Michael Hillas and the Knee in the Galactic Cosmic Ray Spectrum

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- Michael mainly worked on air showers and thus mostly discussed particles with energies above the “knee” energy of about 3PeV.

- However as a good theorist he was well aware of the importance of lower energy particles and in particular he worried about the origin of the well know feature in the all-particle energy spectrum at 3PeV, the so-called “knee”.

- Published a series of papers throughout his long career.

At least 8 publications over 27 years

1	2006JPhCS..47..168H	1.000	10/2006	A Z E	R C U
	Hillas, A. M.	The cosmic-ray knee and ensuing spectrum seen as a consequence of Bell's self-magnetized SNR shock acceleration process			
2	2005JPhG...31R..95H	1.000	05/2005	A Z E	R C U
	Hillas, A. M.	TOPICAL REVIEW: Can diffusive shock acceleration in supernova remnants account for high-energy galactic cosmic rays?			
3	1999foap.conf..391H	1.000	00/1999	Z F G	T U
	Hillas, A. M.	What is happening in the region of the knee of the cosmic ray spectrum?			
4	1990AIPC..198...16H	1.000	01/1990	A Z E	T
	Hillas, A. M.	Experimental test of the anomalous density spectrum of cosmic ray showers, as an adjunct to the South Pole Air Shower Experiment?			
5	1989foap.conf..361H	1.000	00/1989	A Z F G	T C
	Hillas, A. M.	The phenomenology of cosmic rays above 100 TeV in relation to "frontier objects".			
6	1984hea..meet...11H	1.000	00/1984	A Z F G	T U
	Hillas, A. M.	Origin of ultra high energy particles			
7	1981ICRC....2..125H	1.000	00/1981	A Z F G	C
	Hillas, A. M.	Direct evidence for a preponderance of large primary particles at the 'knee' of the primary spectrum			
8	1979ICRC....8....7H	1.000	00/1979	Z F G	C
	Hillas, A. M.	The Knee of the Cosmic-Ray Spectrum: not a Magnetic Trapping Effect?			

First paper is from the Kyoto ICRC in 1979

THE KNEE OF THE COSMIC RAY SPECTRUM:
NOT A MAGNETIC TRAPPING EFFECT?

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ABSTRACT

It is shown that one obtains excellent agreement between the cosmic ray fluxes deduced from air showers, from direct measurements by the Proton satellites, and from muon fluxes, where these overlap, and that the fluxes of protons and iron nuclei obtained in a more model-dependent manner also fit very well onto low-energy data— provided that, in view of a systematic discrepancy of a factor 1.5 in shower sizes between the (old) Chacaltaya experiment and several others, one accepts results closer to the latter. These results exhibit again the steepening in the (calorimetric) energy spectrum near $2 . 10^{15}$ eV, but the steepening does not affect protons at the same magnetic rigidity as heavy nuclei.

Rather than being a consequence of magnetic trapping in and leakage from the Galaxy, the steepening may arise nearer the source, and may be the result of photodisintegration.

Michael's compilation of the then available data

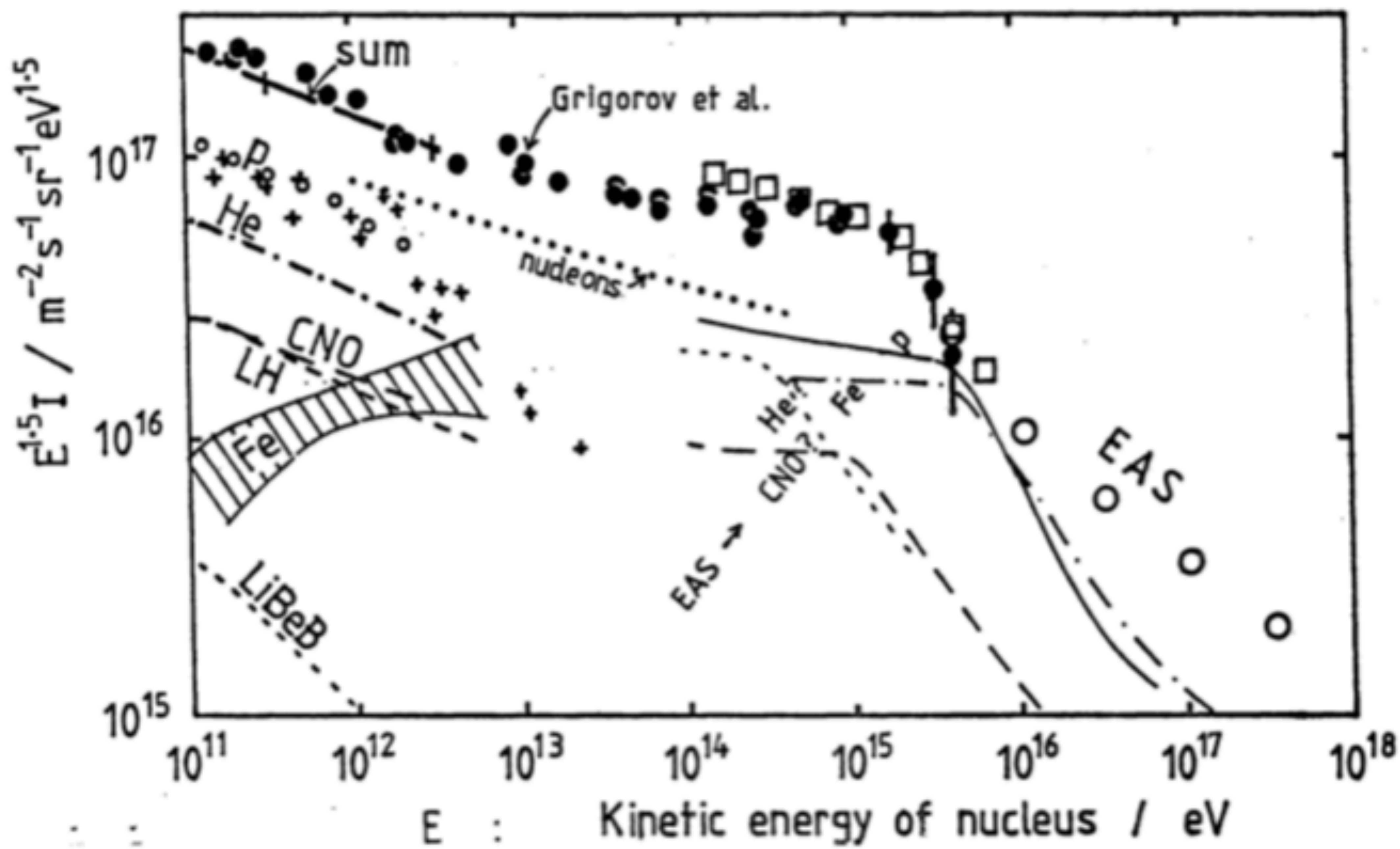

Fig. 2. The primary energy spectrum. (I is the integral flux)

Brave attempt

- Gets EAS data to fit the Grigorov data well by rescaling the Chacaltaya data.
- Tries to use electron and muon EAS data to get some handle on the composition.
- Concludes that the proton knee is at a higher rigidity than for the heavy nuclei, thus not a magnetic trapping (rigidity) effect!
- Suggests photo-disintegration as a possibility, but needs EUV or soft X-ray photons and unreasonable parameters.

Paris ICRC 1981 - a heavy knee!

DIRECT EVIDENCE FOR A PREPONDERANCE OF LARGE PRIMARY PARTICLES AT THE "KNEE" OF THE PRIMARY SPECTRUM

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ABSTRACT

Certain extremely simple air shower experiments, which have been shown to record the central few metres of showers, and which have been operated at different altitudes, show that dense shower cores disappear with astonishing rapidity with increasing depth in the atmosphere. The absorption length for the rate is $\lesssim 30\ g/cm^2$, and the primary particles must have a mean free path considerably shorter than this, independently of detailed models. (Different experiments agree on the short absorption length.) Evidently, at an energy just above 10^{15} eV, heavy primaries or at least particles of large cross-section predominate in the production of showers.

- Illustrates how difficult it is to extract compositional information from air shower data - still a problem today!
- Best current data does indicate that the knee is quite proton-poor, so the Paris paper is quite prescient.
- Interestingly no speculation about the cause of the knee in the Paris paper.

Three years later in 1984 at 4th Moriond meeting

ORIGIN OF ULTRA HIGH ENERGY PARTICLES

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The nature of the "knee" of the spectrum is also discussed. Although the variation in anisotropy is consistent with the interpretation in terms of a change in trapping lifetime (and a universal source spectrum $E^{-2.47}$), the size spectrum of showers clearly shows that the protons do not fall away at lower energy than do the heavy nuclei: so it is probable that the spectrum knee is (at least for heavy nuclei) a feature of the source, and not imposed by the failure of galactic trapping.

- Suggests that anisotropy data can be used as a proxy for the energy dependence of the escape time.
- Considers possibility that the knee is just the result of a more rapid escape from the galaxy setting in.
- If so need sources producing a single power-law all the way up to 10EeV - introduces famous Hillas plot.
- Notes however that this model has clear implications for composition which do not seem to fit the EAS properties.

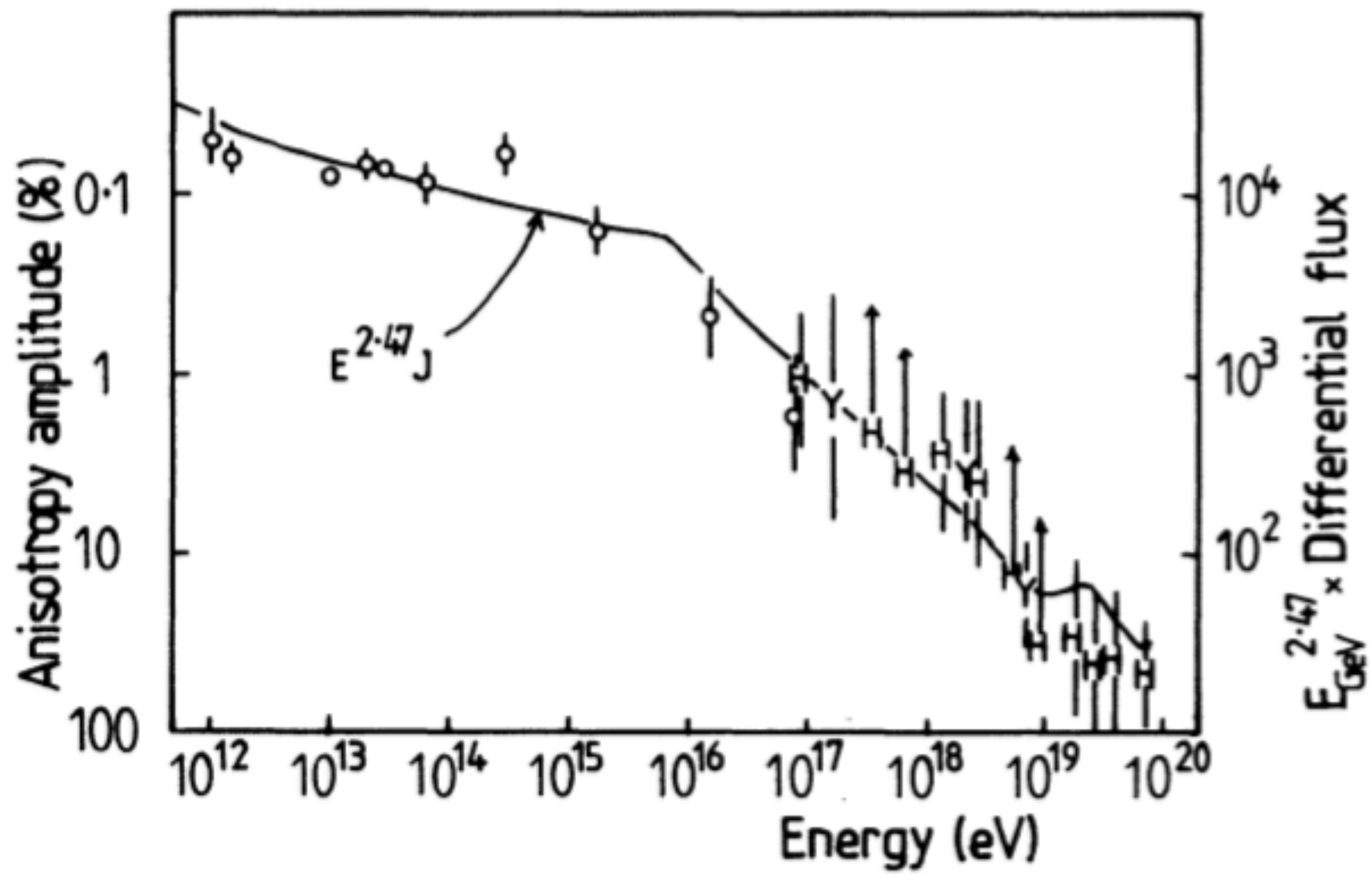

Figure 2. Correlation between anisotropy (amplitude of first harmonic) and particle flux.

Thus if we use the variation of anisotropy with energy as a measure of the variation in trapping time, we find that all the observations are consistent with a *simple power-law source spectrum* $E^{-2.47}dE$ *from* 10^{12} *eV to* 10^{19} *eV!* (This may be compared with $E^{-2.44}dE$ deduced at lower energies: see paper by Koch-Miramonc in these proceedings.)

The "Hillas plot" shown at Moriond

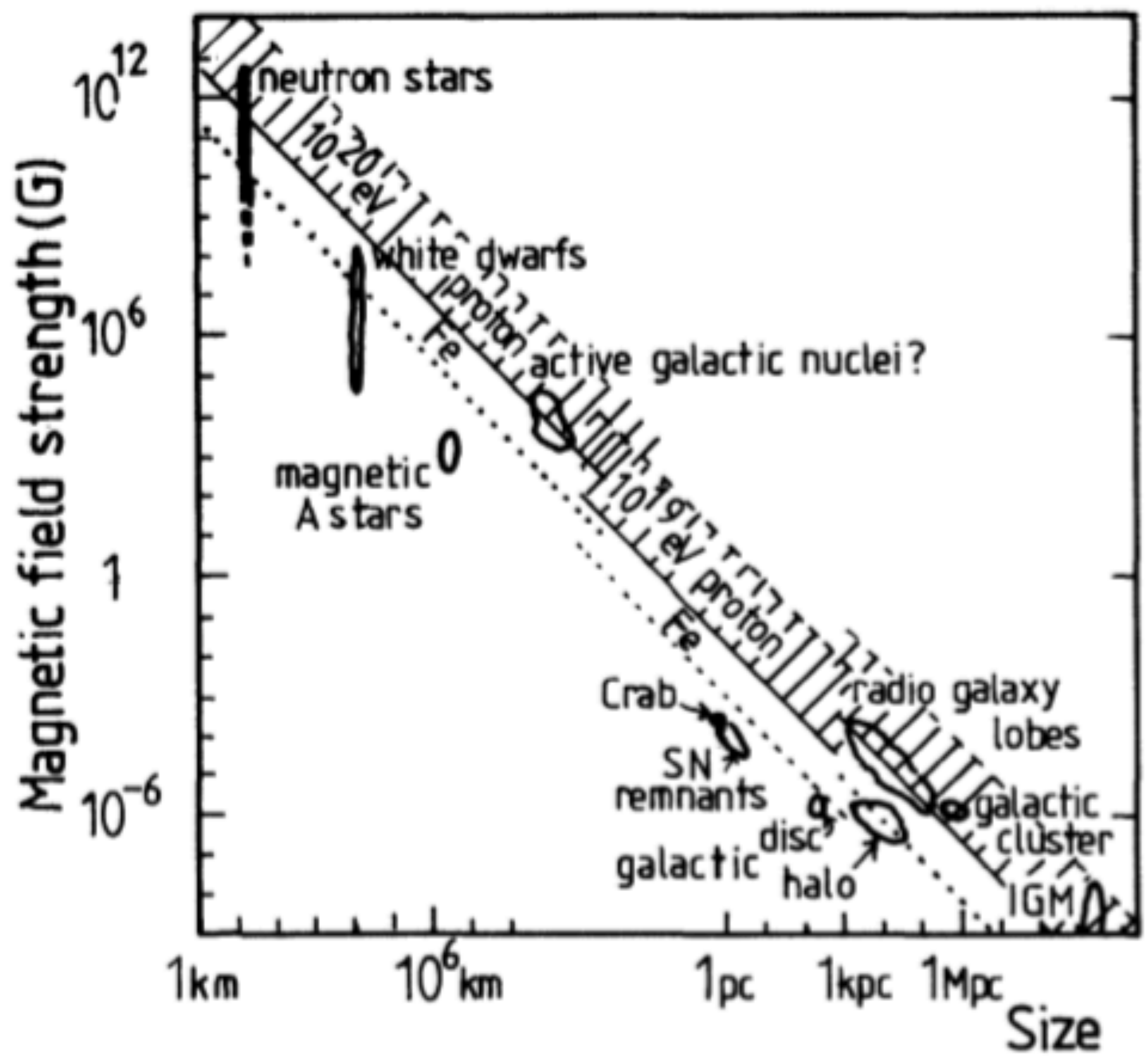

Figure 3. Size and magnetic field strength of sites where cosmic rays might possibly be accelerated to ultra-high energies. To accelerate protons to 10^{20} or 10^{19} eV (as indicated) the object must not lie below the diagonal band (lower edge of band if plasma is relativistic - upper edge if speeds are 1000 km s^{-1}).

However…

III.2 Is the knee of the spectrum really related to trapping?

For different nuclear species, is $E_{knee} \propto Z$?

This is required if the knee marks the onset of more rapid escape from the galaxy, as discussed in the leaky box model in part I. The Maryland group has argued for an "early" knee: E_{knee}(protons) $\sim 2.10^{14}$ eV - with correspondingly higher knee energies for other nuclei - e.g. E_{knee}(Fe) $\sim 5.10^{15}$ eV. (And at this meeting, Yodh is pursuing this interpretation.)

However, such a rigidity-dependent bend in the spectrum should leave very distinctive traces in the shower size spectrum, which are not seen.

In conclusions…

Thus, there should be interesting diagnostic features present in the spectrum near the knee, if different nuclear species can be separated.

Vulcano workshop, 1988

THE PHENOMENOLOGY OF COSMIC RAYS ABOVE 100 TEV
IN RELATION TO "FRONTIER OBJECTS"

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Summary

The energy spectrum of primary cosmic ray particles can now be drawn out from 10^{11} to above 10^{19} eV, and exhibits several distinct domains. The contribution of individual nuclei to the flux remains puzzling in many regions, however. The well-known "knee" in the spectrum might be due to onset of more rapid escape, or to limitations in the accelerator, or to effects of loss processes. On the basis of nuclear composition, anisotropy and a single bend, the first (traditional) explanation seems less attractive, and one sees the likelihood of a second source becoming dominant between 10^{15} and 10^{19} eV, in agreement with Fichtel and Linsley. The possibility that the "gamma ray point sources" are relevant is considered. Also the possibility that anomalies in effects of radiation from these objects points to poor understanding of air shower development, and hence to the contradictions in attempts to deduce the nuclear composition, is pointed out.

- Includes a reference to a mysterious O'Drury who appears to have worked on acceleration theory!
- Points out all the problems identified earlier.
- Speculates about the possibility of a new source related to the then current claims of UHE gamma-rays from some binary neutron star systems (Cyg X-3, Her X-1, Vela X-1)
- Also considers possible role of a Galactic wind terminal shock

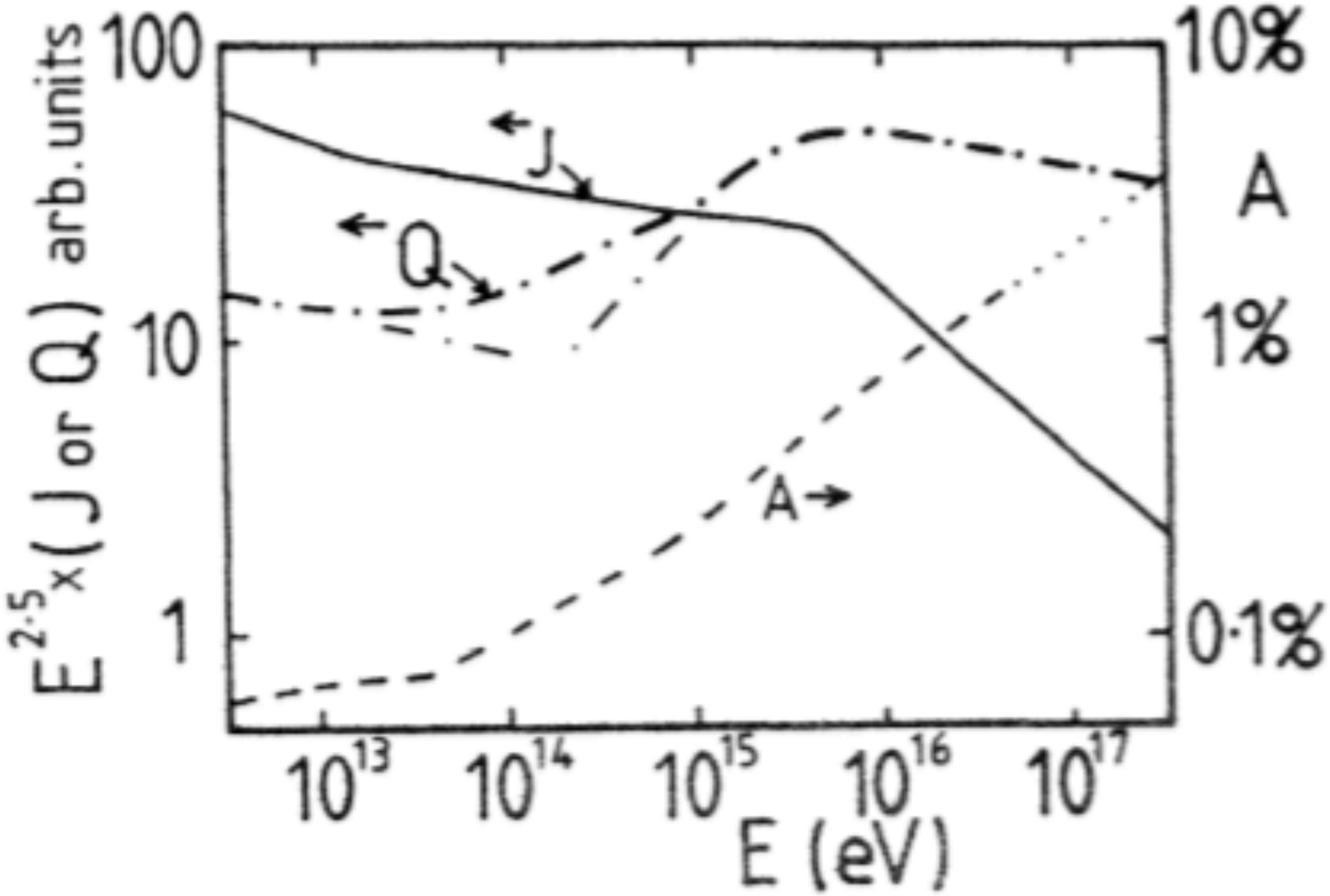

Figure 3. Form of source spectrum Q(E) deduced from local energy spectrum J(E) if trapping time is correctly indicated by the anisotropy A (i.e. $T \propto 1/A$). A proton-rich component from a second source may be important above 10^{15} eV.

Revisited ten years later in Vulcano 1998

Conference Proceedings Vol. 65
«Frontier Objects in Astrophysics and Particle Physics»
F. Giovannelli and G. Mannocchi (Eds.)
SIF, Bologna,1999

WHAT IS HAPPENING IN THE REGION OF THE KNEE OF THE COSMIC RAY SPECTRUM?

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The argument of this paper will be that whereas it is hard to find a substitute for supernovae to inject the cosmic rays into the galaxy, the current models of supernova remnants and their acceleration of relativistic particles still require changes, to take the maximum energy to the region of 10^{17} eV for protons, and to generate a spectrum falling more like $E^{-2.4}$ than $E^{-2.1}$.

Although this model of SNR development and particle acceleration has received the most detailed examination, it is not the only one. A different model of acceleration of particles has been suggested by Biermann (1993), in which postulated details of diffusion of particles within the SNR during acceleration alter the spectrum generated, which becomes $E^{-2.42}$ for protons, and Völk and Biermann (1988) had shown that for a SNR expanding into a stellar-wind cavity instead of a uniform medium the maximum energy could be increased.

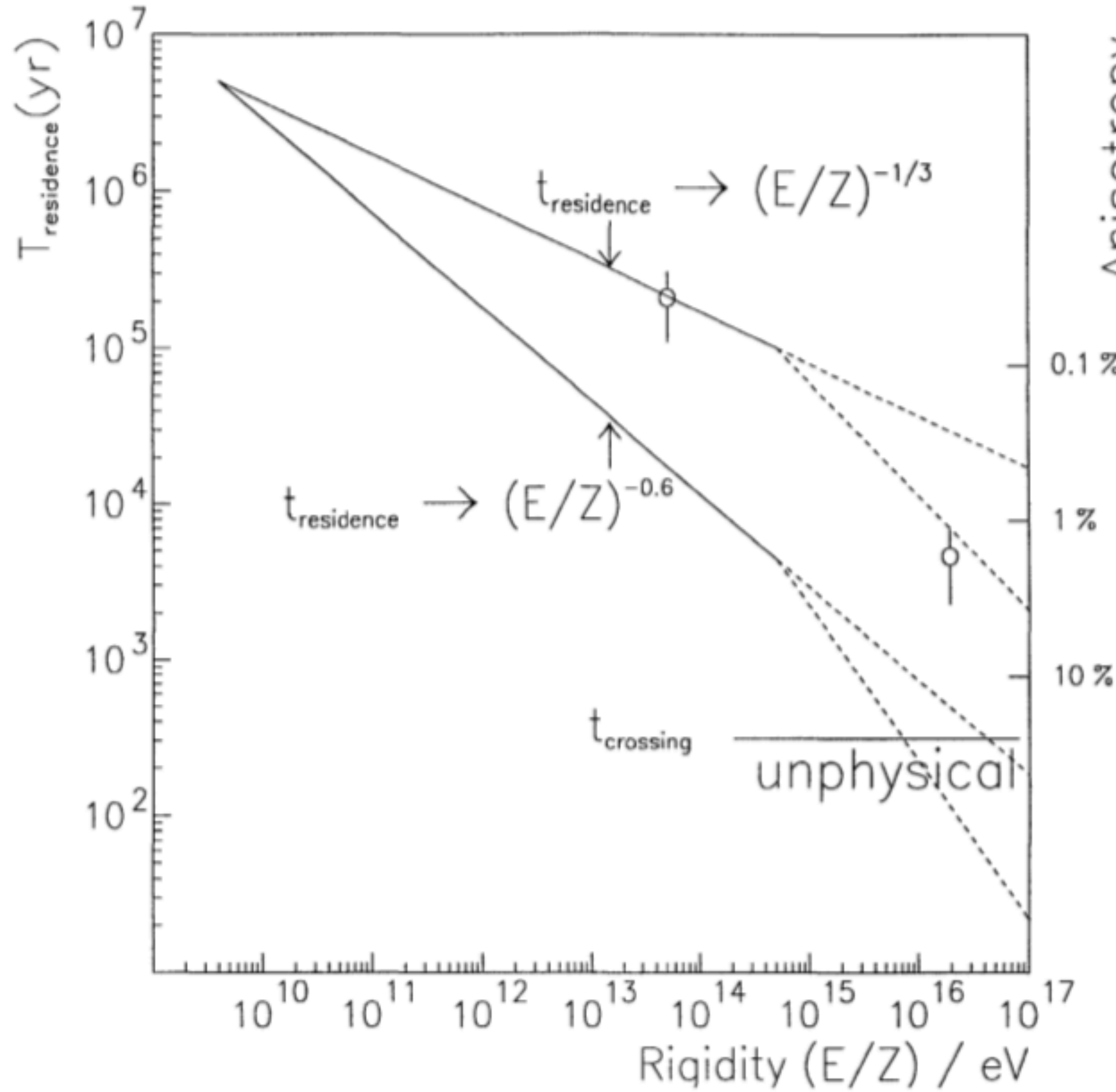

Figure 1: *Energy dependence of residence time and anisotropy. Points refer to anisotropy, observed at* 1.5×10^{14} *eV, plotted taking an effective Z of 3, and* 1.5×10^{17} *eV, plotted taking an effective Z of 8.*

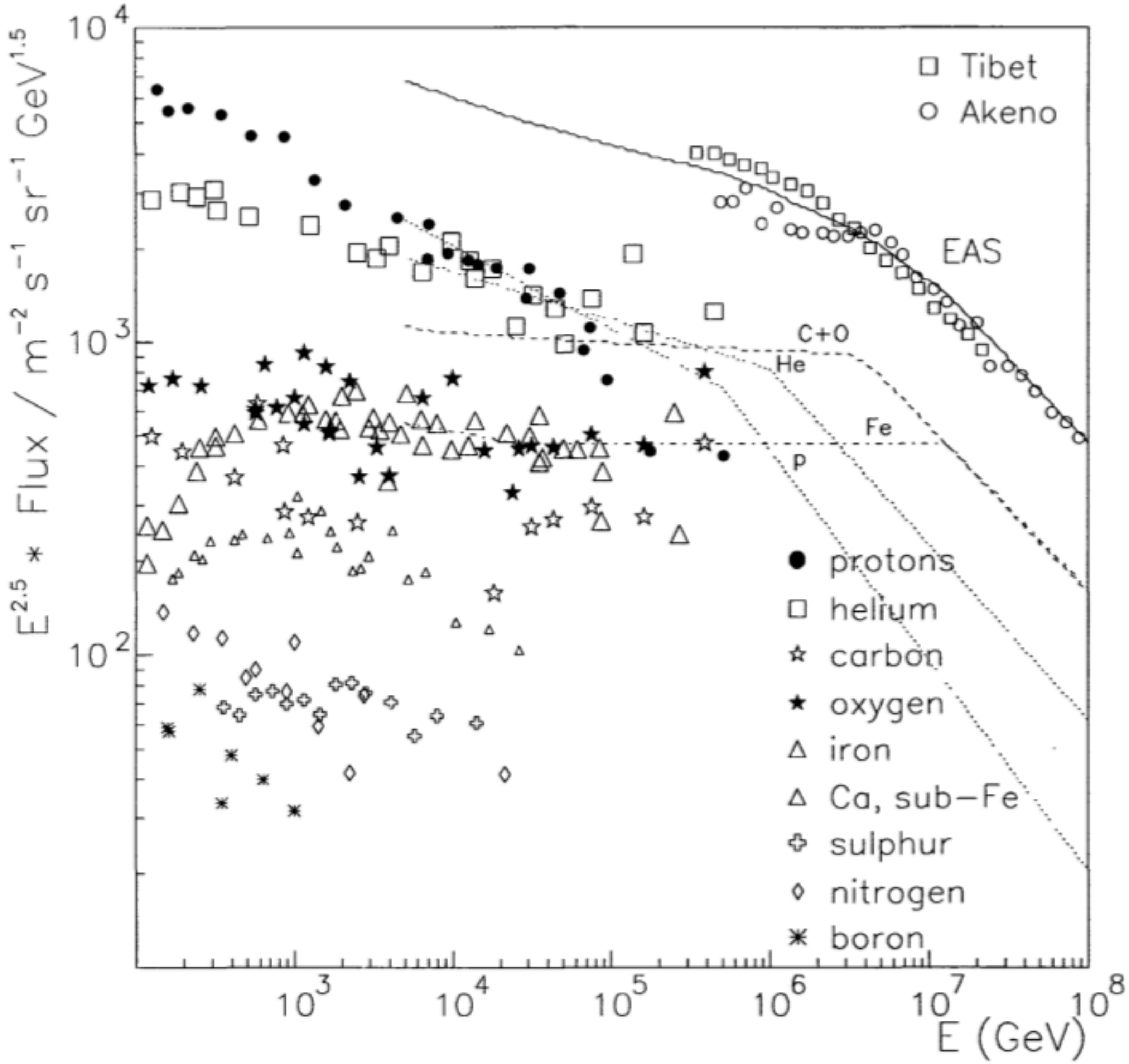

Figure 3: *Spectra of various nuclei (data points), and continuation (lines), with slope change of 0.4 at 500 TeV/nucleon. Full line gives all-particle sum.*

Note assumption of softer proton spectra - long before Pamela and AMS-02 results!

The "knee" is most likely to be a propagation effect, according to the anisotropy evidence. When one compares the air shower spectrum with the spectra of individual elements at somewhat lower energies, one sees that the prominent bend in the all-particle spectrum probably marks the bend in the carbon+oxygen component, if the bend is very sharp, as indicated by the Akeno or Moscow spectra, but if the knee is more rounded, as seen in the Tibet spectrum, the curve covers the region of the bends in individual spectra of helium, carbon-oxygen and iron. The proton flux has already fallen, relative to other elements, before the knee is reached, and so a distinct bend due to the proton component is unlikely to be at all prominent.

A simple simulation of diffusion suggests that with the lifetimes envisaged here, there is $\sim 10\%$ chance that one SNR could dominate the local cosmic ray flux at the present time, and a similar chance that two SNR might produce more than half the flux, in which case we may perhaps be misled about the typical output of SNR by our observations.

Final paper, published 2006, given in 2005

PHYSICS AT THE END OF THE GALACTIC COSMIC RAY SPECTRUM
26–30 April 2005, Aspen, Colorado, USA

The cosmic-ray knee and ensuing spectrum seen as a consequence of Bell's self-magnetized SNR shock acceleration process

To cite this article: A M Hillas 2006 *J. Phys.: Conf. Ser.* **47** 168

Essentially what most of us believe now….

Abstract

Bell's version of diffusive shock acceleration in supernova remnants, in which the (highly contorted) magnetic field is mainly self-generated by the accelerated particles, seems to explain the sharpness of the knee in the cosmic ray spectrum (an effect of the limitation of acceleration in the source), despite contributions from very many supernovae; and the expected knee has a sharp drop near 3 PV rigidity for each nuclear species, and then a lower rounded shoulder extending towards 100 PV contributed by some of the type II SNRs. It is shown that the allparticle flux determined by very different techniques in air shower observations defines a very precise spectrum, below 10^{19} eV, and this spectrum is discussed in terms of separate nuclear components of Galactic and extragalactic origin. An extragalactic component with similar source spectrum to the Galactic component is favoured, but a helium/hydrogen mixture and a pure proton flux from the extragalactic sources have different attractions, and offer different tests through composition, even below 10^{18} eV.

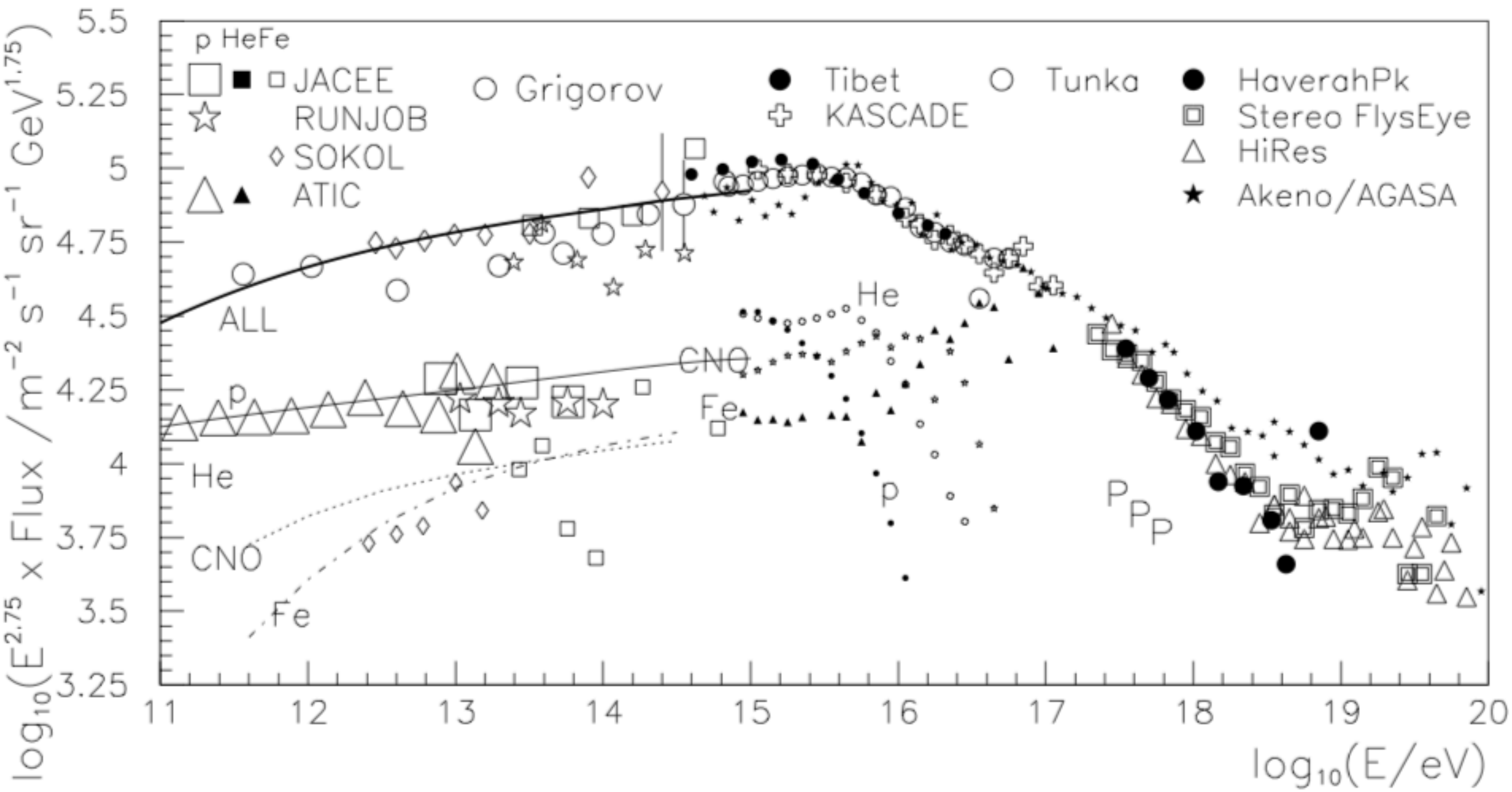

Figure 1. Showing the well-defined shape of cosmic ray energy spectrum above 10^{15} eV derived from air shower experiments using several different approaches to energy measurement, forming a continuous extension of the spectrum obtained from (mainly) balloon-borne experiments at $10^{11}-10^{15}$ eV. At the latter energies, spectra of some individual nuclear groups are shown by lines (He may be a little too high), with a few data points for p, He (filled points) and Fe. Above 10^{15} eV, the small circles (p,He), stars (CNO) and triangles (Fe) show the provisional decomposition of the flux into 4 nuclear groups by KASCADE (15). ppp marks a proton component deduced by Haverah Park (16).

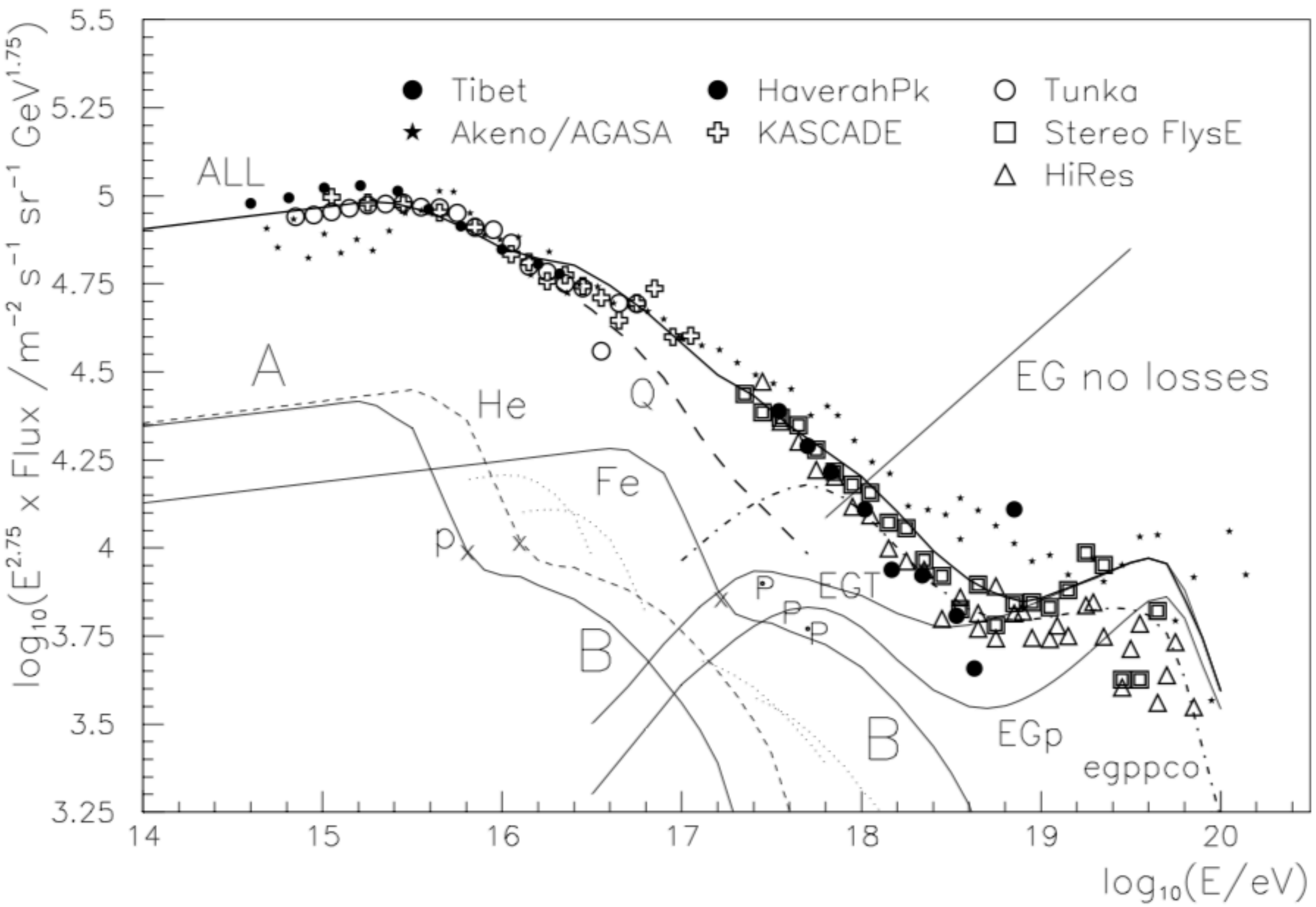

Figure 2. The cosmic ray spectrum as the sum of galactic H, He, CNO, Ne-S and Fe components each having the same rigidity dependence, plus extragalactic H + He (total EGT) having a spectrum $\propto E^{-2.3}$ (and $E_{max} = 10^{22}$ eV) before suffering losses by CMBR and starlight interactions. The galactic components were given a turn-down shape based on KASCADE knee shape as far as the point marked x. The dashed line Q is the total without adding the supposed extended tail B of the galactic flux. The dot-dash line "egppco" above 10^{17} eV refers to an alternative pure proton extragalactic component, with an exponential source cut-off applied at 10^{20} eV to reduce the pile-up peak near 5×10^{19} eV. (Although not shown, such a component could match the total flux even to rather lower energy, without need for a Galactic "B" bump, if the extragalactic sources had a steeper spectrum, say $\sim E^{-2.5}$.)

What can we learn from Michael's long attempt to understand the knee?

- Always data-driven with no cherry-picking - used all available evidence.
- Prepared to consider exotic ideas and non-standard models.
- Persistence - he kept returning to this problem and refining his ideas all through his life.
- A model of how science should be conducted, but rarely is!