Ultrahigh-Energy Cosmic Rays
State of the Art and Implications for Current and Future Multi-Messenger Experiments
Michael Unger, IAP, KIT
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Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)
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![Graph showing the energy spectrum of UHECRs]

\[ E^{-3.1} \]

- Flux / \( (\text{km}^2 \text{Sr} \text{yr}^{-1} \text{eV}^{-1}) \)

Cham\&Whiteson "We have no idea", Penguin, 2018

\[ \sqrt{s_{LHC}} = 7 \times 10^{12} \text{ eV} \]

\[ \sqrt{s_{pp}} = 450 \text{ TeV} \]
Detection of UHECRs: Air Showers

cosmic particle → fluorescence telescope → air shower → particle detector
UHECR Observatories

Telescope Array

Pierre Auger Observatory

NB: Excellent UHEν and γ Detector! (see talks by Viviana Scherini and Michael Schimp, Tuesday Parallel2)
NB: Excellent UHE $\nu$ and $\gamma$ Detector!
(see talks by Viviana Scherini and Michael Schimp, Tuesday Parallel2)
State of the Art of UHECR Research

- Energy Spectrum
- Mass Composition
- Arrival Directions
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### Longitudinal Shower Development (Fluorescence Telescopes)

#### Pierre Auger Observatory

- **Telescope Array**

<table>
<thead>
<tr>
<th>Height a.s.l. (m)</th>
<th>Number of charged particles ($\times 10^9$)</th>
</tr>
</thead>
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<tr>
<td>2000</td>
<td>12000</td>
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<tr>
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<th>Height a.s.l. (km)</th>
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<td>10</td>
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<tr>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>

- **Auger shower**
- **iron, $E=10^{19}$ eV**
- **proton, $E=10^{19}$ eV**
- **$\gamma$-ray, $E=10^{19}$ eV**
Mean and Standard Deviation of $X_{\text{max}}$ Distributions

\begin{align*}
\langle X_{\text{max}} \rangle & [\text{g/cm}^2] \\
\sigma(X_{\text{max}}) & [\text{g/cm}^2]
\end{align*}

Pierre Auger Coll., ICRC17, see also update at ICRC19; TA Coll. ApJ18; TA&Auger Composition WG UHECR18; MIAPP review, FASS19
Inferred Mass Composition

Preliminary

Fe

N

He

P

p-value

lg(E/eV)

10^{-3} 10^{-2} 10^{-1} 10^0 10^1

17.5 18.0 18.5 19.0 19.5
State of the Art of UHECR Research

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Energy Spectrum

Flux / (km$^2$ sr$^{-1}$ yr$^{-1}$ eV$^{-1}$)

$E / \text{eV}$

$10^{17}$ $10^{18}$ $10^{19}$ $10^{20}$

$10^{-12}$ $10^{-14}$ $10^{-16}$ $10^{-18}$ $10^{-20}$ $10^{-22}$ $10^{-24}$

$E^{3.1}$ Flux / (km$^2$ sr$^{-1}$ yr$^{-1}$ eV$^{2.1}$)

$10^{39}$ $10^{40}$

$E / \text{eV}$

$10^{17}$ $10^{18}$ $10^{19}$ $10^{20}$

Pierre Auger Coll., PRD 2020, PRL 2020 (twice editor’s choice)

See Viewpoint: The Anatomy of Ultrahigh-Energy Cosmic Rays
**Energy Spectrum**

![Energy Spectrum Graph](image)

**Measurement of Local CR Energy Density**

\[
\rho = \frac{4\pi}{c} \int_{E_{\text{ankle}}}^{\infty} E \text{ Flux}(E) \, dE \\
= (5.66 \pm 0.03 \pm 1.40) \times 10^{53} \text{ erg Mpc}^{-3}
\]

→ source luminosity density

\[
\mathcal{L} \sim \rho / t_{\text{loss}} = 2 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}
\]

Typical energy loss time \(t_{\text{loss}} \sim 1 \text{ Gpc}/c\) at \(E_{\text{ankle}} = 5 \times 10^{18} \text{ eV}\)

Full calculation with SimProp gives \(\mathcal{L} = 6 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}\)
GZK Flux Suppression? \( (p + \gamma_{\text{CMB}} \rightarrow n/p + \pi^+/0 \text{ or } A + \gamma_{\text{CMB}} \rightarrow (A - 1) + p/n) \)
Maximum Rigidity Model, Peters Cycle?

energy spectrum at source $\propto (E/Z)^{-\gamma}$

A. Castellina for the Auger Coll. ICRC19 and JCAP 1704 (2017) 038

B. Peters, Nuovo Cimento 22 (1961) 800
State of the Art of UHECR Research

Energy Spectrum

Mass Composition

Arrival Directions
Arrival Directions – Blind Search

Auger/TA Anisotropy Working Group UHECR18

$E > 40/52.3$ EeV, $20^\circ$ top-hat $0.21%/2.5$% post-trial
Arrival Directions – Catalogue-based Analysis

TA compatible with both, starburst model and isotropy

Observation of a Dipolar Anisotropy of UHECRs (E > 8 EeV)

amplitude: $6.5^{+1.3}_{-0.9}\%$, significance: 5.2 $\sigma$
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amplitude: $6.5^{+1.3}_{-0.9}\%$, significance: $5.2\sigma$
Charged Particle Astronomy?

average rigidity \( R = \frac{E}{Z} \)

deflection in magnetic field

Galactic: \( \sigma_{\text{coh}} \sim 3^\circ \left( \frac{R}{10^{20} \text{V}} \right)^{-1}, \sigma_{\text{rand}} \sim 3^\circ \left( \frac{\lambda_{\text{coh}}}{100 \text{ pc}} \right)^{\frac{1}{2}} \left( \frac{R}{10^{20} \text{V}} \right)^{-1} \)

Extragalactic: \( \sigma_{\text{rand}} \sim 0.4^\circ \left( \frac{\lambda_{\text{coh}}}{1 \text{ Mpc}} \right)^{\frac{1}{2}} \left( \frac{D}{10 \text{ Mpc}} \right)^{\frac{1}{2}} \left( \frac{B}{10^{-10} \text{ G}} \right) \left( \frac{R}{10^{20} \text{V}} \right)^{-1} \)

Farrar & Sutherland, arXiv:1711.02730

Durrer & Neronov, AAR 21 (2013) 62
Implications for Current and Future Multi-Messenger Experiments
Need Charge Sensitivity and Full-Sky Coverage for UHECR Observations

Under Construction: **AugerPrime**

Under Construction: **TAX4**

Launch 2029: **POEMMA**

arXiv:1604.03637

EPJ 210 (2019) 06001

Parallel03 at 17:30, PRD 101 (2020) 023012
Implications for Neutrino Studies

Particle energy \([\text{GeV}]\)

\[ E^2 \Phi \text{(all-flavor)} \left[ \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right] \]

\(10^1\) \(10^3\) \(10^5\) \(10^7\) \(10^9\) \(10^{11}\)

\(10^{-6}\) \(10^{-7}\) \(10^{-8}\) \(10^{-9}\) \(10^{-10}\)

see talks by Rodrigues, Rudolph, Batista, Murase
Peters Cycle and Cosmogenic Neutrinos

source evolution: \((1 + z)^m\)

![Graph showing source evolution](image)

negative source evolution \((m = -1.6)\) and \(z_{\text{max}} = 1\)

Batista et al, JCAP 01 (2019) 002
source evolution: \((1 + z)^m\)

negative source evolution \((m = -1.6)\) and \(z_{\text{max}} = 1\)  
Batista et al, JCAP 01 (2019) 002
Photonuclear Interactions in Source Environment?

$A + \gamma \rightarrow (A - 1) + p/n$

$p + \gamma \rightarrow n/p + \pi^+/0 \rightarrow 2\gamma/(3\nu + e)$

source environment  EBL/CMB  detection

MU+15, Globus+15, Biel+17, Kachelriess+17, Supanitsky+18, Boncioli+19, Muzio+19

Photonuclear Interactions in Source Environment?

particles at Earth: $1 \leq A \leq 2, 3 \leq A \leq 6, 7 \leq A \leq 19, 20 \leq A \leq 39, 40 \leq A \leq 56$

Multimessenger Studies of Source Properties

Photon field temperature

Source evolution

\[ \frac{dN}{dE} \] (GeV cm\(^{-2}\)sr\(^{-1}\)s\(^{-1}\))

T = 30 K, \(\mu = 3.42\)
T = 50 K, \(\mu = 2.78\)
T = 100 K, \(\mu = 2.41\)
T = 200 K, \(\mu = 2.35\)
Galactic

\[ \frac{dN}{dE} \] (eV cm\(^{-2}\)sr\(^{-1}\)yr\(^{-1}\))

T = 500 K
T = 1000 K
T = 2000 K

\(m = 0\), \(\mu = 4\)
\(m = -4\), \(\mu = 2.86\)
\(m = +2\), \(\mu = 2.12\)
\(m = 0\), \(\mu = 2.36\)
SFR, \(\mu = 2.14\)

IceCube HESE 2017
IceCube 2017
Auger 2017
Auger 2018
HE bin IGRB
TDGRB
IceCube HESE 2017
IceCube 2017

\(E_{\gamma}\) (GeV)

\(E_{\gamma}\) (eV)

Auger 2017
Auger 2018

\(E_{\gamma}\) (GeV)

\(E_{\gamma}\) (eV)
Proton Fraction at UHE?

energy fraction escaping source:

\[ f_p = \frac{\int_{E_{\text{ref}}}^{\infty} E Q_p dE}{\int_{E_{\text{ref}}}^{\infty} E (Q_p + Q_{\text{mix}}) dE} \]

\((Q_p \sim E^{\gamma_p} e^{-E/E_{\text{max}}^{\text{UHE}_p}}, \gamma_p = -1 \text{ and } E_{\text{ref}} = 10^{19} \text{ eV})\)
Source Neutrinos from UHECR Constraints

additional degree of freedom: hadronic interactions with ambient gas
→ unified models  e.g. Kachelriess+17, Fang+2017, Muzio+21 (in prep.)
Summary

• **Golden Age of UHECR Research**
  • high-precision flux measurement
  • unexpected mass composition
  • large scale anisotropy
  • hints for clustering at intermediate angular scales
  • soon equal-exposure sky coverage (TAX4) and charge sensitivity (AugerPrime)
  • next-generation large-exposure facilities? (POEMMA, GCOS...)

• **Multi-Messenger Implications**
  • dawn of charged particle astronomy?
  • low flux of cosmogenic neutral secondaries
  • UHECR proton measurements and $>10^{18}$ eV $\nu$ flux for source evolution
  • detection (or limits on) source-neutrinos is key to understand UHECR sources
  • $10^{16} \sim 10^{17}$ eV $\nu$ flux to constrain source properties
The Pierre Auger 2021 Open Data is the public release of 10% of the Pierre Auger Observatory data presented at the 36th International Cosmic Ray Conference held in 2019 in Madison, USA, following the Auger collaboration open data policy.

This website hosts the datasets for download. An online event display is available to explore the released events, and example analysis codes are provided. See below for a brief overview of the Pierre Auger Observatory and of the Auger Open Data.

**Datasets**  
the complete released datasets and their complementary data

**Visualize**  
an online look at the released pseudo raw data

**Analyze**  
example analysis codes in online python notebooks to run on the datasets