Ultra-High Energy Cosmic Rays: What did we learn, where will we go?

... a very selective review

Karl-Heinz Kampert, University of Wuppertal on behalf of the Pierre Auger Collaboration
Features of CR spectrum

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Image of non-thermal Universe

KASCADE-Grande; 0.5 km²

~$E^{-2.7}$

~$E^{-3.1}$

AMS 02; 0.5 m²

IceTop; 1 km²

Auger; 3000 km²

TA; 700 km²

HERA ($e$-$p$)

RHIC (p-p)

Tevatron (p-p)

LHC (p-p)

Scaled flux $E^{2.5} J(E)$ (m$^{-2}$ sec$^{-1}$)

1 particle per km$^2$ century

Features of CR spectrum

1 particle per cm$^2$

2

1 particle per m$^2$ year

~$E^{-2.7}$

~$E^{-3.1}$

"Knee"

"Ankle"

"GZK?"

Image of non-thermal Universe
Features of CR spectrum

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5}J(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{-1.5}$)

Particle Energy (eV)

Extragal. CRs?

Galactic CRs?

SNR?

magn. confinement

$E_{\text{max}} \sim Z$

$\sqrt{s_{pp}}$ (GeV)

$10^2$ $10^3$ $10^4$ $10^5$ $10^6$

$10^2$ $10^3$ $10^4$ $10^5$ $10^6$

$p, \text{He-knee}$

$p$ $p$ Fe-knee

Fe $\text{p}$

Extragal. component
classical ankle model

Diffusion losses from Galaxis?

AGN?

extragal. component

$\text{SNR ?}$

$\text{p,He-knee}$

Diffusion losses from Galaxis?

AGN?

$\text{Galactic CRs?}$

$\text{Extragal. CRs?}$

$\text{SNR ?}$

extragal. component
classical ankle model

$\text{magn. confinement}$

$E_{\text{max}} \sim Z$
Features of CR spectrum

**Equivalent c.m. energy** $\sqrt{s_{pp}}$ (GeV)

- **Galactic CRs?**
- **p, He-knee**
- **Fe-knee**
- **Extragal. CRs?**
- **Fe-like**
- **p-like**
- **extragal. component**
- **classical ankle model**

**Features of CR spectrum**

- **KASCADE-Grande**
  - $\gamma = -2.95 \pm 0.05$
  - $\gamma = -2.76 \pm 0.02$
  - $\gamma = -3.25 \pm 0.05$
  - $\gamma = -3.29 \pm 0.08$

- **Apel et al.**
  - PRL 107 171104 (2011)
  - PRD 87, 081101(R) (2013)

**Diffusion losses from Galaxis?**

**AGN?**
Features of CR spectrum

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5} S(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{-1.5}$)

Particle Energy (eV)

- Galactic CRs?
- p,He-knee
- Fe-knee
- Extragal. CRs?
- SNR?
- Diffusion losses from Galaxis?
- magn. confinement
- $E_{max} \sim Z$
- extragal. component
- AGN?

Karl-Heinz Kampert - Univ. Wuppertal
UHECR Menu

- The End of the Energy Spectrum: GZK-effect or Exhaustion of Sources?
- Mass Composition: getting heavier?!
- Arrival Directions: surprisingly isotropic
- EeV neutrinos and photons: smoking gun
- Further Searches: neutrons, monopoles, ...
- Future: Upgrades of Auger and TA
Hybrid Observation of EAS

Concept pioneered by the Pierre Auger Collaboration
(Fully operational since 06/2008
Now also used by Telescope Array (TA)

Also:
Detection of Radio- & Microwave-Signals

Fluorescence light
Particle-density and -composition at ground

light trace at night-sky (calorimetric)
Pierre Auger Observatory

1660 detector stations on 1.5 km grid
27 fluore. telescopes at periphery
130 radio antennas

Province Mendoza, Argentina
Auger Hybrid Observatory
3000 km² area, Argentina
27 fluorescence telescopes plus
...1660 Water Cherenkov tanks
Surface Detector (SD)
- 507 plastic scintillator SDs
- 1.2 km spacing
- ~700 km²

Fluorescence Detector (FD)
- 3 stations
- 38 telescopes

TA detector in Utah
- 3 com. towers

Refurbished HiRes
- 14 telescopes

Middle Drum (MD)
- ~30 km

Long Ridge (LR)
- 12 telescopes

CLF
- 2014/3/20 H. Sagawa @ VHEPA2014

ELS

Black Rock Mesa (BR)
- 12 telescopes

FD and SD: fully operational since 2008/May

39.3°N, 112.9°W
~1400 m a.s.l.
Auger and TA can see the same sky

Auger: 01/2004 - 12/2012
TA: 05/2008 - 05/2012

Auger vertical + inclined
Auger vertical (01/2004 - 12/2012)
Auger inclined (01/2004 - 12/2012)
TA (05/2008 - 05/2012)

Auger exposure ~8 times that of TA
Event Example in Auger Observatory

Coihueco

Loma Amarilla

Los Morados

Los Leones

12 km

~ 20 km
Event Example in Auger Observatory

Energy calibration based on experimental data (including invisible energy correction)

colorimetric meas.
Longitudinal Profile

$E = 68\ EeV$
$X_{\text{max}} = 770\ g/cm^2$

$\frac{dE}{dx}\ (\text{PeV/g cm}^2)$

Slant Depth (g cm$^2$)

0
40
80
120
160

0
400
800
1200
1600

$E = 71\ EeV$

S(1000) = 222\ VEM
$\theta = 54^\circ$
$S_{38} = 343\ VEM$

E = 71\ EeV$

Cross Correlation

Infill
Standard
inclined

S(1000) = 222\ VEM
$\theta = 54^\circ$
$S_{38} = 343\ VEM$

OBSERVATORY

Longitudinal Profile

Lateral Profile

Infall
Standard
inclined

Signal (VEM)

Distance to Shower Core (m)

μ+e measurement

$\frac{dE}{dx}\ (\text{PeV/g cm}^2)$

Slant Depth (g cm$^2$)

Distance to Shower Core (m)

$S(1000) = 222\ VEM$
$\theta = 54^\circ$
$S_{38} = 343\ VEM$

E = 71\ EeV

E = 68\ EeV
$X_{\text{max}} = 770\ g/cm^2$

Karl-Heinz Kampert - Univ. Wuppertal

14th Marcel Grossmann Meeting, Rome, July 12-18, 2015
UHECR Energy Spectrum
Good agreement between experiments - some differences at the highest energies -
Good agreement between experiments - some differences at the highest energies -
All Particle Energy Spectrum

Kampert & Tiniakov, CR Physique, 15 (2014) 318

Good agreement between experiments
- some differences at the highest energies -

Updates to be presented @ ICRC2015
Energy spectrum alone remains ambiguous concerning interpretations.
Need Mass Composition to disentangle GZK from maximum energy scenario
Example of a $3 \cdot 10^{19}$ eV EAS event in FD

- Auger event
- Photon
- Proton
- Iron

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KHK, Unger, APP 35 (2012)
EPOS 1.99 Simulations

Longitudinal Shower Development → Primary Mass
Here shown for EPOS-LHC

log\(E/eV\) = 17.8-17.9

\(p = 0.73\)

\(N\)\hspace{1cm} p, \(He\) components diminish for \(N\), \(Fe\) to take over

log\(E/eV\) = 19.0-19.1

\(p = 0.70\)

log\(E/eV\) > 19.5

\(p = 0.53\)
**Decomposition of X_{\text{max}}-Distributions**

Auger collaboration, Phys. Rev. D 90, 122006 (2014)

- **He fraction**
- **N fraction**
- **Fe fraction**

Post-LHC Models

Sibyll 2.1 \quad QGSJET II-4 \quad EPOS-LHC

**data suggest seeing the exhaustion of sources!**

Suppression region?

-no pure beam at ankle!

See also: Yushkov @ ICRC2015
Comparison of $\langle X_{\text{max}} \rangle$: Auger vs TA

Auger; Phys. Rev. D 90, 122005 (2014)

bias-free due to anti-bias cuts

Telescope Array Collaboration, APP 64 (2015) 49

models are folded with exp. acceptance

pre LHC models

Data
QGSJETII–03
QGSJET–01c
SYBILL 2.1

Proton
Iron

EPOS-LHC
Sibyll2.1
QGSJetII-04
Two data sets are in excellent agreement, even without accounting for the respective systematic uncertainties on the $X_{\text{max}}$ scale.

Average diff. between data points: $(2.9 \pm 2.7 \text{ (stat.)} \pm 18 \text{ (syst.)}) \text{ g/cm}^2$
Some Interpretations...
Implications of a heavy composition

Extragalactic propagation of ultrahigh energy cosmic-rays

Denis Allard
Laboratoire Astroparticule et Cosmologie (APC), Université Paris 7/CNRS, 10 rue A. Dantan et L. Duquet, 75205 Paris Cedex 13, France

1. Introduction

After more than 50 yr of experimental efforts, the origin of ultra-high energy cosmic rays (UHECR) spectrum has long been a topic of great interest.

The cosmic-ray spectrum is widely accepted. As a consequence, we find that the shower to shower fluctuation of \( X_{\max} \) was made in 1966, closely following the discovery of the CMB. This prediction started a long series of studies on the extragalactic propagation of these particles.

The cross sections of both these processes rise quickly above the threshold values of about 1 MeV and 10 MeV, implying that the UHECR spectrum contains a large, limiting our knowledge of UHE CR composition.

Provided the propagation time from their sources to Earth is greater than their energy loss time, UHE CRs with an energy flux of \( \frac{E_{\max}}{C_0} \), imply that the UHECR spectrum contains mostly lighter nuclei or protons at lower energies. On one side of the debate, the so called Hillas criterion offers increasingly powerful insights into this question. Firstly, we show some implications of Auger data for source spectra and chemical composition.

Ultra high energy cosmic rays: Implications of Auger data for source spectra and chemical composition

R. Aloisio\(^1,2\), V. Berezinsky\(^2,3\) and P. Blasi\(^1,2\)

Cosmic ray energy spectrum from measurements of air showers

T. K. Gaisser, T. Stanev, S. Tilav

...and many more papers of this type all require very hard injection spectra unless a nearby source (population) is assumed.

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Comparison to Astrophys. Scenarios

Taylor, Ahlers, Hooper; arXiv:1505.06090

$E_{\text{max}}^p = 10^{18.8}$ eV
index $\alpha = 1.1$

cosm. evolution: $m=0$

maximum energy scenario requires very hard (non-Fermi like) injection spectra
**Comparison to Astrophys. Scenarios**

Taylor, Ahlers, Hooper; arXiv:1505.06090

\[ E_{\text{max}}^p = 10^{19.1} \text{ eV} \]

index \( \alpha = 1.6 \)

cosm. evolution: \( m = -3 \)

maximum energy scenario requires very hard (non-Fermi like) injection spectra or local sources

if local sources \( \Rightarrow \) low luminosity
A strong negative cosmological evolution has been found in low-luminosity, high-synchrotron–peaked (HSP) BL Lac objects based on Fermi data


We may see mostly nearby low-power sources!

Anisotropies
may tell us more
UHECR Sky surprisingly isotropic

\[ J(E; E > E_a) \propto E^{-7/2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \]

isotropic distribution

\[ E = 4-8 \text{ EeV} \]

UHECR Sky surprisingly isotropic

\[ J(E; E > E_a) \propto E^{-\eta_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right] \]

\[ E \geq 57 \text{ EeV} \]


Amplitude: (4.4±1.0)%; \( p = 6.4 \cdot 10^{-5} \)


Dipole-like anisotropy

\( E \geq 8 \text{ EeV} \)

Equatorial coordinates

see also: D. Fargion; arXiv:1412.1573
Large scale analysis: First harmonic

Amplitude and phase of first harmonic in right ascension: dipole $\vec{D}$

Fig. 3: Phase of the first harmonic as a function of energy.

If prescription is confirmed, clear signal of transition from galactic to extra-galactic CRs
Point Source Searches

Example:
Correlation to bright SWIFT AGN
best for:
D < 130 Mpc
L > 10^{44} \text{ erg/s}
Ψ < 18°

62 pairs correlate with the 10 AGN, for 32.8 expected
p = 1.3%

Auger Collaboration

No significant excesses were found around the Galactic Center, the Galactic Plane, or the Super-Galactic Plane.

Summary of searches

<table>
<thead>
<tr>
<th>Objects</th>
<th>(E_{\text{th}})</th>
<th>Ψ</th>
<th>D</th>
<th>(L_{\text{min}})</th>
<th>(f_{\text{min}})</th>
<th>(\mathcal{P})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[EeV]</td>
<td>[°]</td>
<td>[Mpc]</td>
<td>[erg/s]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2MRS Galaxies</td>
<td>52</td>
<td>9</td>
<td>90</td>
<td>-</td>
<td>1.5 \times 10^{-3}</td>
<td>24%</td>
</tr>
<tr>
<td>Swift AGNs</td>
<td>58</td>
<td>1</td>
<td>80</td>
<td>-</td>
<td>6 \times 10^{-5}</td>
<td>6%</td>
</tr>
<tr>
<td>Radio galaxies</td>
<td>72</td>
<td>4.75</td>
<td>90</td>
<td>-</td>
<td>2 \times 10^{-4}</td>
<td>8%</td>
</tr>
<tr>
<td>Swift AGNs</td>
<td>58</td>
<td>18</td>
<td>130</td>
<td>10^{44}</td>
<td>2 \times 10^{-6}</td>
<td>1.3%</td>
</tr>
<tr>
<td>Radio galaxies</td>
<td>58</td>
<td>12</td>
<td>90</td>
<td>10^{39.33}</td>
<td>5.6 \times 10^{-5}</td>
<td>11%</td>
</tr>
<tr>
<td>Centaurus A</td>
<td>58</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>2 \times 10^{-4}</td>
<td>1.4%</td>
</tr>
</tbody>
</table>
Conclusions from CR Anisotropy Studies

1) Observed change of phase in RA-analysis and absence of significant correlations to Galactic Center and Galactic Plane

⇒ 10 EeV sources are unlikely of Galactic origin

2) Only small deviations from overall isotropic sky

⇒ either large deflections by B-fields, e.g. due to heavy primaries (supported by Auger composition studies)

⇒ or number of sources is very large (and luminosity low) (bounds by Auger from lack of autocorrelations: \( \rho \gtrsim 10^{-4} \, \text{Mpc}^{-3} \))
Astrophysical Neutrinos
A look to the PeV Neutrino Sky


No significant clustering seen (p=84%)

cross correlations to catalogs ⇒ no signal yet
Constraints from Neutrino-Isotropy

High level of Isotropy $\Rightarrow$ **source density** must be fairly **high**

Int. Flux $F = \rho \cdot L$ is known $\Rightarrow$ Mean **Luminosity** per source must be **low**

---

**Density & Luminosity**

Same sources for UHECR and $\nu$'s?
This analysis: no significant correlations (p-values $\approx 2-4\%$)

with 4-year IC data to be presented @ ICRC $\Rightarrow$ interesting to pursue
Cosmogenic Neutrinos

Recall:

- If flux suppression above $5 \times 10^{19}$ eV is due to GZK-effect: expect cosmogenic neutrinos & photons

- If due to source exhaustion: neutrinos & photons strongly suppressed
EAS are sensitive to all $\nu$ flavors and channels

Charged Current

$\nu_e$  
high energy electron  
hadronic Jet

$\nu_\mu$  
hadronic Jet  
$\mu$

$\nu_\tau$  
high energy tau  
hadronic Jet

Neutral Current

$\nu_X$  
hadronic Jet  
$\nu_X$

4) double-bang shower  
initiated by $\nu_\tau$

1) regular shower  
initiated by proton

2) deep shower  
initiated by $\nu$

3) up-going shower  
initiated by $\nu_\tau$

5) down-going shower  
initiated by $\nu_\tau$

Three selection criteria

Down-going low angle (2 and 4)  \rightarrow  DGL ($60^\circ - 75^\circ$)
Down-going high angle (2, 4 and 5)  \rightarrow  DGH ($75^\circ - 90^\circ$)
Earth-skimming (3)  \rightarrow  ES ($90^\circ - 95^\circ$)
Would have expected to see 1-7 GZK neutrinos (for different models), have seen none

Neutrino upper limits start to constrain cosmogenic neutrino fluxes of p-sources
Cosmogenic neutrino fluxes may be down by ~2-3 orders of magnitudes for exhausted sources!!
## Enormous progress in last 8 years

### 8 years ago...
- did not know whether flux suppression exists
- thought composition is purely protons
- no signatures of anisotropies (on any angular scale)
- no relevant bounds on cosmogenic $\nu$'s and $\gamma$'s

### Now...
- beyond any doubt
- appears to become heavier (unless new physics at $E_{cm} \sim 50$ TeV)
- LS anisotropies seen, but no point sources yet
- cosmogenic $\nu$'s and $\gamma$'s being constrained
- particle physics: $\sigma(pp)$
- smoothness of space-time
- unexpected geophysical effects (elves, ..., )
### Next logical Step

#### Now...
- beyond any doubt
- appears to become heavier (unless new physics at $E_{cm} \sim 50$ TeV)
- LS anisotropies seen, but no point sources yet
- cosmogenic $\nu$’s and $\gamma$’s being constrained
- particle physics: $\sigma(pp)$
- smoothness of space-time
- unexpected geophysical effects (elves, ...)

#### Next...
- **understand** origin of flux suppression
- measure composition into flux suppression region
- composition enhanced anisotropies, $p$-astronomy
- improve limits by better triggers
- particle physics at 100 TeV
- ...

Karl-Heinz Kampert - Univ. Wuppertal
Upgrades of TA and Auger Observatory
500 more SDs
2 more FD stations

- SD: 700 $\Rightarrow$ **2800 km²**
- Hybrid: x3 acceptance
- Optimized for UHECR above cutoff (fully efficient above $\sim$60 EeV)

**TAx4 SD Upgrade**

collect statistics more rapidly

funding of array
Auger Upgrade

measure composition event-by-event into flux suppression region

$E^3 J(E)$

$E \ [eV]$
Auger Upgrade

4 m² to reduce poisson statistics at d > 800 m

Scintillators on top of each Water Cherenkov Tank
(non invasive, fast to install, robust technology, relatively inexpensive)
Reconstructed $\langle X_{\text{max}} \rangle$ and $\sigma(X_{\text{max}})$

**Graphs:**
- $\langle X_{\text{max}} \rangle$ [g/cm$^2$] vs $\lg(E/eV)$
  - Blue line: Fe, EPOS-LHC
  - Red line: p, EPOS-LHC
  - Points: Scenarios 1 and 2
- RMS($X_{\text{max}}$) [g/cm$^2$] vs $\lg(E/eV)$
  - Blue line: Fe, EPOS-LHC
  - Red line: p, EPOS-LHC
  - Points: Scenarios 1 and 2

**Text:**
- Shower fluctuations and detector resolutions included
- Scenarios can be distinguished with high significance
p-Astronomy

use arrival directions of 141 measured events with $\theta < 60^\circ$ and $E > 5.5 \cdot 10^{19}$ eV and randomly assign $X_{\text{max}}$ according to maximum rigidity model with 10% p-like at high E and let 50% of p-like events correlate with Swift-BAT sources

this reproduces well the present situation

$\sim 3\sigma$ effect

p-like events are removed

only p-like events included

$\sim 5\sigma$ effect
The Pierre Auger Observatory Upgrade

Preliminary Design Report

April 17, 2015

Organization: Pierre Auger Collaboration
Observatorio Pierre Auger,
Av. San Martin Norte 304,
5613 Malargüe, Argentina

positively evaluated by International Advisory Committee
endorsed by International Finance Board
R&D well advanced, prototypes running
engineering array 03/2016
construction 11/2016 - 2018
data taking into 2024
costs: 12.5 M€
funding: some positive signs, but not yet approved
Pierre Auger Collaboration

~500 Collaborators; 88 Institutions, 17 Countries:

Argentina
Australia
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands

Poland
Portugal
Romania
Slovenia
Spain

UK
USA
Colombia

New members are welcome!

Full members
Associate members