Astroparticle of Ultra-High Energy Cosmic Rays, Photons and Neutrinos

An overview of what we know about the mass composition of high energy cosmic rays

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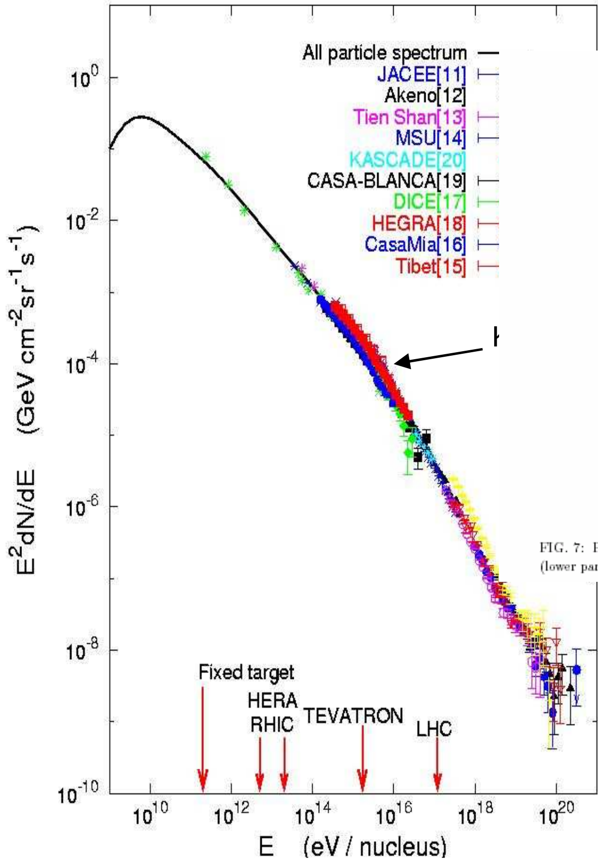
Santa Barbara: KITP: 5 May 2005

see astro-ph/0312475, 0408110, 0410514 (conference talks)

Key Questions about UHECR

- Energy Spectrum above 10^{18} eV?
- Arrival Direction distribution?
- Mass Composition?

Knowledge of the mass is crucial if we are to make sense of interpreting results from the spectrum and the arrival directions.



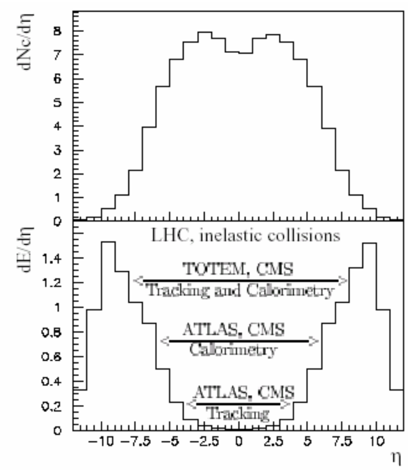


FIG. 7: Pseudorapidity distributions of charged particles (upper panel) and of the energy flow (lower panel) for *pp* collisions at LHC [121].

Problem with lack of knowledge of underlying hadronic physics

$>10^{19}$ eV
1 km^{-2} year^{-1} sr^{-1}

Electromagnetic Acceleration

- **Synchrotron Acceleration**
  $E_{max} = ZeBR\beta c$

- **Single Shot Acceleration**
  $E_{max} = ZeBR\beta c$

- **Diffusive Shock Acceleration**
  $E_{max} = kZeBR\beta c$, with $k<1$

Top Down Mechanisms

If protons dominate (and consequently acceleration is difficult) <u>and</u> there are trans-GZK events

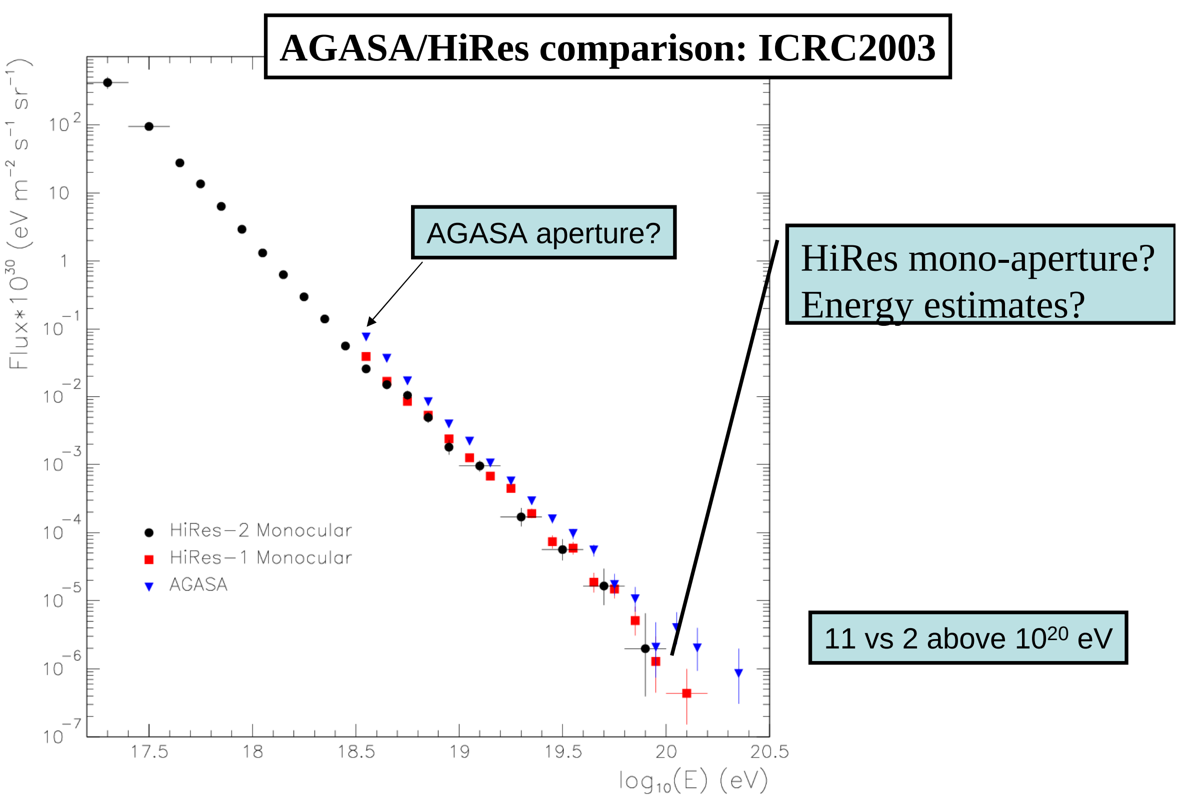
- **Topological defects?**

  Cosmic strings and necklaces

  Decay of monopoles

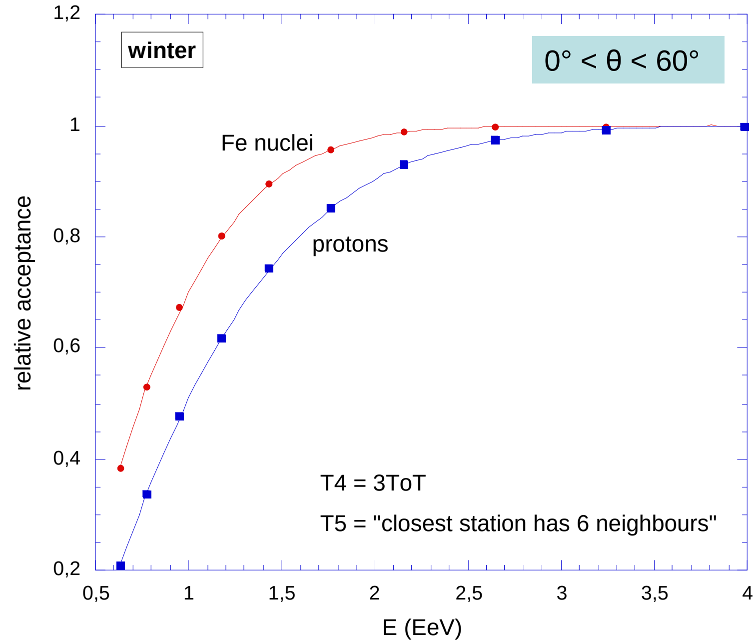
- **Manifestations of Super-Heavy relic particles decaying?**

- **Other exotic physics**

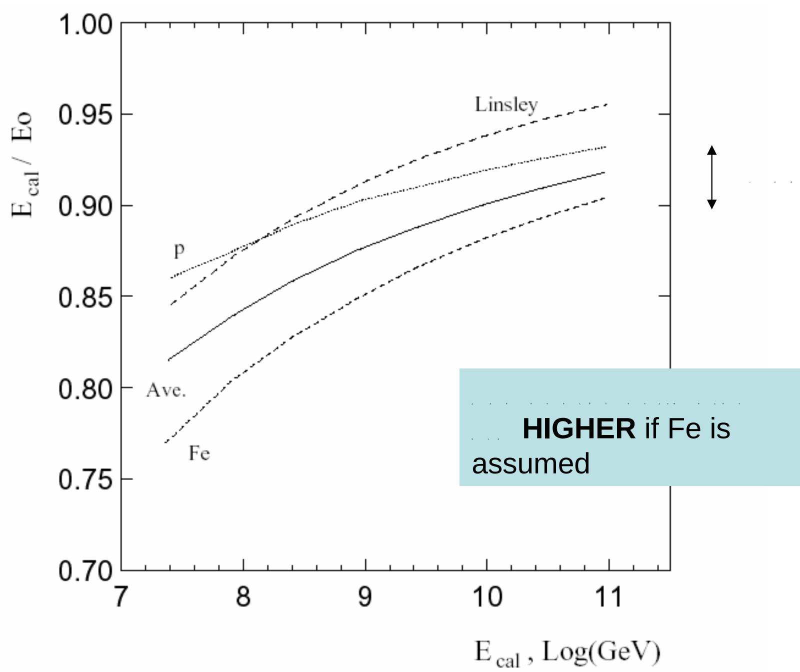


Thanks to D. Bergman: Rutgers

Example of relative acceptance (for the Auger Surface Detector)



Corrections necessary to determine energy from fluorescence



For S(600), the energy estimates are **LOWER** if iron is assumed

Table 1
Energy conversion from $S(600)$. The column "Single Particle" describes the definition of "a single particle" used in the evaluation of $S(600)$. Each formula is evaluated at the altitude given in the column "Altitude".

Simulation Code	Single Particle	Altitude	Interaction Model	Primary Composition	$E = a \times 10^{17} \cdot S_0(600)^b$ a	b	S_0 = 50 vem	Citation
COSMOS	"electrons"	900m	QCDJET	p	2.03	1.02		[15]
CORSIKA (v5.623)	PH^0_{peak}	900m	QGSJET98	p	2.07	1.03	**1.04**	[20]
				Fe	2.24	1.00		
			SIBYLL1.6	p	2.30	1.03	**1.13**	
				Fe	2.19	1.01		
AIRES (v2.2.1)	PW^θ_{peak}	667m	QGSJET98	p	2.17	1.03	**1.09**	[21]
				Fe	2.15	1.01		
			SIBYLL1.6	p	2.34	1.04	**1.13**	
				Fe	2.24	1.02		

Summary of some of problems with the energy spectrum

- At low energies SD apertures can be in error
- At high energies FD apertures are uncertain
- Model/mass uncertainties in conversion from SD
  Fe QGS jet/ p SIBYLL 1/1.6 (Auger tanks: UCLA)
  1/1.15 (AGASA scintillator)
- Fluorescence Yield (still ~20% systematic uncertainty)
- Absolute calibrations of FD and SD:
  Auger Spectrum will have the statistics of SD but the energy accuracy of FD (no mass or model dependence)

BUT: EVENTS ABOVE 100 EeV DO EXIST

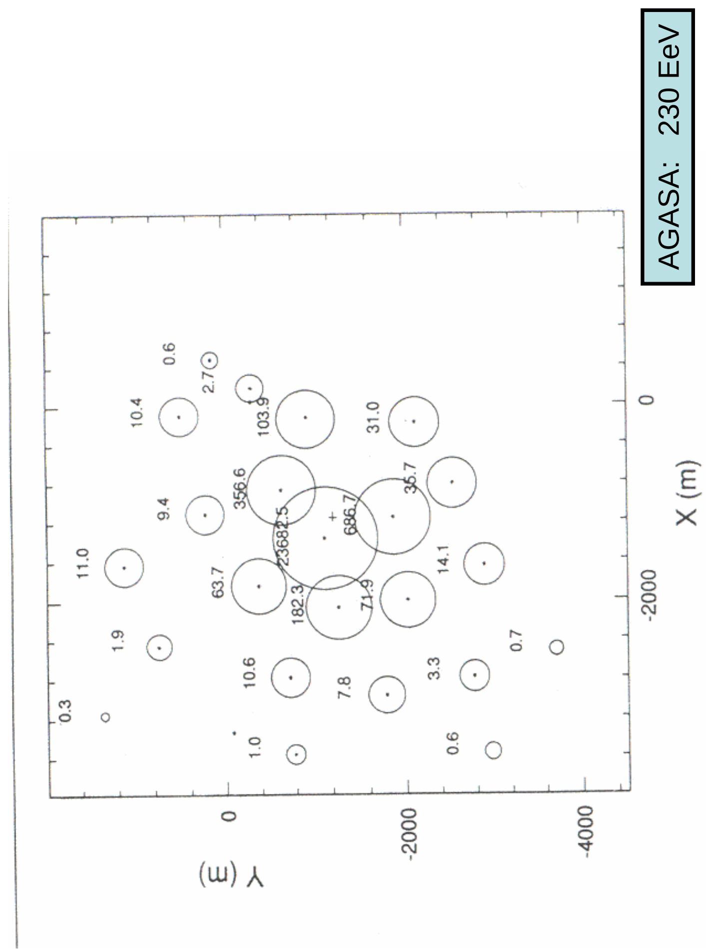
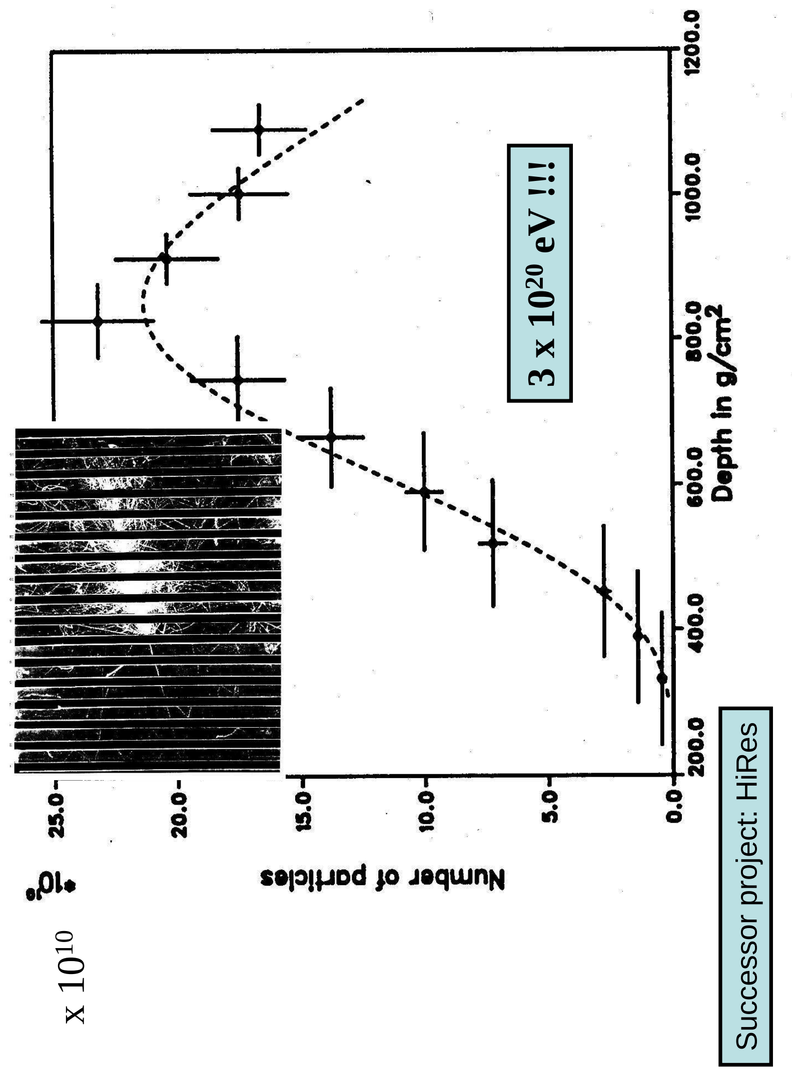
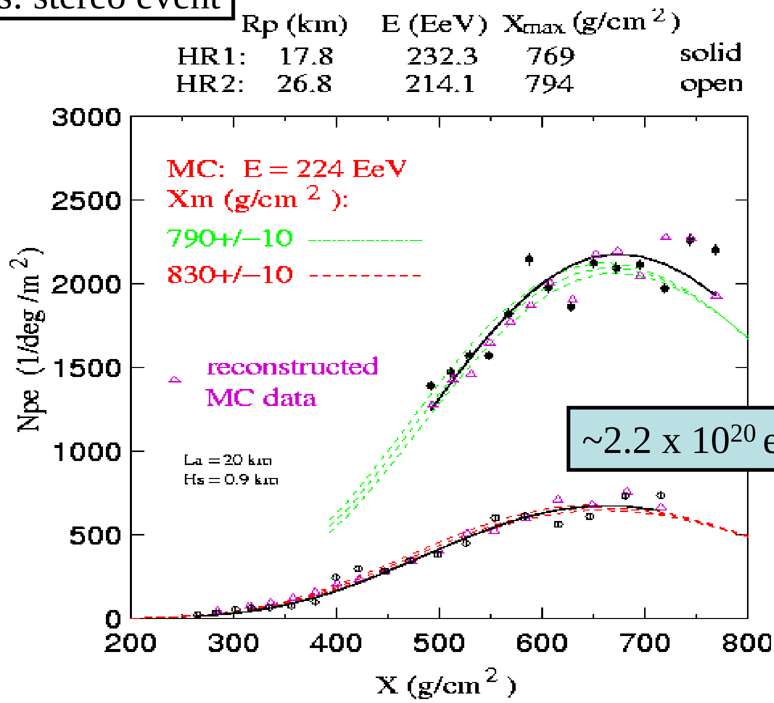


FIG. 1. Map of the density distribution of the giant EAS. The radius of each circle represents the logarithm of the density at each detector location. A cross shows the estimated position of the shower core.



HiRes: stereo event



Question of Mass Composition

"We remain with the dilemma: protons versus heavy nuclei. A clear cut decision cannot be reached yet. I believe that up to the highest energies the protons are th

"Fere libenter homines id, quod volunt, credunt!"

However, I must confess that a leak proof test of the pr

"Men wish to believe only what they prefer"

Thanks to Francesco Ronga

er

problem. Experimentally it is quite a difficult problem."

G Cocconi: Fifth International Cosmic Ray Conference, Guanajuato, Mexico, 1955

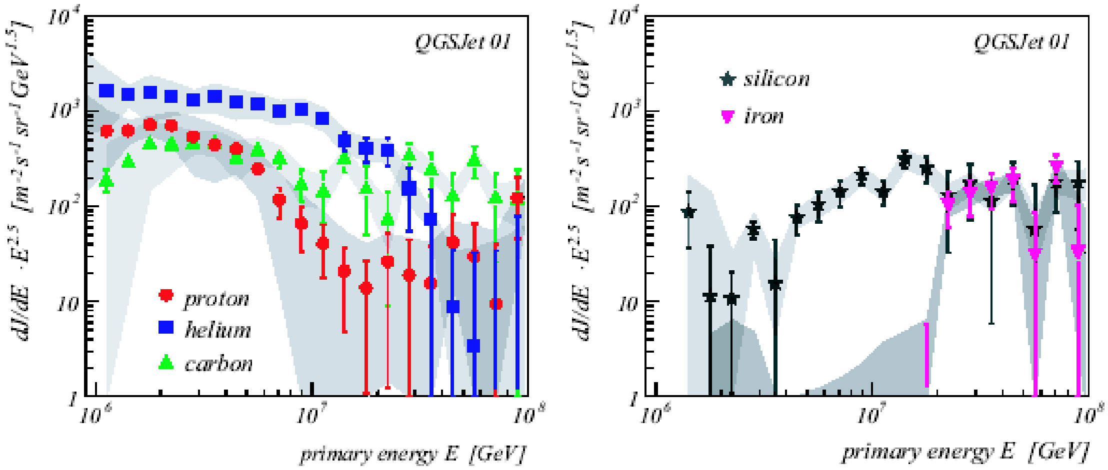


Fig. 14. Unfolded energy spectra for H, He, C (left panel) and Si, Fe (right panel) based on QGSJet simulations. The shaded bands are an estimate of the systematic uncertainties due to the used parametrizations and the applied unfolding method (Gold algorithm).

KASCADE result: Antoni et al: Astroparticle Physics (in press)

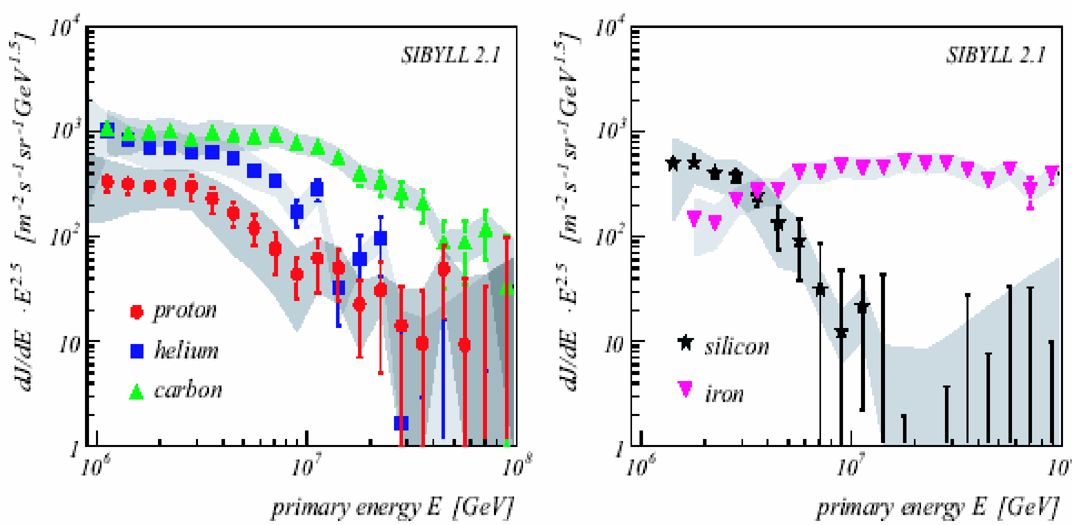


Fig. 15. Unfolded energy spectra for H, He, C (left panel) and Si, Fe (right panel) based on SIBYLL simulations. The shaded bands are estimates of the systematic uncertainties due to the used parameterizations and the applied unfolding method (Gold algorithm).

Comparison of features at the knee
ALL PARTICLE SPECTRUM

	Knee	γ_1	γ_2
QGSJET01	4.0 +/-0.8 PeV	-2.70 +/- 0.01	-3.10 +/- 0.07
Sibyll 2.1	5.7 +/- 1.6 PeV	-2.70 +/- 0.06	-3.14+/- 0.06

This gives a warning about the sensitivity of spectral details to mass and models – and this is at LOW energies.

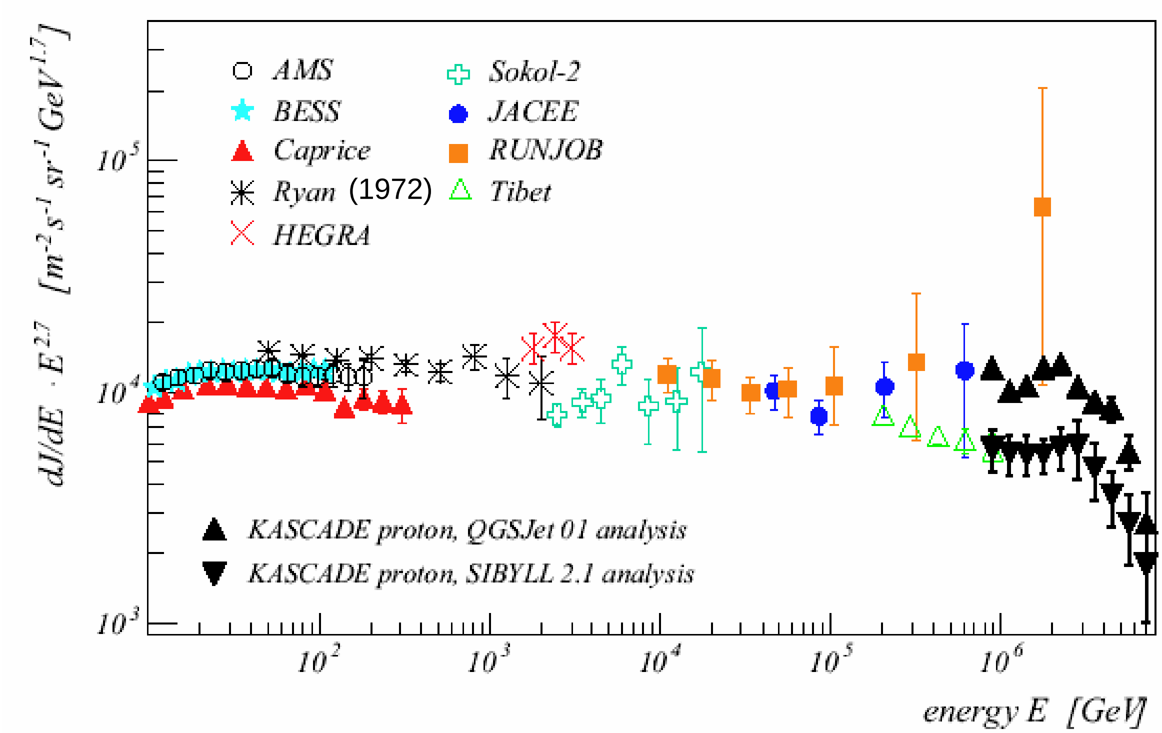


Fig. 23. Results for the proton energy spectrum for both of our analysis together with results from direct (AMS[42], BESS[43], CAPRICE[44], Ryan[45], SOKOL-2 [46], RUNJOB[31], JACEE[32]) and indirect (HEGRA[47], Tibet[48]) measurements.

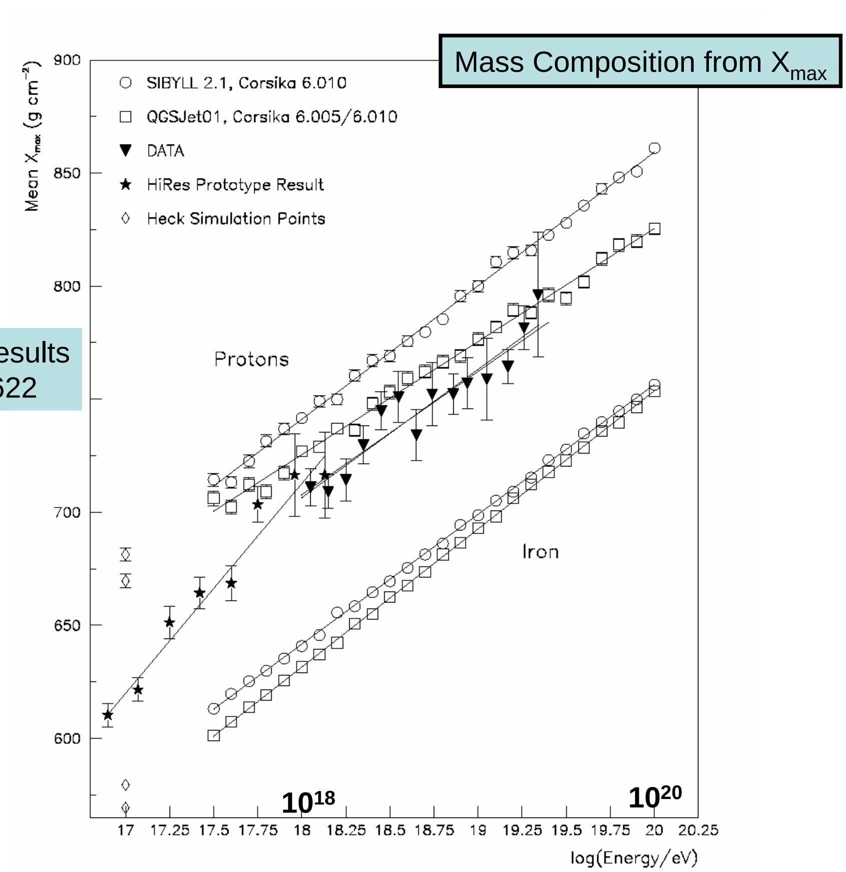
Approach to Mass at Higher Energies

- X_{max} and fluctuations in X_{max}
- Muon content of showers
- Lateral Distribution
- Time spread
- Comparison of rates at different angles
- Comparison of X_{max} with photon predictions

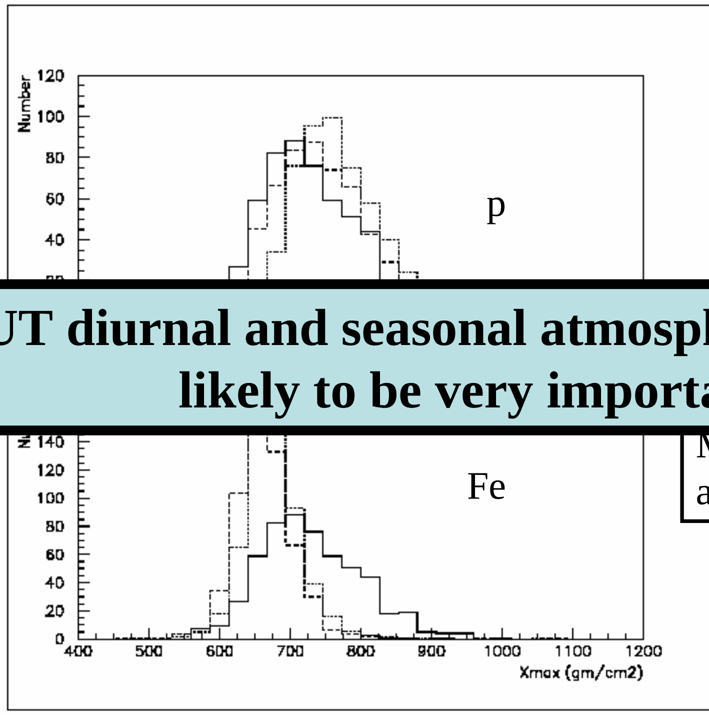
Except for N_{μ} , all can be used at Auger

Latest HiRes results
astro-ph/0407622

X_{max}



HiRes Composition at ICRC03



BUT diurnal and seasonal atmospheric changes likely to be very important

Models are Sibyll and QGSjet

Astroparticle Physics 22 249 2004 and data at ICRC 2003

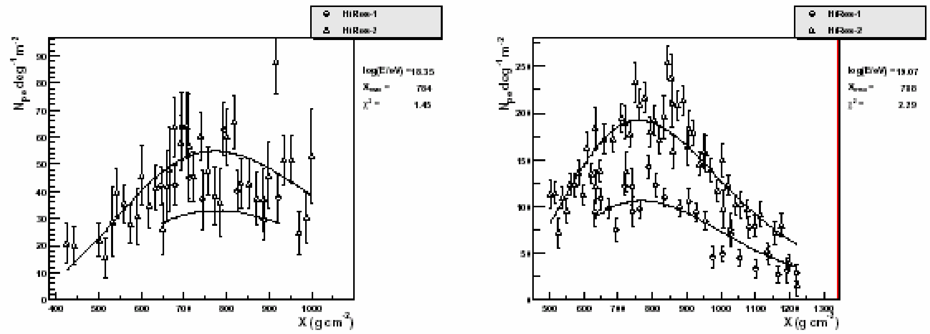


Fig. 9.— Typical reconstructed shower profiles. In both cases the track was over 20%

from astro-ph/0407622 and ApJ 622 910 2005

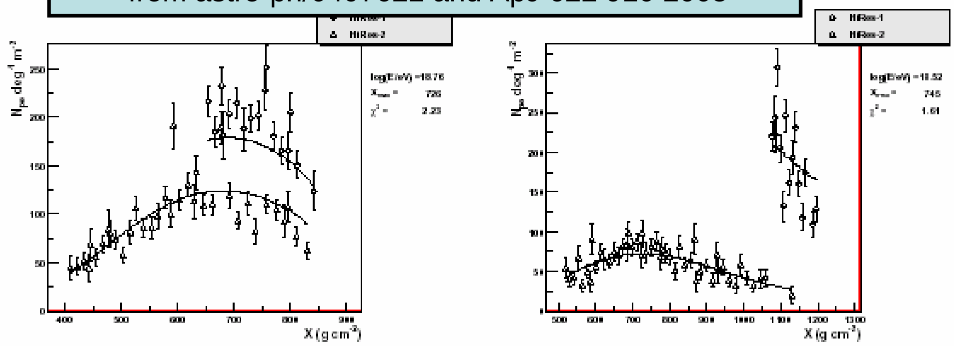


Fig. 10.— Typical reconstructed shower profiles. Even though HiRes-1 only observed a small portion of the shower, the SDP from HiRes-1 stringently constrains the global fit. The

Mass Composition: muon content

N_μ (>1 GeV) = $AB(E/A\varepsilon_\pi)^p$ (depends on mass/nucleon)

N_μ(>1 GeV) = $2.8A(E/A\varepsilon_\pi)^{0.86}$ ~ $A^{0.14}$

So, more muons in Fe showers

Muons are about 10% of total number of particles

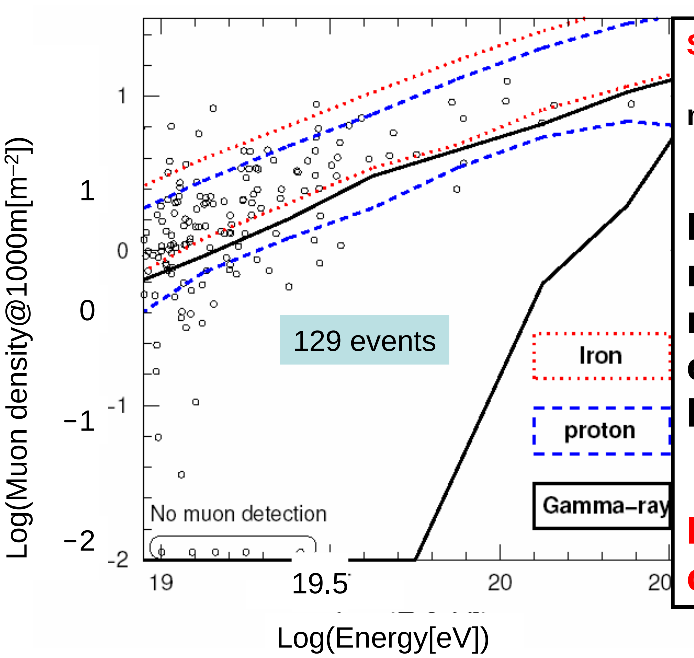
Used successfully at lower energies (KASCADE)

VERY expensive - especially at high energies

– Yakutsk and AGASA: muon density at 1000 m

Results from the AGASA array

"Consistent with proton dominant component"

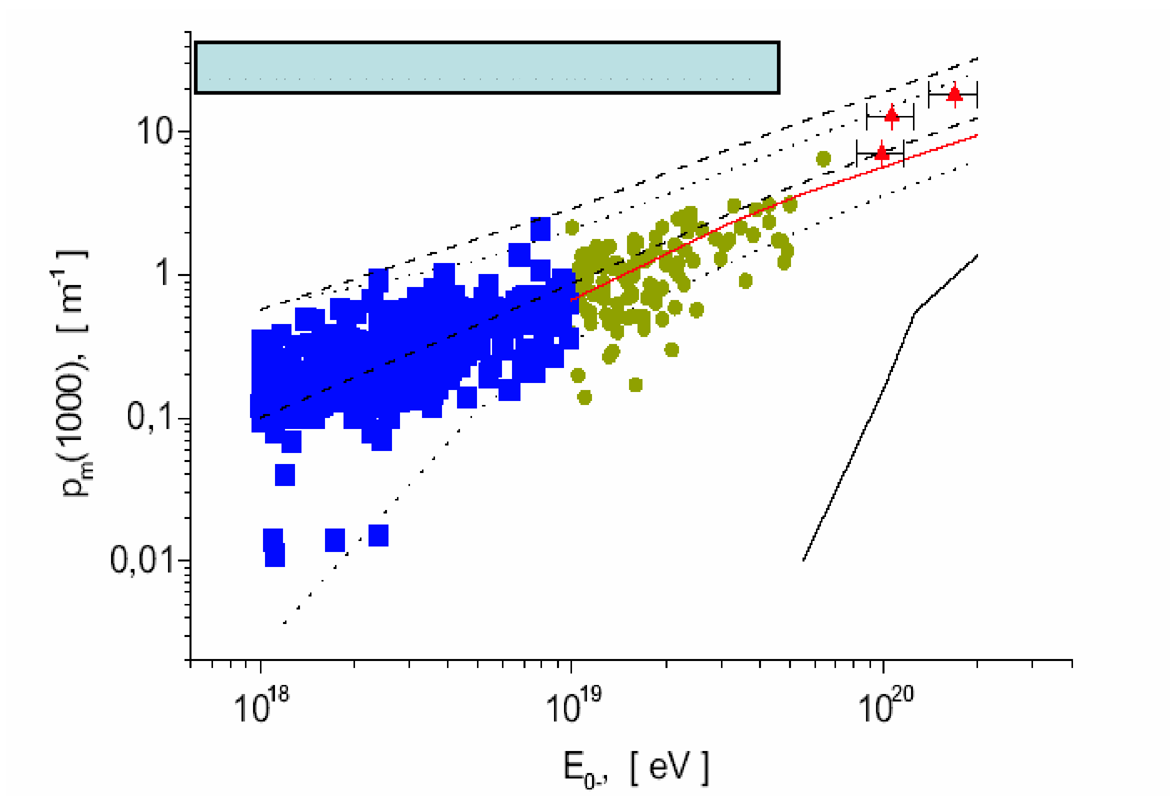


Sibyll 1.7: Sibyll 2.1: QGSjet98

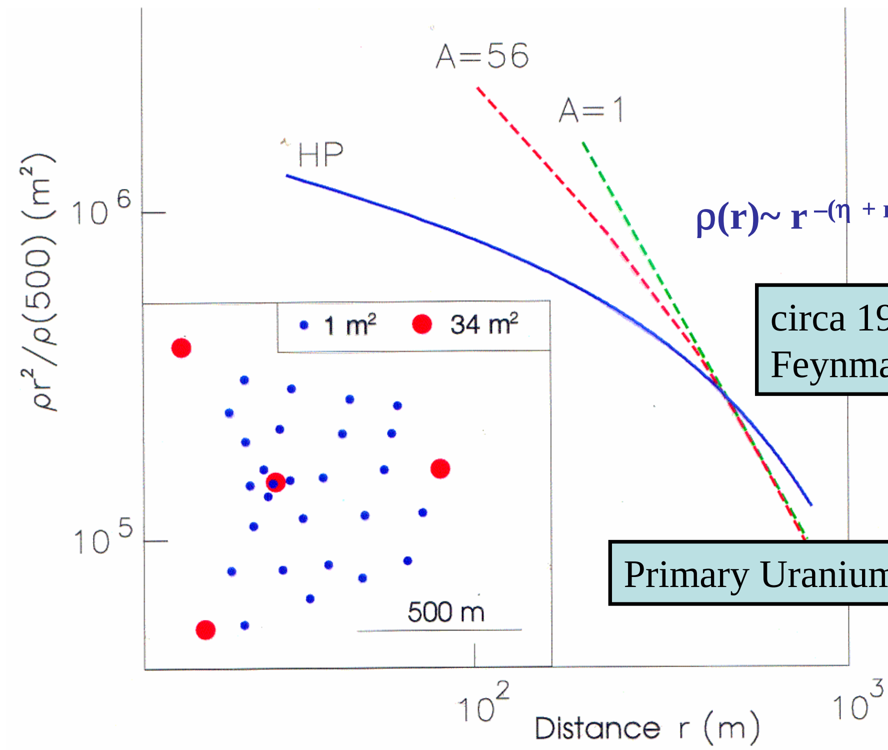
muon numbers 1: 1.17:1:45

Forthcoming QGS jet model will predict fewer muons – so mass estimates will be become HIGHER

LHC CMS energy corresponds to ~ 10^{17} eV



Mass Composition (iv): Using the lateral distribution

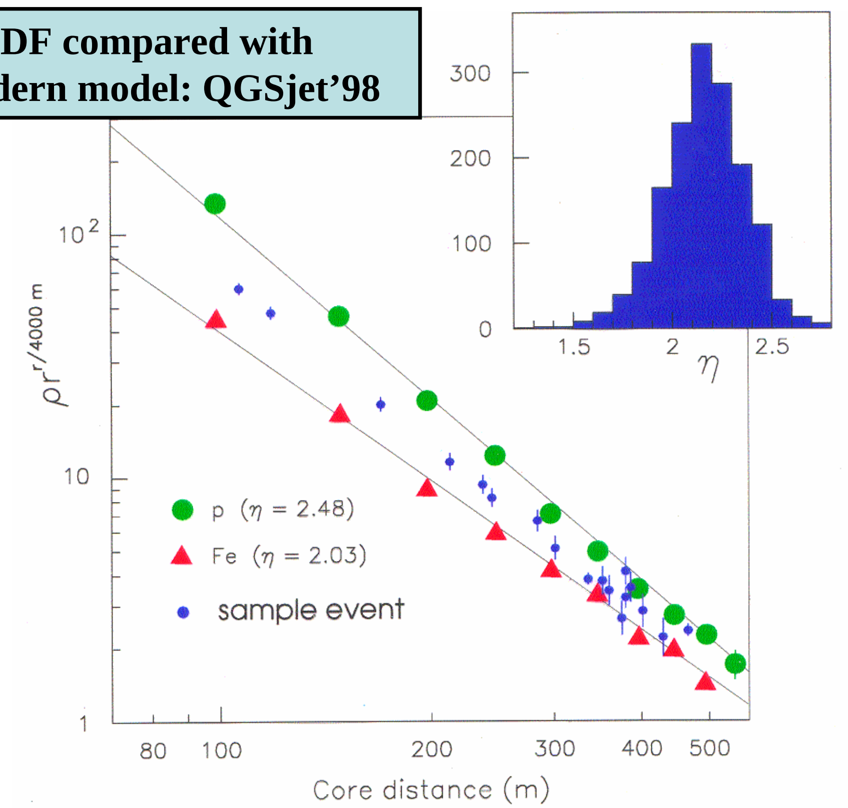


$\rho(r) \sim r^{-(\eta + r/4000)}$

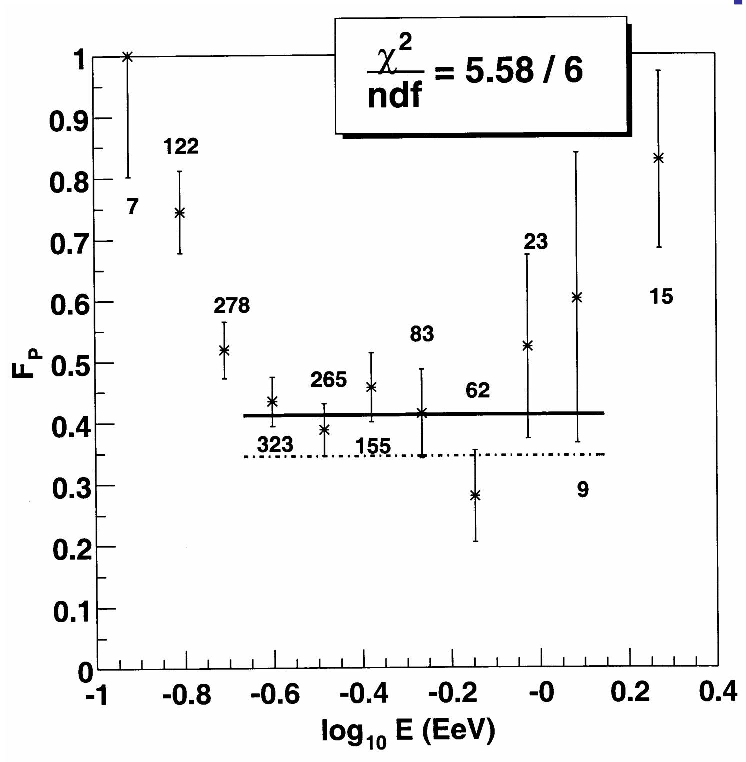
circa 1978:
Feynman Scaling

Primary Uranium?!

Sample LDF compared with more modern model: QGSjet'98

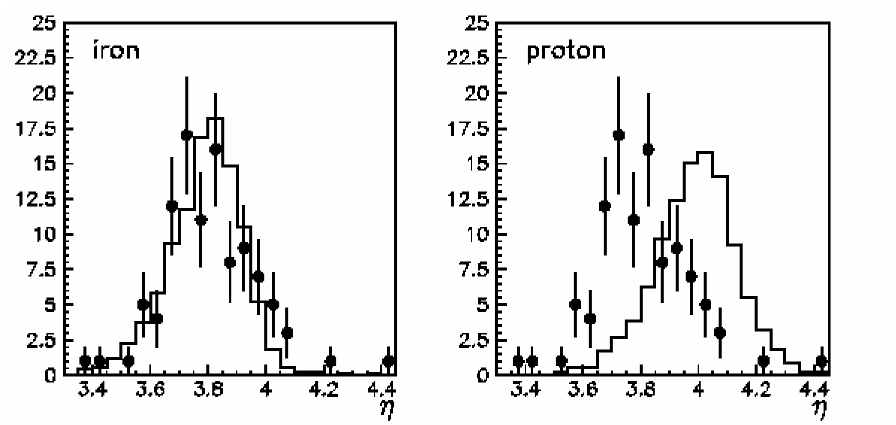


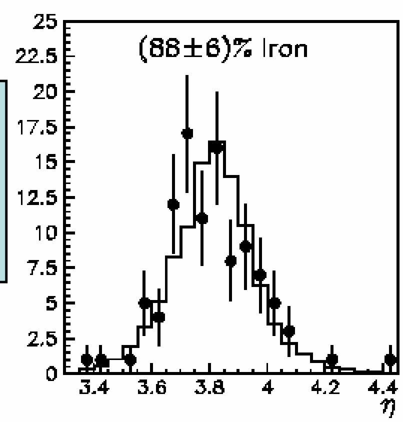
Estimate of Mass Composition



QGSjet models ('98, dotted line and '01, solid line).

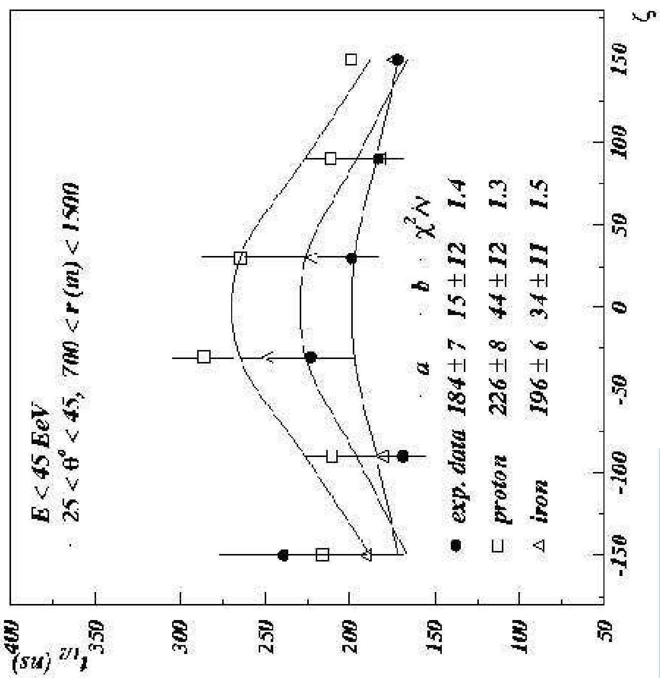
First 3 points: trigger bias





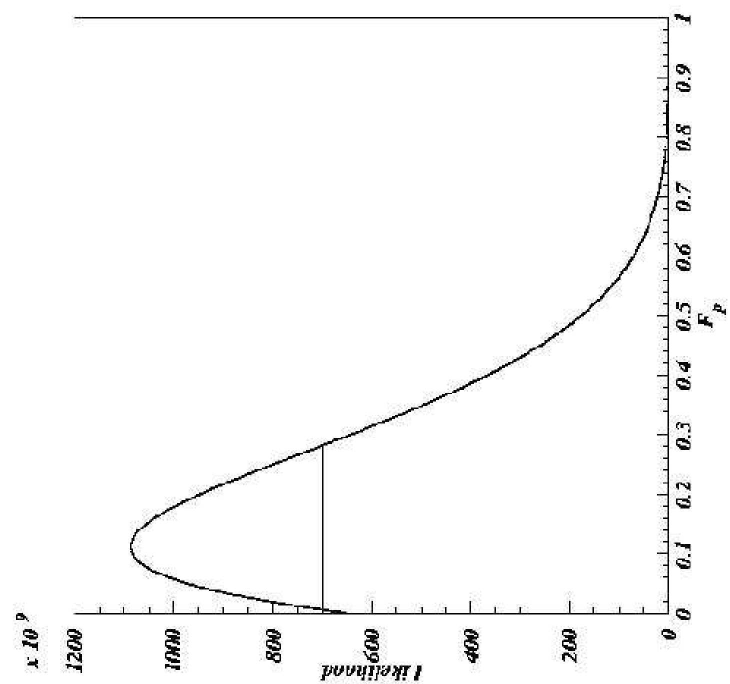
Lateral distribution data from Volcano Ranch interpreted by Dova et al Astropart Phys (2004)

Thickness of the shower disc

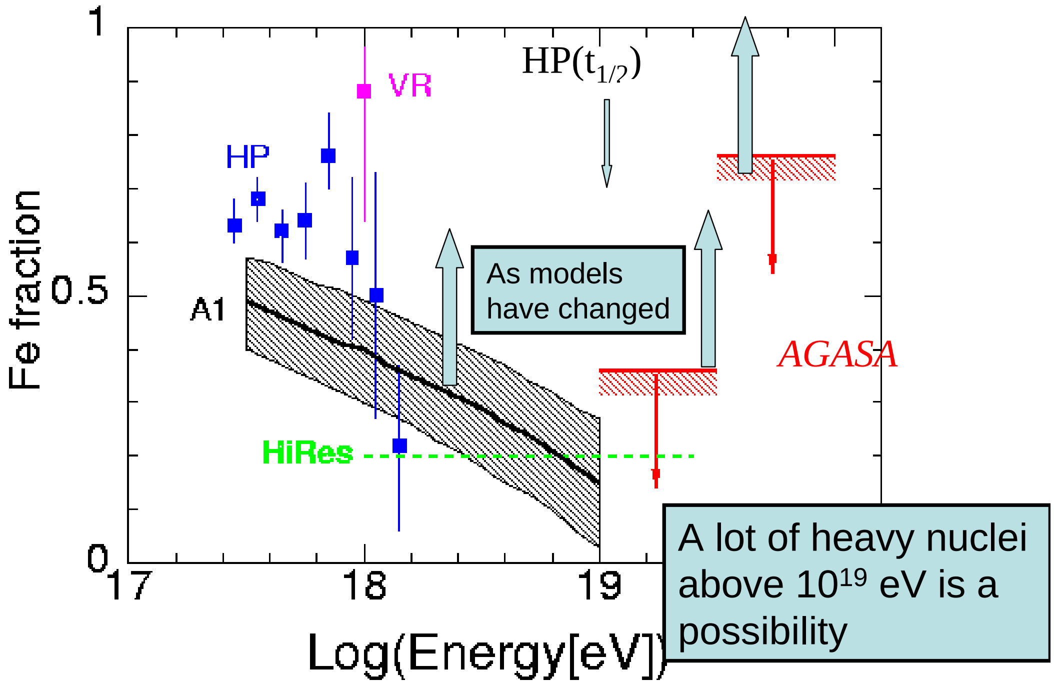


t1/2 ns

Haverah Park: ICRC 2003



Summary of baryonic mass composition claims



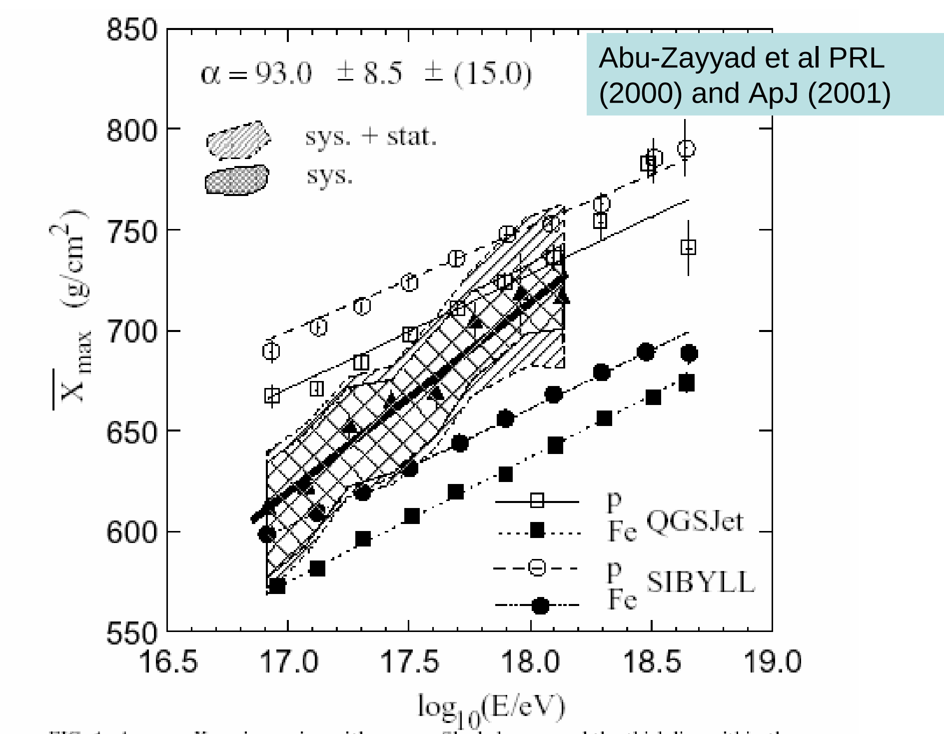


FIG. 1. Average X_{max} increasing with energy. Shaded areas and the thick line within the area represent HiRes data and the best fit of the data respectively. The closed triangles represent the data set corresponding to the central values of the parameters in the reconstruction. The circles, squres and lines refer to the simulation results. See text for details.

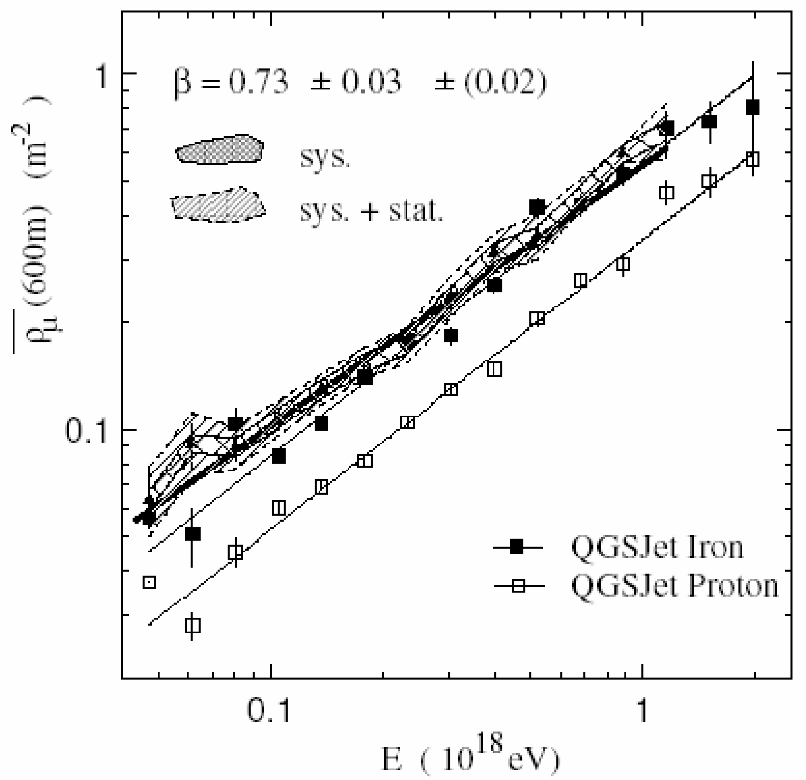
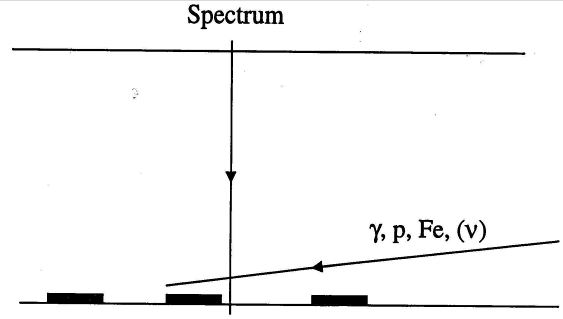


FIG. 2. Average Muon density at 600 m from the shower core. Same as FIG 1.

Mass information from study of Inclined Showers

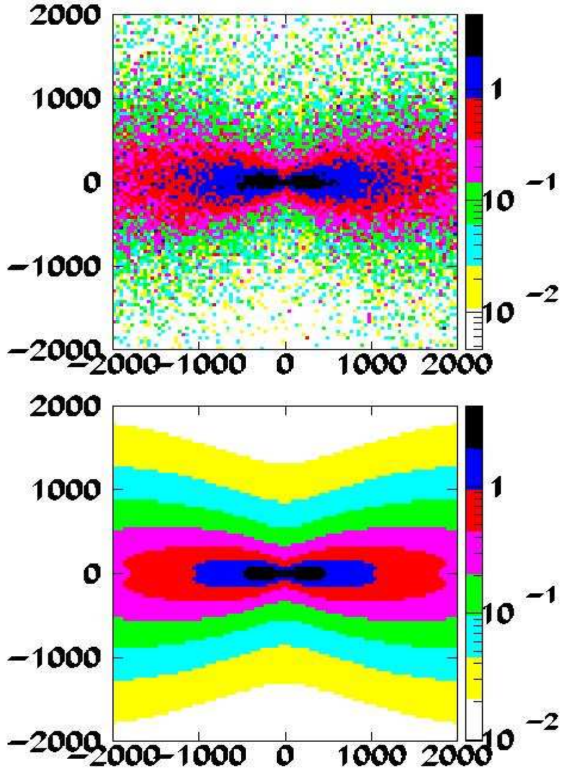


INPUT: Spectrum (mass-independent) e.g. FLUORESCENCE
Assumptions about mass

OUTPUT: Predicted Spectrum

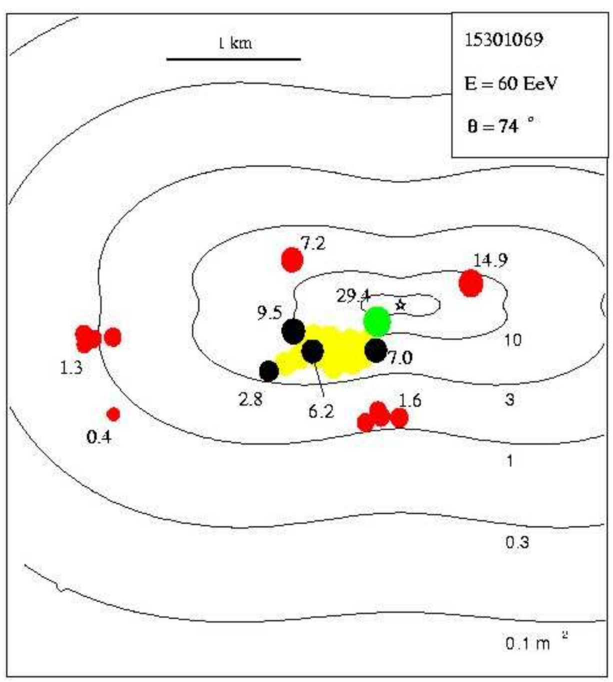
COMPARISON: Measured Rate

Example: Photon limit at 10^{19} eV
(Ave et al. Phys Rev Lett 2000)



Developed during effort to understand background against which neutrinos might be seen

Ave, Vazquez and Zas, Astroparticle Physics 14 91 2000



Ave et al. PRL 85 2244 2000

^{19} eV

< 40%

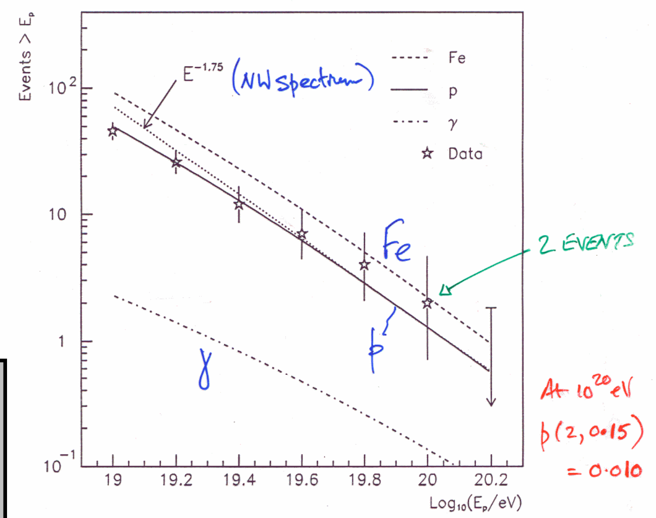
(@95% CL)

AGASA: muon poor events

Gamma-ray fraction upper limits (@90%CL)

34% (>10^{19}eV) (γ/p<0.45)

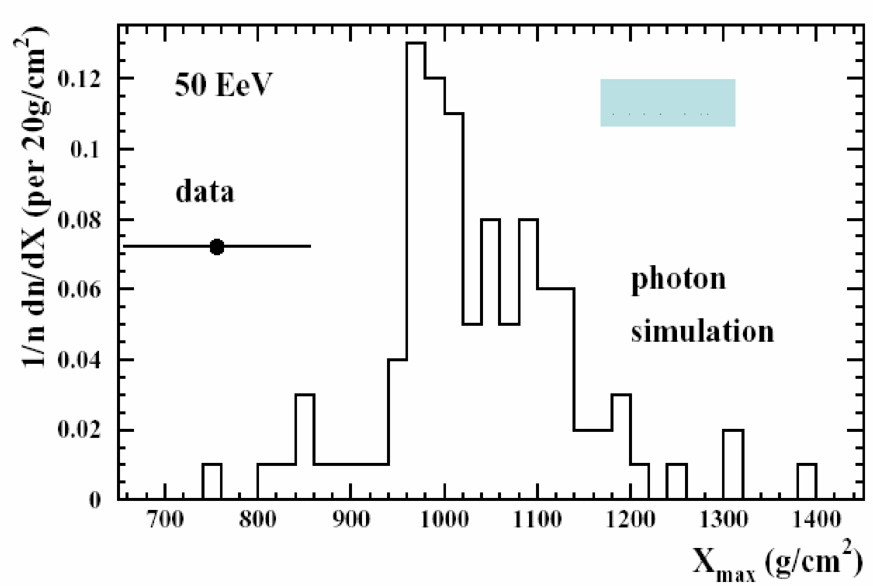
56% (>$10^{19.5}$eV) (γ/p<1.27)



60° < θ < 80°

Ave, Hinton, Vazquez, aaw, and Zas

PRL 85 244 2000



Ideas to explain the Enigma

- Decay of super heavy relics from early Universe (or top down mechanisms)

Wimpzillas/Cryptons/Vortons

Few photons: <40% at 10^{19} eV

Theorists have moved their model to higher energies

or is it 'simple'?

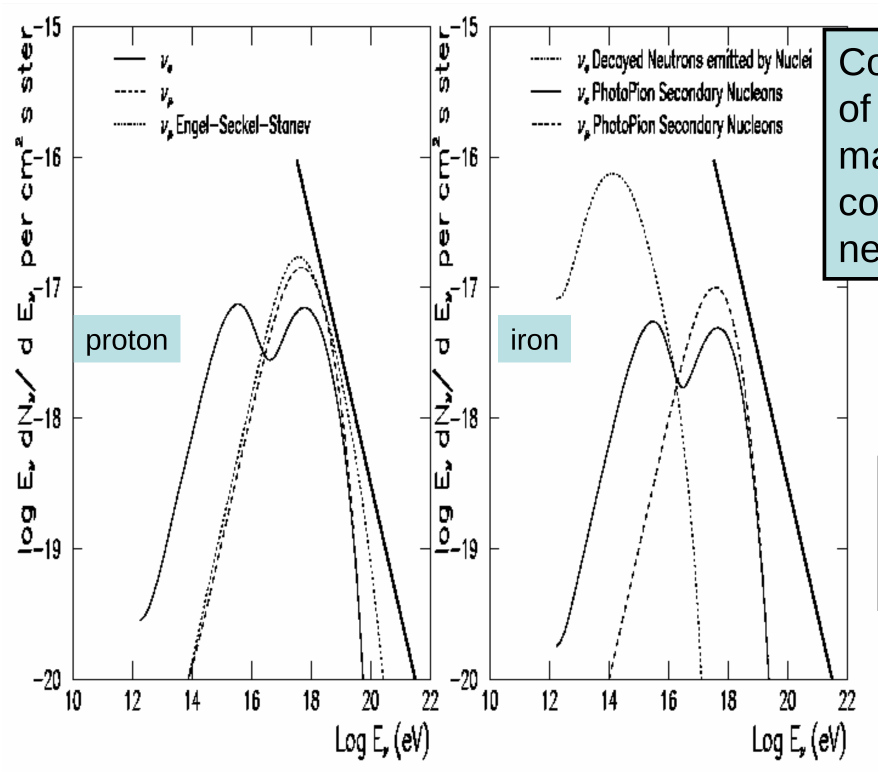
- Are the UHE cosmic rays iron nuclei?
- Are magnetic field strengths really well known?

Consequences of fewer protons

- Acceleration is Z-times easier
- Isotropy easier to understand
- Some reconciliation of AGASA and HiRes spectra
- Less need for exotic physics

BUT:

- Perhaps even more of a puzzle to think of a source as iron is (said to be) fragile
- Fewer neutrinos



Consequences of different masses for cosmogenic neutrino fluxes

Ave, Busca, Olinto, aaw and Yamamoto Astroparticle Phys (2005)

Electron and muon neutrino fluxes obtained from the nominal choice of astrophysical and cosmological parameters used by Waxman. The protons and iron primaries were assumed to have a maximum energy at production of 4Z x 10^{20} eV. The proton flux from the Waxman and Bahcall model is represented by a solid line.

Potential of the Auger Observatory

- **Directions** ✓✓✓
- **Energy** ✓✓
- **Mass**
  - **photons** ✓✓ **X_{max}, shower front thickness, inclined events**
  - **neutrinos** ✓✓✓
  - **protons or iron?**

HARDER: will use X_{max}, LDF, FADC traces, inclined events, radius of curvature…