Distribution of charged particles in pseudorapidity. Data are from CMS, CDF and UA5 [46–49]. The 13 TeV data are shifted by one unit to increase readability. 13 TeV measurement is inelastic events, the rest are non-single diffractive. Note how, as the interaction energy increases large parts of forward phase space fall outside the coverage of the detectors. The central region, that is sensitive to the number of interactions, is always covered and can be used to constrain the model for multiple interactions.

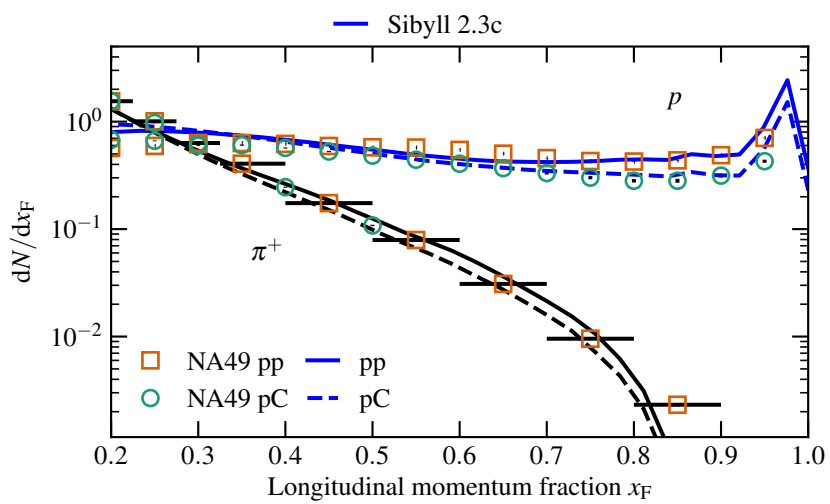


E0 (GeV)	<N>
100	2.55
450	2.6
900	2.93
3500	3.28
6500	3.28

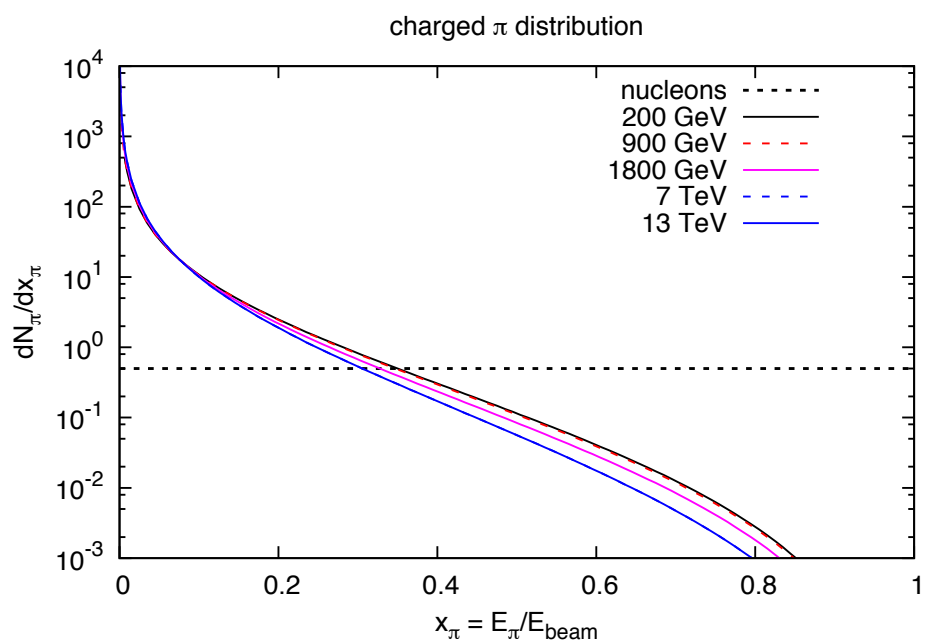
Plateau saturates

Use Hillas' splitting algorithm to fit the data from colliders by allowing N > 2

Rising plateau + energy conservation imply softening of pion spectrum for x > 0.1 as energy increases



NA49 158 GeV with Sibyll2.3c



Hillas splitting

1985

II. Problem: *Observe* the sources of Galactic cosmic radiation (1985-1990)

vol. 9 pp 407–4

"Highlight talk" given at the 19th International Conference on Cosmic Rays, La Jolla, August 1985

1 Hillas

WHY IS CYGNUS X-3 (WITH "RELATED SOURCES")
A HIGHLIGHT OF COSMIC-RAY ASTROPHYSICS?

A. M. Hillas
Physics Department
University of Leeds, Leeds LS2 9JT, UK.

At La Jolla, discussions initiated by Hillas with Alan Watson and Martin Pomerantz led to the proposal to build SPASE (*South Pole Air Shower Experiment*) to detect PeV photons from Galactic accelerators

Hillas proposes SPASE at Vulcano 1986

ON THE ADVANTAGES OF MONITORING GAMMA-RAY BINARIES FROM THE SOUTH POLE

A. M. Hillas

Physics Department, University of Leeds, Leeds, UK

TeV and PeV gamma-ray sources are highly variable, and astronomers argue about which are real. This is reminiscent of the early days of X-ray astronomy, when sources were observed from rockets which spent only a few minutes above the atmosphere, and one observer could not find a source reported by another. We need an UHURU.

How should we find the real pattern behind these variations? We need

1) Detectors placed where several sources are always in view.
2) The declination band viewed should contain many potential sources.
3) A high altitude, allowing a scintillator array to have a low threshold energy, to increase the counting rate.

The above requirements were obvious, but this visit to Vulcano has provided the final constraint that confirms completely the choice of site:

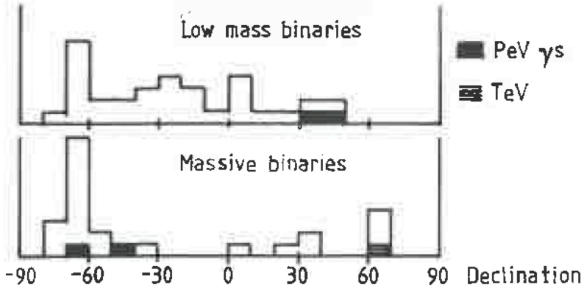
4) The climate and general environment should differ as much as possible from Vulcano, or very little work would be done after the first week.

The unique site that meets all these requirements is the South Pole!

At this location -

1) Those sources that are visible at all are visible all day, every day, at constant altitude - no corrections for varying threshold energy during observation. (Until now, typical sources have been sufficiently close to the zenith for observation for only 4-7 hours each day.)
2) If one assumes that potential u.h.e. gamma-ray emitters are in essence all the X-ray binaries, many of these have far southern declinations -

Fig. 1. Declination distribution of X-ray binaries (Bradt and McClintock).



A.M.H. at Vulcano, 1986-1990

- Vulcano 1986:
  - He proposes SPASE
- Vulcano 1988:
  - He reports on SPASE
- Vulcano 1990:
  - He itemizes the problems with Her X-1, Cyg X-3

1989

AIP CONFERENCE PROCEEDINGS 198

RITA G. LERNER
SERIES EDITOR

ASTROPHYSICS IN ANTARCTICA

NEWARK, DELAWARE 1989

EDITORS:
DERMOTT J. MULLAN,
MARTIN A. POMERANTZ, &
TODOR STANEV

BARTOL RESEARCH INSTITUTE
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AIP
American Institute of Physics New York

1989

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Vulcano 1990: Problems with PeV point sources

WHAT ARE WE TO MAKE OF THE TeV-PeV "GAMMA-RAY POINT SOURCES"?

A. M. Hillas and P. A. Johnson,

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

Abstract

In VHE-UHE gamma-ray sources such as Cyg X-3 and Her X-1 it has been estimated that the source luminosity in protons may exceed the X-ray luminosity. Taken together with the un-gamma-like nature of the showers generated by these radiations, the plausibility of these objects as real sources is undermined. However, it now seems that the VHE luminosity of some of these objects could be lower than estimated previously, because TeV observations on Her X-1 suggest that the source may emit a narrow wandering beam, requiring the VHE particle luminosity to be only ~ 10^{35} - 10^{36} erg s^{-1} – a few percent of the X-ray luminosity. Brief episodes of UHE emission from the Crab suggest that a narrow beam may also be present there. The Her X-1 observations also leave open a slight possibility that the radiation from this source does not generate abnormal showers. Cygnus X-3 is a different kind of system — probably an ejector rather than an accretor — but the rotational power available now appears to be < 10^{39} erg s^{-1}, so again a beam of limited angular extent may be emitted.

1990

A SEARCH FOR 100 TEV γ-RAY EMISSION FROM SOURCES VISIBLE FROM THE SOUTH POLE

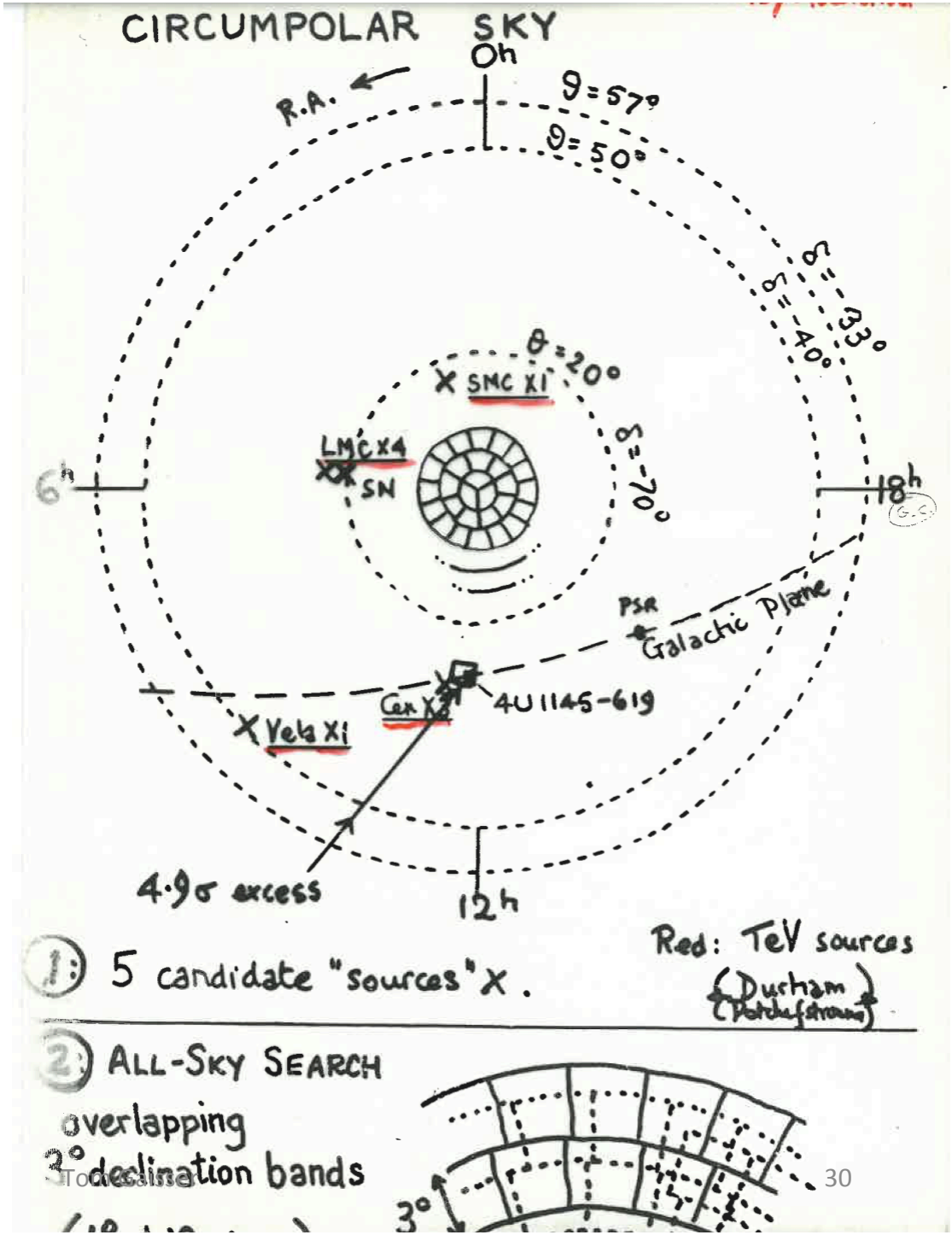
Hillas, ICRC 21, Adelaide 1990

T.K. Gaisser, A.M. Hillas, J.C. Perrett, M.A. Pomerantz, R.J.O. Reid, N.J.T. Smith, T. Stanev & A.A. Watson.

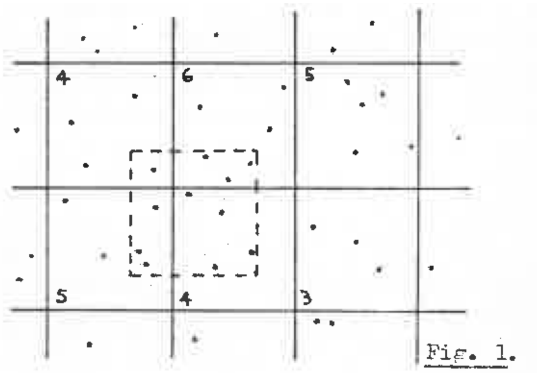
BARTOL – LEEDS

South Pole Air Shower Experiment

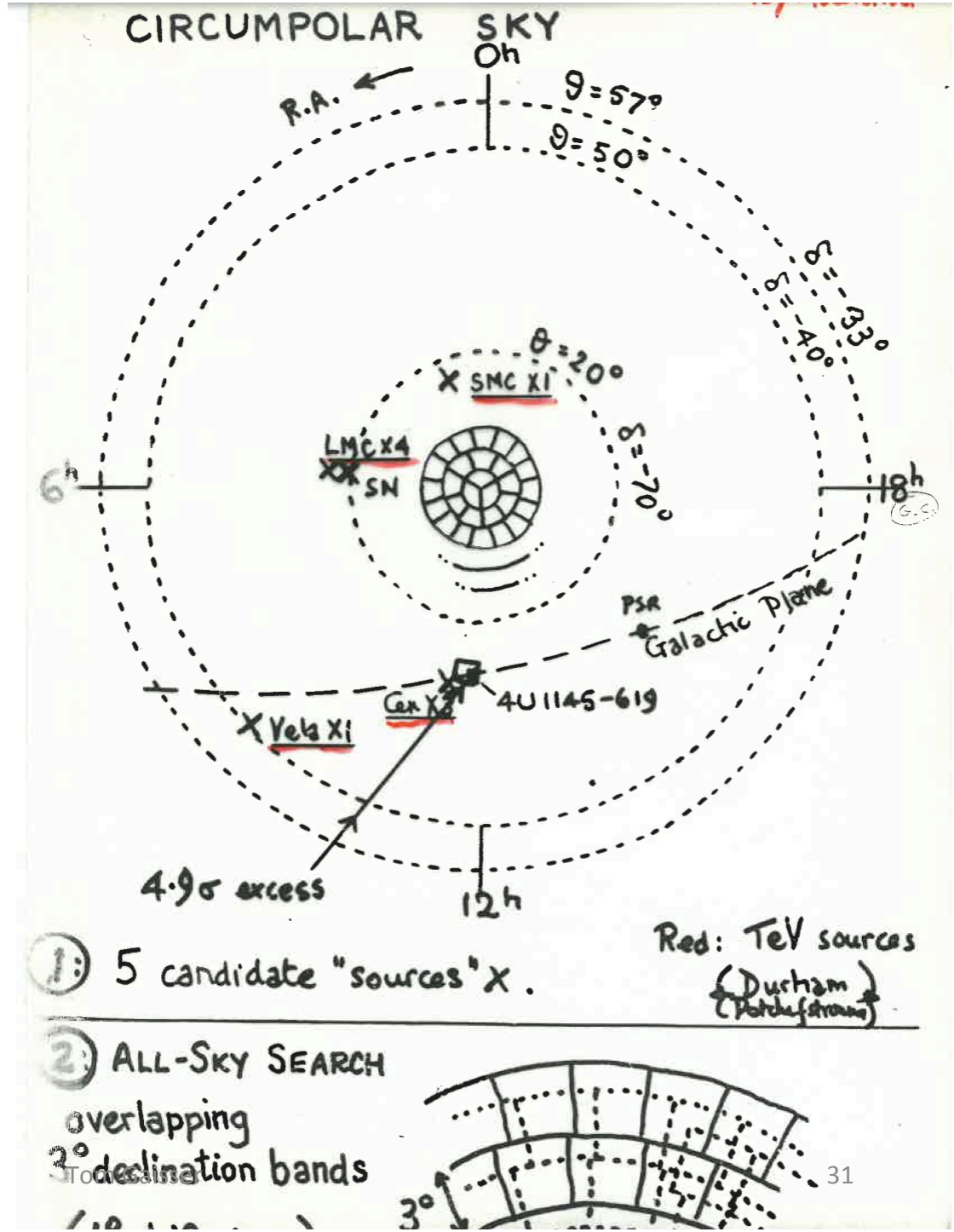
from presentation by Hillas at ICRC 21, Adelaide 1990



from presentation by Hillas at ICRC 21, Adelaide 1990



Hillas, ICRC 14, Munich, 1975 T-volume, p. 3439: Explains why 5 σ is necessary to claim a pt src discovery in a binned, all-sky search (with formulas!)



Results from SPASE, 1989-1993

VOLUME 62, NUMBER 13 PHYSICAL REVIEW LETTERS 27 MARCH 1989

Search for Photons of Energy > 50 TeV from SN 1987A in Early 1988

T. K. Gaisser,[1] A. M. Hillas,[2] J. C. Perrett,[1] M. A. Pomerantz,[1] R. J. O. Reid,[2] N. J. T. Smith,[2]
Todor Stanev,[1] and A. A. Watson[2]
[1]*Bartol Research Institute, University of Delaware, Newark, Delaware 19716*
[2]*Department of Physics, University of Leeds, Leeds LS2 9JT, England*
(Received 24 October 1988)

We report analysis of data from the South Pole Air Shower Experiment taken in January and February 1988 while the array was being commissioned. These first results are already of interest because they lead to a limit on an air-shower signal from SN 1987A comparable to the best existing limit and also because the supernova produced a high x-ray flux and a possible TeV signal during that period.

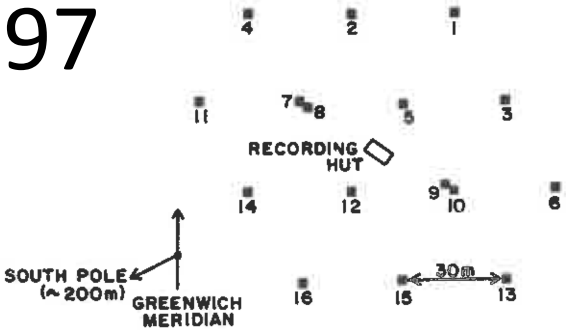
PHYSICAL REVIEW D VOLUME 48, NUMBER 10 15 NOVEMBER 1993

Search for point sources of ultrahigh energy γ rays in the southern hemisphere with the South Pole Air Shower Experiment

J. van Stekelenborg, T. K. Gaisser, J. C. Perrett, J. P. Petrakis, and T. S. Stanev
Bartol Research Institute, University of Delaware, Newark, Delaware 19716

J. Beaman, A. M. Hillas, P. A. Johnson, J. Lloyd-Evans, N. J. T. Smith, and A. A. Watson
Physics Department, University of Leeds, Leeds LS2 9JT, United Kingdom
(Received 18 June 1993)

SPASE at the South Pole, 1987-1997



AN EXPERIMENT TO SEARCH FOR ULTRA HIGH ENERGY γ-RAY SOURCES FROM THE SOUTH POLE

N.J.T. SMITH

Amundsen – Scott Station, South Pole, Antarctica

J.C. PERRETT and M.A. POMERANTZ

Bartol Research Institute, University of Delaware, Newark, DE 19716, USA

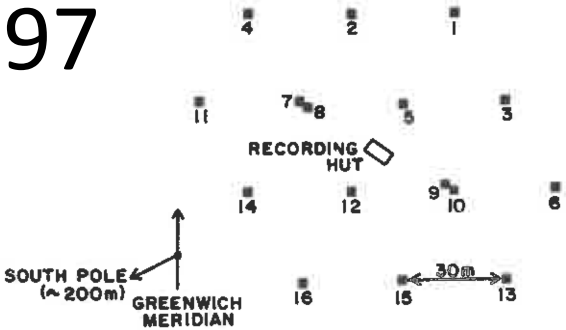
A.M. HILLAS, P.A. OGDEN, M. PATEL, R.J.O. REID and A.A. WATSON

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

Received 7 November 1988

NIM A276 (1989) 622-627

SPASE at the South Pole, 1987-1997



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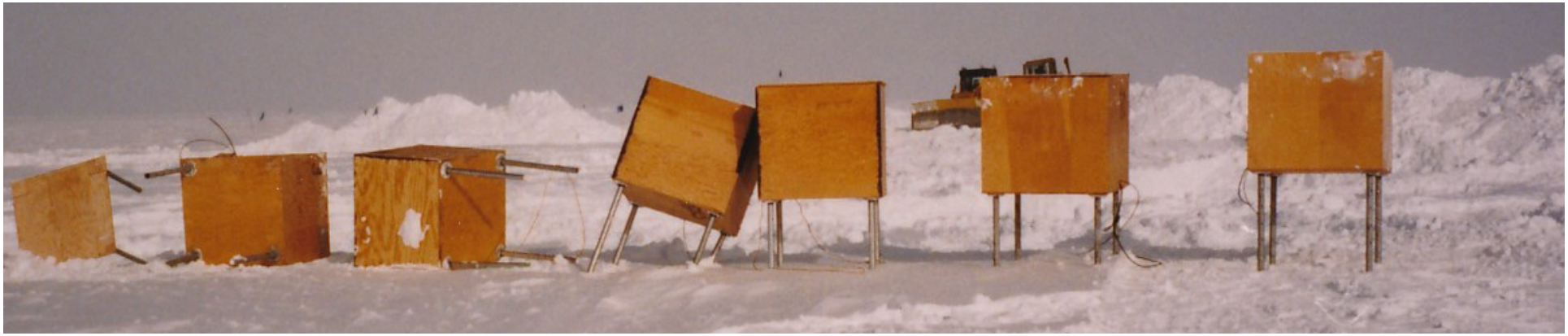
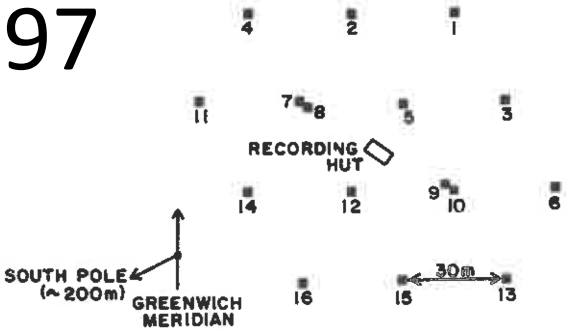


SPASE at the South Pole, 1987-1997



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Dec. 1997, SPASE removal

SPASE–2 AMANDA (1995 – 2005)

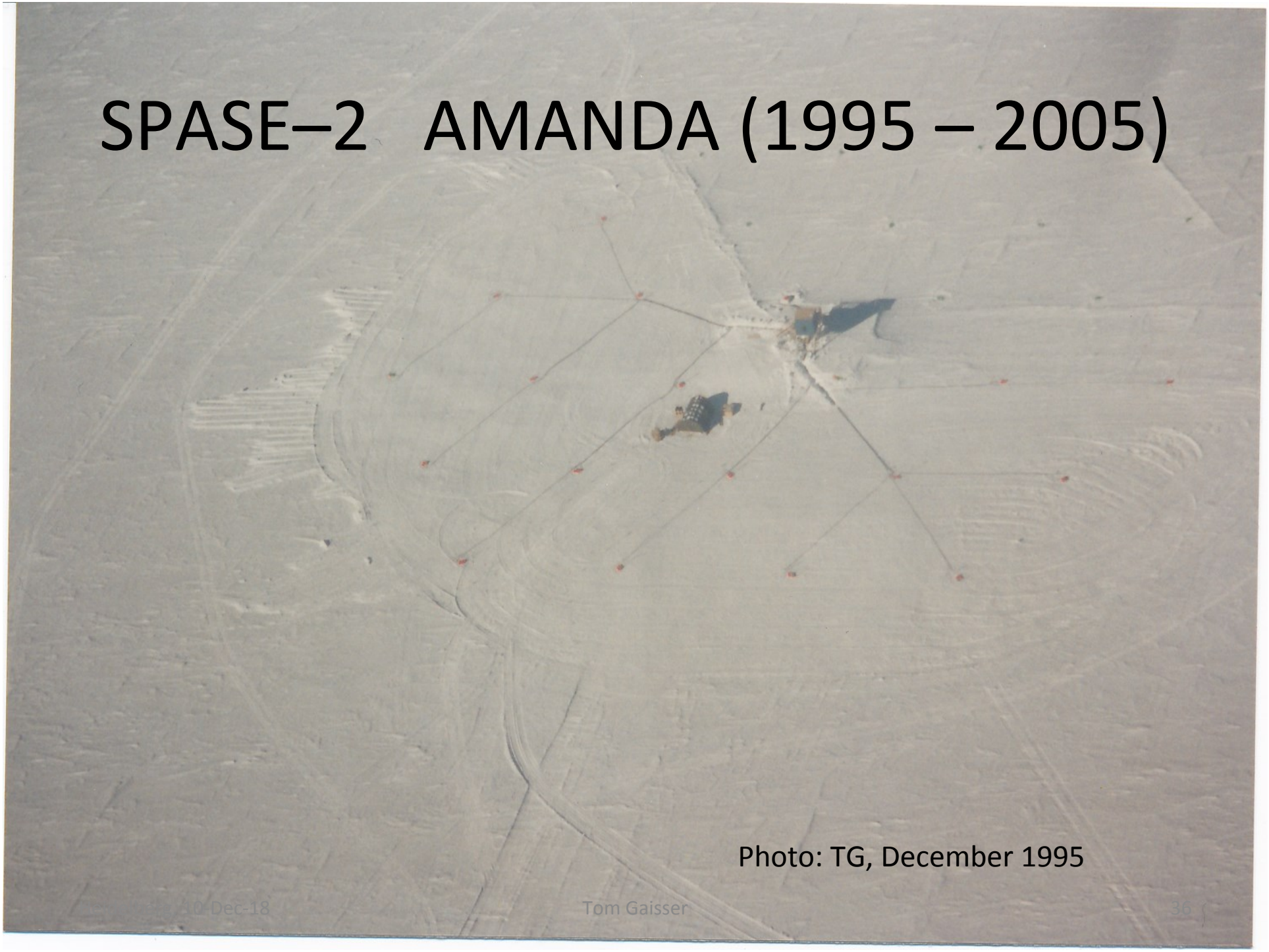
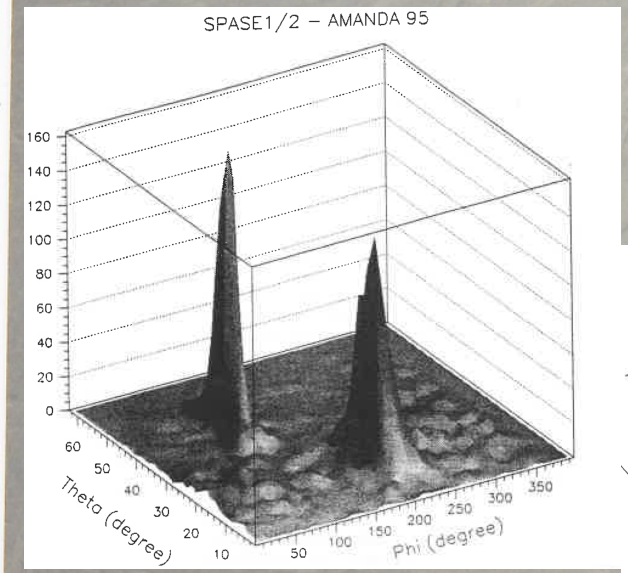


Photo: TG, December 1995

SPASE–2 AMANDA (1995 – 2005)



From TG talk at Hillas retirement symposium, Leeds, 1998

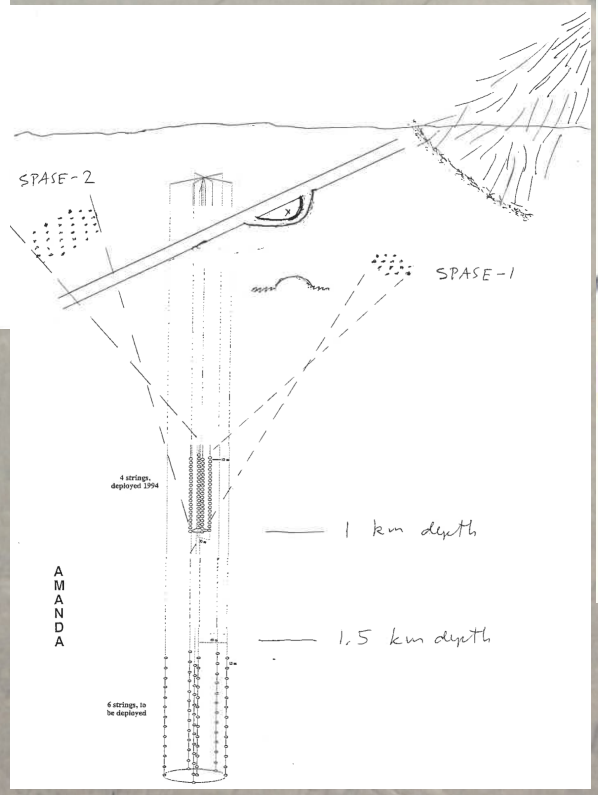


Photo: Glenn Spiczak, January, 1997

1998

The Electron, Muon and Čerenkov Components of Extensive Air Showers Studied at the South Pole

James Anthony Hinton

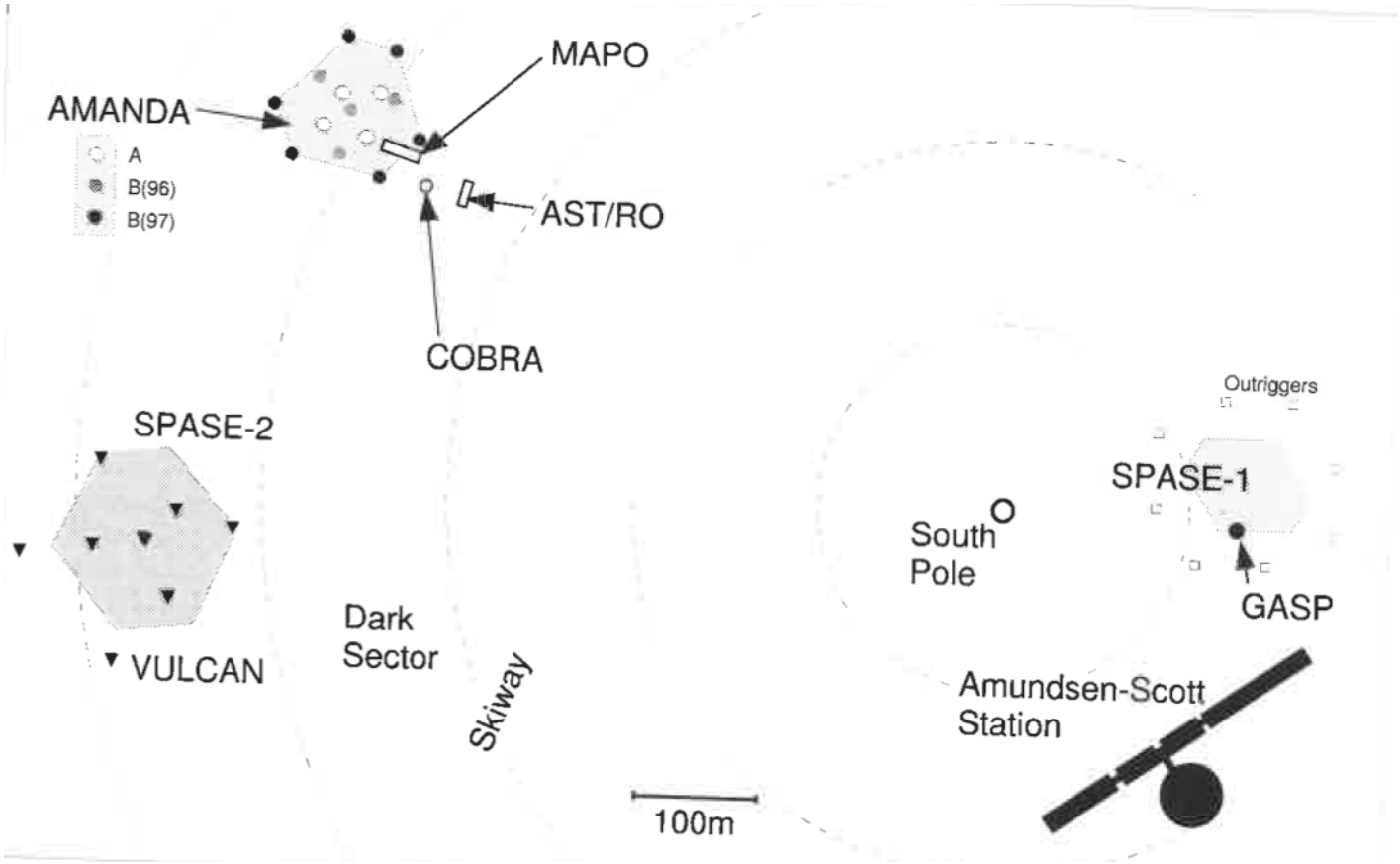
September 1998

Submitted in accordance with the requirements for the degree of Doctor of Philosophy.

The University of Leeds
Department of Physics and Astronomy

1998

SPASE-2 + VULCAN



1995

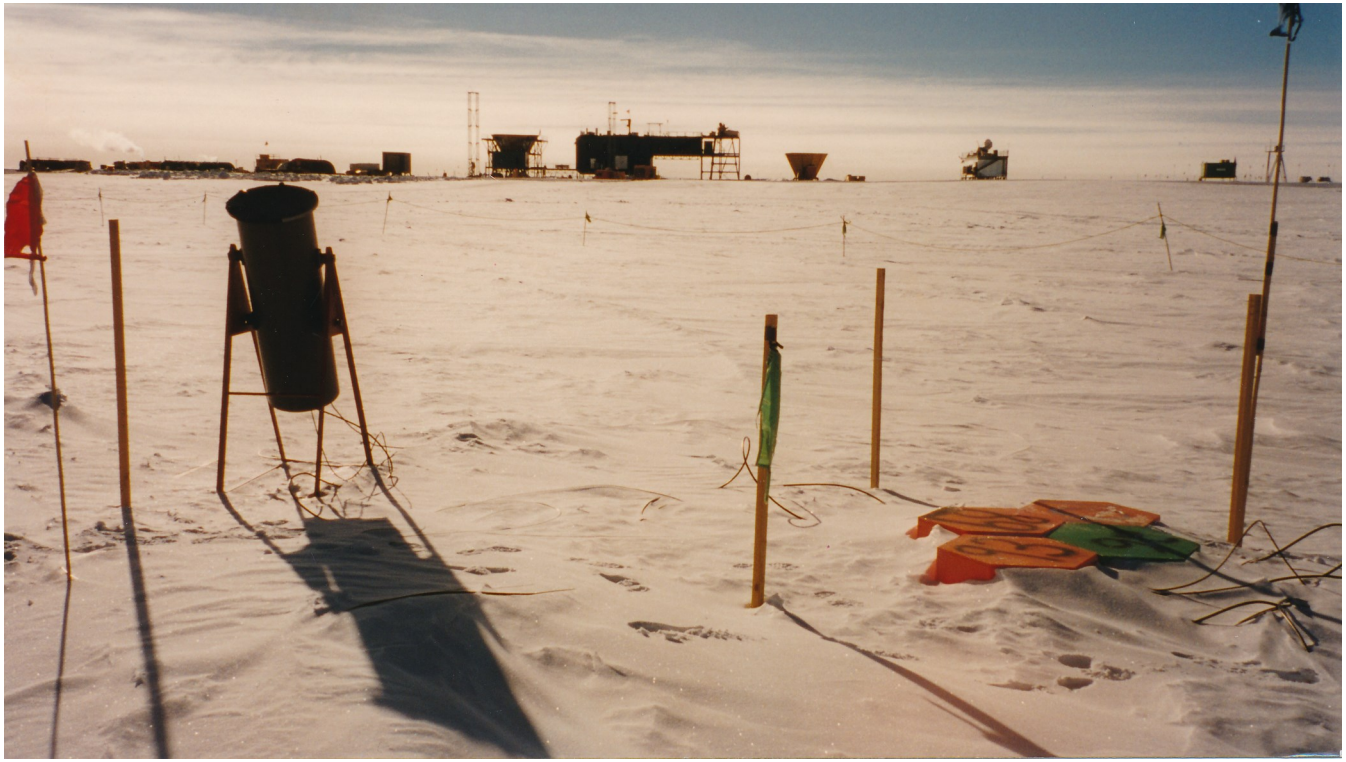


Photo: TG, December 1995

1998

Xmax with VULCAN + SPASE-2

- Simulations relate
  - E to S30 measured by SPASE-2 scintillators
  - Xmax to lateral distribution of Cherenkov light measured by VULCAN

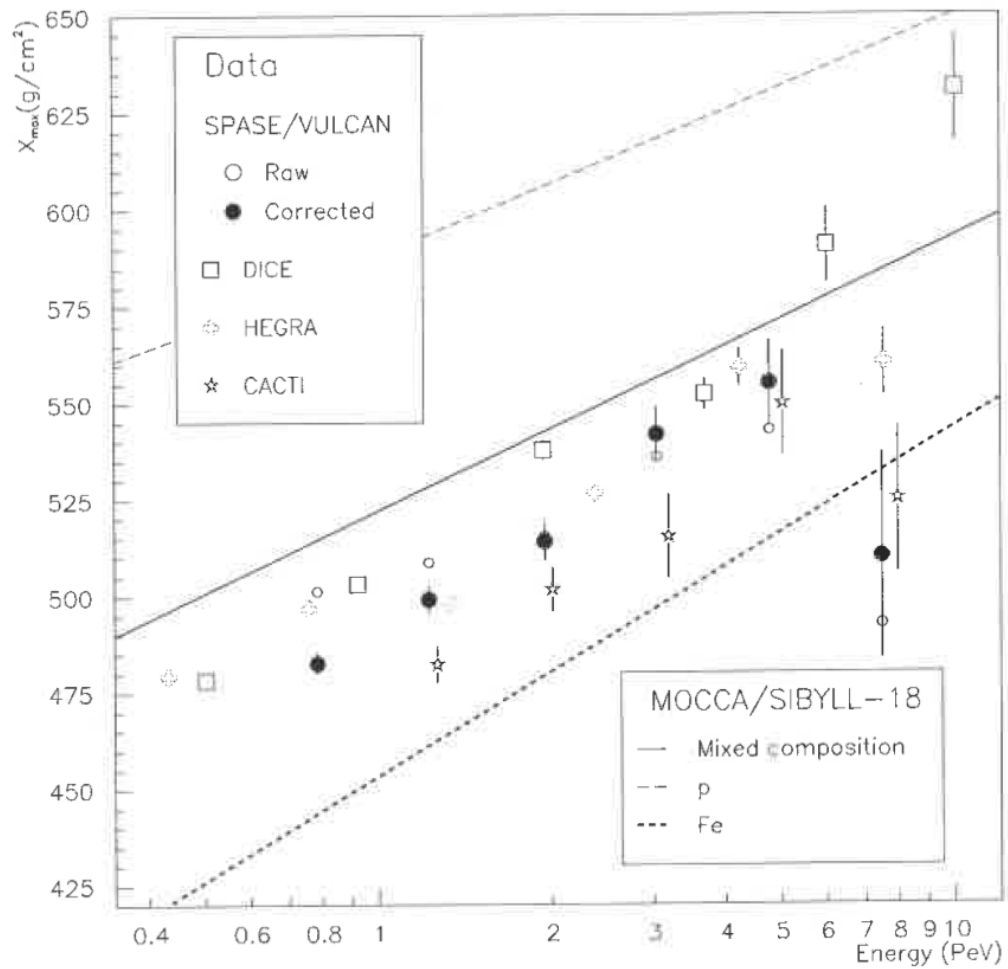


Figure 8.6: The measured depth of maximum from SPASE-2/VULCAN compared with predications from MOCCA/SIBYLL and data from other experiments. Data is taken from: DICE(Boothby et al., 1997b), HEGRA(Cortina et al., 1997) and CACTI(Paling et al., 1997).

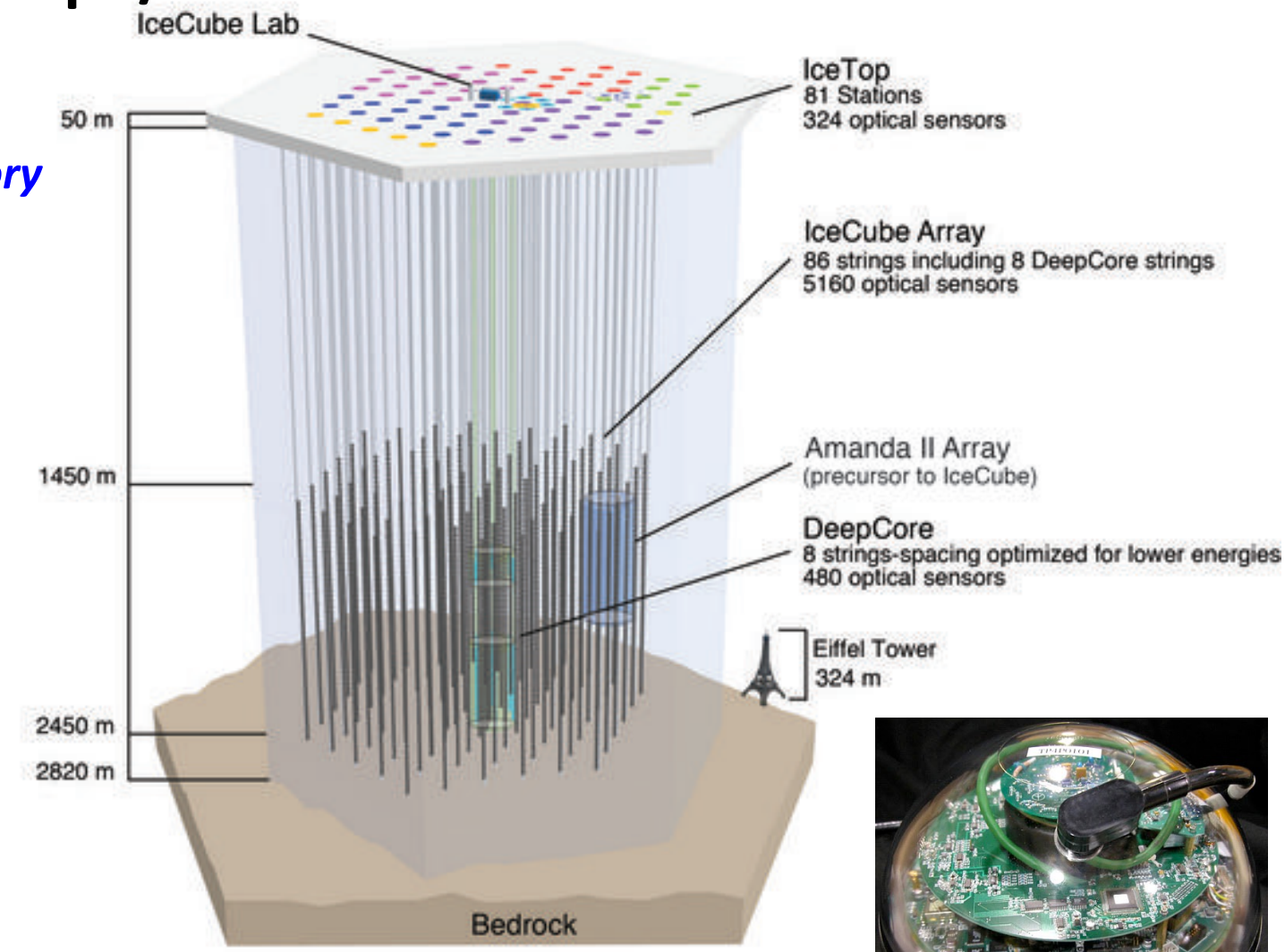
IceTop / IceCube

Deployment history

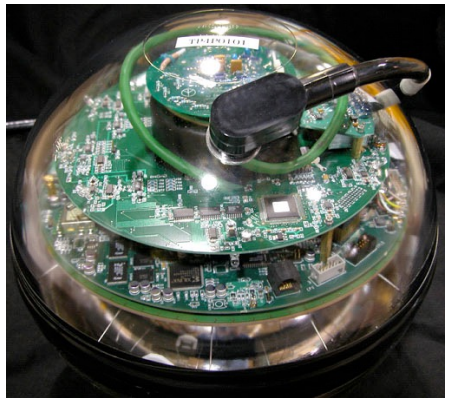
2002: proposal		
2003-04 staging		
2004-05	**1**	**4**
2005-06	**9**	**16**
2006-07	**22**	**26**
2007-08	**40**	**40**
2008-09	**59**	**59**
2009-10	**79**	**73**
2010-11	**86**	**81**

Deep strings

Surface stations



> 5400 Digital Optical Modules



2004

III. Problem: Where is the transition from Galactic to extra-galactic CR?

- If the ankle at 3 EeV marks the transition, how to explain the smooth spectrum from 3 PeV?
- If the knee at 3 PeV marks the beginning of the end of CR accelerated by SNR, what fills in the gap?
  - Hillas suggests a Galactic population B
  - 3 population model: Gal-1, Gal-2, extra-galactic
  - Assume Gal-1 and Gal-2 depend on rigidity and consider implications for composition

2005

Hillas' Galactic population B

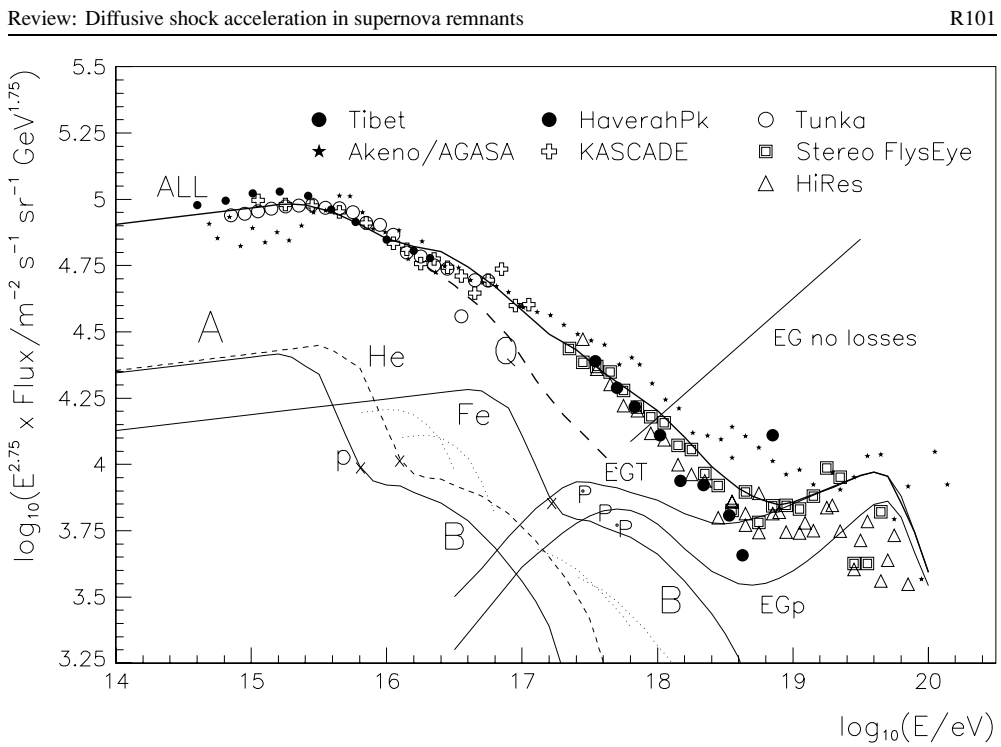


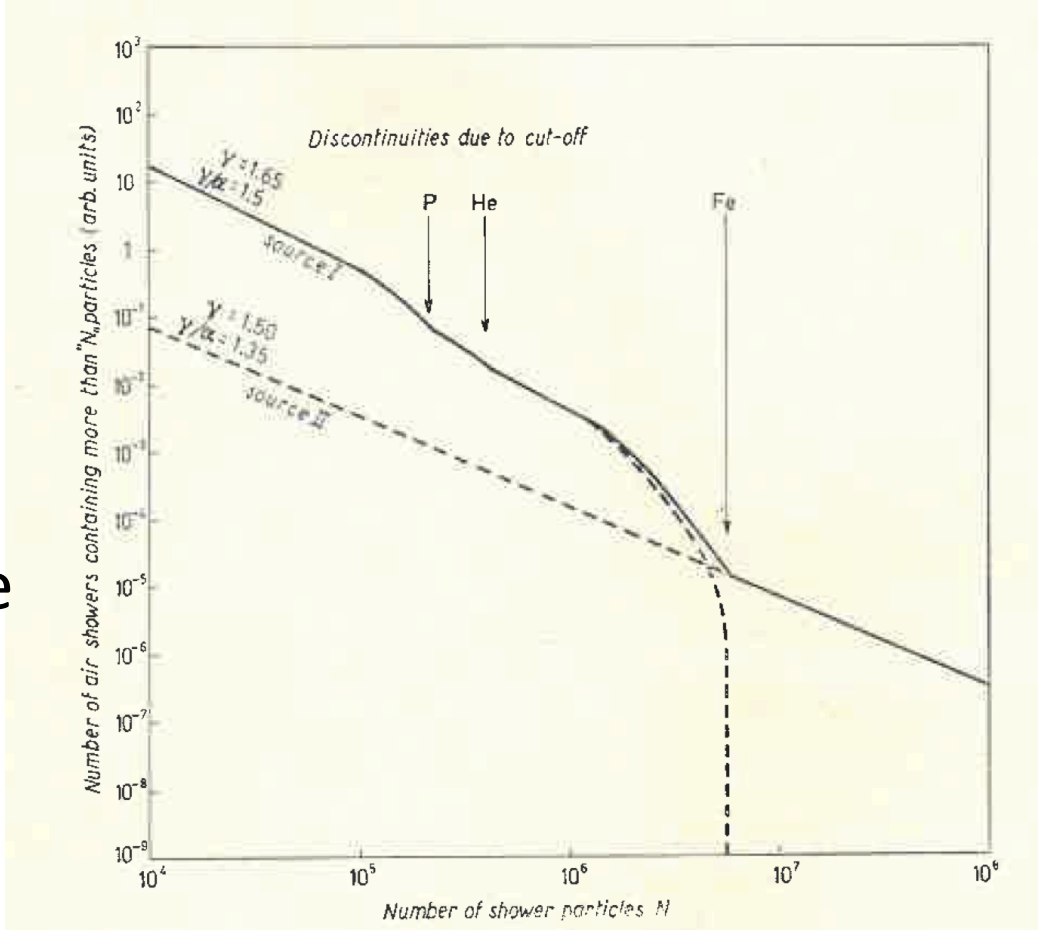
Figure 2. The cosmic ray spectrum as the sum of galactic H, He, CNO, Ne–S and Fe components with the same rigidity dependence, and extragalactic H + He (total EGT) having a spectrum $\propto E^{-2.3}$ before suffering losses by CMBR and starlight interactions. The galactic components were given a turn-down shape based on KAS CADE knee shape as far as the point marked x. The dashed line Q is the total if the extended tail B of the galactic flux is omitted.

I first saw this plot and analysis at the 2004 Auger meeting at Leeds in honor of Alan Watson

A.M. Hillas, J. Phys. G: Nucl. Part. Phys. **31** (2005) R95–R131

Peters cycles and particle populations

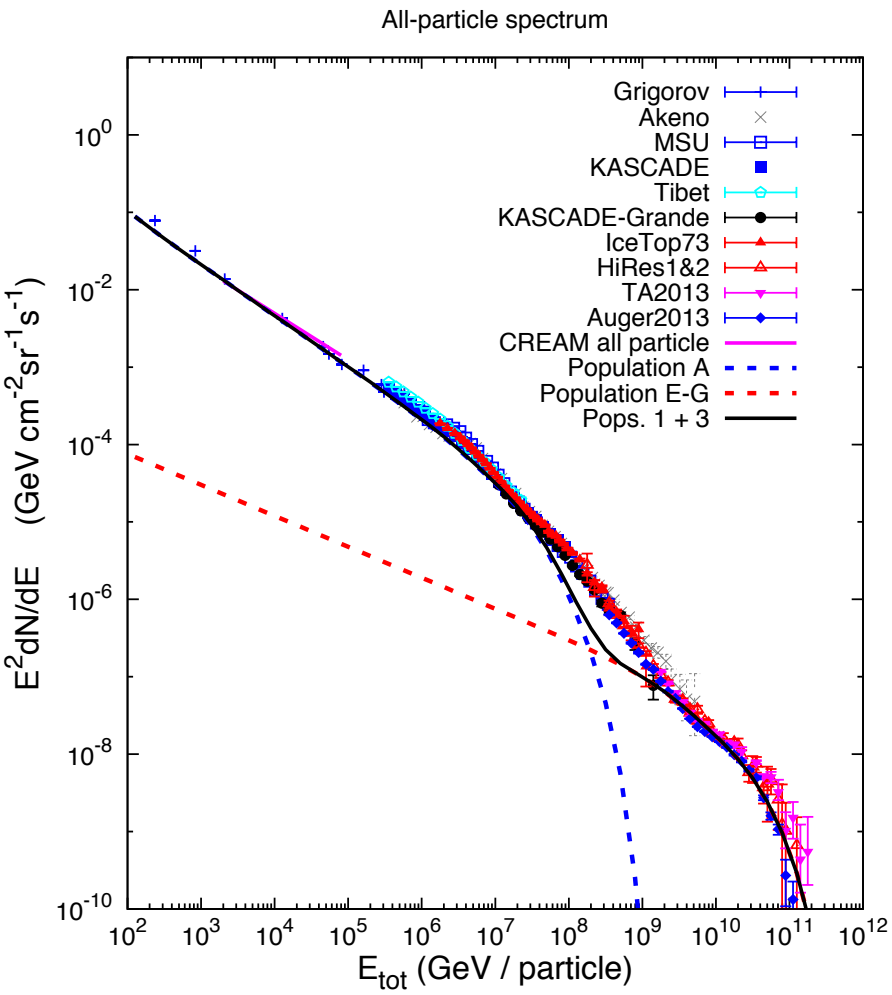
- Rigidity dependence
  - $R = P_{tot}\, c / Z\, e$
  - Implies sequence: p, He, C, … Fe
- Spectral hardening
  - Suggests new particle population
- Galactic and extra-galactic populations

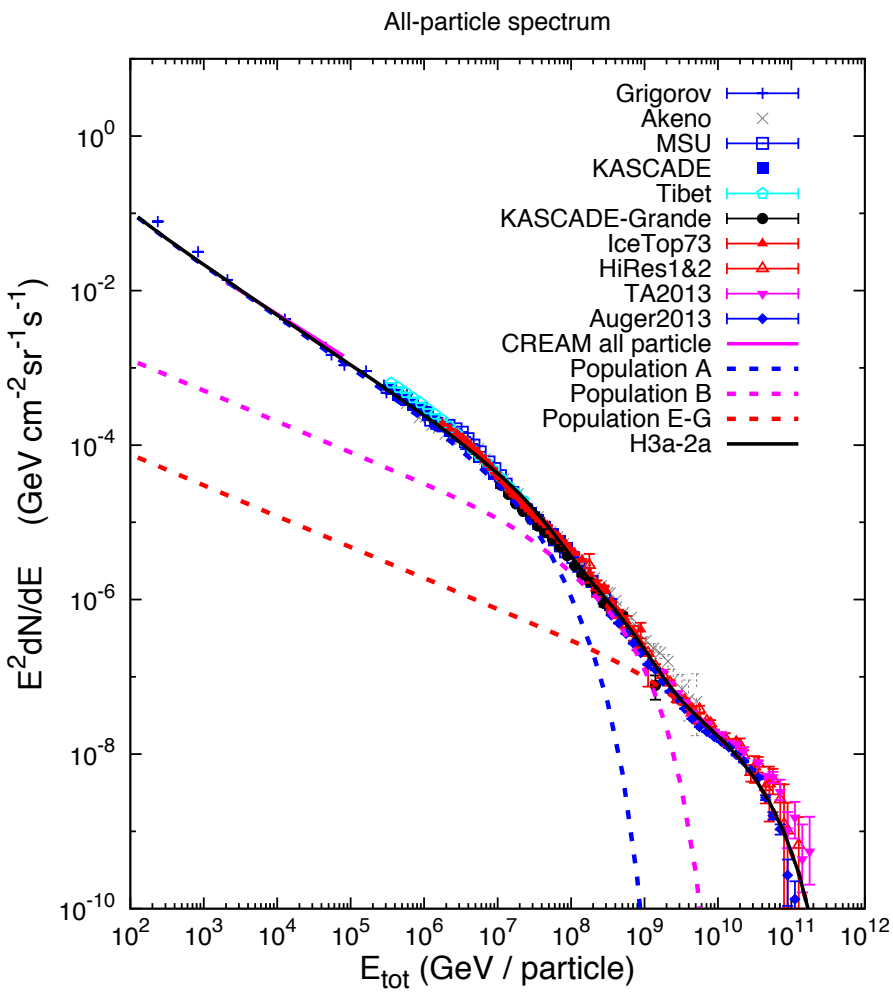


B. Peters, Il Nuovo Cimento 22 (1961) 800

2012

2 components is not enough





Plots of H3a model (TKG, Astropart. Phys. 35 (2012) 801)

July 2016

- Michael Hillas influenced my career
  - In several important ways
- My last meeting with Michael
  - I visited him at home in Guiseley
  - He told me of his work with Andrew Taylor