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

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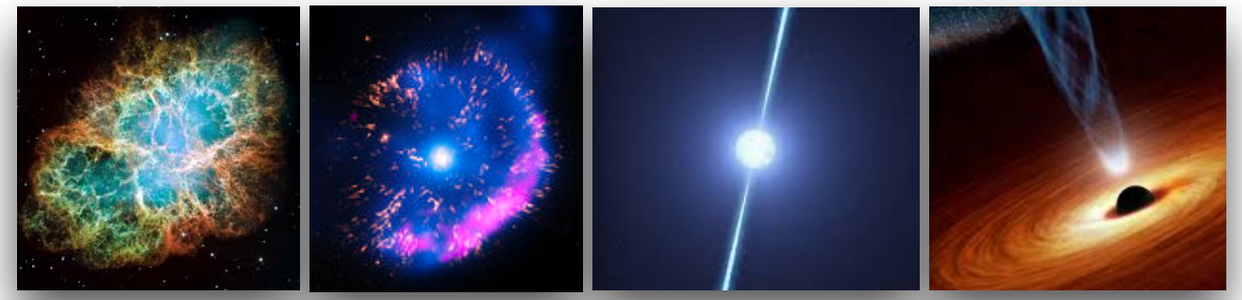
# In this talk

- **Goal:** Measure cosmic-ray mass composition (p, He, …, Fe, …)

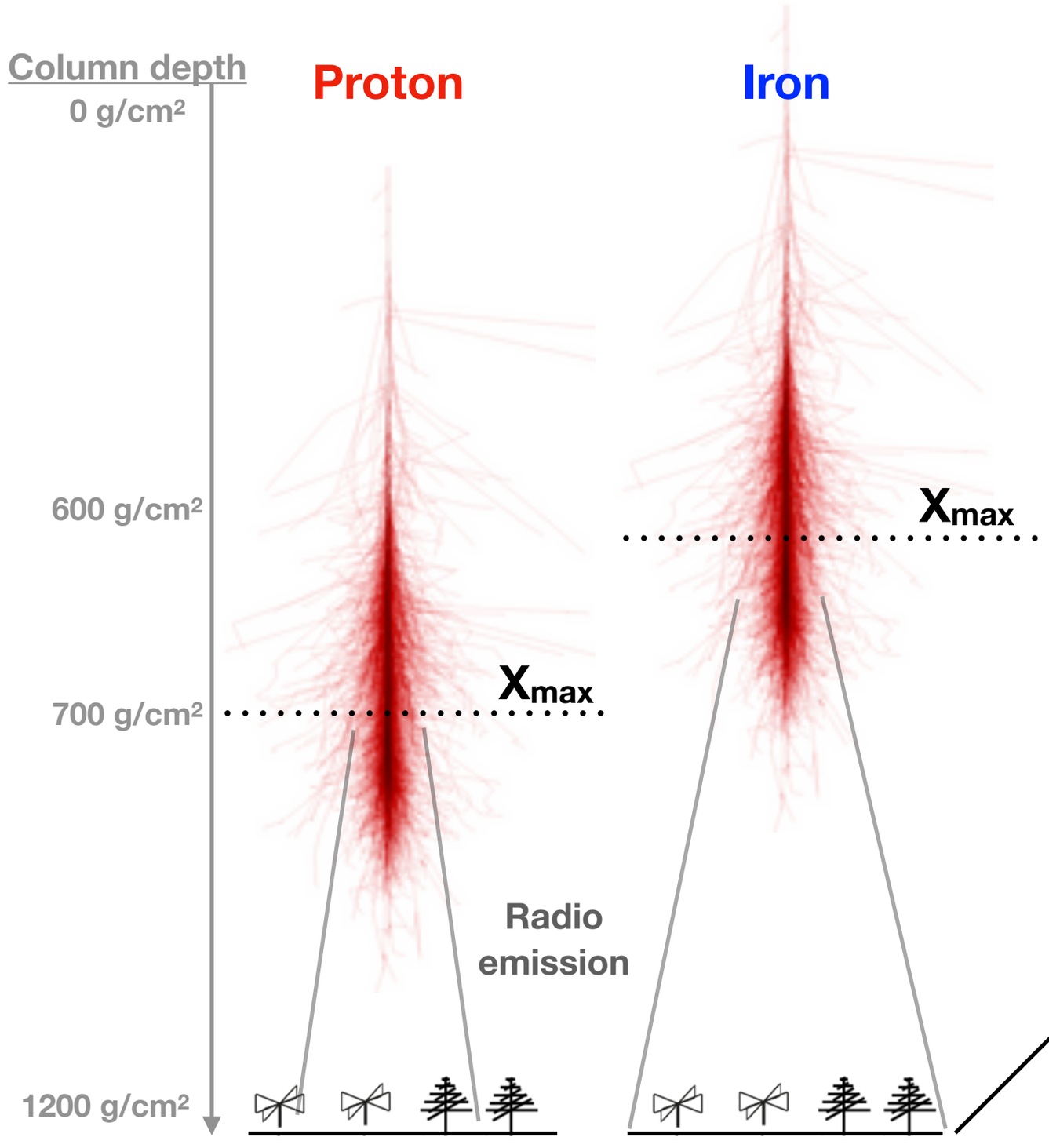
- **Motivation:** Mass composition <—> sources of cosmic rays at transition between Galactic and extra Galactic (~$10^{17-19}$eV)



Contents:

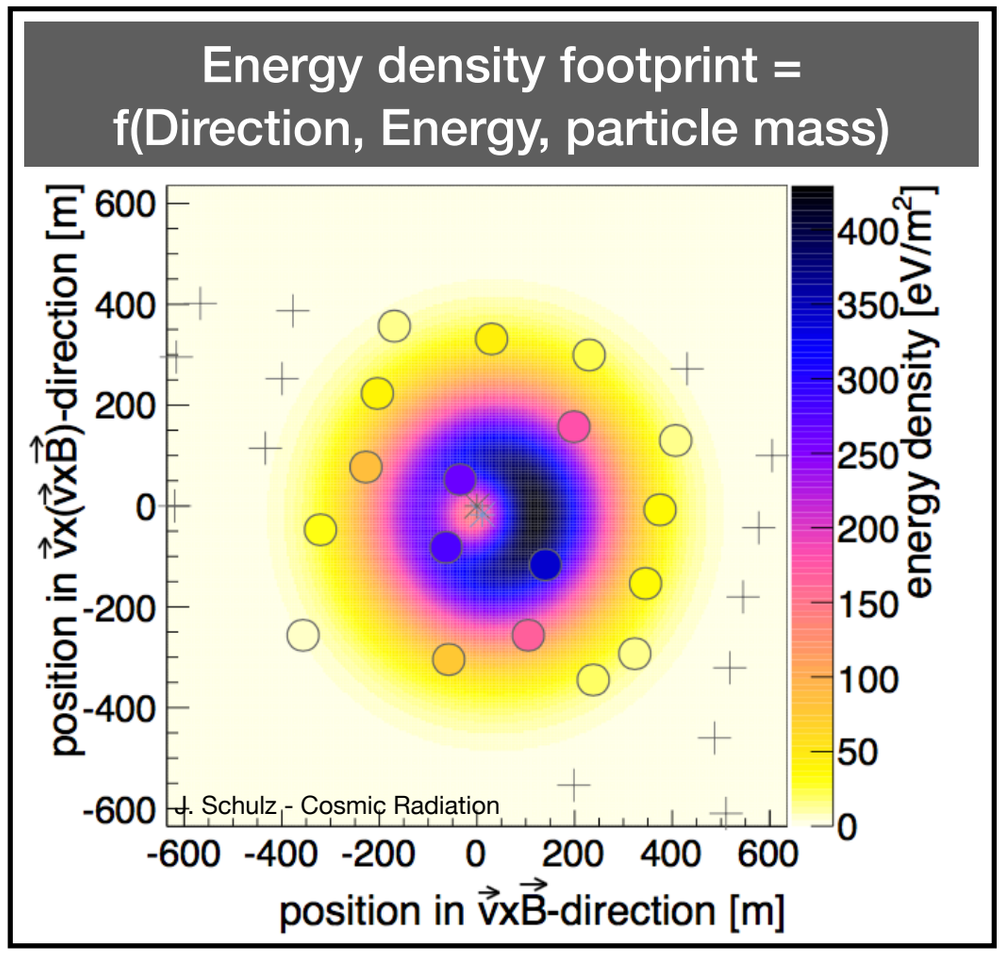
- **Introduction**: *mass sensitivity & AERA*
- **Method**: *Matching air shower simulations to measured radio signals*
- **Results**:
  - *Hybrid Radio-Fluorescence measurements* —> *unique cross-check*
  - *Method resolution* —> *competitive technique*
  - *Moments of the $X_{max}$ distribution* —> *compatible*

# Introduction: Radio footprint is sensitive to mass

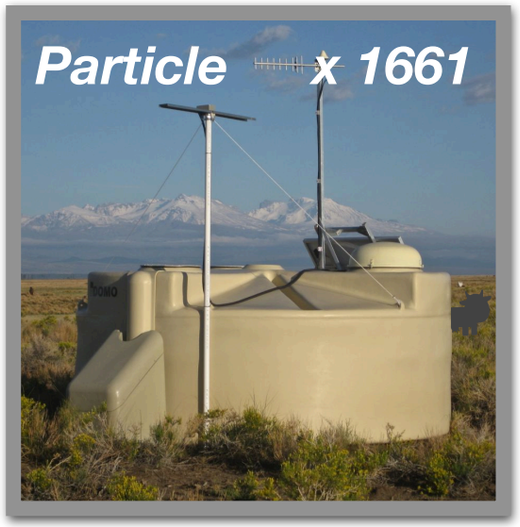


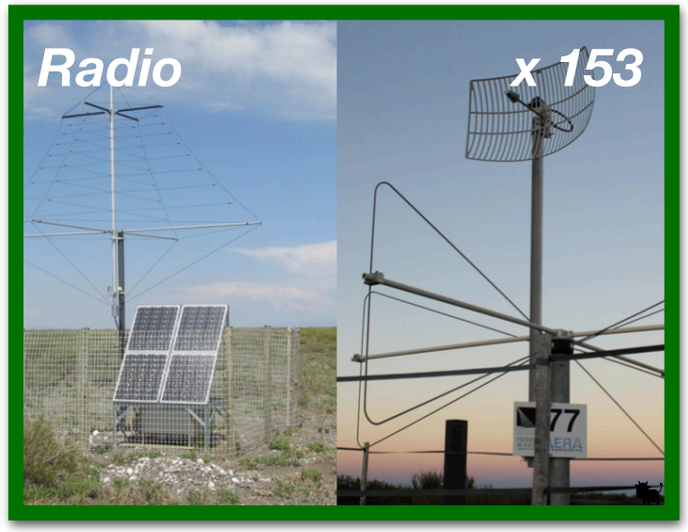

- $X_{max}$ [g/cm²]: *column depth* where *Extensive Air Shower* is maximally developed.
  —> $X_{max}$ depends on mass (particle type)

- Shape of radio footprint changes with $X_{max}$
  —> Radio footprint is probe for $X_{max}$.



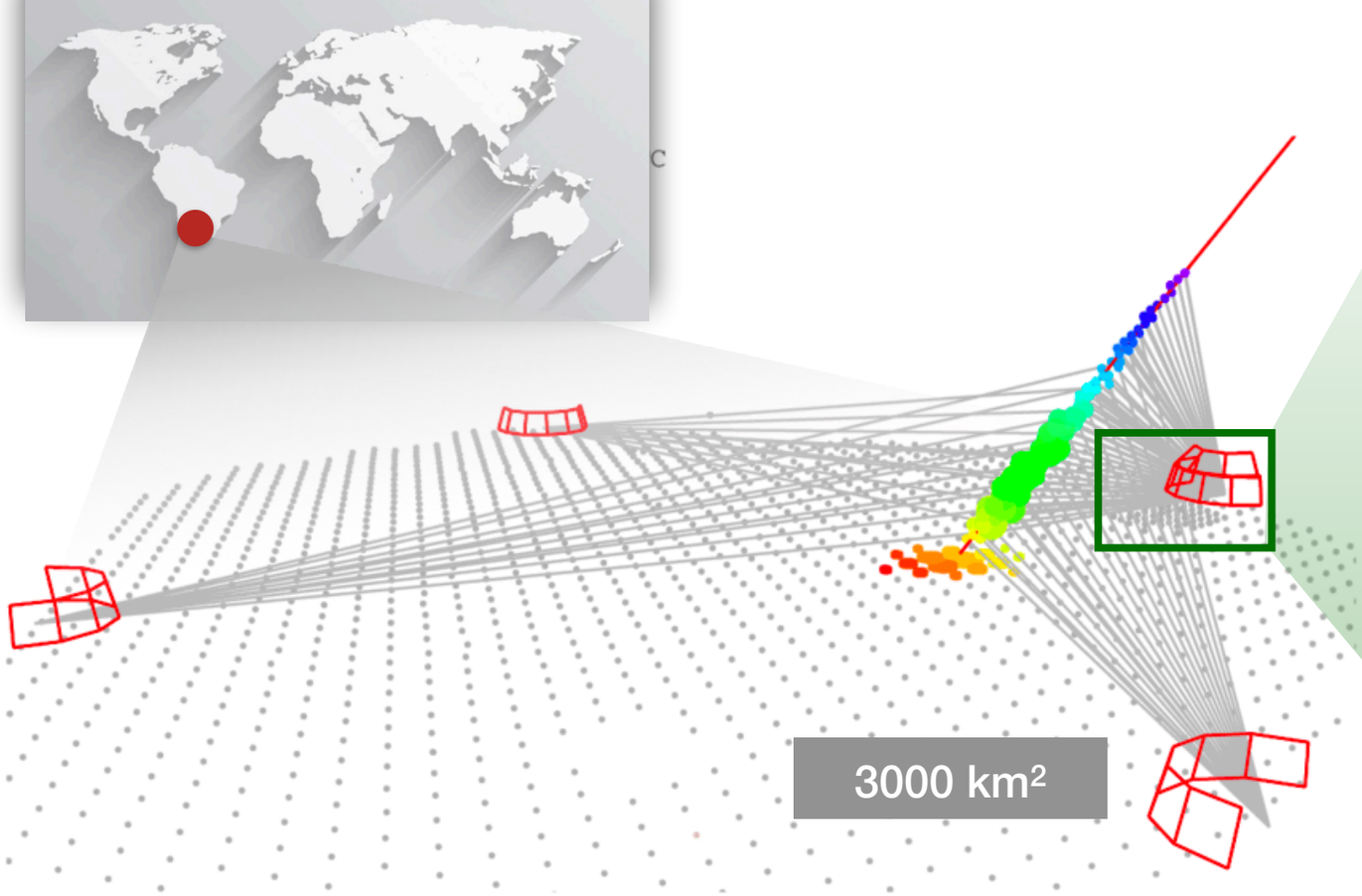
# Introduction: AERA at the Pierre Auger Observatory

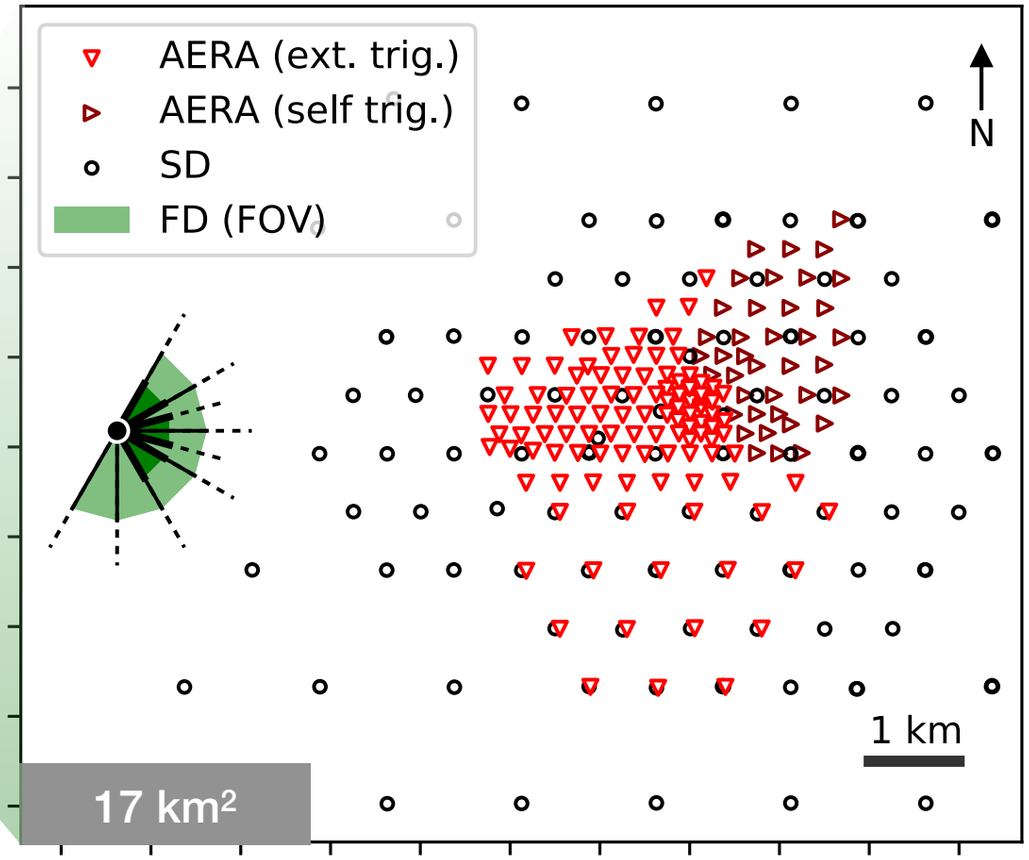



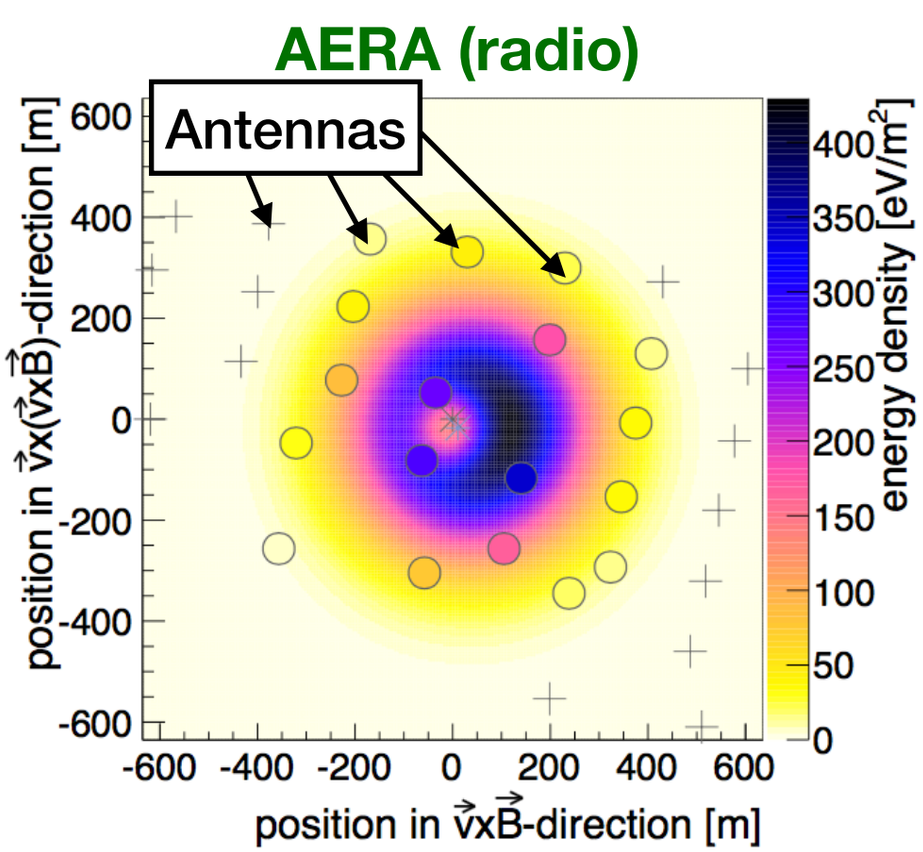

Auger Engineering Radio Array

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

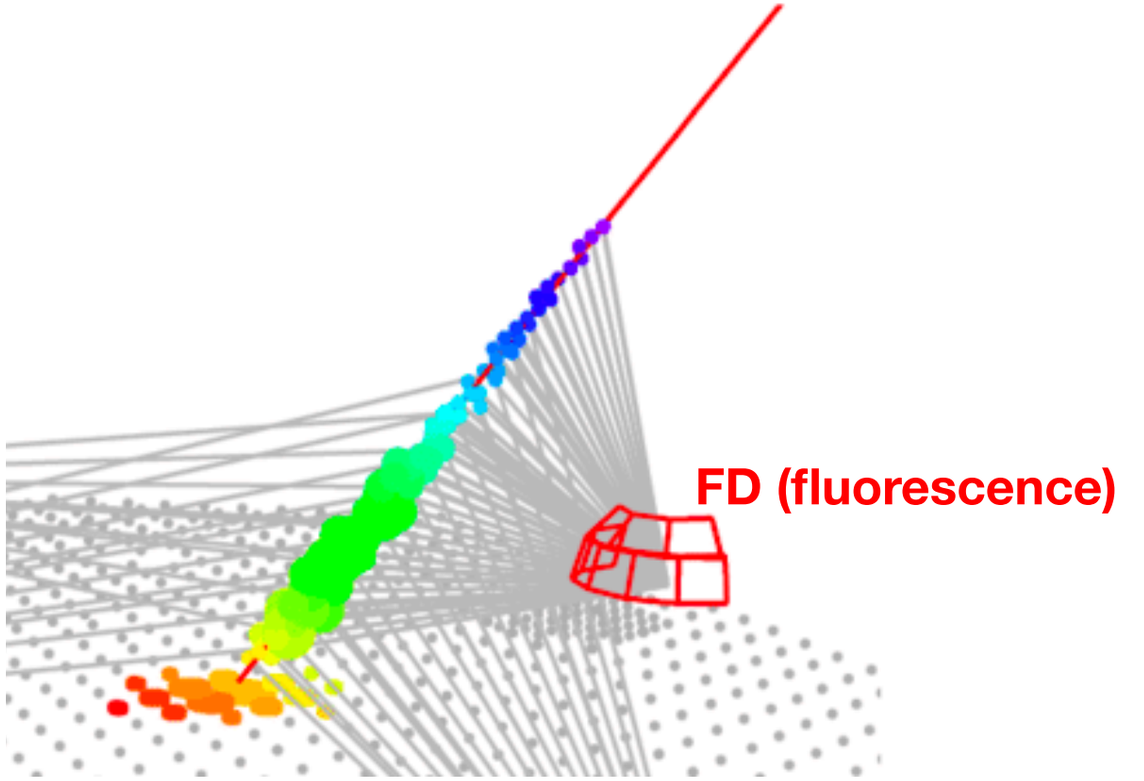


# Introduction: Our data set — "getting the most out of Auger"




+




7 years of AERA data for $X_{max}$ analysis:

- ~600 high-quality showers after anti-bias and reconstruction cuts (E=$10^{17.5}$ to $10^{18.8}$ eV)
- Each also has shower energy from SD
- 53 hybrid showers with independent FD and AERA reconstructions of $X_{max}$

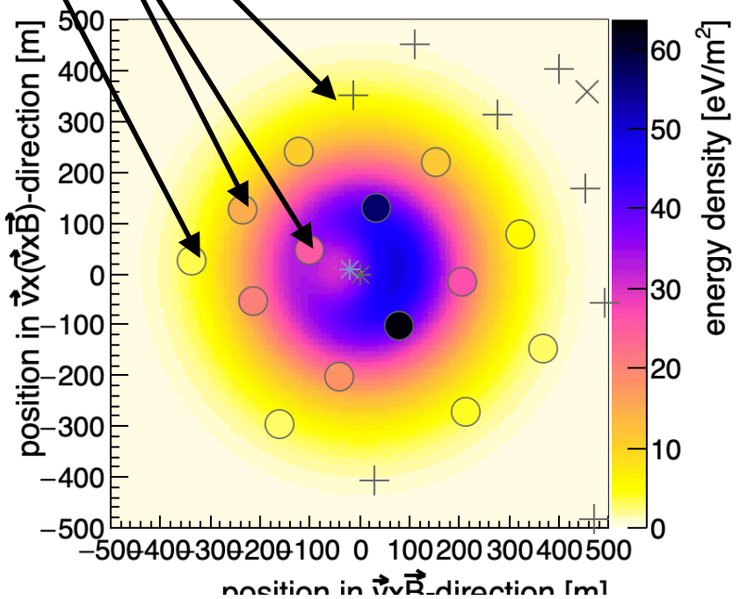
# Method: Reconstructing $X_{max}$ from the radio footprint

**Reconstruction Air Shower**

$E_{SD}$, θ, ϕ, …

Antennas

**Measured**



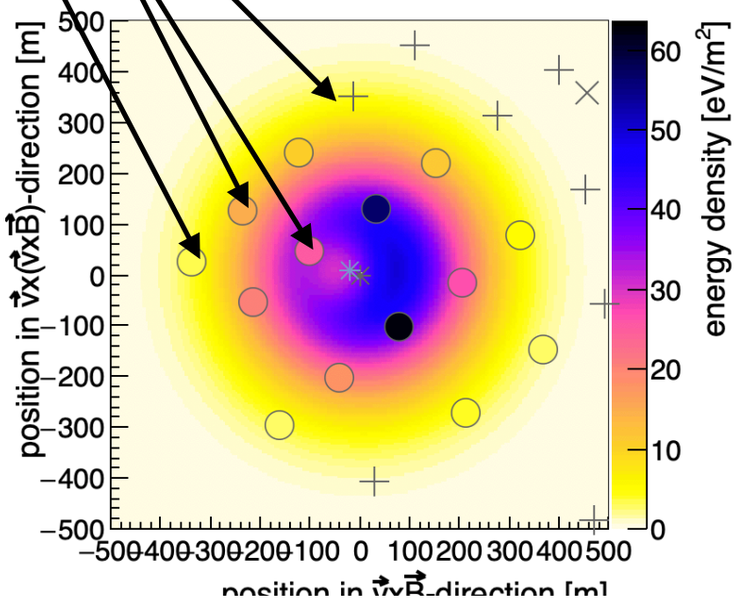
# Method: Reconstructing $X_{max}$ from the radio footprint

Reconstruction Air Shower → CORSIKA

$E_{SD}$, θ, ϕ, … {$X_{max}$}

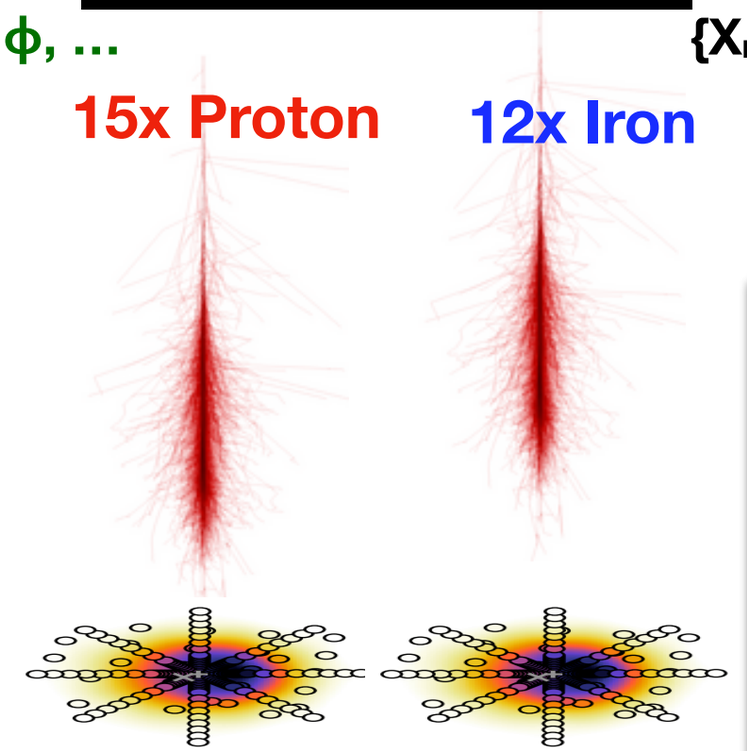
Antennas

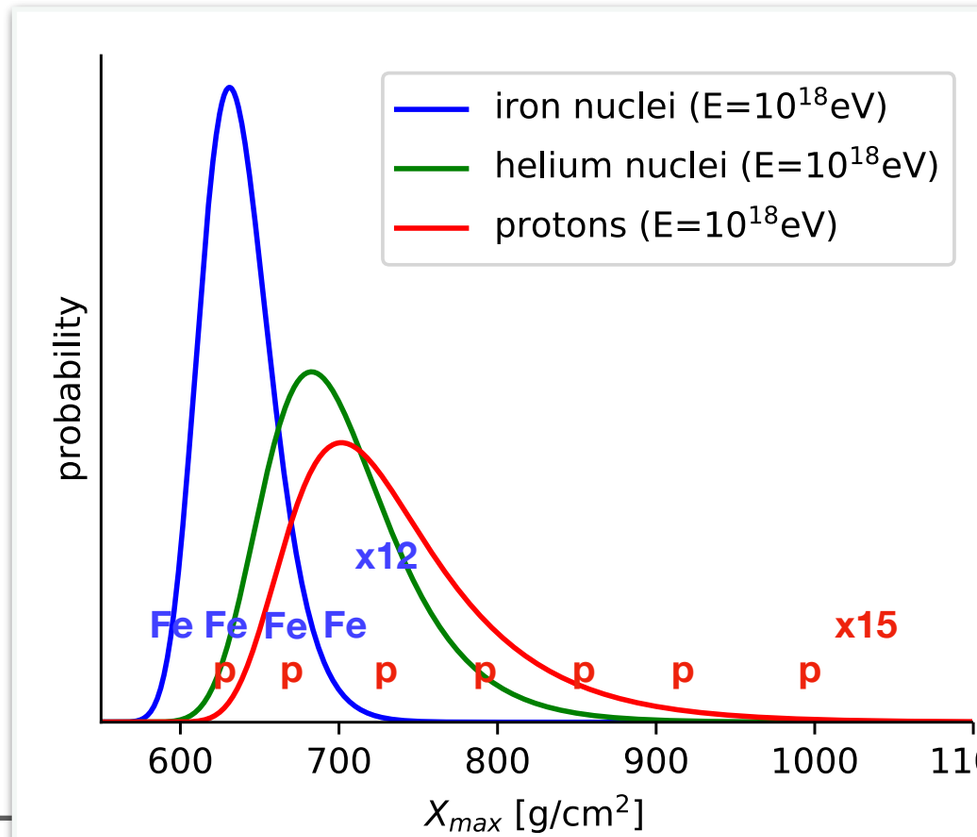
Measured




15x Proton

12x Iron






*Technical details*

- **CORSIKA** 7.71 (QGSJetII-04, UrQMD 1.3cr, CoREAS)

Event-specific setup:

- + **AERA station layout** + 240 additional '**star-shape**' stations centered around core (for interpolation)
- + **GDAS atmospheres** (**G**lobal **D**ata **A**ssimilation **S**ystem) at Auger at time of data
- + **Magnetic field** model at time of data

# Method: Reconstructing $X_{max}$ from the radio footprint

Reconstruction Air Shower → CORSIKA → Reconstruction Simulations

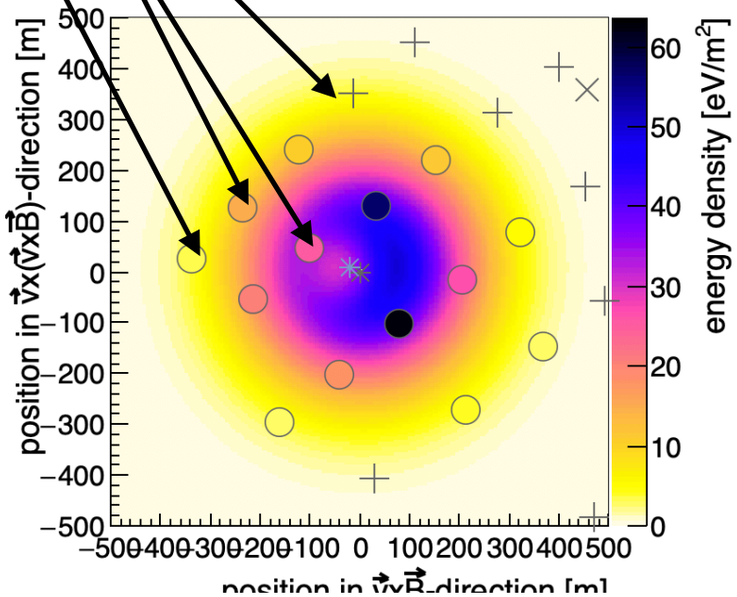
$E_{SD}$, θ, ϕ, …

{$X_{max}$}

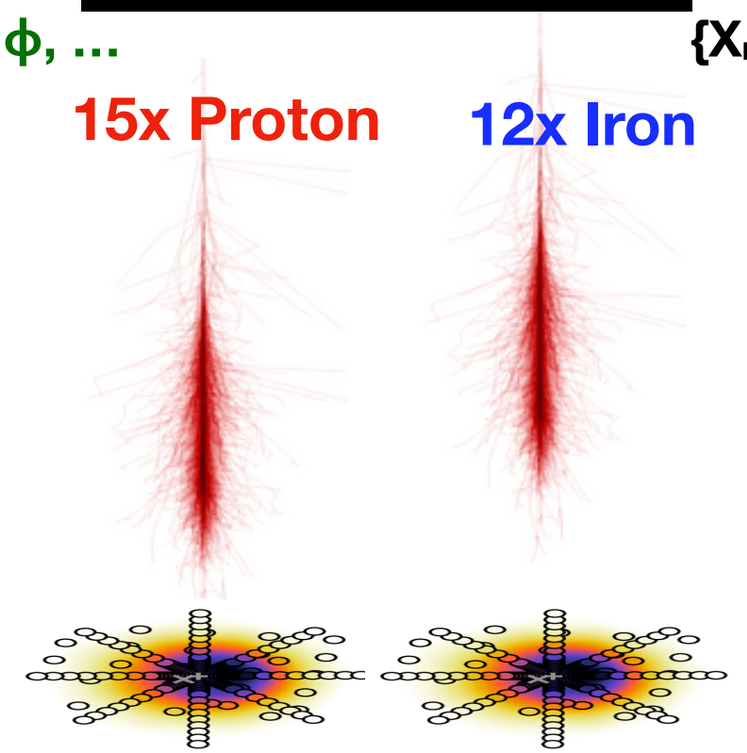
**Using same reconstruction code**
*(includes detector and reconstruction effects)*

Antennas

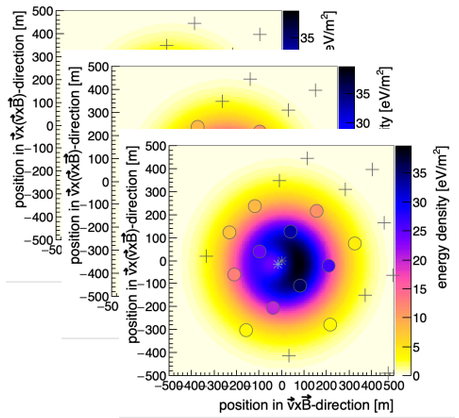
**Measured**



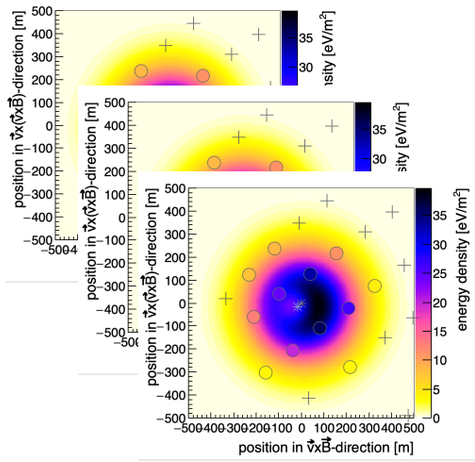

**15x Proton** **12x Iron**



**Proton**




**Iron**



# Method: Reconstructing $X_{max}$ from the radio footprint

Reconstruction Air Shower → CORSIKA → Reconstruction Simulations

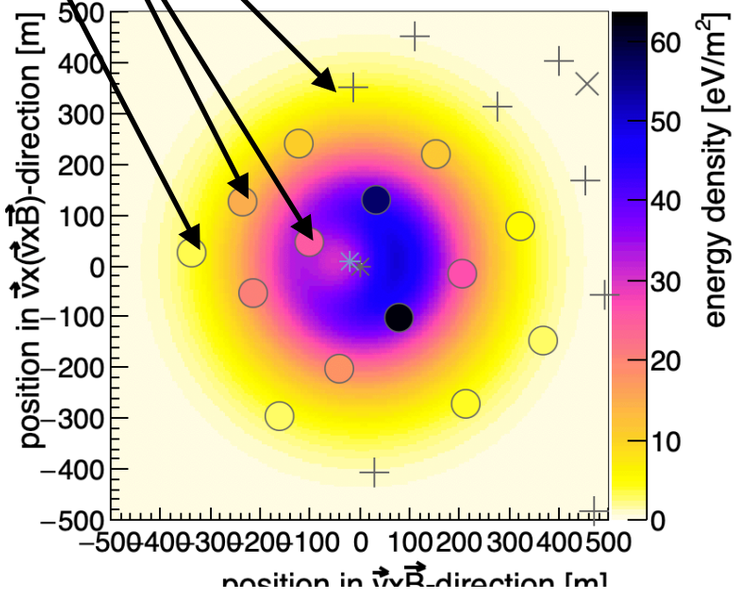
$E_{SD}$, θ, ϕ, …

$\{X_{max}\}$

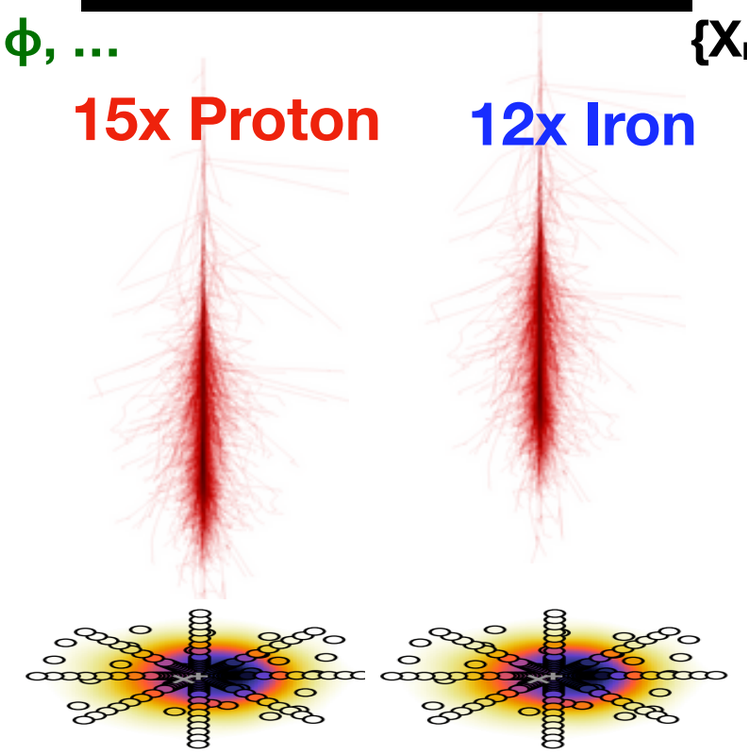
**Using same reconstruction code**
*(includes detector and reconstruction effects)*

Antennas

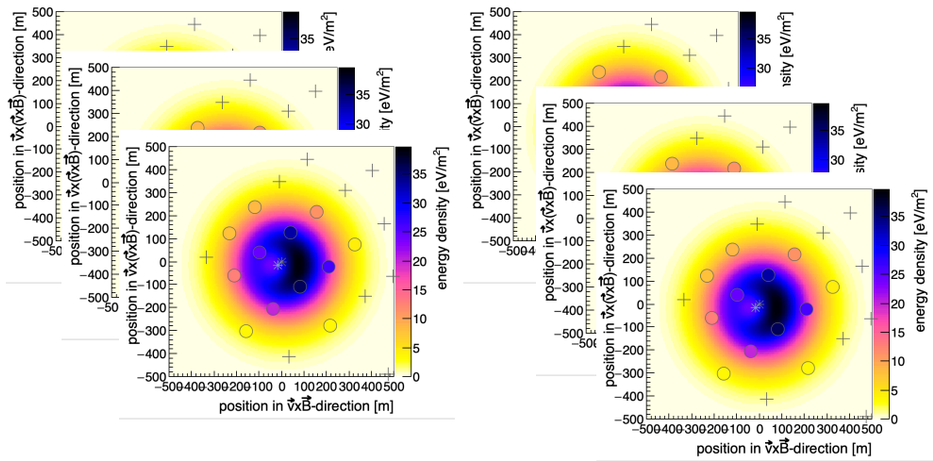
**Measured**




**15x Proton** **12x Iron**

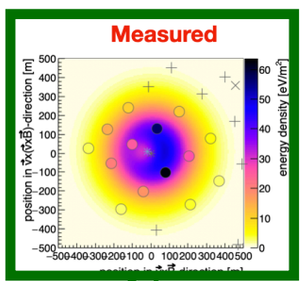


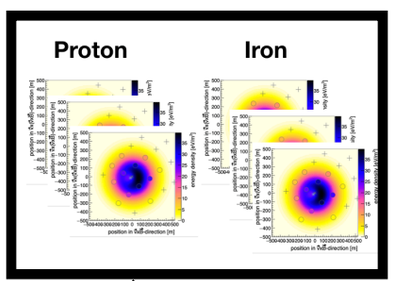
**Proton** **Iron**




## Minimise to find $X_{max}$ of measured shower:

*Based on Buitink+(2016)*

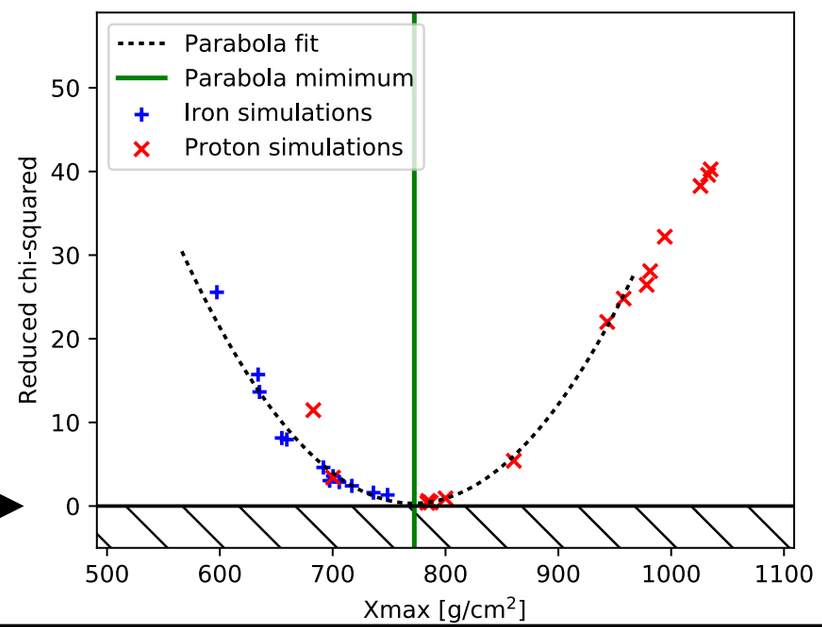



$$\chi^2 = \sum_{\text{AERA Stations}} \left( \frac{u_{\text{data}} - S \cdot u_{\text{sim}}(\Delta \vec{r}_{\text{core shift}})}{\sigma u_{data}} \right)$$

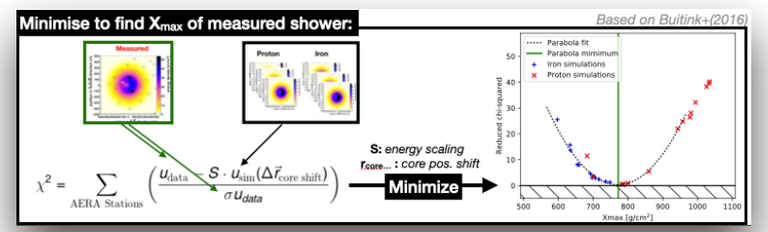
**S:** *energy scaling*
**$r_{core...}$ :** *core pos. shift*

**Minimize** →



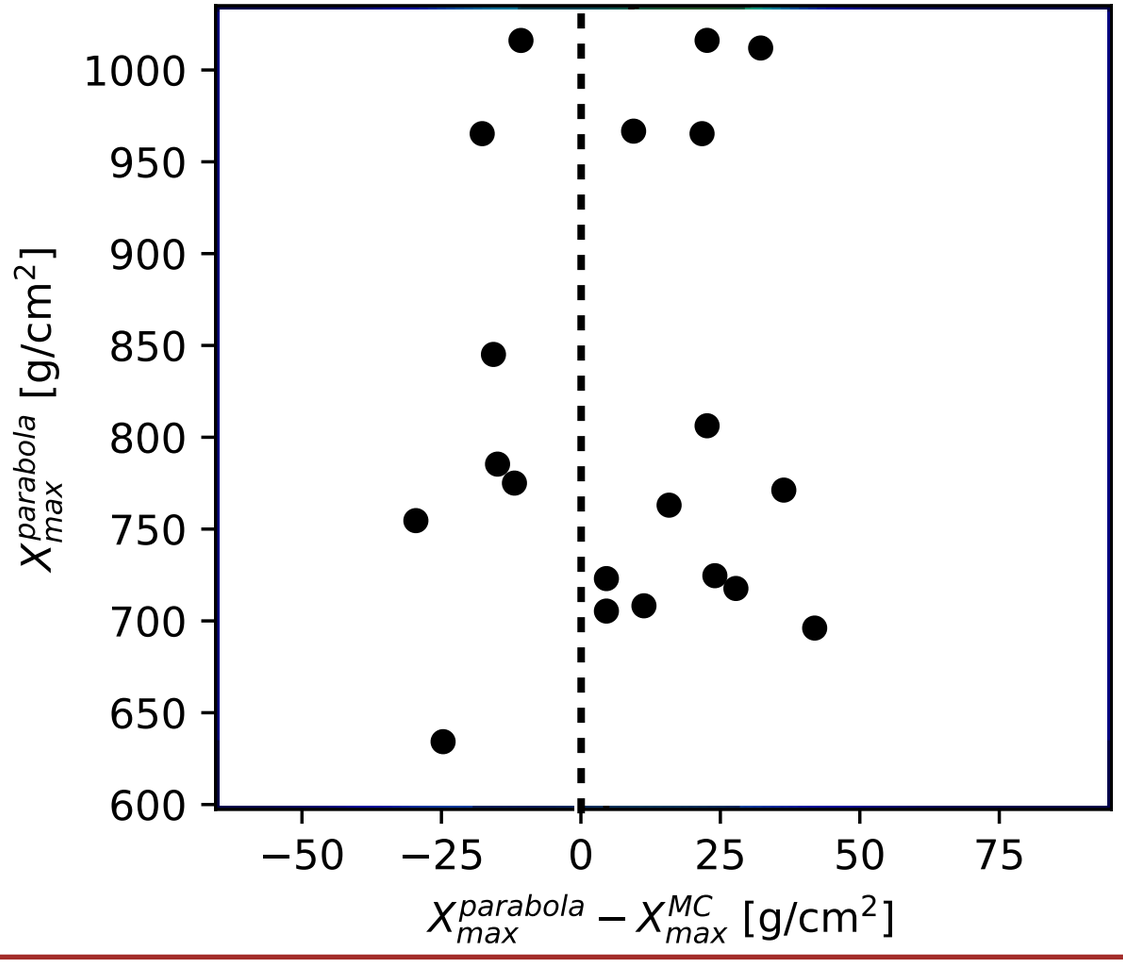
# Method: Bias correction on the parabola-$X_{max}$

- Step 2 — **bias correction per event:**
  Reconstruct $X_{max}$ for each simulation with *leave-one-out cross validation.*




**—> {Parabola vs MC} values of all 15+12 simulations:**
Allows to correct for bias & estimate σ$X_{max}$ at any parabola-Xmax value; (KDE model)

*For simulations of a single measured event*




- *Points are the simulations*

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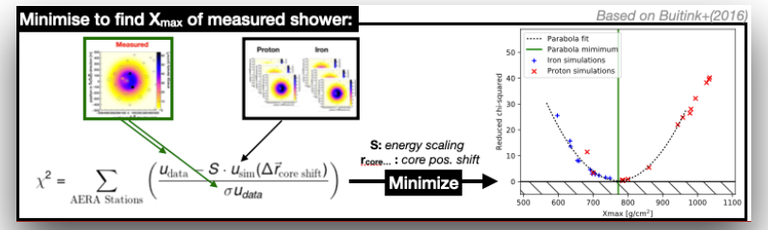


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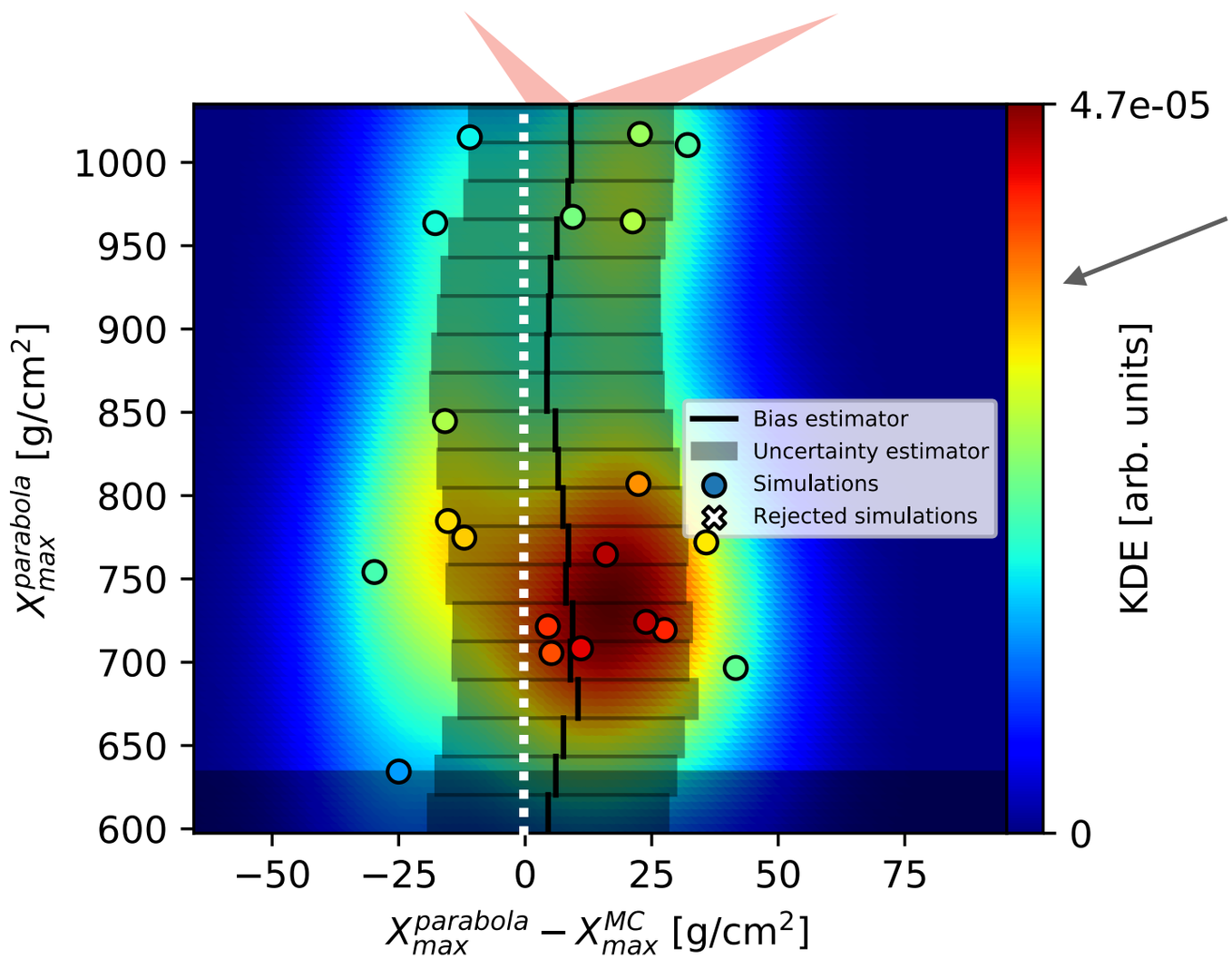
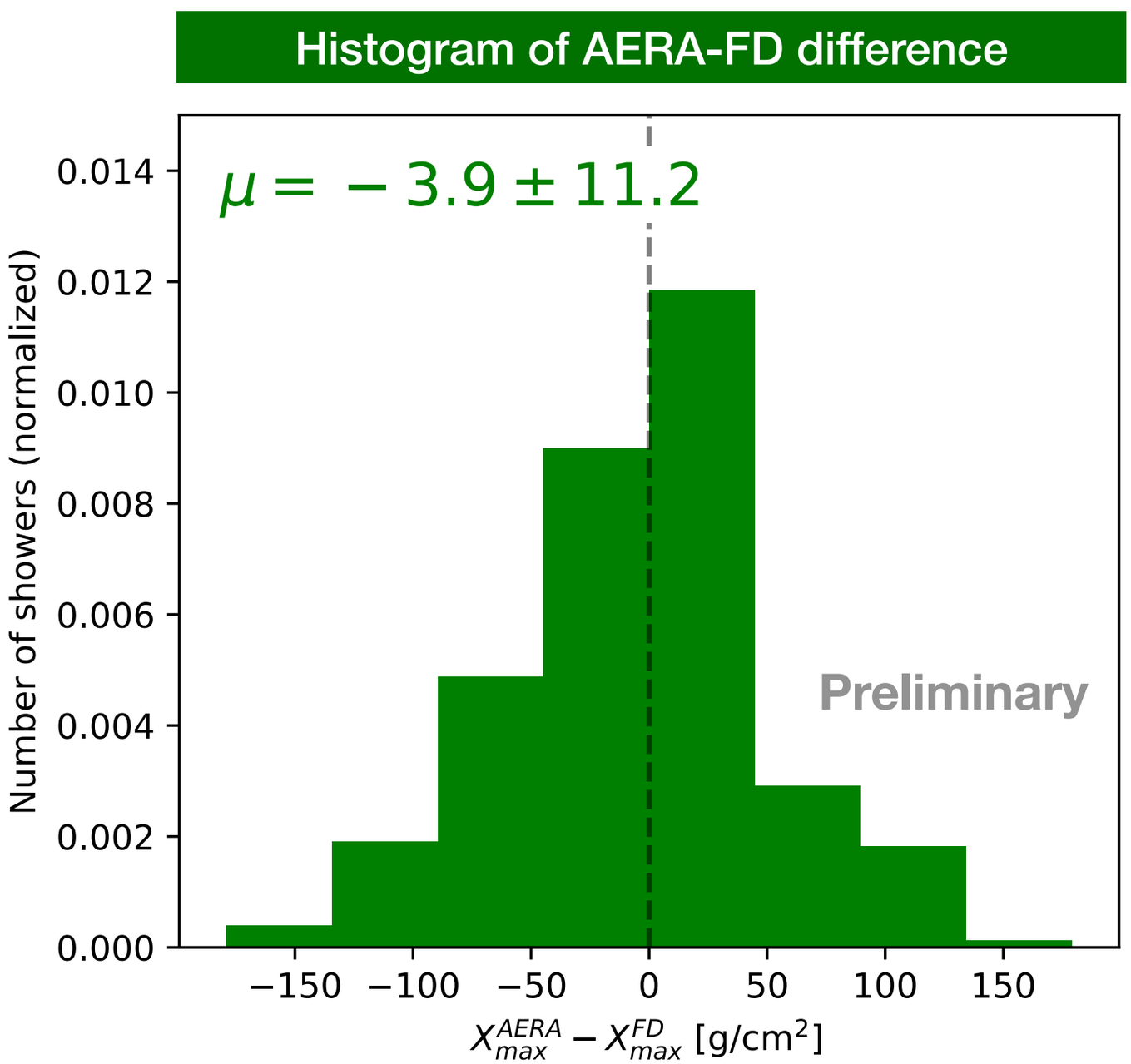
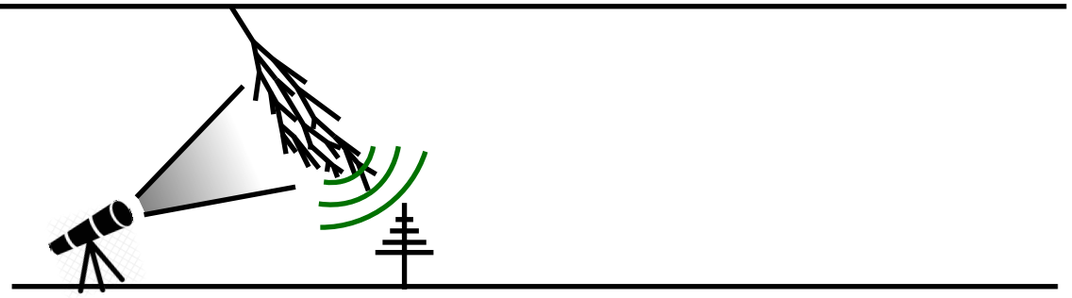



- *Points are the simulations*
- *Background is 2d-KDE of that*
- *Black region: extracted 1σ bias and uncertainty model of KDE*

**<— Such a bias-model is created for every measured shower!**

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



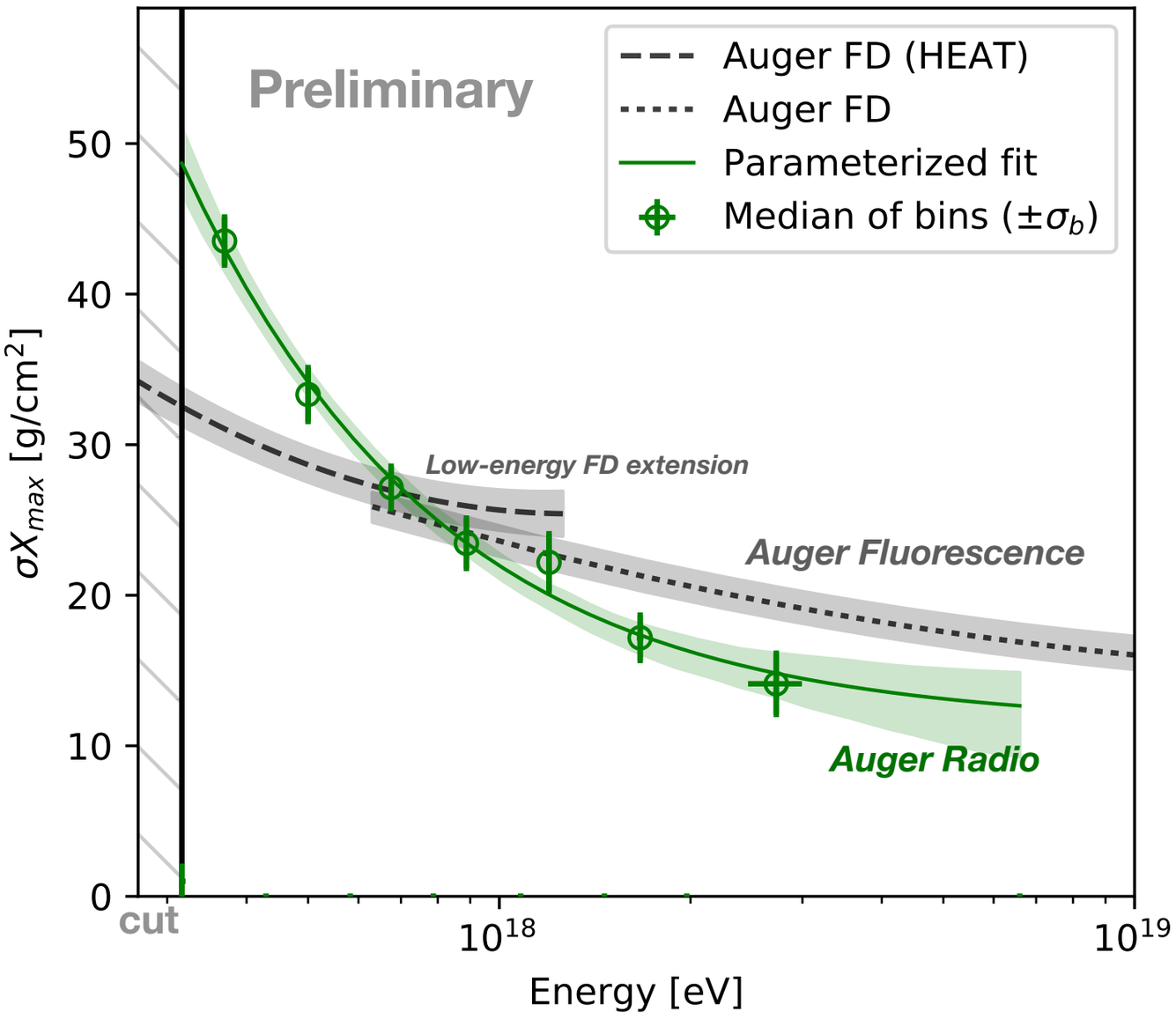



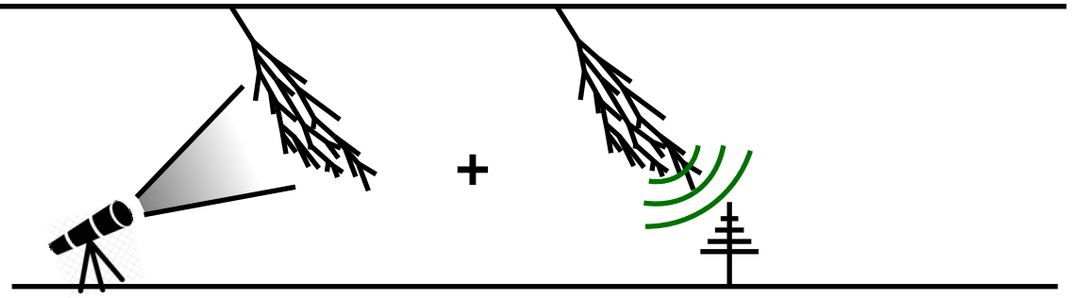
**Auger has unique Radio-Fluorescence setup:**

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

# Results: Resolution of AERA $X_{max}$ method

## Radio $X_{max}$ resolution



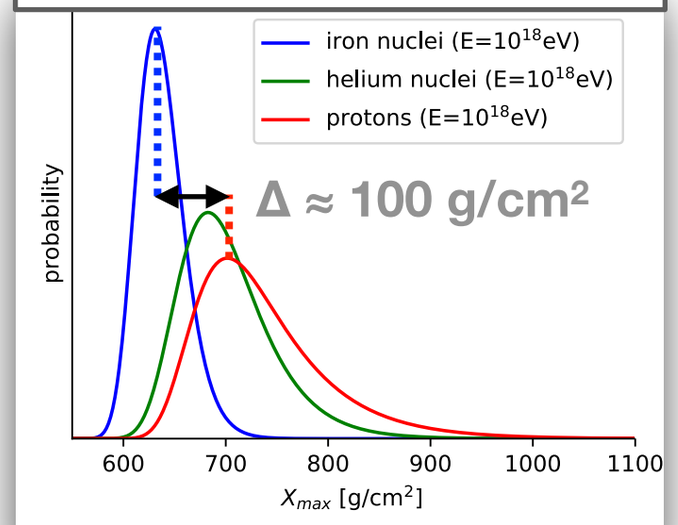
Resolution improves with energy.

- 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]

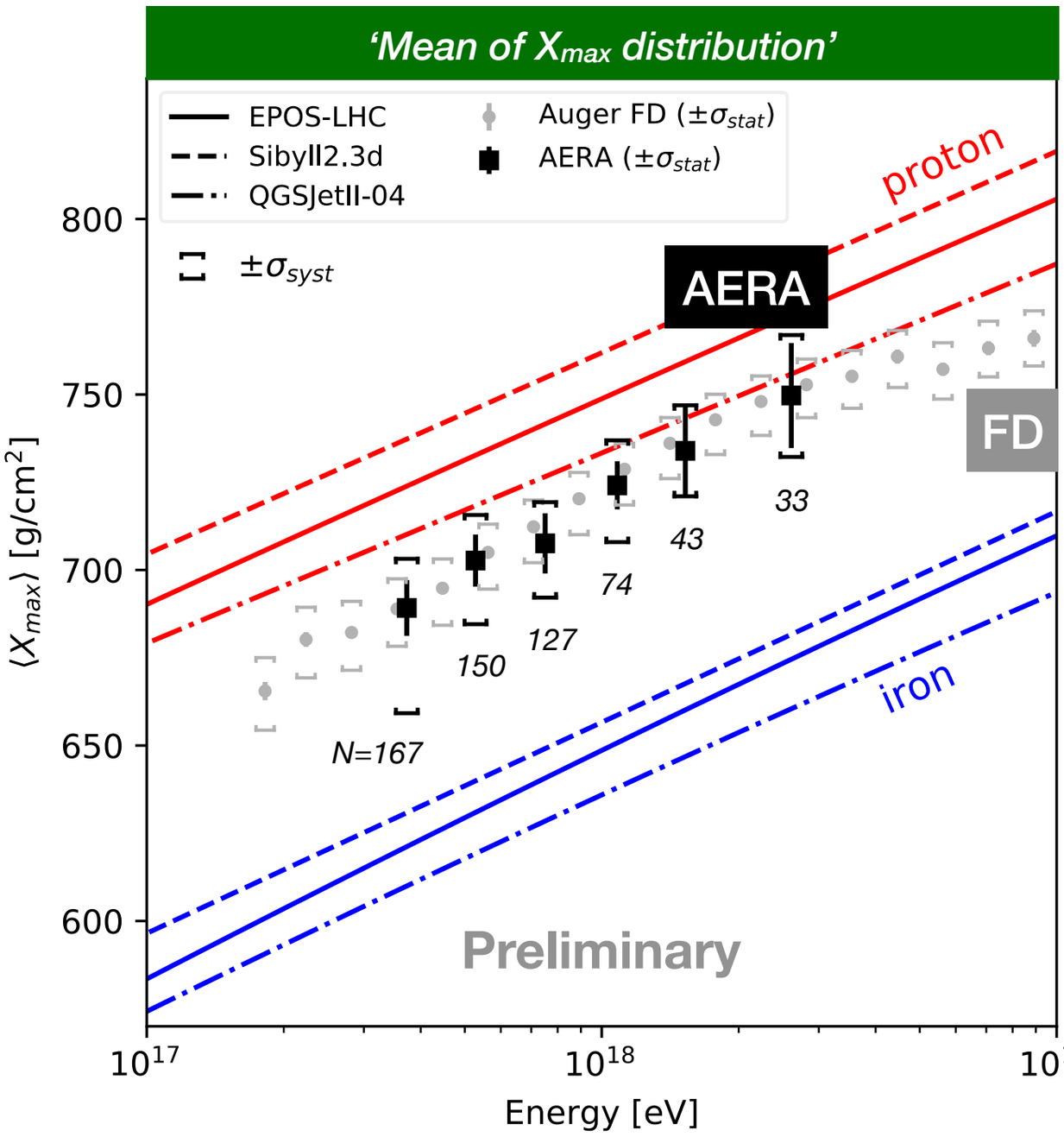
**Side note:**
High resolution is crucial for mass composition studies.



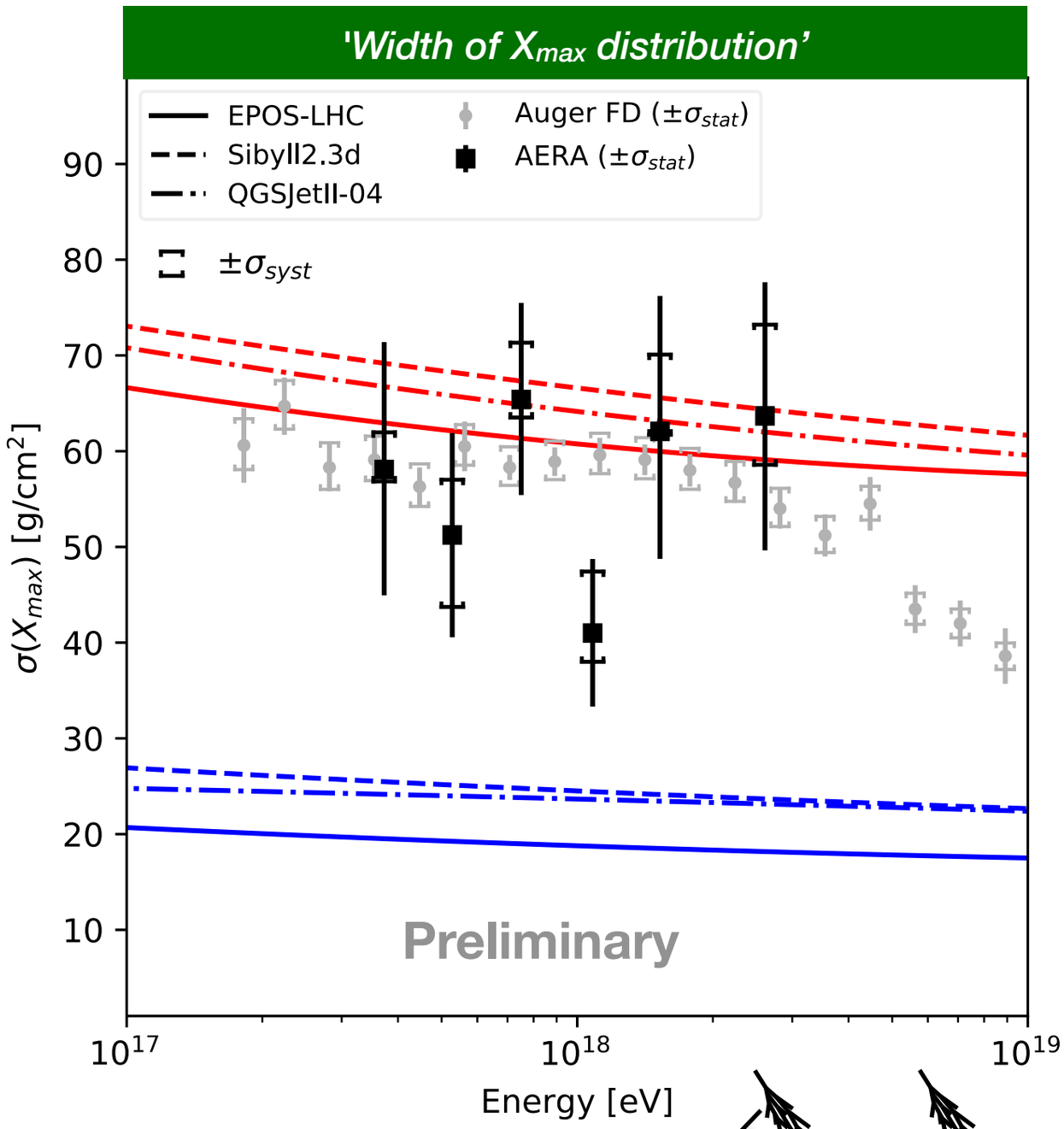
# Results: Measured AERA $X_{max}$ distribution

Radboud University

## *'Mean of $X_{max}$ distribution'*

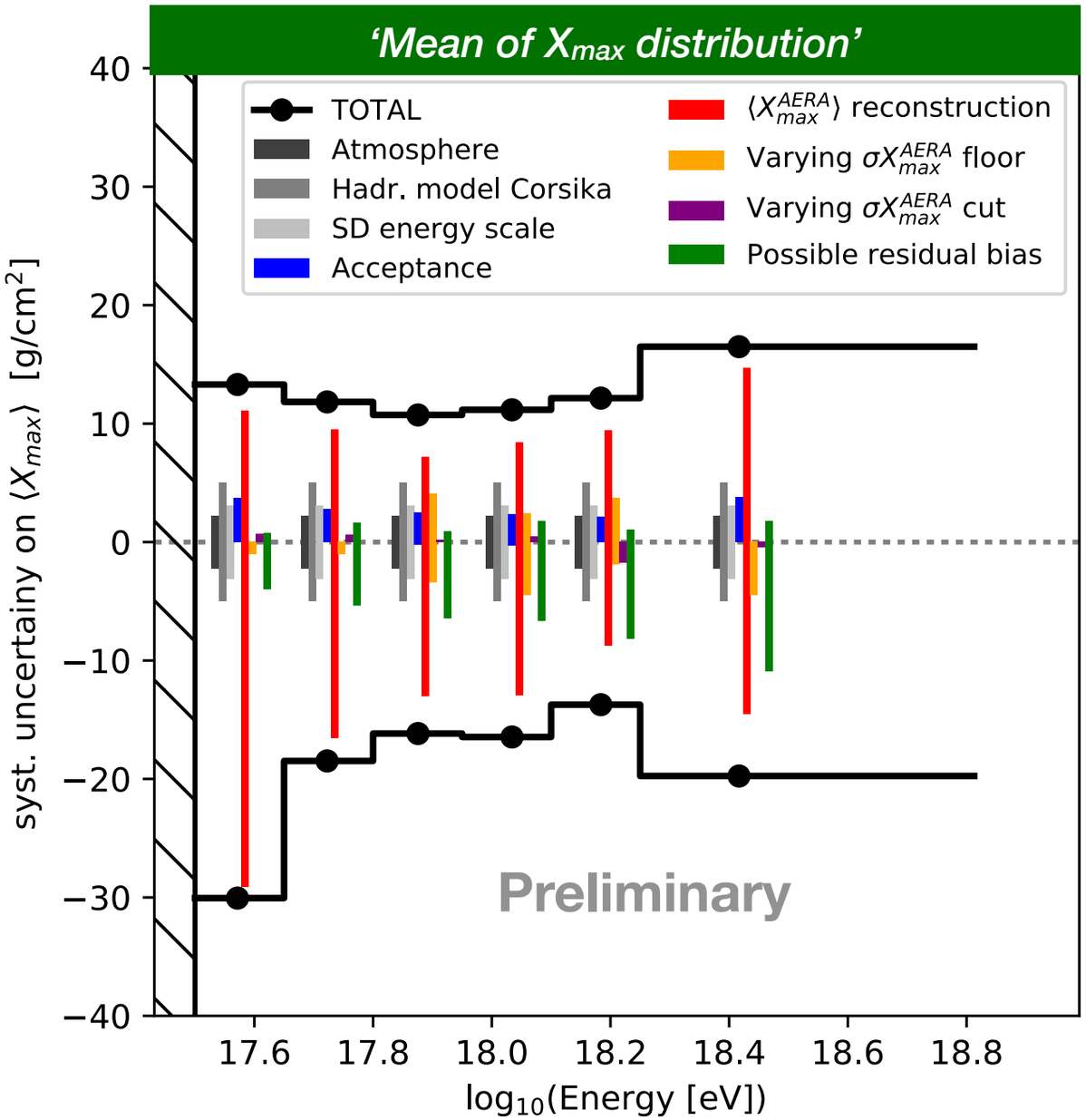


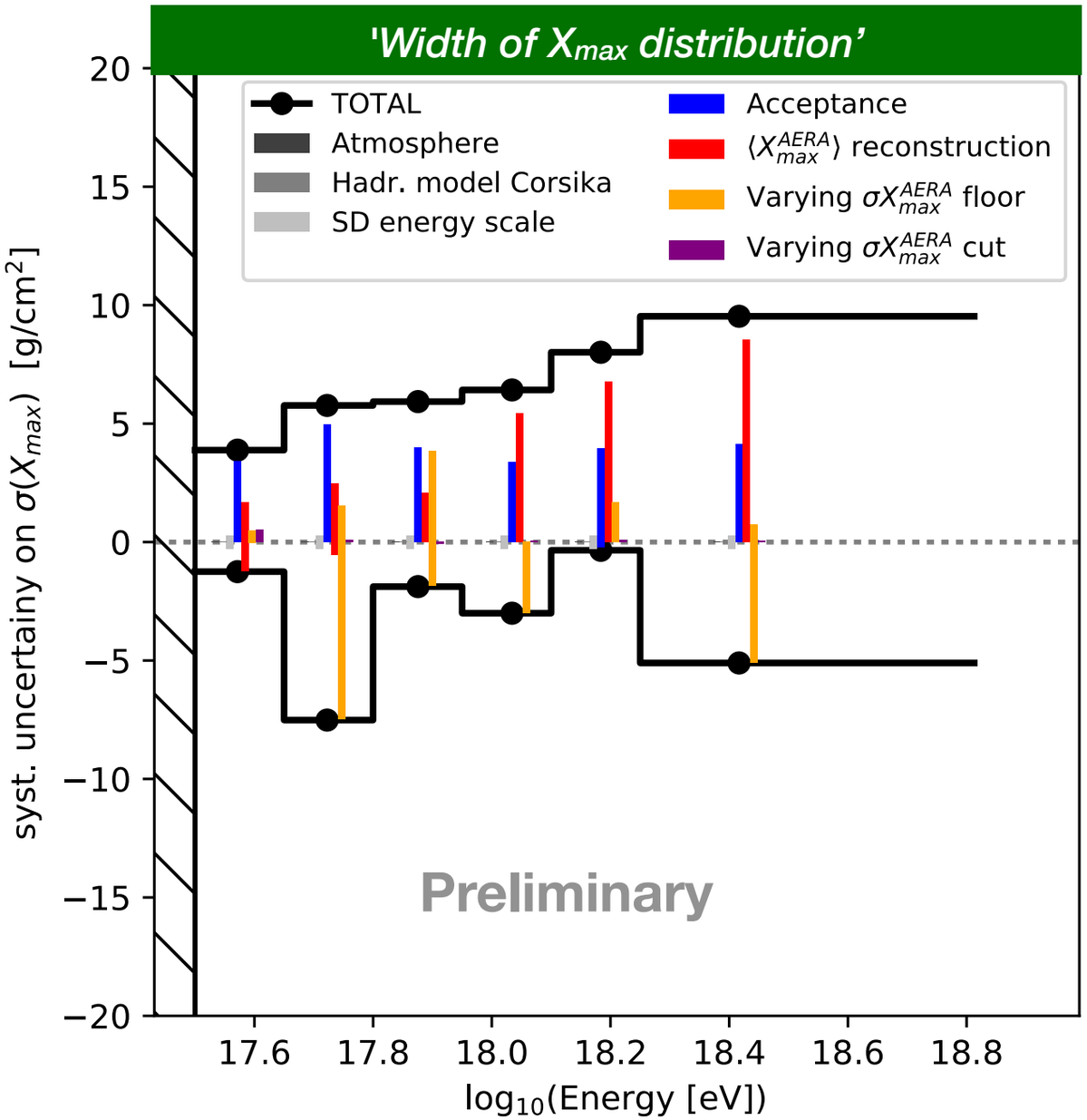

## *'Width of $X_{max}$ distribution'*




- ~600 showers after quality and anti-bias cuts.
- In agreement with Auger FD in mean and width.
- (Mixed)-light composition at E=$10^{17.5}$ -$10^{18.5}$ eV.

# Systematic uncertainties on the $X_{max}$ distribution

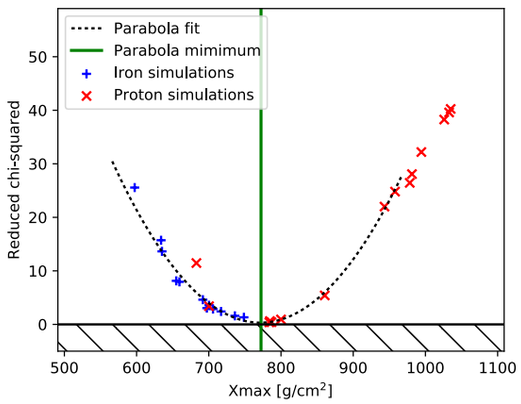


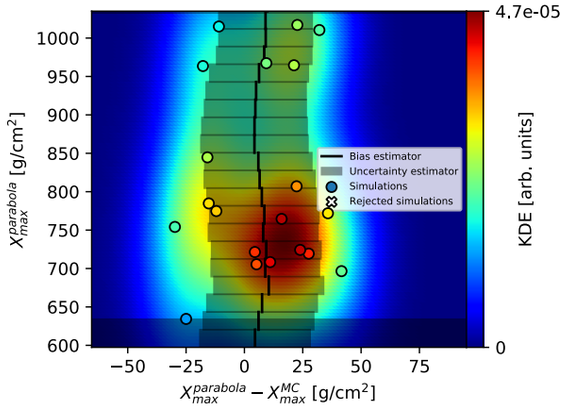




- **Basic effects** : *hadronic model in CORSIKA, GDAS atmosphere, Auger SD energy scale*
- **Method specific effects** : *data selection (acceptance), $X_{max}$ reconstruction*
- **low-number statistics** : effects of *possible outlier values* and *reconstruction quality cuts*
- **Cross-checks** : *residual bias checks with Zen/Az/core/… vs $\langle X_{max} \rangle$ and E*

# Take home messages

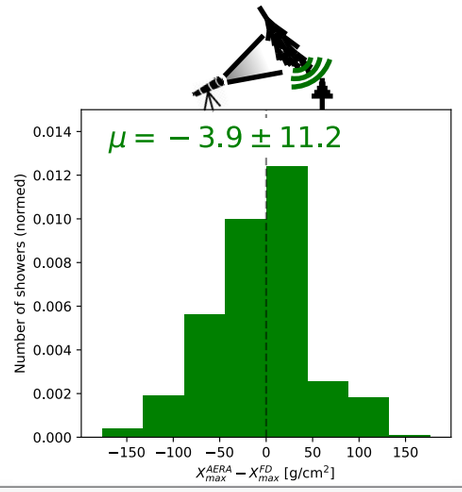
## Developed an improved method to reconstruct $X_{max}$ with AERA.

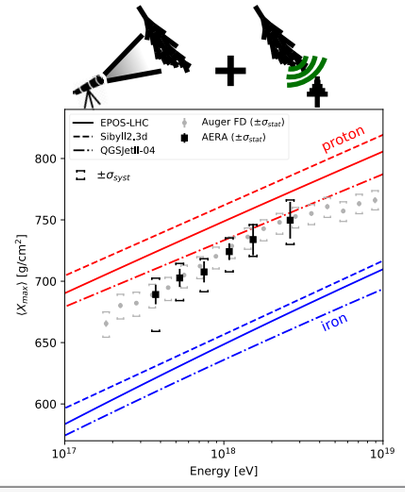


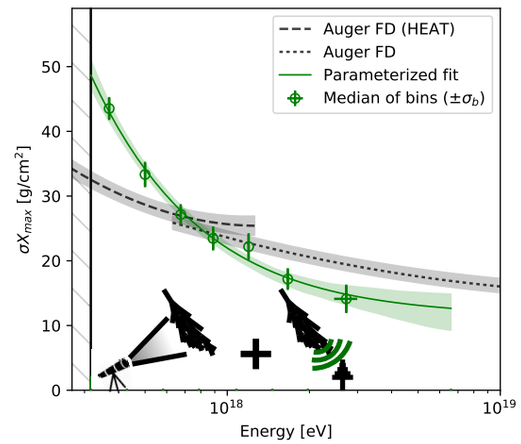

## AERA $X_{max}$ compatible with Auger Fluorescence

*Independent support to our understanding of shower physics.*

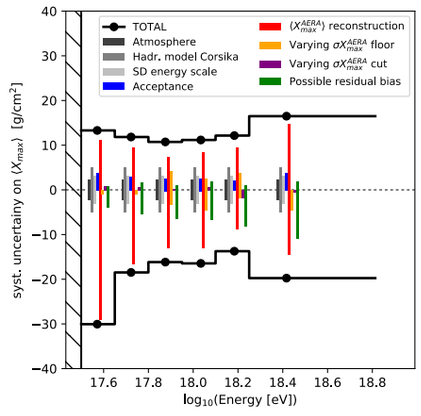


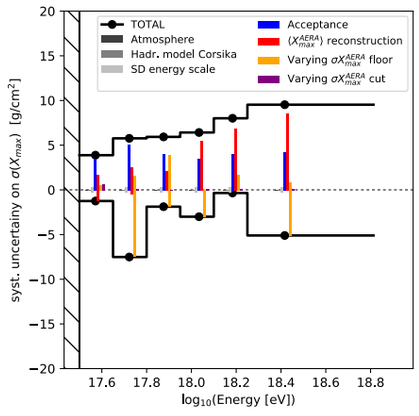




## Competitive AERA $X_{max}$ resolution




## Extensive systematic uncertainty studies are key

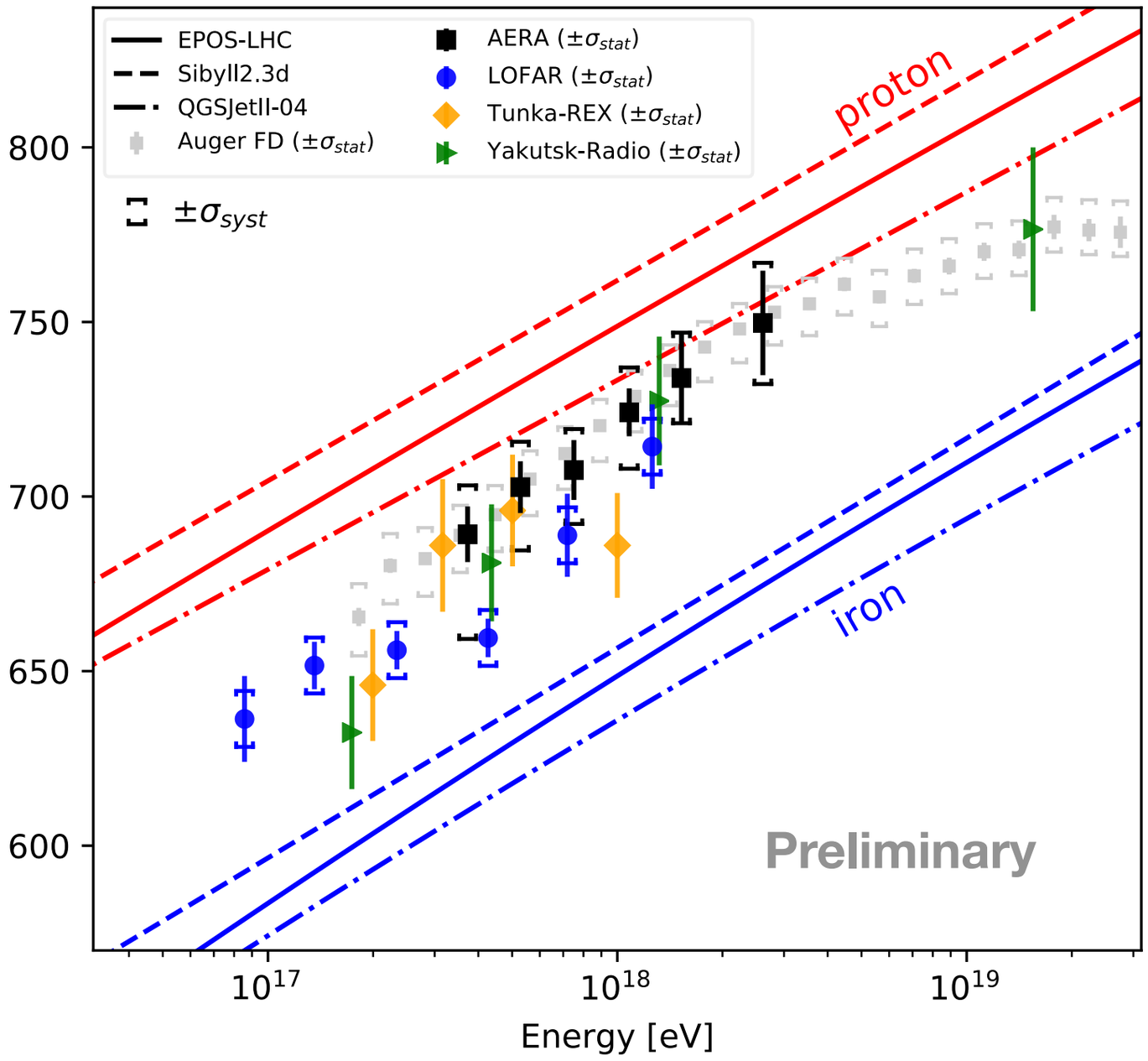


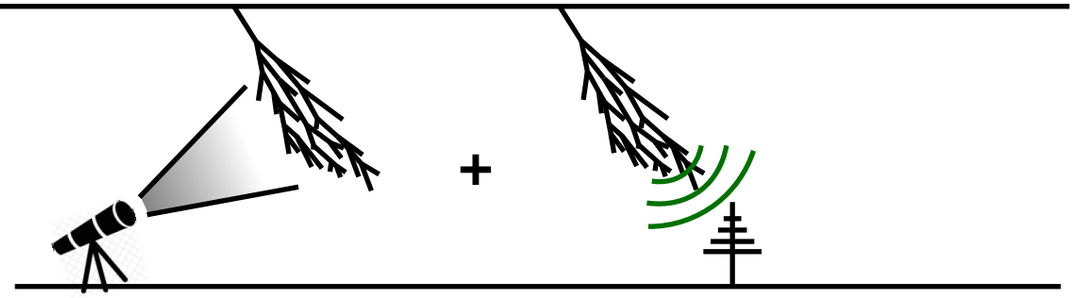




**What's next? The technique is ready for next-gen radio experiments (SKA, …)**

# Backup

# Results: AERA vs other (radio) experiments

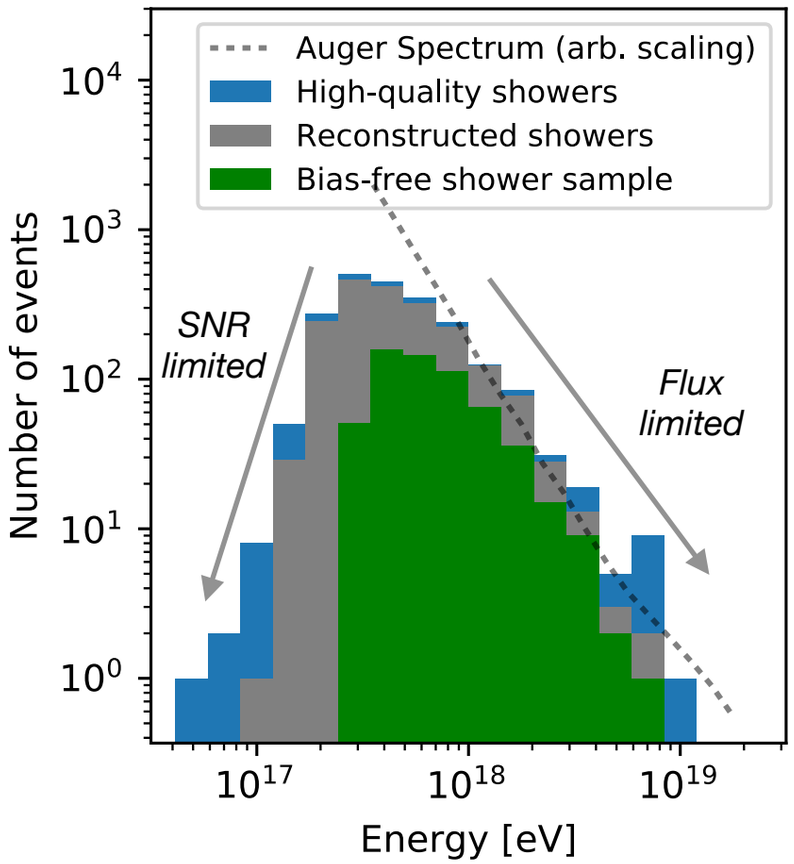


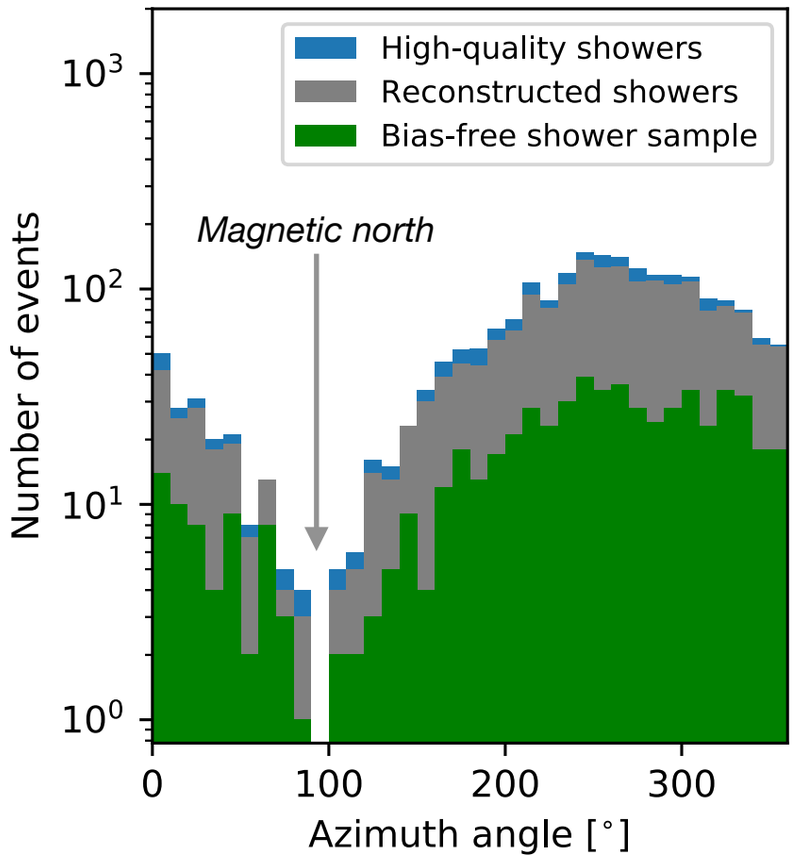
- No general radio-bias w.r.t Auger fluorescence (within uncertainties).
- Highlights that systematic uncertainties are key to interpret and compare.
- **LOFAR-AERA** differences are being investigated in a working group

# Event selection

## Energy




## Azimuth




## Zenith