Pierre Auger Observatory

Radboud University

The depth of the shower maximum of air showers measured with AERA

ICRC2021 | CRI | Cosmic Ray Indirect

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
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Bjarni Pont for the
Pierre Auger Collaboration

Talk overview

1. Introduction:

   ‘How to measure the cosmic-ray particle types with radio antennas?’

2. Method:

   ‘How do we determine this as accurately as possible at AERA?‘

3. Results:

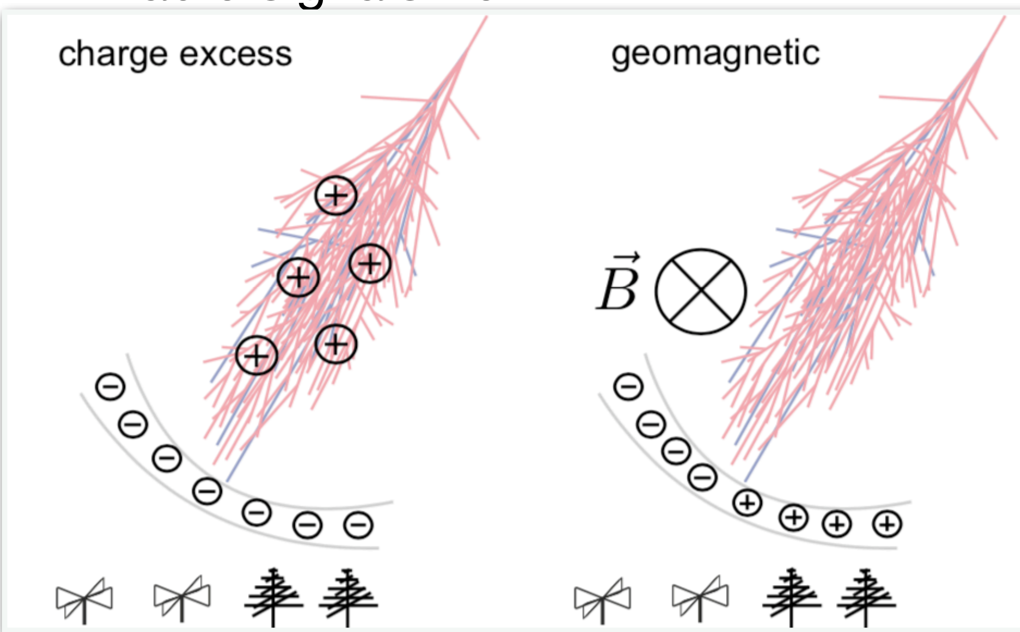
   ‘What is the cosmic-ray mass composition?’

   ‘How does this compare to the Auger fluorescence and other measurements?’

Introduction: *Depth of the shower maximum* (X_{max}) as '*mass composition*'

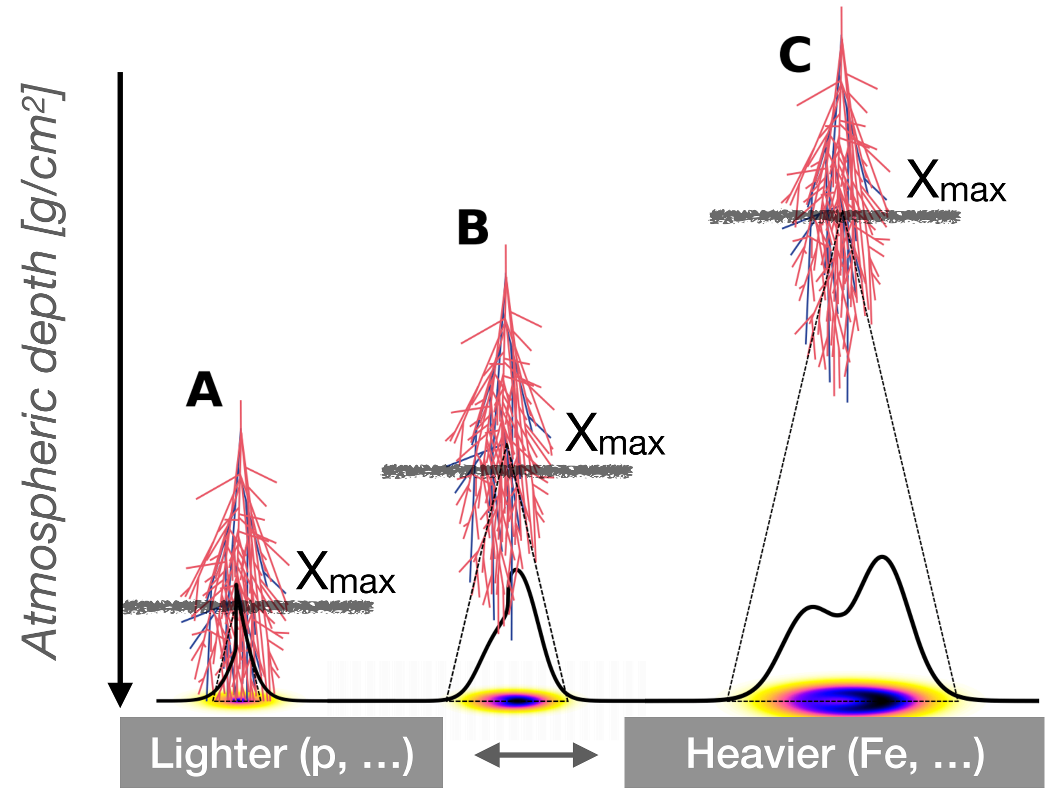
1. Heavy particles interact earlier than light
—> Depth of the shower maximum (X_{max}) is probe for cosmic-ray mass.

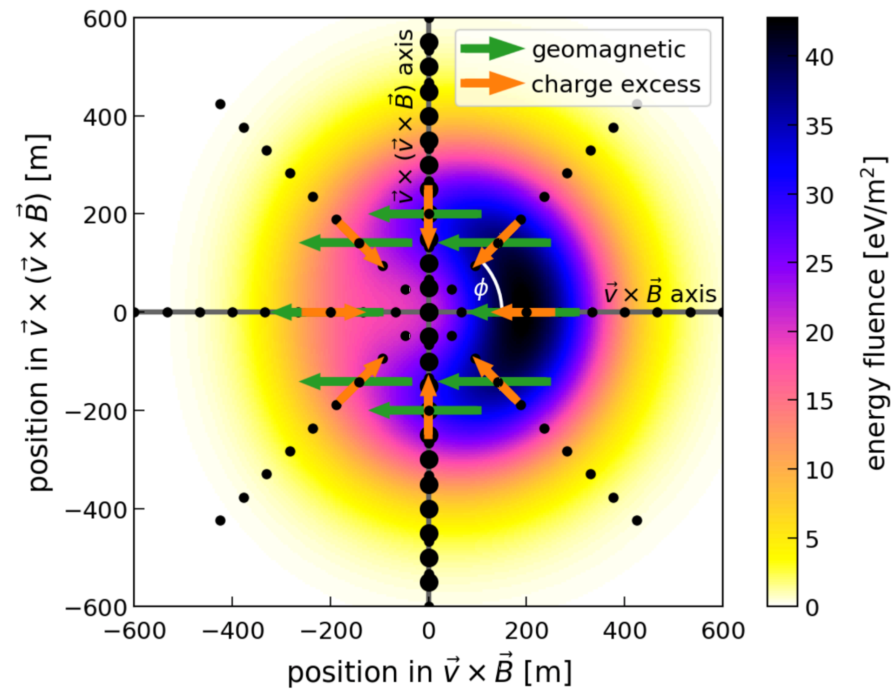
2. MHz radio signals from:



3. Radio emission footprint on the ground is sensitive to Xmax.

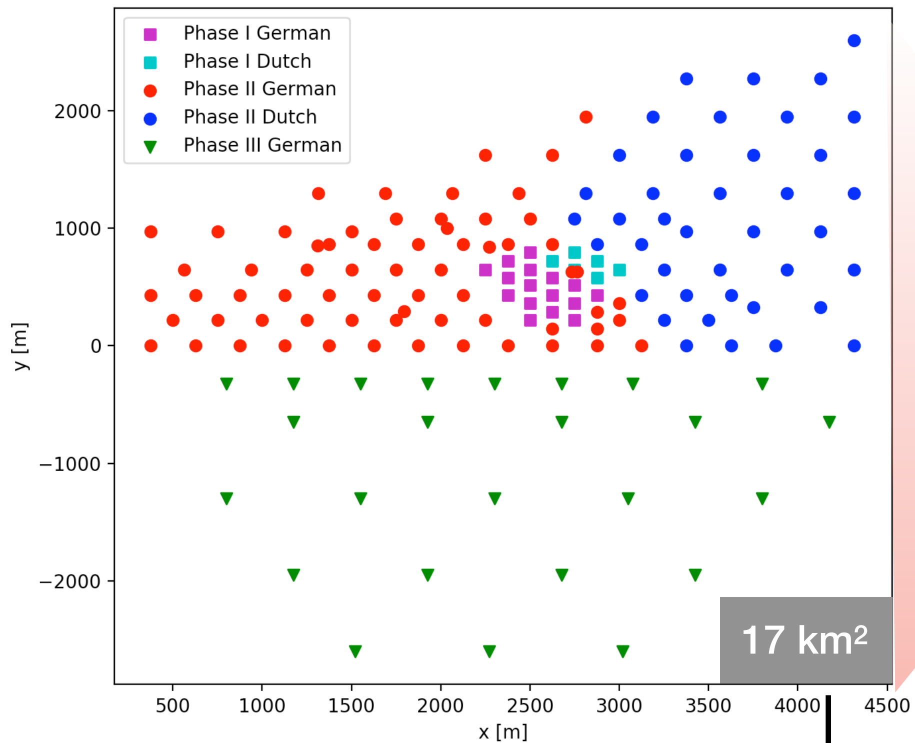
4. Compare measured footprint to footprint from CORSIKA air shower simulation
—> minimise for Xmax of measured shower.

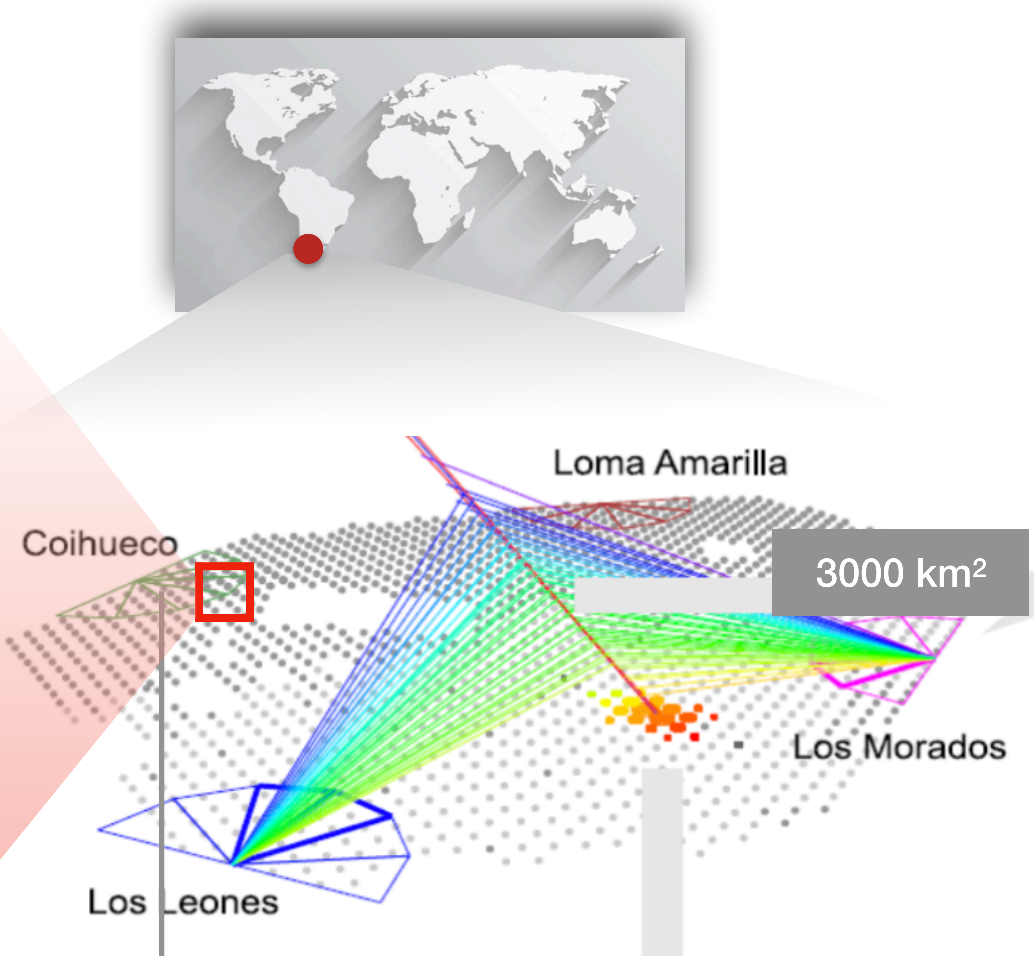




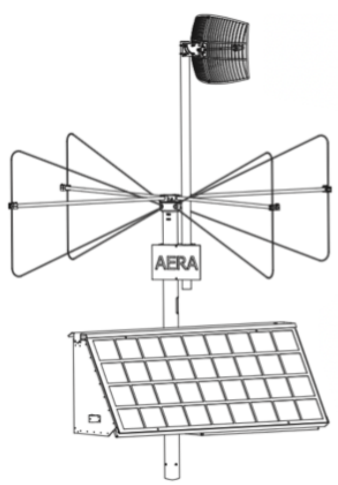
Introduction: AERA at the Pierre Auger Observatory

Auger Engineering Radio Array (AERA):
153 autonomous radio antennas





Radio



Fluorescence

Both measure mass composition of cosmic ray

Introduction: Motivation for AERA X_{max}

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1) AERA: largest radio array for cosmic-ray detection
Statistics in transition Galactic/Extra-galactic (10^{17}-10^{19} eV)

2) Discrepancy at 10^{17}–10^{18} eV?
- AERA method similar to LOFAR/Tunka-Rex.
- AERA shares systematic effects and events with Auger FD.

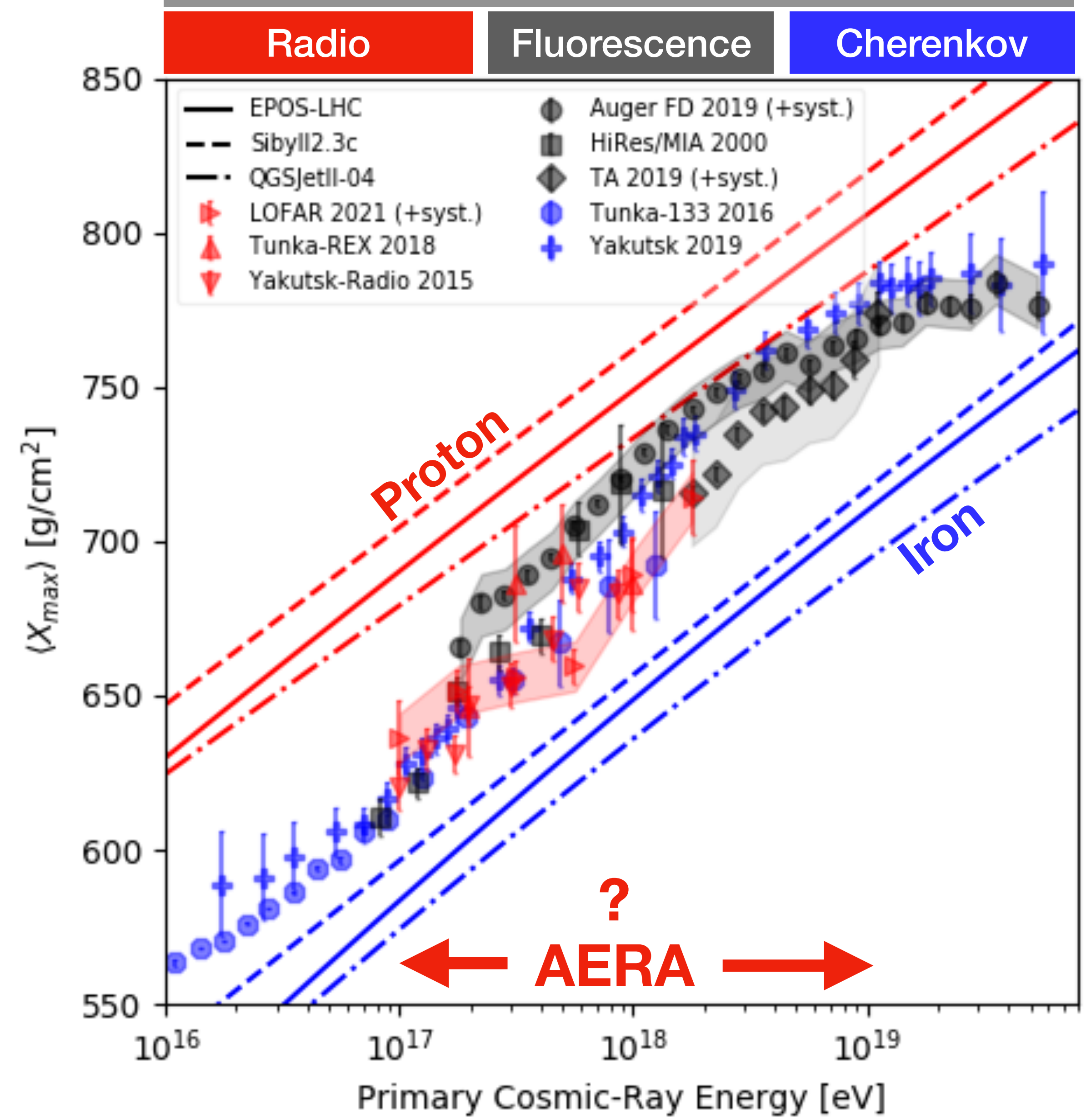
—> AERA can give new insights.

Approach:
Derive AERA X_{max} by comparing measured AERA signals to set of CoREAS/Corsika simulations.

Measured air showers (2013-2019)
- ~600 after all reconstruction-, quality-, and anti-bias cuts.
- ~60 measured in hybrid with Auger fluorescence.

Simulation dataset:
- Simulations of each event:
  CORSIKA/CoREAS v7.7100 + QGSJETII-04 + GDAS atmosphere.
- 15 p + 12 Fe covering X_{max} distribution in nature (Gumbel).

A collection of previous X_{max} measurements



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Method: X_{max} from data-sim matching

Step 1) comparing measured AERA signals to simulated and Offline-reconstructed signal.

$$\chi^2 = \sum_{\text{AERA Stations}} \left(\frac{u_{\text{data}} - S \cdot u_{\text{sim}}(\Delta \vec{r}_{\text{core shift}})}{\sigma u_{data}} \right)^2$$

u : energy density [eV/m²]
S : scale factor for syst. & SD energy uncertainty
Δr : shift for AERA core uncertainty

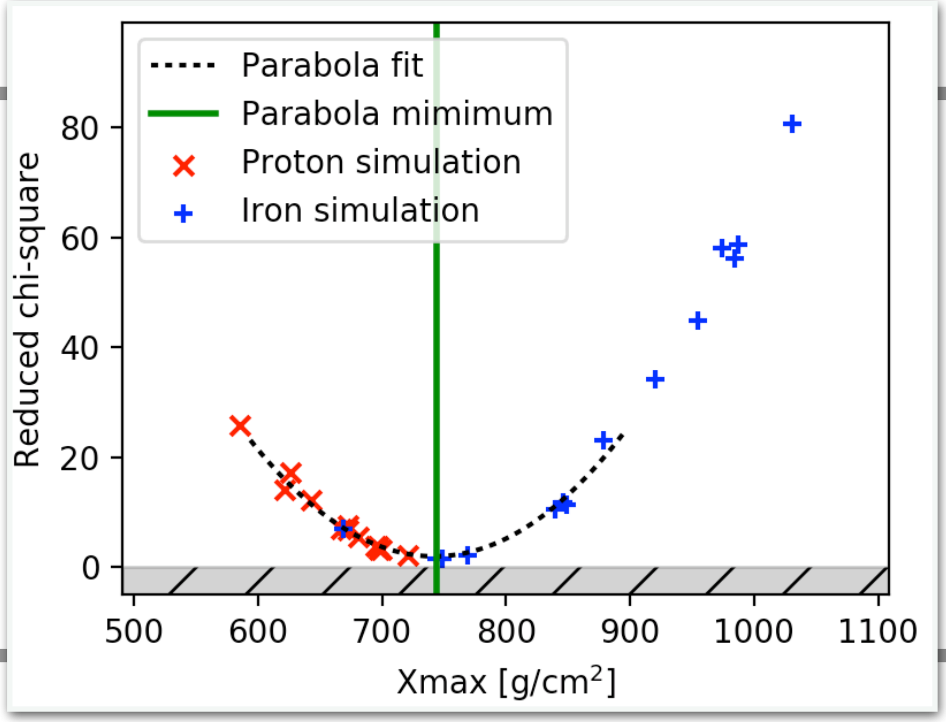
(based on 'Lofar method'. Buitink et al. 2014)

Step 2)

- Fitting X^2/ndf(X_{max}) of (12Fe+15p) simulations with parabola.
- Chi-squared minimisation procedure with free *core shift (Δr)* and *Energy scaling (S)*

—> X_{max} of measurement at the minimum.

But, parabola-X_{max} estimator is a biased estimator!



Step 3) Q: "How well can the method reconstruct MC truth for this event?"
Designed procedure for: X_{max} uncertainty estimation and bias estimation using reconstruction of simulated showers

Result $X^{AERA}_{max} = (X^{Parabola}_{max} + \Delta X^{bias}_{max}) \pm \sigma X_{max}$

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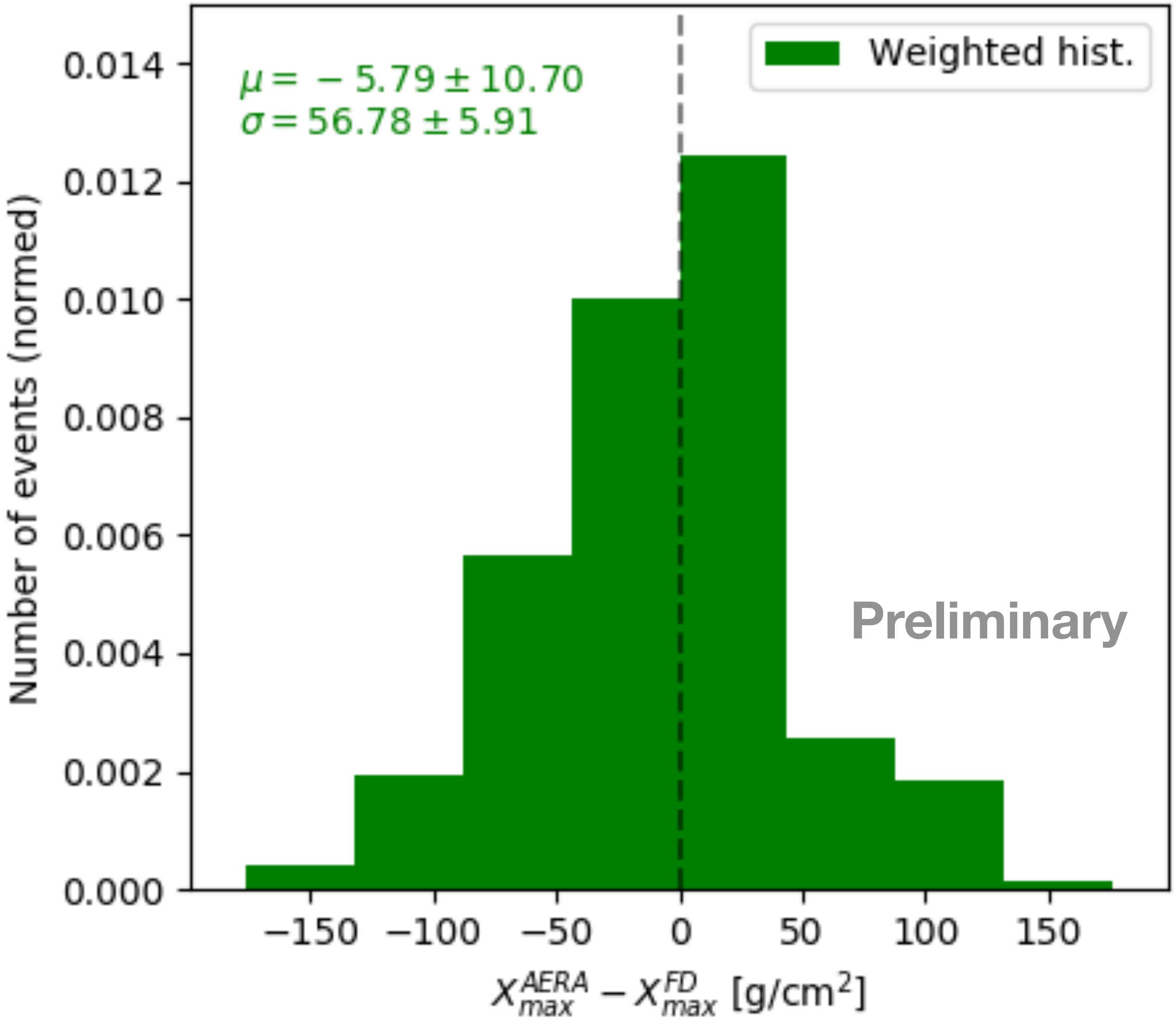
Results: Event-by-event FD vs AERA X_{max}

Histogram of AERA-FD difference



- 60 showers with AERA and FD; (Are independent observations!)
- No significant bias radio X_{max} w.r.t. fluorescence X_{max}.
- Provides independent checks:
  - consistency X_{max} methods
  - probing different shower physics

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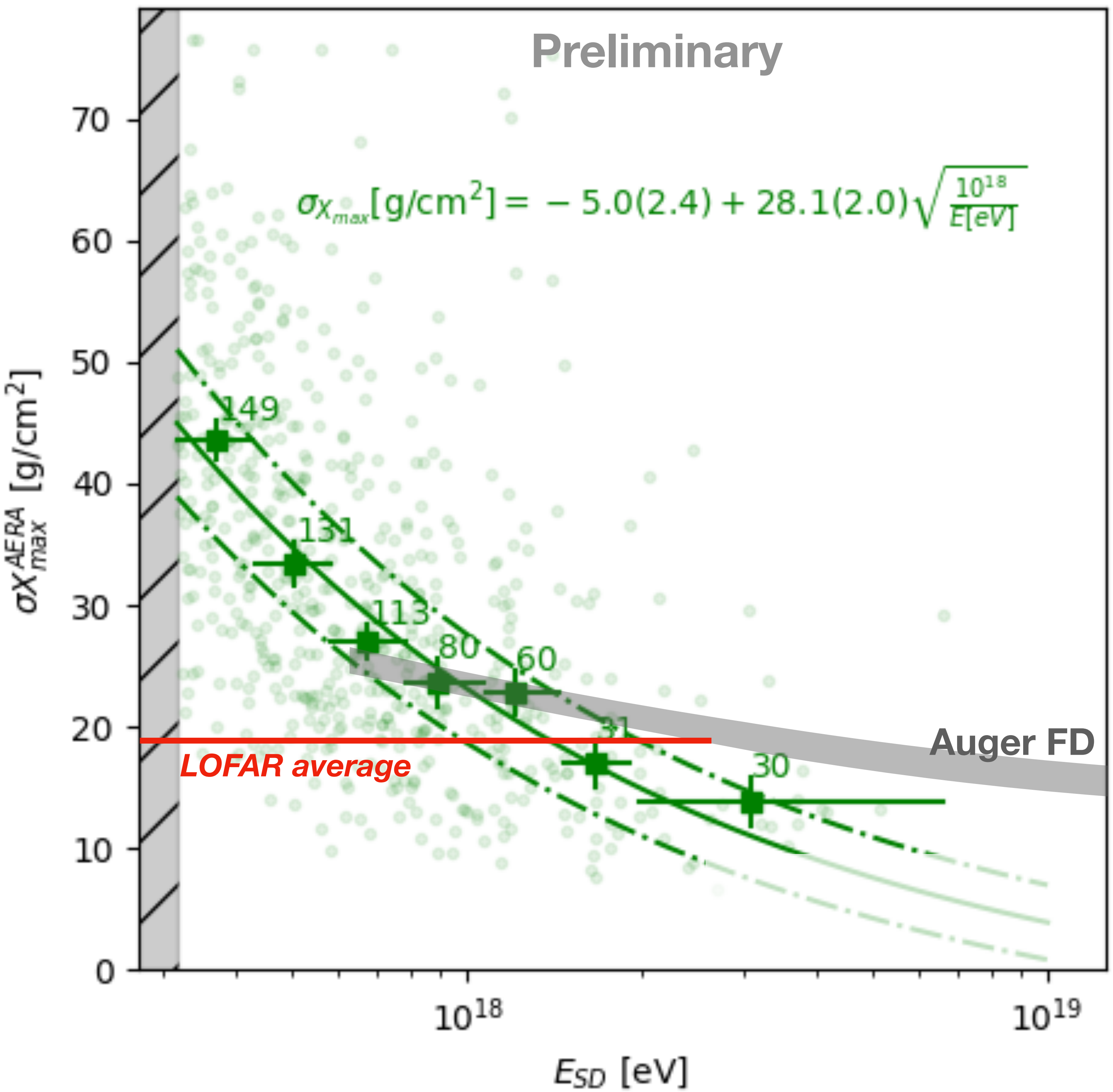
Results: Resolution of AERA X_{max} method

Radio X_{max} resolution



Resolution improves with energy.

- Roughly follows 1/sqrt(E)
- Driven by SNR increasing with E.

Resolution competitive with e.g.:

- Auger fluorescence
  25-17 g/cm² [arxiv:1409.4809].
- LOFAR radio (E=$10^{16.8...18.3}$eV)
  <19 g/cm²> [arxiv:2103.12549v2
  (smaller but much denser array)

Results: Measured AERA X_{max} distribution

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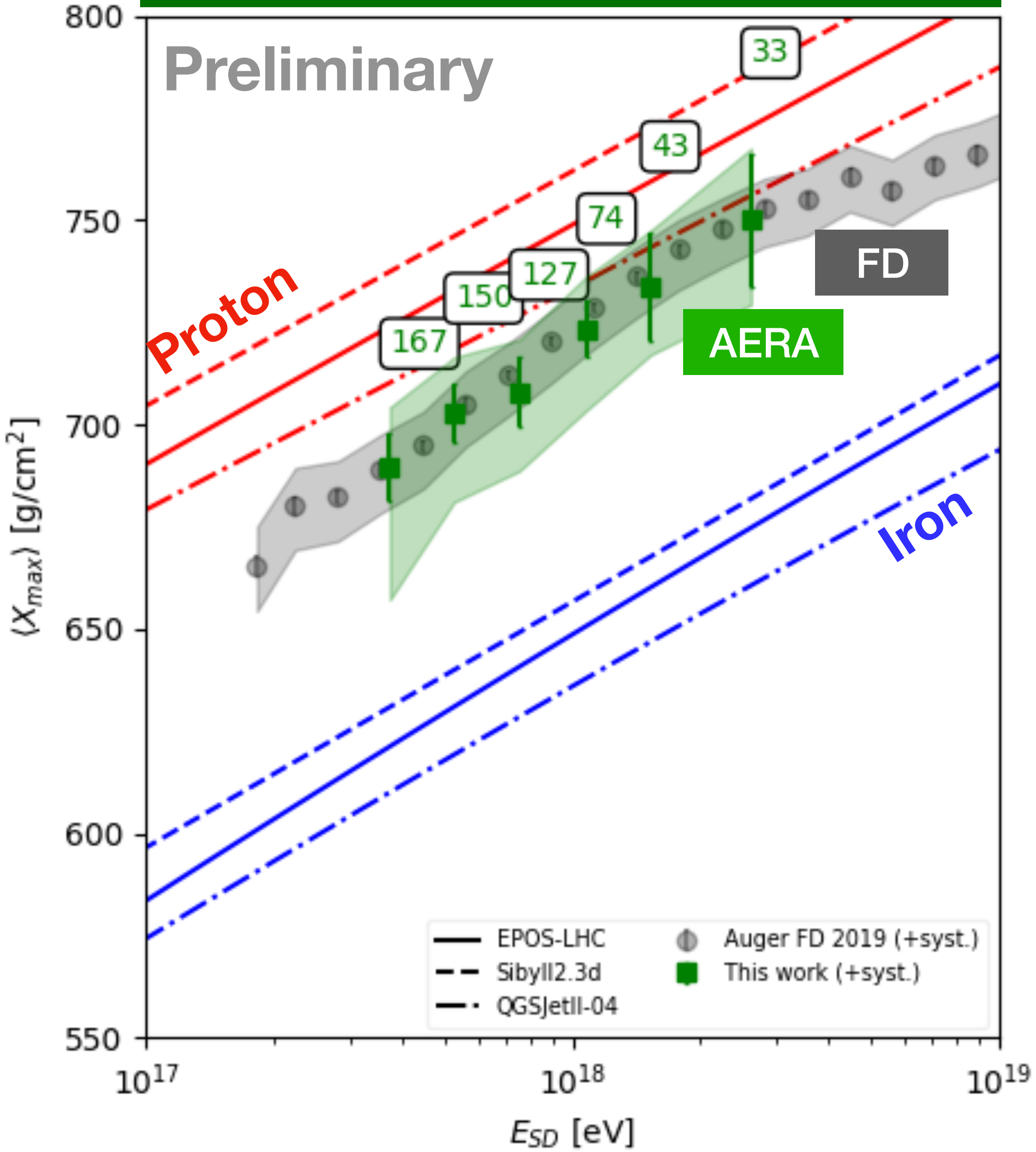
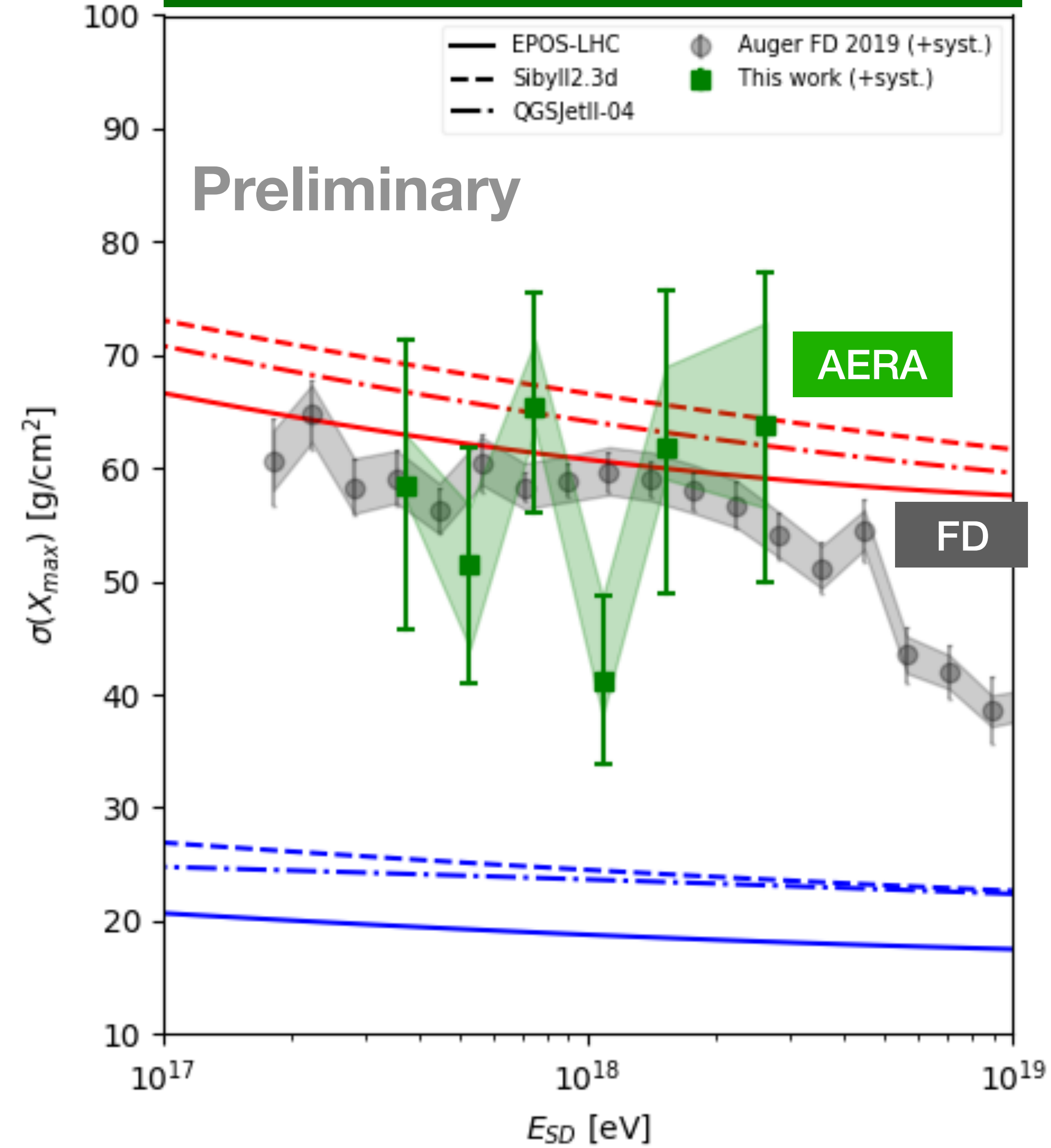
'Mean of X_{max} distribution'



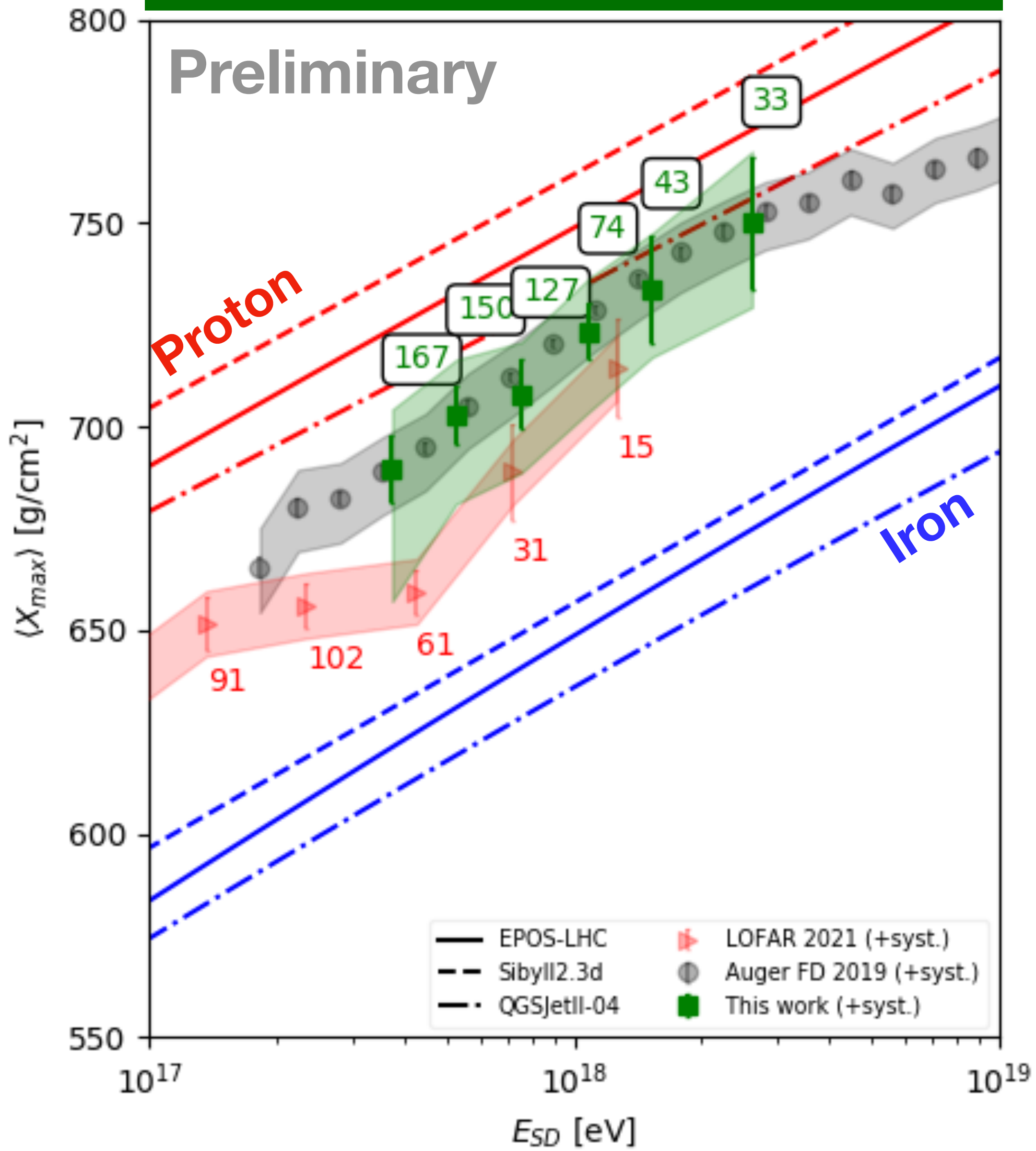
'Width of X_{max} distribution'



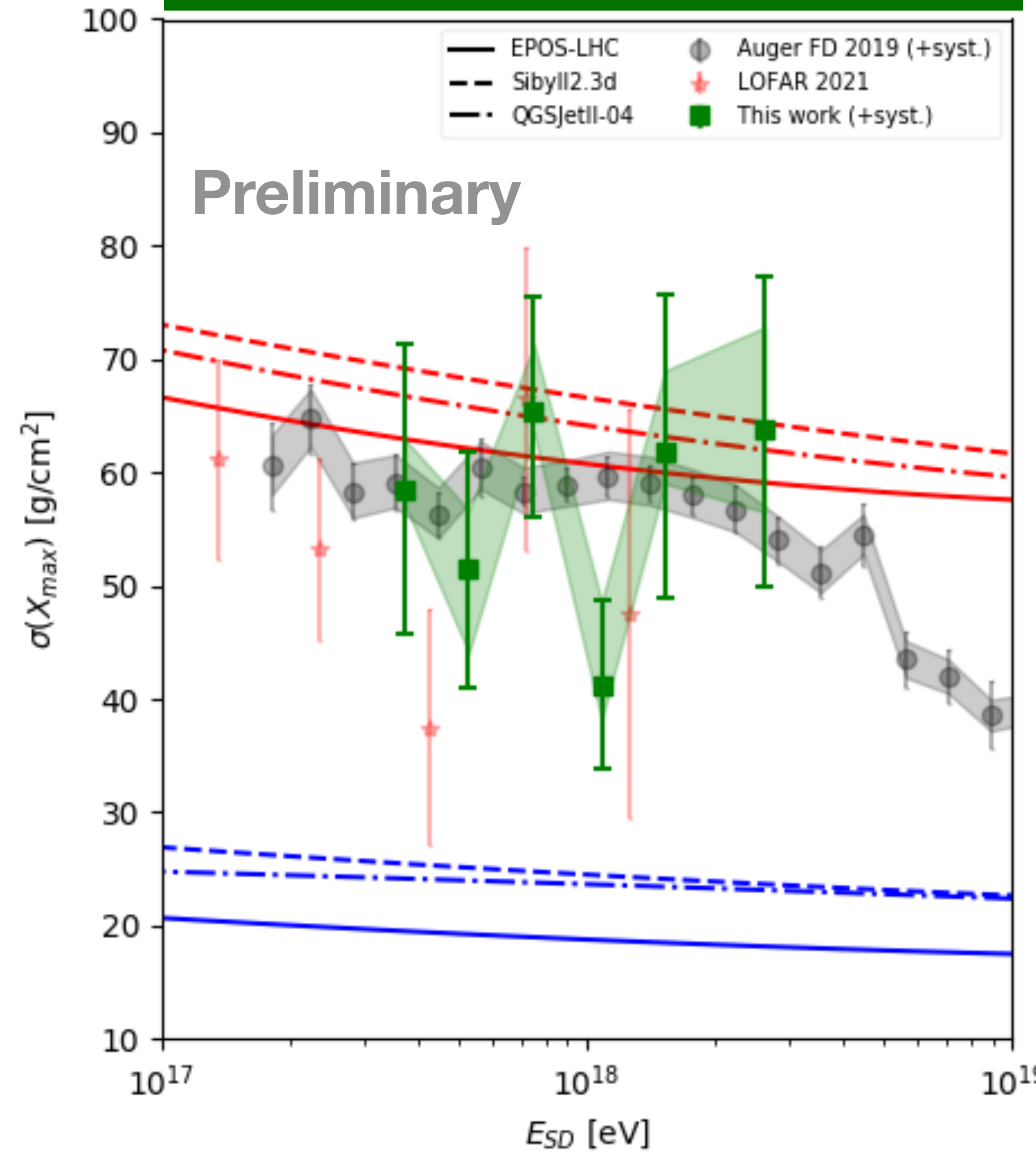
- Light composition (p-He mix) at $E=10^{17.5}$ eV, becoming lighter (mostly p) towards $E=10^{18.5}$ eV.
- Supports e.g. Auger FD (in mean, width, and general shape of X_{max} distribution).

Results: Measured AERA X_{max} distribution

'Mean of X_{max} distribution'

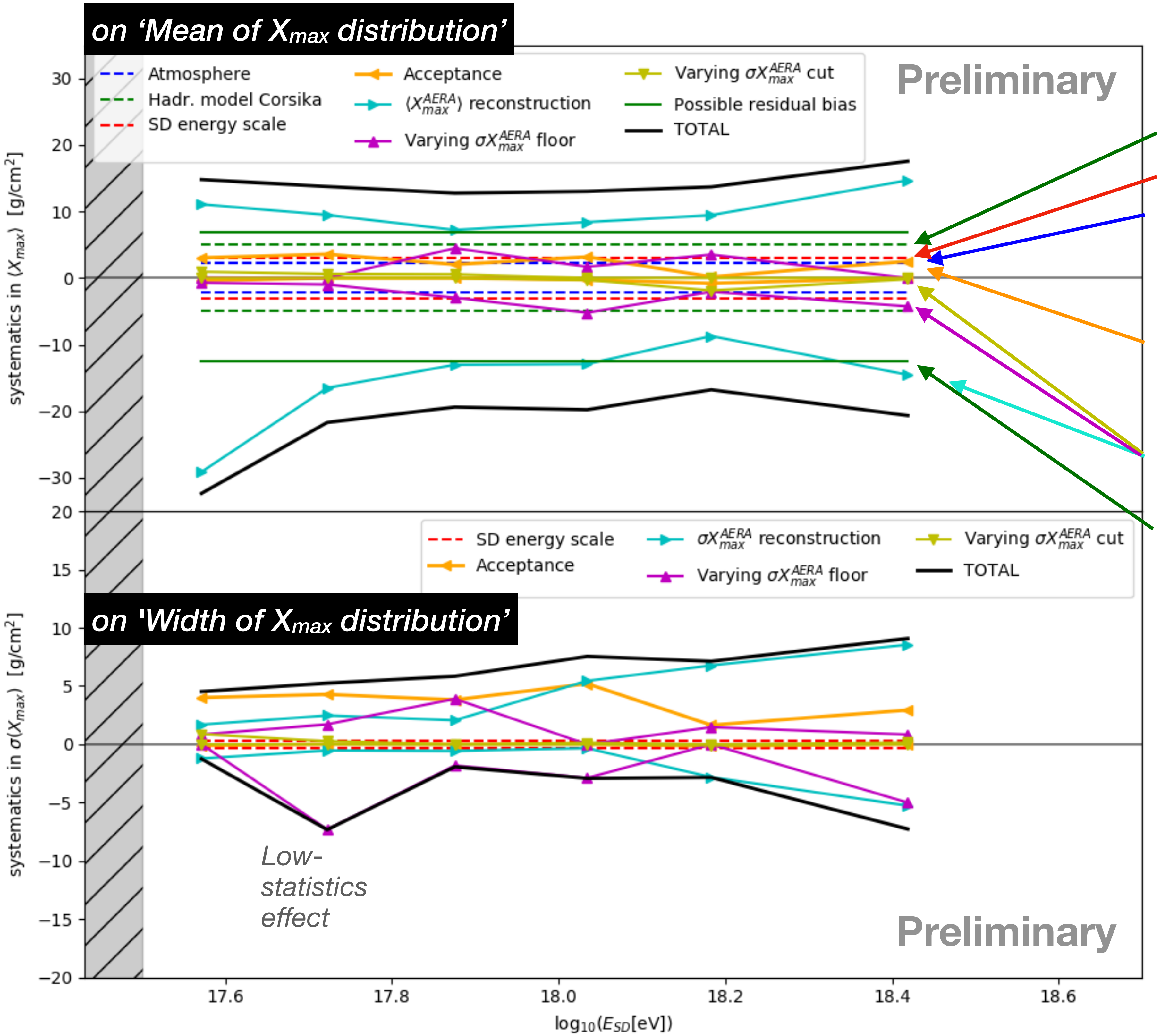


'Width of X_{max} distribution'



- No general 'radio-bias' w.r.t. other methods such as fluorescence.
- Study of systematic uncertainties similar to LOFAR.
  - Cross-checks have not found single simple cause.
  - Differences to be found in study of systematic uncertainties.
  - Physical origin difficult to propose.

Results: Systematic uncertainties on AERA X_{max}



General systematic uncertainties

- CORSIKA hadr. model.
- Auger energy scale
- Atmosphere

Method/data systematics

- Selection bias/Acceptance
  Evaluated using reconstruction of simulated showers.
- X_{max}-method bias
  Evaluated using reconstruction of simulated showers.
- Possible residual bias
  Quantified possible residual trends in X_{max} vs geometry (shower core position, azimuth angle, and zenith angle).

Note:
mass-dependent terms (acceptance & method bias) are estimated conservatively. Possible to reduce them with further study.

Take home messages

Conclusions:

1. Developed an improved method to reconstruct X_{max} with AERA.
    - Can account for sparse and irregular radio arrays.
    - Method applicable to other arrays.

2. AERA X_{max} systematic uncertainties quantified.
    - Data-driven method applicable to other arrays.—> way to study discrepancies.

3. Competitive AERA X_{max} resolution, following ~1/sqrt(E).
    - Should be considered when quoting/interpreting single resolution values.

4. AERA X_{max} compatible with Auger Fluorescence on event-to-event basis.
    - Independent support to our understanding of shower physics.

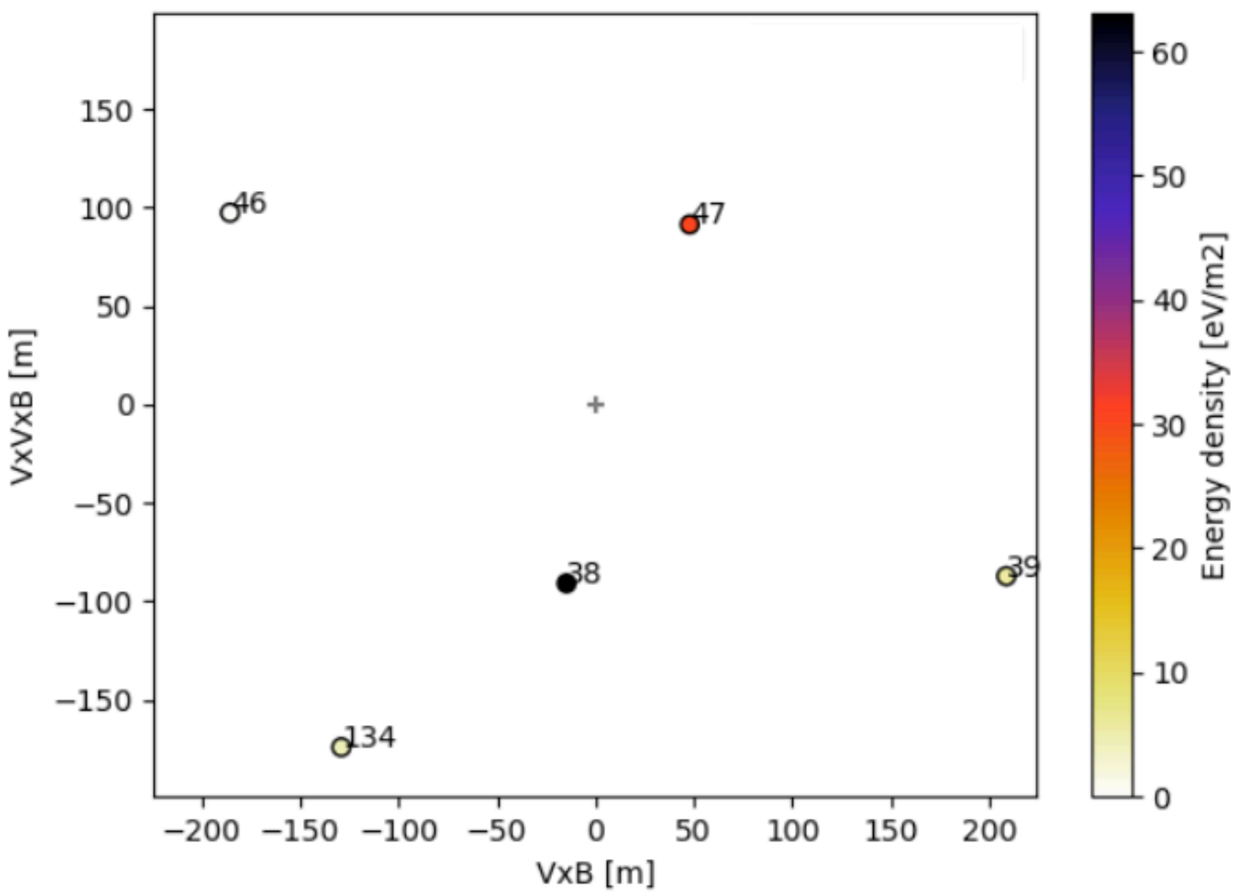
5. AERA mass composition supports light (mixed) composition in *transition region*.
    - In agreement with with full Auger FD dataset.
    - No hints of general radio-X_{max}-specific bias.
    - Stresses the need for careful systematic uncertainty study.

Backup

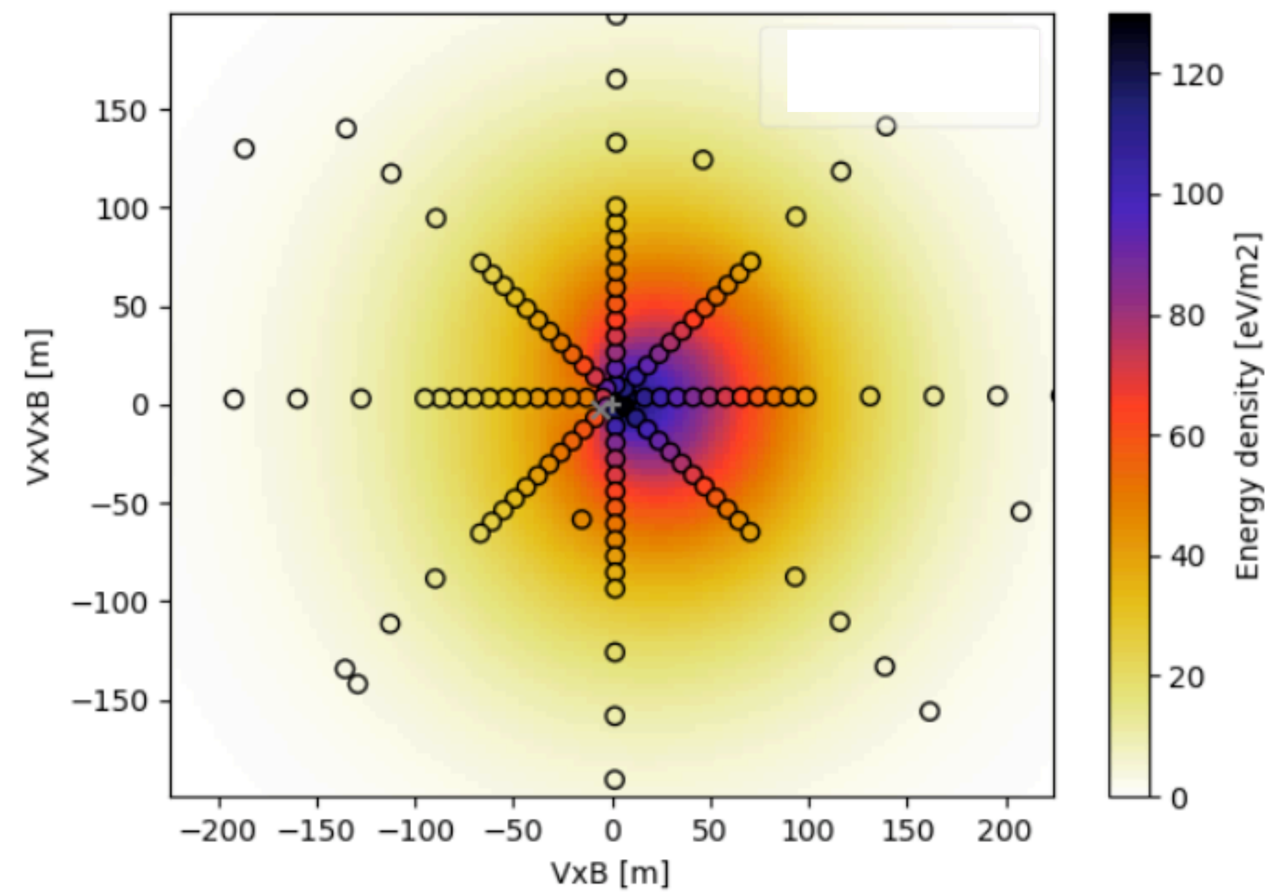
Method: Xmax from data-sim matching

Step 1/3) comparing measured AERA signals to simulated and Offline-reconstructed signal.

measured AERA event: signals in shower plane



Simulated stations (+ signal interpolation)



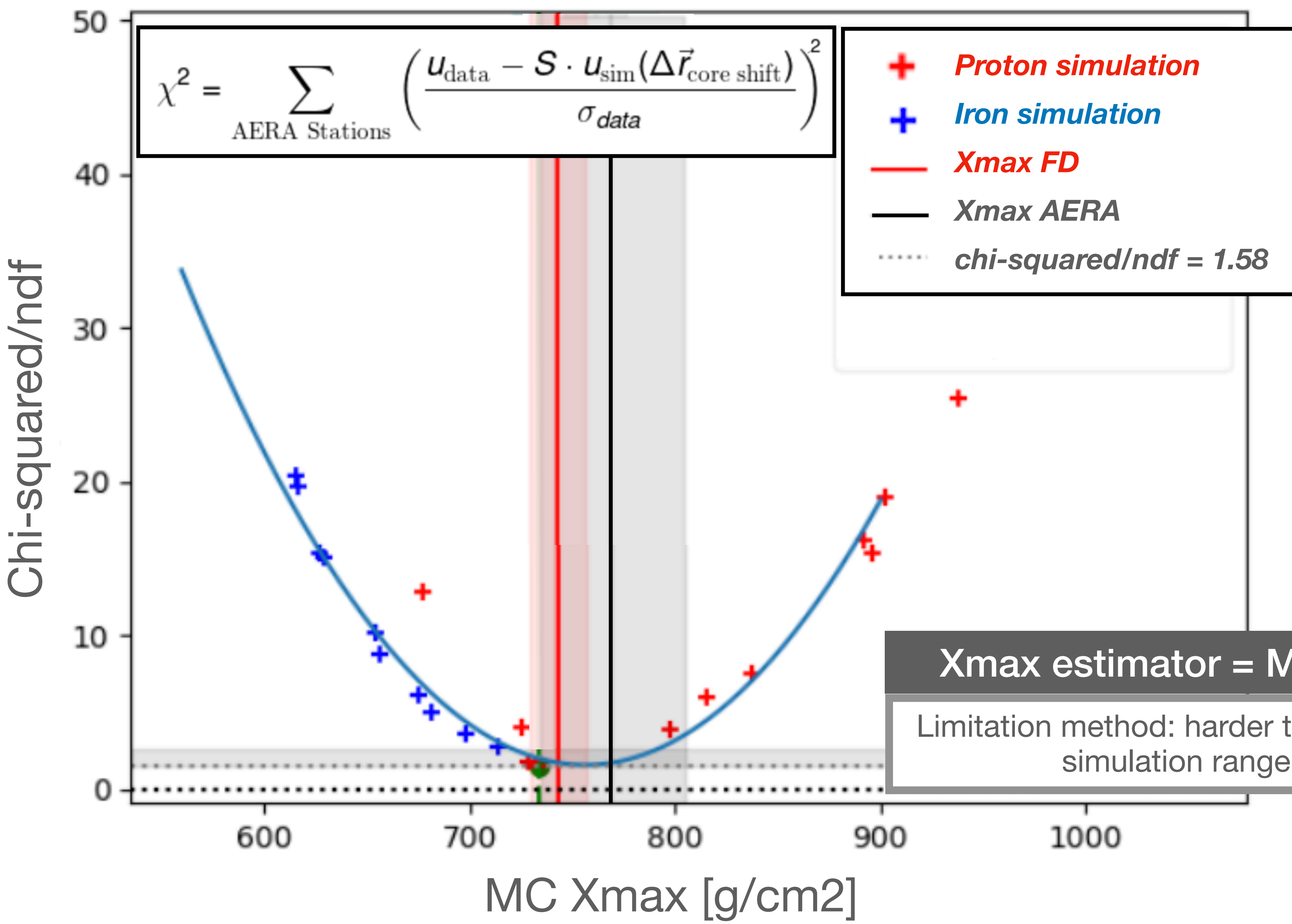
Compare with: Chi-squared of energy density (u); allowing core shift (Δr) and energy shift (S):

$$\chi^2 = \sum_{\text{AERA Stations}} \left(\frac{u_{\text{data}} - S \cdot u_{\text{sim}}(\Delta\vec{r}_{\text{core shift}})}{\sigma u_{\text{data}}} \right)^2$$

u **:** *energy density [ev/m2]*
S **:** *scale factor for syst. & SD energy uncertainty*
Δr **:** *shift for AERA core uncertainty*

Method: Xmax from data-sim matching

Step 2/3) Chi-squared minimisation procedure with free *core shift (Δr)* and *Energy scaling (S)*
Fit parabola around the minimum. *(based on 'Lofar method'. Buitink et al. 2014)*



Xmax estimator = MC Xmax at parabola minimum

Limitation method: harder to reconstruct Xmax near the edge of the simulation range —> estimator is not bias free

Method: Xmax from data-sim matching

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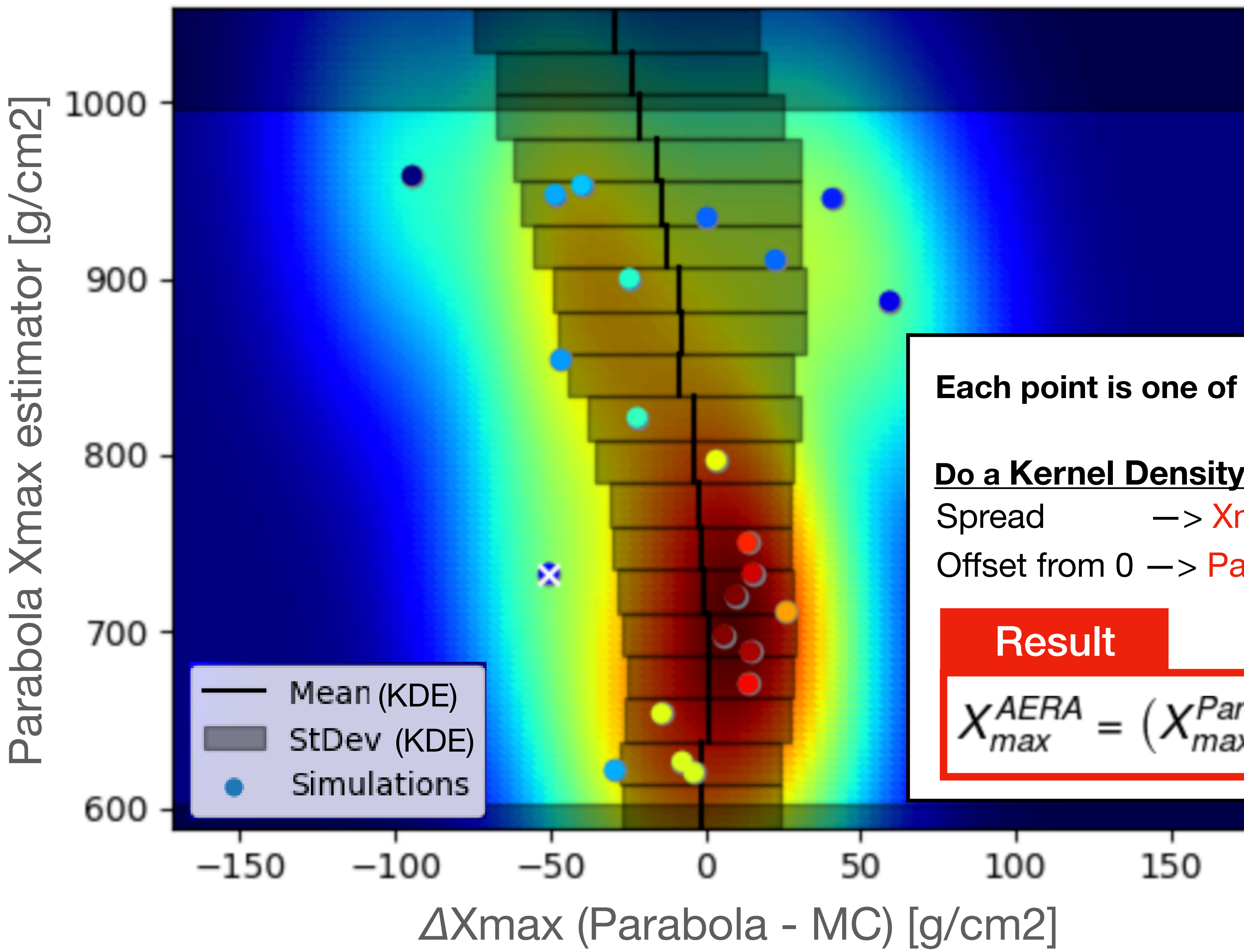
Step 3/3) Q: "How well can the method reconstruct MC truth for this event?"
Error estimation and *Parabola-bias estimator* from reconstruction of each of the 10Fe+15p simulations (*including measured Noise*) just like data would be reconstructed.



Each point is one of 10Fe+15p simulations reconstructed.

<u>Do a Kernel Density Estimator:</u>

Spread —> Xmax uncertainty estimator σX_{max}^{KDE}

Offset from 0 —> Parabola-Xmax-bias correction ΔX_{max}^{KDE}

Result

$$X_{max}^{AERA} = \left(X_{max}^{Parabola} + \Delta X_{max}^{KDE}\right) \pm \sigma X_{max}^{KDE}$$

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