Highest Energy Cosmic Rays: 
Probe of the Extreme Universe 

Colloquium
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1. Background ... highest energy cosmic rays

2. Status ...

3. Emerging model ...

4. Next (generation) experiments ...

5. Summary ...
1. Background ... what are cosmic rays?

Cosmic ray detection depends on cosmic ray type and energy

- Cosmic Rays (CRs) ... google Web definition:

  1. Highly energetic sub-atomic particles, mostly protons and helium nuclei, which travel across space at close to the speed of light and then rain down on the earth.

  2. The lowest energy cosmic rays originate in the Sun; higher energy ones from supernovae and pulsars within the Galaxy, whilst those with the highest energy of all may be extragalactic in origin, possibly from quasars and active galactic nuclei.
1. Background ... more than “p and He”!

![Solar System Abundances vs GCR Abundances](image)

- Composition (at ~GeV):
  - 85% H (p)
  - 12% He (α)
  - 1% heavier nuclei
  - 2% e± (≥90% e−)
  - 10⁻⁵⁻¹0⁻⁴ antiprotons.

Cosmic ray abundance normalized to silicon

Source physics is best unraveled using many different observations e.g. radio, visible, X-ray, ...

Particle astrophysics experiments extend these measurements to include:

- “protons” (special case of light nuclei)
- “iron” (special case of heavy nuclei)
- “gamma”-rays
- neutrinos
1. Background ... the actual observables!

- **Energy:**
  - the number of CR events *versus* energy is called the CR *spectrum*
  - the reconstructed energy of each primary CR has a precision $\sim 20\%$

- **Arrival direction:**
  - the reconstructed direction of each primary CR has a precision of $\sim 1^\circ$
  - as (conventional) CRs are charged, galactic and extra-galactic magnetic fields influence the CR arrival directions!

- **Particle type:**
  - the particle type, at a given CR energy, is called the CR *composition*
  - for (conventional) CRs this is the least well determined quantity because of: large shower-to-shower fluctuations and Monte Carlo (shower simulation) uncertainties ... more later!
1. Background ... end of the spectrum!

Cosmic ray energy spectrum

- **Most interest at** $\gtrsim 10^{20}$ eV ... more later!
- **Rate:** low ($\sim 1$/km²/century) ... so need large experiments ... about the area of Rhode Island! Fluorescence based experiments need dry (desert) air with good visibility.
1. Background ... not simple power law!

![ 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!

- 10 $\sim$ 20 events have been observed $> 10^{20}$eV!
1. Background ... more than “fine print”!

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

- Why do it? ... 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 ($\lesssim 50$ Mpc) sources.
1. Background ... only ideas at this time!

“Hillas Plot”

Minimum size of B field to contain particles being accelerated.

Achievable energy:

\[ E [\text{EeV}] \sim Z \cdot R [\text{kpc}] \cdot B [\mu \text{G}] \]

Acceleration to \(10^{20}\) eV is difficult ...

- **Classes of possible sources:**
  1. *Extreme* astrophysical sources: super-massive black holes, GRBs, colliding galaxies, ...
  2. *Particle physics* motivated: massive relic particles or relics of early universe
  3. OR new astrophysics
  4. OR new physics
1. Background ... CMB wall at $10^{20}$ eV!

![Graph showing energy loss attenuation length, $\Lambda_{\text{atten}}(z = 0)$]

- **Greisen-Zatsepin-Kuz’min (GZK) cutoff:**
  1. Cosmic rays interact with the cosmic micro-wave background (CMB) radiation; after a distance, $d$:

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

  2. Steep drop of $\Lambda_{\text{atten}}$ near $10^{20}$ eV from the onset of $\pi$ photo production: $\gamma_{\text{CMB}} p \rightarrow \pi X$. 
1. Background ... p spectrum $V S z_{source}$!

- GZK simulation (proton primary):
  1. (Assumed) source spectrum: $\text{Flux}(E) \propto E^{-2}$
  2. Observed spectrum scaled by $E^3$ ...
  3. Only sources with red-shift $z \leq 0.03$ (about 150Mpc) should have any flux above $\sim 10^{20} \text{eV}$.
  4. But cosmic rays with energies $> 10^{20} \text{eV}$ have been observed ... so sources should be nearby!
1. Background ... **will sources match?**

Galaxies (*pink*) and Dark Matter (*blue*) within 93Mpc
[courtesy A. Kravtsov]

- **For the highest energy (> $10^{20}$eV) particles:**
  - High magnetic rigidity of primaries *if protons*
  - Nearby universe is not isotropic ... thus highest energy particles should not be isotropic
  - Baring magnetic field surprises, arrival directions should *cluster* ... but will they and in which directions?
1. Background ... experimental details!

![Schematic of extensive air shower cascade](image)

- **Energy scale:** \(10^{20}\text{eV} = 16\text{ Joules} \ldots\) well above future collider energies.

  1. cosmic rays are observed via the extensive air shower produced when they reach the earth’s atmosphere
  2. 16 Joules/\(\sim 16\mu\text{sec}\) (typical shower time) \(\approx 1\text{ MW}\)!
1. Background ... atmosphere = detector!

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 $\mu/e$ ratio.
  3. $\sim 50$ppm of shower energy is re-emitted as nitrogen fluorescence light (290 $\sim 440$nm) ... thus a 1-MW shower appears as a 50W relativistic light bulb!
2. Status ... the bigger the better!

Pre-ICRC03 exposures

- **Experiments probing** $10^{20}\text{eV}$ cosmic rays:
  1. Fly’s Eye, Utah, $\sim 30\text{km}^2$ (equivalent)
  2. Haverah Park, UK, 12km² ground array area
  3. Yakutsk, Russia, 7 $\sim 16\text{km}^2$ ground array area
  4. **AGASA**, Japan, 100km² ground array area
  5. **HiRes**, Utah, $\sim 300\text{km}^2$ (equivalent)
  6. **Pierre Auger**, Argentina, 3000km² (building)
2. Status ... **AGASA above GZK curve!**

![AGASA spectrum above $10^{18}$eV](image)

**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 $J(F) \propto F^{-2}$, plus detector resolution
  3. 11 events above $10^{20}$eV and 2 well above $10^{20}$eV!
  4. Number of events above $10^{20}$eV *inconsistent with the curve!*
2. Status ... HiRes consistent with GZK!

- Combined HiRes I and II monocular spectra

- HiRes flux versus energy:
  1. Most recent data as of the ICRC 2003 conference
  2. Only one event $> 10^{20}\text{eV}$ ... but exposure $\geq$ AGASA!
  3. HiRes I and II monocular spectra consistent with “old” Fly’s Eye stereo spectrum.
  4. Something may be happening that is GZK-like ... but we can not be sure!
Too Low Statistics for clear GZK or no-GZK determination

\[ E_{\text{max}} = 10^{21.5} \text{ eV} \]

AGASA

- \( \gamma = 2.8 \)
- \( E > 10^{19} : 866 \)
- \( E > 10^{19.6} : 45.76 \pm 6.77 \)
- \( E > 10^{20} : 2.02 \pm 1.35 \)

HiRes

- \( \gamma = 2.6 \)
- \( E > 10^{19} : 300 \)
- \( E > 10^{19.6} : 31.29 \pm 5.56 \)
- \( E > 10^{20} : 1.92 \pm 1.39 \)

DeMarco et al (ICRC03)

number of events above \( 10^{20}\text{eV} \):
- no GZK @ 2.5 sigma
- GZK cutoff
2. Status ... look at the RAW data!

- Data consistent with 20 $\sim$ 30\% systematic energy difference between AGASA and HiRes ... in agreement with experimental energy-scale uncertainties.

- Confirmation of GZK-structure, or not, requires significantly reduced statistical errors!
2. Status … AGASA arrival directions

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

No significant clustering seen yet.
“Bananas are harder than circles…”
Flux upper limits of on point sources
with $E > 10^{18.5}$ eV Cygnus X-3
Dipole limit: Gal. Center, Centaurus A, M-87

HiRes-1 Monocular Data, $E > 10^{19.5}$ eV

- *Monocular* data have asymmetrical pointing errors ...
- No “exact” match with AGASA ... but some clusters are close!
- **Significantly more events are needed ... !**
2. Status ... B-field alters CR trajectories!

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

- But what if the fields are more extensive or stronger?
1. Galaxies have magnetic fields.
   • Protons and nuclei will be deflected by the \( B \approx 5 \, \mu \text{G} \) galactic field.
   
   Larmor radius \( r = \frac{R}{cB} \)
   
   \[
   \begin{array}{ll}
   R & r \\
   10^{15} \text{eV} & 0.3 \text{pc} \\
   10^{20} \text{eV} & 30 \text{kpc} \leftarrow \text{size of galaxy}
   \end{array}
   \]

2. Intergalactic fields may also be significant
   • Clusters (e.g. Coma) have field strengths \( B \approx 0.1 \text{–} 2 \, \mu \text{G} \), perhaps extending out along sheets and filaments.

Charged CR directions will be scrambled by \( B \) fields. But we can still learn a lot from their composition.
2. Status ... CR average composition

- Average depth of shower maximum ($X_{max}$) is sensitive to primary cosmic ray composition:
  - Interpretation clouded by shower simulation (different curves) uncertainties!
  - To first approximation: nucleus of atomic number $A$ and energy $E$ results in $A$ sub-showers each with average energy $E/A$. As $X_{max} \propto \log(E)$, thus $X_{max}^{Fe} < X_{max}^{p}$!
  - Data trends: intermediate-to-heavy at $\sim 4 \times 10^{16}$eV to light = proton at $10^{18} \sim 10^{19}$eV!
2. Status ... **when do protons dominate?**

- ... on average consensus

- **in detail experiments disagree:** *e.g.* at $1 \text{ Eev} = 10^{18}\text{eV}*

  Haverah Park measures *intermediate-to-heavy* composition and HiRes measures *light = proton* composition!
2. Status ... new analysis developments!

Unfolding of cosmic ray spectra near the knee
Note: horizontal-axis units are GeV where 1 GeV = $10^9$eV

- KASKADE results ... astro-ph/0201109:
  1. With more sophisticated experiments more detailed analyses are possible.
  2. One KASKADE analysis has attempted to extract individual element group fluxes versus energy.
  3. The results are consistent with rigidity-dependent breaks in flux for different element-groups.
  4. Rigidity-dependent breaks would be consistent with CR lifetime/retention limitations in the galaxy.
2. Status ... simulations also improve!

- Simulations are needed to link e.g. depth of shower maximum ($X_{max}$) with composition:
  1. Several Monte Carlo (hadronic interaction) models are under development to interpret the data.
  2. (Systematic) uncertainties remain ...
3. Emerging model ... listen to the data!

Conceptual model for cosmic ray flux ...  

- 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 1st and 2nd knee, from acceleration or lifetime/retention limitations
  3. Spectrum flattening, at the ankle, consistent with a new, CR-III, (2nd) component
3. Emerging model ... “theory” guidance!

Theoretical model for cosmic ray flux ...

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

1. Slope breaks at the 1^{st} and 2^{nd} kncc follow constant rigidity physics observed by KASKADE ... i.e. energy features scale in nuclear charge: \( E_{Fe} \equiv 26 \times E_p \).

2. 2^{nd} break, \( E_p \approx 4 \times 10^{17} \text{eV} \), proton Larmor radius:
\[
\left( \frac{R_p}{1 \text{ kpc}} \right) \approx \left( \frac{E_p}{10^{18} \text{eV}} \right) \cdot \left( \frac{1 \mu G}{B} \right) \approx \text{galaxy thickness}.
\]
3. Emerging model ... initial summary!

![Graphs showing cosmic ray arrival directions](image)

**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))
3. Emerging model ... testable implications!

D. Bergman GZK-model fits to HiRes Flux(E) data

The green curve simulates the galactic flux
The red curve simulates the extra-galactic (proton) flux

- Propose a model (e.g. like Biermann model):
  - Particle composition, above $\sim 10^{18}\text{eV}$ should have two components: heavy\(\geq\)Fe from galactic sources and light\(=\)p from extra-galactic sources.
  - If light is truly protons, then the data should show the GZK structure.
  - Measure fraction of light (protons) primaries, \(f_p(F)\), versus energy.
  - Then GZK model predictions can be meaningfully compared to \(f_p(E) \times \text{Flux}(E)\).
3. Emerging model ... don’t skip the fun!

Bachall et al GRB model *showing* GZK-cutoff, hep-ph/0206217

Even though we would like to ... there is simply not enough data to answer the issues of $10^{20}\text{eV}$ CRs!

- AGASA, Fly’s Eye and HiRes have observed (a few) events above $10^{20}\text{eV}$ ... **but:**
  - What is the detailed shape of the spectrum?
  - What is the *composition* versus energy?
  - Are there arrival direction anisotropies and are there *point source clusters*?
4. Next step ... need bigger and better!

*Hybrid Fluorescence + Ground Array*

**precision measurements**

- **The next step** ... high quality data are needed from $\lesssim 10^{17}\text{eV}$ to several $\times 10^{20}\text{eV}$:
  1. need to link with galactic source(s) measurements
  2. need to tune the Monte Carlo (hadronic interaction) models
  3. need to constrain the models with much reduced error bars ... especially above $6 \times 10^{19}\text{eV}$
  4. In a post-CZK cutoff era, need to look carefully where we expect *no* signal
4. Next step ... SW U.S. and Argentina!

*HiRes Dugway, Utah or Auger Southern Observatory*

*Malargue, Argentina*

- **HiRes** ... (now):
  1. 2 fluorescence detector sites separated by 12.6km
  2. Will run for a few more years

- **Telescope Array (TA)** ... (in a few years):
  1. 25km × 25km surface detector (SD) array
  2. Overlooked by 3 fluorescence detectors (FDs) ... to *resolve* AGASA-HiRes “controversy”

- **Auger** ... (now):
  1. 55km × 55km SD array overlooked by 4 FDs
  2. Construction of the full experiment is well underway
  3. Data taking simultaneous with construction ... *already biggest running experiment!*
Auger Sites

Northern site
Millard County
Utah, USA

Stefano Argirò, “Status ... of the Pierre Auger Observatory”
Auger Project

- Southern site in Argentina
- 1600 water detect., 4 fluorescence.
- > 3,000 km².
- Construction complete in 2006.

Surface detector in place.
Current Status of the Array

January 23, 2004

199 detectors with electronics out of 287 deployed.

No kit - No data - Alarm - Warning - Running well - Acquisition (100%)
The Hybrid Detector Concept

- **Surface Array**
  - Simple and reliable detectors
  - 100% duty cycle
  - Energy Determination relies on simulation

- **Fluorescence Detector**
  - Quasi calorimetric energy measurement
  - Tracks directly shower development
  - 10-15% duty cycle
  - Sistematics from atmospheric transparency

- **Combination**
  - Cross Calibration
  - Better control of systematics
  - Superior Angular resolution
  - Independent measurement of Energy
    Composition: $\rho_\mu/\rho_e$, $X_{\text{max}}$

*Stefano Argirò, “Status ... of the Pierre Auger Observatory”*
The Surface Detector

- Electronic box: 40 Mhz sampling, 12+12 bit FADC, Local Trigger
- Three 8" PM Tubes
- Solar panel
- GPS antenna
- Comm antenna
- Plastic tank
- White light diffusing liner
- 12 m³ of de-ionized water

Stefano Argirò, “Status ... of the Pierre Auger Observatory”
self-calibrating detectors...
Air Shower Detectors -
Surface Detector Array

- Shower timing
- Particle density
- Muon number
- Pulse rise time

→ Shower angle
→ Shower energy
→ Measure of primary mass
Event timing and direction determination
Shower Density Lateral Distribution (simulation)

Detector Signal Density (equiv. muons/m²)

Core Distance (km)

Paul Mantsch February 2002
Date of this event: Mon Dec 29 09:23:45 2003 (GESE 756725038)

Mon Dec 29 09:23:45 2003
Easting= 470347 ± 7m
Northing= 6905443 ± 11m
dt= 114.0ns

Theta= 34.4 ± 0.3 deg
Phi= 140.2 ± 0.3/sin(theta) deg

R= 12.5 ± 0.8 km

Preliminary Xmax= 1040 ± 66 g/cm^2

S(1000)= 365.51 ± 20.78 VEM
E= 74.81 EeV ± 6%
Stefano Argirò, “Status ... of the Pierre Auger Observatory”
Fluorescence Detector

- 30° x 30° fov
- Schmidt optics
- 440 pixels
- 1.5° Ø pixel
- 12 bit FADC
- 10 Mhz \( f_s \)
- < 4 g/cm²
- Digital trigger

Stefano Argirò, “Status ... of the Pierre Auger Observatory”
FD Calibration

- **Absolute**: End to End Calibration

  The **Drum** device installed at the aperture uniformly illuminates the camera with light from a calibrated source (1/month)

- **Relative**: UV LED + optical fibers (1/night)

- Alternative techniques for cross checks
  - Scattered light from laser beam
  - Statistical

  All agreed within 10% for the EA

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Stefano Argirò, “Status ... of the Pierre Auger Observatory”
FD Event Display

Stefano Argirò, “Status ... of the Pierre Auger Observatory”
Analysis procedures with the FD

this event: initial viewing angle 15°, i.e. large direct Cherenkov contribution
iterative procedure, converges in <4 steps; suggested energy here 2e18 eV
Atmosphere

calibrated (movable) light sources
cloud monitors

balloon sondes

LIDAR
lasers

2. Intl Workshop
Liebenzell Castle
Dec 11-14

Fluorescence spectrum
Using Horizontal Air Showers

Atmosphere: 1000g/cm² thick vertically
36000g/cm² thick horizontally

⇒ Look for interactions at deep column densities
  i.e. large zenith angles: $75^\circ < \theta < 90^\circ$
Neutrino Air Showers / Hadron Air Showers

\(\nu\) : “new” showers

hadrons: “old” showers

Signal is:
- Few events per year
- EM rich, curved and thick front
- Broad signals

Background is:
- Thousands events per year
- EM poor, muon rich, flat and thin front
- Prompt signal
Eastings = 458740 ± 35m
Northing = 6083187 ± 11m
dt = 32.4 ns

Theta = 13.3 ± 0.7 deg
Phi = 50.1 ± 2.2 deg

R = 4.0 ± 0.2 km

S(1000) = 67.27 ± 5.96 VEM
E = 16.05 EeV ± 9%
Near PMT
Distance ratio = 3.7  Density ratio = 134
this is a 'young shower', lots of electrons

Far PMT
### Lateral Distribution Function Fit

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<th>Date</th>
<th>Time</th>
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<th>Northing (ns)</th>
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**Event Information**

- **Easting**: 458900 ± 183m
- **Northing**: 6084974 ± 78m
- **dt**: 10.0 ns
- **Theta**: 75.8 ± 0.5 deg
- **Phi**: 11.6 ± 0.4 deg
- **R**: 27.1 ± 11.6 km
- **S(1000)**: 2.64 ± 0.57 VEM
- **E**: 5.40 EeV ± 21%

**Trigger of this event**: NEA3
Near PMT
Distance ratio = 3.5   Density ratio = 7.5
this is an old shower', mostly muons

Far PMT
Tau Neutrino Detection

- Principle:
  - Interaction length in the earth ~ 300 km at $10^{18}$ eV
  - Tau time of flight ~ 50 km at $10^{18}$ eV
  - 1° below horizon $\Rightarrow$ 200 km of rock
  - Shower maximum ~10 km after decay

In practice $85^\circ < \theta_z < 95^\circ$

AUGER window: $10^{17}$ to $10^{20}$ eV
5. Summary ... highest energy cosmic rays

- Cosmic rays are observed by AGASA and HiRes to energies above $10^{20}\text{eV}$. Low statistics permit interpretation of the spectrum shape as GZK-like ... but we can not say for sure.

- 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 $> 10^{20}\text{eV}$ but biggest events remain.

- Arrival directions of events $> 4 \times 10^{19}\text{eV}$ are isotropic supporting the extra-galactic source of these cosmic rays. AGASA clusters interesting ... but could be a statistical fluctuation.

- Sources of the events above the cosmic microwave background GZK cutoff “must” be (relatively) nearby ... but are not yet identified. More data are essential!

- New data are consistent with light (p,He) primaries at the highest energies. What is needed to make this firm ... e.g. can better data and data analyses circumvent hadronic interaction uncertainties?

- Much larger and more sophisticated hybrid experiments are being built! Auger is already running ... and has plans for a Northern observatory to provide essential full sky coverage. So stay tuned!