



チャカルタヤにおける
Knee領域宇宙線観測結果

B A S J E

日本ーボリビア

空気シャワー共同実験

東工大・理 垣本史雄

2006.Aug.31st at ICRR

共同研究者(大学院生を除く)

- 東工大 垣本、常定
- 大阪市大 荻尾
- 名古屋大 松原
- 国立天文台 水本、白崎
- 理科学研究所 田島、山田、霜田
- 武蔵工大 門多
- MPI 手島
- 無所属 吉井, 豊田、金子、後藤、西、中谷
以上17名
- LaPaz大学 A. Velarde、P. Miranda 他
- Torino大学 O. Saavedra 他

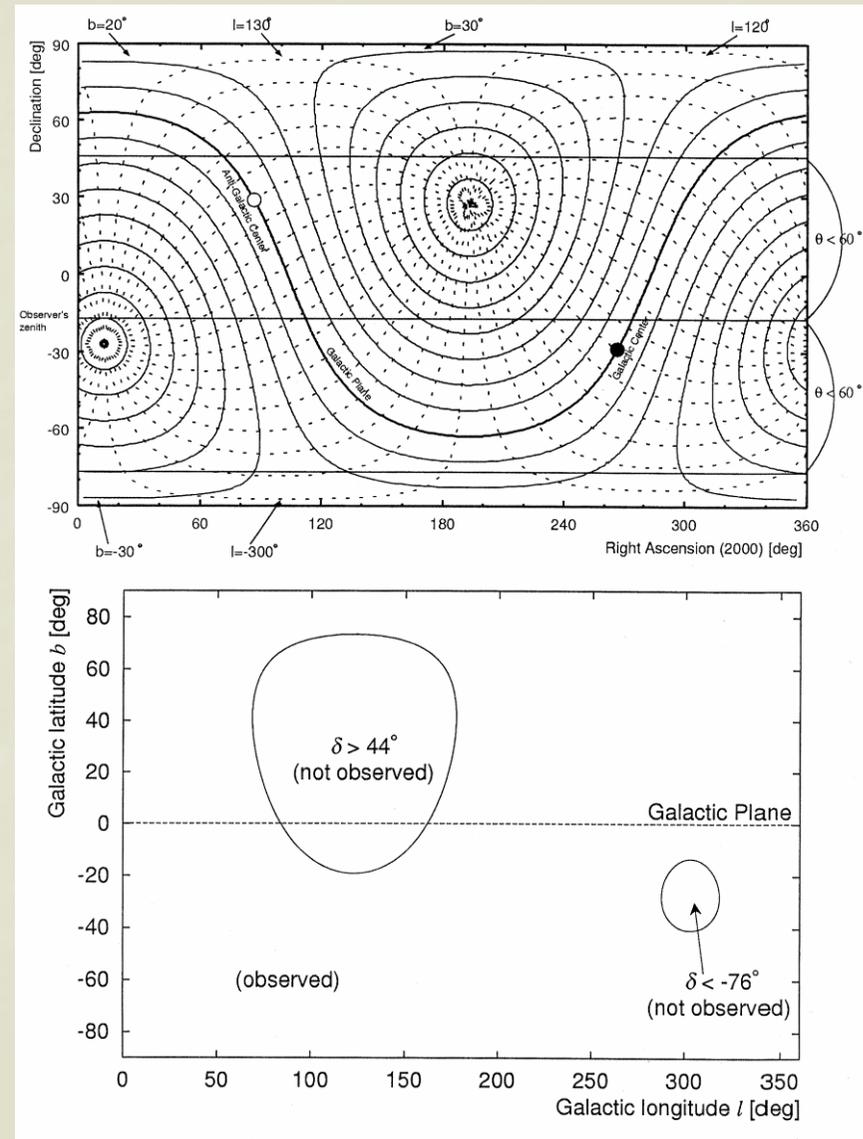
Chacaltaya山宇宙物理学研究所

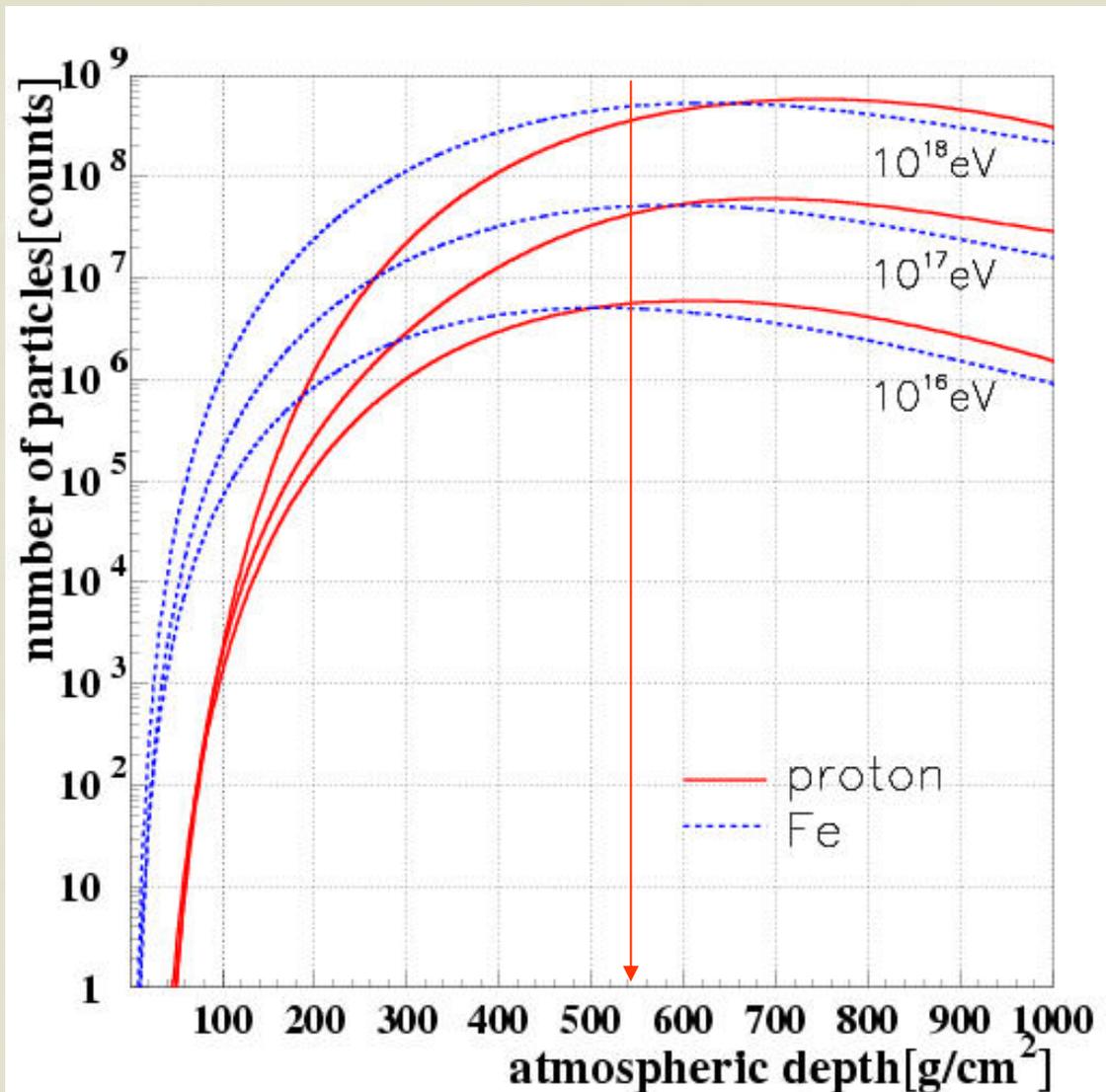
- 西経 $68^{\circ} 08'$
- 南緯 $16^{\circ} 21'$
- 標高 5200m

$$= 550 \text{ g/cm}^2$$

世界最高高度

- AS最大発達付近での観測 →
- 発達初期段階の観測 →
- 銀河面の広い領域が視野





- エネルギー、到来方向決定精度が良い

$$N_{\max} \rightarrow E_0$$

- 低いエネルギー宇宙線の観測が可能

- 縦方向発達

⇒ 化学組成、高エネルギー原子核相互作用

Chacaltaya山宇宙物理学研究所

- 1941年 開所 by I. Escobar
- 1947年 π 中間子の発見 by C.F. Powell
- 1959年 Moscow会議
小田稔—B. Rossiの立案
- 1962年 空気シャワー観測 by 菅浩一ほか

■ 1960～1966年

ミュールスシャワー観測による一次宇宙ガンマ線観測 ($10^{14} \sim 10^{16} \text{eV}$)

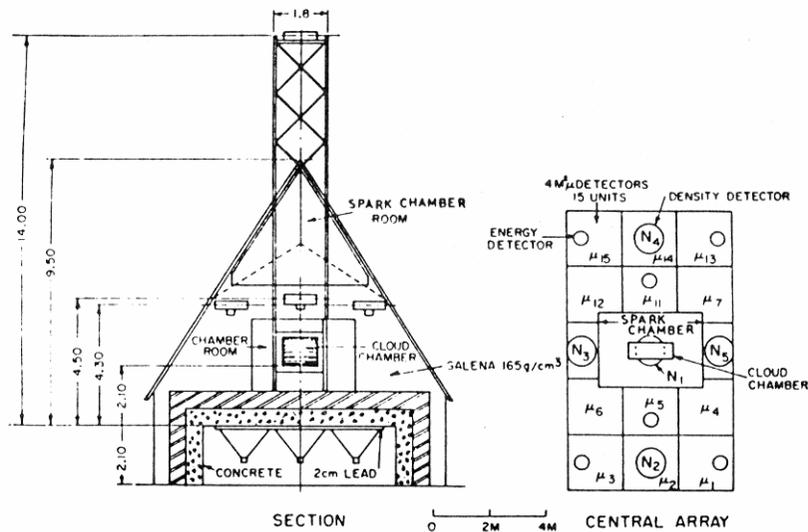


図2. シールド検出器

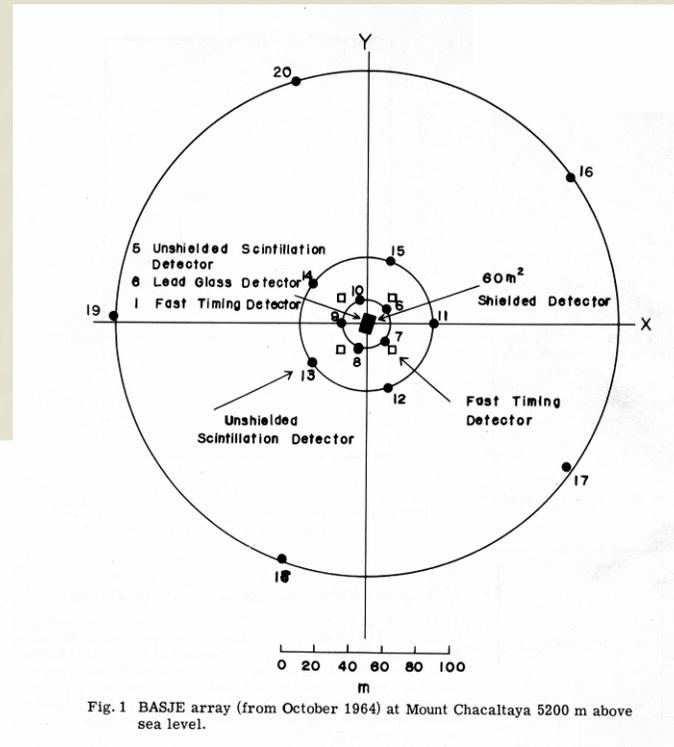


Fig. 1 BASJE array (from October 1964) at Mount Chacaltaya 5200 m above sea level.

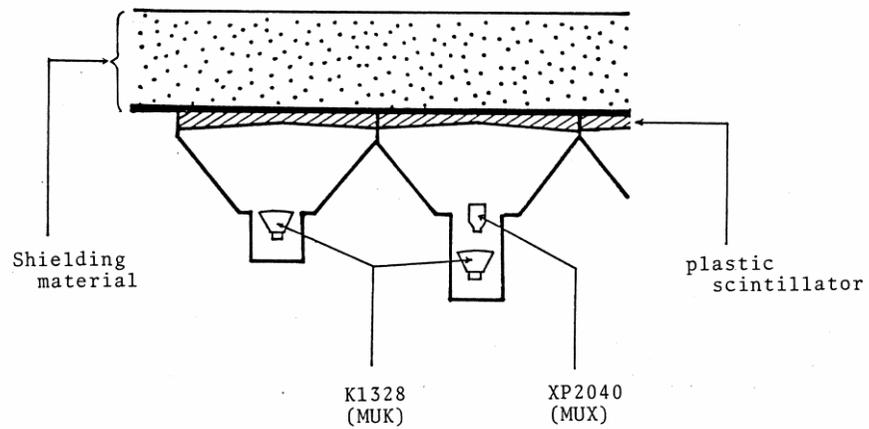
シンチレーション検出器～40台

ミュオン検出器～60m²

ミュオン検出器

MUK 3	MUK 6	MUK 9	MUK 12	MUK 15
	MUX 6	MUX 9	MUX 12	
MUK 2	MUK 5	MUK 8 N19 MUX 8	MUK 11	MUK 14
	MUX 5	MUX 8	MUX 11	
MUK 1	MUK 4	MUK 7	MUK 10	MUK 13
	MUX 4	MUX 7	MUX 10	

(a)



(b)



■ 成果

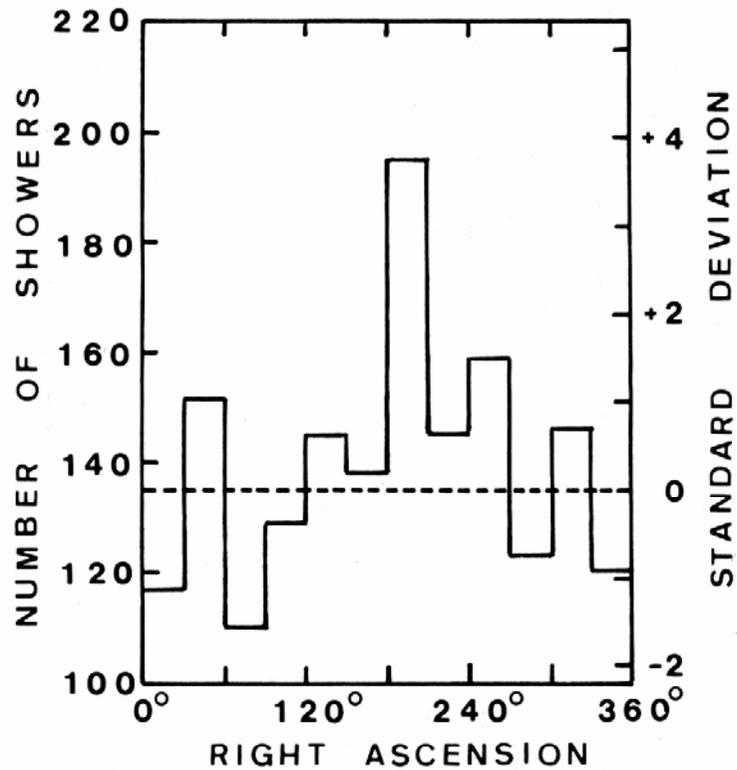


FIG. 1.—Distribution of arrival directions of EAS with low contents of muons and hadrons and initiation depths smaller than 80 g cm^{-2} from a declination band of 0° to -40° . Abscissa is right ascension (α) in degrees. Ordinate on left side is the number of EAS observed in a bin of 30° width. Dashed line is the average number of EAS obtained from the distribution excluding a bin of $\alpha = 180^\circ$ – 210° . Ordinate on right side is the deviation from the average in the standard deviation (σ).

RA=200~220° 約 3σ のexcess

現在の研究テーマ

- 一次宇宙線化学組成とエネルギースペクトラム
- 到来方向異方性

1985年～ 1991年一次宇宙ガンマ線の観測

観測対象： 10^{14} eV以上 \Rightarrow 1991年 6×10^{12} eV以上

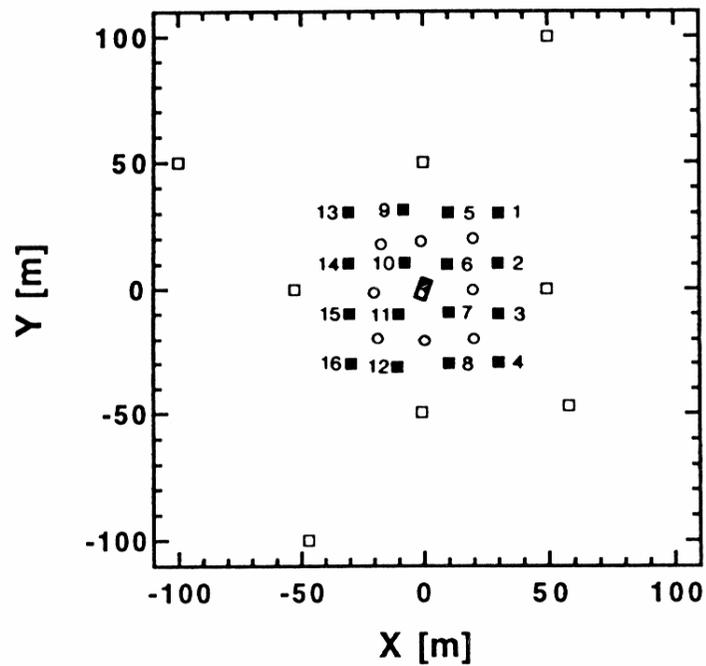


Fig. 1. Arrangement of detectors in the SAS array: G-detectors with detector numbers (■), N-detectors (□), and NT-detectors (○). The shadow rectangle is a 60 m² shielded detector.

1987～1990年 SN1987Aからの一次ガンマ線観測

南向き斜面(傾斜 30°)に $4\text{m}^2 \times 12$ 台、 $1\text{m}^2 \times 32$ 台のシンチレーション検出器を設置

10^{14}eV 以上のガンマ線の検出を目的とする



電子サイズ決定精度

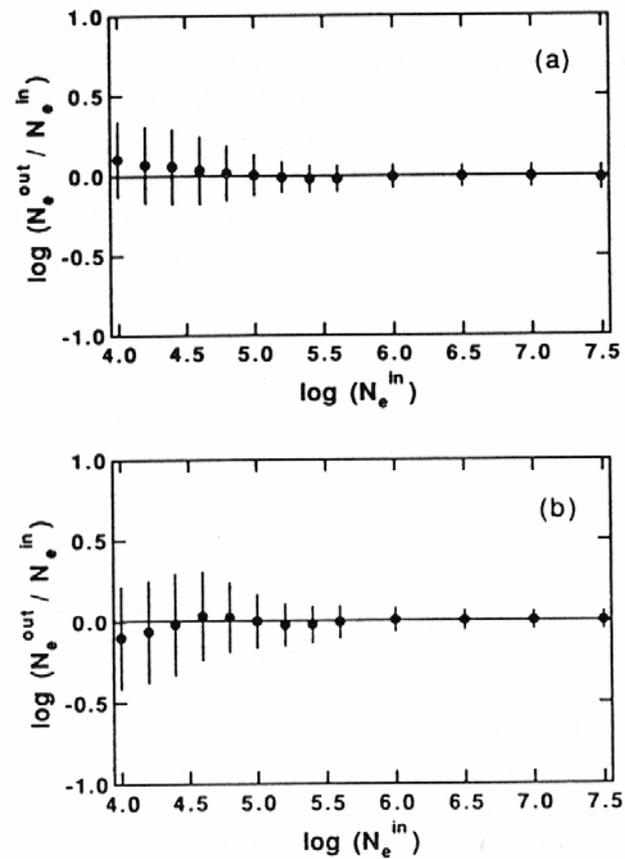


Fig. 8. Logarithm of $N_e^{\text{out}}/N_e^{\text{in}}$ for simulated air showers; (a) that with $\sec \theta = 1.0$ and (b) that with $\sec \theta = 2.0$.

到来方向決定精度

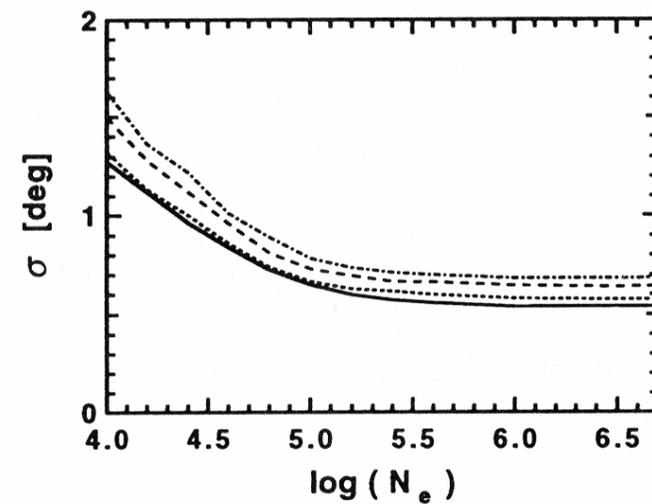


Fig. 12. Standard deviation of the Gaussian distribution fitted to ψ distribution as a function of N_e^{out} with $\sec \theta = 1.0$ (solid line), 1.4 (dotted line), 1.8 (dashed line) and 2.0 (dash-dotted line).

点源探查結果

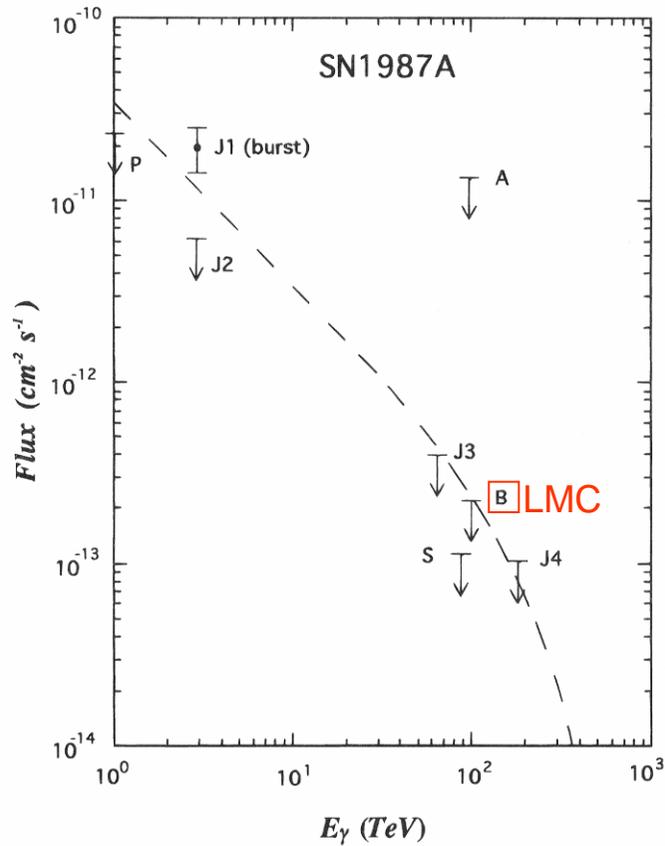


FIG. 7.—Upper limits on the flux of gamma rays from SN 1987A. The dashed line represents a spectrum of photons calculated by Gaisser et al. (1989b) assuming that photons are produced by protons accelerated with a differential energy spectrum $\propto E_p^{-2}$ up to a maximum energy $E_p^{\max} \sim 10^5$ TeV at the source. *P*: Potchefstroom (Raubenheimer et al. 1988); J1–J4: JANZOS (Bond et al. 1988a, 1988b; Allen et al. 1993a, 1993b); A: Adelaide (Ciampa et al. 1988); S: SPASE (Stekelenborg et al. 1993); B: present result (LMC array).

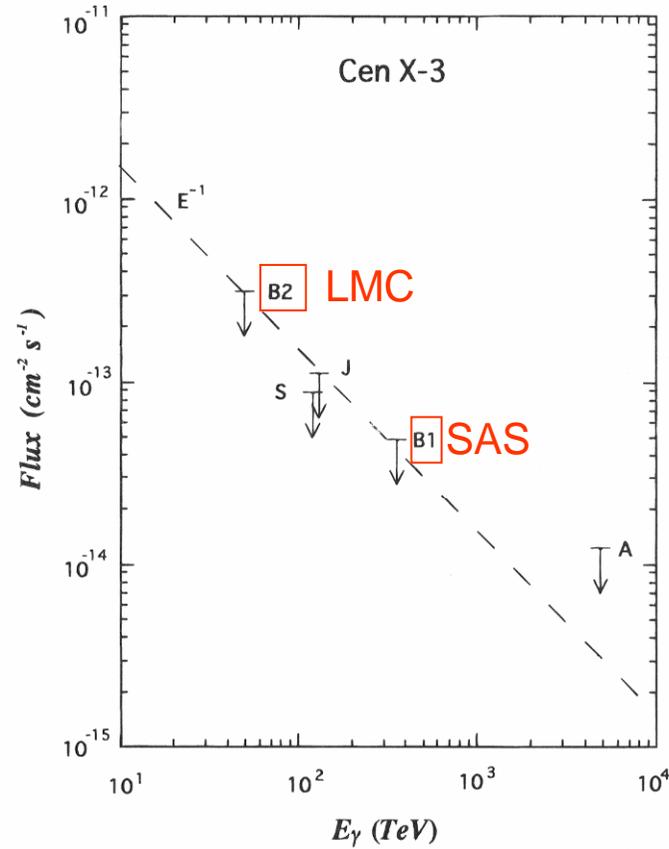
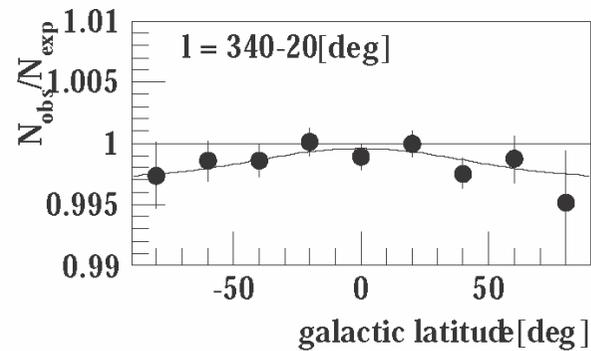
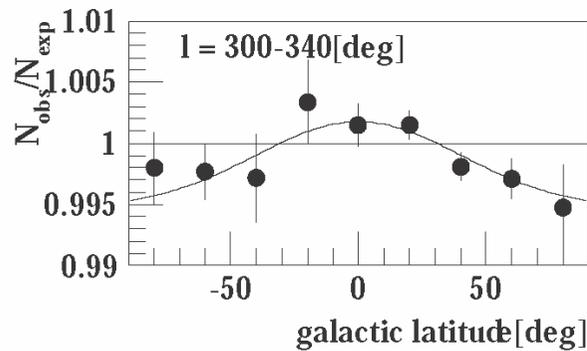
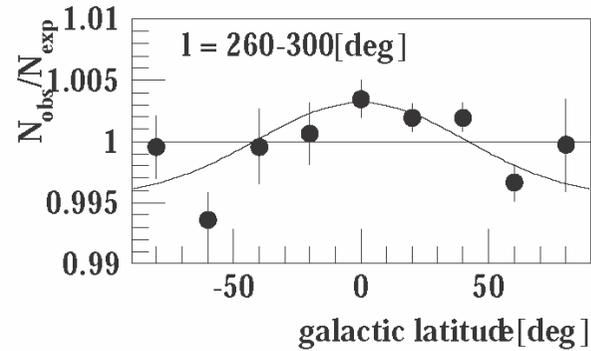
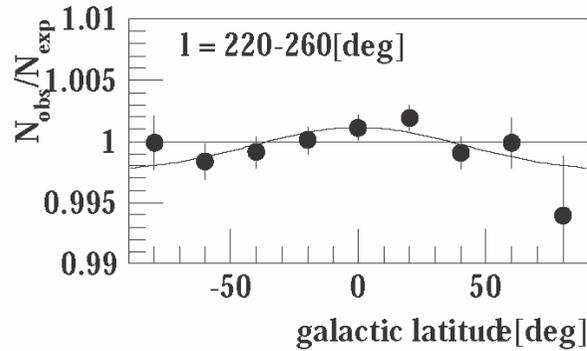
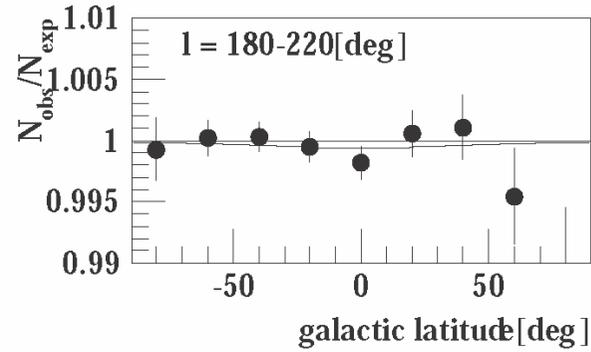
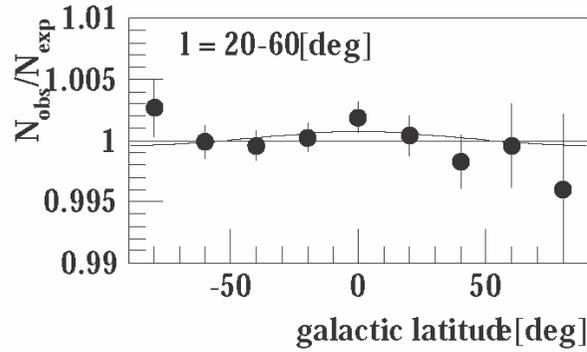


FIG. 8.—Upper limits on the flux of gamma rays from Cen X-3. The dashed line represents an E^{-1} integral spectrum. J: JANZOS (Allen et al. 1993b); S: SPASE (Stekelenborg et al. 1993); A: Adelaide (Protheroe & Clay 1985); B1: BASJE (SAS array) (Kaneko et al. 1991); B2: present result (LMC array).

Source	2A1822-37.1	Cen A	Cen X-3	Center of Galaxy	Sco X-1	SS433	Vela Pulsar	Vela X-1
$E_0(\times 10^{14} eV)^{-1}$	2.37	2.37	3.72	2.08	2.08	2.30	2.37	2.37
Collecting area \times running time ($\times 10^{15} cm^2 s$)	2.53	1.97	1.04	2.24	2.41	2.00	1.83	2.25
Upper limit flux ($\times 10^{-14} cm^{-2} s^{-1}$) All events	7.86	9.92	5.99	6.70	14.4	20.4	16.3	13.3
Upper limit flux ($\times 10^{-14} cm^{-2} s^{-1}$) Low-mu	6.40	5.38	4.79	11.4	6.24	6.85	7.45	6.51

Table I. Upper limit on the flux of gamma ray emission.

到来方向異方性の結果(1985年以降)



$$\frac{I^{obs}(l, b)}{I^{exp}(l, b)} = c[(1 - f_e(l)) + 1.402 f_e(l) \exp(-b^2)],$$

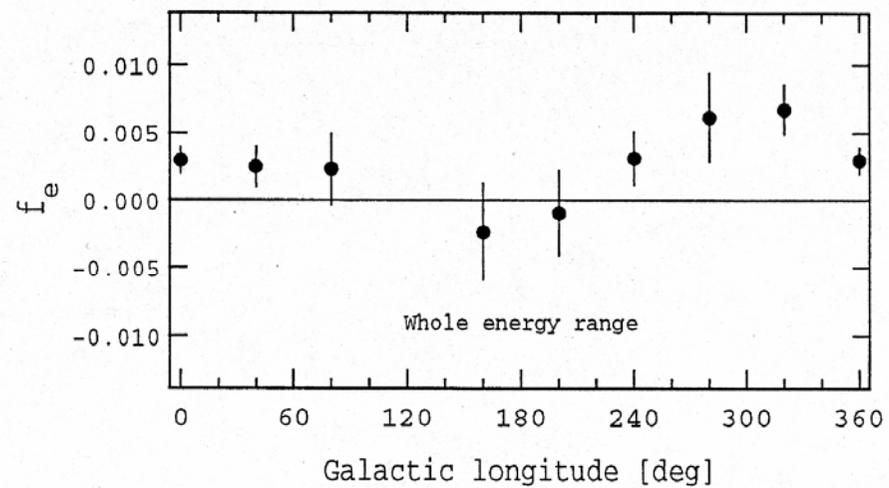


Figure 2: The galactic enhancement factor f_e vs. the galactic longitude l with SAS array.

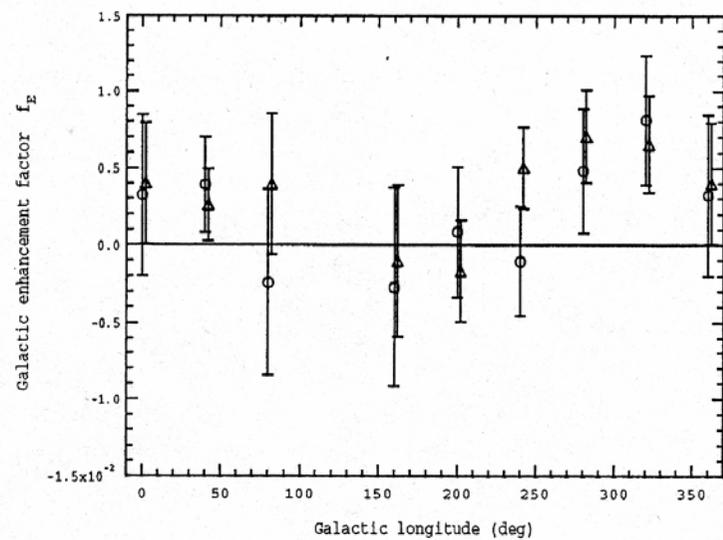


Figure 3: f_e vs. l ; \circ is for muon-less air showers and \triangle for muon-rich air showers (see text).

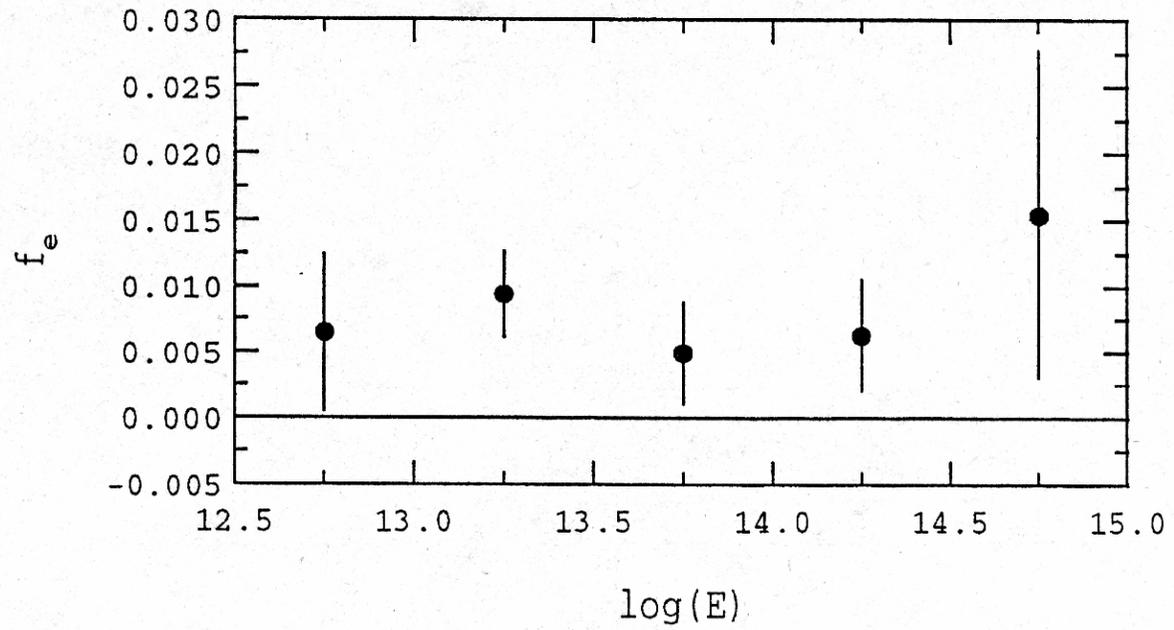


Figure 4: f_e vs. the primary energy.

Vela SNR起源の宇宙線

- 誕生時期 10^4 年前

→ 10^5 年前

- 距離 500pc

→250pc

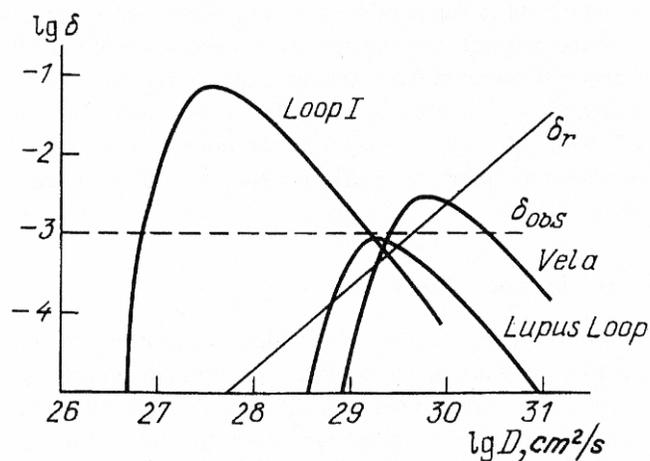
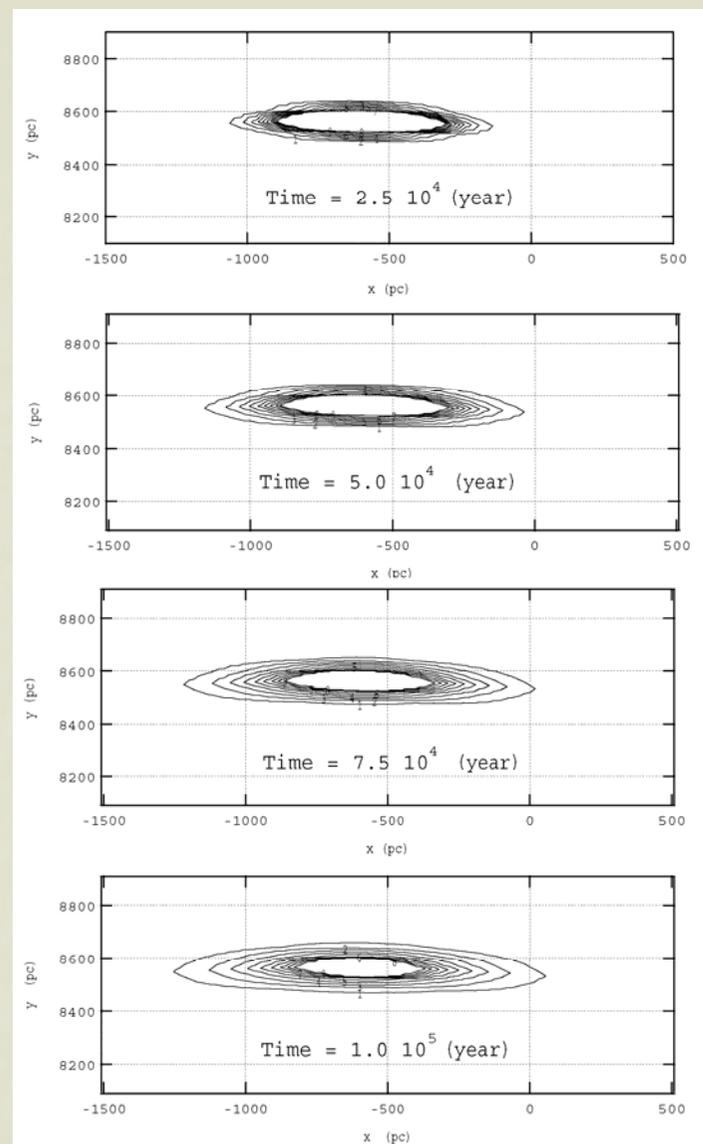
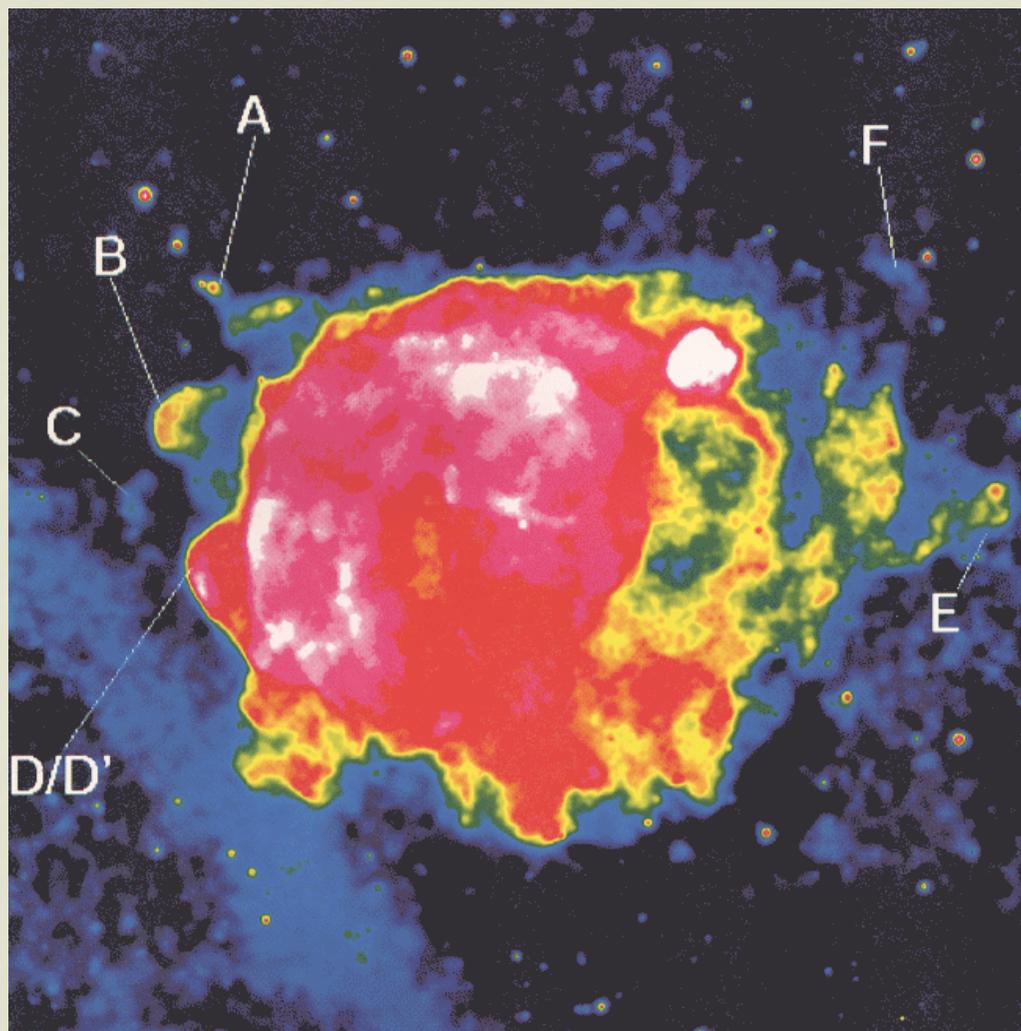


Figure 2.8: Anisotropy amplitudes expected from the contribution of local supernova remnants [28]

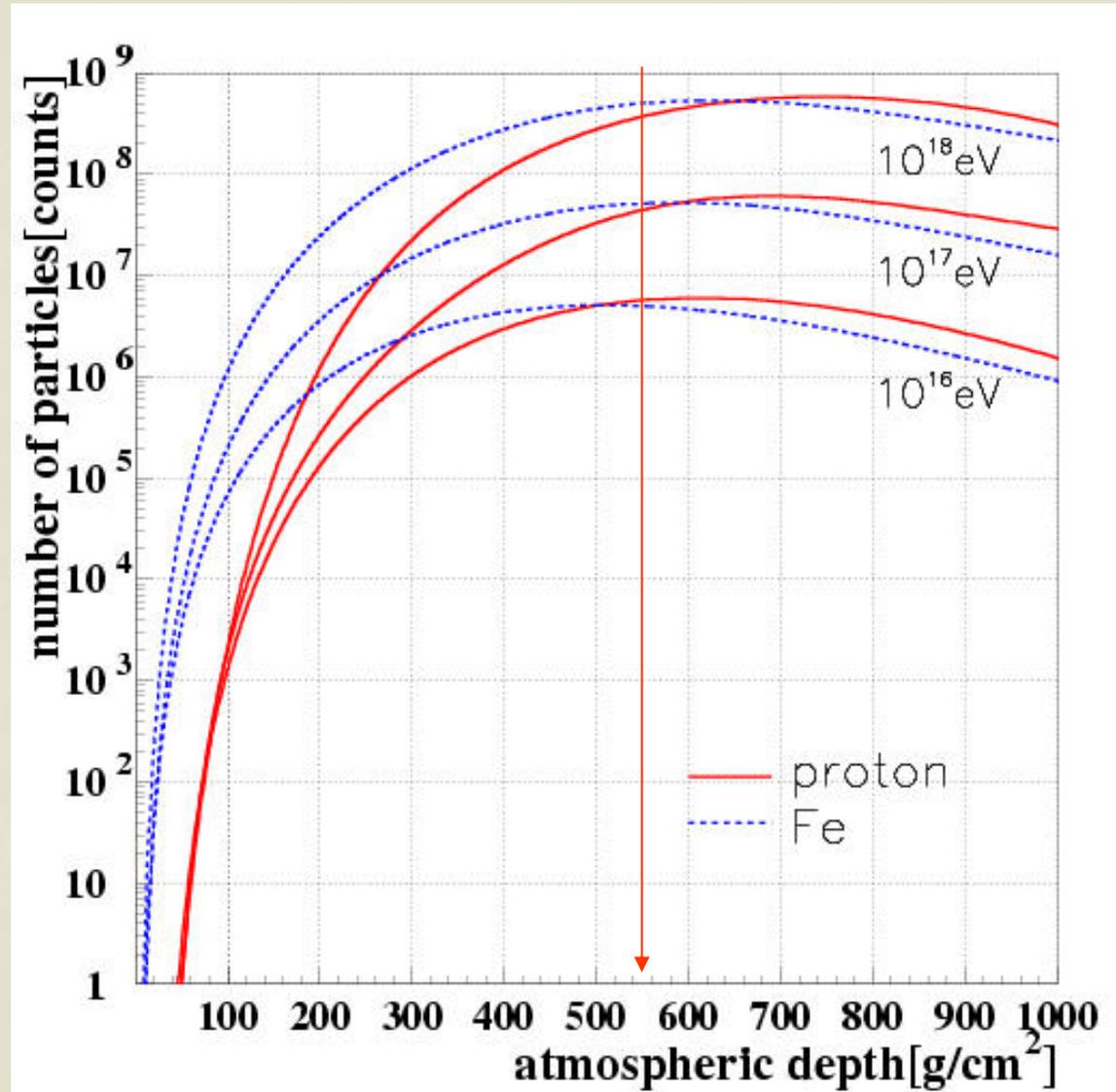


Vela 超新星殘骸



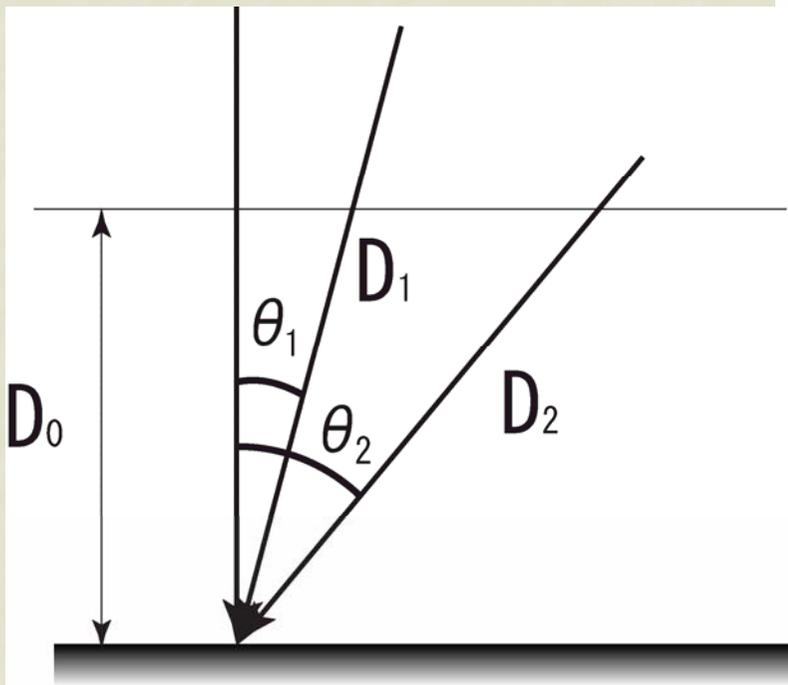
B. Aschenbach et al., *Nature*, 373, 587 (1995)

一次宇宙線化学組成の研究(1989年以降)



等頻度法による平均的縦方向発達の測定

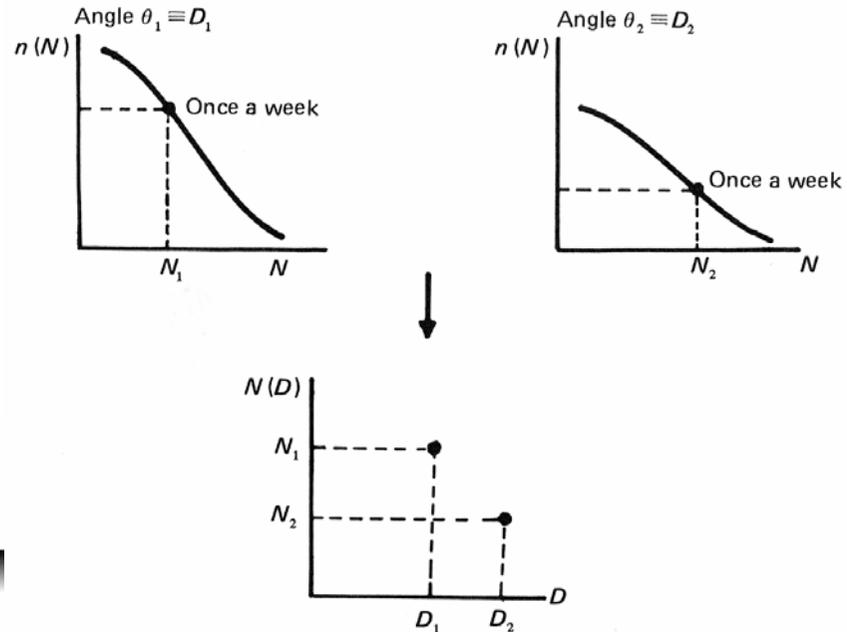
同一の頻度＝同一の一次エネルギー



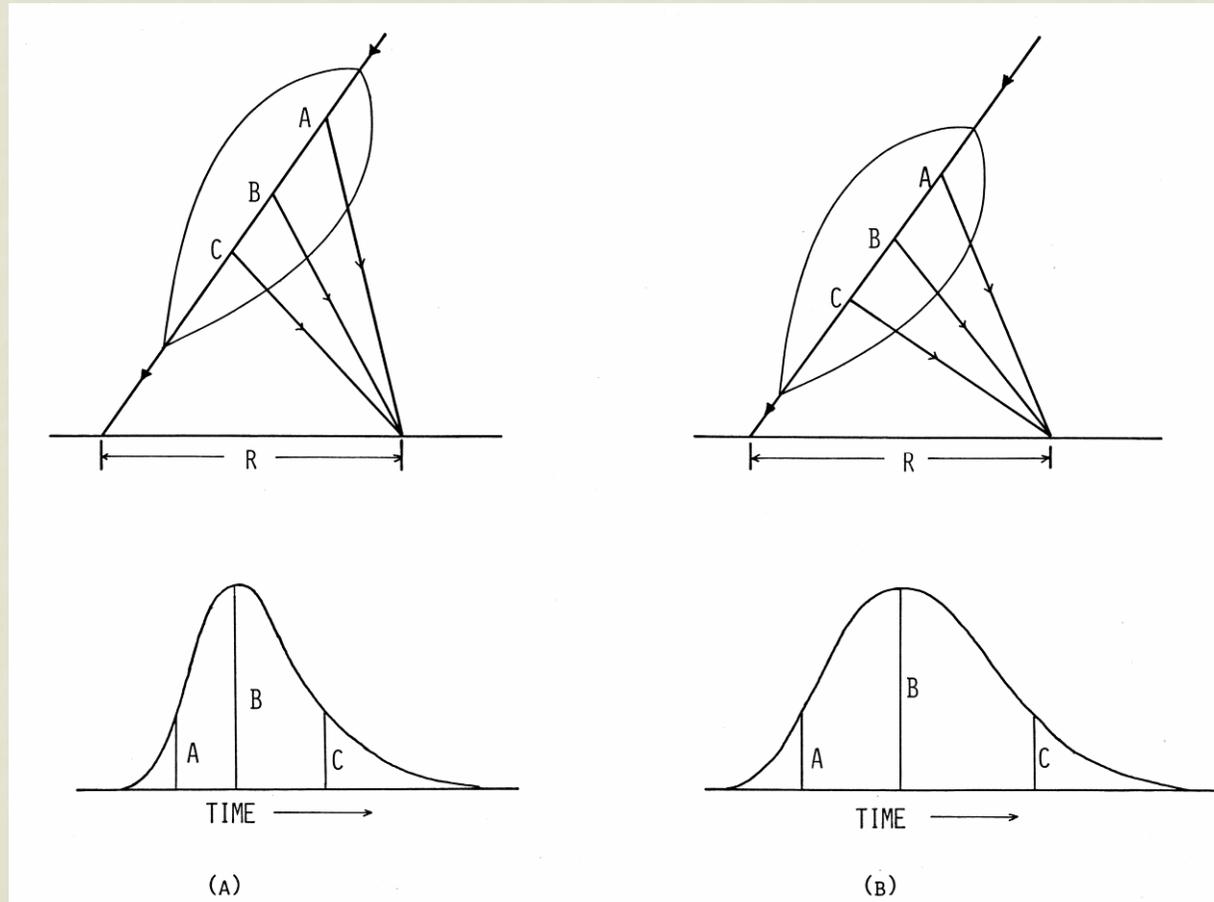
$$D_1 = D_0 \times \sec \theta_1$$

$$D_2 = D_0 \times \sec \theta_2$$

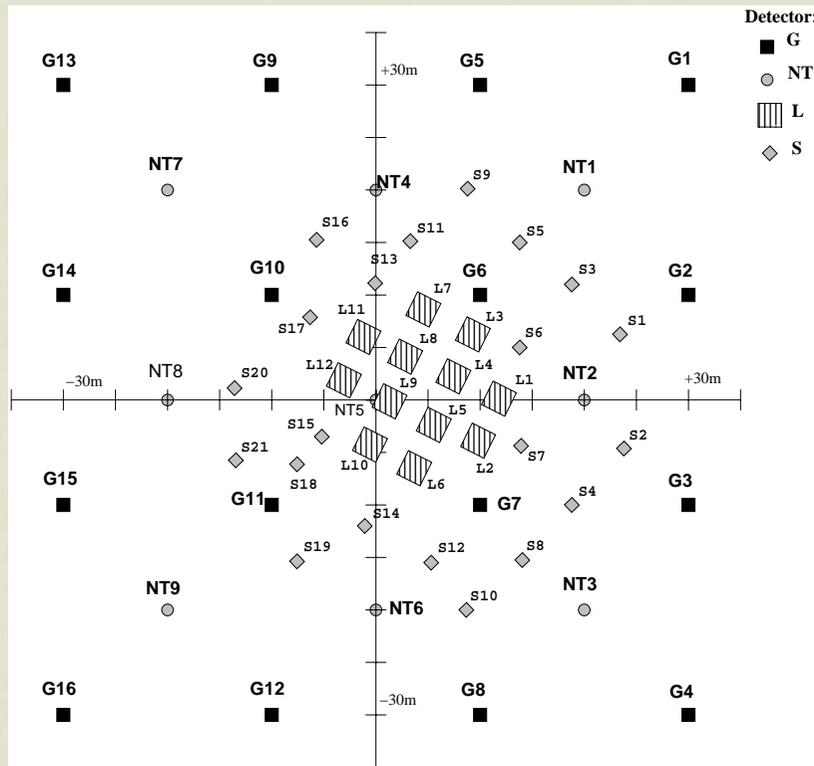
Fig. 10.3. The determination of the development of extensive air showers of different sizes through the atmosphere from observations at different zenith angles θ ; $n(N)$ is the rate of occurrence of showers of N particles. A zenith angle θ_1 , is equivalent to a depth through the atmosphere of $D_1 = 520 \sec \theta_1 \text{ g cm}^{-2}$.



到着時間分布測定によるAS発達初期段階の観測



1989年～2005年 Knee領域宇宙線化学組成の研究



$E > 6 \text{ TeV}$

等頻度法

← 2成分モデル

空気チェレンコフ光

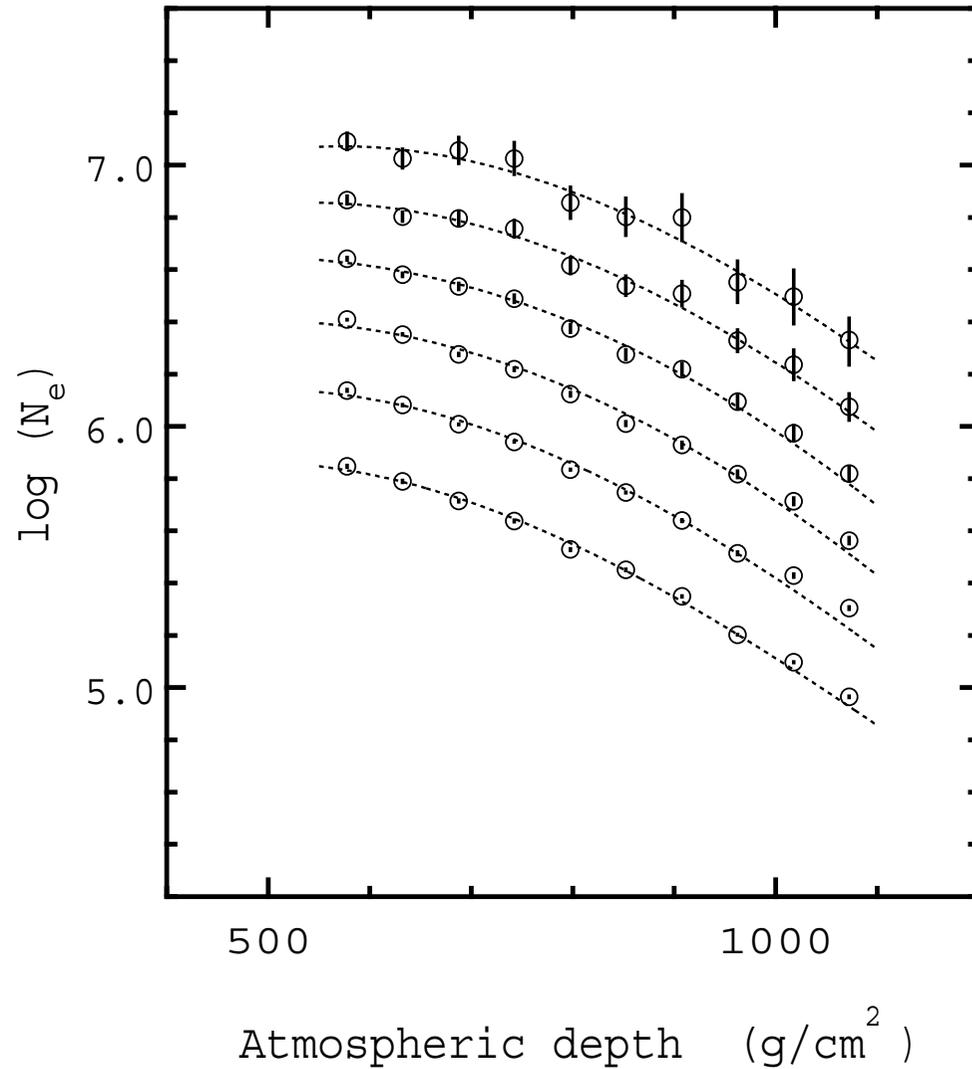
▪ 到着時間分布

← 5成分モデル

▪ 横方向分布

← 3成分モデル

等頻度曲線による化学組成の検討



計算：一次宇宙
線は陽子と鉄の
混合と仮定

→Least χ^2 法で
混合比を決定

空気チェレンコフ光到着時間分布(1995 - 1997)

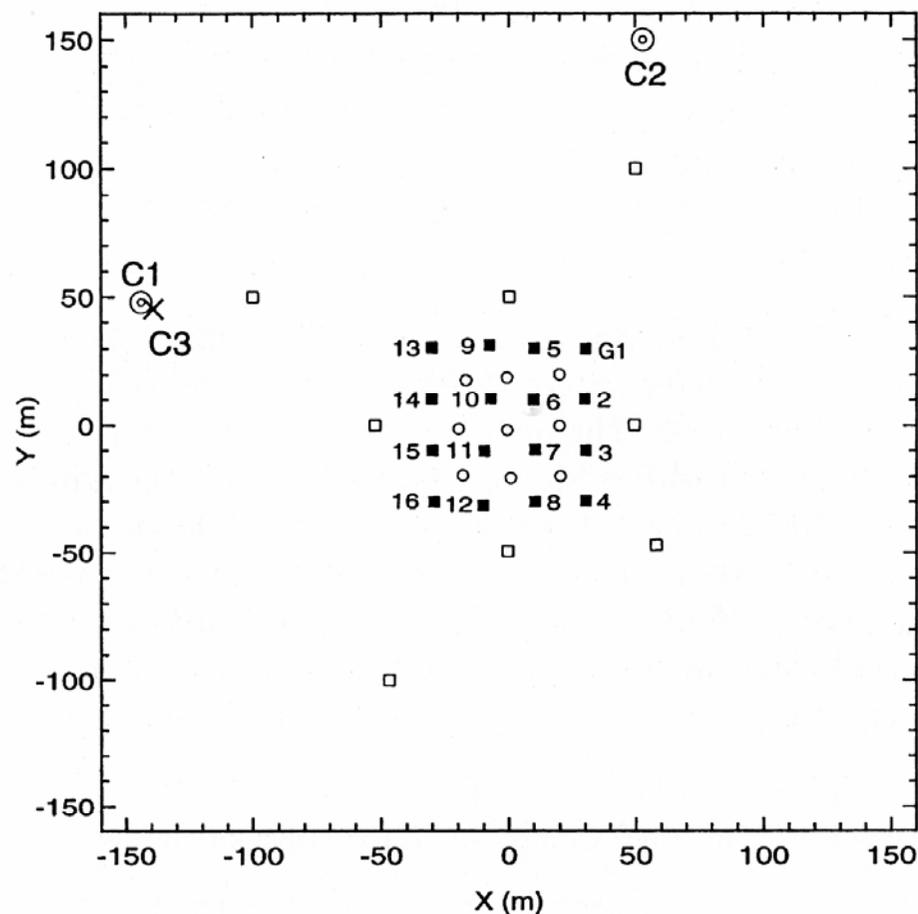
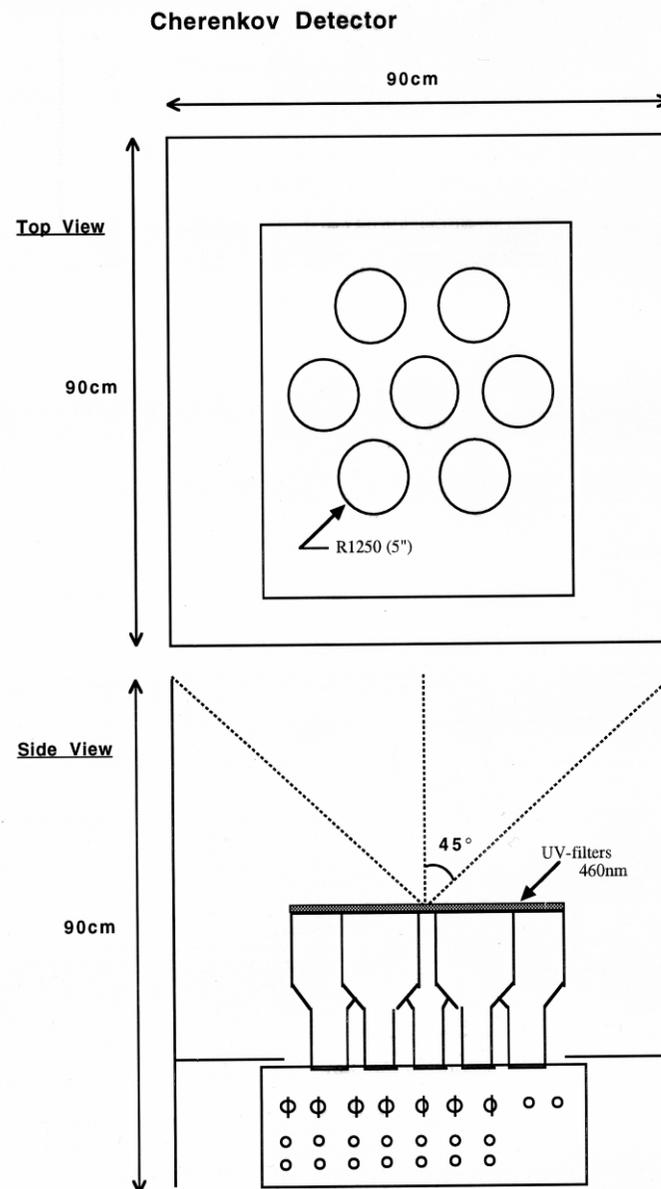


Fig. 1. Arrangement of scintillation detectors in the SAS array and Čerenkov detectors. G-detectors with detector numbers (■), N-detectors (□), and NT-detectors (○). Čerenkov detectors were installed at the distance of about 150 m from the center of SAS array: C1 and C2 (double circle; high energy mode), and C3 (cross; low energy mode).



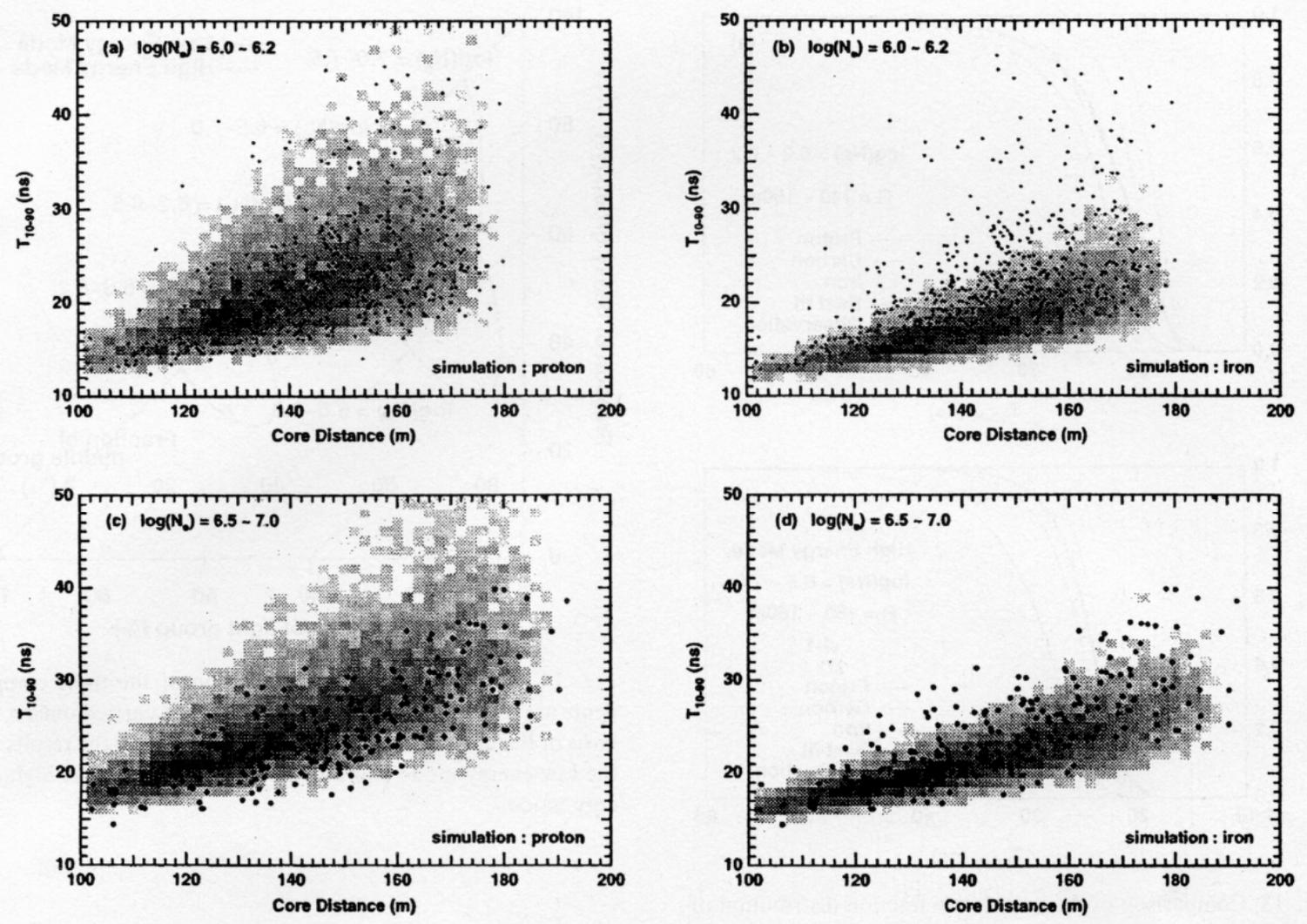


Fig. 12. Scatter plots between T_{10-90} and core distance; experimental results ($\cdot \cdot \cdot$) are compared with the simulation results (grey-scaled image plot) for each shower size range. (a) and (b) are for $\log(N_c) = 6.0-6.5$ and (c) and (d) are for $\log(N_c) = 6.5-7.0$. The simulation is performed for proton ((a) and (c)) and iron ((b) and (d)) primary cosmic rays.

Lateral dist. of Cherenkov photons (2001 – 2003)

$$\rho(r) = \alpha \cdot r'^{-(\beta+r')}$$

CORSIKA/QGSJET simulation

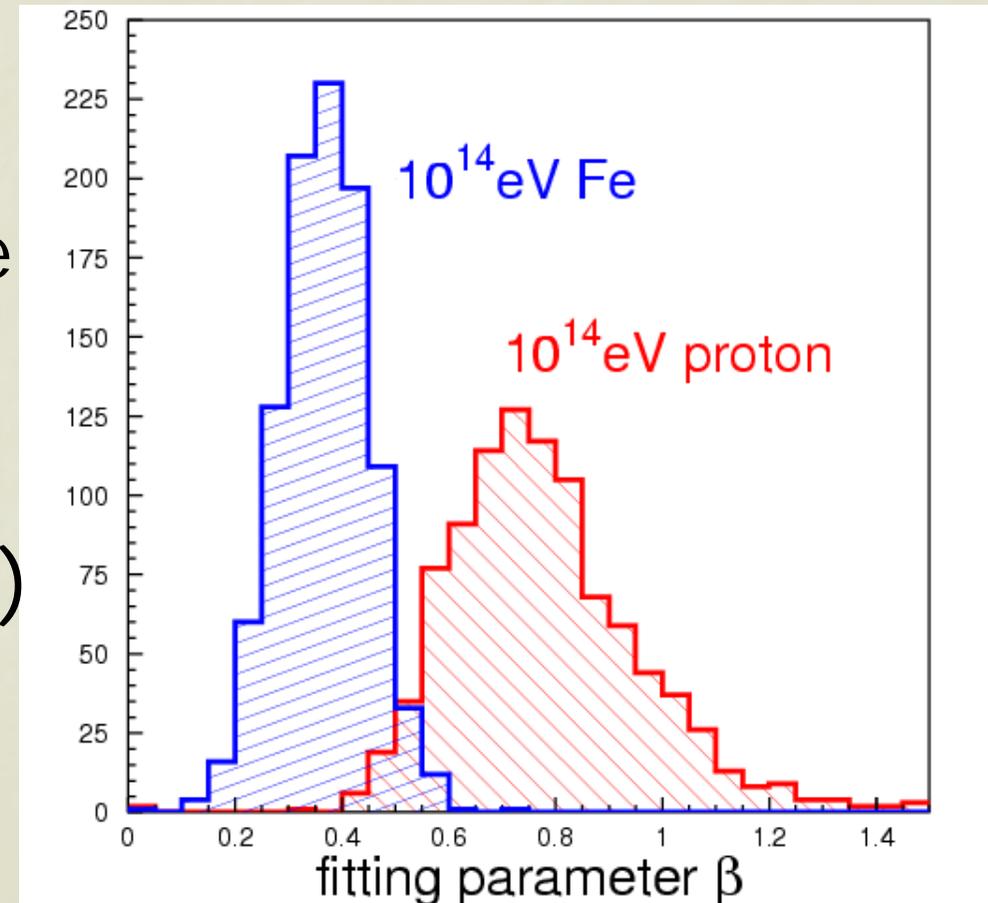
ρ : Cherenkov photons
 r : distance from the core
 $r' : r / R_0$ ($R_0 = 90m$)

■ Simulation

CORSIKA code(v5.61)

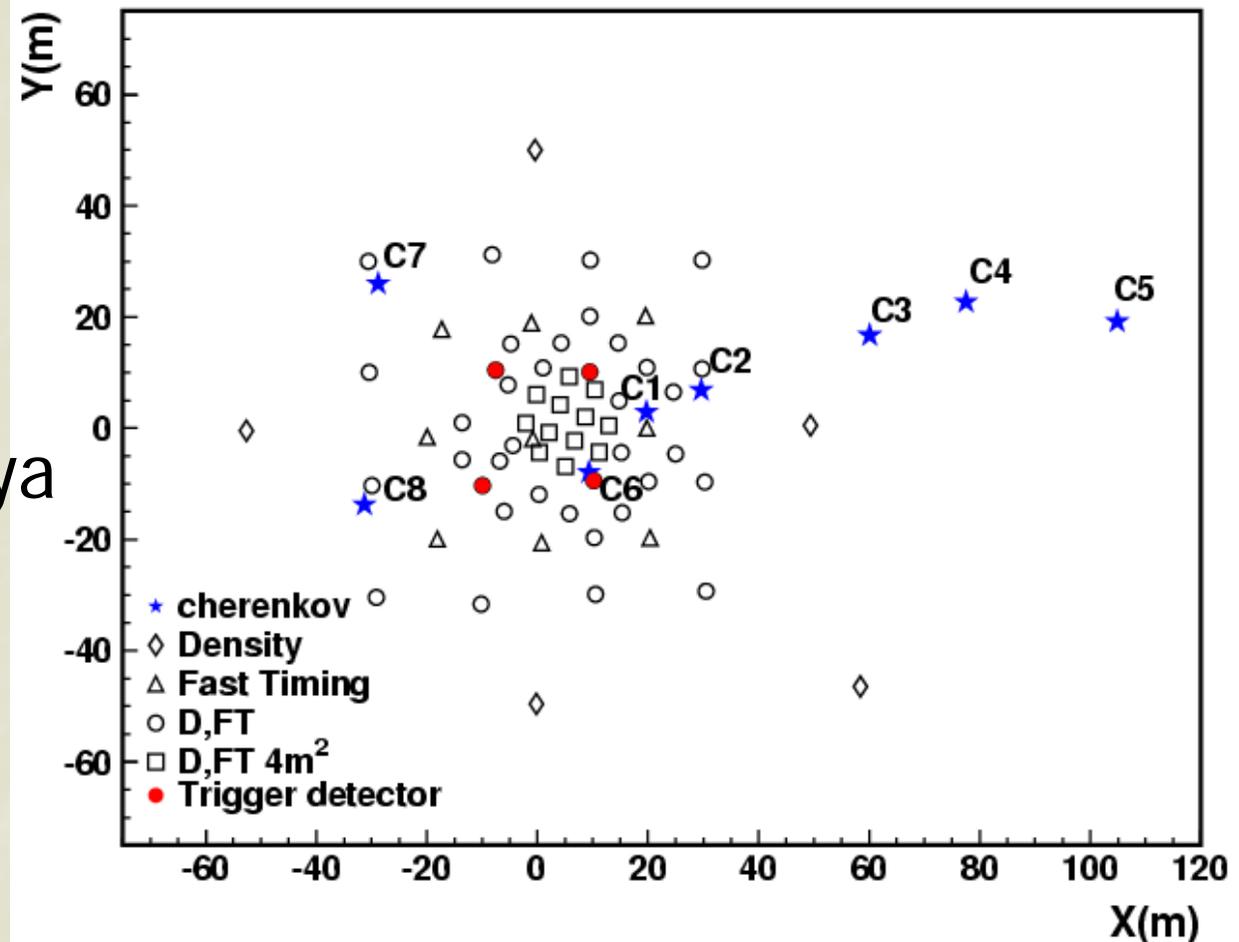
QGSJET model

Proton, C, Fe



MAS array(2002)

BASJE
MAS array
at Mt. Chacaltaya
in Bolivia
5200m a.s.l.

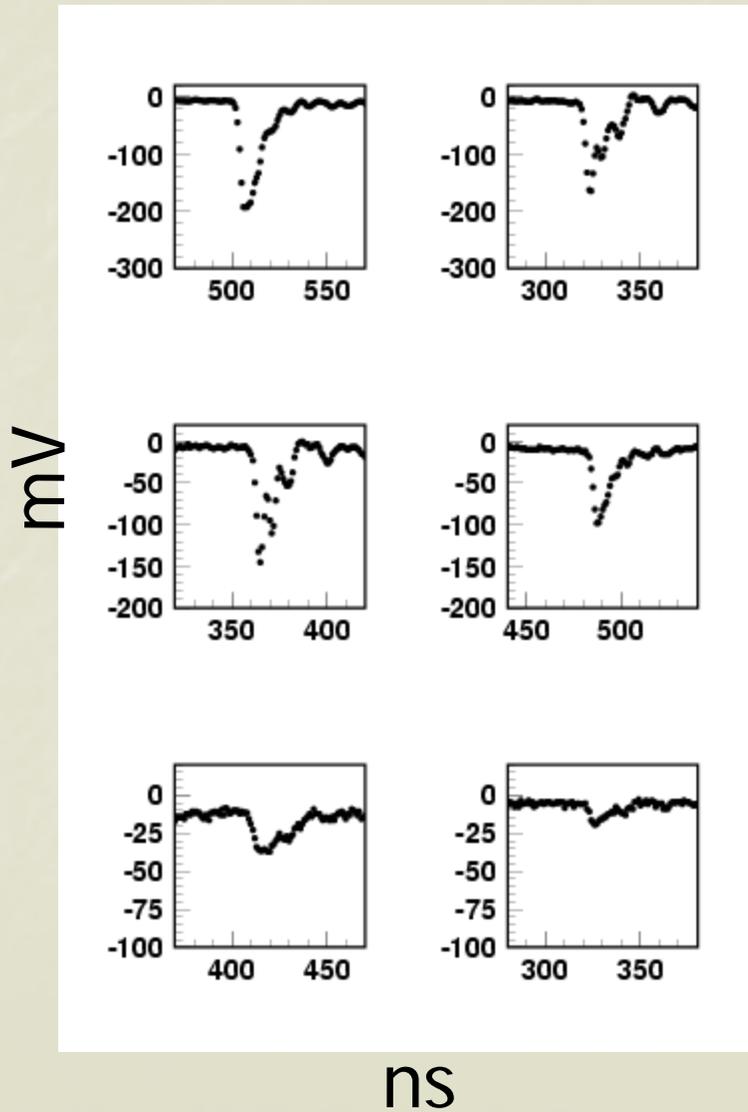


High energy mode (above 10^{15} eV)
Eight Cherenkov photon detectors

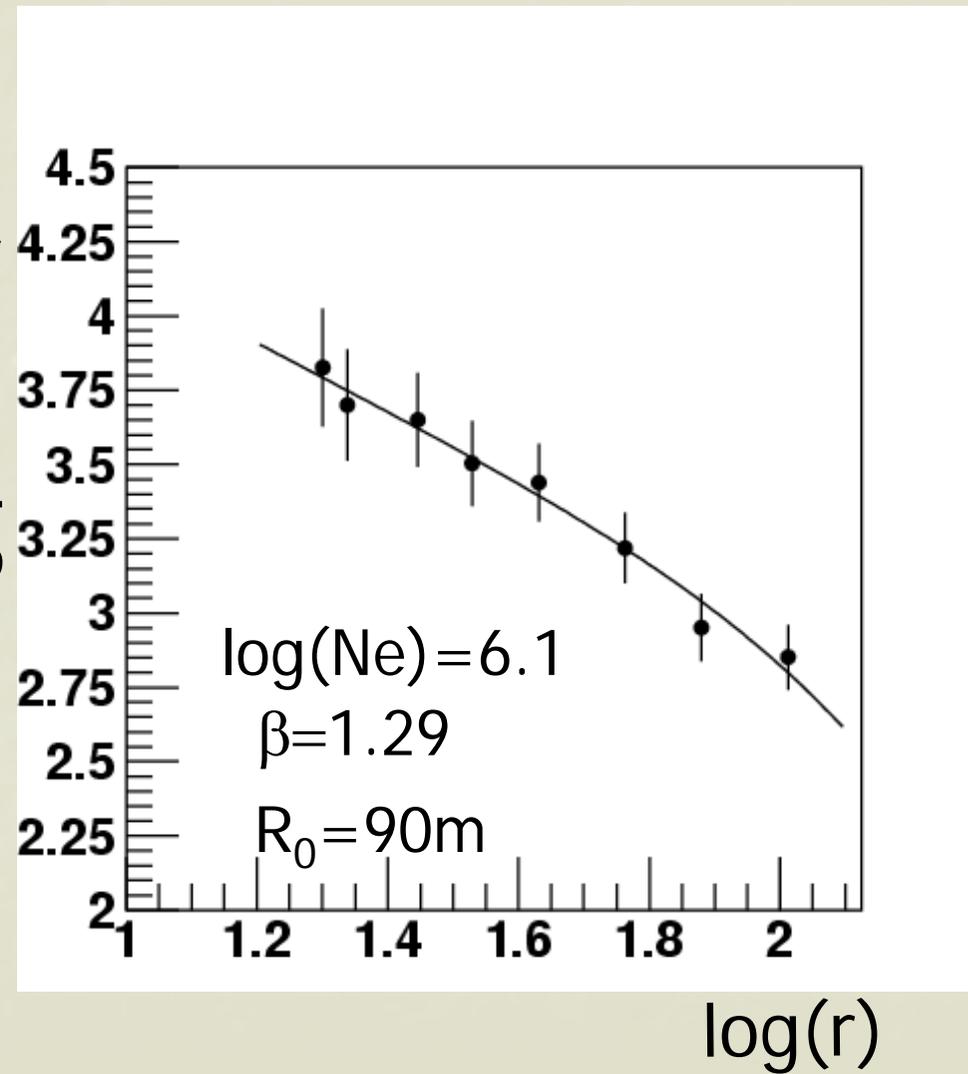




Observed event



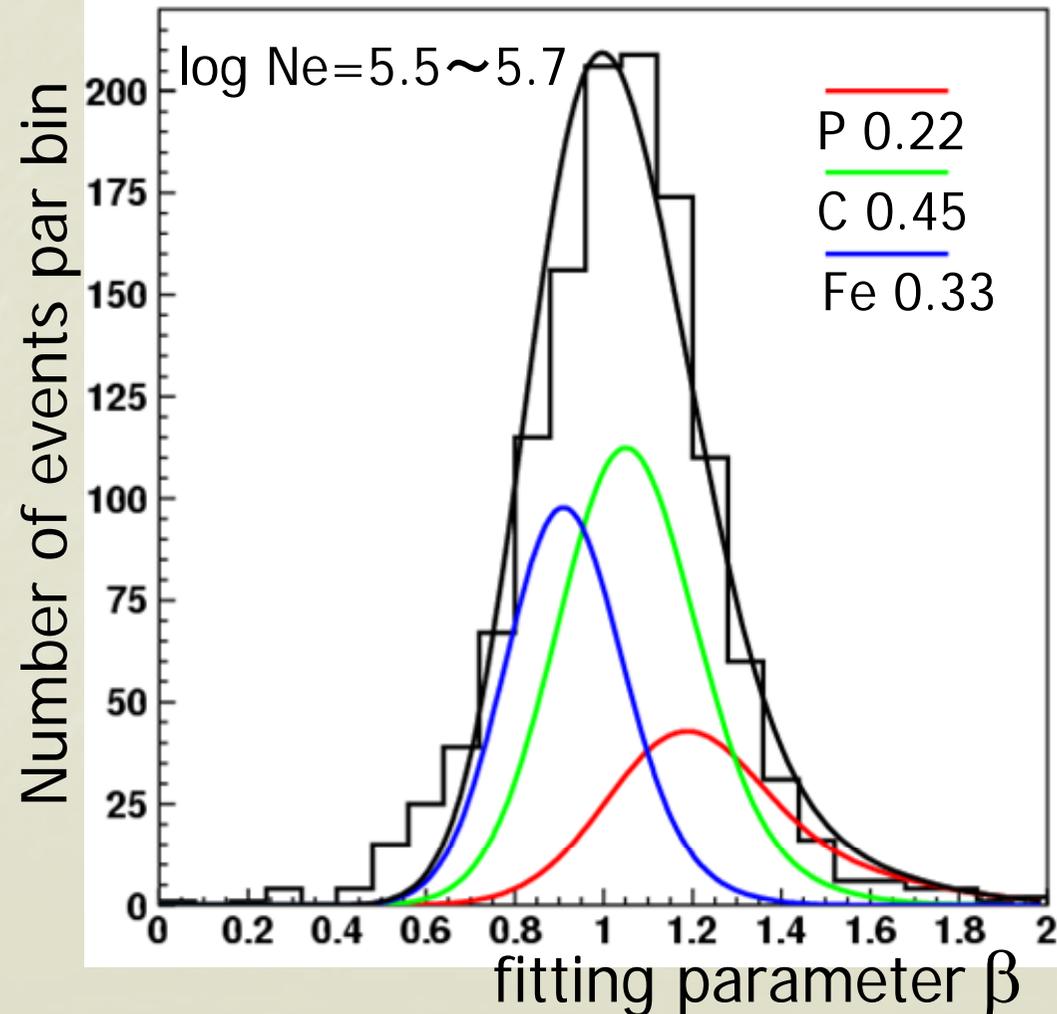
log(photon) arb.

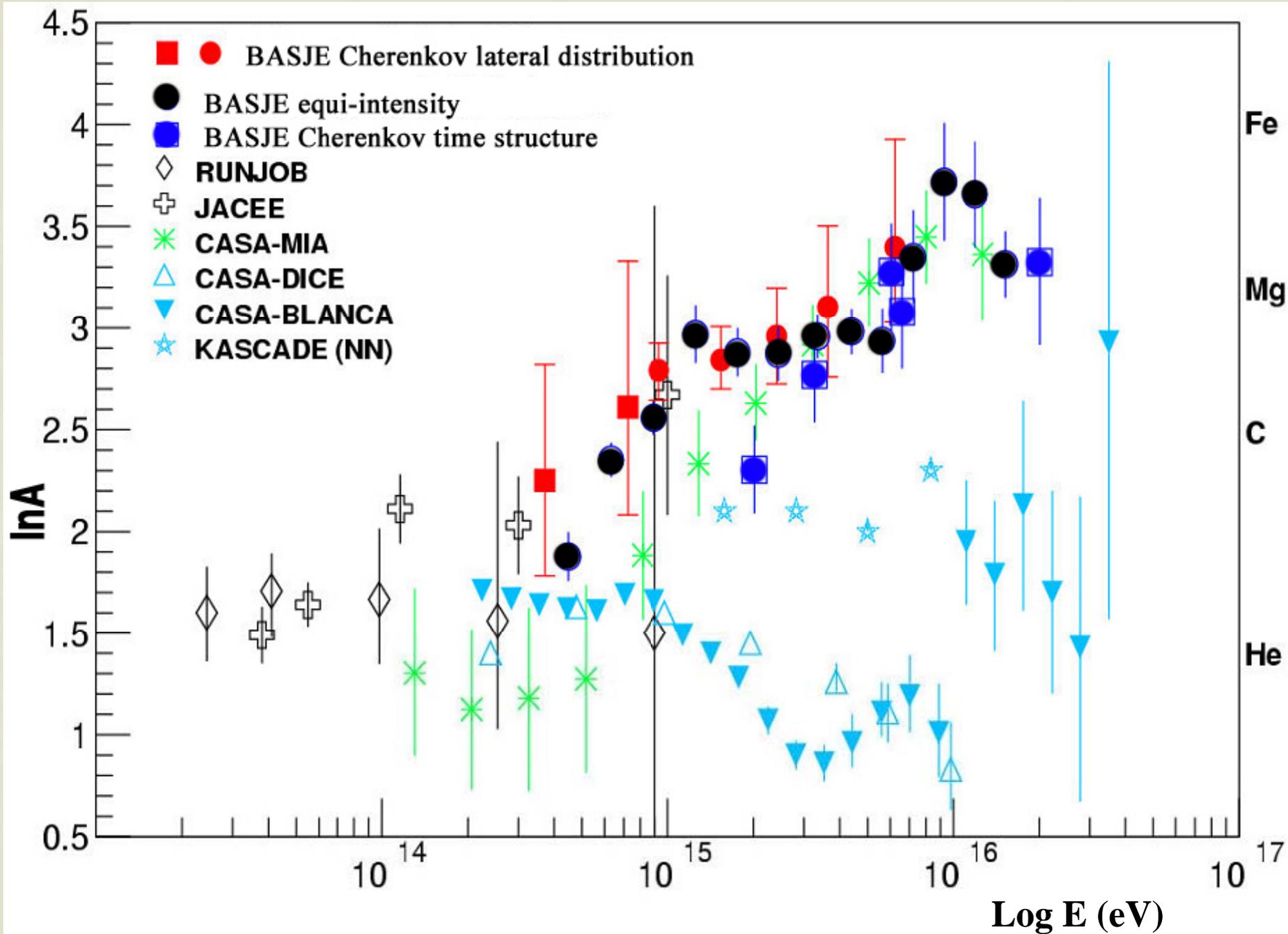


Analysis (3 species model)

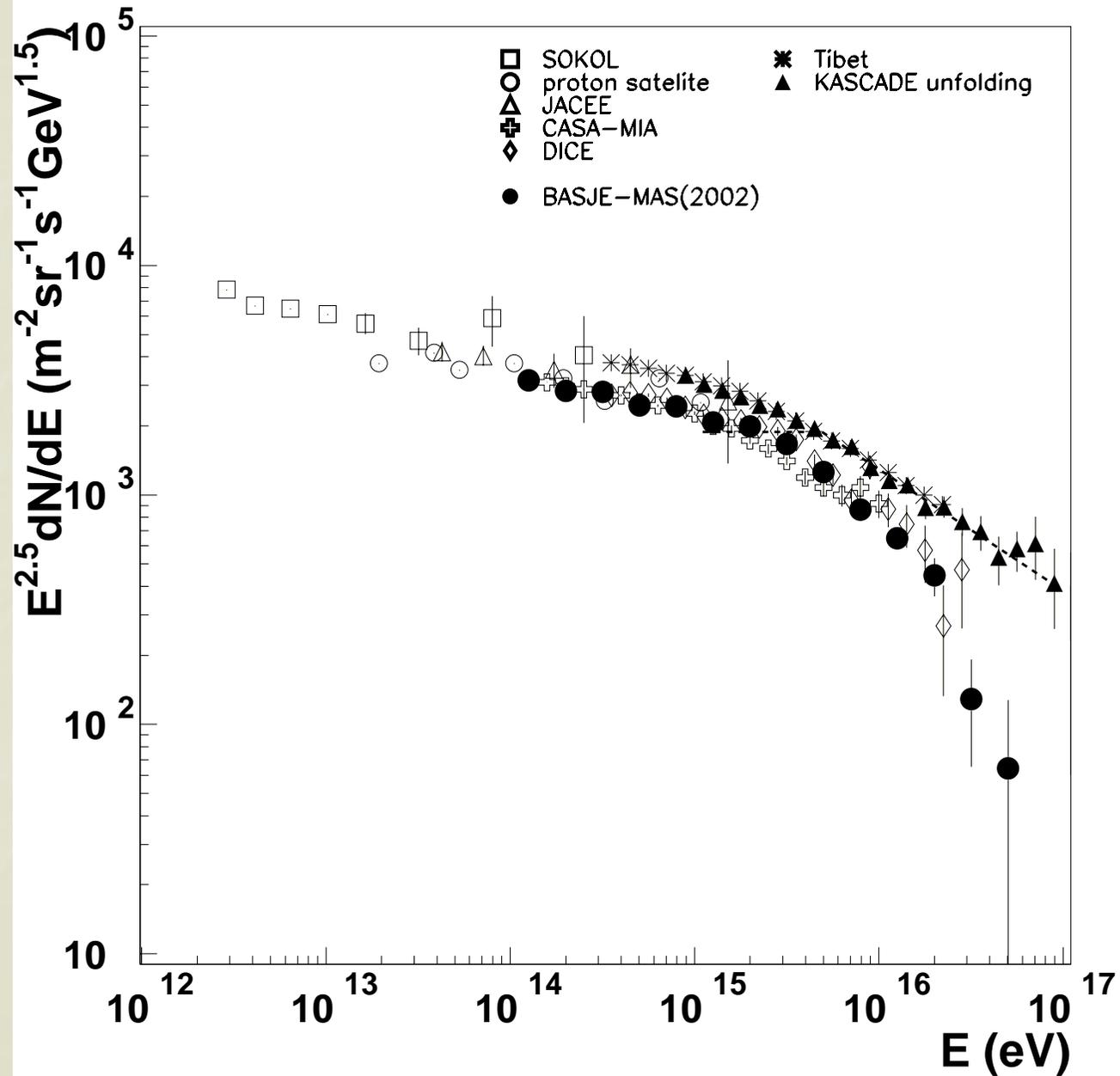
The contribution of each species was determined by a maximum-likelihood method using β - distribution for each size bin

log(Ne)	events
5.0~5.3	327
5.3~5.6	383
5.5~5.7	1260
5.7~5.9	626
5.9~6.1	293
6.1~6.3	130
6.3~6.6	74





エネルギースペクトラム



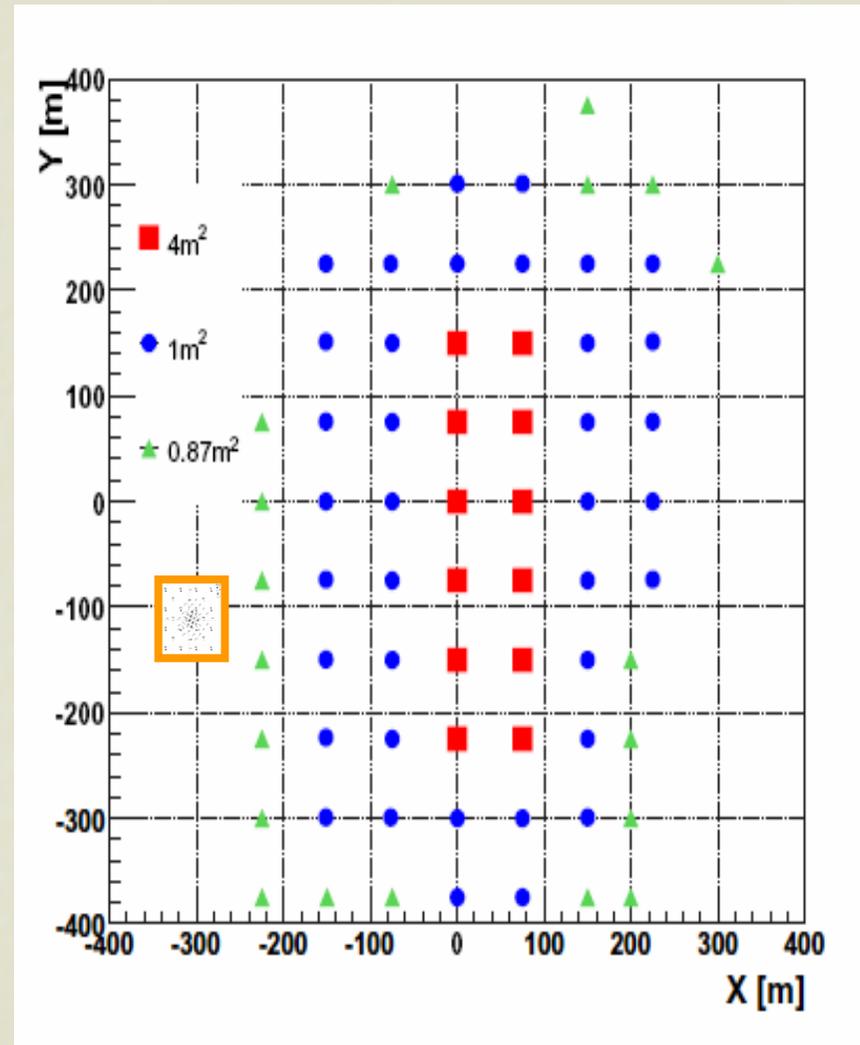
次期計画

Kneeおよびそれ以上の宇宙線起源の解明

- 10^{16} eV以上の化学組成
 - ・等頻度法
 - ・空気シンチレーション光測定
 - ⇒ 到来方向別の化学組成、エネルギー
スペクトラム
- 異方性のエネルギー依存性

次期BASJE宇宙線観測

- 検出器
 - 検出器間隔75m
 - Timing & Density 68台
- トリガー方式
 - 4m^2 の検出器12台
any-4
- 検出面積
 - $100,000\text{m}^2$ 超
 - トリガー効率
(95~%)
- イベントレート
 - 10^4 超 $[\text{year}^{-1}]$
(10^{16} ~ $[\text{eV}]$)



アレイ性能

基本性能

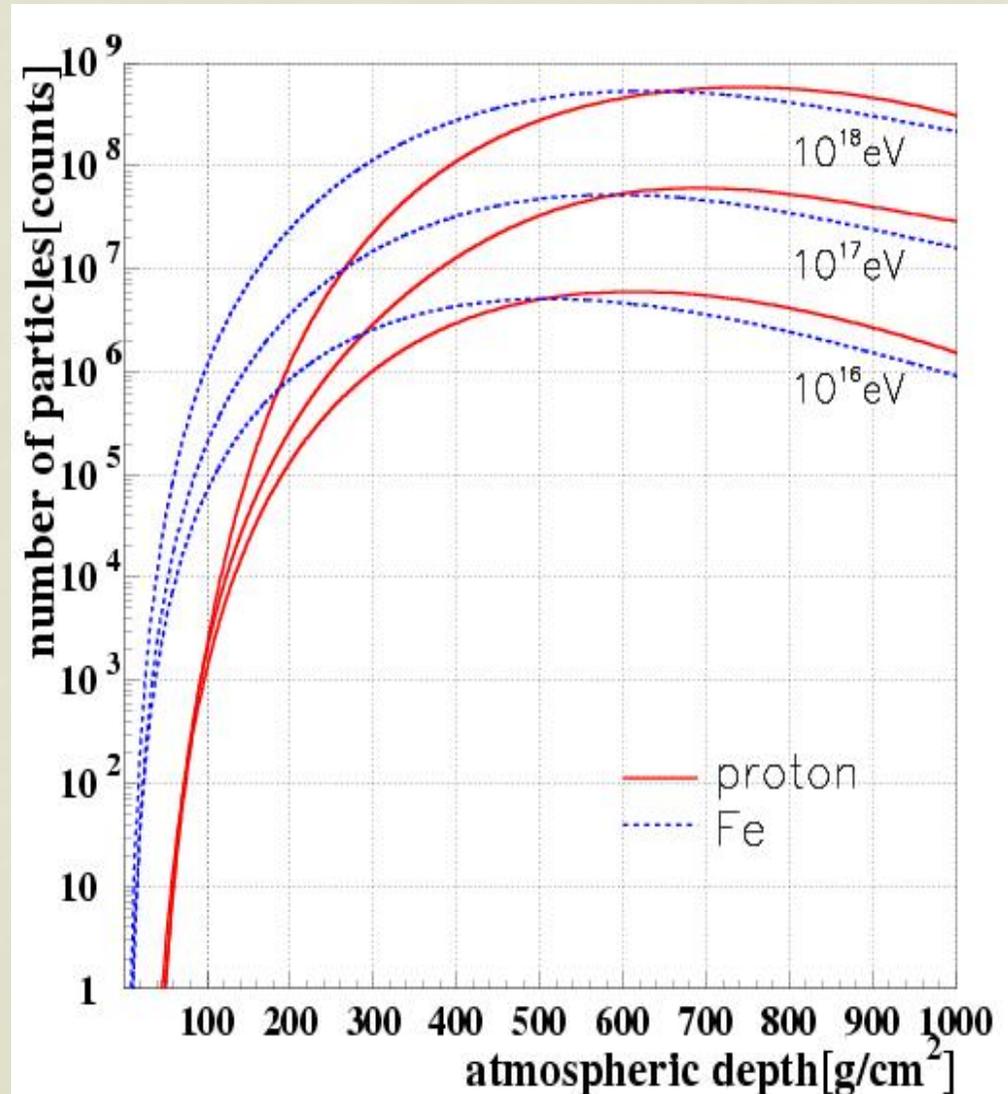
トリガー効率 (~100%)	10^{16} eV以上の イベント数
約 $10^{15.3}$ eV	約10,000(year)

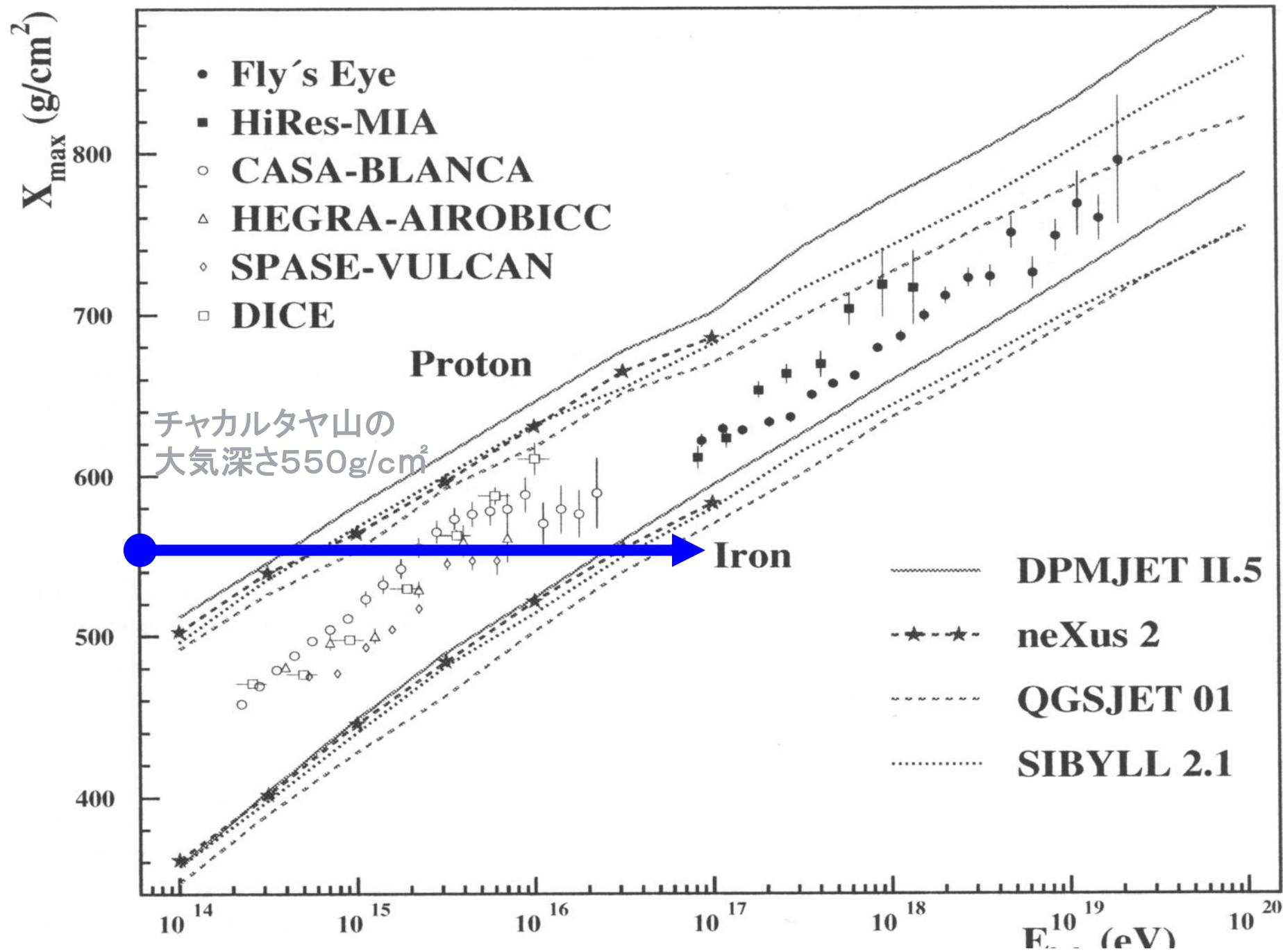
パラメータ決定精度

天頂角が 0° の時	10^{16} eV	10^{17} eV
到来方向決定精度(open-angle)	0.46	0.35
サイズ決定精度($\Delta \log N$)	0.11	0.08

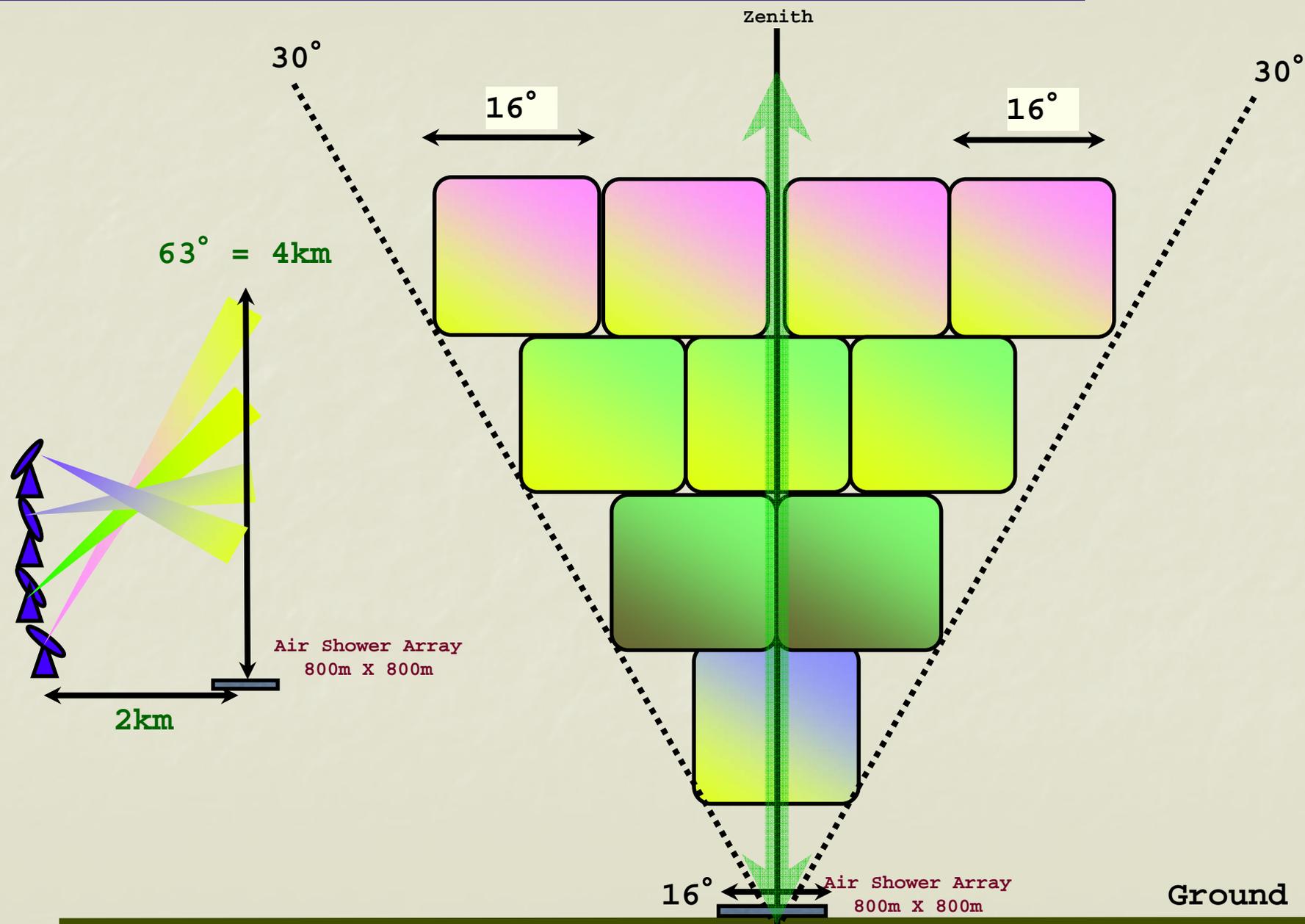
等頻度法による組成比決定

- 等頻度法のメリット
 - 天候等に影響されない
 - $10^{16.0} \sim eV$ のシャワーの最大発達が見える





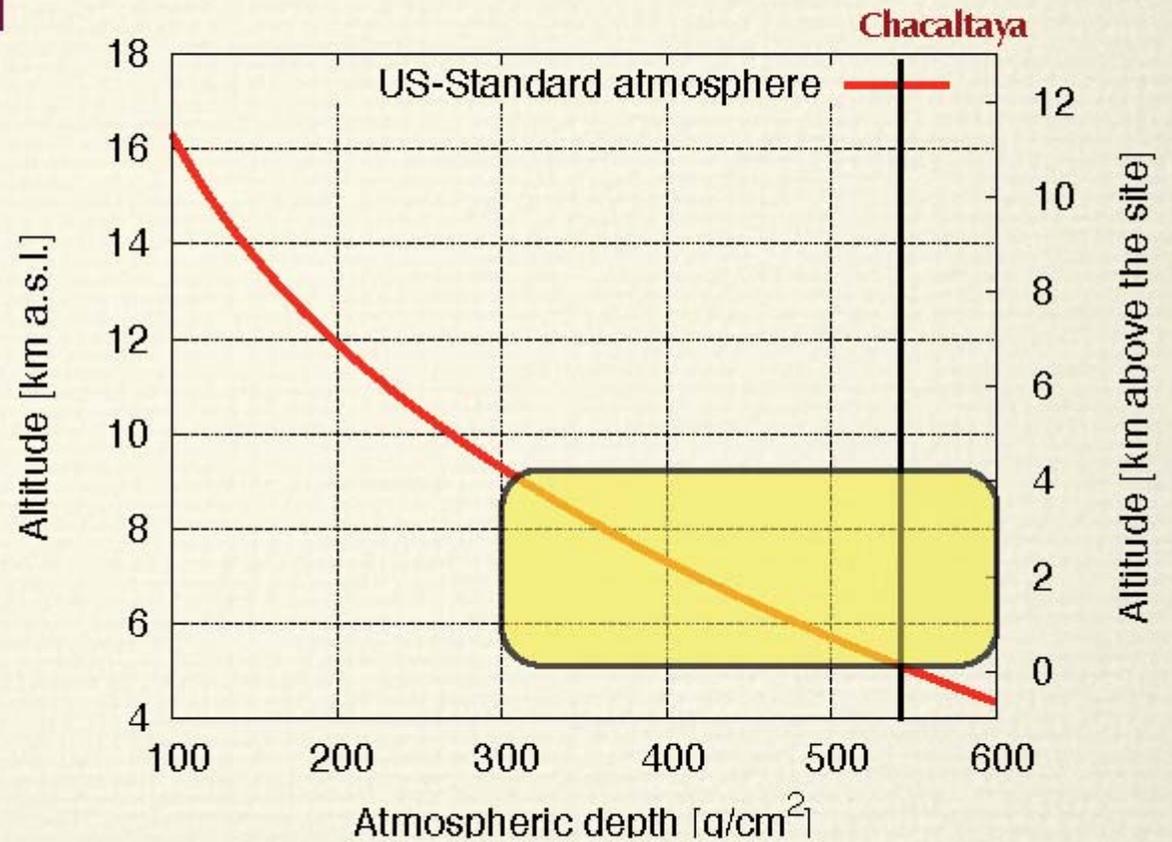
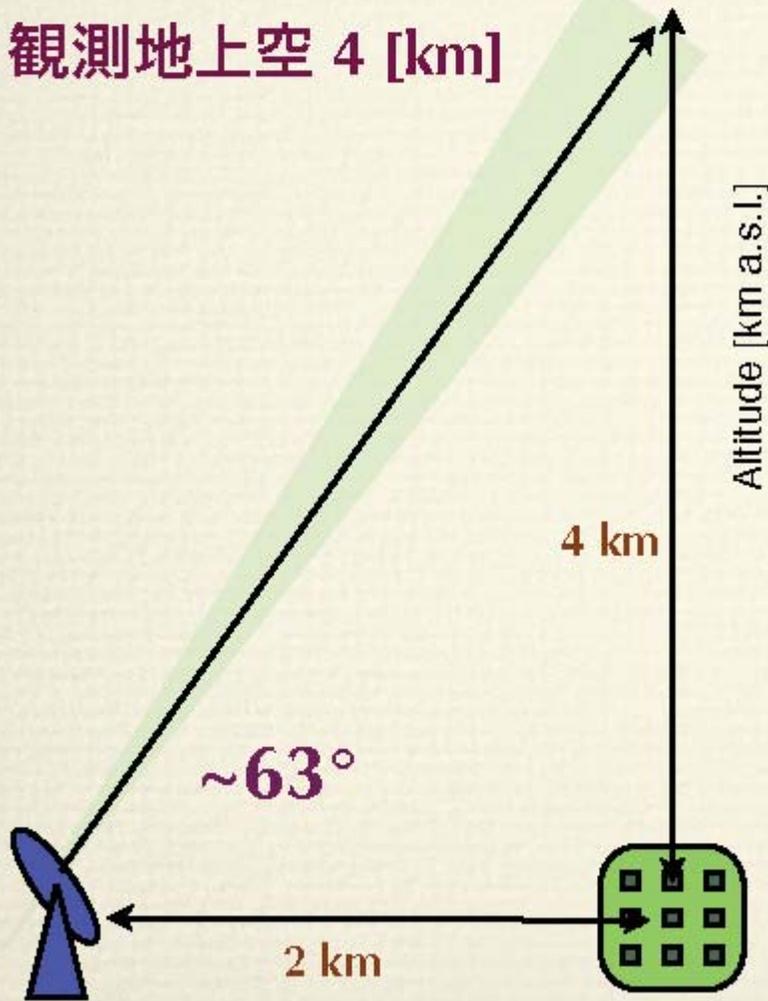
空気シンチレーション光観測



300 [g/cm²]

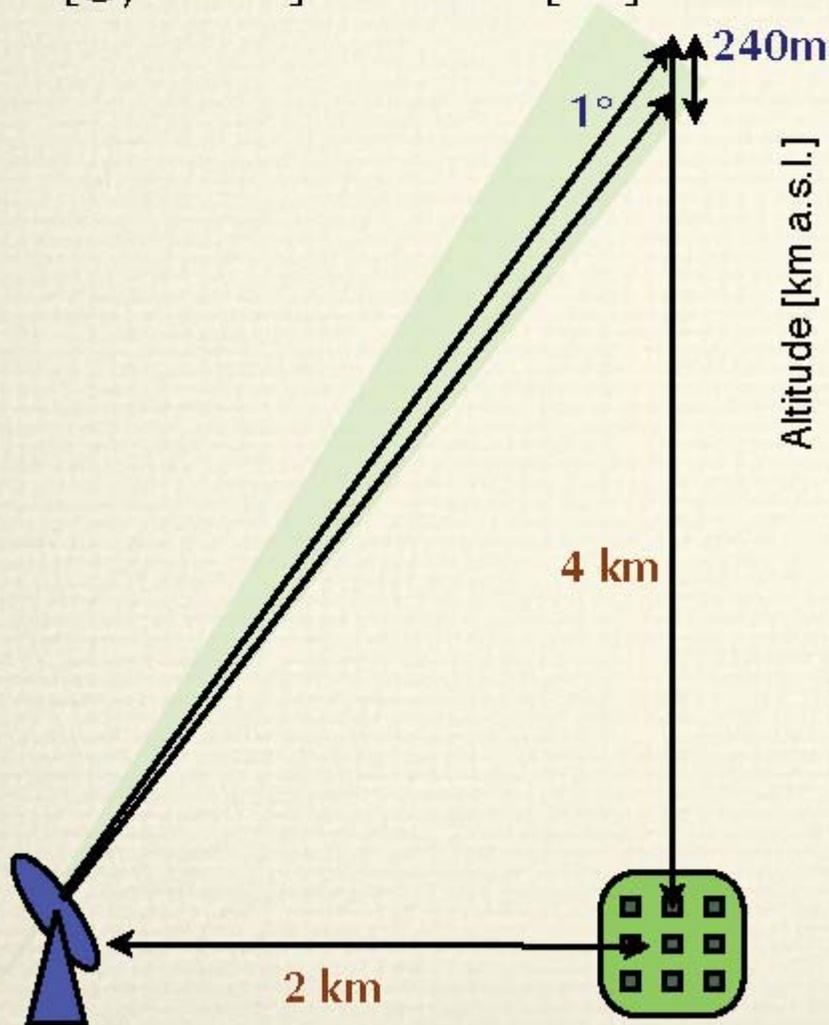
300 [g/cm²] = 海拔 9 [km]

觀測地上空 4 [km]

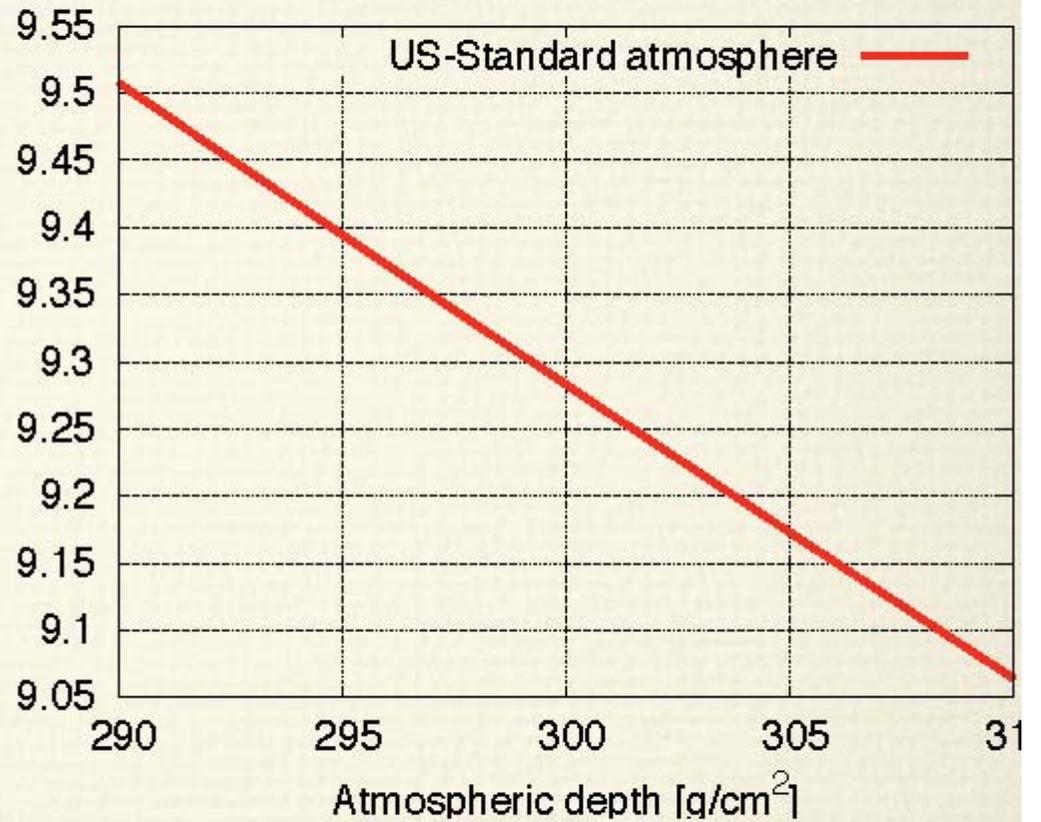


10 [g/cm²]

$$10 \text{ [g/cm}^2\text{]} = 240 \text{ [m]}$$



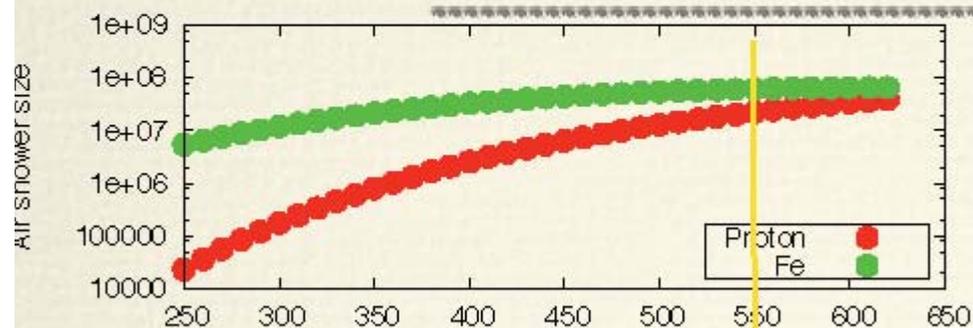
Altitude [km a.s.l.]



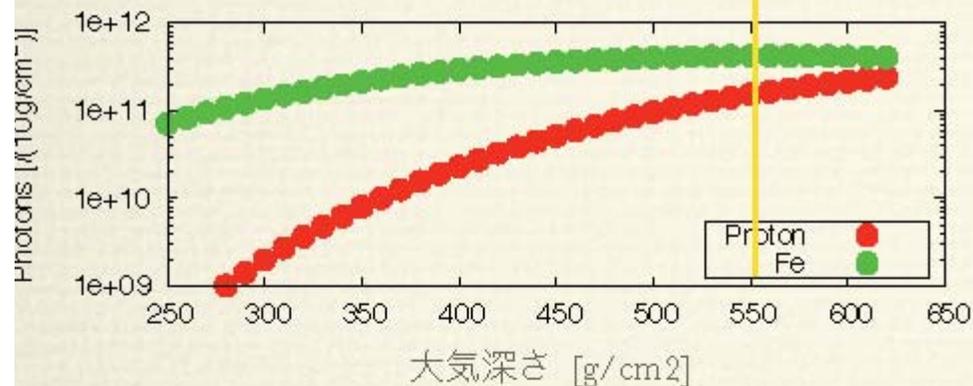
検出器の解像度 ~1°で

精度 $\Delta X \sim 10 \text{ [g/cm}^2\text{]}$ が達成される

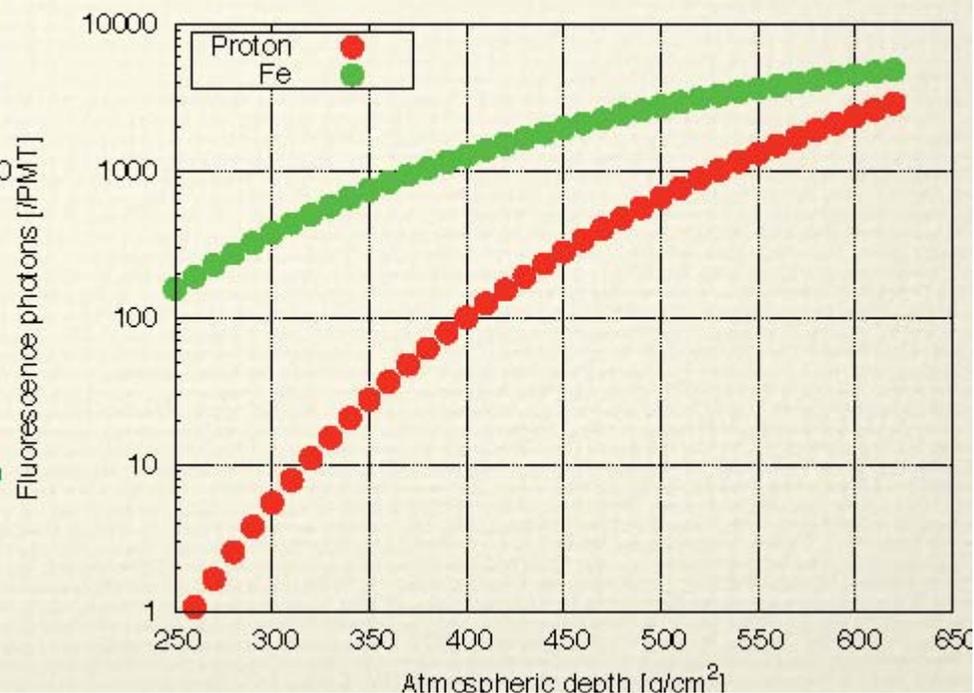
観測される光子数



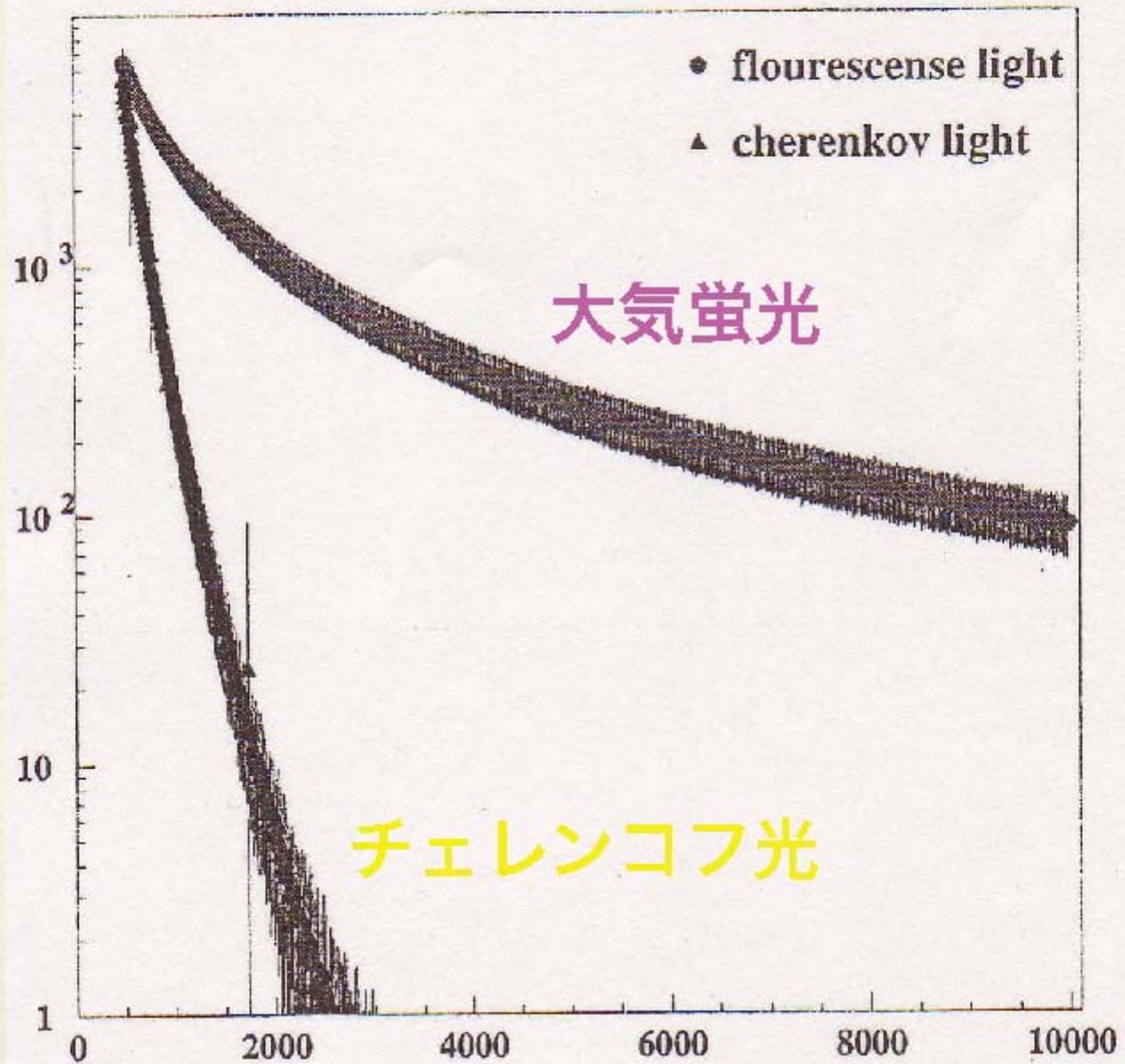
シャワー発達と
大気蛍光光子数



PMTで検出される
光子数



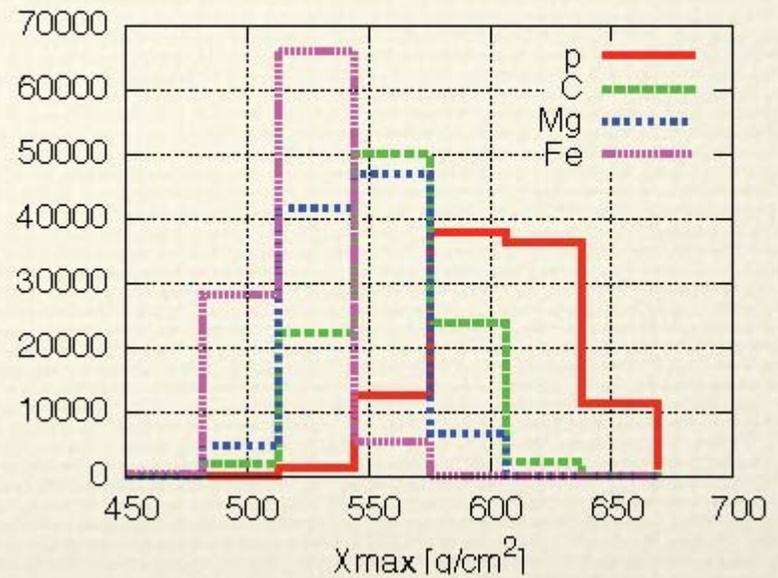
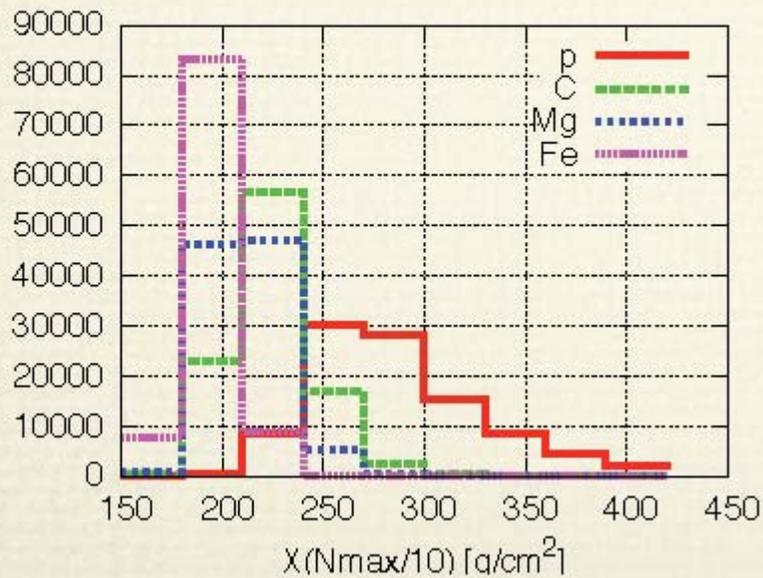
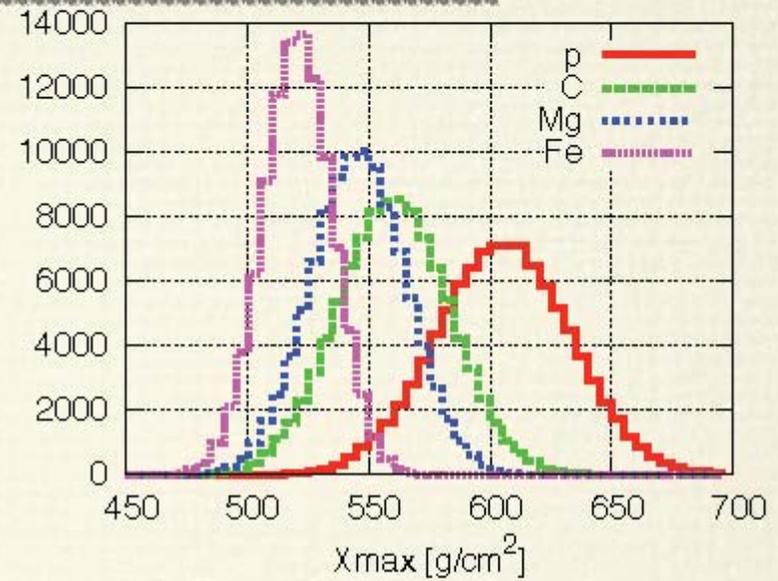
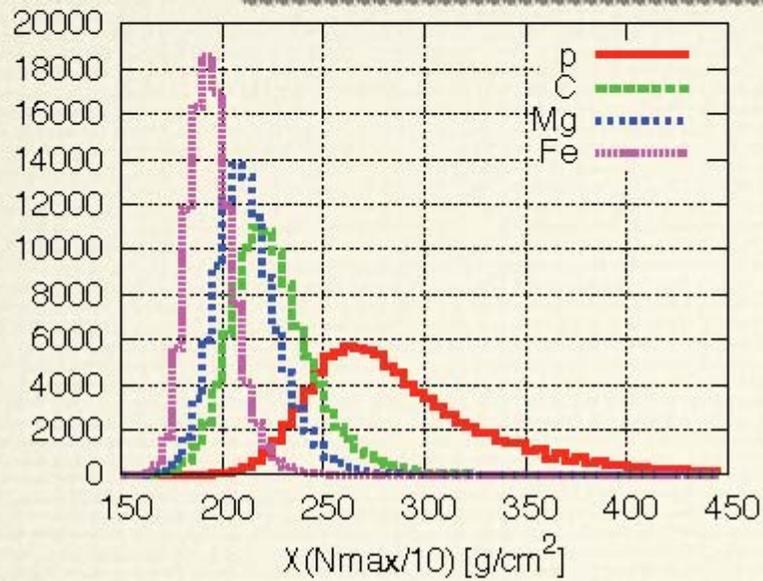
チェレンコフ光の影響



期待されるイベント数

	Aperture [km ² str]	Events/yr >10 ¹⁶ [eV]
地表アレイ	0.5	60000
大気蛍光	0.03	3000

核種分離



核種分離

