AGASA

Akeno Giant Air Shower Array

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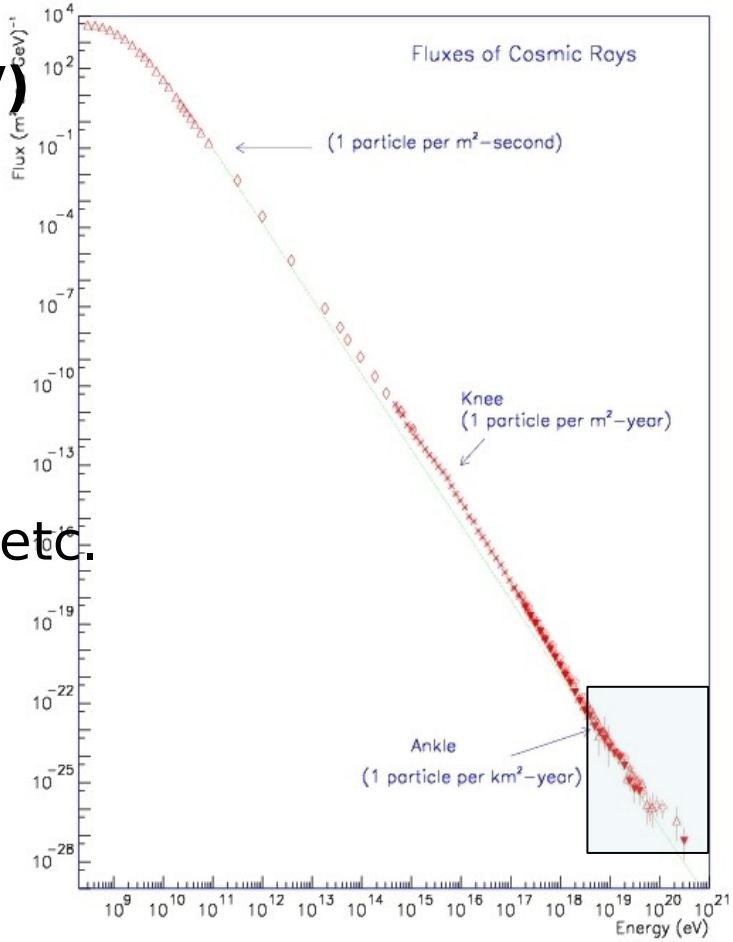
Outline

- **Introduction**
  - Physics motivation
  - Apparatus of AGASA
- **Results from standard analysis**
  - **Energy spectrum of UHECRs**
  - **Anisotropy**
    - Large scale anisotropy in 10^{18}eV energies
    - Small scale anisotropy in GZK energies
  - **Chemical composition**
    - Gamma-ray 1ries limit
- **Energy spectrum based on CORSIKA Sim.**
- **Summary & Outlook**

Physics motivation

- **Nature & origin of UHECRs (>10^{19}eV)**
  - Energy spectrum
  - Arrival direction distribution
  - Chemical composition
- **Proposed models**
  - ***Bottom-up*** scenarios
    - BL Lacs / GRBs / Galactic clusters etc.
      → Hadronic primaries predicted
  - ***Top-Down*** scenarios
    - Topological defects
    - Super heavy dark matter
    - Z-burst
      plus Gamma-ray 1ries predicted

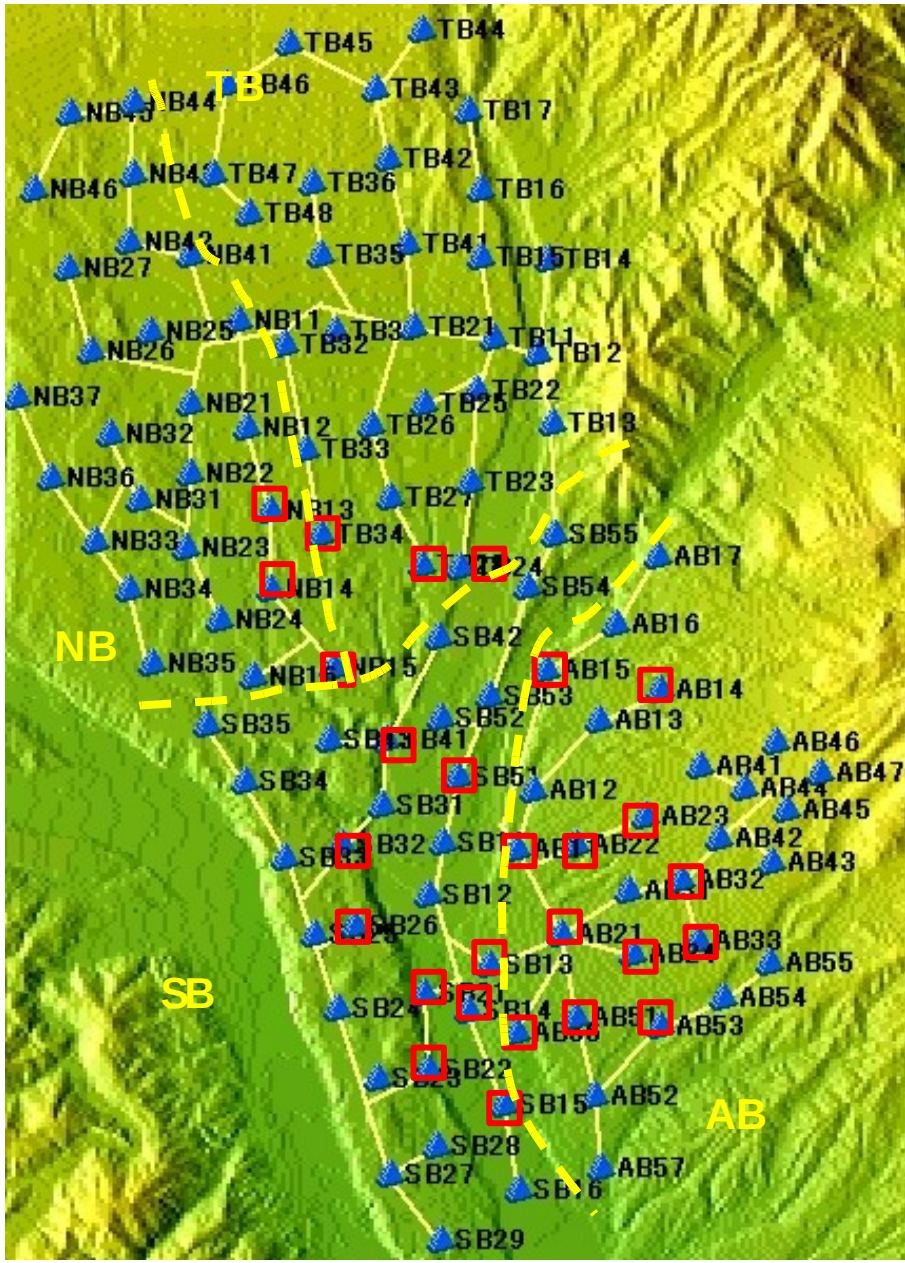


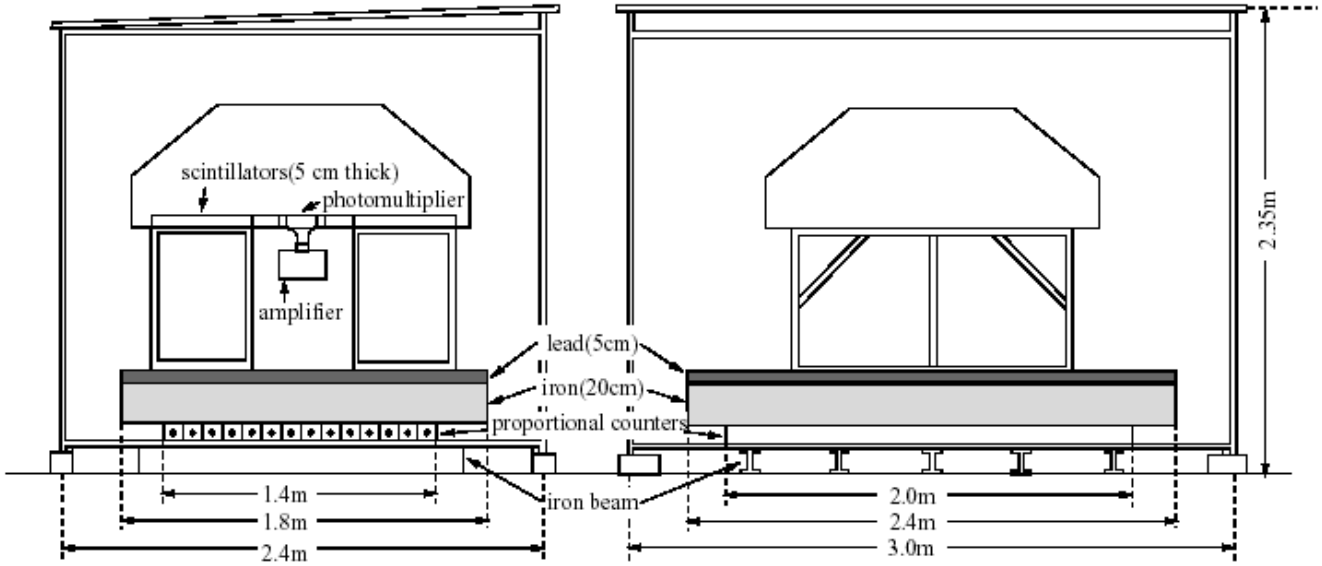
$p_{UHECR}\ \gamma_{CMB} \rightarrow N\ \pi^{+}$
($E_0 \sim 5 \times 10^{19}$eV)

AGASA (Akeno Giant Air Shower Array)

- 35°7N 138°5E 900m asl.
- **Detector station**
  - 111 surface detectors
    - Effective area ~100km²
    - Optical fibre cable connection to observatory

    Triggered by 5-neighbouring hit detector within 25μs
  - 27 muon detectors
    - Southern region ~30km² coverage
- **Operation**
  - Feb. 1990–Dec.1995 4 separate-array operation
  - Dec. 1995–Jan.2004 **Unified operation**

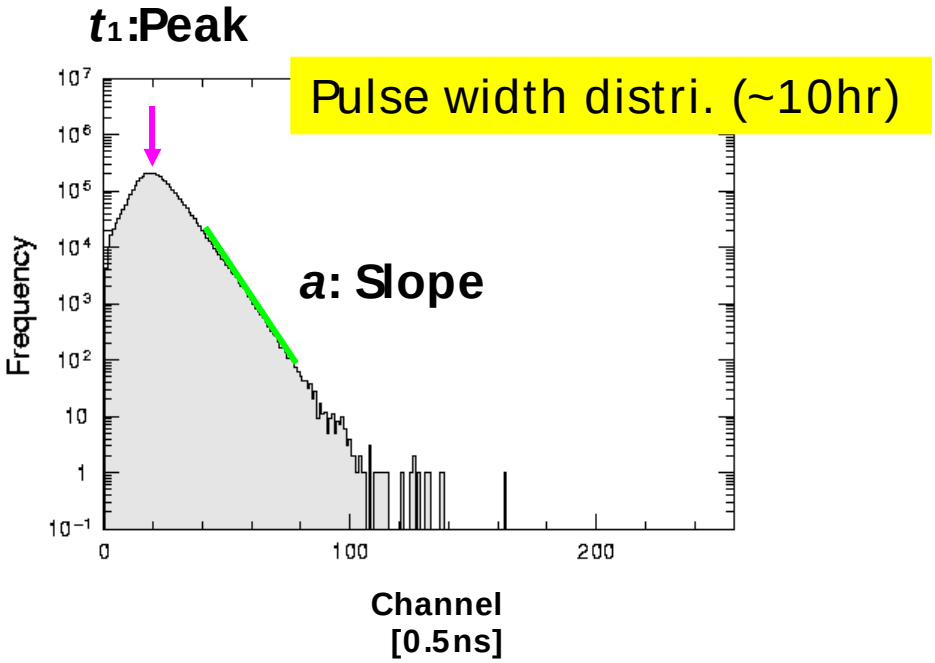


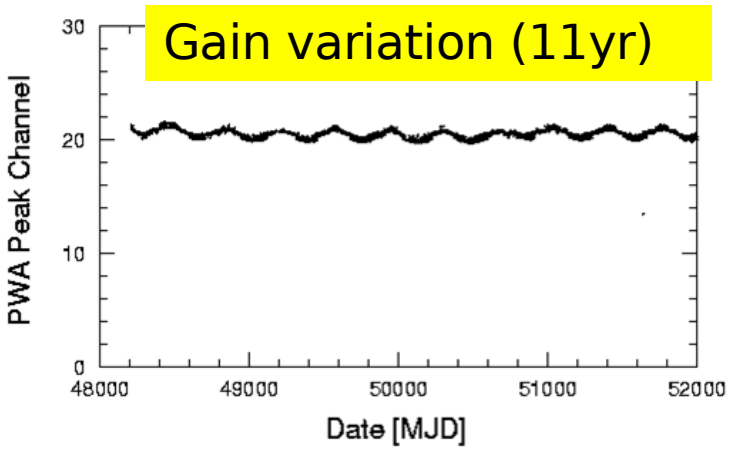


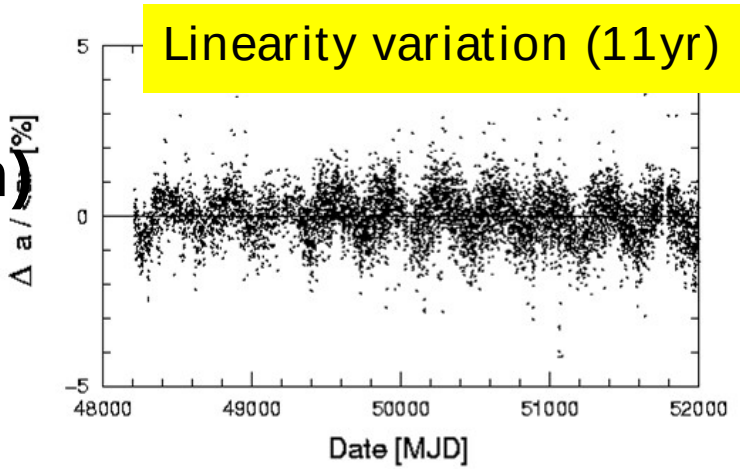
- **Surface detector**
  - 5cm thick scintillator
  - Hamamatsu 5” R1512 PMT

- **Muon detectors** (2.8–10m^2;south region)
  - 14–20 Proportional counters
  - Shielded by 30cm Fe or 1m concrete
    - Threshold energy: 0.5GeVxsecθ
  - Triggered by accompanying surface detecto

Detector calibration



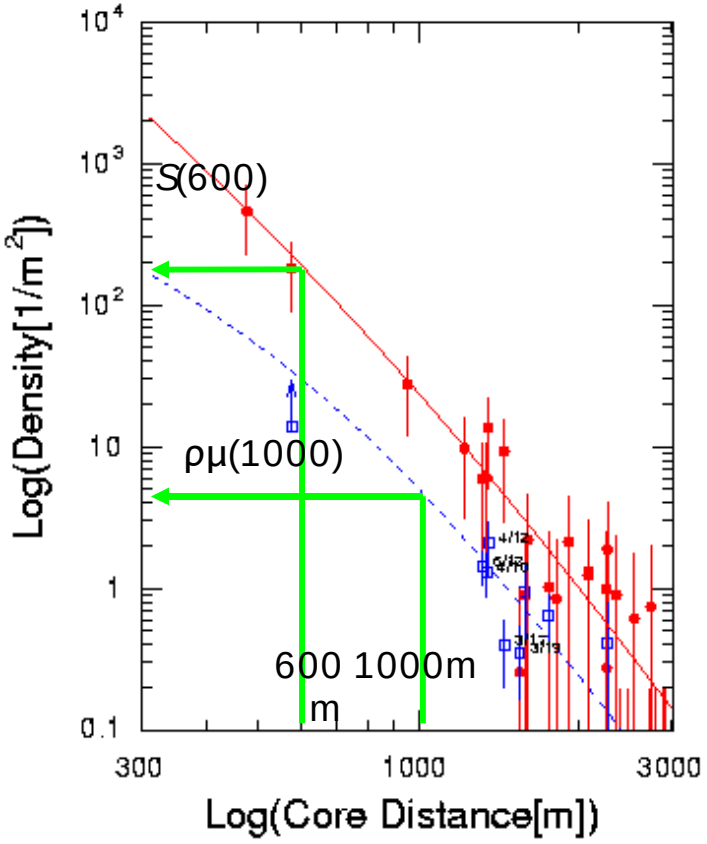


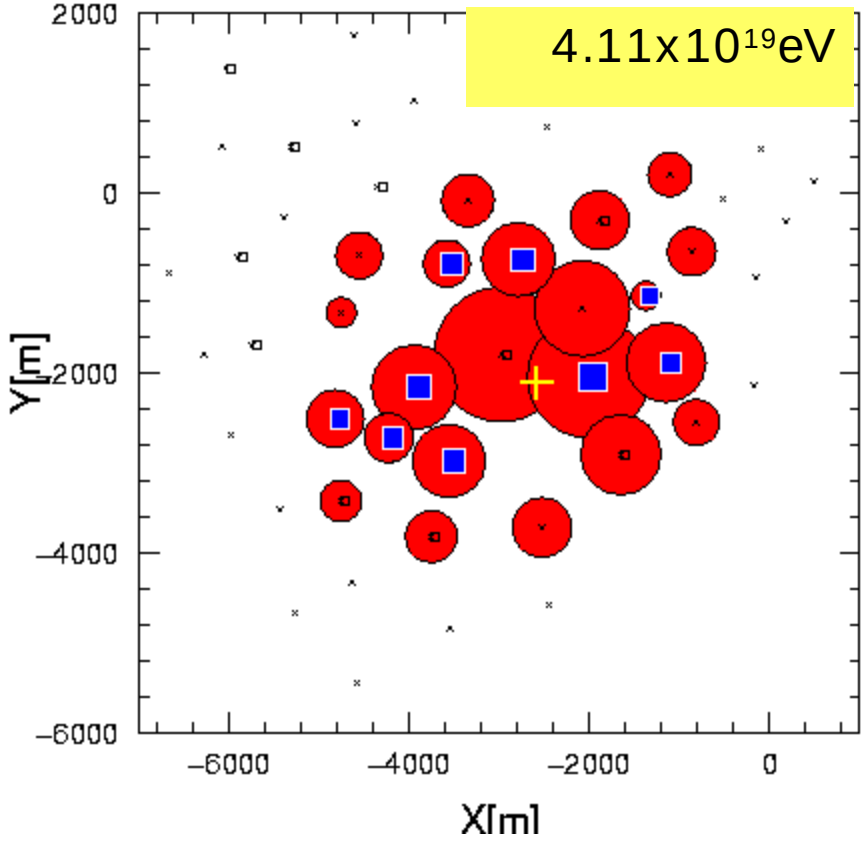


- **PWD monitored every RUN (~10h)**
  - Info taken into account in analysis
- **Stability of detector**
  - Gain variation (peak of PWD) :± 0.7%
  - Linearity variation (slope of PWD) :± 1.6%

Cf. $\Delta\tau/\langle\tau\rangle = -\Delta a/\langle a\rangle$

Event sample & observables





- Energy estimator (charged particle density @600m): $S(600)$
- Primary mass estimator (muon density@1000m): $\rho_\mu(1000)$

Event selection criteria (standard)

Dataset: February 1990 – January 2004

- Energy: $\geq 10^{17}$eV ($\geq 10^{18.5}$eV for spectrum)
- Zenith angle: $\leq 45°$
- Core location: inside AGASA boundary
- Number of hit detector ≥ 6
- Good reconstruction
  - $\chi^2 \leq 5$ for arrival direction fitting
  - $\chi^2 \leq 1.5$ for core location fitting

Event reconstruction

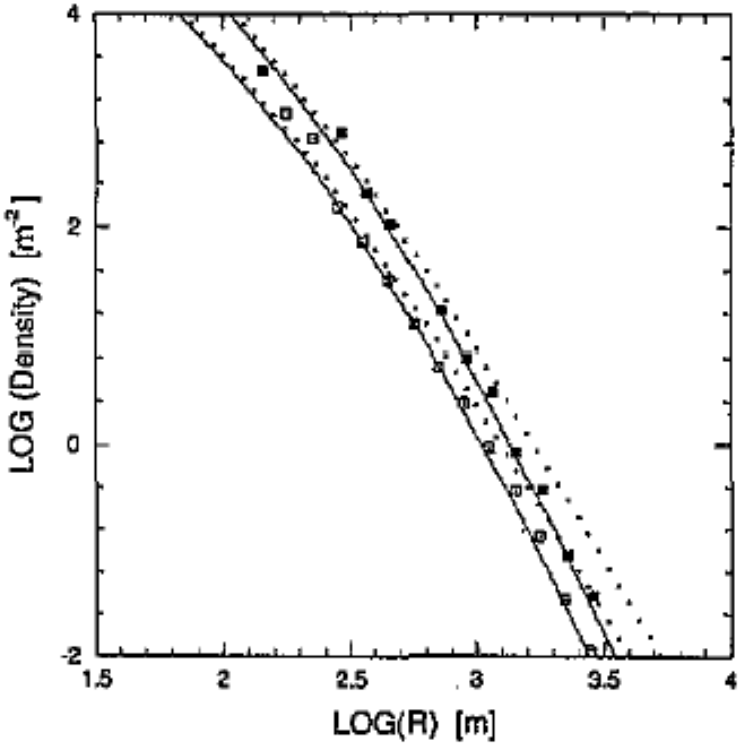
- Centre of gravity in charged particle density distribution$\rightarrow$ a priori core location

- Geometry fitting
  - Arrival direction optimisation (fitting shower front structure)
  - Core location estimation (fitting lateral distribution)
  - Iterative recalculation of fitting processes till satisfying quality cuts (otherwise rejected)

- S_{θ} (600)$\rightarrow$ S_0 (600) translation

- Energy estimation by S_0 (600) vs. E_0 relation

Lateral distribution (empirical)



$\sec\theta \leq 1.1$

$S(600) = 10{,}30\,[m^{-2}]$

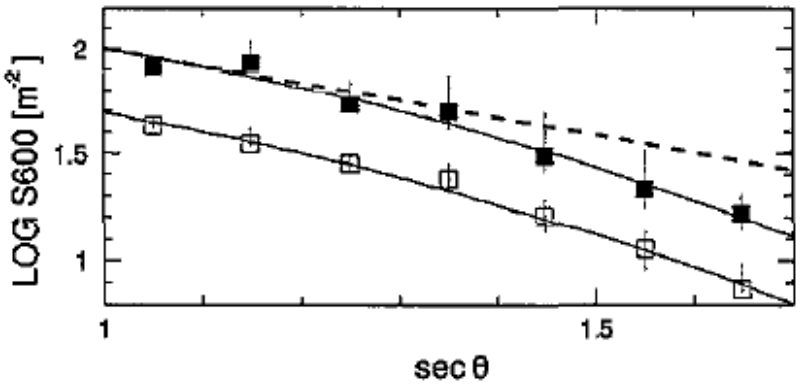
- ***Modified* Linsley formula**

$$\rho(R) = C\,(R/R_M)^{-\alpha}\,(1+R/R_M)^{-(\eta-\alpha)}\,\{1+(R/1000)^2\}^{-\delta}$$

  - C: Normalisation constant, $\alpha=1.2$, $\delta=0.6$
  - R_M: Moliere unit @ Akeno (=91.6m)
  - $\eta = (3.97\pm0.13) - (1.79\pm0.62)\,(\sec\theta - 1)$

Energy estimating relationships

- **Energy vs. S(600) for vertical showers**
  - Dai *et al.*'s MC result by COSMOS+QCDJET (1988)
    E_0 [eV] = 2.03×10^{17} S_0 (600)
- **S(600) Attenuation curve**



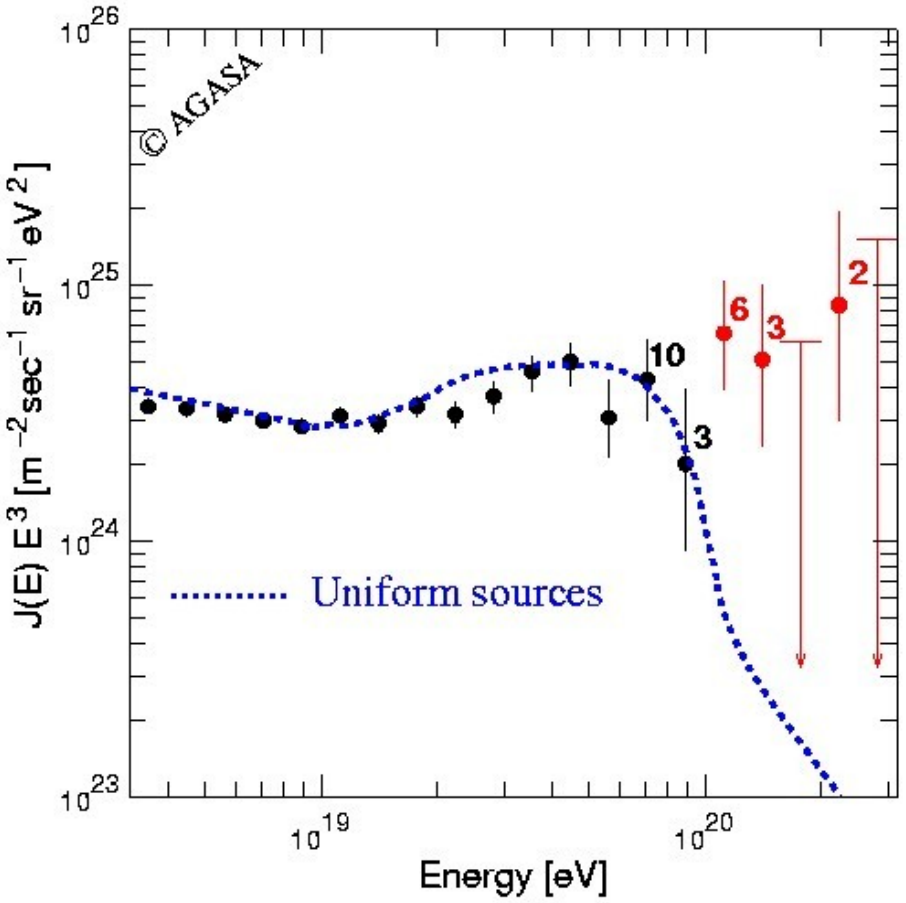
2×10^{19}eV
1×10^{19}eV

  - **Empirical relationship** (equi-intensity cut method)

$$S_\theta(600) = S_0(600)\exp\{-X_0/\Lambda_1(\sec\theta-1) - X_0/\Lambda_2(\sec\theta-1)^2\}$$

    - X_0: Atmospheric depth @ AKeno (920 g/cm^2)
    - Λ_1 = 500 g/cm^2
    - Λ_2 = 594 g/cm^2

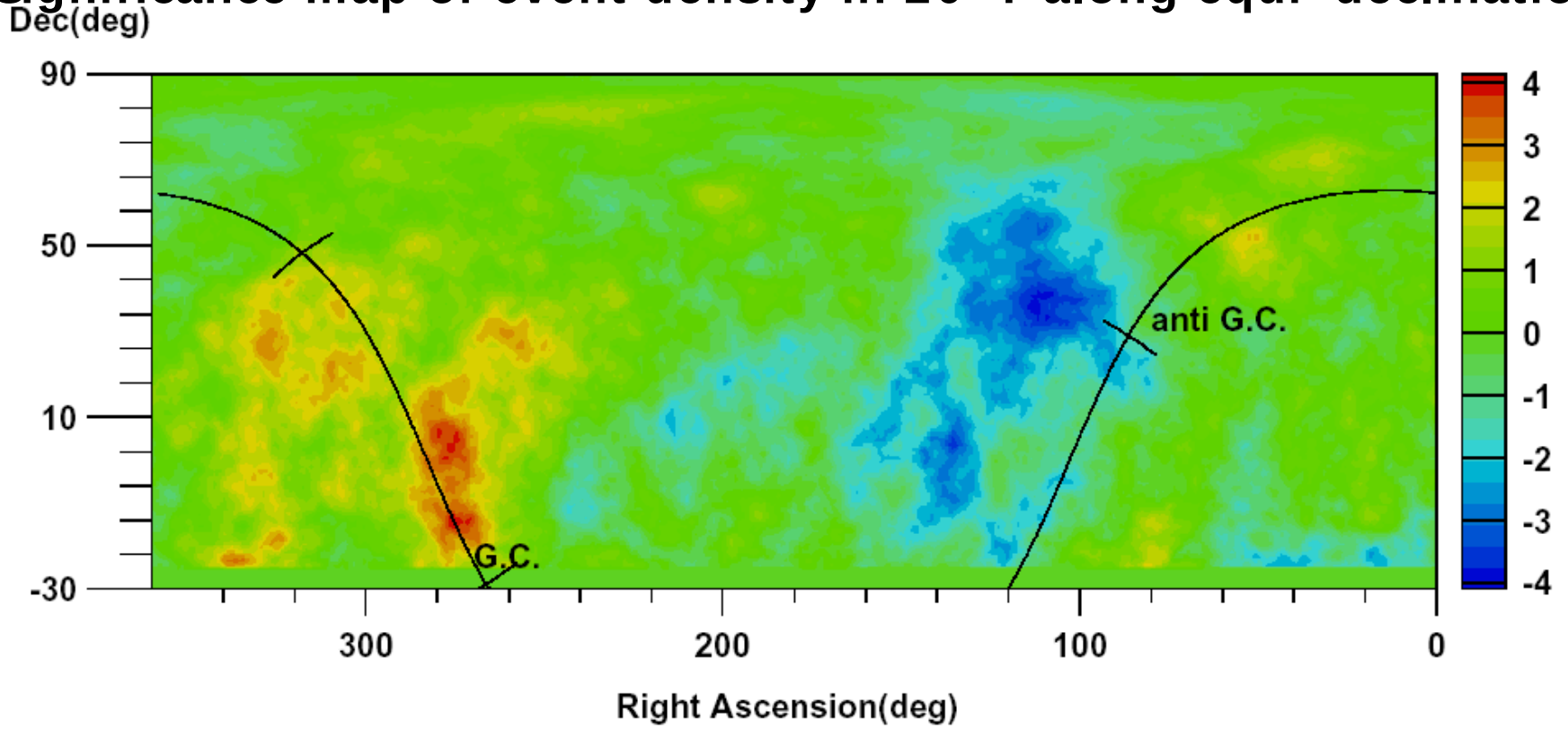
Energy spectrum (θ< 45°)



- 11events above 10^{20}eV
- Exposure: 5.8×10^{16} [m^2 s sr] ~18.4 km^2 century sr

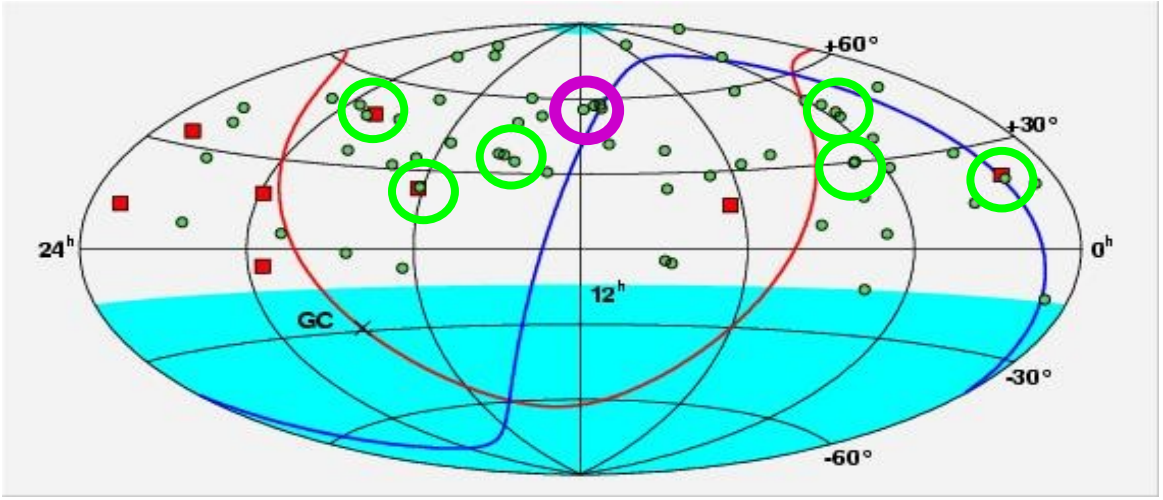
Anisotropy around 10^{18}eV

Significance map of event density in 20°Φ along equi- declination

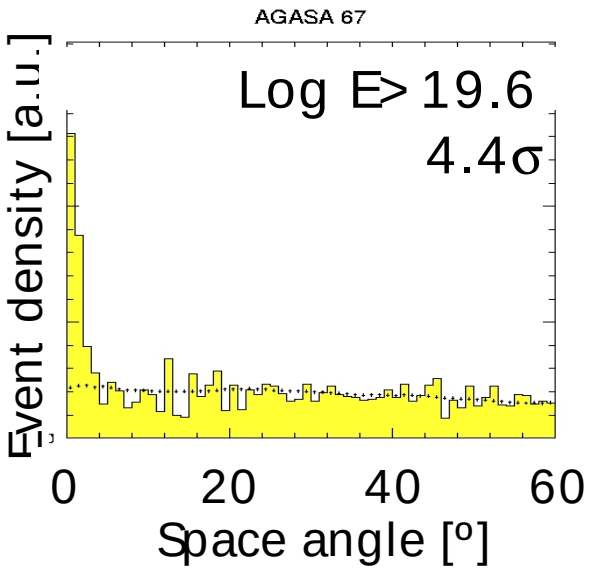


- **Large scale anisotropy clearly found**
  - **~4σ excess @~ Galactic Centre**
  - **~4σ deficit @~ anti- Galactic Centre**
  - **Implication of Galactic cosmic rays up to 10^{18}eV**

Arrival direction distribution
(> 4x10^{19}eV; θ< 50°)

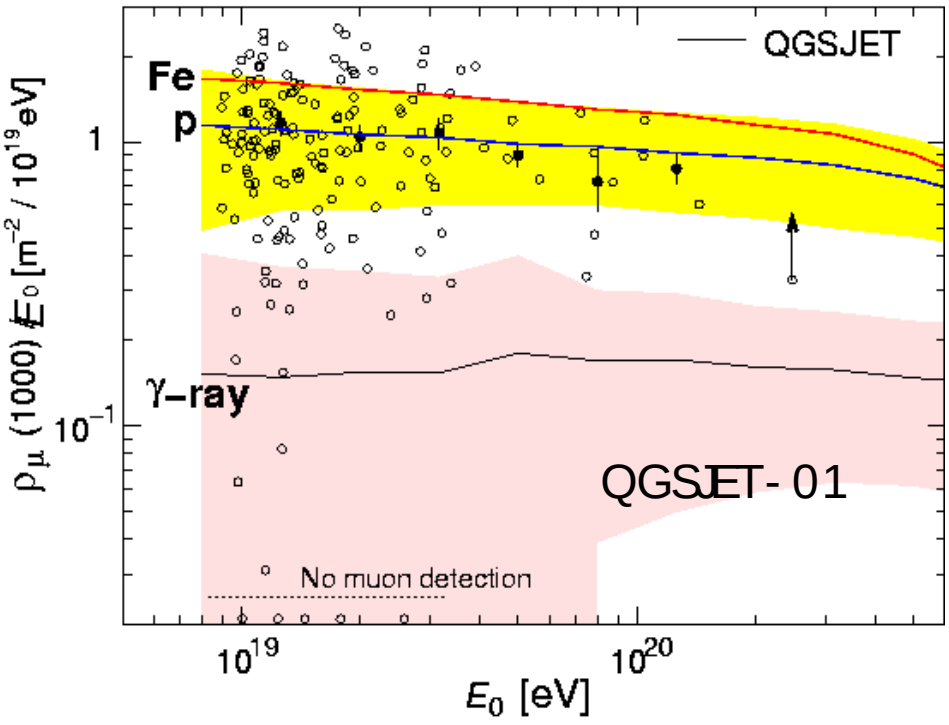


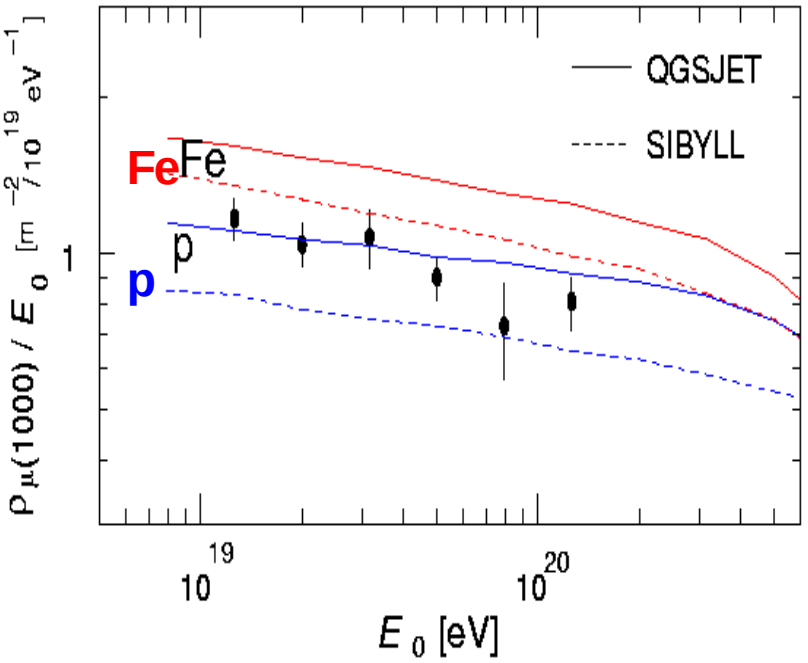
●:4x10^{19} – 10^{20}eV ■:> 10^{20}eV



- **Small scale anisotropy**
  - Event clustering (> 4x10^{19}eV within 2.5°)
    6 doublets (○) &1 triplet (○) observed
    - Against expected 2.0 doublets (P_{ch} < 0. 1%)

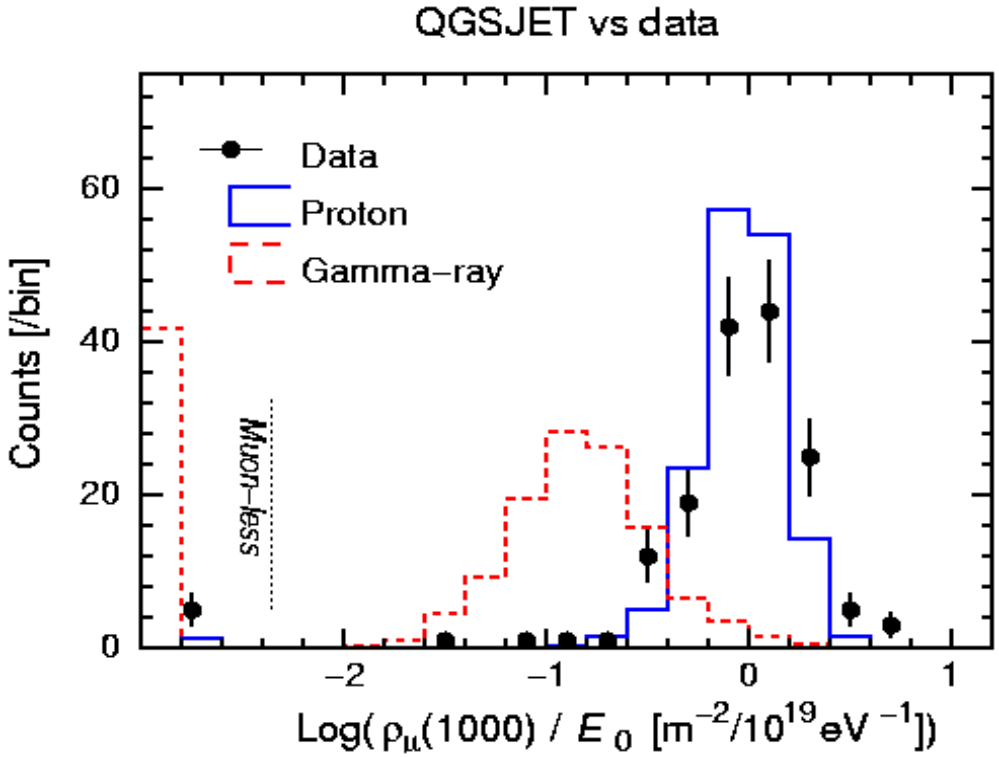
Muon component (vs CORSIKA)





- Average $\rho\mu$ (1000) vs energy (θ<36°)
  - $\rho\mu$ (1000) [m^{-2}]= (1.34±0.12) (E_0 / 10^{19}eV)$^{0.75\pm0.08}$
  - Consistent with p+QGSJET or mixed+SIBYLL

ρμ (1000) distribution

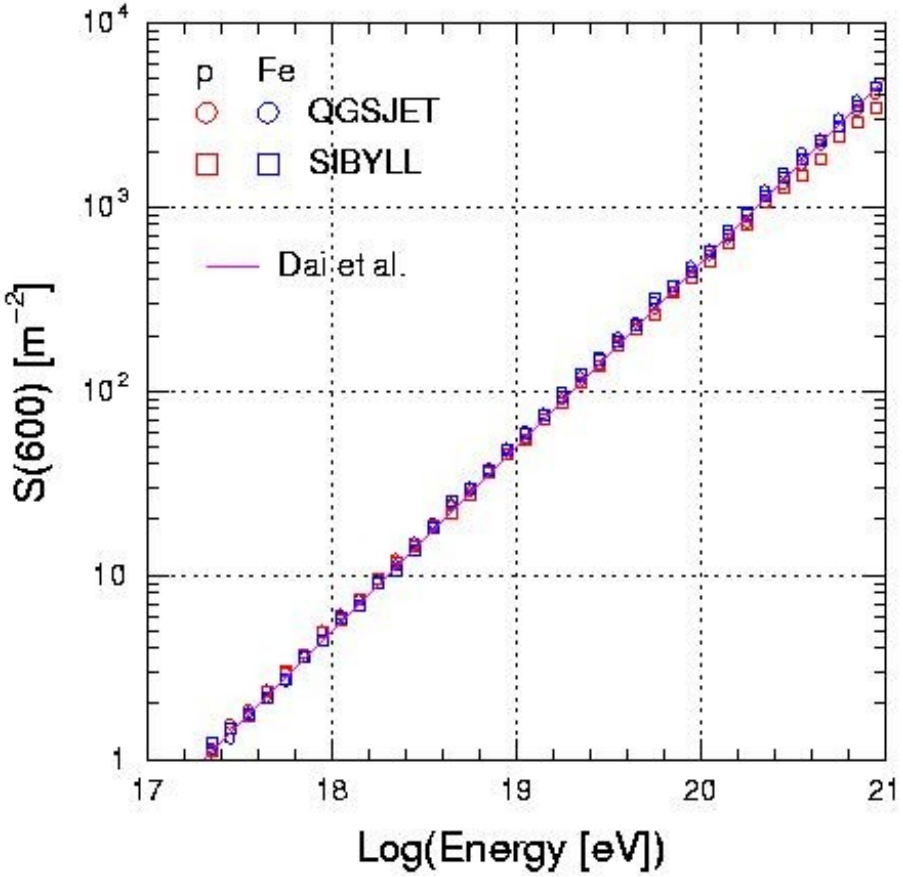


- Assuming p+gamma-ray composition
  - Fraction of gamma-rays
    - 43% (>$10^{19.5}$ eV) @ 95%CL (QGSJET01)

Re-analysis scheme MC-based

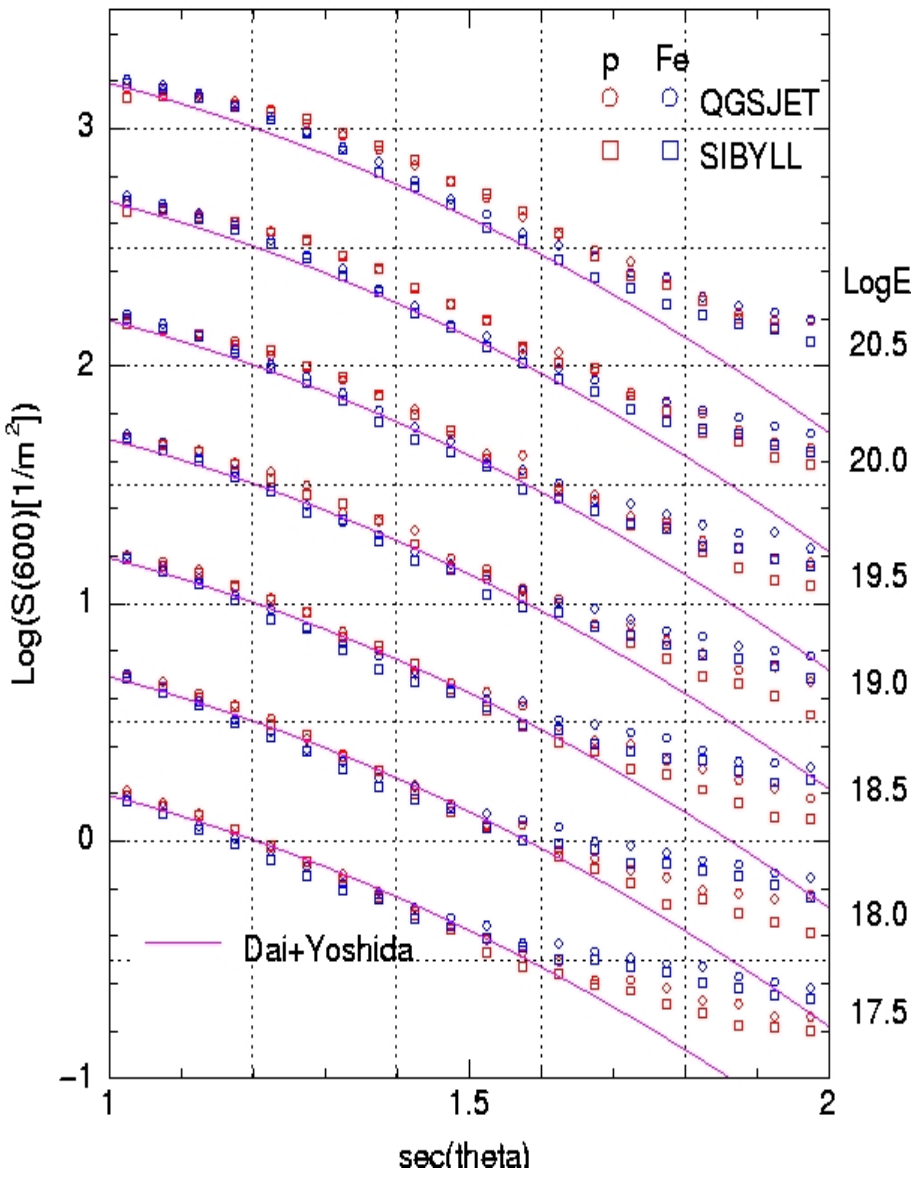
- **Simulation**
  - CORSIKA version 6.203
  - Interaction models
    - QGSJET01 & SIBYLL
  - Detector simulation with GEANT
  - Artificial shower data analysed by 'standard' reconstruction programme but...
    assuming MC-based results of:
    - Shape of lateral distribution
    - Attenuation correction
    - Energy conversion with CORSIKA results

$S_0(600)$ vs energy by CORSIKA



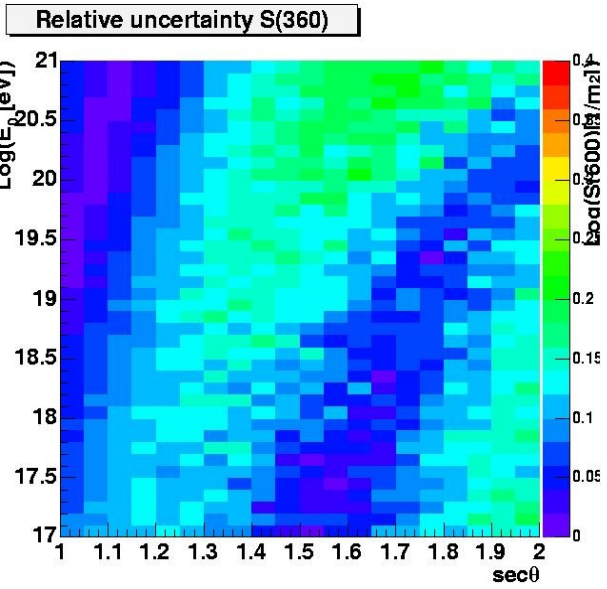
- Vertical showers
  - Consistent with conventional formula
    E_0 [eV] = (1.98±0.30) x 10^{19} (S_0(600)/100m^{-2}) $^{1.01}$

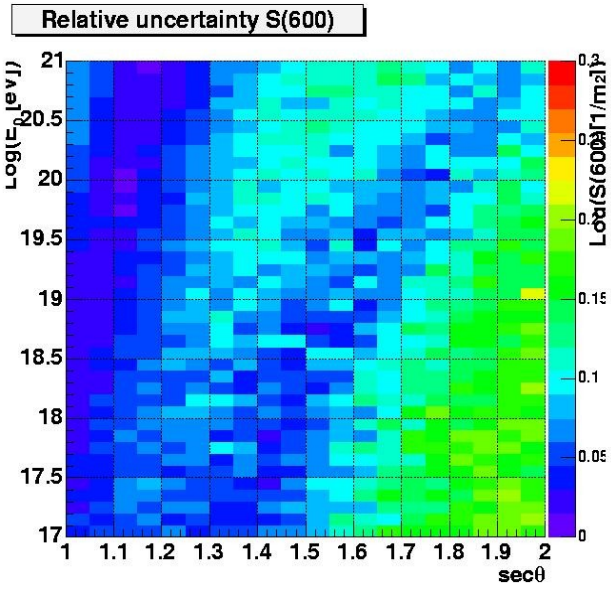
S(600) attenuation by CORSIKA

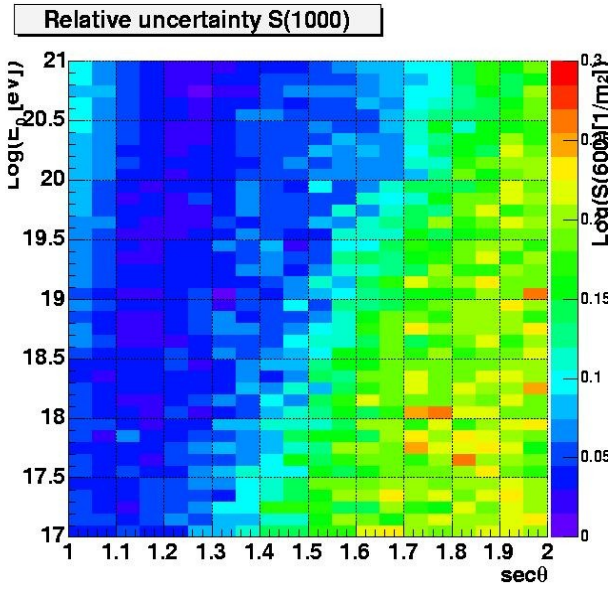


- Consistent with empirical formula around 10^{19}eV
- 1ry dependence esp. at large zenith angles
  - p+SIBYLL
    - Slowest developing
  - Fe+QGSJET
    - Most developed
- Trend of E_0 dependence
  - Flattening at highest energy regions

1ry/model uncertainty vs. zenith angle and energy



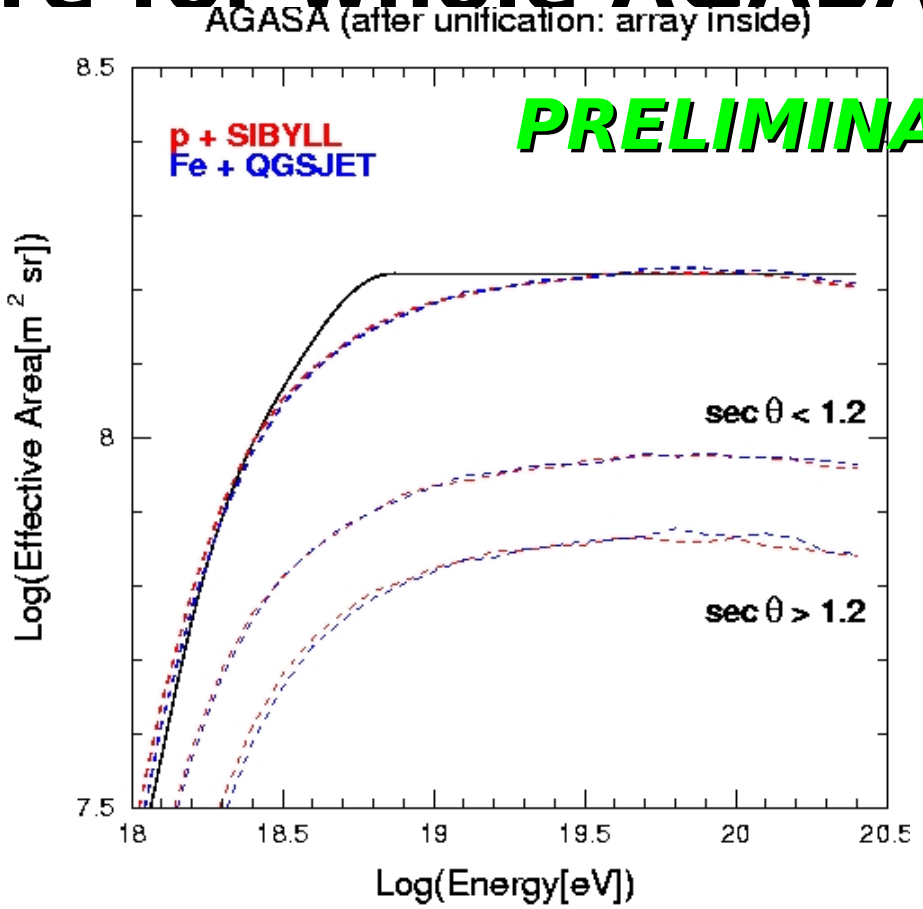




- Most stable distance and angle varying as energy

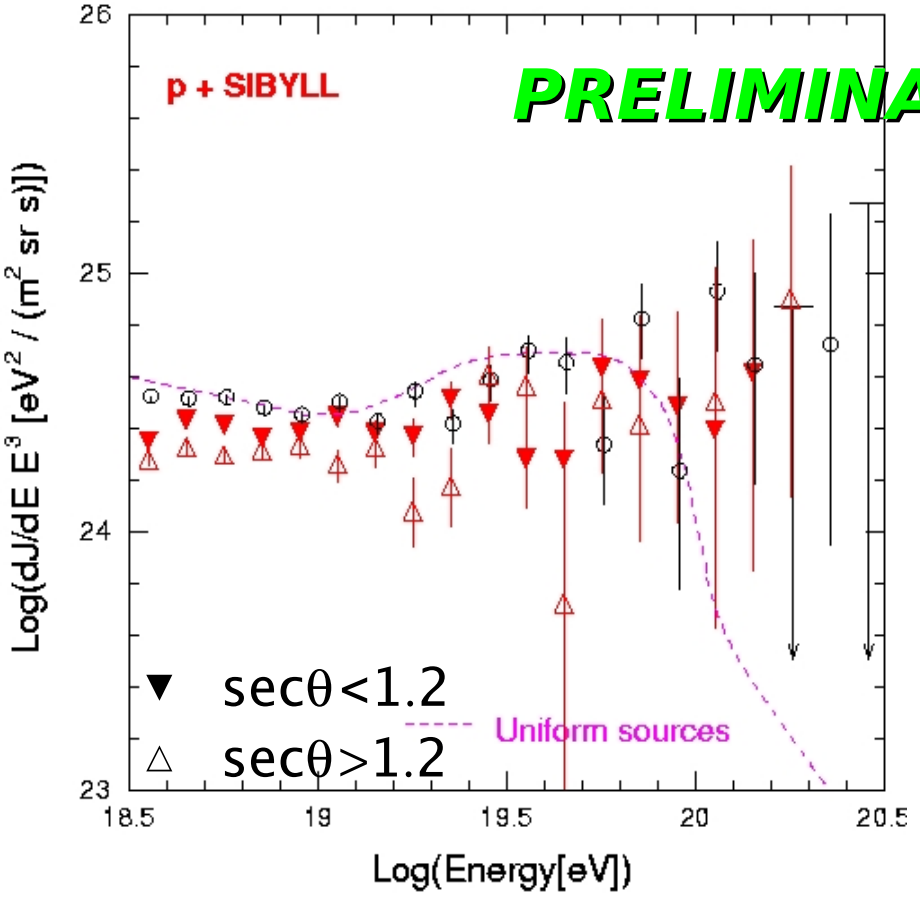
  This paticular study: we emply *S(600) converting at 33.5 deg. (sec(theta)=1.2)*

Aperture for whole AGASA-inside

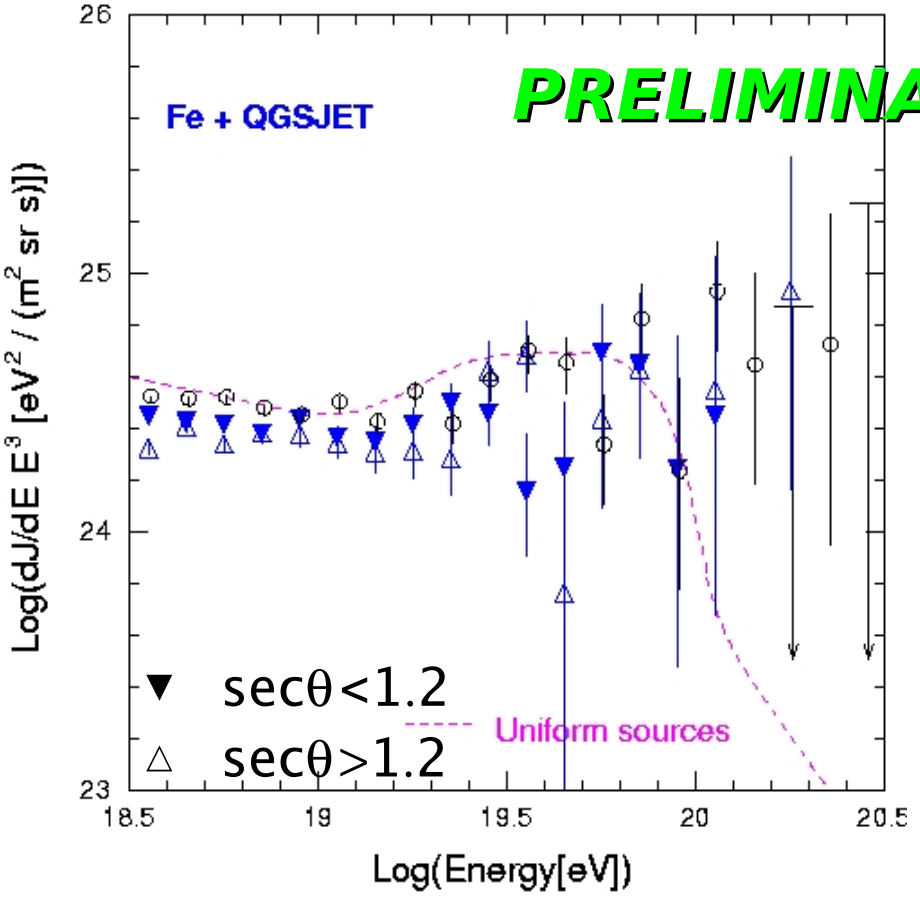


- Evaluated from analysing artificial showers by CORSIKA

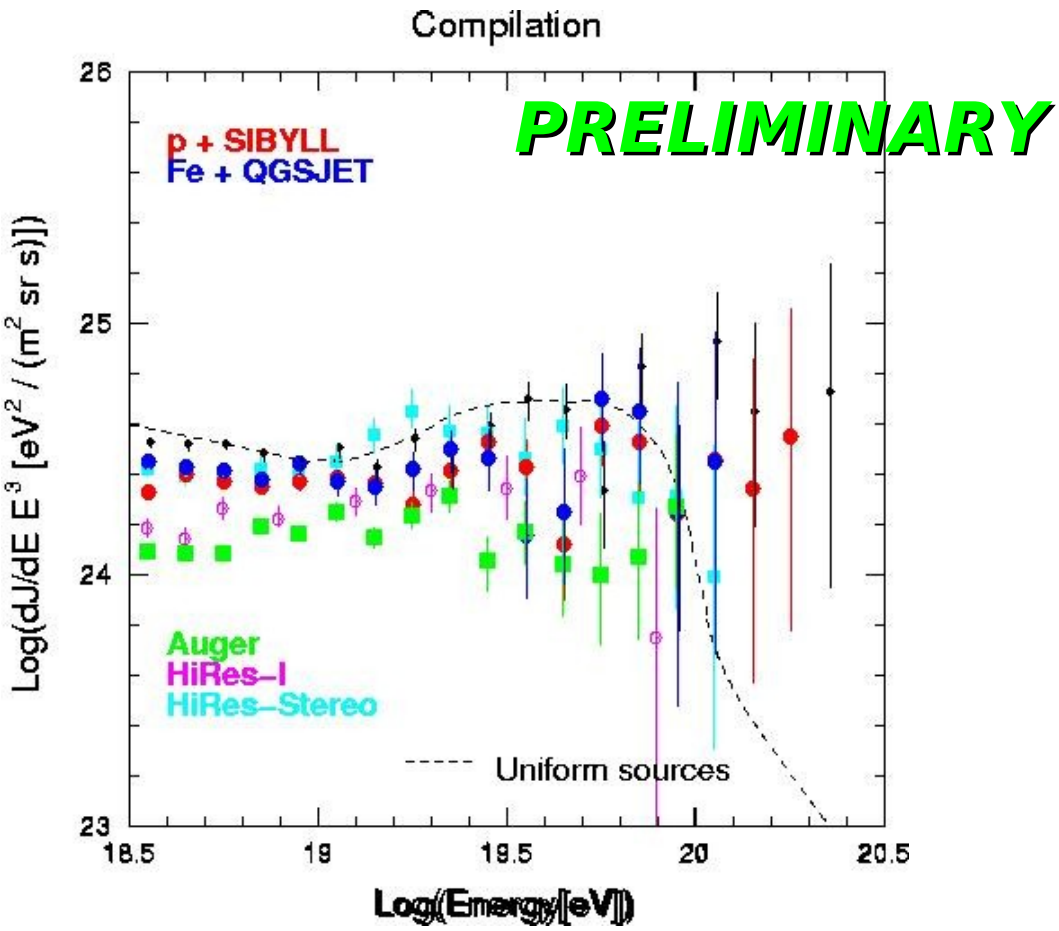
Spectra@low & middle zenith angles (MC-derived vs standard)



Spectra@low & middle zenith angles (Fe+OGSIET vs standard)



Compilation



- 6 / 5 events above 10^{20}eV for p+SIBYLL/Fe+QGSJET
- Conclusion (y/n) against GZK-cut off still open from present re-analysis

Summary

- AGASA Experiment (1990—2004)
  - 14 years stable observation ($5.8 \times 10^{16} m^2$ s sr@10^{20}eV)
  - ~1000 evens observed above 10^{19}eV
- Standard analysis
  - Eleven events above 10^{20}eV
  - Characteristic anisotropy
    - Events cluster (6 doublets + 1 triplet) above 4×10^{19} eV
    - Excess @~Galactic Centre in 10^{18} eV energies
  - Muon component
    - Gamma-ray fraction <43%@95%CL (>$10^{19.5}$ eV)
- PRELIMINARY results form *re*-analysis study (2006)
  - MC-based S(600) -> energy estimation giving lower E_0
    From CORSIKA 6.203 (QGSJET01 / SIBYLL2.1) tested
  - Current result not conclusive to (dis-/)prove GZK cut-off
    5 or 6 events remain >100EeV
  - Checking consistency in shower cahracateristics
    with experimental data to be done