Highlights from the Auger Engineering Radio Array

Bjarni Pont
For the Pierre Auger Collaboration

Postdoc
Radboud University (NL)

Introduction: AERA at the Pierre Auger Observatory

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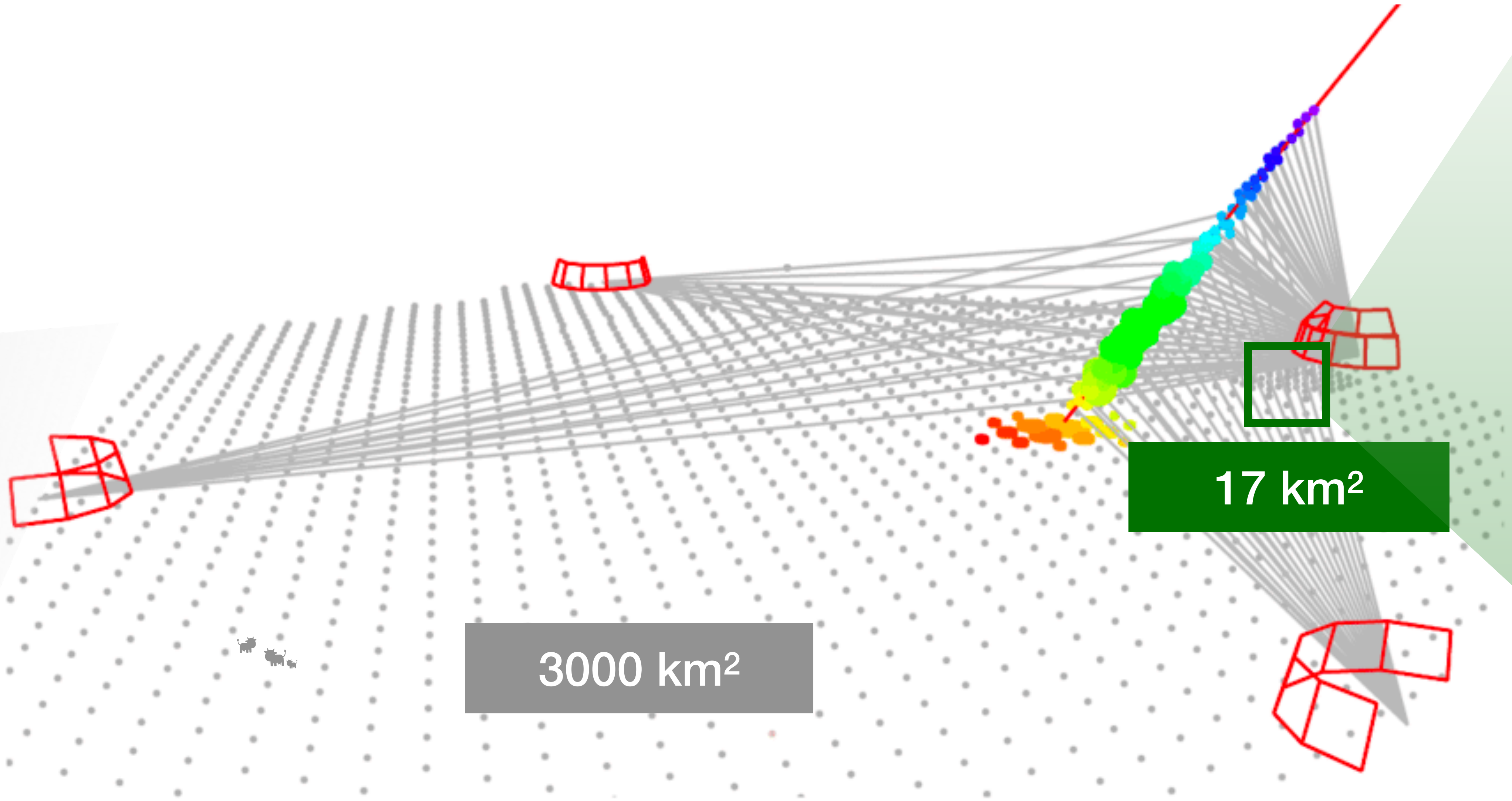
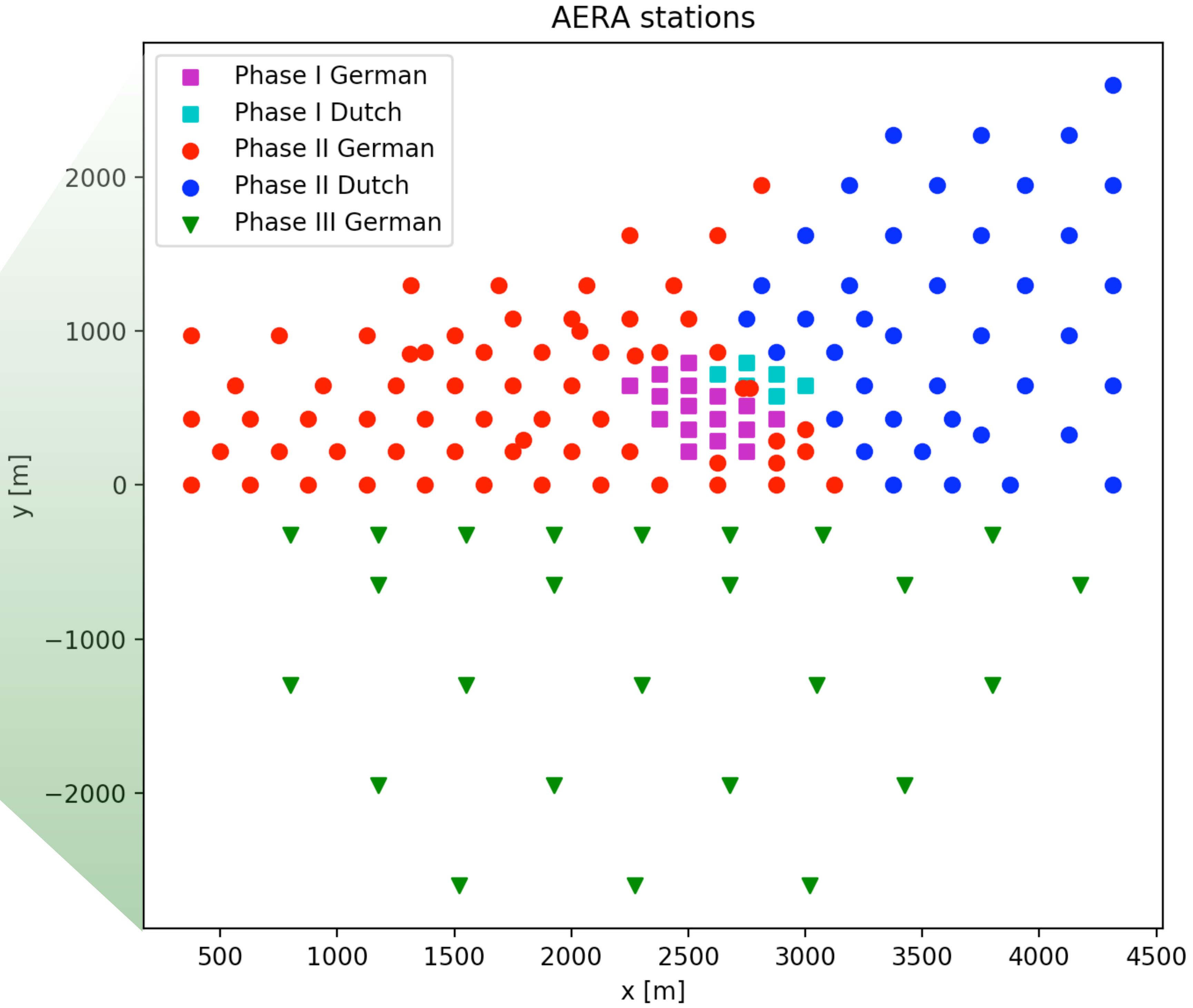
Auger **Engineering** Radio Array

- 153 autonomous radio antennas
  - Dense Phase-I grid of **LPDA**-type antennas
  - Large Phase-II grid of **Butterfly**-type antennas
- Energy range: 10^{17}-10^{19} eV
- Frequency range: 30-80 MHz
- A decade of data for long-term calibration
- >2000 high quality events over 7 years for mass composition
- Beacon system for nanosecond timing calibration: —> Interferometry





Overview — ”on energy and mass”

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On CR energy

Radio as a stable calibration source for (multi-)hybrid detectors

(AERA & RD)

On mass composition

X_{max} from the radio footprint

Vertical showers
(AERA)

X_{max} from radio interferometry

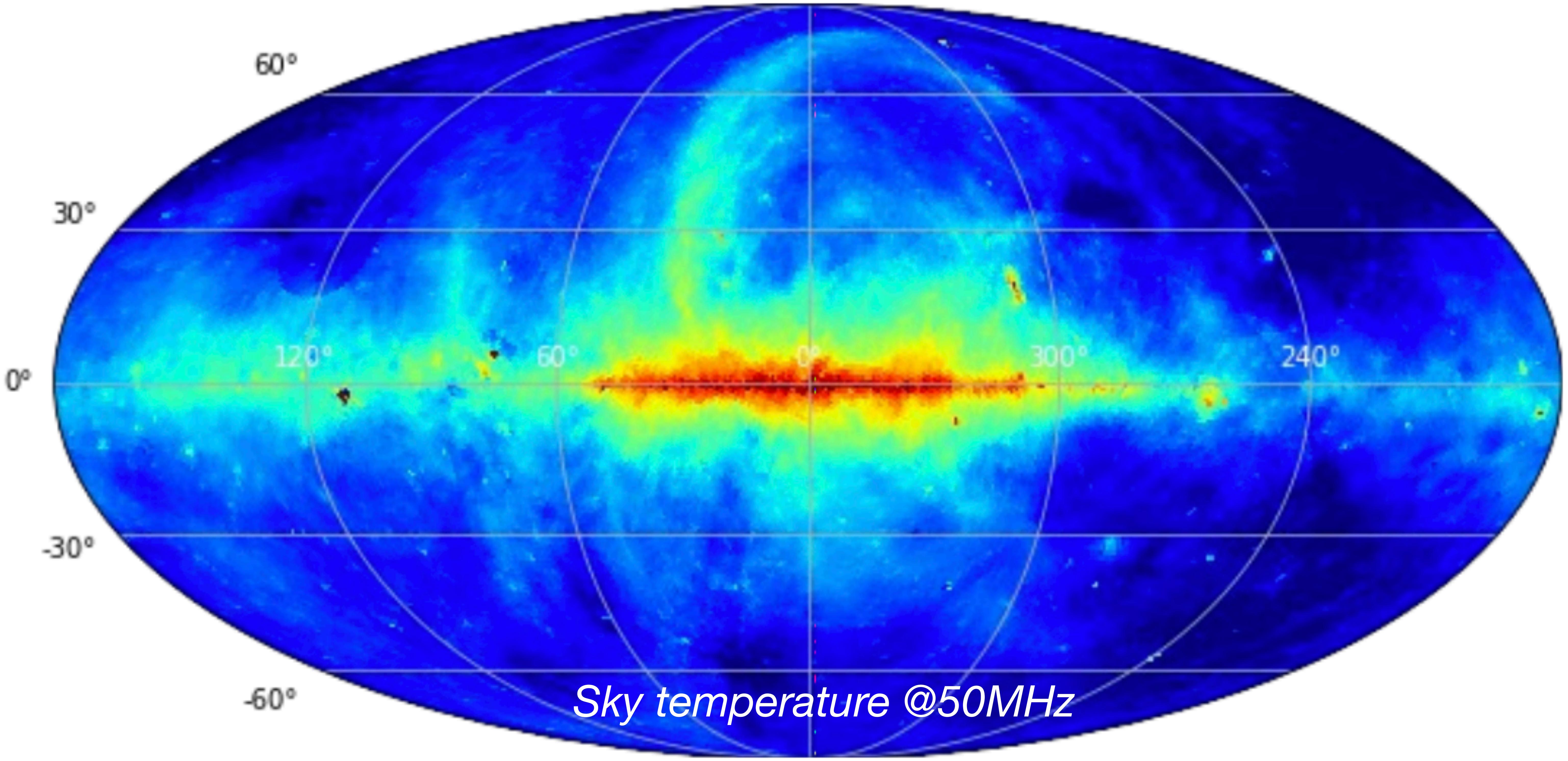
Inclined air showers
(AERA & RD)

Mass composition with WCD(muon) + Radio(em)

—> See Marvin Gottowik’s poster! (AERA)
—> See Jörg Hörandel’s poster! (RD)

Part 1:

Long-term calibration and the stability of the radio signal



Motivation

- **Absolute calibration** provides a stable scale for cosmic ray energy.
- CR detectors usually suffer from ageing (dust accumulation, PMT ageing, …).
  —> Radio does not age (as will be shown)
  —> Radio can reduce systematic uncertainty on CR energy scale.

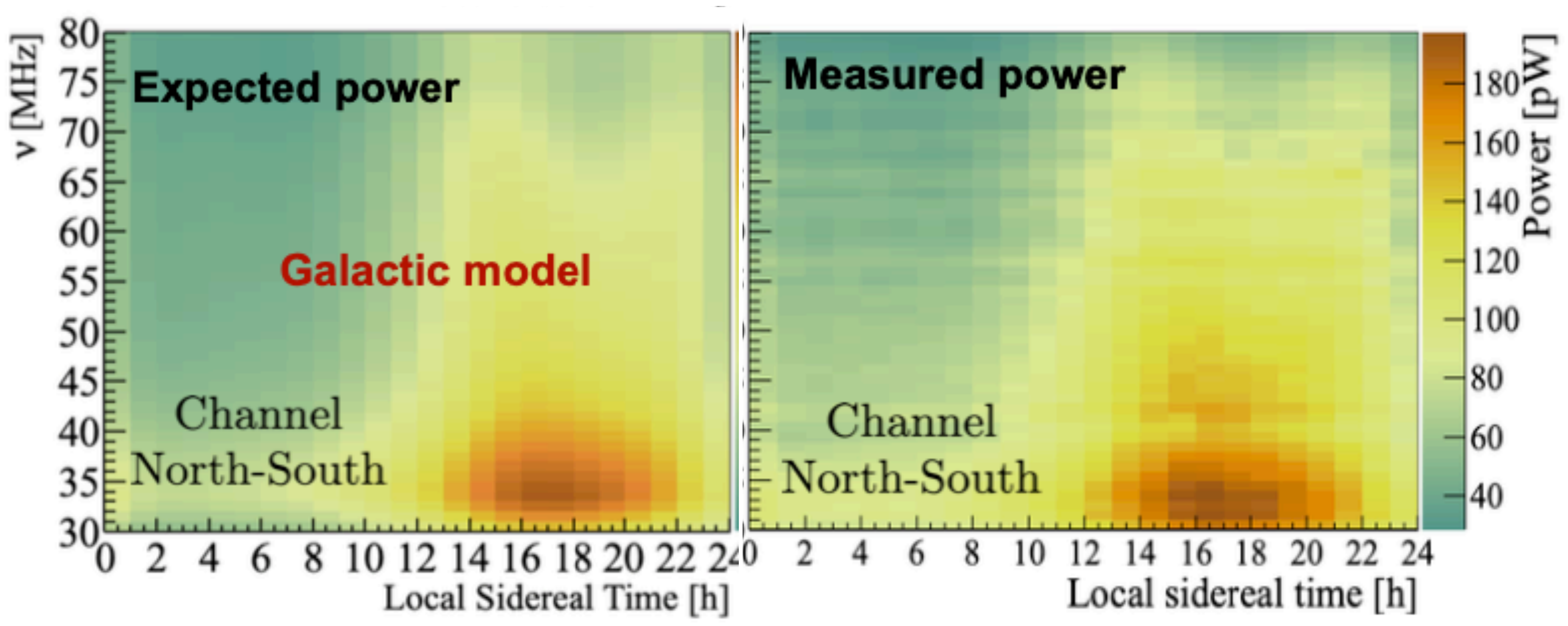
Method: measurements vs expected power

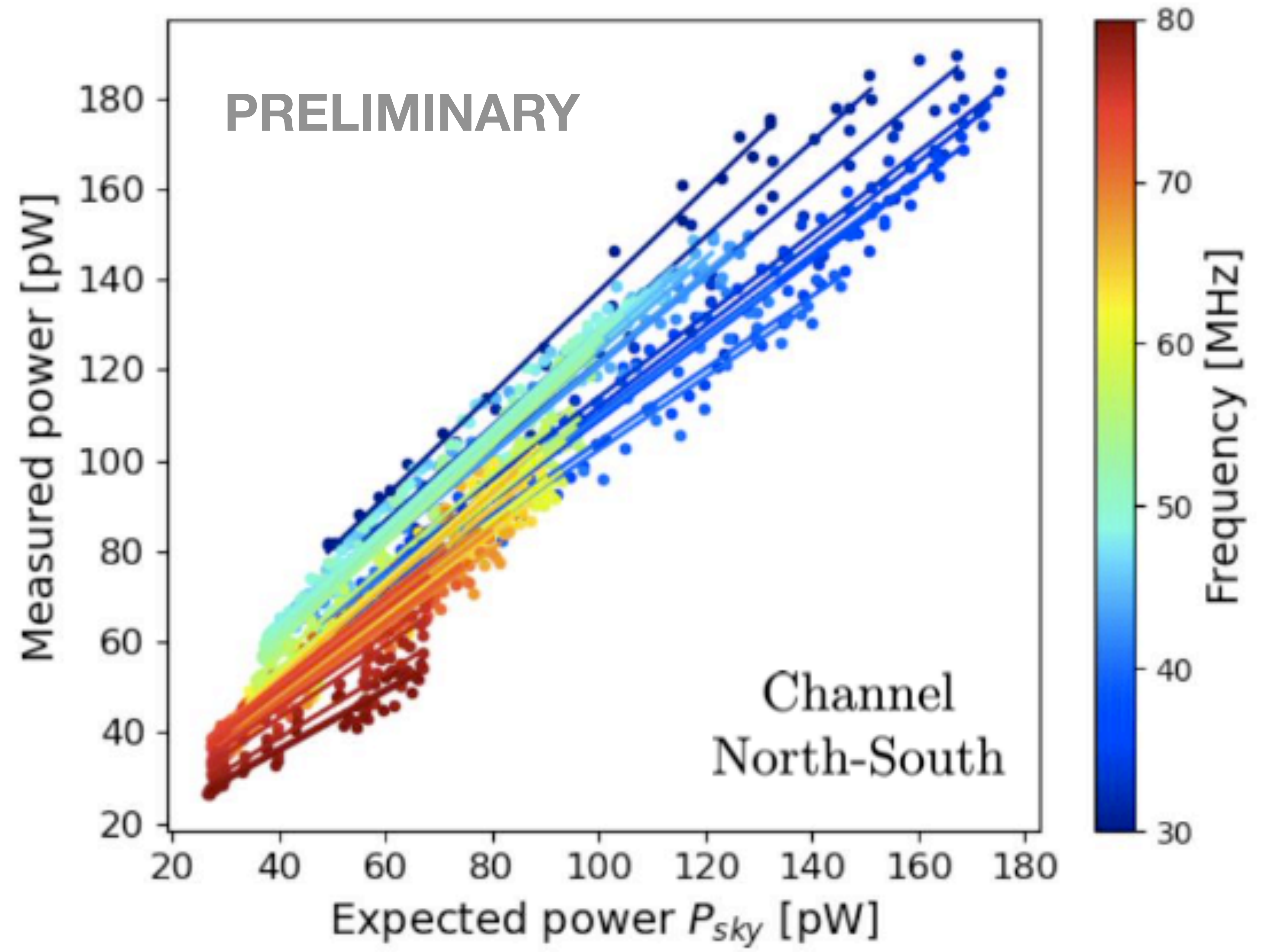
- **Expected power** from model (one is shown here)
- **Measured power** (after RFI cleaning)

$$P_{model}(t,\nu) = P_{sky}(t,\nu)G_{ant}(\nu)G_{RCU}(\nu)C_0^2(\nu) + N_{tot}(\nu)$$

- Fit expected vs measured power at each frequency:
  - C_0 = **calibration constant**
  - N_{tot} = background noise

- Independent linear fit for each frequency band





Galactic calibration agrees with lab calibration

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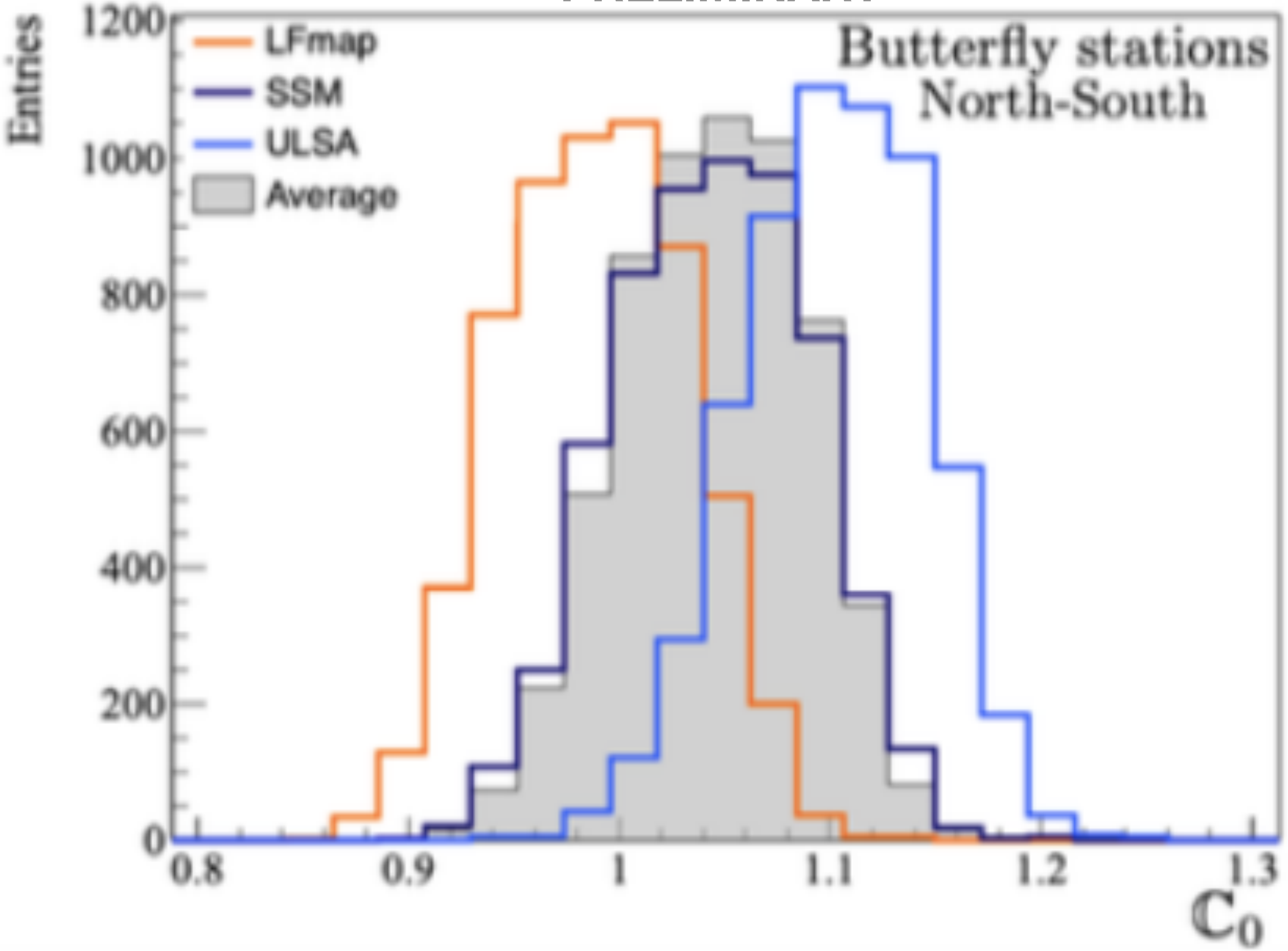
- Averaged over frequency, $\mathbb{C}_0 \equiv \frac{1}{N_\nu}\sum_\nu \mathbb{C}_0(\nu)$ per station, per month, over a decade:
  *153 *12 *10
- The **lowest**, **central**, and **highest** sky models are shown
  - Range between distribution: systematic uncertainty.
  - Width of each distribution: statistical spread

Station (channel)	$\widehat{\mathbb{C}}_0 \pm \sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{syst}}$
Butterfly (East-West)	$1.08 \pm 0.05 \pm 0.05$
Butterfly (North-South)	$1.04 \pm 0.04 \pm 0.06$
LPDA (East-West)	$1.01 \pm 0.07 \pm 0.06$
LPDA (North-South)	$1.01 \pm 0.04 \pm 0.06$

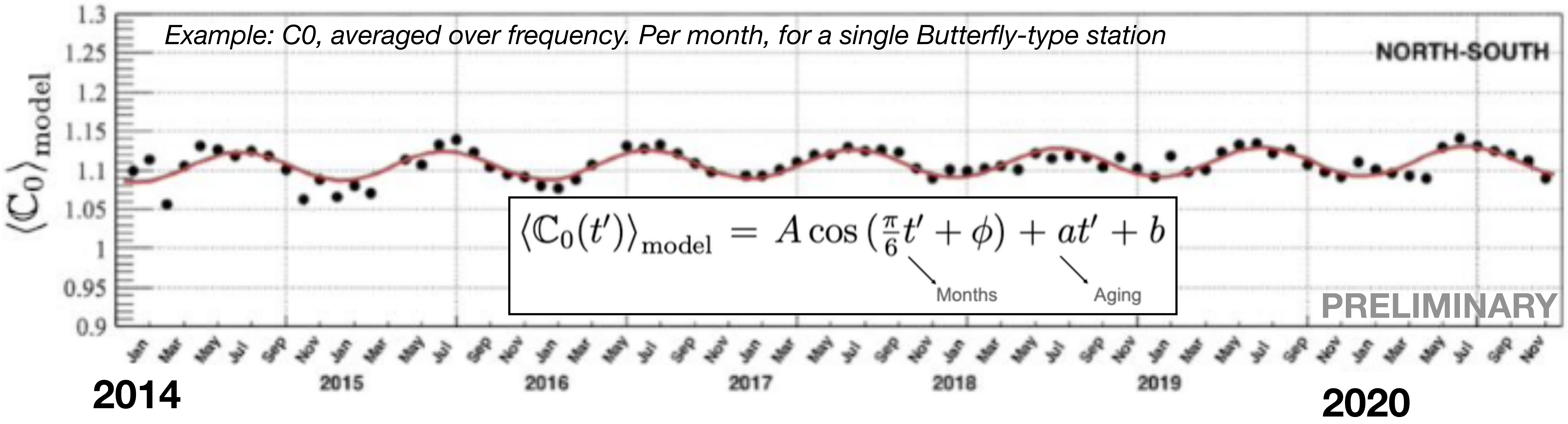
Compatible with 1
"Lab-measured signal chain is well-understood"

PRELIMINARY



Calibration shows no ageing

- Evolution over time? — no: single station example



Seasonal modulation is an understood method artefact, due to varying noise background

- All data together: per station type and antenna arm:

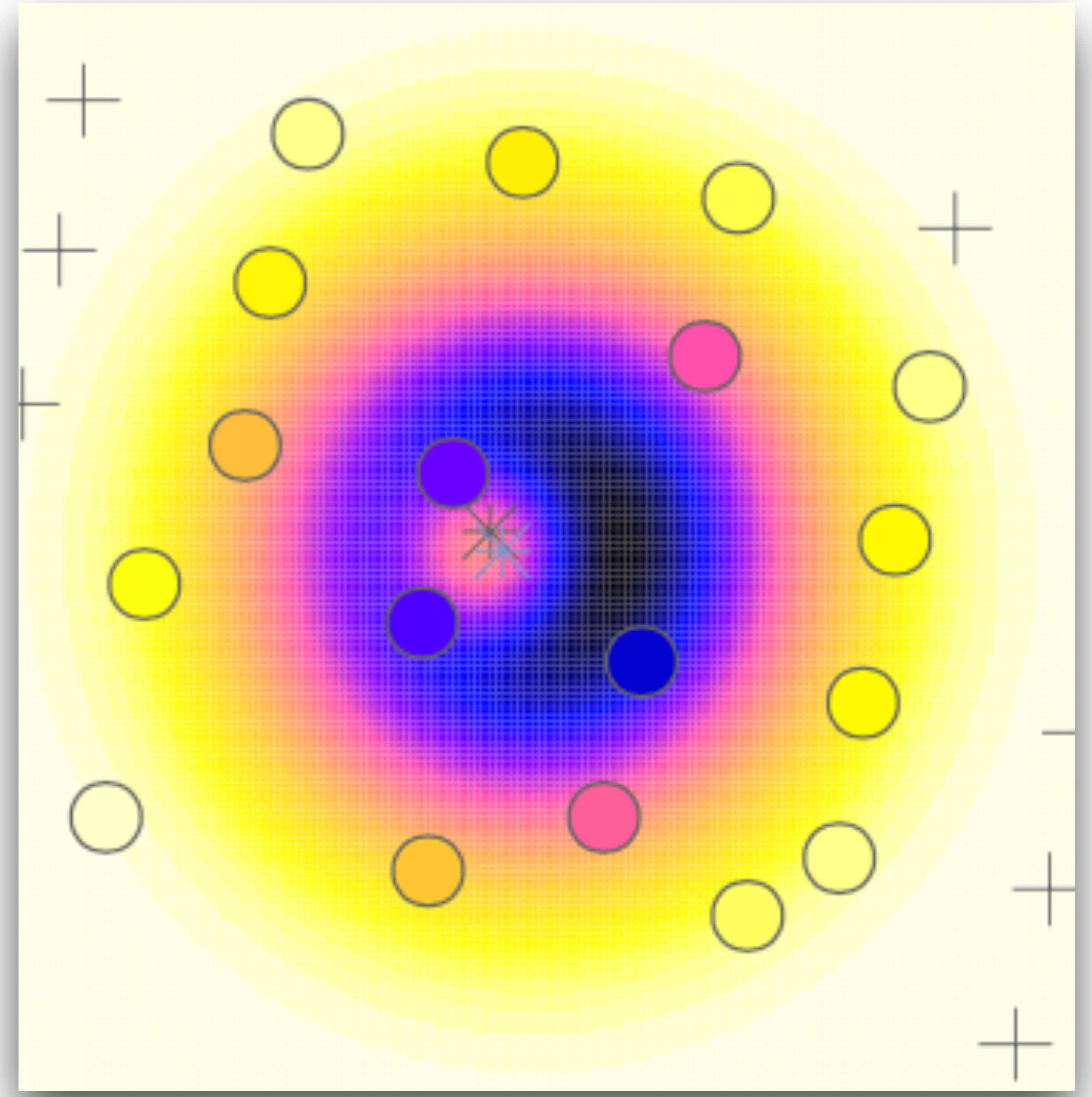
Station (channel)	Aging per decade (%)
Butterfly (East-West)	0.28 ± 0.82
Butterfly (North-South)	-0.14 ± 0.76
LPDA (East-West)	-1.7 ± 1.7
LPDA (North-South)	-2.1 ± 1.6

- Combined: -0.32 ± 0.51 % per decade (on both measured radio signal and on cosmic ray energy)

"Compatible with no ageing"
"Radio can function as a calibrator for other detectors (FD, WCD, …)"

Part 2:

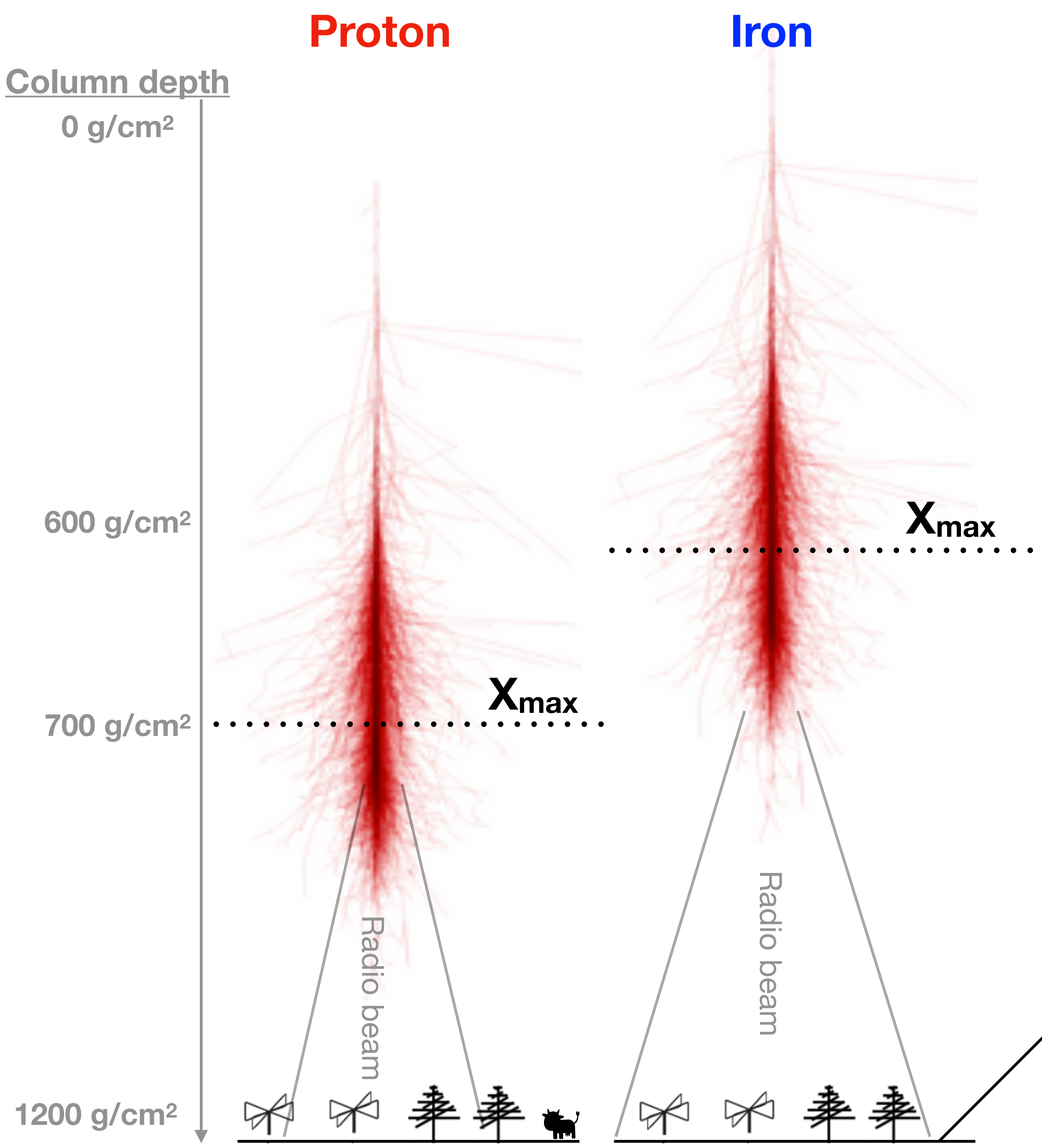
X_{max} from the radio footprint



- Phys. Rev. Lett. 132, 021001 (2024):
  Demonstrating compatibility Fluorescence and Radio X_{max}

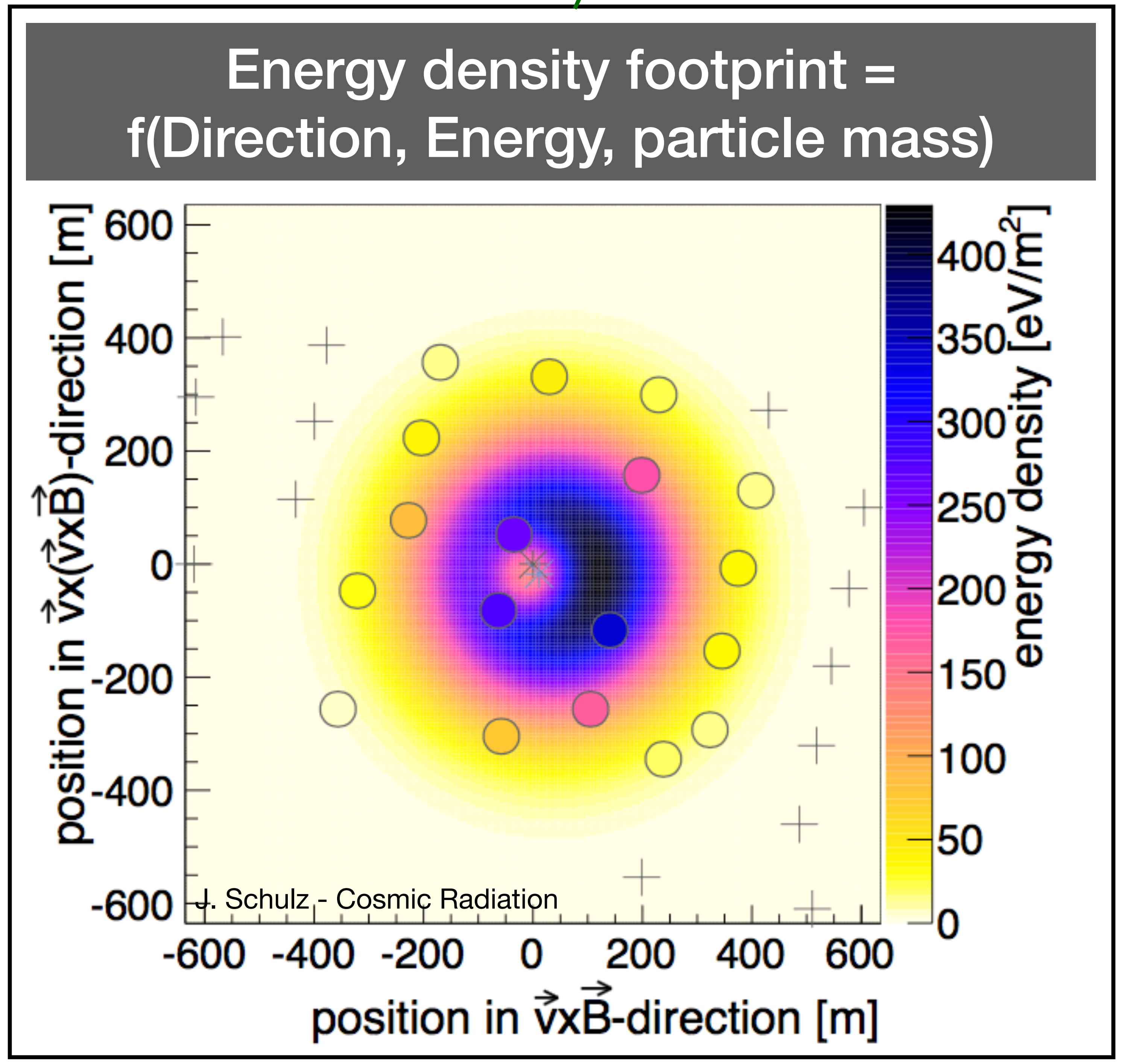
- Phys. Rev. D 109, 022002 (2024):
  Method and detailed results of AERA X_{max}

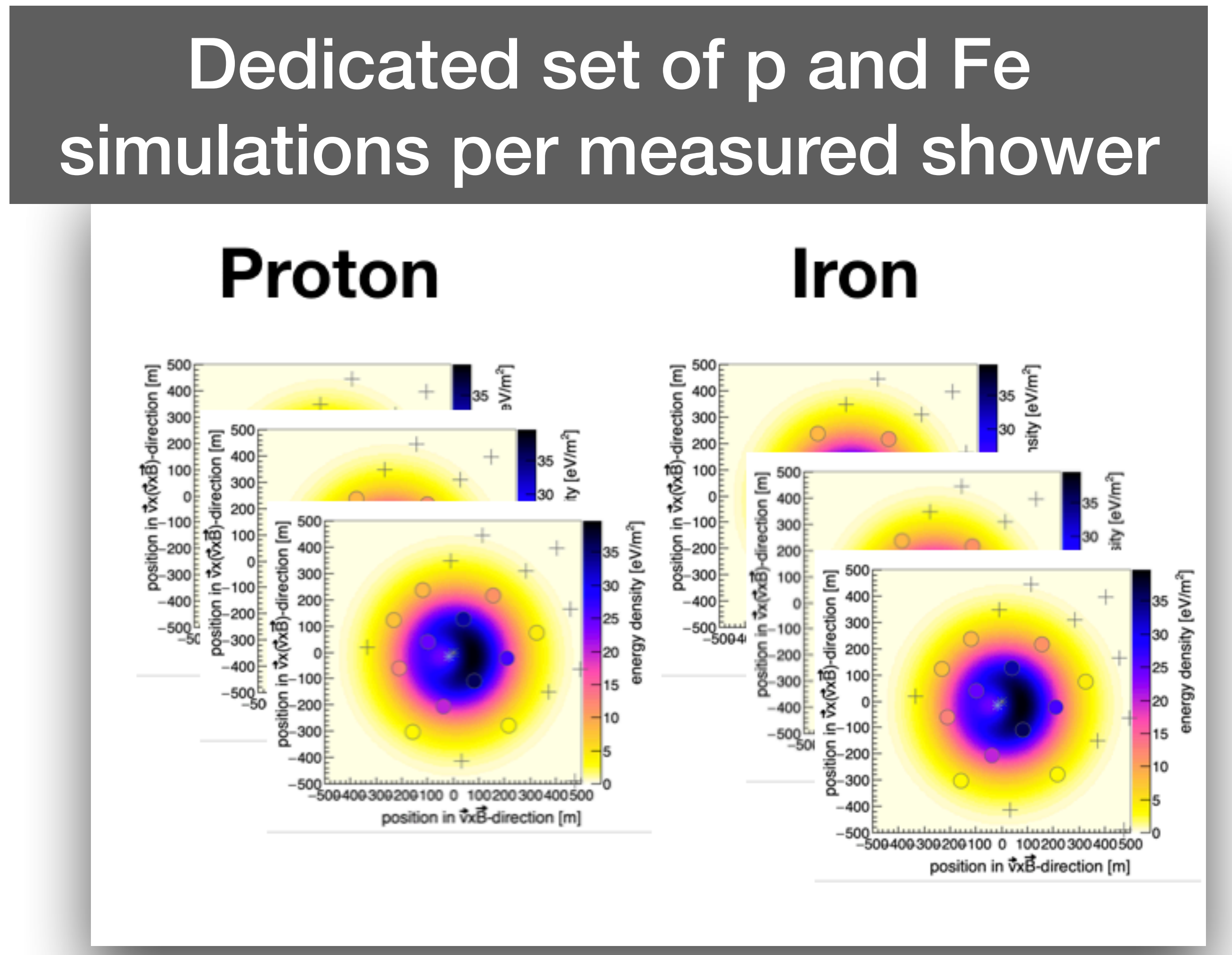
Reconstructing X_{max} from the radio footprint



- 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**: simulation-template fitting + many anti-bias corrections and checks *

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





X_{max} resolution

Event-level resolution obtained from reconstruction

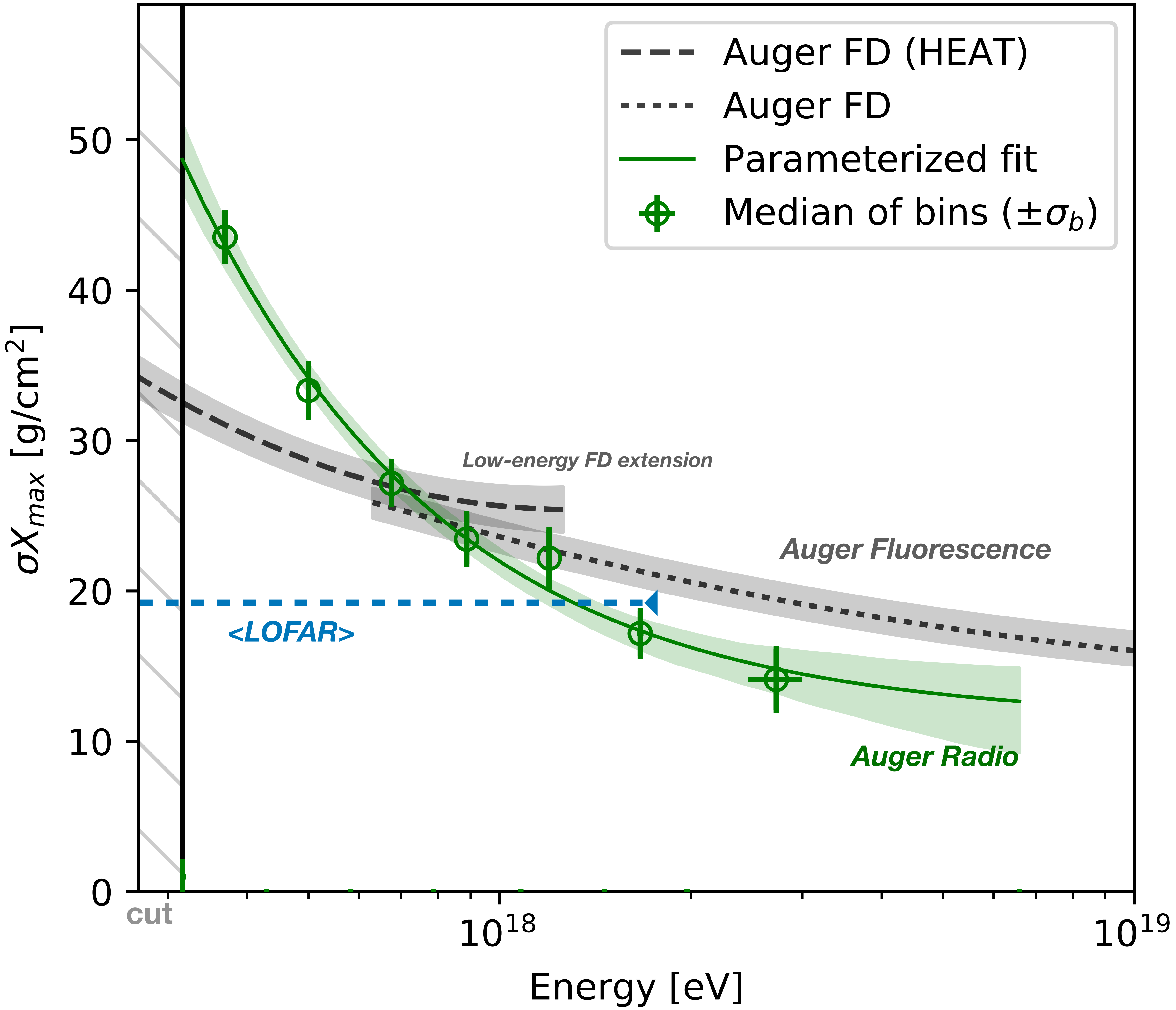
Resolution improves with energy.

- Up to 'better than 15 g/cm² '
- Trend driven by low SNR at low energy.

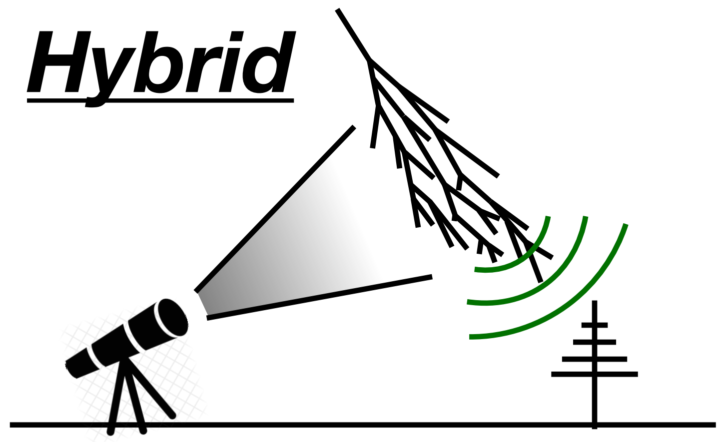
Resolution competitive with e.g.:

- Auger fluorescence [arXiv:1409.4809]
- LOFAR radio ($E=10^{16.8...18.3}$eV) [arXiv:2103.12549v2]

Radio X_{max} resolution

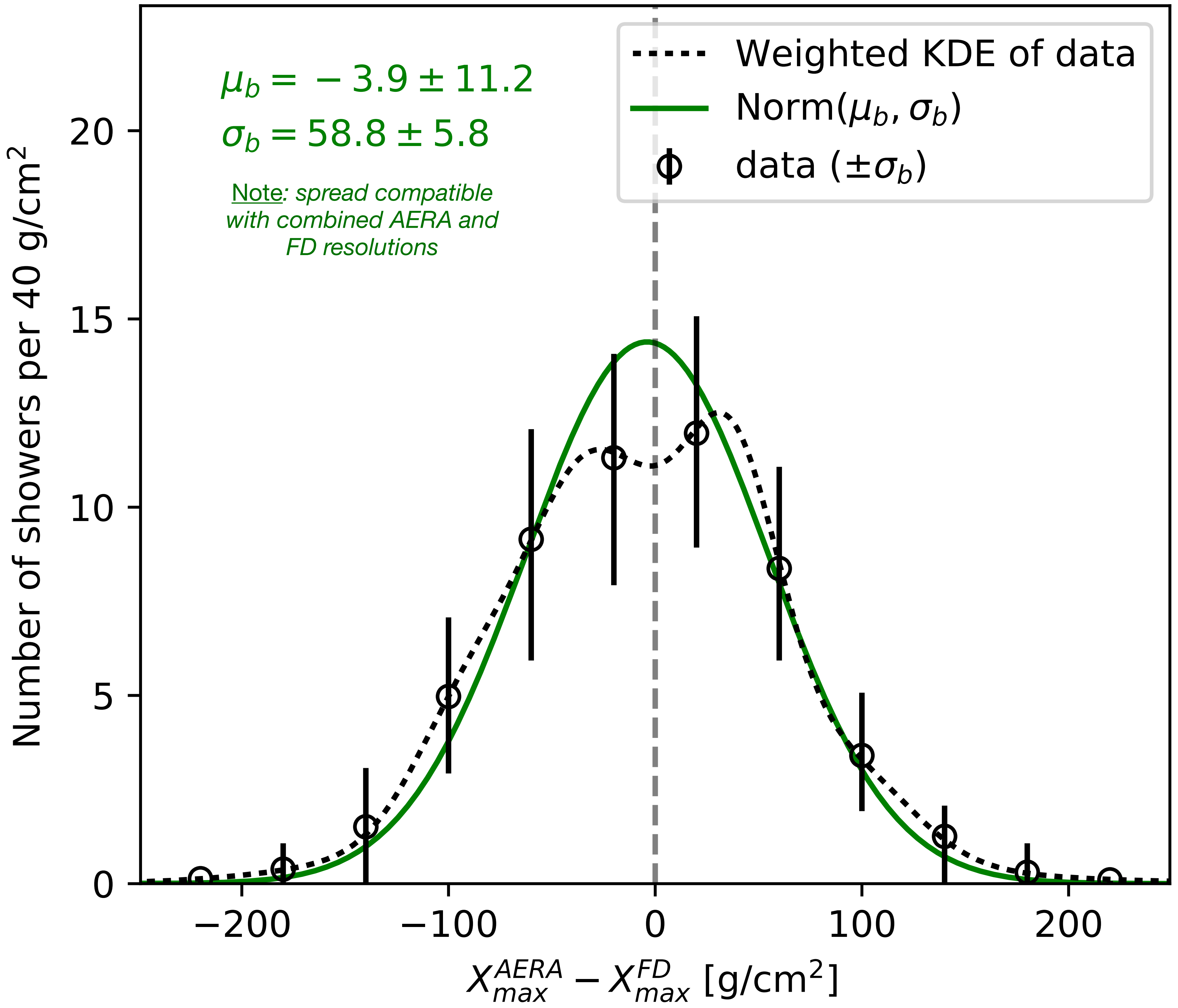


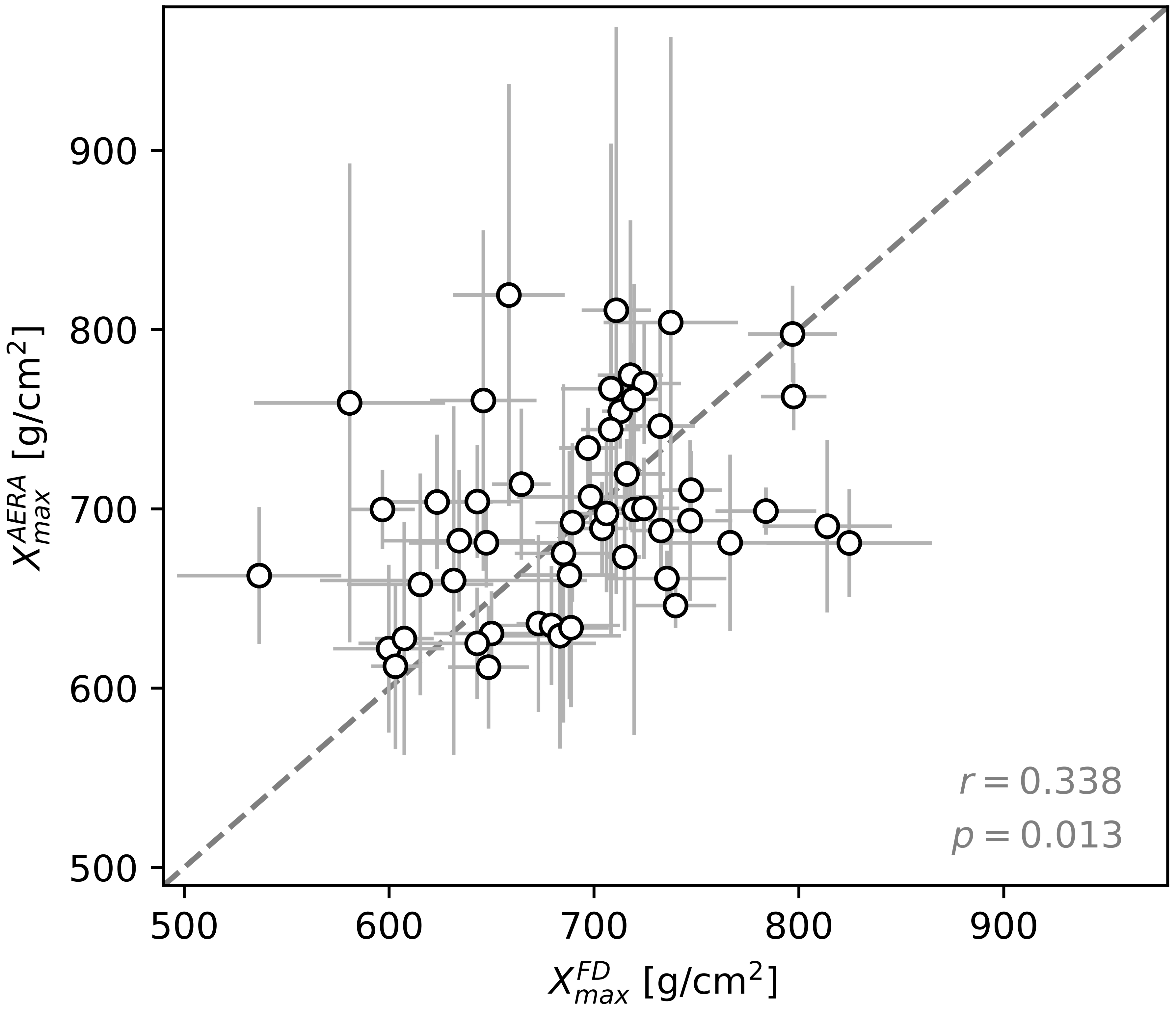
Event-by-event FD vs AERA X_{max}



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 (AERA and FD probe different aspects)





Distribution AERA X_{max} vs Auger-mix

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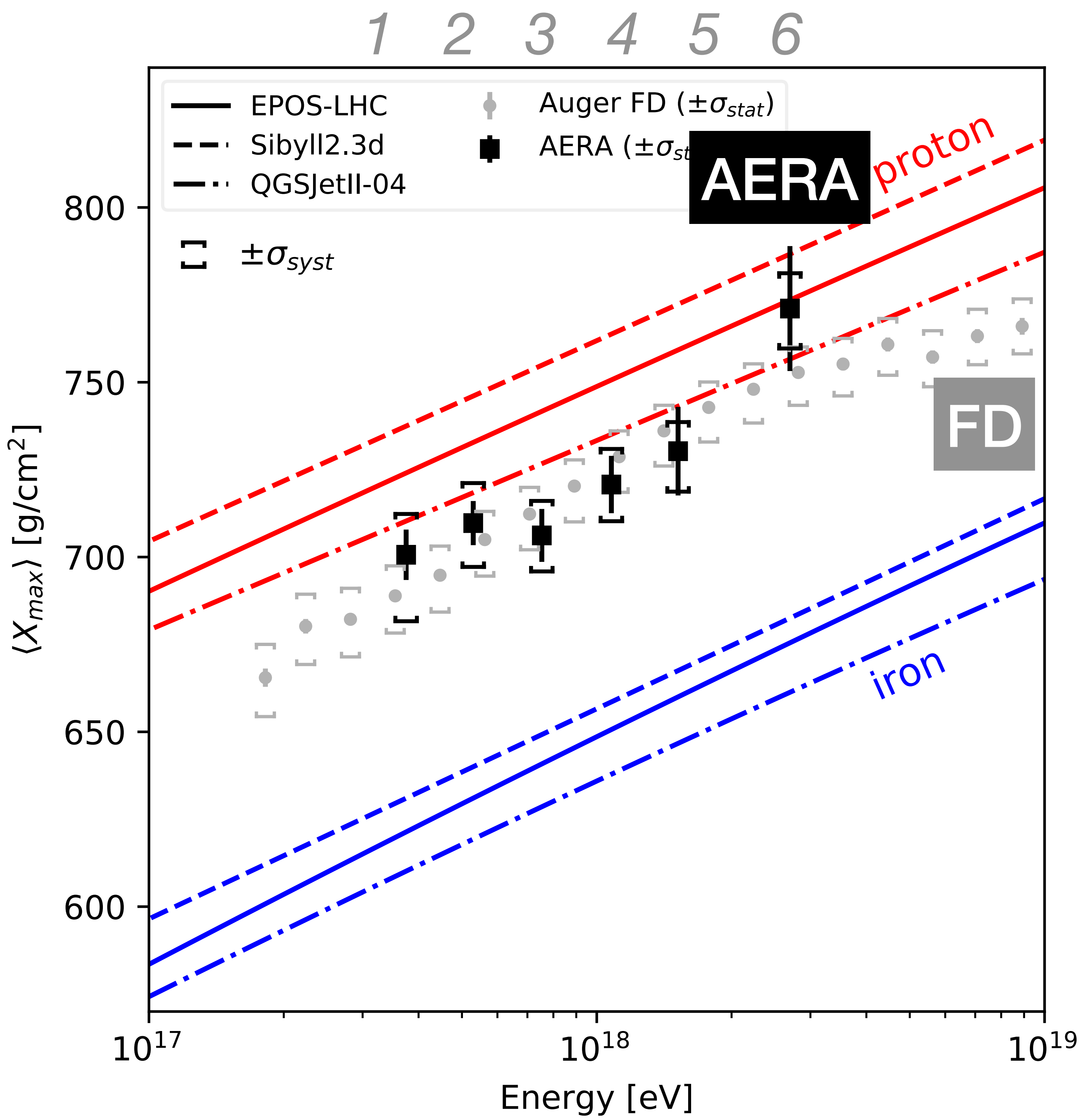
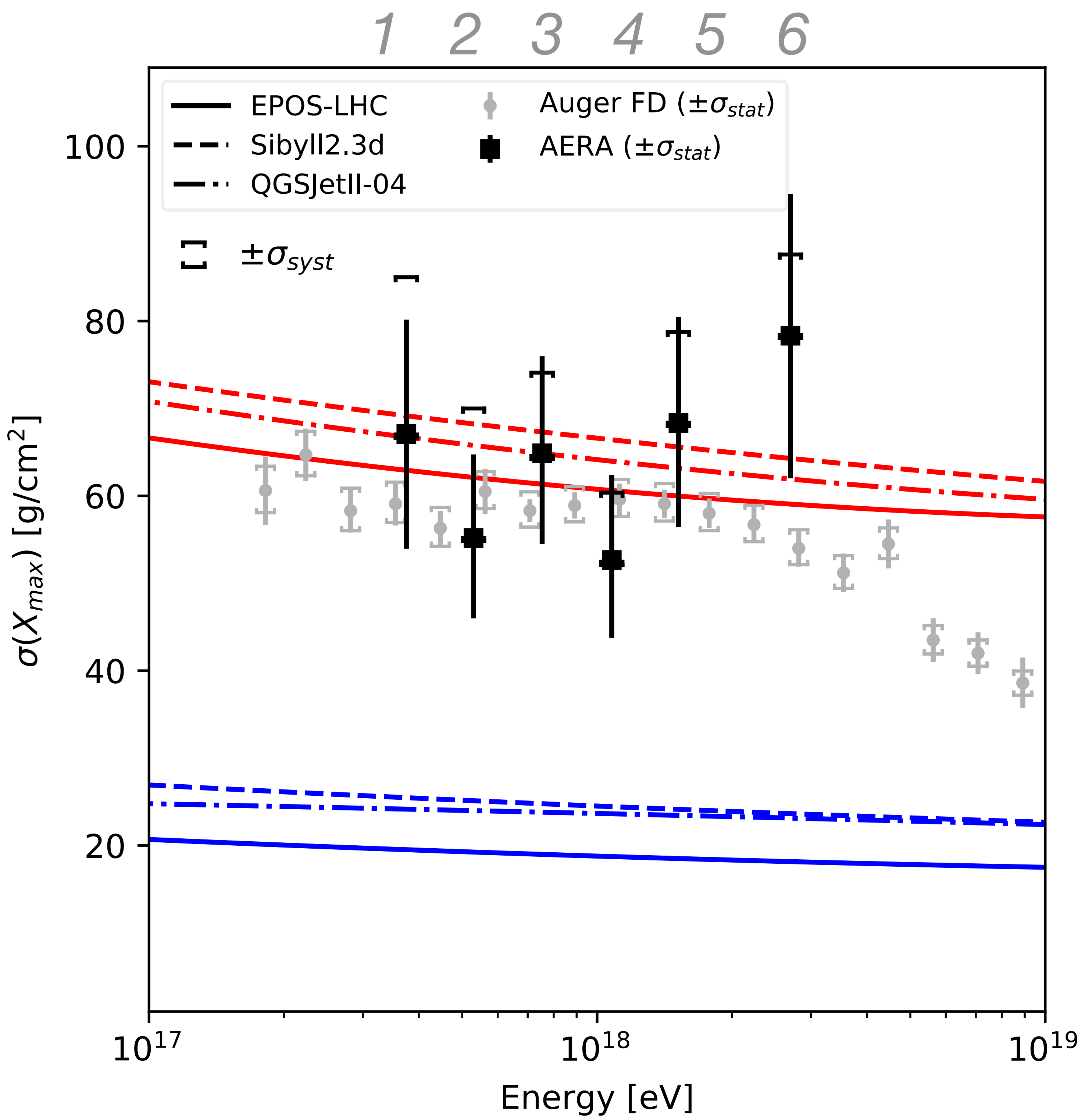
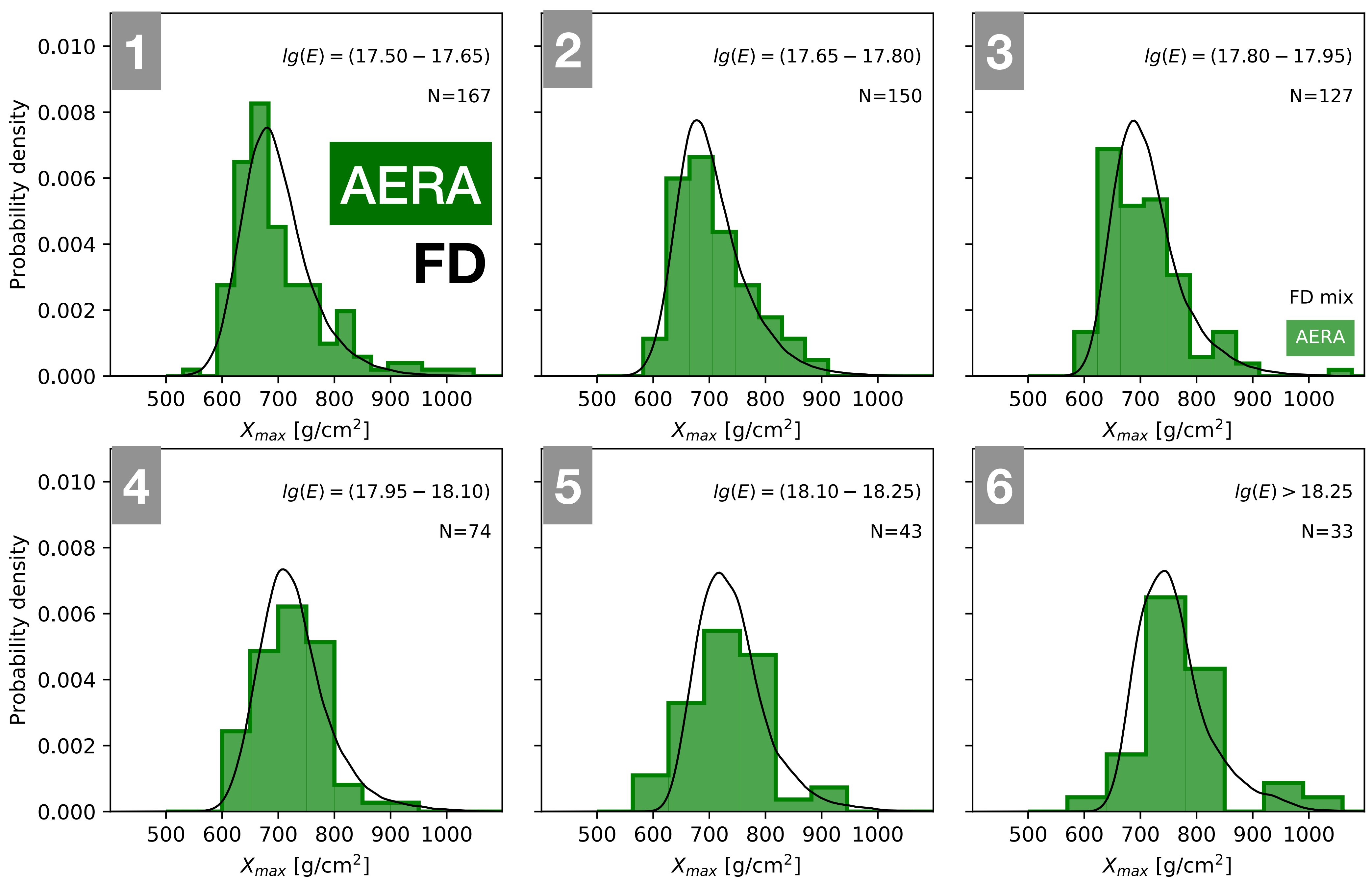
'Mean of X_{max} distribution'



'Width of X_{max} distribution'



'X_{max} distribution in 6 energy bins'

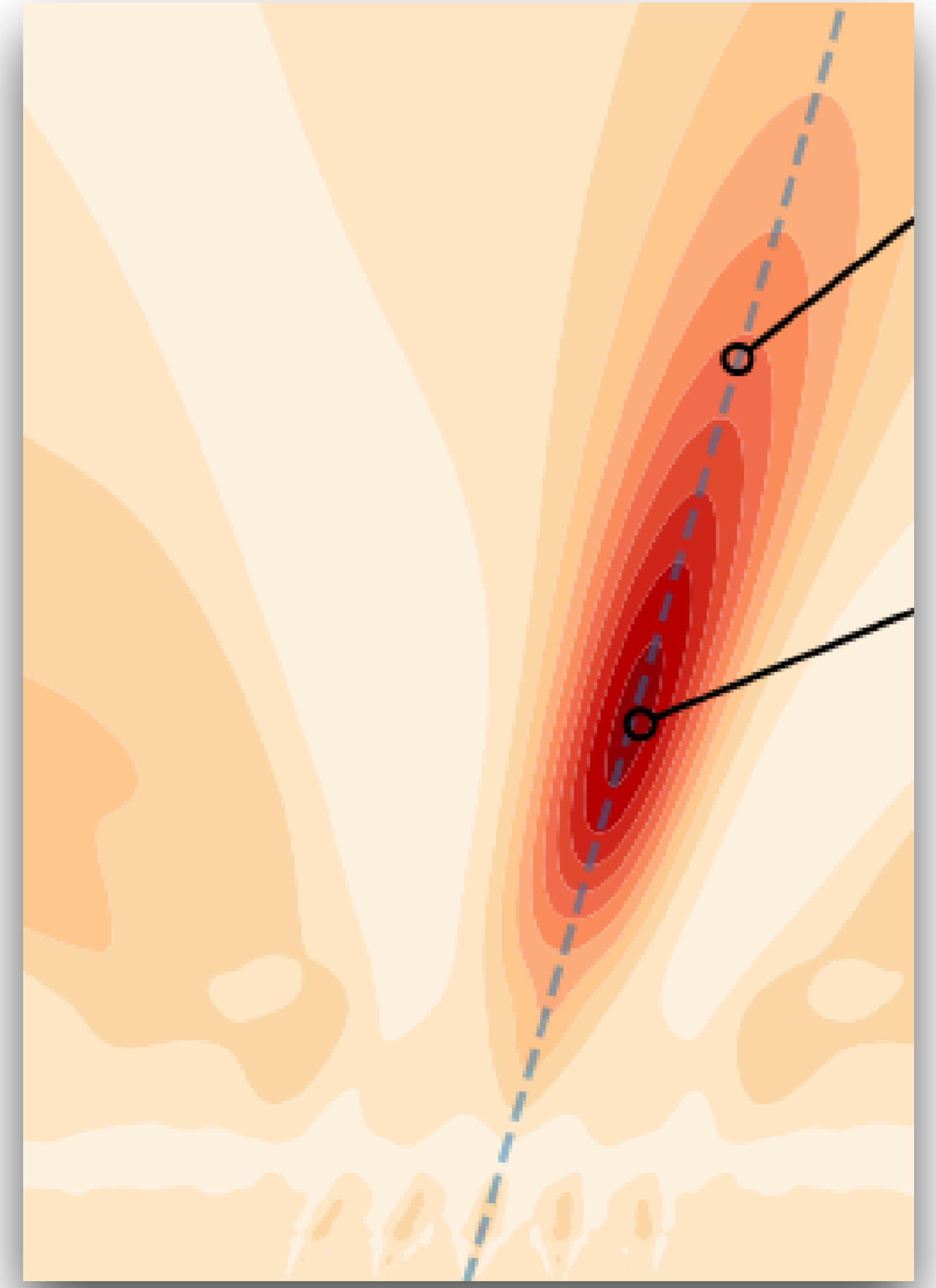


- ~600 showers after quality and anti-bias cuts.
- In agreement with Auger FD in mean and width.
- Light composition (p-He?) in $E=10^{17.5}$ eV to $E=10^{18.5}$ eV range.

- AD test: **AERA** vs **Auger-mix,** (incl. effects of AERA resolution, acceptance, and reconstruction bias}
  —> All energy bins compatible with AugerMix
- Validation that:
  - (1) that we understand our procedure.
  - and (2) of compatibility FD and AERA.

Part 3:

X_{max} *from the 3d emission region (with interferometry):*



X_{max} from Interferometry

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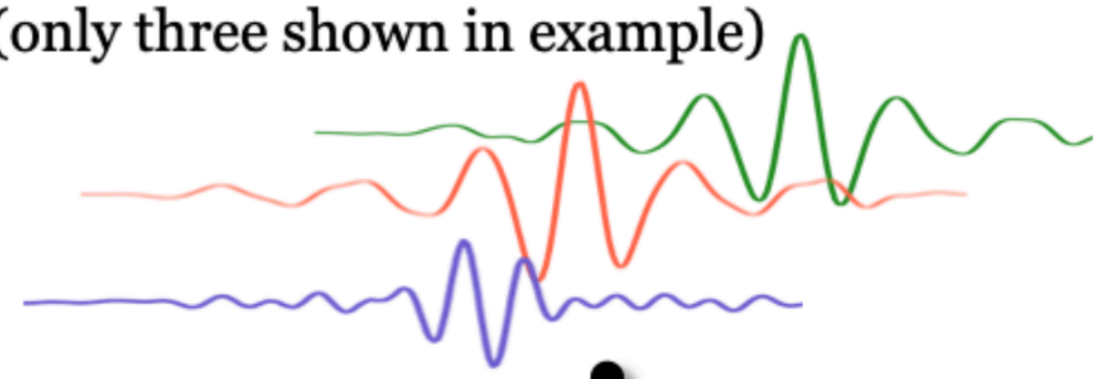
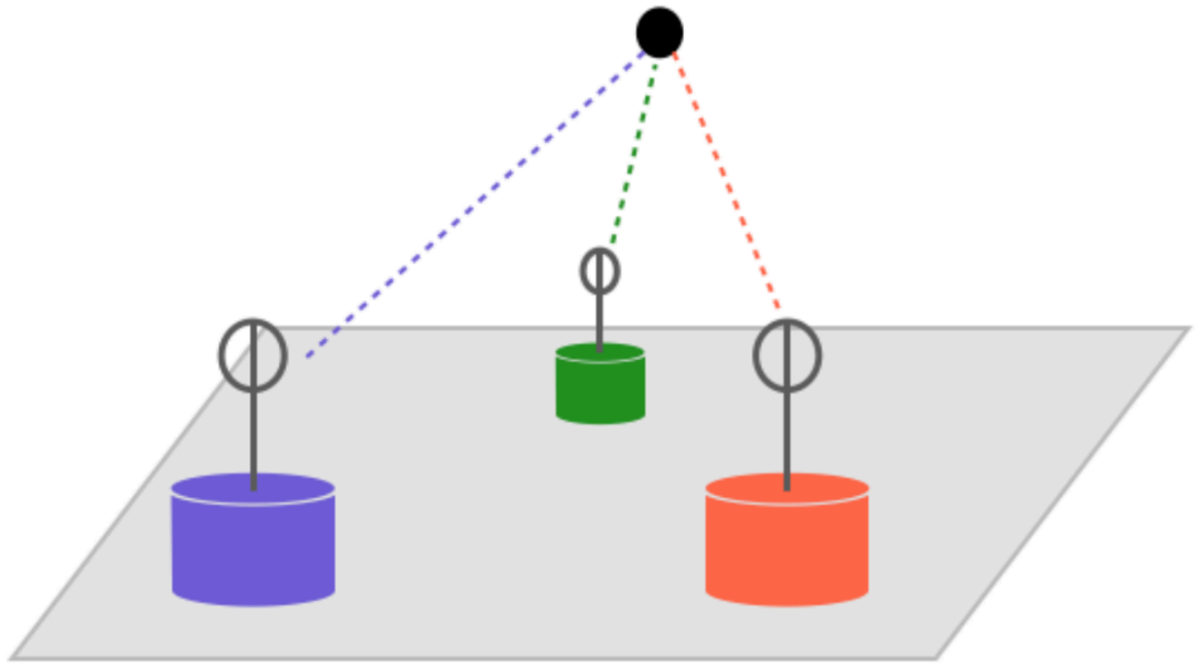
Method at ICRC2023

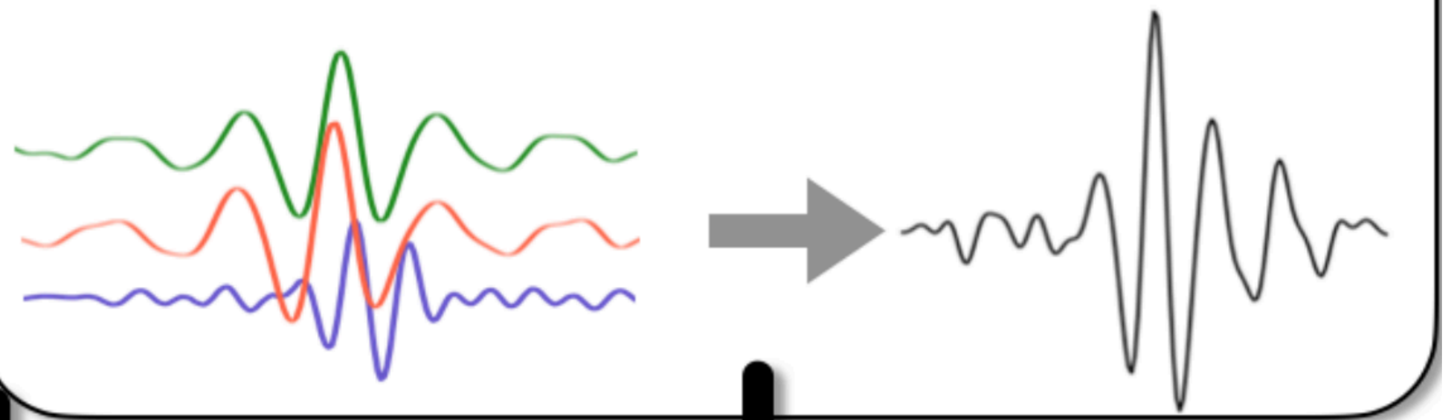
1) Measure signals
(only three shown in example)



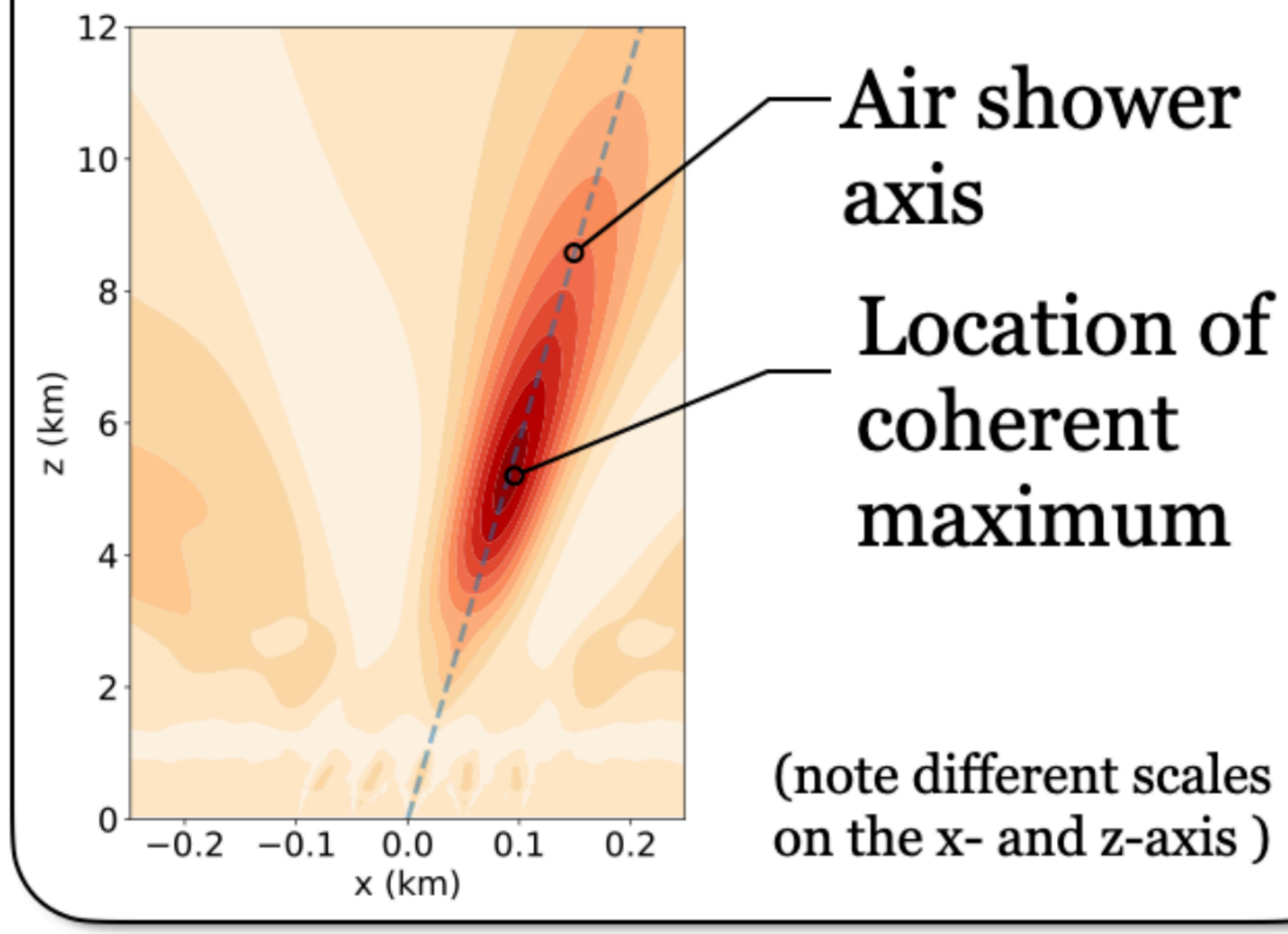
2) Calculate time delay for each antenna to a location in space



3) Delay the signals and sum them

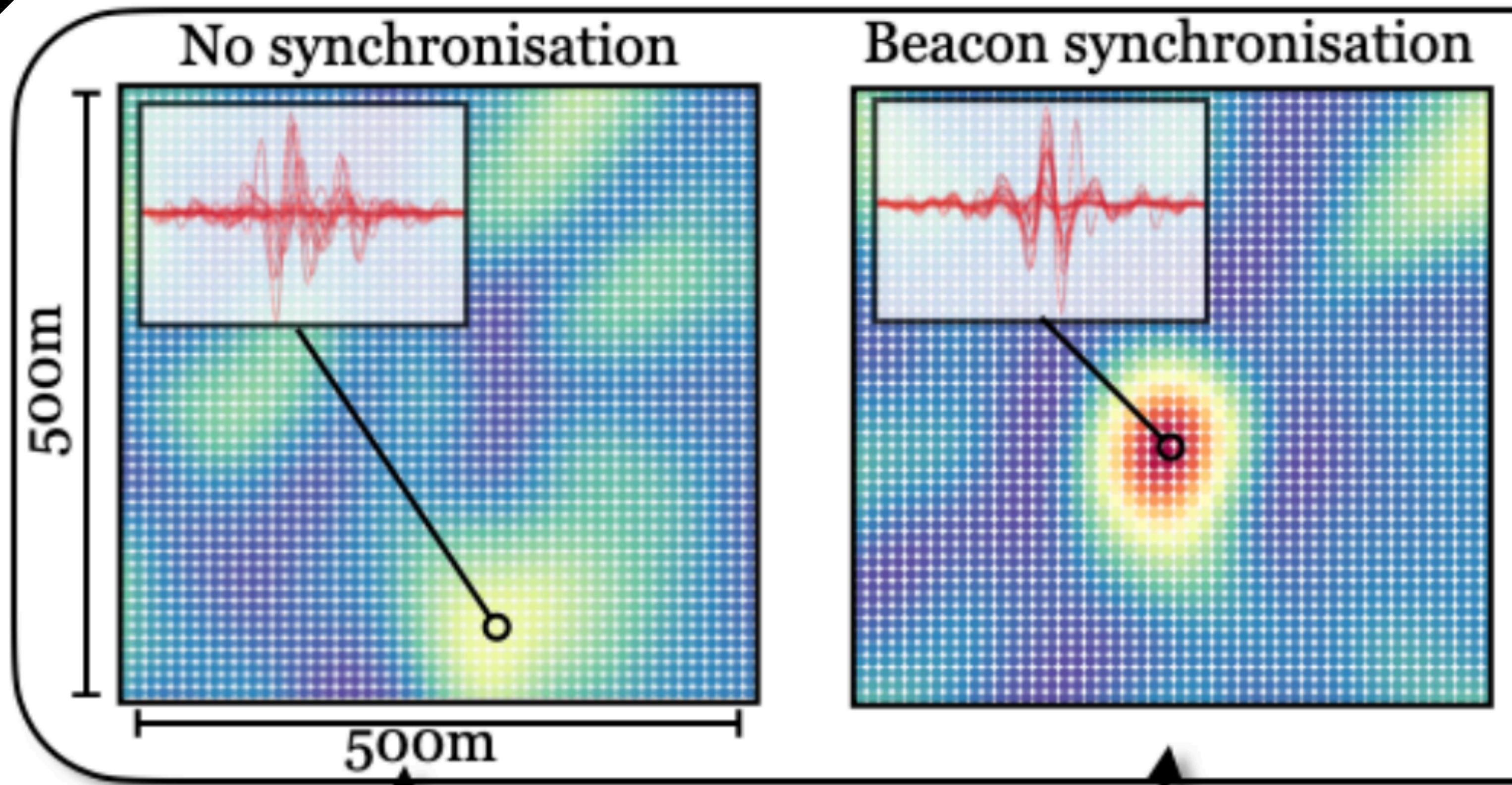


4) Scan through space to identify the air shower

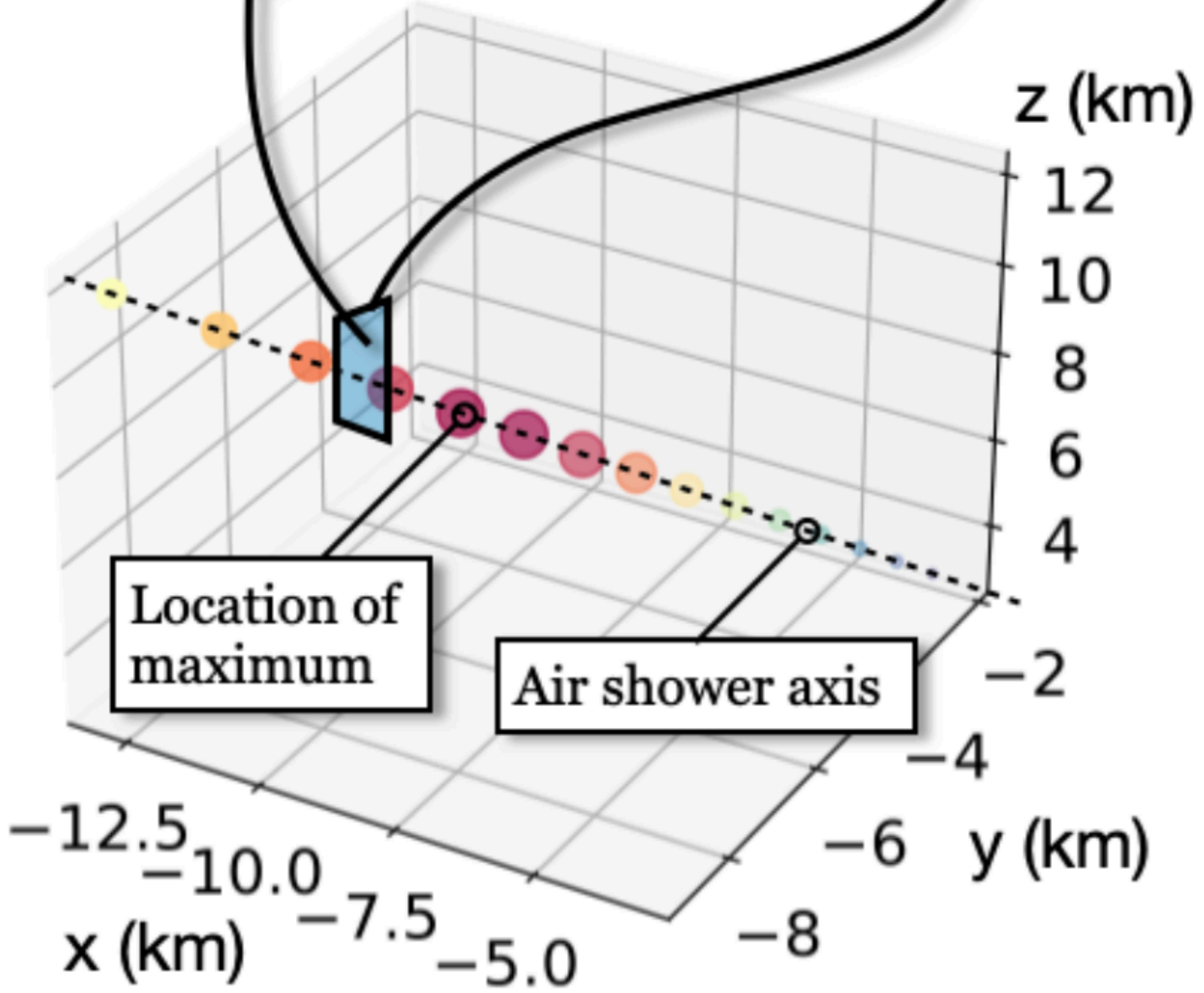


(note different scales on the x- and z-axis)

Nanosecond timing is crucial



1) Apply beacon synchronisation and locate the air shower axis in a plane perpendicular to initial guess of the axis.



2) Reconstruct air shower properties:
a) track the axis
b) fit axis with a straight line,
c) find location of maximum of the coherent sum on the axis.

1:1 comparison to footprint method

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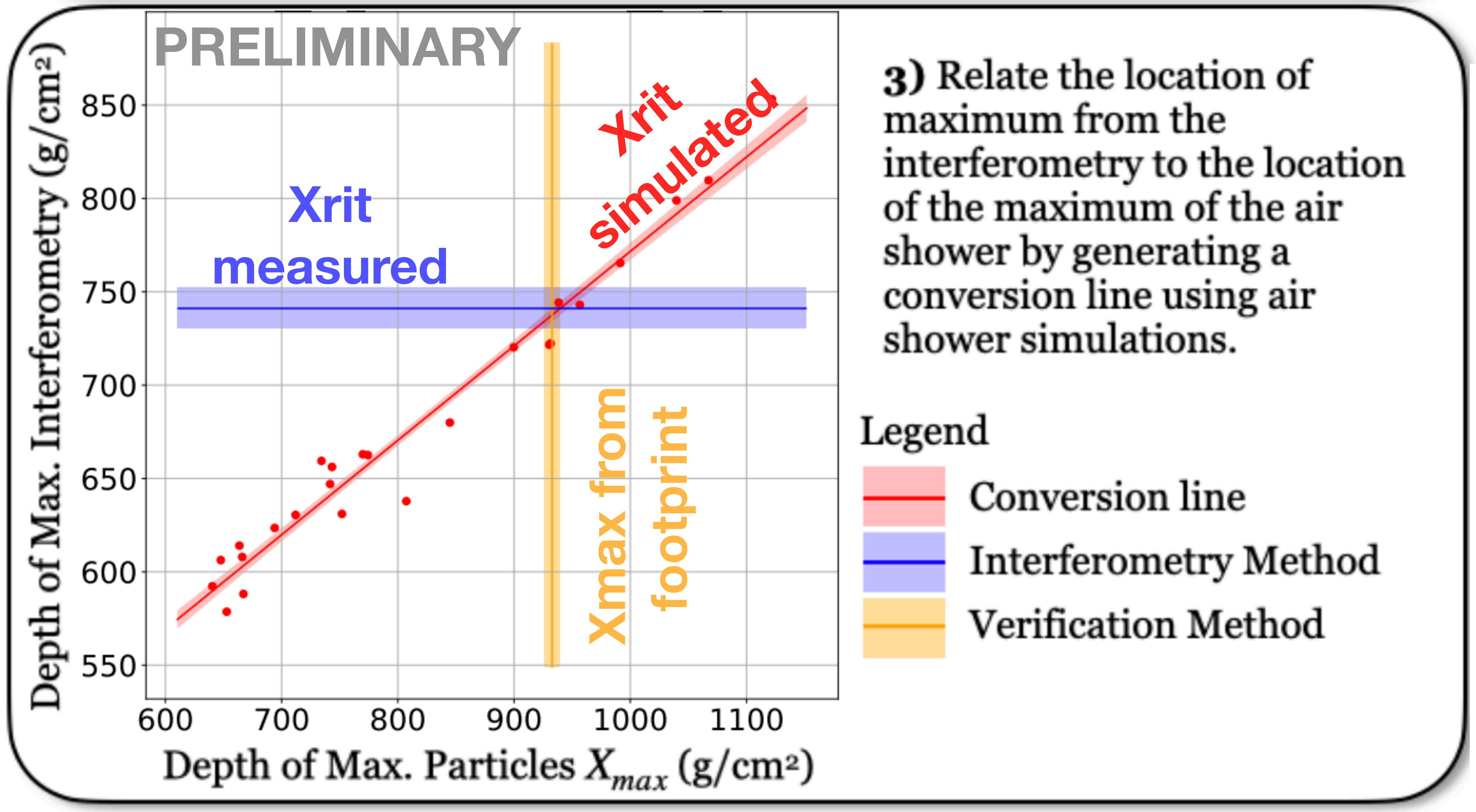
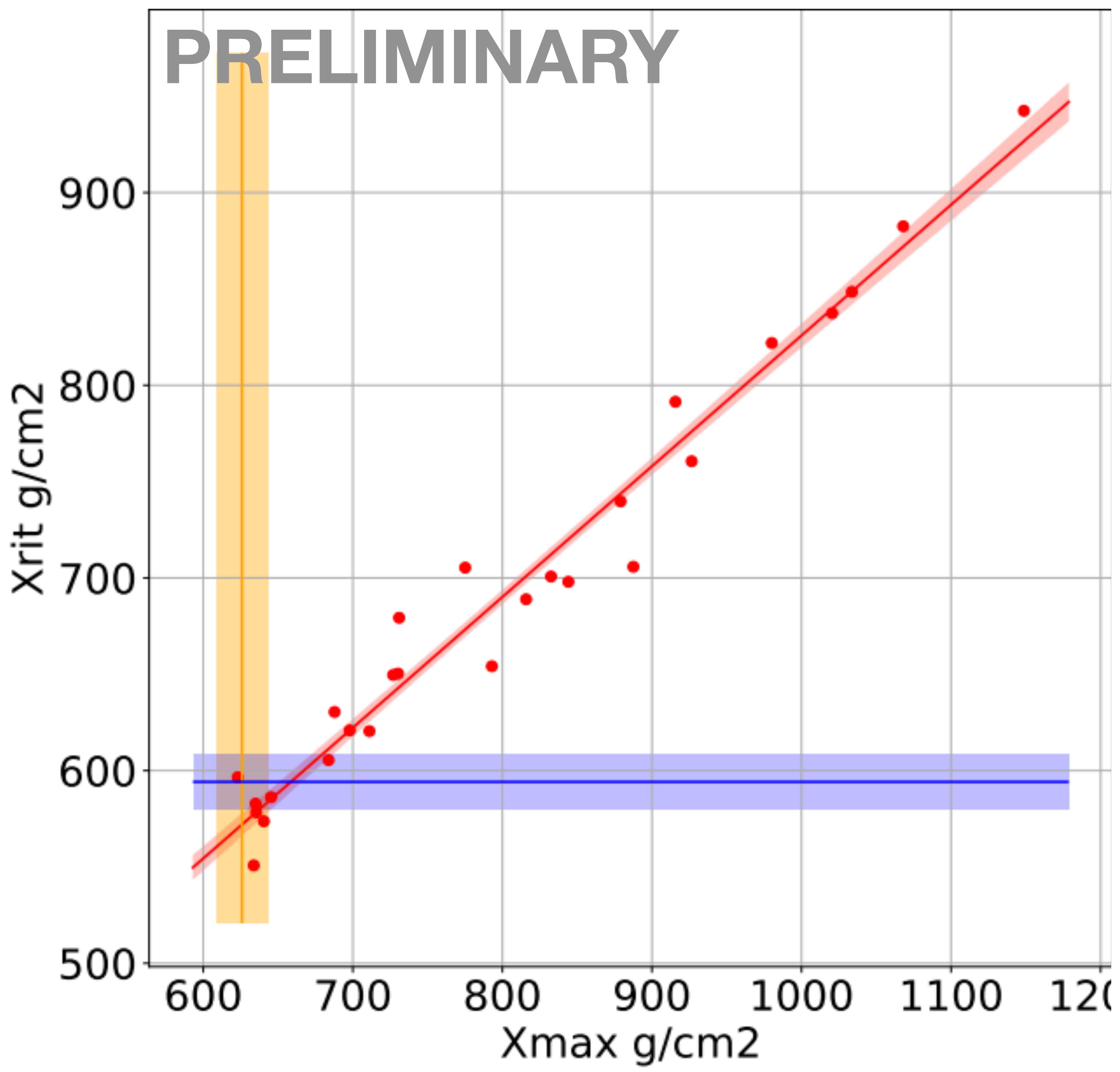
Deep shower example

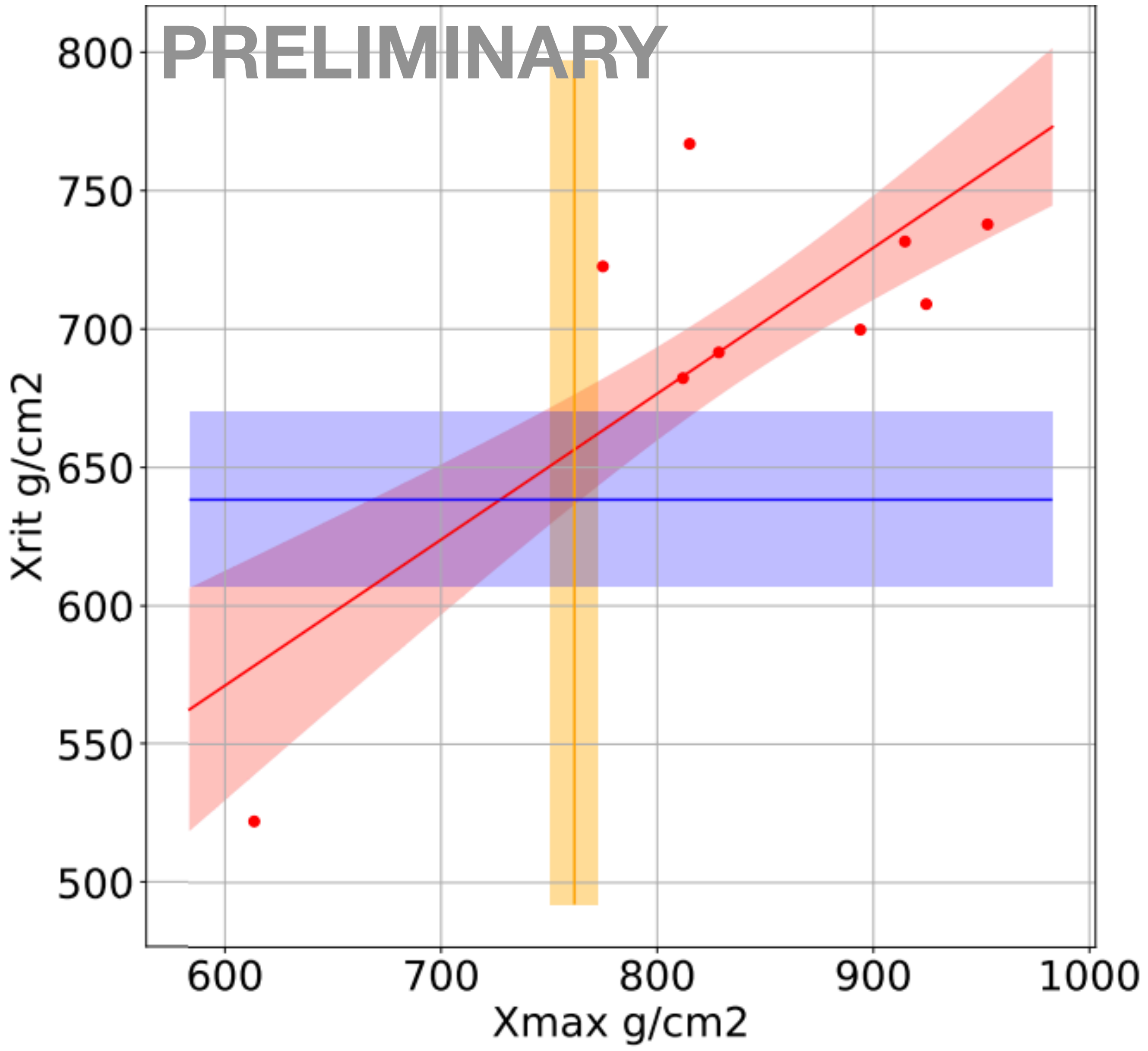


Shallow shower example



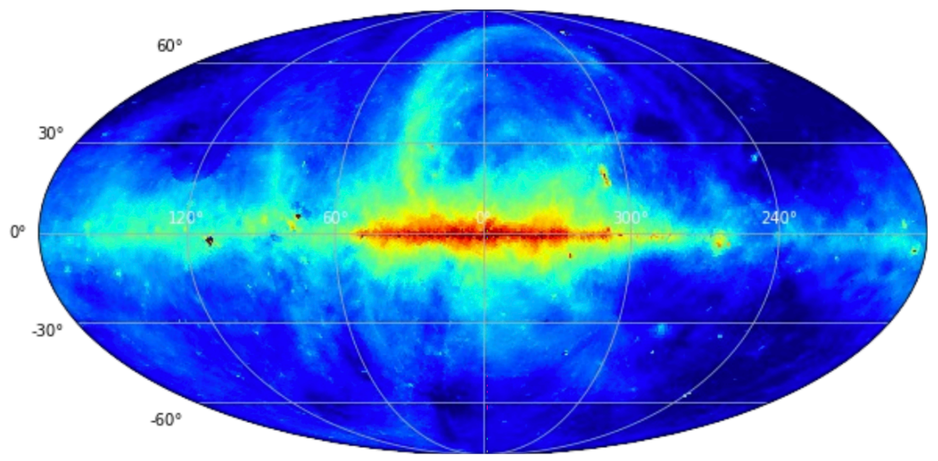
Low-quality example

*AERA layout and event geometry not optimal



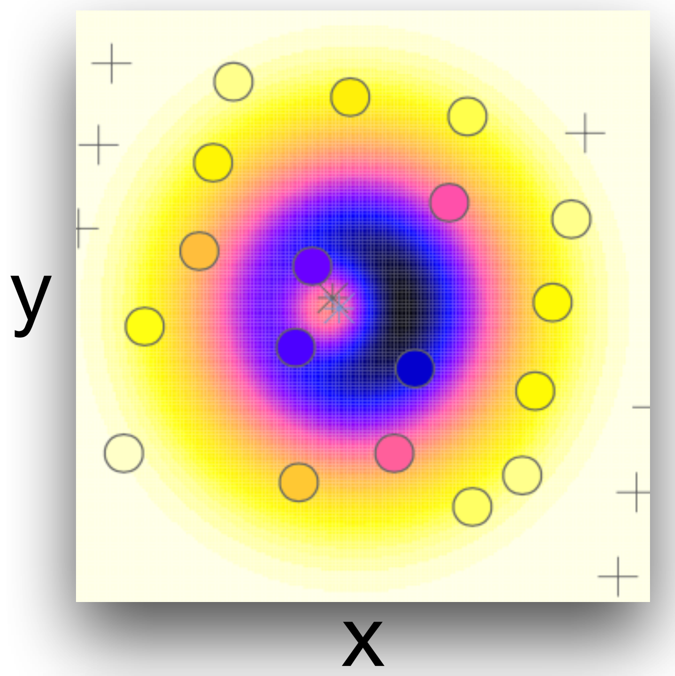
- Similar to footprint method: compare to simulation set per event.
- Generally good agreement. 3 examples shown. Works well at both low and high X_{max}.
- Station multiplicity & geometry governs the resolution (spread of points).
  —> still needs proper error estimation on fit (for now simple fit uncertainty).
- Proof of concept for the radio upgrade at the Pierre Auger Observatory (1700 detectors, 3000km2). More to come!!

Conclusions



Long-term calibration and the stability of the radio signal

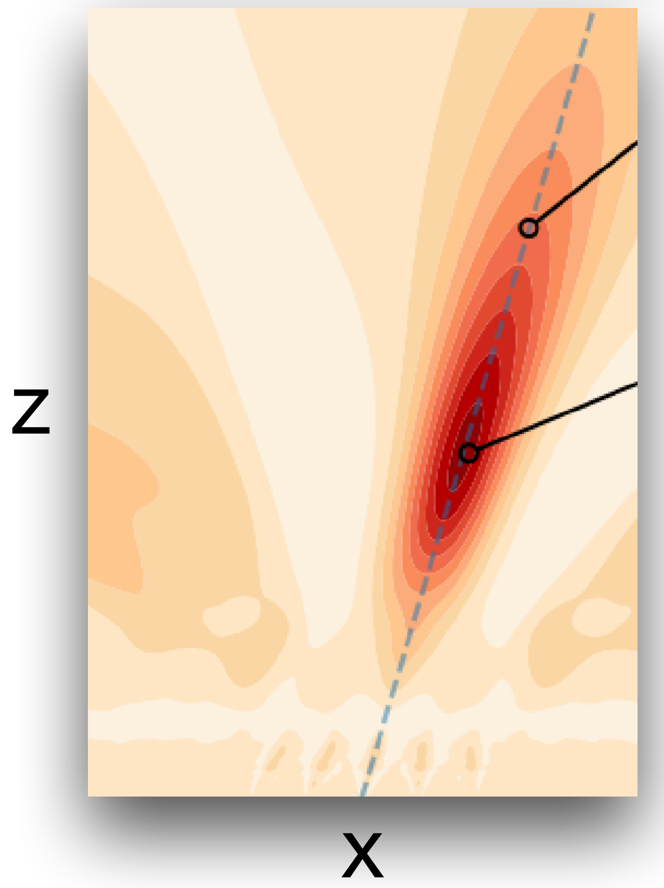
- **Absolute calibration** shows system is well-understood
- No evolution over a decade —> **Radio is a stable reference for hybrid detectors**
- Publication in prep.



X_{max} from the radio footprint (LDF):

- Demonstrated **FD-AERA compatibility**
- X_{max} resolution shows competitiveness

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 (with interferometry):

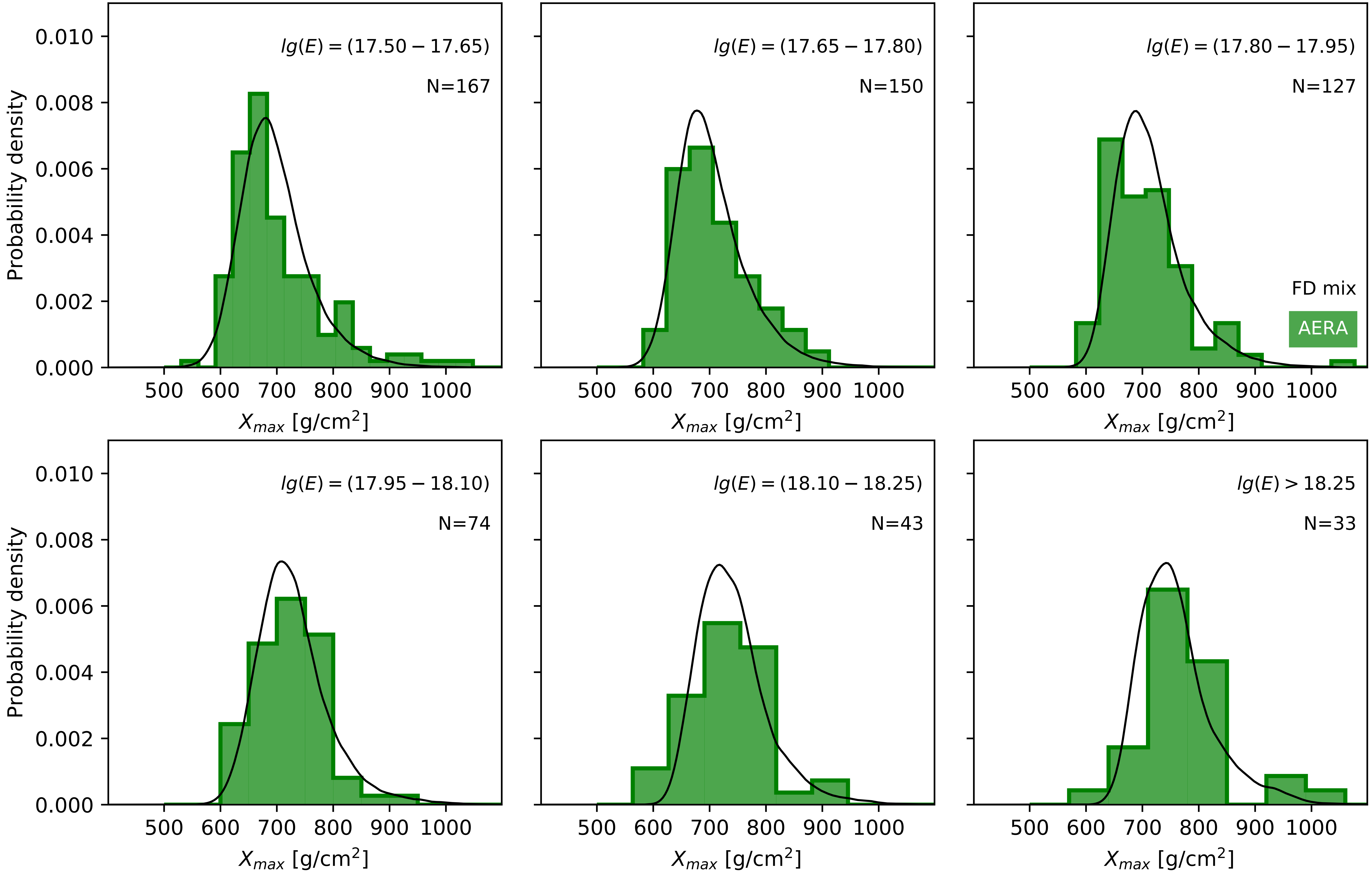
- Cross-check of LDF and interferometry method
- **Prospects for a 2nd mass composition method with inclined showers** (3000km^2 Auger RD)

Backup

x

AERA X_{max} vs Auger-mix

- **Distributions of reconstructed AERA X_{max} in 6 energy bins**
- All energy bins compatible with AugerMix (optimal for single shift of)
- Validation that:
  - (1) that we understand our procedure.
  - and (2) of compatibility FD and AERA.



$$X_{\rm max}^{\rm AERA} - X_{\rm max}^{\rm FD} = -5.5 \ \ {\rm g\,cm^{-2}}$$

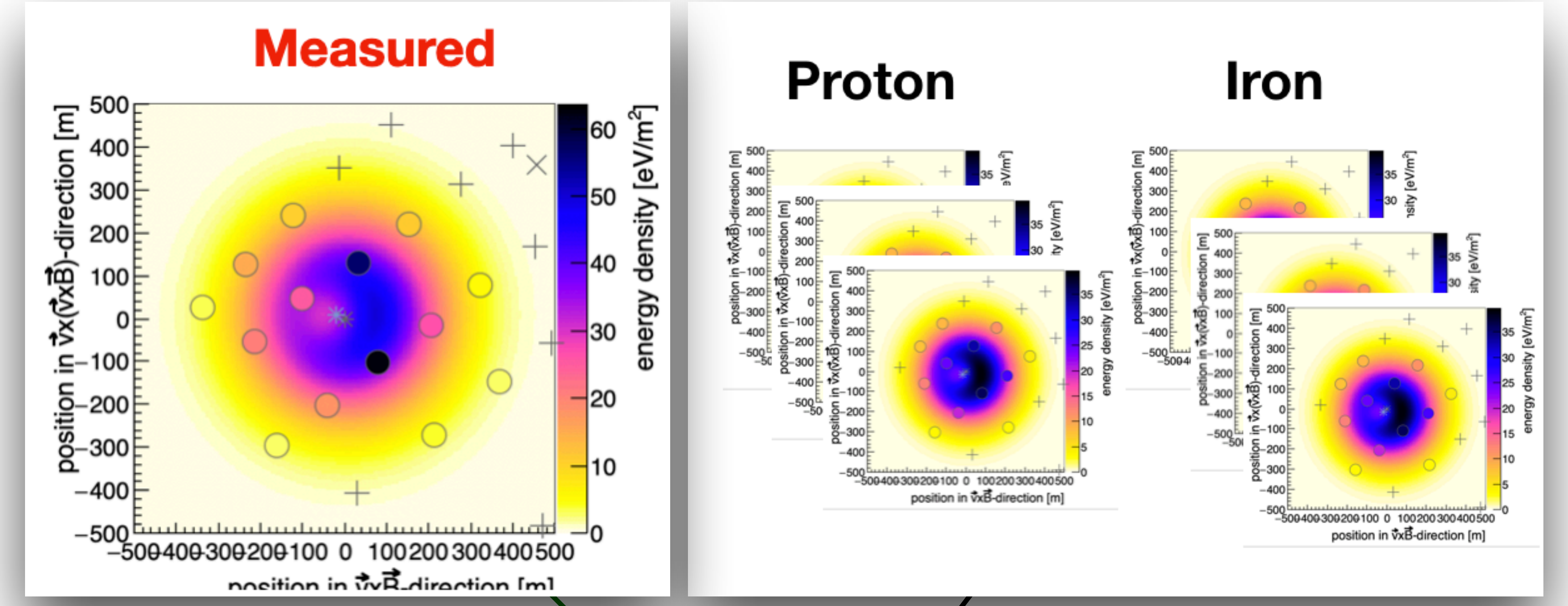
(Note, hybrid set showed -3.9±11.2)

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



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

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 remaining reconstruction bias given composition scenarios

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)*

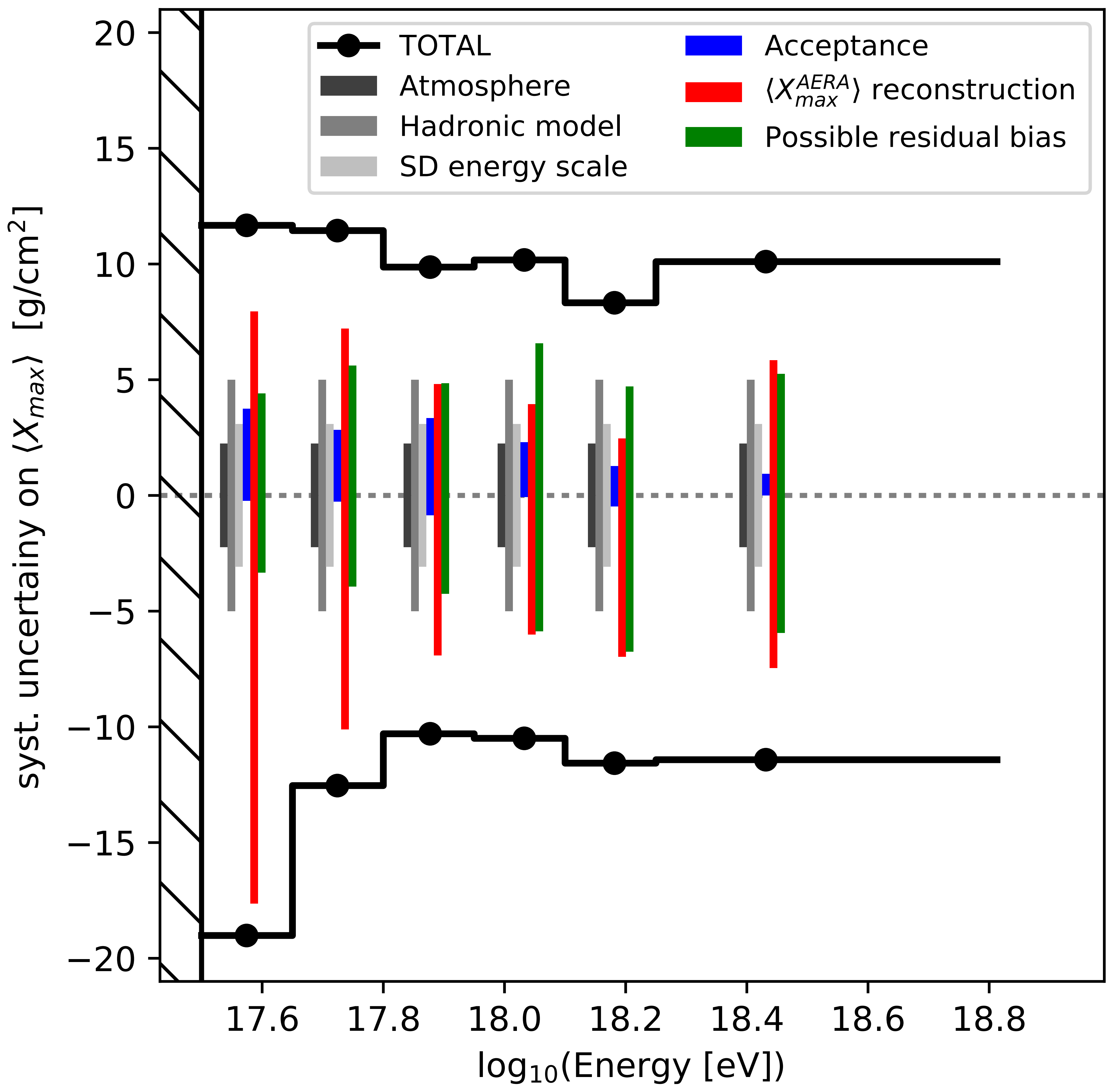
* Phys. Rev. D 109, 022002 (2024): *Method and detailed results of AERA X_{max}*

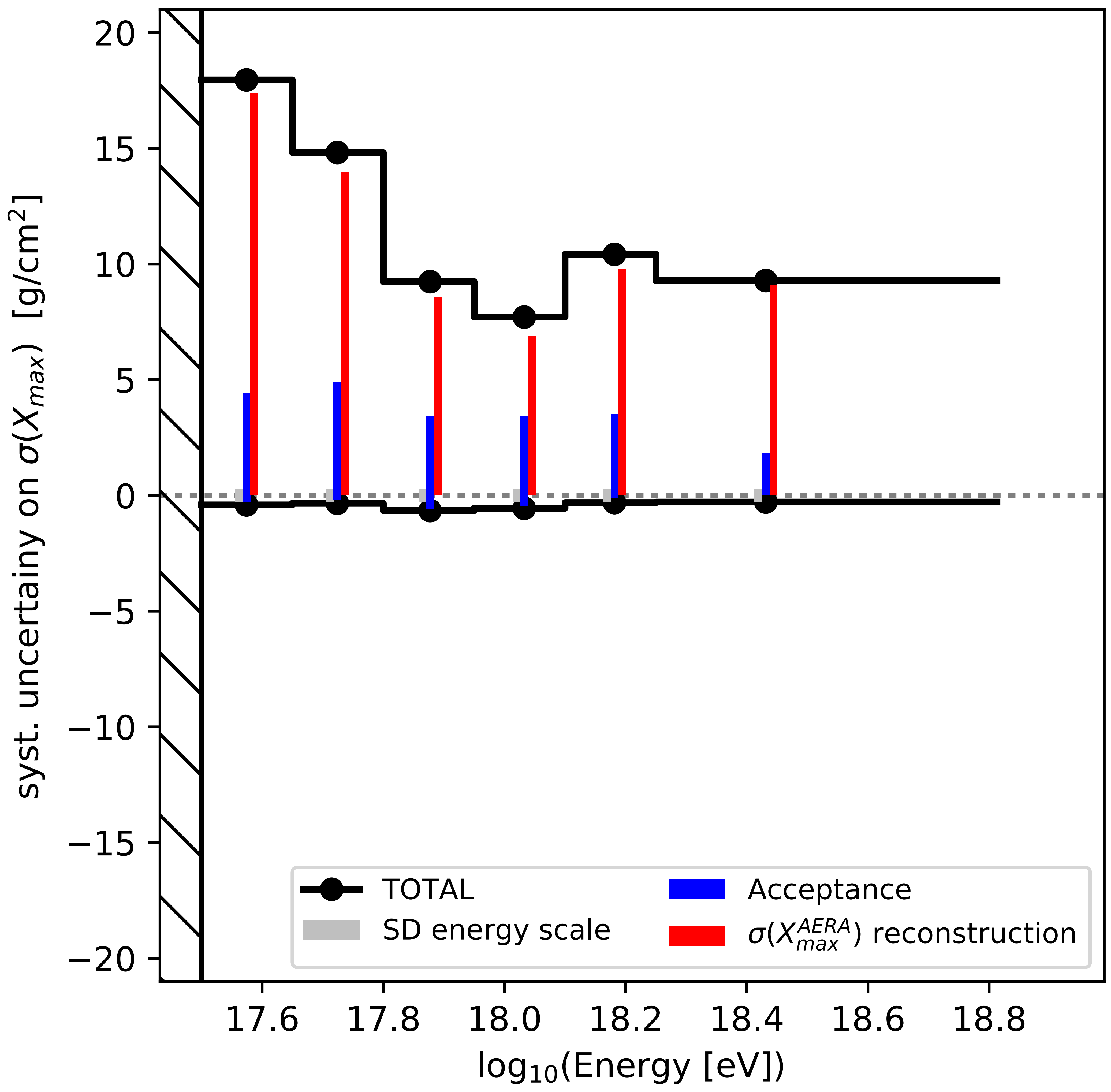
Event selection

* Phys. Rev. D 109, 022002 (2024): *Method and detailed results of AERA X_{max}*

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*





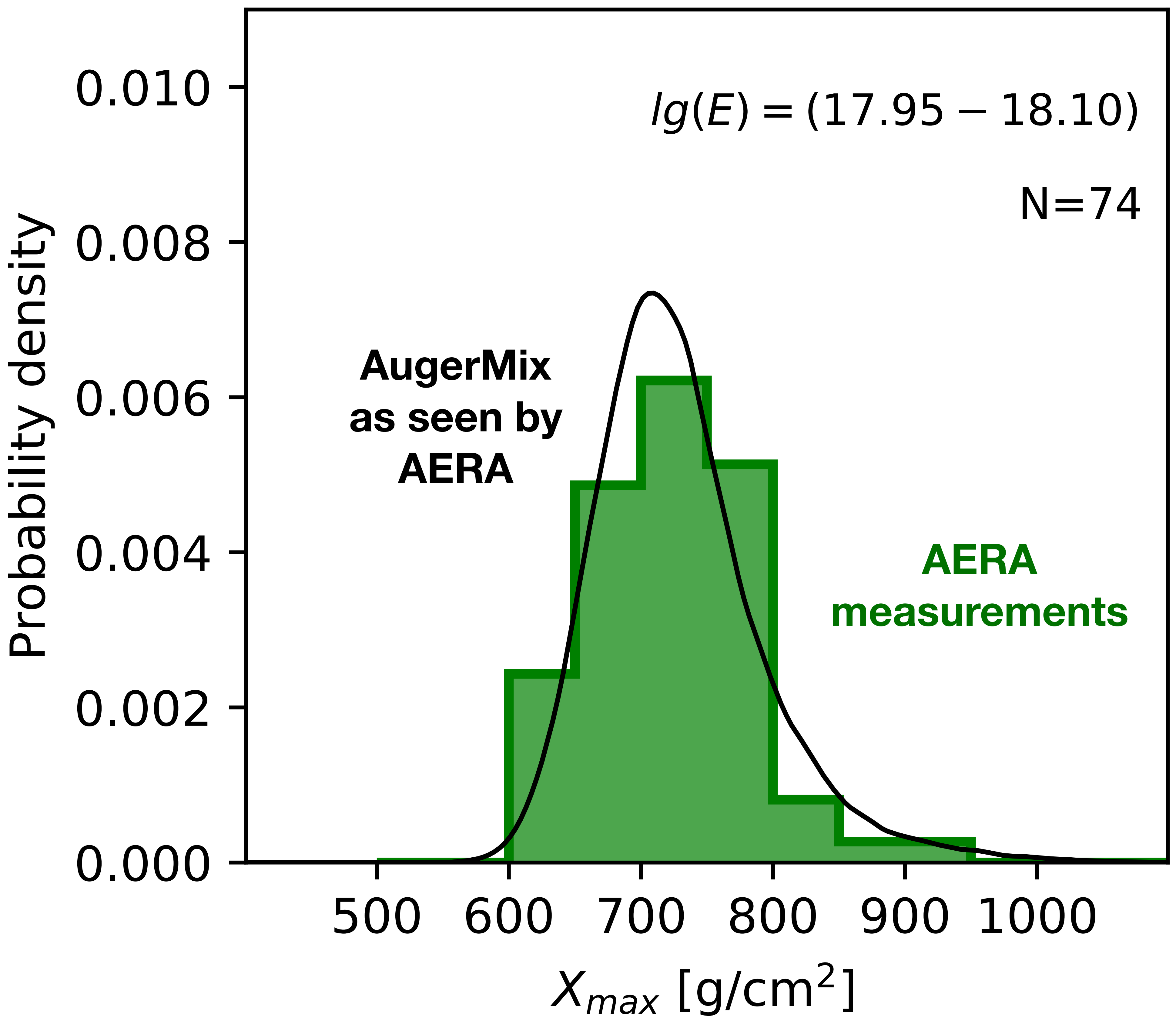
Results: Distribution AERA X_{max} vs Auger-mix

- **Distributions of reconstructed AERA X_{max} in 1/6 energy bins**
- vs **Auger-mix, drawn with AERA {i.e., incl. resolution, acceptance, and reconstruction bias}.**

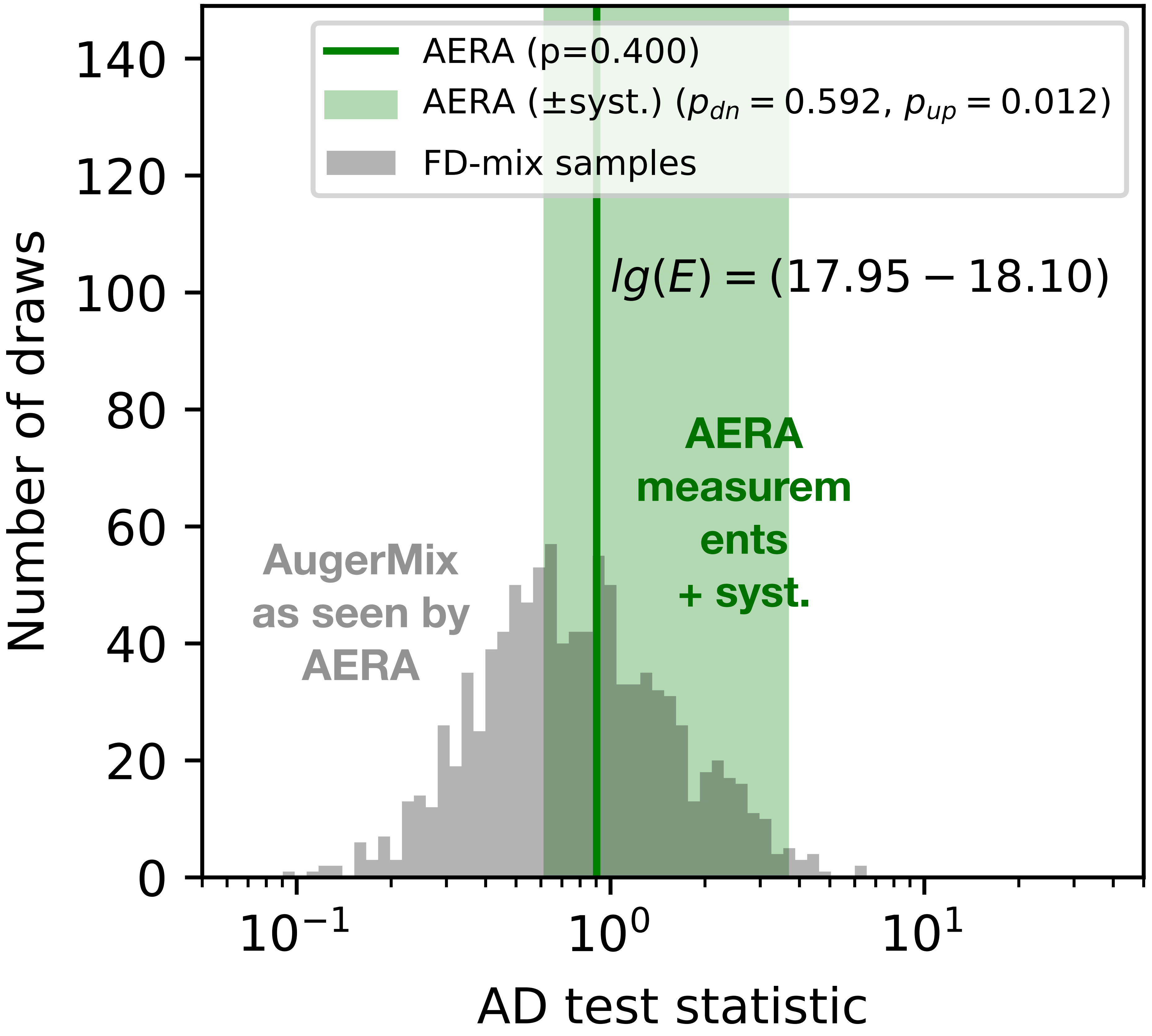
AD test statistic checks if measured distribution could have been drawn from Auger-mix with detector effects.

- Compatible with Auger-mix (within stat+syst unc)

AERA results and **'AugerMix'**



AD test: **AERA** is compatible with **'AugerMix'**



Reconstruction bias (for one energy bin)

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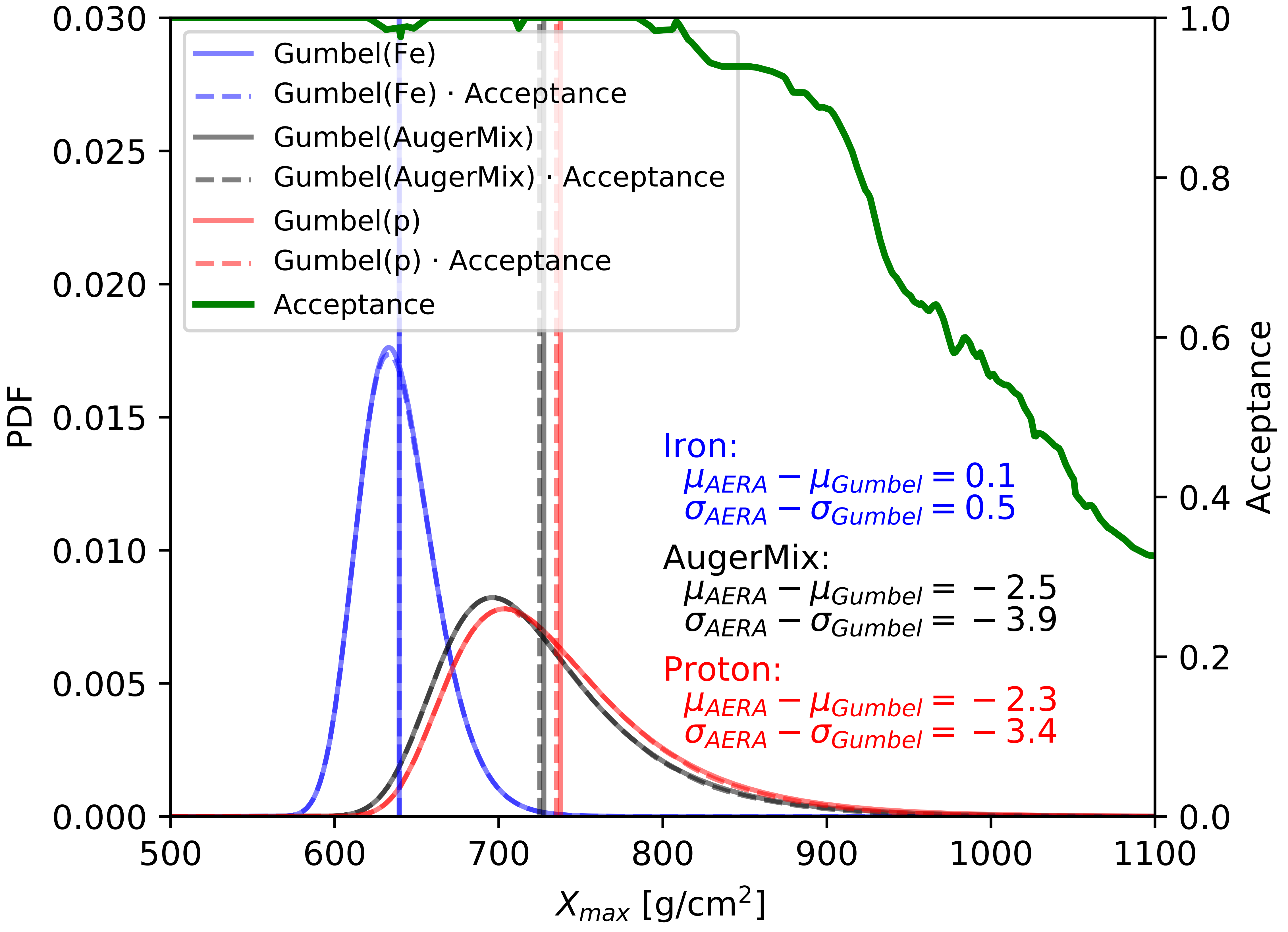
- Using reconstruction of X_{max} for our simulations we can calculate the bias when we assume the range of possible underlying compositions.
- Similarly, we can try to reconstruct all our simulations and see what fraction would be seen (acceptance) and what the effect is on the X_{max} distribution.

Acceptance calculation (1 energy bin)



Reconstruction bias calculation (1 energy bin)