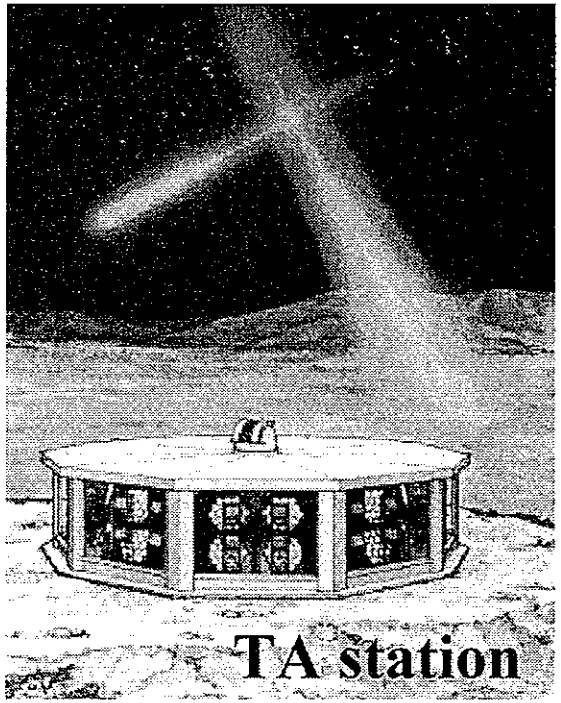
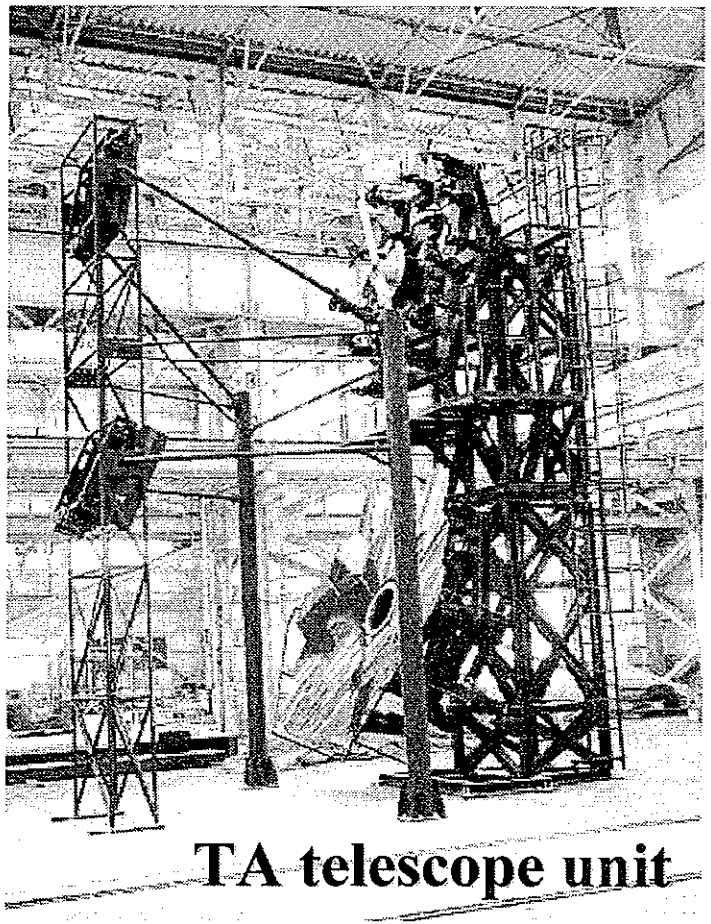
High Energy ν Detection with a Large Air-fluorescence Detector


TA station


TA telescope unit

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http://www-ta.icrr.u-tokyo.ac.jp/

何が言いたいのか？

- 最高エネルギー宇宙線と超高エネルギーニュートリノ
- 活動銀河核からの超高エネルギーニュートリノ
- テレスコープアレイのニュートリノ検出能力
- 展望

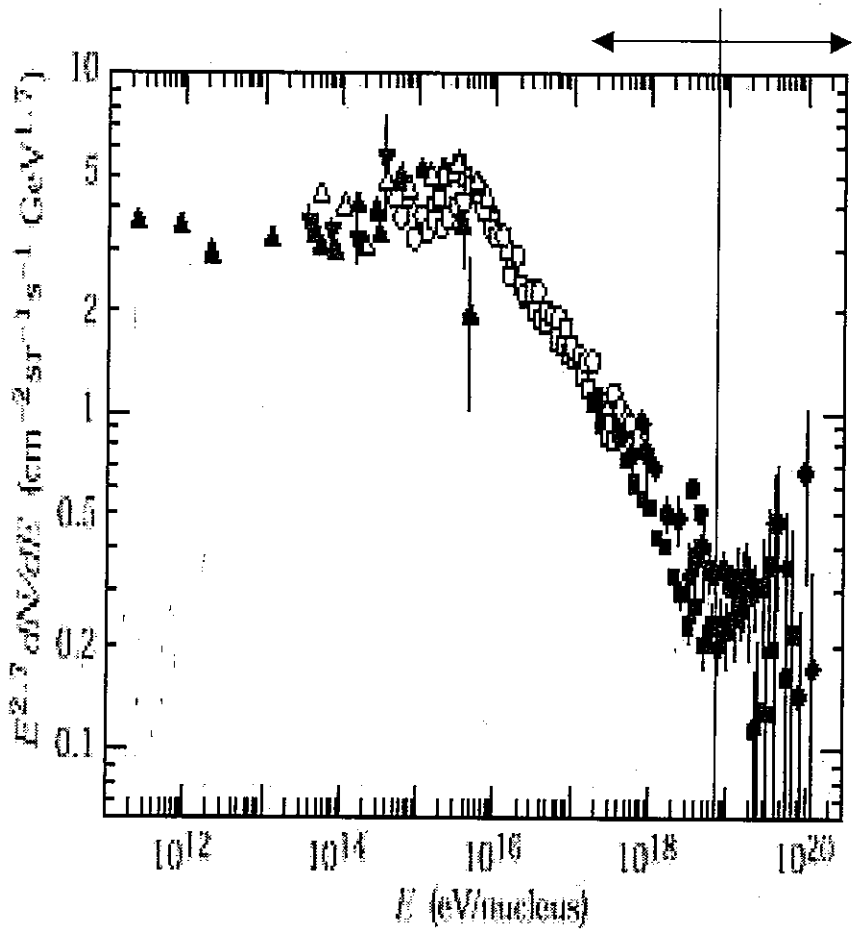
Extragalactic Proton Accelerator?

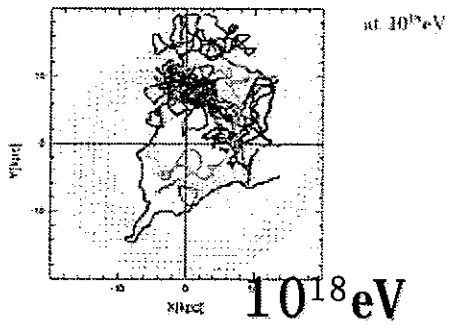
- **Galactic magnetic field:**

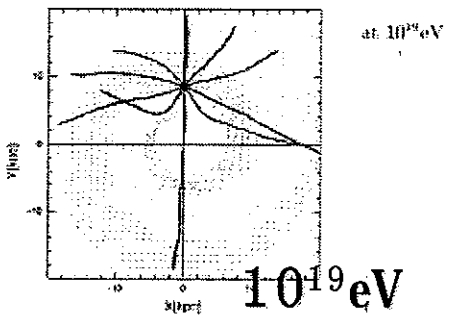
$$R_{kpc} \approx \frac{E_{18}}{ZB_{\mu G}}$$

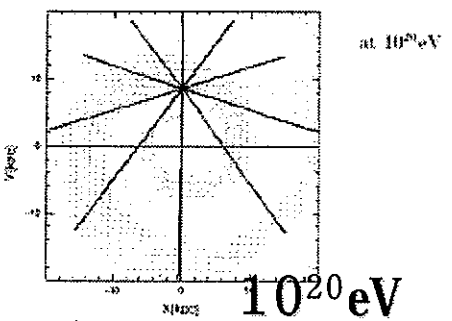
- **E>1 0^{19}eV**

Extra-galactic.





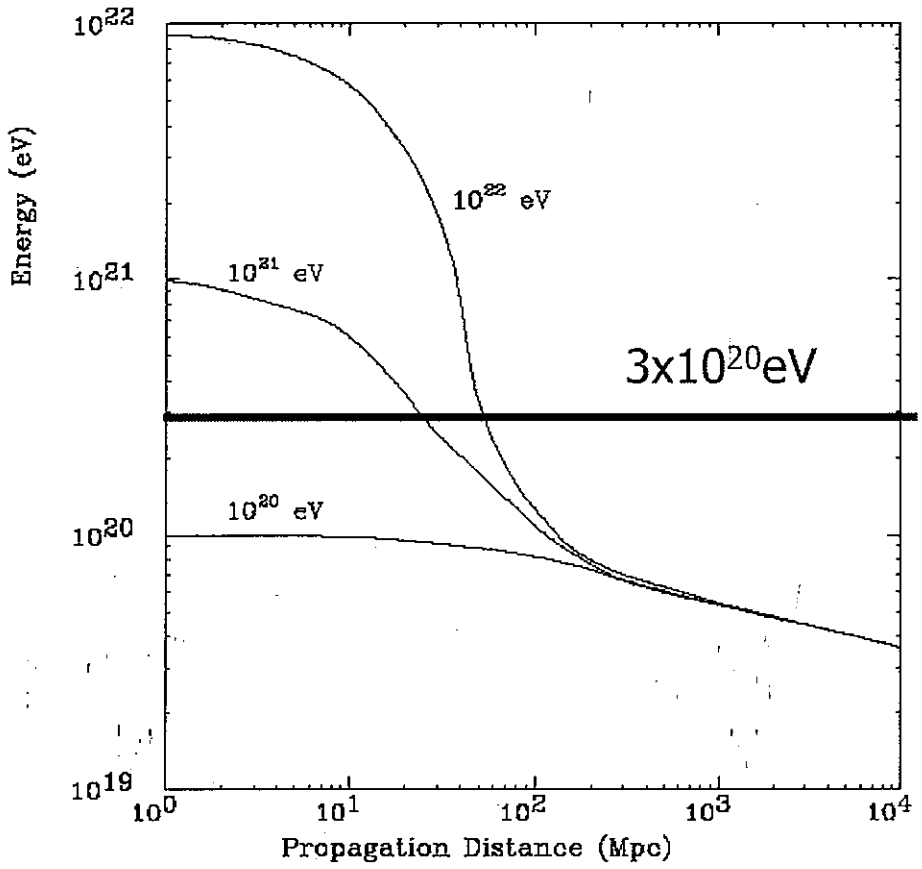


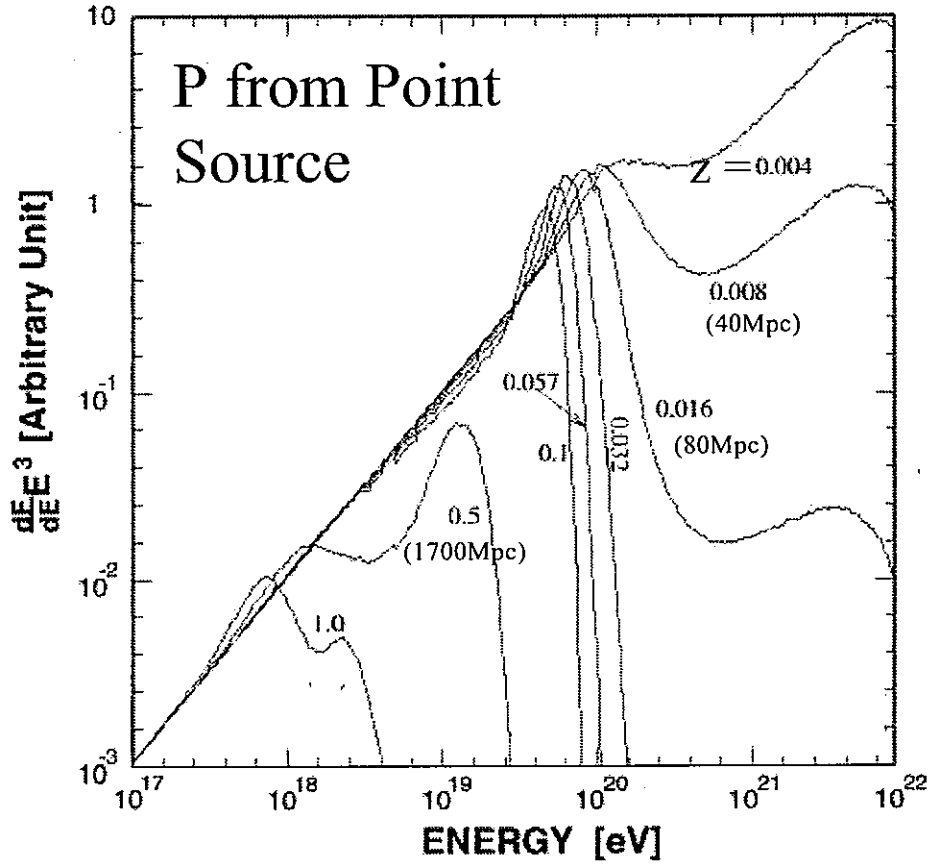


- **How is the energy frontier?**

GZK Mechanism

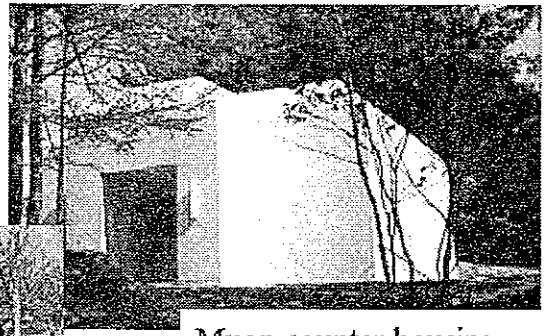
$$p + \gamma_{3K} \rightarrow \Delta \rightarrow p + \pi^0 \; or \; n + \pi^+$$



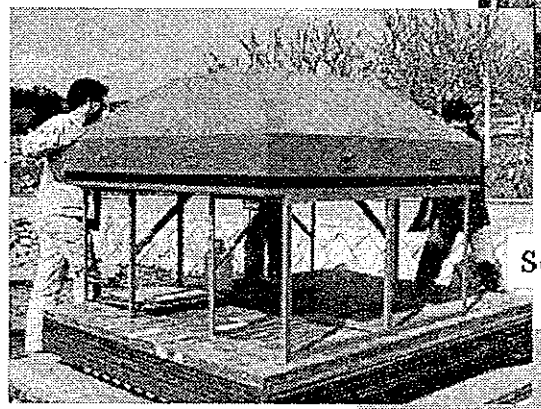


Long propagating protons ⇒ Cutoff in the spectrum

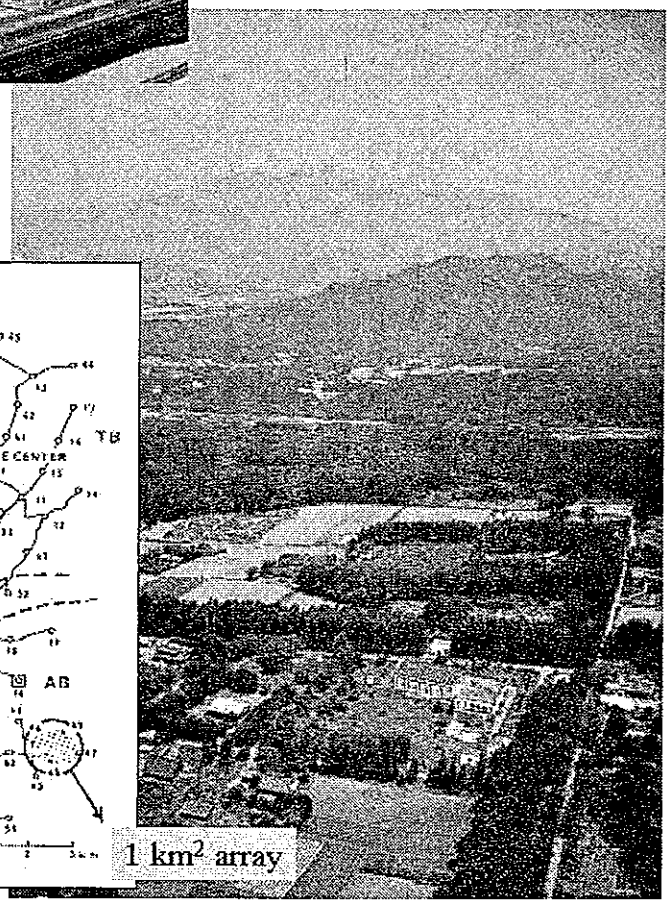
Akeno Giant Air Shower Array (AGASA)



Muon counter housing
(x 8). Other types (x 19)

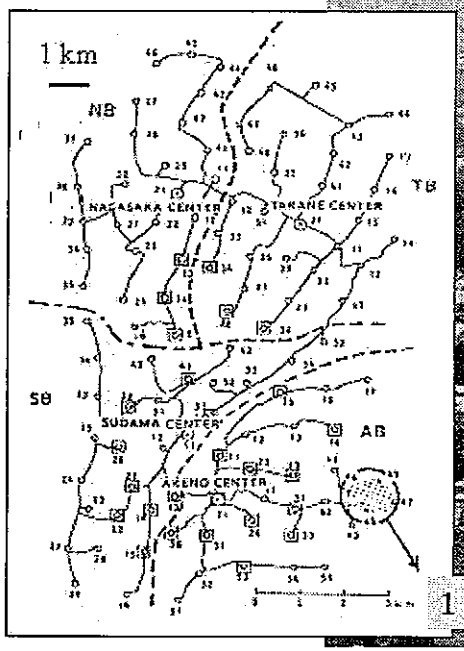


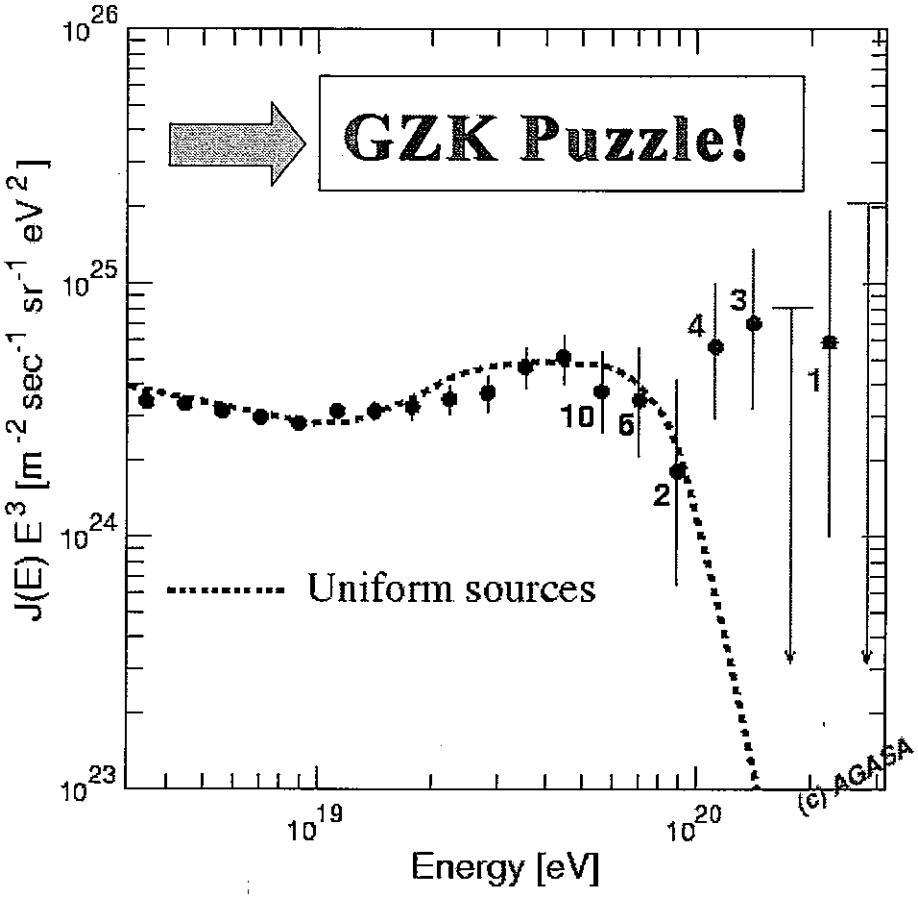
Scintillation counter (x 111)

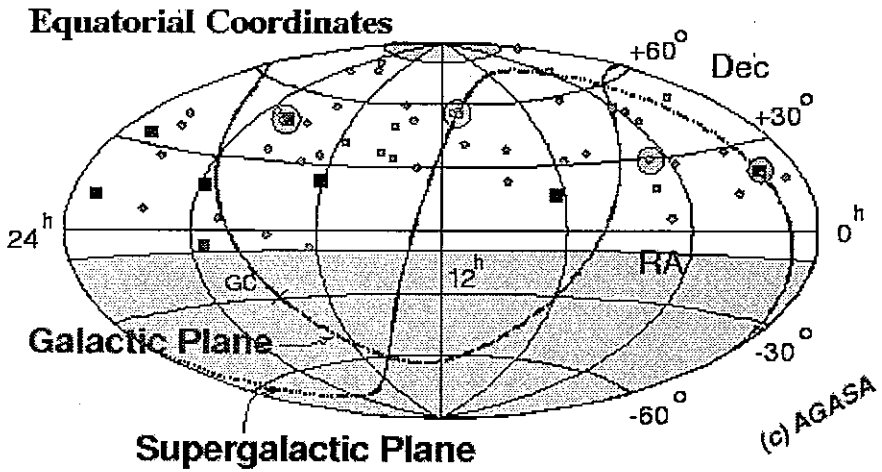


1 km^2 array

100 km^2 array

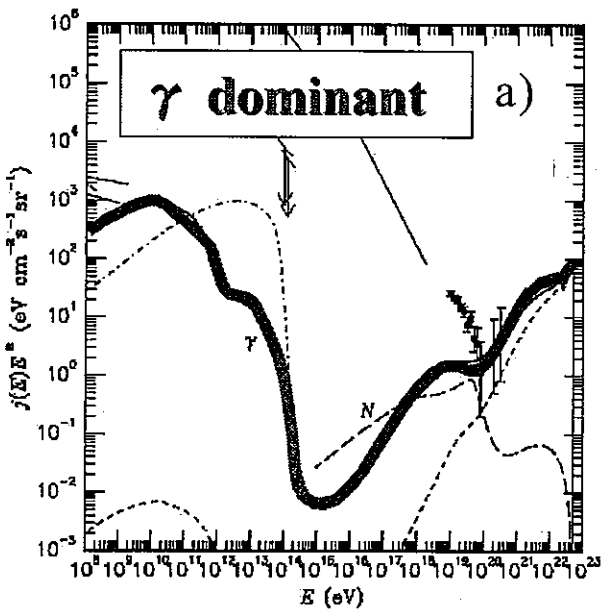






Top Down or Bottom up?

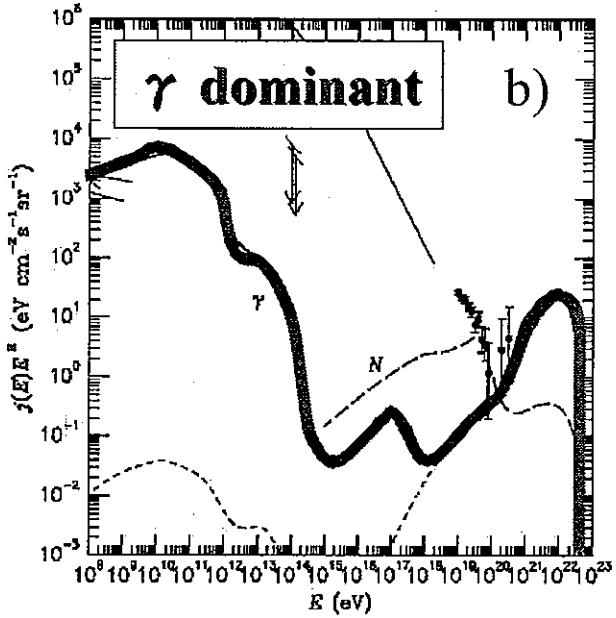
Sigl,Lee,&Coppi, astro-ph/9604093



Cosmic String

$M_x = 2 \times 10^{16}$GeV

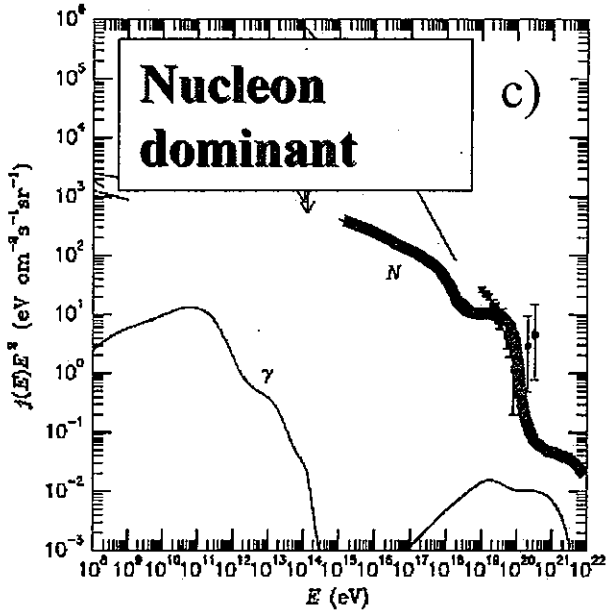
B= 0 Gauss



Cosmic String

$M_x = 2 \times 10^{16}$GeV

B= 1 nGauss

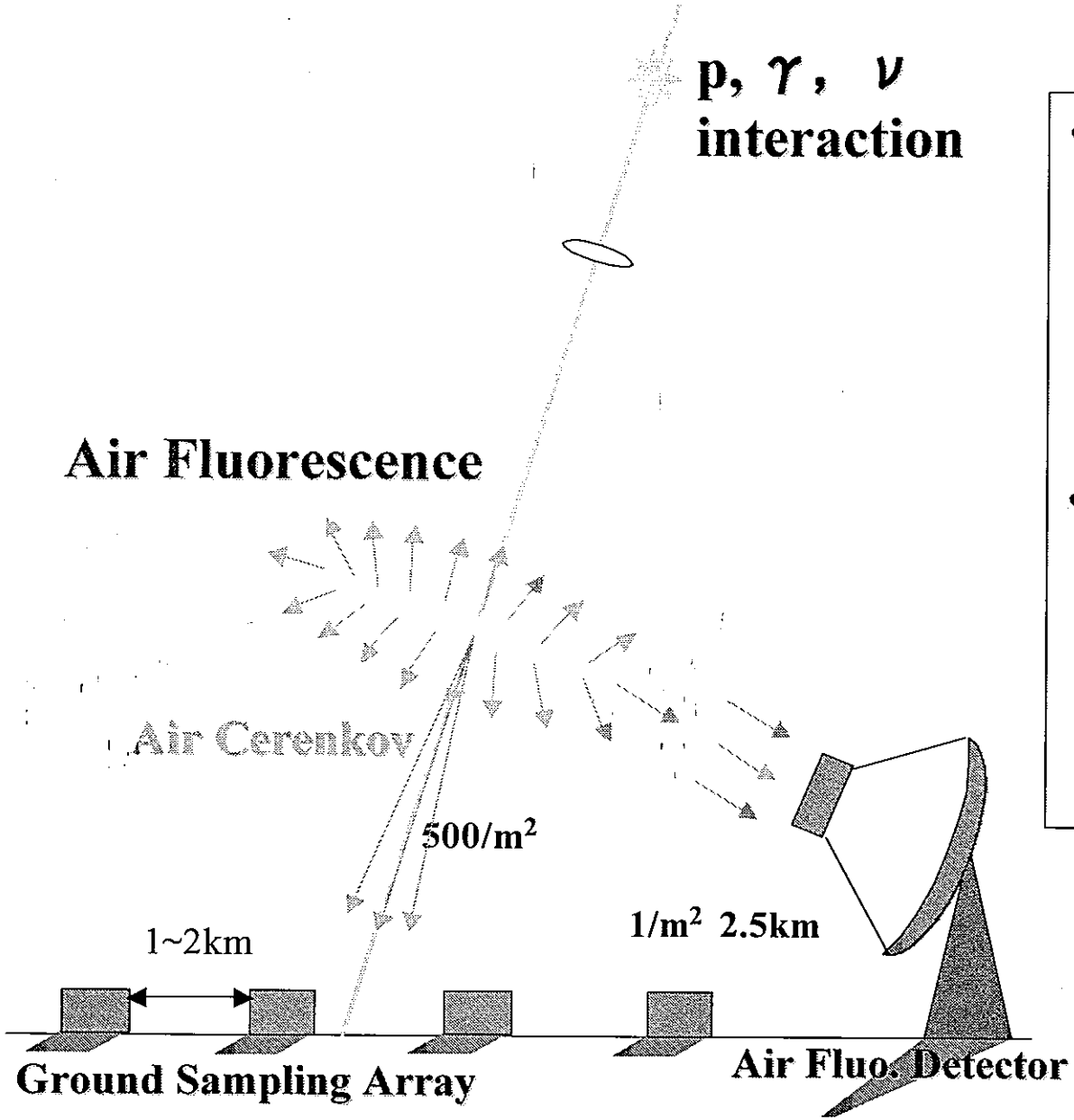


Proton Accelerators

Uniform z<4

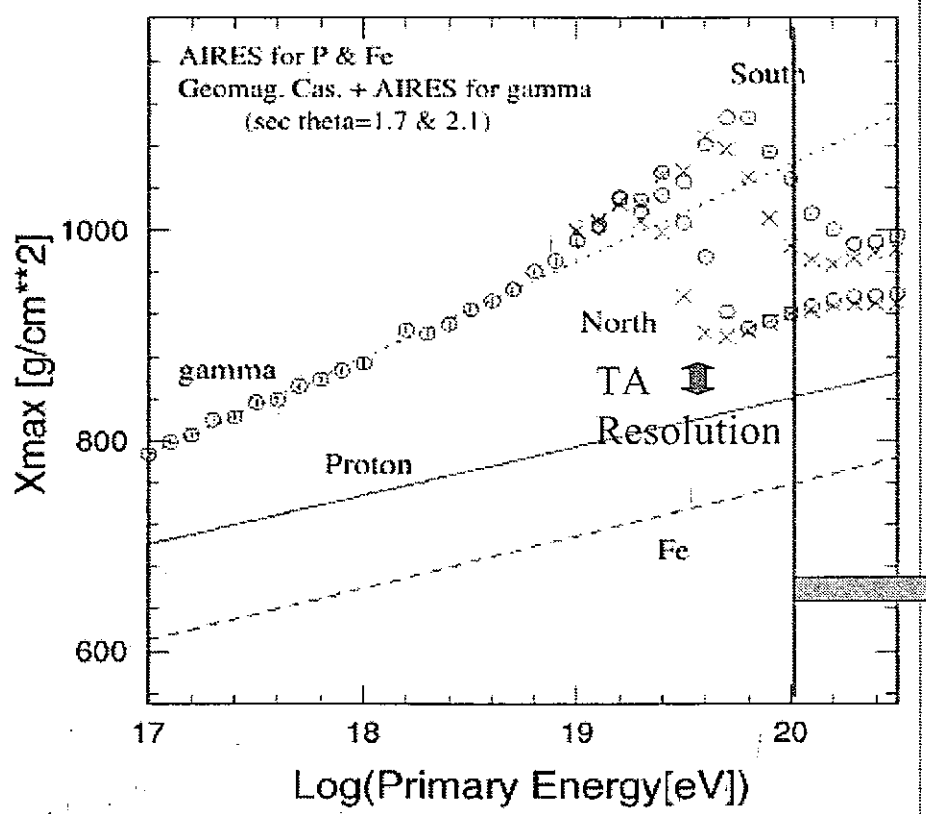
=> Particle Identification (PID) is key

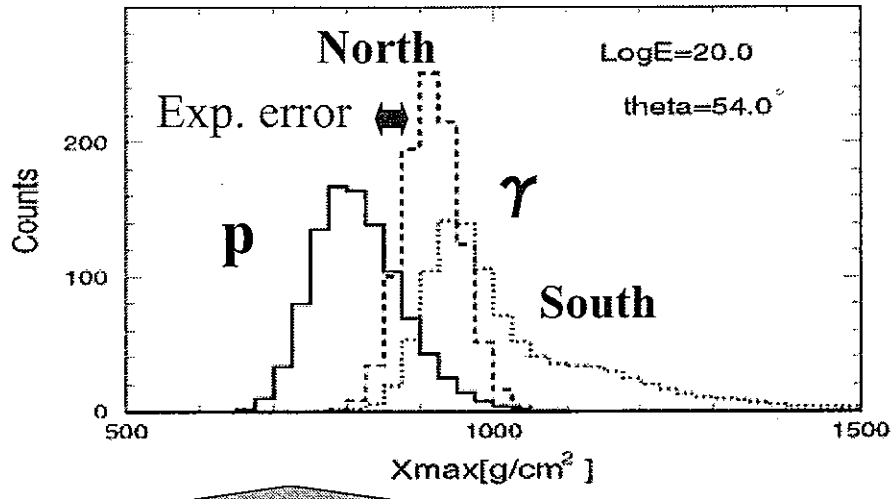
Cosmic Ray Air Shower Detection

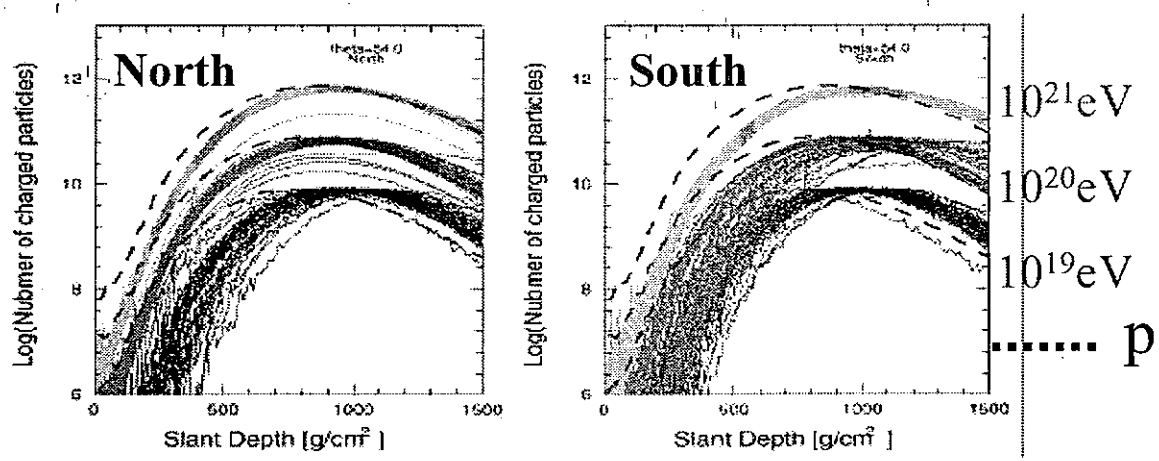


- **Air Fluorescence Detector**
  - Calorimetric
  - **Long. Development => PID**
  - **Fly's Eye, HiRes, TA**
- **Ground Sampling Array**
  - 2D-sampling e & γ
  - Energy: MC+ ρ (600m)
  - μ - ratio => PID
  - **AGASA, AUGER, etc**

γ -IDENTIFICATION



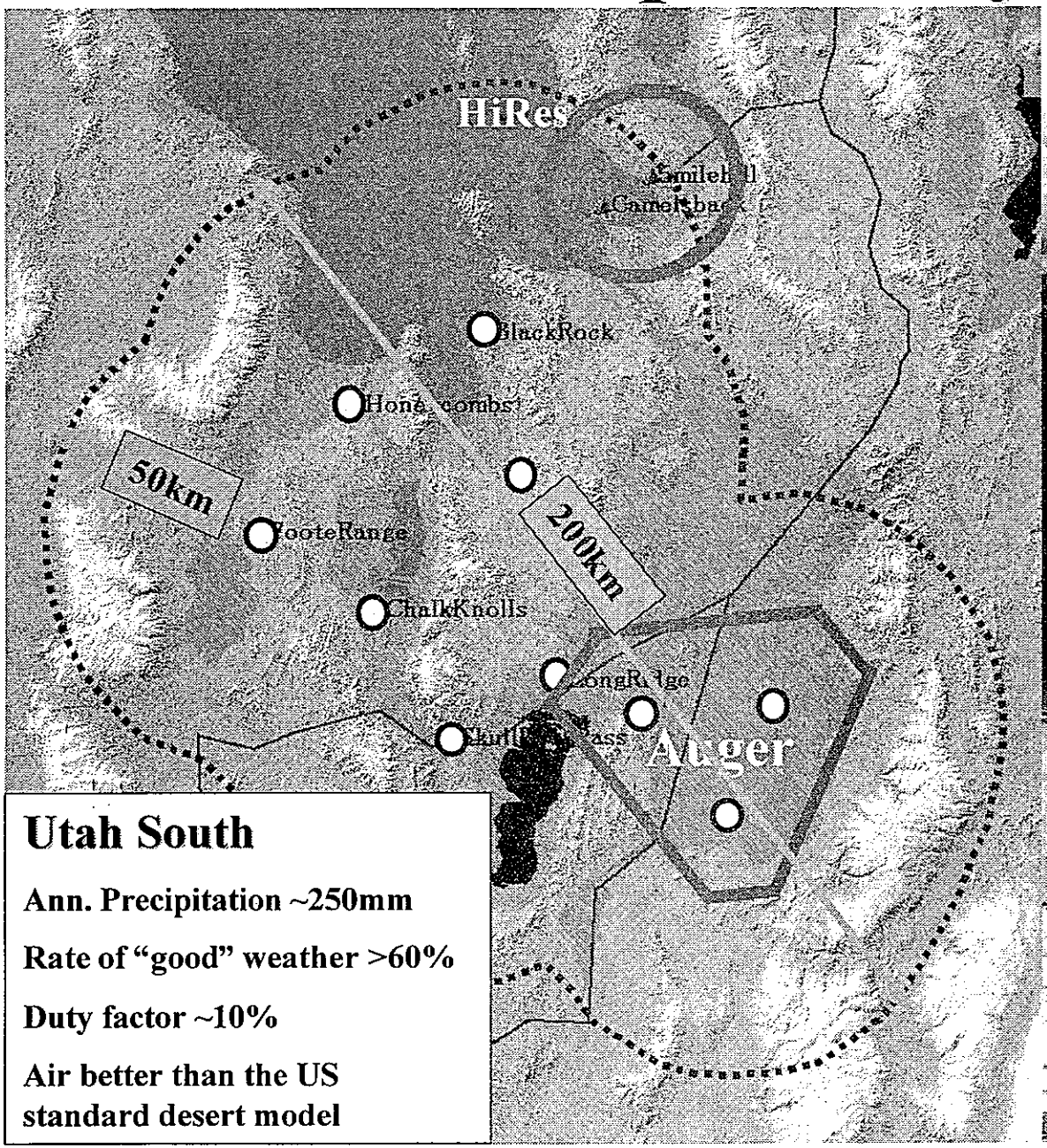




EHE- γ suffers:

1. Decrease of Bethe-Heitler crossection by LPM effect.
2. Geomagnetic Cascade

Telescope Array Project



Utah South

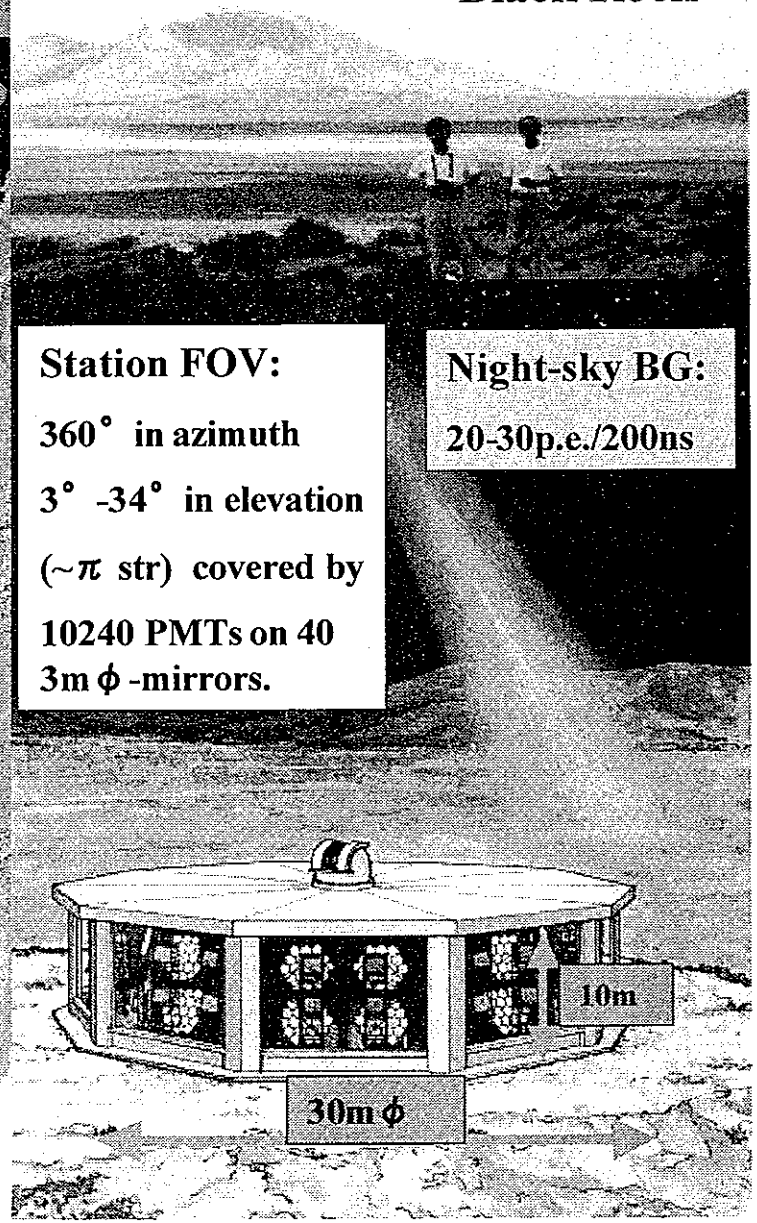
Ann. Precipitation ~250mm

Rate of "good" weather >60%

Duty factor ~10%

Air better than the US standard desert model

Black Rock



Station FOV:

360° in azimuth

3° -34° in elevation

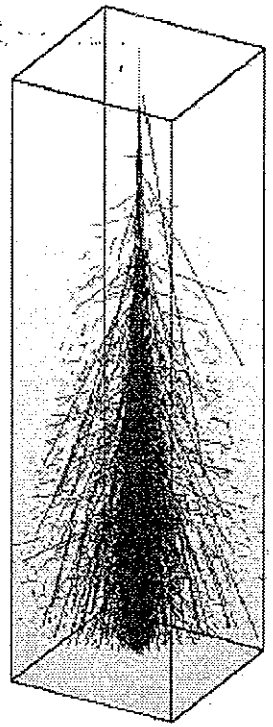
(~π str) covered by

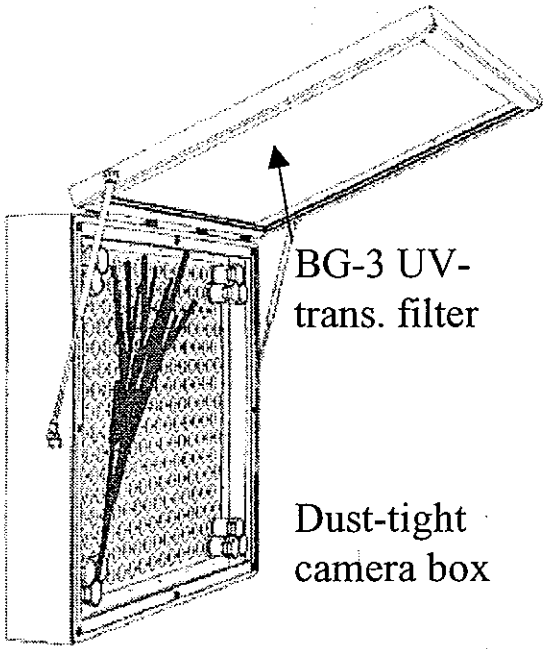
10240 PMTs on 40 3m ϕ -mirrors.

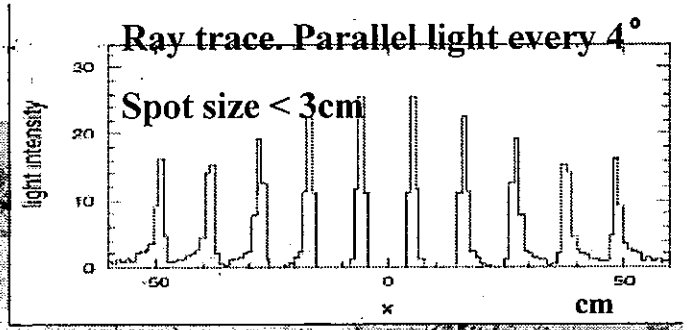
Night-sky BG:

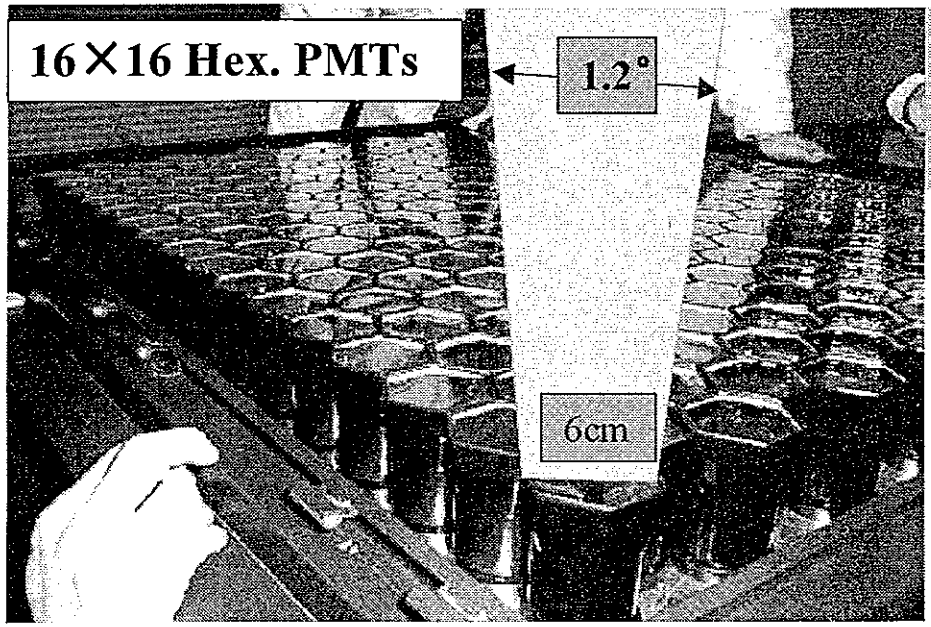
20-30p.e./200ns

OPTICS







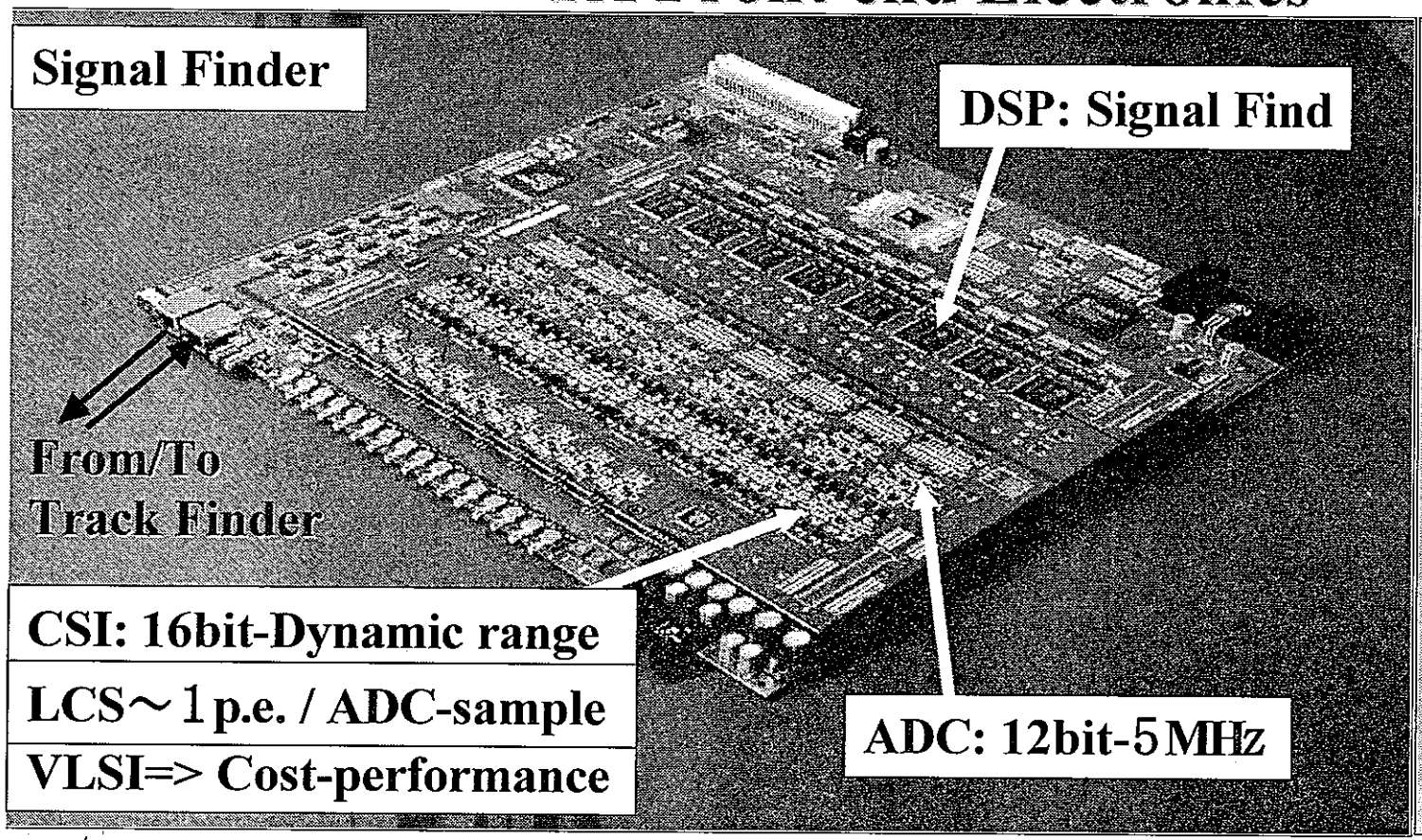


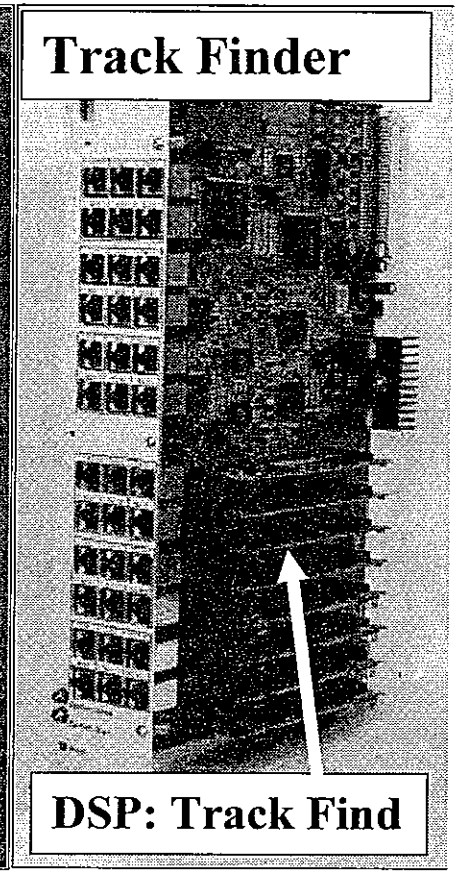
3.3m ϕ spherical mirror system is composed of 18 segment mirrors .

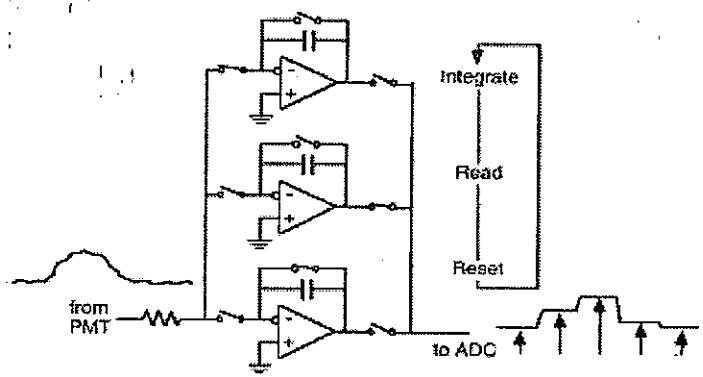
Front aluminized TEMPAX glass with curvature radius of 6m.

90% reflectivity @ 350-400nm

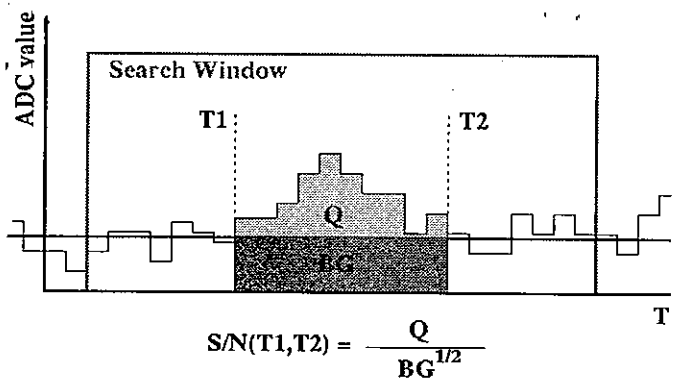
TA Front-end Electronics



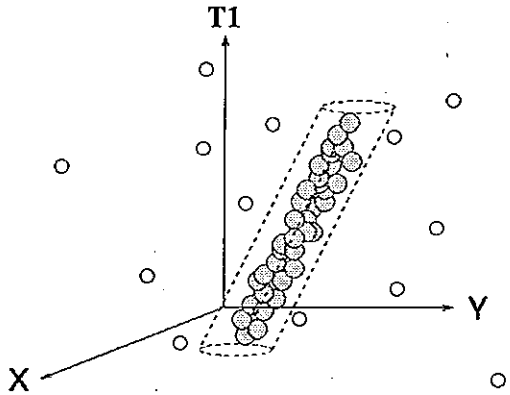




Charge Successive Integrator



Signal Find maximizing S/N

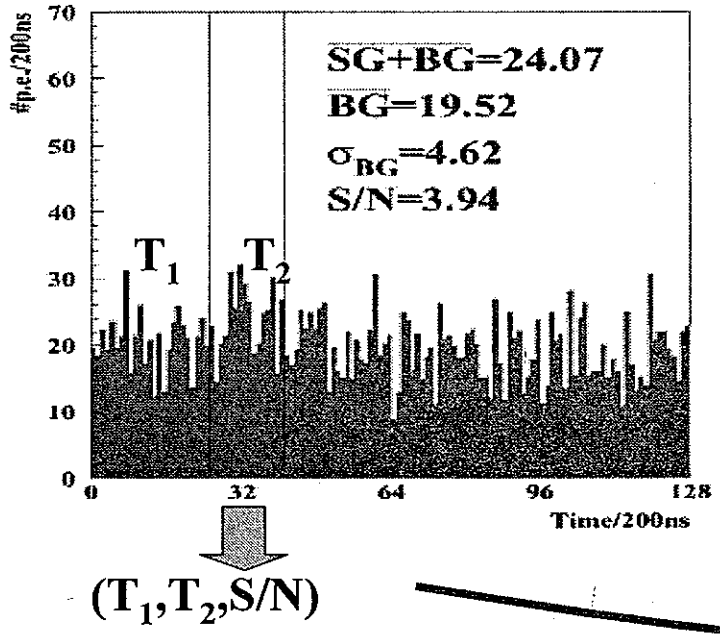


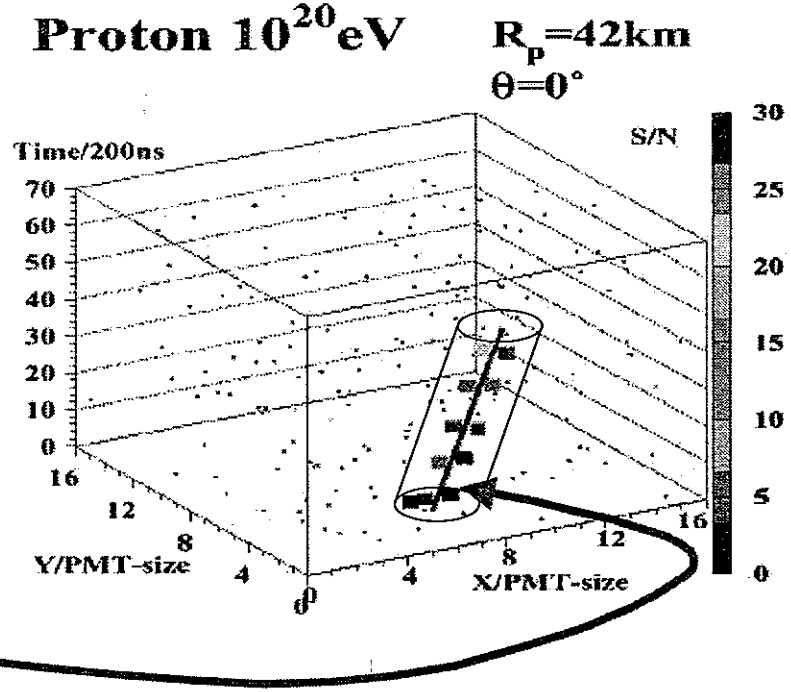
3D Track Find

TRIGGER

$$S/N = N_e N_\gamma c \frac{(1+\cos\theta)}{4\pi R_P^2} e^{-r/\lambda_R} \left(\frac{\varepsilon A}{4B\Delta\Omega}\right)^{1/2} \left(\frac{\Delta t_S}{\Delta t_I^{1/2}}\right)$$

Δt_S signal time, Δt_I integration time





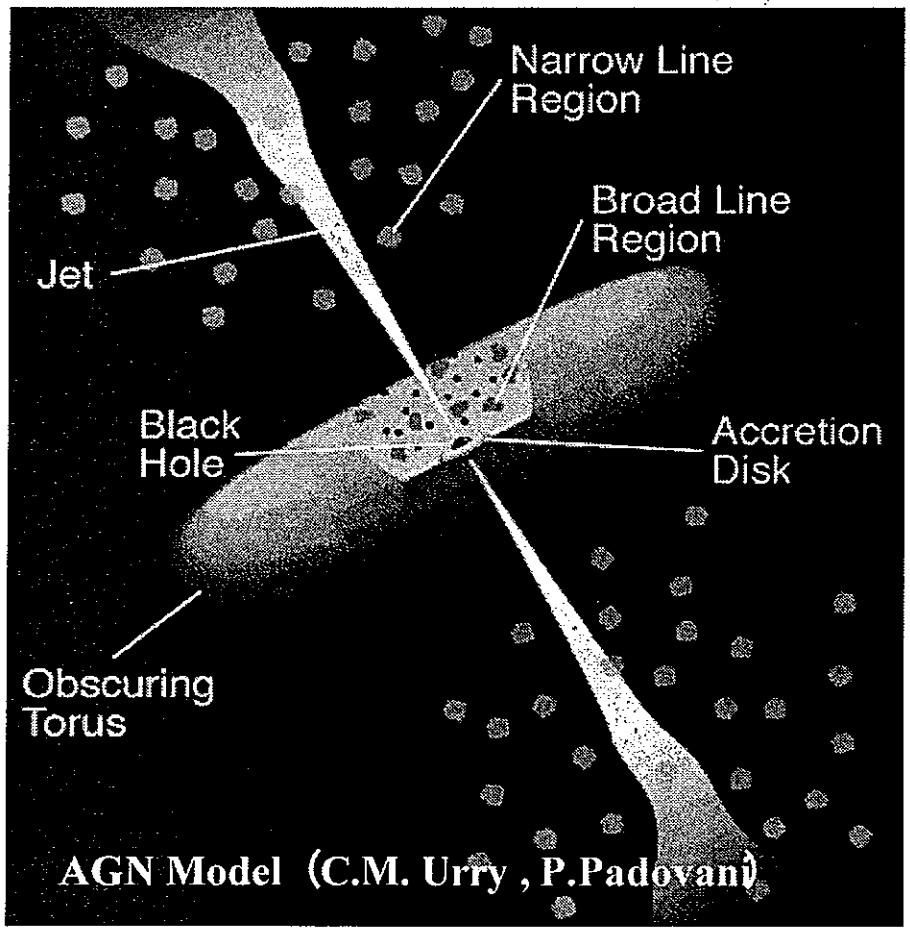
1. Signal Finding

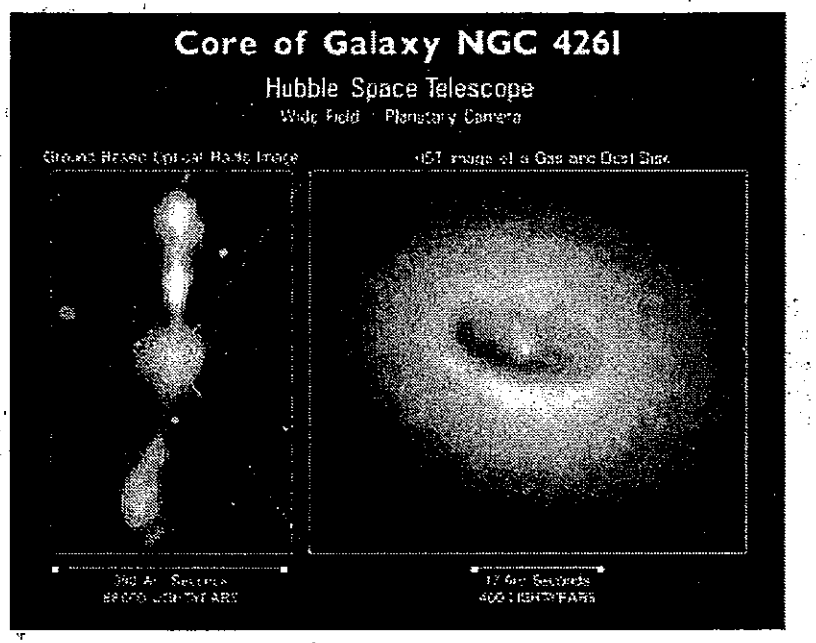
2. Track Finding

1. SF-DSP program finds (T_1,T_2) which maximizes S/N in 25.6 μs search window.
2. TF-DSP program finds a cylindrical boundary in 3D space; XY(camera) coordinates and T(time) coordinate, which maximizes the S/N density in the volume.
3. TF makes a trigger decision if the obtained S/N-density is above threshold where the threshold is determined for the trigger rate to be <10Hz.

AGN-ν

- **Highly compact bright objects powered presumably by BHs causing acceleration and accretion of matter, characterized usually by jet emission.**

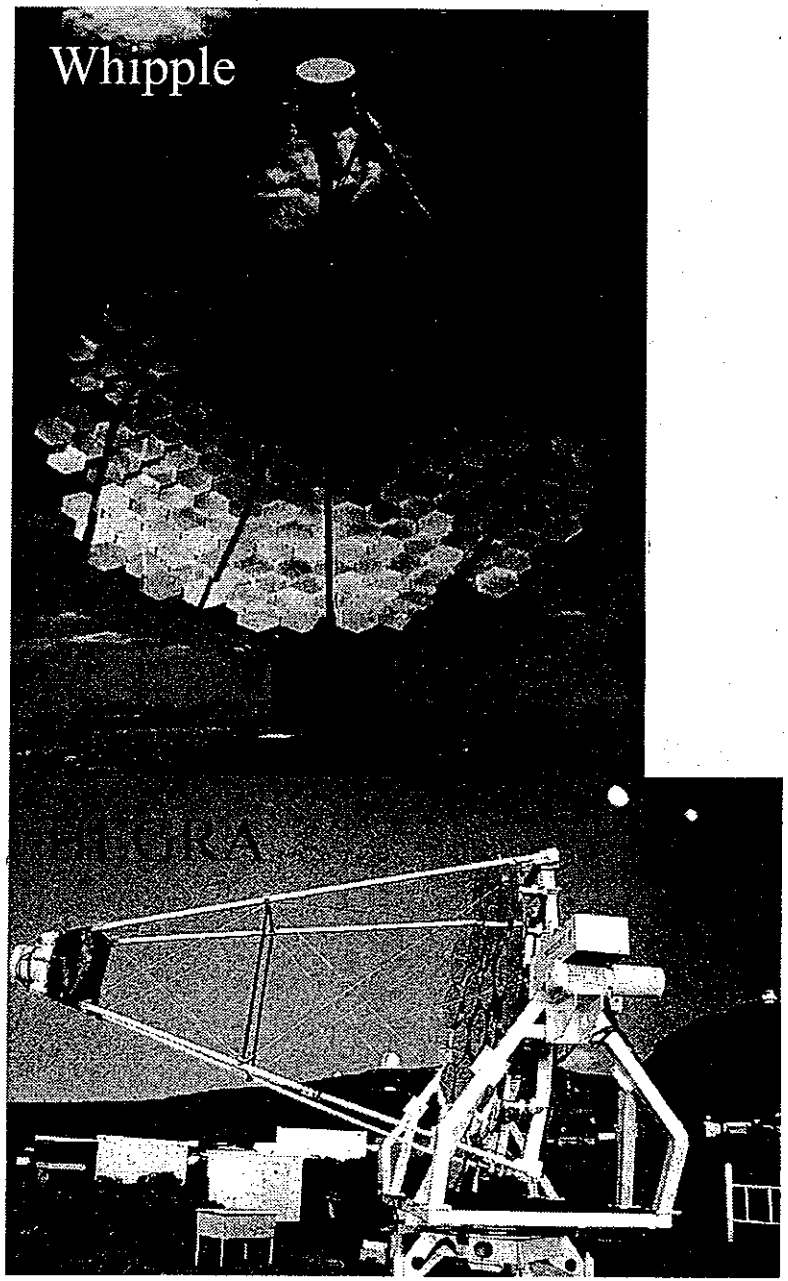


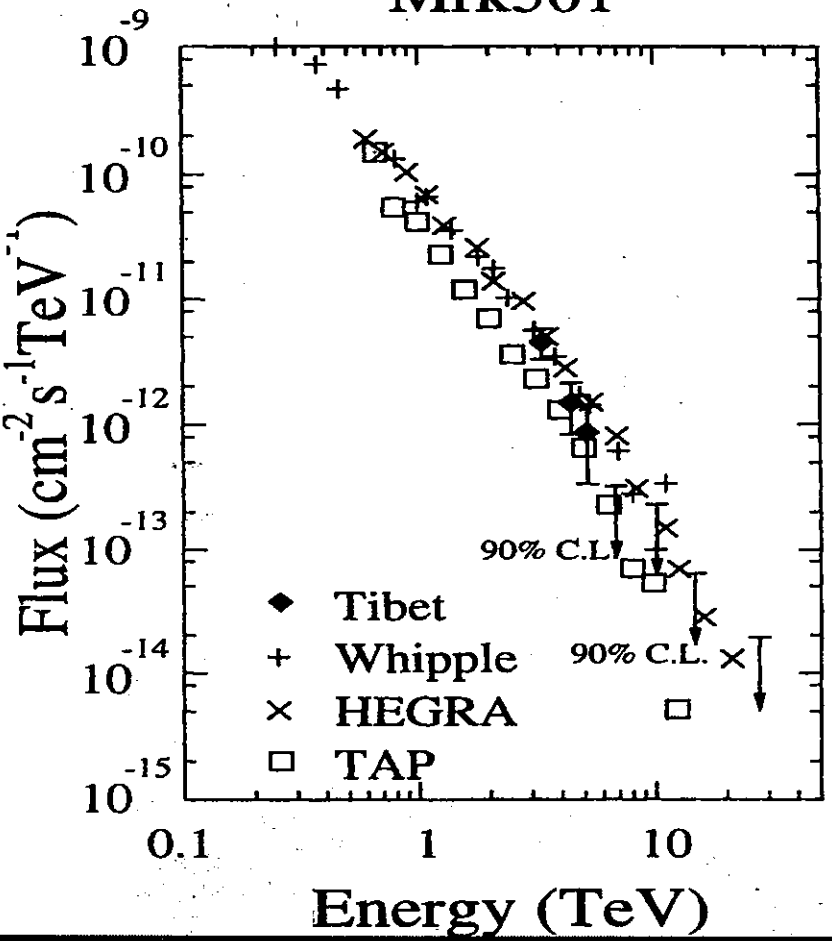


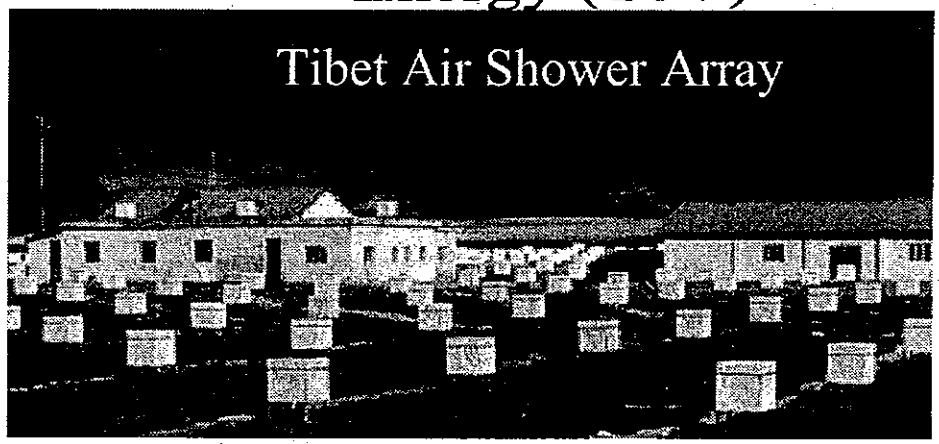
- **93 observations** by EGRET.
- TeV-γ observations from **3 blazar sites**.
- **Electron blazar models:**
  - predict no neutrinos and no gammas above a few TeV at most.
- **Proton blazar models:**
  - p-γ , pp interactions are expected to occur resulting in HE neutrino fluxes and gammas extending to >10TeV.

EHECR Origin?

AGN TeV-γ Observation

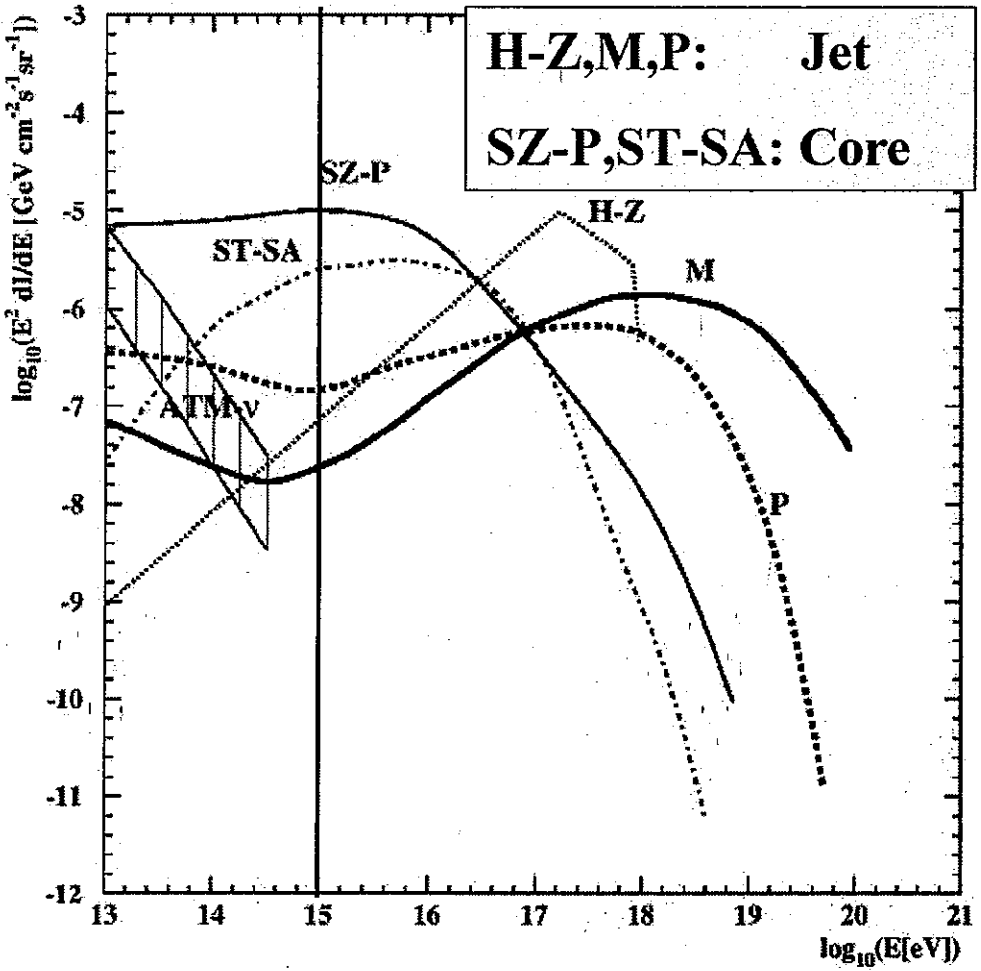






Evidence for Proton Acceleration

EHE-ν Observation



$$p\gamma \rightarrow p\pi^0 \rightarrow p\gamma\gamma$$

$$p\gamma \rightarrow n\pi^+ \rightarrow n\nu_\mu\mu^+ \rightarrow n\nu_\mu e^+\nu_e\bar{\nu}_\mu$$

$$\frac{dN_\nu}{dE_\nu} \sim Nrm \cdot \left(\frac{E_\nu}{E_\nu^{Max}}\right)^{-1}$$

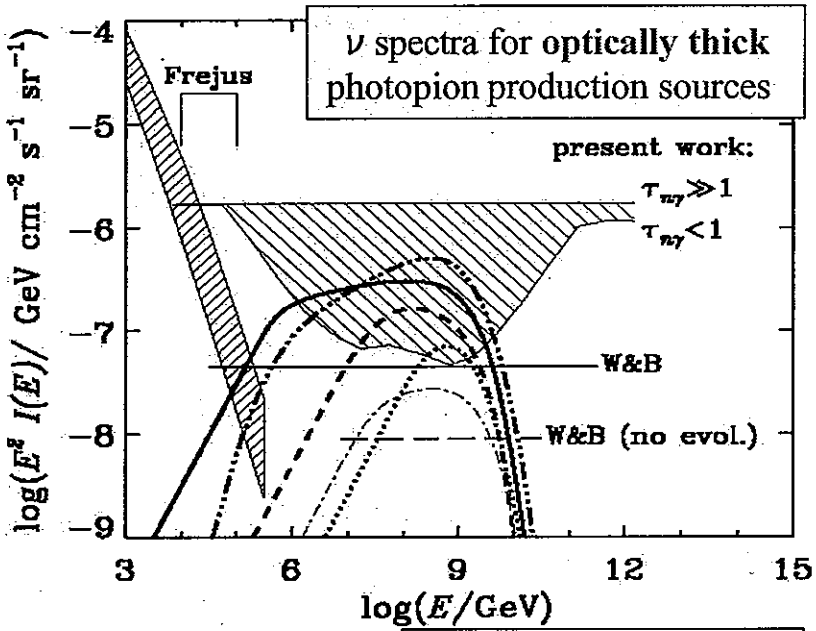
$$L_\nu \sim \frac{L_\gamma}{3} \sim \int^{E_\nu^{Max}} dE_\nu E_\nu \frac{dN_\nu}{dE_\nu} \sim Nrm \cdot \left(E_\nu^{Max}\right)^2$$

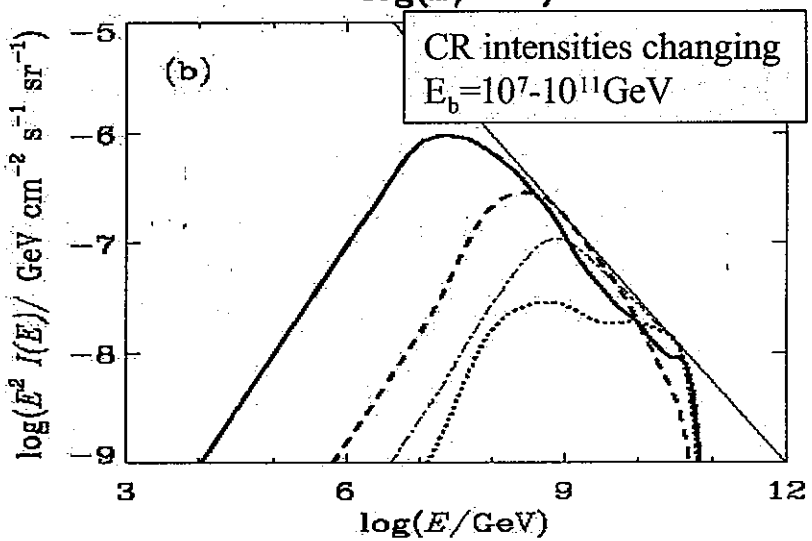
$$E_\nu \frac{dN_\nu}{dE_\nu} \sim \frac{L_\gamma}{3}\left(E_\nu^{Max}\right)^{-1}.$$

- AGN can explain 25% of diffuse γ by EGRET
- Overwhelm ATM-ν above 10^{15}eV
- AGN-ν detection $\Rightarrow$ p model
- Spectrum shape $\Rightarrow$ prod. location

Relation of extragalactic CR and ν -fluxes

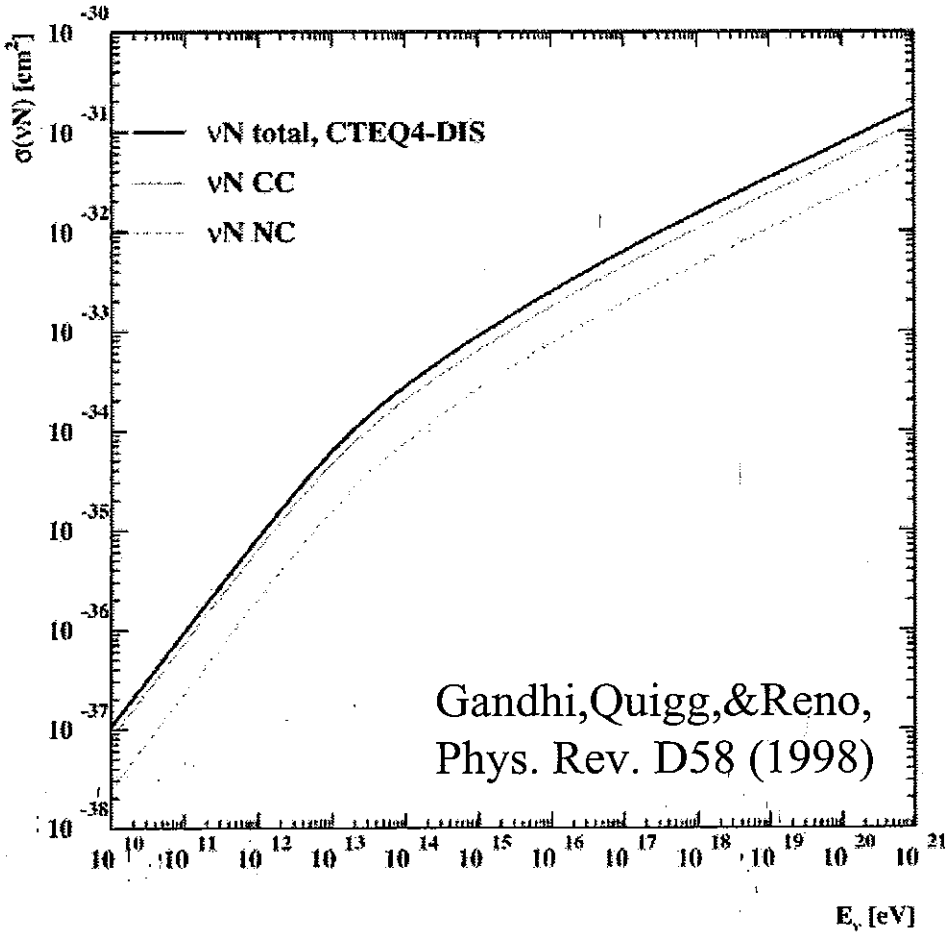
- **The Upper Bound Debate:**
  - **Waxman-Bahcall**
    - If HE-ν s are produced in optically thin sources via p-γ interactions, the observed CR spectrum constrains the HE-ν flux in a model-independent way.
    - Contradiction with γ BG observations for normalizing the HE-ν flux.
  - **Rachen-Protheroe-Mannheim**
    - Overall CR injection spectrum $\propto E^{-2}$ extending to the highest energies?
    - Neutron and γ opacities?
    - Effect of magnetic fields?
    - **The WB bound relies on very special model assumptions. New bounds are estimated.**
  - **The exploration of the energy range between 10^7GeV and 10^9GeV, where the cosmic ray/neutrino connection is most rigid, will thereby play a crucial role.**

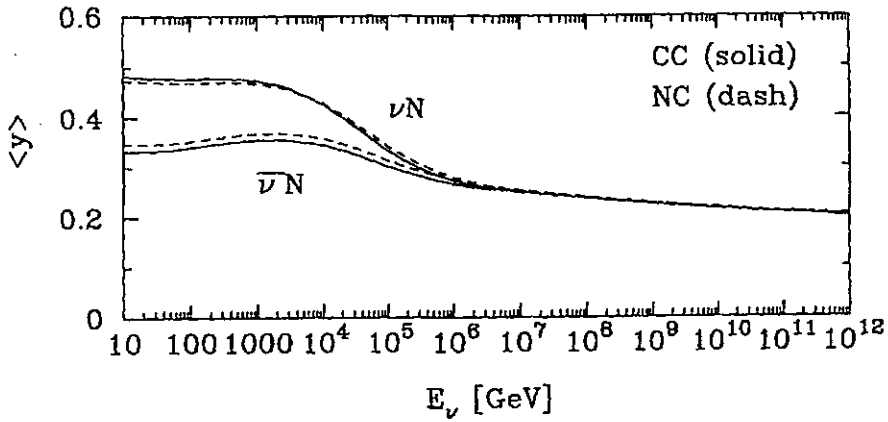


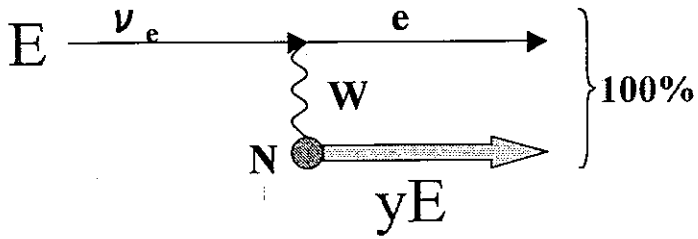


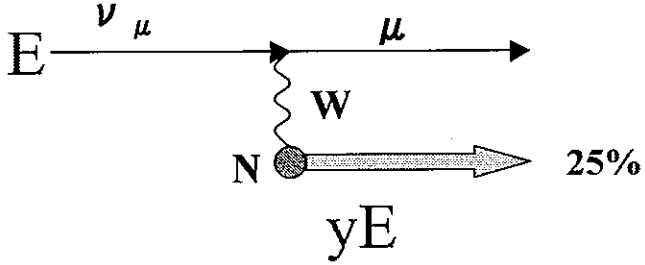
RPM, Astro-ph/9812398

ν N INTERACTION







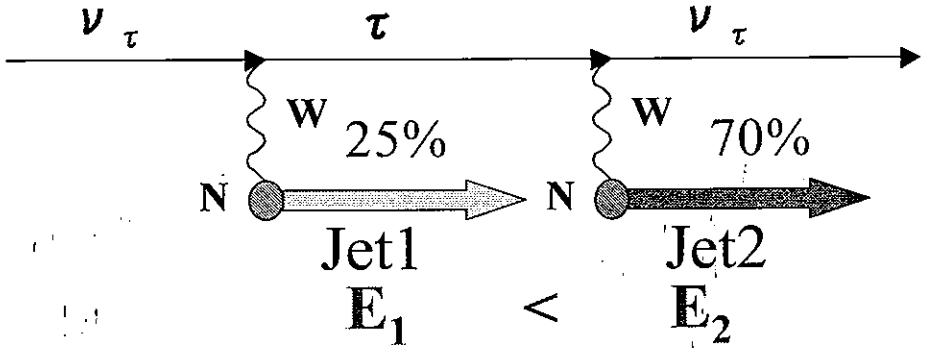


Tau Neutrino Appearance

$$L_{\nu_\mu-\nu_\tau} = 4\times10^{-3}\, pc\left(\frac{E_\nu}{10^{16}eV}\right)\cdot\left(\frac{\Delta m^2}{(10^{-2}eV)^2}\right)$$

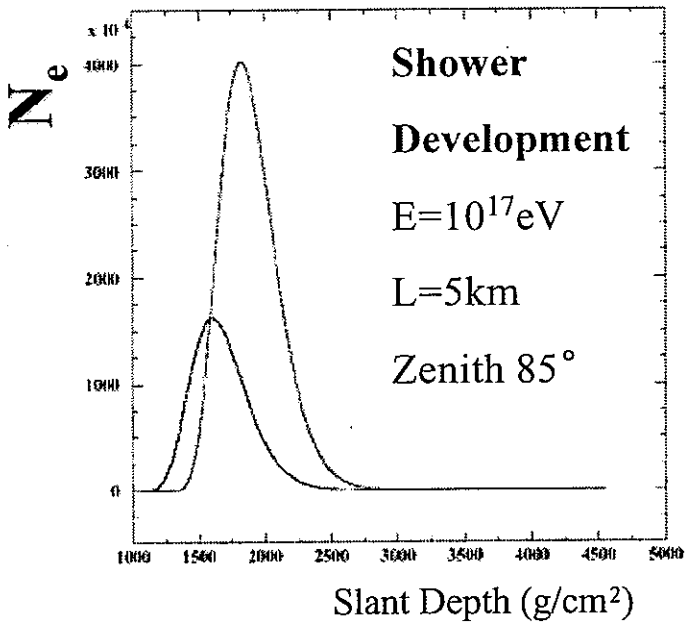
M87: D=20Mpc~5×10⁹×L

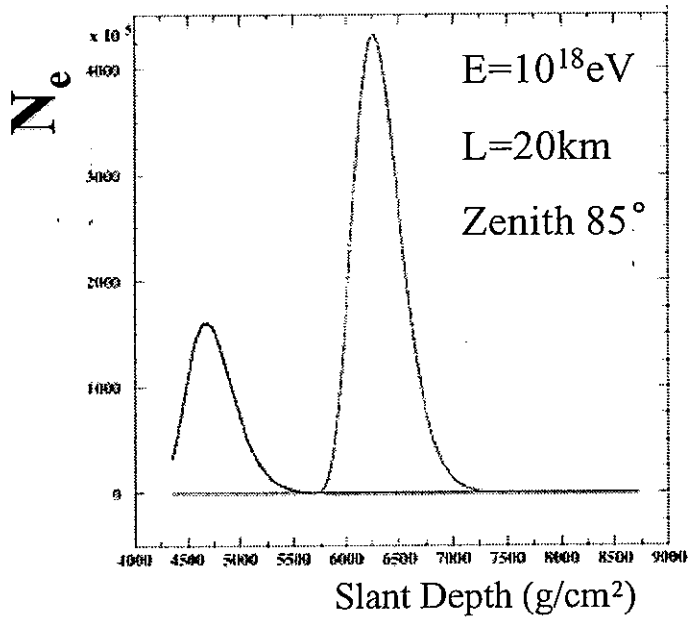
- **$\nu_e : \nu_\mu : \nu_\tau = 1:1:1$ @ Earth**
- **"Double-bang"** (Learned&Pakvasa)

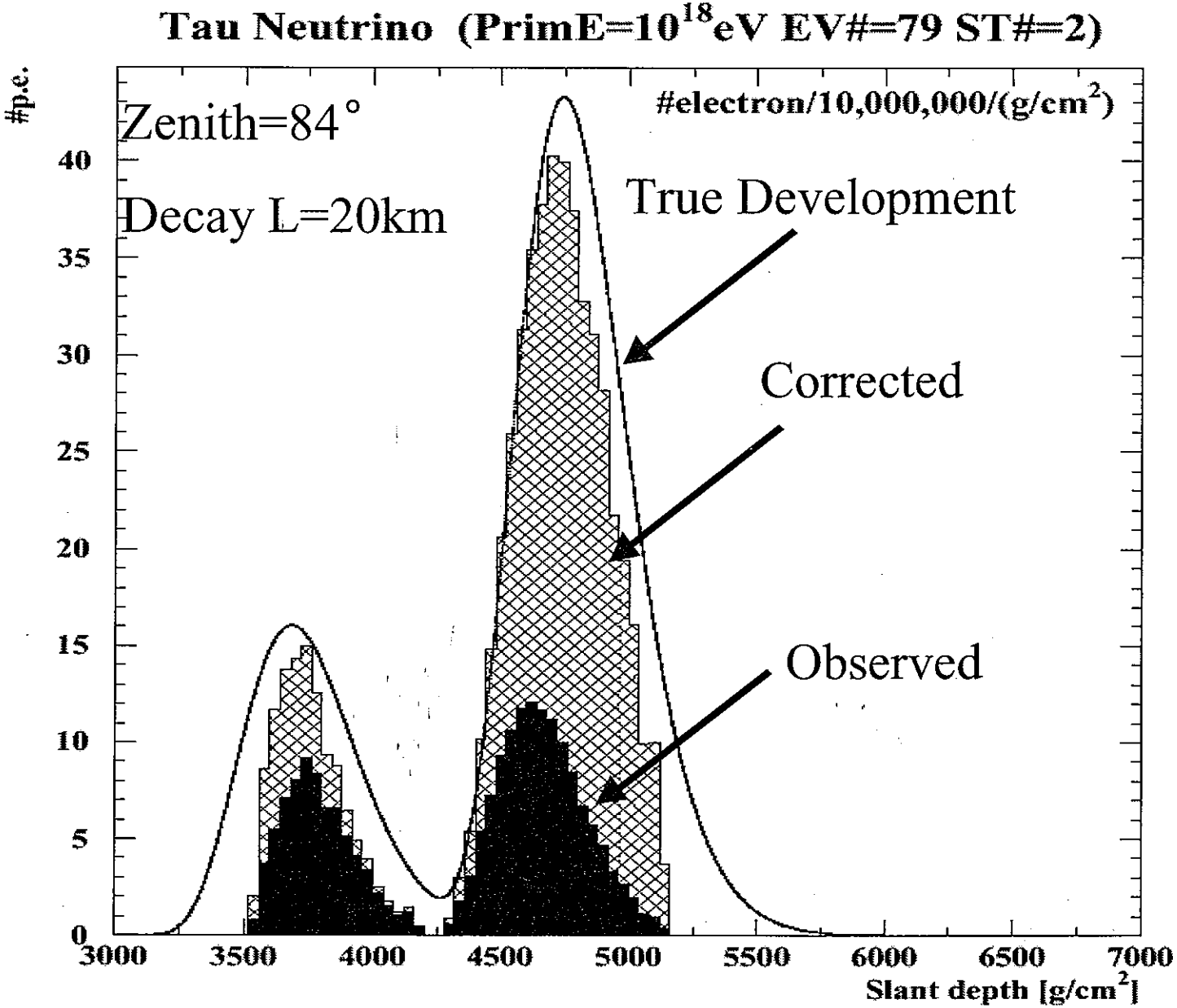


- **τ_τ = 291 fs =>**

$$\gamma c\tau_\tau = 5km\left(\frac{E_\tau}{10^{17}eV}\right)$$






Tau Neutrino (PrimE=10^18eV EV#=79 ST#=2)
#p.e.
#electron/10,000,000/(g/cm^2)
Zenith=84°
Decay L=20km
True Development
Corrected
Observed
0
5
10
15
20
25
30
35
40
3000
3500
4000
4500
5000
5500
6000
6500
7000
Slant depth [g/cm^2]

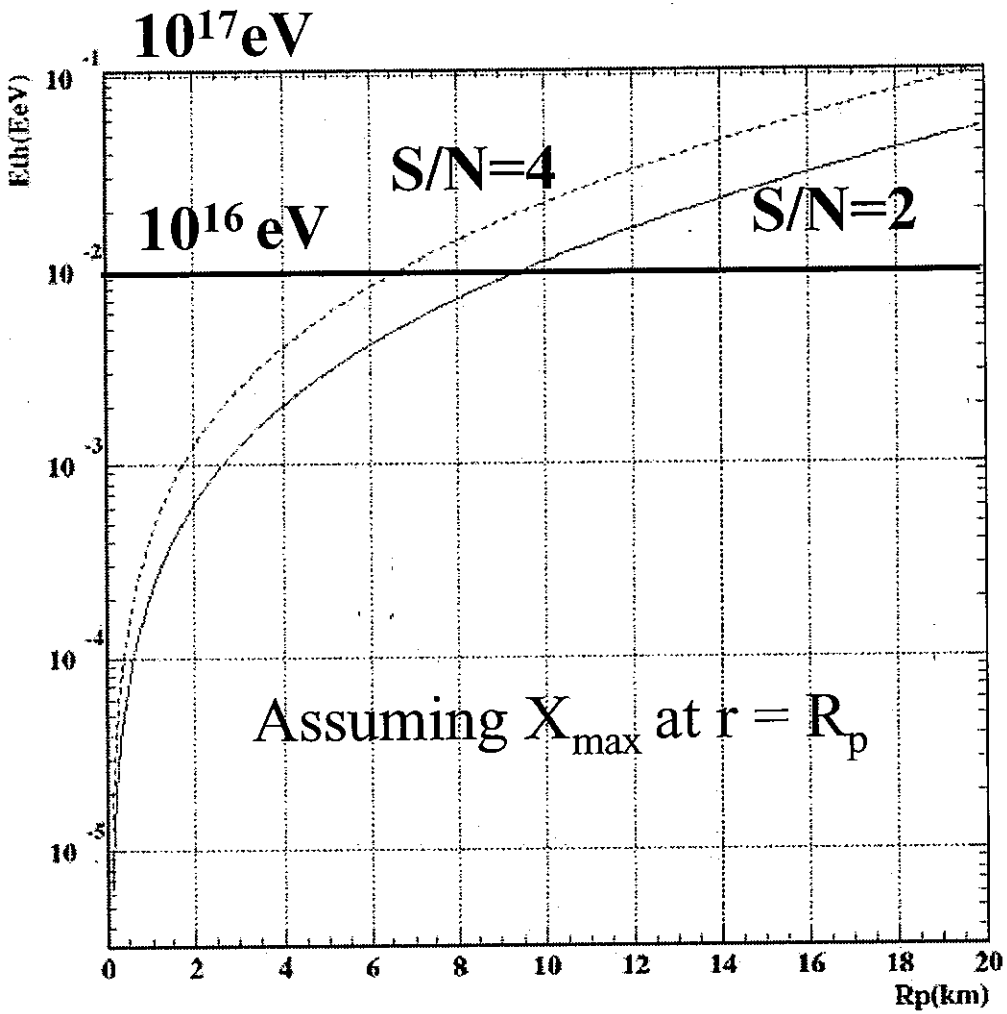
Threshold and Target Mass

- Signal-to-Noise Ratio in PMT

$$S/N \propto E \frac{e^{-r/\lambda_R}}{R_P^{3/2}} \left(\frac{D^3}{d}\right)^{1/2}$$

D : Mirror diameter,

d : PMT diameter



- TA target mass @ 10^{17} eV

  => 1-2×10^{10} ton

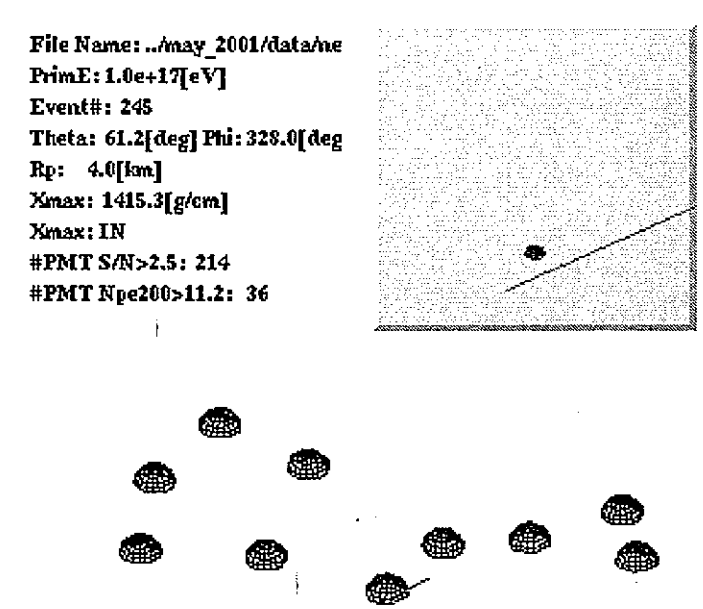
  = 10-20 km^3-w.eq

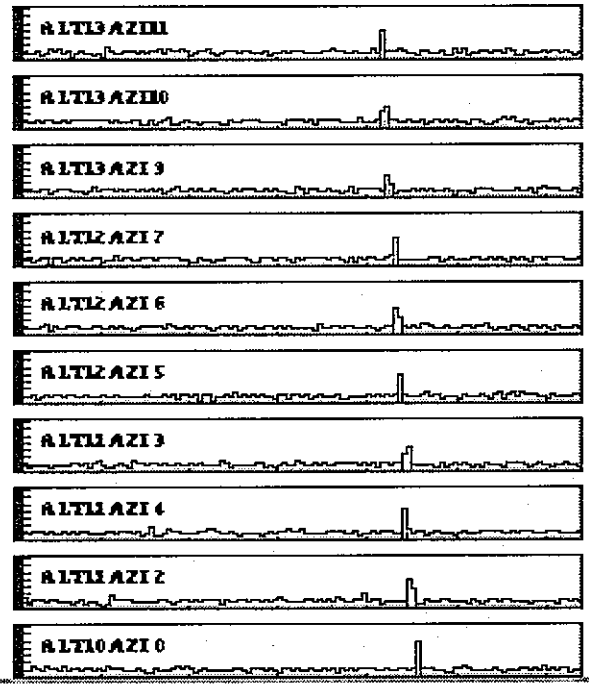
- Assuming duty 10% ,

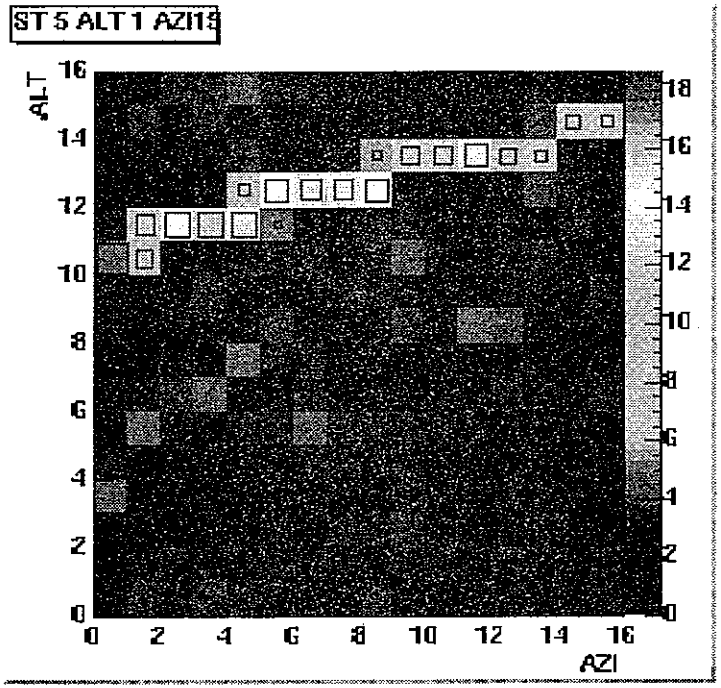
  Competitive with KM3 @10^{17}eV

e Neutrino

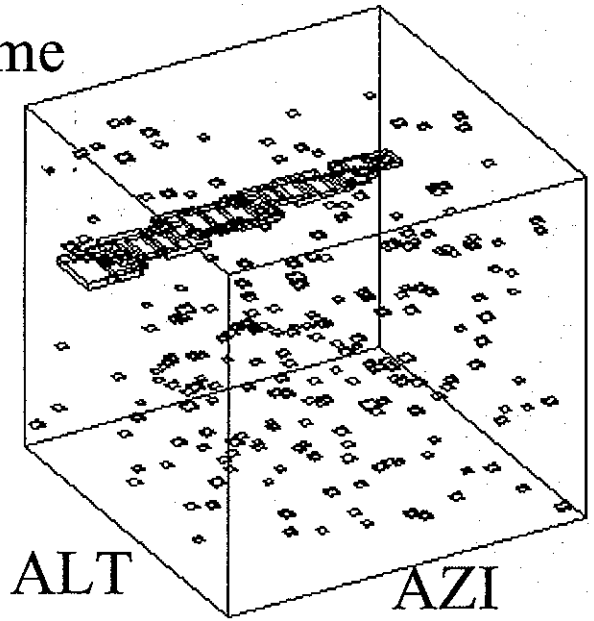
$E=10^{17}eV$





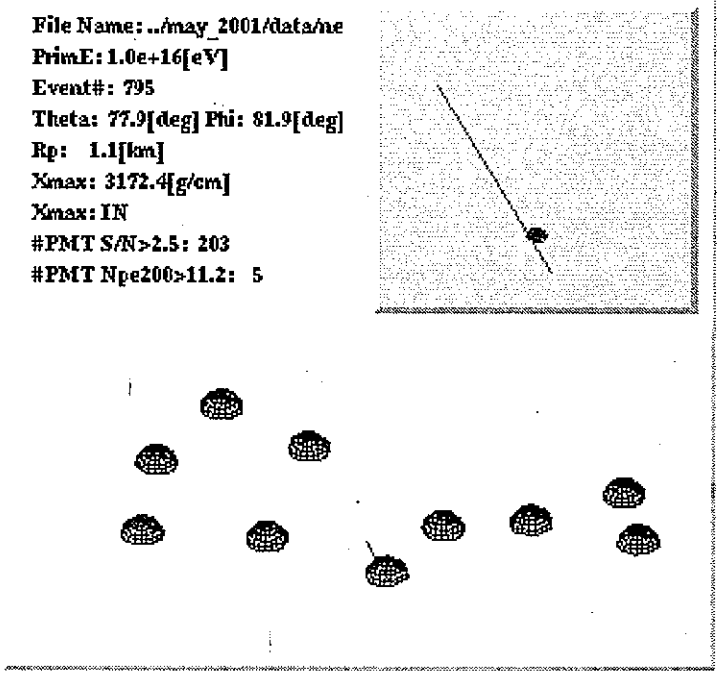


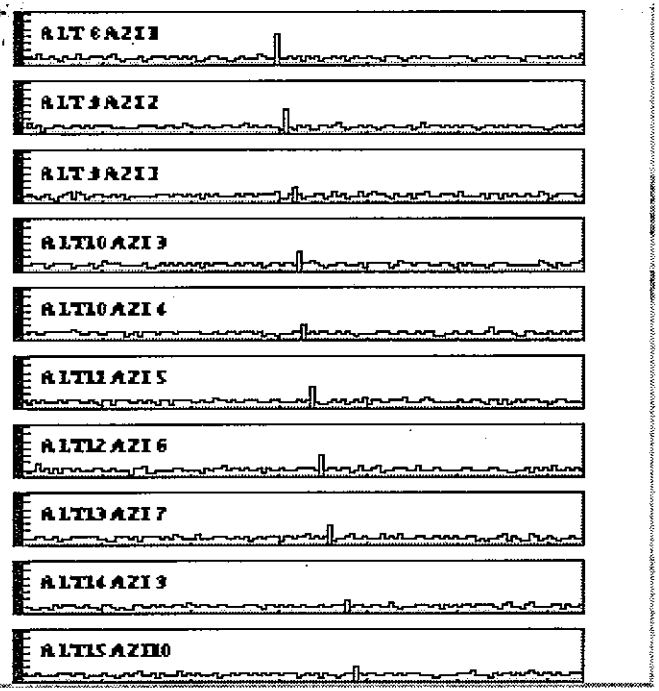
Time

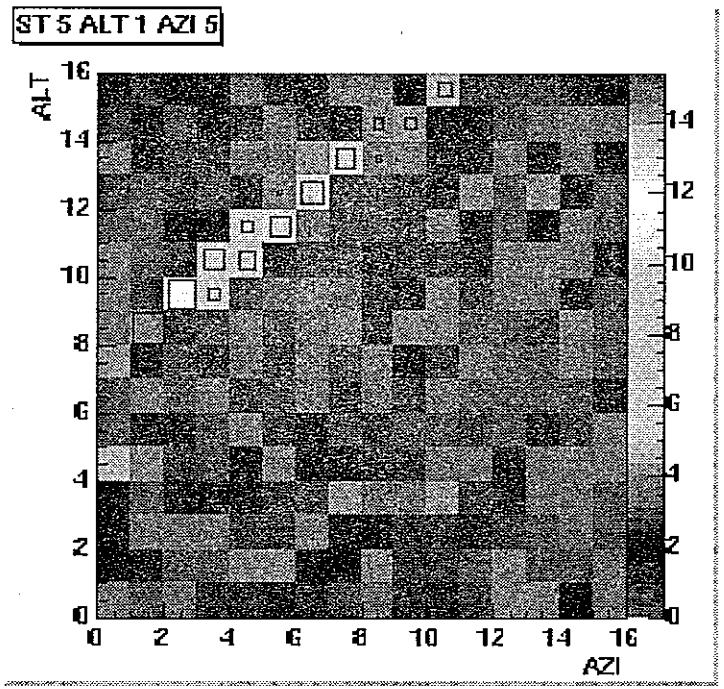


e Neutrino

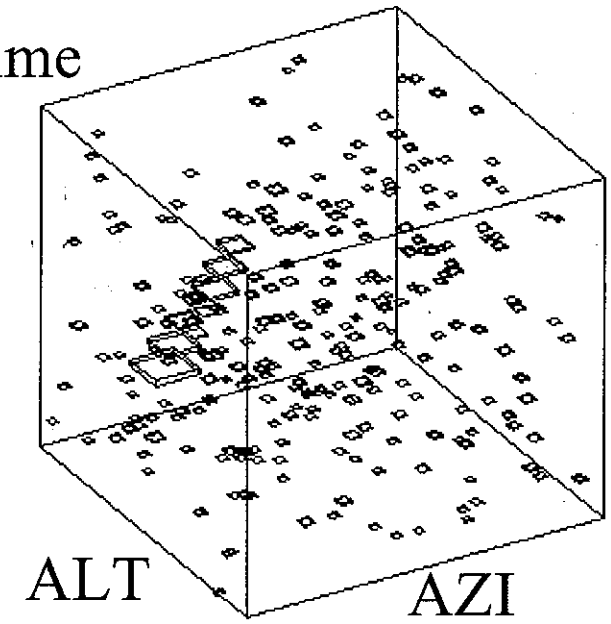
$E=10^{16}$eV







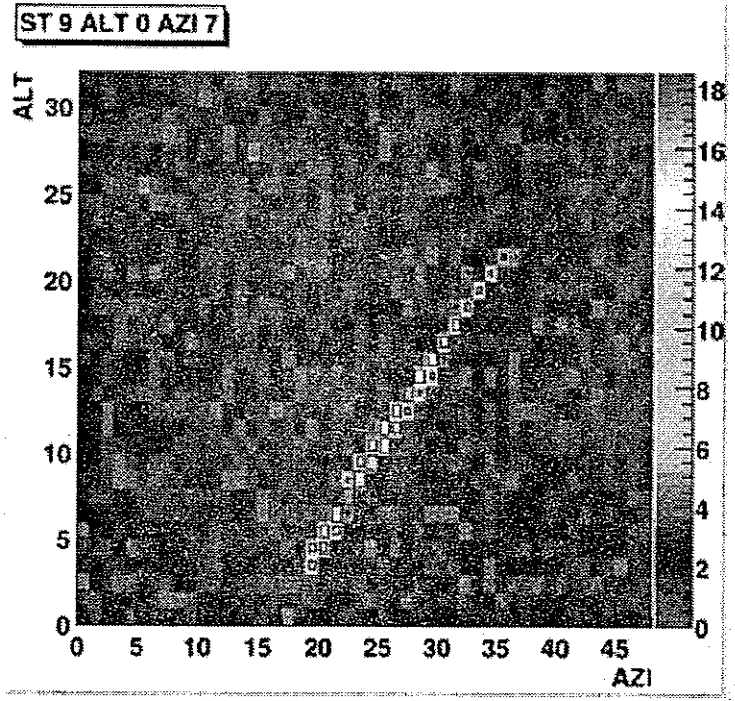
Time

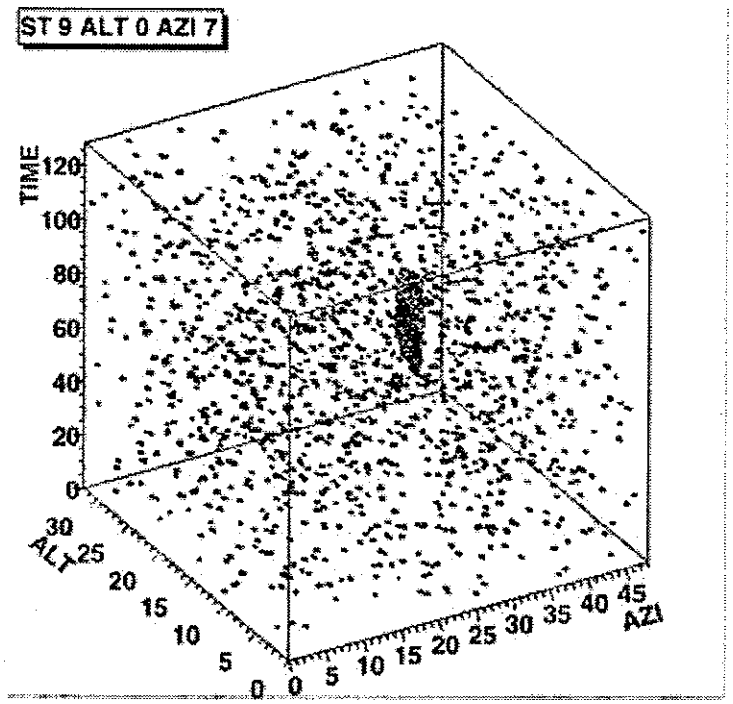


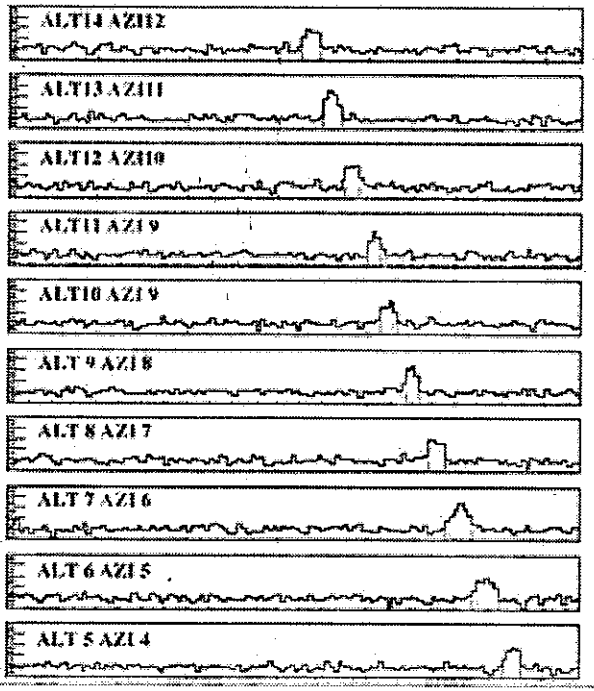
Tau Neutrino

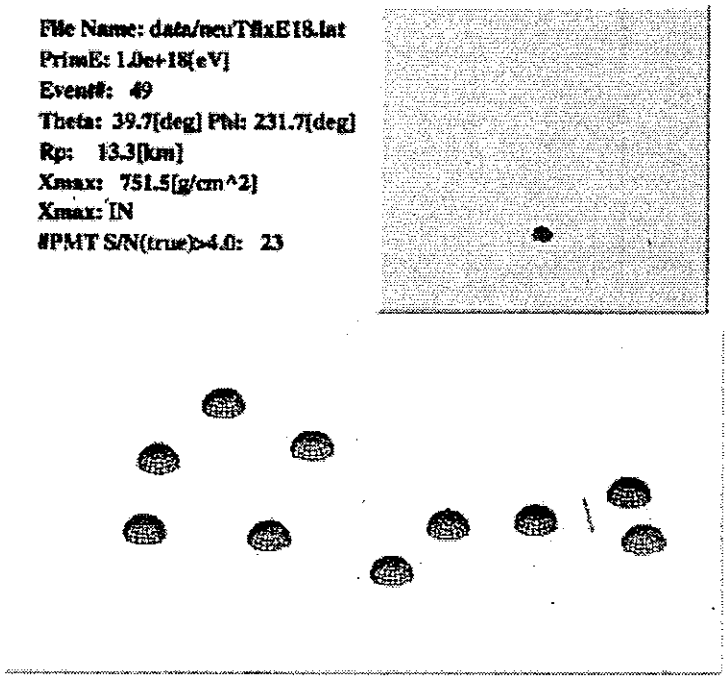
$E=10^{18}$eV

L=5km









ν -IDENTIFICATION

- **Neutrino induced air-shower:**

Must be identified as deeply penetrating air-shower.

- **Slant depth of shower maximum (X_{max}) :**

Excellent cut parameter to distinguish between hadron and neutrino induced air-showers.

- **BG proton rate is zero after cut of X_{max}>1500g/cm^2 by MC:**

$X_{max} > 1700$g/cm^2 is fairly safe even if taking into account detector systematic error on Xmax.

⇒ Truly BG-free ν Detection

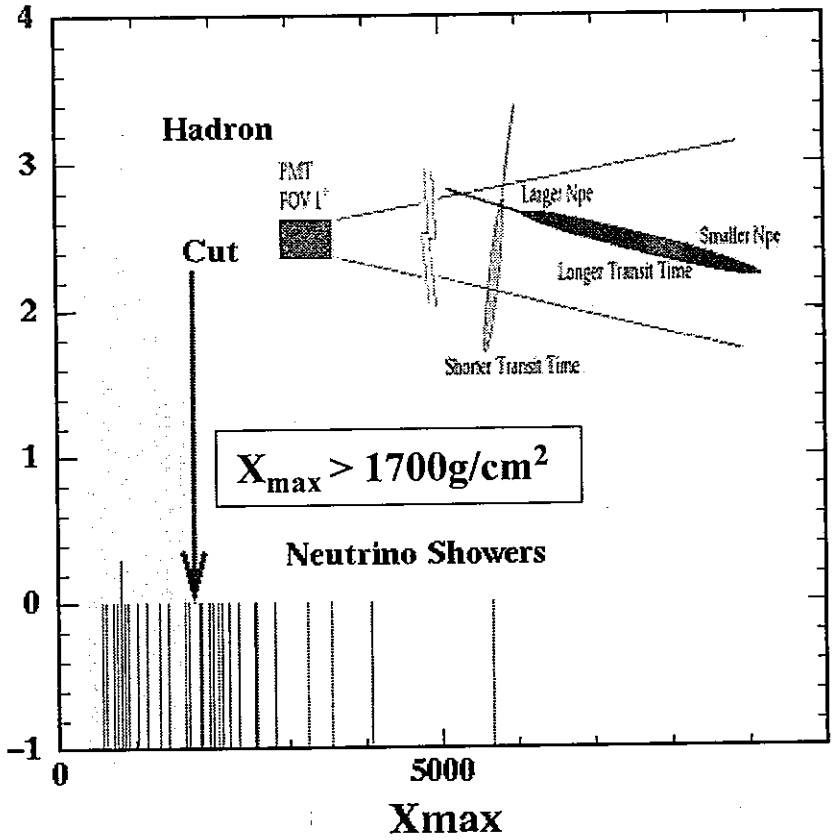


Table: BG Proton annual rate by MC

E (eV)	X_{max}>1300g/cm^2	X_{max}>1500g/cm^2
10^{16}-10^{17}	146	0
10^{17}-10^{18}	8	0
10^{18}-10^{19}	0.4	0

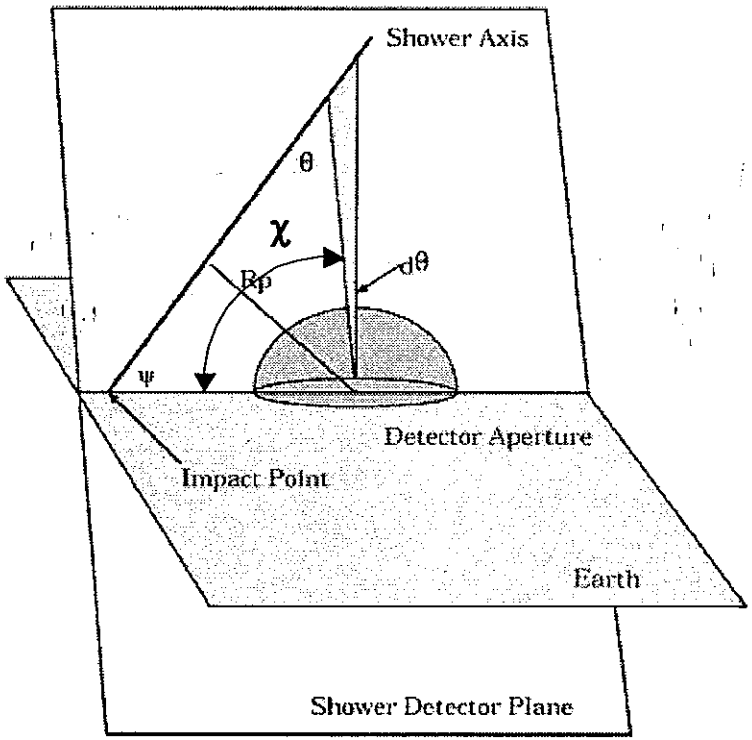
Angular Resolution

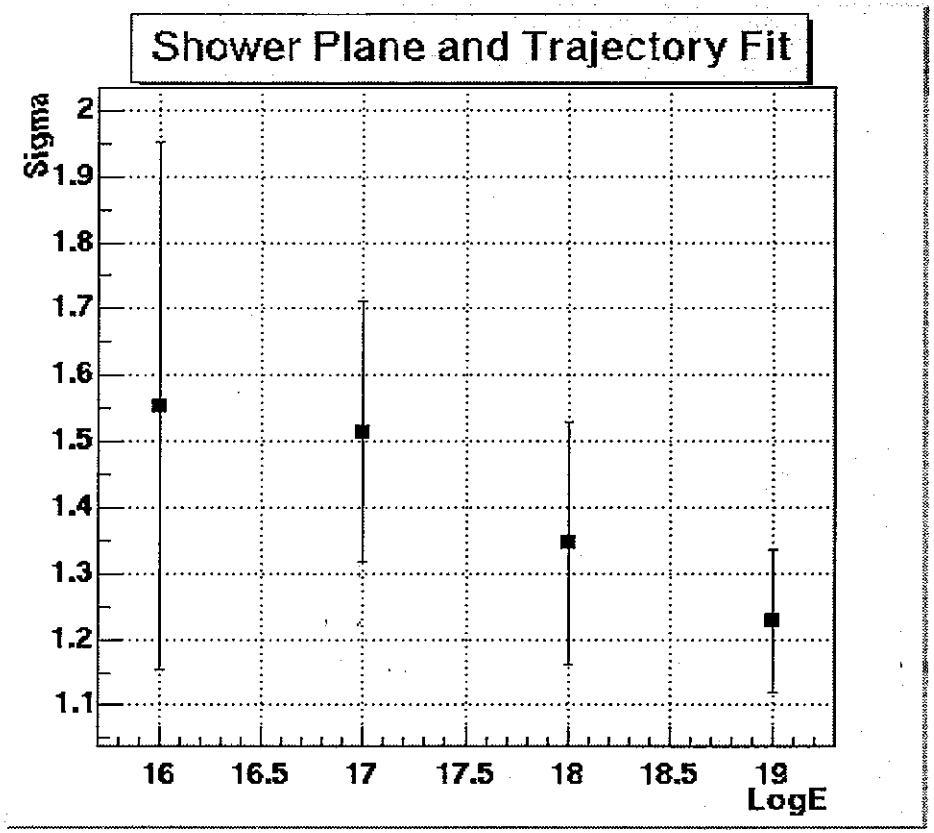
• Monocular technique:

- PMT hit pattern => Shower-Detector Plane

- ADC time profile => ψ and R_p

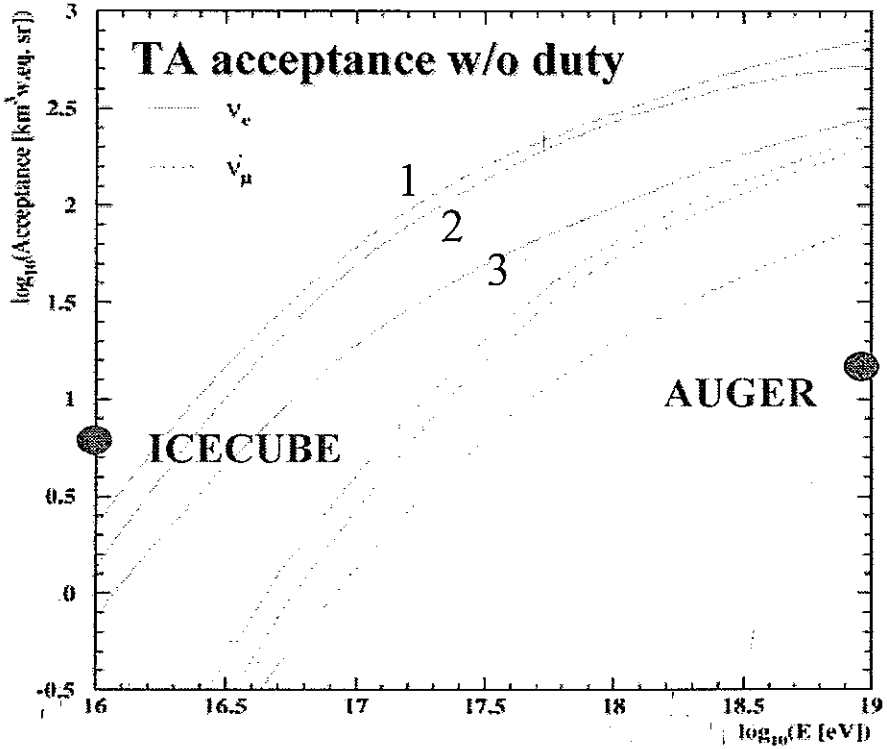
$$\chi(t) = \pi - \psi - 2\tan^{-1}\left(\frac{c(t-t_0)}{R_p}\right)$$

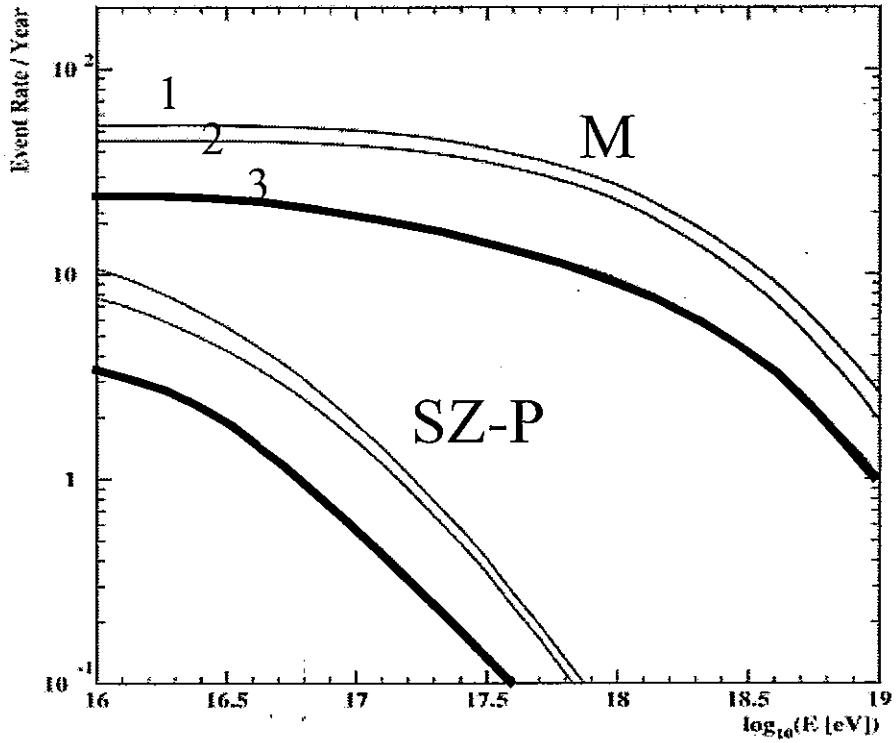




Acceptance & Event Rate

$$Rate[E_{sh} > E_{th}] = N_A \rho_{air} \int_{E_{th}}^{\infty} dE_{sh} \int_0^1 dy \frac{d\sigma}{dv}(E_\nu, y) \frac{dN_\nu}{dE_\nu}(E_\nu) A(E_{sh})$$





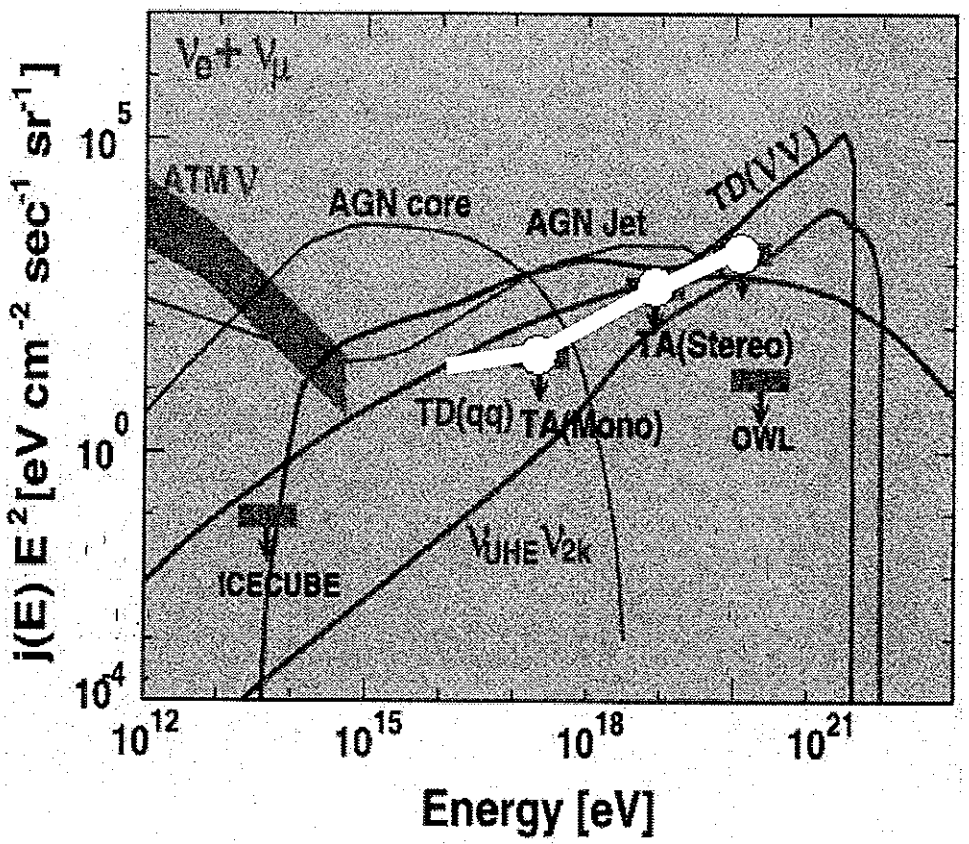
Cuts:

1. Track quality: **6PMT with S/N>4**
2. X_{max} viewing in FOV.
3. Neutrino ID: **X_{max}>1700g/cm^2**

MC Annual rates from AGN-jet (Mannheim)

CC ν_e	CC ν_μ	CC ν_τ	NC all	Total
9.2	2.4	8.5	7.2	27.3

ν -SENSITIVITY



TA 10 years observation with duty 10%

?	ν_{2K}	*Z^0 Burst*	*0.1-1*
★★	ν_{HE}	*AGN core*	*30-40*
★★	ν_{HE}	*AGN jet*	*200-300*
?	ν_{GZK}	*GZK cascade*	*0.2-1*
★	ν_{EHE}	*TD and SH Relic*	*0.5-8*

何が言いたかったのか？

- 最高エネルギー宇宙線と超高エネルギーニュートリノ

  ニュートリノ検出はγ-IDとともに“GZKの謎“解明の鍵

- 活動銀河核からの超高エネルギーニュートリノ

  ニュートリノ検出は陽子加速サイトの同定に強力

- テレスコープアレイのニュートリノ検出能力　ユニーク！

  光学・電子設計=>10^{16}eV以上のν検出可能。角度精度1.5度

  大気蛍光検出法　⇒　クリーンなAGN-ν　１００事例以上？

  タウニュートリノ　明示的な検出の可能性

- 展望

  とにかく、超高エネルギーニュートリノ観測を始めましょう。

  Optical thicknessに依存しない天体観測

Conclusion

- **New window of HE- ν astronomy:**
  - Origin of HE- ν = EHECR origin
  - Important role to solve super-GZK puzzle
  - Astronomy independent of optical thickness
- **Advanced air-fluorescence detector:**
  - PID with longitudinal development of air-shower
  - Aperture, optical & electronics design of Telescope Array Project
    - Lower threshold: 10^{16}eV from 3.3m ϕ -mirror and intelligent front-end signal & trigger process
    - Highly pure neutrino by selecting deeply penetrating air-shower.
    - 27 neutrino events / yr from AGN-jet model are expected for example.
    - Tau neutrino appearance!
- **Comprehensive understanding of the universe:**
  - Complementary with water-Cerenkov ν telescope at lower energy
  - Toward multi-particle analysis with ν, γ, and hadron for astroparticle objects at various energies.