Signatures for a Cosmic Flux of Magnetic Monopoles

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Outline

- GUT Monopoles
- Flux Bounds
- Monopole Acceleration - Relativistic Monopoles
- EM Energy Losses
- Monopole–Induced Shower
- Signature for RICE
- Monopole Tomography
- Monopole–Initiated Super-GZK Air Showers

GUT Monopoles

"Topological Defects" from symmetry breaking, e.g.

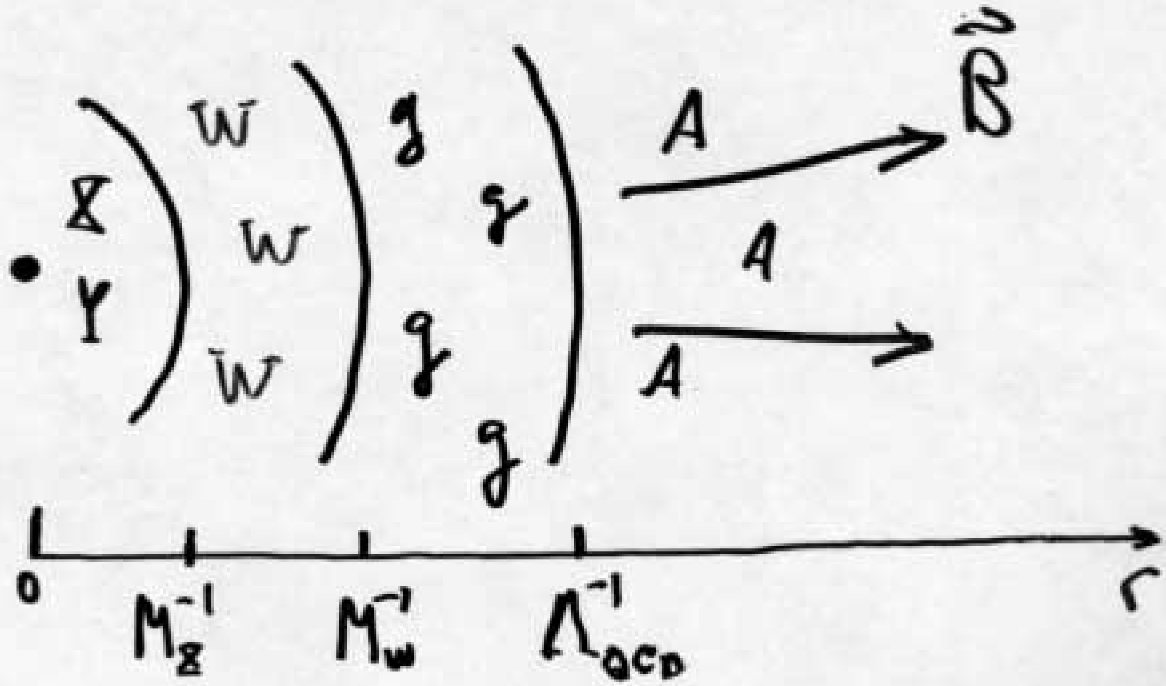
$$\mathcal{G} \rightarrow \mathcal{H}$$

where $SU_C(3) \times SU_L(2) \times U_Y(1) \subset \mathcal{H}$

Symmetry Breaking Scale: Λ

Monopole Mass: $M \sim 100\,\Lambda \gtrsim 40$ TeV

Cartoon of GUT Monopole Structure:



Monopole Classification

coarse:

Topological Charge, winding number, $n = 1, 2, \ldots$

(Kibble, 1976)

fine:

Bound States of GUT Monopoles, e.g., 5 types for $n = 1$ in $SU(5) \rightarrow$ SM

(Gardner and Harvey, 1984; "*Dual Standard Model*," Vachaspati, 1996)

for generality:

We Consider *Lepton–type* and *Quark–type* Monopoles

l–type: $U(1)$ Magnetic Charge → EM Interactions.

q–type: *Color* Magnetic Charge → Hadronic Interactions.

Monopole Flux Bounds

Large Scale Magnetic Fields – "Parker Bound":

$$F_{\rm M} \lesssim 10^{-15}{\rm cm}^{-2}{\rm sec}^{-1}{\rm sr}^{-1}$$

(galactic fields)

Direct Cherenkov (reported at ICRC-99)
for Velocity $\beta \simeq 1$

AMANDA: $F_{\rm M} \lesssim 1.6 \times 10^{-16}{\rm cm}^{-2}{\rm sec}^{-1}{\rm sr}^{-1}$

MACRO: $F_{\rm M} \lesssim 4.0 \times 10^{-16}{\rm cm}^{-2}{\rm sec}^{-1}{\rm sr}^{-1}$

BAIKAL: $F_{\rm M} \lesssim 6.0 \times 10^{-16}{\rm cm}^{-2}{\rm sec}^{-1}{\rm sr}^{-1}$

Monopole Acceleration

Kinetic Energy:

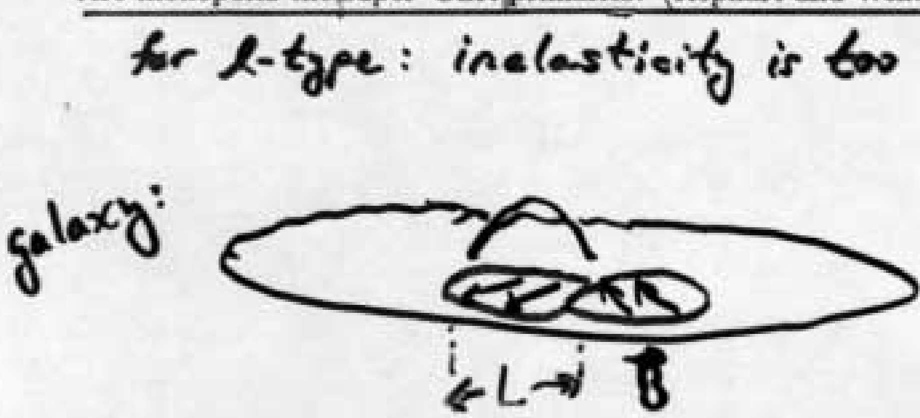
$$E_{\mathrm{K}} = g\,L\,B$$

Typical Galaxies:

$$E_{\mathrm{K}} \sim (.3 \,\mathrm{to}\, 1) \times 10^{21}\mathrm{eV} \left(\frac{\mathrm{L}}{300\,\mathrm{pc}}\right) \left(\frac{\mathrm{B}}{3\,\mu\mathrm{G}}\right)$$

Are monopoles the super–GZK primaries? (Kephart and Weiler, 1996)

for l-type: inelasticity is too low.



Other Large–Scale B–fields

(galactic clusters, extra-galactic sheets):

$$E_{\mathrm{K}} \text{ up to } 5 \times 10^{23}\,\mathrm{eV}$$

Relativistic Monopoles

Free monopoles will be relativistic for

$$M \lesssim 10^{14} \text{ GeV}$$

$$\gamma \lesssim 10^{10}$$

Consider relativistic monopoles where

$$\underline{4 \times 10^{4}\text{GeV} \lesssim \text{M} \lesssim 10^{14} \text{ GeV}}$$

"light" monopoles.

What are the Signatures of l–monopoles?

EM Energy Loss Processes

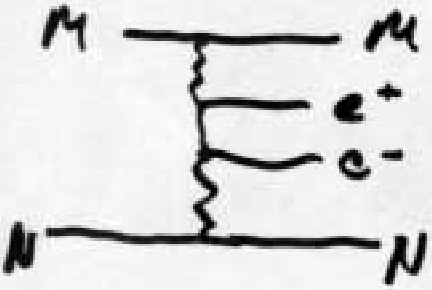
Ionization: $dE/dx \propto \ln \gamma$

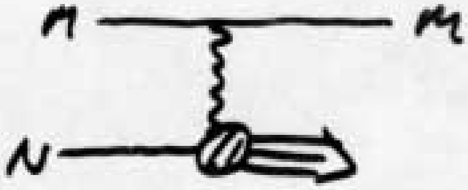
Bremsstrahlung: $dE/dx \propto \frac{\gamma}{M}$

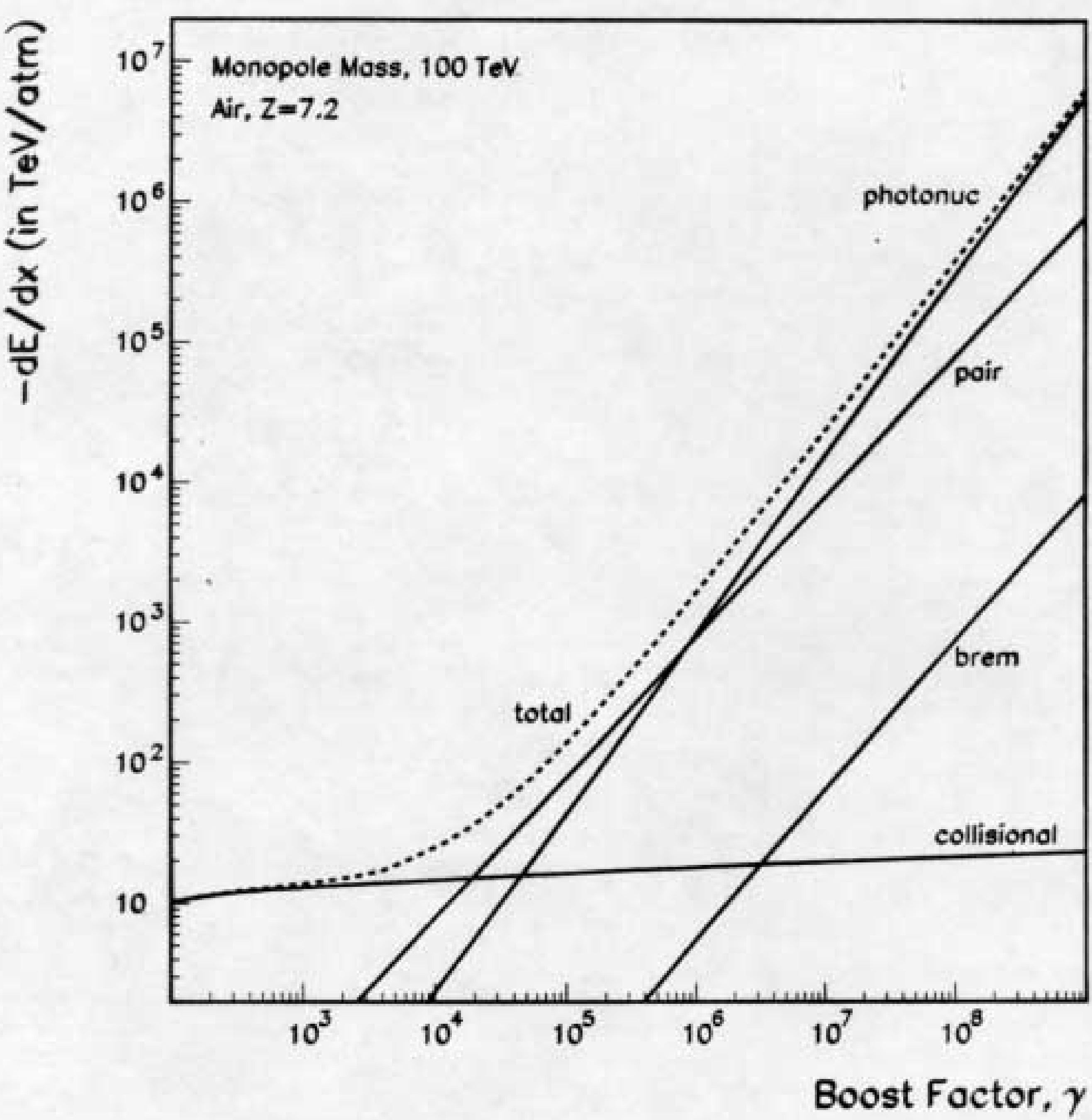
* $e^{+}e^{-}$ production: $dE/dx \propto \gamma$

* Photonuclear: $dE/dx \propto \gamma^{1.28}$ — Rano et al.

(*)







Monopole Mass, 100 TeV
Air, Z=7.2
photonuc
pair
brem
total
collisional
−dE/dx (in TeV/atm)
Boost Factor, γ

Monopole–Induced Shower

l–Monopoles are Highly Penetrating

i.e., low inelasticity (η) per interaction

Pair Production, for $\eta > \frac{200\text{MeV}}{E}$ and $\gamma >> 1$, not a signif. restriction

gives an Electromagnetic Shower: $$N \simeq \frac{dE_{\text{pair}}/dx}{E_c/\xi_e}$$

where $E_c \sim 200\,\text{MeV}$ is the critical energy

and where $\xi_e \sim 35\,\text{g/cm}^2$ is the electron radiation length.

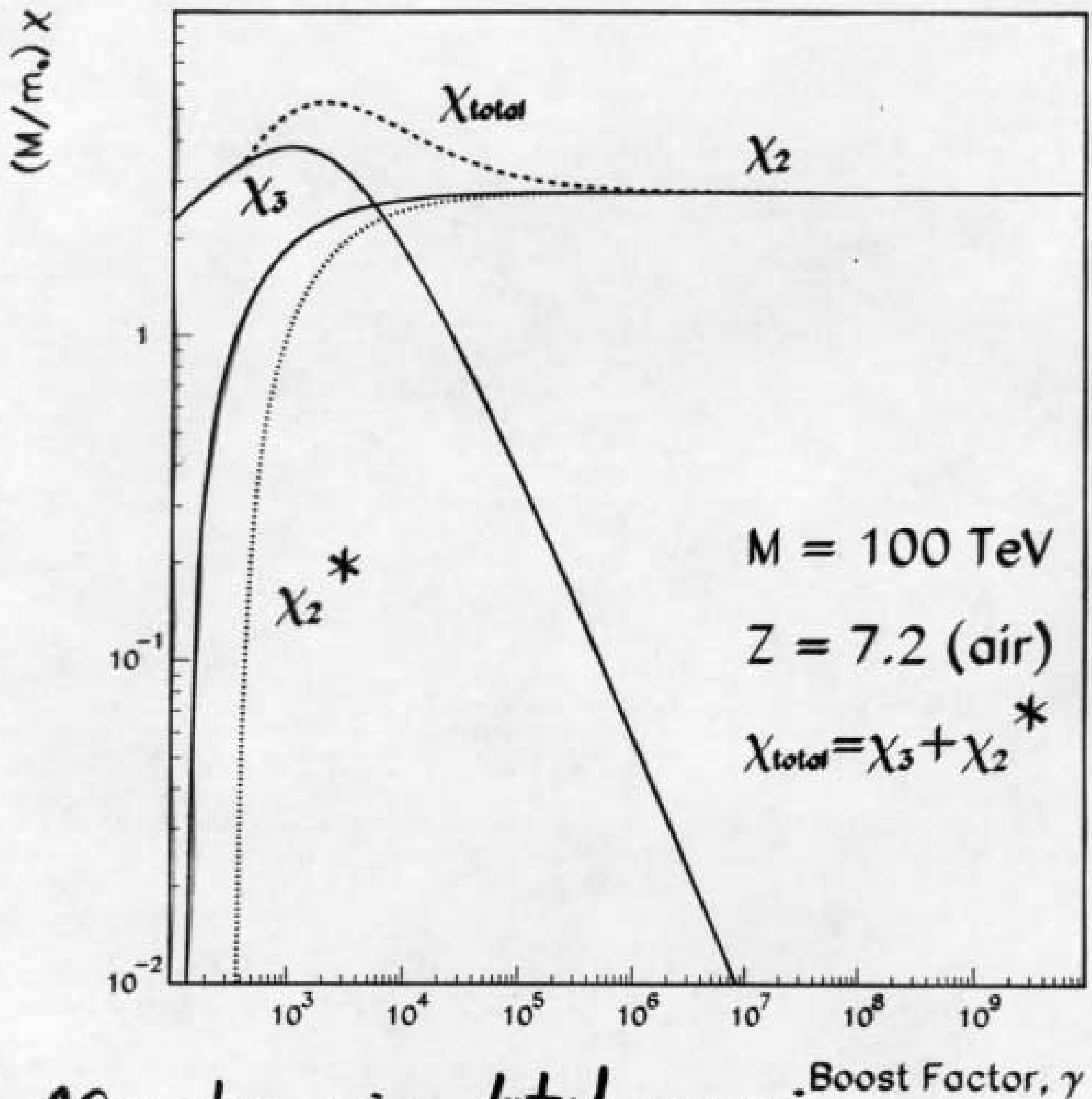
The photonuclear contribution to the EM shower?

upper limit: $\mathcal{O}(1)$ of $\frac{dE_{\gamma-\text{nuc}}}{dx}$ goes into the EM shower.

l - monopoles

(Kel'ner & Kotov, 1969)

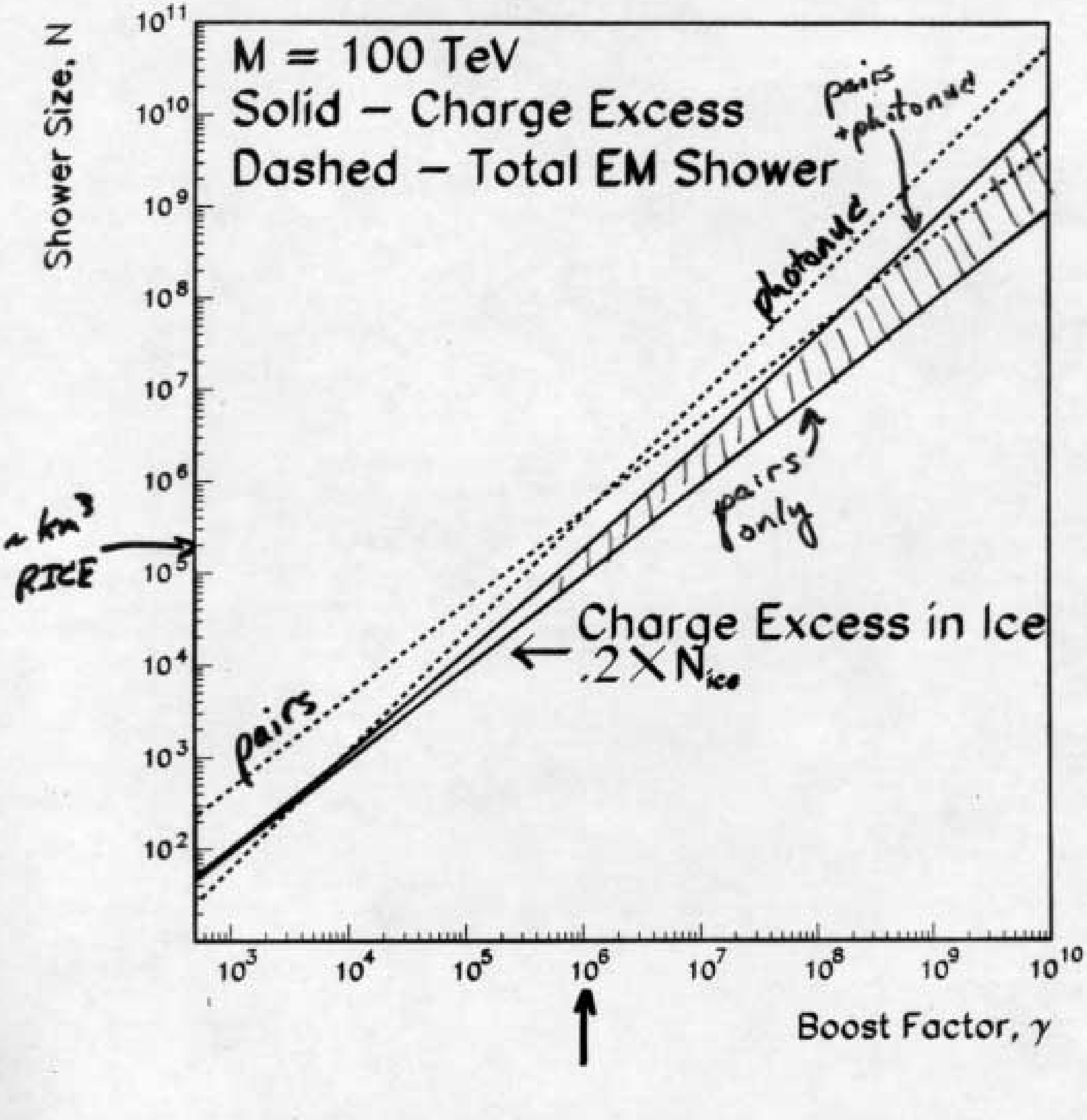
e-pair production



$\chi_2 \sim$ slow pairs, total screening

$\chi_3 \sim$ fast pairs, no screening

$$\chi_2^* = \chi_2 \Big|_{\eta > \eta_{crit}} \qquad \eta_{crit} \simeq \frac{200\text{ MeV}}{E}$$



M = 100 TeV
Solid – Charge Excess
Dashed – Total EM Shower
Shower Size, N
Boost Factor, γ
Charge Excess in Ice
.2 X N_ice
pairs
photonuc
pairs +photonuc
pairs only
~km³ RICE

Coherent Radio–Cherenkov

For the Cherenkov wavelength: $\lambda >> R_{\text{Moliere}}$

the power radiated is $\propto Z^2 \lesssim 10^{20}$

where Z is the shower charge excess

and where R_{Moliere} is the lateral shower size.

the RICE effective volume for monopoles $\gtrsim$ km^3 — estimate from Frichter, Ralston, McKay

for $\gamma \gtrsim 10^6$

Monopole Flux Limit with RICE

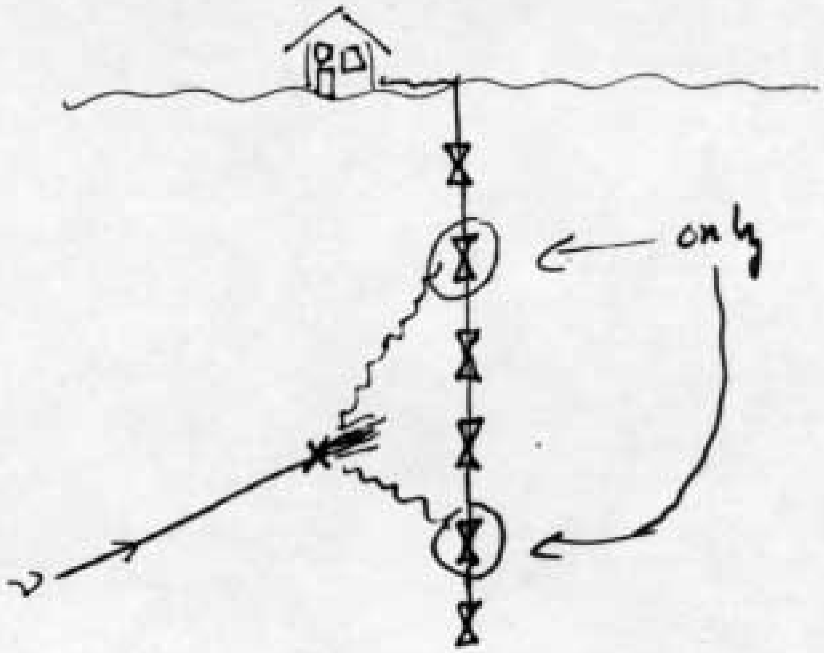
1 year of non-observation:

$F_{\text{M}} \lesssim 10^{-18}\,\text{cm}^{-2}\,\text{sec}^{-1}\,\text{sr}^{-1}$

Is direct Cherenkov observation problematic (AMANDA, MACRO, Baikal)?

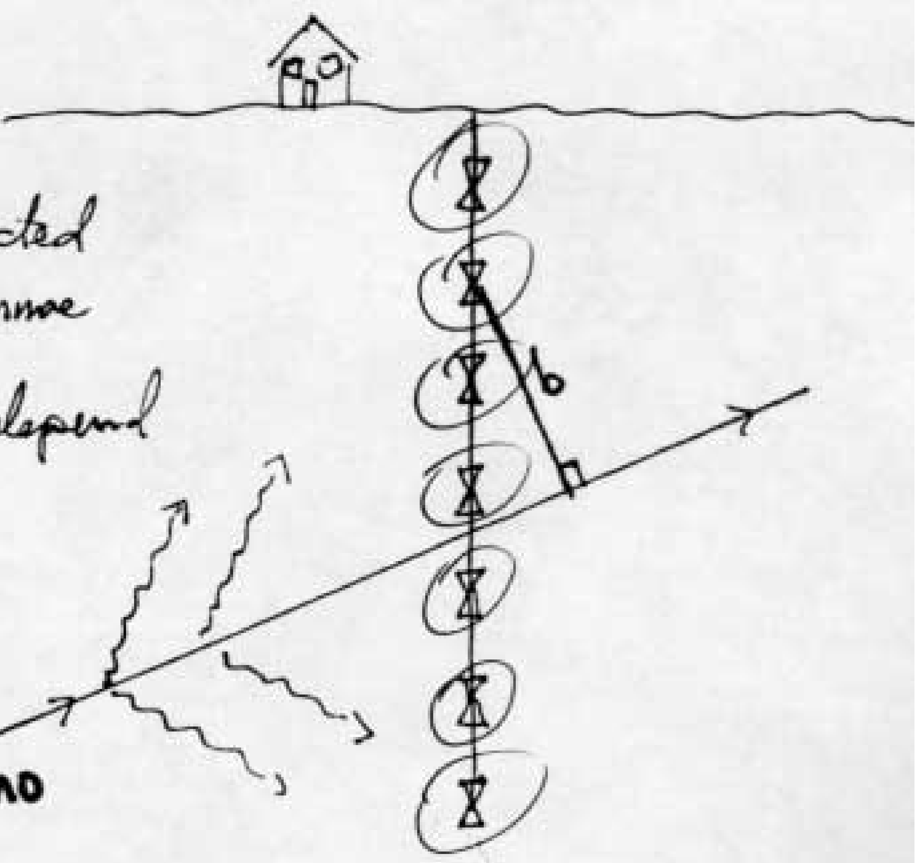
RICE

ν-event



mono-event

- should be detected by many antennae
- signal should depend on impact parameter $\sim \frac{1}{b}$



Monopole Tomography

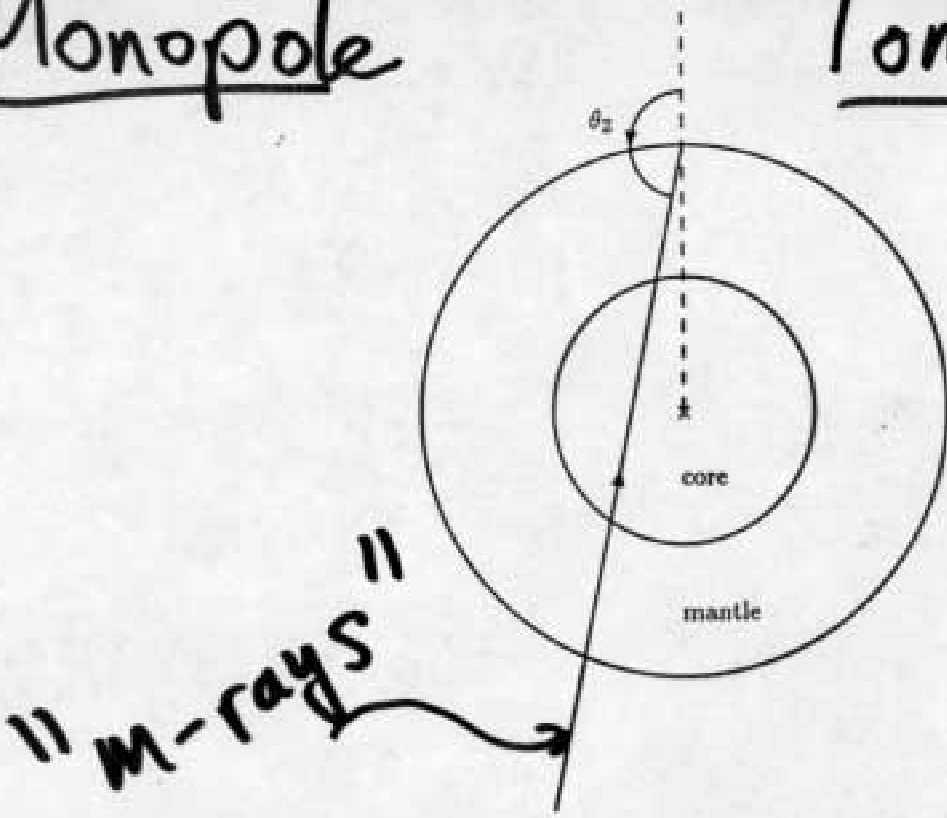
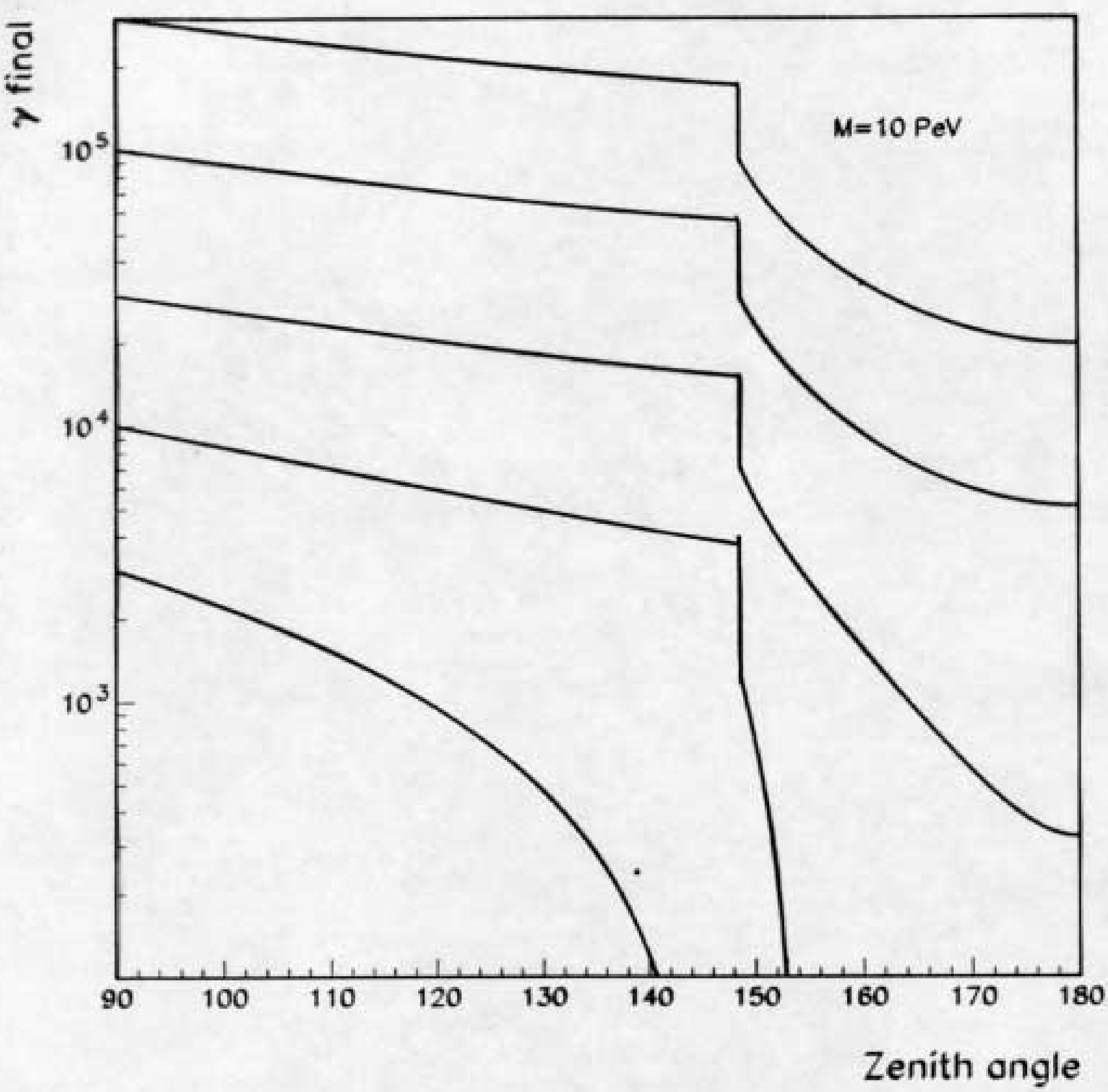


FIG. 2. A schematic representation of earth tomography with a highly penetrating particle. Monopole energy losses differ in passing through the core or mantle and so affect the energy spectrum of upcoming monopoles as a function of zenith angle θ_Z. For a zenith angle $\theta_Z^{core} \simeq 147°$, the upcoming particle grazes the edge of the core.

$$\rho_{core} \simeq 3 \times \rho_{mantle}$$

Find $E_{final}(\theta_Z)$



γ final
M=10 PeV
10^5
10^4
10^3
90
100
110
120
130
140
150
160
170
180
Zenith angle

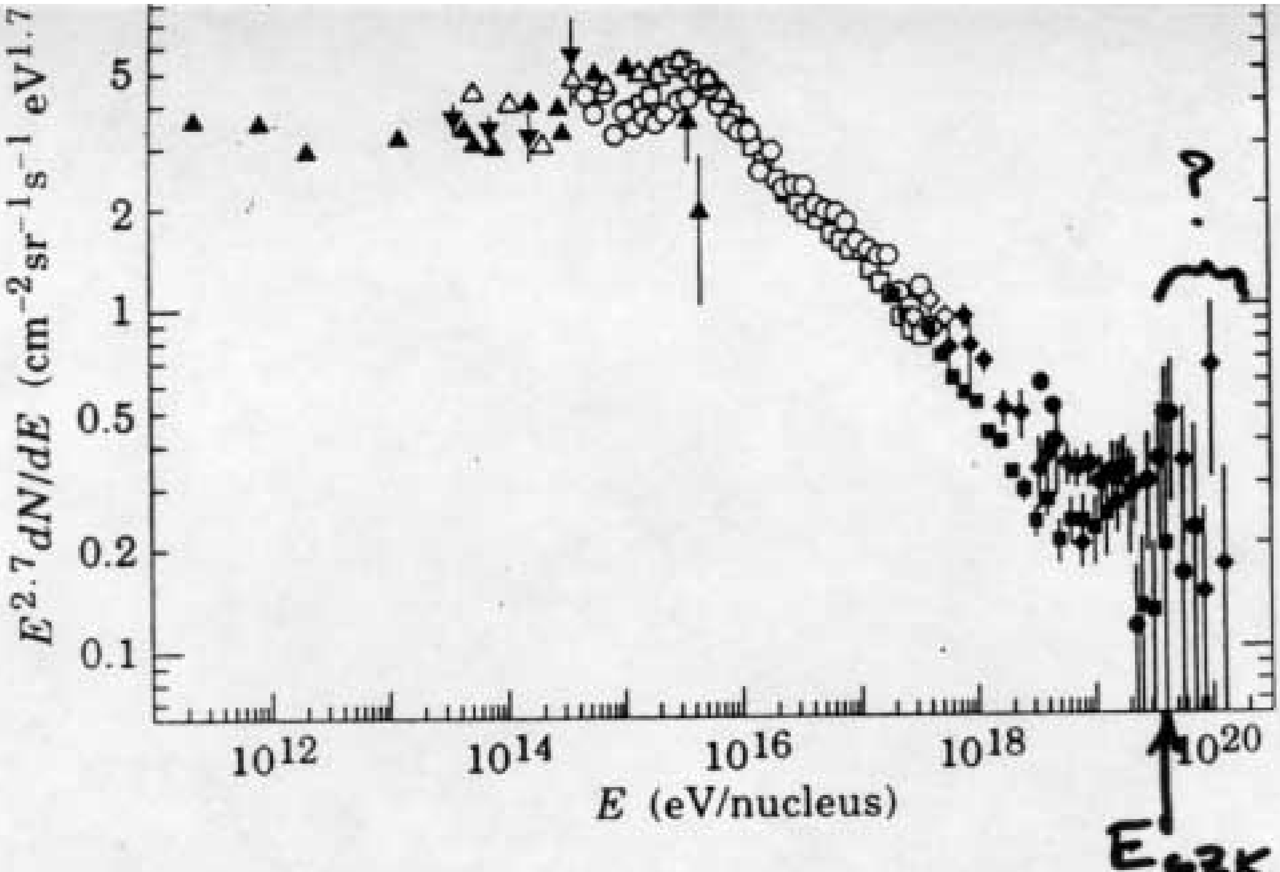


Figure 20.7: The all-particle spectrum: ▲ [37], ▼ [38], △ [39], □ [40], ○ [35], ■ [48], ● [42], ♦ [43].

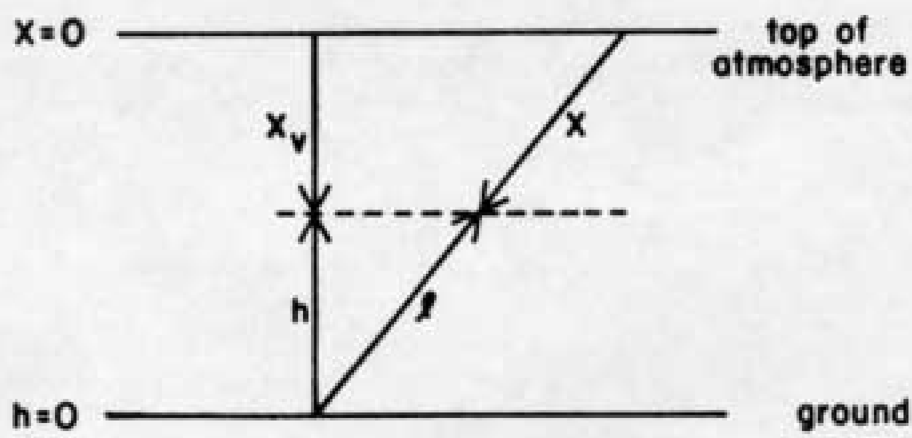


Figure 3.1: Definition of variables to describe the atmosphere.

The nucleon interaction length in air is

$$\lambda_N = \frac{\rho}{\rho_N \sigma_N^{air}} = \frac{A\, m_p}{\sigma_N^{air}}, \tag{3.3}$$

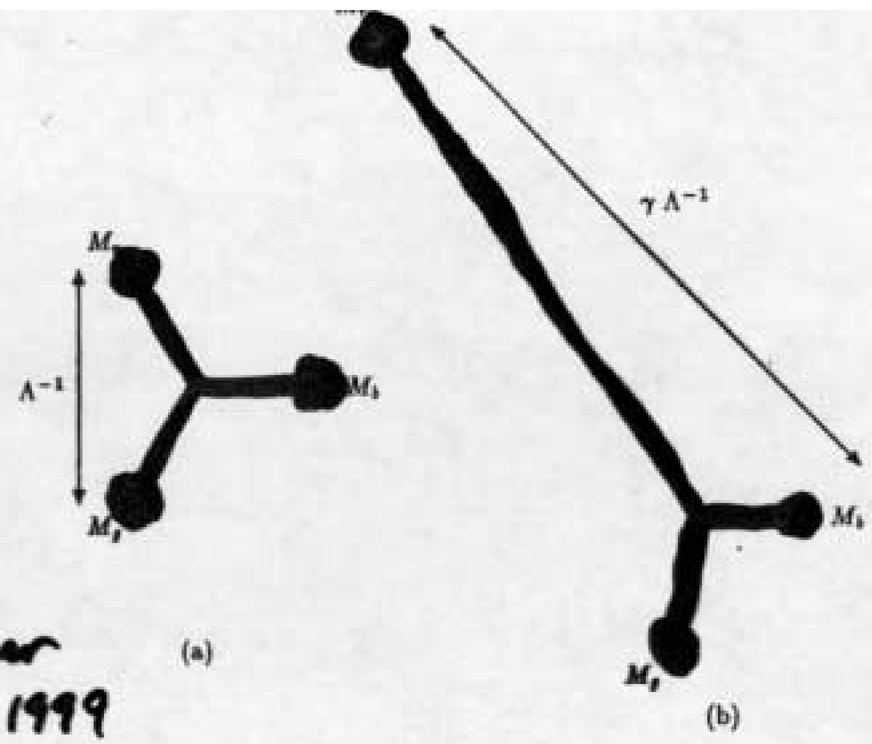
where $\rho(h)$ is the density of the atmosphere at altitude h and ρ_N is the corresponding number density of nuclei. For a calculation of the atmospheric cascade we can take the target nucleus to be an average "air" nucleus with $A \approx 14.5$ and omit the target designation from the notation. For $\sigma_N \approx 300$ mb (appropriate for nucleons interacting with air in the TeV range) $\lambda_N \approx 80$ g/cm^2.

$$\frac{dE}{dx} \sim \eta \frac{E}{\lambda} \propto \eta \sigma$$

			ℓ-monos	B-monos
boost	η	?	N	N
boost	σ	?	N	Y

η - inelasticity per interaction

σ - cross section



A.S. Goldhaber
Phys Repts, 1999
"Dual Confinement of Grand Unified Monopoles"

FIG. 3. The baryonic-monopole in its ground state (figure (a)) and after one interaction with an air nucleus (figure (b)).

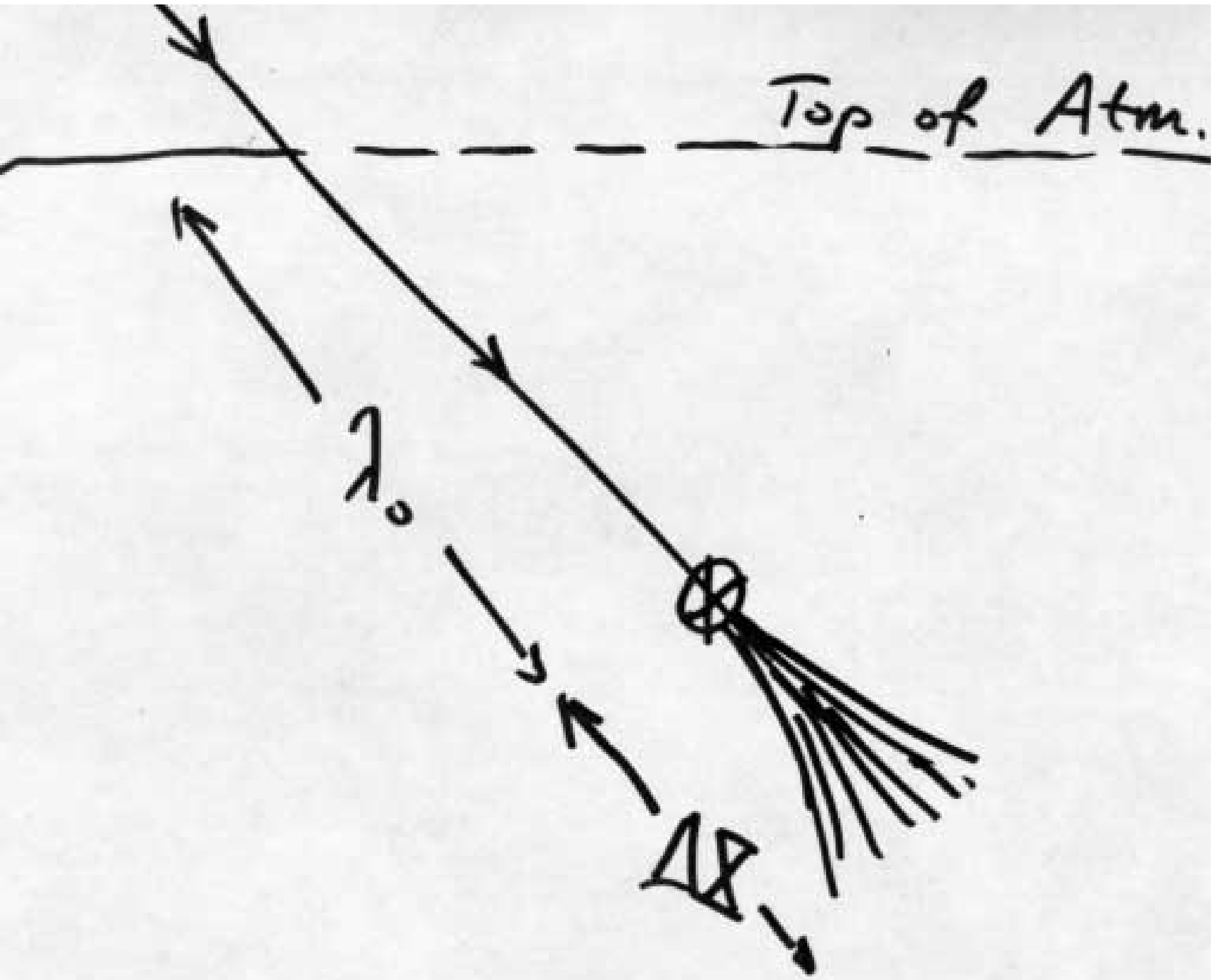
Fig (a) $\quad \sigma_0 \simeq \Lambda_{QCD}^{-2}$

After 1 interaction $(\Delta E \simeq \gamma \Lambda_{QCD})$

Fig (b) $\quad \sigma_1 \simeq (1 + \gamma) \Lambda_{QCD}^{-2}$

→ Z_3-string is easily stretched

<u>monopole</u> pair-production is suppressed.



String Stretching

→ Cross-Section Grows

After n-interactions:

$$\sigma_n \sim (1 + n\gamma)\,\Lambda_{QCD}^{-2}$$

Small Inelasticity:

$$\eta = \frac{\Delta E}{E} = \Lambda_{QCD}/M \lesssim 10^{-6}$$

$\mathcal{O}(1)$ energy transfer after

η^{-1} interactions.

$$\lambda_n = 1/N\sigma_n \simeq \Lambda^2/Nn\gamma$$

$$\Delta X \sim \sum_{i=1}^{\eta^{-1}} \lambda_i \sim \frac{\Lambda_{QCD}^2}{N\gamma} \sum_{i=1}^{\eta^{-1}} \frac{1}{i}$$

$$\Delta X \sim \frac{\Lambda_{QCD}^2}{N\gamma} \ln\left(\frac{M}{\Lambda_{QCD}}\right) \ll \lambda_0$$

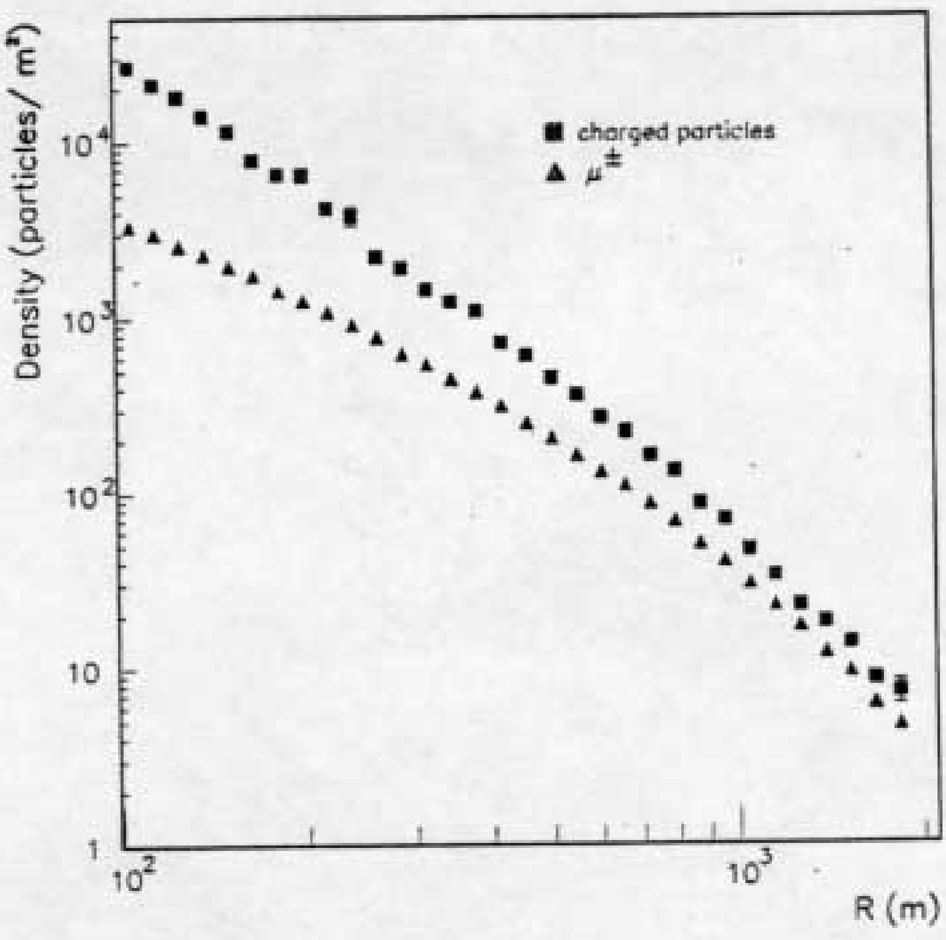


FIG. 2. Lateral distributions of charged particles and muons from AIRES simulations of a 100 EeV monopole with $M = 100$ TeV as a function of the distance to the shower core R. The error bars (obscured by the points themselves in most cases) indicate the RMS fluctuations of the means.

Anchordoqui et al, 2000

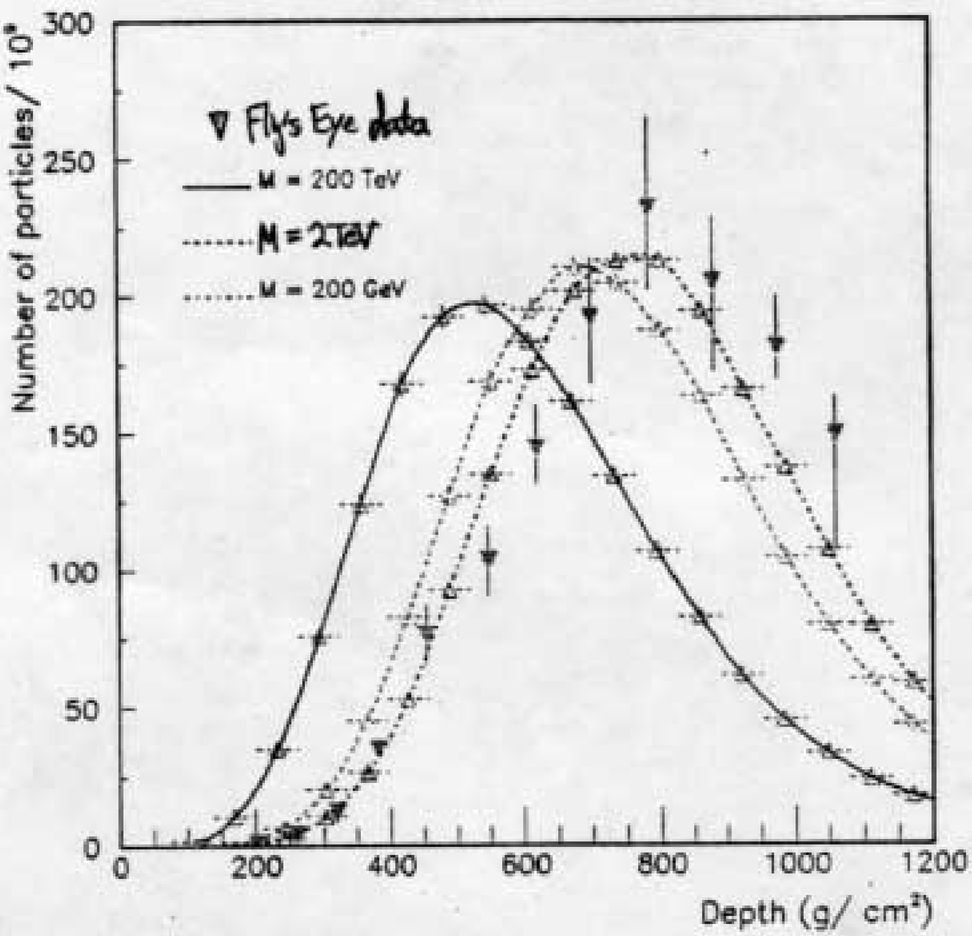


FIG. 3. Atmospheric cascade development of 300 EeV monopole induced showers, superimposed over the Fly's Eye data. The error bars in the simulated curves indicate the RMS fluctations of the means.

Anchordoqui, et al., 2000