New Results on the Highest Energy Cosmic Rays

American Astronomical Society 200^{th} Meeting

Albuquerque, New Mexico

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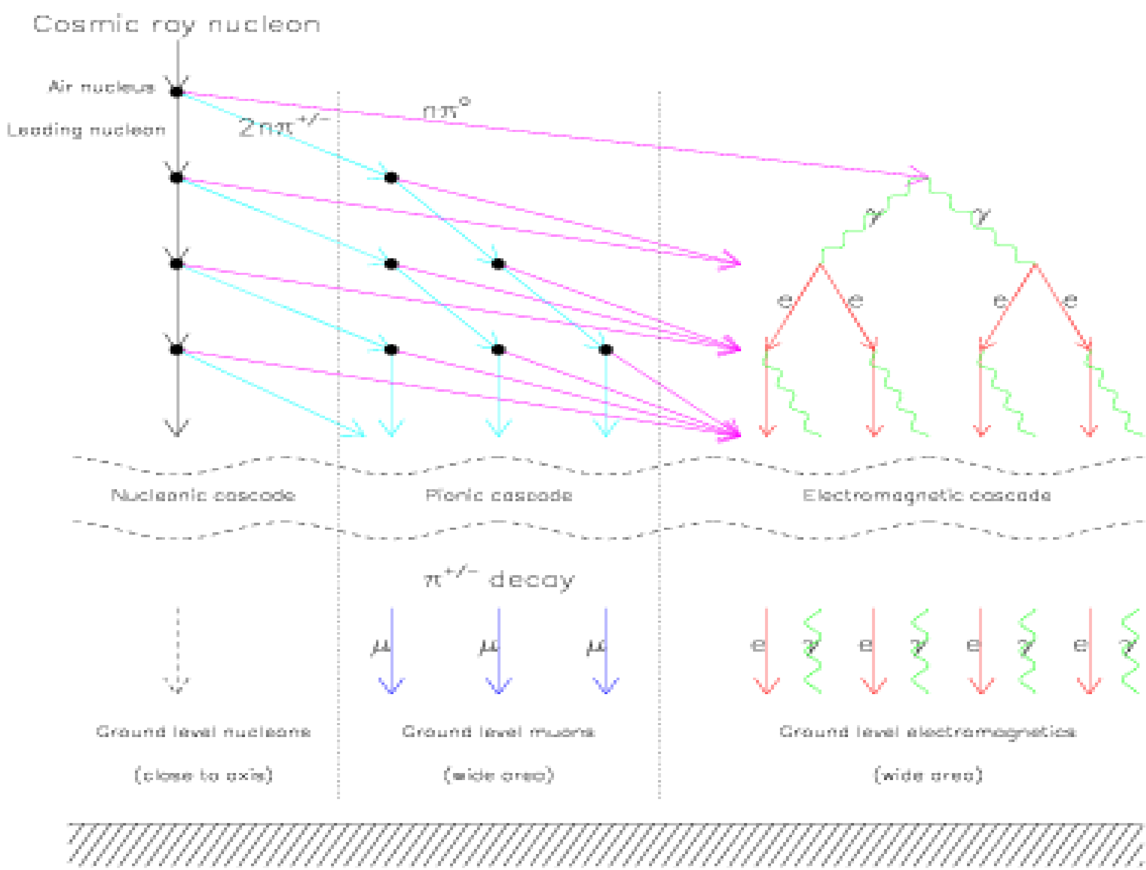
1. Background ... highest energy cosmic rays
2. Status ...
3. New results ...
4. Emerging model ...
5. Next step ...
6. Summary ...

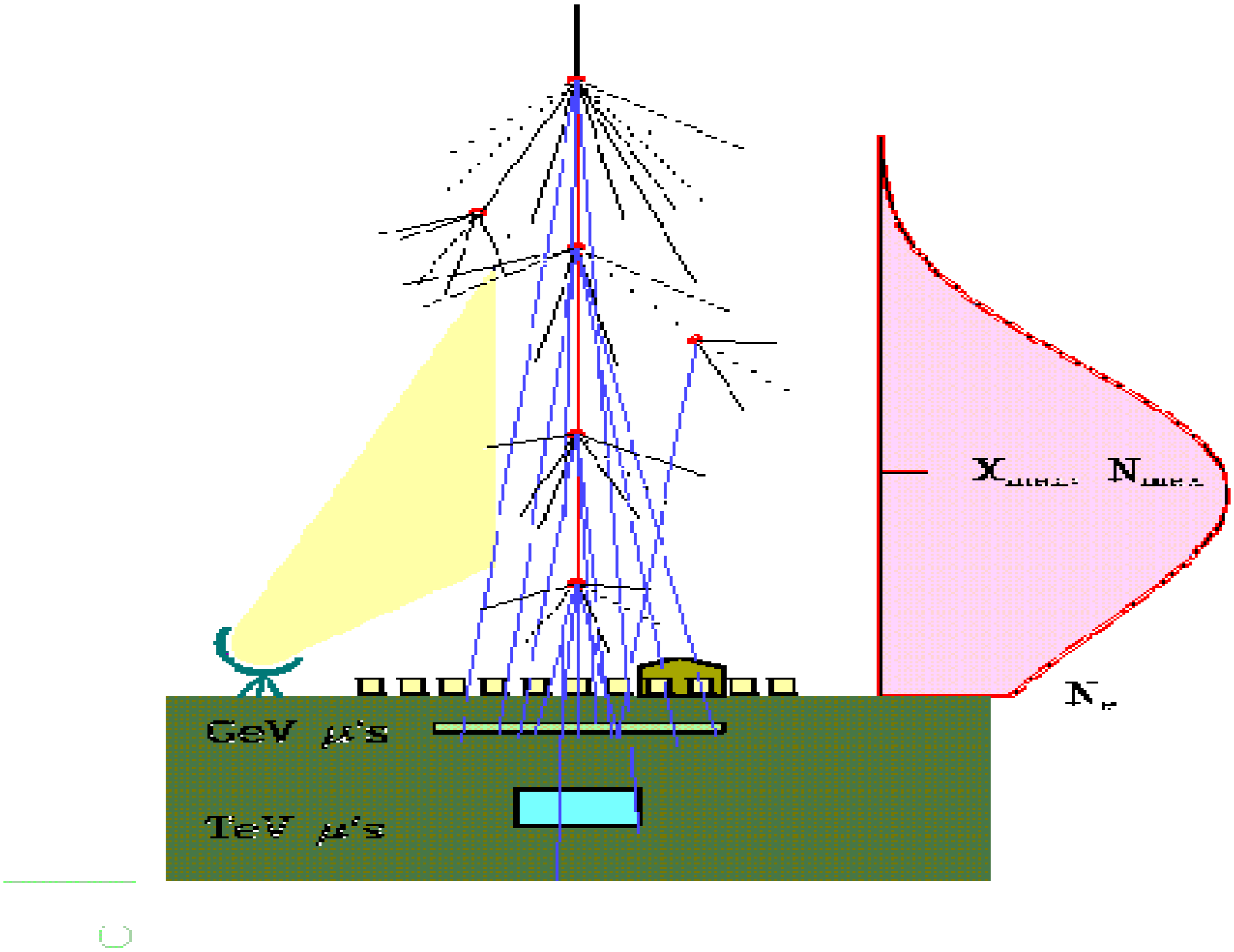
1. Background ... highest energy cosmic rays



Schematic of extensive air shower cascade

- **Energy scale:** - 10^{20} eV $\approx$ 16 Joules **...** <u>well</u> above future collider energies.
  1. cosmic rays are ***observed*** via the extensive air shower produced when they reach the earth's atmosphere
  2. 16Joules/$\sim$ 16μsec (typical shower time) $\approx$ 1 MW !

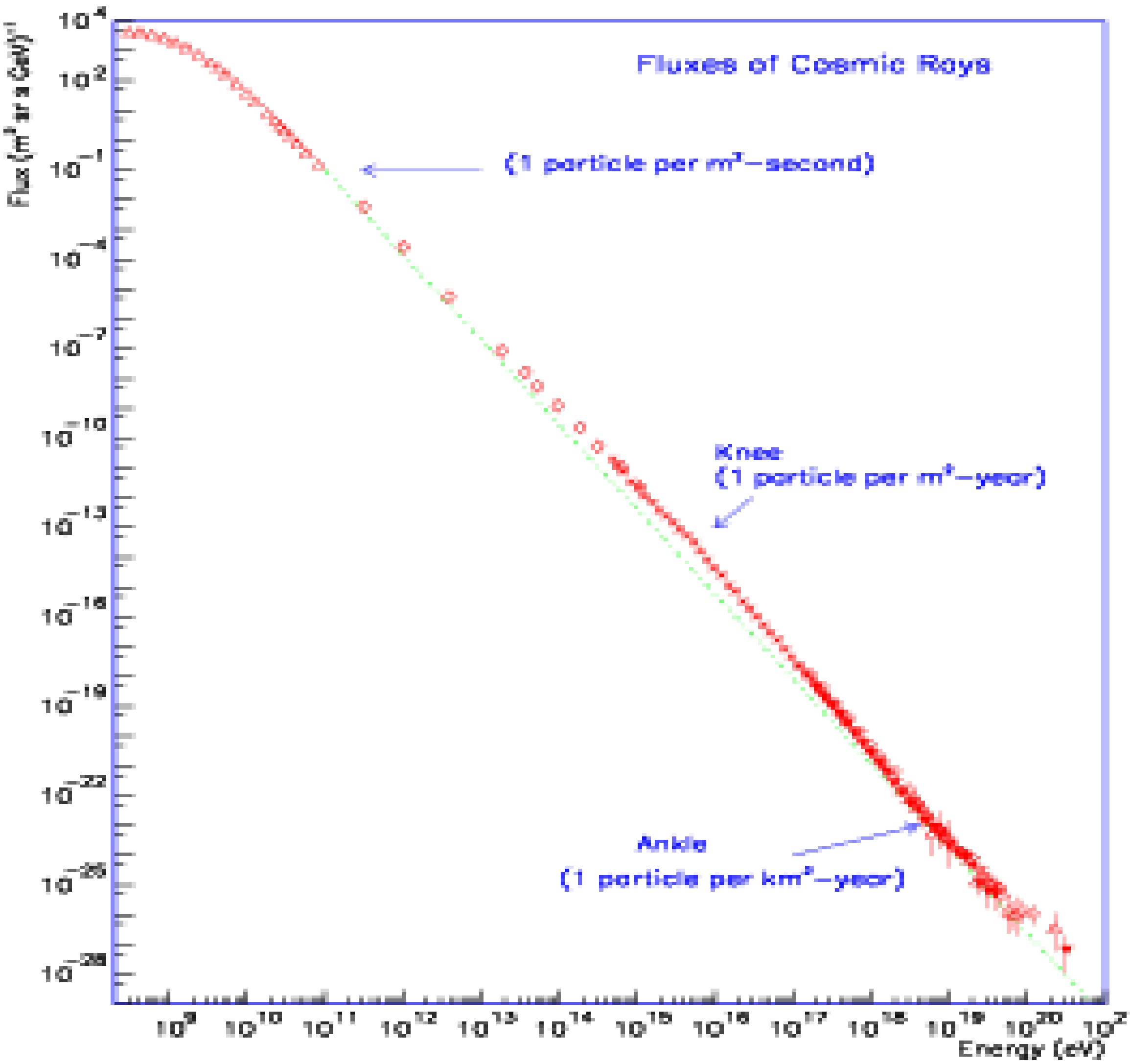
1. Background (con't) ...



Schematic of air shower measurements

- **Measurement of 10^{20}eV air showers:**
  1. km's *wide* at ground level ... sparse sampling OK!
  2. Composition of *primary* cosmic rays from depth of shower maximum, X_{max}, and/or from μ/e ratio.
  3. $\sim$ 50ppm of shower energy is re-emitted as nitrogen *fluorescence* light (290 $\sim$ 440nm) ... thus a 1-MW shower appears as a 50W relativistic *light bulb*!

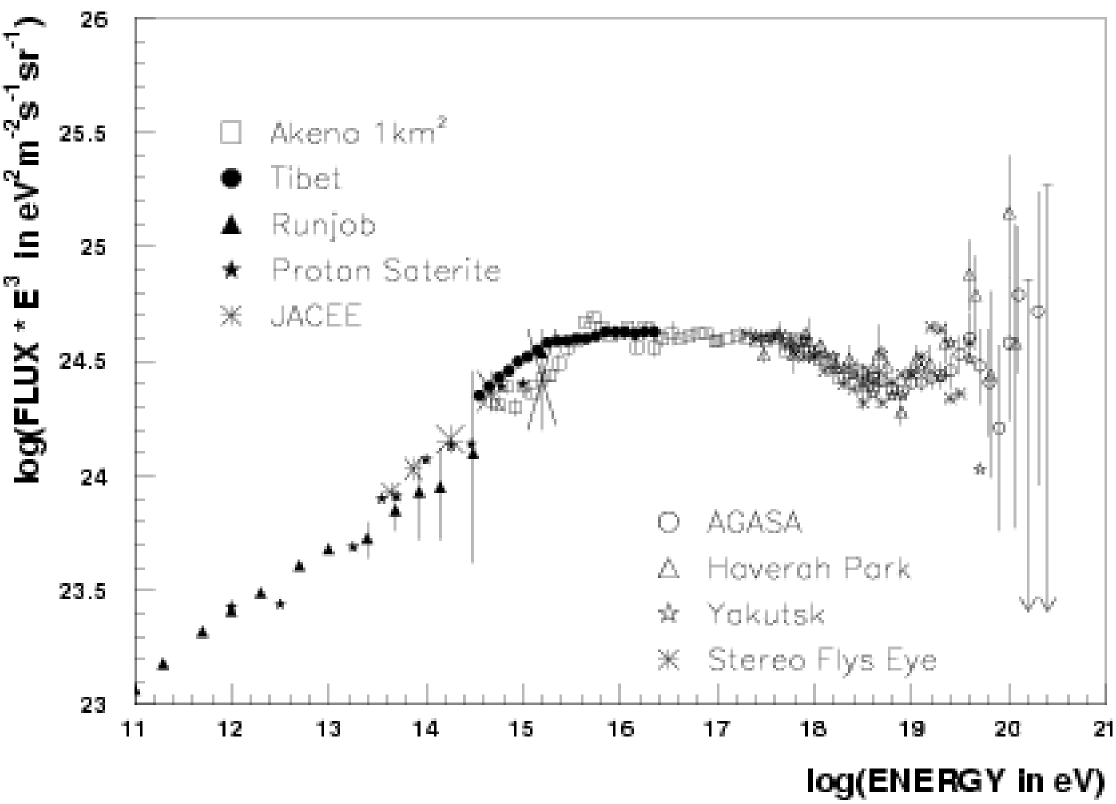
1. Background (con't) ...



Cosmic ray energy spectrum

- **Rate:** - low ($\sim 1/\mathrm{km}^2$/century) **...** so need large experiments ... about the area of Rhode Island! Fluorescence based experiments need dry (desert) air with good visibility.

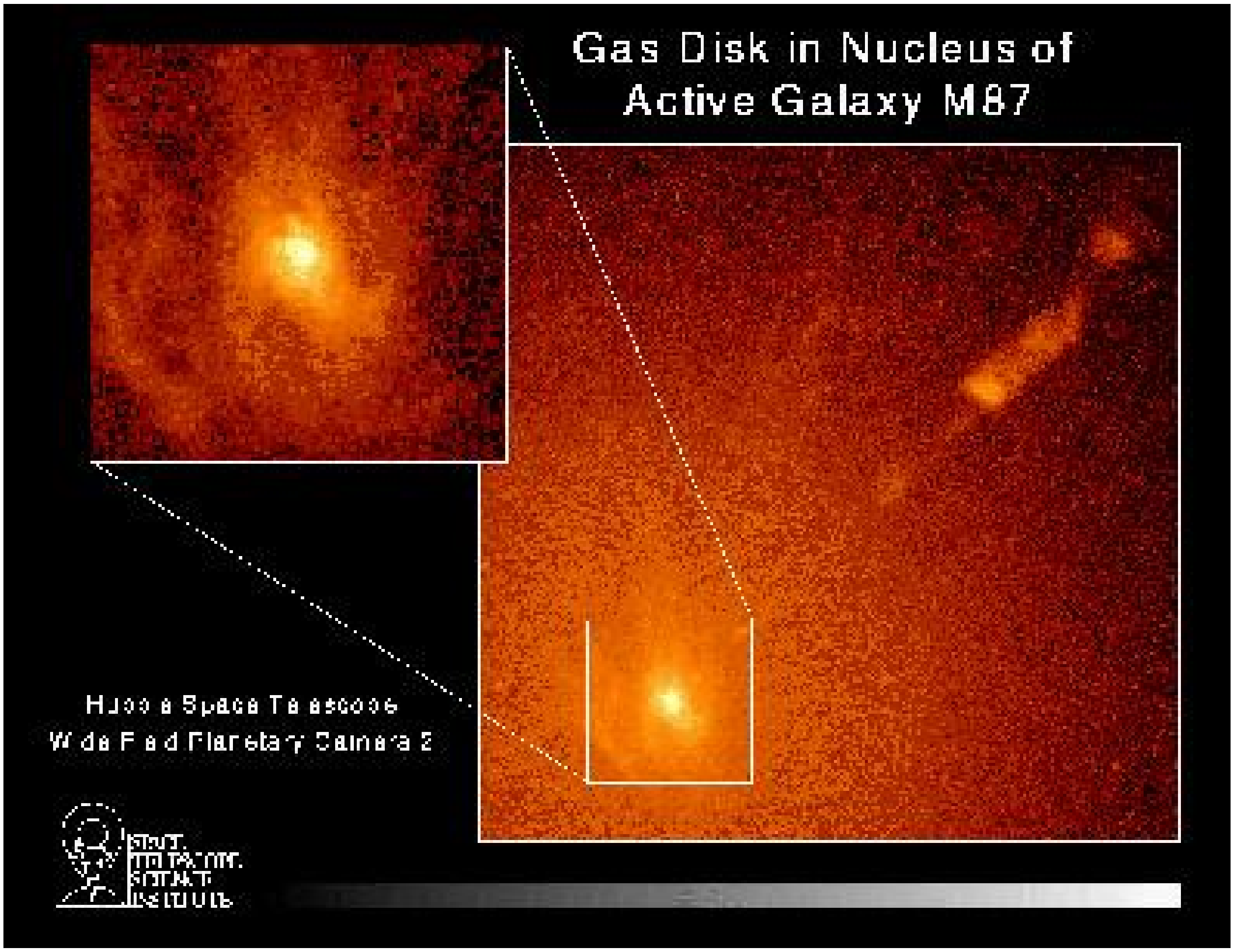
1. Background (con't) ...



Cosmic ray flux scaled by E^3

- **Structure in a power law spectrum:**
  1. *knee* at $\sim 4 \times 10^{15}$eV
  2. second *knee* at $\sim 4 \times 10^{17}$eV
  3. *ankle* $\sim 4 \times 10^{18}$eV
  4. *cutoff* at $\sim 10^{20}$eV ... or not!

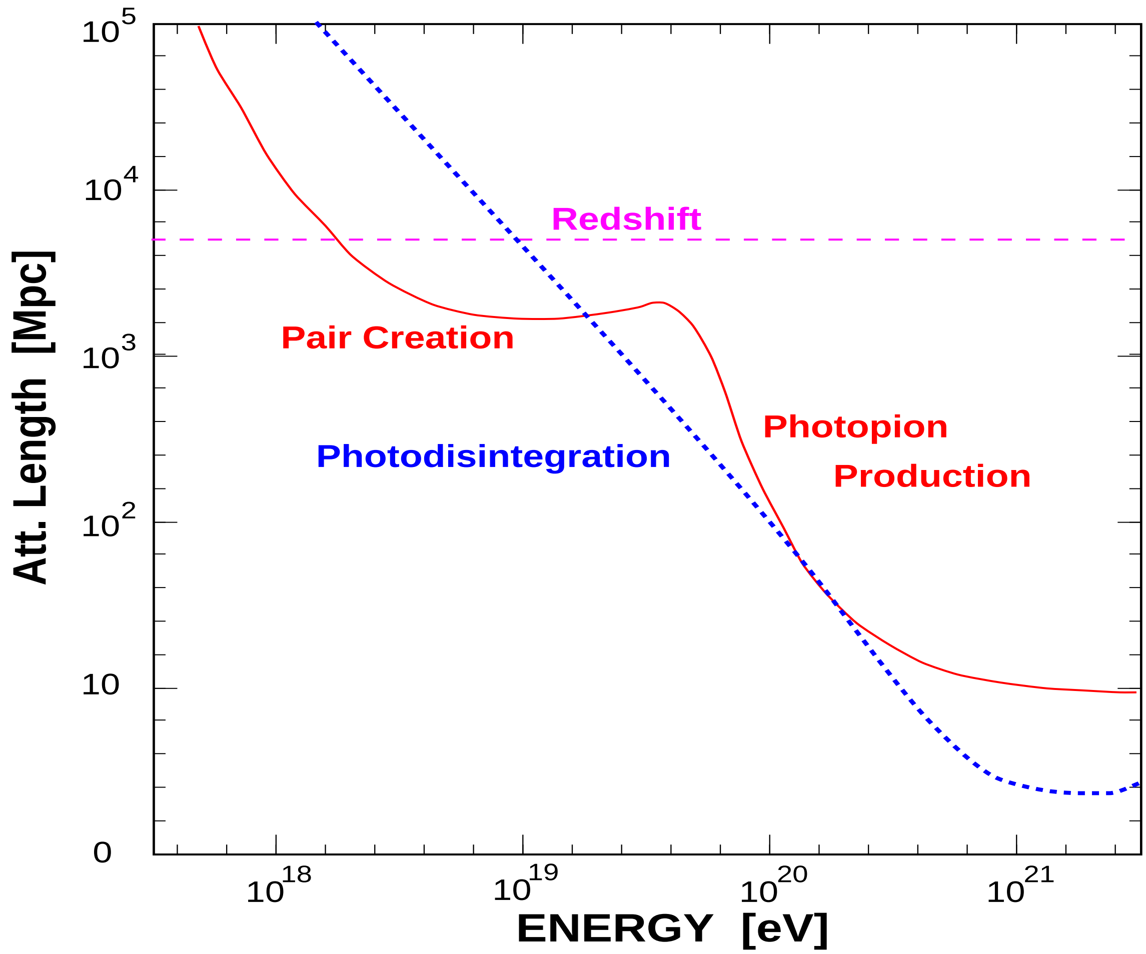
1. Background (con't) ...



(One) possible source of 10^{20}eV cosmic rays

- **Why (... just a couple of reasons):**
  1. At these energies extra-galactic cosmic rays probably dominate local (galactic) sources.
  2. At the same time the GZK cutoff *predicts* an end to the cosmic ray spectrum ... except for nearby (< 50Mpc) sources

1. Background (con't) ...



Energy loss attenuation length, $\Lambda_{atten}(z = 0)$

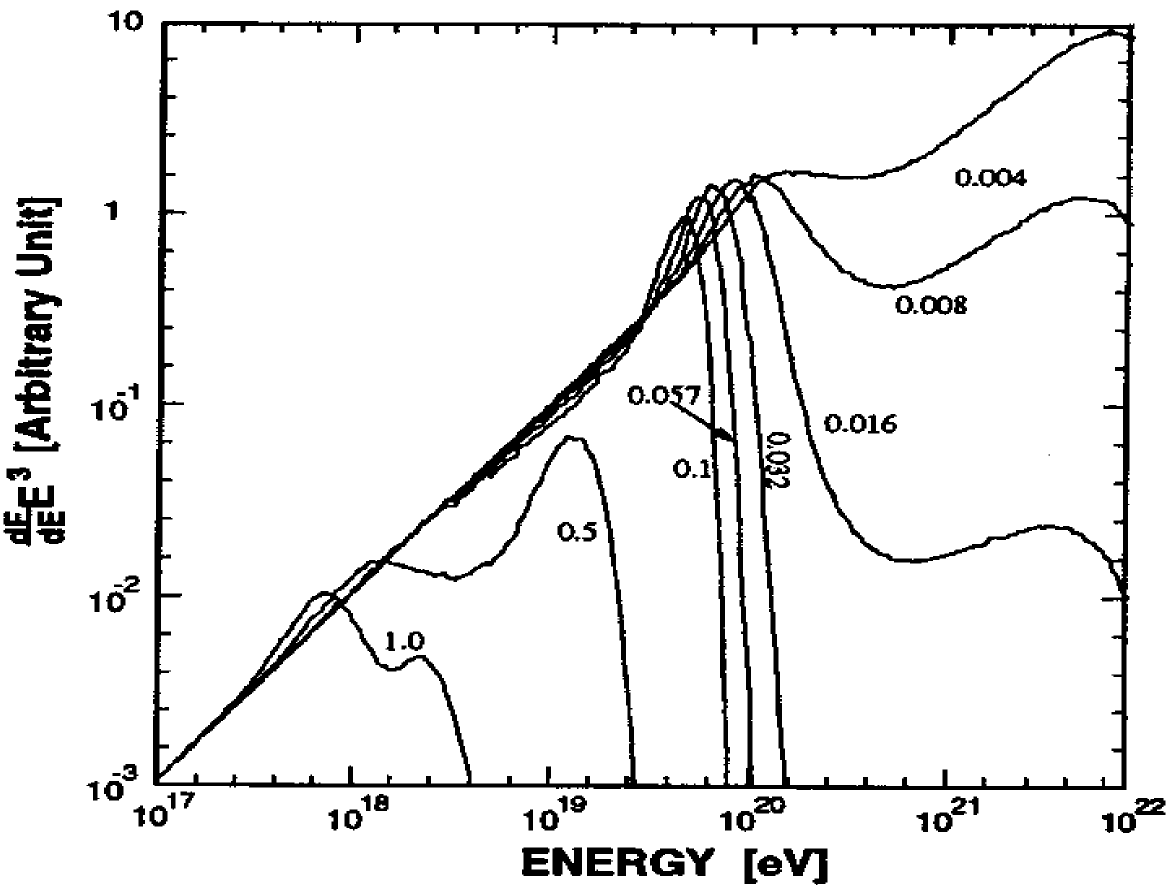
- **Greisen-Zatsepin-Kuz'min (GZK) cutoff:**

  1. Cosmic rays interact with the cosmic micro-wave background (CMB) radiation; after a distance, d:

  $$E = E_0 \cdot e^{-d/\Lambda_{atten}}$$

  2. Steep drop of Λ_{atten} near 10^{20}eV from the onset of π photo-production: $\gamma_{CMB}\, p \rightarrow \pi\, X$.

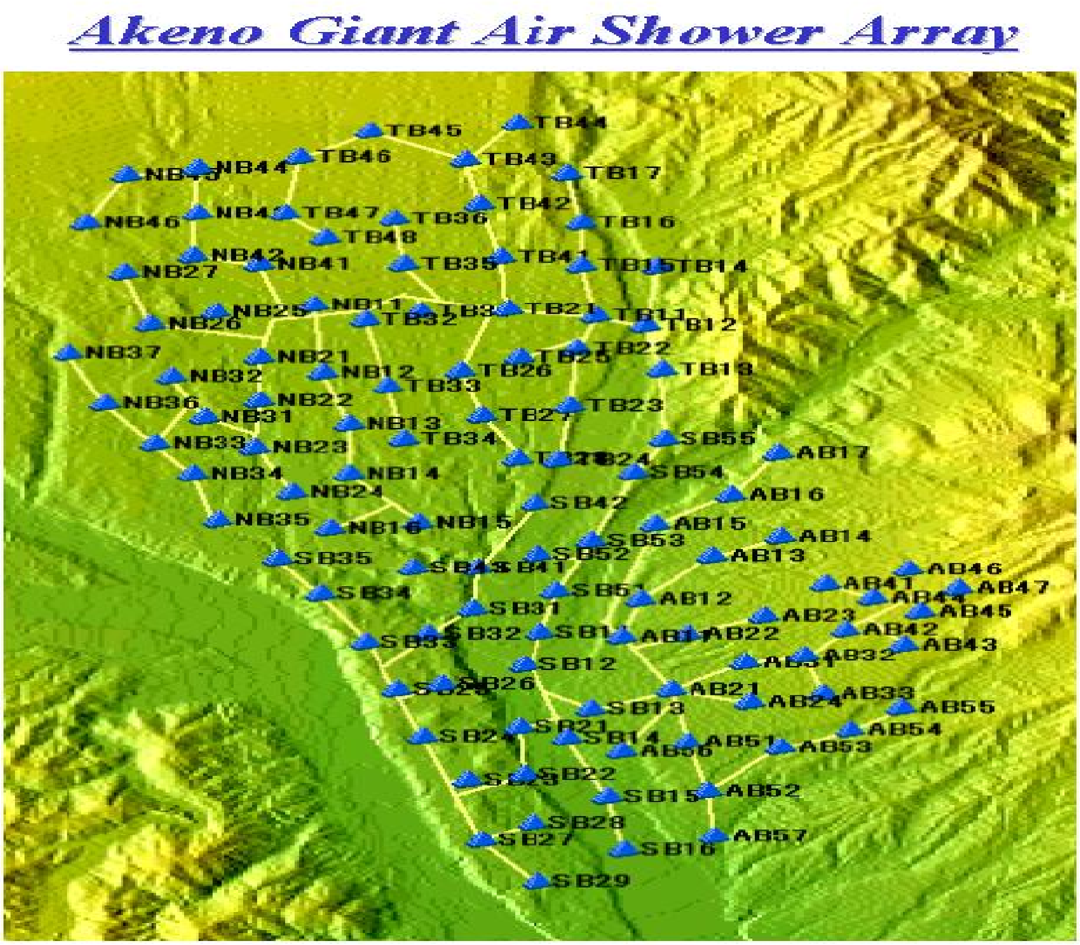
1. Background (con't) ...



Proton energy spectrum *versus* **source red-shift,** z

- **GZK simulation (*proton* primary):**
  1. (Assumed) source spectrum: Flux(E) $\propto E^{-2}$
  2. *Observed* spectrum scaled by E^3 ...
  3. Only sources with red-shift $z \leq 0.03$ (about 150Mpc) should have any flux above $\sim 10^{20}$eV.

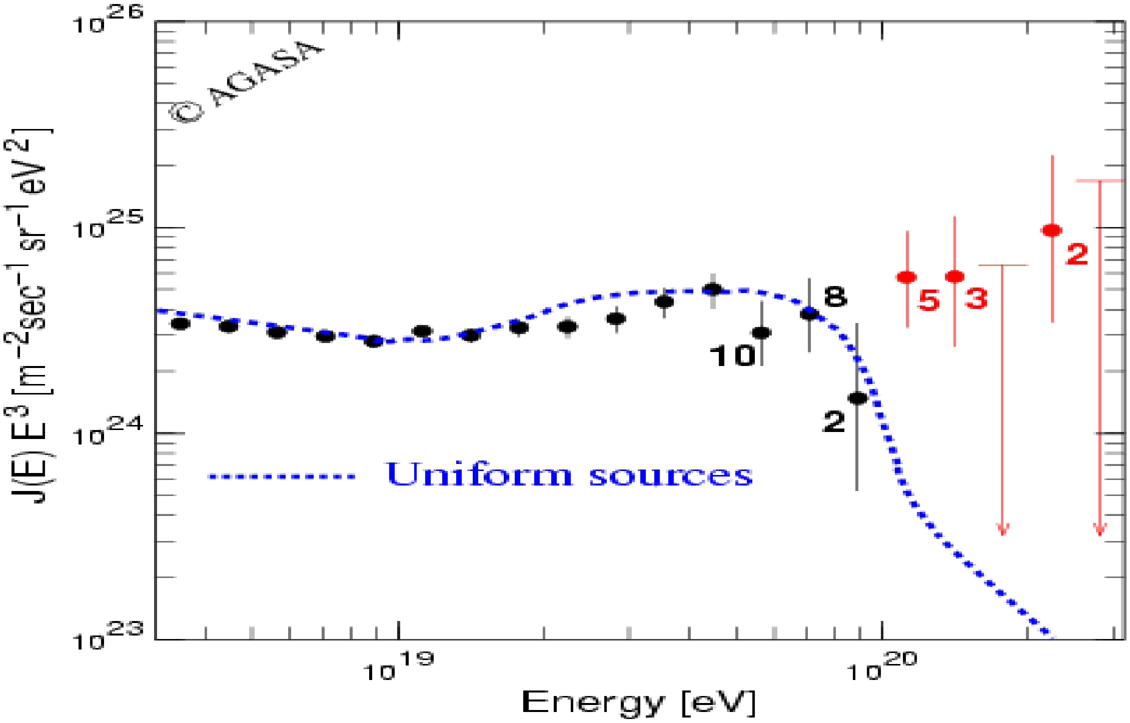
2. Status ... highest energy cosmic rays



AGASA detector *layout*

- **Experiments probing** 10^{20}**eV cosmic rays:**
  1. **Haverah Park**, UK, 12km^2 ground array area
  2. **AGASA**, Japan, 100km^2 ground array area
  3. **HiRes**, Utah, $\sim$ 300km^2 (equivalent)
  4. Pierre Auger, Argentina, 3000km^2 (building)

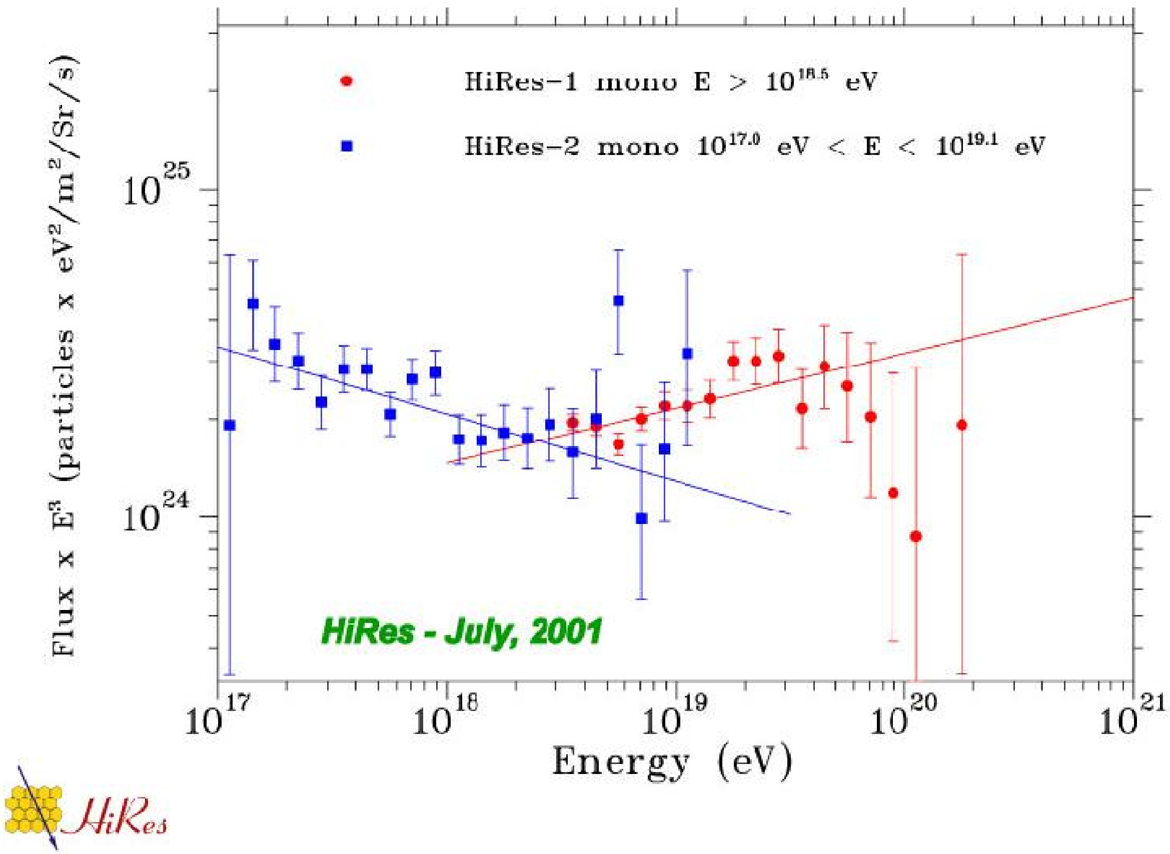
2. Status (con't) ...



AGASA spectrum above 10^{18}eV

- **AGASA flux *versus* energy:**
  1. (Published) experiment with the largest *exposure*
  2. *GZK* model: uniform distribution of extra-galactic sources, proton primary, source flux $J(E) \propto E^{-2}$, plus detector resolution
  3. Two events well above 10^{20}eV!
  4. Number of events above 10^{20}eV **inconsistent with the curve**!

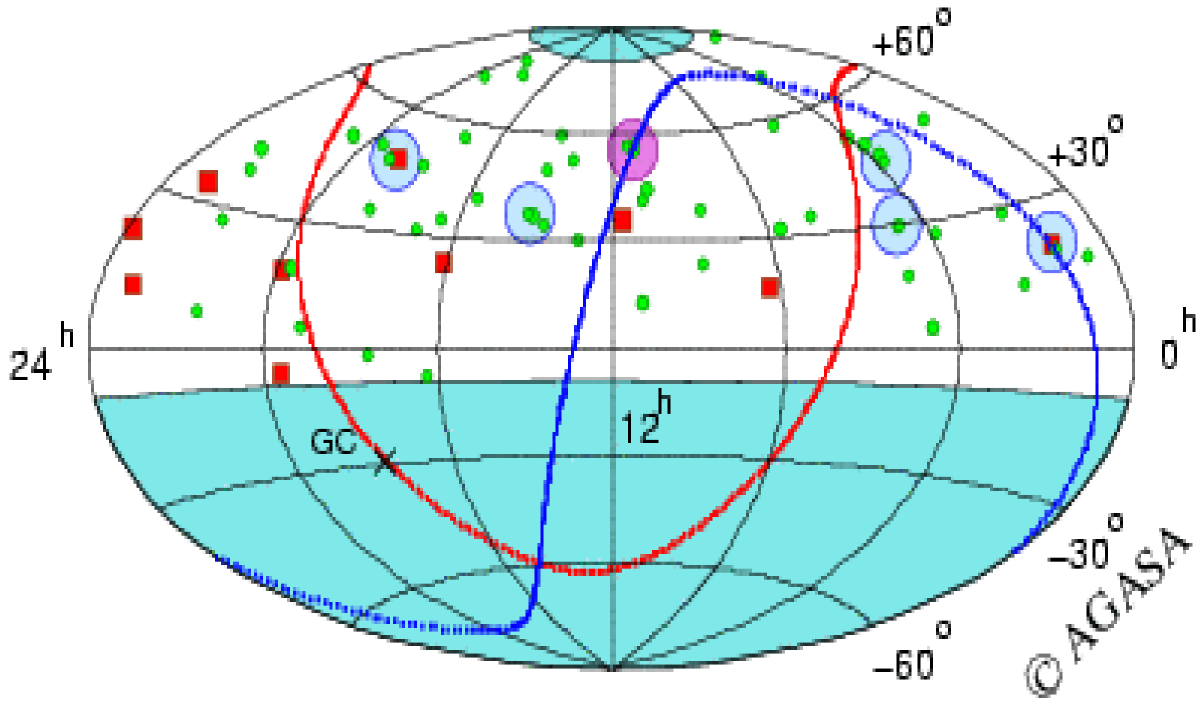
2. Status (con't) ...



(Preliminary) **HiRes spectrum above** 10^{17}**eV**

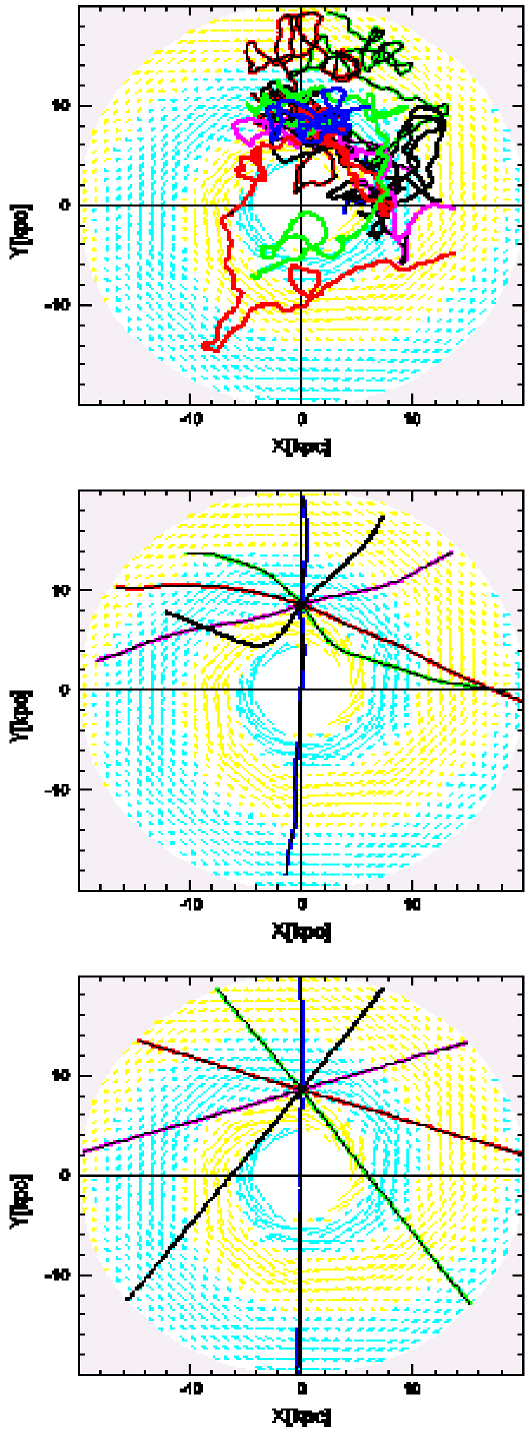
- (Preliminary) **HiRes flux** *versus* **energy:**
  1. Similar data *exposure* to AGASA
  2. Fewer (2 *versus* 10) events above 10^{20}eV!
  3. One event well above 10^{20}eV!

2. Status (con't) ...



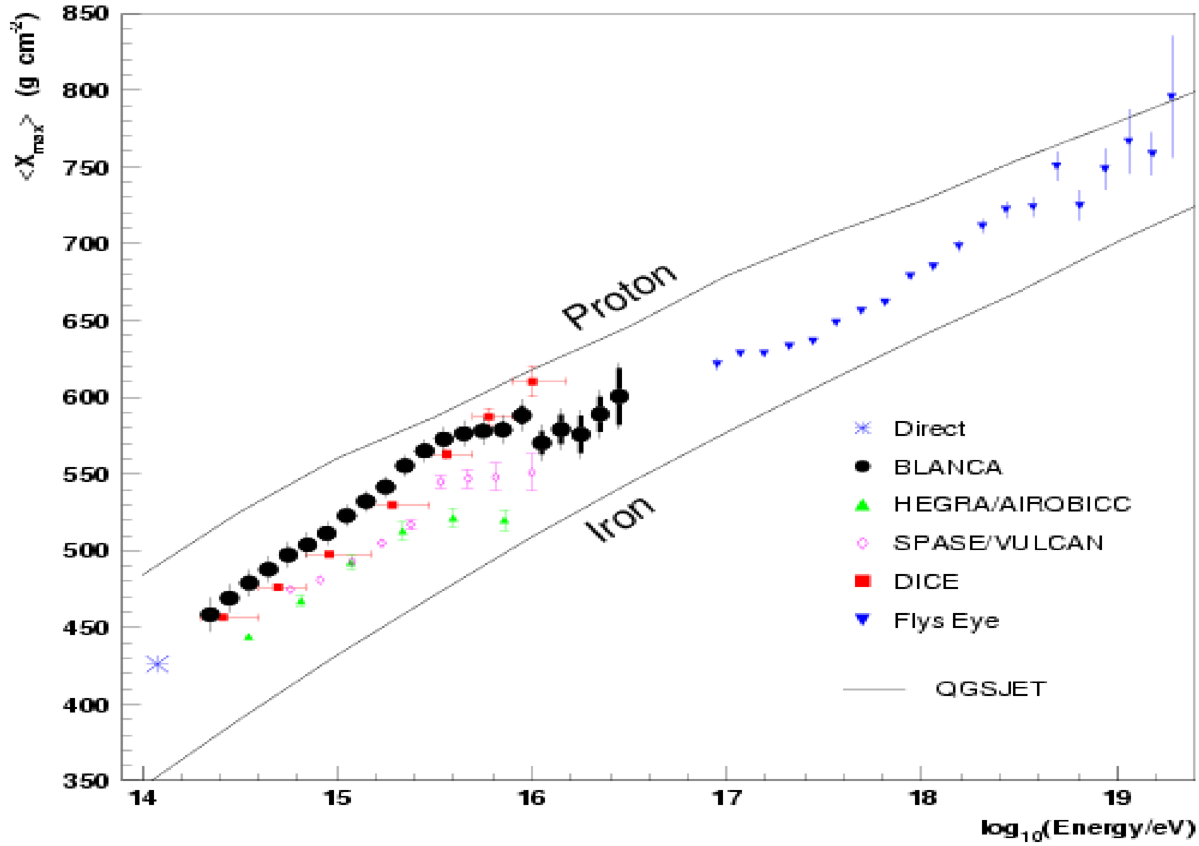
AGASA arrival directions above 4×10^{19}**eV**

- **AGASA arrival directions:**
  1. Primary cosmic ray direction measured to $\sim 1°$
  2. *red* squares (events $> 10^{20}$eV) and *green* dots ($4 - 10 \times 10^{19}$eV) are **consistent with large-scale source uniformity**
  3. Six *2.5° clusters* of events: 5 doublets and 1 triplet
  4. Two of the clusters lie *in* the super-galactic plane (blue line)



Simulated *proton* **trajectories:** $10^{18}, 10^{19}$ **and** 10^{20}**eV in** 2μ**G fields** ... $\geq 4 \times 10^{19}$eV protons are deviated little by local (galactic) magnetic fields.

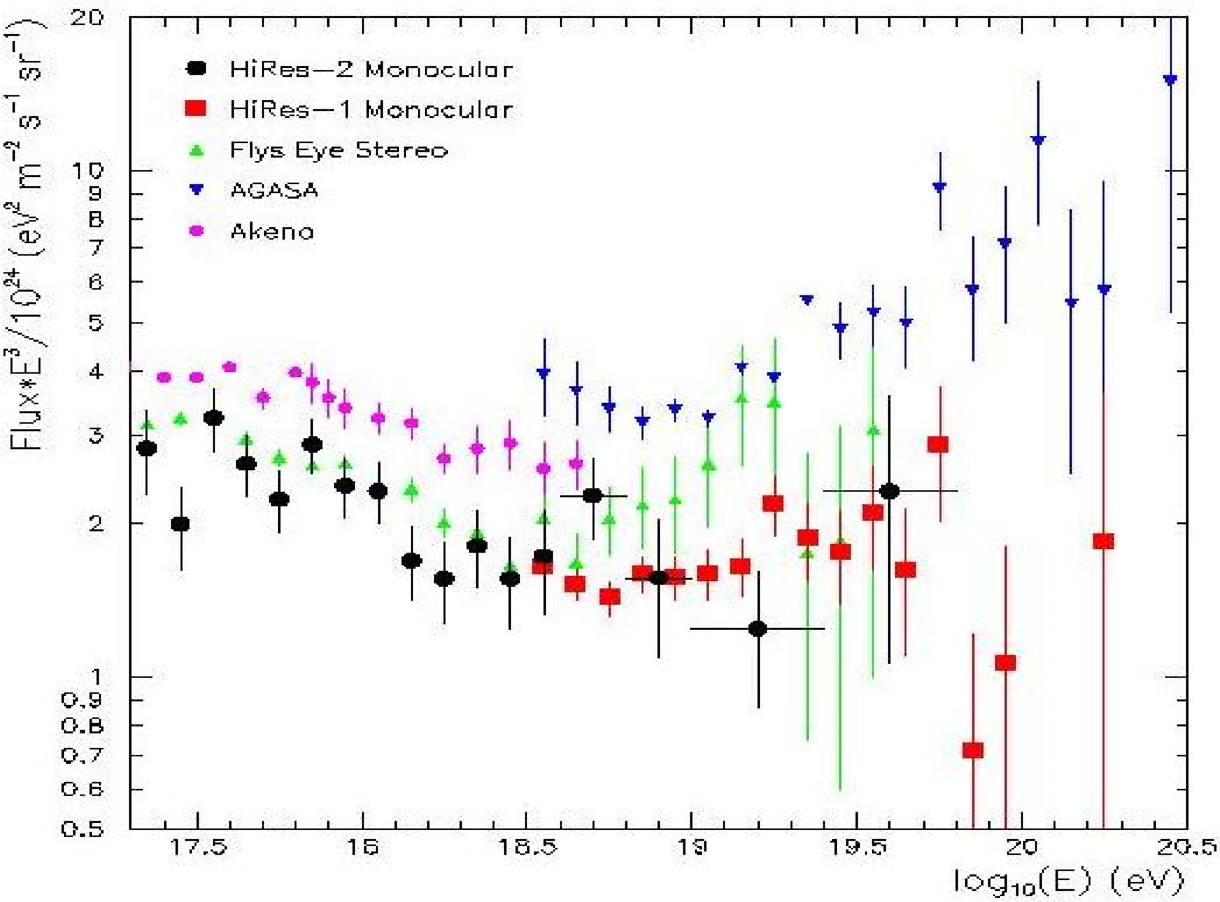
2. Status (con't) ...



Cosmic ray *composition*

- **Average depth of shower maximum (X_{max}) is sensitive to primary cosmic ray** *composition*:
  1. *light* (p,He) dominate near 3×10^{15}eV
  2. *intermediate* (C,N,O) to *heavy* (Si,Fe) dominate near 10^{17}eV!
  3. *light* appear to dominate at the highest energies!

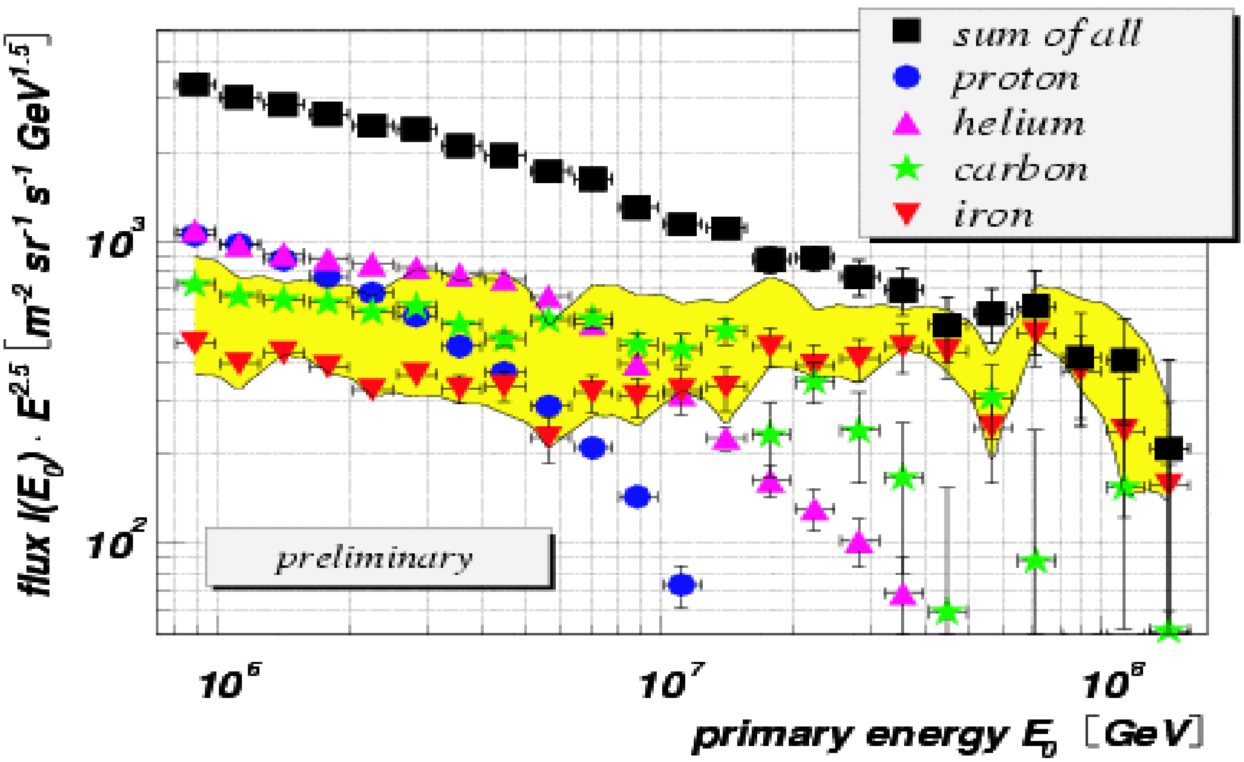
3. New results ... highest energy cosmic rays



Comparison of latest spectra

- **Possible differences in energy scales:**
  1. (Preliminary) HiRes data are consistent with the earlier Fly's Eye experiment
  2. Re-analyzed Haverah Park data [not shown] are consistent with HiRes.
  3. AGASA data lie higher ... consistent with *relative* energy scale differences of 20 $\sim$ 30%

3. New results (con't) ...

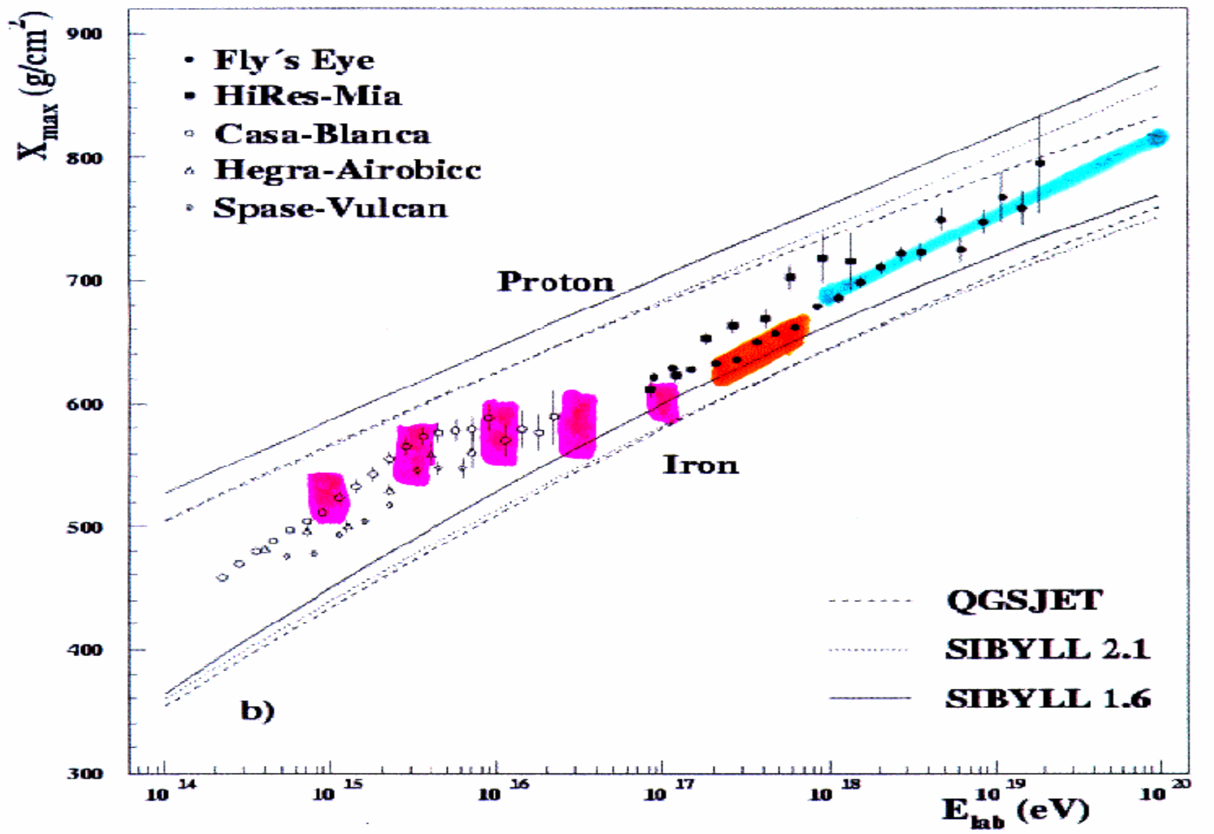


Unfolding of cosmic ray spectra near the ***knee***

Note: horizontal-axis units are GeV where 1 GeV = 10^9eV

- **KASKADE results ...** *astro-ph/0201109***:**
  1. **Confirm** Casa-Blanca result: composition is *light* (p,He) near 3×10^{15}eV (3×10^6GeV) changing to *intermediate* near 3×10^{16}eV (3×10^7GeV).
  2. **Extends** previous studies to show that *intermediate* (C,N,O) to *heavy* (Si,Fe) dominate near 10^{17}eV!
  3. **Data are consistent with** *rigidity-dependent* **breaks in flux for different element groups.**

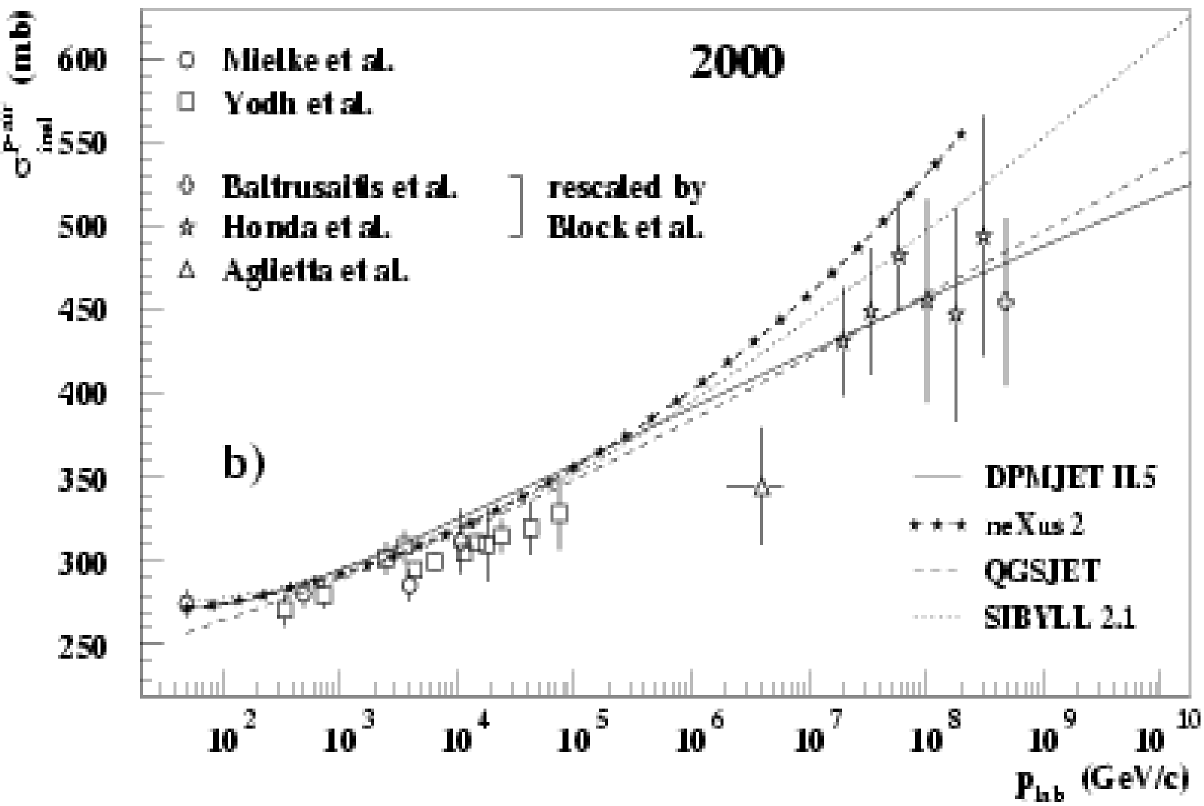
3. New results (con't) ...



Cosmic ray *composition* including new results

- **Average depth of shower maximum (X_{max}) is sensitive to primary cosmic ray *composition*:**
  1. *red* - KASKADE (preliminary): astro-ph/0201109
  2. *orange* - Haverah Park (re-analyzed): astro-ph/0203150, consistent with *mixed* composition [34%-light (p), 66%-heavy (Fe)]
  3. *blue* - HiRes (preliminary): K. Reil, Thesis, March 2002

3. New results (con't) ...

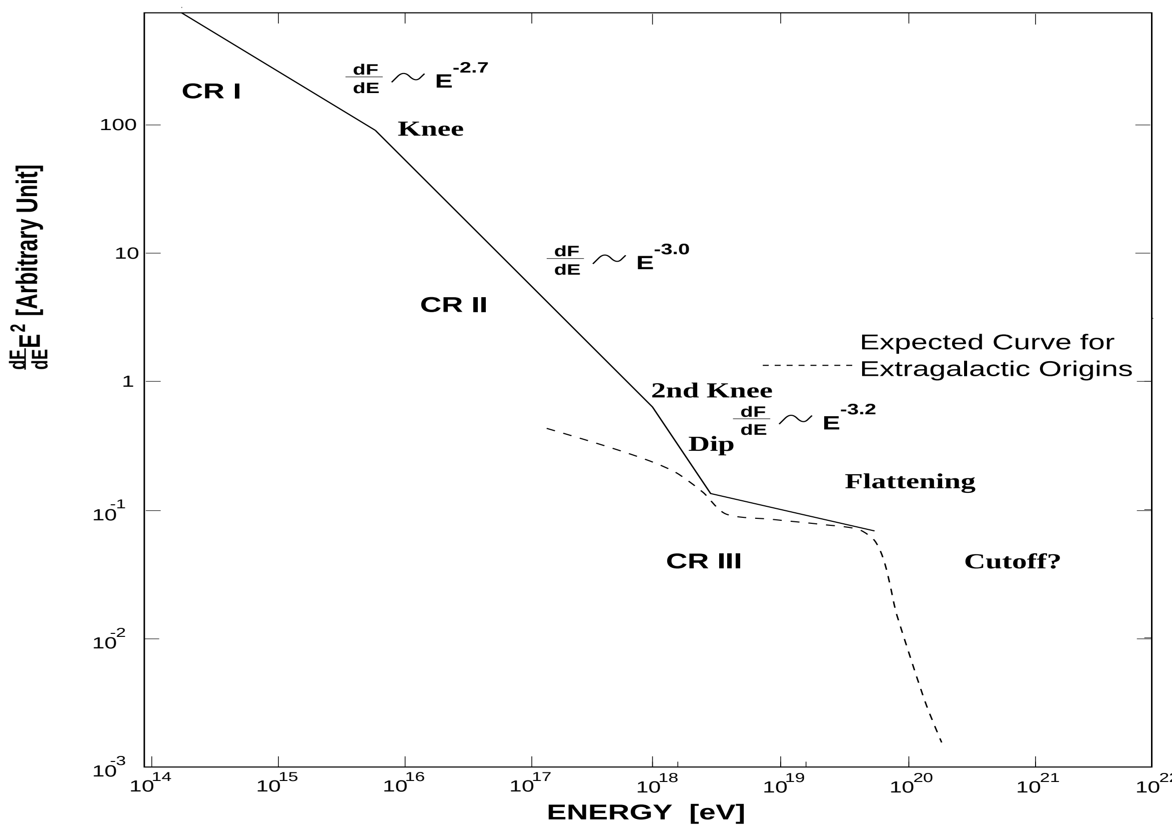


Simulations evolve to describe the data better ...

Note: horizontal-axis units are GeV where 1 GeV = 10^9eV

- **Simulations are needed to link** *e.g.* **depth of shower maximum (X_{max}) with** *composition***:**
  1. Two Monte Carlo (hadronic interaction) models (QGSJet and SIBYLL) are used to interpret the data; *e.g.* D. Heck et al astro-ph/0103073; J. Alvarez-Muniz et al astro-ph/0205302
  2. (Systematic) uncertainties remain ...

4. Emerging model ... highest energy cosmic rays

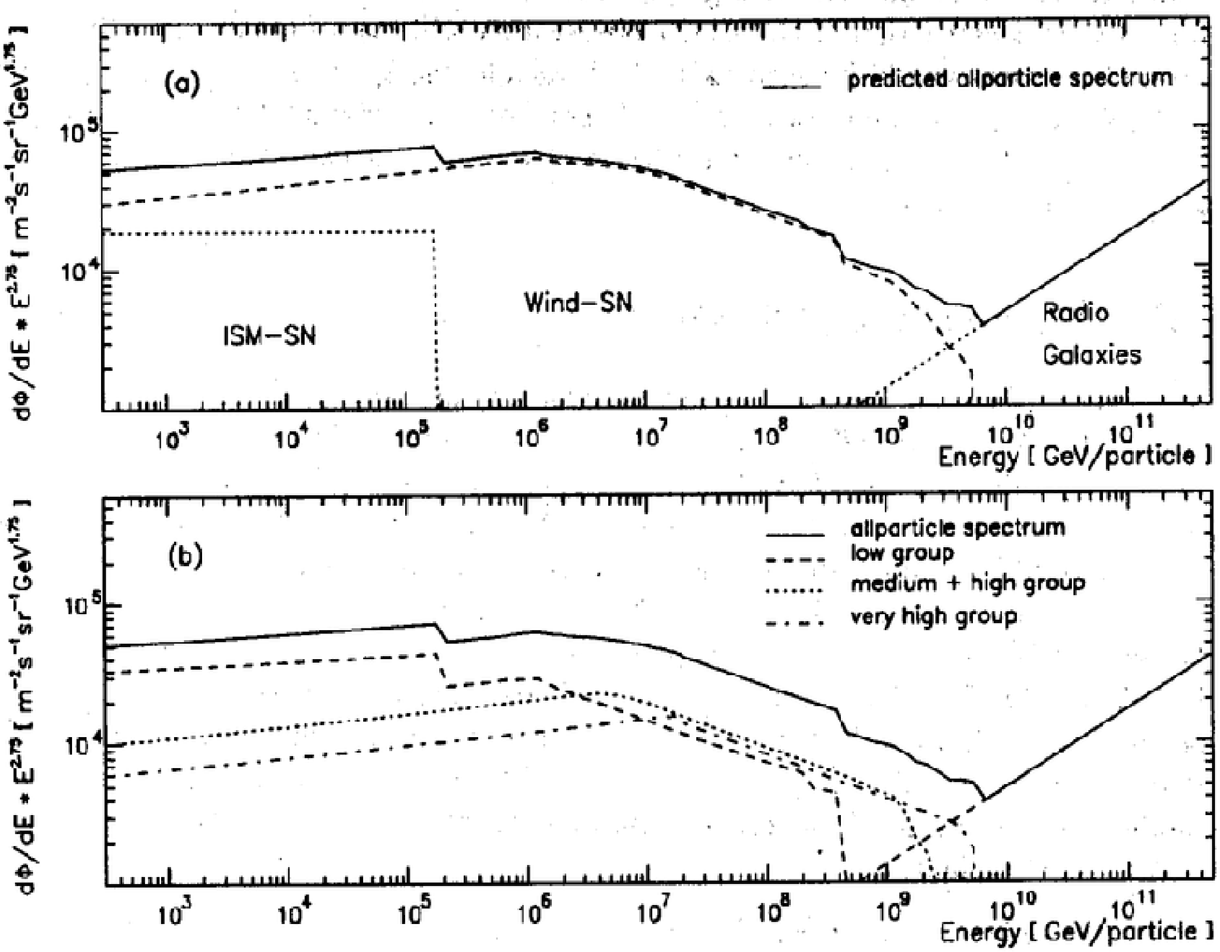


Conceptual model for cosmic ray flux ...

S. Yoshida and H. Dai, astro-ph/9802294

- **Consider a 2-component model:**
  1. KASKADE data consistent with *one* component for CR-I and CR-II (*e.g.* galactic super-novas ...)
  2. **Spectrum steepening**, at 1^{st} and 2^{nd} knee, from acceleration or lifetime/retention limitations
  3. **Spectrum flattening**, at the ankle, consistent with a new (2^{nd}) component

4. Emerging model (con't) ...



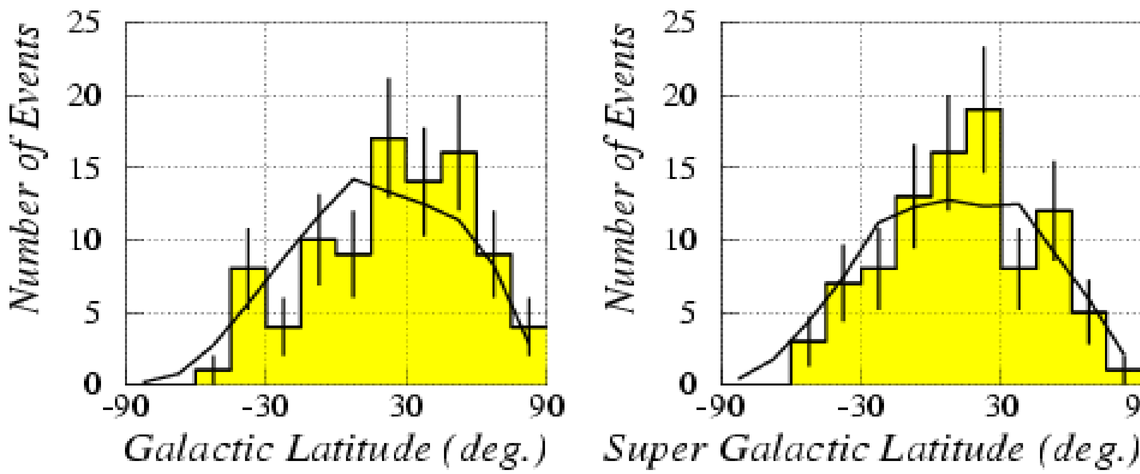
Theoretical model for cosmic ray flux ...

B. Wiebel-Sooth and P. Biermann, Springer Verlag, Sept 1998

Note: horizontal-axis units are GeV where 1 GeV = 10^9eV

1. Slope *breaks* at the 1^{st} and 2^{nd} knee follow constant *rigidity* physics observed by KASKADE ... *i.e.* energy features scale in atomic charge: $E_{Fe} \equiv 26 \times E_p$.
2. 2^{nd} break, $E_p \approx 4 \times 10^{17}$eV, proton Larmor-radius: $(\frac{R_p}{1kpc}) \approx (\frac{E_p}{10^{18}eV}) \cdot (\frac{1\mu G}{B}) \approx$ galaxy thickness.

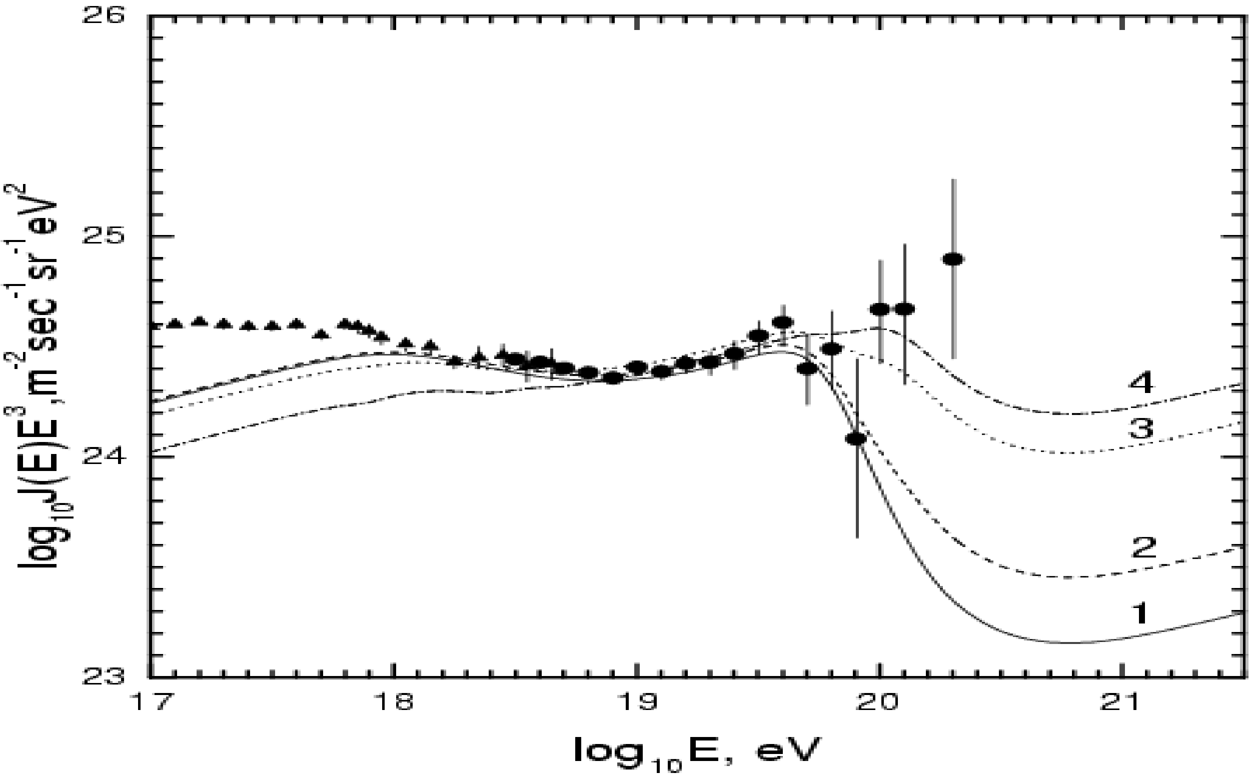
4. Emerging model (con't) ... *Simple* summary



Cosmic ray ($> 4 \times 10^{19}$eV) arrival directions ...

1. 1^{st} component: broad *composition* light (p,He) to heavy (Si,Fe,..); may extend to energies $\sim 10^{19}$eV
2. 2^{nd} component: lighter (significant proton) composition; possibly measurable implications to below 10^{18}eV
3. **Primary motivations for the 2^{nd} component**: **flattening** of the flux above the ankle ($\sim 4 \times 10^{18}$eV) and a **change to lower mass composition** at the highest cosmic ray energies: above $\sim 10^{18}$eV
4. The primary motivation for identifying the 2^{nd} component as **extra-galactic** is the **isotropy of the highest energy cosmic rays** (strengthened if *light* (p,He))

4. Emerging model (con't) ... EXTRA-galactic(I)

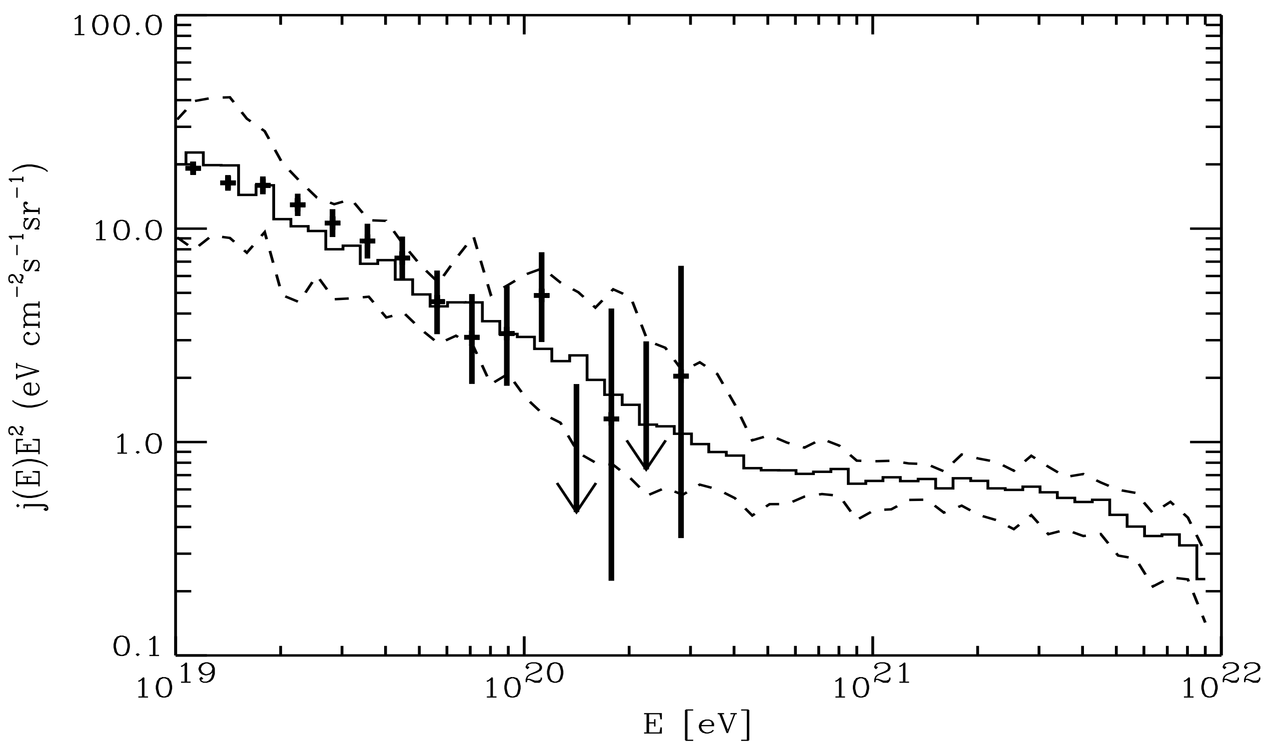


Theoretical model for EXTRA-GALACTIC flux ...

V. Berezinsky et al, astro-ph/0204357

1. Several *conventional* astro-physical models studied: uniform sources, local *over-dense* sources, with GRB or AGN constraints
2. Figure shows "local *over-dense*" case: over-dense region size, $R_{overdense} = 30$Mpc, and 4 over-densities: $n/n_0 = 1, 2, 10, 30$ for curves 1 - 4
3. Actual $n/n_0 \approx 2$, thus **can *not* describe the highest energy events; models well to $\leq 10^{18}$eV!**

4. Emerging model (con't) ... EXTRA-galactic(II)

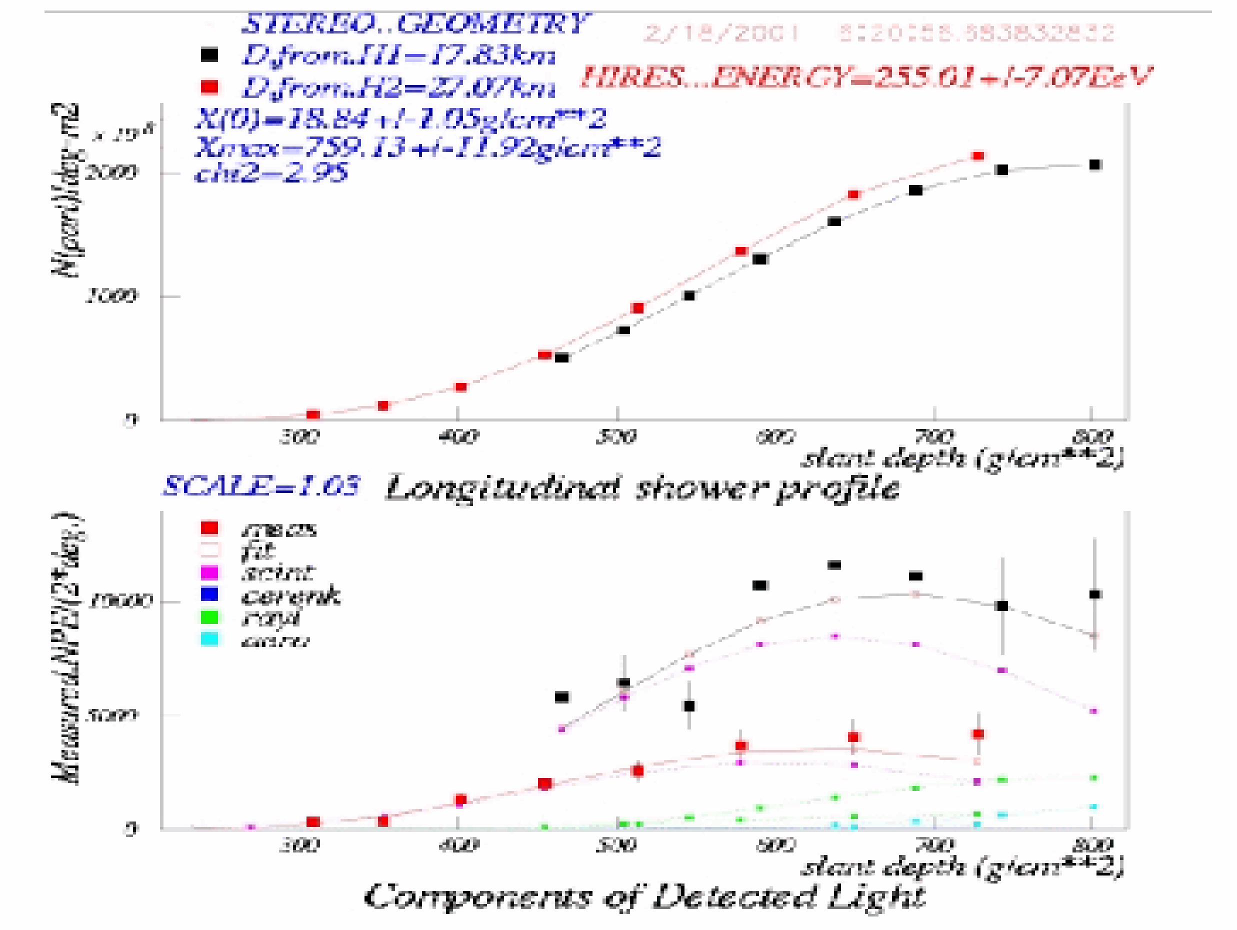


Theoretical model for EXTRA-GALACTIC flux ...

G. Sigl et al, astro-ph/9806283

1. Model assumes local ($\sim$ 10Mpc *Virgo cluster*) source with turbulent, super-galactic magnetic fields ($\sim$ 0.1μG) ... **sensitive to field parameters!**
2. Figure shows case with source at 10Mpc, $B_{rms} = 0.1\mu$G, *proton* (injection) spectrum $\propto E^{-2.4}$
3. Model describes the (AGASA, Fly's Eye and Haverah Park) data above 10^{19}eV ... **but single source, tuning of source distance and field parameters!**

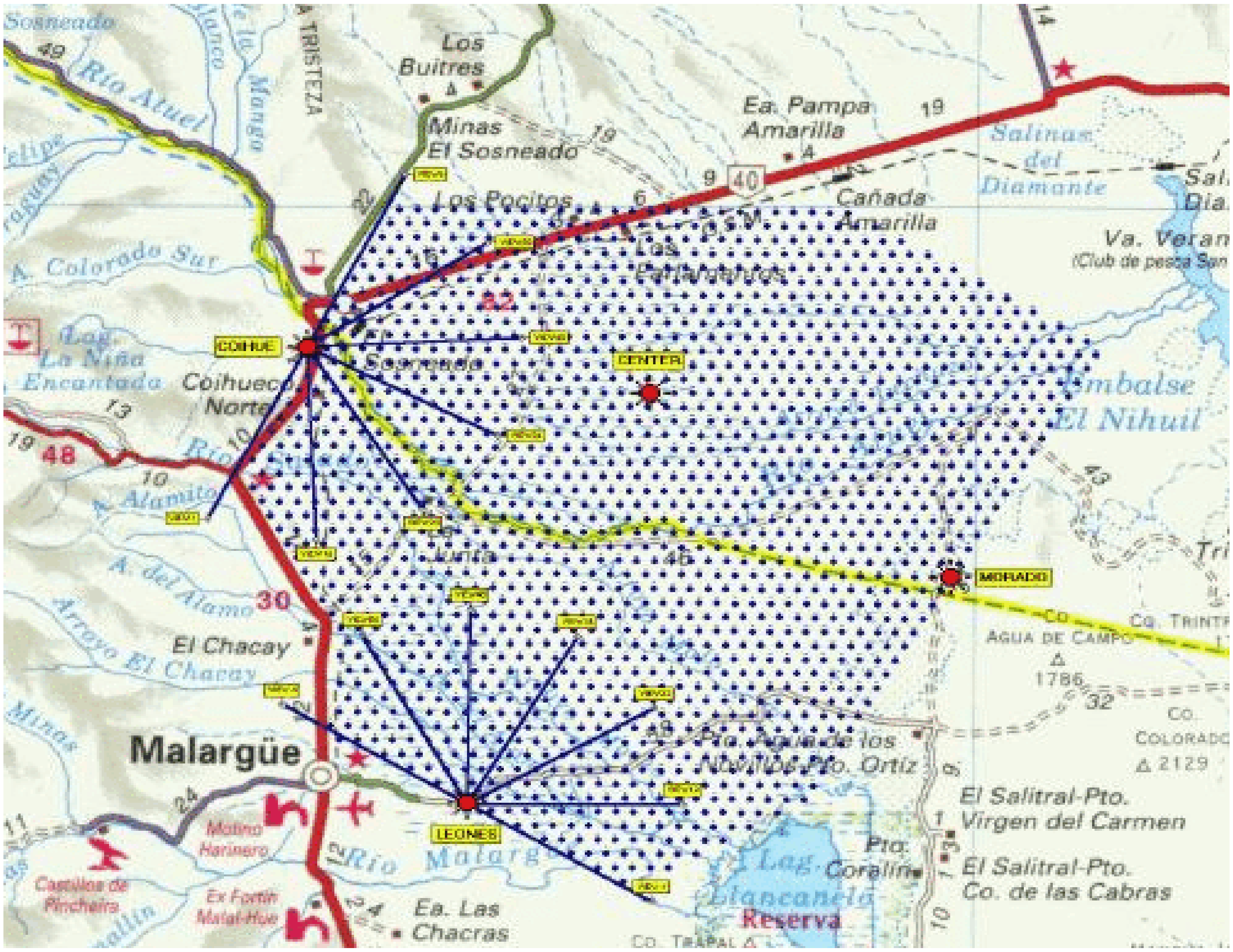
4. Emerging model (con't) ...



HiRes *stereo* **event with** $E \approx 2.5 \times 10^{20}$**eV**

- **We can't resolve the** 10^{20}**eV puzzle today!**
  1. AGASA, Fly's Eye and HiRes observe (a few) events well above 10^{20}eV
  2. What is the detailed shape of the spectrum?
  3. What is the *composition*?
  4. What are the arrival directions (and clustering)?

5. Next step ... highest energy cosmic rays

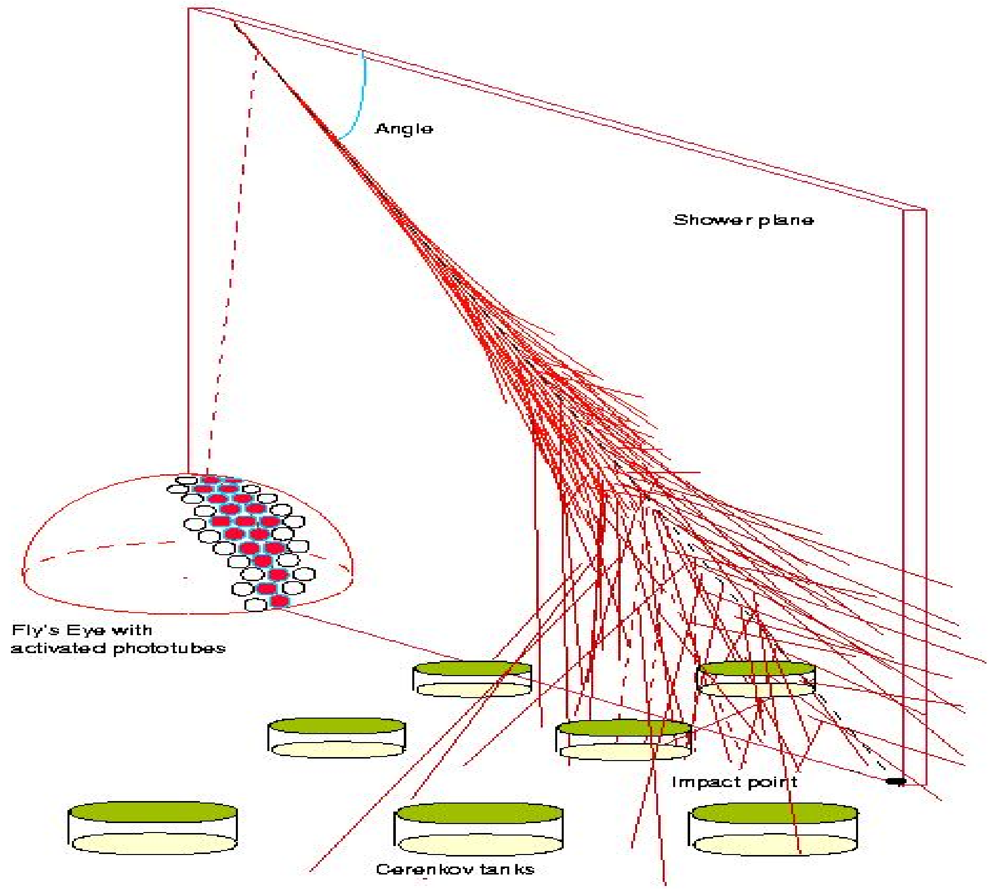


Pierre Auger (south) experiment ... Malargue, Argentina

- **Biased opinion ...** high quality (hybrid) data are needed from $< 10^{18}$eV (10^{17}eV?) to a few $\times 10^{20}$eV:
  1. need to link with galactic source(s) measurements
  2. need to remove (reduce) the model dependence of the significance of the *big* events $> 10^{20}$eV
  3. need to tune the Monte Carlo (hadronic interaction) models

5. Next step (con't) ...

Detection method



Pierre Auger *hybrid* detection ...

1. Hybrid detection: simultaneous measurement of the air shower by a ground array and by fluorescence telescopes
2. Hybrid events cross-check and cross-calibrate the two types of detectors and provide the best *composition* measurement
3. Ground array (only) events provide most statistics (*i.e.* highest energy events)

5. Next step (con't) ...

Typical Pierre Auger ground array detector ...

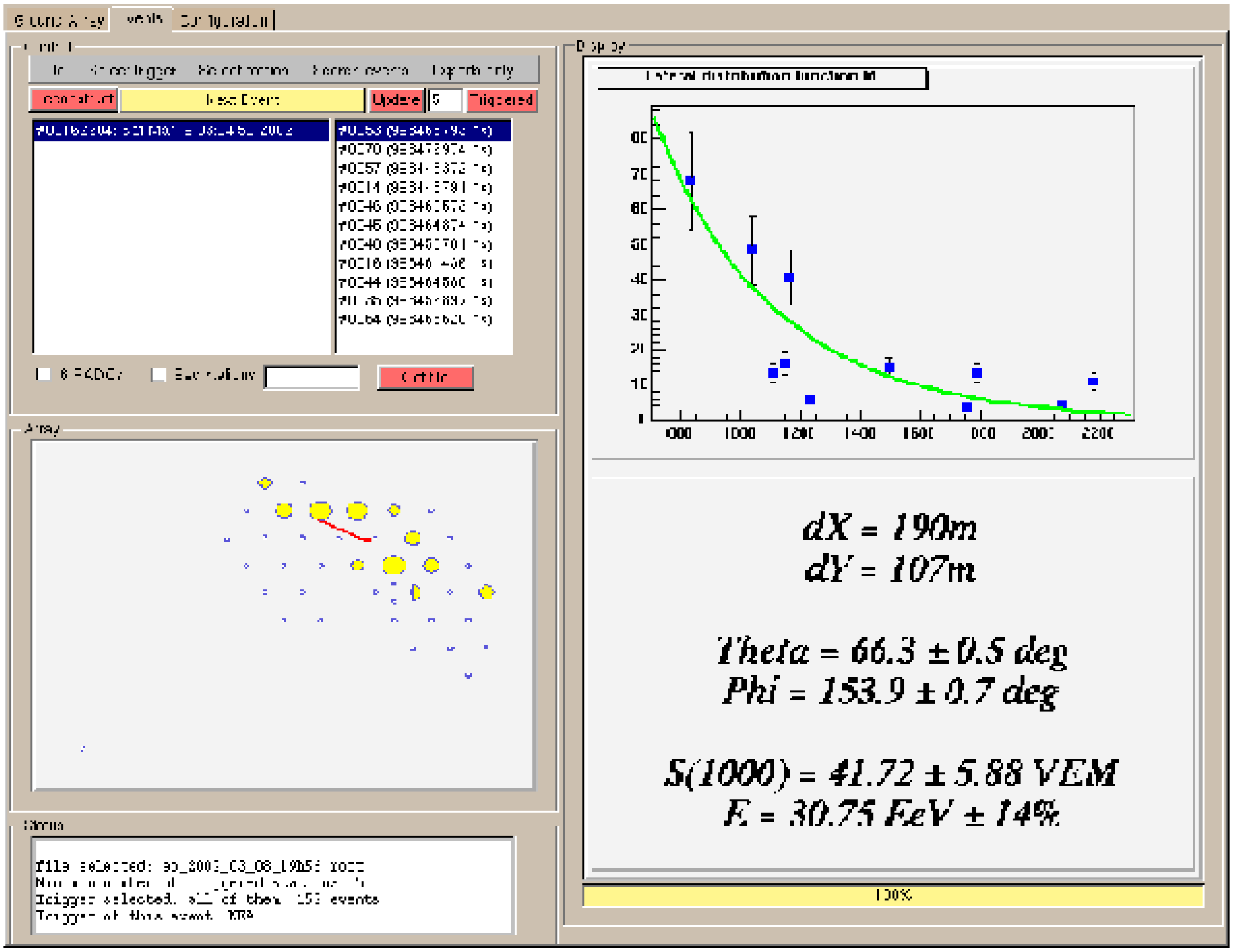
10m^2, 1.2m deep, water cherenkov detector

Solar powered, radio communication to central trigger

Site environment very similar to Albuquerque ...

1. $>$ 30 of 1600 ground array detectors installed and running (initial *engineering array* test)
2. $\sim$ 100 ground array detectors and 12 of 24 fluorescence telescopes scheduled to be operational by spring 2003

5. Next step (con't) ...



Biggest **Pierre Auger hybrid event ...** $\sim 3 \times 10^{19}$**eV**

$\sim$ 70 hybrid events observed during recent 5-month run

1. Event triggered 11 ground array detectors
2. Event was observed (simultaneously) by 1 fluorescence telescope
3. Hybrid events are already helping to *tune* both detector subsystems.

5. Next step (con't) ... some "perspective"!

John Linsley ... a little NW of the Abq. convention center

- **February 1962:** $1^{st} - 10^{20}$**eV event (Volcano Ranch)**
  1. Event triggered 14 ground array detectors
  2. Event was about as un-expected then as it would be today!

6. Summary ... highest energy cosmic rays

- Cosmic rays are observed by three experiments: AGASA, Fly's Eye and HiRes to energies above 10^{20}eV.
- AGASA energy scale may be $20 \sim 30\%$ higher than Fly's Eye, Haverah Park and HiRes. **IF AGASA energies scaled down then fewer events $> 10^{20}$eV but *biggest* events remain.**
- **Sources of the events above the cosmic microwave background *GZK cutoff* "must" be (relatively) nearby ... but are still unknown!**
- **New data are consistent with light (p,He) primaries at the highest energies. Hadronic interaction uncertainties weaken this conclusion.**
- Arrival directions of events $> 4 \times 10^{19}$eV are isotropic supporting the extra-galactic source of these cosmic rays. AGASA *clusters* interesting ... but could be a statistical fluctuation.
- **New data increase the support for (predominantly) 2-component model of cosmic rays above 10^{15}eV. However limited data, particularly at the highest energies, often provide little constraint to theoretical models.**