Astroparticle Physics at the highest energies

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Amazing two decades

• **Cosmology and particle astrophysics**: tremendous progress in the last two decades.

• Constructive *interplays* between observational/experimental *data* and theoretical concepts have greatly enhanced our *fundamental* understanding of the universe.

• Such advancement in turn triggers *new questions* to be further addressed.

• We are currently living in an era of *renaissance* in *cosmology* and *particle astrophysics*. 
Amazing two years 2012-2013

★ Planck results
   Excluding many inflation models
   B mode detection
   New robust limits on Neff, $\Sigma m_\nu$
   Whole sky dark matter maps

★ Neutrinos
   $U_{\text{MNSP}}$
   Conventional longbaseline experiments can measure the mass hierarchy independently of the value of $\delta CP$

★ Higgs
   A triumph. Higgs found where expected.
   No signs of SUSY yet.
The **Astroparticle theme** after LHC/PLANCK/ν

**two fundamental questions:**

- Intermediate scales between the EW and Inflation? how many? where are they?
  - Dark matter and energy
  - Neutrino properties and proton decay

- How particles and fields of the intermediate scales shape cosmic structures?
  - High energy photons, neutrinos, CR
  - Gravitational waves
The **Astroparticle theme** after LHC/PLANCK/ν 
two fundamental questions:

★ Intermediate scales between the EW and Inflation? how many? where are they?
★ **Dark matter** and energy
★ Neutrino properties and proton decay

★ How particles and fields of the intermediate scales shape cosmic structures?
★ **High energy photons, neutrinos, CR**
★ Gravitational waves
Two persistent questions about UHECRs:
★ What are those particles with energies that can reach \( E > 10^{20} \text{ eV} = 100 \text{ EeV} \) ?
★ Where do they come from?

Their study has impact on
★ Astrophysics
★ Particle Physics
Cosmic rays flux vs. Energy

(nearly) uniform power-law spectrum, 10 orders of magnitude in $E$ and 32 in flux!

structures:
$\sim 3 \times 10^{18}$ eV: ankle
★onset of the extragalactic CR component
★energy losses of extragalactic protons by pair production
$\sim$ GZK "cuttof"

S. Swordy

UHECR
- one particle / century / km$^2$
- many interesting questions
GZK suppression

- Cosmic rays $E = 10^{20}$ eV interact with 2.7 K photons

- In the proton frame $E_\gamma = 300$ MeV

  $p + \gamma_{3k} \rightarrow \Delta^+ \rightarrow p + \pi^0$

  $\rightarrow n + \pi^+$

  $p + \gamma_{3k} \rightarrow \Delta^+ \rightarrow p + e^+ + e^-$

- Proton looses energy, eventually below cutoff energy $E_{\text{GZK}} = 5 \times 10^{19}$ eV

Universe is opaque for $E > E_{\text{GZK}}$!
Direct test of Lorentz transformations at extreme energies!
GZK horizons

\[ E = 6 \times 10^{19} \text{ eV} \]

Fraction of cosmic rays from distance \( D \) to \( D(Mpc) \):

- He
- CNO
- Fe
- p

Allard et al, 2008
The Hillas criterion gives a useful estimate of possible sources that may reach the maximum accessible energy but it should be taken with care as it does not easily apply to relativistic systems and most candidate accelerators of UHECRs are relativistic. The maximum accessible energy depends on many details of the acceleration region but can be estimated by comparing the acceleration time $t_{acc}$, the escape time of particles from the acceleration region $t_{esc}$, the lifetime of the source $t_{age}$, and the energy loss time due to expansion and to interactions with the ambient medium $t_{loss}$. The condition for successful acceleration can then be written:

$$t_{acc} \leq t_{esc}, t_{age}, t_{loss}$$

The escape time scale $t_{esc} = \frac{R^2}{D}$ where $D$ is the diffusion coefficient depends on the characteristics of the transport of particles in the ambient medium, on the magnetic field, and on the turbulence features. Detailed studies on this subject can be found in Jokipii, Giacalone, Casse et al., Yan, and Costantini et al. Energy losses during acceleration are generally due to synchrotron radiation, to interactions with the radiative background, or to hadronic interactions, the latter process being mostly inefficient in dim.

$E_{max} \approx Z \left( \frac{B}{\mu G} \right) \left( \frac{R_{source}}{kpc} \right) \times 10^9 \text{GeV}$

acceleration site: containment of the accelerated cosmic ray

Larmor radius
Problemi3:

Anisotropies and Composition

The UHECR composition: protons? Heavier nuclei? (deviation in magnetic fields)

Anisotropies expected for protons at $E > 10^{19}$ eV

Is astronomy with CR possible?
The Pierre Auger Observatory

Hybrid detector: improve precision and reduce dependence on models

Fluorescence Detector
- 27 telescopes overlooking the array

Surface Detector
- 1660 Cherenkov stations, in a grid of 1.5 km

3000 km²

17 countries, ~500 physicists

Auger SD station
Cherenkov water tank
Pierre Auger Observatory in Vitória
Detecting UHECRs

**Fluorescence Detector**

UV photons (4 ph/particle/m) emitted in the de-excitation of the atmospheric nitrogen

- $X_{\text{max}}$

**Direct measurement of $X_{\text{max}}$ (mass composition)**

- Calorimetric energy meas. (model independent)
- 10% duty cycle (moonless)
- Lower energy threshold

**Surface Detector**

Sample shower particles at ground

- 100% duty cycle (statistics)
- Energy threshold (full eff.) 3 EeV
- Geometrical aperture (no MC, no mod.)

**“Golden hybrid” data sample:**

- Detector cross-calibration
- Systematics, cross-checks, etc.
Detector Performance

32000 km$^2$ sr yr
about 5000 km$^2$ sr yr each year

The SD exposures are illustrated only for the energy range of full trigger efficiencies.

Number of active WCDs normalised to the nominal number of WCDs in the array, as a function of time

Bonifazi for Auger Collab, ICRC 2013
Auger energy measurements

Energy calibrations to FD energies for all three SD measurements from the energy estimators

\[ E_{SD} = A (S_{38})^b \]

SD energy resolution < 12% above 10 EeV

SD angular resolution < 1° above 10 EeV
Auger combined spectrum
Auger combined spectrum

$E^3 J(E) \left[ \text{eV}^2 \text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1} \right]$ vs. $\log_{10}(E/eV)$

Schulz for Auger Collab, ICRC 2013
To characterize the spectral features we describe the data with a power law below the ankle $J(E) \propto E^{-\gamma_1}$ and a power law with smooth suppression above.
Auger combined spectrum

$J(E) \propto E^{-\gamma_1}$

$J(E; E > E_a) \propto E^{-\gamma_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1}$

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$$\gamma_1 = 3.23 \pm 0.07$$

$$\log_{10}(E_{\text{ankle}}/\text{eV}) = 18.7$$

$$\log_{10}(E_{1/2}/\text{eV}) = 19.6$$

$$\beta = 2.63 \pm 0.04$$
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Auger 2013 preliminary

Precise measurement of spectral indexes, ankle position and the flux suppression at highest energies
Simple models: vary particle type, source injection spectrum index and source evolution fit the data surprisingly well.

Constraining models need composition measurement.
Anisotropy

84 events
E > 5.7 \cdot 10^{19} \text{ eV}

★ Correlation with AGN as tracers of extragalactic sources
33\pm5 \%, p=0.006

★ 21\% expected for an isotropic distribution
★ 2007 correlation 68\%
★ Isotropy of UHECR rejected at 99\% CL

Auger High Energy Sky 2010
Aitoff projection galactic coordinates

blue dots: AGN
position within 3.1^\circ
black dot: CR

K. Kampert, Proceedings for ICRC 2011: highlight Auger talk
Large scale anisotropy

Multipole expansion of the CR flux

\[
\Phi(\delta', \alpha) = \sum_{l,m} a_{lm} Y_{lm}^{*}(\delta', \alpha)
\]

\[
\delta' = \frac{\pi}{2} - \delta
\]

\[
\Phi(\alpha, \delta) = \frac{\Phi_0}{4\pi} \left(1 + d \cdot \hat{n}\right)
\]

\[
l = 1 \quad \text{dipole}\]

\[
(\alpha_d, \delta_d)
\]

Rayleigh analysis

First harmonic

\[
\Phi(\alpha) = \sum_{N} c_{\alpha} e^{in2\pi\alpha} = \Phi_0 + (1 + r \cos(\alpha - \phi) + r' \cos(2(\alpha - \phi')) + \ldots)
\]

\[
r = \left| \frac{\langle \cos \delta \rangle d_{\perp}}{1 + \langle \sin \delta \rangle d_{\parallel}} \right|
\]

\[
\alpha_d
\]

★ If cosmic rays have a galactic origin, their escape from the Galaxy might generate a dipolar large-scale pattern as seen from the Earth.

★ For isotropic extragalactic cosmic rays, a dipole anisotropy may exist due to our motion with respect to the frame of extragalactic isotropy.
Subtle detector effects

To detect a % level anisotropy, subtle detector effects must be kept under control.

Examples

geomagnetic field

Tilt of the array

\[
\frac{dN_{obs}}{d\Omega dE dt} = \Phi(n, E) \omega(n, E)
\]

\[
\omega(t, \theta, \phi, S_{38^\circ}) = n_{cell}(t) \times a_{cell} \cos \theta \times \epsilon(S_{38^\circ}, \theta, \phi).
\]
Dipole amplitude

Three energy bins above 1 EeV with probability < 1% to come from isotropy

We can see hints for large scale anisotropies important to further scrutinize it with independent data;

Sidelnik for Auger Collab, ICRC 2013
For isotropic distribution, expect uniform distribution, uncorrelated in energy.

Prescription to check with new data at 99% CL: constancy of phase at $E<1$ EeV with the Infill data, Transition in phase at high energies.

NOTE: galactic center $\alpha = 268.4^\circ$

Sidelnik for Auger Collab, ICRC 2013
Figure 11: Upper limits on the anisotropy amplitude of first harmonic as a function of energy from this analysis. Results from EAS-TOP, AGASA, KASCADE and KASCADE-Grande experiments are displayed too. An analysis of the KASCADE-Grande data with the East/West method delivers an additional limit for $10^{15}$ eV. Also shown are the predictions up to 1 EeV from two different galactic magnetic field models with different symmetries (A and S), the predictions for a purely galactic origin of UHECRs up to a few tens of $10^{19}$ eV (Gal), and the expectations from the Compton-Getting effect for an extragalactic component isotropic in the CMB rest frame (C-G XGal).

Drift motions are expected to induce a modulation in this energy range. These predictions depend on the assumed galactic magnetic field model as well as on the source distribution and the composition of the UHECRs. Two alternative models are displayed in Fig. 11, corresponding to different geometries of the halo magnetic fields [9]. The bounds reported here already exclude the particular model with an antisymmetric halo magnetic field (A) and a starting to become sensitive to the prediction of the model with a symmetric field (S). We note that those models assume a predominantly heavy composition galactic component at EeV energies, while scenarios in which galactic protons dominate at those energies would typically predict anisotropies larger than the bounds obtained in Fig. 11. Maintaining the amplitudes of such anisotropies within our bounds necessarily translates into constraints upon the description of the halo magnetic fields and/or the spatial source distribution. This is particularly interesting in the view of our composition measurements at those energies compatible with a light composition [35]. Alternatively to a leaky galaxy model, there is still the possibility that a large scale magnetic field retains all particles in...
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Transition Gal-XGal CR mostly Gal, escape by diffusion and drift, heavy composition.

The dependence of the detection efficiency on the primary mass below 3 EeV could affect the details of a direct comparison between models based on light composition.
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Dipole amplitude and models
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The dependence of the detection efficiency on the primary mass below 3 EeV could affect the details of a direct comparison with models based on mixed composition.

XGal protons, relative motion of observer with respect to the sources: Compton-Getting effect.
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Full Sky Map E \geq 10 \text{ EeV}

(30° smoothing)

Auger and Telescope Array joint analysis, ICRC, 2013 (Deligny)

\(N_{\text{TA}} \sim 1800\)

\(N_{\text{Auger}} \sim 10900\)

In the overlap:

\(N_{\text{TA}} \sim 650\)

\(N_{\text{Auger}} \sim 3400\)
**Electromagnetic cascade**

\[ \lambda = 37 \text{g/cm}^2 \]

(radiation length)

After \( n \) generations

\[ X = n \lambda \]

\[ N_{part} = 2^n = 2^{X/\lambda} \]

\[ E_{part} = \frac{E_0}{N_{part}} \]

Cascade stops when:

\[ E_{part} < \epsilon_0 = 100 \text{ Mev} \]

\[ N_{max} = \frac{E_0}{\epsilon_0} \]

\[ X_{max} \sim \lambda \frac{\ln(E_0/\epsilon_0)}{\ln 2} \]

Hadronic cascade

\[ X^p_{\text{max}} = X_0 + \lambda \ln\left[ E_0 / \left( 6N\pi \epsilon_0 \right) \right] \]

Elongation rate

Good agreement with Monte Carlo simulations!

$X_{\text{max}}$ observables

Mixed primary composition: p, Fe, etc

- Superposition principle
- Shower produced by nucleus with energy $E_A$, mass $A$: modeled by $A$ proton showers each with $A^{-1}$ of the nucleus energy

\[
X_{\text{max}} \sim \ln \left( \frac{E_0}{A} \right)
\]

\[
\frac{dX_{\text{max}}}{d \log E} = \lambda(1 - B) \left[ 1 - \frac{\partial < \ln A >}{\partial \ln E} \right]
\]
Composition measurement

\[ X_{\text{max}} \sim \ln(E) \]

\[ X_{\text{max}} \sim \ln \left( \frac{E}{A} \right) \]

The role of the FD: Longitudinal Profile

MC of proton showers, $10^{19}$ eV

MC of iron showers, $10^{19}$ eV

Distribution of maxima $X_{\text{max}}$ reflects mainly the properties of the first interaction.

$X_{\text{max}}$ distribution, mean value, RMS and shape are sensitive to the shower primary mass composition.

The tail of the 'deep-shower' part of the distributions reflects the properties of the p-Air interaction (cross section measurement).

Shower development accessible through the FD

\[ X_{\text{max}} = \ln E - \ln A \]

mean $X_{\text{max}}$ and $\text{RMS}(X_{\text{max}})$ are sensitive to composition.
At the highest energies $<X_{\text{max}}>$, $\sigma(X_{\text{max}})$, muon production depth and shower depth from asymmetry of risetimes show consistently that our data better resemble the simulations of heavier primaries than pure protons.
From $\langle X_{\text{max}} \rangle$ and $\sigma(X_{\text{max}})$ to $\langle \ln A \rangle$ and $\sigma(\ln A)$

\[
\langle X_{\text{max}} \rangle \approx \langle X_{\text{max}}^p \rangle - D_p \langle \ln A \rangle \\
\sigma(X_{\text{max}})^2 \approx \langle \sigma_i^2 \rangle + D_p^2 \sigma(\ln A)^2
\]

one–to–one relation between the experimental observables to the moments of the mass distribution on the top of the atmosphere

transition: medium $\rightarrow$ light $\rightarrow$ heavy?

Ahn for Auger Collab, ICRC 2013
From $<X_{\text{max}}>$ and $\sigma(X_{\text{max}})$ to $<\ln A>$ and $\sigma(\ln A)$

transition: mixed $\rightarrow$ pure?

Auger Collab., JCAP 1302(2013)02

The different values obtained for measurement of in the selected range and thus contribute directly to the on model assumptions. We emulate the measurement of particle production requires the use of air-shower simulations \cite{2}. Accordingly we can values of the slope, goodness fit of an exponential function over the range 768 to 1000 events and the result of an unbinned maximum likelihood analysis of fiducial event selection, modified values of \( \Lambda_\eta \) for these events follows a power-law with index \( \sqrt{2} \) with the average energy of these events being \( \Lambda_\eta \pm 0.05 \text{(stat)} \) TeV in proton-proton collisions. The di differencess are consistent with statistical uncertainties by the available models. For example, the di differences for QGSJet01, QGSJetII, SIBYLL and EPOS derived for \( Q_{\text{GS}} \text{Jet01} \) \cite{8}, QGSJetII.3 \cite{9}, SIBYLL 2.1 \cite{10} and EPOS1.99 \cite{11}. While in general for air shower simulations: QGSJet01 \cite{8}, QGSJetII.3 \cite{9}, SIBYLL 2.1 \cite{10} and EPOS1.99 \cite{11}. While in general for air-shower analyses is larger, but this cannot be estimated within one model by parametric approaches in these models. Furthermore, certain features described at different phenomenological levels using different references between the models used in the analysis are typically bigger for air shower simulations empirically by tuning models. This technique of modifying the original predictions of the cross-section during accelerator data up to the energies of our analysis.

\[ \Lambda_\eta = 55.8 \pm 2.3 \text{ g/cm}^2 \]

\[ \frac{dN}{dX_{\text{max}}} \sim \exp \left( -\frac{X_{\text{max}}}{\Lambda_\eta} \right) \]

\( \Lambda_\eta \rightarrow \sigma_{\text{p} \rightarrow \text{Air}} \)

by tuning models to reproduce tail seen in data

The cross-section for proton-air interactions is given by

\[ \sigma_{p\text{-air}}^{\text{prod}} = \left[ 505 \pm 22(\text{stat}) \pm 28(\text{sys}) \right] \text{ mb} \]
UHECRs and LHC

Inelastic pp Xsec at 57 TeV: standard Glauber theory + propagation of modeling uncertainties

\[ \sigma_{pp}^{\text{inel}} = [92 \pm 7(\text{stat})^{+9}_{-11}(\text{sys}) \pm 7(\text{Glauber})] \text{ mb} \]

\[ \sigma_{pp}^{\text{tot}} = [133 \pm 13(\text{stat})^{+17}_{-20}(\text{sys}) \pm 16(\text{Glauber})] \text{ mb} \]

Pseudo-rapidity distributions at LHC and Monte Carlo simulations

★ central distributions well bracketed by the model predictions,
★ true predictions as the models were tuned years before LHC data became available


UHECRS 2012 Hadronic Interactions report
Hadronic interactions and muons

Hybrid events (both FD and SD)

Signal dominated by muons for inclined showers

Muon excess (over hadronic models predictions) consistently observed

10^{19} \text{ eV proton}
Neutrino induced showers

★ Neutrino observations are a unique probe of the universe’s highest-energy phenomena.
★ Neutrinos are able to escape from dense astrophysical environments that photons cannot and are unambiguous tracers of cosmic ray acceleration.
★ As protons and nuclei are accelerated, they interact with gas and background light near the source to produce subatomic particles such as charged pions and kaons, which then decay, emitting neutrinos.
Neutrino induced showers

Only a neutrino can induce a young horizontal shower!

'old' showers ($h$)
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

'young' showers ($\nu$)
- Wide time distribution
- Strong curvature
- Steep lateral distribution
Auger neutrino limits

**young ν induced showers**

- wide time distribution in surface stations
- elongated footprint of inclined shower
- propagation speed of shower front at ground

Limits start to dig into potential sources and cosmogenic “GZK” neutrinos

Pieroni, Auger Collab. ICRC, 2013
ICECUBE extraterrestrial neutrinos
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*
ICECUBE extraterrestrial neutrinos
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*

Introduction:
Neutrino observations are a unique probe of the universe's highest-energy phenomena: Neutrinos are able to escape from dense astrophysical environments that photons cannot and are unambiguous tracers of cosmic ray acceleration. As protons and nuclei are accelerated, they interact with gas and background light near the source to produce subatomic particles such as charged pions and kaons, which then decay, emitting neutrinos. We report on results of an all-sky search for these neutrinos at energies above 30 TeV in the cubic kilometer Antarctic IceCube observatory between May 2010 and May 2012.

Methods:
We have isolated a sample of neutrinos by rejecting background muons from cosmic ray showers in the atmosphere, selecting only those neutrino candidates that are first observed in the detector interior rather than on the detector boundary. This search is primarily sensitive to neutrinos from all directions above 60 TeV, at which the lower-energy background atmospheric neutrinos become rare, with some sensitivity down to energies of 30 TeV. Penetrating muon backgrounds were evaluated using an in-data control sample, with atmospheric neutrino predictions based on theoretical modeling and extrapolation from previous lower-energy measurements.

Results:
We observed 28 neutrino candidate events (two previously reported), substantially more than the 10.6 expected from atmospheric backgrounds, and ranging in energy from 30 to 1200 TeV. With the current level of statistics, we did not observe significant clustering of these events in time or space, preventing the identification of their sources at this time.

Discussion:
The data contain a mixture of neutrino flavors compatible with flavor equipartition, originate primarily from the Southern Hemisphere where high-energy neutrinos are not absorbed by Earth, and have a hard energy spectrum compatible with that expected from cosmic ray accelerators. Within our present knowledge, the directions, energies, and topologies of these events are not compatible with expectations for terrestrial processes, deviating at the 4σ level from standard assumptions for the atmospheric background. These properties, in particular the north-south asymmetry, generically disfavor any purely atmospheric explanation for the data. Although not compatible with an atmospheric explanation, the data do match expectations for an origin in unidentified high-energy galactic or extragalactic neutrino accelerators.

FIGURES IN THE FULL ARTICLE
Fig. 1. Drawing of the IceCube array.
Fig. 2. Distribution of best-fit deposited energies and declinations.
Fig. 3. Coordinates of the first detected light from each event in the final sample.
Fig. 4. Distributions of the deposited energies and declination angles of the observed events compared to model predictions.
Fig. 5. Sky map in equatorial coordinates of the TS value from the maximum likelihood point source analysis.
Fig. 6. Distribution of deposited PMT charges (\(Q_{\text{tot}}\)).
Fig. 7. Neutrino effective area and volume.

SUPPLEMENTARY MATERIALS
Materials and Methods
Event Displays 1 to 28
Neutrino Effective Areas

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READ THE FULL ARTICLE ONLINE
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in the sky, we tested a point source hypothesis

likely point source analysis (sible neutrino sources, we conducted a maximum

Search for Neutrino Sources

allowing an extraterrestrial contribution. The final signif

Results remain, which could be explained either as a

energy extraterrestrial population would be ex-

result of absorption in Earth above tens of TeV

Materials and Methods). The observed zenith

through the sky.

Materials and Methods). The observed zenith

through the sky.

Materials and Methods). The observed zenith
Top down models

• acceleration models (astrophysics):
  • active galactic nuclei, gamma-ray bursts...
  • not easy to reach > 100 EeV;
  • photon fractions typically < ~ 1%

• non-acceleration models (particle physics)
  • UHECR: decay products of high-mass particles (> $10^{21}$eV)
  • super-heavy dark matter (SHDM): from early universe and concentrated on the halo of galaxies and clusters of galaxies
  • topological defects (TD) produced throughout the universe
  • UHECR produced as secondary particles (hadronization process) and are most photons and neutrinos, with minority of nucleus
  • photon fraction typically > ~ 10%
Upper limits on flux of photons

Photons characterised by:
★ deep Xmax in FD
★ small signal in SD

The observation of a photon flux compatible with the cosmogenic prediction could provide an independent proof of the GZK process.

disfavour exotic “particle physics” origin of UHECR

★ Models disfavoured down to 1 EeV
★ (optimistic) GZK in reach

M. Settimo, Auger Col., ICRC 2011
Scientific landscape

The measurement of the GZK suppression together with photon limits and other recent measurements: the scientific landscape is deeply modified!

The study of the UHECR is now predominantly an essential branch of the High Energy Astrophysics!

Speculations and searches for "New Physics" effects can and will continue.

Some interesting ideas have been put forward and their test and study remain valid goals:

- Violation of Lorentz invariance
- Search for exotic states of matter - strangelets, disoriented chiral condensates, etc...
Perspectives: AUGER next 10 years

★ Keep acquiring more data (next 10 years: three times our current statistics)
★ Add more mass information in the UHE region (muons)
★ Construct a world observatory (10 times the Auger exposure)

Perspectives: Astroparticle group IF - UFRJ next 5 years

★ Keep working in Auger (upgrade)
★ Direct dark matter search (DAMIC?)
Conclusion

★ 2012–2013 extraordinary years for astroparticle physics!
★ The Pierre Auger experiment is complete since 2008 and it is taking data since 2004
★ Very robust hybrid technique to detect CRs at the highest energies

Many interesting results on astrophysics and particle physics

● Measurement of the spectrum suppression: GZK?
● Large scale anisotropy:
  ★ Most stringent upper limits at present on the amplitudes
  ★ Phase does not follow a random distribution
  ★ With higher statistics the galactic/extragalactic transition may be established

● Weak correlation with VCV catalogue
  ★ Correlation is stabilizing

● Very competitive neutrino limits
● Stringent limits on photon primaries and top–down models
● Measurement of p–air cross section at 57 TeV
● Direct DM search: conflicting results, need more statistics and inovative experimental techniques
Thank you