Mass Composition and More: Results from the Auger Engineering Radio Array

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Introduction: **AERA** at the Pierre Auger Observatory

**Auger Engineering Radio Array**
- 153 autonomous radio antennas
- Energy range: $10^{17}$-$10^{19}$ eV
- Frequency range: 30-80 MHz

3000 km$^2$

17 km$^2$
Recent results from AERA:

- Measurements of the muon content of inclined air showers
- Long-term stability of the air-shower radio signal over time
- Mass composition
  - Measurements of the depth of shower maxima ($X_{\text{max}}$) with AERA
  - Compatibility with fluorescence measurements
  - $X_{\text{max}}$ resolution as a function of energy
Muon deficit in air-shower simulations

Work by M. Gottowik

- Number of muons $N_\mu$ underpredicted by all current-generation hadronic interaction models
- For inclined WCD-AERA hybrid events separation of electromagnetic and muonic component in the atmosphere
  - WCD: muon estimator
  - AERA: electromagnetic energy
- Independent analyses at Auger
Muon content in measured air showers

Work by M. Gottowik

- First measurement of the muon deficit with AERA-WCD hybrid events
  - WCD: muon estimator
  - AERA: electromagnetic energy
- Analysis of 59 events in ~6 years of data shows fewer muons in simulations than in measured data
- Major science case for the AugerPrime Radio Detector
  → larger statistics at highest energies (order of magnitude more than hybrid FD-WCD event)

-> See talk by J. Hörandel: today 17:00, parallel 1
Stability of the radio signal over time

Work by D. dos Santos & R. de Almeida

Radio as a calibrator for hybrid detectors

- ‘Ageing’ effects known for e.g. PMTs / dust on mirrors.  
  --> Adds uncertainties on energy estimators
- Radio was hypothesized/assumed to be stable.

7yr of data: amplitude radio signal very stable:

- Constrained to ±1% per decade

- Some residual (seasonal) variation remains  
  --> Investigation ongoing to restrict stability further

- Shows potential for stable calibration source in hybrid detector setups such as the Pierre Auger Observatory

Example of calibration constant $C_0$ over time for a single AERA antenna:
Introduction: Radio footprint is sensitive to Mass

Work by B. Pont

• $X_{\text{max}}$ [g/cm$^2$]: *column depth* where Extensive Air Shower is maximally developed.  
  $\rightarrow$ $X_{\text{max}}$ depends on mass (particle type)

• Shape of radio footprint changes with $X_{\text{max}}$  
  $\rightarrow$ Radio footprint is probe for $X_{\text{max}}$.

**Proton**

<table>
<thead>
<tr>
<th>Column depth</th>
<th>Proton</th>
<th>Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 g/cm$^2$</td>
<td><img src="image1" alt="Proton Radio Emission" /></td>
<td><img src="image2" alt="Iron Radio Emission" /></td>
</tr>
<tr>
<td>600 g/cm$^2$</td>
<td><img src="image3" alt="Proton Emission" /></td>
<td><img src="image4" alt="Iron Emission" /></td>
</tr>
<tr>
<td>700 g/cm$^2$</td>
<td><img src="image5" alt="Proton Emission" /></td>
<td><img src="image6" alt="Iron Emission" /></td>
</tr>
<tr>
<td>1200 g/cm$^2$</td>
<td><img src="image7" alt="Proton Emission" /></td>
<td><img src="image8" alt="Iron Emission" /></td>
</tr>
</tbody>
</table>

**Energy density footprint = $f$(Direction, Energy, particle mass)**

**Position in $\hat{v} \times \hat{B}$-direction [m]**

**Position in $\hat{v} \times \hat{E}$-direction [m]**

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Bjarni Pont, for the Pierre Auger Collaboration — ECRS2022 — July 2022
Method: Reconstructing $X_{\text{max}}$ from the radio footprint

Build upon simulation-template fitting method [Buitink+2016]

- From 7yr of data:
  - ~600 high-quality showers after anti-bias and reconstruction cuts ($E=10^{17.5}$ to $10^{18.8}$ eV)
  - 53 hybrid showers with independent FD and AERA reconstructions
- 15 proton +12 iron Corsika/CoREAS simulation for each air shower

$\Rightarrow$ likelihood analysis: template fitting to find $X_{\text{max}}$ for each shower [details]

Using the $\sim 600 \times (15+12)$ set of simulations

- Correct for reconstruction bias on an event-by-event basis
- Determine reconstruction uncertainty on an event-by-event basis
- Determine detection acceptance
- Determine reconstruction bias

Investigation of systematic uncertainties. Accounting for:

- **Basic effects**: hadronic model in CORSIKA, GDAS atmosphere, Auger SD energy scale
- **Method specific effects**: data selection (acceptance), $X_{\text{max}}$ reconstruction pipeline
- **low-number statistics**: effects of possible outlier values and reconstruction quality cuts
- **Residual bias checks**: investigation of shower zenith/azimuth/core/… vs $<X_{\text{max}}>(E)$
**Results: Resolution of AERA \(X_{\text{max}}\) method**

**Radio \(X_{\text{max}}\) resolution**

- Resolution improves with energy.
  - Up to ‘better than 15 g/cm\(^2\)’
  - Trend driven by low SNR at low energy.

Resolution competitive with e.g.:
- **Auger fluorescence**
  [arXiv:1409.4809]
- **LOFAR radio (E=10\(^{16.8...18.3}\) eV)**
  [arXiv:2103.12549v2]
Results: **Event-by-event FD vs AERA $X_{\text{max}}$**

Auger has unique Radio-Fluorescence setup:

- $X_{\text{max}}$ of $53$ hybrid-showers with AERA and FD; (Are independent observations!)
- No significant bias radio $X_{\text{max}}$ w.r.t. fluorescence $X_{\text{max}}$.
- Provides independent checks on:
  - $X_{\text{max}}$ reconstruction methods
  - shower physics (probe different aspects)

**Histogram of AERA-FD difference**

$$\mu = -3.9 \pm 11.2$$

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Results: Measured AERA $X_{\text{max}}$ distribution

- Preliminary

<table>
<thead>
<tr>
<th>'Mean of $X_{\text{max}}$ distribution'</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPOS-LHC</td>
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<tr>
<td>Sibyll2.3d</td>
</tr>
<tr>
<td>QGSJetII-04</td>
</tr>
<tr>
<td>Auger FD ($\pm \sigma_{\text{stat}}$)</td>
</tr>
<tr>
<td>AERA ($\pm \sigma_{\text{stat}}$)</td>
</tr>
</tbody>
</table>

- 'Width of $X_{\text{max}}$ distribution'

- ~600 showers after quality and anti-bias cuts.
- In agreement with Auger FD in mean and width.
- Light composition (p-He) at $E=10^{17.5}$ eV, seemingly becoming lighter towards $E=10^{18.5}$ eV.
Take home messages

Work on AERA is ongoing: Physics & survey-studies for upcoming AugerPrime Radio

First muon deficit measurements with AERA-WCD
Very promising for the upcoming AugerPrime Radio Detector

Radio signal is very stable over time
Potential for calibration source for hybrid detectors

Competitive radio $X_{\text{max}}$ resolution

AERA $X_{\text{max}}$ compatible with Auger Fluorescence
Independent support to our understanding of shower physics.