INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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SCHOOL ON
NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

LARGE EXISTING UNDERGROUND DETECTORS (3)

BY

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LARGE EXISTING UNDERGROUND DETECTORS
PART III

COSMIC RAY PHYSICS WITH UNDERGROUND MUONS & MUON BUNDLES

- THE SCOPE OF UNDERGROUND DETECTORS IN COSMIC RAY PHYSICS.
- POINT-LIKE SOURCES.
  - ν Sources (High Energy)
  - γ-ray Sources ? Exotic sources ?
- MUON BUNDLES & CHEMICAL COMPOSITION IN THE PeV RANGE.
  - Sensitivity to primary composition.
  - Recent FRÉJUS results.

THE SCOPE OF UNDERGROUND DETECTORS IN COSMIC-RAY-PHYSICS

ORIGIN OF HIGH ENERGY COSMIC RAY ?

- USE NEUTRINOS (OR γ-RAYS ?):
  - UNSENSITIVE TO GALACTIC MAGNETIC FIELDS
  - POINT BACK TO THEIR SOURCES

ACCELERATED PROTONS
+ NEARBY MATTER
$$\downarrow \qquad \downarrow \qquad \downarrow$$
$$\pi^0 \qquad \pi^\pm \qquad K^\pm \ldots$$
$$\downarrow \qquad \downarrow \qquad \downarrow$$
$$\gamma\gamma \qquad \mu\nu \qquad \mu\nu \ldots$$

- UNDERSTAND E SPECTRUM & CHEMICAL COMPOSITION OF ORDINARY CHARGED PRIMARIES.
  IN THE ENERGY REGION NOT ACCESSIBLE TO DIRECT MEASUR^T. (FLUX TOO LOW).
  UNDERSTAND THE "KNEE" OF THE SPECTRUM.
  UNDERGROUND REMNANTS OF THE MOST ENERGETIC AIR SHOWERS = MUON BUNDLES.

WARNING: REQUIRE PARTICLE PHYSICS ABOVE ACCEL^e ENERGIES:

PROTONS	$E_{CR} > 1700$ TeV
HEAVY IONS	$E_{CR}/A > 200$ GeV/nucl
γ AND ν	

THE SCOPE OF UNDERGROUND DETECTORS IN COSMIC RAY PHYSICS

- ONE EXPECTS MUONS & NEUTRINOS, UNDERGROUND REMNANTS FROM EXTENSIVE AIR SHOWERS.

ATMOSPHERIC MUONS
- SINGLE MUONS : Depth vs Intensity $I(h)$
- MUON BUNDLES : Primary Energy in PeV range if $h \sim 4000 - 5000$ m.w.e.

(ALL DOWN-GOING ↓)

ATMOSPHERIC NEUTRINOS
- Vertex-contained events — already discussed
- THROUGH-GOING μ's GENERATED BY ν INTERACTIONS IN THE ROCK
- PART IS UPWARD-GOING ($10^{-12}\ cm^{-2} s^{-1}$)

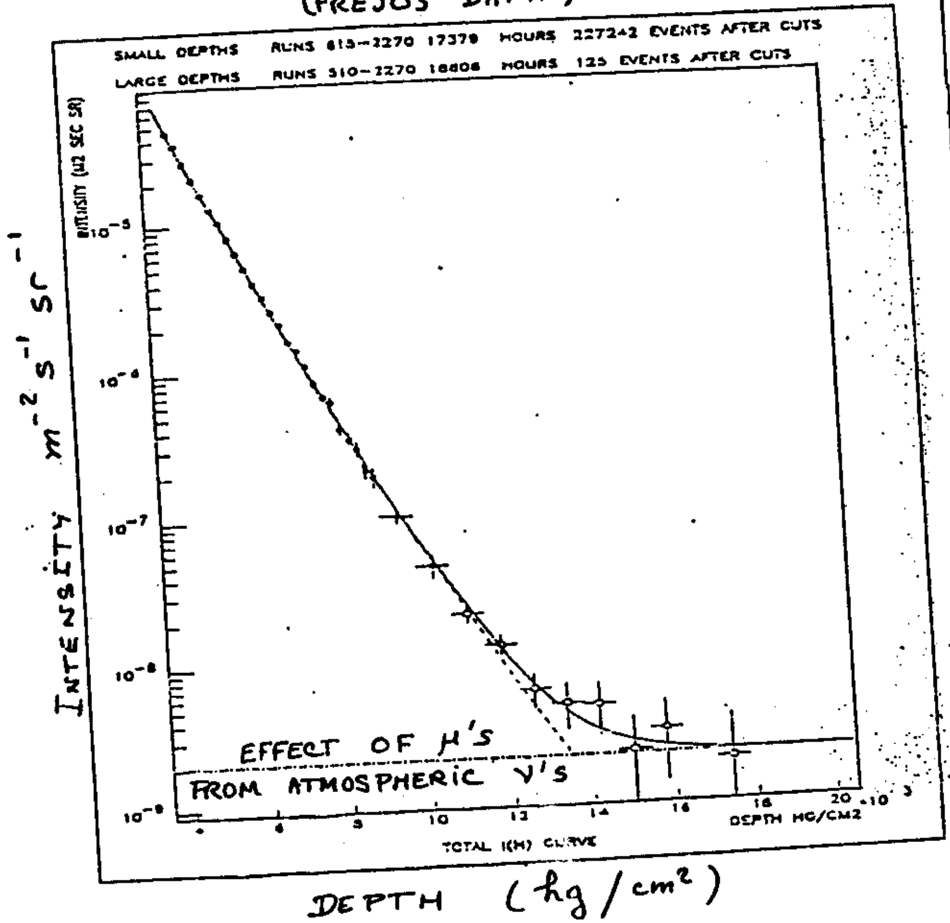
- EXTRA-TERRESTRIAL POINT-LIKE SOURCES OF COSMIC RAYS

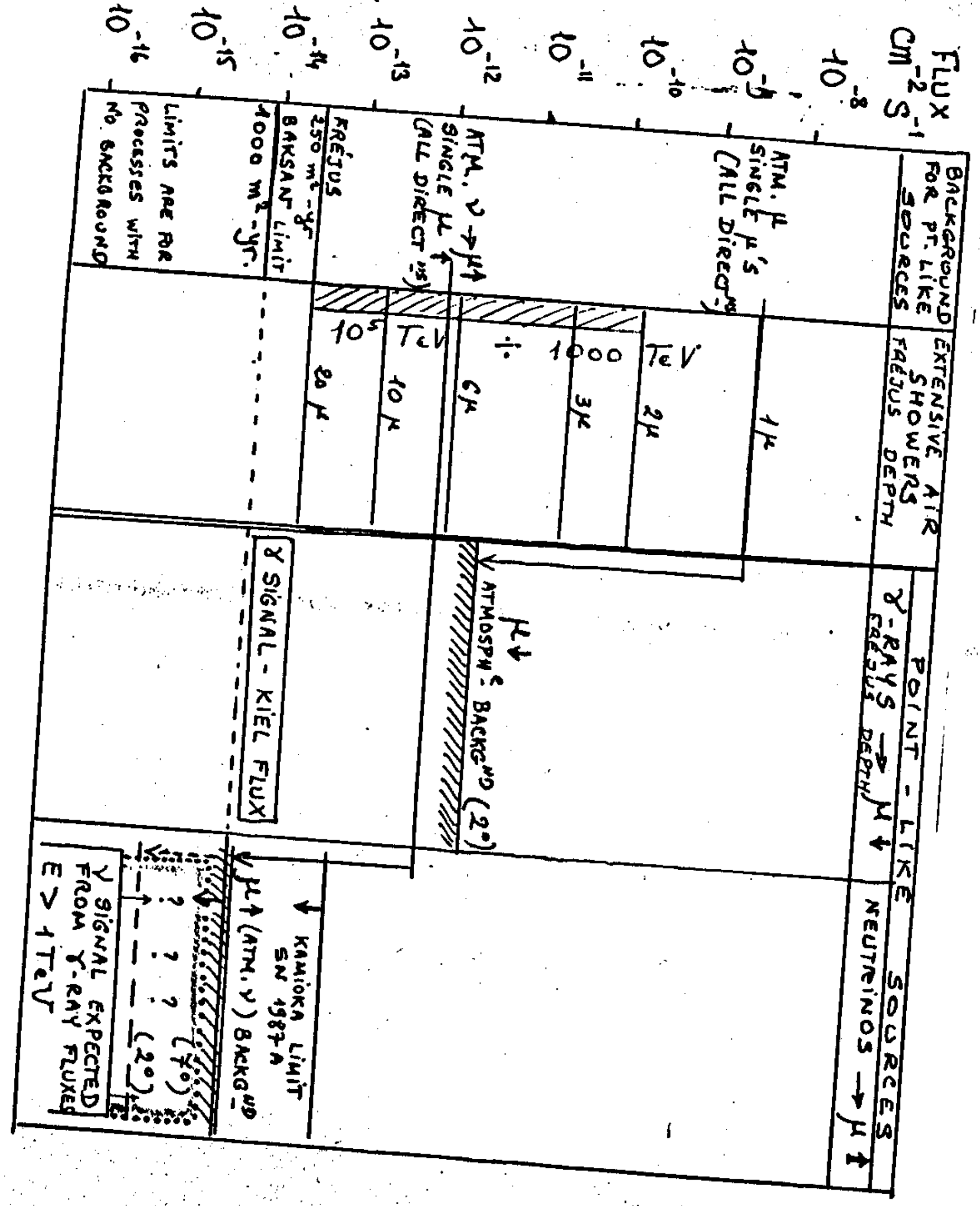
NEUTRINO SOURCES : DISCRIMINATE AGAINST ATMOSPHERIC NEUTRINOS
Use UPW^D GOING μ's (μ↑)
SOURCES IN SOUTHERN HEMISPH. (SN 1987 A)
BACKG^ND : μ↑ FROM ATM^C NEUTRINOS WITHIN ANGULAR RESOLUTION

GAMMA-RAY SOURCES : DISCRIMINATE AGAINST ATMOSPH^C MUONS (μ↓) WITHIN ANGULAR RESOLUTION
IF γ-RAY SHOWERS PRODUCE ENOUGH MUONS

ATMOSPHERIC MUONS

VERTICAL INTENSITY VS. DEPTH (FRÉJUS DATA)





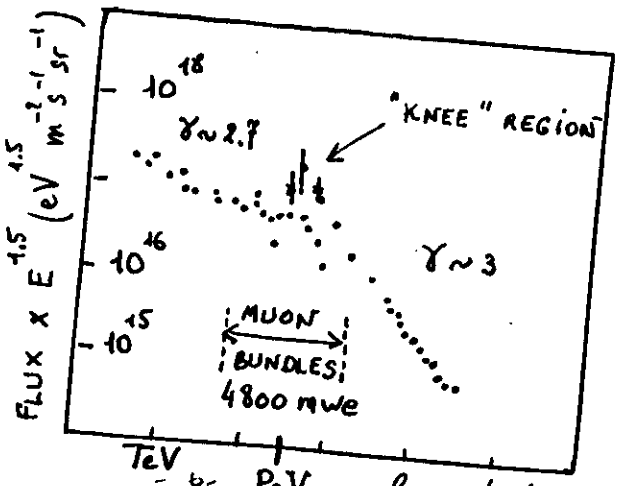
- EXTRA - TERRESTRIAL SOURCES OF COSMIC RAYS.

  * Other possibility of discrimination against background
  Time structure of signal (e.g. periodicity) if known from other spectroscopy:
  e.g. Cyg. X 3 is a PERIODIC SOURCE IN X-RAY AND INFRA-RED ASTRONOMY.

- MUON BUNDLE PHYSICS.

  WHEN THE SITE DEPTH is $\gtrsim$ 3500 mwe MUON BUNDLES ARE PRODUCED BY PRIMARIES IN THE "KNEE" REGION (PeV RANGE).

  { CHEMICAL COMPOSITION OF COSMIC-RAYS (PeV RANGE)
  vs.
  PARTICLE PHYSICS IN PeV RANGE.



$$\frac{d\phi}{dE} = \frac{K}{E^{\gamma}}$$

POINT-LIKE SOURCES.

NEUTRINOS

- ONE MEASURES A FLUX OF UPWARD-GOING μ's $\Phi_{\mu\uparrow}$

- IN ORDER TO RELATE IT TO THE NEUTRINO FLUX Φ_ν, ONE MUST MAKE AN ASSUMPTION ON THE ν SPECTRUM.

  USUALLY: $$\frac{d\Phi_\nu}{dE_\nu} = \frac{K}{(E_\nu)^\gamma}$$

  γ = SPECTRAL INDEX ; POSSIBLE CUT-OFF ENERGY

- NEUTRINO INTERACTION IN THE ROCK:

  $\left\{ \begin{array}{l} \nu\text{-}\mu \text{ ANGLE } \theta \text{ AT VERTEX} \\ \text{MUON ENERGY AT VERTEX} \end{array} \right.$

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi}\left[\frac{1}{1+\frac{2ME_\nu xy}{M_W^2}}\right]^2 \left\{ \left[1-y+\frac{y^2}{2}\right]F_2(x,q^2) \pm \left[y-\frac{y^2}{2}\right]xF_3(x,q^2) \right\}$$

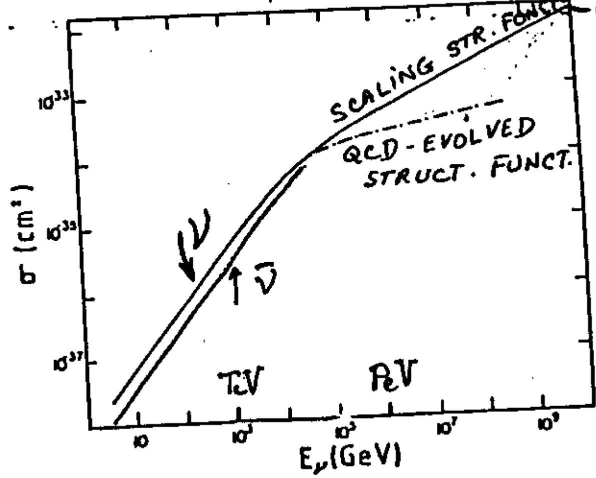
$$x = \frac{q^2}{2M(E_\nu - E_\mu)} \quad ; \quad y = 1 - \frac{E_\mu}{E_\nu}$$

$$\theta \approx \sqrt{\frac{2Mxy}{E_\nu(1-y)}} \quad (x \sim 0.1 \; ; \; y \sim 0.5)$$

$$\approx 2{,}5^\circ \sqrt{\frac{100\,\text{GeV}}{E}}$$

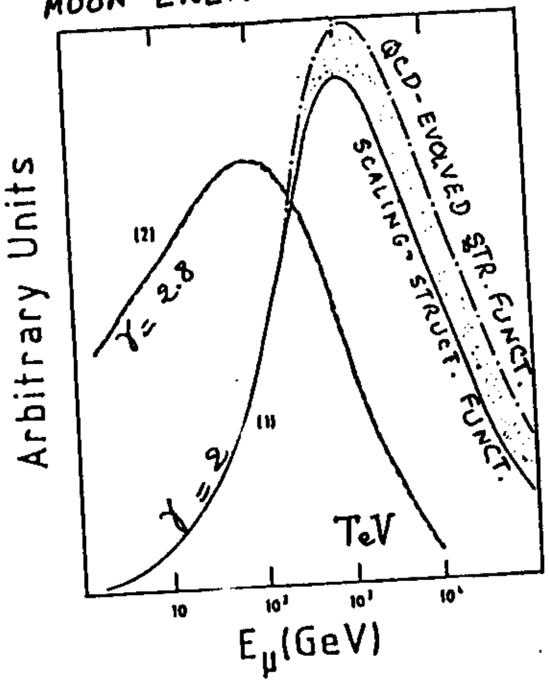
IF $S = 2ME_\nu \gg M_W^2$ ($E_\nu \gg 3.6$ TeV)
W PROPAGATOR RESTRICTS Q^2 UP TO $\sim M_W^2$
SMALL $\{x, y\}$ FAVOURED → KNOWLEDGE OF STRUCTURE FUNCTION AT SMALL x

$\nu\,\bar{\nu}$ CROSS SECTIONS



FROM T. GAISSER & A. GRILLO Phys. Rev D36 (1987) 2752

MUON ENERGY AT DETECTOR



DETECTION OF ν-INDUCED MUONS

NEUTRINO SOURCES

- MUON PROPAGATION IN THE ROCK UP TO THE DETECTOR.

  - ENERGY LOSS (pair production, bremsstrahlung, nuclear inter.^{s}, ionisation)
  - MULTIPLE SCATTERING

  → MUON DIRECTION AT THE DETECTOR: Angle (ν, Detected μ) — ANGULAR RESOLUTION
  → MUON ENERGY AT THE DETECTOR.

ONE DEFINES AN **ANGULAR WINDOW** AROUND THE DIRECTION OF THE SOURCE. The preceding calculations yield THE ACCEPTANCE OF THIS ANGULAR WINDOW AS A FUNCTION OF THE SPECTRAL INDEX γ.

* EFFECTIVE TARGET MASS is PROPORT.^{L} TO $\sigma_\nu(E) \times \underbrace{R(E_\mu)}_{\text{MUON RANGE}}$

- WHAT COULD BE THE ORDER OF MAGNITUDE OF A GENUINE NEUTRINO SIGNAL ?
  - FROM A REVIEW OF γ-RAY SOURCES ($E_\gamma > 1\,TeV$) (D. FEGAN, MORIOND '87) $\Phi_\gamma \approx 10^{-10}\ cm^{-2} s^{-1}$
  - ASSUME THAT THIS FLUX HAS NOT BEEN ATTENUATED DURING PROPAGATION → EARTH (PESSIMISTIC)
    ASSUME $\Phi_\nu \approx \Phi_\gamma$ AT SOURCE
  - ASSUME A POWER-LAW SPECTRUM $\frac{d\Phi_\nu}{dE_\nu} \propto \frac{1}{E_\nu^{\gamma}}$ (γ IN THE RANGE 2.1 TO 3.5)

THEN $\mu\uparrow$ SIGNAL $\sim 6\ 10^{-16}\ cm^{-2} s^{-1}$ | MORE, IF γ-RAY FLUX IS ATTENUATED

NEUTRINO SOURCES
& UPWARD-GOING MUONS
EXPERIMENTAL RESULTS

BACKGROUND : $\mu\uparrow$ FROM ATMOSPHERIC NEUTRINOS
$(\Phi_{\mu\uparrow})_{Atm.\,\nu} \sim 10^{-12}\ cm^{-2} s^{-1}$
* FRACTION IN ACCEPTANCE WINDOW

- THIS YEAR ('87 - '88) : SN 1987 A.
  KAMIOKANDE (Phys. Rev. Lett. 59 (1987) 2604)
  FIRST SIX MONTHS.
  $E_\mu > 1.7$ GeV   Window : 7°
  $\Phi_{\mu\uparrow} < 1.2\ 10^{-13}\ cm^{-2} s^{-1}$
  * Note that background is $\sim 10^{-14}\ cm^{-2} s^{-1}$
  Present limit is an order of magnitude higher.

- LIMITS FROM BAKSAN (MORIOND '87, Mikheiev) FOR OTHER POINT-LIKE SOURCES
  BAKSAN : Sensitivity = 1000 m^2 × years
  377 $\mu\uparrow$ in 5 years
  $\Phi_{\mu\uparrow} \lesssim 10^{-14}\ cm^{-2} s^{-1}$

- WITH A GOOD ANGULAR RESOLUTION (~ 2°)
  BACKGND $\sim 6 \times 10^{-16}\ cm^{-2} s^{-1}$ may be comparable to or lower than expected ν signal. 1000 m^2 REQUIRED (MACRO)

POINT-LIKE SOURCES
γ-RAYS & EXOTICS

- STANDARD PHYSICS PREDICT :

γ-RAY SHOWER = MUON-POOR SHOWER
CALCULATION : T. STANEV (Phys Rev D 33, 2740 1986)

100 TeV γ-ray PRODUCES ON AVERAGE
$\sim 10^{-3}$ MUON WITH $E_\mu > 2$ TeV

* KIEL SURFACE ARRAY claimed a periodic signal from Cyg X 3 with significant muon content. (NOT CONFIRMED)
EVEN IF THE OPTIMISTIC FLUX GIVEN BY KIEL IS CHOSEN : $6\ 10^{-7}\ cm^{-2} s^{-1} \left(\frac{E_\gamma}{1\,GeV}\right)^{-1.11}$
FOR ENERGIES $> E_\gamma$

$$\frac{\text{MUON SIGNAL (from γ's)}\downarrow}{\text{ATMOSPH}^{C}\text{ MUON BACKG}^{ND}\downarrow} < \frac{1}{150}$$

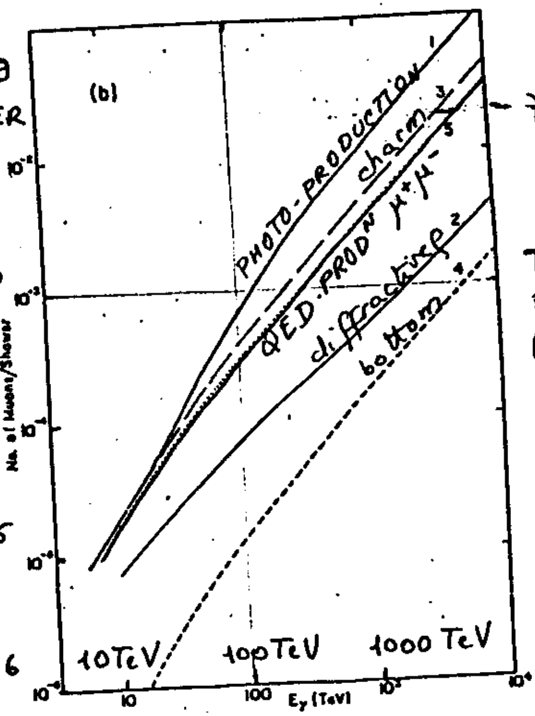
for angular window of 1° at 4000 mwe

NO HOPE IF NO EXOTIC γ INTERACTION IN THE TeV RANGE

- EXOTIC PHENOMENA ?
  - Exotic γ-interactions $E_\gamma >$ TeV ?
  - Exotic neutral particles ?

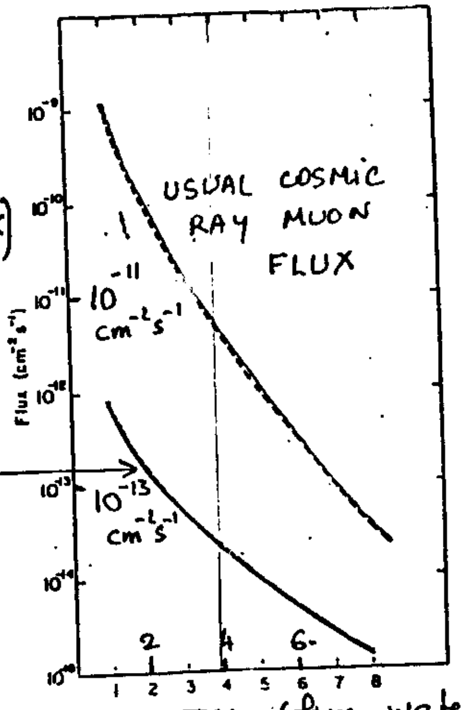
INVOKED TO ACCOUNT FOR PERIODIC MUON SIGNALS SEEN BY SMALL UNDERGND DETECTORS IN 1985 (SOUDAN I + NUSEX)
BUT SIGNAL NOT CONFIRMED BY LARGE DETECTORS (KAMIOKA / FRÉJUS) IMB : possible optimized signal in 1983 radio-burst

MUON YIELD PER γ-SHOWER $E_\mu > 2$ TeV



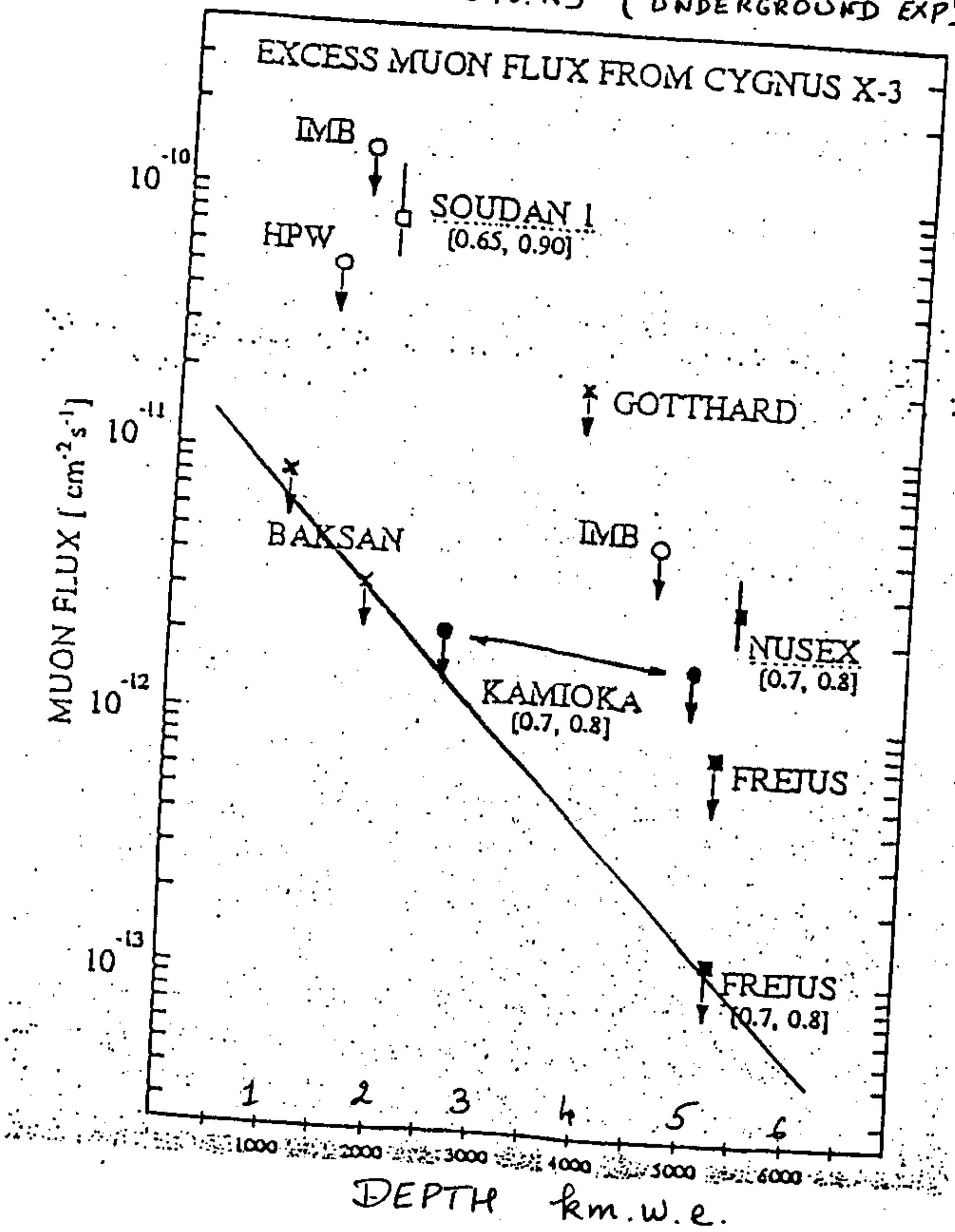
γ-RAY INDUCED MUONS from T. STANEV Phys Rev D33 (1986) 2740

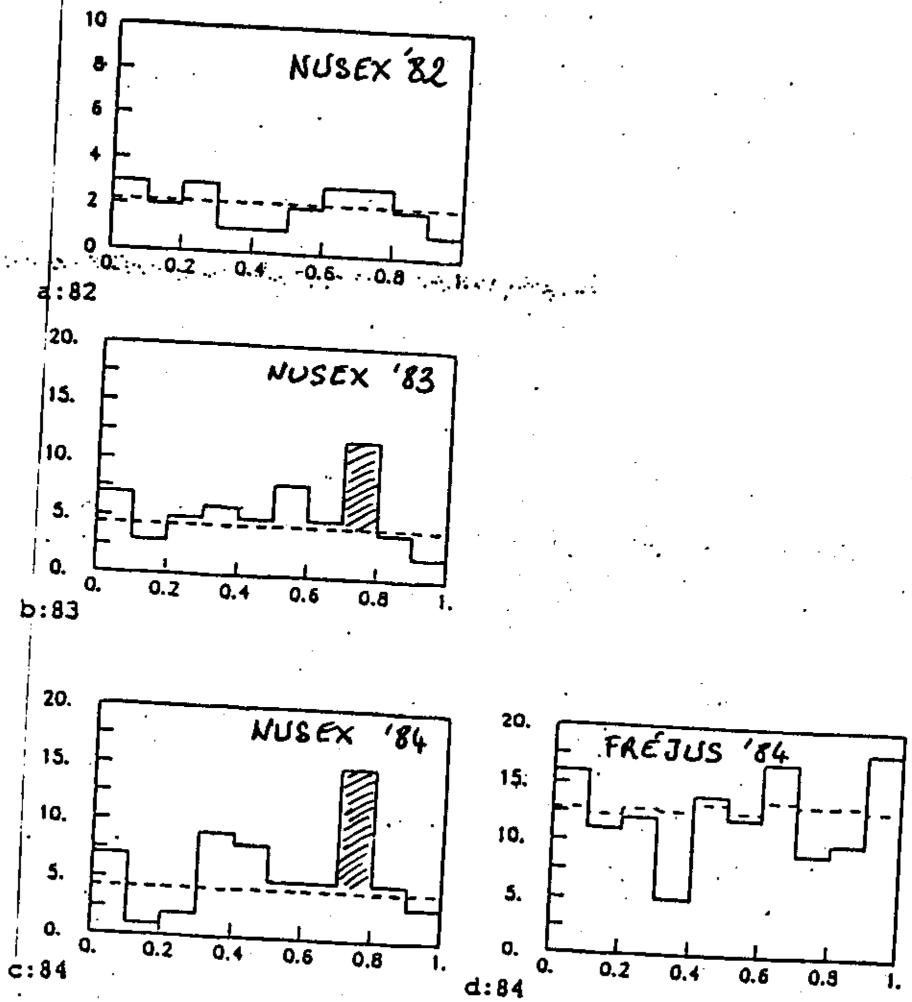
VERTICAL FLUX OF γ-INDUCED MUONS ("KIEL" FLUX) optimistic 1° ANGULAR RESOL^N



DEPTH (km water equivalent)

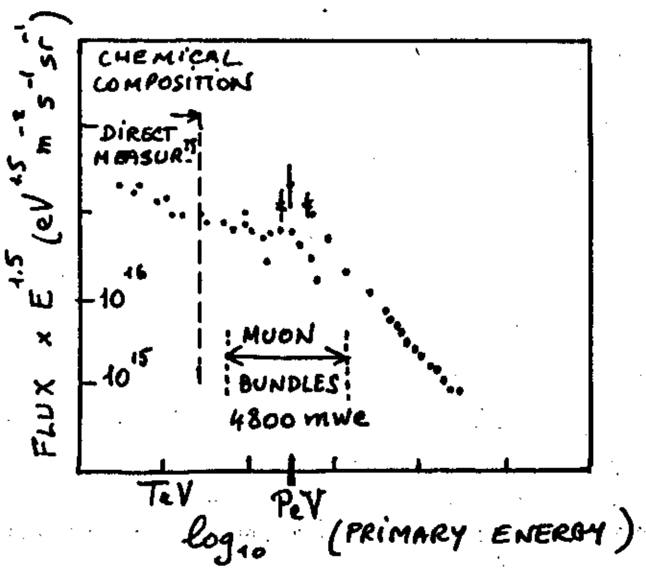
CYG. X3 (UNDERGROUND EXPTS)



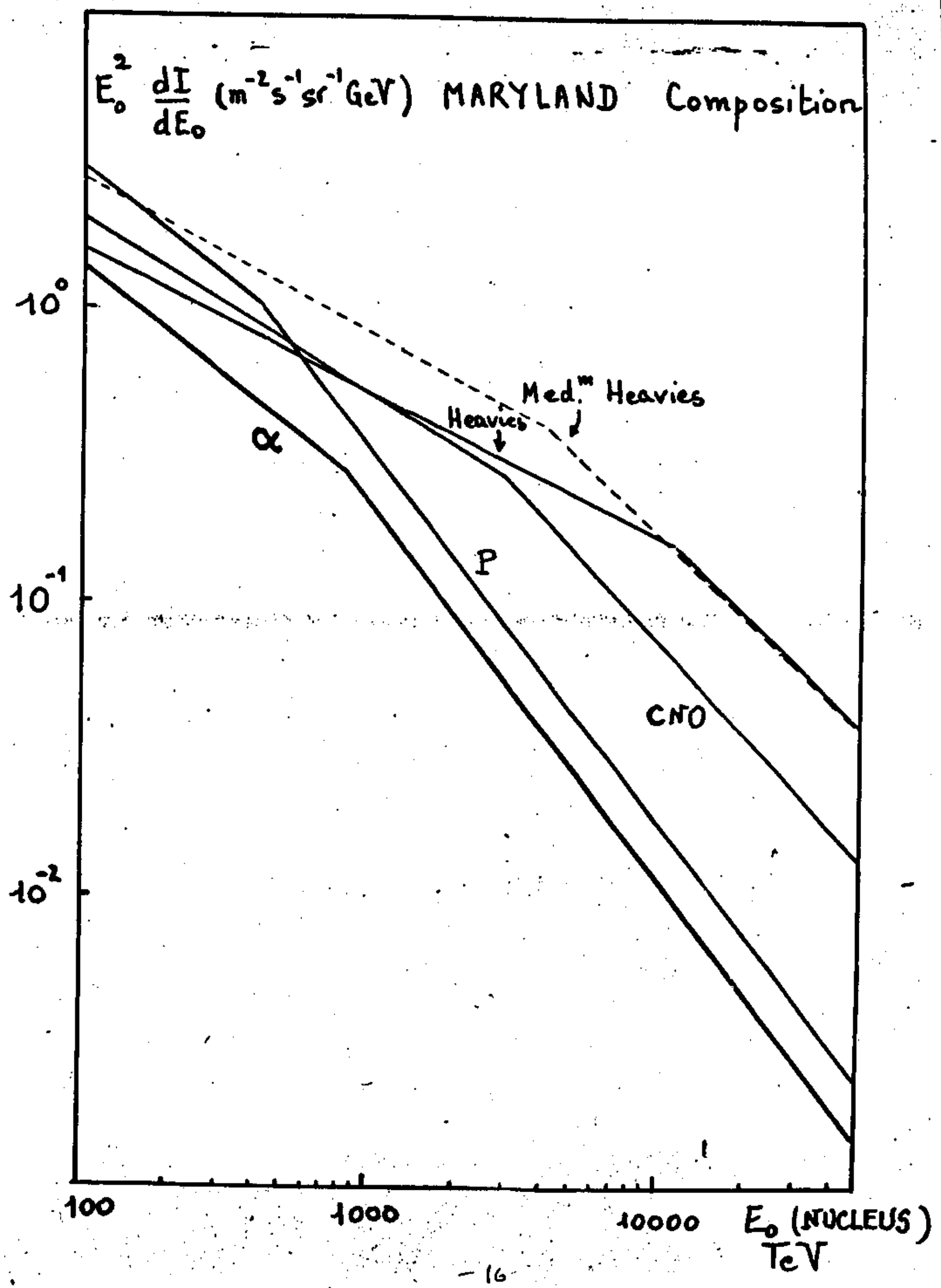


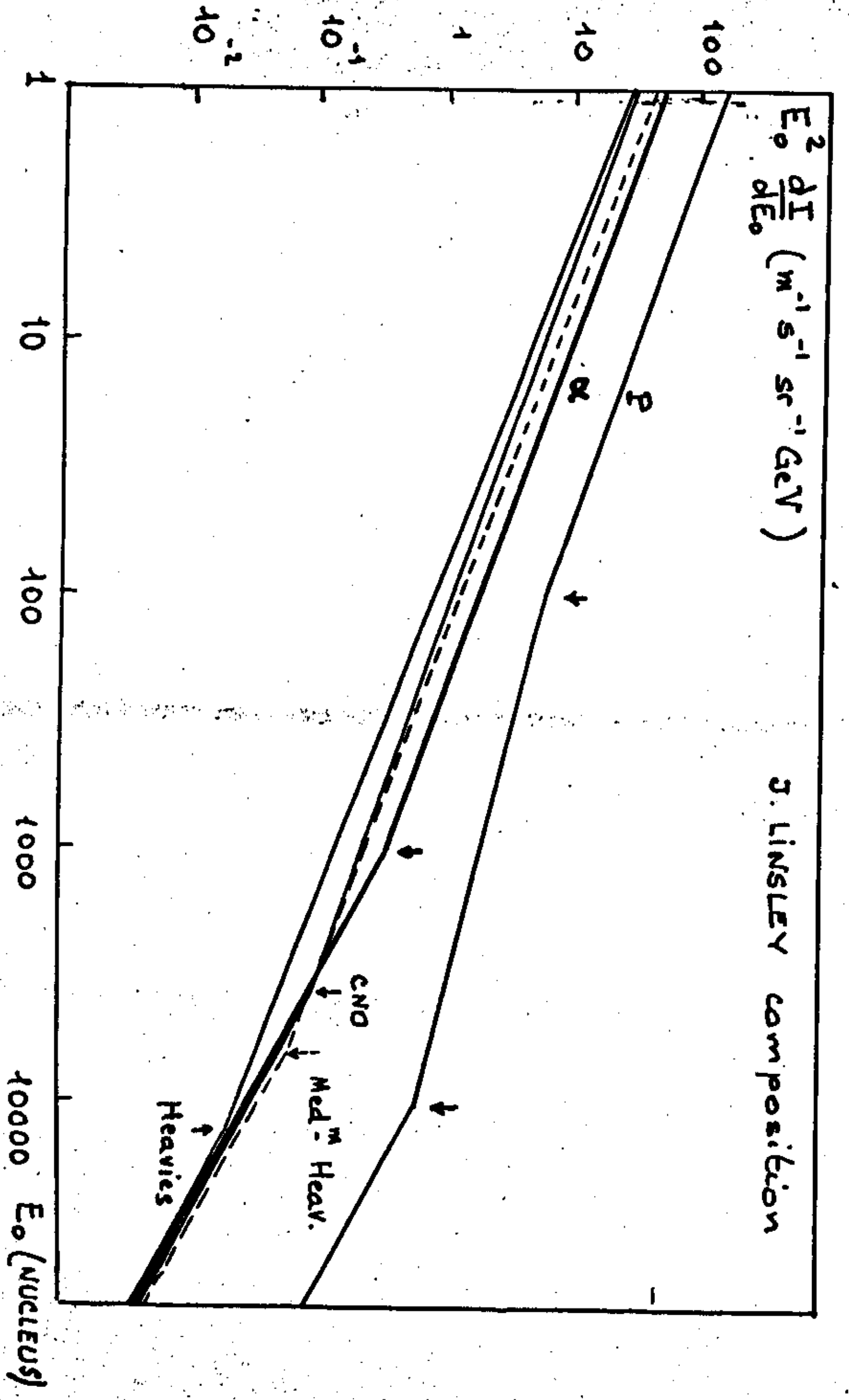
CYGNUS X3 PHASE HISTOGRAMS

UNDERGROUND MUON BUNDLES & COSMIC-RAY CHEMICAL COMPOSITION IN THE PeV RANGE



- PRIMARY COSMIC-RAY COMPOSITION IS DIRECTLY MEASURED UP TO ~ 100 TeV (Satellites & Balloons). FLUX IS TOO LOW ABOVE.
- WHAT IS THE KNEE?
  - MAGNETIC DECONFINEMENT?
    AT HIGH ENERGY, PARTICLES ARE LESS CONFINED BY GALACTIC MAGNETIC FIELDS AND START LEAKING → EXPECT HIGH Z (CHARGE) TO BE MORE CONFINED
    INCREASE OF THE CONTRIBUTION OF HEAVIES
  - NEW COSMIC-RAY SOURCE ABOVE PeV?
    SUPPORTED BY SOME FEATURES OF VERY ENERGETIC SHOWERS, SUGGESTING SIGNIFICANT PROTON CONTRIBUTIONS.

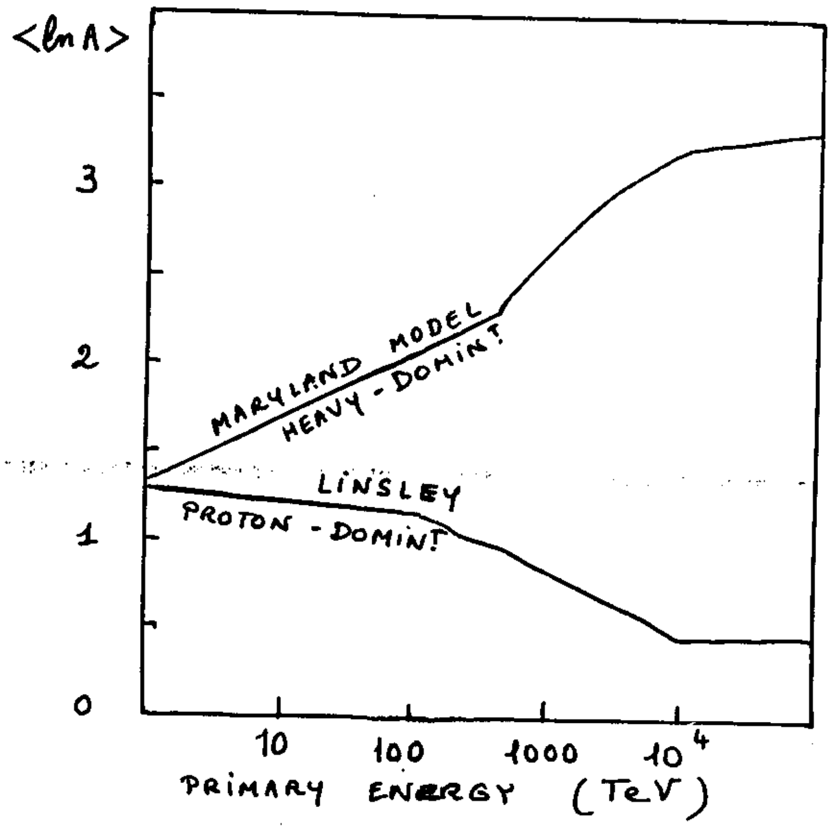




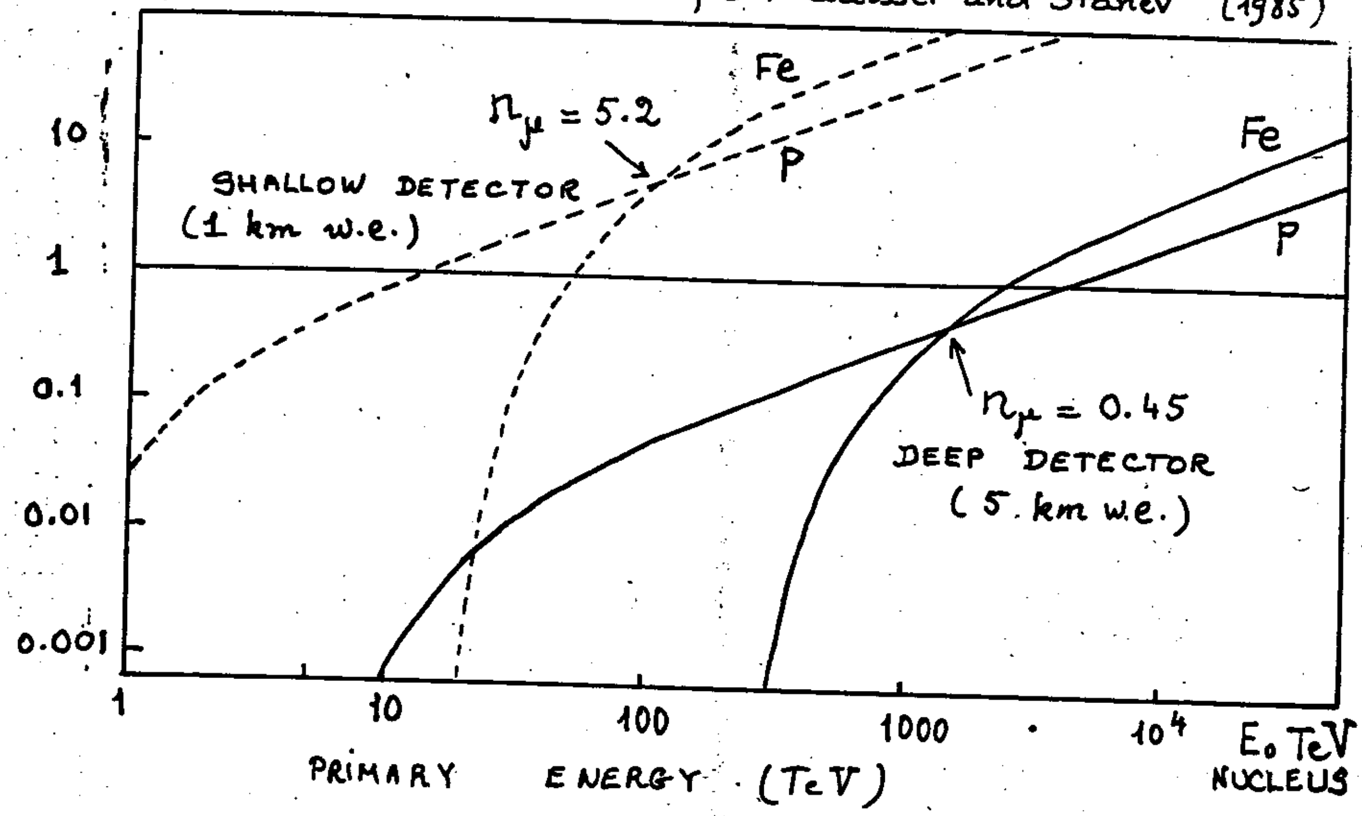
TWO "EXTREME" COMPOSITION MODELS COMPATIBLE WITH

a) ALL-PARTICLE SPECTRUM.

b) COMPOSITION BELOW TeV RANGE.

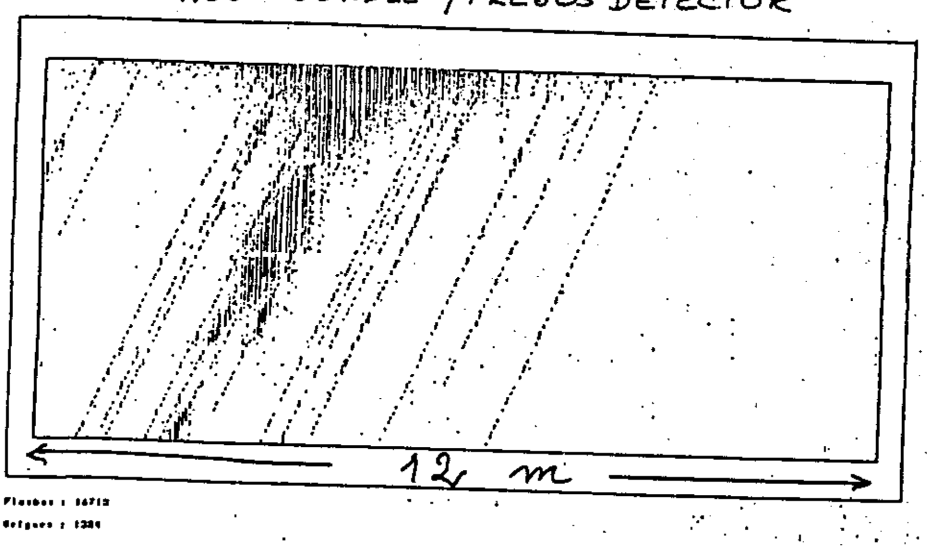


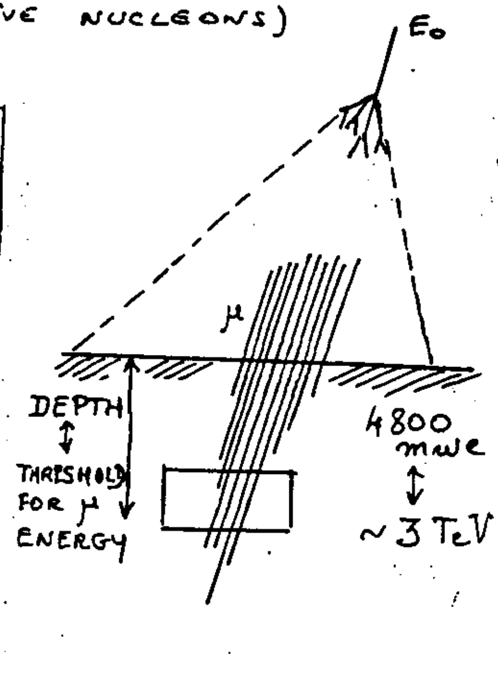
$\langle n_\mu \rangle$ AT DETECTOR DEPTH from Gaisser and Stanev (1985)



- PRIMARY ENERGY PER NUCLEON $\left(\frac{E_0}{A}\right)$ ⟹ MUON ENERGIES
  - THRESHOLD ON μ ENERGY (SET BY DEPTH) ⟹ HIGHER THRESHOLD FOR HIGHER A (e.g. IRON HAS A SMALL EFFECT ON UNDERGND μ's FOR $E_0 < 1000$ TeV AT 4800 mwe.)
  - ONCE, IRON THRESHOLD IS OVERCOME, HEAVY NUCLEI ARE MORE PRODUCTIVE THAN LIGHT ONES. (A PRODUCTIVE NUCLEONS)

MUON BUNDLE / FRÉJUS DETECTOR





A MORE QUANTITATIVE RELATION WITH MUON BUNDLES

PRODUCTION	MODEL : PRIMARY	{ ENERGY E_0 ; A NUCLEONS
SIMULATE	NUCLEUS - NUCLEUS COLLISIONS	
	PARTICLE PRODUCTION	
	PARTICLE INTERACTIONS AND DECAYS	

⇓

DISTRIBUTION OF THE NUMBER OF μ's WITH ENERGY $> \underbrace{E_\mu}_{\text{THRESHOLD (SITE DEPTH)}}$

- DISTRIBUTION is POISSONIAN in the primary energy range of interest
- SUMMARIZE MODEL BY MEANS OF A SEMI-EMPIRICAL FORMULA → AVERAGE μ MULTIPLICITY $E > E_\mu$

e.g. GAISSER & STANEV 1985

- PROTONS :

$$n_\mu^{(P)} = \frac{a}{E_\mu \cos\theta} \underbrace{\left(\frac{E_0}{E_\mu}\right)^\alpha}_{\text{ASYMPTOTIC BEHAVIOUR}} \underbrace{\left(1 - \frac{E_\mu}{E_0}\right)^\beta}_{\text{THRESHOLD behaviour}}$$

$$\begin{cases} a = 0.014 \text{ TeV} \\ \alpha = 0.775 \\ \beta = 5.96 \end{cases}$$

from Gaisser & Stanev Monte-Carlo

- NUCLEI : "SUPERPOSITION" ASSUMPTION

$$\boxed{n_\mu^{(A)}(E_0) = n_\mu^{(P)}\left(\frac{E_0}{A}\right) \times A}$$

PREDICTIONS FOR THE MUON MULTIPLICITY DISTRIBUTION AT THE ~~SITE~~ DEPTH

P_N = PROBABILITY TO HAVE A SHOWER WITH N MUONS WITH ENERGY $> E_\mu$.

$$P_N = \sum_A \int \underbrace{I_A(E_0)\, dE_0}_{\text{PRIMARY SPECTRUM}} \underbrace{\exp\left(-n_\mu(E_0,A)\right) \frac{\left(n_\mu(E_0,A)\right)^N}{N!}}_{\text{POISSON}}$$

- IN PARTICULAR, IF ALL NUCLEI HAVE THE SAME SPECTRAL INDEX γ AT HIGH ENERGY, THE ASYMPTOTIC BEHAVIOUR OF P_N (LARGE N) CAN BE CALCULATED :

$$P_N \propto \frac{\Gamma\left(N - \frac{\gamma-1}{\alpha}\right)}{N!} \approx \frac{1}{N^{\frac{\gamma-1}{\alpha}+1}}$$

EXPONENT $\nu^{As.} = \frac{\gamma-1}{\alpha} + 1$ is INDEPENDENT OF CHEMICAL COMPOSITION.

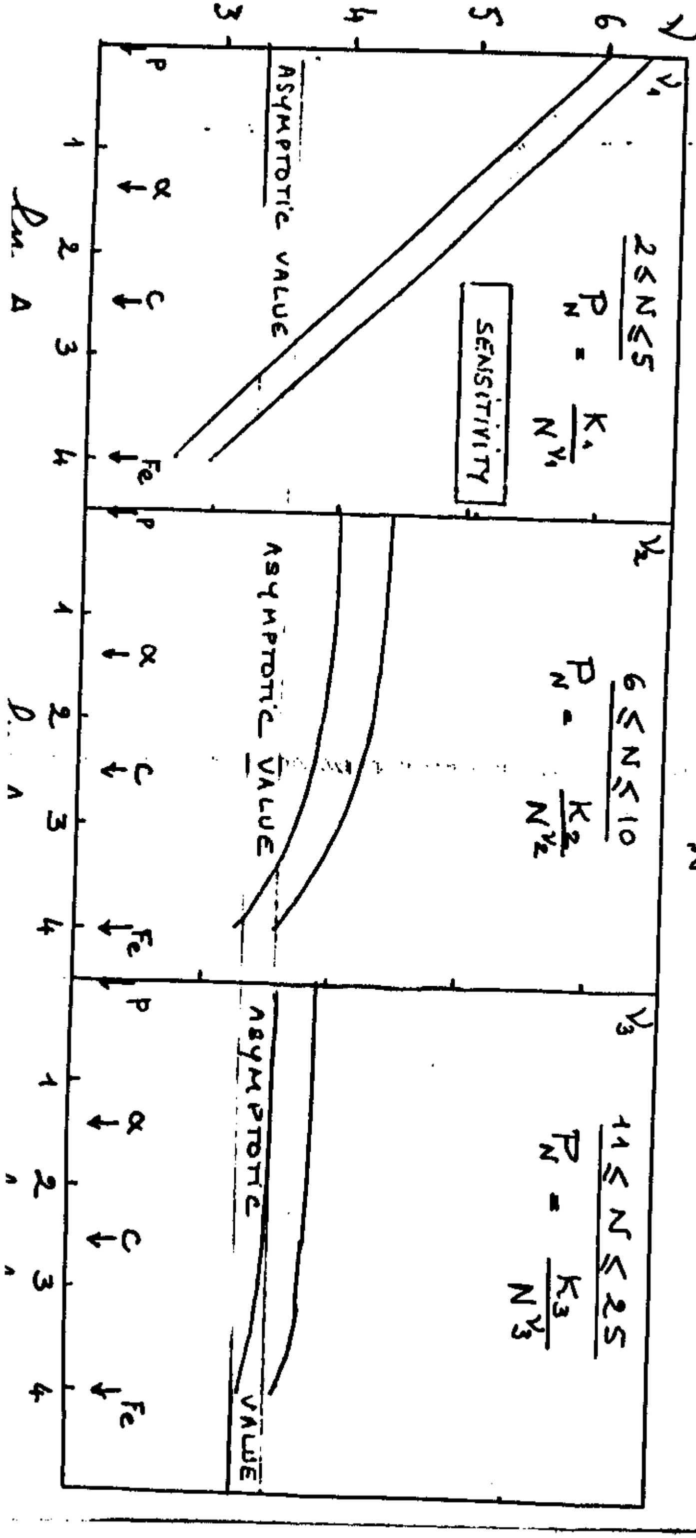
γ = Spectral index ≈ 3

α governs asymptotic behaviour of n_μ: $n_\mu \propto E_0^\alpha$ far above the threshold

- SENSITIVITY TO CHEMICAL COMPOSITION COMES FROM A RESTRICTED RANGE IN N WHICH DEPENDS ON THE SITE DEPTH.
- IN THE "KNEE REGION" OF THE PRIMARY SPECTRUM, ALL SPECIES HAVE NOT THE SAME γ. SENSITIVITY IS ENHANCED IF THE ENERGY REGION PRODUCING μ BUNDLES IS $\approx$ KNEE

WHAT IS THE RANGE IN μ MULTIPLICITY SENSITIVE TO COMPOSITION ?

- USE GAISSER-STANEV FORMULA FOR VERTICAL SHOWERS
  $E_\mu = 3$ TeV (FRÉJUS SITE)
- ONE KIND OF NUCLEUS A. VARY THE POSITION OF THE "KNEE" — 50 TeV
- FIT P_N TO A POWER LAW $\frac{K}{N^\nu}$ IN 3 INTERVALS OF N



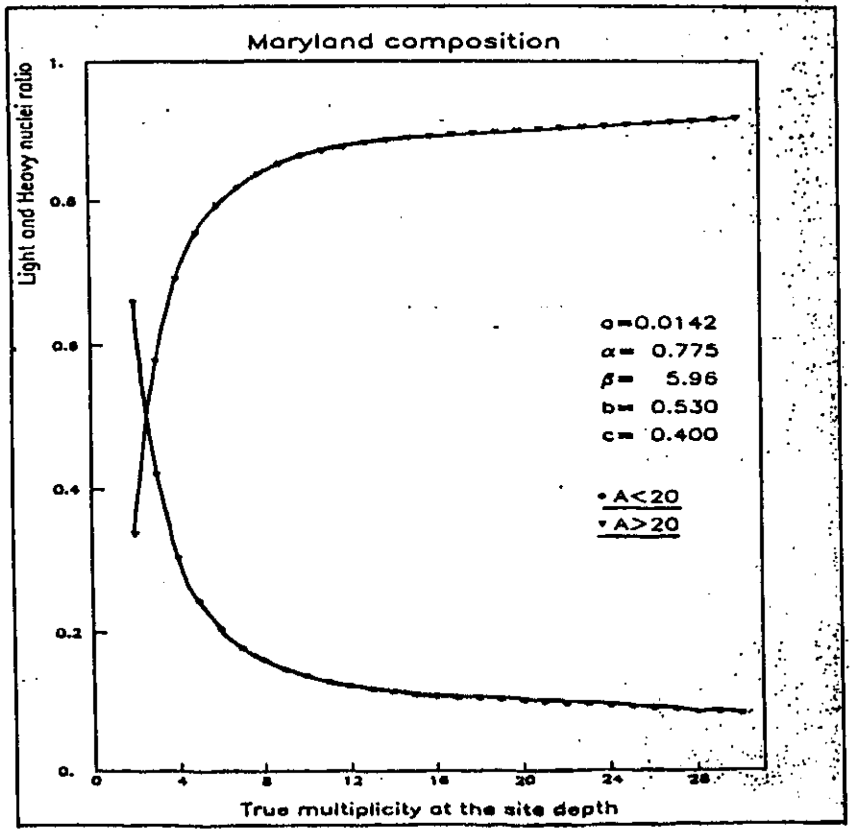
PRIMARY COSMIC RAY COMPOSITION FROM MUON MULTIPLICITY DISTRIBUTION

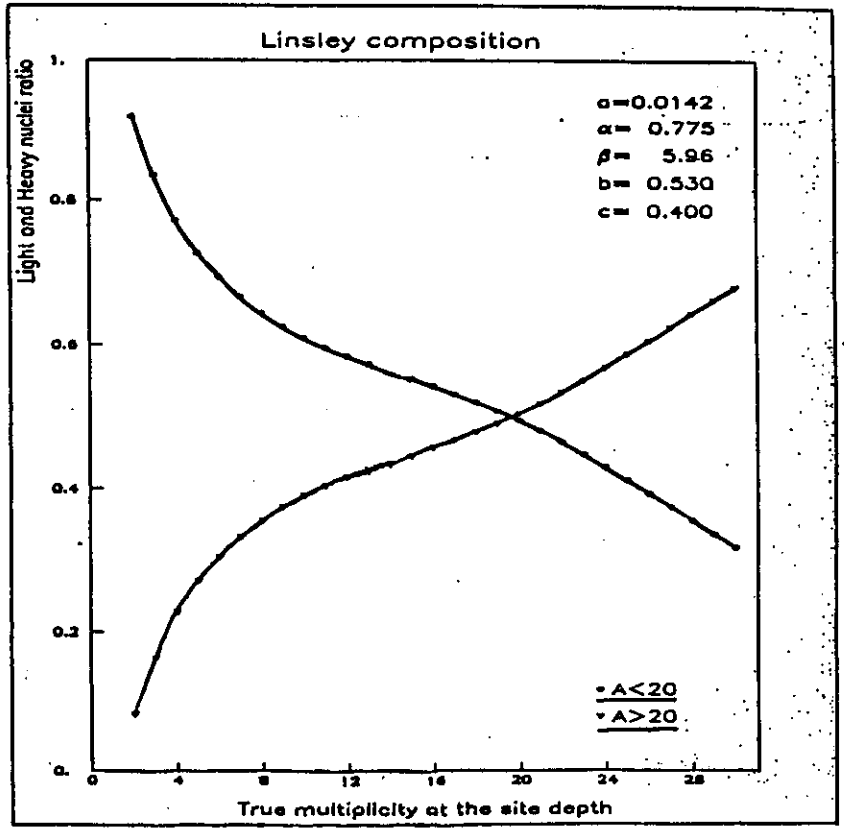
- TRY TO FIT A POWER LAW : $P_N = \frac{K}{N^\nu}$
  - DOMINANCE OF HEAVY NUCLEI :
    A SINGLE VALUE OF $\nu \sim 3.7$ (CLOSE TO THE ASYMPTOTIC VALUE) WILL FIT FOR $N \geq 2$.
  - DOMINANCE OF LIGHT NUCLEI.
    A VALUE OF ν SIGNIFICANTLY GREATER THAN ~ 3.7 WILL FIT THE DATA FOR $N << 10$, BUT THIS POWER LAW WILL UNDERESTIMATE THE NUMBER OF EVENTS AT HIGH N (since the asymptotic behaviour $\sim \frac{K'}{N^{3.7}}$)
- EXPLANATION

  HEAVY NUCLEI EVENTUALLY DOMINATE AT HIGH N IN ANY MODEL.

  DOMINANCE OF HEAVY NUCLEI :
  They dominate even at low multiplicities ($N \sim 4$)

  DOMINANCE OF PROTONS :
  They dominate for very large N only.


Maryland composition
Light and Heavy nuclei ratio
a=0.0142
α= 0.775
β= 5.96
b= 0.530
c= 0.400
A<20
A>20
True multiplicity at the site depth


Linsley composition
Light and Heavy nuclei ratio
a=0.0142
α= 0.775
β= 5.96
b= 0.530
c= 0.400
A<20
A>20
True multiplicity at the site depth

MUON BUNDLE EXPERIMENTS

- OBSERVABLES
  - MUON MULTIPLICITY DISTRIBUTION
    - RATES.

      ABSOLUTE RATES ARE DIFFICULT TO INTERPRETE SINCE PRIMARY FLUX IS NOT KNOWN ACCURATELY.
    - SHAPE.

      SENSITIVE TO COMPOSITION

      $N \lesssim 6$ AT FRÉJUS DEPTH
  - MUON LATERAL DISTRIBUTION

    $\mu - \mu$ DISTANCES

- TWO CONDITIONS TO BE SENSITIVE TO COMPOSITION
  - EXPERIMENTAL : DETECTOR SIZE MUST MATCH SHOWER SIZE

    D (Axis of a shower - μ) $\sim$ 3 m (Fréjus)

    FRÉJUS DETECTOR AREA : 12 m x 6 m
  - DEPTH : SUCH AS TO HAVE

    MULTIMUONS PRODUCTION $\longleftrightarrow$ KNEE REGION

    IN PRACTICE $h > 3500$ mwe

AREA VS. DEPTH

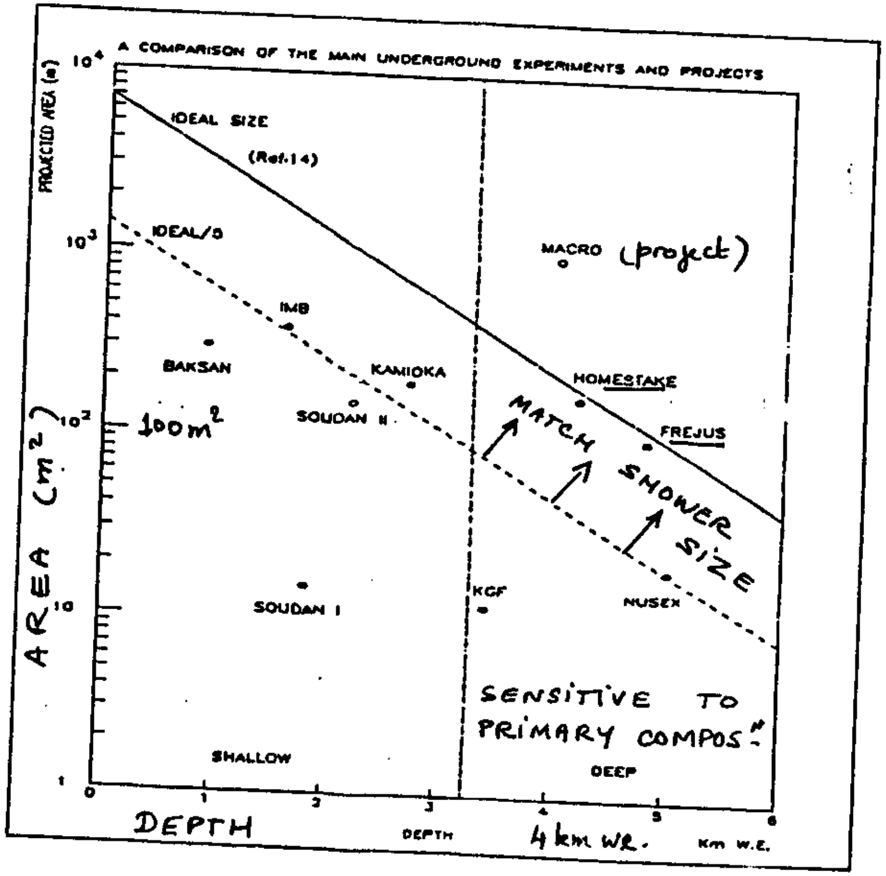
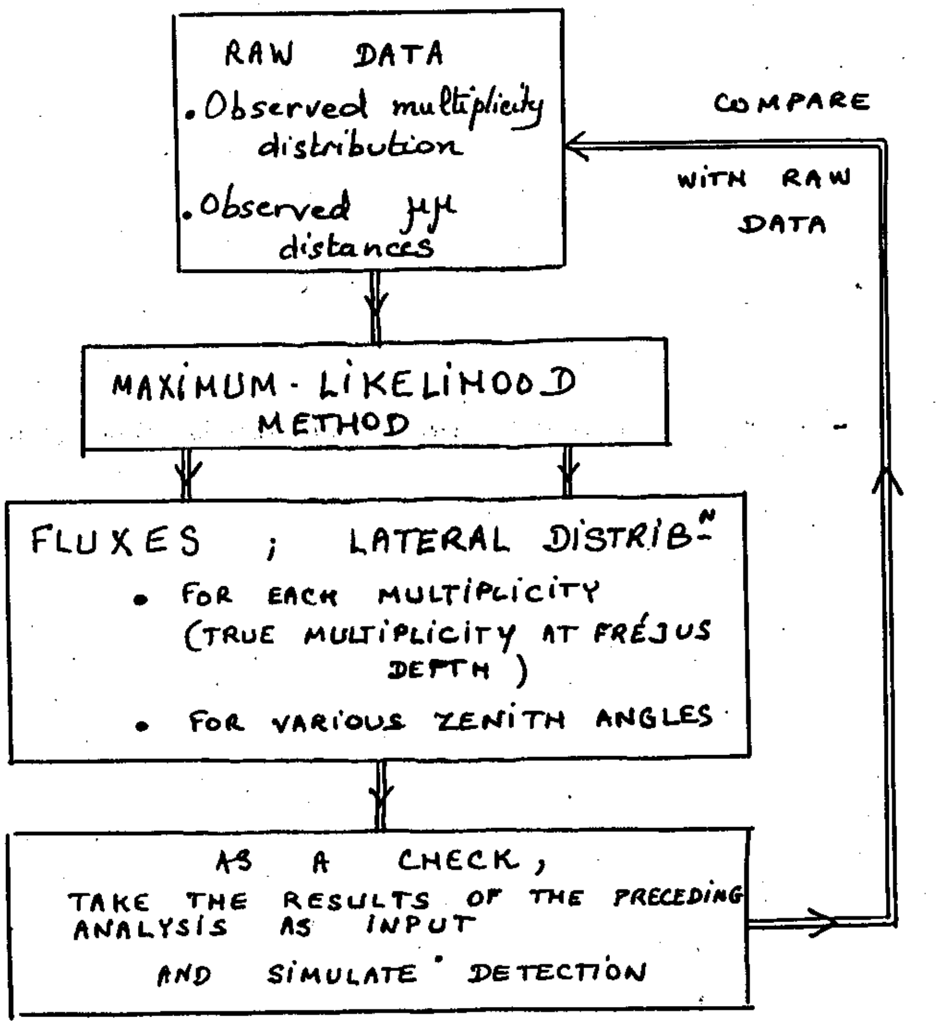


Figure 5

FRÉJUS ANALYSIS ON MUON BUNDLES

FIRST EXPERIMENT IN WHICH DATA ARE PRESENTED CORRECTED FOR DETECTOR SIZE EFFECTS



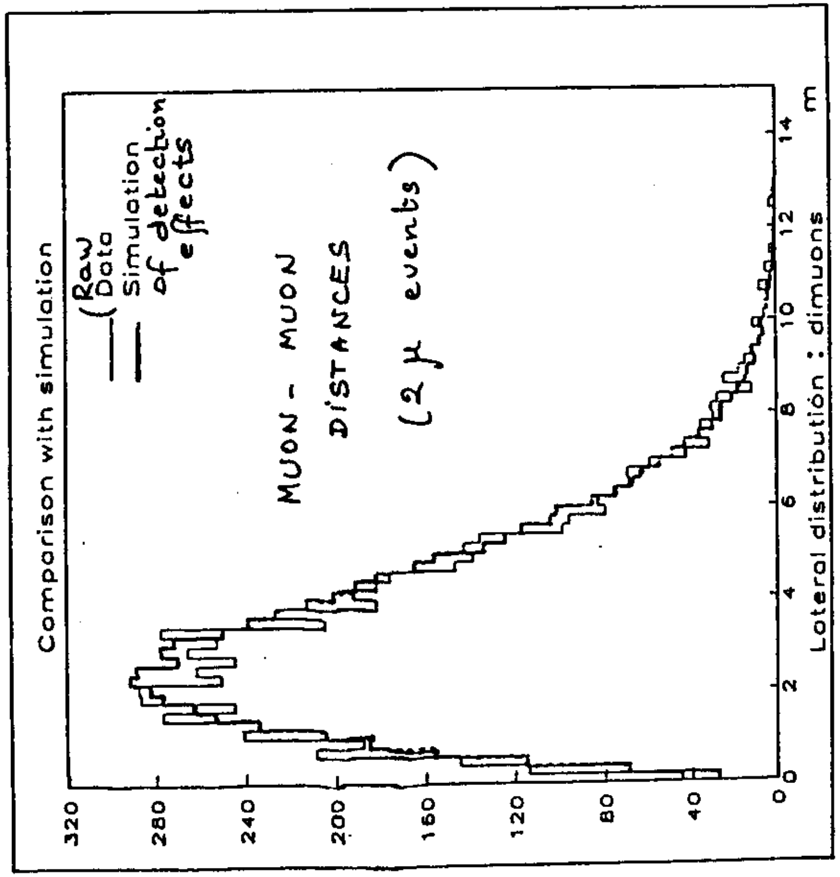


Figure 3 a

FRÉJUS RESULTS & INTERPRETATION

- **MULTIPLICITY DISTRIBUTION**

1) TRY A POWER LAW

$$\underbrace{\Phi_N}_{\text{flux for } N \text{ muons (Fréjus site)}} = \frac{K}{N^{\nu_0}}$$

$$\nu_0 = 4.28 \pm 0.04$$

1) SIGNIFICANTLY > 3.7
2) FAILS TO REPRODUCE THE OBSERVED DISTRIB^N FOR $N \gtrsim 10$ (UNDERESTIMATE)

2) MODIFY POWER LAW TO FIND A GOOD FIT

ν DECREASES WITH N $\quad \nu = \frac{\nu_1}{1+aN}$

$$\Phi_N = \frac{K}{N^{\nu(N)}} \qquad \begin{cases} \nu_1 = 4.62 \pm 0.16 \\ a = (0.69 \pm 0.24)\, 10^{-2} \end{cases}$$

THIS IS WHAT IS EXPECTED FOR A RATHER LIGHT COMPOSITION. IF α (governing the growth of average n_μ with E_0) is $\gtrsim 0.7$

THEN $\boxed{\langle \ln A \rangle \leq 1.5 \quad \text{FOR } 10^3 \div 10^4 \text{ TeV}}$

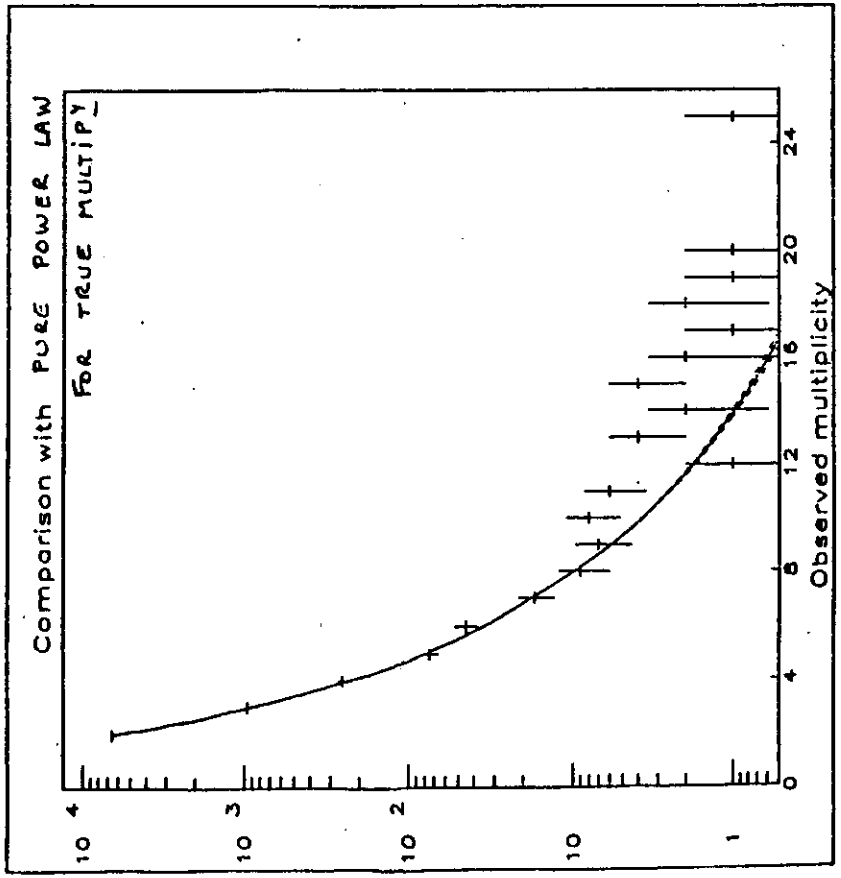
HEAVY COMPOSITION WOULD REQUIRE $\alpha \lesssim 0.65$

- **LATERAL DISTRIBUTION**

$$\frac{dN}{dr} = C^{te}\ r \cdot \exp\left(-\frac{r}{r_0}\right)$$

SHRINKAGE FOR $N \geq 4$:

$$\begin{cases} r_0(N=2) = 173 \pm 4 \text{ cm} \\ r_0(N=3) = 170 \pm 8 \text{ cm} \\ r_0(N \geq 4) = 138 \pm 3 \text{ cm} \end{cases}$$



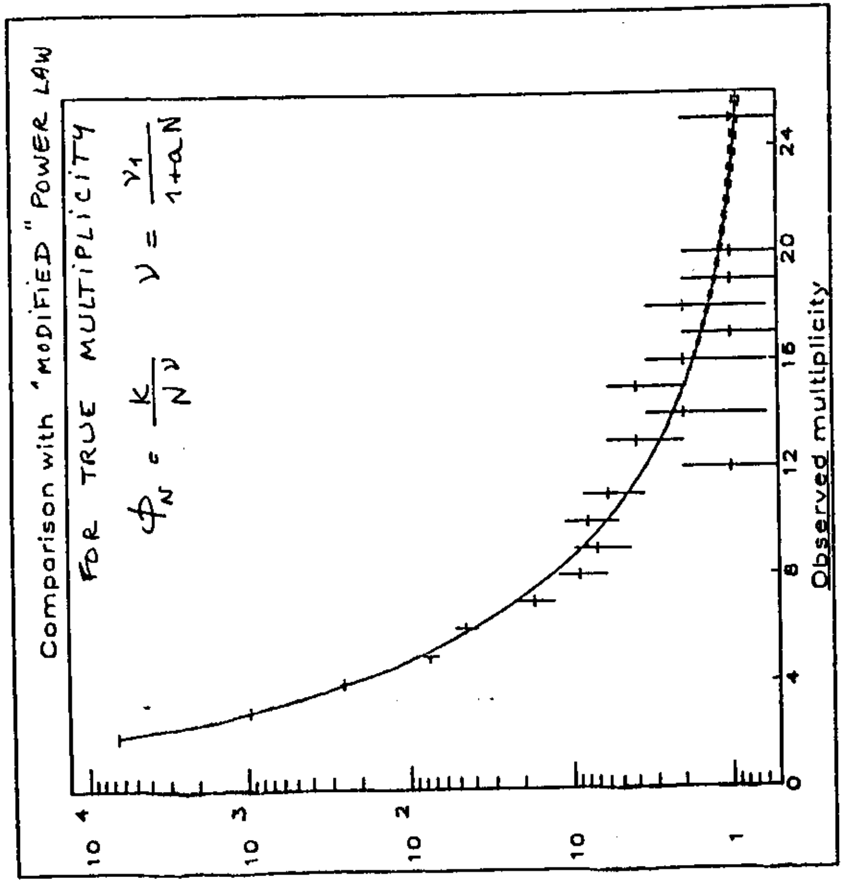
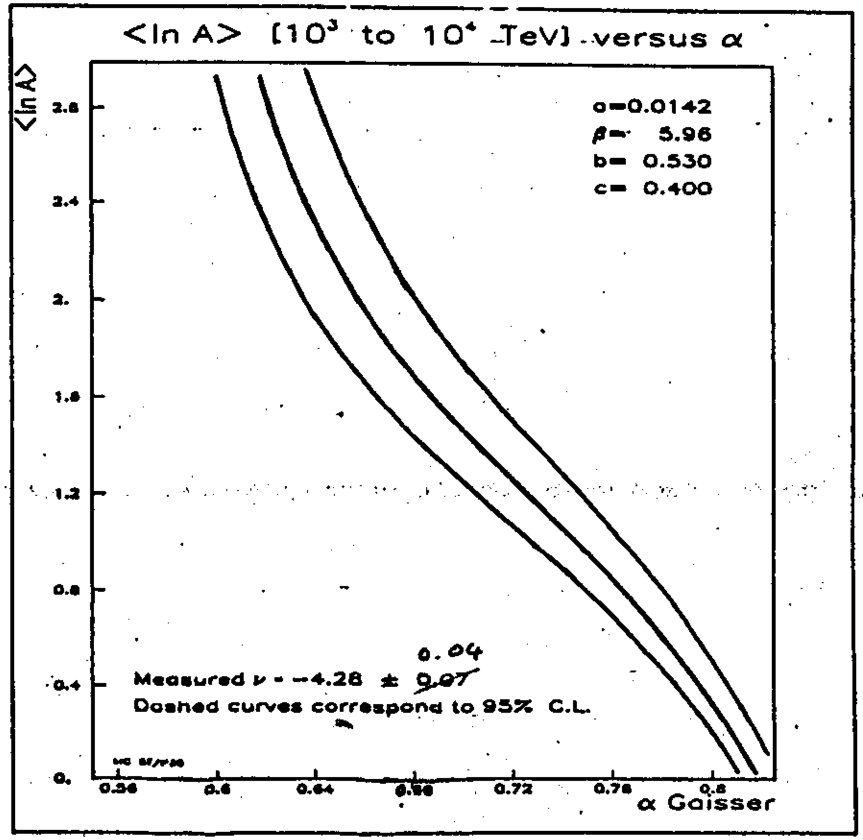


Figure 2



- FOR USUAL VALUES OF α ($\alpha \geq 0.7$) OUR EXPERIMENTAL RESULT FAVOURS A LIGHT COMPOSITION ($\langle \ln A \rangle \leq 1.5$)
- A HEAVY COMPOSITION CAN BE ACCOUNTED FOR WITH LOWER VALUES OF α.

COSMIC RAY PHYSICS WITH PRESENT UNDERGROUD DETECTORS

SUMMARY & PERSPECTIVES.

- ONLY NEGATIVE RESULTS IN ν_μ ASTRONOMY

  $\Phi_{\mu\uparrow} \lesssim 10^{-14}\ cm^{-2}s^{-1}$ BAKSAN
  for some galactic possible sources

  $\Phi_{\mu\uparrow} < 1.2\ 10^{-13}\ cm^{-2}s^{-1}$ KAMIOKANDE II
  for SN 1987 A, 6 months

  PRESENT DETECTORS TOO SMALL.

  MACRO $900\ m^2$ OR DUMAND $6000\ m^2$ MORE ADAPTED.

- NO COMPELLING RESULT IN FAVOUR OF EXOTIC SOURCES OR EXOTIC INTERACTIONS OF γ-rays (Underground ⟷ Cyg X3)

- MUON BUNDLES :
  - FRÉJUS DETECTOR MATCHES THE SIZE OF UNDERGROUND SHOWERS.
  - SENSITIVE TO PRIMARY COSMIC RAY COMPOSITION FAVOURS $\langle \ln A \rangle \lesssim 1.5$ FOR $10^3 \div 10^4$ TeV PRIMARY ENERGIES PROVIDED THERE IS NO MAJOR CHANGE IN HADRONIC PHYSICS IN THIS RANGE; (α parameter)
  - MACRO WILL HAVE MORE STATISTICS IN VERY HIGH MULTIPLICITIES (α measured) + Constraints of surface array; (E_0 measured in a sub-sample)!