Commissioning of AixNet & Universality $X_{\max}$ reconstruction for arrival-direction analyses

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AixNet is a deep neural network (DNN)

- **Input:** signal trace information.
- **Output:** atmospheric depth of the shower maximum X_{max} of the event as output.
- **Training:** simulated air shower footprints in Water Cherenkov Detectors (WCDs).

Universality is a model for SD traces that can (also) estimate X_{max}

- Based on the concept of the **universality** of parametrization for air showers.
- It uses **time evolution** of the signal to reconstruct X_{max}.
- **Fitted** on simulated air showers.

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→ When both methods are applied to data, they present detector-related dependences.

- $X_{\max}$ can be used as a **mass estimator** for the primary particle.
- With $X_{\max}$ is possible to apply mass-dependent cuts in the dataset, to enhance significance in arrival-direction studies.
- The cuts should not be biased by the mass estimator.

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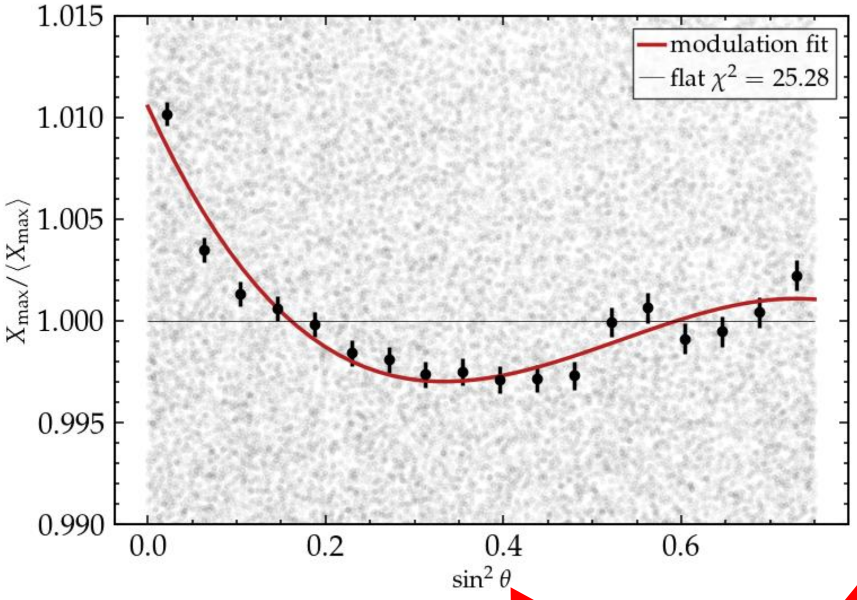
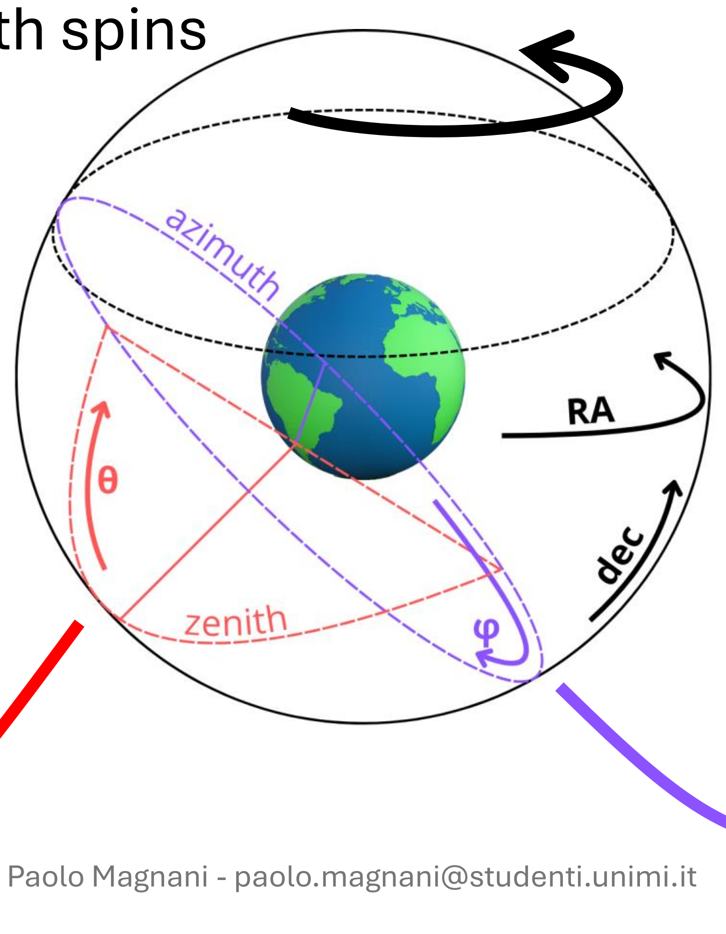
- The cuts should not be biased by the mass estimator.

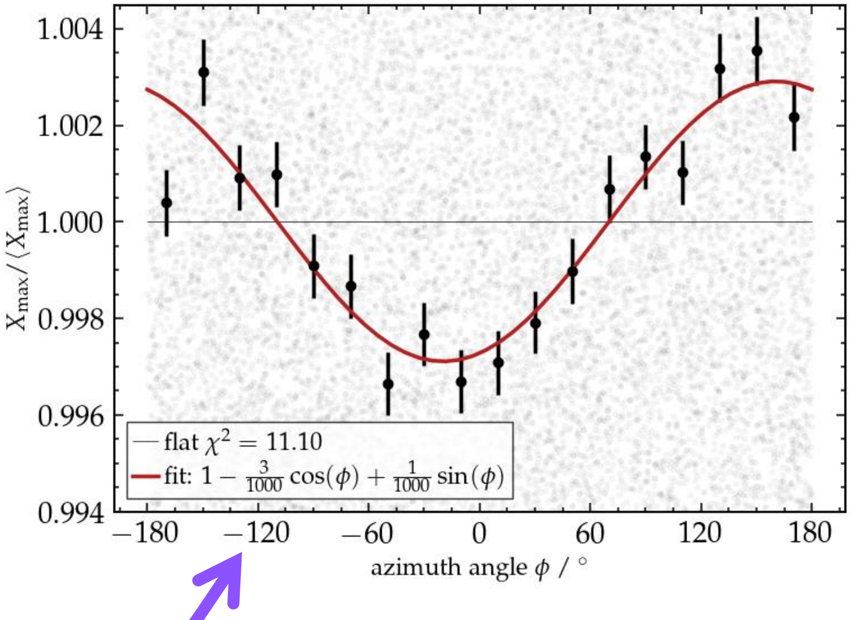
Examples:

Zenith modulation:





East-West modulation:



Once all other dependences are removed, $X_{\max}$ is still energy-dependent.

$\longrightarrow$ The energy dependency should be removed.

It is removed by subtracting the decadal elongation rate D_{10}:

$$X_{\max} \to X_{\max}^{19} \equiv X_{\max} - D_{10} \log_{10}\left(\frac{E}{10^{19}\ \mathrm{eV}}\right),$$

where

$$D_{10} \equiv \frac{\mathrm{d}\langle X_{\max}\rangle}{\mathrm{d}\log_{10} E} = 58\ \mathrm{g\ cm^{-2}}$$

AixNet data set

- 125 000 6T5 events above 3 EeV from 2004 to 31st august 2018, zenith $\theta \in (0°, 60°)$.
- ICRC19 reconstruction
- X_{max} estimates of AixNet without fiducial cuts.
- Corrections already implemented:
  - detector-aging effects,
  - seasonal day-based calibration,
  - diurnal hour-based calibration,
  - absolute calibration on FD.

Universality dataset

- 209 000 5T5 and 6T5 events from Phase I above 4 EeV, zenith $\theta \in (0°, 60°)$.
- ICRC25 Offline reconstruction.

Dependences correction - AixNet

- Modulations have been searched and corrected for:
  - zenith angle,
  - pressure,
  - position in the detector array,
  - geomagnetic field,
  - year.

$\longrightarrow$ generate $X_{\max}^{19}$.

  - rescaling $X_{\max}^{19}$ distribution in zenith.

Dependences correction - AixNet

- Modulations have been searched and corrected for:
  - zenith angle,
  - pressure,
  - position in the detector array,
  - geomagnetic field,
  - year. Not seen in Universality

$\longrightarrow$ generate $X_{\max}^{19}$.

- rescaling $X_{\max}^{19}$ distribution in zenith.

Dependences correction - Universality

- Modulations have been searched and corrected for:
  - pressure,
  - months, Already corrected in AixNet
  - geomagnetic field,

$\longrightarrow$ generate $X_{\max}^{19}$.

- position in the detector array,
- zenith angle,
- rescaling $X_{\max}^{19}$ distribution in zenith.

Implemented method for searching and correcting the dependences

Search for an observable that can affect $X_{\max}$ prediction

→

Quantify the dependence through a χ^2 evaluation over the null hypothesis (i.e., no dependence)

Fit $X_{\max}/\langle X_{\max}\rangle$ with a function of the given observable;
Apply the correction element-wise

→

Quantify the correction through another χ^2 evaluation over the null hypothesis

Corrections have been implemented using physics-motivated fits.

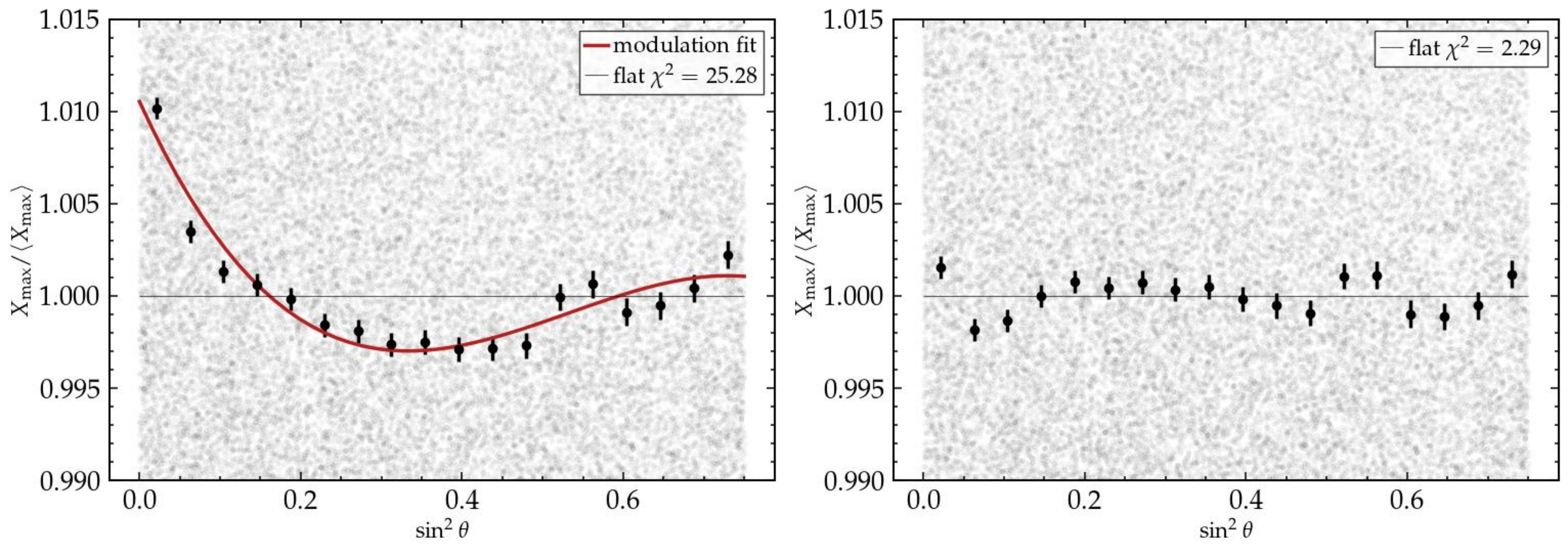
Zenith angle - AixNet

No sky region is uniquely defined by a zenith angle.

→ Like the constant intensity cut, expected isotropy.

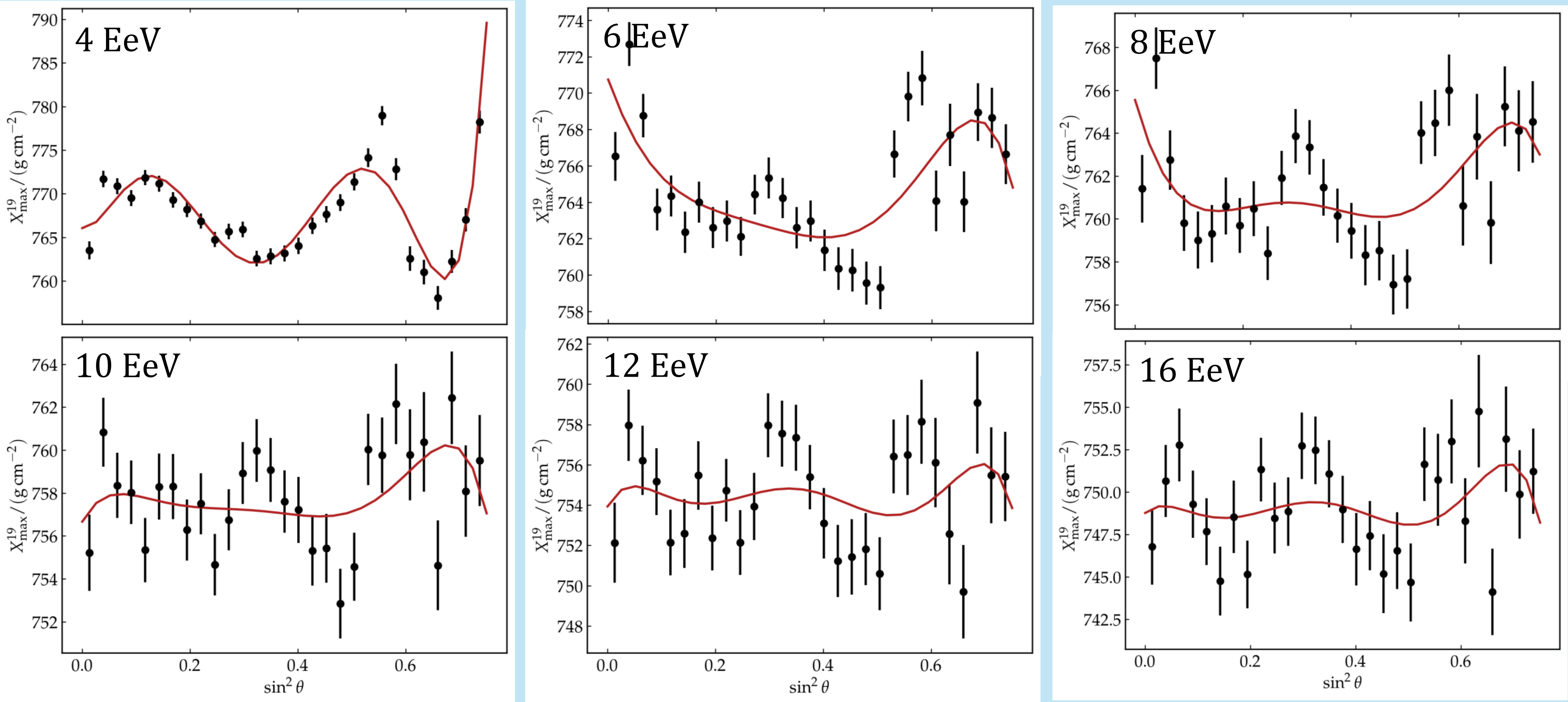
Corrected with 3rd degree polynomial fit:

$$f(\sin^2\theta) = a + b\sin^2\theta + c\sin^4\theta + d\sin^6\theta$$



Zenith angle - Universality

Dependence corrected with a 6th degree polynomial fit in $\sin^2\theta$, iteratively calculated for increasing energies: $4, 6, 8, 10, 12, 16, 20, 32$ EeV.

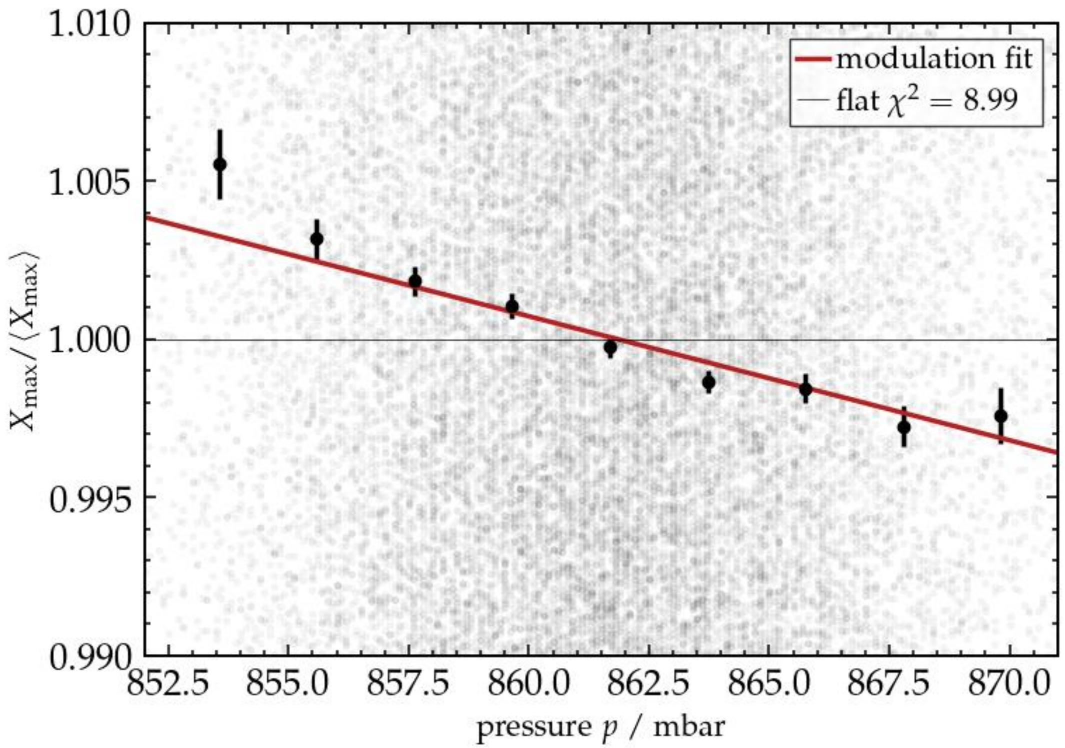


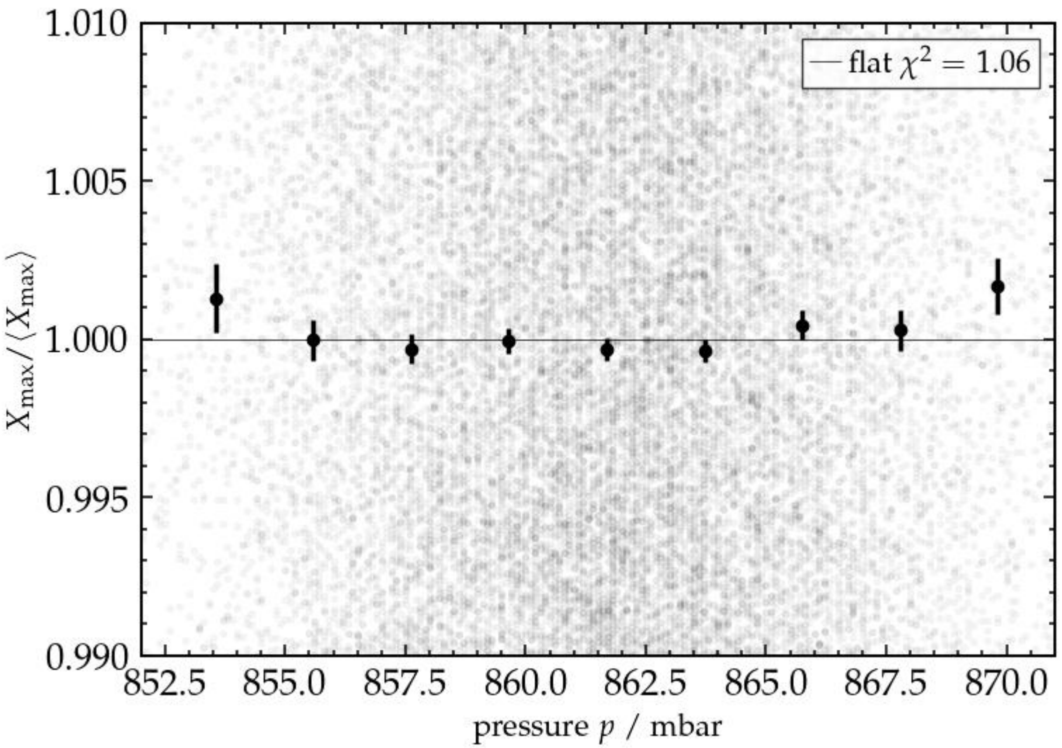
Pressure - AixNet & Universality

Pressure depends linearly on atmospheric density.

→ Linear dependence on pressure, + cos θ term to account for inclination.

Correction fit: $$f(p, \theta) = a + b\frac{p}{\cos\theta}$$





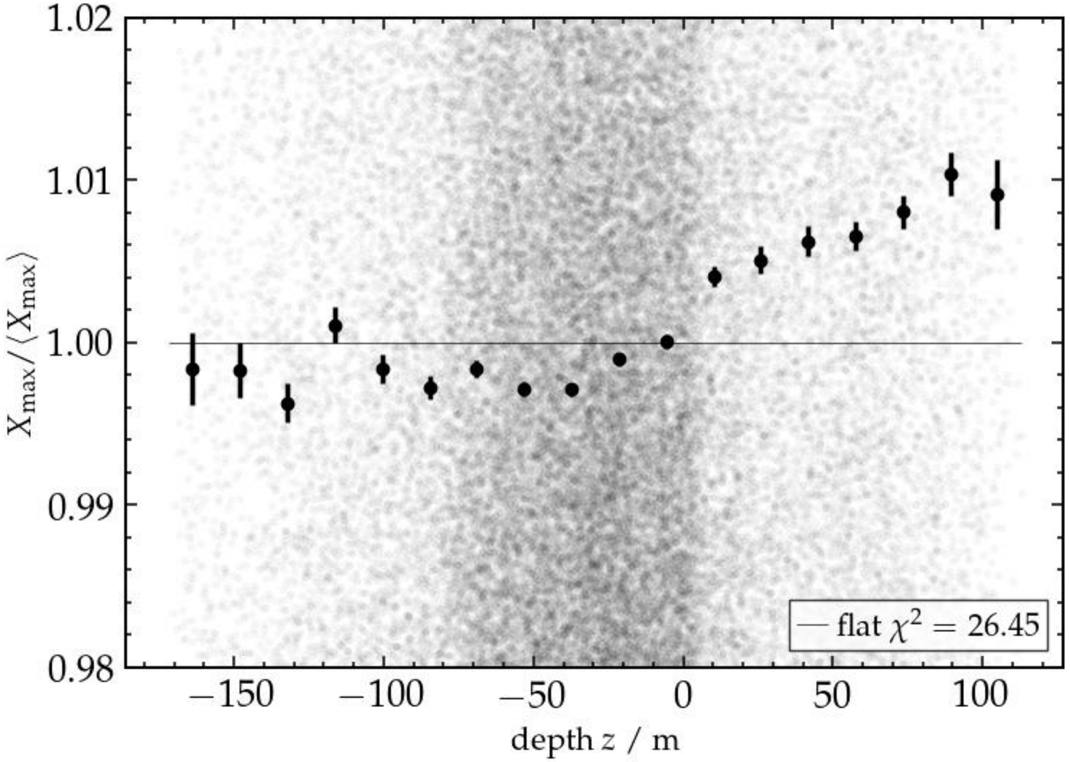
Position in the detector array - AixNet & Universality

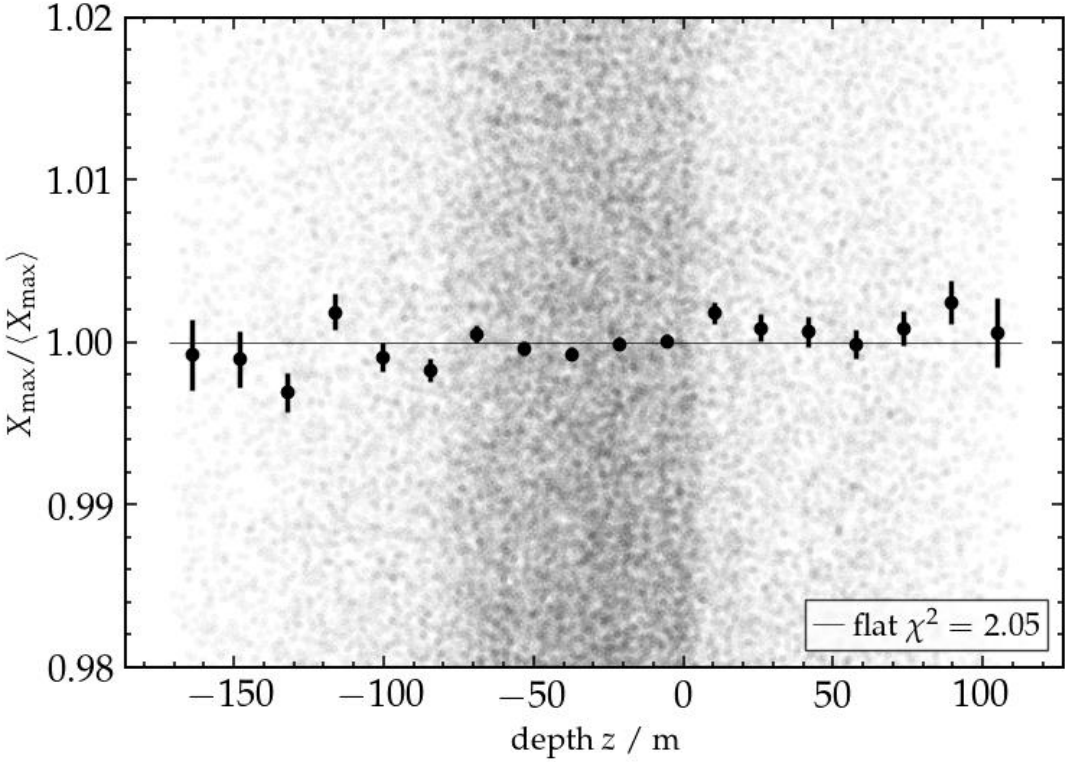
The simulations feature a flat detector array, but the surface detector is not flat.

$\rightarrow$ The modulation is corrected both for the East-West and North-South

3rd degree polynomial fit: $\mathrm{f(x)} = a + b\mathrm{x} + c\mathrm{x}^2 + d\mathrm{x}^3$

The correction removes the altitude dependence of data.



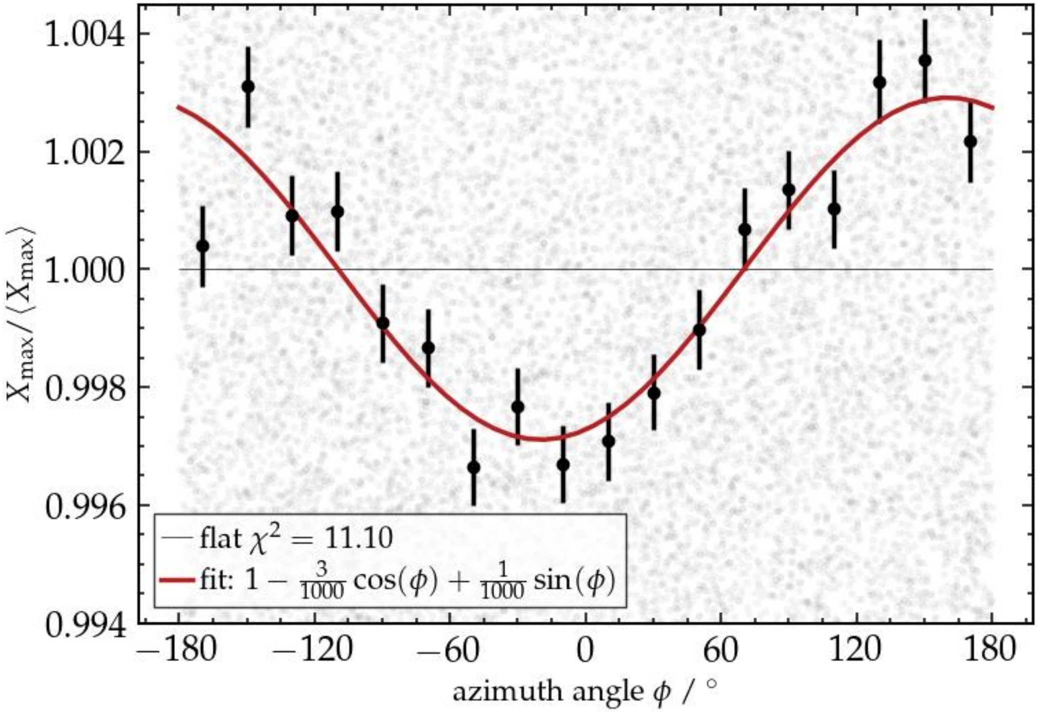


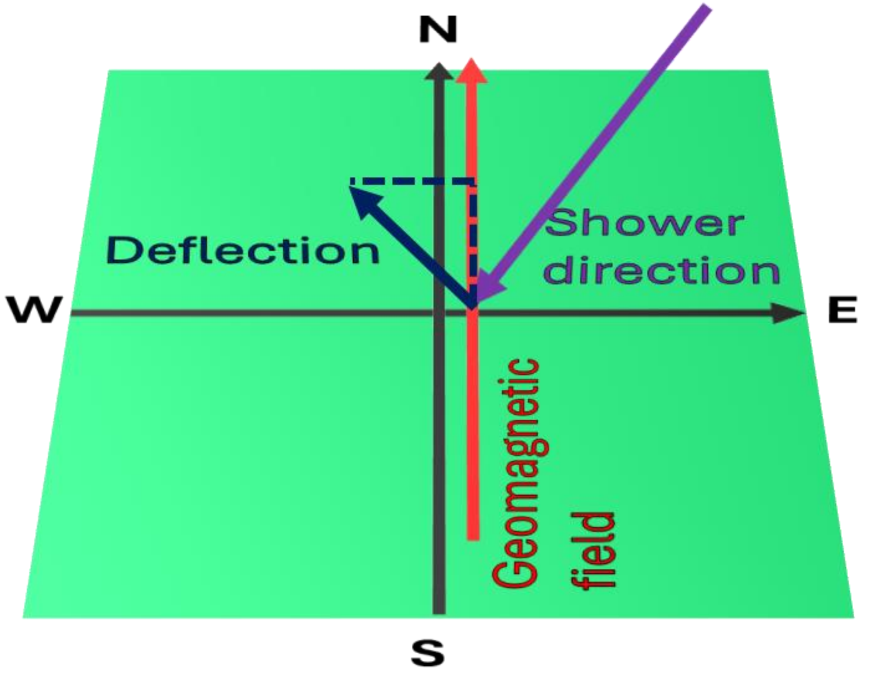
Geomagnetic field - AixNet & Universality

The simulations on which AixNet was trained accounted for the geomagnetic field, but the East-West azimuth modulation shows that there's still some interaction.

The geomagnetic field is in the North-South direction:

→ the modulation is mainly on the East-West direction,



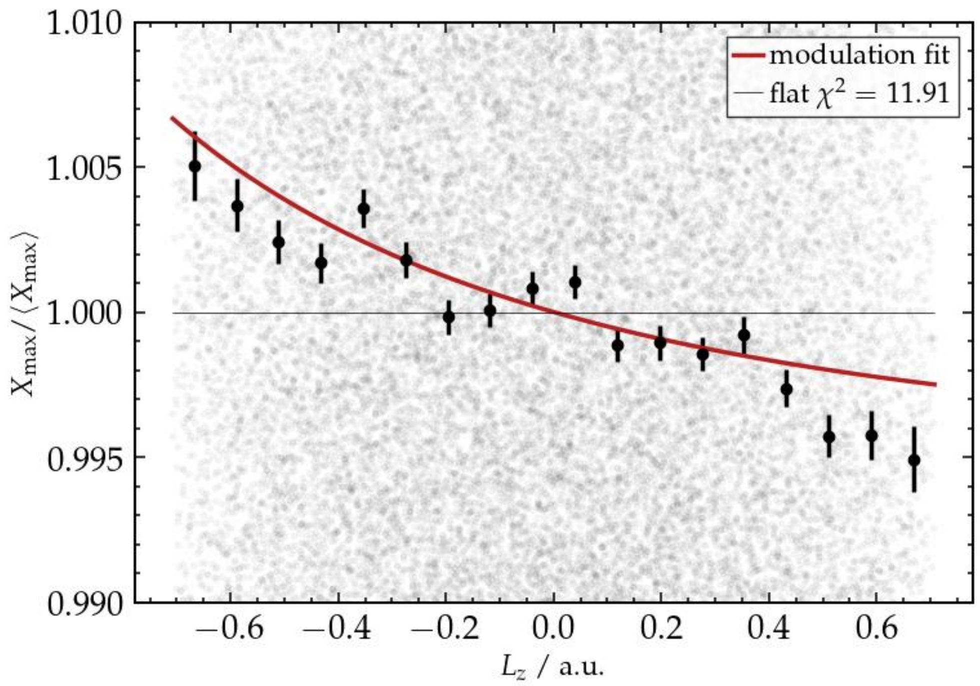


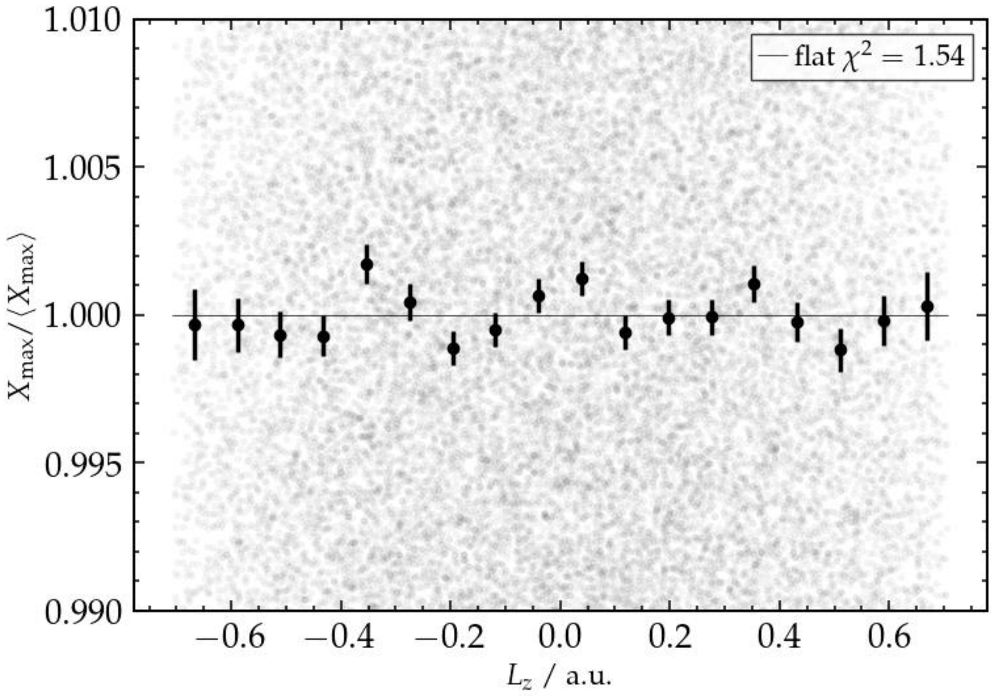
Geomagnetic field - AixNet & Universality

The modulation is corrected by a fit that mimics the interaction treatment in simulations in Offline: $\mathrm{f}(L_z, \theta) = a + c\,\frac{L_z}{\cos^b \theta}$

where $L_z = \left(\hat{r} \times \hat{B}_g\right)_z = \sin\theta\cos\phi\sin\theta_B\sin\phi_B - \sin\theta\sin\phi\sin\theta_B\cos\phi_B$,

with $\hat{r}$ the arrival direction of the event, $\hat{B}_g$ the direction of the geomagnetic field.

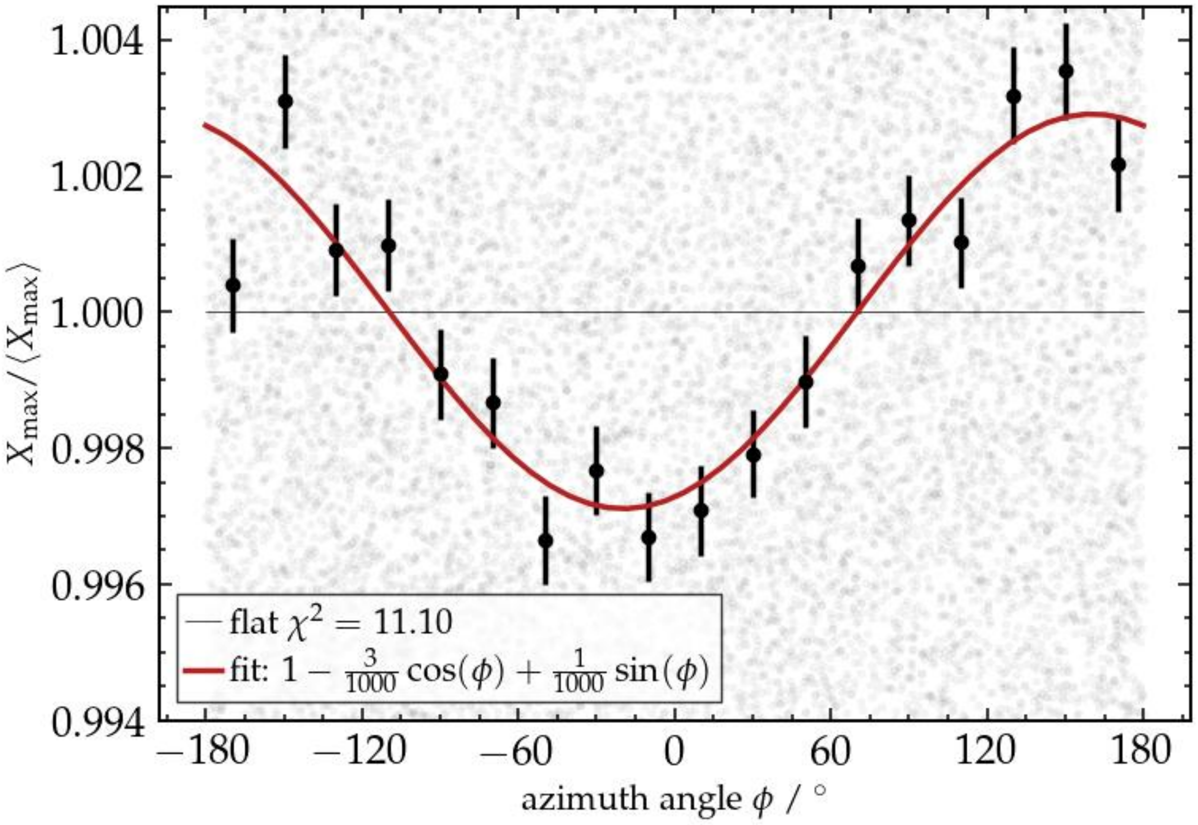




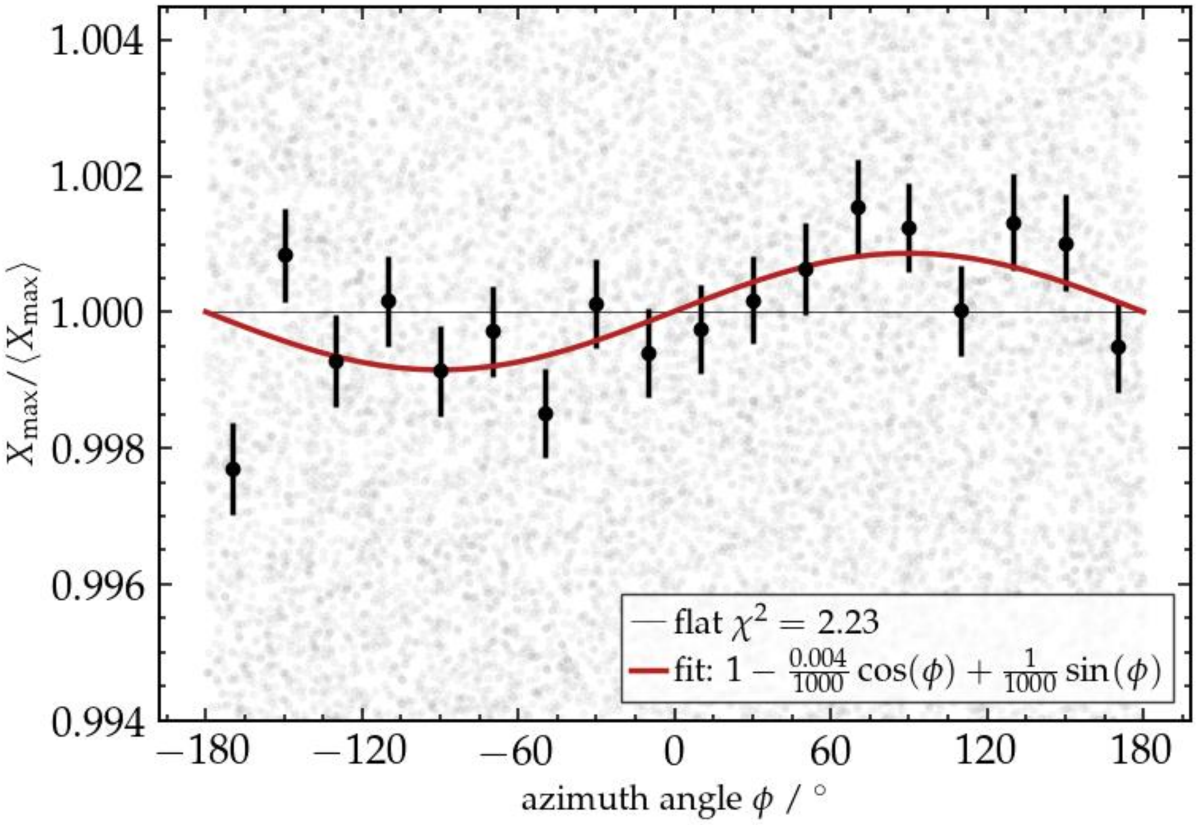
Geomagnetic field - AixNet & Universality

The removal of the geomagnetic modulation removes the East-West azimuth modulation.

Before corrections



After corrections

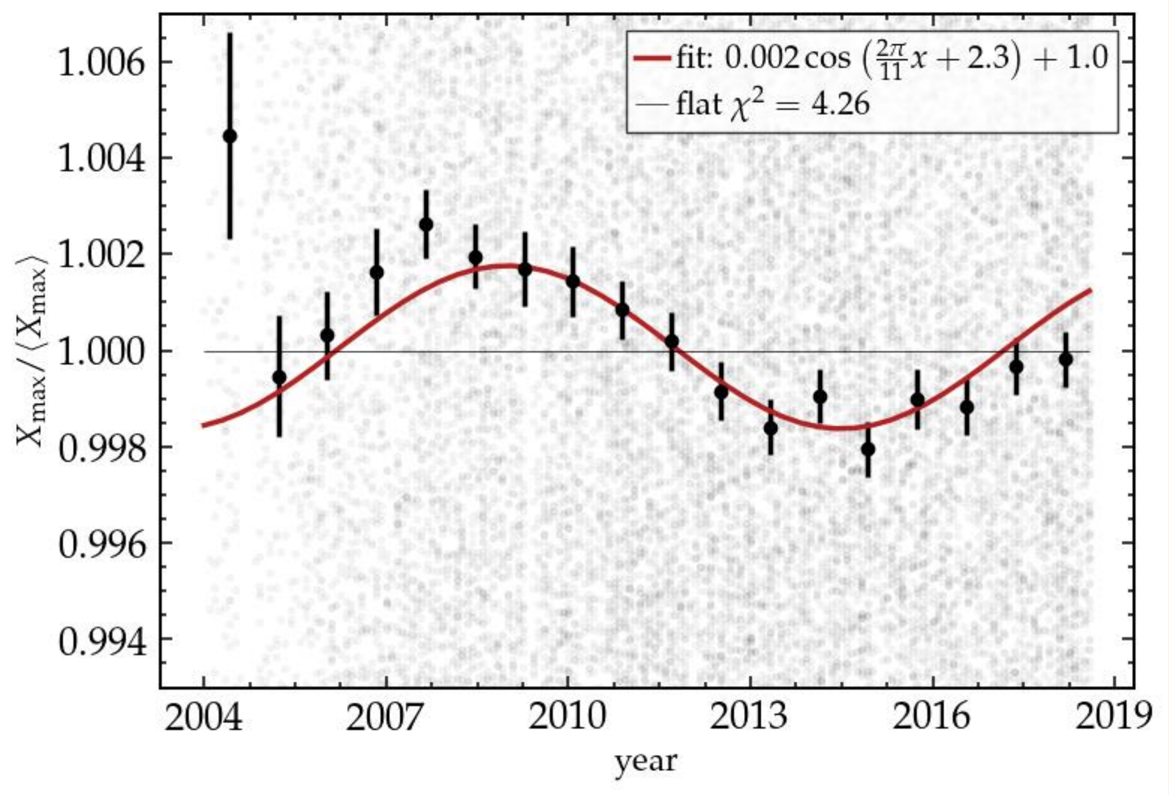


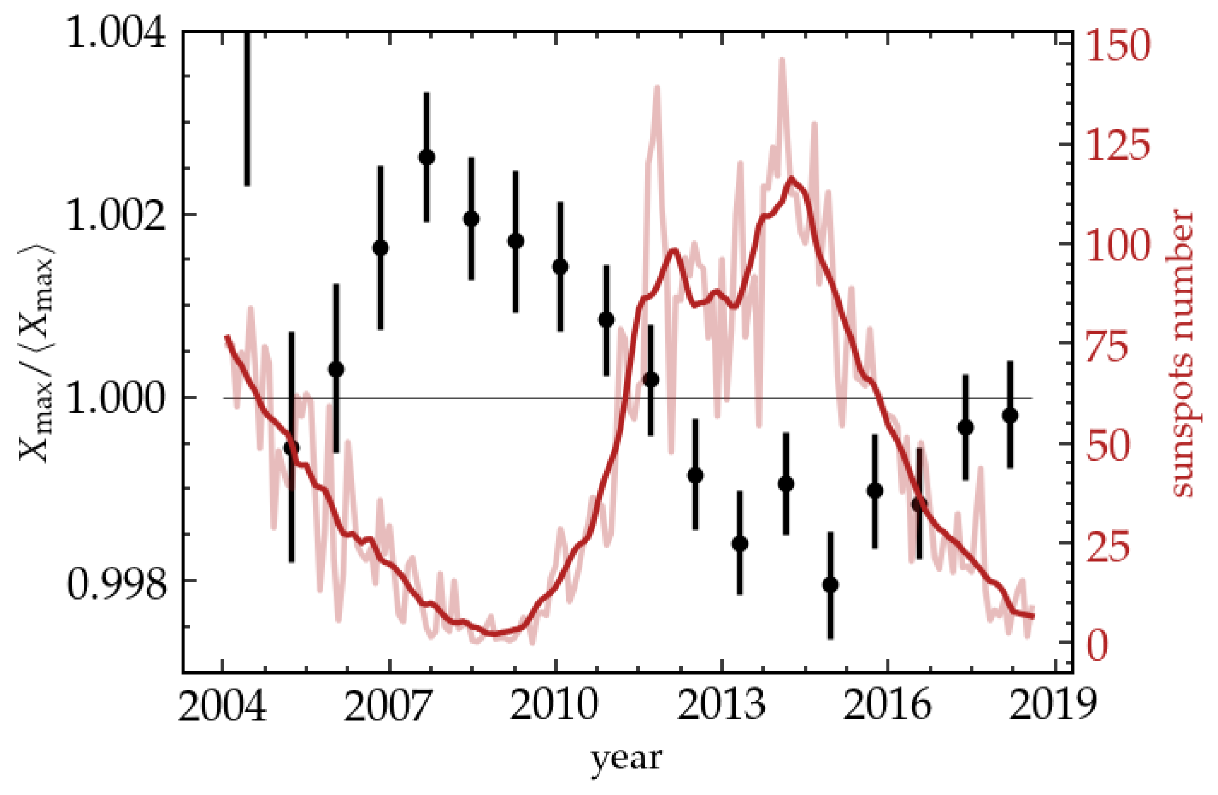
Year - AixNet

Predictions for $X_{\max}$ follow a wave pattern when plotted against years.

If data is compared to the 11-year Solar cycle, it suggests anticorrelation.

Post-trial p-value for a modulation in anticorrelation with the Solar cycle is 6×10^{-4}.



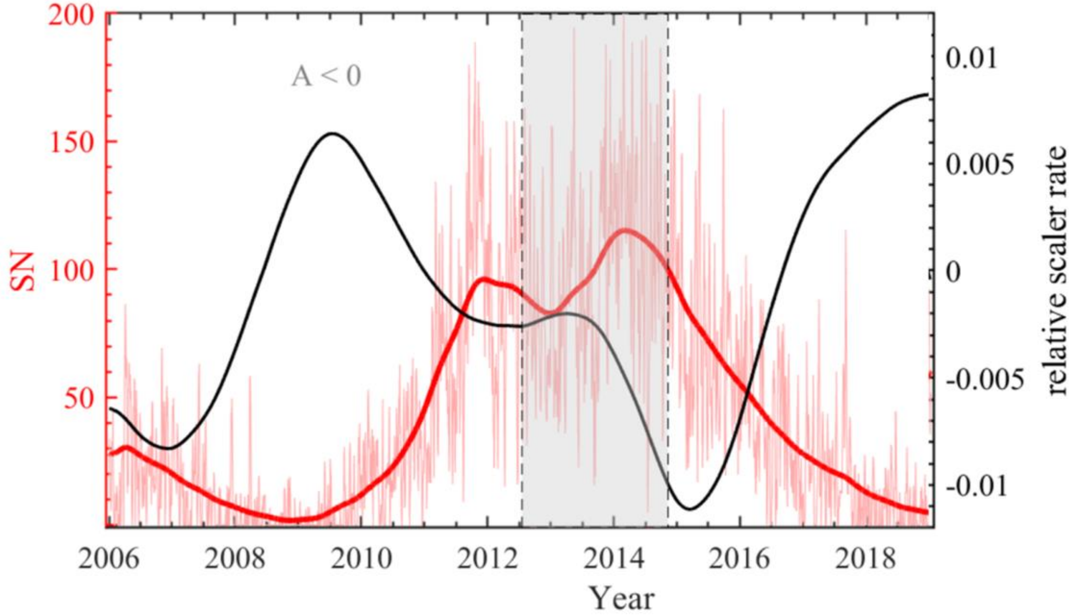


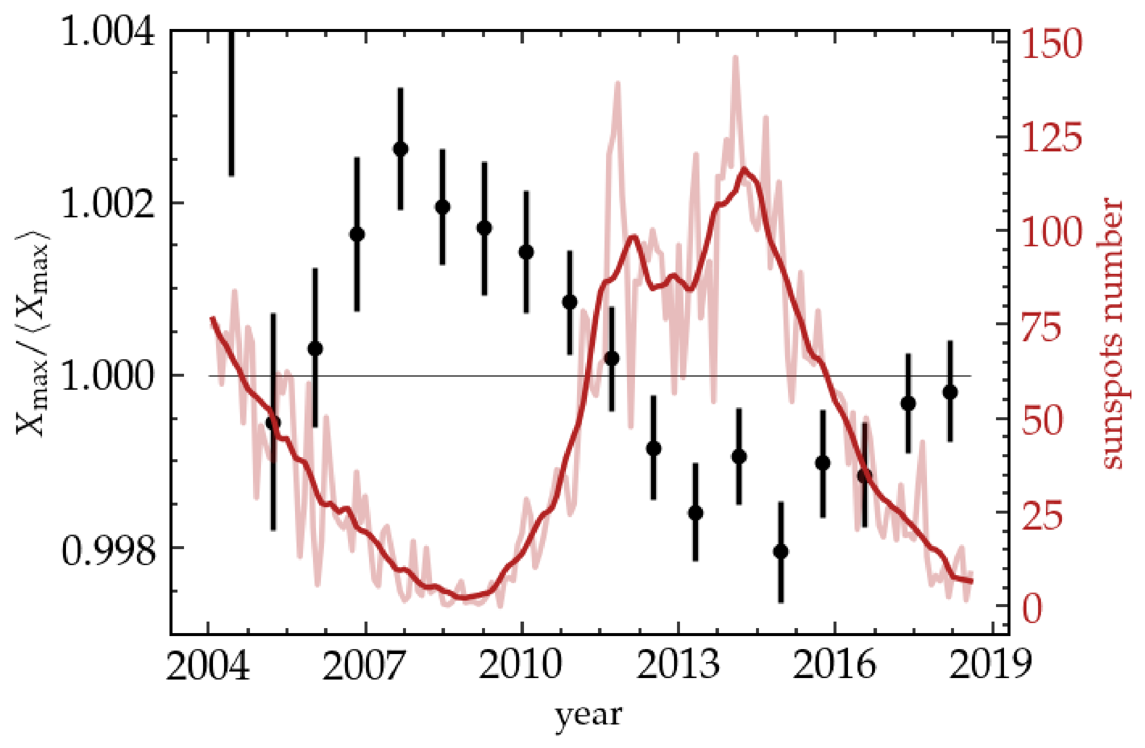
11-year cycle - AixNet

- An anticorrelation in the rate of cosmic rays with the Solar cycle has been seen by Auger in the Scaler mode.
- The influence of the Sun magnetic field is only seen for Galactic cosmic rays.
- A signal in the Scaler mode belongs to the background in the WCDs and is caused by lower energy cosmic rays.
- Corrected with a cosine function of period 11 years:

$$f(y) = a + b\cos\left(\frac{y}{11} + c\right)$$

From GAP note 2023-023



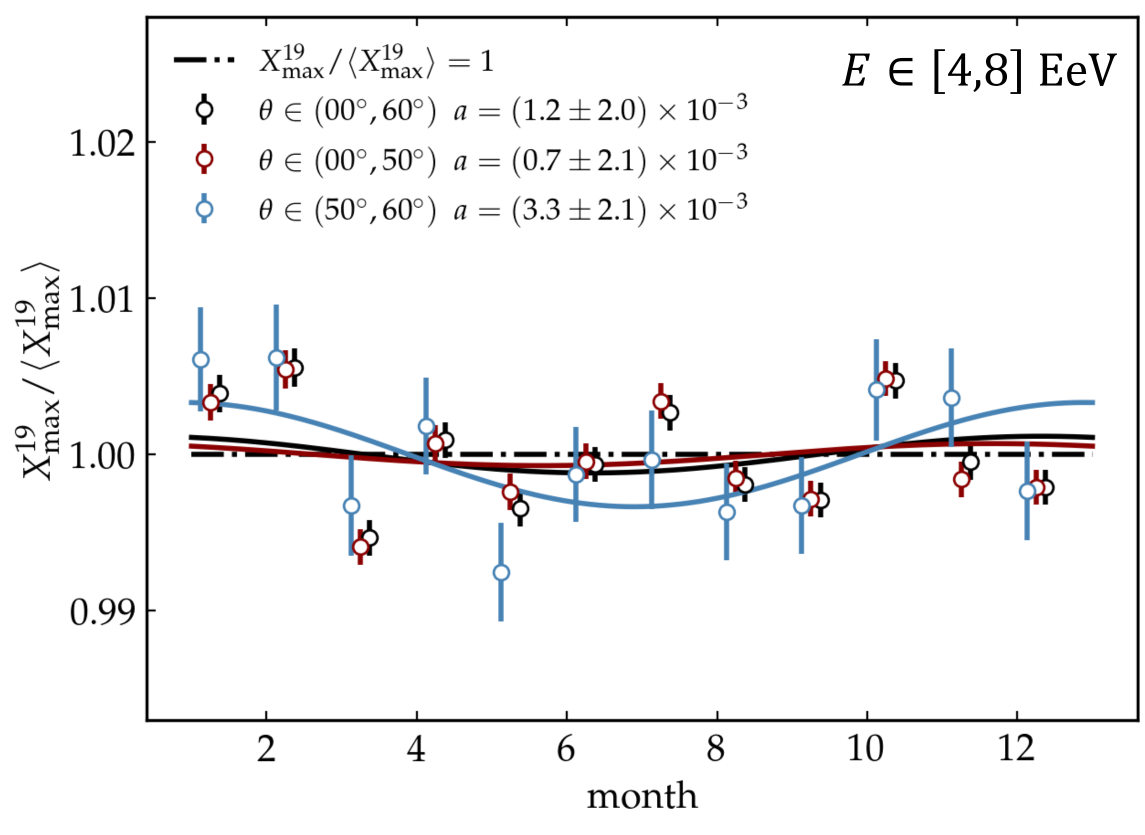


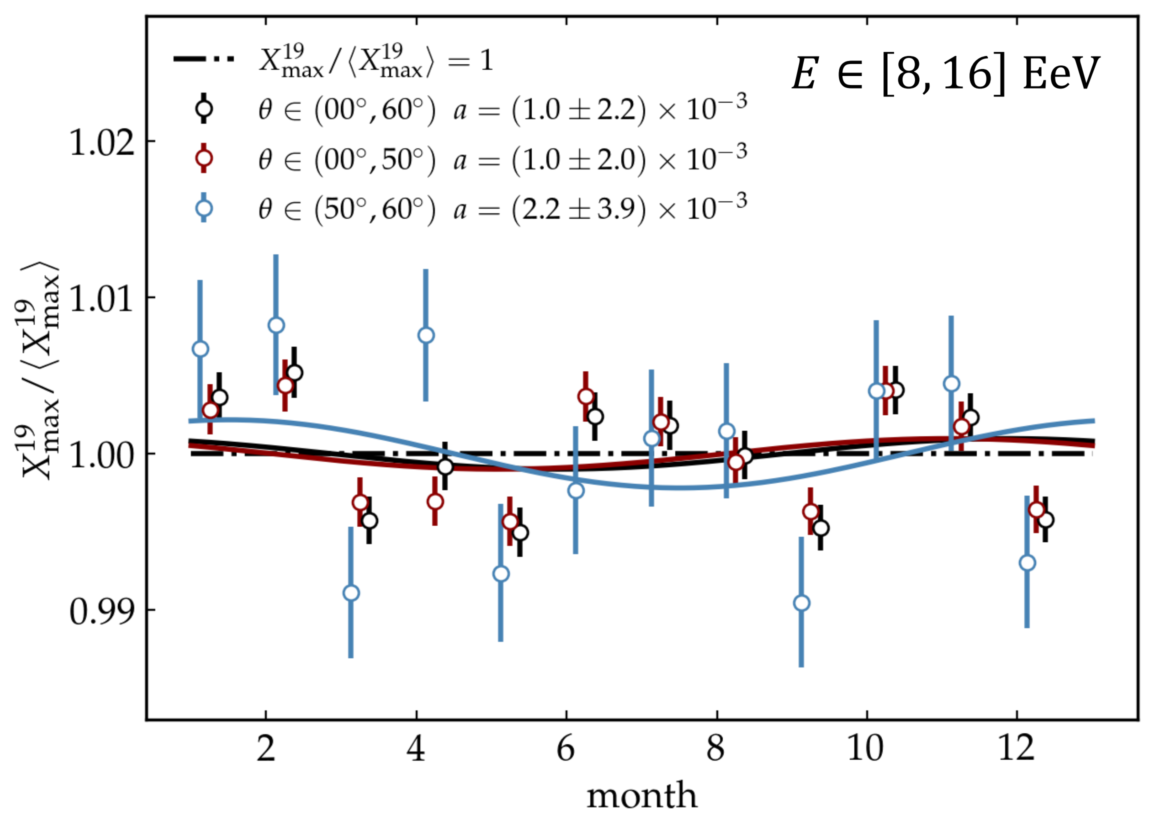
Seasonal modulation - Universality

$X_{\max}$ estimates are sensible to yearly changes of the detector environment.

→ a cyclic modulation in months appear.

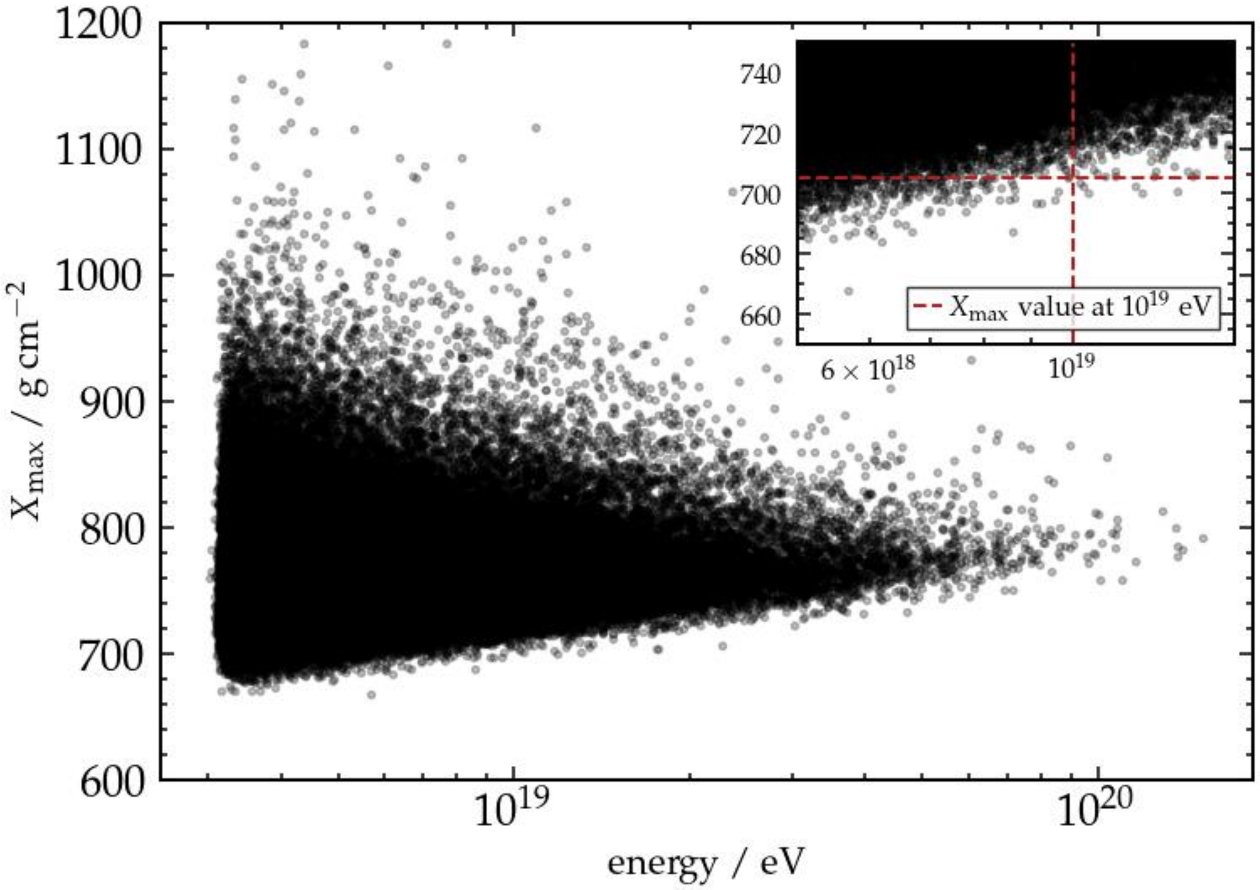
Corrected with a periodic fit: $$f(m) = a\cos\left(\frac{m}{6}\right) + b\sin\left(\frac{m}{6}\right) + 1$$

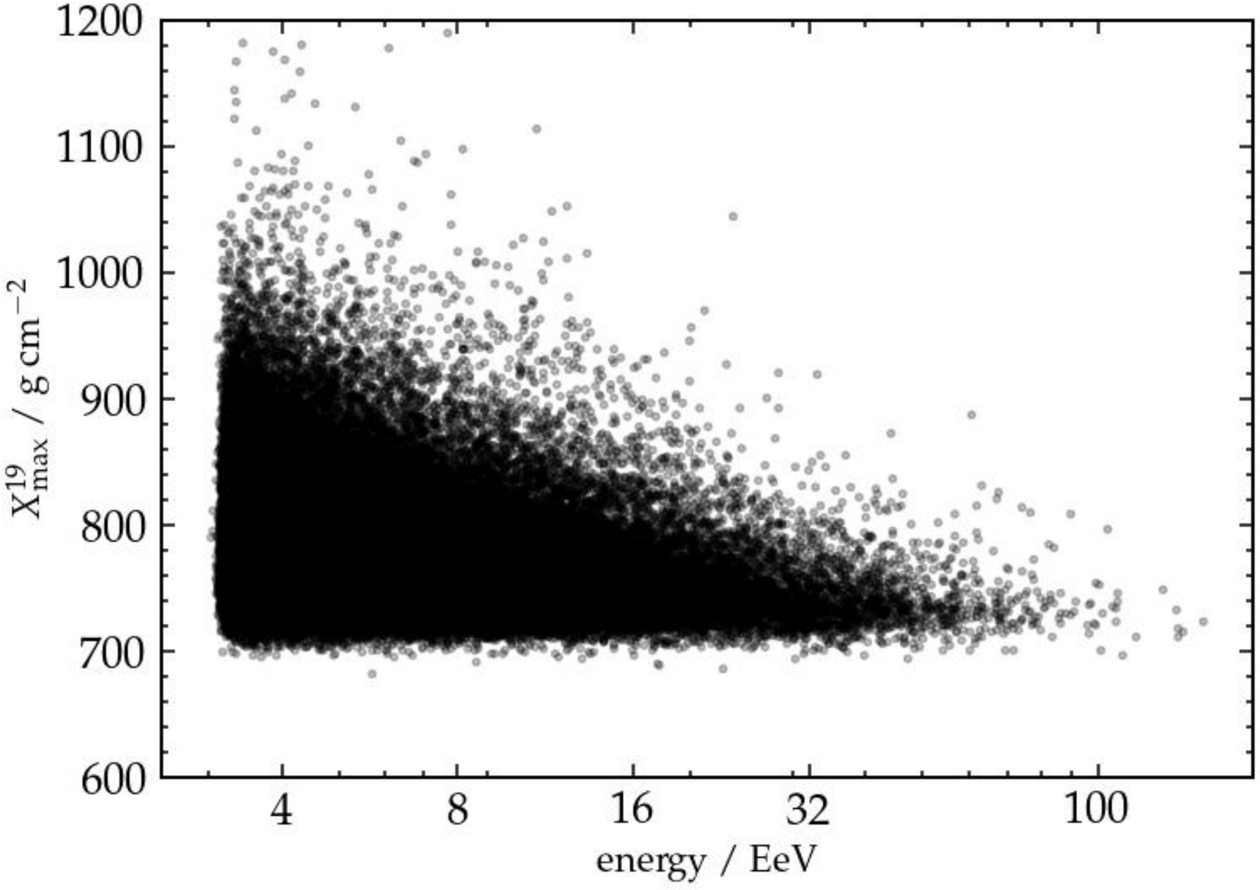




Generating $X_{\max}^{19}$

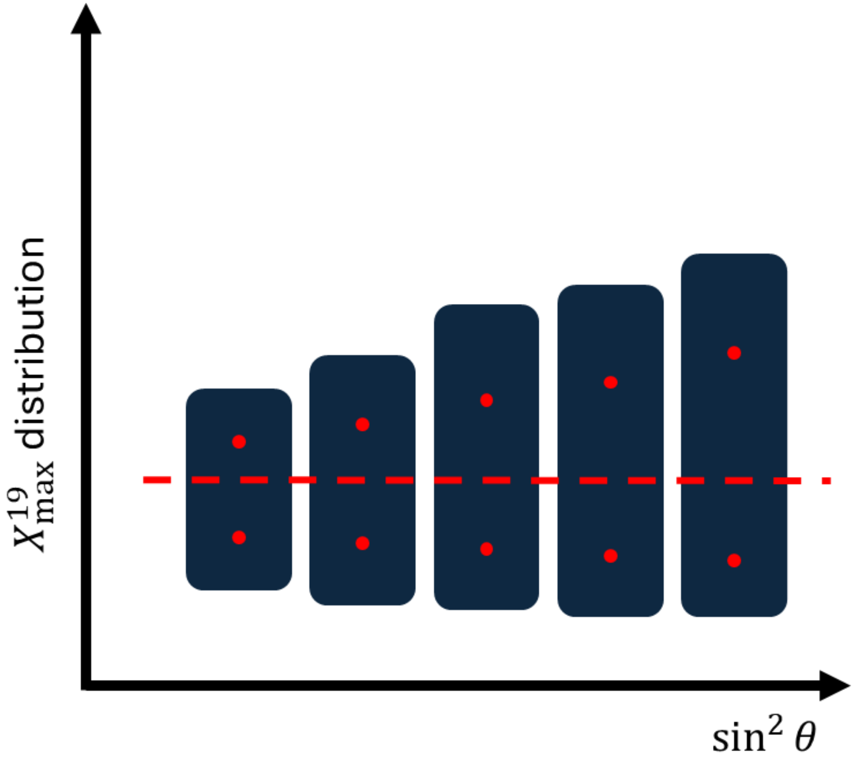
$$X_{\max}^{19} = X_{\max} - D_{10} \log_{10}\left(\frac{E}{10^{19}\ \mathrm{eV}}\right)$$

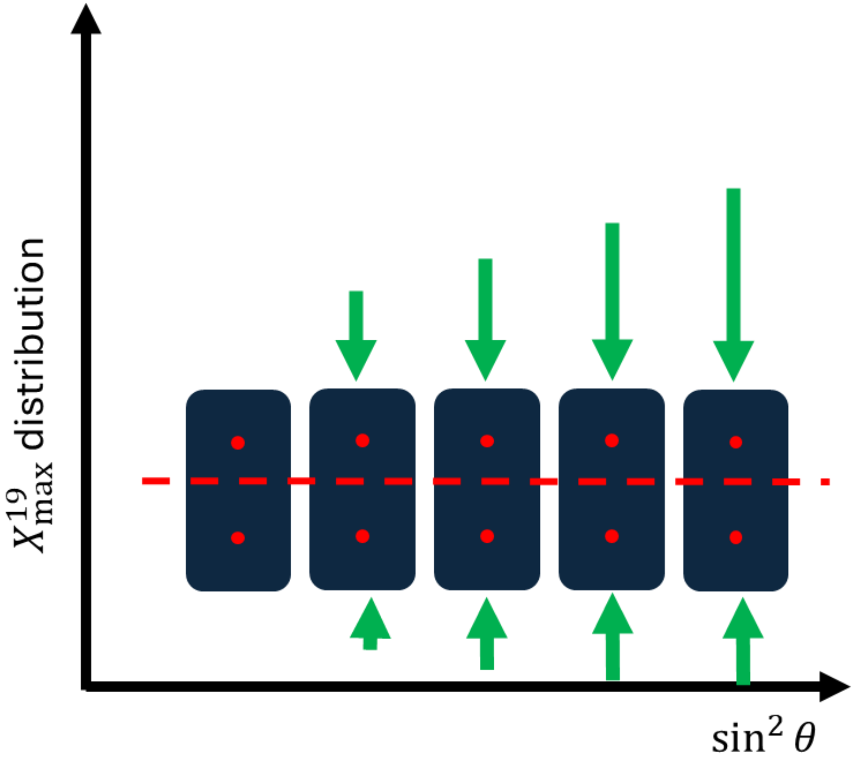




- $X^{19}_{\max}$ is a mass-dependent, energy-independent parameter.
- On $X^{19}_{\max}$ is possible to apply a cut, separating a light component and a heavy one.
- The light-heavy cut leads to a **zenith selection bias** in composition that is due to the widening of the distribution in θ.

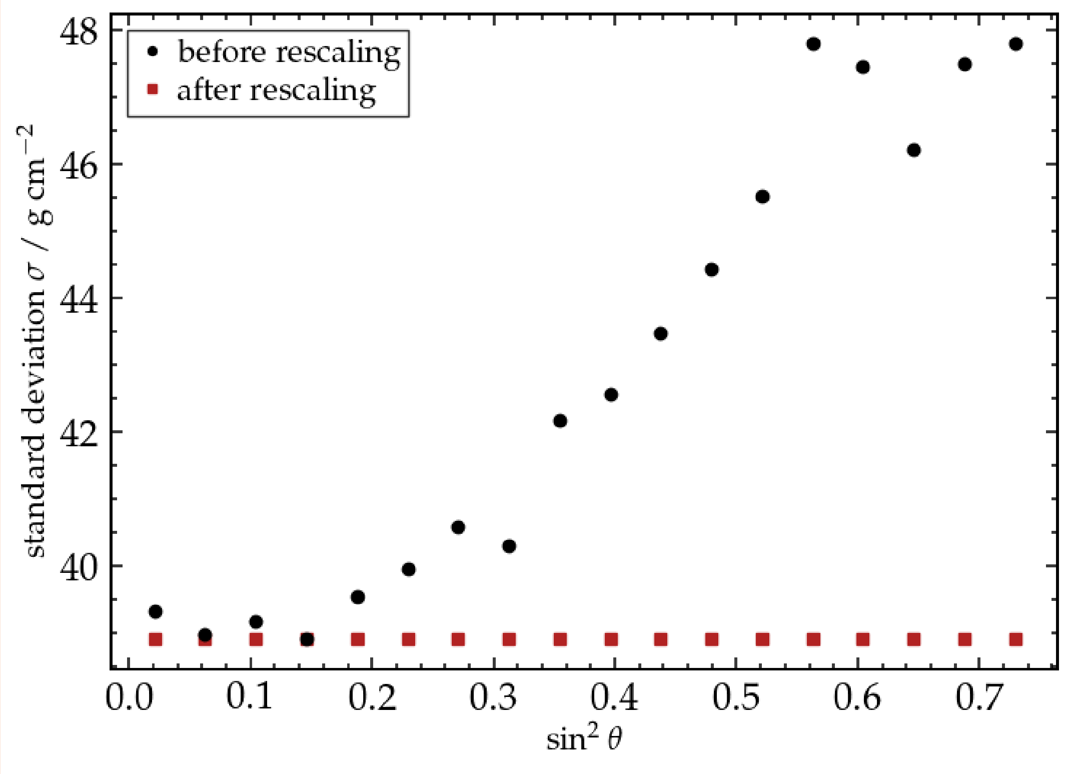
  $\rightarrow$ it is fixed by rescaling the distribution in zenith.

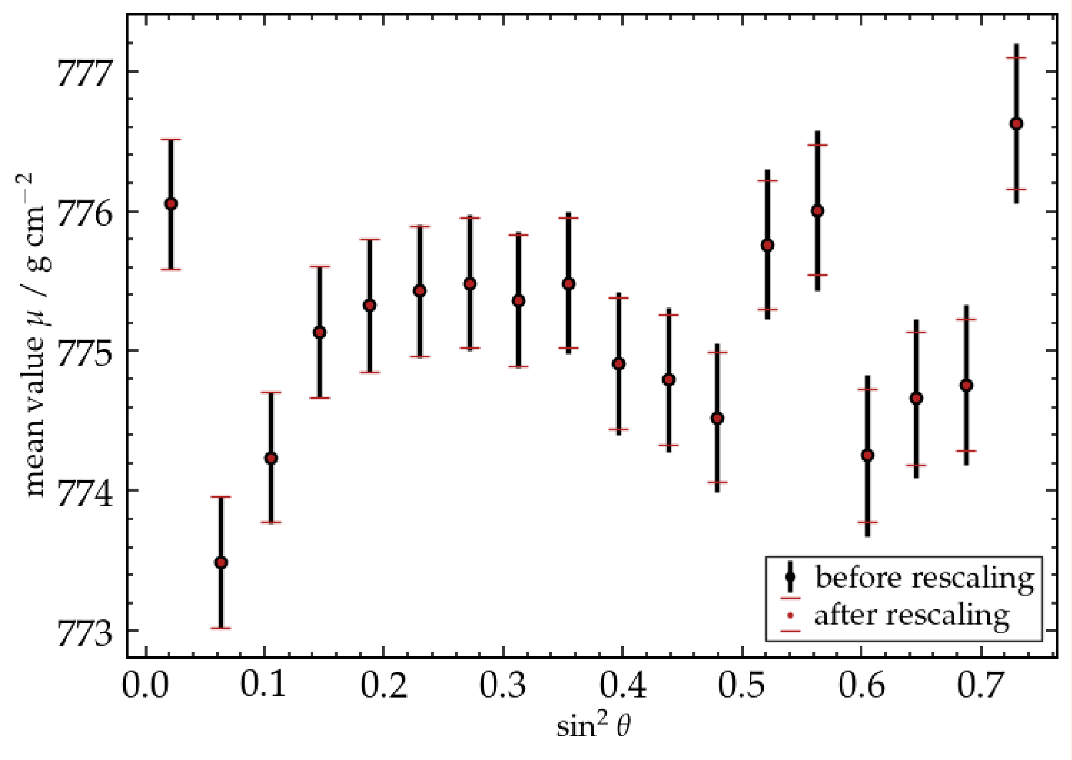




Rescaling method - AixNet

1. Bin the distribution in $\sin^2\theta$ and evaluate mean μ and standard deviation σ.
2. Find the minimum σ_{min}.
3. Rescale in every bin i: $X_{\max}^{19} \to (X_{\max}^{19})' = (X_{\max}^{19} - \mu) \cdot \frac{\sigma_{min}}{\sigma_i} + \mu$





Rescaling method - Universality

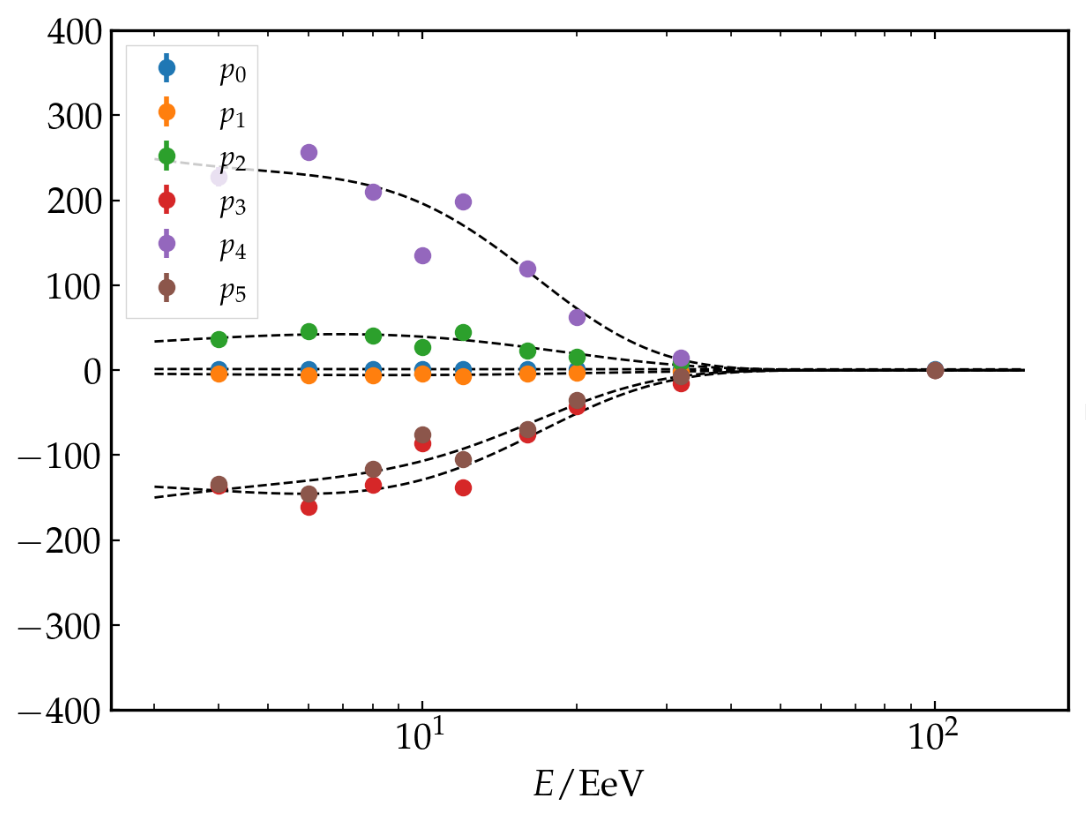
1. Define energy limits $4, 6, 8, 10, 12, 16, 20, 32$ EeV.
2. Iteratively fit a 5th degree polynomial $f_\sigma(\mathrm{E})$ in $\sin^2\theta$ of $\sigma_{X_{\max}^{19}}$.
3. Fit the 6 parameters p_i of $f_\sigma(\mathrm{E})$ in the energy limits:

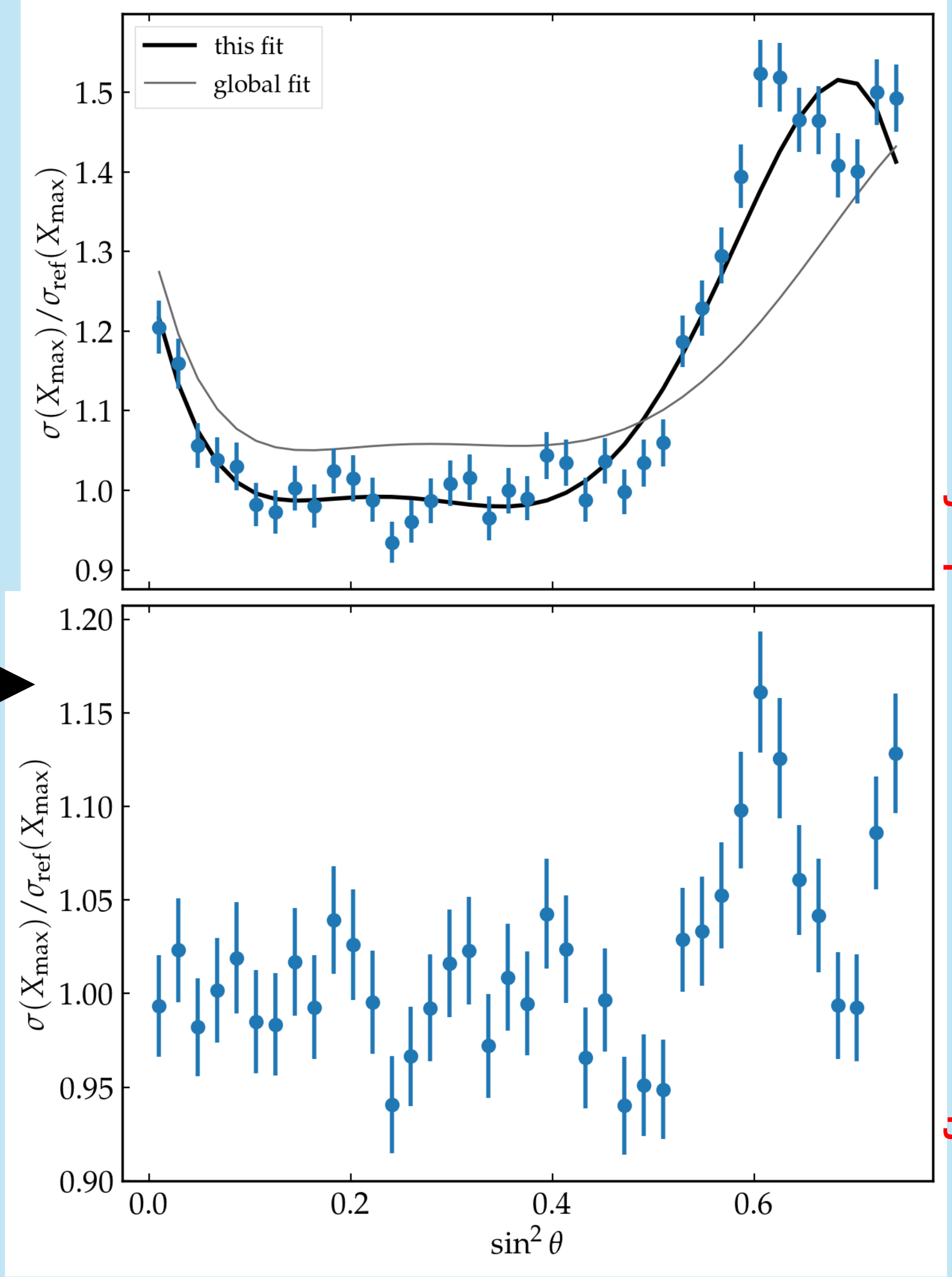
$$\mathrm{g}(\mathrm{E}, \mathrm{p}_i) = \left(a + b\mathrm{p}_i + c\mathrm{p}_i^2\right)\exp\left(-\frac{\mathrm{E}}{E_{0_i}}\right).$$

4. Iteratively rescale in energy:

$$(X_{\max}^{19})' = (X_{\max}^{19} - \mu) \cdot f_\sigma(\mathrm{E}) + \mu$$

Rescaling method - Universality





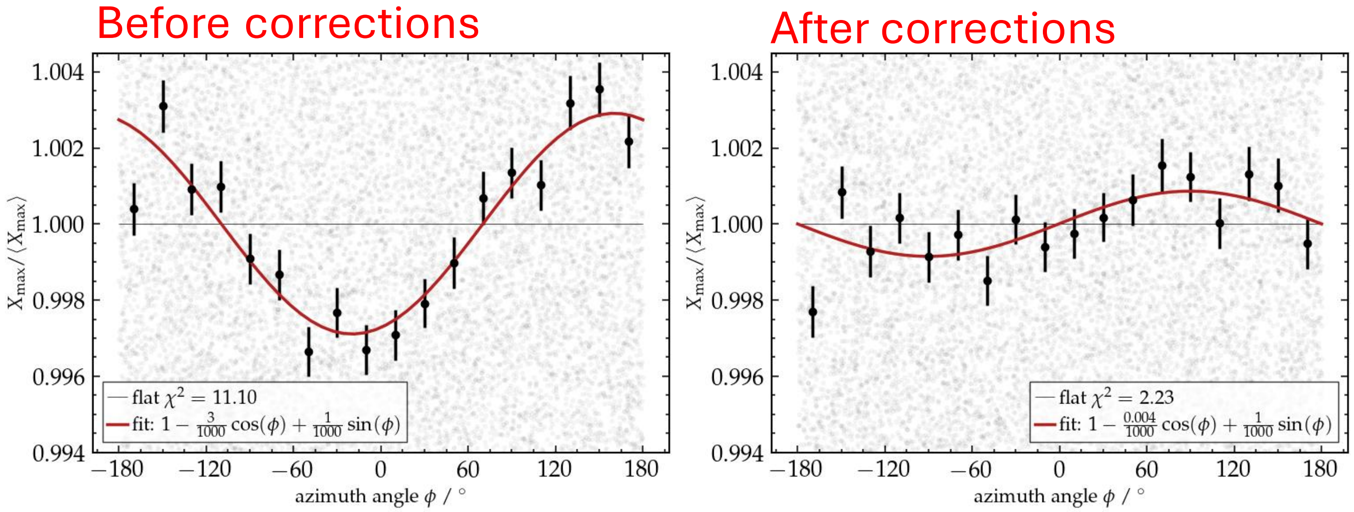
before

after

Outlook

- Universality and AixNet are simulation-based, SD-based $X_{\max}$ reconstruction methods.
- The data sets produced with the methods need to be corrected from detector-based biases.
- Dependences on
  - zenith angle,
  - pressure,
  - position in the array,
  - geomagnetic field,
  - year/month.

  were searched, found and corrected

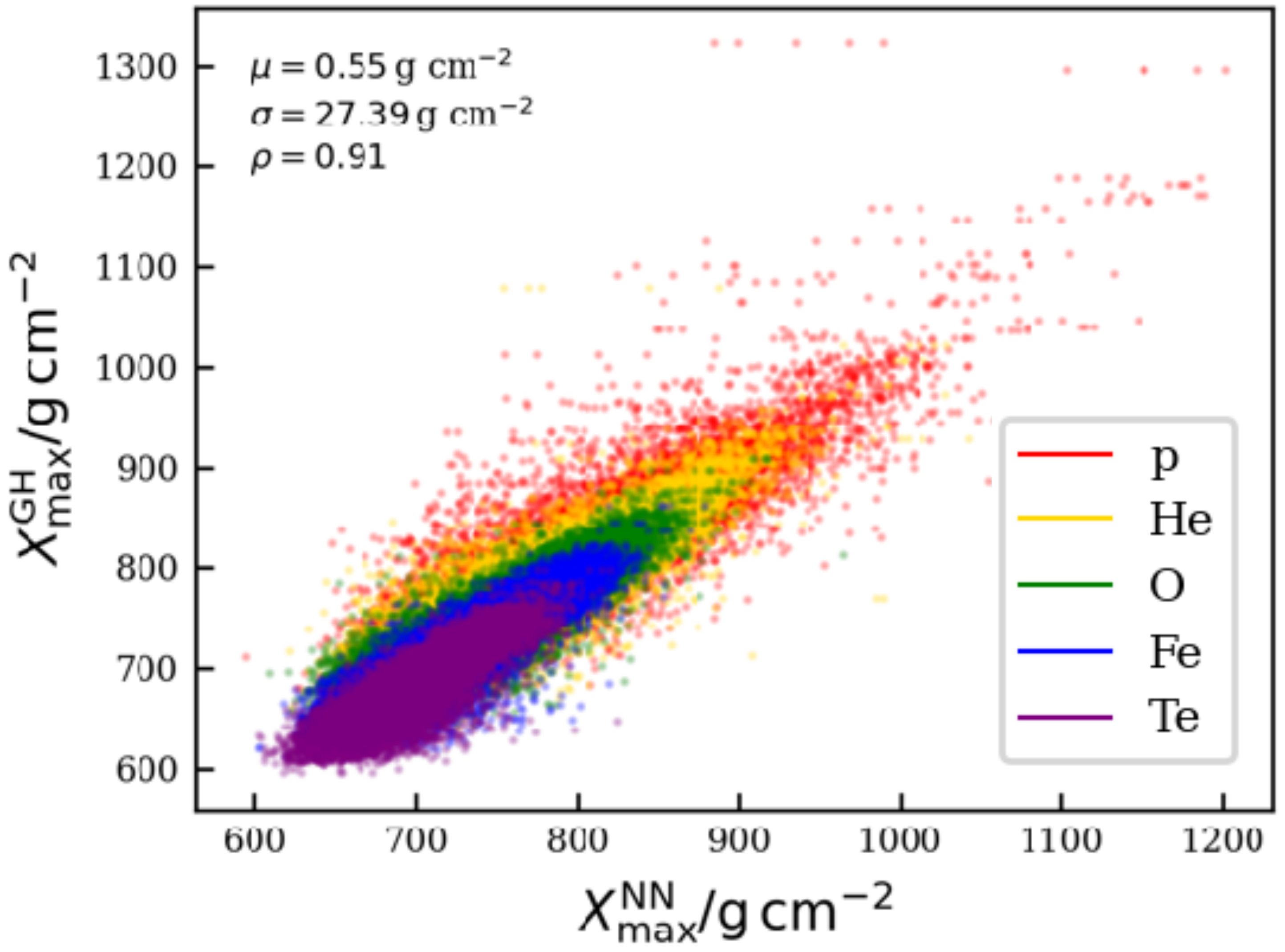


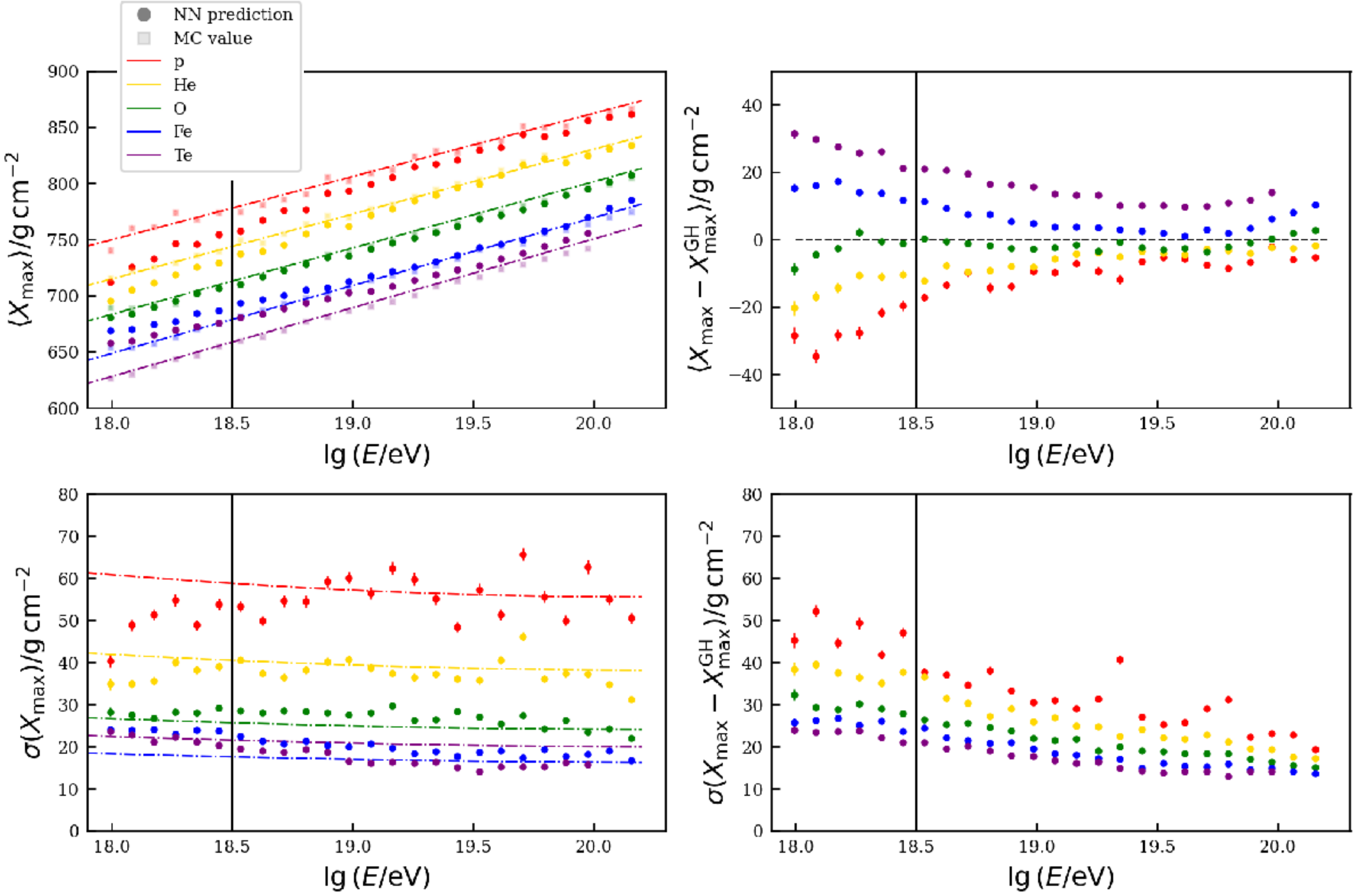
- From $X_{\max}$, a mass estimator $X_{\max}^{19}$ has been extracted.
- The widening of the $X_{\max}^{19}$ distribution in $\sin^2\theta$ due to the detector resolution has been rescaled.

News: ICRC25 dataset with KANE (DNN from Karlsruhe) is currently under commissioning

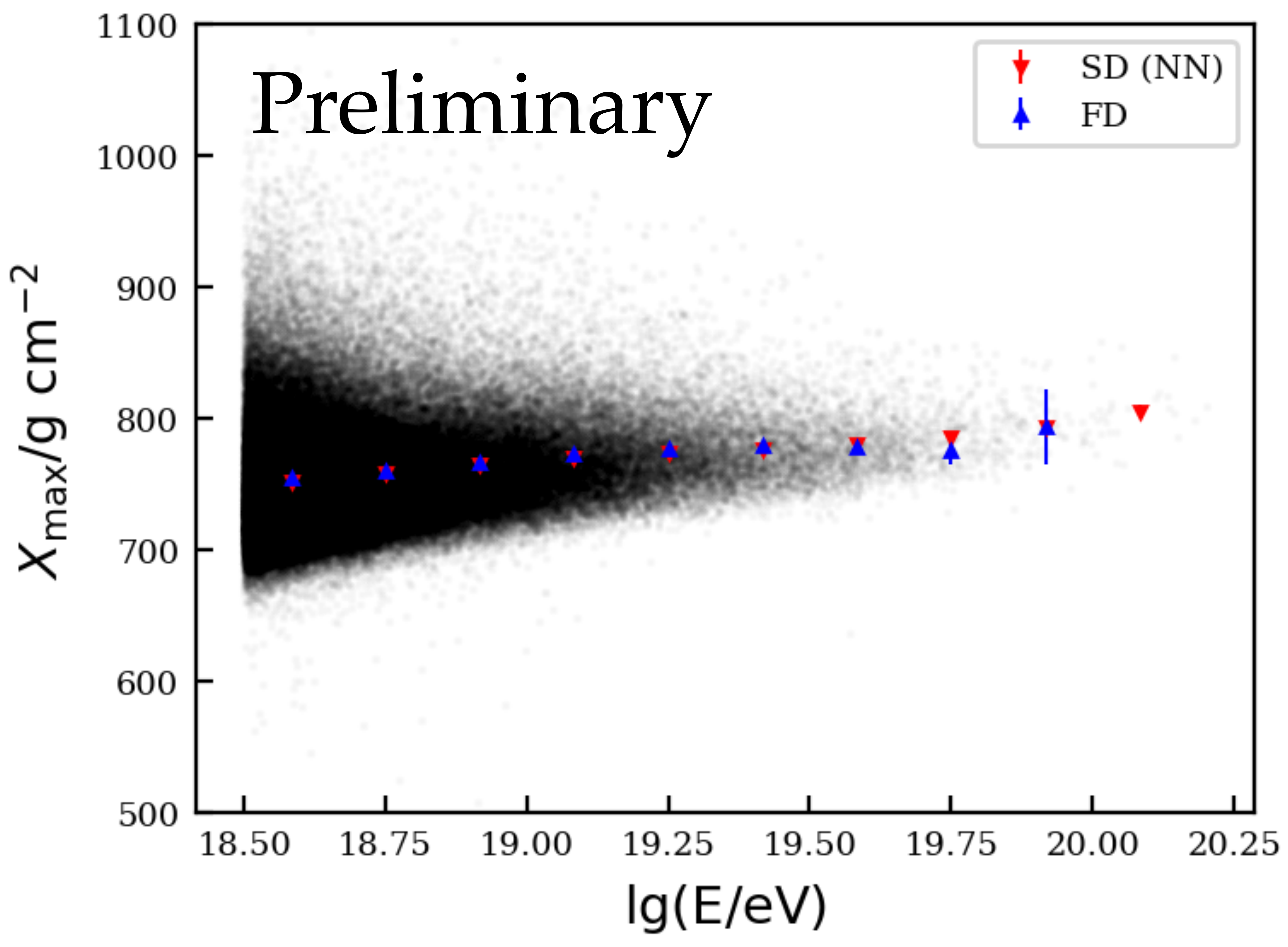
KANE

- **Simulation library:**
  - 5 primaries (p, He, O, Fe, Te)
  - zenith: 0-65 deg
  - lg(E/eV): 18.0 - 20.2
  - 4 atmospheres (01, 03, 08, 09)
  - ~300 000 showers
  - Offline icrc2025-test2

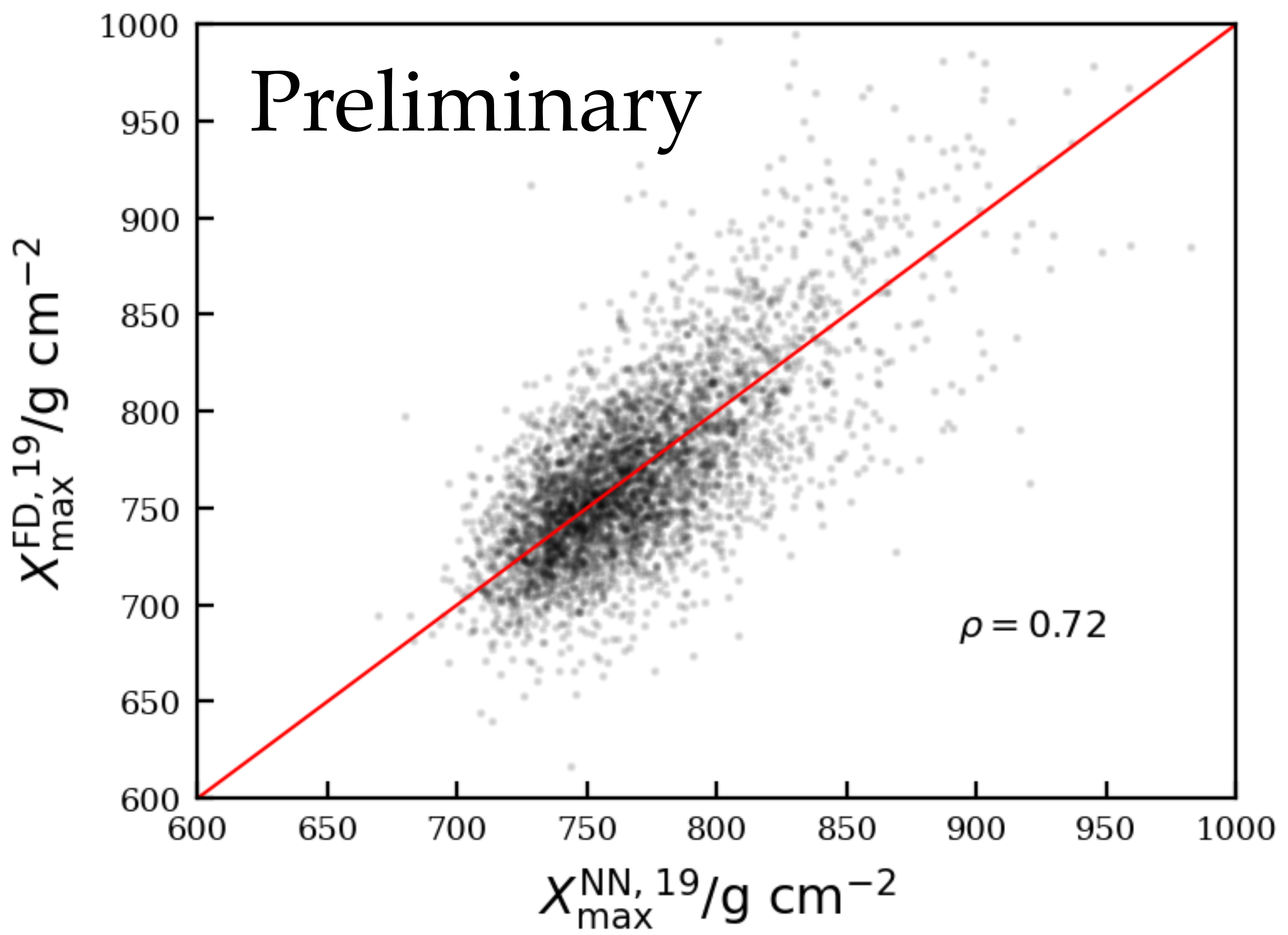




SD PhaseI 6T5



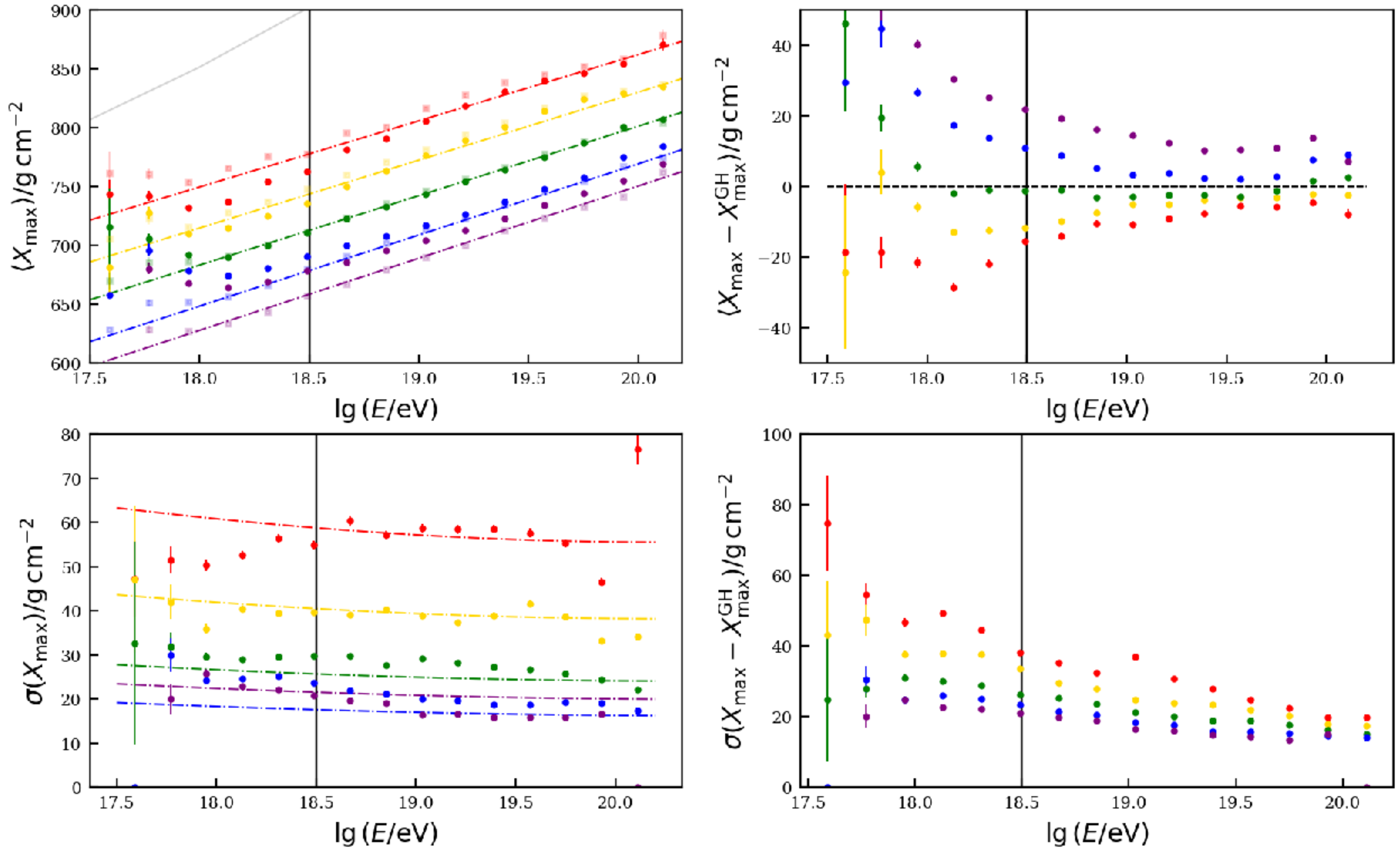
Golden PhaseI 6T5



- More information - the next ML call

Backup

Reconstructed energy

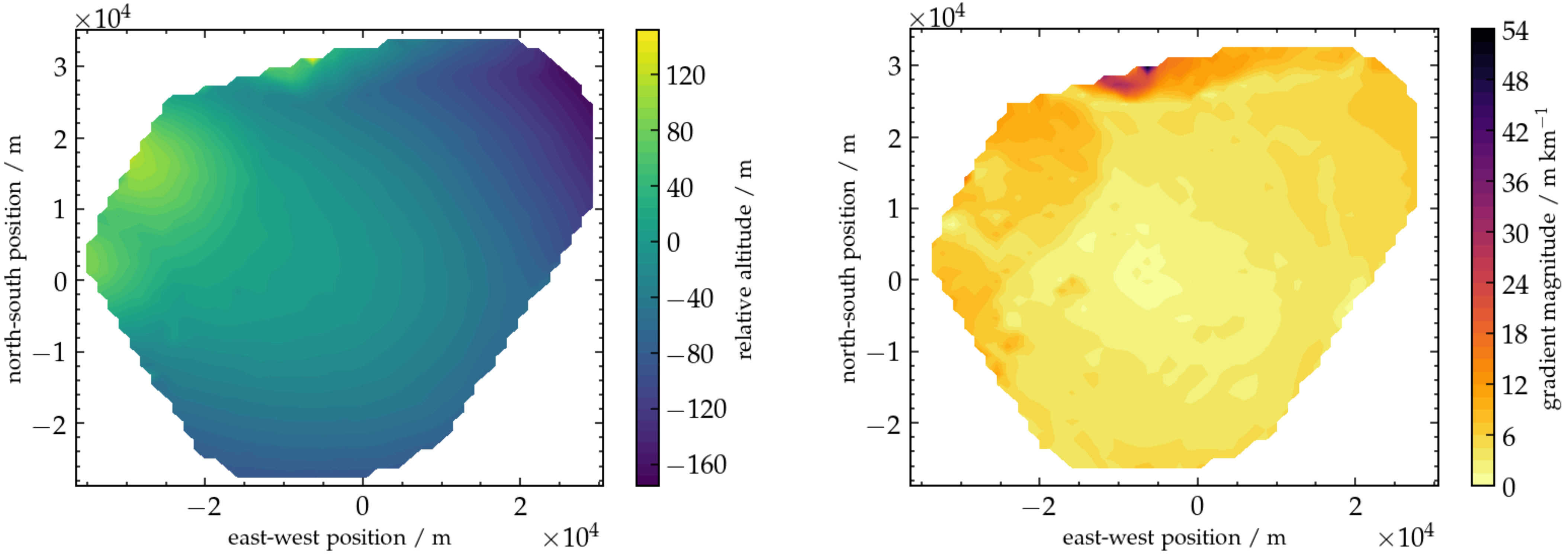


Grazie per l'attenzione!

Backup slides

Position in the detector array

- AixNet was trained on flat simulated detector array.
- The surface detector is instead not flat
  - → it leads to a modulation on the position of the air shower event.

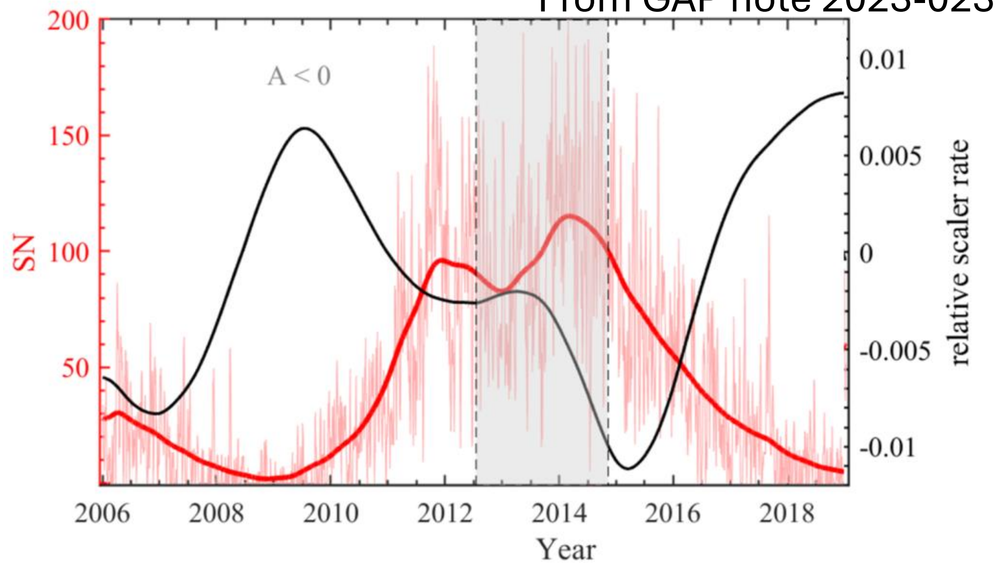


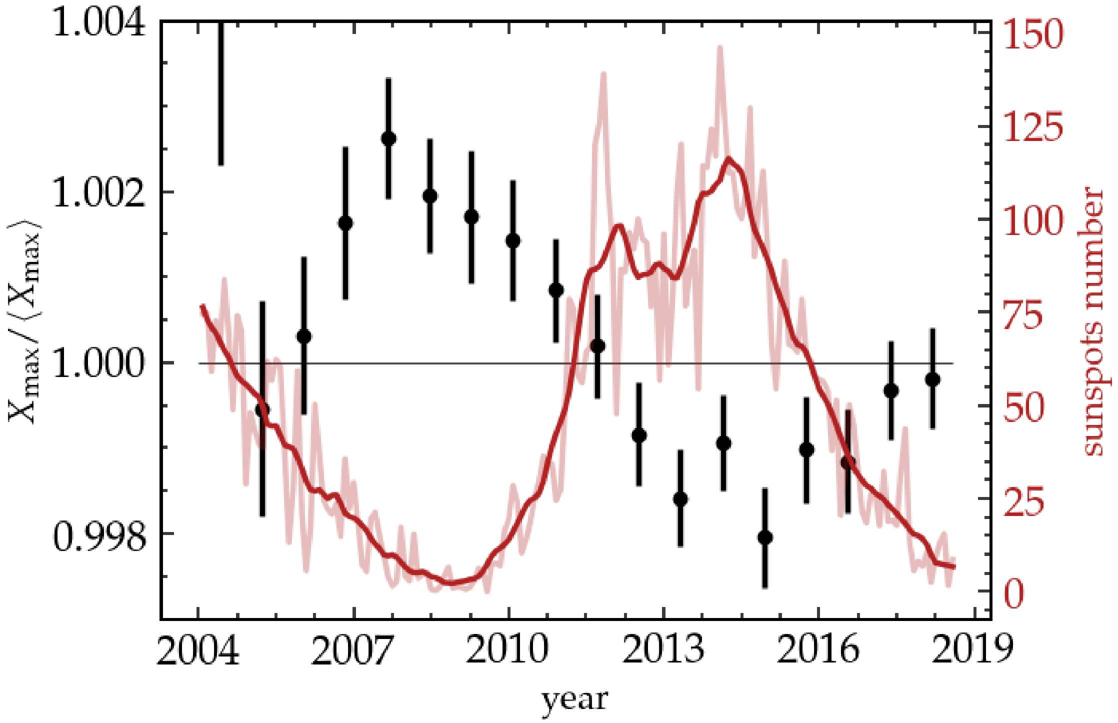
11-year cycle

- The tests show that Scaler data and $X_{\max}$ predictions can be related.
- Data from Universality does not show any modulation.
- In any case, the increase needed to obtain the modulation is far larger than the 1% variation reported in the Scaler rate.

↓

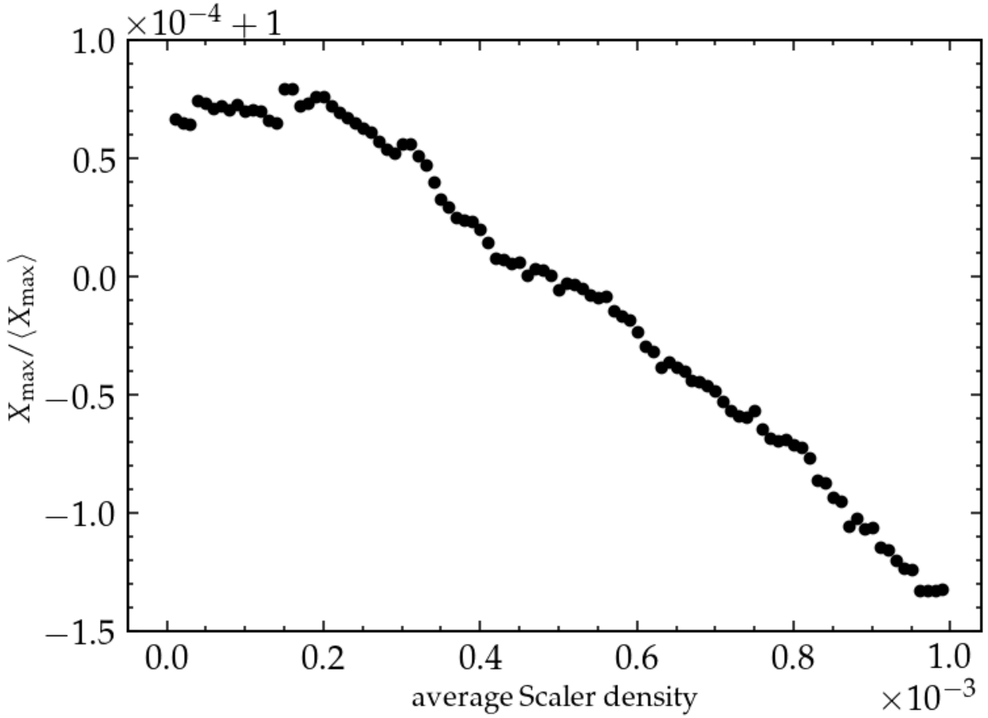
Still no clear answer.





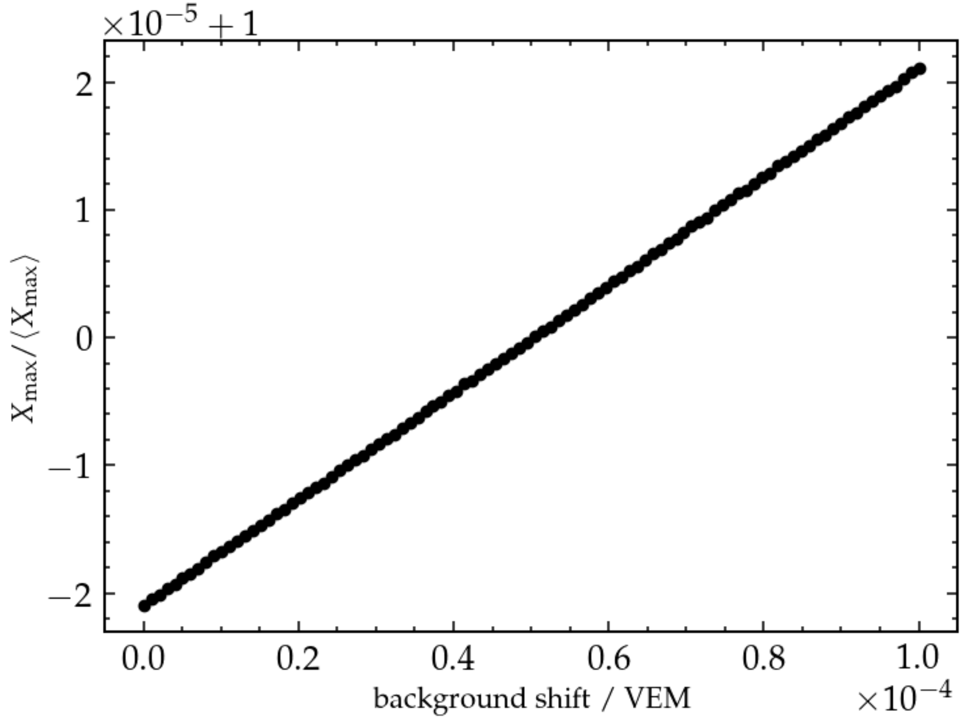
11-year cycle

Test 1: increase density of Scaler-like peaks of 0.25 VEM.



The pattern suggests anticorrelation.

Test 2: increase uniformly the background.



The predictions increase in a linear fashion.

average Scaler rate: 2000 cts/s

average Scaler peak: 0.25 VEM

time-step in simulation: 25 ns

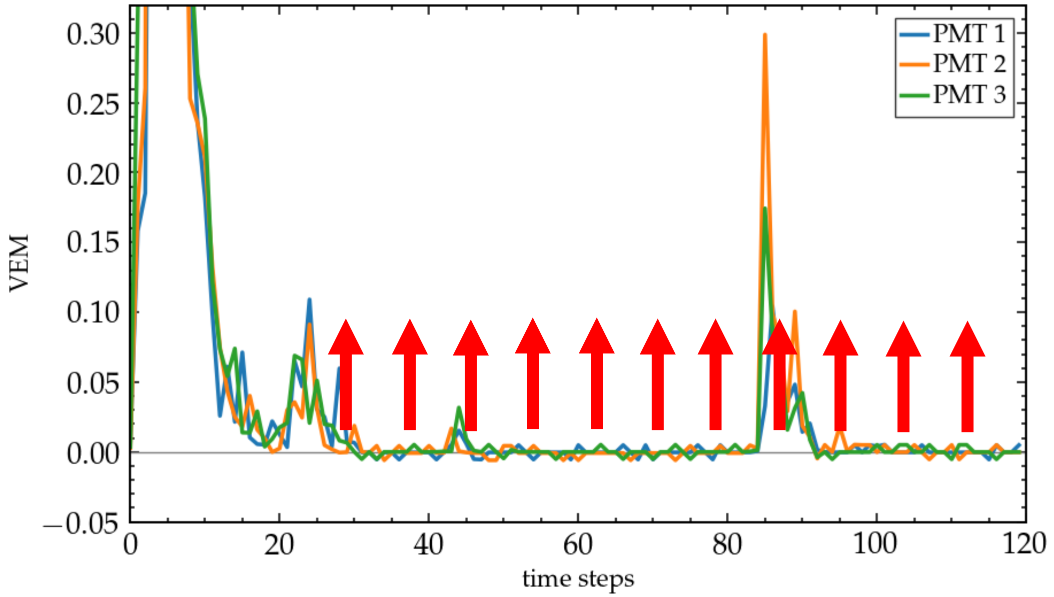
2011 JINST 6 P01003

→

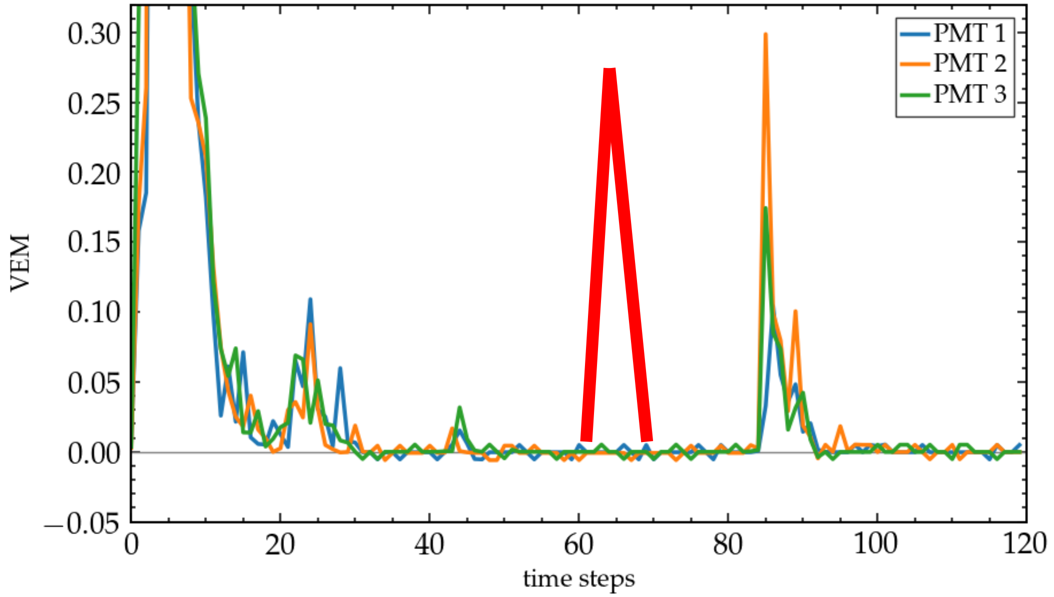
Every time-step gets on average $\sim 5 \times 10^{-5}$ cts

mean energy per time-step: $\sim 1.3 \times 10^{-6}$ VEM

Test 1: increase uniformly the background.

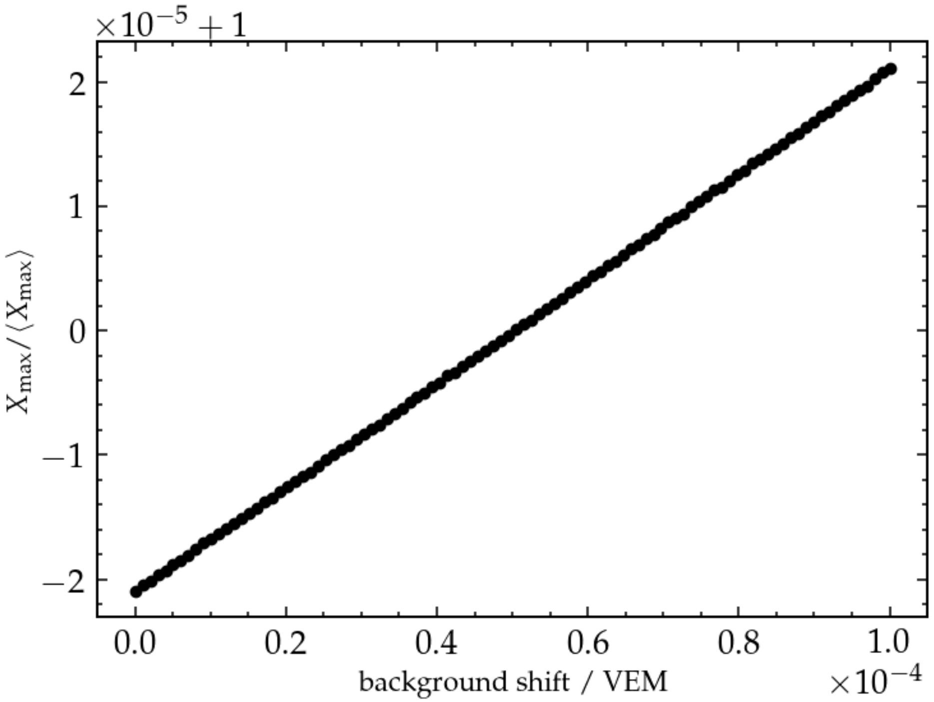


Test 2: increase density of Scaler-like peaks of 0.25 VEM.



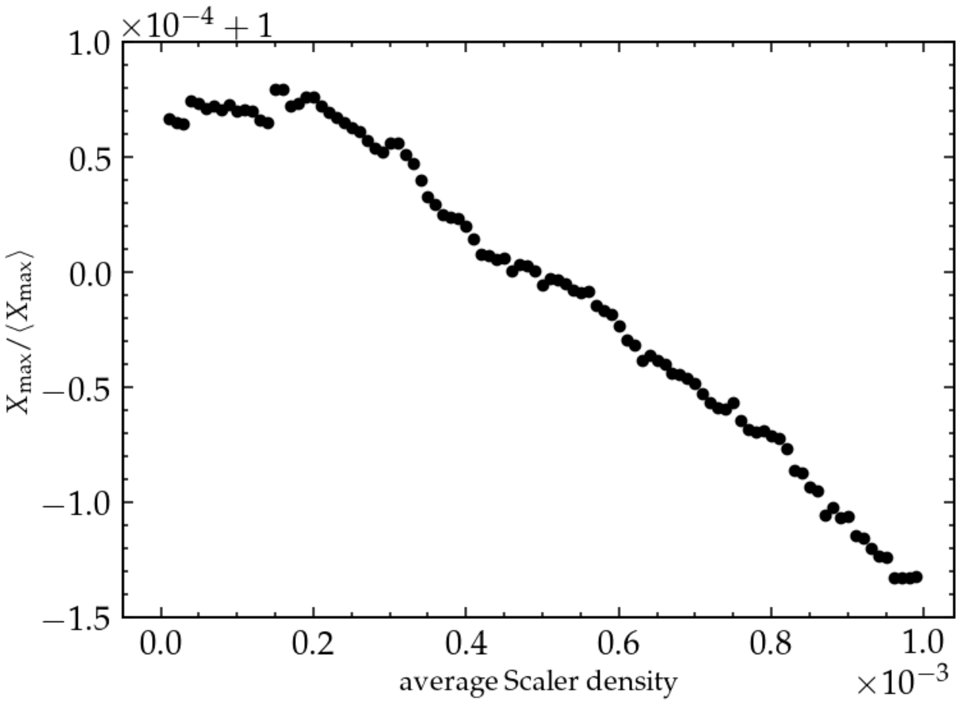
11-year cycle

Test 1: **Possible explanation**



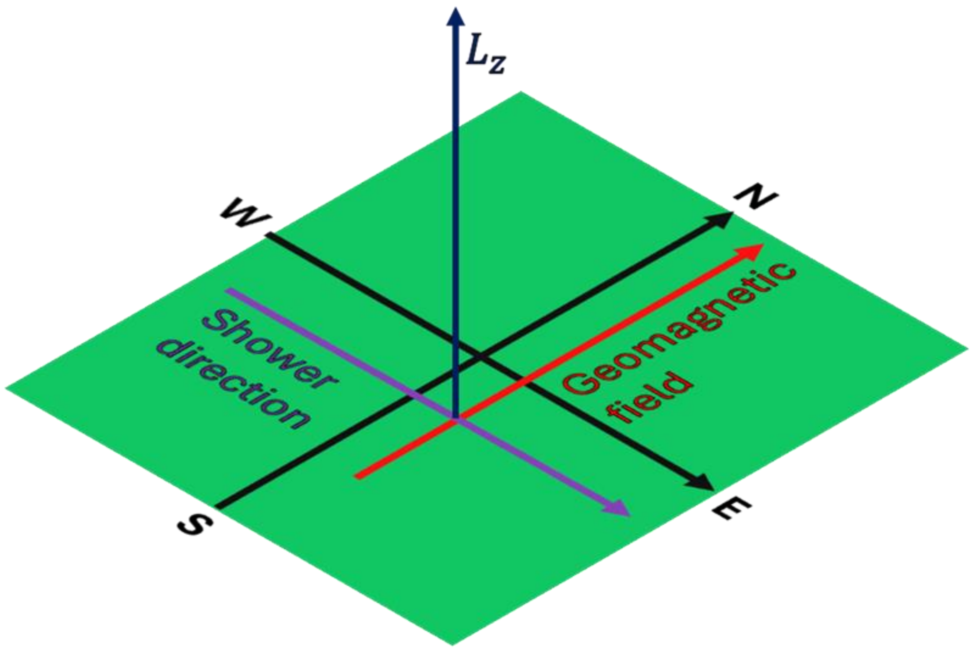
Since energy deposition is cumulative, increasing the background leads to increasing of the peak → deeper $X_{\max}$.

Test 2: **Possible explanation**



Secondary peaks are generated also by muons, whose number anticorrelates with $X_{\max}$.

Geomagnetic field



- The observable for the geomagnetic field is the Lorentz vector:

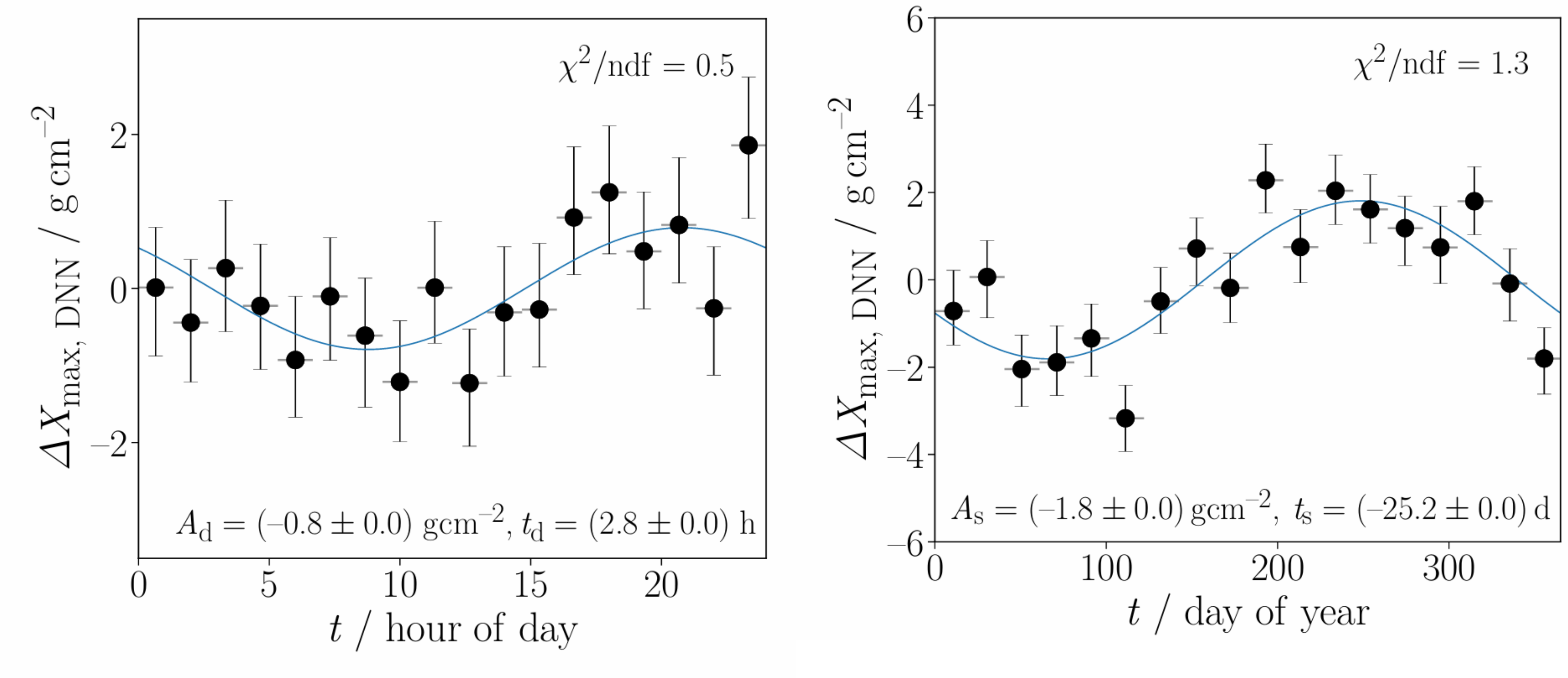
$$\vec{L} = \hat{r} \times \hat{B}_g$$

- $\hat{r}$ is the arrival direction of the primary particle, $\hat{B}_g$ is the direction of the geomagnetic field.
- In cylindrical coordinates, the z-component of the Lorentz vector reads

$$L_z = \left(\hat{r} \times \hat{B}_g\right)_z$$

$$= \sin\theta \cos\phi \sin\theta_B \sin\phi_B - \sin\theta \sin\phi \sin\theta_B \cos\phi_B$$

AixNet tests already performed by Jonas Glombitza – seasonal and daily calibrations



AixNet tests already performed by Jonas Glombitza
FD calibration