Telescope Array became fully operational in 2008.
9 years of data are now collected and analyzed.
TA can exploit its different facilities to measure air shower $X_{\text{max}}$.
Though data sets are not completely independent, different analyses may complement each other.
In particular, $X_{\text{max}}$ systematics can be directly measured for the different techniques employed in their measurements.

I will present four different analysis efforts
- BR/LR hybrid A
- BR/LR hybrid B
- Stereo
- MD hybrid

BR/LR hybrid A and BR/LR hybrid B are analyses performed using hybrid shower observation and the BR and LR FD detectors, analyses performed by W. Hanlon and D. Ikeda, respectively.
Each analysis was independently developed.
Different assumptions may be made, e.g., Monte Carlo generation, GH parameterization, atmospherics, profile fitting, etc.
CRI070 - TA SD Composition Results, Yana ZHEZHER

CRI167 - Testing the Agreement Between the $X_{\text{max}}$ Distributions Measured by the Pierre Auger and Telescope Array Observatories, Vitor DE SOUZA

CRI123 - Telescope Array Composition Summary, William HANLON

CRI107 - Telescope Array Measurement of UHECR Composition from Stereoscopic Fluorescence Detection, Tom STROMAN & Douglas BERGMAN

### TA Composition - MD Hybrid

- **7 years of MD FD hybrid data - 613 events**
  \[ \log_{10}(E/eV) > 18.4 \]

Improved reconstruction via *pattern recognition* method → ensures curvature of profile is well measured.

- **X\textsubscript{max} resolution ~ 22 g/cm\textsuperscript{2}, reconstruction bias < 2 g/cm\textsuperscript{2}**
- **Energy resolution ~ 7%**

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**Two composition measurements:**

1. **Middle Drum hybrid**
   (5 year set published 2014)
2. **Black Rock/Long Ridge hybrid**

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**J.P. Lundquist, ICRC2015**

**R. Abbasi et al., Astropart.Phys. 64 (2014)**
QGSJet II-03 models shown, reconstruction systematics ± 15 g/cm², $X_{\text{max}}$ resolution = 21 g/cm², energy resolution = 5%
TA SD only measurement of composition.

Nearly 100% ontime.
Much higher statistics.

$X_{\text{max}}$ not observed.

Boosted decision tree is built using SD 13 observables and trained using model dependent two-component MC (proton and iron).

Observed composition can be inferred by KS test of proton/iron fraction.
Hybrid composition measured using TA Black Rock (BR) and Long Ridge (LR) FD stations.

Differs from MD in distance to SD array, mirror size, electronics ⇒ acceptance (esp. low energy) is different between MD and BR/LR.

BR/LR is TA’s highest statistics measurement of $X_{\text{max}}$.  

$X_{\text{max}}$ resolution: $\sim 18 \text{ g/cm}^2$ @ $10^{18.2} \text{ eV}$  

$X_{\text{max}}$ reconstruction bias: $\sim 1 \text{ g/cm}^2$ (proton)  

Energy resolution: 7%  

9 years exposure: $\sim 650 \text{ km}\cdot\text{sr}\cdot\text{s}^2 (E > 3 \text{ EeV})$

Two hybrid BR/LR analyses independently developed by Ikeda and Hanlon. Provides valuable insight into reconstruction systematics.
Four TA independent $<X_{\text{max}}>$ measurements:

- 2 BR/LR hybrid
- 1 MD hybrid
- 1 Stereo (BR $\otimes$ LR $\otimes$ MD)

Event numbers shown are for BR/LR hybrid (A) data.

The gray band are model-independent systematics on BR/LR hybrid (A) data.

All models shown are QGSJet II-04 as reconstructed by BR/LR hybrid analysis.

Within systematics all independent measurements agree.
\( \sigma(X_{\text{max}}) \) of all TA \( X_{\text{max}} \) measurements.

Event numbers shown are for BR/LR hybrid (A) data.

\( \sigma(X_{\text{max}}) \) appears to agree with protons for all current \( X_{\text{max}}^{18.2} \) - \( 10^{19} \) eV.

Above \( 10^{19} \) eV, statistics are falling too rapidly to make an accurate measurement. Even a couple of events will cause \( \sigma(X_{\text{max}}) \) to change by ~25%.

All models shown are QGSJet II-04 as reconstructed by BR/LR hybrid analysis.
Model Testing: Data vs MC

- Mean and especially RMS may be influenced by what happens in the tails → sampling bias.
- Utilize Cramér-von Mises (CvM) non-parametric goodness of fit test to measure agreement with models.
- Ask the question: how much does data need to be shifted to find agreement with CORSIKA models?
- Apply the CvM test to evaluate the agreement of the entire distribution without relying on the moments of the distribution.

Shift data $+25 \text{ g/cm}^2$

Shift data $-47 \text{ g/cm}^2$
Amount that data needs to be shifted to match CORSIKA models. Find the best value of the two-sample CvM test statistic.

$s$-value is the $p$-value under the assumption both samples were drawn from the same parent distribution after shifting the data.

To find agreement with heavy elements, large shifts are needed and the $s$-values are too small.

Light composition is favored by systematic shift and $s$-value. In the highest energy bins, tails might be clipped by acceptance, hence $s$-value for proton and iron increases.

$X_{\text{max}}$ systematics: $\pm 20.3 \text{ g/cm}^2$
Looking at simply the first moment of the distributions (agreement with minimal $<X_{\text{max}}>$ shift) one is tempted to say TA data looks like helium, but the shapes of the distributions do not agree with helium ($s$-value).

Above $10^{19}$ eV, QGSJet II-04 proton, helium, and nitrogen shapes begin to look plausible by this test, even QGSJet II-04 iron in the last energy bin, but TA exposure is insufficient in this energy range to collect enough events to make a convincing measurement in the tails of the $X_{\text{max}}$ distributions. Additionally iron is implausible given the shift required to make it agree with data is much larger than our systematic uncertainties.

Are the tails diminished due to composition or statistics (undersampling)?

We need more data to find out.
\begin{align*}
18.2 \leq \log_{10}(E) < 18.6 \\
18.6 \leq \log_{10}(E) < 19.0 \\
19.0 \leq \log_{10}(E) < 19.4 \\
\log_{10}(E) \geq 19.4
\end{align*}

\begin{itemize}
\item All analyses exhibit similar shapes. Tails characteristic of light primaries are seen up to until statistics begin to be severely depleted above $10^{19.4}$ eV.
\item Undersampling in the tails due to insufficient exposure is a risk at these energies.
\end{itemize}
<table>
<thead>
<tr>
<th>log$_{10}$(E/eV)</th>
<th>$N_{\text{BR/LR,A}}$</th>
<th>$N_{\text{BR/LR,B}}$</th>
<th>$N_{\text{stereo}}$</th>
<th>$N_{\text{MD}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.2 - 18.6</td>
<td>2526</td>
<td>2330</td>
<td>561</td>
<td>221</td>
</tr>
<tr>
<td>18.6 - 19.0</td>
<td>671</td>
<td>676</td>
<td>640</td>
<td>262</td>
</tr>
<tr>
<td>19.0 - 19.4</td>
<td>114</td>
<td>163</td>
<td>251</td>
<td>110</td>
</tr>
<tr>
<td>&gt; 19.4</td>
<td>19</td>
<td>40</td>
<td>72</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>3330</td>
<td>3209</td>
<td>1524</td>
<td>613</td>
</tr>
</tbody>
</table>

Number of events collected for the four analyses. BR/LR A & B and stereo exposure is nearly nine years. MD exposure shown here is for seven years. Stereo analysis acceptance begins to overcome hybrid analysis above $10^{19}$ eV due to its larger zenith angle acceptance (60° max for hybrid versus 80° max for stereo). Below $10^{19}$ eV, the distances between FD detectors (~ 30 km) hampers coincident observation between FD stations.
Hybrid $X_{\text{max}}$ acceptance as a function of zenith angle in three energy ranges.

Low zenith angle events (near vertical) have lower acceptance. This will mostly affect deeply penetrating events (low mass primaries). $X_{\text{max}}$ must be bracketed to ensure a profile fit with small $\Delta X_{\text{max}}$.

We have a steeply falling spectrum, higher energy events on average penetrate deeper, statistics are rapidly depleted for $E > 10^{19}$ eV.

TA needs greater exposure for accurate measurement of composition for $E > 10^{19}$ eV. Nearly 9 years of data $\Rightarrow$ 133 events above $10^{19}$ eV.

TAx4 will give us the exposure needed to measure composition here.
Stereo $X_{\text{max}}$ acceptance as a function of zenith angle in three energy ranges.

Low zenith angle events (near horizontal) have lower acceptance similar to hybrid. Overall acceptance looks similar to hybrid but stereo accepts events beyond 60°. Stereo acceptance for $E > 10^{19} \text{ eV}$ is larger. This may be a better analysis to measure composition above $10^{19} \text{ eV}$.

Hybrid analysis can be extended to these energies using single SD counter analysis. MC is less important for $E > 10^{19} \text{ eV}$, because SD efficiency is flat above $10^{19} \text{ eV}$. 
TA and Auger data can not be directly compared because they use different approaches to data analysis.

We can indirectly compare our data by using a composition mixture made up of proton, helium, nitrogen, and iron that is fit to their data. Then TA generates and reconstructs a Monte Carlo data set using the same composition mix. This simulates acceptance and biases of the TA detector and reconstruction algorithms.

Compare the agreement of this reconstructed mix to TA data.

\[(A = B \land B = C) \Rightarrow A = C\]

TA and Auger data are in agreement within systematic uncertainties.
TA and Auger data cannot be directly compared. TA data is presented as *biased* by the detector, Auger is presented as *unbiased*.

Auger fits their unbiased data to a composition mixture of proton, helium, nitrogen, iron → TA reconstructs this mixture → exposure to full detector and reconstruction → now we can compare for compatibility.

Nonparametric tests (KS and AD) fail to reject the null hypothesis at the 90% confidence level.

TA data agrees with Auger data within TA systematics.

**CRI167 - Testing Agreement of \( X_{\text{max}} \) Between Auger and TA, V. De Souza**
Summary

- TA has nine years of data collected.
- Five different analyses of composition are ongoing.
  - BR/LR hybrid x 2, 9 years, ~3300 events each.
  - MD hybrid, 7 years, ~ 613 events.
  - Stereo, 9 years, ~ 1524 events.
  - SD BDT, 9 years, ~ 18,000 events.
- Between $10^{18.2}$ - $10^{19}$ eV $X_{\text{max}}$ distribution moments and shapes favor light composition.
  - Is it helium, is it proton?
    - Difficult to tell given reconstruction resolutions of ~20 g/cm$^2$ and our systematic uncertainties of ~20 g/cm$^2$.
  - Is it iron?
    - No
- Current TA exposure is insufficient to make accurate statements about composition above $10^{19}$ eV.
  - Possible statistical undersampling in the tails of the distributions is a real hazard that must be addressed.
- TAx4 exposure will give us 20 years of current TA statistics by 2020.
- This is necessary to make meaningful statements about composition at the highest energies.
- Within systematics TA data is statistically compatible with Auger below $10^{19}$ eV. Means of TA/Auger agree above $10^{19}$ eV as well.
TA Expansion (TA × 4)

Fourfold increase in the size of the TA SD array.

Add 500 scintillator SDs @ 2.08 km spacing.

Add 2 FD stations, 28 telescopes

Get 20 TA years of data by 2020.

Increased statistics for highest energy range (> 57 EeV) to answer the question of the hotspot.
TA Expansion (TA × 4)

Fourfold increase in the size of the TA SD array.
Add 500 scintillator SDs @ 2.08 km spacing.
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1st SDs begin operation in 4th quarter 2017!
MISCELLANEA
Telescope Array Collaboration

5 nations, 33 institutions, 124 members
Largest cosmic ray observatory in the Northern hemisphere.

\[ \sim 700 \text{ km}^2 \rightarrow \lesssim \text{land area of New York City.} \]

Millard County, Utah

39° 17' 48.90457"
112° 54' 31.43708"
1370 m

876 g/cm² vertical depth

Light pollution map of the U.S.

http://telescopearray.org

Scintillator surface counters
Air fluorescence telescopes
25 kW radar transmitter
Lightning detection array
40 MeV linear accelerator
**TA Detectors**

- 507 scintillation counters surface detector
- 1.2 km grid spacing (3 m² area)
- Total detection area: ~700 km²
- ~100% duty cycle
- 3 fluorescence detector stations
- 48 FD telescopes
- ~10% duty cycle

*In operation since March 2008*
**TA Fluorescence Detectors**

**BRM & LR FD stations:**
12 telescopes each
256 pixels/telescope @ 1°/pixel
108° azimuth, 3°-33° elevation view
10 MHz FADC readout

**MD FD station:**
14 telescopes
256 pixels/telescope @ 1°/pixel
112° azimuth, 3°-31° elevation view
S/H electronics (HiRes1)
Operation start date: Oct. 2007

Operation start date
BR: Jun. 2007
LR: Nov. 2007
**TA Surface Detectors**

- Solar cell and battery
- Wireless LAN (2.4 GHz) communications
- 12 bit FADC, 50 Msps: 20 nS time resolution, dynamic range of 4096 FADC counts
- Event readout/monitoring/calibration via 3 communication towers
- Scintillator:
  - 2 layers (upper and lower), each 3 m² x 1.25 cm
  - 1 PMT for each layer
Shower is observed by fluorescence detectors to measure position and depth of $X_{\text{max}}$. 

Hybrid Reconstruction Method
Shower is observed by fluorescence detectors to measure position and depth of $X_{\text{max}}$.

Coincident surface detectors constrain the geometry and shower timing, improving $X_{\text{max}}$. 

Hybrid Reconstruction Method
Hybrid combines SD information (core, timing at the ground) with FD information (profile, timing in the atmosphere) to make improved shower measurement.

Energy: $1.3 \times 10^{20}$ eV  
$R_p$: 21 km  
zenith: 55.7 deg
TA Stereo Composition
TA Stereo Composition

Proton $X_{\text{max}}$ resolution, $E > 10^{16.4}$ eV

- Entries: 20628
- Mean: -0.741
- RMS: 21.63
- $\chi^2$/ndf: 719.1/96
- Constant: 822.2 ± 8.3
- Mean: -0.8952 ± 0.1366
- Sigma: 19.21 ± 0.14

Proton energy resolution, $E > 10^{16.4}$ eV

- Entries: 20628
- Mean: 0.05125
- RMS: 0.07291
- $\chi^2$/ndf: 702.9/86
- Constant: 1270 ± 12.4
- Mean: 0.05106 ± 0.00045
- Sigma: 0.06247 ± 0.00042

Proton vector resolution, $E > 10^{16.4}$ eV

- Entries: 20628
- Mean: 0.9227
- RMS: 0.8486
Monte Carlo Reconstruction - BR/LR Hybrid

QGSJet II-04 resolutions: zenith angle 0.4 degrees, psi angle 0.4 degrees, $R_p$ 40 meters
Reconstruction Resolution - BR/LR Hybrid

$X_{\text{max}}$ resolution is between 12 - 18 g/cm$^2$ for protons and 6 - 14 g/cm$^2$ for iron.
For comparison, monocular resolution is 54 g/cm$^2$ and 46 g/cm$^2$ for proton and iron.

Reconstruction bias is $\sim$ -1 g/cm$^2$ for proton and $\sim$ -3 g/cm$^2$ for iron.
$18.2 \leq \log_{10}(E) < 18.6$

$18.6 \leq \log_{10}(E) < 19.0$

$19.0 \leq \log_{10}(E) < 19.4$

$log_{10}(E) \geq 19.4$

$X_{\text{max}}$ distributions for all TA $X_{\text{max}}$ analyses.

QGSJet II-04 models for four different primary species are also shown: proton, helium, nitrogen, and iron.

All analyses exhibit similar shapes. Tails characteristic of light primaries are seen up to until statistics begin to be severely depleted above $10^{19.4}$ eV.

Undersampling in the tails due to insufficient exposure is a risk at these energies.
History of $X_{\text{max}}$ measurements with TA systematics (Auger data is “unbiased”).

Deeper understanding of $X_{\text{max}}$ systematics will help close the gap between composition measurements at the highest energies.