Today we will discuss the new data on UHECR presented during the last couple of years by the Auger observatory in Argentina. These data do not match previous analyses and partially disagree with the data from HiRes Fly's Eye, the second most powerful UHECR observatory.

The data of Auger set the beginning of a new type of astronomy: Cosmic ray astronomy.
The Auger observatory is the first *hybrid* UHECR detector
The Telescope Array

Surface Detectors:
607 plastic scintillators (like AGASA)
1.2 km spacing

680 km²

Located in Utah

Japan
US
Korea
Russia
Belgium
While Auger observes both the air shower signals at ground and the shower profile, HiRes consisted only of fluorescent detectors. As a reminder we show here the profile of the highest energy shower seen by the Fly's Eye. Showers of heavy nuclei will have maxima and lower atmospheric depth, gamma ray showers would penetrate deeper.
HiRes uses the integral of the shower longitudinal profile and accounts for the *invisible* (non EM) energy. Auger uses $S(1000)$ scaled to the fluorescent energy as $E_{FD} = 1.5 \times 10^{17} \text{ eV} \times S(1000)^{1.08}$. The two energy estimates should be the same and they are not. Note: the Auger aperture is fixed by the size of the surface array, HiRes aperture comes from MonteCarlo.

**Problem**

Why are the energy assignments different when they should be identical?

*From: M. Roth for the Auger collaboration*
Fri May 21 20:59:07 2004
Easting = 474720 ± 16m
Northing = 6087364 ± 8m
dt = 127.9 ns

Theta = 59.2 ± 0.2 deg
Phi = -22.9 ± 0.2/sin(theta) deg

R = 18.9 ± 0.8 km
S(1000) = 205.30 ± 4.40 VEM
E = 115.69 EeV ± 2%
Not everything is fine for Auger either. When the MonteCarlo EM component is subtracted from $S(1000)$ the fraction of the muon component is much higher than predicted by interaction models. 

From: R. Engel for the Auger collaboration.

Is there a problem with the hadronic interaction models that are used for the giant air shower analysis?
TA uses similar technique as shown on the left.
The biggest excitement in 2007-08 came from the field of the ultrahigh energy cosmic rays (UHECR): from the results of Auger and HiRes.

These two detectors proved that UHECR are charged nuclei by observing the GZK effect, the steep change of the cosmic ray spectrum at about $10^{19.7}$ eV which is due to interactions with the photon fields of the Universe, mostly with the MBR. Apart from this statement the two groups do not agree on much else.

Let us go through some of the arguments. Do not forget that most arguments were raised by the experimental groups themselves.
Ultrahigh Energy cosmic ray spectrum:

with the exception of the AGASA events (note that there is a re-analysis of AGASA, not shown) above $10^{20}$ eV all other measurements show approximately the same spectral shape.

The highest energy events of AGASA inspired the top-down models for UHECR production.

The differences are small but lead to different interpretations.

The HiRes spectrum has a slope of 2.8 between log10(E) of 18.65 and 19.75 with a steepening to 5.1 at higher energy. Auger has a flatter slope of 2.69 between log10(E) of 18.6 to 19.6 with a steepening to 4.2.
The HiRes spectrum is fully consistent with the model of Berezinsky et al (protons, $\gamma = 1.7$, no cosmological evolution) while the Auger spectrum is well fit by several different models, some involving mixed composition at the sources. Proton models include ($\gamma = 1.55$, no evolution) and ($\gamma = 1.30$, $(1+z)^5$ evolution)

From: Yamamoto et al (Auger Collaboration)
UHECR composition is measured by the depth of shower maximum $X_{\text{max}}$.

$\langle X_{\text{max}} \rangle$ is sensitive to the mass of the primary cosmic ray:

$$\langle X_{\text{max}} \rangle = D_{10} \left[ \ln(E/E_0) - \langle \ln A \rangle \right] + X_{\text{max}}(E_0),$$

where the elongation rate $D_{10}$ is $dX_{\text{max}}/d(\log_{10} E)$ and $X_{\text{max}}(E_0)$ is the depth of maximum of proton showers of that energy. The common wisdom is that extragalactic cosmic rays should be H and He nuclei in a standard 9:1 ratio and one should see much lighter cosmic ray composition in the transition of galactic to extragalactic cosmic rays. This would show up as an elongation rate significantly bigger than $D_{10}$ of the hadronic interaction model.
The Fly's Eye, HiRes-MIA and HiRes data show very light cosmic ray composition.

The Auger elongation rate is, however, not constant – it is 71 g/cm$^2$ up to $10^{18.35}$ eV and decreases to 40 g/cm$^2$ at higher energy.

This indicates a 'lightening' of the composition up to that energy and a transition to heavier composition at higher energy.
The width of the $X_{\text{max}}$ distribution also depends heavily on the mass of the primary particle. Protons have the highest RMS and Fe nuclei have the lowest.
The big achievement of the Auger collaboration is the setting a 2% limit on the gamma-ray fraction in UHECR at energies above $10^{19}$ eV, much lower than any other attempt. This measurement almost eliminates the Top/Down models for UHECR production.
The Auger Observatory reported a correlation of their highest energy events (E>57 EeV) with AGN from the Vèron-Cetty and Vèron catalog at redshifts less than 0.018. The search angle around the UHECR direction is 3.2 degrees. The HiRes does not see this correlation or any anisotropy.
The discovery of anisotropy, if confirmed, is very important. All the questions, including that of the energy assignment, define another problem.

Problem: What do we know about the sources of the highest energy particles in the Universe? What are the galactic and extragalactic magnetic fields that UHECR propagate from their sources to us?

Ultrahigh energy cosmic ray astronomy can answer many questions related to the general conditions of extragalactic space that are very difficult to study with the classical astronomical devices and means. The main problem here is the low UHECR statistics. After HiRes and Auger we expect not more than 0.2 UHECR per 1,000 km².sr.yr.
Auger did not claim that the AGN are the sources of the UHECR. Sources may correlate with AGN, the anisotropy is the important discovery. There were still many questions.

1) Why these particular low luminosity AGN?
2) Why there are no UHECR close to the Virgo cluster?
3) What is going on in Cen A?
4) Why 3.2 degrees angle?
5) Why only redshifts to 0.018?

3.2 degrees scattering suggests protons, while $X_{\text{max}}$ indicates heavier nuclei.

If these are protons, why $z<0.018$ when more distant objects should contribute. Is the energy assignment correct?
Arrival directions of the current 69 events of energy above 55 EeV. The distribution of these events is clearly not isotropic.
The correlation with AGN also raises interesting questions about the cosmological evolution of the UHECR sources. It is the cosmological evolution of star forming regions (SFR) that is studied the best. AGN, however, may have faster cosmological evolution if the observations in infrared give identical results to these in soft X-rays.

The lower data sets are from observations of SFR, while the faster evolving points are AGN observations of ROSAT in 0.5-2 KeV X-rays. The evolution is close to $(1+z)^5$. 
Cosmological evolution of the 0.5-2 KeV X-ray flux emitted by all AGN - \((1+z)^5\) evolution to \(z=2\)

**UHE cosmic rays and UHE neutrinos**

Such an interpretation of the Auger energy spectrum is extremely important for the production of secondary signals in propagation – gamma-rays and neutrinos. We will discuss the relevant neutrino fluxes in the next lecture.