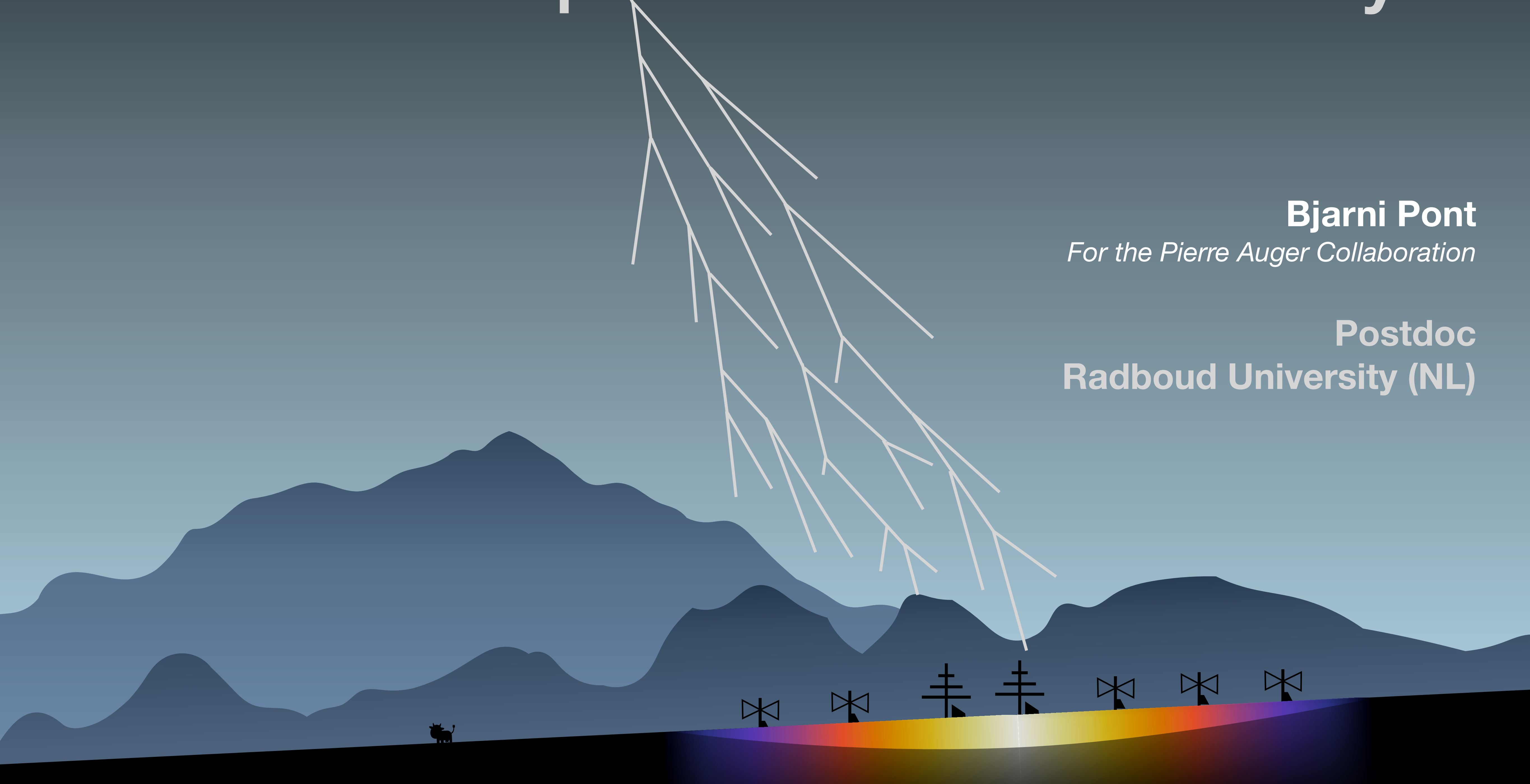
Highlights from AERA: X_{max} from the shower footprint and interferometry



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For the Pierre Auger Collaboration

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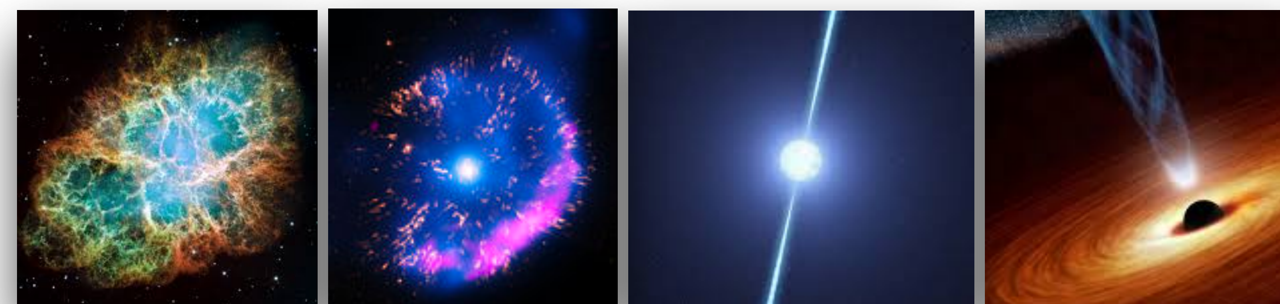
In this talk

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

- **Motivation:** Mass composition <—> sources of cosmic rays at transition between Galactic and extra Galactic (~10^{17-18}eV)



Contents:

- **X_{max} from the radio footprint (LDF):**
  FD-AERA comparison, X_{max} resolution, X_{max} distributions
  Phys. Rev. Lett. 132, 021001 (2024): *Demonstrating compatibility Fluorescence and Radio X_{max}*
  Phys. Rev. D 109, 022002 (2024): *Method and detailed results of AERA X_{max}*

- ***X_{max} from the 3d emission region (interferometry):***
  Interferometric reconstruction, LDF-interferometry comparison, prospects for inclined showers

Introduction: AERA at the Pierre Auger Observatory

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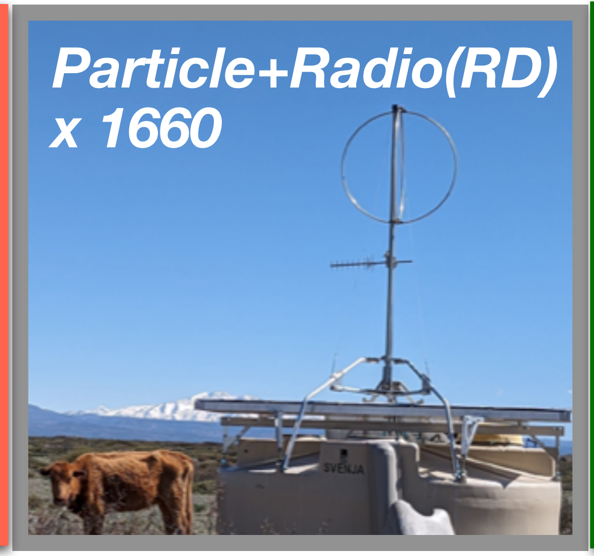
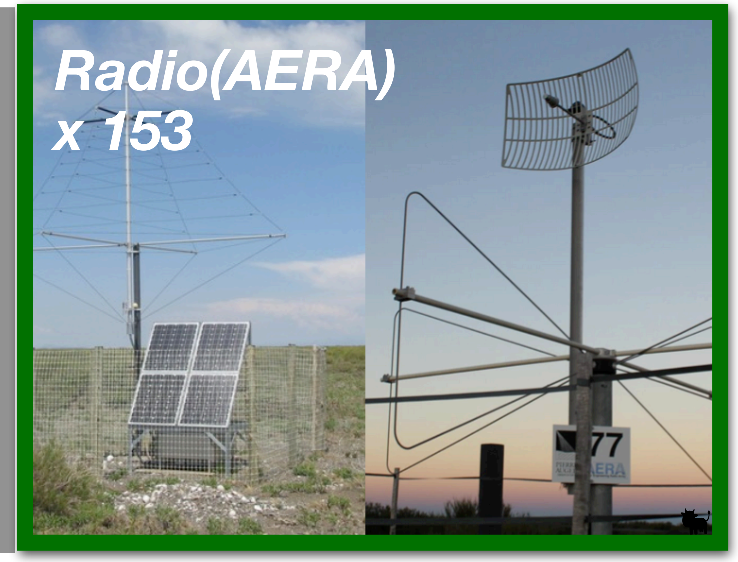
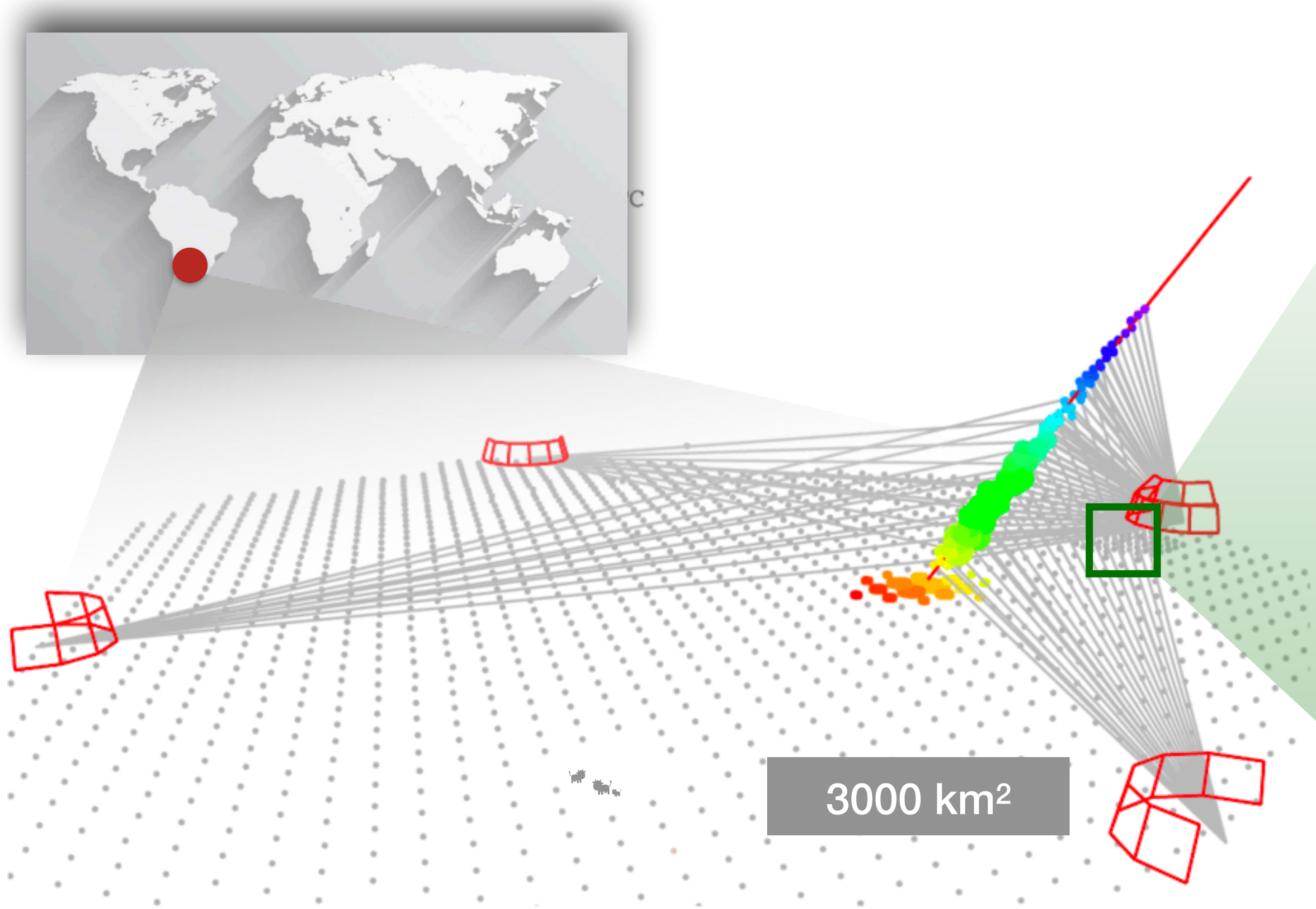
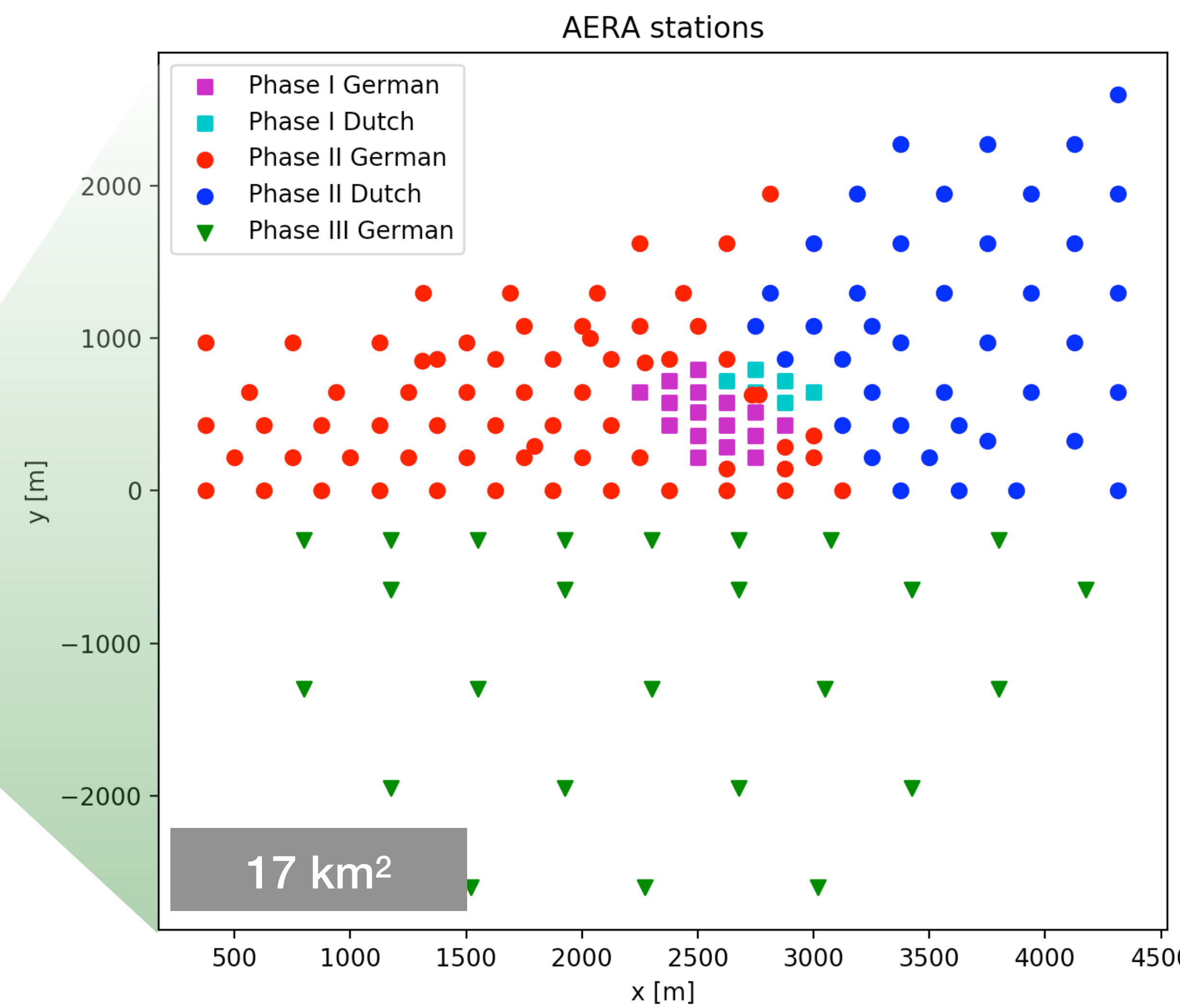




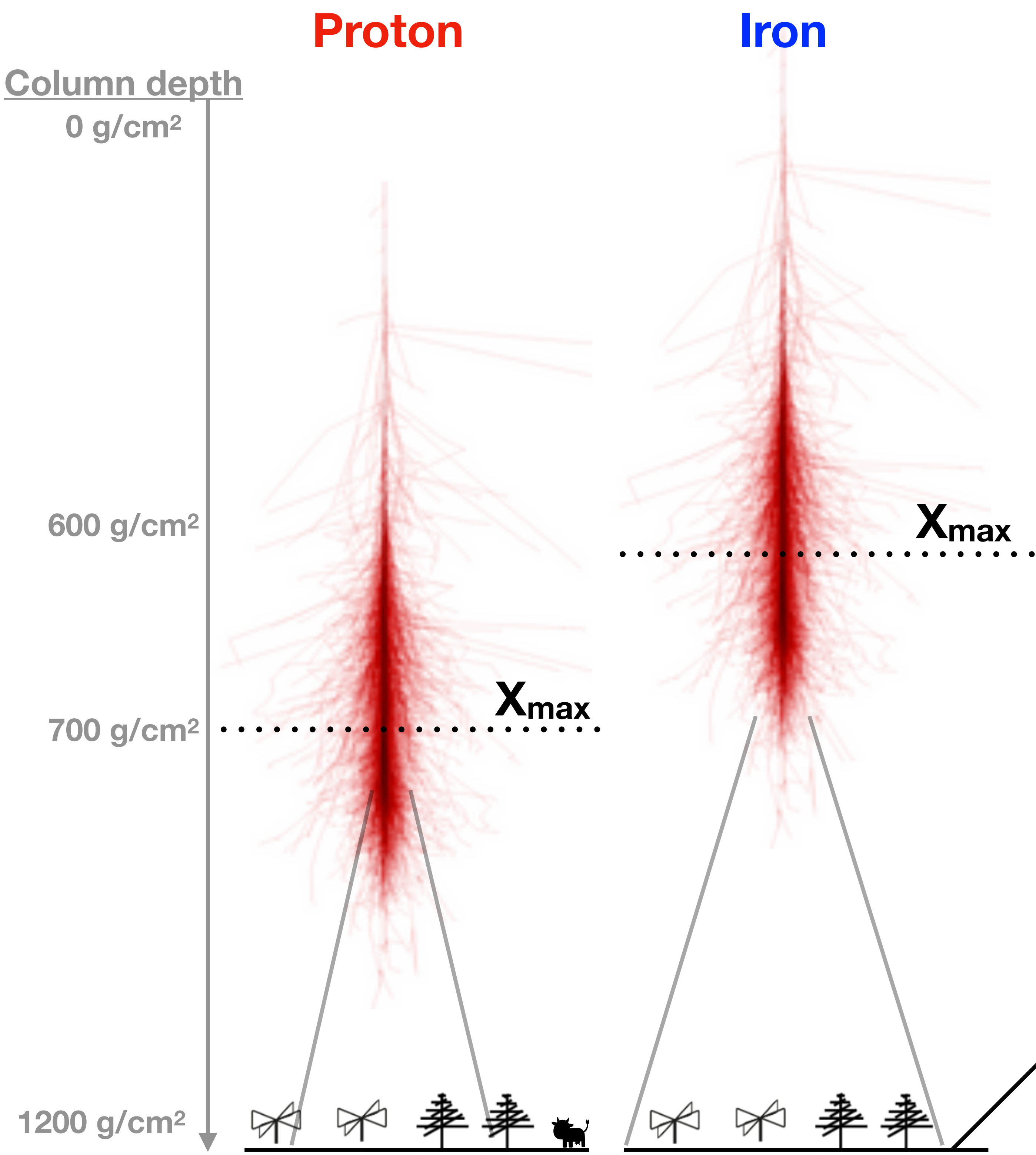
Auger Engineering Radio Array

- 153 autonomous radio antennas
- Energy range: 10^{17}-10^{19} eV
- Frequency range: 30-80 MHz
- >2000 high quality events over 7 years (with ≥5 stations at 'SNR'>10).
- Beacon for nanosecond timing calibration.

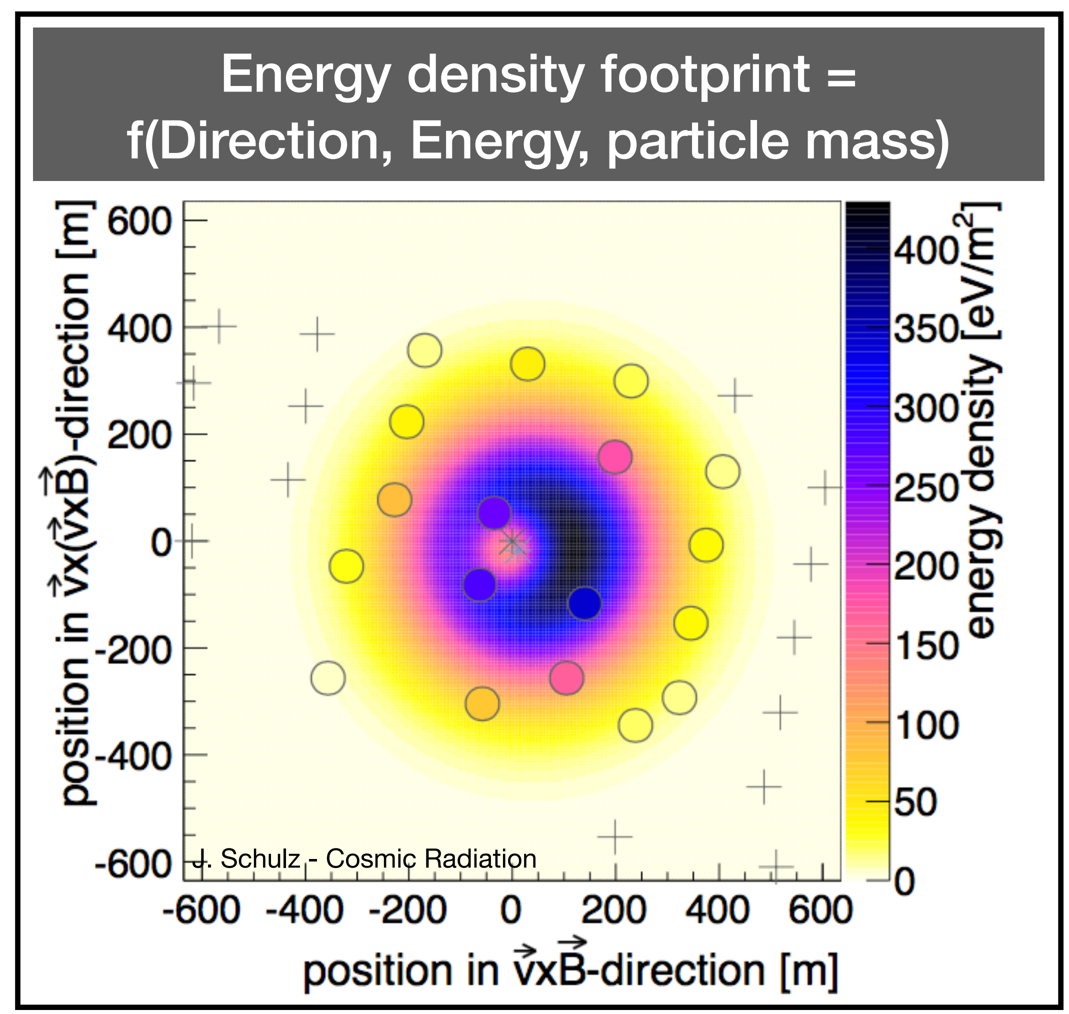




Introduction: Radio footprint is sensitive to mass



- 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}.

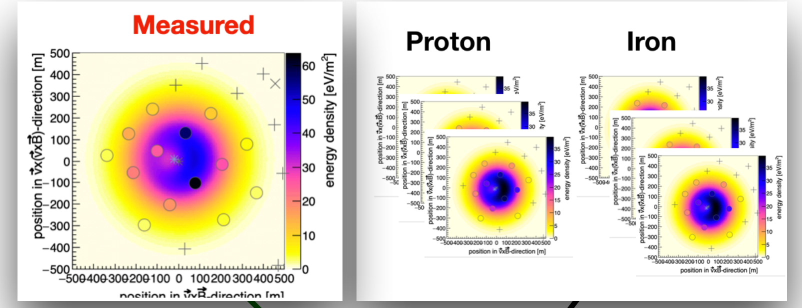


Method: Reconstructing X_{max} from the radio footprint

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

—> likelihood analysis: template fitting to find X_{max} for each shower



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

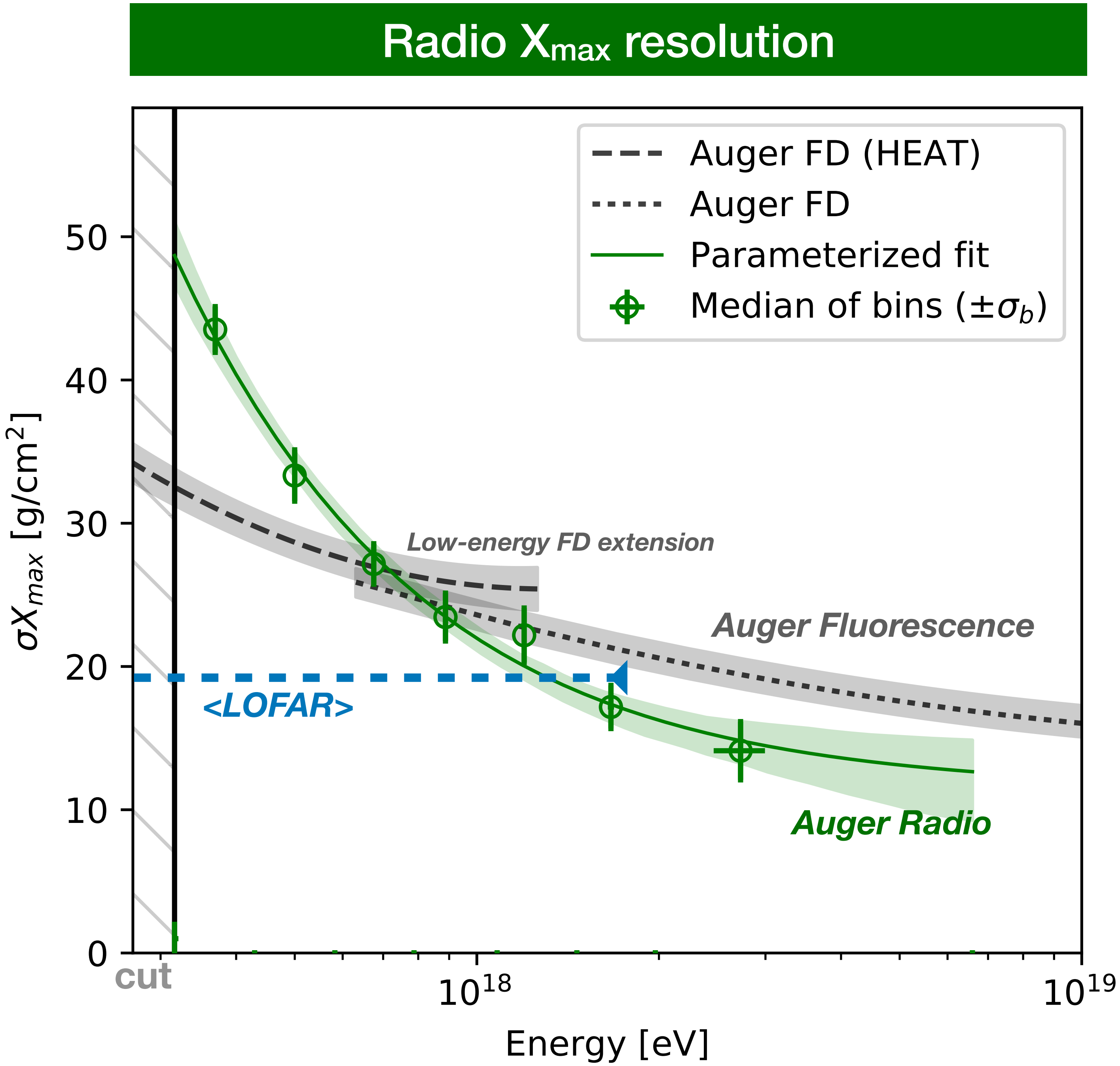
Using the ~600 x (15 p +12 Fe) set of simulations

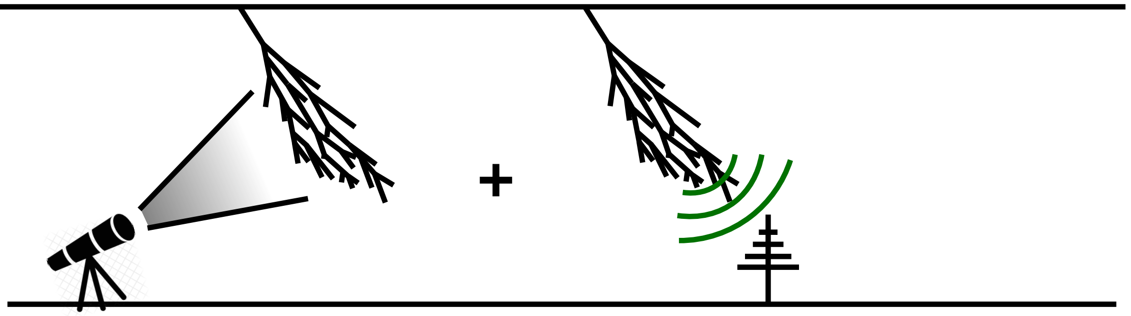
- Correct for reconstruction bias on an event-by-event basis
- Determine reconstruction uncertainty on an event-by-event basis
- Determine detection acceptance
- Determine reconstruction bias

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_{max} reconstruction pipeline*
- **Residual bias checks** : investigation of *shower zenith/azimuth/core/… vs <X_{max}>(E)*

Results: Resolution of AERA X_{max} method





Resolution improves with energy.

- Up to 'better than 15 g/cm² '
- 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_{max}

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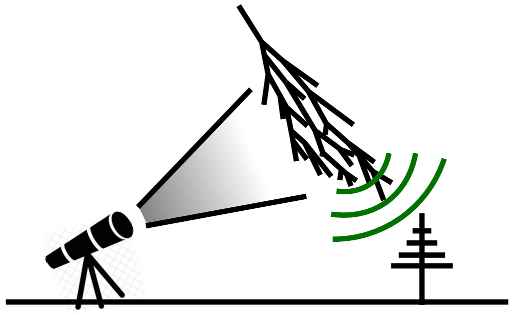
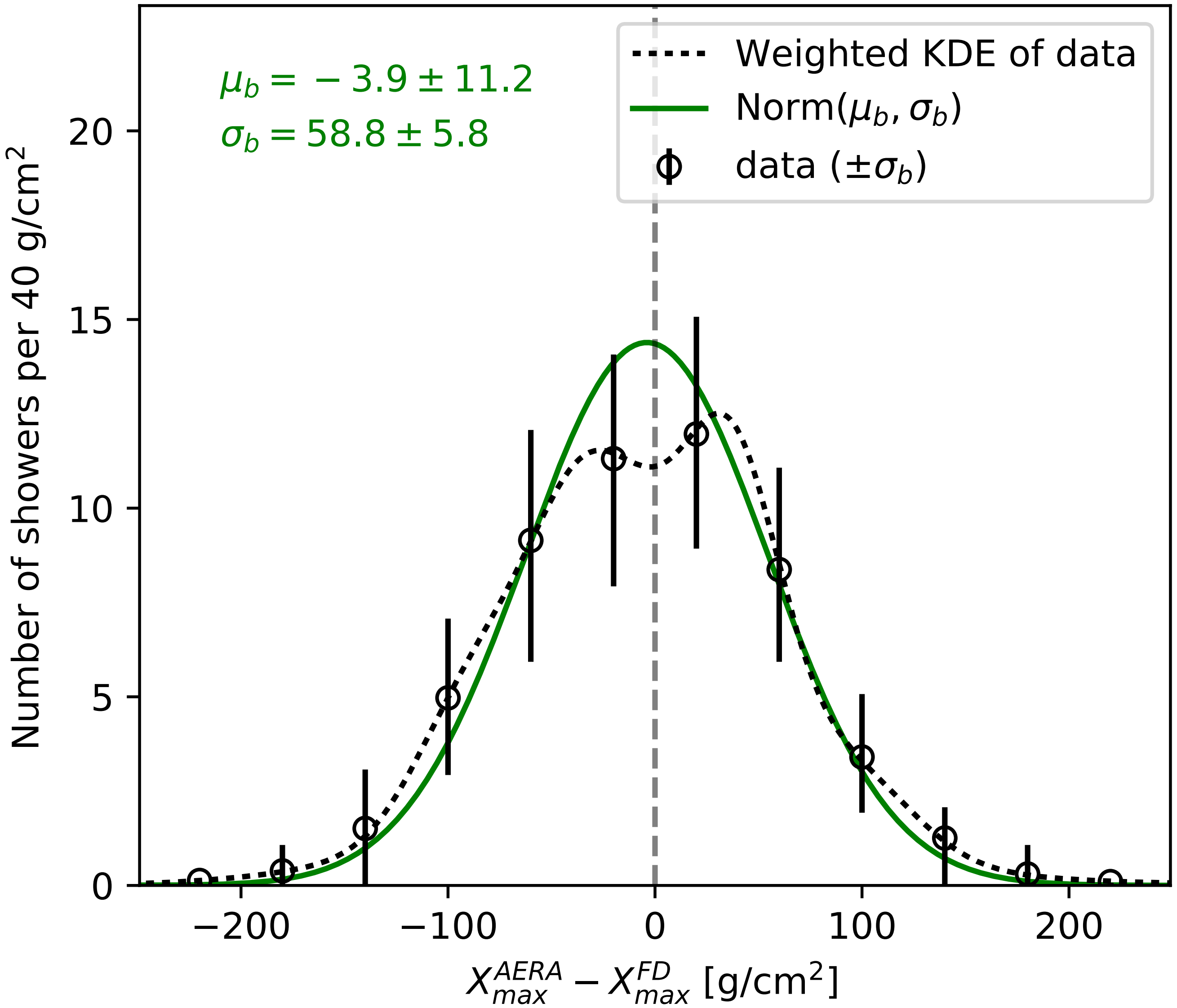
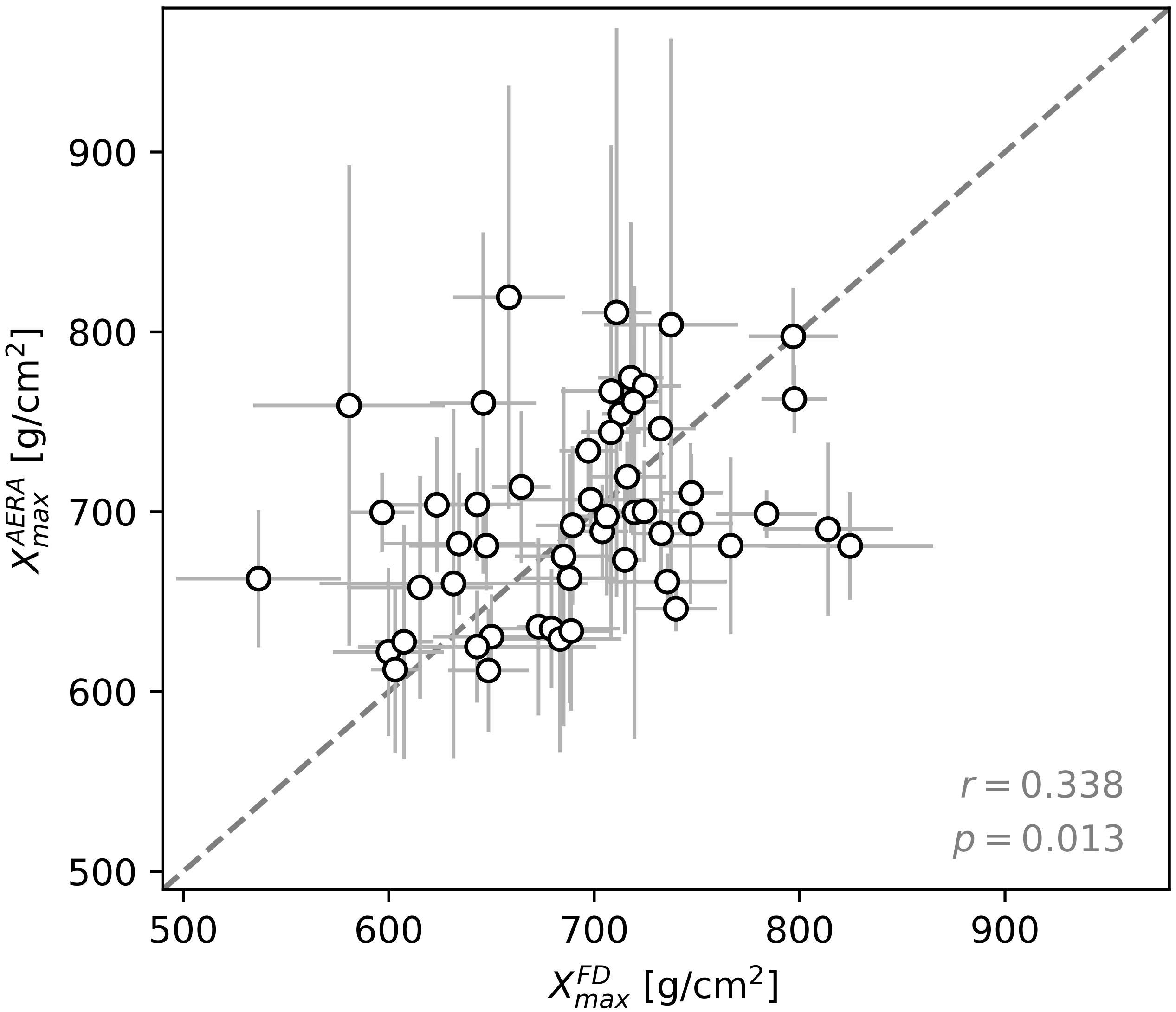


Auger has unique Radio-Fluorescence setup:

- 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)



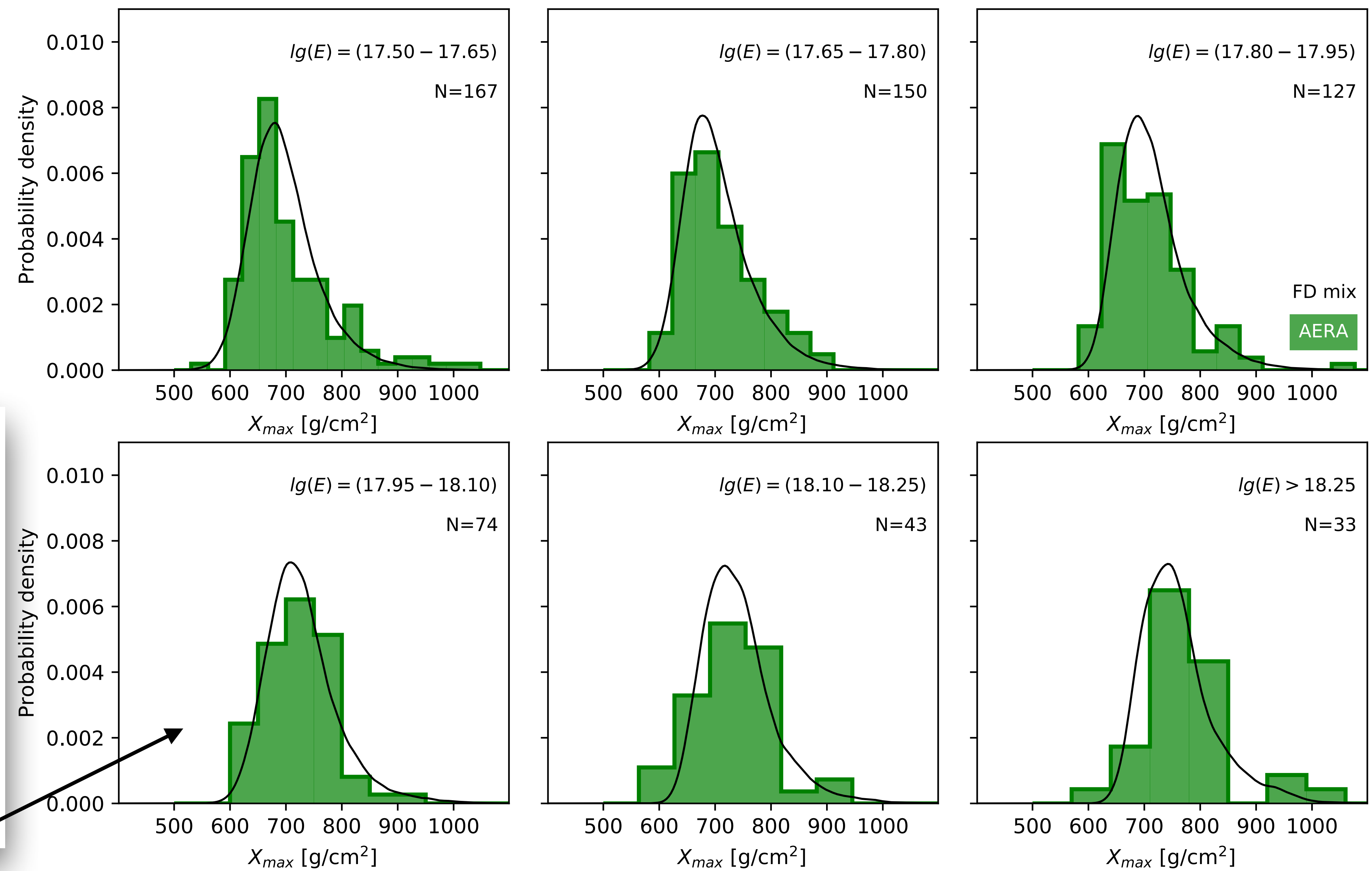


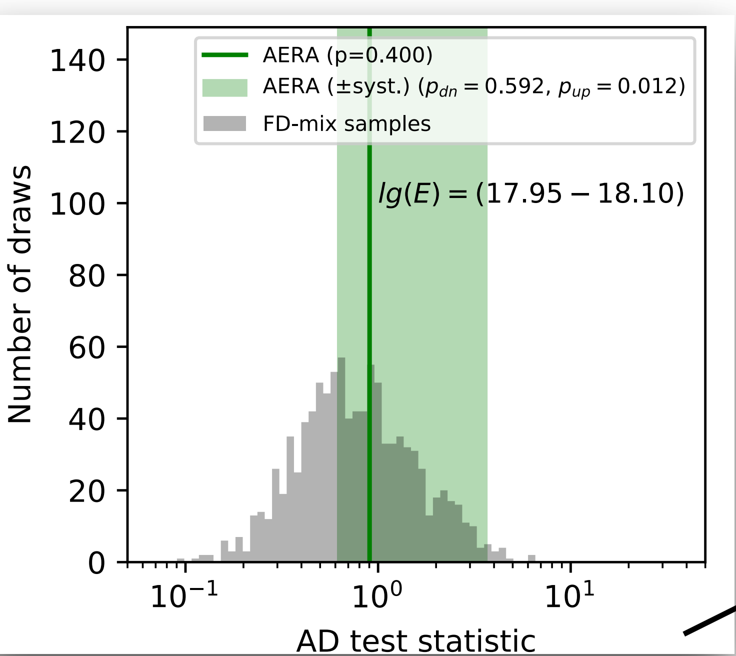
Results: Distribution AERA X_{max} vs Auger-mix

- **Distributions of reconstructed AERA X_{max} in 6 energy bins**
- vs **Auger-mix, drawn with AERA {i.e., incl. resolution, acceptance, and reconstruction bias}.**

AD test statistic checks if measured distribution could have been drawn from Auger-mix with detector effects.

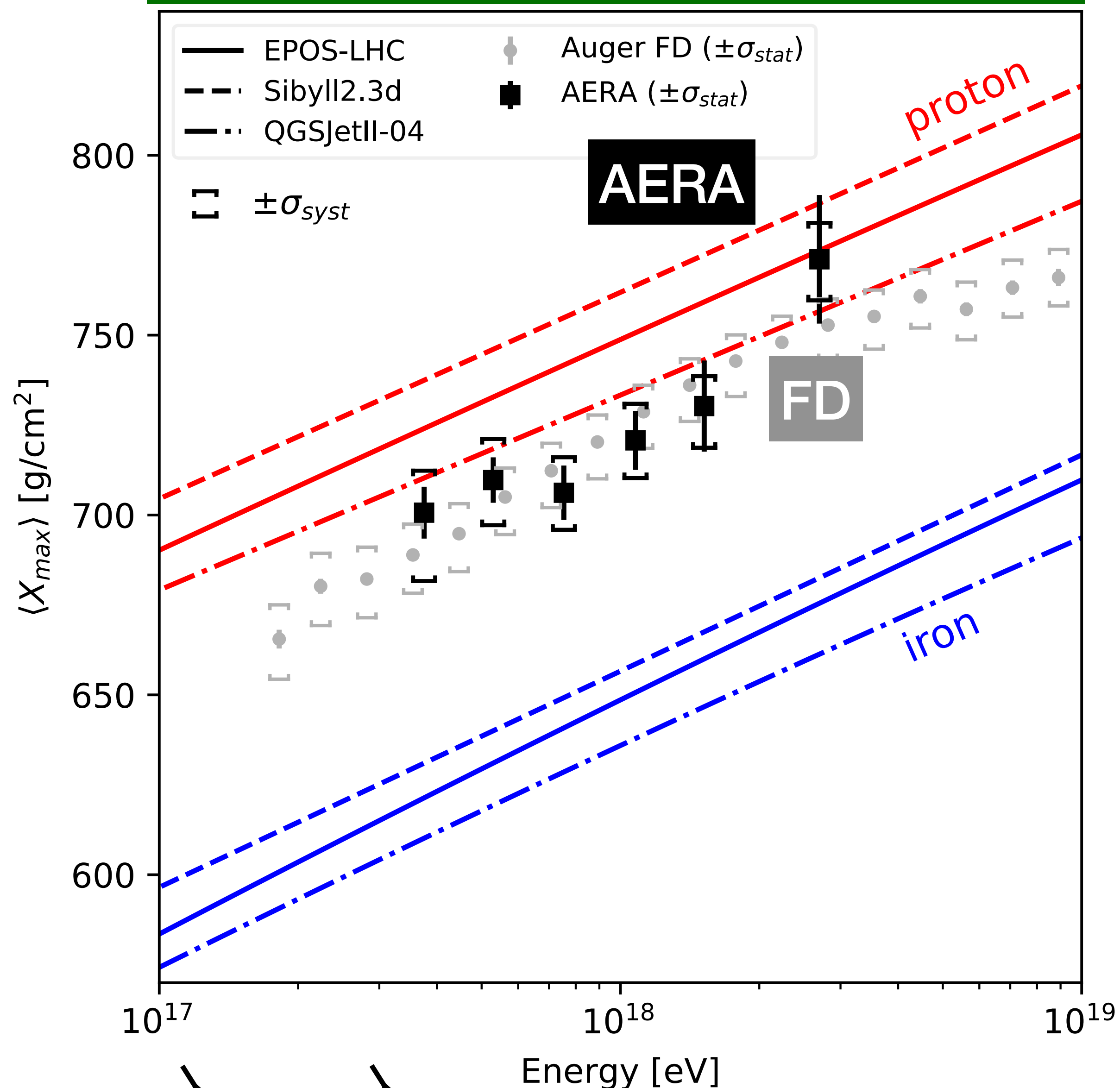
- Compatible with Auger-mix for each energy bin (within stat+syst unc)
- Validation (1) that we understand our procedure and (2) of compatibility FD and AERA.



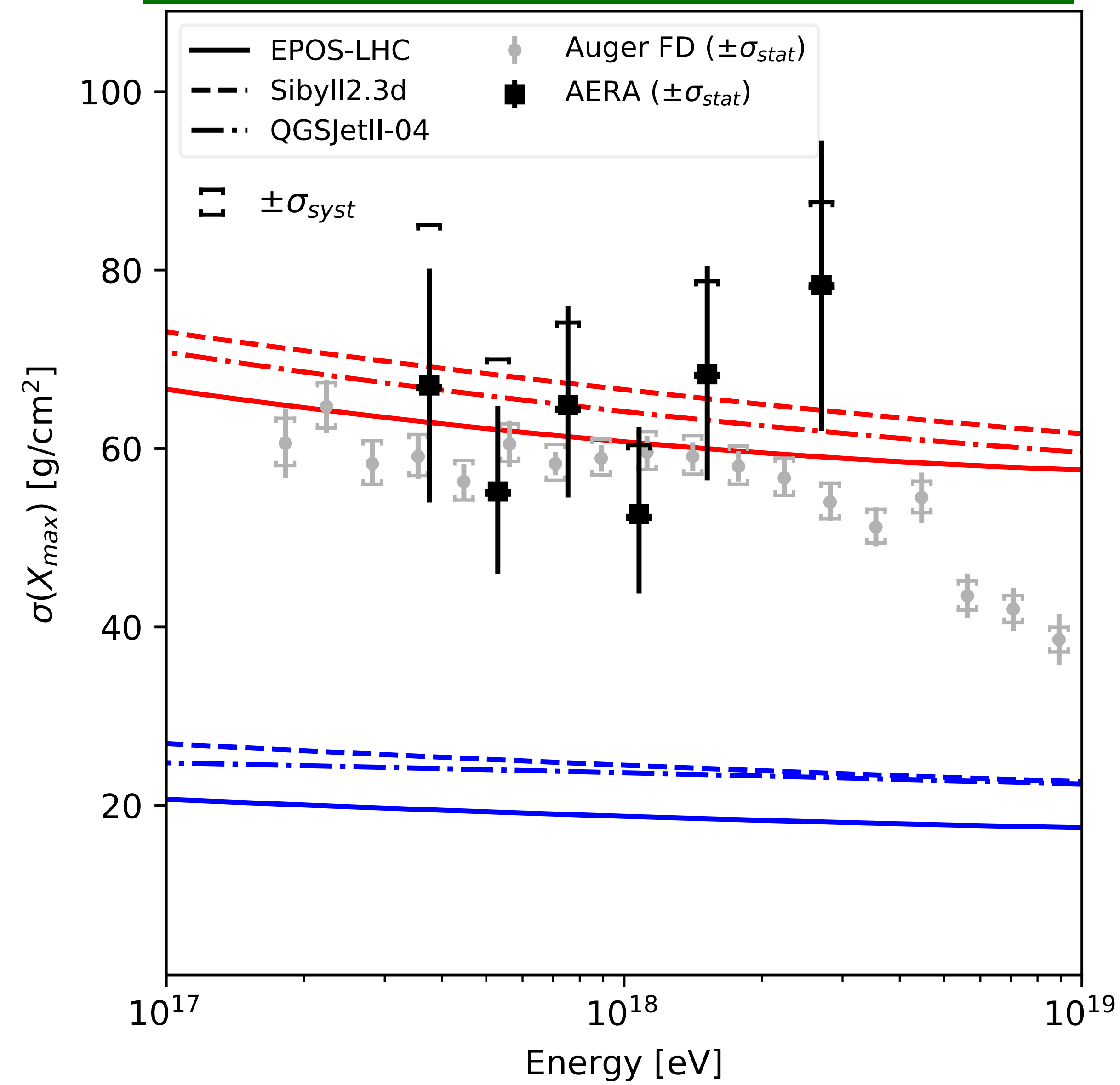


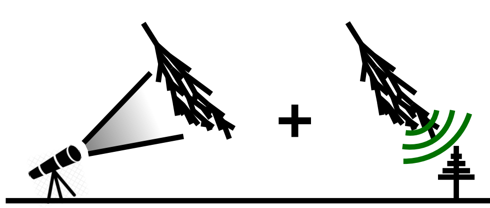
Results: Measured AERA X_{max} moments

'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, width, and the X_{max} distribution.
- Light composition (p-He?) at $E=10^{17.5}$ eV, seemingly becoming lighter towards $E=10^{18.5}$ eV.

Preliminary: X_{max} from Interferometry

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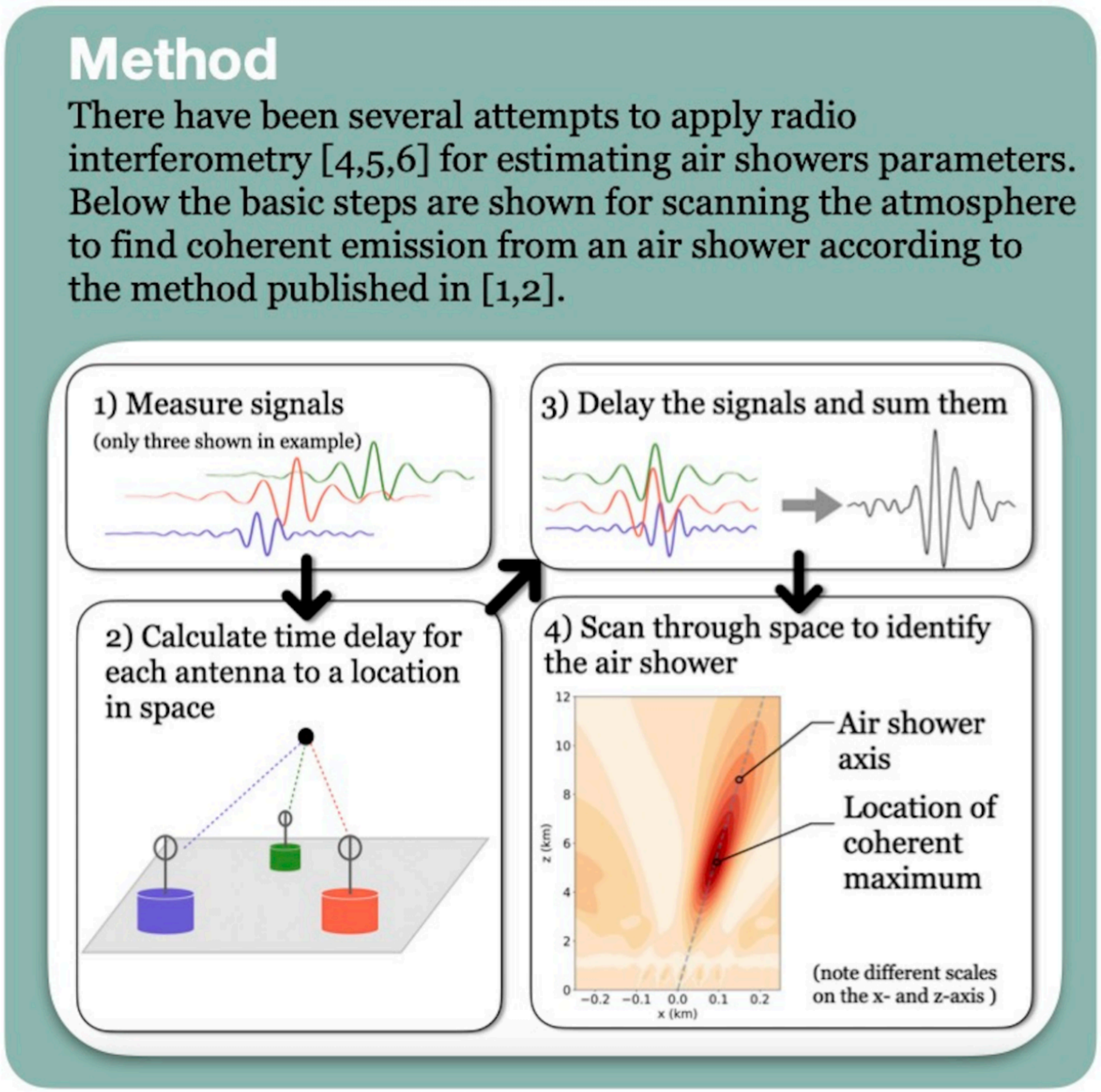
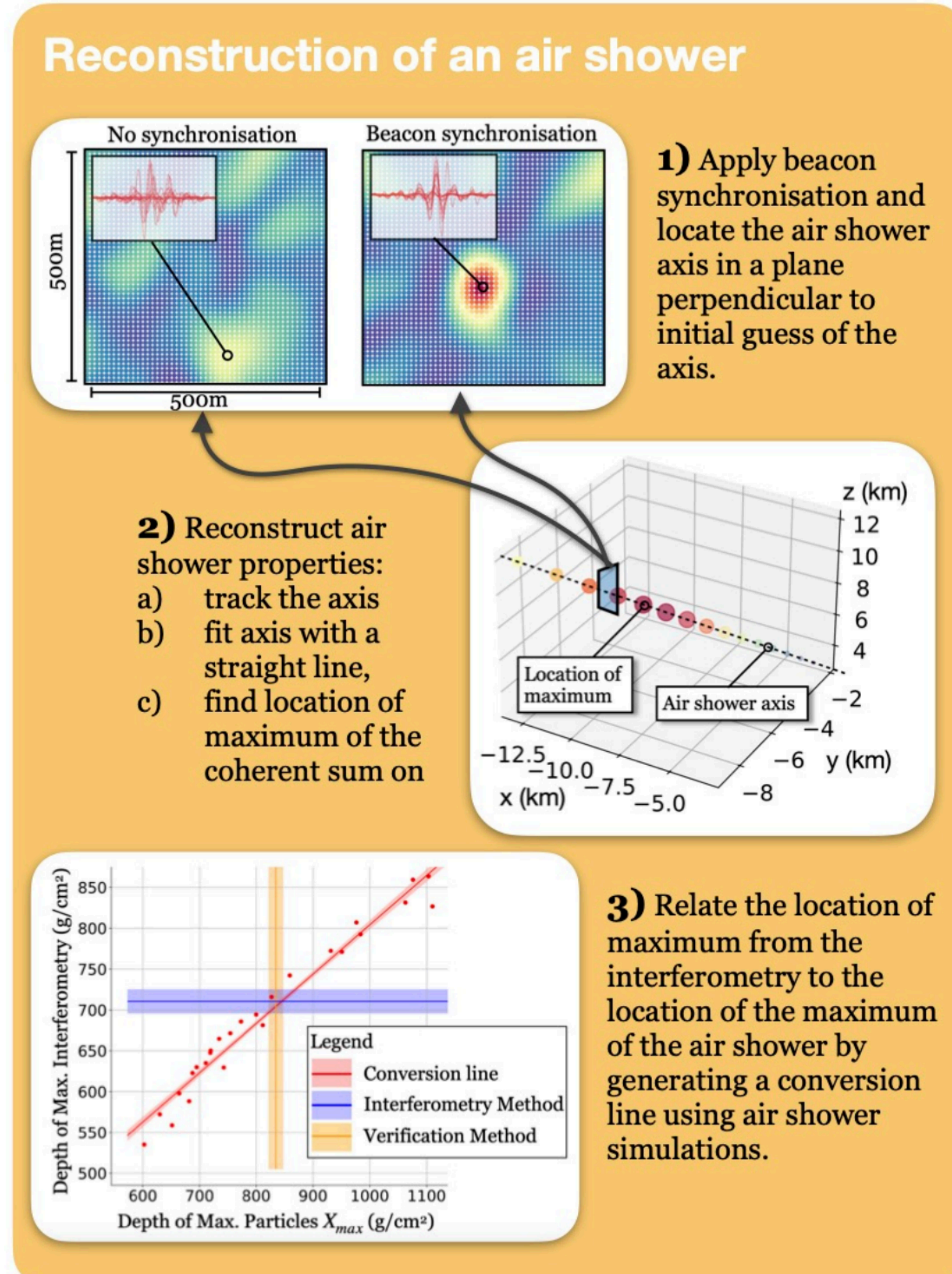
PIERRE AUGER OBSERVATORY

[Work by Harm Schoorlemmer]

Method at ICRC2023





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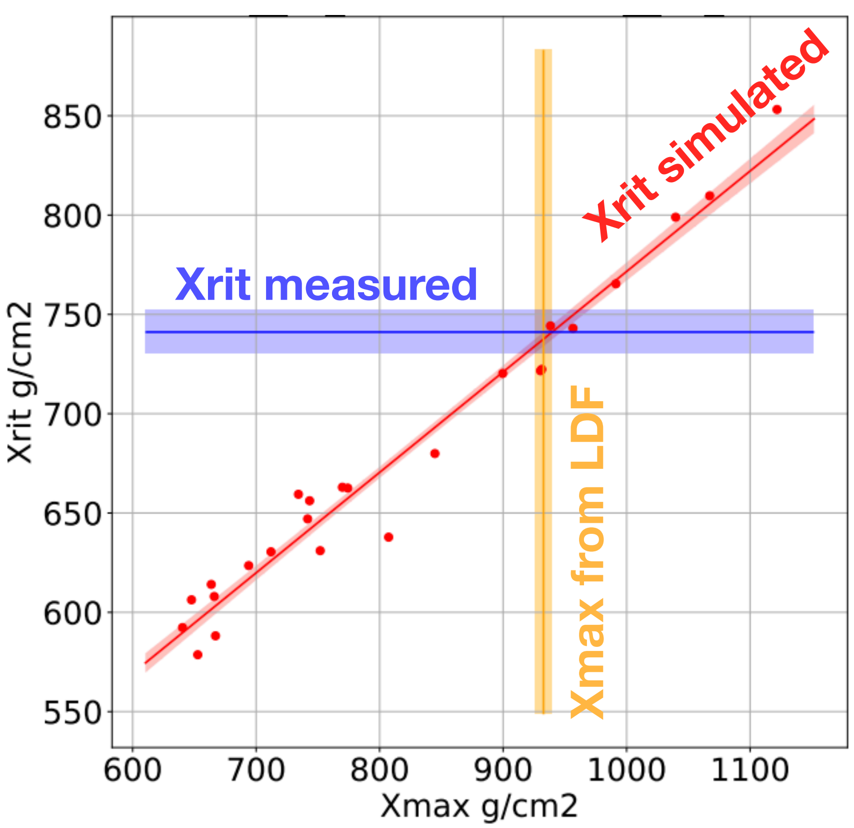
Preliminary: 1:1 comparison to footprint method

[Work by Harm Schoorlemmer]

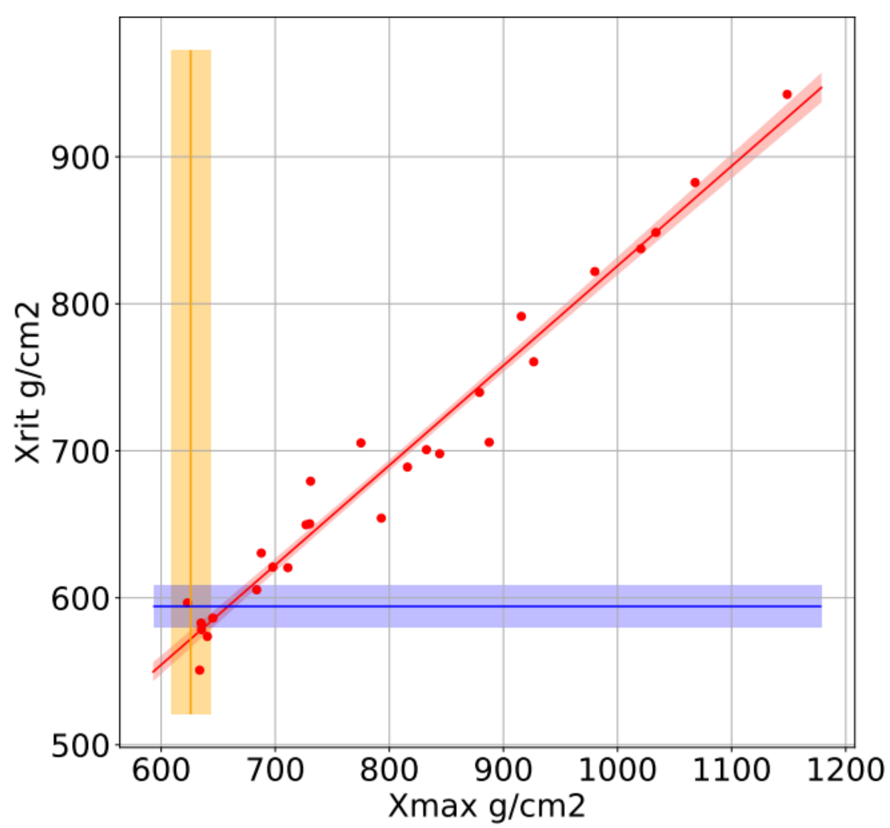
- Starting from the same AERA X_{max} simulation library (PRL/PRD papers)
  (high quality events: $N_{stations} \geq 10$, ns-beacon timing, Z<55°, E>10^{18} eV, σX_{max} <30g/cm^2)
- Generally good agreement. Examples below. Works well at both low and high X_{max}.
- Station multiplicity & geometry governs the resolution (spread of points)
  —> still needs proper error estimation on fit (for now simple fit uncertainty)

  Outlook:
  - Understanding performance of the algorithm
  - Quality/reconstruction cuts.
  - Extra simulation set for interpretation
  - Paper on X_{rit} with AERA data in preparation

Deep shower example

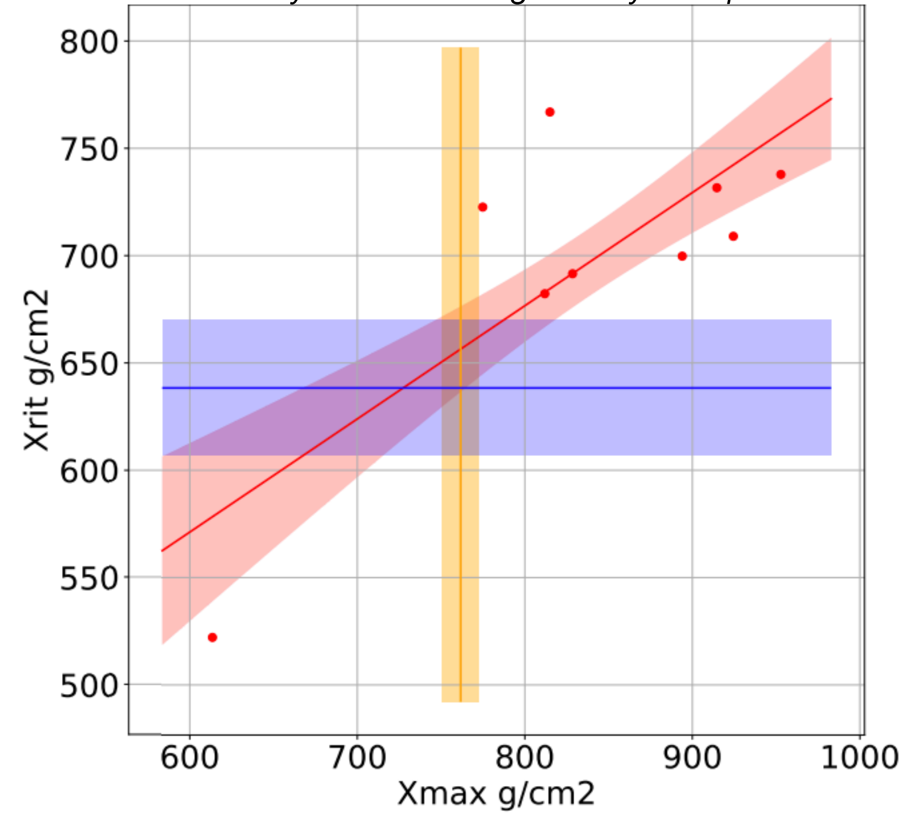


Shallow shower example



Low-quality example

AERA layout and event geometry not optimal

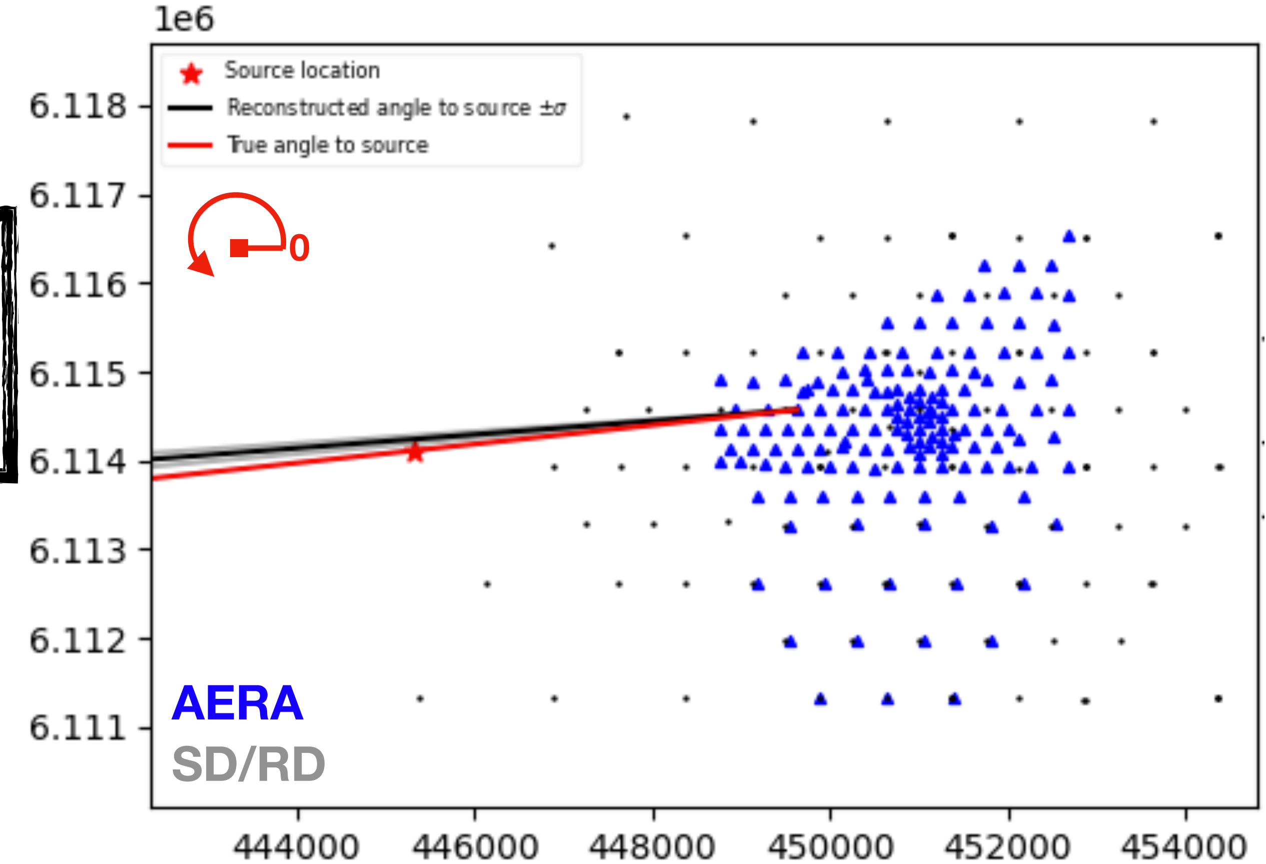


Bonus slide: using a beacon signal to get antenna alignment

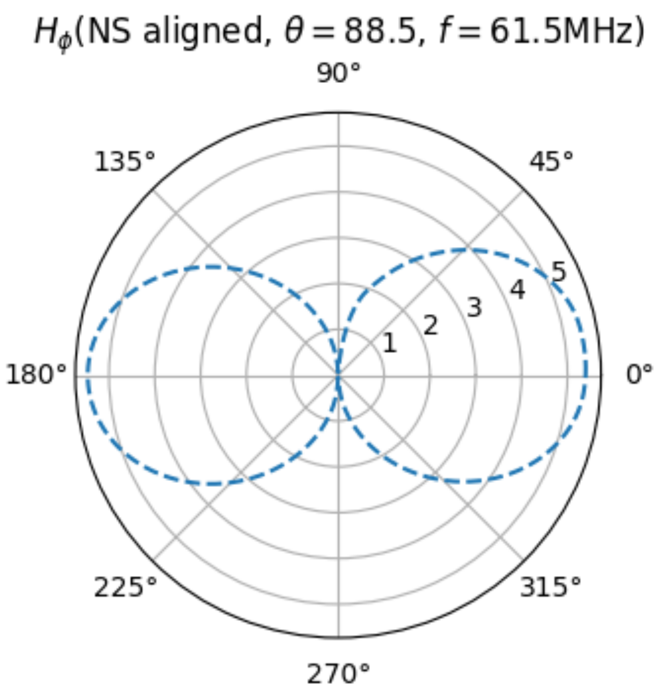
Beacon: 4-frequency sine-wave emitter deployed for AERA
(Also, strong AM TV emitter seen by whole Auger)

Ch0(EW) and ch1(NS) amplitudes —> measured channel ratio
antenna pattern & source location —> expected channel ratio
—> offset to source location = antenna rotation

- Can remotely look at:
  - rotation over time (if any)
  - swapped channels
  - Validation of (NEC) antenna pattern at horizon angles
  - …

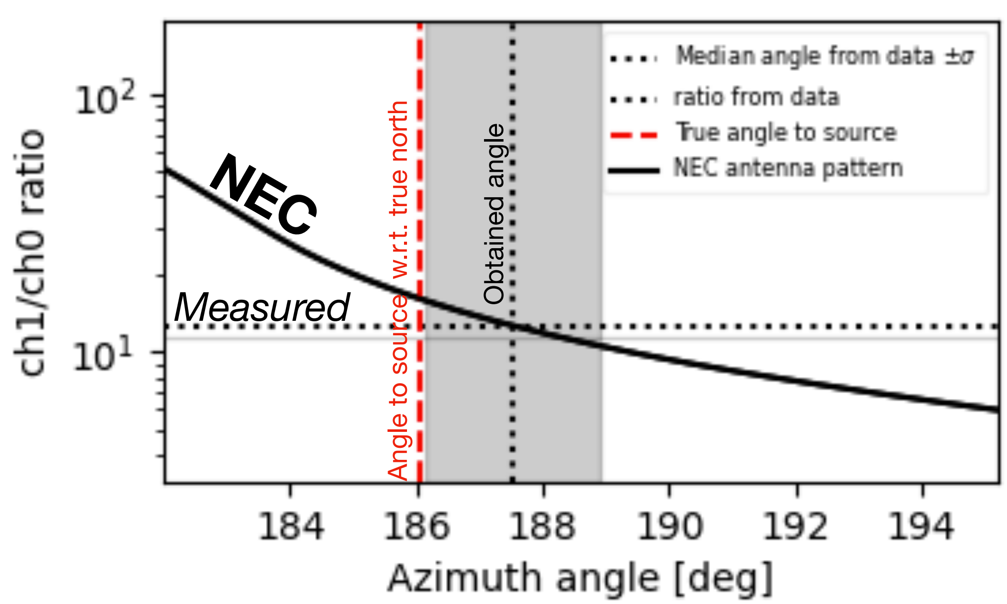


1) NEC antenna pattern



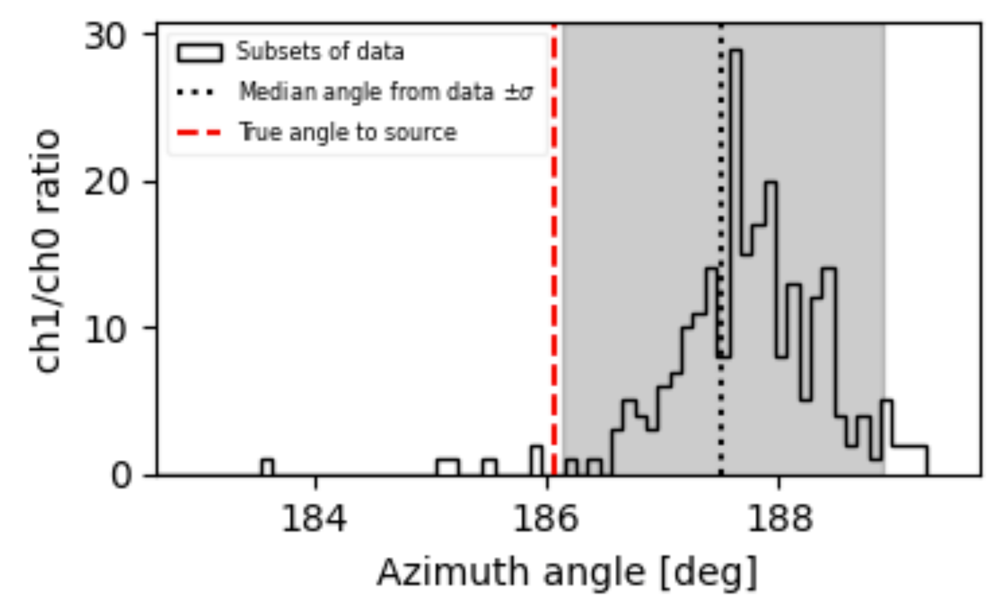
2) Matching ratios

**Antenna deployed to magnetic north. Alignment here w.r.t. true north. (Δ=2.6deg).*



3) Bootstrap uncertainties

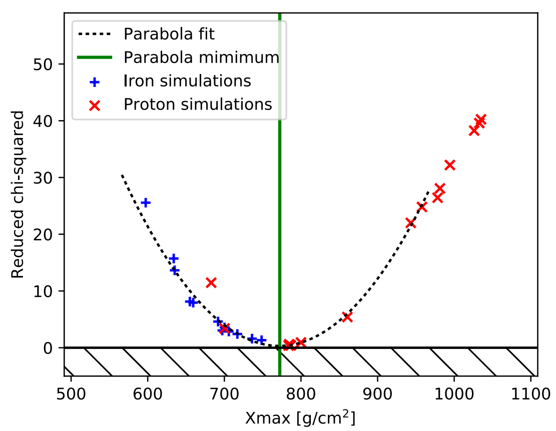
**repeatedly take 50% of recorded traces to propagate uncertainties to the angle estimation.*

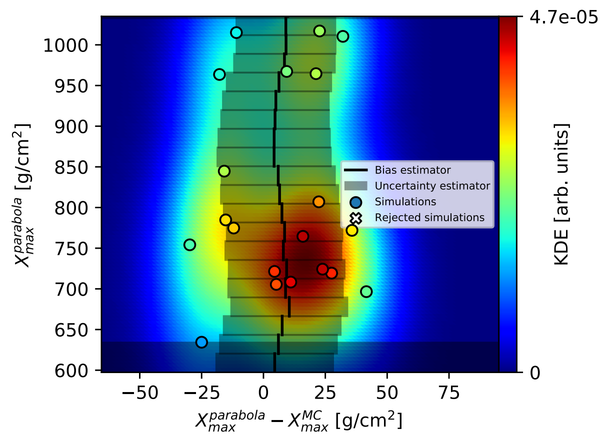


Take home messages

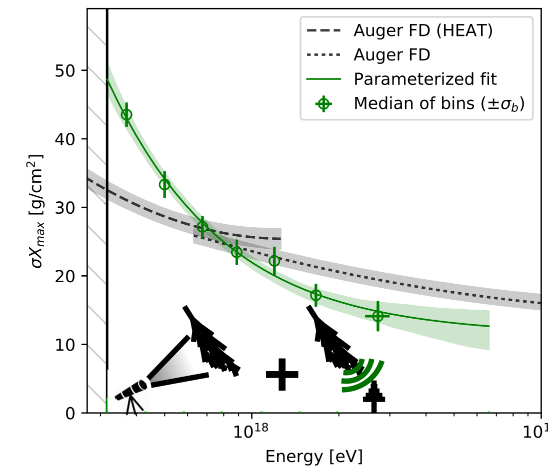
Published AERA X_{max} , upcoming interferometry AERA X_{max} publication

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



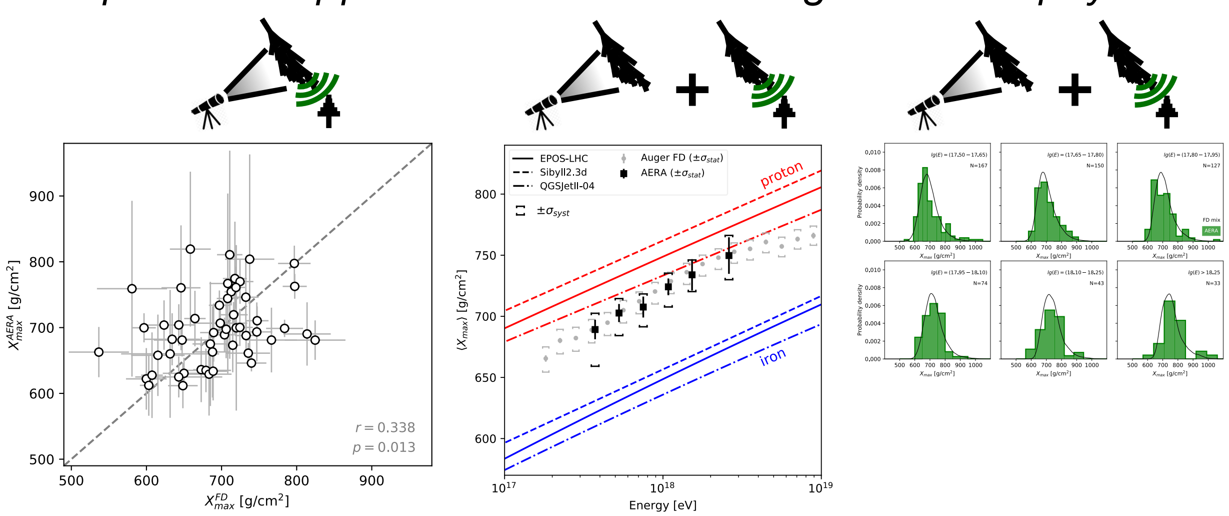


Competitive AERA X_{max} resolution

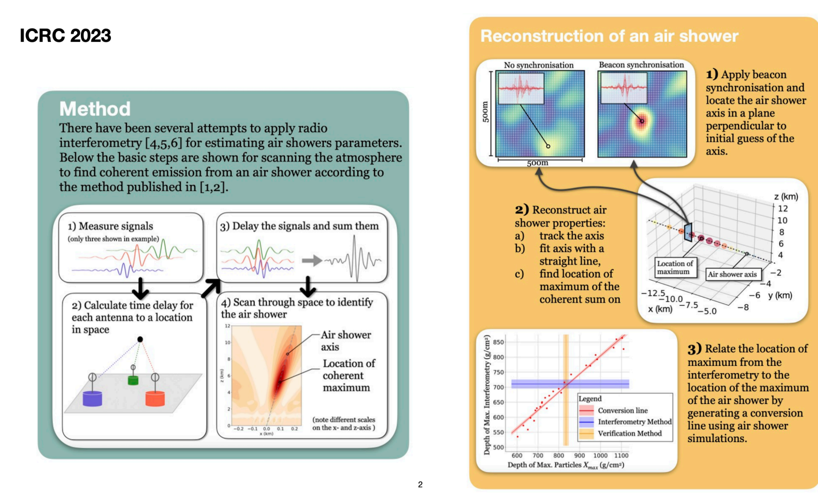


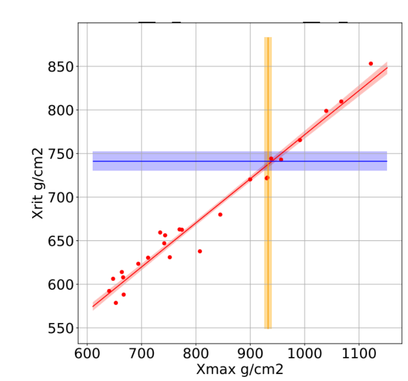
AERA X_{max} compatible with Auger Fluorescence

Independent support to our understanding of shower physics.



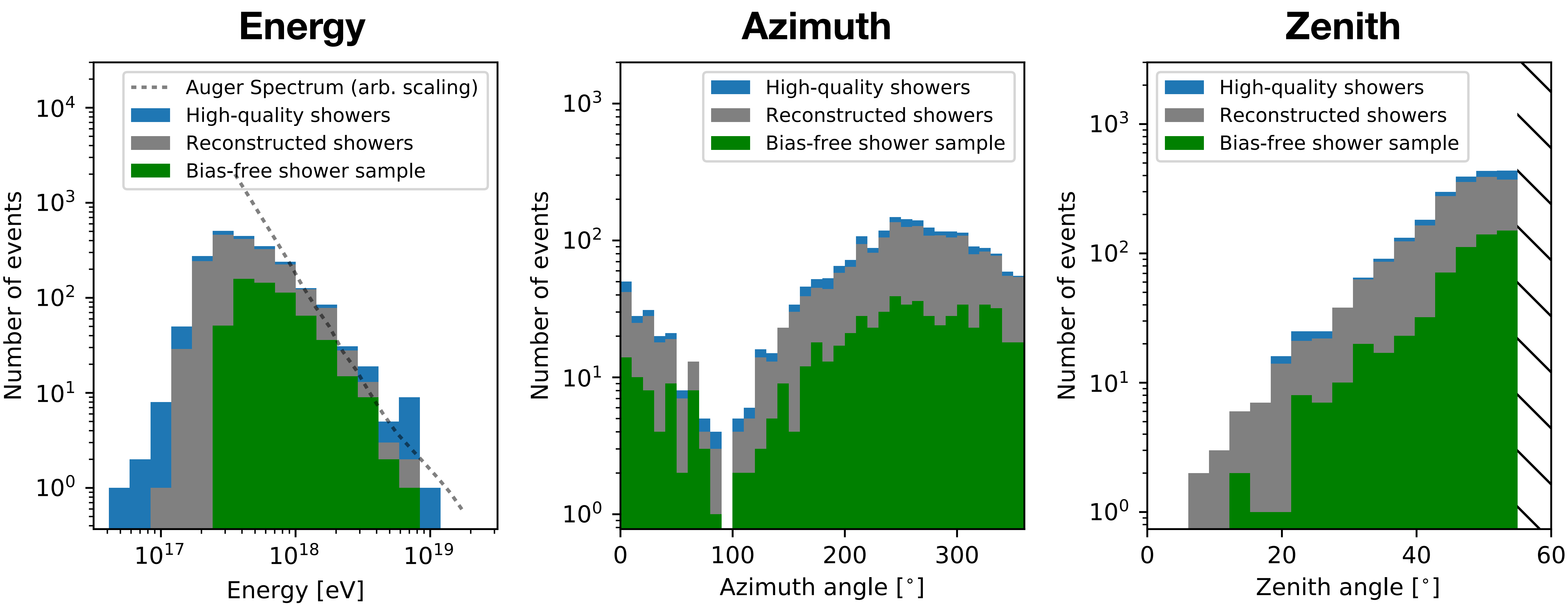
Validation & extension to horizontal showers with interferometry





Backup

Event selection



Method: Reconstructing X_{max} from the radio footprint

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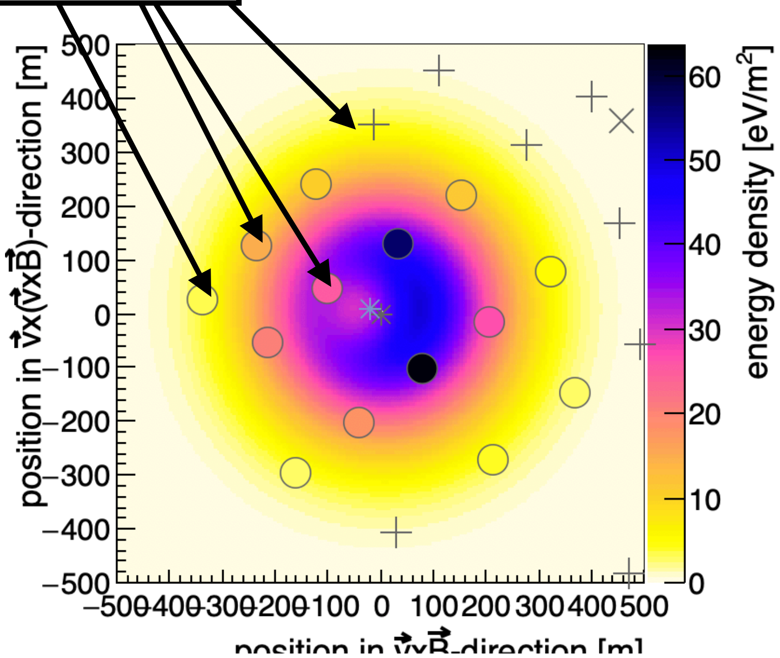
Reconstruction Air Shower

E, θ, ϕ, …

Antennas

Measured



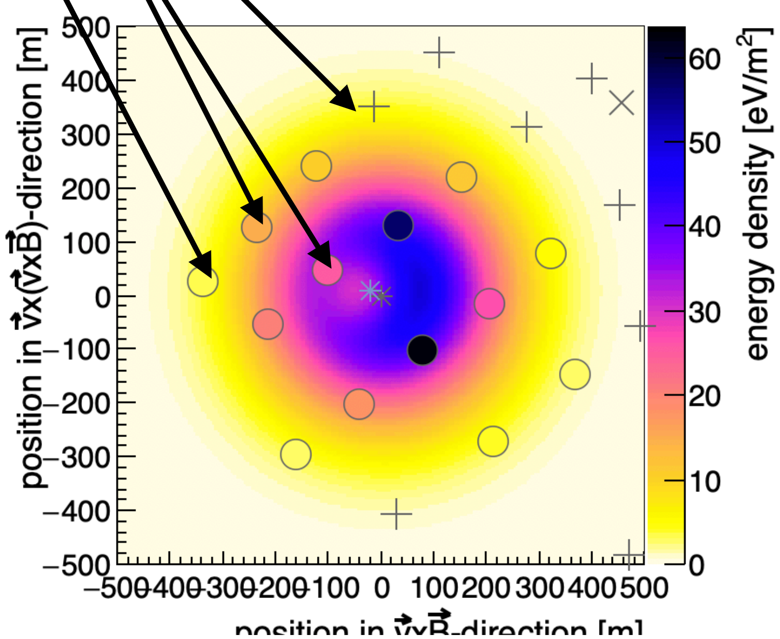
Method: Reconstructing X_{max} from the radio footprint

Reconstruction Air Shower → CORSIKA

E, θ, ϕ, … {X_{max}}

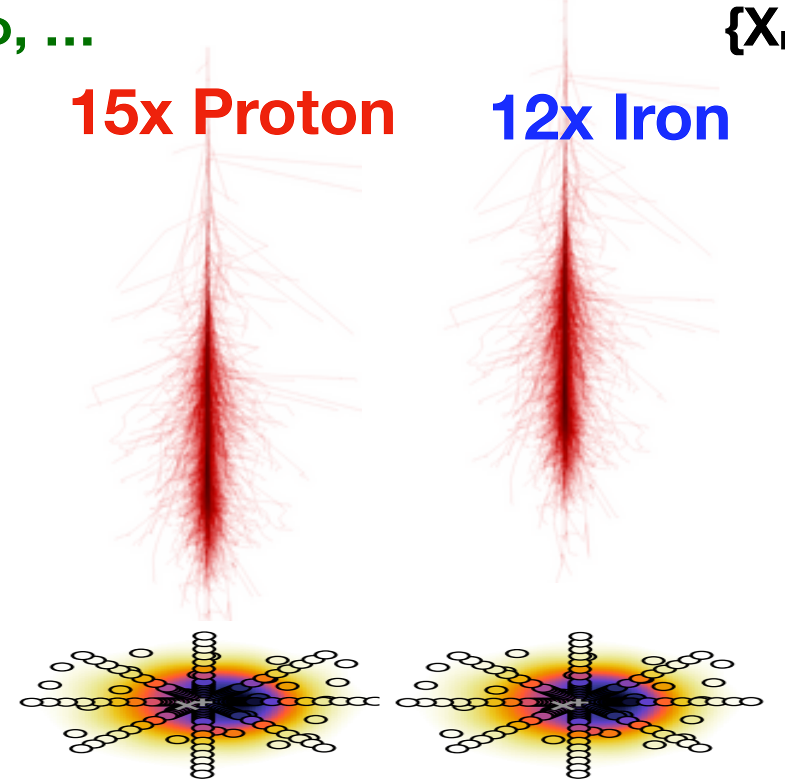
Antennas

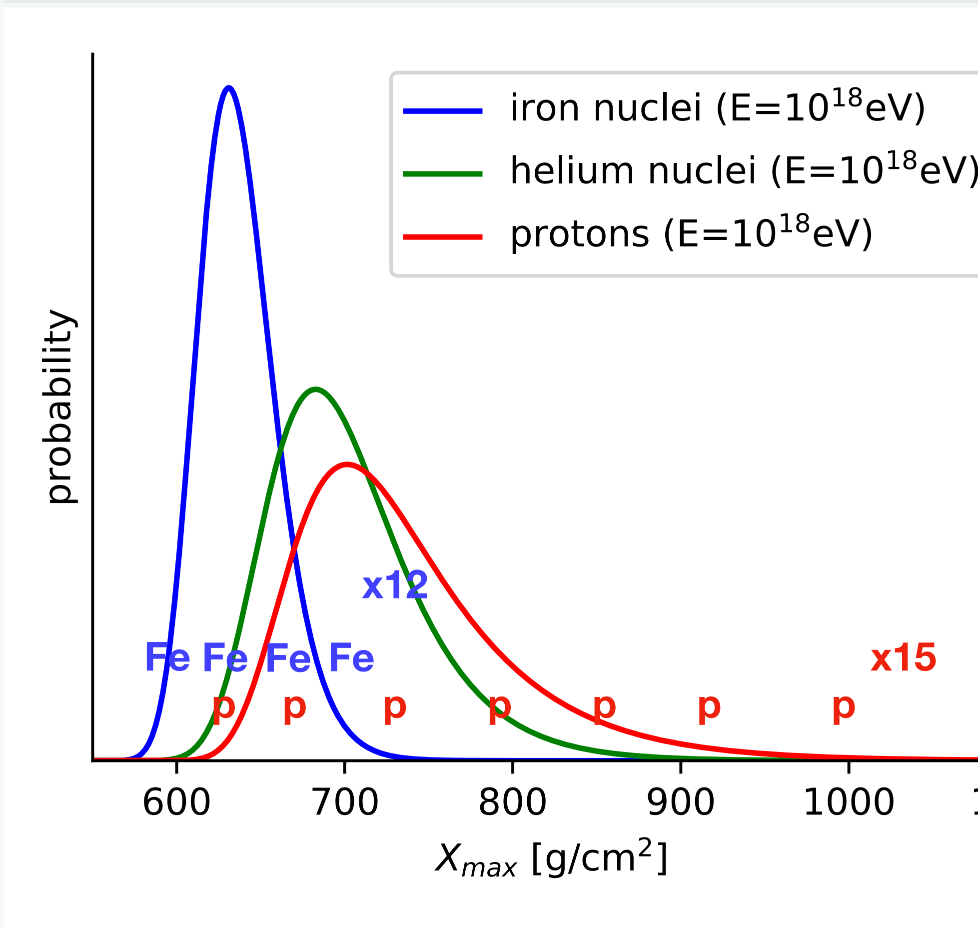
Measured



15x Proton

12x Iron





- **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

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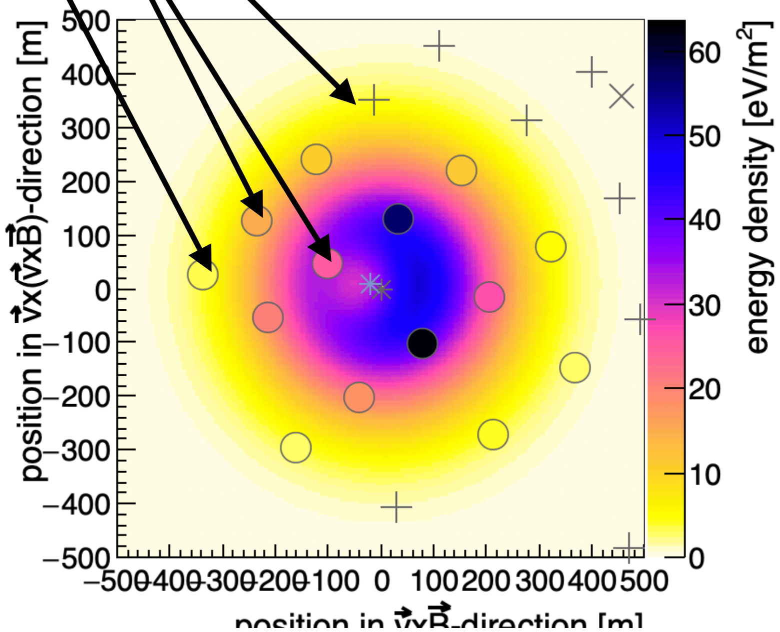
Reconstruction Air Shower → **CORSIKA** → **Reconstruction Simulations**

E, θ, ϕ, …

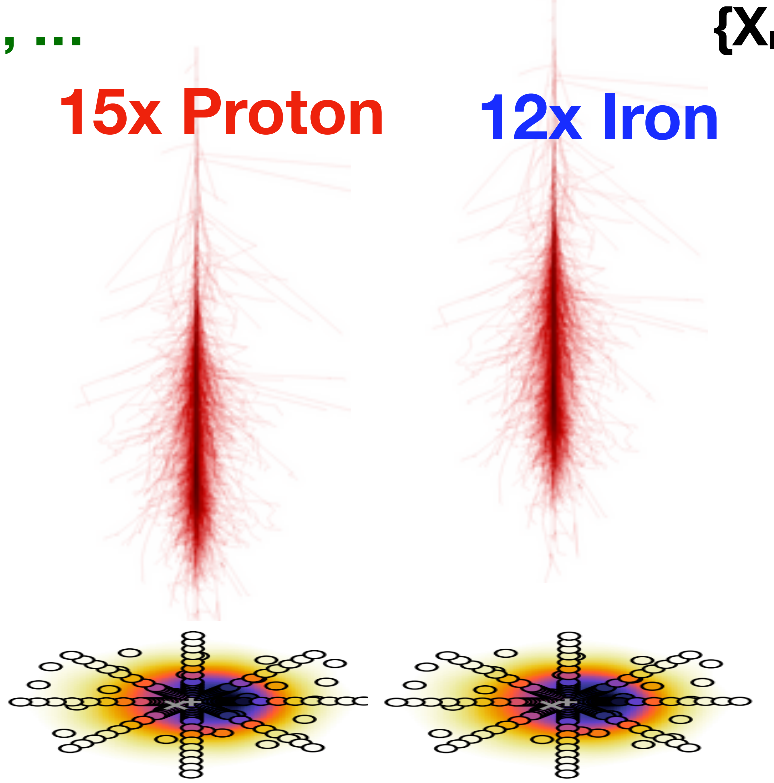
$\{X_{max}\}$

Antennas

Measured

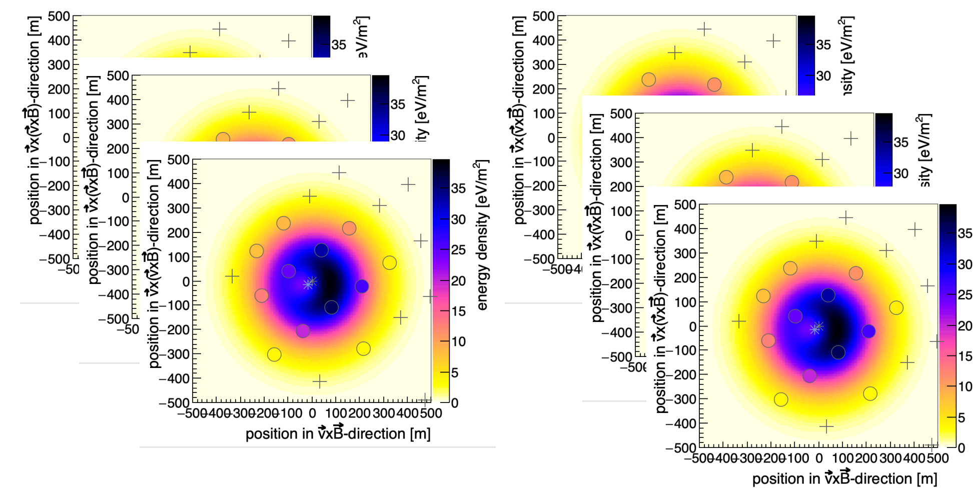


15x Proton **12x Iron**



Using same reconstruction code
(includes detector and reconstruction effects)

Proton **Iron**



Method: Reconstructing X_{max} from the radio footprint

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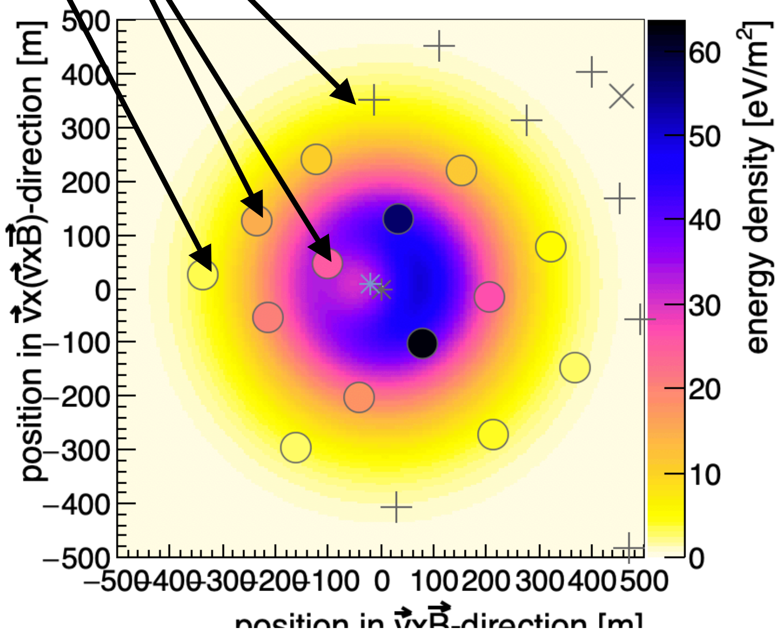
Reconstruction Air Shower → CORSIKA → Reconstruction Simulations

E, θ, ϕ, … {X_{max}}

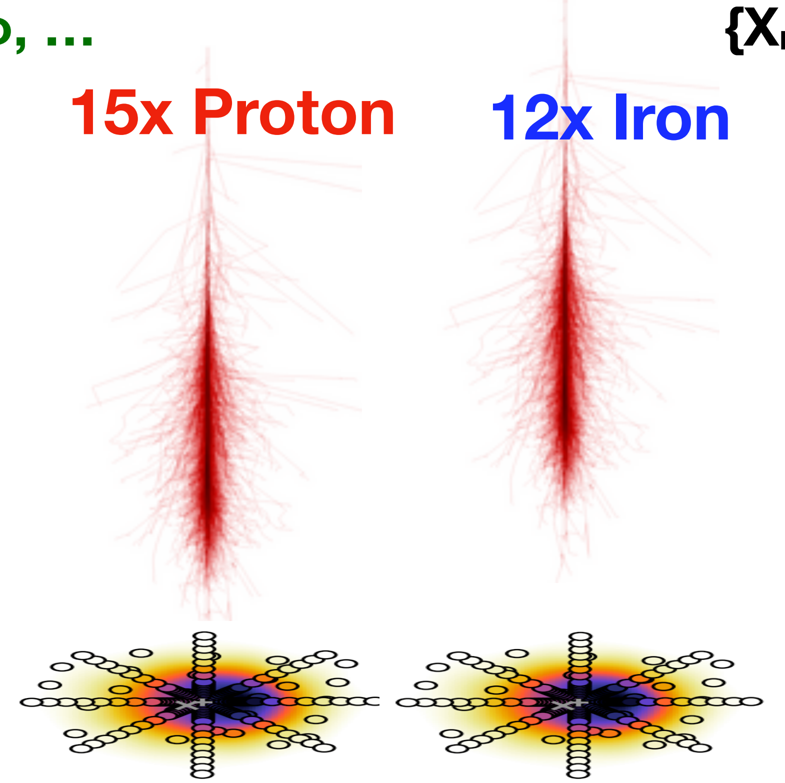
Using same reconstruction code
(includes detector and reconstruction effects)

Antennas

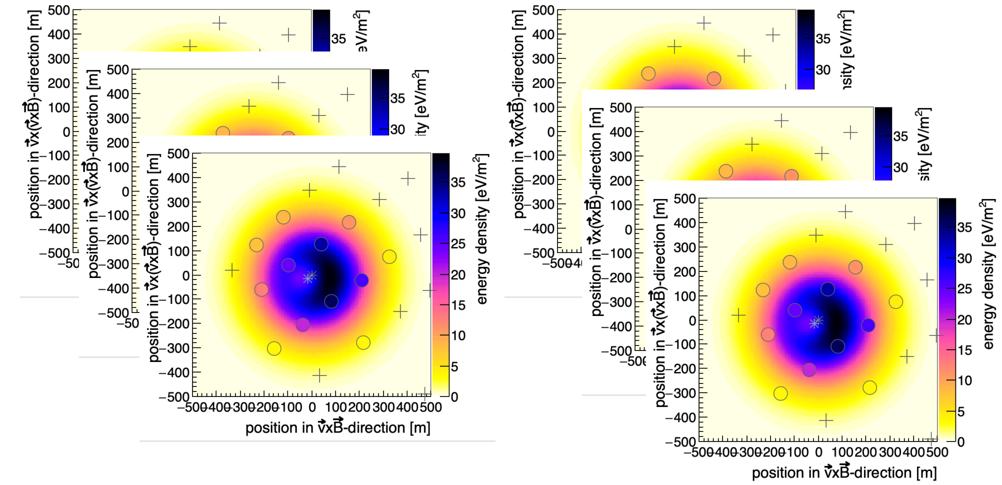
Measured



15x Proton **12x Iron**



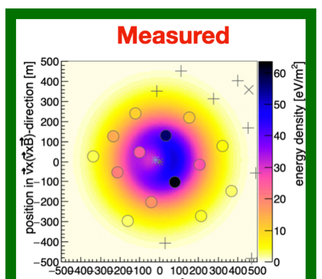
Proton **Iron**



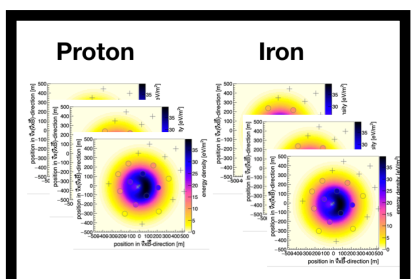
Minimise to find X_{max} of measured shower:

Based on Buitink+(2016)

Measured

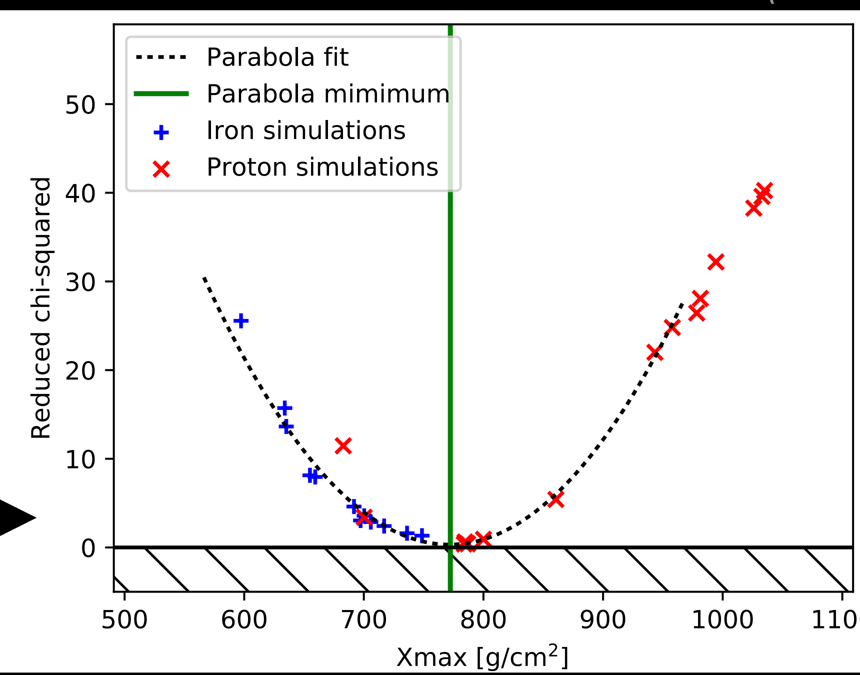


Proton Iron



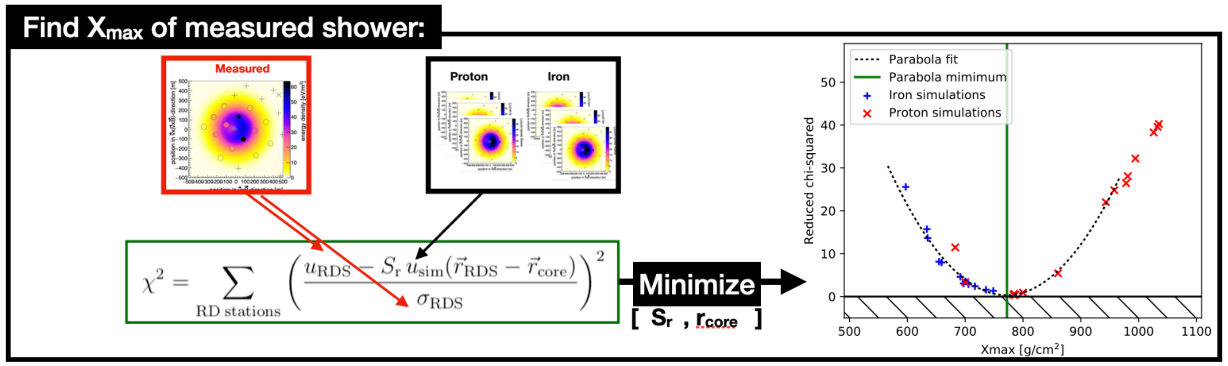
$$\chi^2 = \sum_{\text{AERA Stations}} \left(\frac{u_{\text{data}} - S \cdot u_{\text{sim}}(\Delta \vec{r}_{\text{core shift}})}{\sigma u_{data}} \right)$$

Minimize [S , r_{core}]

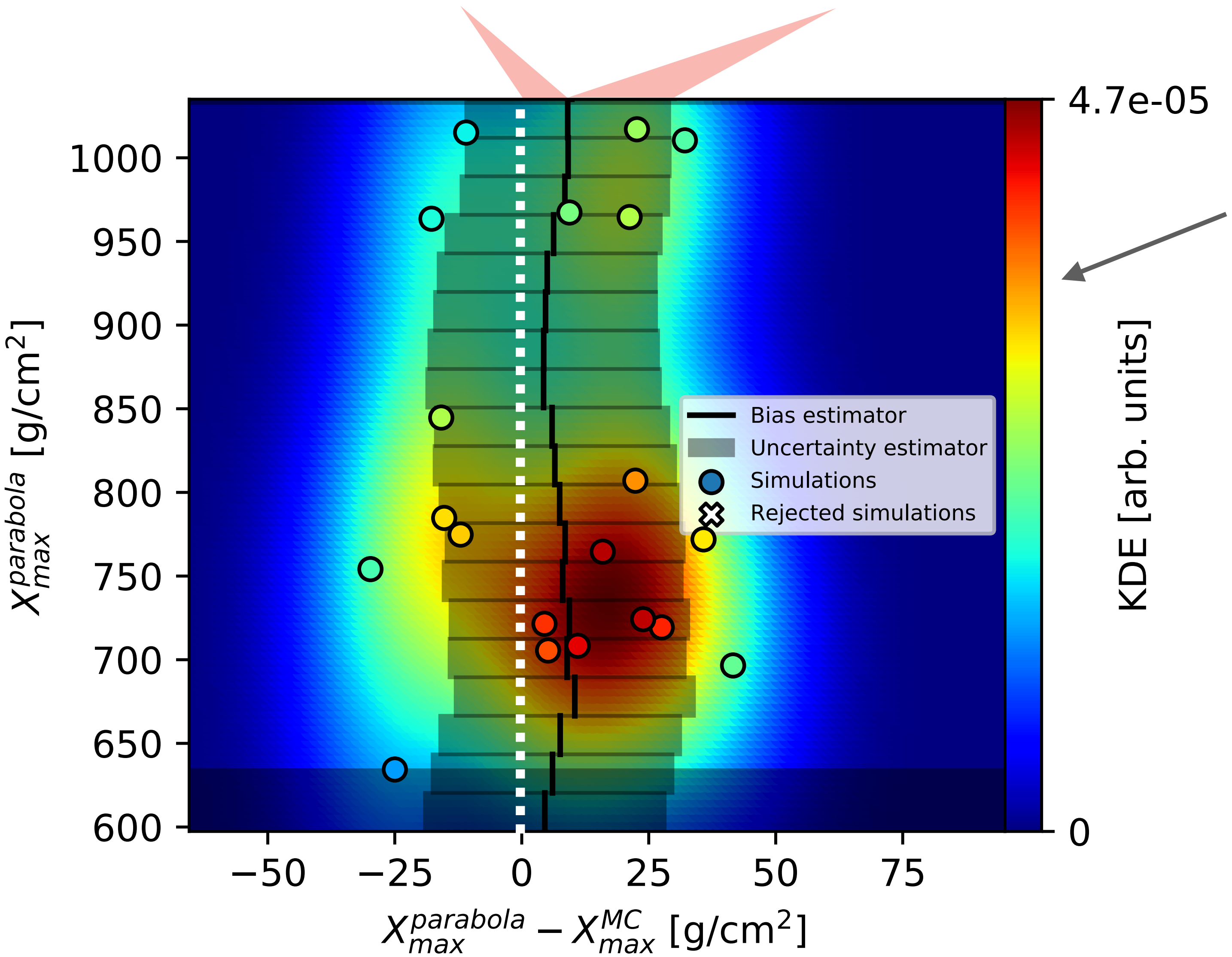


Method: Bias correction on the parabola-X_{max}

- <u>Step 2</u> — **bias correction per event:** Also, reconstruct X_{max} for each simulation with *Leave-one-out cross validation.*



- **Compare {Parabola vs MC} values of 27 simulations:** Allows to correct for bias & estimate σX_{max} ; (KDE modelled)

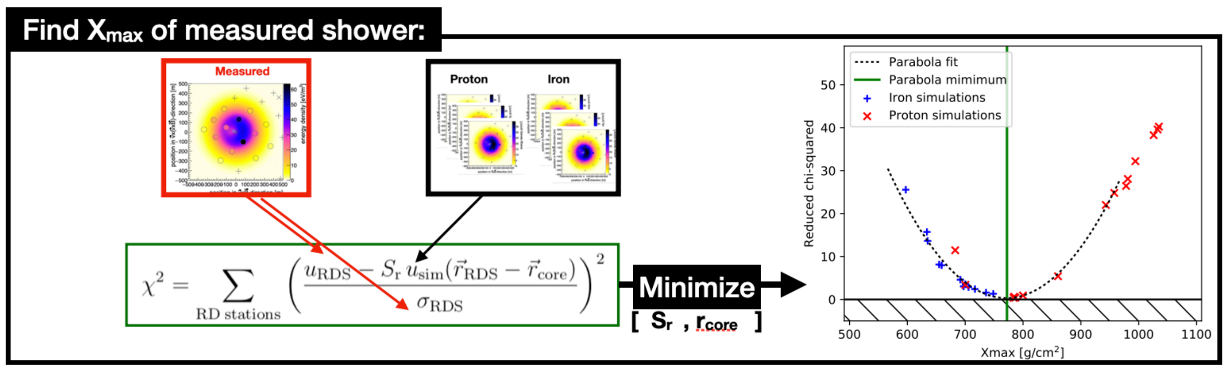


- *Points are the simulations*
- *Background is KDE of that*
  —> it provides pdf at any $X_{max,parab}$ slice
- *Black region is the 1sigma bias model*

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

Some other examples of event bias corrections

- <u>Step 2</u> — **bias correction per event:** Also, reconstruct X_{max} for each simulation with *Leave-one-out cross validation.*



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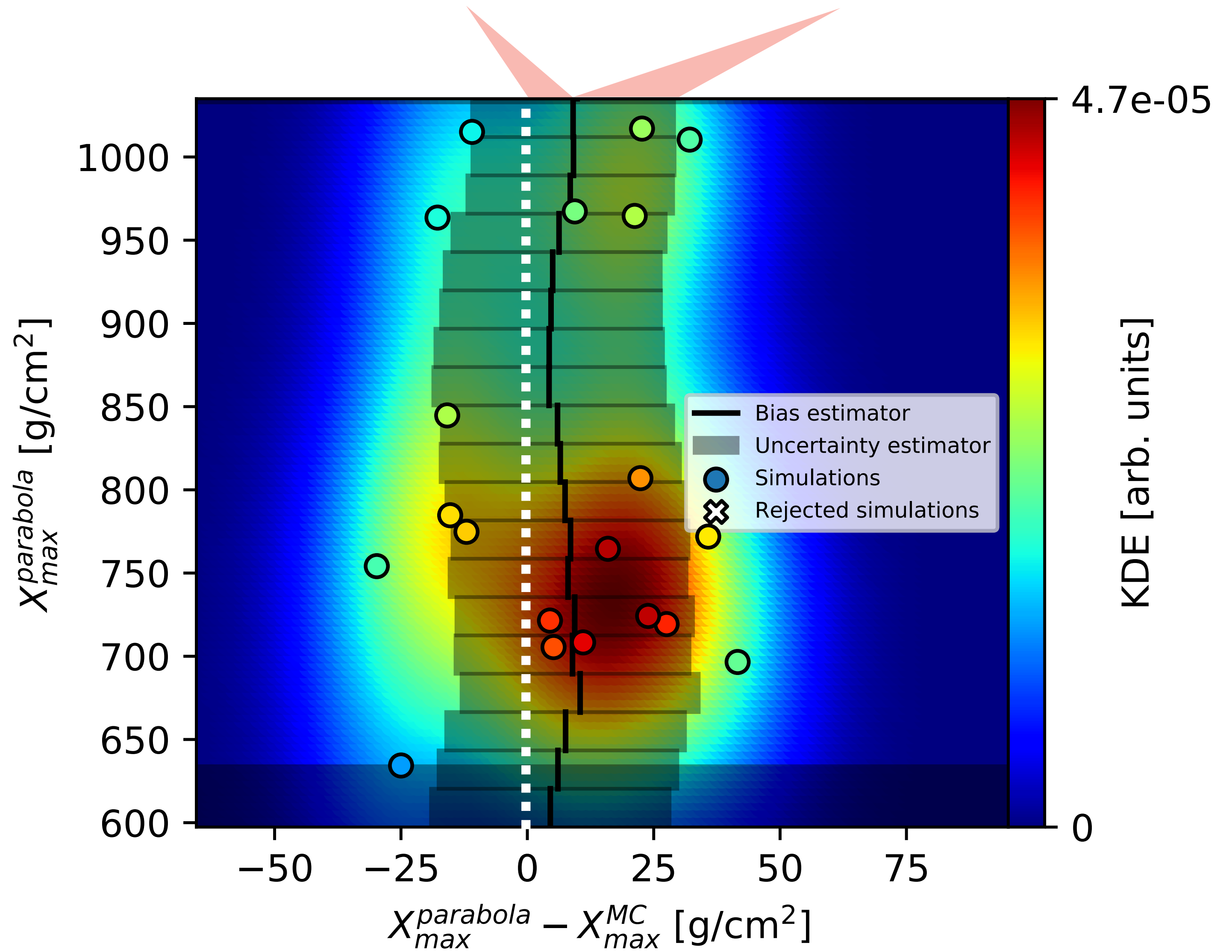
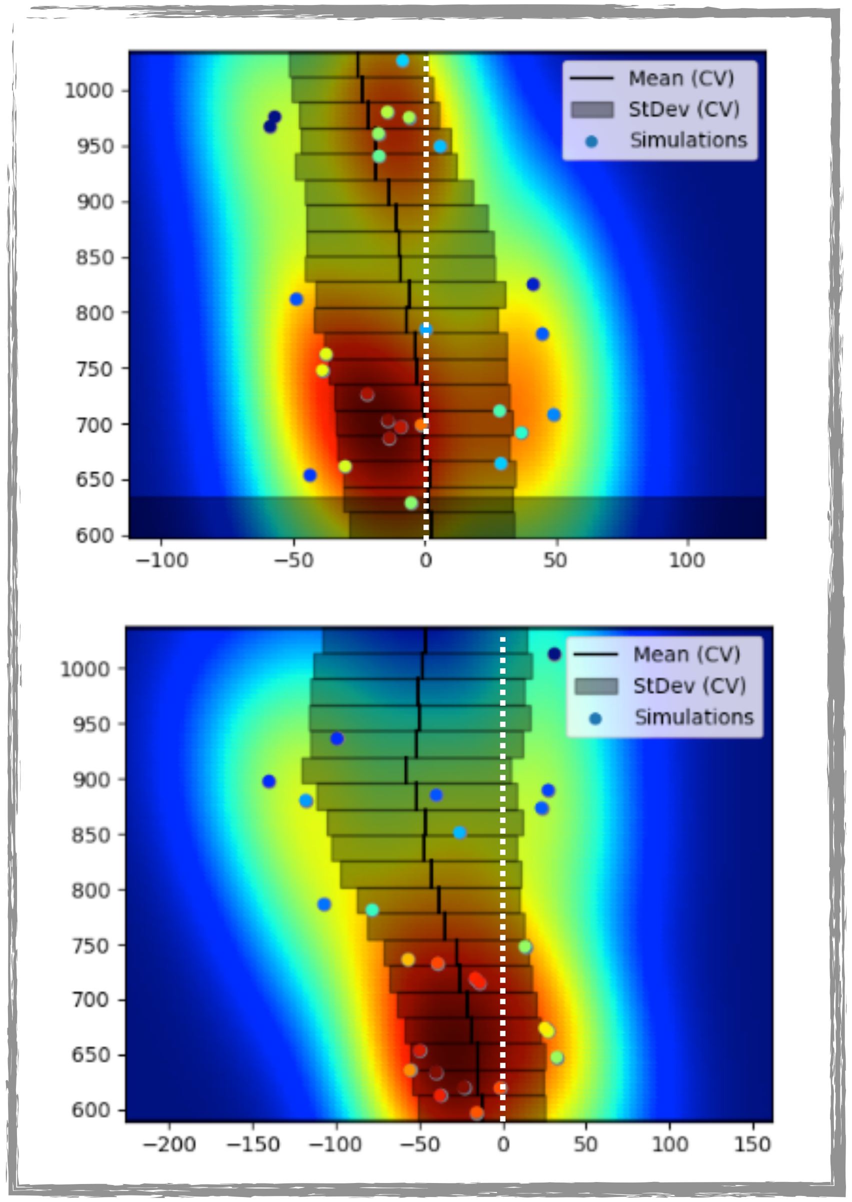


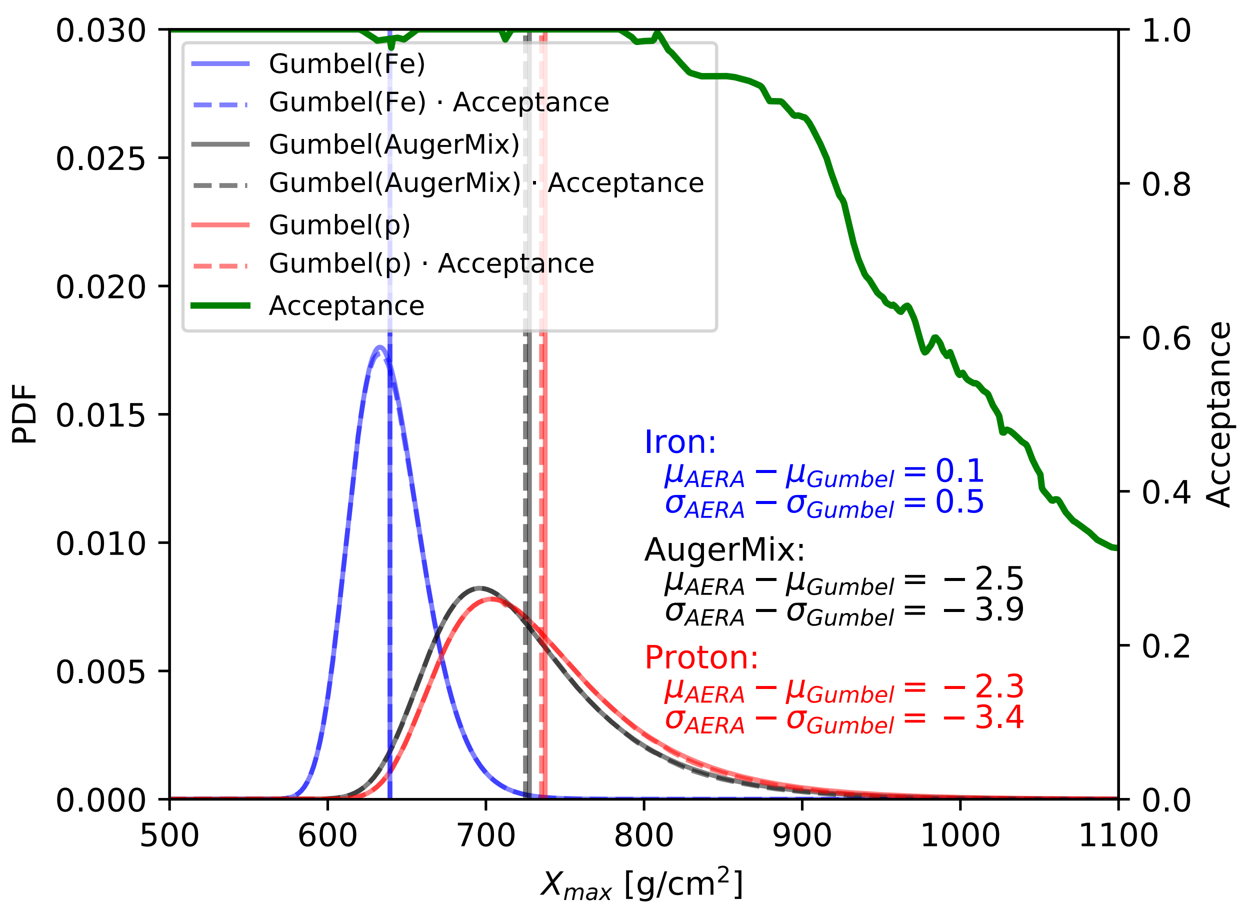
Some other examples



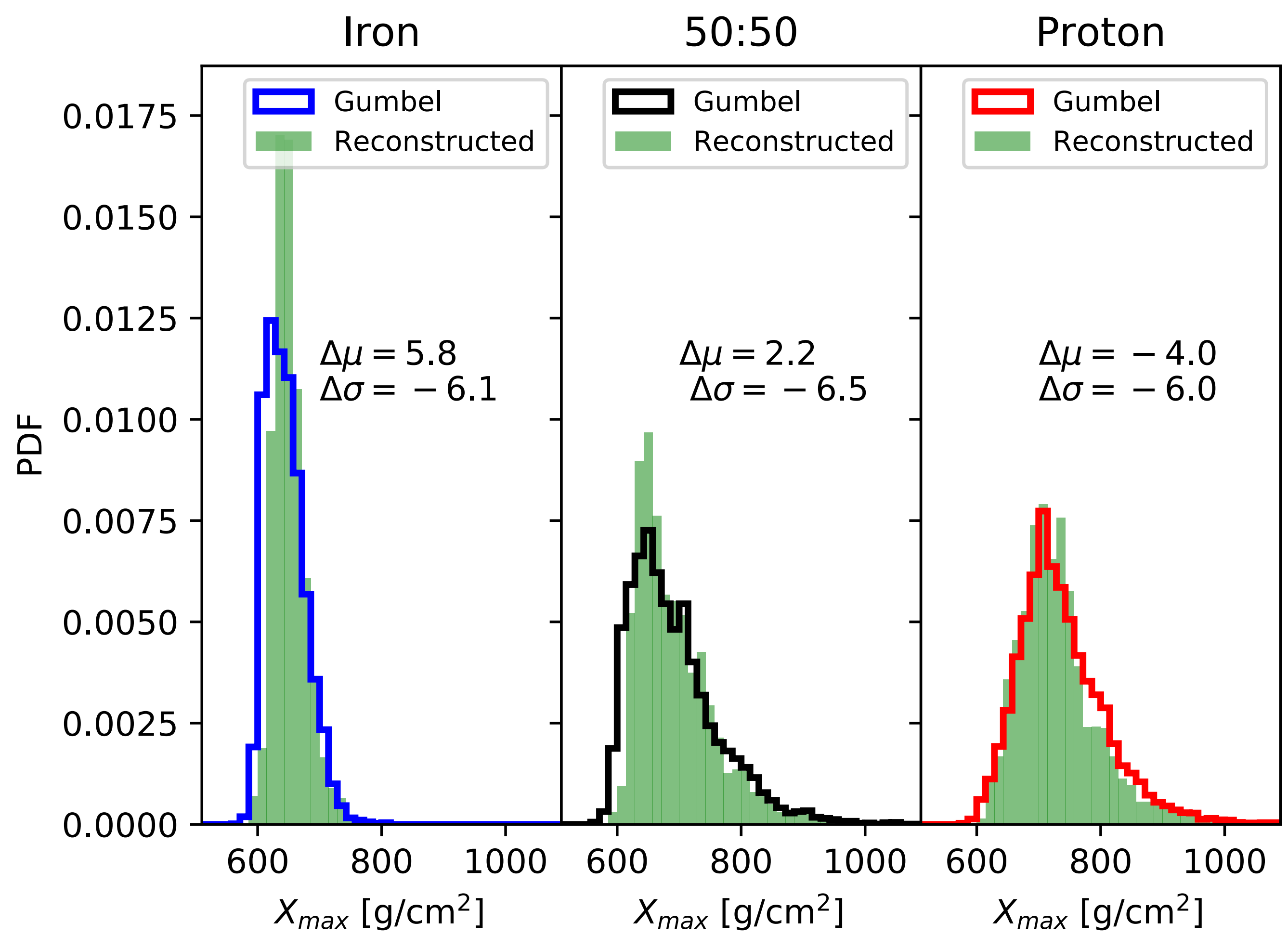
Reconstruction bias (for one energy bin)

- Using reconstruction of X_{max} for our simulations we can calculate the bias when we assume the range of possible underlying compositions.
- Similarly, we can try to reconstruct all our simulations and see what fraction would be seen (acceptance) and what the effect is on the X_{max} distribution.

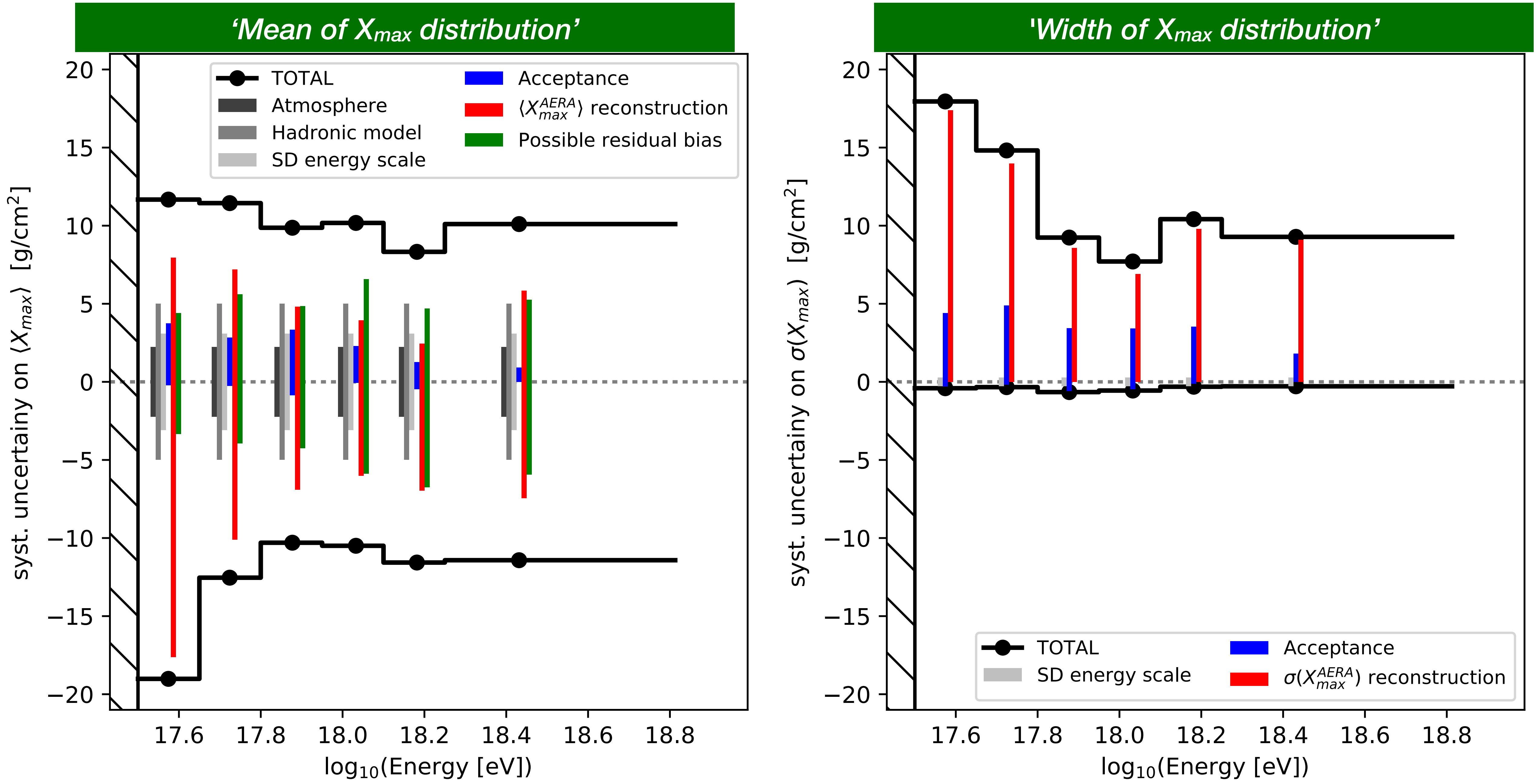
Acceptance calculation (1 energy bin)



Reconstruction bias calculation (1 energy bin)



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*
- **Cross-checks** : *residual bias checks with Zen/Az/core/… vs <X_{max}> and E*