UHE CR
and
The GZK Suppression
Ultra High Energy Cosmic Rays (E > 10^{19} eV)

Energy Loss Mechanisms for
of High Energy Particles

Interactions on the photons of the
Microwave Cosmic Background
(2.7 °K background)
Energy Loss Mechanisms

- Redshift

- \( p + \gamma \rightarrow p + \text{hadrons} \) PhotoProduction

- \( p + \gamma \rightarrow p + e^+ + e^- \) Pair Production

- \( A + \gamma \rightarrow (A - 1) + N \) Photo Disintegration
Average Photon Density in the Universe

- Cosmic (2.7 K) Background Radiation
- Stellar Light reprocessed by dust
- Stellar Light
Threshold for photoproduction:

\[ p + \gamma \rightarrow p + \text{hadrons} \]

Is determined by the threshold for pion production

\[ p + \gamma \rightarrow p + \pi^0 \]
\[ p + \gamma \rightarrow n + \pi^+ \]

\[ s = m_p^2 + 2 E_p \epsilon (1 - \beta \cos \theta_{\gamma p}) > (m_p + m_\pi)^2 \]
The Greisen -Zatsepin-Kuzmin “cutoff”

\[ p + \gamma \rightarrow p + \pi^0 \]
\[ p + \gamma \rightarrow n + \pi^+ \]

Photoproduction Threshold

\[ s = m_p^2 + 2 E_p \epsilon (1 - \beta \cos \theta_{\gamma p}) > (m_p + m_\pi)^2 \]

\[ E_p \geq \frac{(m_p + m_\pi)^2 - m_p^2}{2 \epsilon (1 - \cos \theta_{\gamma p})} \geq \frac{(m_p + m_\pi)^2 - m_p^2}{4 \epsilon} \]

\[ \cos \theta_{\gamma p} = -1 \]

\[ E_p > 6 \times 10^{19} \left( \frac{10^{-3} \text{ eV}}{\epsilon} \right) \text{ eV} \]
Energy Loss in one interaction

At threshold:
The pion and the proton are produced at rest in the center of mass frame, therefore they have the same velocity (and the same Lorentz Factor)

\[
E_{p,f} = m_p \gamma \\
E_{\pi} = m_\pi \gamma \\
\frac{\Delta E}{E} \sim \frac{m_\pi}{(m_p + m_\pi)} \sim 0.1
\]
Laboratory (Proton Rest) Frame

\[ m_p \varepsilon \gamma \geq (m_p + m_\pi)^2 - m_p^2 \]

General Frame

\[ E_p \varepsilon \gamma \geq m_p m_\pi \]

\[ E_p \varepsilon \gamma \geq 10^{17} \text{ eV}^2 \]

\[ E_p \varepsilon \gamma \geq 10^9 \text{ eV} \times 10^8 \text{ eV} \]

\[ 10^{20} \text{ eV} \times 10^{-3} \text{ eV} \]

\[ 2E_p \varepsilon + m_p^2 \geq (m_p + m_\pi)^2 \]
Computation of the Absorption Length of a proton in the intergalactic photon Field.

\[
\frac{1}{\lambda_{\text{int}}} = \int d^3 p_\gamma \ n_\gamma(p) \ (1 - \cos \theta_{p\gamma}) \ \sigma_{\gamma p}(s)
\]

Peak $\Delta^{++}$ at $\epsilon_\gamma \sim 300$ MeV
Qualitative analysis

\[ \lambda \underset{\sim}{\approx} \left( n_\gamma \sigma \right)^{-1} \]
\[ \sim \left( \frac{400 \text{ cm}^{-3} \left( 0.5 \times 10^{-27} \text{ cm}^2 \right)}{\text{cm}^{-1}} \right)^{-1} \]
\[ \sim \left( 2 \times 10^{-25} \text{ cm}^{-1} \right)^{-1} \]
\[ \sim 5 \times 10^{24} \text{ cm} \]
\[ \sim 2 \text{ Mpc} \]
Size of the visible Universe

GZK on CMB

GZK on all γ
Effect of Pair Production interactions
The threshold is lower
The cross section is higher
The energy loss per interaction is smaller

Photoproduction of pions

\[ E \gtrsim \frac{m_\pi \ m_p}{\varepsilon} \]

Pair production

\[ E \gtrsim \frac{(2 \ m_e) \ m_p}{\varepsilon} \]

\[ \frac{\Delta E}{E} \ < \ \frac{2 \ m_e}{m_p} \ \leq \ 10^{-3} \]
$p + \gamma \rightarrow p + e^+ e^-$
Absorption of High Energy Photons

Center of mass cross section

\[\gamma + \gamma \rightarrow e^+ + e^-\]
Inverse of absorption length for pair creation
Absorption for extragalactoc sources in Cherenkov Telescopes (TeV) is important. Due to starlight where there is high uncertainties.
Propagation of Nuclei

\[ A + \gamma \rightarrow \text{Nuclear Fragments} \]

\[ A + \gamma \rightarrow (A - 1) + N \]

\[ E \geq \frac{\left( m_{(A-1)} + m_N \right)^2 - m_A^2}{4 \varepsilon} \]

\[ E \geq \frac{\epsilon_{\text{binding}} m_p}{\varepsilon} \]

\[ \epsilon_{\text{binding}} \sim 8 \text{ MeV} \]
Discrepancy between the two largest experiments

AGASA
HIRES
The GZK cutoff energy, defined as the minimum energy predicted for a flux decrease of $1/e$ owing to intergalactic photomeson production interactions, as a function of redshift (Scully and Stecker 2002).
Structure in the Spectrum

\[ n(E, t) = \int_0^t dt \ S_{cr}(E_0, t) \times P[E; E_0, t] \]

Density of Cosmic Rays at the Present Epoch

Injection Rate at the epoch \( t \)

\[ S_0(E_0) \times f(t) \]

Energy Loss

\[ S_0(E_0) \times f(z) \]
Magnetic Deviation

\[ R = \frac{1}{300} \frac{E_{\text{eV}}}{Z B_{\text{Gauss}}} \text{ cm} \]

\[ R = 10 \frac{E_{19}}{Z B_{-9}} \text{ Mpc} \]

\( D \): distance from the source
\( d \): size of the region where the magnetic field is coherent
\[ \delta \theta_j \sim \frac{d}{R} \]

\[ \langle \delta \theta^2 \rangle = N (\delta \theta_j)^2 = \frac{D}{d} \left( \frac{d}{R} \right)^2 \]

\[ \langle \delta \theta \rangle = 2.8 \left( \sqrt{D \cdot d} \right)_{\text{Mpc}} \frac{Z B_{-9}}{E_{19}} \text{ degrees} \]

\[ \Delta t = N \frac{1}{6} \frac{d^3}{R^2} \approx 5000 \frac{D \cdot d^2 \cdot Z^2 \cdot B_{-9}^2}{E_{19}^2} \text{ years} \]
Models for the UHECR

**BOTTOM-UP**  (Acceleration of particles)
Active Galactic Nuclei
Gamma Ray Bursts

......

**TOP-DOWN**  (Decay of Massive Objects)
Topological Defects
Super-Massive Particles - Wimpzillas
Absence of Cutoff:

- Excess of Nearby Sources

- Neutrinos with anomalous large cross section

- New Particles

- Z-burst Model ("Neutrino Carrier")

- VIOLATIONS of LORENTZ INVARIANCE
WIMPZILLA's $M = 10^9 - 10^{19}$ GeV
TOP - DOWN Models

High Energy Cosmic Rays as DECAY products of Massive "Exotic" Objects (Relics of the Early Universe)

Topological Defects. SuperMassive Particles
Phenomenology of QUANTUM GRAVITY

Effective speed of photons in quantum space foam

\[ c(E) = c \times \left( 1 - \xi \frac{E}{M_{\text{Planck}}} + \ldots \right) \]

\[ \Delta t \simeq \xi \frac{E}{M_{\text{Planck}}} \frac{L}{c} \]

\[ \Delta t \simeq 0.06 \xi E_{\text{GeV}} \sim \text{sec} \]

High Energy Photons delayed
SHORTEST GRB: \sim 6 \text{ ms}

GRB 910711 (Trig. # 512)

200 \mu s

Rate (count/s)

Time (s since trigger)  \textbf{Bhat et al. 1992}
Modifications of Reaction Thresholds

\[ p + \gamma \rightarrow p + \pi^0 \]

\[ \gamma + \gamma \rightarrow e^+ + e^- \]

\[ E \times \varepsilon = m_e^2 \]

\[ E \times \varepsilon - \xi' \frac{E^3}{M_{\text{Planck}}} = m_e^2 \]
Results from the Pierre Auger Observatory and Future Prospects for Particle Physics and Cosmic Ray Studies
Flux of Cosmic Rays

32 decades in intensity

1 particle m\(^{-2}\) s\(^{-1}\)

Air-showers

‘Knee’
1 particle m\(^{-2}\) per year

AMS
ATIC
PAMELA
CREAM

Auger Telescope Array

Ankle
1 particle km\(^{-2}\) per year

LHC

32 decades

Direct Measurements

12 decades
Greisen-Zatsepin- Kuz’min – GZH effect (1966)

\[ \gamma_{2.7\,\text{K}} + p \rightarrow \Delta^+ \rightarrow n + \pi^+ \text{ or } p + \pi^0 \]

and

\[ \gamma_{\text{IR}/2.7\,\text{K}} + A \rightarrow (A - 1) + n \]

• Sources must lie within \( \sim 100 \) Mpc at 100 EeV

• Note that neutrinos - of different energies come from the decay of \( \pi^+ \) and \( n \)

• Photons from decay of \( \pi^0 \)
### The Pierre Auger Collaboration

<table>
<thead>
<tr>
<th>Country</th>
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<tbody>
<tr>
<td>Croatia*</td>
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<td>Australia</td>
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<td>France</td>
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<td>Germany</td>
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<td>Poland</td>
<td>USA</td>
</tr>
<tr>
<td>Portugal</td>
<td>Vietnam*</td>
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<tr>
<td>Rumania</td>
<td></td>
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<tr>
<td>Slovenia</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>~ 400 PhD scientists from</td>
</tr>
<tr>
<td>(United Kingdom)</td>
<td>~ 100 Institutions in 17</td>
</tr>
</tbody>
</table>

#### Aim:
To measure properties of UHECR with unprecedented precision to discover properties and origin of UHECR.
Water-Cherenkov, Haverah Park (UK): A tank was opened at the ‘end of project’ party on 31 July 1987. The water shown had been in the tank for 25 years - but was quite drinkable.

Jim Cronin: “An existence proof”

Schematic of the Fly’s Eye Fluorescence Detector of University of Utah
The Design of the Pierre Auger Observatory marries these two techniques in the ‘HYBRID’ technique.

- Fluorescence →

- Array of water-Cherenkov detectors →
The Pierre Auger Observatory

- 1600 water-Cherenkov detectors: 10 m² x 1.2 m distant: 1.5 km
- 3000 km²
- Fluorescence detectors at 4 locations
- Two laser facilities for monitoring atmosphere and checking reconstruction
- Lidars at each FD site
- Radio detection at AERA
- Muon detectors – buried
Important feature of the hybrid approach

Precise shower geometry from degeneracy given by SD timing

Essential step towards high quality energy and $X_{\text{max}}$ resolution

Times at angles, $\chi$, are key to finding $R_p$
GPS Receiver and radio transmission
The Surface Detector
Fluorescence detector at Los Leones
Figure 6.3: A real FD event with reconstructed energy $7 \times 10^{19}$ eV. In the left panel are measured data (clear sky and no scattered moonlight, a baseline variance of 25 (ADC counts)$^2$) and in the right panel the same data after adding random noise corresponding to a 40 times higher NSB.
Angular and core location resolution from Central Laser Facility

355 nm, frequency tripled, YAG laser, giving < 7 mJ per pulse: GZK energy
Reconstruction of an Auger Event using water-Cherenkov detectors

(i) Reconstruction of arrival direction

Angular Accuracy: better than 0.9° for more than 6 stations (arXiv 1502.01323)
(ii) Reconstruction of shower size, $S(1000)$

Signal in event, $E = (104 \pm 11)\ eV$ and $\theta = 25.1^\circ$

Choice of $S(1000)$ as the ‘shower size’ is dictated by the spacing of the detectors

It is distance at which signal has minimum spread for a range of lateral distributions

Accuracy of $S(1000) \sim 10\%$. Details at arXiv 0709.2125 and 1502.01323

(compare TA: 1.2 km spacing and parameter is $S(800)$)
Reconstruction of fluorescence event

(a) Light at aperture.

(b) Energy deposit.
A Hybrid Event

Energy Estimate from area under curve 

\((2.1 \pm 0.5) \times 10^{19} \text{ eV}\)

must also account for ‘invisible energy’

Core location
Easting 468693 ± 59
Northing 6087022 ± 80
Altitude = 1390 m a.s.l.

Shower Axis
\(\theta = (62.3 \pm 0.2)°\)
\(\phi = (119.7 \pm 0.1)°\)

E_{em} = (21 \pm 5) \text{ EeV}
E_{tot} = (23 \pm 6) \text{ EeV}
$f = \frac{E_{\text{tot}}}{E_{\text{em}}}$

Invisible Energy

For more detailed discussion, see arXiv 1307.5059
Checking the energy and $X_{\text{max}}$ resolution

$E = 7.1 \pm 0.2 \times 10^{19} \text{ eV} \quad - \quad X_{\text{max}} = 752 \pm 7 \text{ g/cm}^2$
Auger Energy Calibration for Vertical Showers

839 events

$7.5 \times 10^{19}$ eV
Auger Energy Spectrum from Vertical Events: 2013

- Approximately 175,000 events from 32,000 km$^2$ sr y
Figure 2.10: Examples of fluxes of different mass groups for describing the Auger spectrum and composition data. Shown are the fluxes of different mass groups that are approximations of the maximum-energy scenario (left panel) and one photodisintegration scenario (right panel). The colors for the different mass groups are protons – blue, helium – gray, nitrogen – green, and iron – red. The model calculations were done with SimProp [30], very similar results are obtained with CRPropa [29].
Analysis of inclined showers (> 60°)

- Particles must penetrate more atmosphere and at observation level the signals are almost entirely muons with contemporaneous component of electromagnetic radiation from \( \mu \)-decay and knock-on electrons.

- Muons are energetic but strongly deflected in geomagnetic field.

- Shower loses circular symmetry.

FADC traces are short in inclined events.

1 km, 22°: 1 km 80°: \( \sim 5000 \text{ g cm}^{-2} \)
37 stations
71°
54 EeV

Fit made to density distribution

Energy measured with ~20% accuracy
Deconvolved spectrum based on 15614 events
AUGER results: GZK
Comparison of two Auger Spectra with Telescope Array

$E$ (eV)

$(J/J_{ref}) - 1$

- Auger SD inclined
- Auger SD vertical (ICRC 2013)
- Telescope Array SD (2013)
Comparison with Telescope Array

• Auger spectrum is now measured up to a declination of 25.3° N, well into Telescope Array range

• Up to suppression region, TA and Auger spectra agree well
  Average TA residual is 23%.

• In suppression region the differences are large and may be due to
  Anisotropy effects
  Atmospheric (Vertical aerosol depth as function of height)
  Detector effects: energy dependence of systematic uncertainties
  Different assumptions about composition, invisible energy, fluorescence yield
The well-established steepening of the spectrum itself is **INSUFFICIENT** for us to claim that we have seen the Greisen-Zatsepin-Kuz’min effect.

It might simply be that the sources cannot raise particles to energies as high as $10^{20}$ eV.

It would be enormously helpful if the arrival directions were Anisotropic and sources could be identified.

**Deflections in magnetic fields:**

- at $\sim 10^{19}$ eV: still $\sim 10^\circ$ in Galactic magnetic field - depending on the direction
\[ E_{\text{max}} = k Z e B R \beta c \]

\[ k < 1 \]

Hillas 1984
ARA&A
B vs R

Magnetars
Active Galactic Nuclei?
Synchrotron Losses
Colliding Galaxies
Correlation has fallen from ~ 68% to ~ 28% (2007–> 2014) compared with 21% for isotropy: about 1.4% probability

Cen A may be a source: in 13º circle around: 12 seen/1.7

A clear message from the Pierre Auger Observatory:-

We made it too small (See near the topmost/first part).
Auger and Telescope Array Hot-Spots
AUGER results: anisotropy

(a) Auger sky map, 2007

(b) Evolution of correlation signal, 2009

(c) Angular distance from AGN, 2009
chance probability: 1.4% ; is there an energy dependence?
First scan gave $\psi < 3.1^\circ$, $z < 0.018$ (75 Mpc) and $E > 56$ EeV
Figure 3.20: Arrival distribution and angular correlation of cosmic rays of the modified Auger data set with AGNs of the Swift-BAT catalog [138]. Shown are events with $E > 4 \times 10^{19}$ eV. The top row of plots show the complete data set (454 events), the middle row the selection deprived of ligl elements (326 events), and the bottom row the proton-enriched selection (128 events).
Taylor, arXiv:1107.2055

\[ E_{\text{max}, \text{Fe}} = 10^{21} \text{ eV} \]
\[ \alpha = 1.8 \]
100% Iron

\[ E^2 \frac{dN}{dE} \left[ \text{eV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right] \]

Monte Carlo
Analytic
Auger 2009

0-3 Mpc
3-9 Mpc
9-27 Mpc
27-81 Mpc
81-243 Mpc

\[ \sigma_{\text{sys}}(E) \]
Figure 5. Amplitude of the first term in the Fourier expansion of the flux measured at the Auger Observatory in terms of R.A. as a function of energy. It can be related to

Galactic Centre: 266°

Galactic Anti-Centre: 85.5°

Figure 6. Phase of the first harmonic in R.A. as a function of energy using data from the Pierre Auger Observatory from January 1, 2004 to December 31, 2010 for the larger array,
Recently we have completed analysis of inclined events above 4 EeV and the addition of 30% more data from inclined events.

This has:

(i) given a broader sky coverage up to declination 25.3° and
(ii) improved the significance of anisotropy the largest energy bin

Note that the phase is in good agreement with previous work

Table 1: Rayleigh analysis in right ascension

<table>
<thead>
<tr>
<th>$E$ [EeV]</th>
<th>$N$</th>
<th>$k$</th>
<th>$a_k^\alpha$</th>
<th>$b_k^\alpha$</th>
<th>$r_k^\alpha$</th>
<th>$\varphi_k^\alpha$</th>
<th>$P(\geq r_k^\alpha)$</th>
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<tbody>
<tr>
<td>4 - 8</td>
<td>50,417</td>
<td>1</td>
<td>0.0030 ± 0.0063</td>
<td>0.0008 ± 0.0063</td>
<td>0.0031</td>
<td>15°</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>-0.0012 ± 0.0063</td>
<td>-0.0004 ± 0.0063</td>
<td>0.0013</td>
<td>99°</td>
<td>0.98</td>
</tr>
<tr>
<td>&gt; 8</td>
<td>19,797</td>
<td>1</td>
<td>-0.004 ± 0.010</td>
<td>0.044 ± 0.010</td>
<td>0.044</td>
<td>95°</td>
<td>6.4×10^{-5}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.009 ± 0.010</td>
<td>0.027 ± 0.010</td>
<td>0.028</td>
<td>36°</td>
<td>0.021</td>
</tr>
</tbody>
</table>
To interpret the arrival direction data a crucial question is

“What is the mass of the cosmic ray primaries at the highest energies?”

• Answer is dependent on unknown hadronic interaction physics at energies up to ~ 30 times CM energy at LHC

• In particular, cross-section, inelasticity and multiplicity and, in addition, pion-nucleus and nucleus-nucleus interactions

• Here is an important link between particle physics and astroparticle physics
How we try to infer the variation of mass with energy

Energy per nucleon is crucial

Need to assume a model

\[ \frac{dX_{\text{max}}}{\log E} = \text{elongation rate} \]
Some Longitudinal Profiles measured with Auger

$1000 \text{ g cm}^{-2} = 1 \text{ Atmosphere} \approx 1000 \text{ mb}$
AUGER results: composition
Xmax compared to Pre-LHC models

\[
\langle X_{\text{max}} \rangle
\]

\[
\text{RMS}(X_{\text{max}})
\]

Xmax compared to Post-LHC models

\[
\langle X_{\text{max}} \rangle
\]

\[
\text{RMS}(X_{\text{max}})
\]

LHC data have been very useful for tuning of interaction models
Distribution of $X_{\text{max}}$ as function of energy

PRD 90 1220005 2014

19759 events above $6 \times 10^{17}$ eV

$7 \times 10^{17}$ eV

$3 \times 10^{19}$ eV
Auger Interpretation: Phys Rev D 90 1222006 2014 (arXiv 1409.5083)

\[ 7 \times 10^{17} \text{ eV} \quad 1.1 \times 10^{19} \text{ eV} \quad > 3 \times 10^{19} \text{ eV} \]
Discussion of Auger/Telescope array data: arXiv 1503.07540
Report of Joint Analysis Working Group

Direct comparison is not possible because of different approaches to analysis.
A joint TA/Auger working group has studied this problem

The mass composition inferred from the Auger measurements, in terms of p, He, N and Fe has been simulated with the TA fluorescence analysis methods.

$X_{\text{max}}$ measured by TA is consistent with that found with Auger mass distribution

$$\Delta X_{\text{max}} = 2.9 \pm 2.7 \text{ (statistical)} \pm 18 \text{ (syst) g cm}^{-2}$$
Photon Limit:
new results — to be reported at ICRC 2015

Searches for photons make use of anticipated differences in showers arising from:

- the steeper fall-off of signal with distance
- the slower risetime of the signals in the water-Cherenkov detectors
- the larger curvature of the shower front
- the deeper development in the atmosphere resulting in greater $X_{\text{max}}$

The limits rule out exotic, super-heavy relic models
On the detection of ultra high energy neutrinos with the Auger observatory

K.S. Capelle, J.W. Cronin, G. Parente, E. Zas

1) Regular proton shower
2) Deep Down-going $\nu$ shower
3) Up-going Earth-skimming $\nu_\tau$ shower
4) Down-going $\nu_\tau$ interacting in the mountains

Charged current
- $\nu_e$ (High energy electron)
- $\nu_\mu$ (Hadronic jet)
- $\nu_\tau$ (Hadronic jet)

Neutral current
- $\nu_x$ (Hadronic jet)
The neutrino search strategy

Are showers seen at very large zenith angles with the characteristics of vertical showers?

The right-hand type of event is the hadronic background: the left-hand type of event is what is expected from the signal.

No candidates yet found.
Latest result on search for neutrinos: submitted to Phys Rev D
Hadronic Interactions

Demonstrations of some successes
- and of some problems
Cross-section measurements from Auger Observatory: PRL 109 062002 2012

$\Lambda_\eta = 55.8 \pm 2.3$ g/cm$^2$

$10^{18} < E \text{ (eV)} < 10^{18.5}$
\[ \sigma_{pp}^{\text{inel}} = [92 \pm 7(\text{stat})^{+9}_{-11}(\text{syst}) \pm 7(\text{Glauber})] \text{ mb}, \]

\[ \sigma_{pp}^{\text{tot}} = [133 \pm 13(\text{stat})^{+17}_{-20}(\text{syst}) \pm 16(\text{Glauber})] \text{ mb}. \]
Summary of main results from Auger Observatory

• Spectrum suppression above ~ 40 EeV

• Large scale dipole in arrival distribution above 8 EeV

• Large scale anisotropy indicated by phase shift in RA below the knee

• Indications of anisotropy above 40 EeV – but hugely more events needed

• $X_{\text{max}}$ shows (i) distinct change of slope with energy
  (ii) rms becomes smaller with energy

  These changes suggest mass becomes heavier as energy increases

Important limits to fluxes of neutrinos and photons

• Major question: Is suppression GZK or photodisintegration?
To answer this question we need mass information in more detail and at higher energies. This is the main aim of the plans being evaluated now for the next phase of the Observatory.

**What we plan to do:-**

- FD on-time will be extended to 19% to access higher energies.
- Radio technique will be developed to get many more data on $X_{\text{max}}$ at lower energies.
- Scintillators will be added above water-Cherenkov detectors to deduce muons with method calibrated with buried muon detectors.

Aim is to identify mass of primary on event-by-event basis.
(i) Detection of Showers using Radio antennas

with AERA-24 data (126 HQ events)

Energy resolution better than 22%

15.7 MeV in 1 EeV shower

40 – 80 MHz

Energy resolution better than 22%
(ii) $4 \text{ m}^2$ Scintillators above Water-Cherenkov detectors

Scintillators respond to muons and electromagnetic component

Water-Cherenkov detectors absorb all of the em component and are fully sensitive to muons

It has been demonstrated with simulations that techniques exist to separate out the muon component

Figure 4.1: 3D view of a water-Cherenkov detector with a scintillator unit on top.
(iii) Buried Muon Detectors (1.3 m below surface)

Figure 5.1: Scintillators strips: left: general mounting in the PVC housing, right: detail of the 64-pixel optical connectors.

60 x 20 m²