最高エネルギー領域宇宙線研究のレビュー

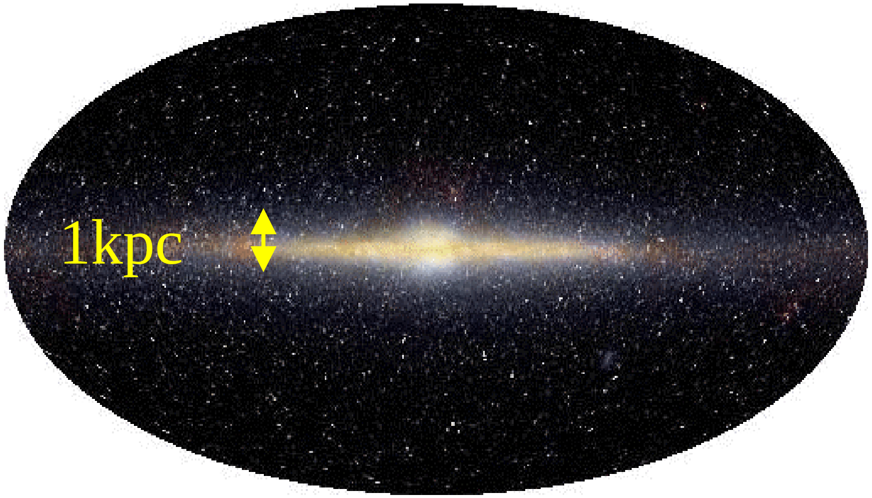
早大理工総研　鳥居祥二

- 最高エネルギー観測でわかること
- 観測の現状（AGASA, Fly's Eye)
- 今後１０年で得られる結果
  （Auger, TA, EUSO?)
- LHCf: LHCによる10^{17}eVでの相互作用モデルの検証
- GZKパズルが解決したら
  ..... さらに重要な問題？

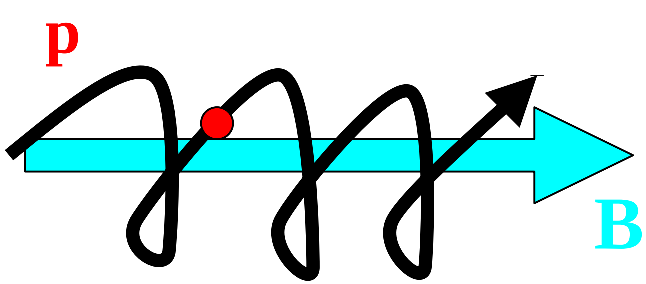
出典:

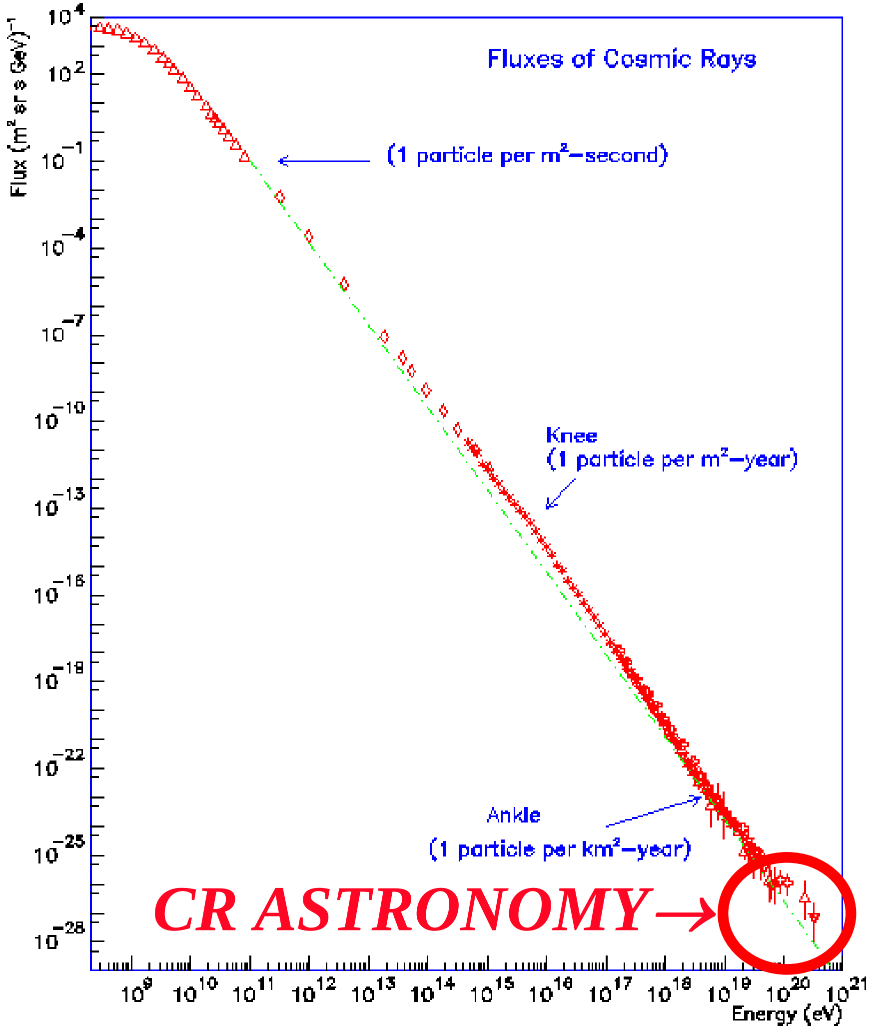
Angela V. Olinto	Space Part (2003)	Washigngton D.C.
Tom Gaisser	Aspen (2005)	
S. Yoshida	ICRC29 (2005)	Pune
T.Yamamoto	JPS Invited Talk (2005)	
M.Fukushima	CRC Symp. (2004), JPS Invited Talk (2005)	
S.Ebisuzaki	CRC Symp.(2004)	

Cosmic Ray Astronomy at Extreme Energies



$$R_{gyro} = 3.7\ \mathrm{kpc}\ E_{19}/ZB_{3\mu G}$$



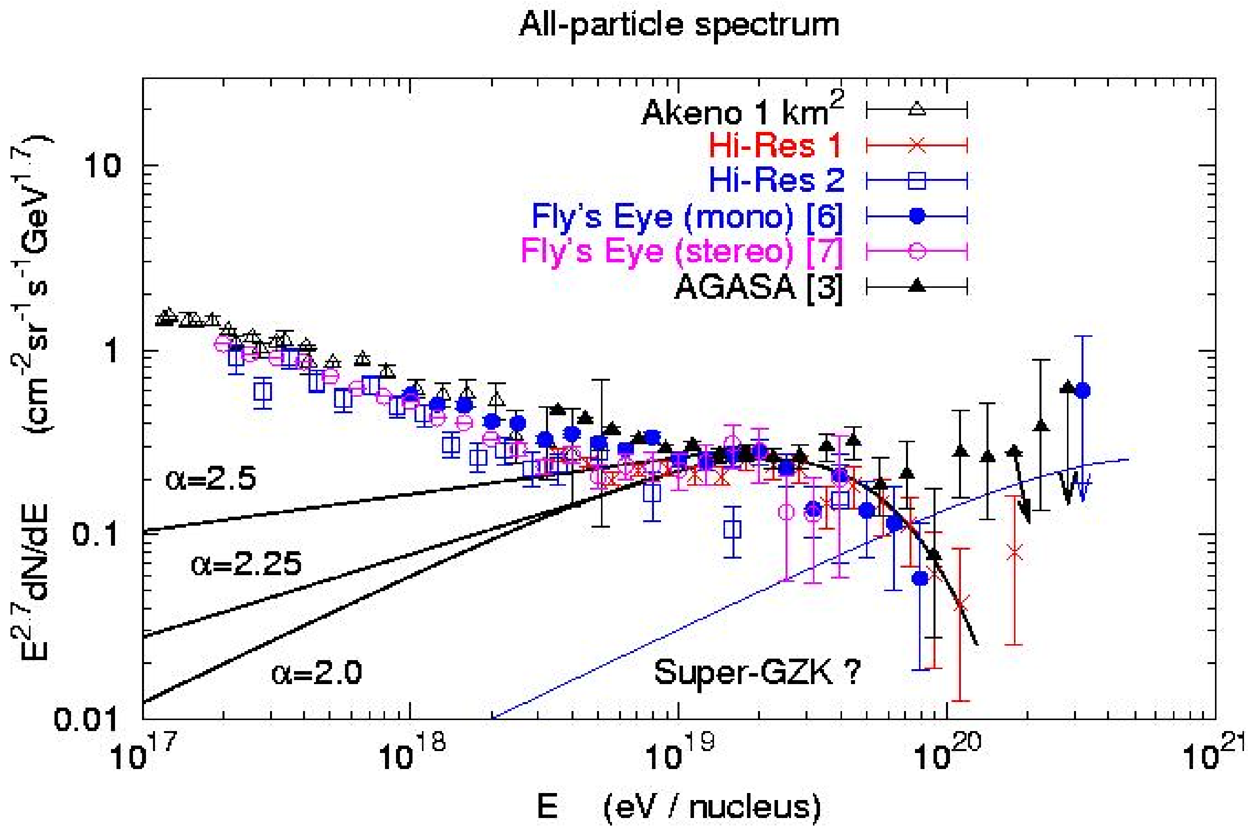


Transition to Extra-Galactic Component

- Composition signature: transition back to protons

Uncertainties:
- Normalization point:
  10^{18} to $10^{19.5}$ used
  Factor 10 / decade

- Spectral slope
  α=2.3 for rel. shock
  =2.0 non-rel.

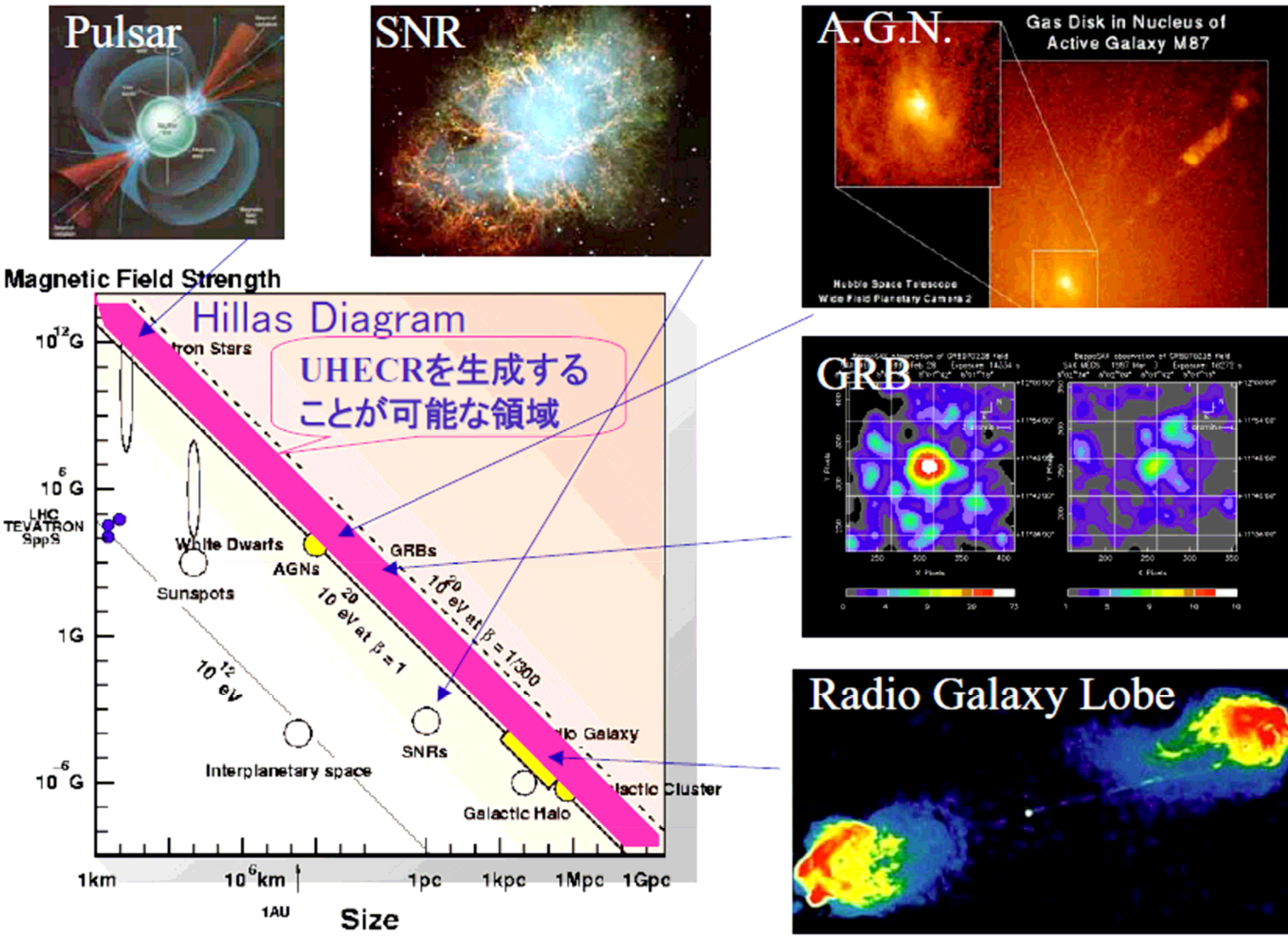


Power Needed for Extragalactic Cosmic Rays (assuming transition at 10^{19} eV)

- Energy in extra-galactic, $\rho_{CR} \sim 2 \times 10^{-19}$ erg/cm^3
  - Includes extrapolation of UHECR to low energy
  - $\rho_{CR} = (4\pi/c) \int E\phi(E)\, dE = (4\pi/c)\{E^2\phi(E)\}|_{E=10^{19}eV} \times \mathit{ln}\{E_{max}/E_{min}\}$
  - This gives $\rho_{CR} \sim 2 \times 10^{-19}$ erg/cm^3 for differential index $\alpha = 2$, $\phi(E) \sim E^{-2}$; significantly more if $\alpha > 2$,

- Power required ~ $\rho_{CR}/10^{10}$ yr ~ 1.3×10^{37} erg/Mpc^3/s
  - Estimates depend on cosmology + extragalactic magnetic fields:
  - 3×10^{-3} galaxies/Mpc^3 — 5×10^{39} erg/s/Galaxy
  - 3×10^{-6} clusters/Mpc^3 — 4×10^{42} erg/s/Galaxy Cluster
  - 10^{-7} AGN/Mpc^3 — 10^{44} erg/s/AGN
  - ~1000 GRB/yr — 3×10^{52} erg/GRB

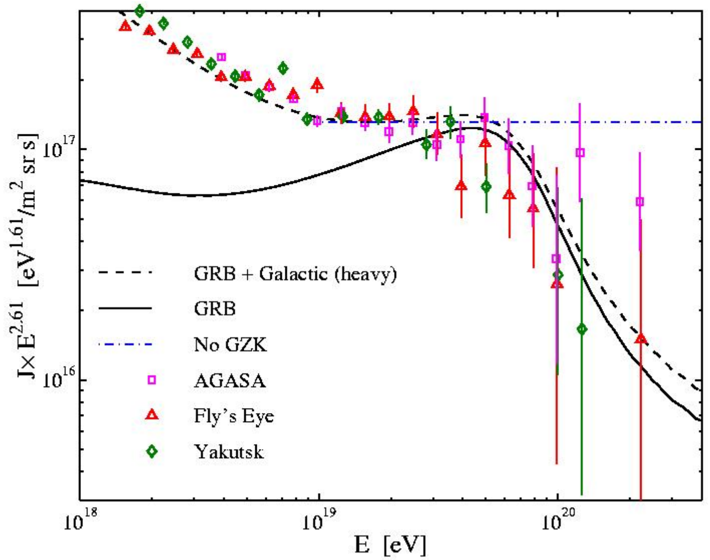
極限エネルギー宇宙線を生成できる候補天体

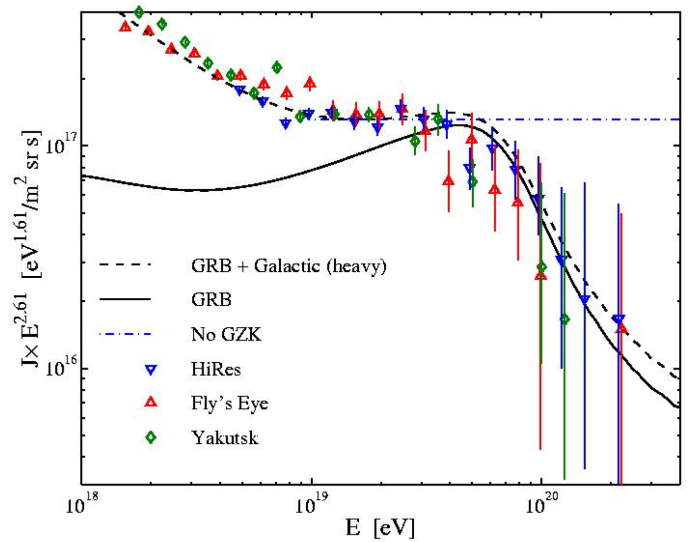


GRB: Bahcall & Waxman

Physics Letters B556 (2003) 1

- **Galactic→ extragalactic transition**
  ~ 10^{19} eV
- **Assume E^{-2} spectrum at source, normalize @ $10^{19.5}$**
- **10^{45} erg/Mpc^3/yr**
- **~ 10^{53} erg/GRB**
- **Evolution ~ star-formation**
- **GZK losses included**

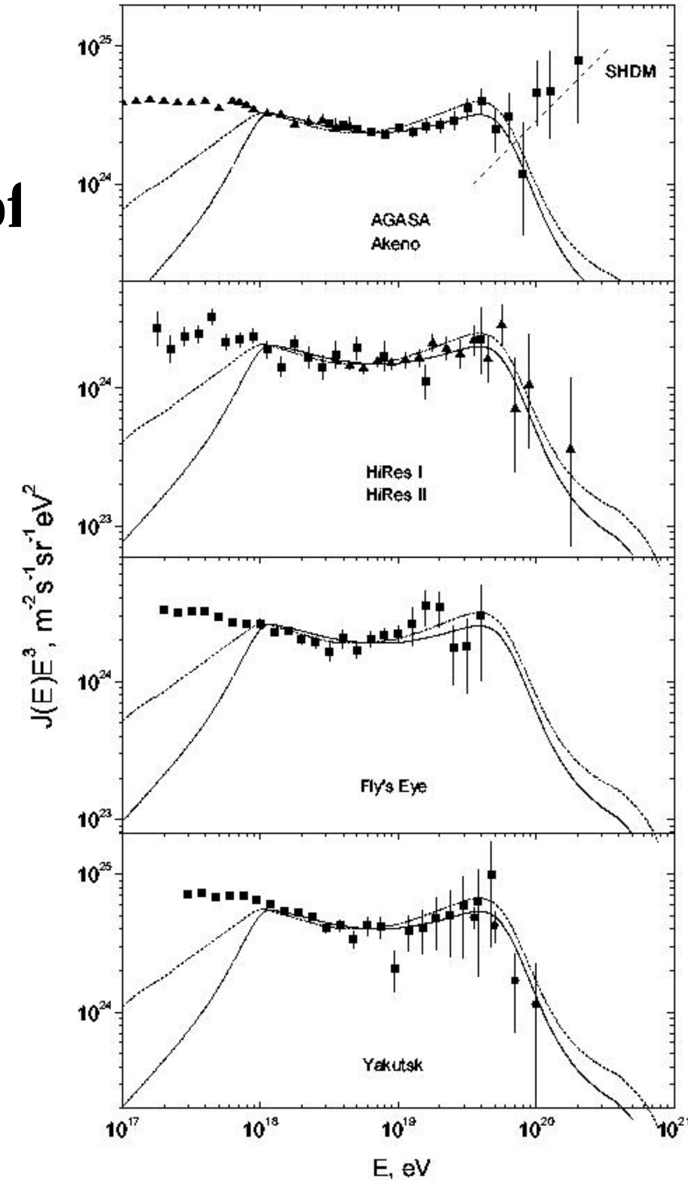




AGN: Berezinsky et al.

astro-ph/0410650

- G → E-G transition $\leq 10^{18}$ eV
- Assume a cosmological distribution of sources with:
  - $dN/dE \sim E^{-2}$, $E < 10^{18}$ eV
  - $dN/dE \sim E^{-g}$, $10^{18} < E < 10^{21}$
  - $g = 2.7$ (no evolution)
  - $g = 2.5$ (with evolution)
- Need $L_0 \sim 3 \times 10^{46}$ erg/Mpc^3 yr
- Interpret ankle at 10^{19} as
  - $p + g_{2.7} \rightarrow p + e^+ + e^-$

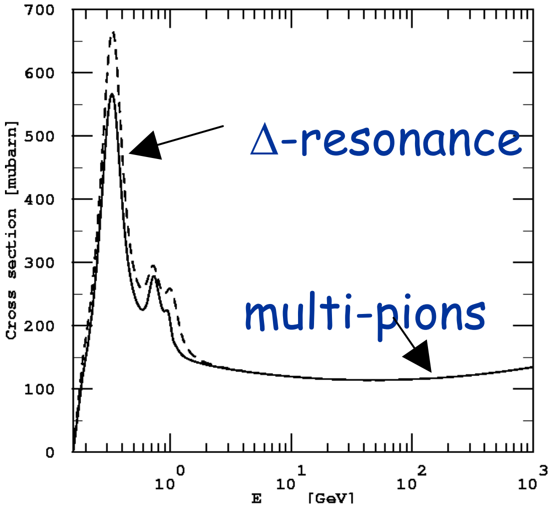


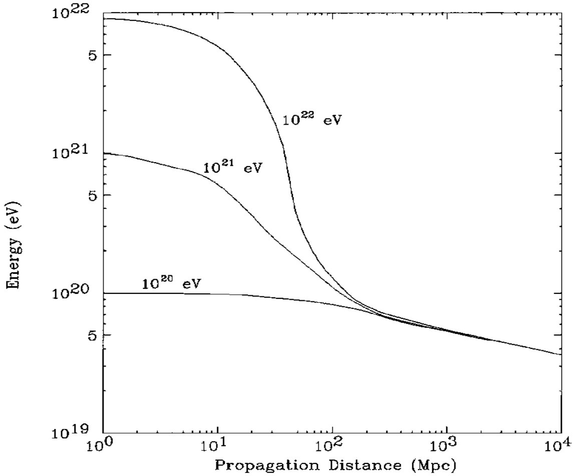
Questions to ponder

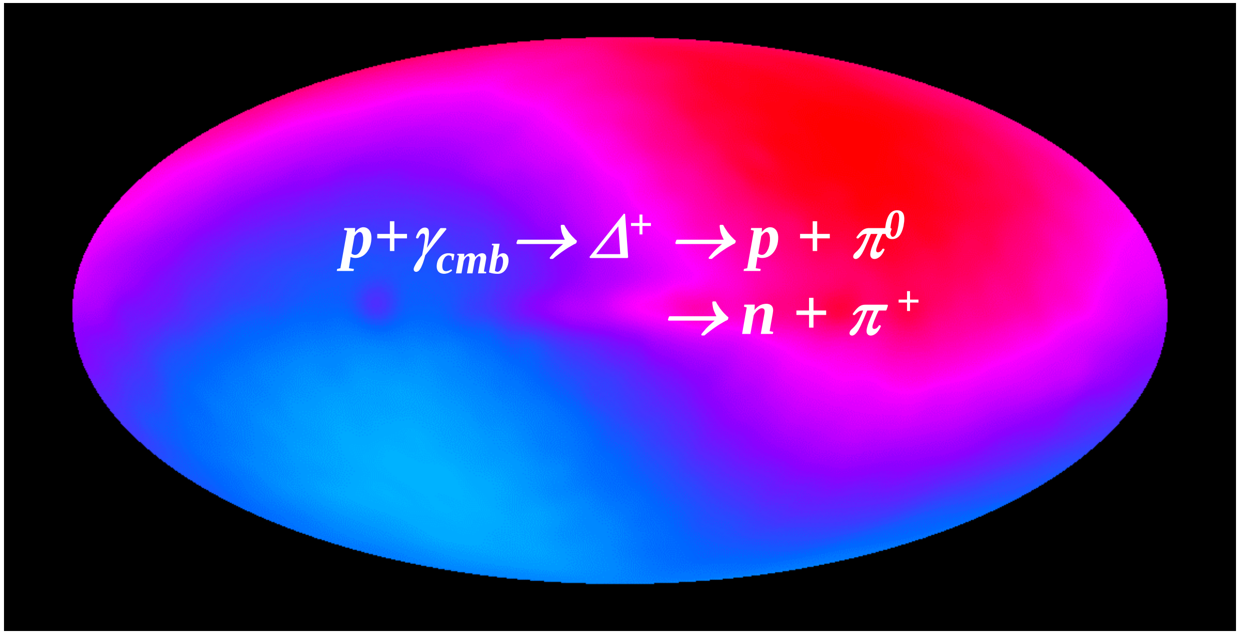
- How to boost E_{max} to 100 PeV
  - perpendicular shocks?
  - self-generated higher magnetic fields?
- What is the energy-dependence of diffusion?
- What is the source spectrum?
  - Are there different slopes for different sources?
  - How to use the characteristic concave shape of non-linear diffusive shock acceleration?
- How many sources? How are they distributed?

High Energy Proton sees Cosmic Microwave Background

Proton Horizon





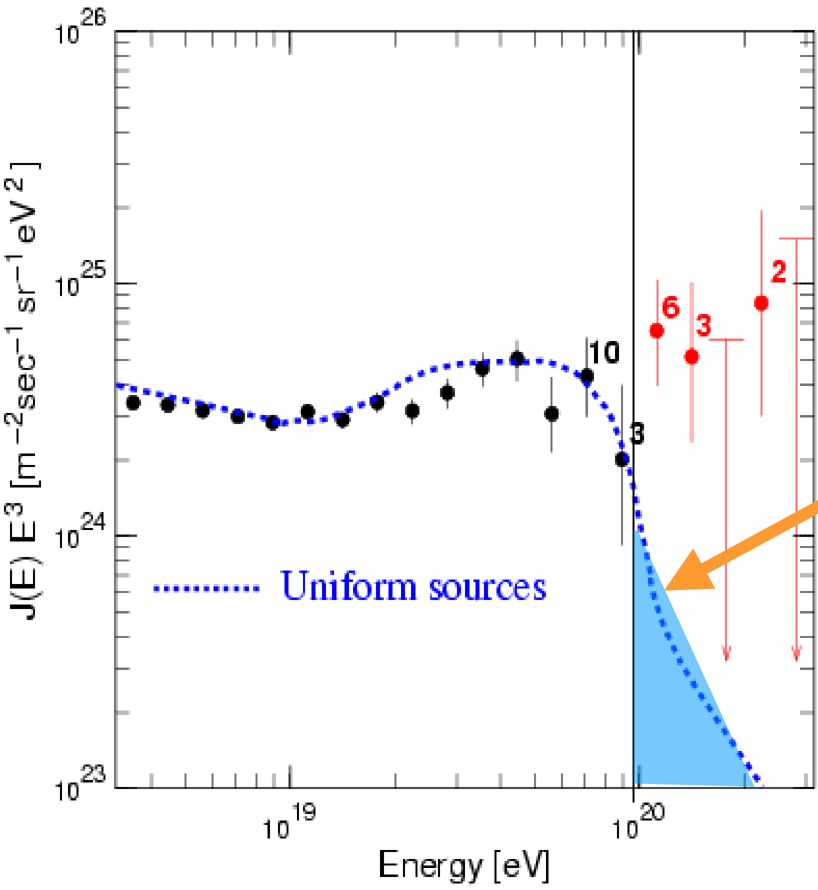


$$p+\gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

⇒ **GZK Cutoff**

Greisen '66, Zatsepin & Kuzmin '66

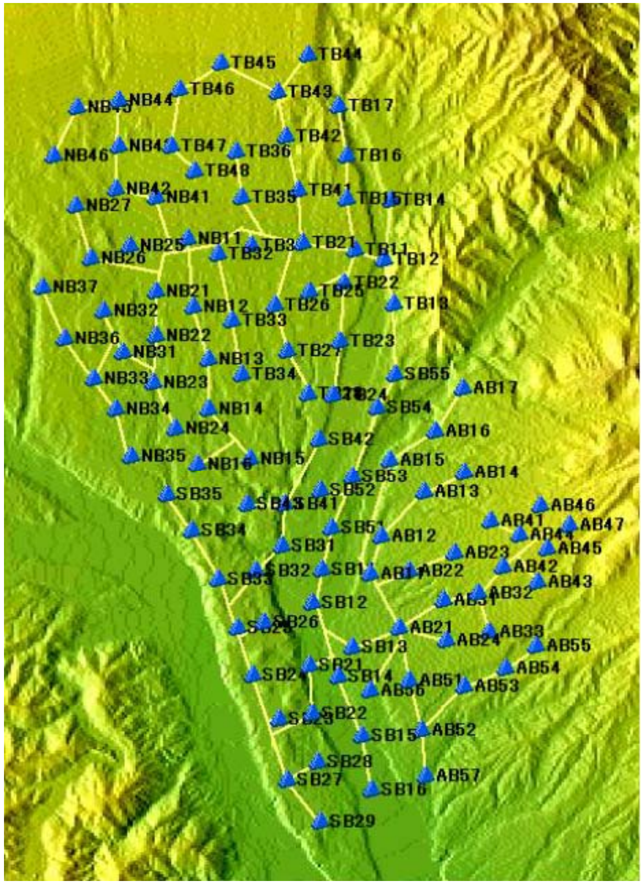
AGASAの観測結果：すべてのはじまり



AGASA

~2 ev expected

4.0 σ



100 km^2 scintillators
+ muon detectors

EHECR Puzzle

Why no GZK cutoff?

Extragalactic Proton Sources $\Rightarrow$ GZK feature

Nearby EG Source such as M87 or Cen A?

No! GZK feature from other sources
+ hot spot in the sky - not isotropic!

Galactic Source such as Young Neutron Stars?

Only if primary is heavy & $B_{gal\ halo}$ stronger!

Other Astrophysical ZeVatrons?

No good candidates - all show GZK feature!

Some Possible Resolutions…

- ***If Photons,*** **NEW PHYSICS: TD, Super Heavy Dark Matter**
  : only at EHE

- ***If Protons,*** **B strong local source + very hard injection spectrum**
  + GZK feature
- ***If Protons + no GZK feature ,*** **violation of Lorenz Invariance**

- ***If Heavies,*** **Galactic or Extragalactic Zevatrons + strong Magnetic Fields**

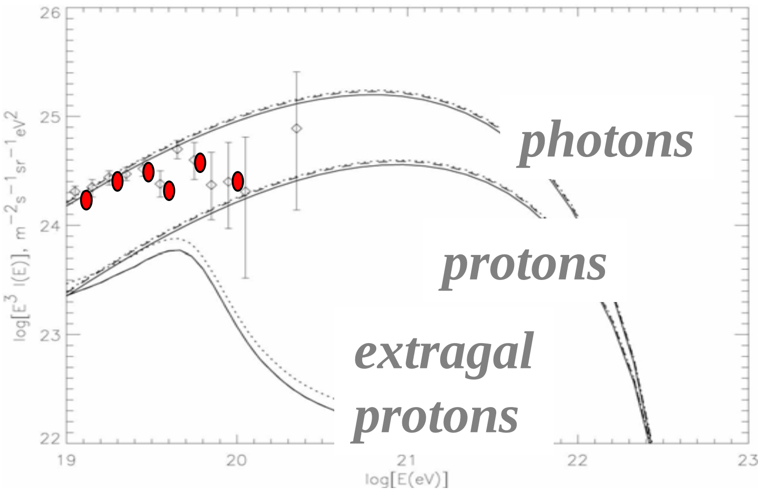
To Solve the Puzzle - need a lot More Data:

- **Full Sky Coverage**
- **Many More Events**
- **Composition**

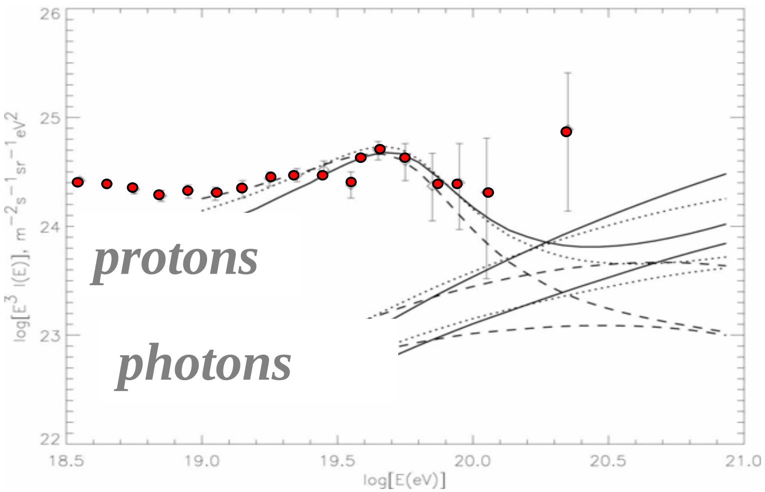
New Physics Option

Berezinsly, Blasi, Vilenkin `99

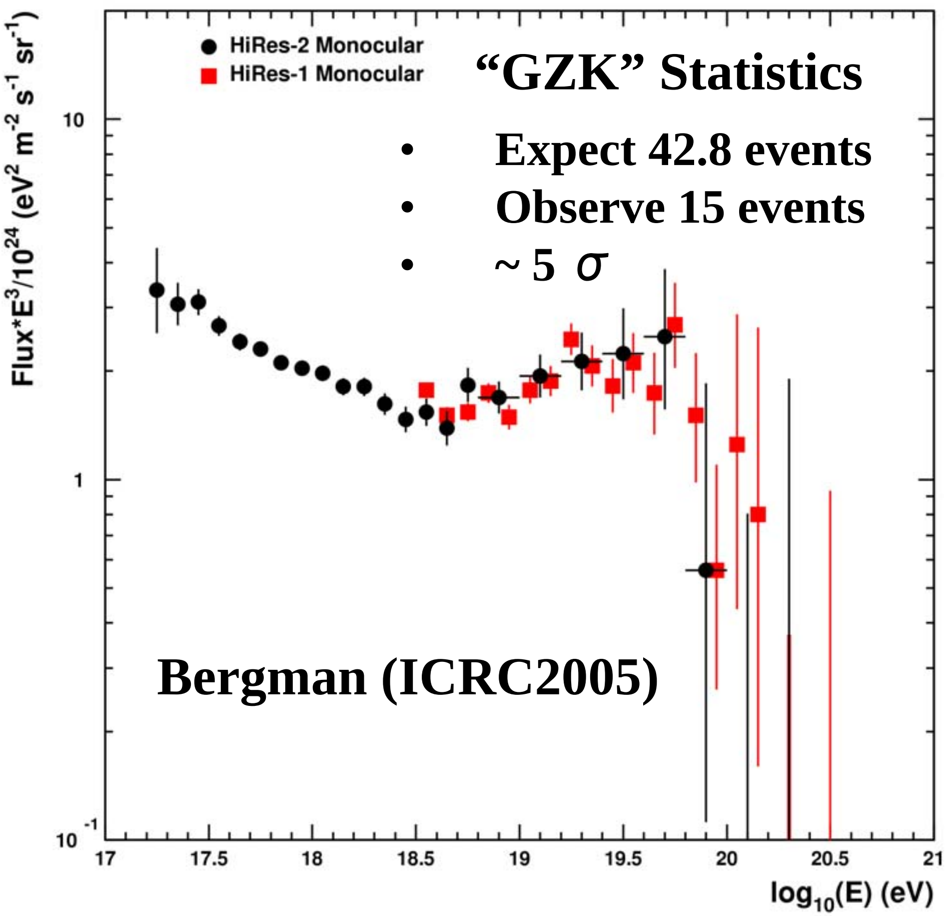
Super-Heavy Particle Relics
(in Galactic halo)
⇒ no GZK feature for Protons
⇒ Photons at all Energies
⇒ New component



Topological Defects = extragalactic
⇒ GZK feature for Protons
⇒ Photons at the Highest Energies



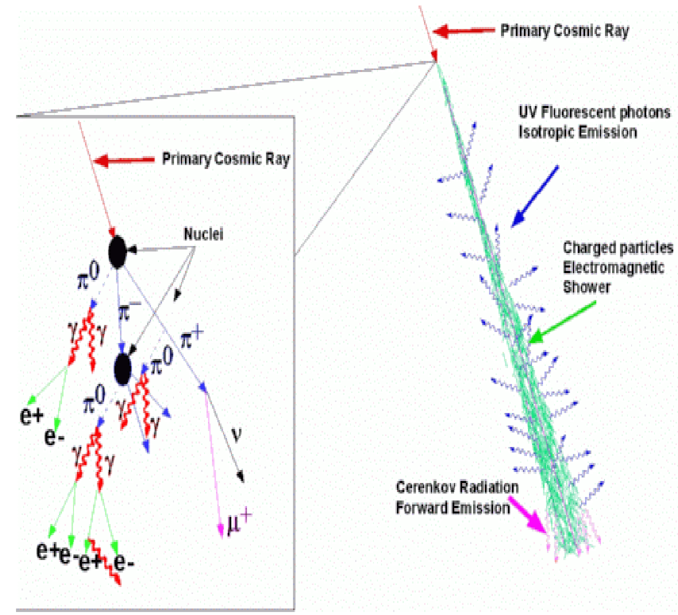
HiRes (mono)

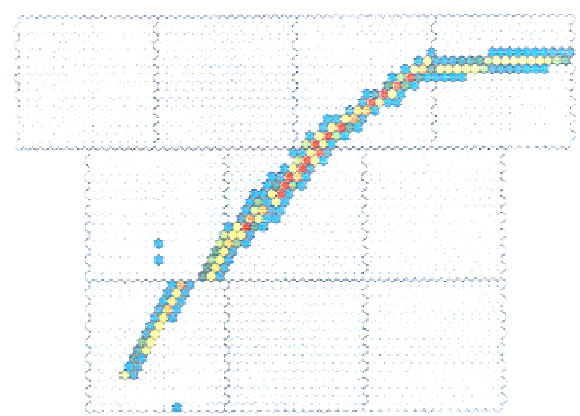


"GZK" Statistics

- Expect 42.8 events
- Observe 15 events
- ~ 5 σ

Bergman (ICRC2005)

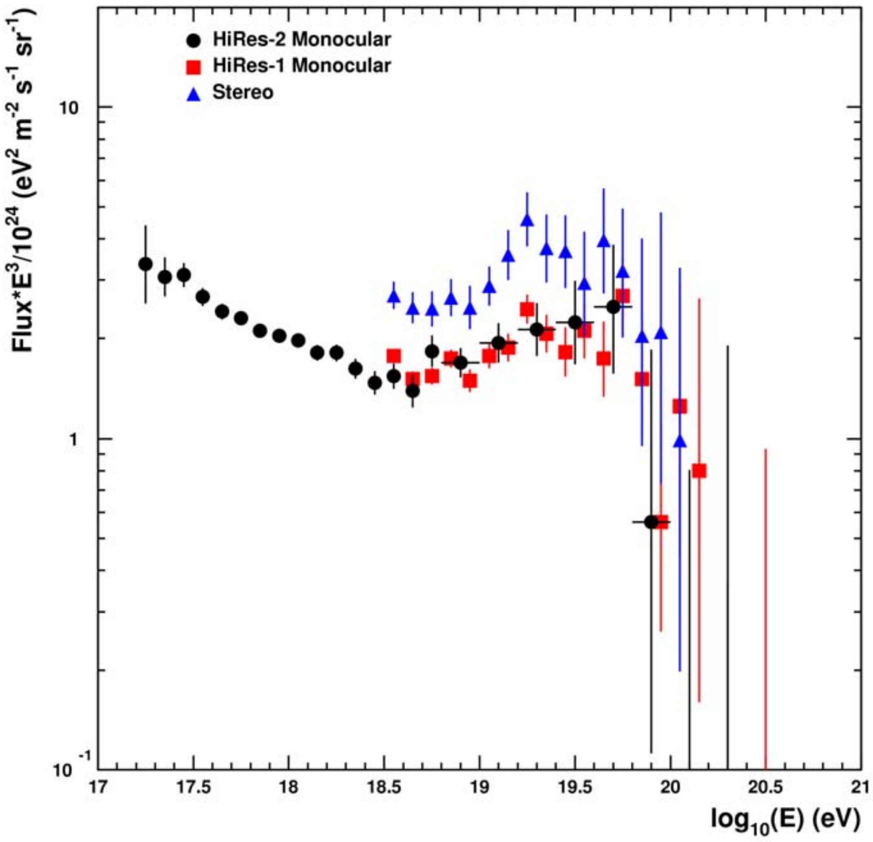




Fluorescence Detector

HiRes Stereo (and others)

(Fukushima: HiRes STEREO DATA is NOT authorized by HiRes collab..)



Exhibits cutoff structure

Expect 33.7 events

Observe 9 events

~4.8 σ

Some details

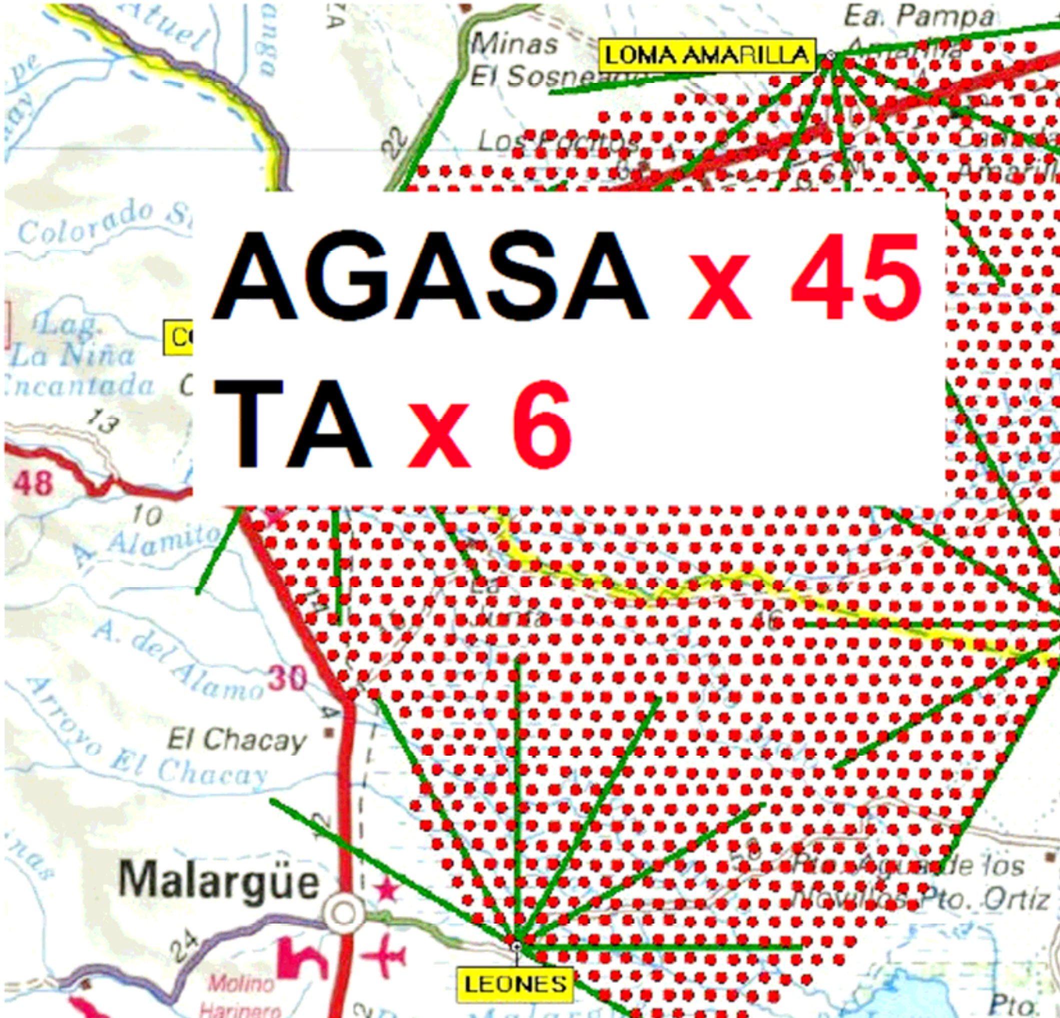
DIFFERENT from mono!

The Mono spectrum may contain unknown systematic errors.

The Auger Observatory

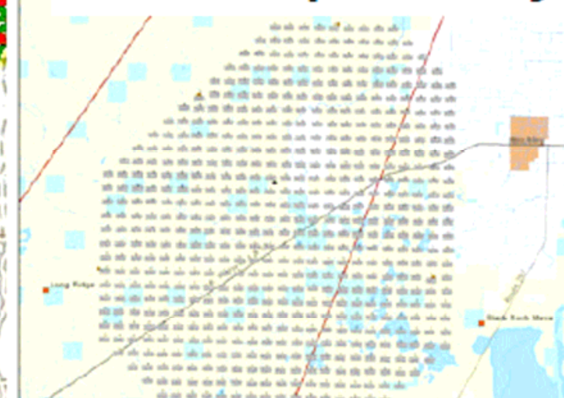
地上アレイ
1600 検出器
1.5 km 間隔
3000 [km^2]x2.6[sr]

AGASA x 45
TA x 6

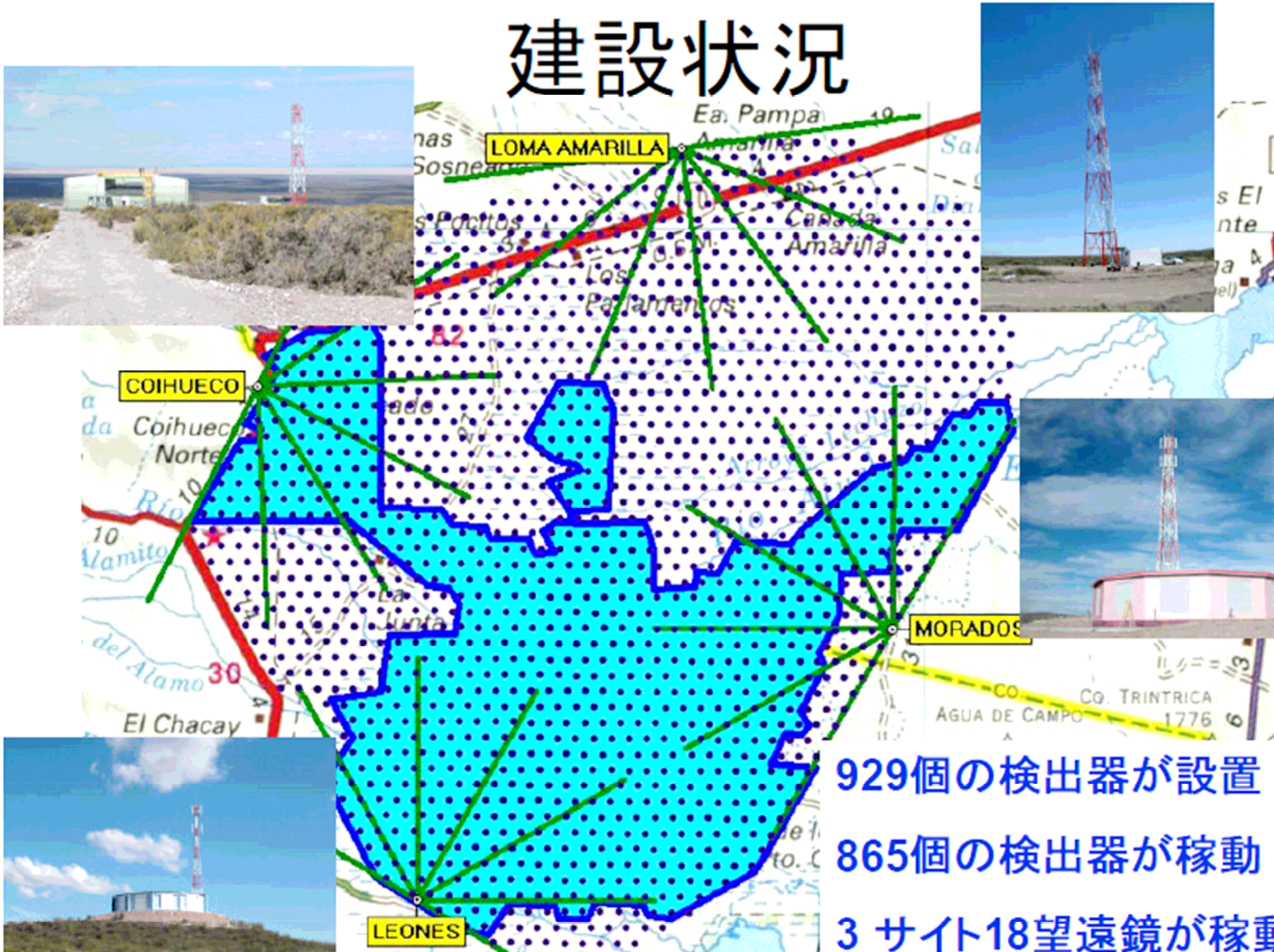


AGASA

Telescope Array



建設状況

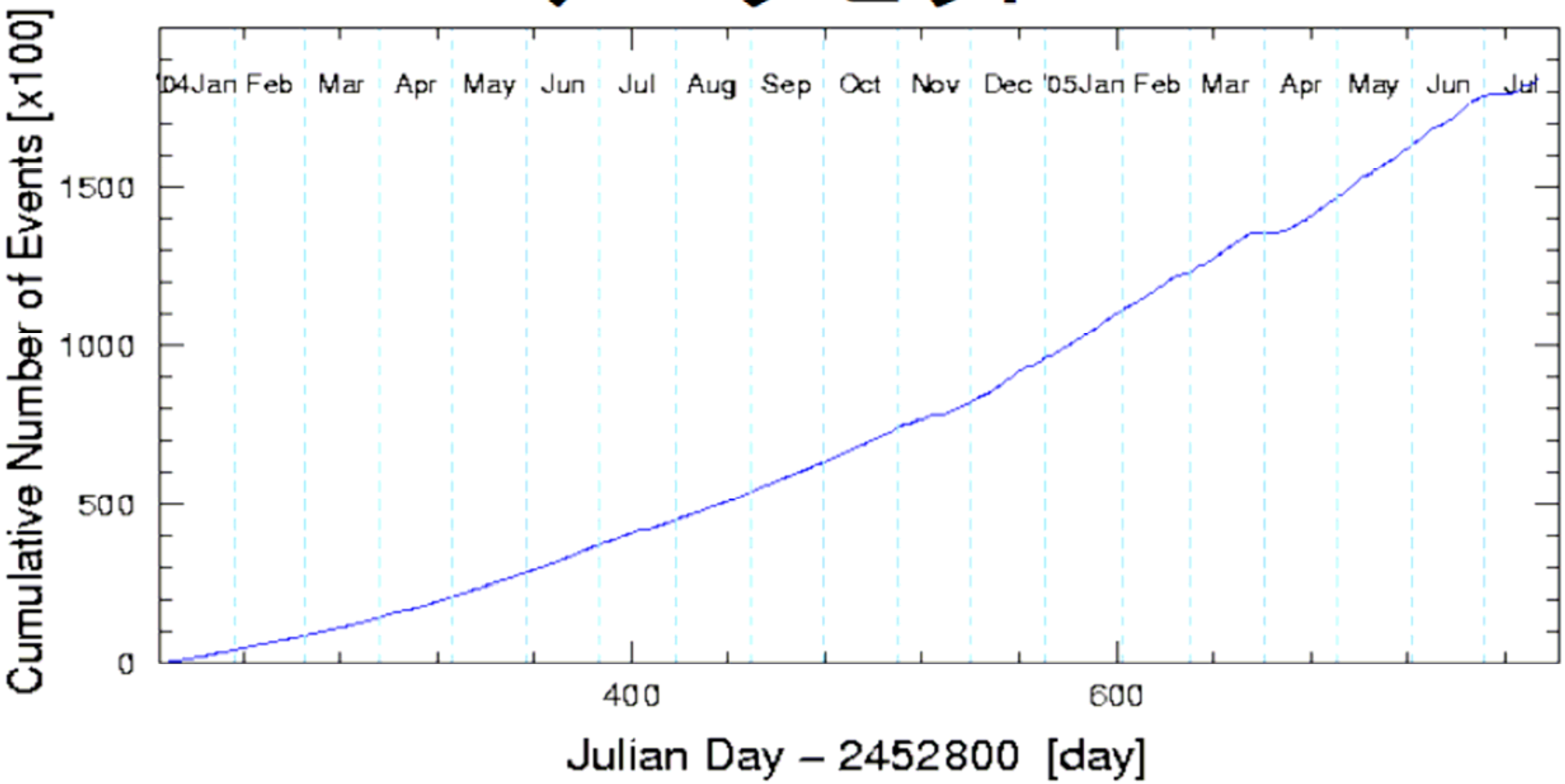


929個の検出器が設置

865個の検出器が稼動

3 サイト18望遠鏡が稼動

データセット



2004年1月– 2005年6月

天頂角　0 - 60°

Total exposure 1750km^2 sr yr　(~ 1.07 * AGASA)

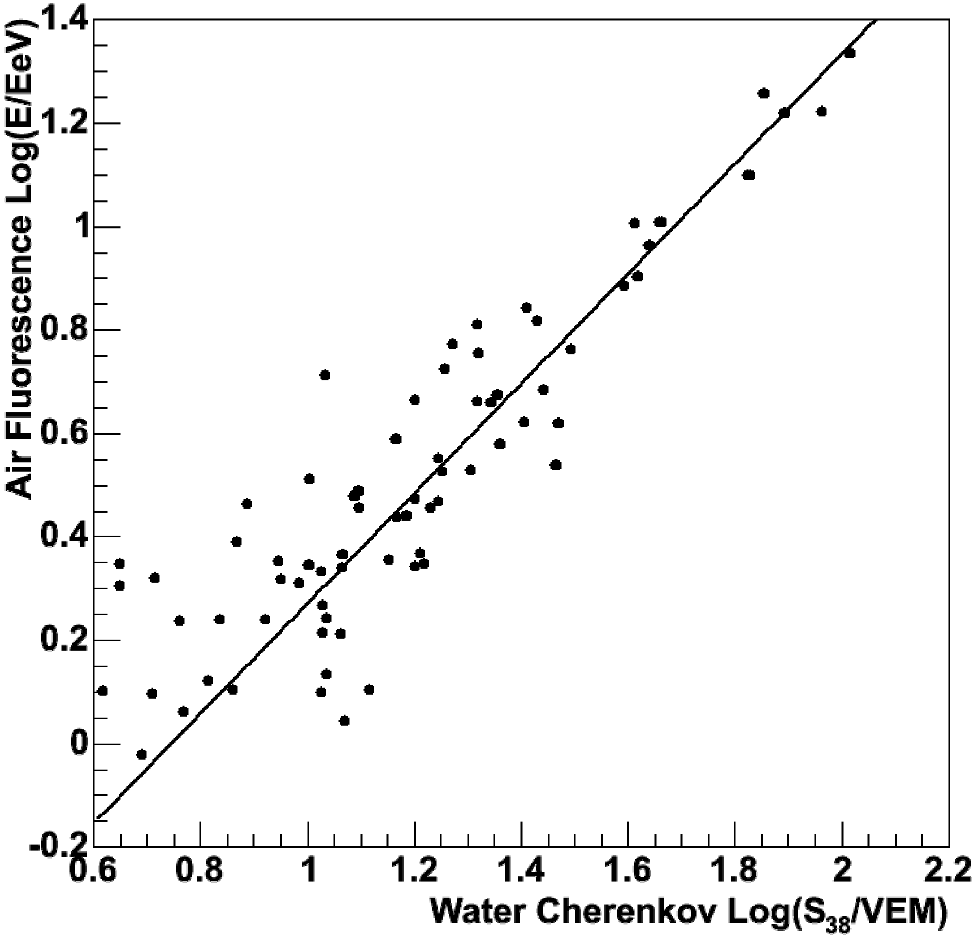
18,000 events / 月　　Total – 1,500,000 events

Auger の出した解

2 つの方法の利点を使う:
大気蛍光法からエネルギー：地上アレイから統計量

- 地上アレイ データから シャワーサイズ パラメータを測定
  S1000 --- シャワー軸から 1000 [m] での 粒子数
- S1000 →エネルギーの関係を実験データのみから決定
  - 宇宙線の到来方向が一様であることを利用し、天頂角依存性を測定
  - ハイブリッド データから:
    - エネルギー絶対値の更正
    - S1000 のエネルギー依存性の推定
- 地上アレイデータのエネルギー分布と有効面積から スペクトラムを算出

Energy Measurement in Auger Hybrid



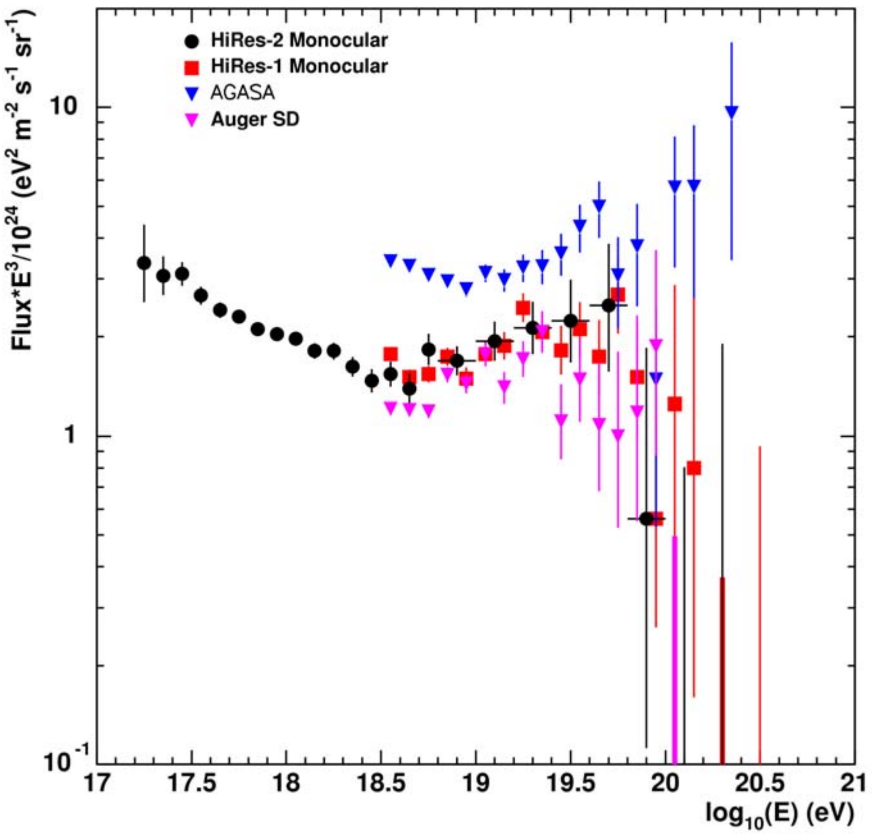
$\text{Log (E)} = -0.79 + 1.06\ \text{Log}(S_{38})$

$E = 0.16\ S_{38}^{1.06}$

(E in EeV, S_{38} in VEM)

Uncertainty in this rule increases from 15% at 3 EeV to 40% at 100 EeV

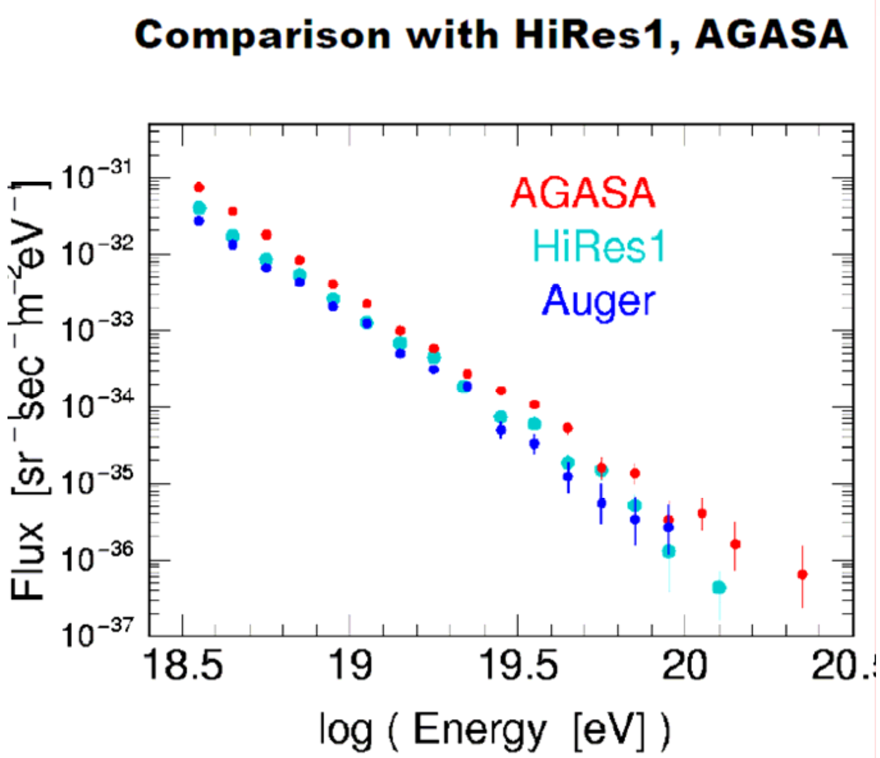
Auger SD spectrum

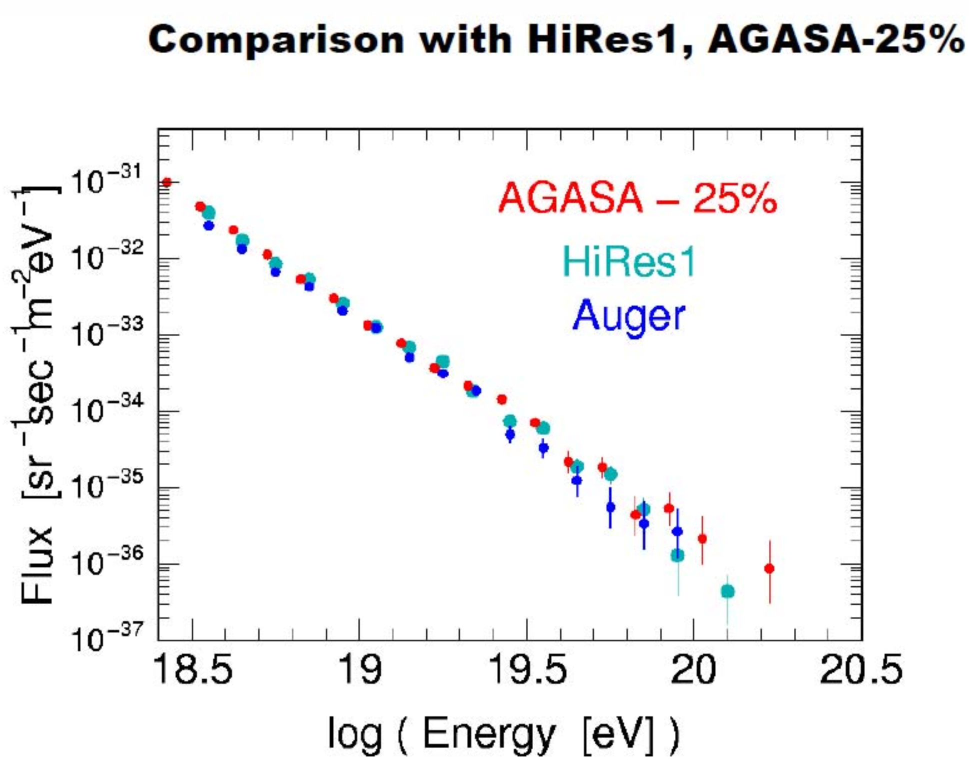


Energy scale uncertainty is still large....

~40 % in 100 EeV improvement will come soon

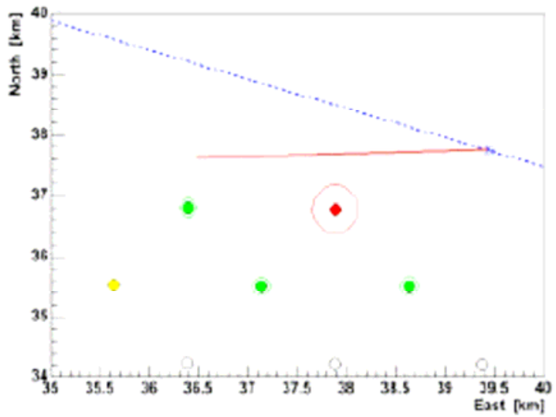
AGASA, HiRes1, Auger の比較

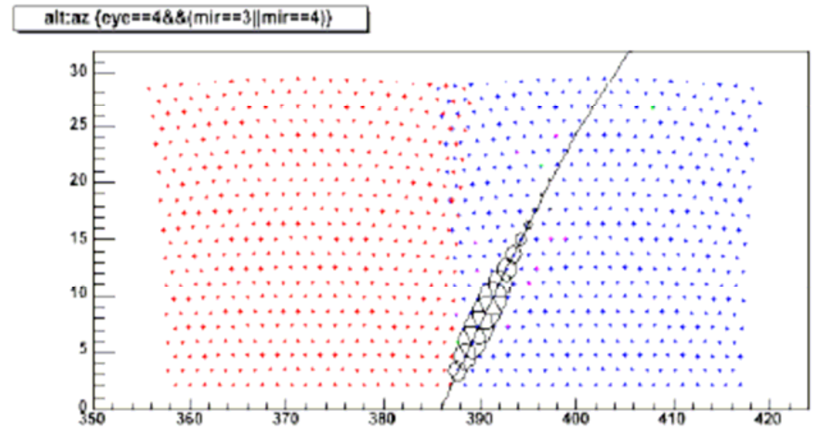


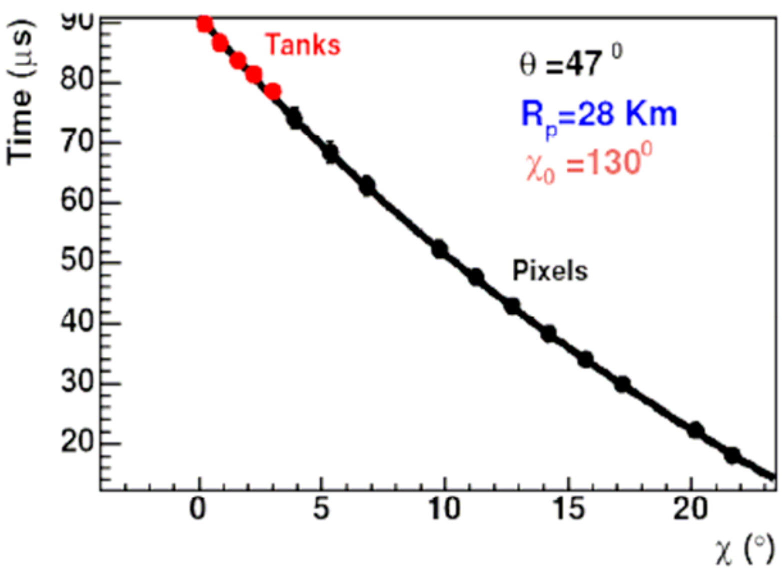


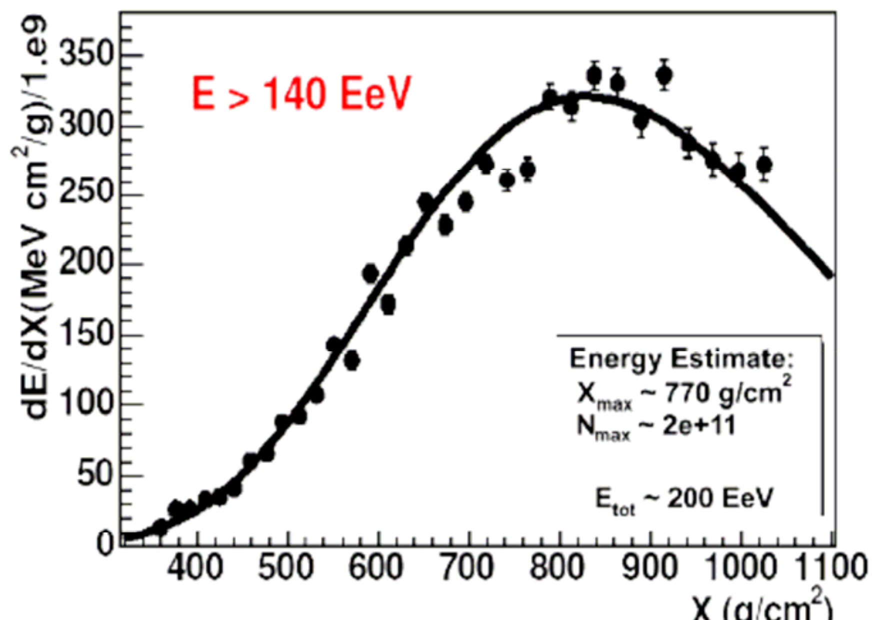
Our Highest Energy Event E_{FD}~2 10^{20}eV

Landed just outside the array, so not used in spectrum!









S(1000): The energy indicator

- **Less mass composition sensitive**

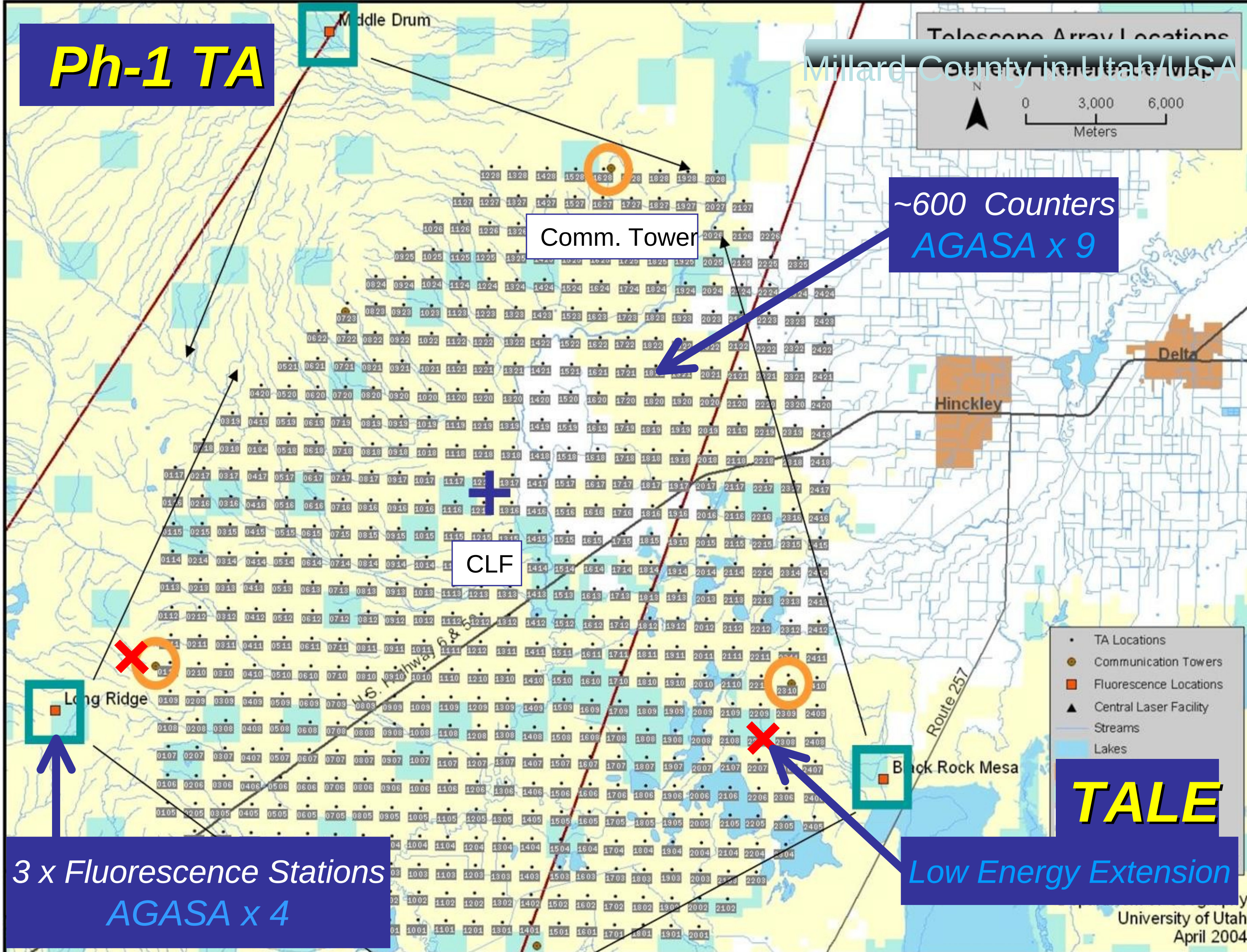
  Not just muons but emg component make sizable contributions (Alan Watson, private comminication)

- **S(1000)Fe-P** **~10 % difference (Paul Sommers, private com)**

- **σ s(1000)** **~15% @ 10 VEM (Ghia, this conference)**

BUT ALL these rely on EAS MC!!

S.Yoshida


Ph-1 TA
Middle Drum
Telescope Array Locations
Millard County in Utah/USA
N
0
3,000
6,000
Meters
~600 Counters
AGASA x 9
Comm. Tower
Delta
Hinckley
CLF
U.S. Highway 6 & 50
Route 257
Long Ridge
Black Rock Mesa
TA Locations
Communication Towers
Fluorescence Locations
Central Laser Facility
Streams
Lakes
TALE
Low Energy Extension
3 x Fluorescence Stations
AGASA x 4
University of Utah
April 2004

SD+FD Hybrid Detectorのメリット

次期大型装置(TA & Auger）は　SD＋FD
- SDの規模を確保する（統計量）
- FDの絶対較正（エネルギー精度）

↓

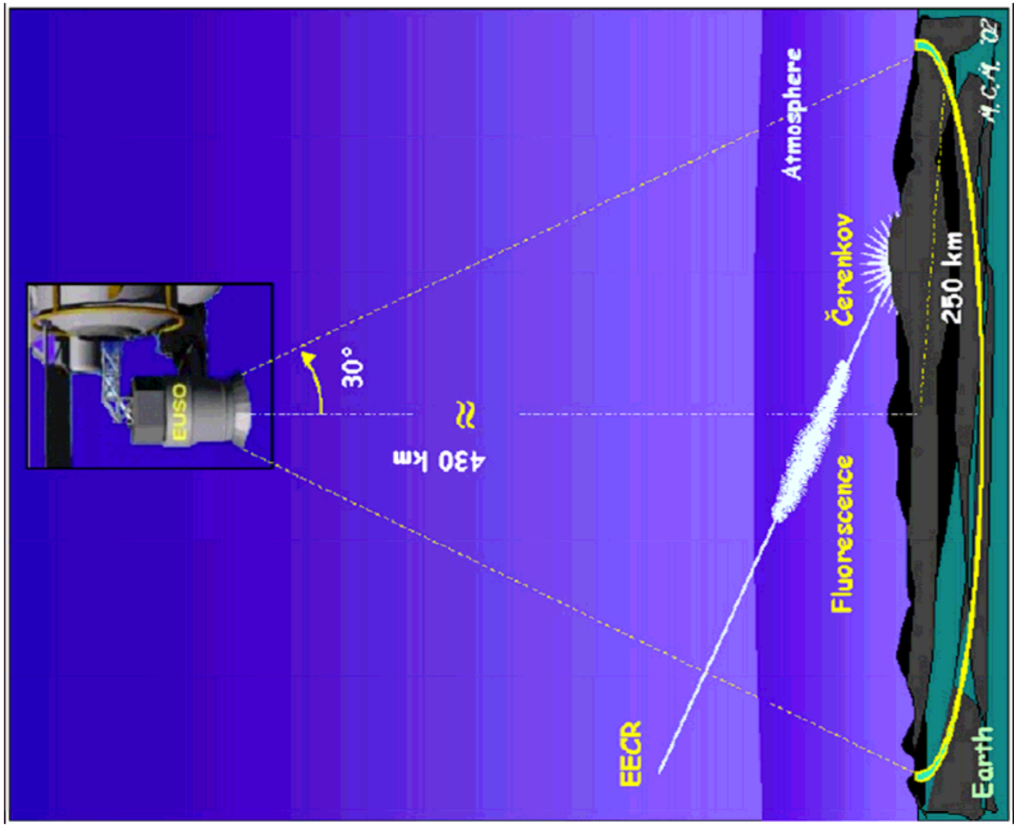
2007（メキシコ　ICRC）までに
南半球で、Auger は　x 7　AGASA exposure
北半球で、TAは　x 1　AGASA exposure

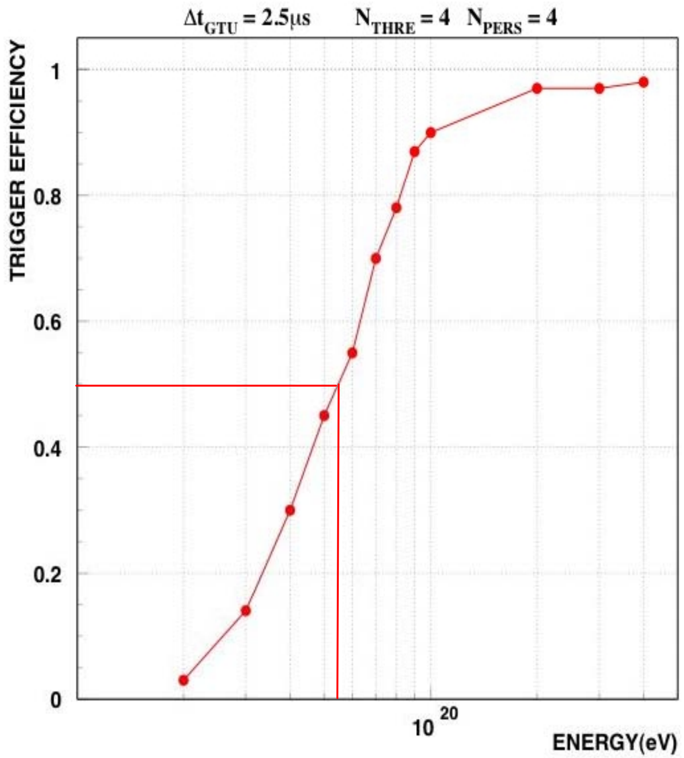
UHECRのスペクトルについては、ほぼ結論が出る。

EUSO

トリガ効

5.5x10^{19}eVで50%



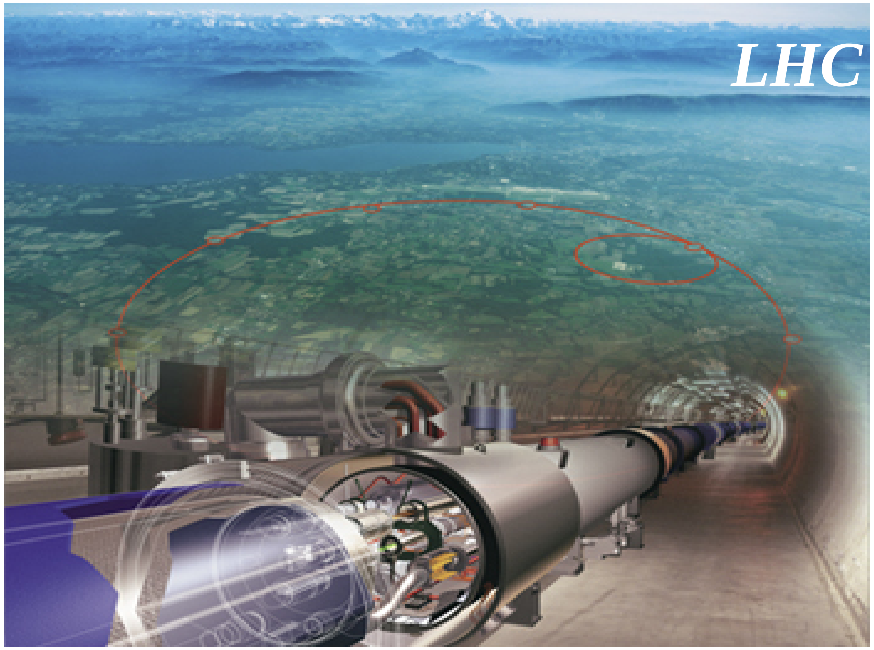


実験量の比較

Experiment	Acceptance (km^2 sr)	Assumed Operation	Energy Res. (%)	Total Exposure till 2016 (km^2sr year)	(in AGASA Unit)
AGASA	160	Completed		1.6×10^3	1
HiRes (@10^{19}eV)	3,000 (d.c.10%)	~2006		5×10^3 (Mono) 2.5×10^3 (x1.7) (Stereo)	~3.1 ~2.6
TA	~1,400 (~ 1 AGASA)	2007~	~20	1.5×10^4	9
Auger (Auger North)	7,800 (7,800) (~ 5 AGASA for each)	2006~ (2009~)	~15	8.6×10^4 ($+6.2 \times 10^4$)	54 (+40)
EUSO (@10^{20} eV)	600,000 (d.c. 10%)	2012~	20	3.0×10^5	187

LHCf: CERN LHCによる10^{17} eVでの相互作用モデルの検証

Calibration of the models at
high energy is mandatory



We propose to use LHC,
the highest energy accelerator

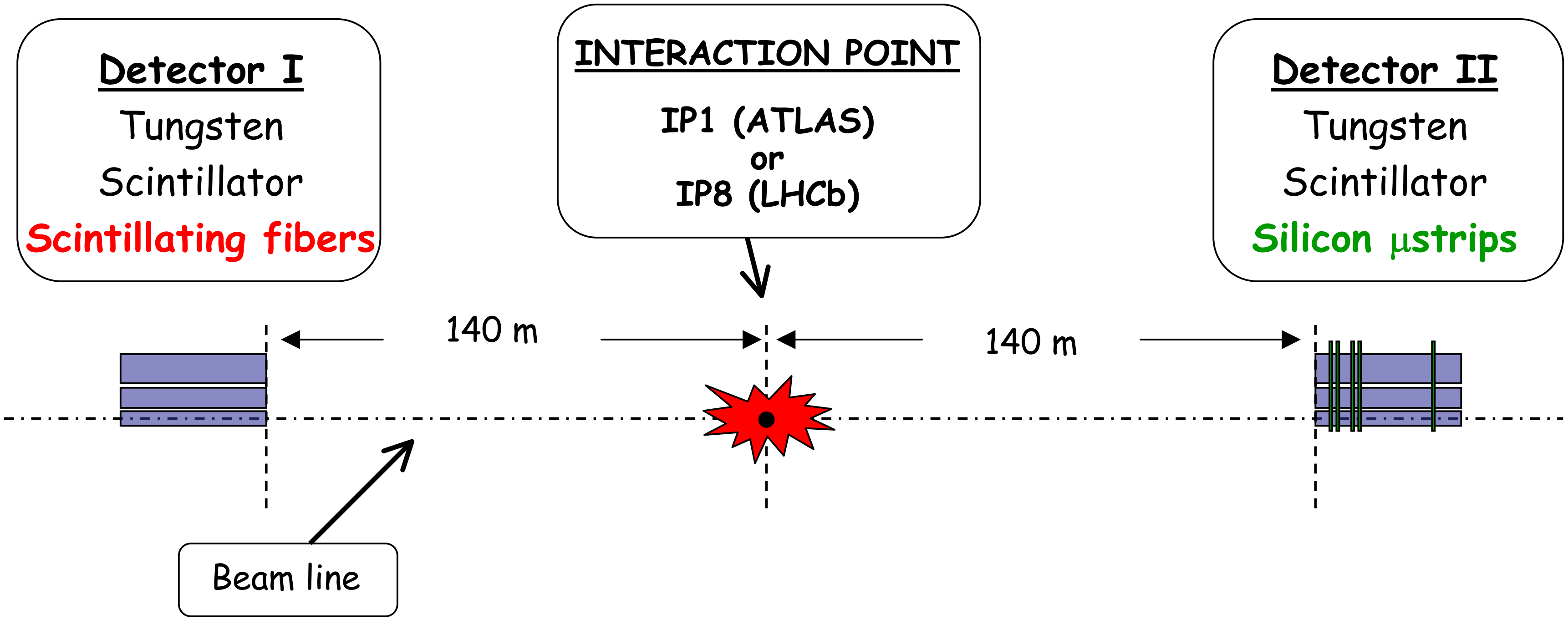
7 TeV + 7 TeV protons
14 TeV in the center of mass

$E_{lab}=10^{17}$ eV   ($E_{lab}= E^2_{cm}/2\ m_p$)

Major LHC detectors (ATLAS, CMS, LHCB) will
measure
the particles emitted in the central region

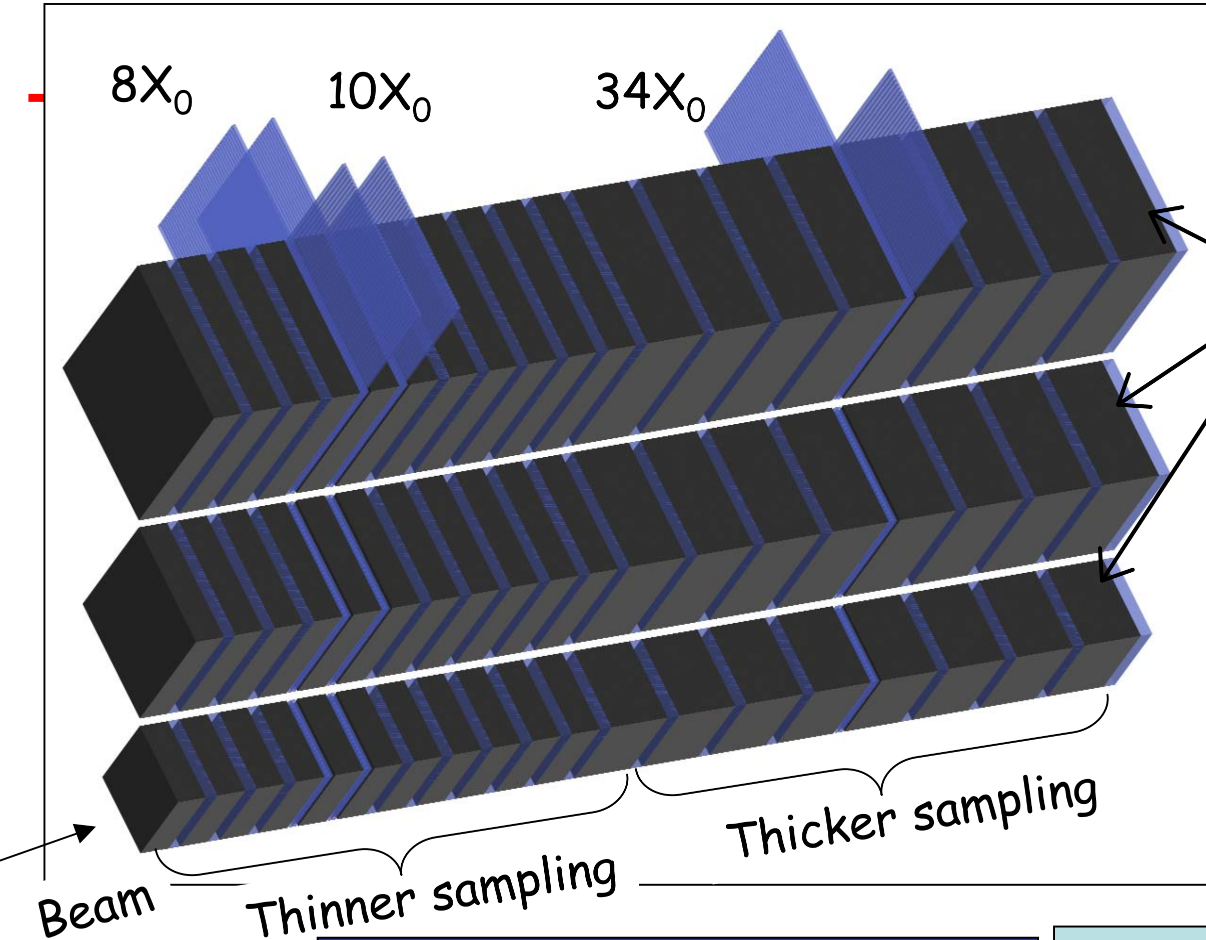
LHCf will cover the very forward part
May be also Pb-Pb collisions????

2 independent detectors on both sides of IPX



Detectors should measure energy and position of γ from π^0 decays ➡ e.m. calorimeters with position sensitive layers

Detector #1



3 towers with the same longitudinal structure but with different transverse dimensions

Dimensions max

(90 × 335 × 290) mm^3

Absorber

20 layers of tungsten, with different thickness (7 mm – 14 mm)

(W: X_0 = 3.5mm, R_M = 9mm)

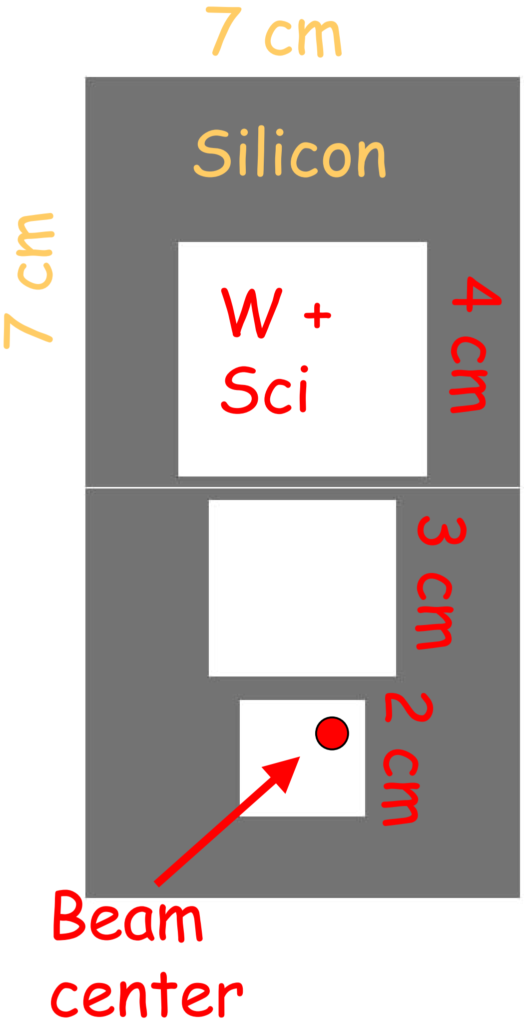
Scintillators

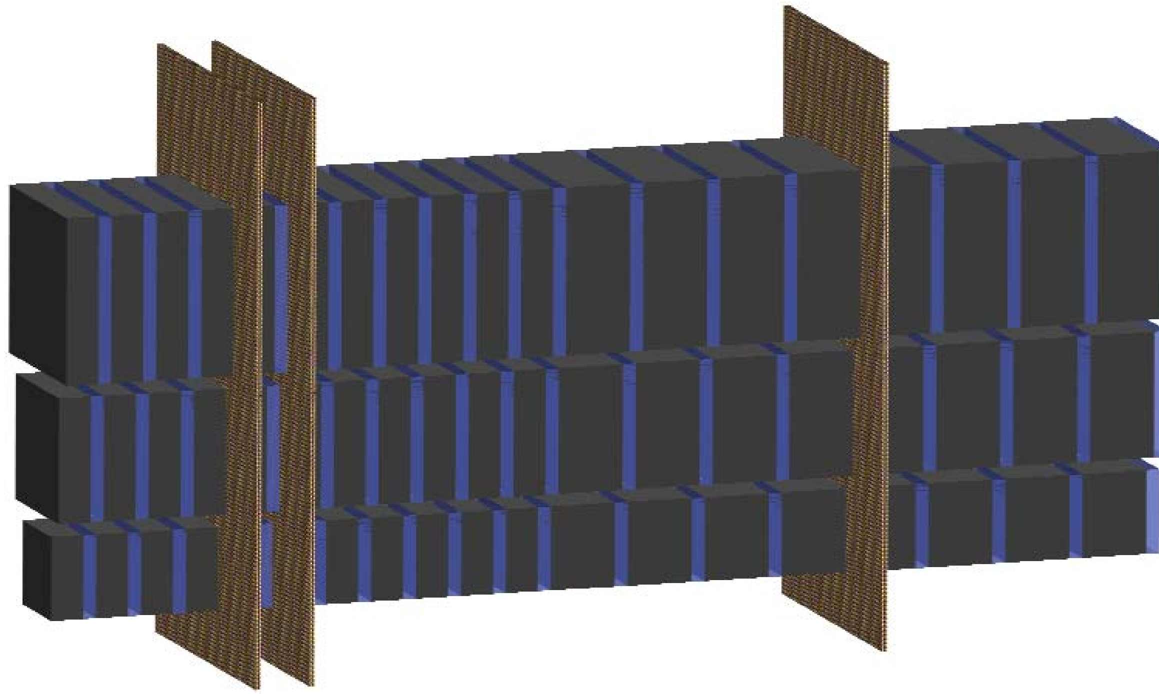
Trigger system and energy profile measurement: 3 mm plastic scintillator

Scintillating fibers

3 double layers of 1 mm^2 scintillating fibers to measure the transverse shower profile

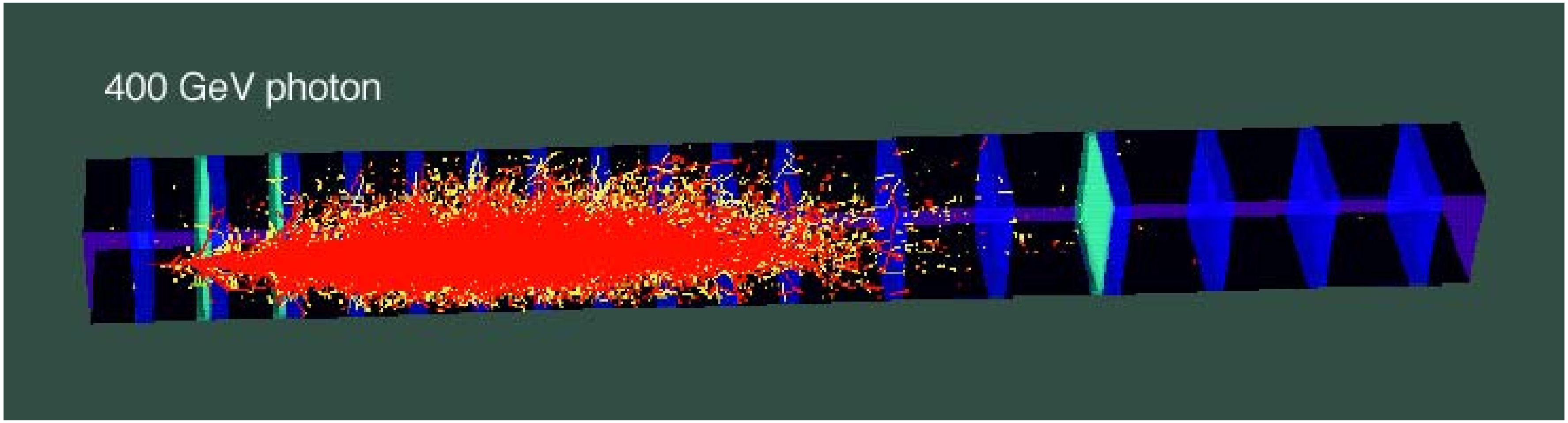
Detector #2

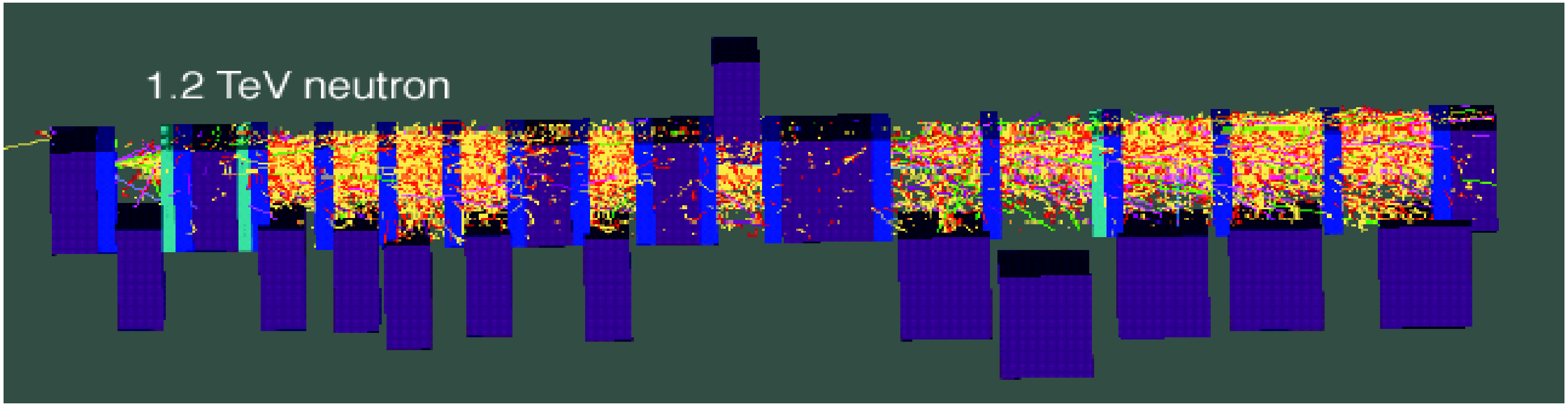




SciFi are replaced by silicon μstrips detectors
70x70 mm^2
Pitch 80 μm
3 double layers (x-y)
1 double layer in front of the calorimeter?

Particle discrimination





まとめ

- **最高エネルギー領域でのGZKカットオフの有無は、Auger+TAによるHybrid観測で今後2年間である程度明らかになるであろう.**

- **AGASAデータが確認されれば新しい物理が開かれる.**
  → AGASAの100倍規模の観測（~2016）で物理の内容が明らかなる？

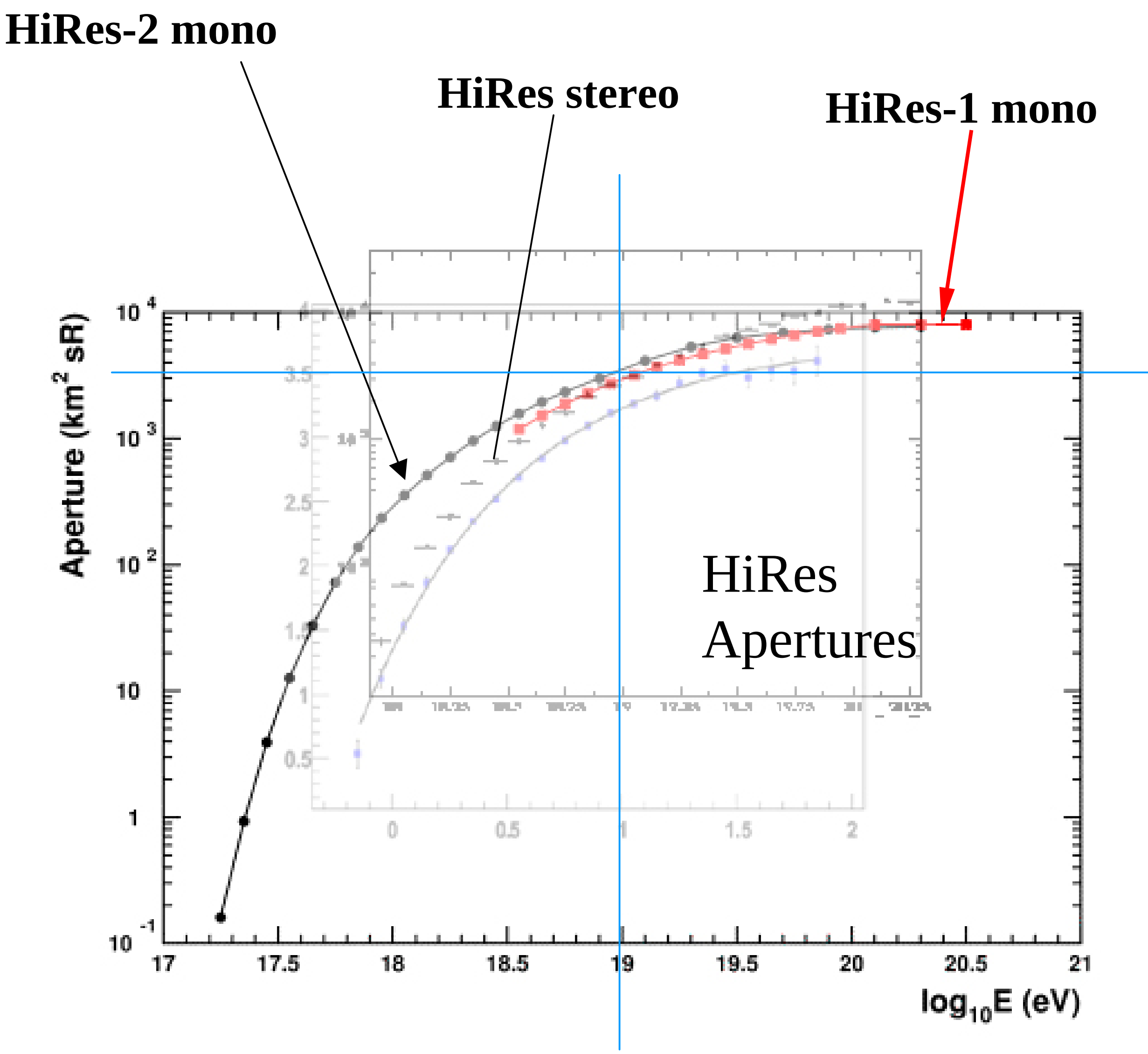
- **TAは北半球での観測として必須である. → Auger (North) との共同?**

- **EUSOは、2012年より大幅に観測開始が遅れると、重要なサイエンスを行うためにAugerの統計を有意に上回ることができない.**
  課題　1. Fly's Eyeの経験 → Stereo観測 （特に雲の影響） OWL?
  2. Energy Calibration
  3. エネルギー閾値をさげる → GZKの有無に関わらない観測計画

- **EeV領域でのニュートリノ、γ線の観測は極めて重要. → GZKパズルの後？**
  EAS detector, IceCube, ANITA etc.

HiRes Aperture

- **Stereo data**: best resolution, optimized for E>3×10[18]eV Uses time-dependent calibration of detector and atmosphere
- **HiRes-2 monocular**: can reach down to as low as 10[17.2]eV
- **HiRes-1 monocular** data began ~3 years earlier: largest statistics,
  - Uses profile constrained fit (PFC) unreliable <10[18.5]eV



2000.12.5

Yoshida et al PRD 69 103004 (2004)