

# 最高エネルギー宇宙線観測

## 宇宙線望遠鏡実験

荻尾 彰一(大阪市立大学)

On behalf of the Telescope Array Collaboration

(「地文台によるサイエンス」@甲南大学 2006年3月9日での講演より抜粋)

# The Telescope Array (TA) Collaboration

H.Kawai<sup>a</sup>, S.Yoshida<sup>a</sup>, H.Yoshii<sup>b</sup>, K.Tanaka<sup>c</sup>, F.Cohen<sup>d</sup>, E.Kido<sup>d</sup>, M.Fukushima<sup>d</sup>, N.Hayashida<sup>d</sup>, K.Hiyama<sup>d</sup>, D.Ikeda<sup>d</sup>, M.Ohnishi<sup>d</sup>, H.Ohoka<sup>d</sup>, S.Ozawa<sup>d</sup>, H.Sagawa<sup>d</sup>, N.Sakurai<sup>d</sup>, T.Shibata<sup>d</sup>, H.Shimodaira<sup>d</sup>, M.Takeda<sup>d</sup>, A.Taketa<sup>d</sup>, M.Takita<sup>d</sup>, H.Tokuno<sup>d</sup>, R.Torii<sup>d</sup>, S.Udo<sup>d</sup>, H.Fujii<sup>e</sup>, T.Matsuda<sup>e</sup>, M.Tanaka<sup>e</sup>, H.Yamaoka<sup>e</sup>, K.Hibino<sup>f</sup>, T.Benno<sup>g</sup>, M.Chikawa<sup>g</sup>, T.Nakamura<sup>h</sup>, M.Teshima<sup>i</sup>, K.Kadota<sup>j</sup>, Y.Uchihori<sup>k</sup>, K.Hayashi<sup>l</sup>, Y.Hayashi<sup>l</sup>, S.Kawakami<sup>l</sup>, K.Matsumoto<sup>l</sup>, Y.Matsumoto<sup>l</sup>, T.Matsuyama<sup>l</sup>, M.Minamino<sup>l</sup>, T.Nonaka<sup>l</sup>, S.Ogio<sup>l</sup>, A.Ohshima<sup>l</sup>, T.Okuda<sup>l</sup>, N.Shimizu<sup>l</sup>, H.Tanaka<sup>l</sup>, D.R.Bergman<sup>m</sup>, G.Hughes<sup>m</sup>, S.Stratton<sup>m</sup>, G.B.Thomson<sup>m</sup>, K.Endo<sup>n</sup>, N.Inoue<sup>n</sup>, S.Kawana<sup>n</sup>, Y.Wada<sup>n</sup>, K.Kasahara<sup>o</sup>, M.Fukuda<sup>p</sup>, T.Iguchi<sup>p</sup>, F.Kakimoto<sup>p</sup>, S.Machida<sup>p</sup>, R.Minakawa<sup>p</sup>, Y.Murano<sup>p</sup>, Y.Tameda<sup>p</sup>, Y.Tsunesada<sup>p</sup>, J.W.Belz<sup>qs</sup>, J.A.J.Matthews<sup>r</sup>, T.Abu-Zayyad<sup>s</sup>, R.Cady<sup>s</sup>, Z.Cao<sup>s</sup>, P.Huentemeyer<sup>s</sup>, C.C.H.Jui<sup>s</sup>, K.Martens<sup>s</sup>, J.N.Matthews<sup>s</sup>, J.D.Smith<sup>s</sup>, P.Sokolsky<sup>s</sup>, R.W.Springer<sup>s</sup>, S.B.Thomas<sup>s</sup>, L.R.Wiencke<sup>s</sup>, T.Doyle<sup>t</sup>, M.J.Taylor<sup>t</sup>, V.B.Wickwart<sup>t</sup>, T.D.Wilkerson<sup>t</sup>, K.Hashimoto<sup>u</sup>, K.Honda<sup>u</sup>, T.Ishii<sup>u</sup>, K.Ikuta<sup>u</sup>, T.Kanbe<sup>u</sup>

(a) Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba-shi, Chiba, 263-8522 Japan

(b) Ehime University, 2-5 Bunkyo-cho, Matsuyama, 790-8577 Japan

(c) Hiroshima City University, 3-4-1 Ozuka-Higashi, Asa-Minami-Ku, Hiroshima, 731-3194 Japan

(d) ICRR, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8582 Japan

(e) Institute of Particle and Nuclear Studies, KEK, 1-1 Oho, Tsukuba, Ibaraki, 305-0801 Japan

(f) Kanagawa University, 3-27-1 Rokkakubashi, Kanagawa-ku, Yokohama, Kanagawa, 221-8686 Japan

(g) Kinki University, 3-4-1 Kowakae, Higashi-Osaka City, 577-8502 Japan

(h) Kochi University, 2-5-1 Akebonocho, Kochi, 780-8520 Japan

(i) Max-Planck-Institute for Physics, Foerhinger Ring 6, 80805 Muenchen, Germany

(j) Musashi Institute of Technology, 1-28-1 Tamazutsumi, Setagaya-ku, Tokyo, 158-8557 Japan

(k) National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba-shi, 263-8555 Japan

(l) Osaka City University, 3-3-138 Sugimotocho, Sumiyoshi-ku, Osaka, 558-8585 Japan

(m) Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA

(n) Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama, 338-8570 Japan

(o) Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama, 337-8570 Japan

(p) Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8550 Japan

(q) University of Montana, 32 Campus Drive, Missoula, MT 59812, USA

(r) University of New Mexico, Albuquerque, NM 87131 USA

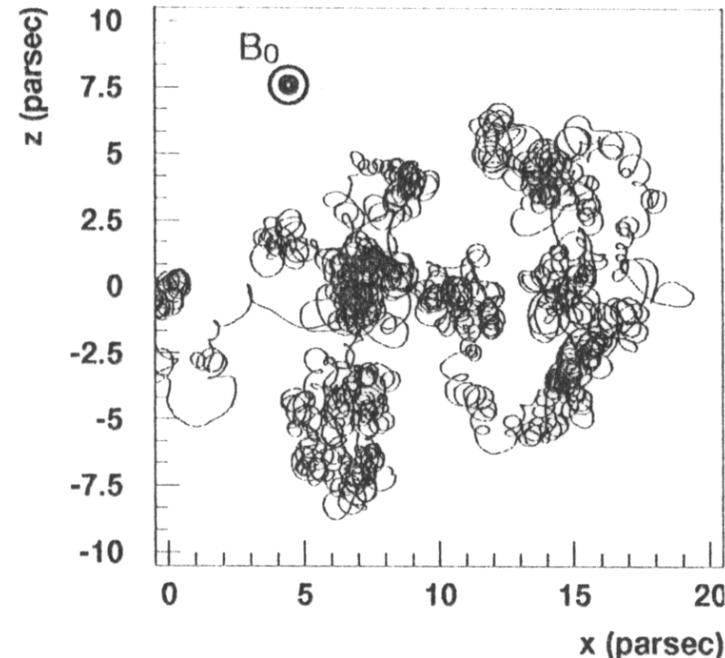
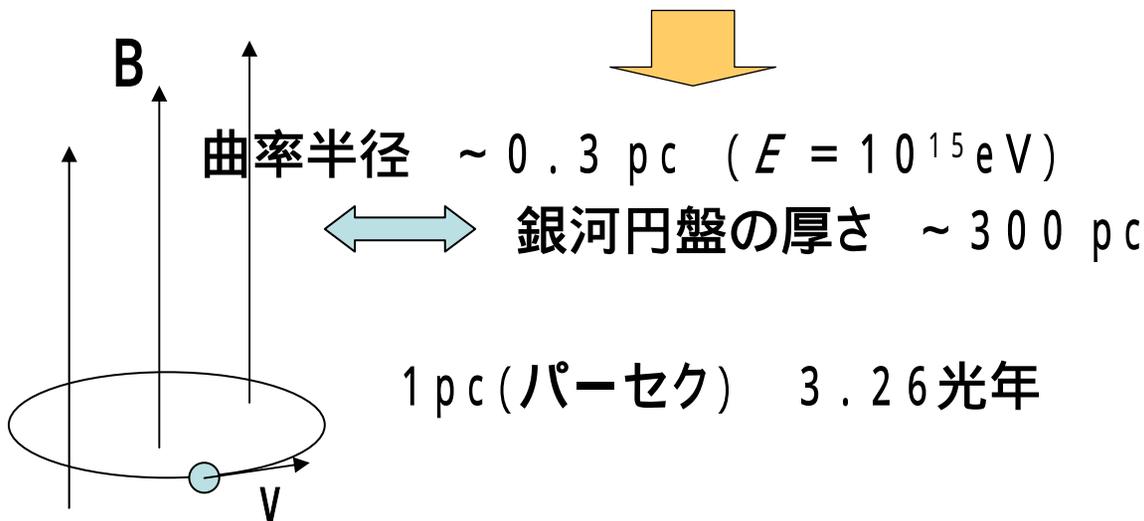
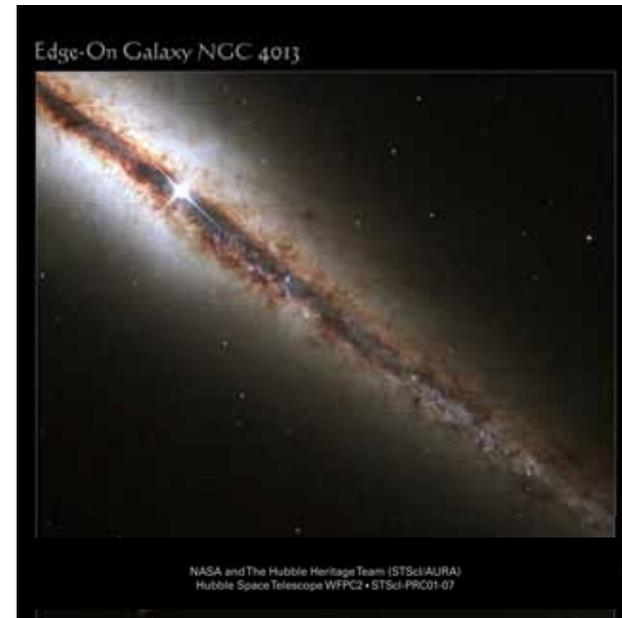
(s) University of Utah, 115 S 1400 E, Salt Lake City, UT 84112, USA

(t) Utah State University, Logan UT 84322, USA

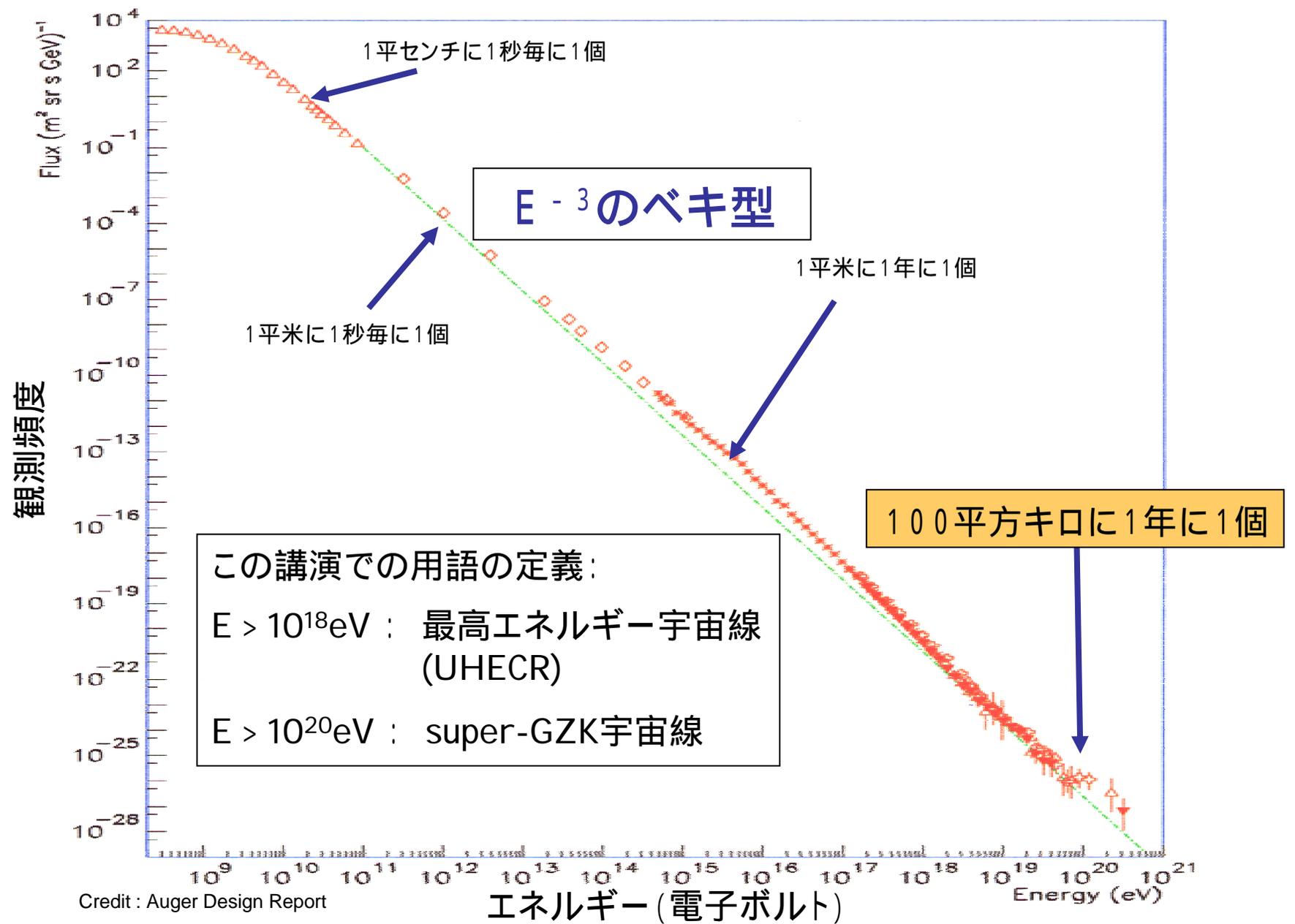
(u) Yamanashi University, 4-4-37 Takeda, Kofu, Yamanashi, 400-8510 Japan

# 宇宙線とは？

- 宇宙空間を飛び交う高エネルギー粒子  
ほとんどは陽子・原子核  
 $10^9 \text{ eV} - 10^{20} \text{ eV}$ 以上
- 電荷を持つ = 銀河磁場と相互作用  
直進しない = 点源が見えない  
銀河磁場  $3 \text{ マイクロガウス} \sim 3 \times 10^{-10} \text{ テスラ}$   
(ちなみに地磁気は  $3 \times 10^{-5} \text{ テスラ}$ )



# 宇宙線のエネルギースペクトル

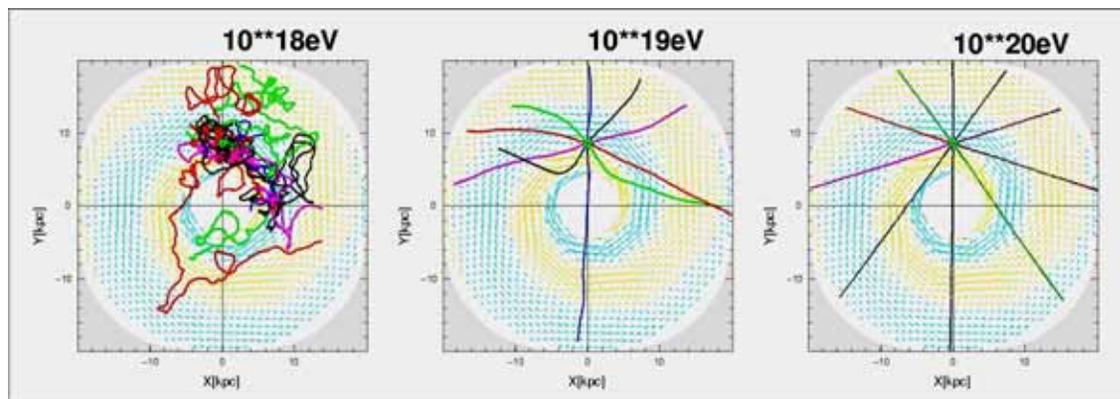


# 最高エネルギー宇宙線

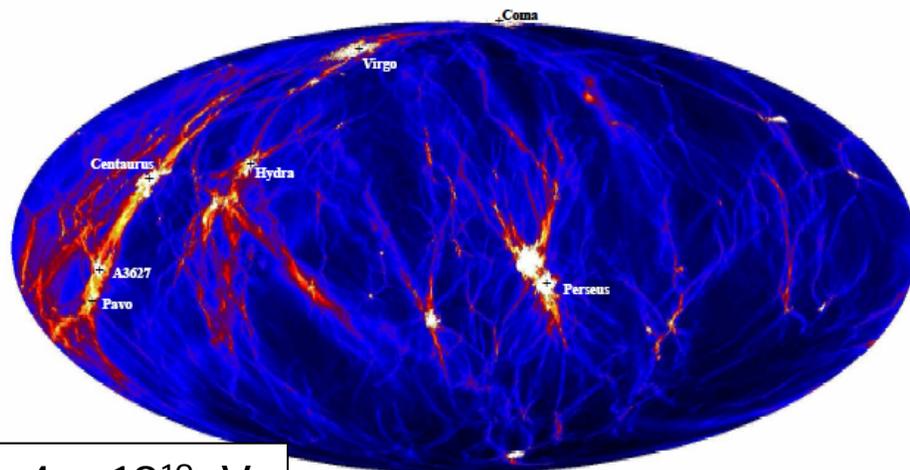
巨視的なエネルギー

$$E_{max} = 3 \times 10^{20} \text{ eV} \quad 60 \text{ ジュール}$$

(ほぼ)直進する

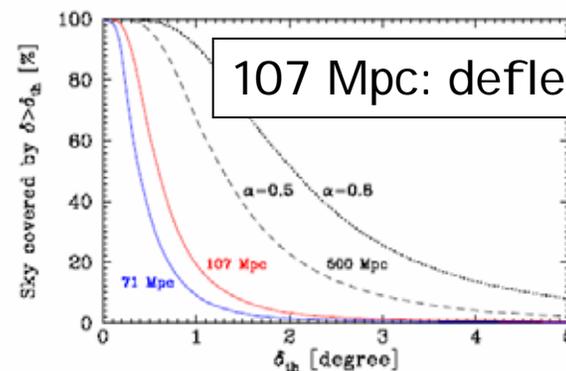


M.Honda, M.Teshima



$E > 4 \times 10^{19} \text{ eV}$

0 1 2 3 4 5 [Degrees]



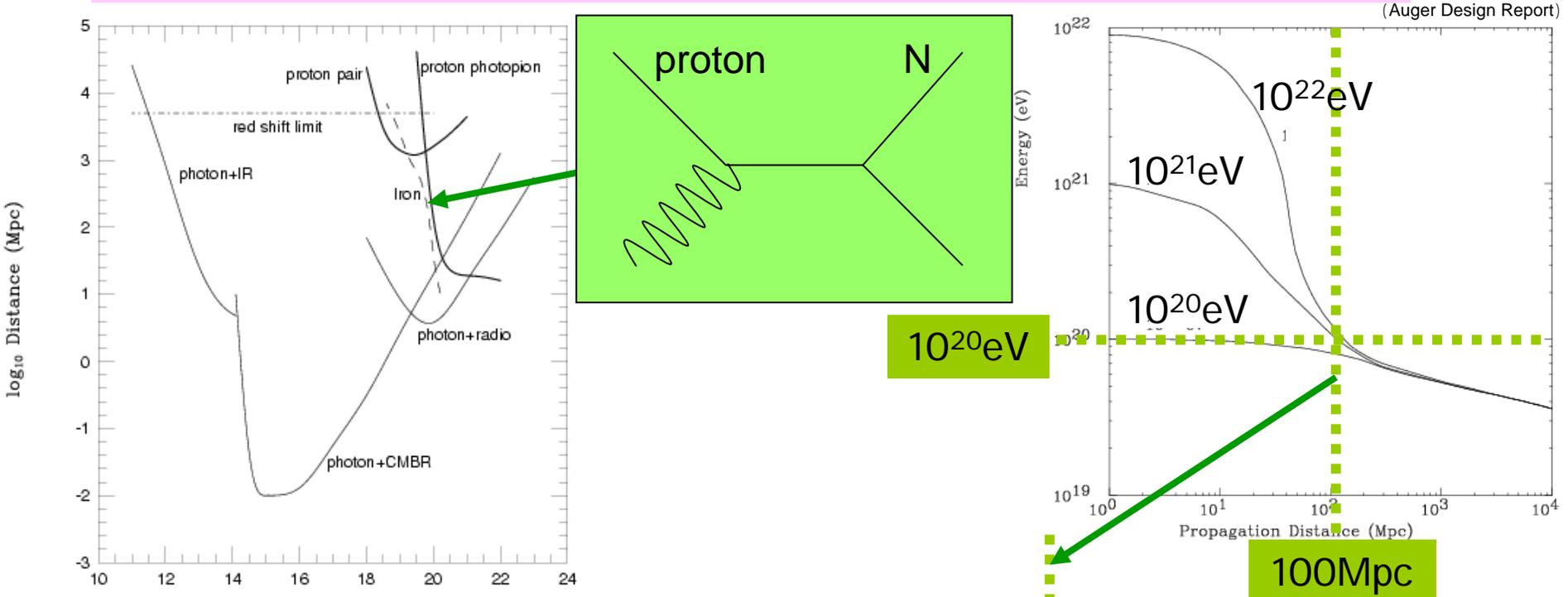
107 Mpc: deflection < 1°

FIG. 2: Cumulative fraction of the sky with deflection angle larger than  $\delta_{th}$ , for several values of propagation distance (solid lines). We also include an extrapolation to 500 Mpc, assuming self similarity with  $\alpha = 0.5$  (dashed line) or  $\alpha = 0.8$  (dotted line). The assumed UHECR energy for all lines is  $4.0 \times 10^{19} \text{ eV}$ .

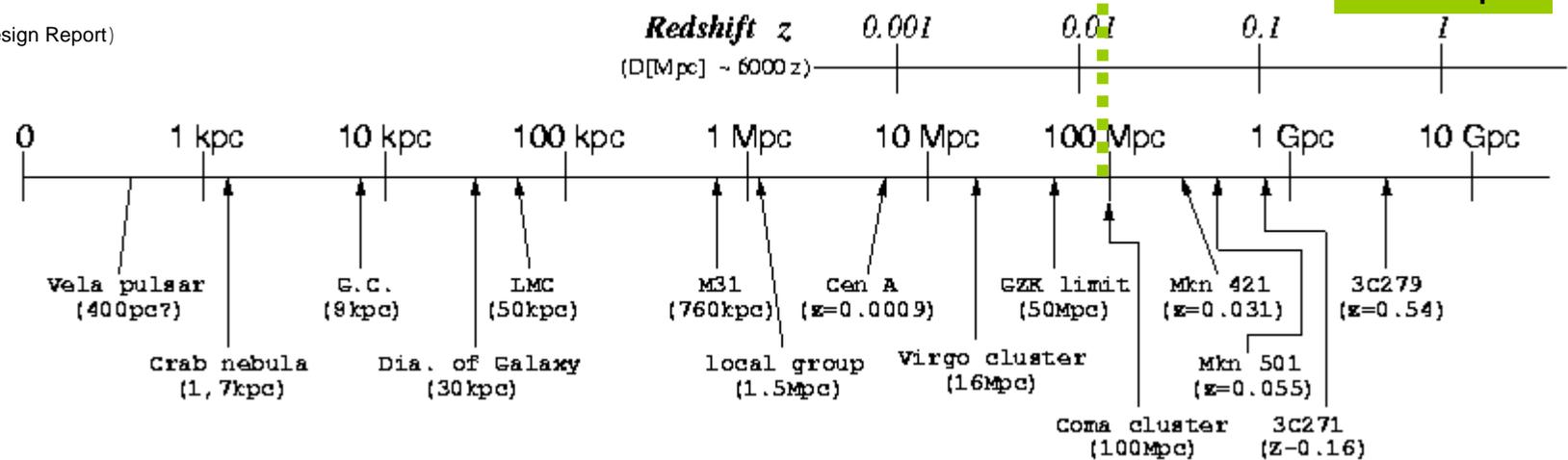
FIG. 1: Full sky map (area preserving projection) of deflection angles for UHECRs with energy  $4 \times 10^{19} \text{ eV}$  using a linear color scale. All structure within a radius of 107 Mpc around the position of the Galaxy was used. The coordinate system is galactic, with the galactic anti-center in the middle of the map. Positions of identified clusters are marked using the locations of the corresponding halos in the simulation.

# GZK cut off

高エネルギー粒子ほど、近くから (CMB  $\sim 6 \times 10^{-4} \text{ eV}$  と反応)



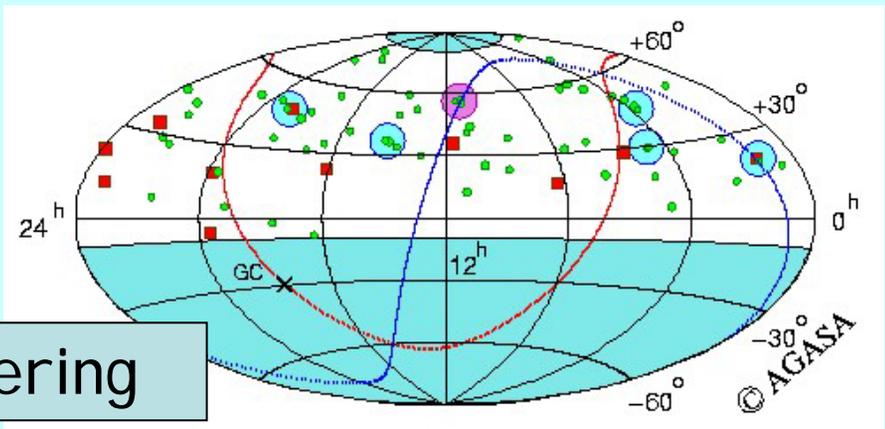
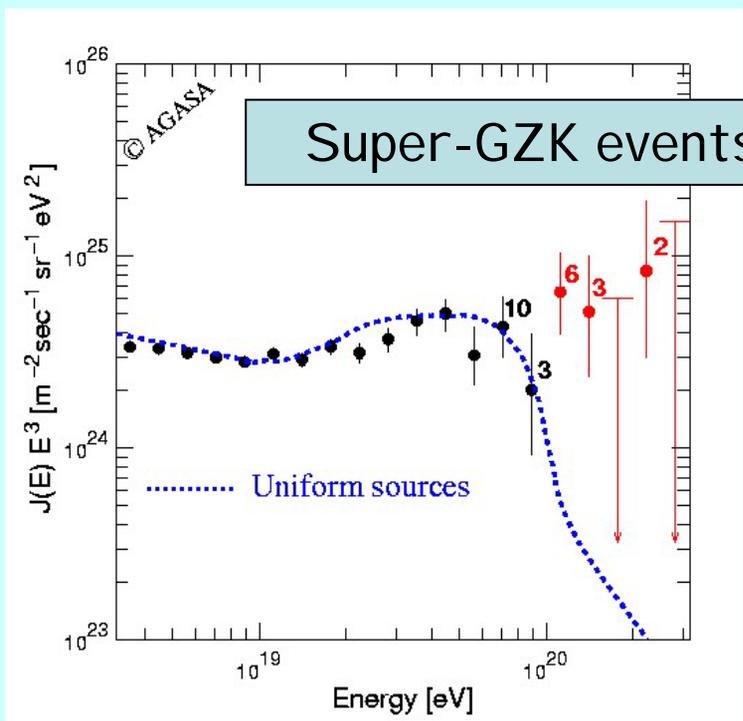
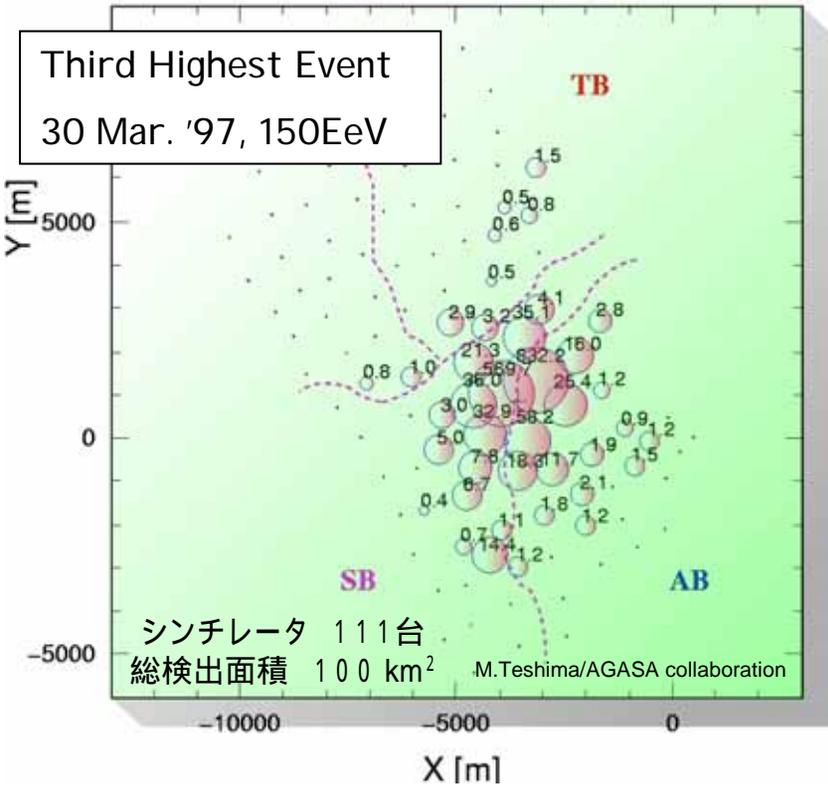
(Auger Design Report)



# AGASA (Akeno Giant Air Shower Array)

(山梨県北杜市明野, ~2004年)

Third Highest Event  
30 Mar. '97, 150EeV

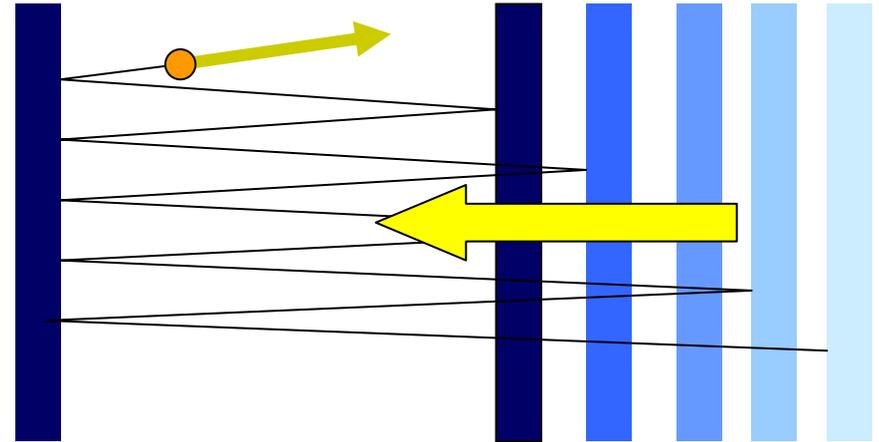
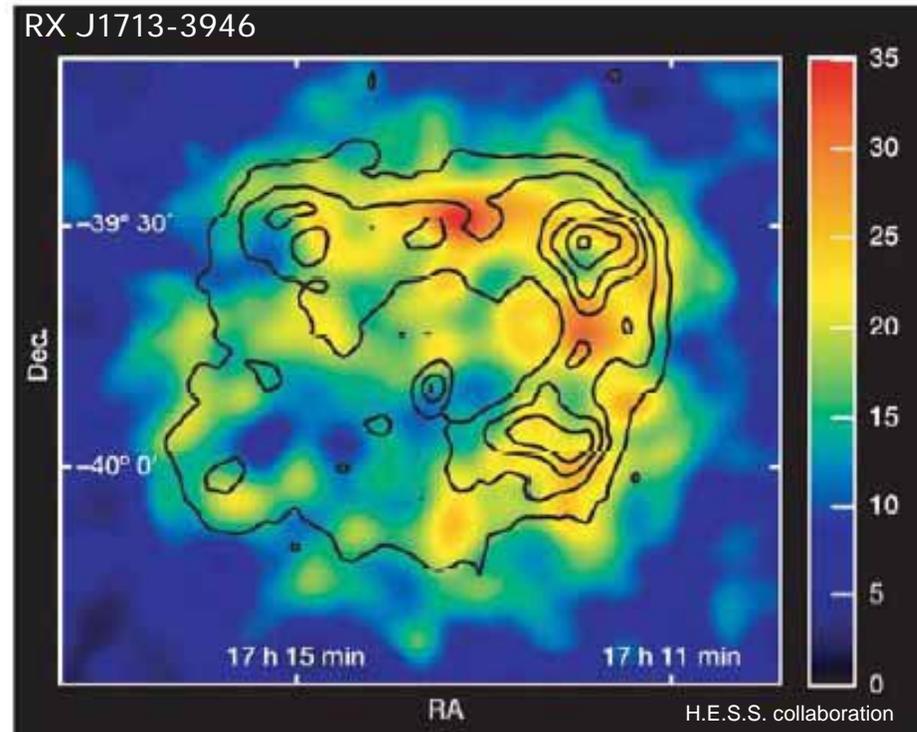


# Origin of UHECRs?

**Astrophysical? or Cosmological?**

**Super-GZK?**

# Astrophysical Origin: フェルミ加速 (衝撃波加速)



衝撃波の前後での磁場が2枚の「板」の役割をする。

$$\Delta E = \xi E, \quad \frac{dE}{dt} = \frac{\xi E}{T_{\text{cycle}}}$$

$$N(> E) \propto \frac{1}{P_{\text{esc}}} \left( \frac{E}{E_0} \right)^{-\gamma}, \quad \gamma \approx \frac{P_{\text{esc}}}{\xi}$$

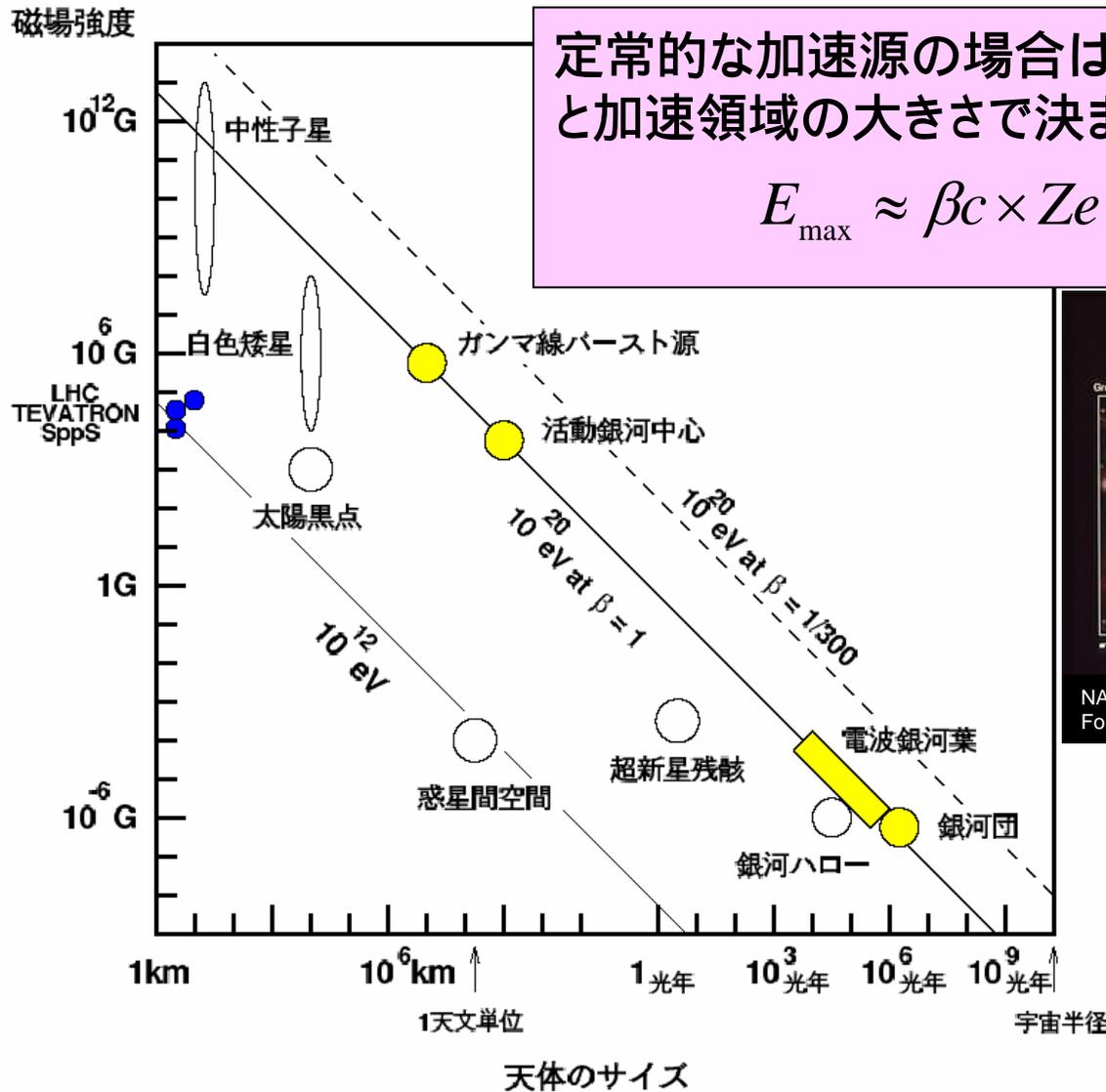
$T_{\text{cycle}}$ : 加速の1サイクル

$P_{\text{esc}}$ : 加速領域から抜け出す確率

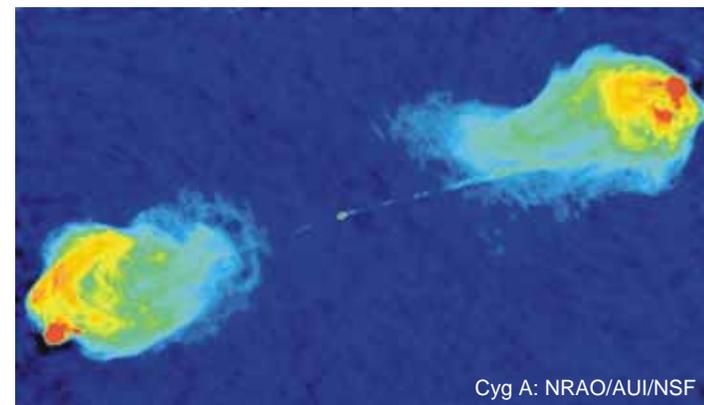
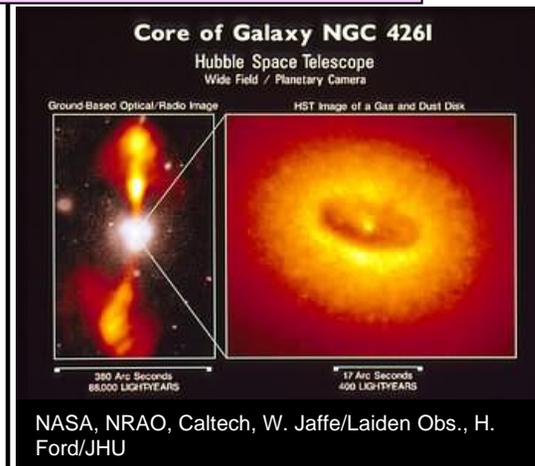
$E_0$ : 初期エネルギー

$\sim 1$  で フラックス  $F \propto E^{-(\gamma+1)} \sim E^{-2}$   $\longleftrightarrow$  観測  $F \propto E^{-3}$

# 加速天体の大きさと磁場の関係： Hillas ダイアグラム



定常的な加速源の場合は、磁場の強さと加速領域の大きさで決まる。

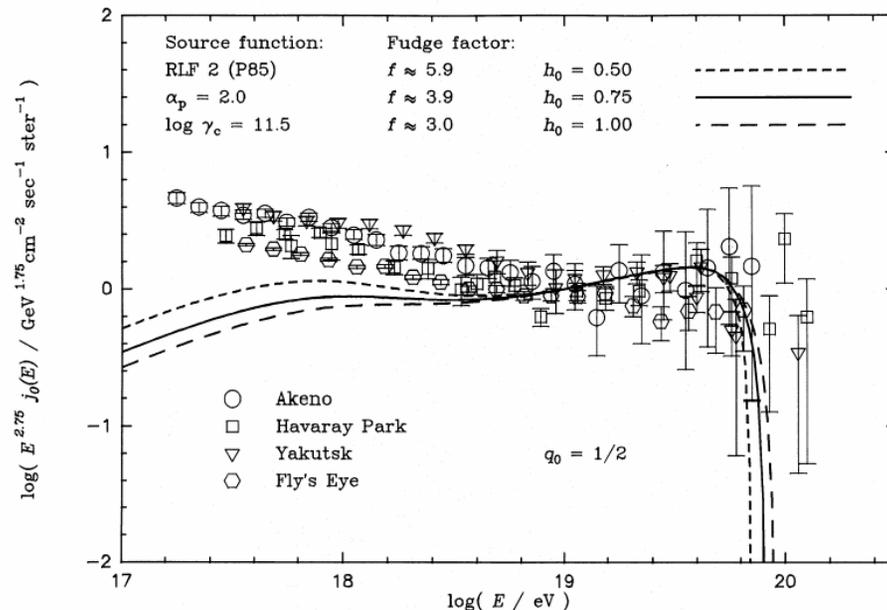
$$E_{\max} \approx \beta c \times Ze \times B \times L$$


# AGN/Galaxies

## AGNモデルの基礎( ? )

(J. P. Rachen and P. L. Biermann, 1993)

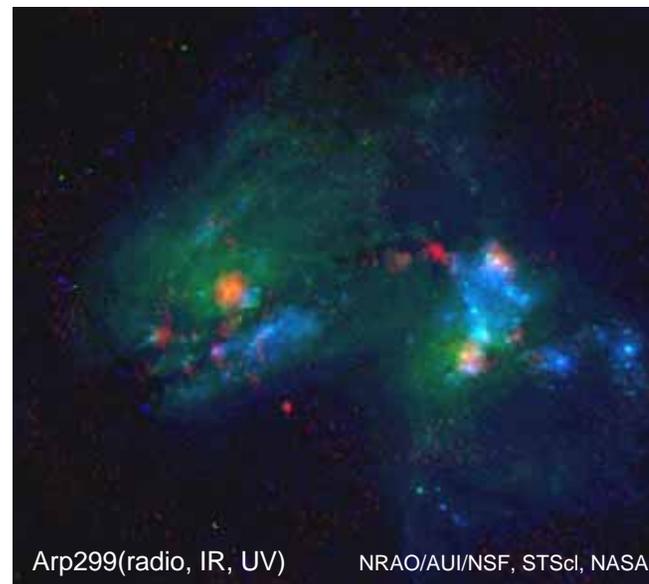
- ✓GZK cutoffは必ず現れる。  
80 EeVくらい。
- ✓近傍のソースの数は限られるので異  
方性が現れるだろう。
- ✓High Energy Endで組成が重くなる。



## Luminous Infrared Galaxiesとの相関

(A. Smialkowski, M. Giller and W. Michalak, 2001)

- ✓AGASAのtripletとArp299(colliding galaxy pair, 70Mpc以内では最も明るい赤外線源)の  
よい位置相関。
- ✓80 EeV以上のイベントについては、等方的で  
あるとする仮説、Luminous Infrared Galaxies  
からの放射であるとする仮説、, どちらとも矛盾。



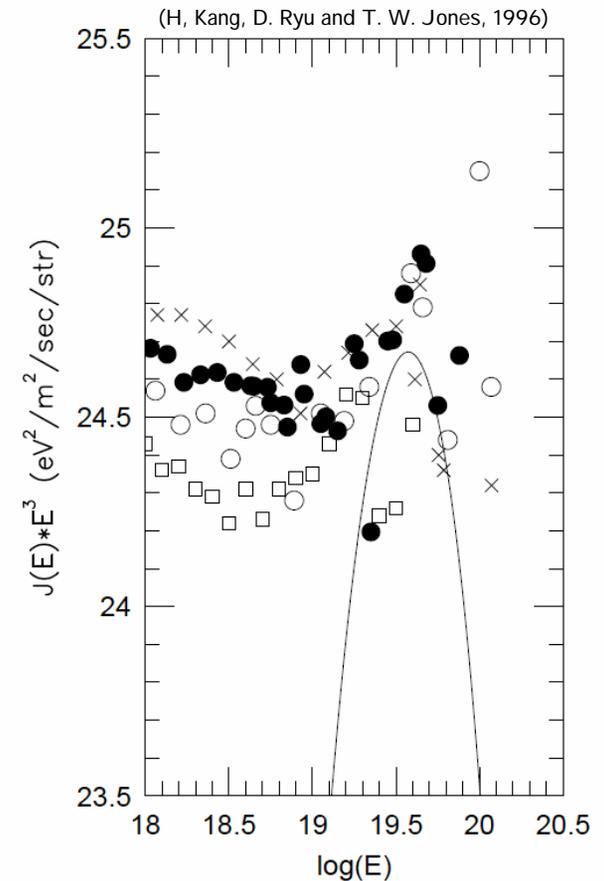
# Cluster of galaxies

Cluster accretion shock (H, Kang, D. Ryu and T. W. Jones, 1996)

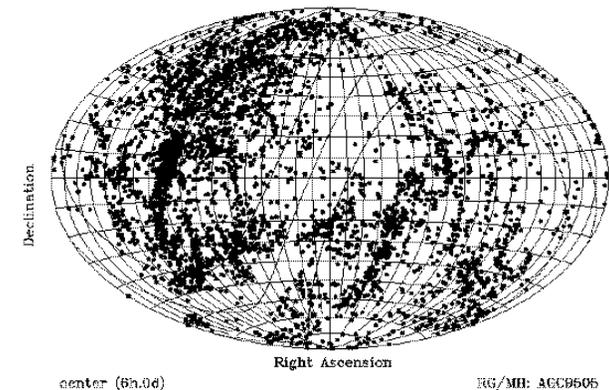
- ✓ typical velocity  $\sim 1000\text{-}3000$  km/s, radius  $\sim 5$  Mpc
- ✓ 磁場  $\sim 1 \mu\text{G}$
- ✓  $E_{\text{max}} \sim 6 \times 10^{19}$  eV (for protons)

Local Super Cluster中での伝播 (P. Blasi and A. V. Olinto)

- ✓  $10^{19}$  eV以下の宇宙線は拡散的に伝播する.
- ✓  $10^{20}$  eV以上ではほぼ直進する.
- ✓ 10-15 Mpc以内に少なくとも1つのsource.
- ✓ North-South asymmetryがあるはず. 北側が優勢
- ✓ 点源は見えなくてもよい(いままでの観測では).
- ✓ 強い磁場( $10^{-8}\text{-}10^{-7}\text{G}$ )を仮定.

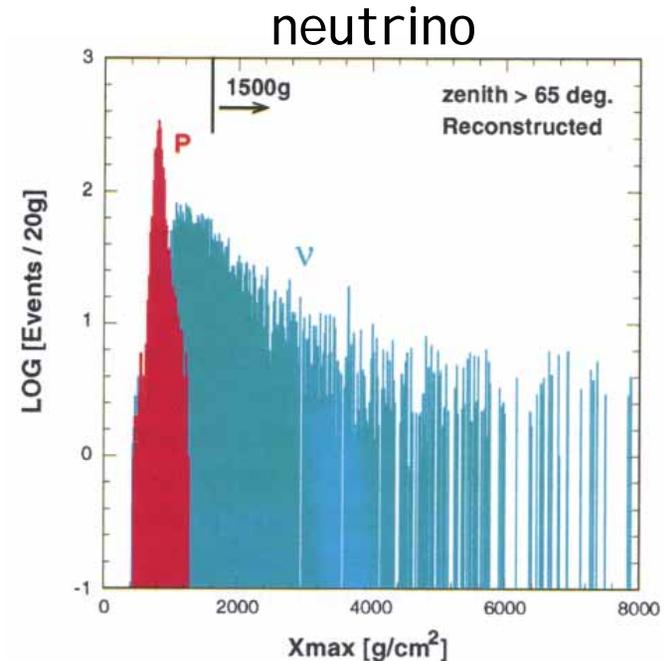
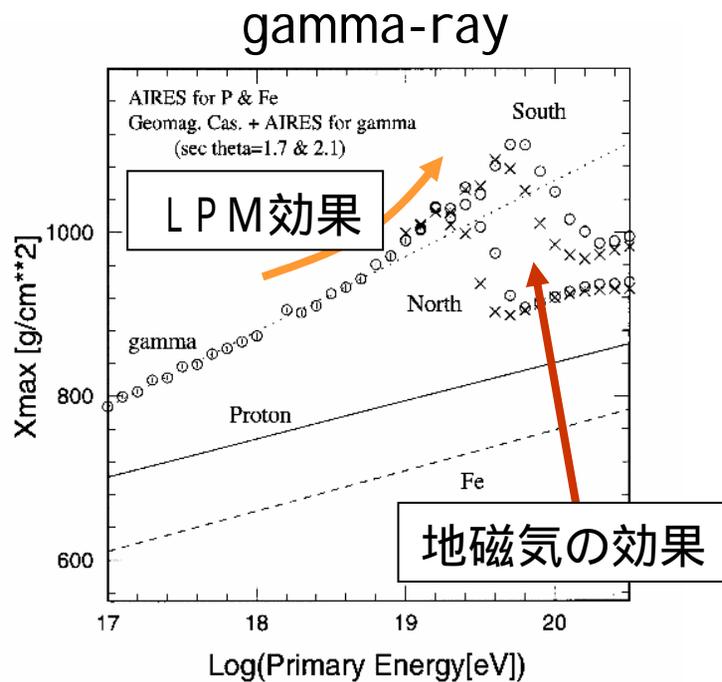


V: -500,3000



# Cosmological Origin

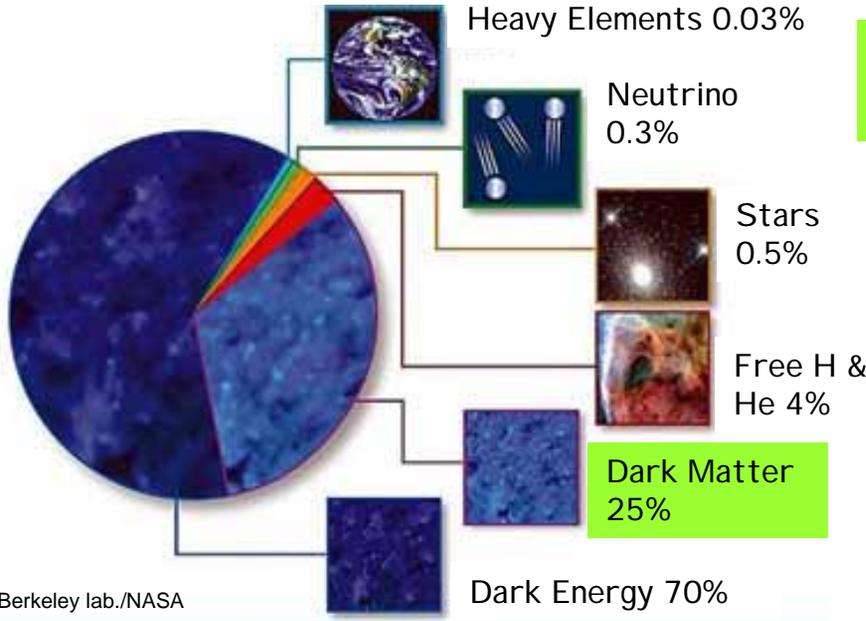
→ primary particles ~ gamma-ray, neutrino



## Z-burst model

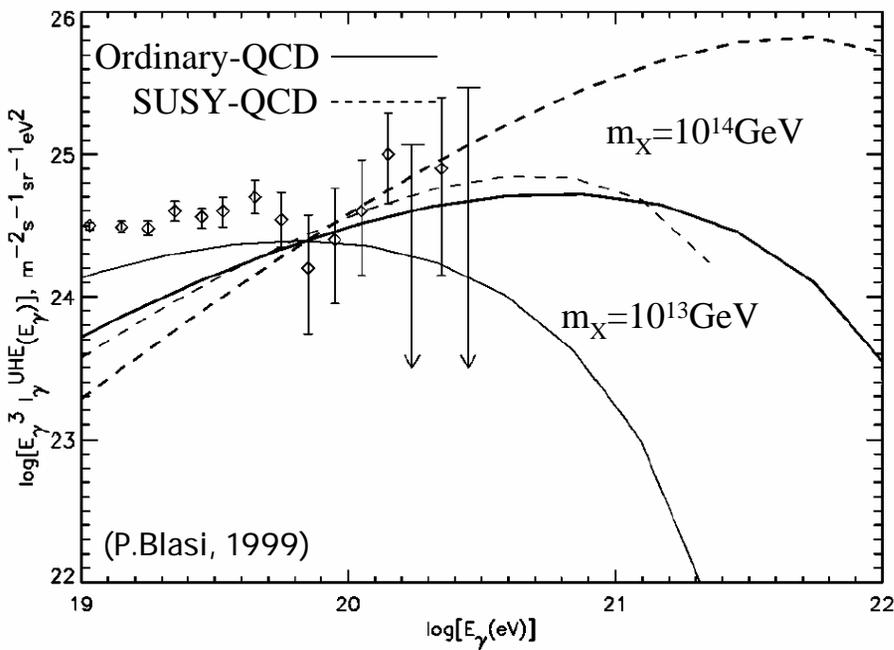
- ✓ UHE- と Clustering- ( $m = 0.3\text{eV}$ で平均より10倍高密度)
- ✓ Virgo, Perseus-Pisces, Hydra, Centaurus, Coma に集中( $m > 0.3\text{eV}$ )
- ✓ GeV gammaとの相関を見る必要あり

# Cosmological: Super Heavy Relic Particles



## X UHECRs

- ✓  $M_X \sim 10^{13} - 10^{14}$  GeV
- ✓ Galactic halo
- ✓ Dipole型の異方性 (太陽系 - 銀河中心)  
(P.Blasi and R.K.Sheth, 2000)
- ✓ Gamma rayが主成分 (factor  $\sim 7$ )
- ✓ Virgo cluster方向にexcess ( $\sim 6 \times 10^{-3}$ )  
(V.Berezinsky, M.Kachelreiss and A.Vilenkin, 1997)



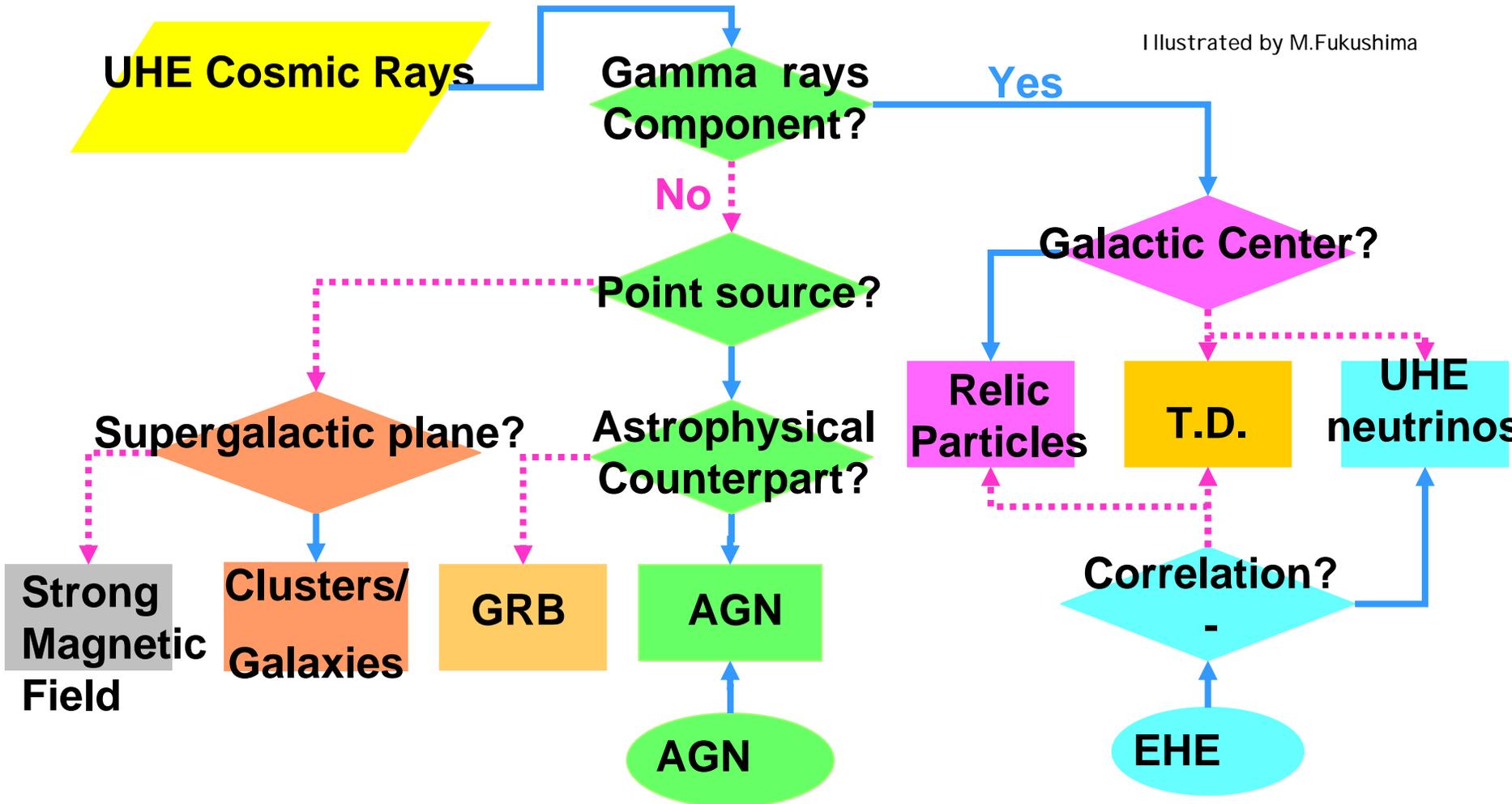
- ✓ Multiple UHECR events from SHR decay  
(Parizot, 2003)

$$\tau_2 \approx (2.1 \text{ yr}) \times \left( \frac{S_d}{3000 \text{ km}^2} \right)^{-\frac{3}{2}} \left( \frac{\delta}{100\%} \right)^{-1} \times \left( \frac{E_{th}}{10^{19} \text{ eV}} \right)^{\frac{3}{2}} \left( \frac{M_x}{10^{25} \text{ eV}} \right)^{-\frac{1}{2}}$$

$$\approx 0.48 \text{ yr (EUSO, } \theta_{jet} \approx 2 \times 10^{-11} \text{)}$$

# Source/Mechanism Identification

Illustrated by M.Fukushima

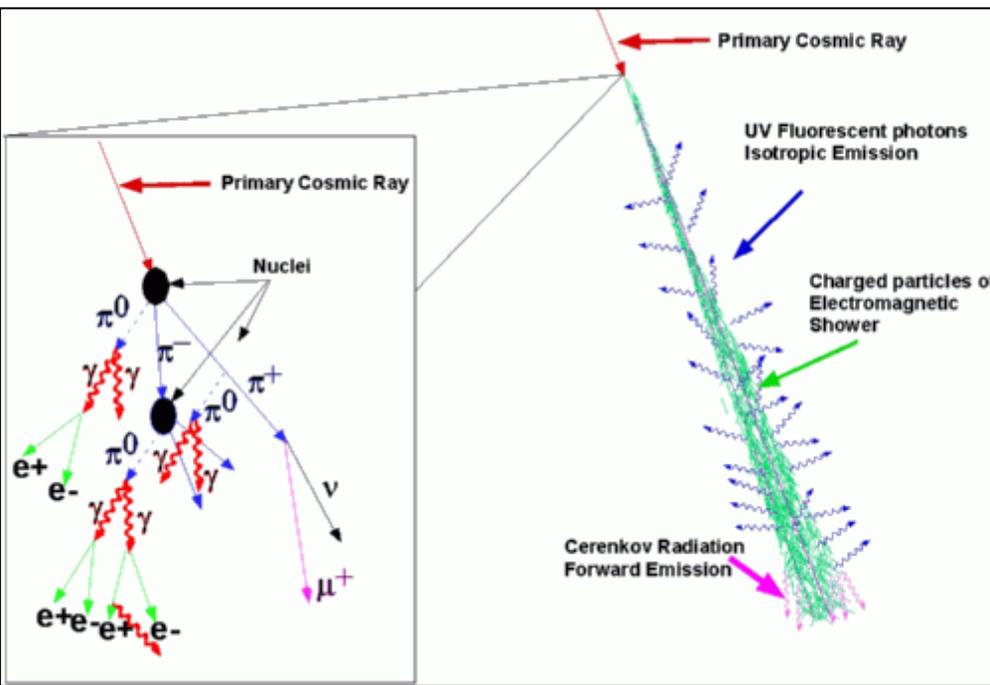
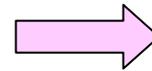


- high statistics    ➡ large exposure
- angular/energy resolution    ➡ HYBRID
- particle identification    ➡ shower development measurement

# 宇宙線觀測 / 宇宙線望遠鏡計畫

# 空気シャワー観測

エネルギー  
粒子種同定

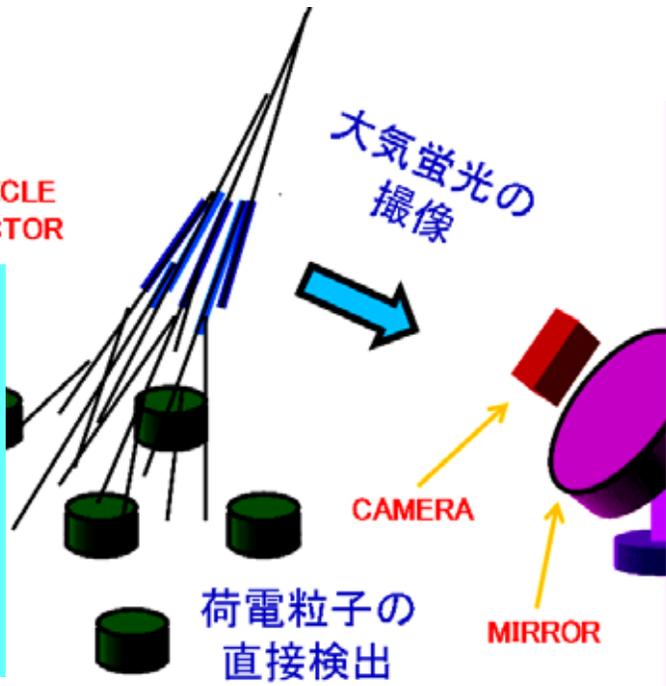


統計精度  
点源探索

**地表検出器法**

- 粒子数の横方向分布
- 地表での総粒子数
- 粒子種によるエネルギー推定の系統誤差

PARTICLE DETECTOR



## 大気蛍光法

- 縦方向発達
- カロリメトリックなエネルギー推定
- ステレオ観測による幾何学的な到来方向の推定
- 蛍光の散乱、量子効率、反射率などの補正

# 宇宙線望遠鏡実験：観測装置

## 地表検出器 (SD)

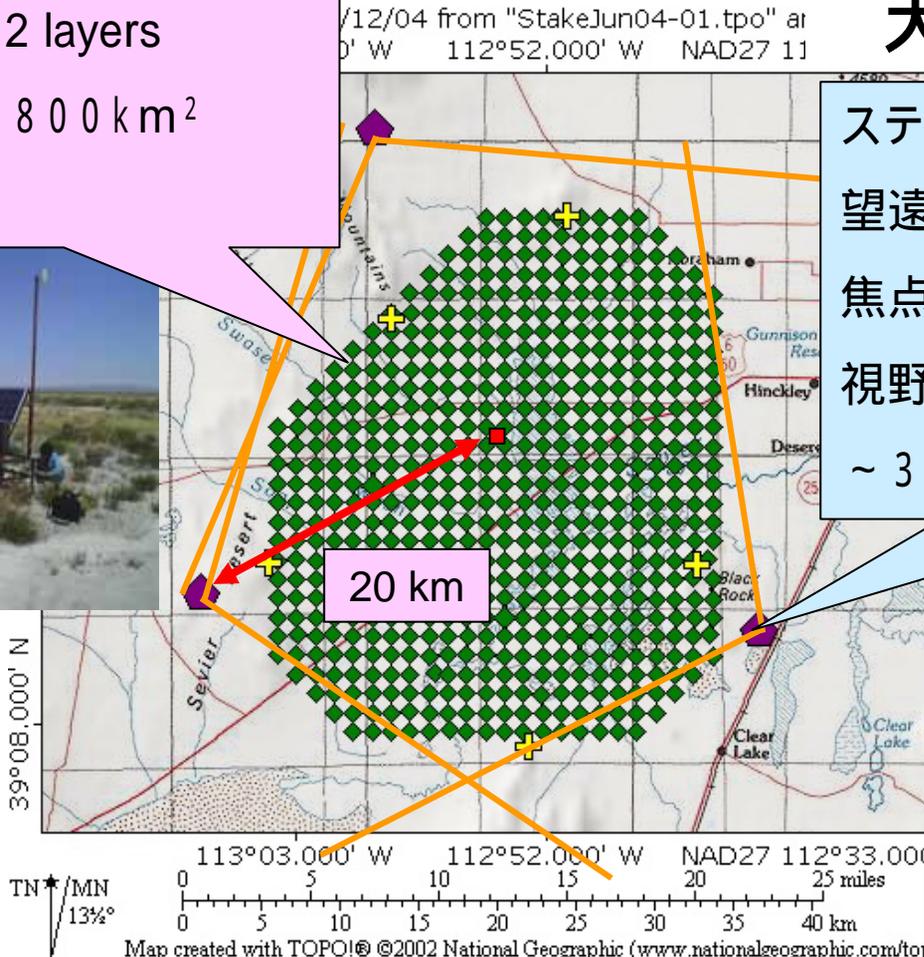
シンチレーション検出器 576台  
 3 m<sup>2</sup> x 1.2cm x 2 layers  
 1.2 km 間隔, 800 km<sup>2</sup>  
 E > 10<sup>19</sup> eV



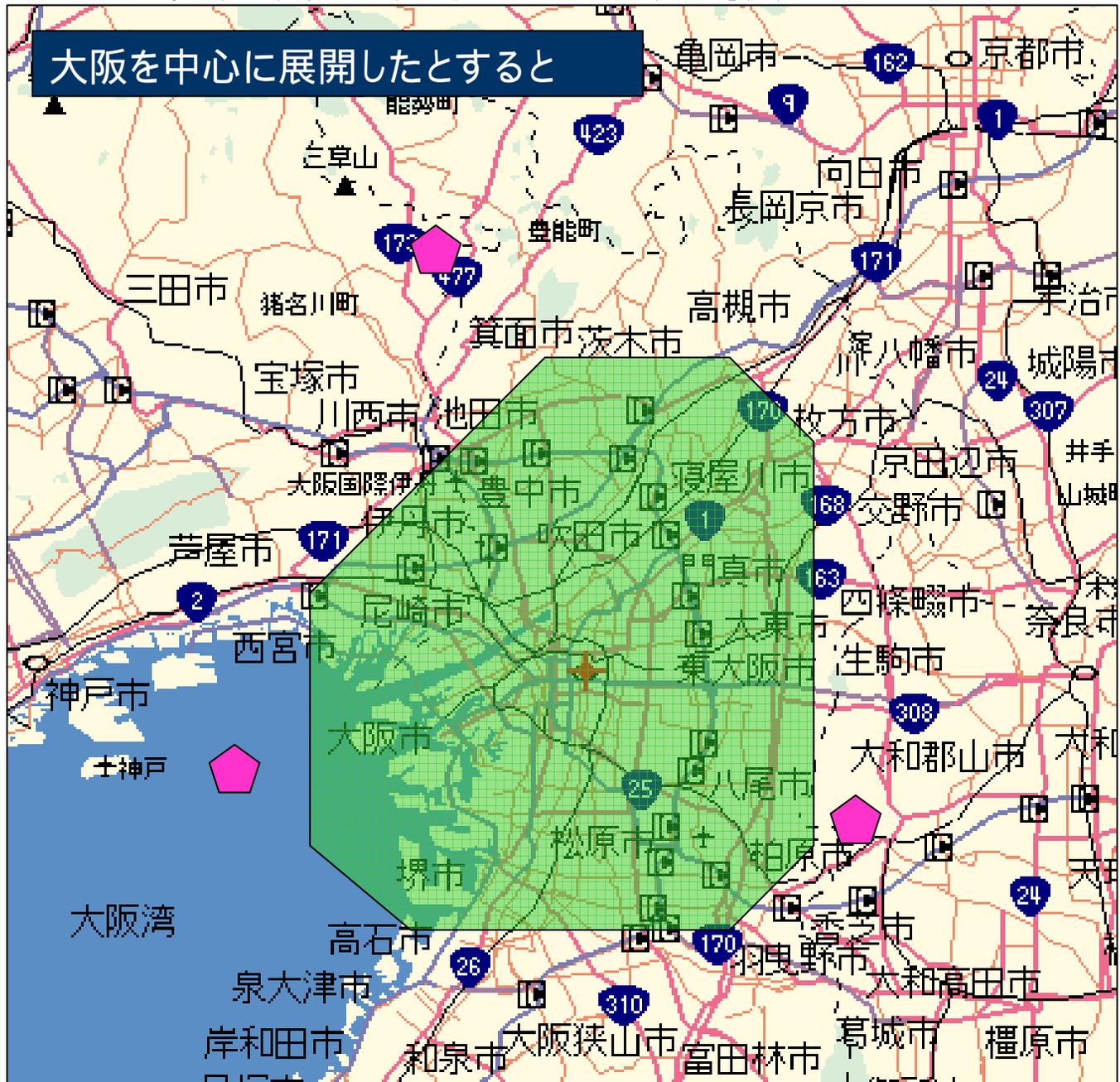
ユタ州・ミラード郡(北緯39.1°, 西経122.9°)  
 海拔1400 m

## 大気蛍光望遠鏡 (FD)

ステーション: 3ヶ所  
 望遠鏡: 12台 / ステーション,  
 焦点距離: 3.3 m  
 視野: 3° 33' x 108°  
 ~ 35 km 間隔

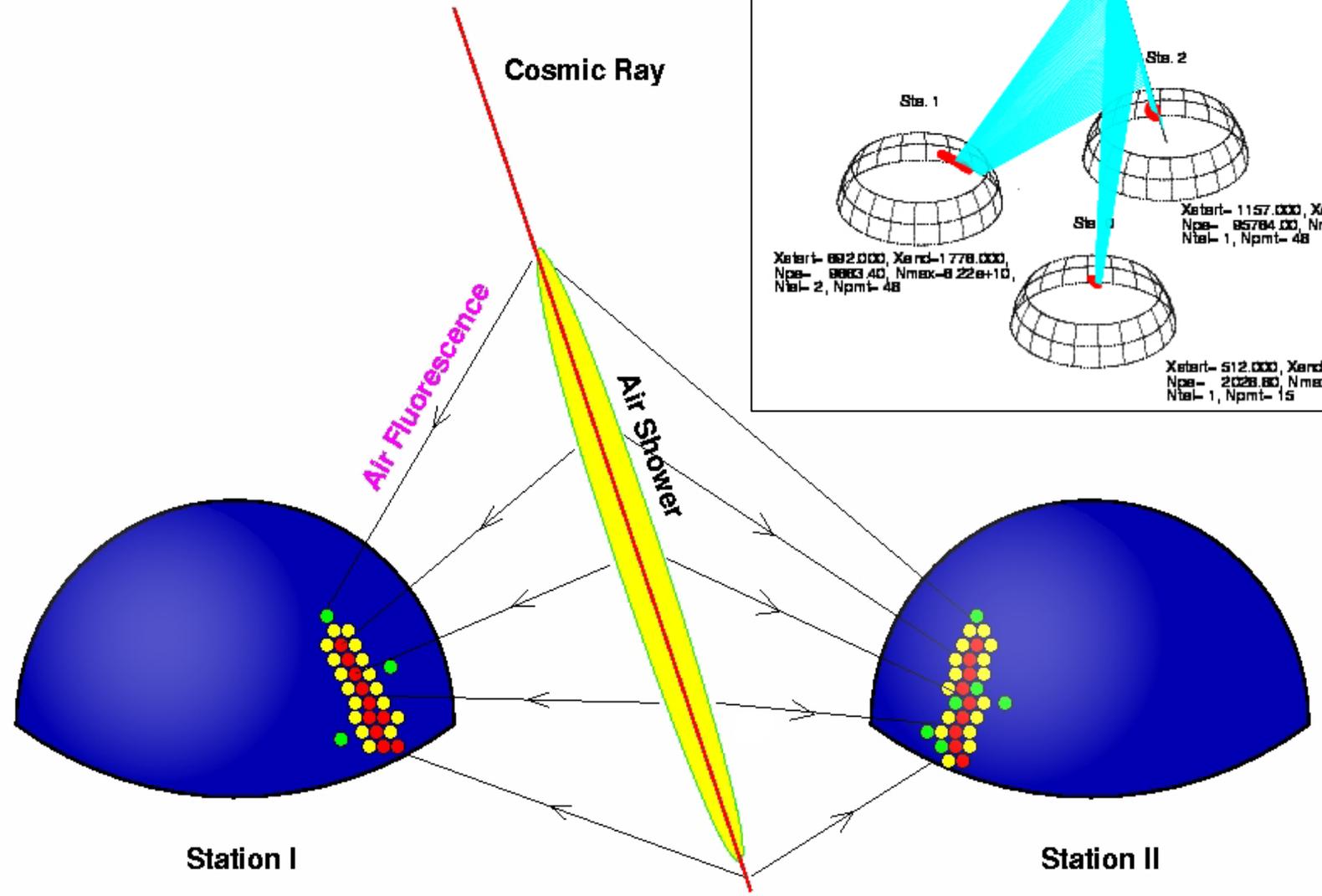
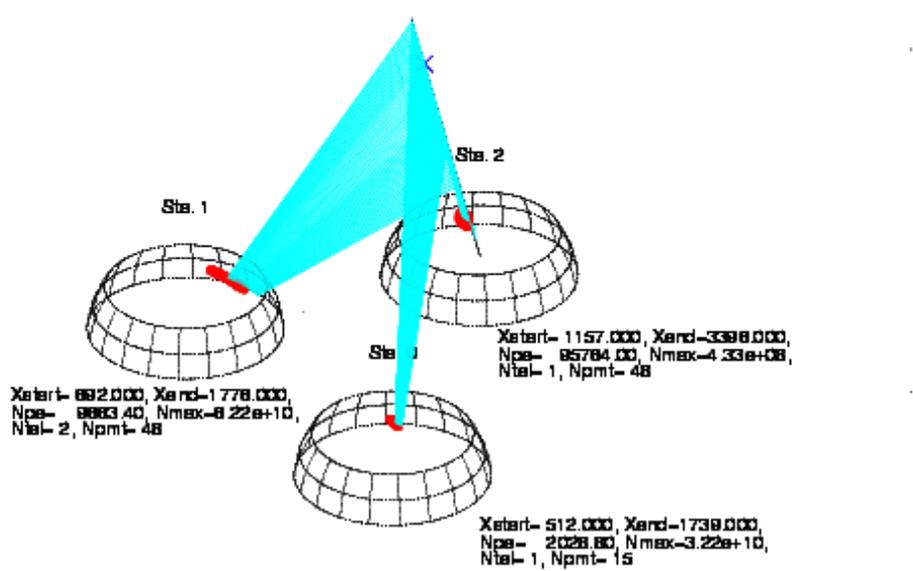


# 宇宙線望遠鏡実験：大きさの比較

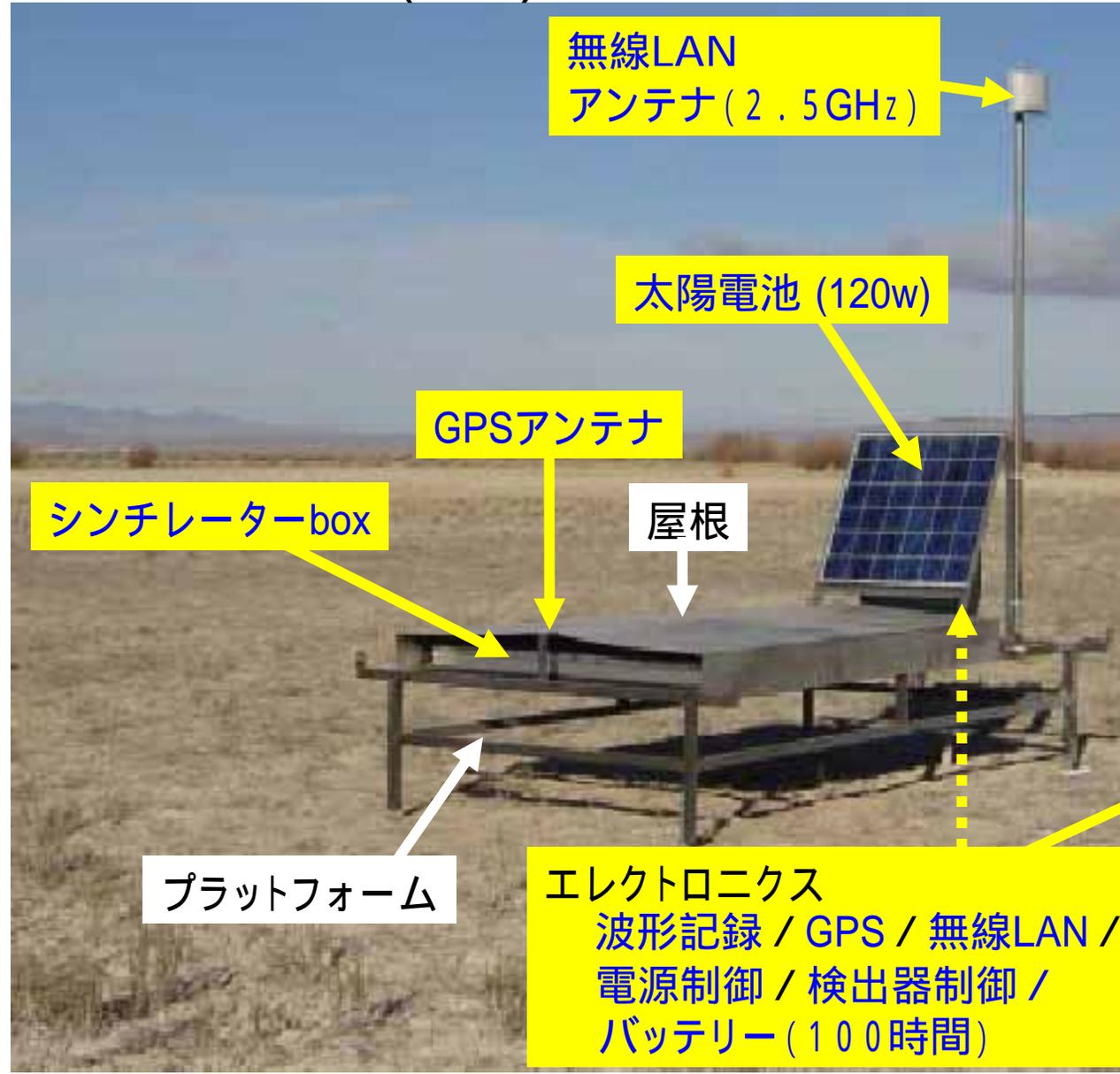


# 宇宙線望遠鏡実験：大気蛍光をステレオ観測する

event= 88, trial= 74,  $\theta_{\text{min}}= 413.360, \theta_{\text{org}}= 8.430$   
 $\log E= 20.000, X1= 16.278, X_{\text{max}}= 81.2278, (\theta, \alpha)= (70.7, 268.8), (x, y)= (-18280.89, 30881.88)$   
 $\log E= 17.807, X1= 1.207, X_{\text{max}}= 1833.885, (\theta, \alpha)= (77.1, 268.3), (x, y)= (-8417.08, 23838.71)$



# 地表検出器(SD)



**検出器box**  
ステンレス  
230x170x10(cm<sup>3</sup>)  
1.5 mm thick

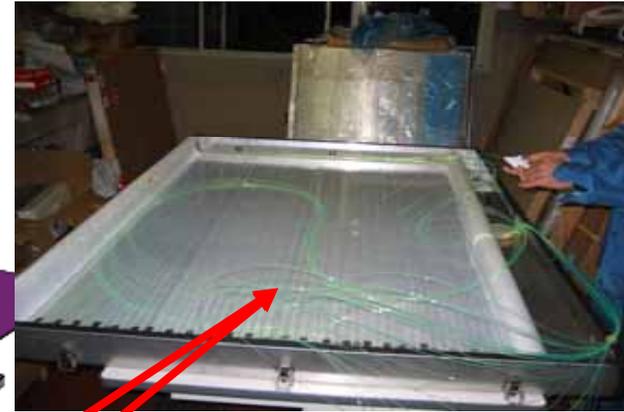
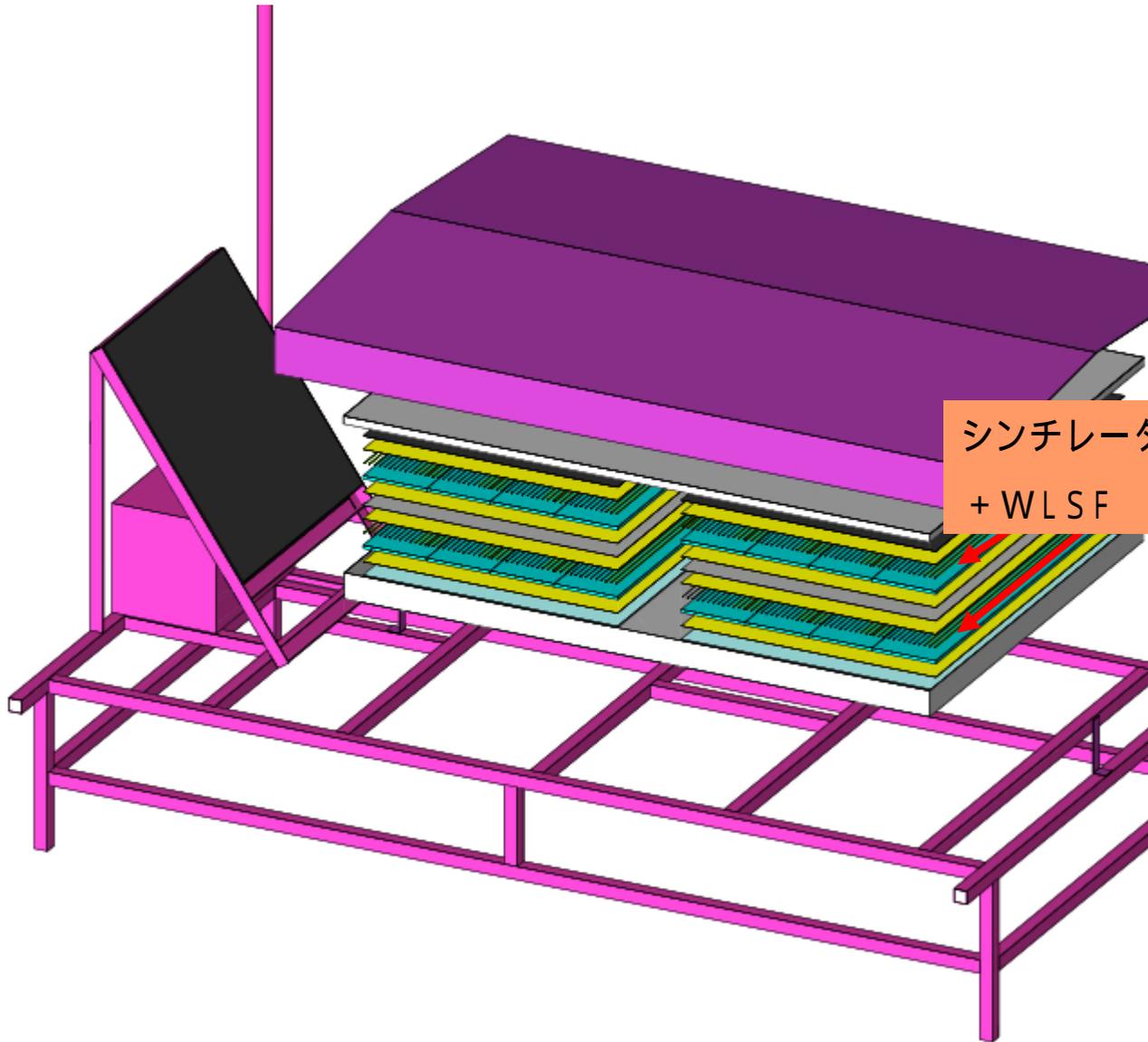
**信号出力**  
光電子増倍管 2本  
(Electrontubes 9124SA)

**総重量** ~ 190 kg

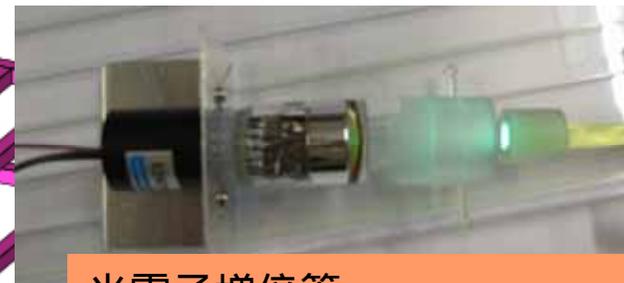


エレクトロニクス  
波形記録 / GPS / 無線LAN /  
電源制御 / 検出器制御 /  
バッテリー (100時間)

# S D の内部構造



シンチレーター  $1.5 \times 1.0 \text{ m}^2 \times 1.2 \text{ cm} \times 4$   
+ WLSF

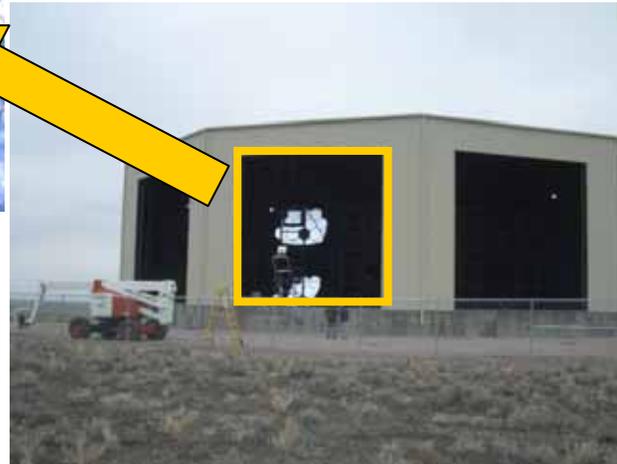
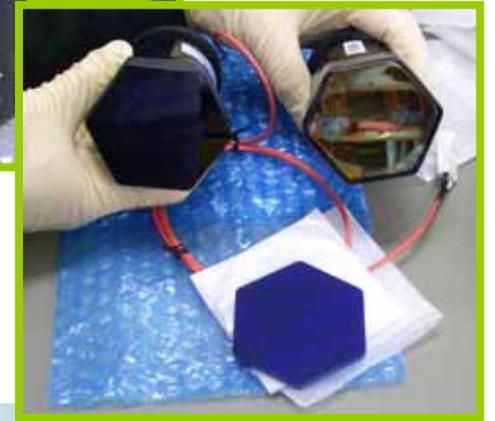
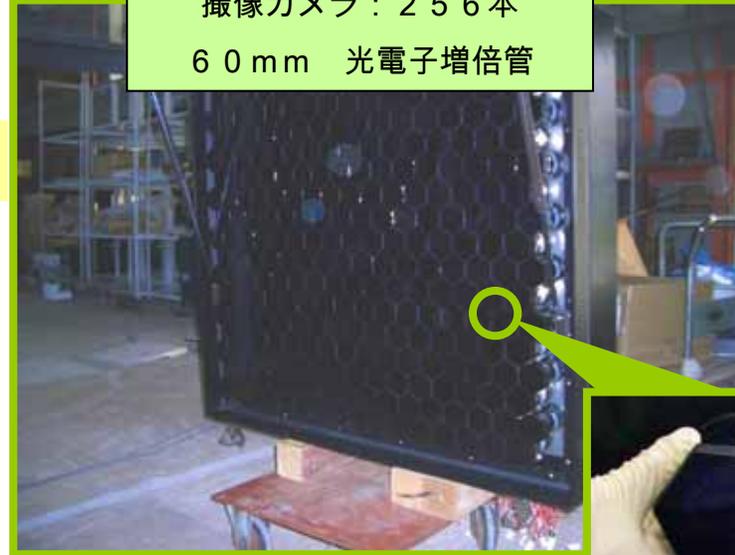
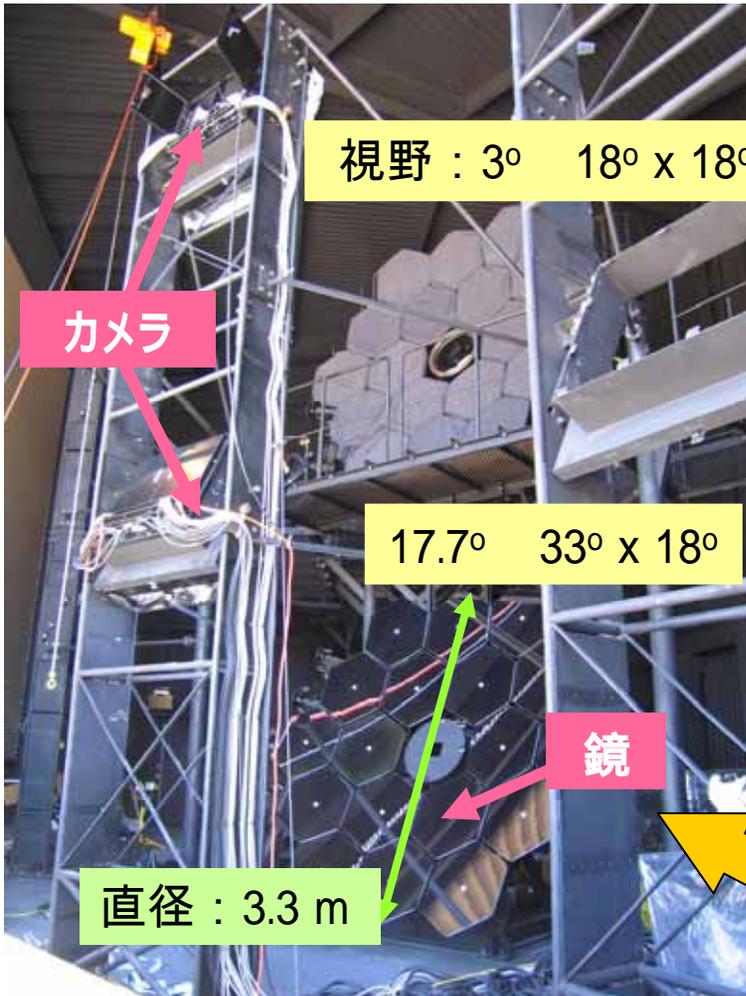


光電子増倍管  
(ETL9124A, 9 / 8インチ)

# S Dの製作と設置(写真)



# 大気蛍光望遠鏡 (FD): 望遠鏡

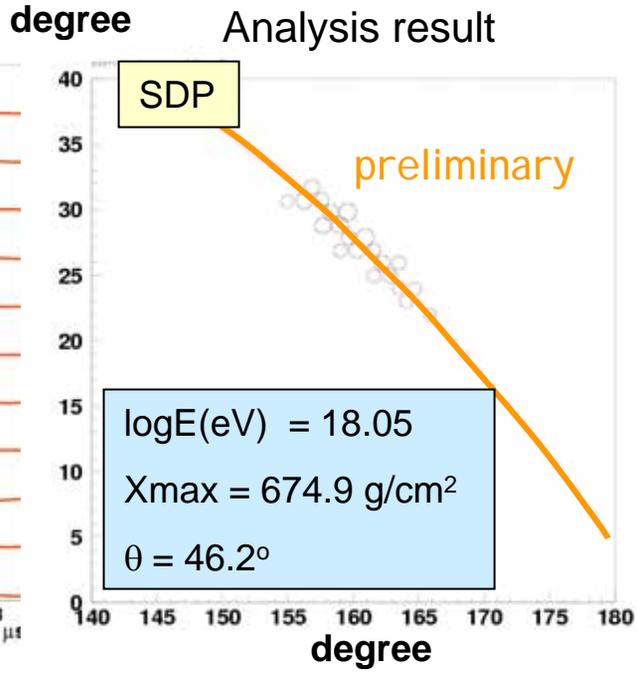
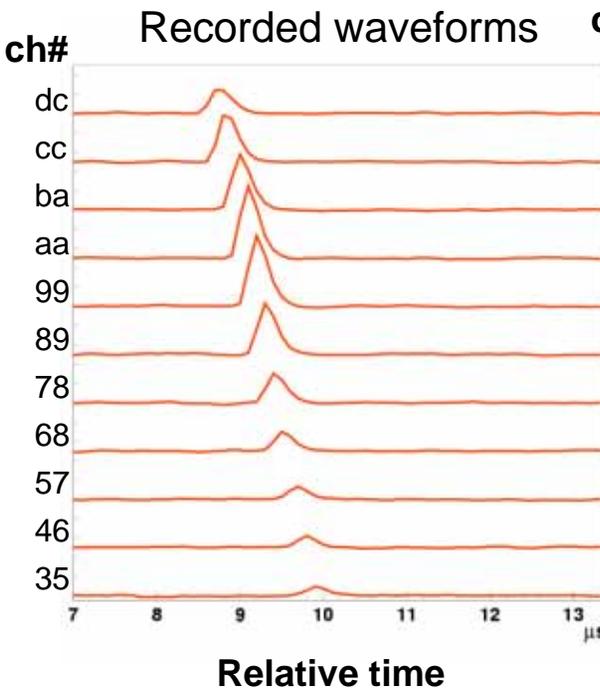
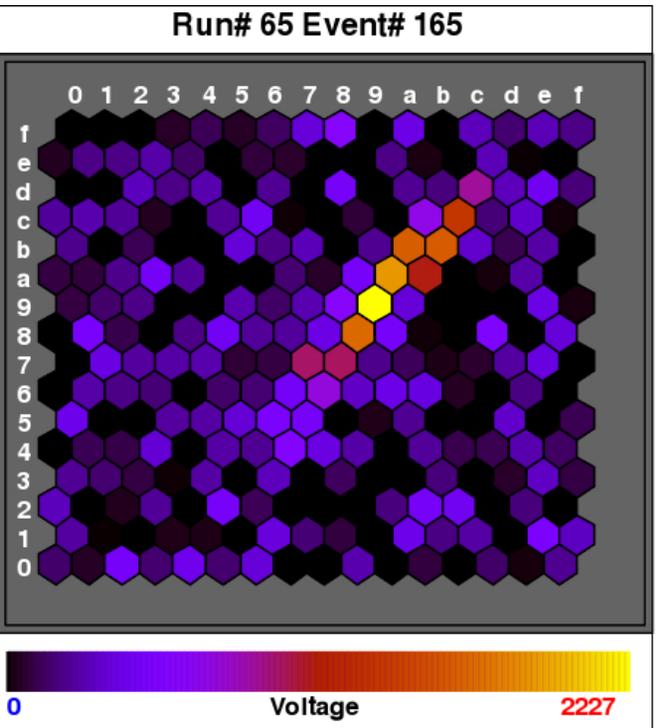
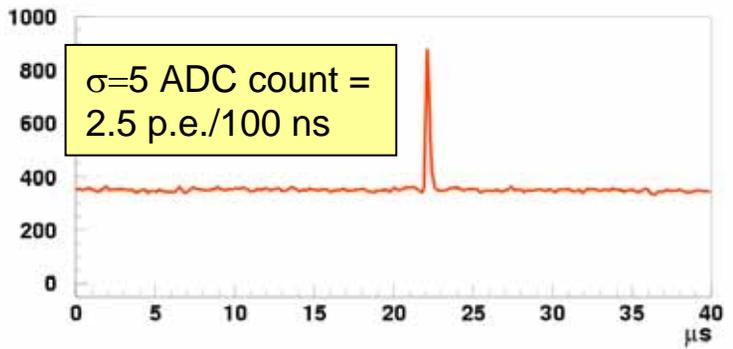


# テスト観測@ Millard county, Utah

- ◆ 3-13 July, 2005 @ Black Rock Mesa site
- ◆ Single telescope with 256ch PMTs camera
- ◆ Total observation time: 31.5 hours
- ◆ 1<sup>st</sup> level trigger threshold: 6 - 6.5 sigma
- ◆ Trigger rate: 0.6 - 1.5 Hz

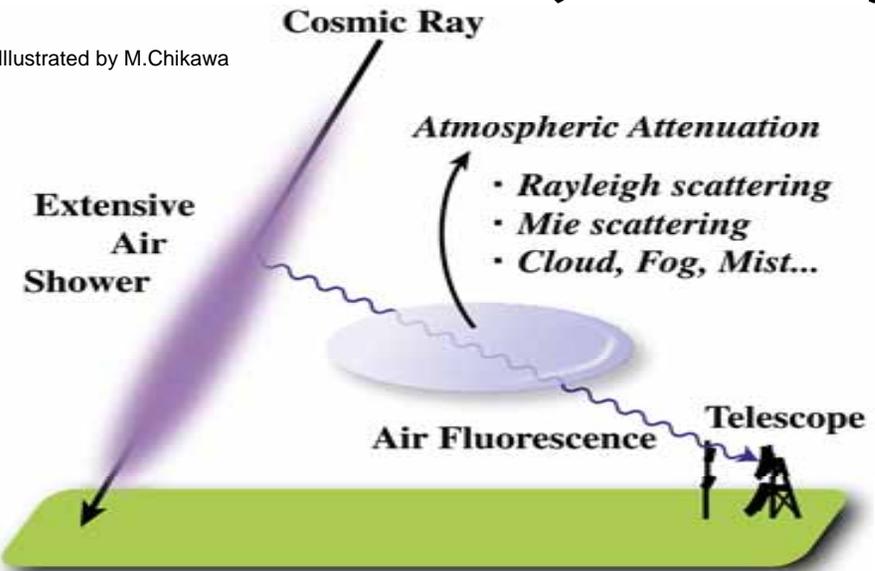
An observed shower-like track (11 July, 2005)

Typical waveform with fluorescence light  
(RUN65, TRIG165, CH89)



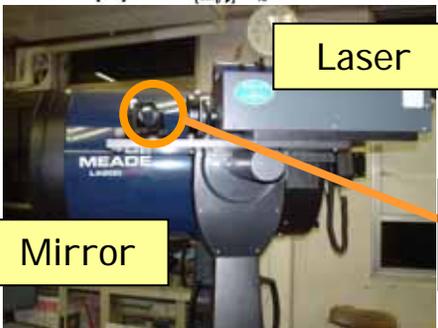
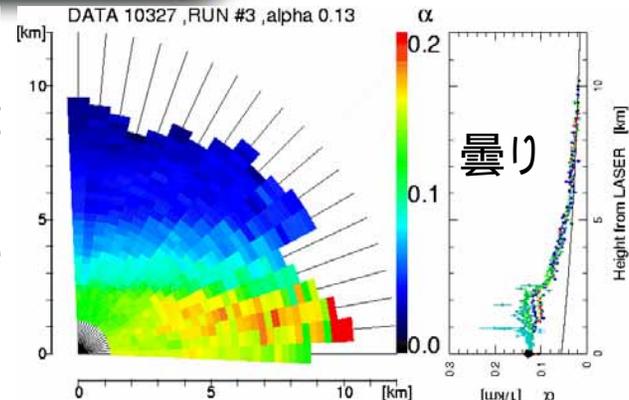
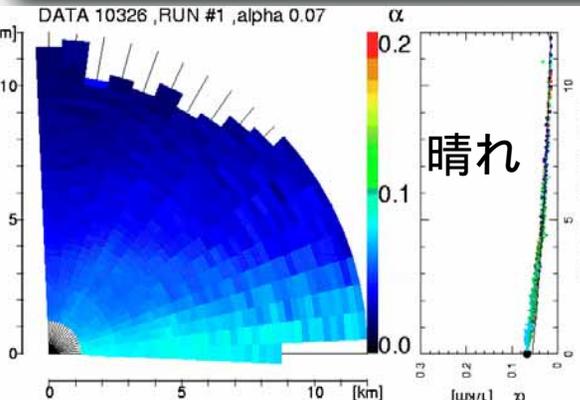
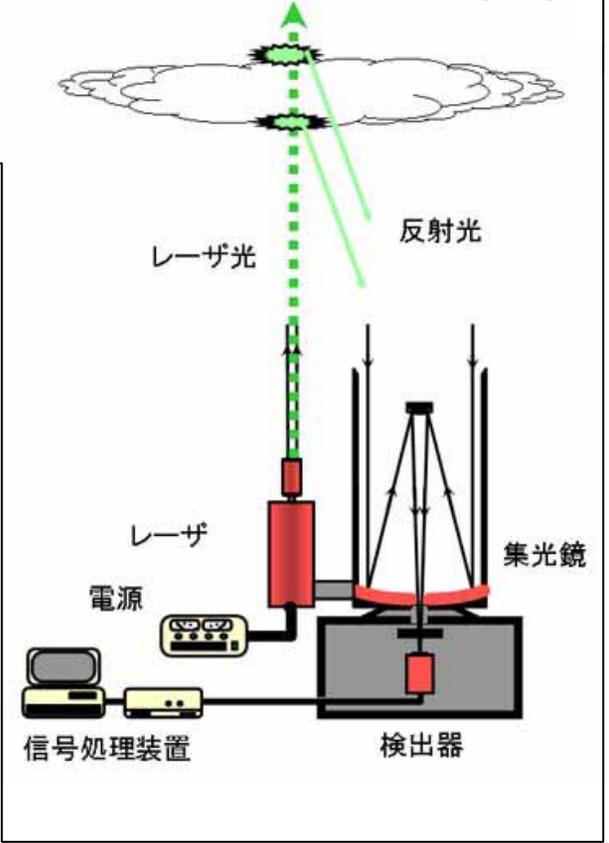
# 大気モニター (LIDAR)

Illustrated by M.Chikawa



## ライダーの概念図

(LIDAR: Light Detection And Ranging)



Laser

Mirror

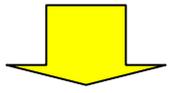
Beam splitter / Energy meter

# Linac calibration

Geant4を用いた40MeV電子ビームSim.

E	光子数(大気蛍光)	~ 10%
	大気透明度の補正	~ 10%
	光子数 ADC数	~ 10%

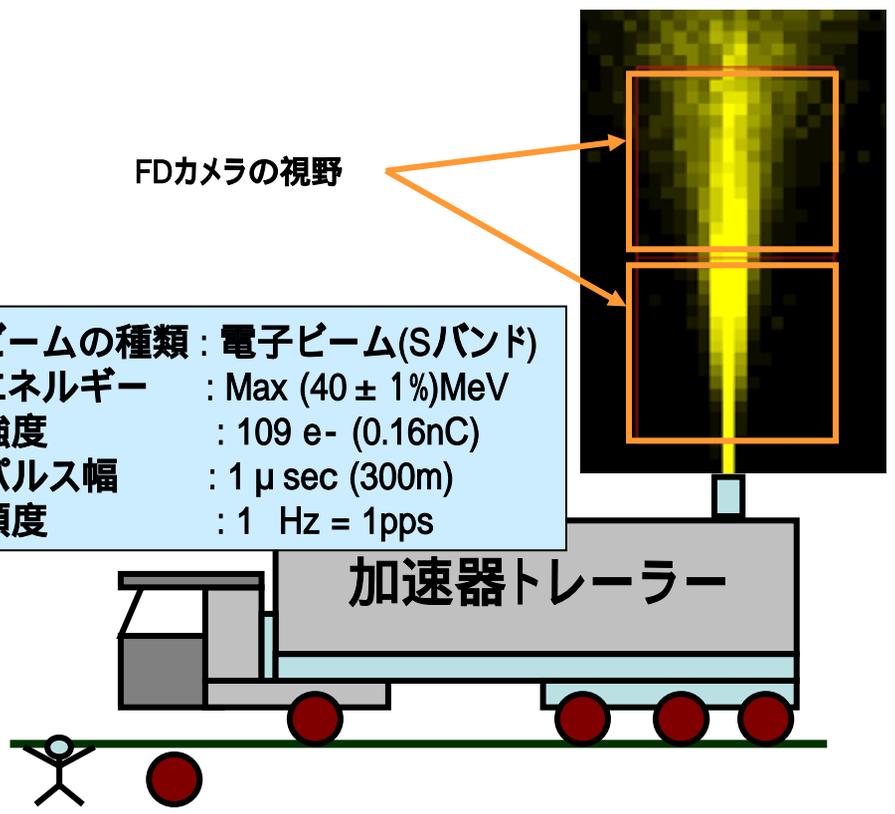
これらを一括して校正する



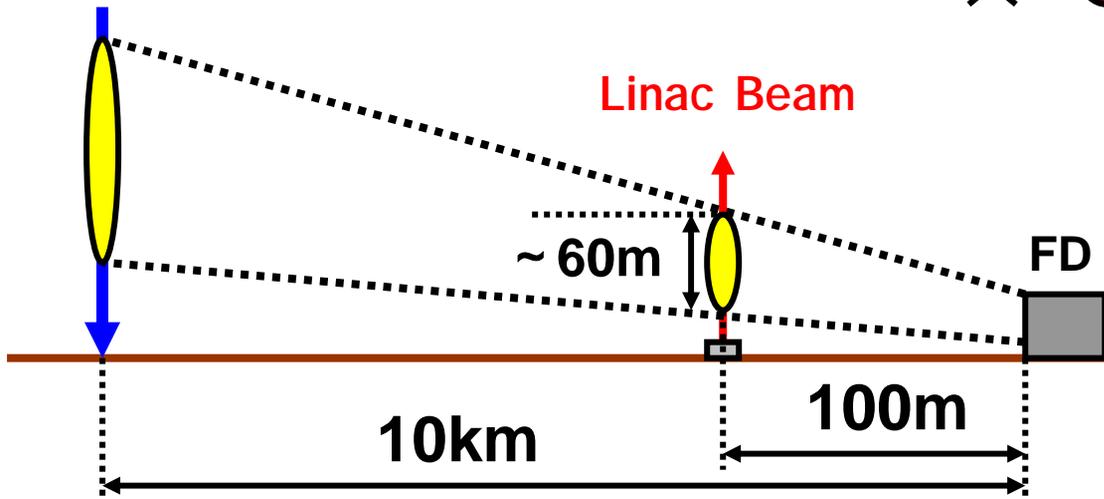
加速器を用いたエネルギー校正

エネルギー分解能 20% → 14%

ビームの種類	: 電子ビーム(Sバンド)
エネルギー	: Max (40 ± 1%)MeV
強度	: 109 e- (0.16nC)
パルス幅	: 1 μ sec (300m)
頻度	: 1 Hz = 1pps



Air shower



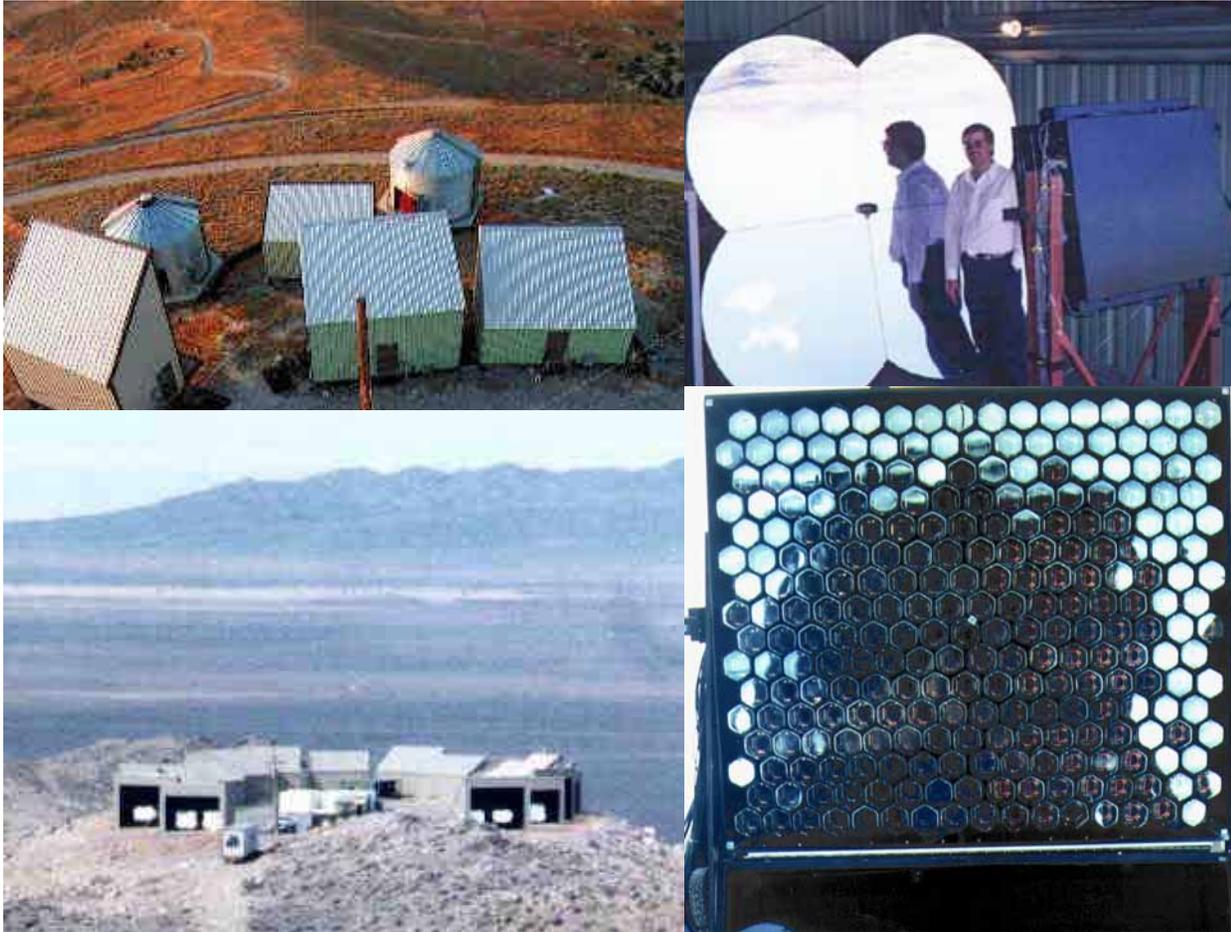
2つのカメラ視野に収まる

100m先: 40MeV × 10<sup>9</sup> ~ 10<sup>16</sup>eV

10km先: ~ 10<sup>20</sup>eVに相当

# 他の観測グループ

# HiRes Experiment Air Fluorescence detector



- Spherical Mirrors:  $\text{Area} = 5.1 \text{ m}^2$
- 256 PMT pixels/mirror: 1 degree resolution

# Pierre Auger Observatory

Hybrid measurement

1500 water tanks

3 Air fluorescence stations

Aperture  $\sim$  x30 AGASA

SD  $>$ 50%, FD 3-station



3.5m x 3.5m mirror

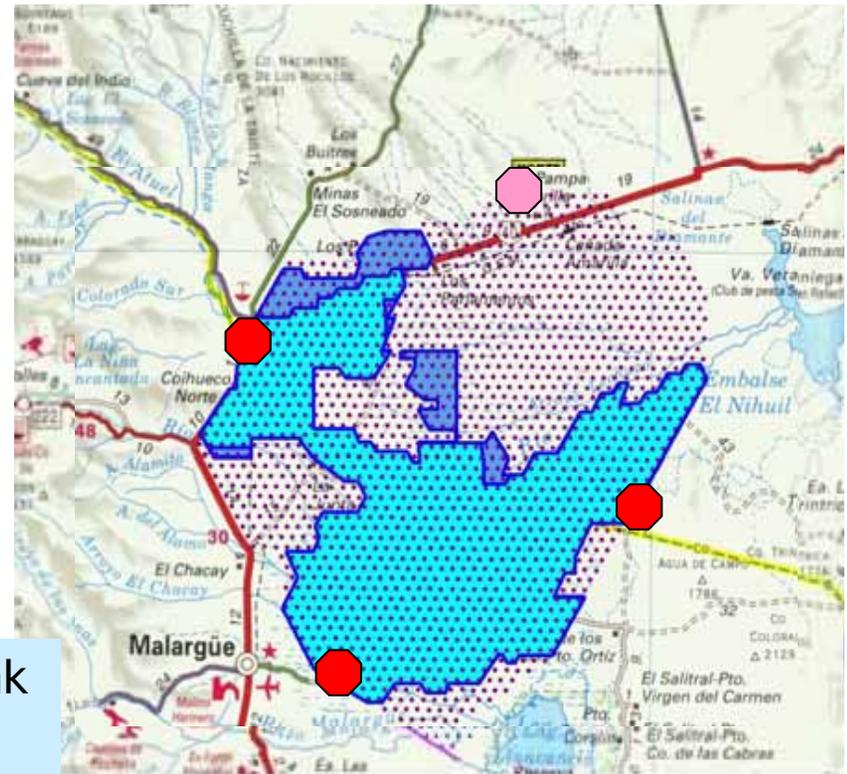
440 PMTs

30° x 29° F.O.V

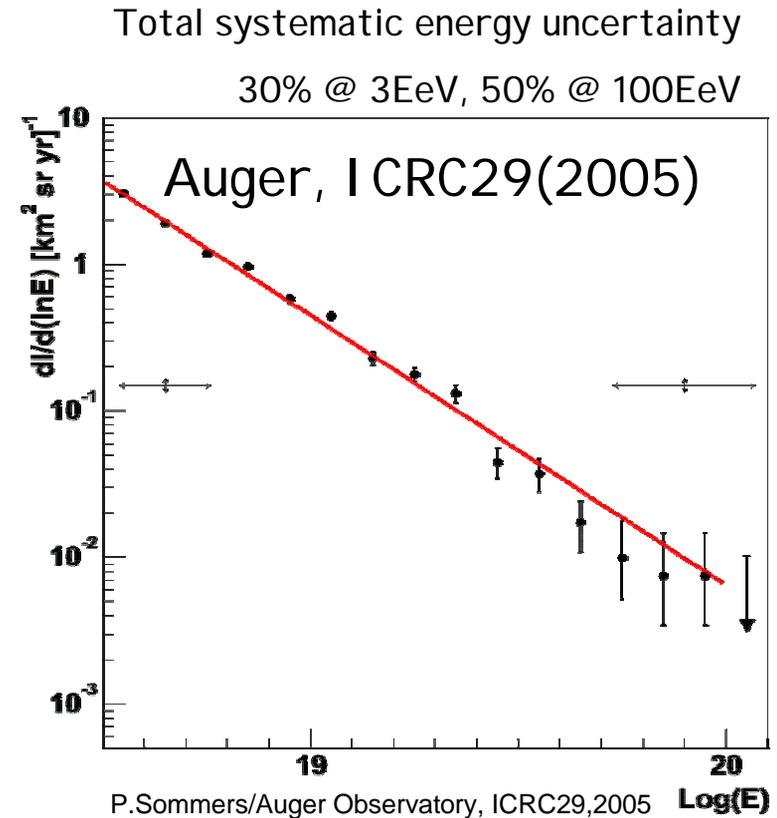
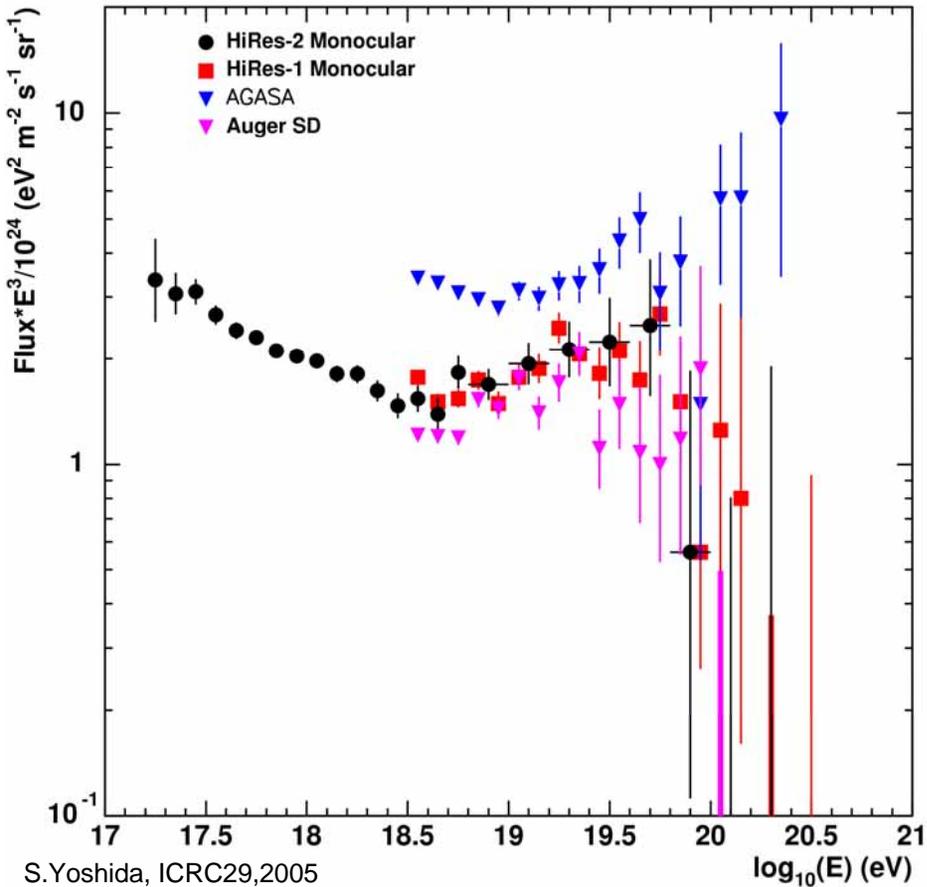


10m<sup>2</sup> x 1.5m water tank

1.5km separation



# Auger SD/Hires Mono/AGASA spectrum

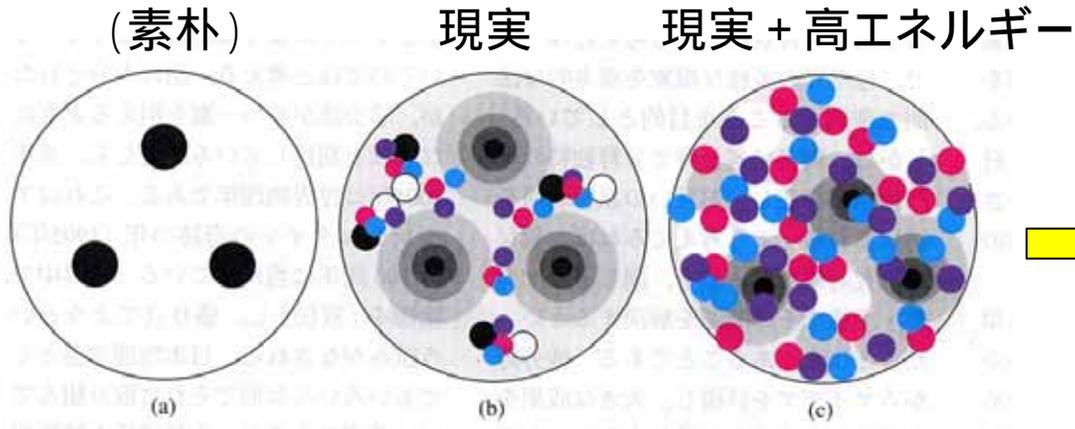


Systematic error の原因は？

- ◆ 大気蛍光の発光量， 大気透明度・大気の状態， 観測装置の状態
- ◆ 空気シャワーシミュレーション， 宇宙線の化学組成， エネルギー決定法

# High Density QCDと空気シャワー

陽子の描像 (板倉, 日本物理学会誌, 59, 3, 148, 2004)

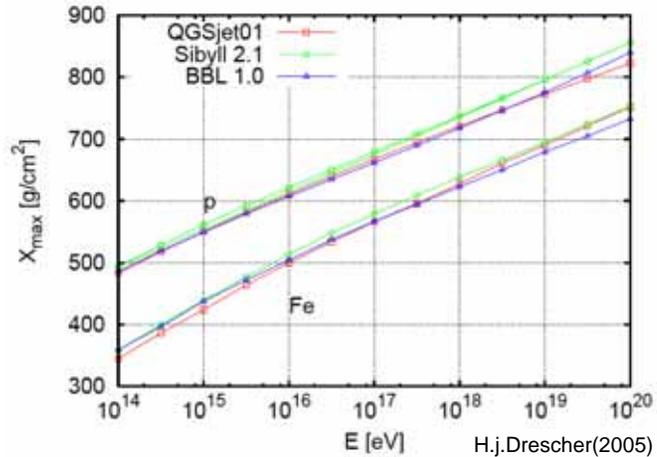


カラーガラス凝縮  
グルオンの増加と「再結合」  
で飽和した状態

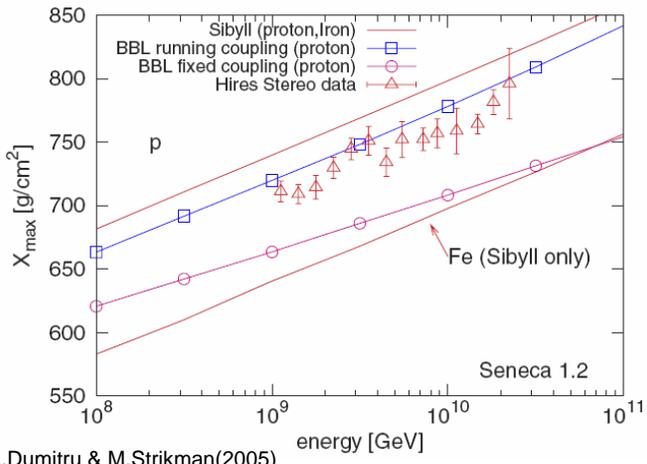
BBLモデルと標準的なSibyllモデル, QGSjetモデルを比較

- 1) H. J. Drescher, A. Dumitru, and M. Strikman, P. R. L., 94, 231801(2005)
- 2) H.J. Drescher, Proc. of ICRC HE.1.4, astro-ph/0512564

予想される $X_{max}$ は, QGSjetとSibyllの中間



HiRes stereo  
 $10^{18}$  eV以上で  
purely - proton?



H.j.Drescher, A.Dumitru & M.Strikman(2005)

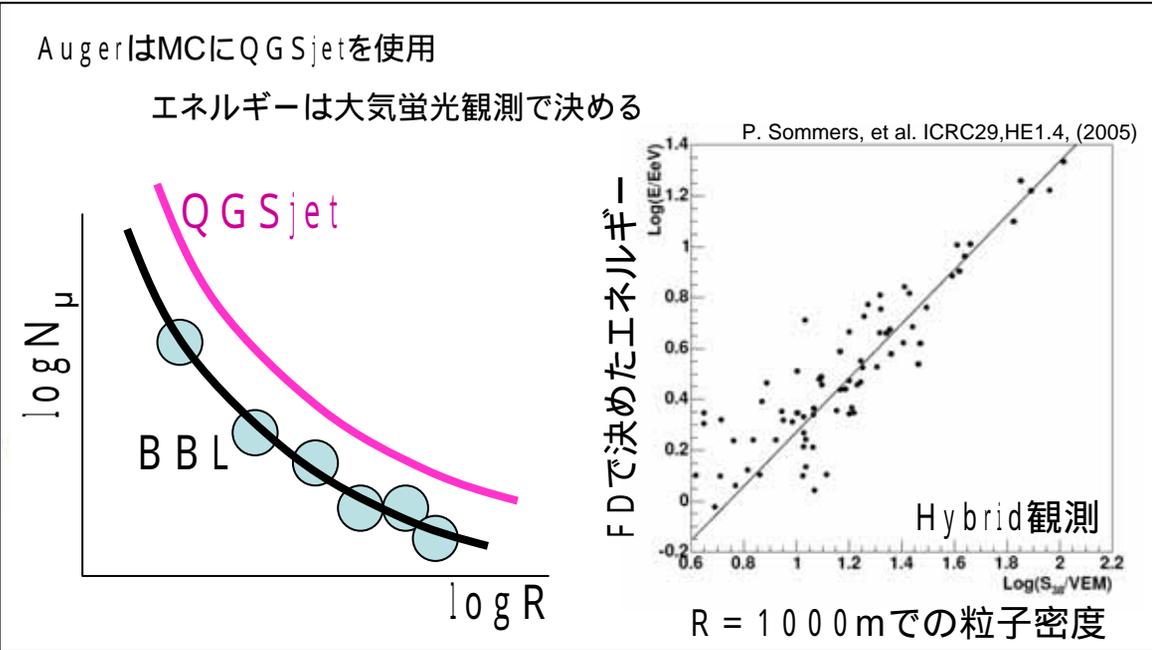
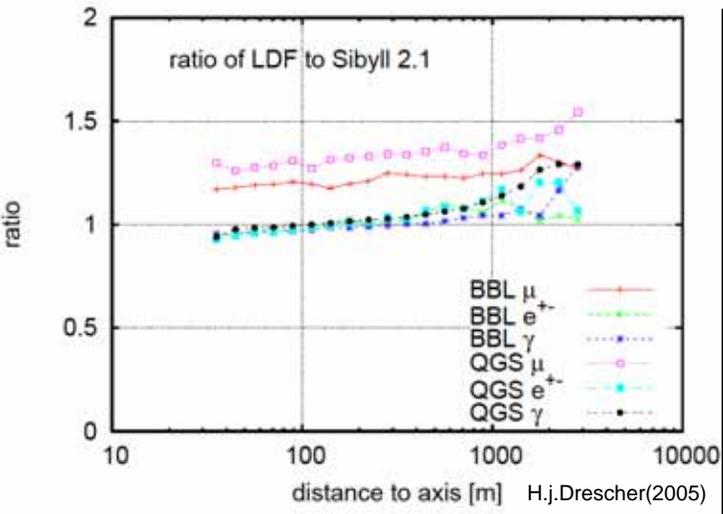
# High Density QCDと空気シャワー

BBLモデルと標準的なSibyllモデル, QGSjetモデルを比較

- 1) H. J. Drescher, A. Dumitru, and M. Strikman, P. R. L., 94, 231801(2005)
- 2) H.J. Drescher, Proc. of ICRC HE.1.4, astro-ph/0512564

予想される $\mu$ のLDFは, QGSjetとSibyllの中間

一方, 電磁成分のLDFは相互作用モデルにほとんど依らない



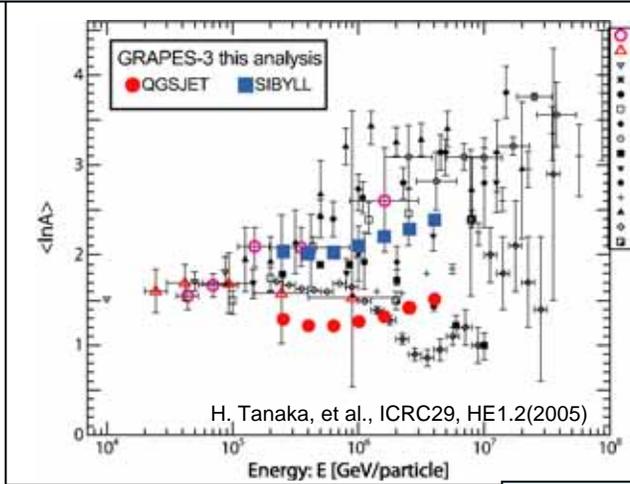
TA実験では, エネルギー決定の系統誤差に相互作用モデルの影響がほとんどない.

➡ SD単独でエネルギーを決定できる (FDとSDの系統誤差の検証)

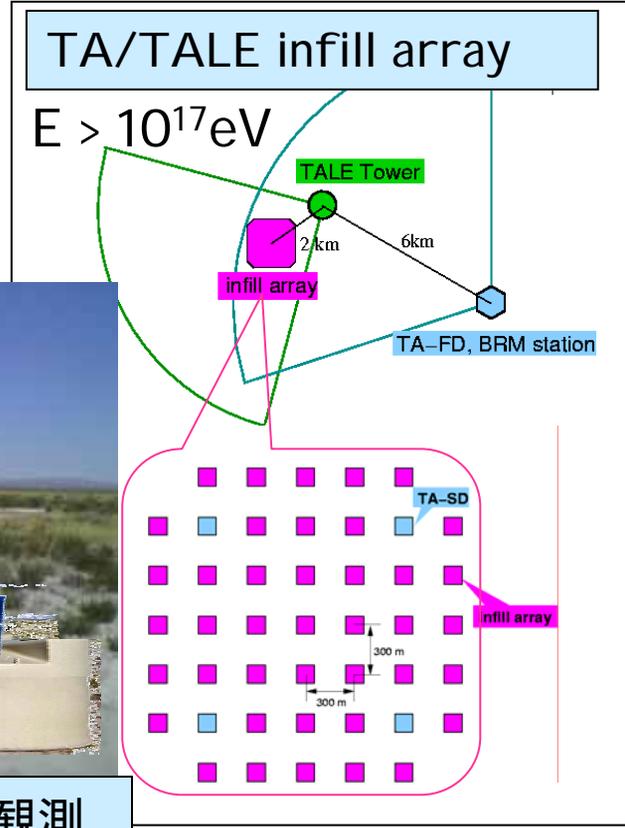
(その他) 蛍光発光量, ステレオ観測, LINAC, 大気モニター

# 相互作用の検証

もっと低いエネルギー (Knee領域  $\sim 10^{15}$  eV)  
で検証可能? (化学組成?)

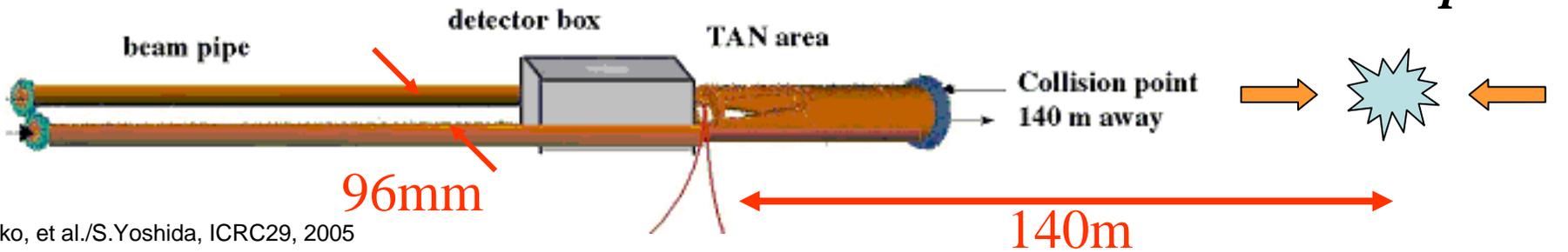


シンチレーターと水タンクで同時観測



# LHCf

Low energy beam profile at the top of the detector



Sako, et al./S.Yoshida, ICRC29, 2005

# まとめ

## 最高エネルギー宇宙線

- ◆ Astrophysical: Cluster, AGN, GRB
- ◆ Cosmological: Relic particle, TD
- ◆ ,

## Telescope Array

- ◆ FD stereo ( $165 \text{ km}^2 \text{ sr}$ )  
+ scintillator SD ( $800 \text{ km}^2$ )
- ◆ 大気モニター, LINAC
- ◆ 2007年本格稼働開始
- ◆ 他の利用法

## Super-GZK?

TA (Stereo-Hybrid,  
Scintillator-SD, Calib.)

