# Results from LOFAR on mass composition of cosmic rays

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# Publication on mass composition at LOFAR

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**Depth of shower maximum and mass composition of cosmic rays from 50 PeV to 2 EeV measured with the LOFAR radio telescope**

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We present an updated cosmic-ray mass composition analysis in the energy range $10^{16.8}$ to $10^{18.3}$ eV from 334 air showers measured with the LOFAR radio telescope and selected for minimal bias. In this energy range, the origin of cosmic rays is expected to shift from galactic to extragalactic sources. The analysis is based on an improved method to infer the depth of the maximum $X_{max}$ of extensive air showers from radio measurements and air shower simulations. We show results of the average and standard deviation of $X_{max}$ versus primary energy and analyze the $X_{max}$ dataset at the distribution level to estimate the cosmic ray mass composition. Our approach uses an unbinned maximum likelihood analysis, making use of existing parametrizations of the $X_{max}$ distributions per element. The analysis has been repeated for three main models of hadronic interactions. Results are consistent with a significant light-mass fraction, at best fit 23% to 39% protons plus helium, depending on the choice of hadronic interaction model. The fraction of the intermediate-mass nuclei dominates. This confirms earlier results from LOFAR, with systematic uncertainties on $X_{max}$ now lowered to 7 to 9 g/cm$^2$. We find agreement in mass composition

Results published in May 2021

Corstanje et al.,
Phys Rev D 103, 102006 (2021)

arXiv: **2103.12549**

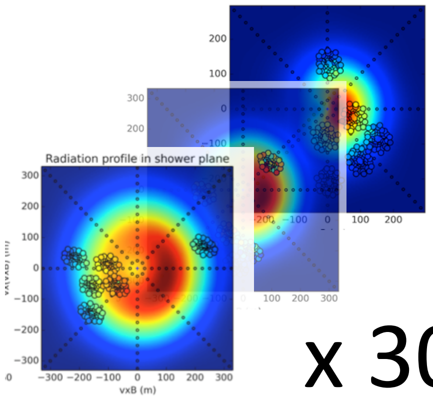
**This talk:** overview published paper

Additional material & cross-checks in proceedings paper

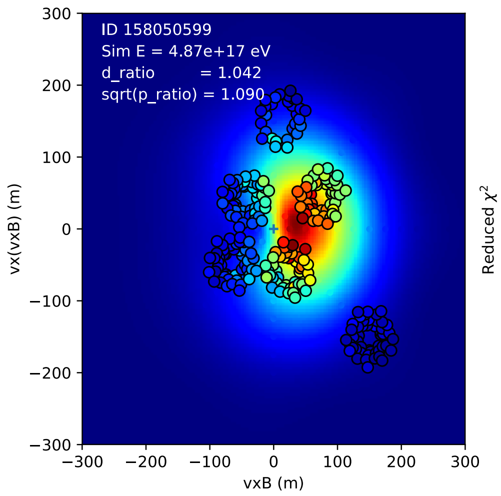
# Matching simulated footprints to data

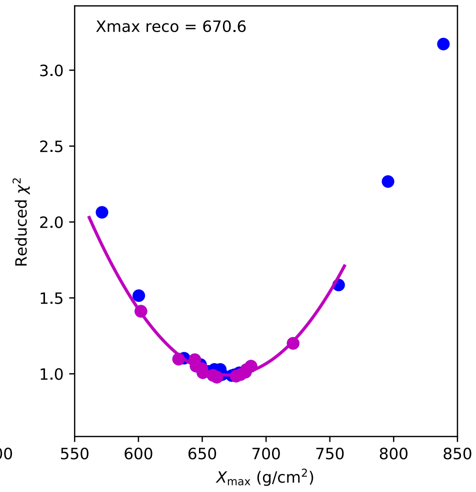
- Simulate about 30 showers per measured shower
- Fit them to data, observe $X_{max}$ of best fit

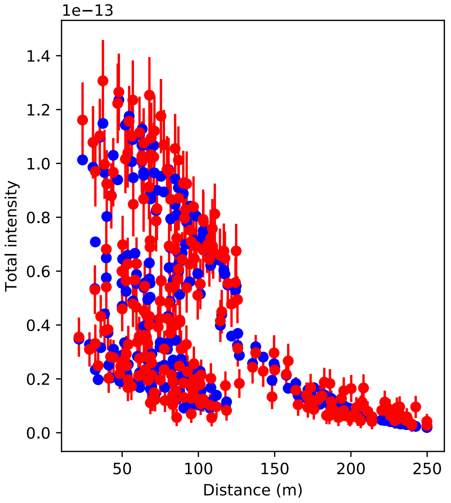
- $X_{max}$ resolution about **20 g/cm²**
- Energy resolution **9 %**
- Systematic uncertainties < **9 g/cm²** on $X_{max}$, **14 %** on energy




x 30

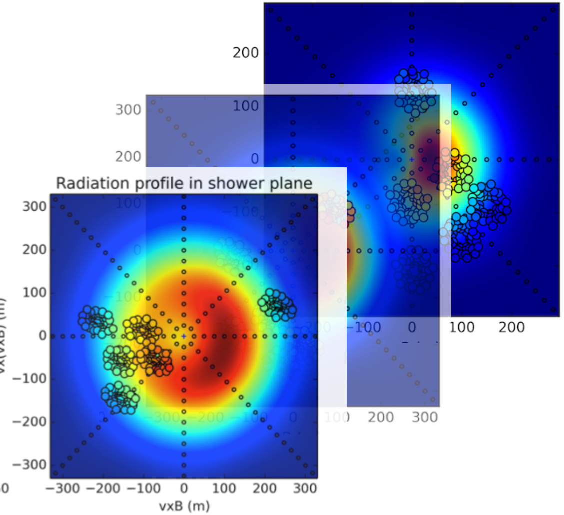


# Matching simulated footprints to LOFAR data

- Simulate ~ 30 showers per event, spanning $X_{max}$ range
- Reconstruction uncertainty from Monte Carlo procedure
  - Take one simulated shower, add LOFAR noise levels, reconstruct with other showers from ensemble
- Require core position precision < 7.5 m




Air shower dataset:

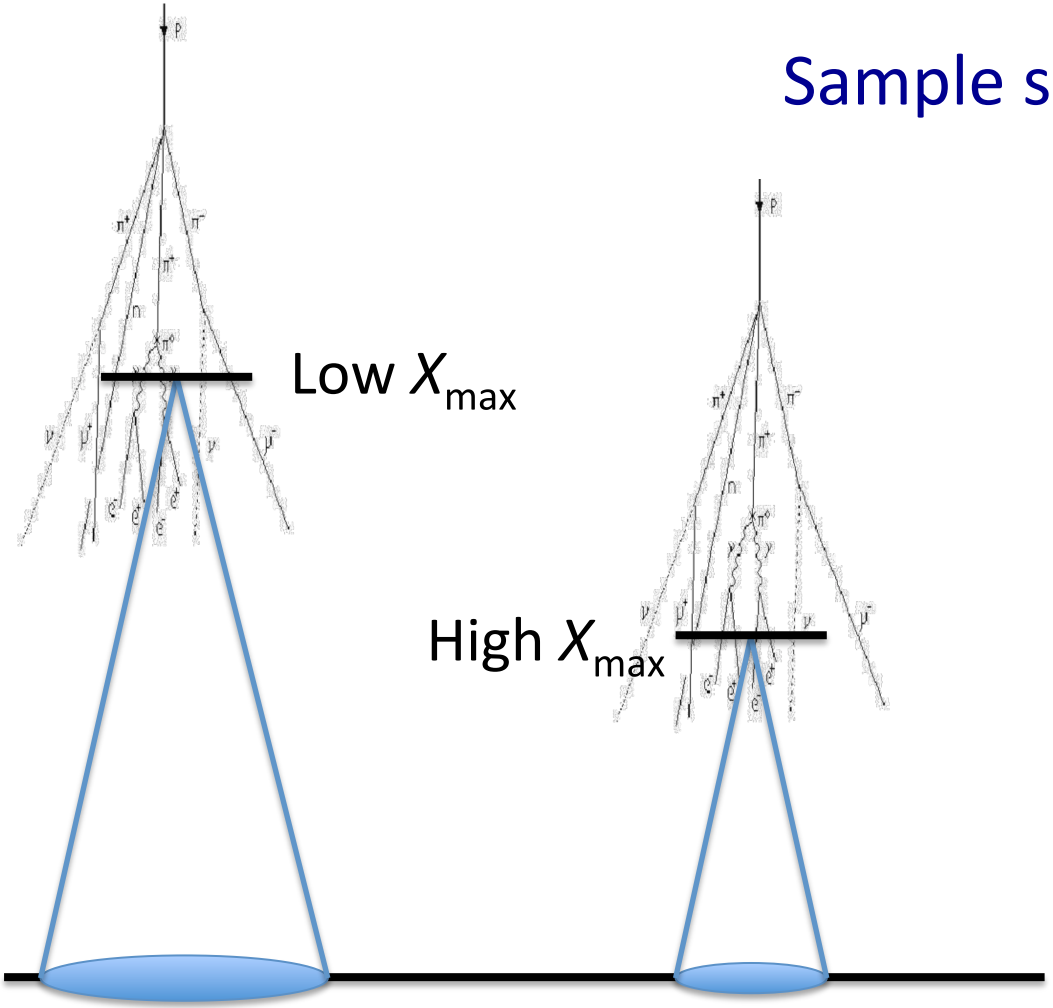
data points

**($X_{max} \pm \sigma_X$, $\log E \pm \sigma_{\log E}$)**

Selected for minimal bias

x N = 334

# Sample selection

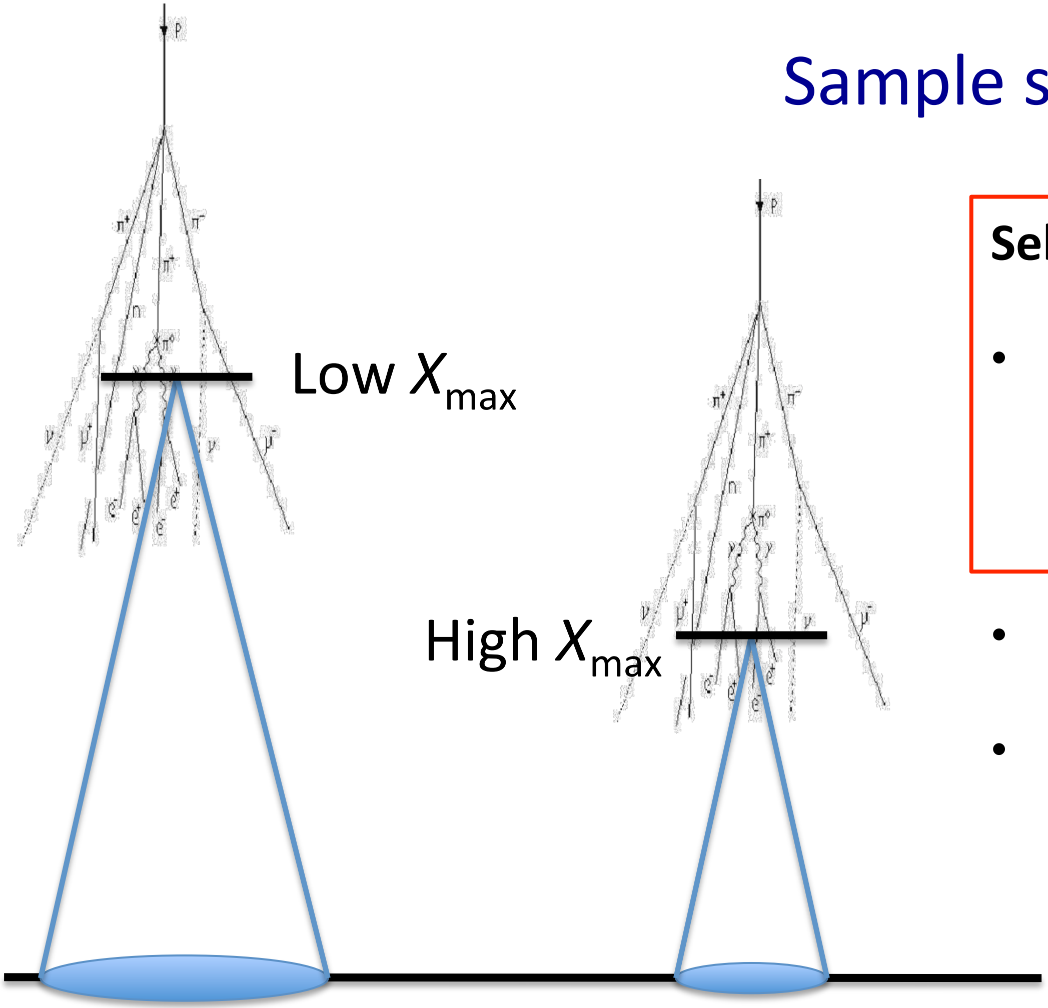



Opposite sources of bias:

- **low $X_{max}$**:
  fewer particles reach ground,
  may not trigger
- **high $X_{max}$**:
  radio footprint is smaller,
  harder to trigger 3 LOFAR stations

for a shower at given energy
and core position

# Sample selection

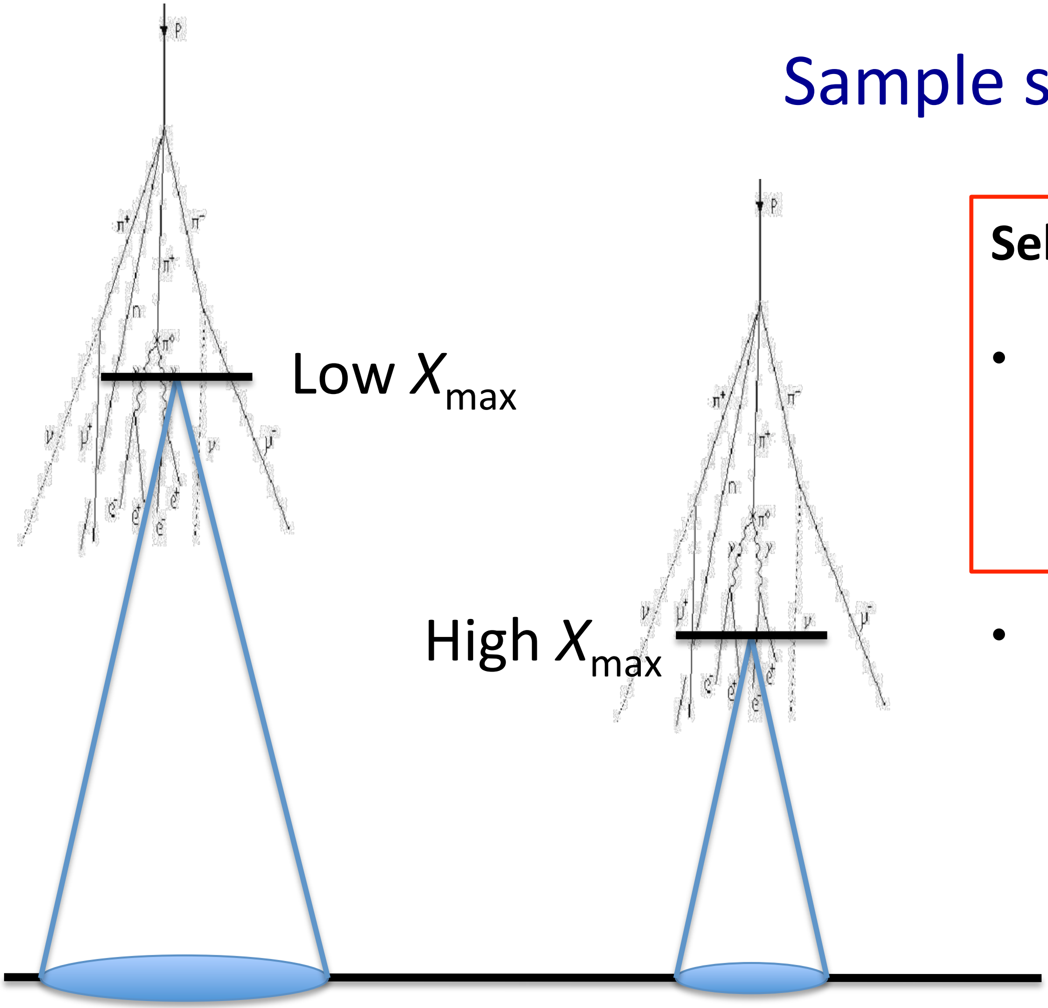



**Selection criterion**:

- Each measured shower, given energy and core position, must be able to trigger in both particles and radio, would it have any other $X_{max}$ level within natural range

- LOFAR has irregular layout, fiducial volume hard to construct
- Number of showers is modest, allows treatment per shower

# Sample selection

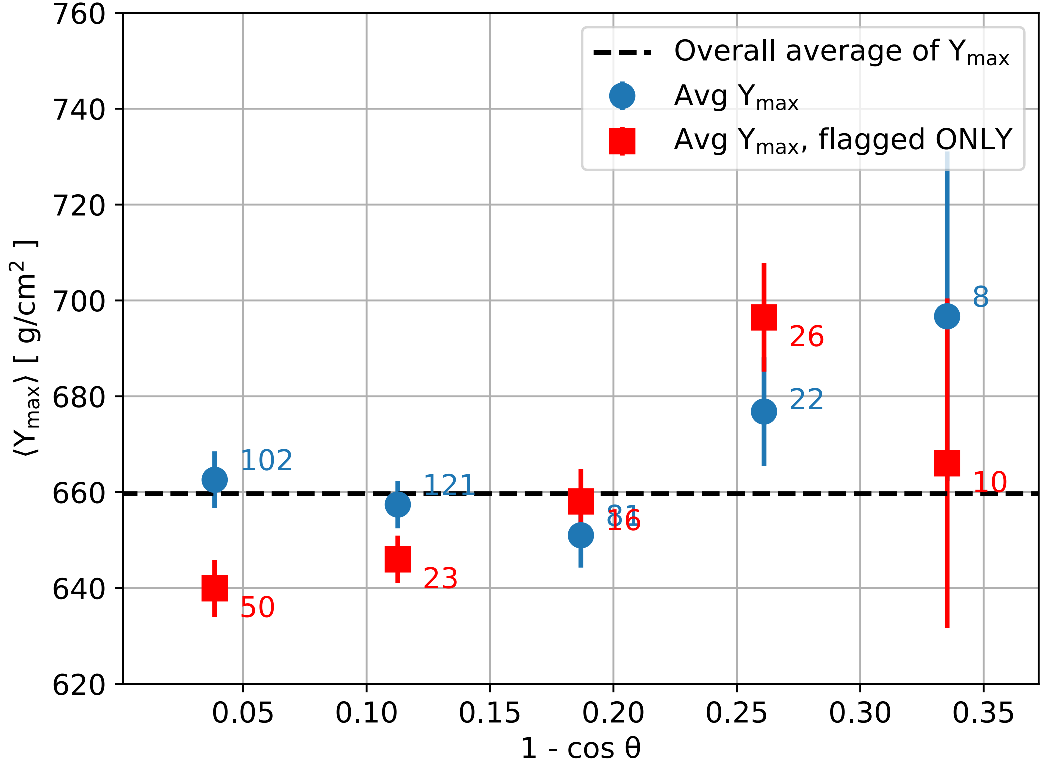



**Selection criterion**:

- Each measured shower, given energy and core position, must be able to trigger in both particles and radio, would it have any other $X_{max}$ level within natural range

- Use simulated ensemble spanning $X_{max}$ range:
  - Particle content and detector simulation
  - Radio (energy) footprint

# Sample selection: result and test for residual bias




Retained 334 out of 459 events (**73 %**)

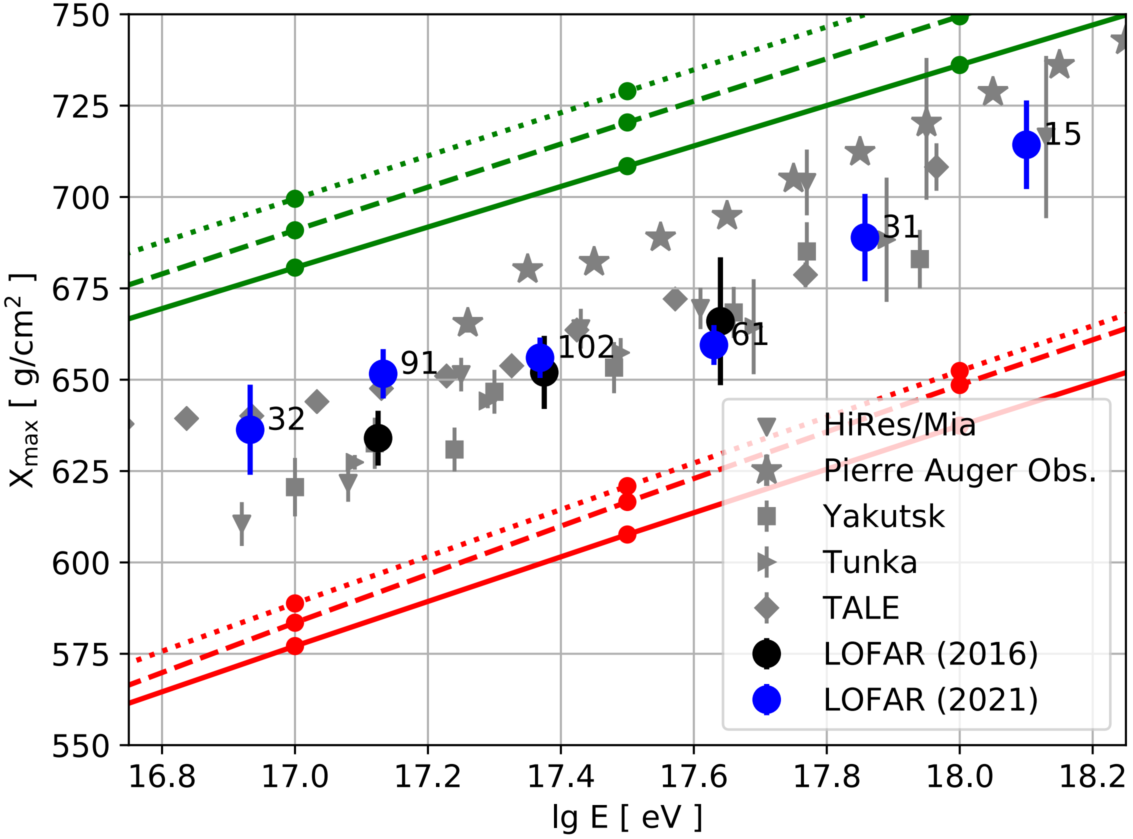
Test $Y_{max}$ , which is $X_{max}$ corrected for average energy (elongation rate)

Versus zenith angle (cos theta)

Final set, blue points: consistent with a constant

Flagged events: positive trend with increasing zenith angle – as expected

# Result: Average $X_{max}$ versus primary energy



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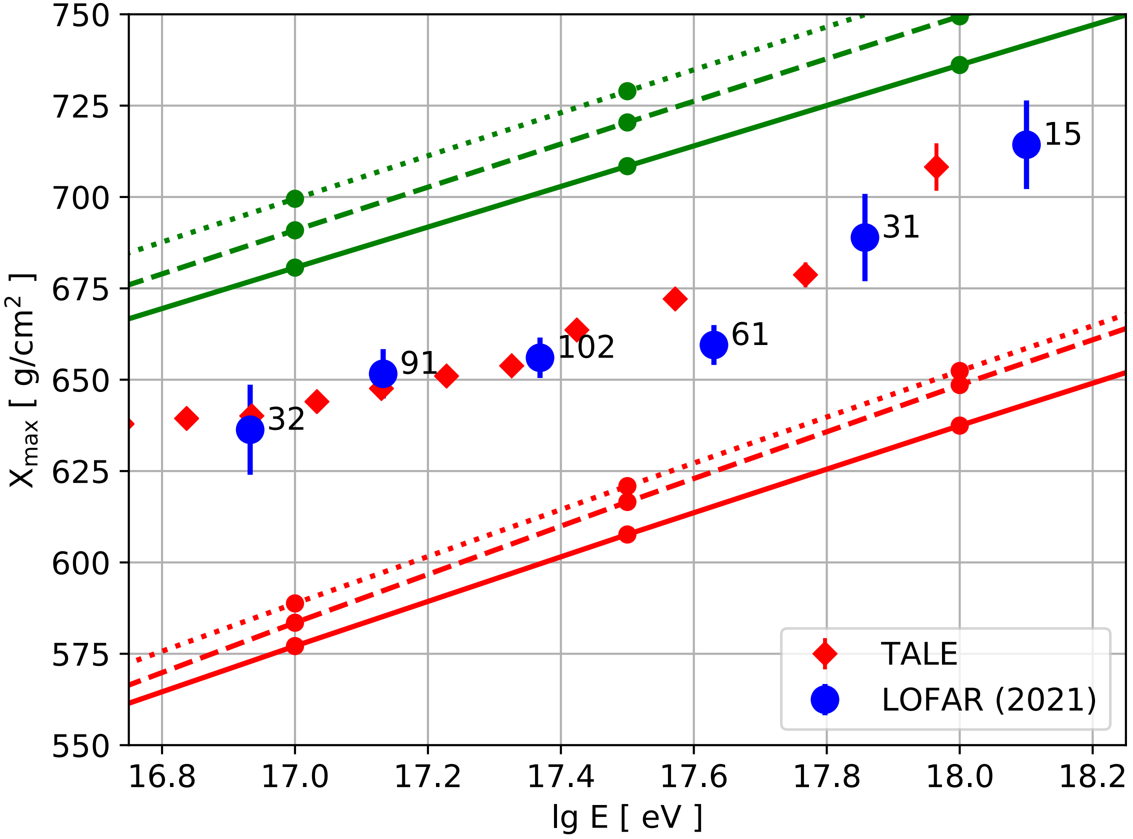
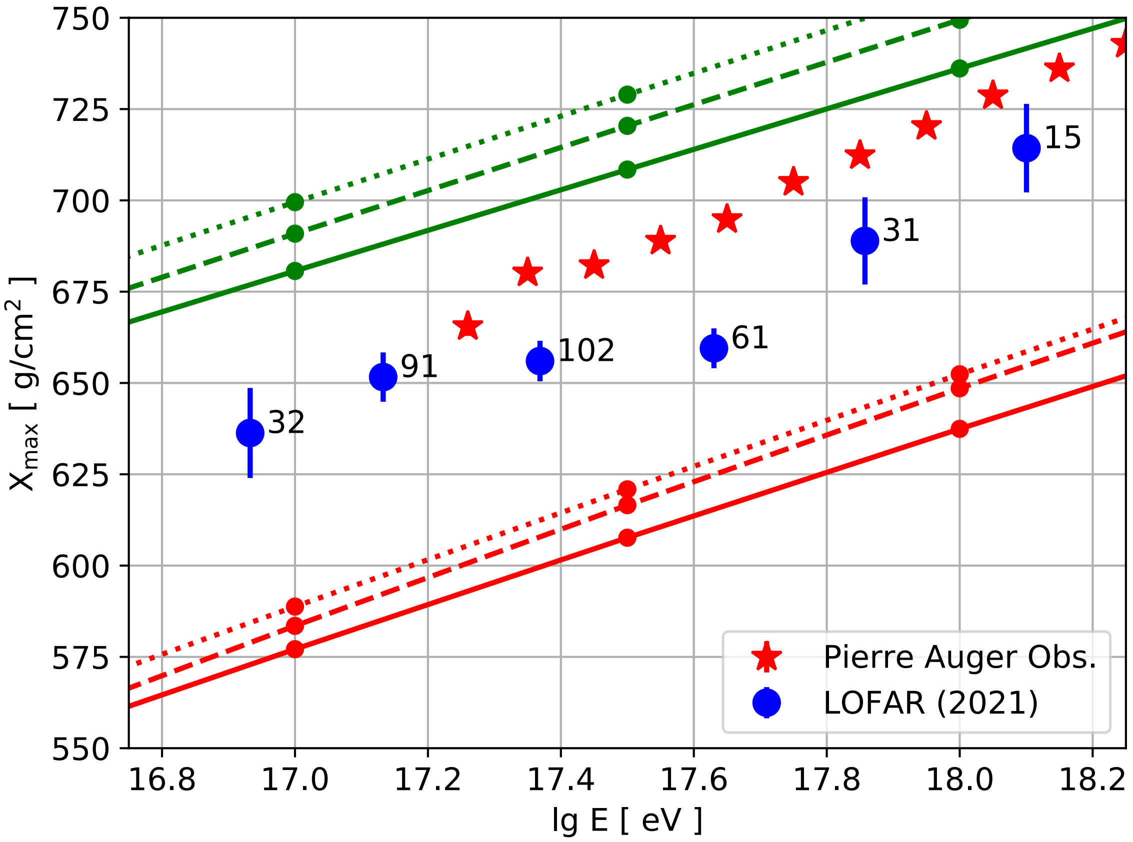


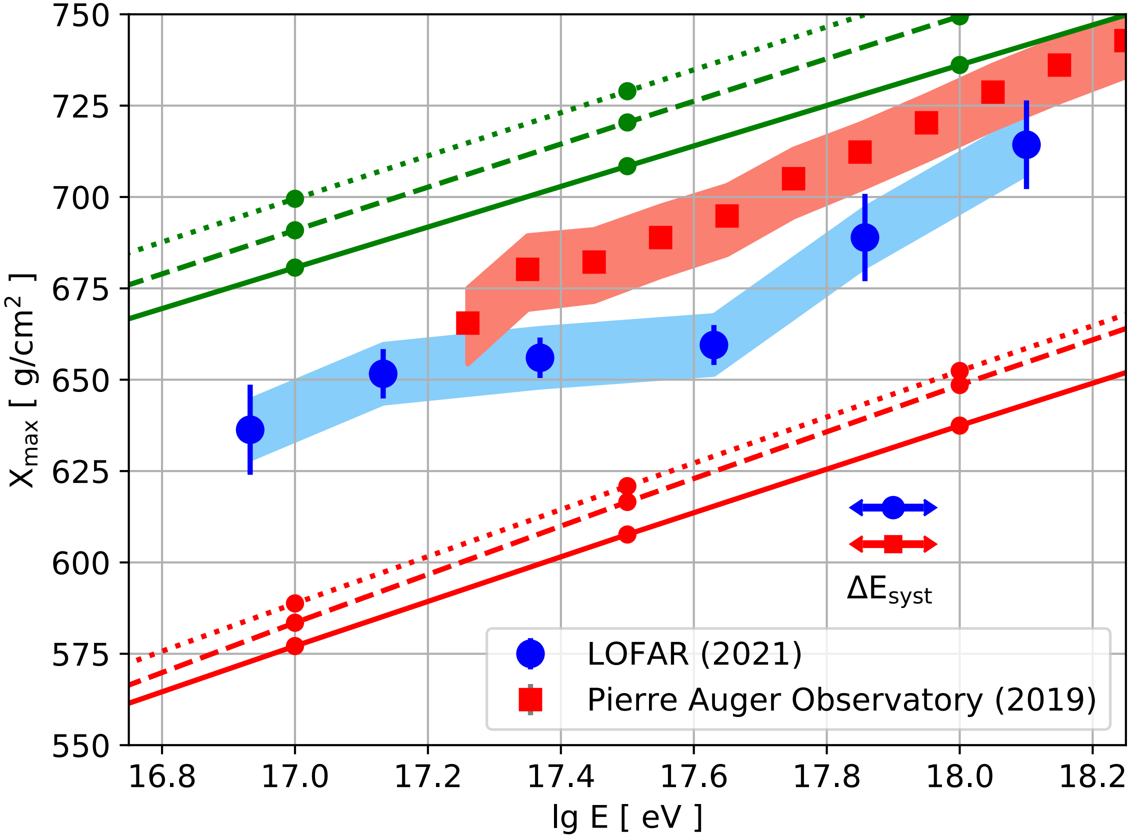

- Consistent with TALE
- Also with Tunka, Yakutsk , for lg E > 17.3, HiRes/Mia , for lg E > 17.2

# Result: Average $X_{max}$ versus primary energy



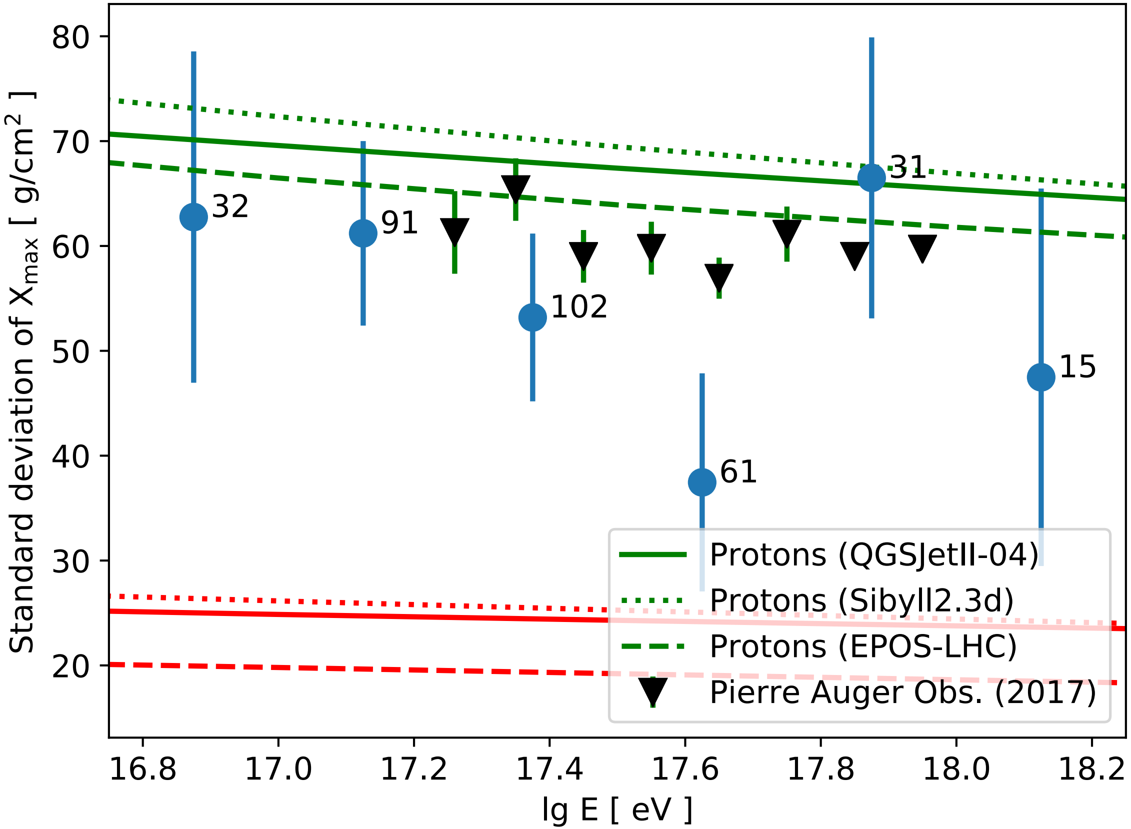

- Discrepancy with Auger, where both have data (lg E > 17.2)
  - Not fully explainable from statistics and systematic uncertainties
  - Unclear if would agree below lgE = 17.25, lack of data

# Result: Average $X_{max}$ versus primary energy




- LOFAR and Pierre Auger results, with systematic uncertainties
- Tension as yet unexplained

# Result: Standard deviation of $X_{max}$ versus energy



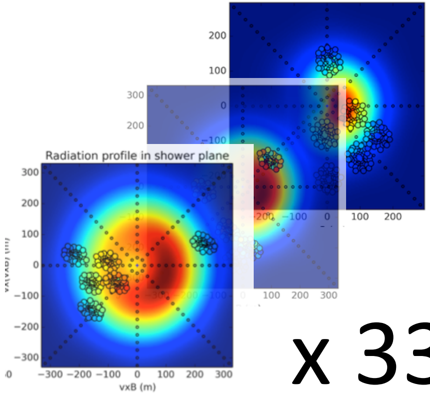

- Mostly consistency between LOFAR and Pierre Auger
- Statistical uncertainties considerable due to size of dataset

# Result on mass composition

Intermediate-mass component dominates (C/N/O)

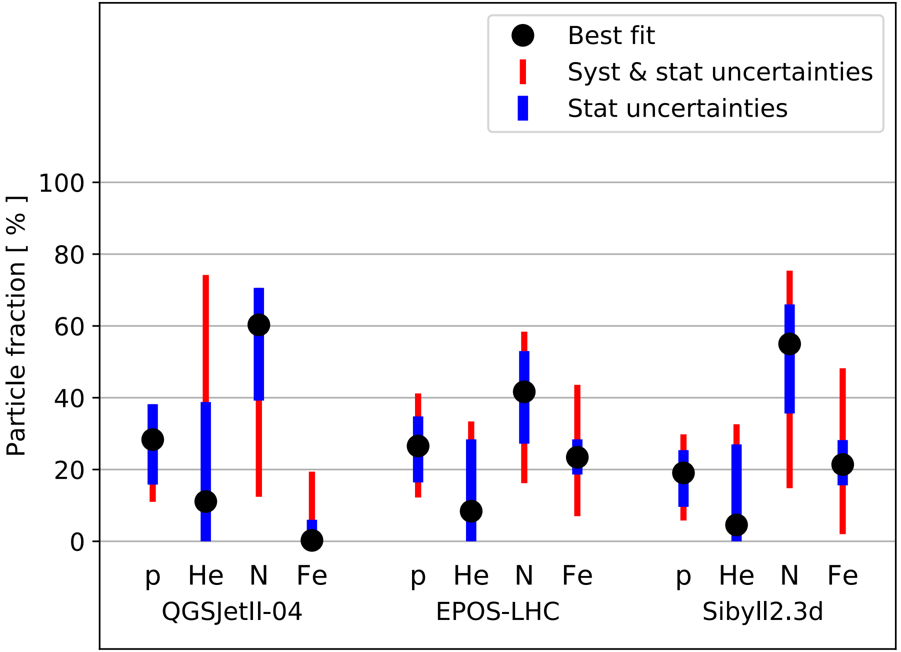
Significant light-mass component (p+He)
Still considerable uncertainties, some inevitable

- overlap of $X_{max}$ distributions
- Hadronic interaction models




x 334

From unbinned analysis:
main coverage in lg E: **17.39 +/- 0.32**



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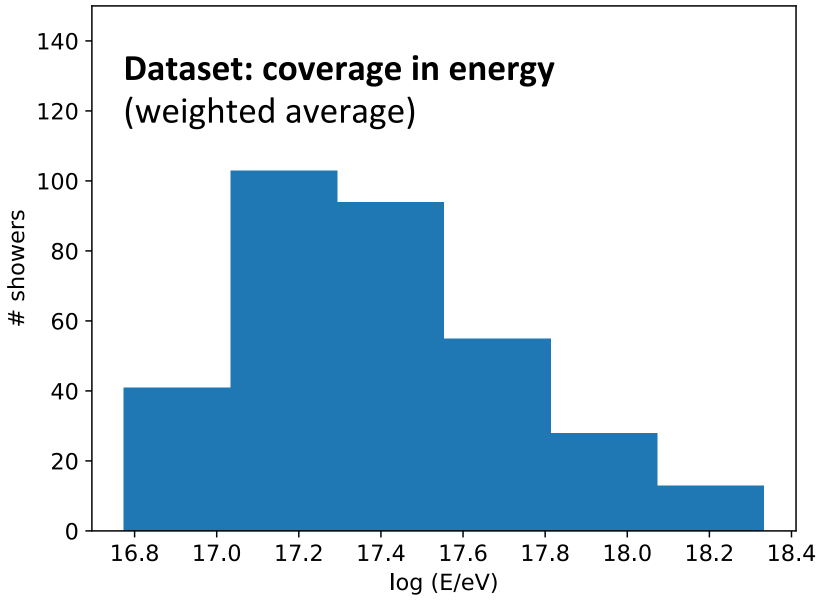


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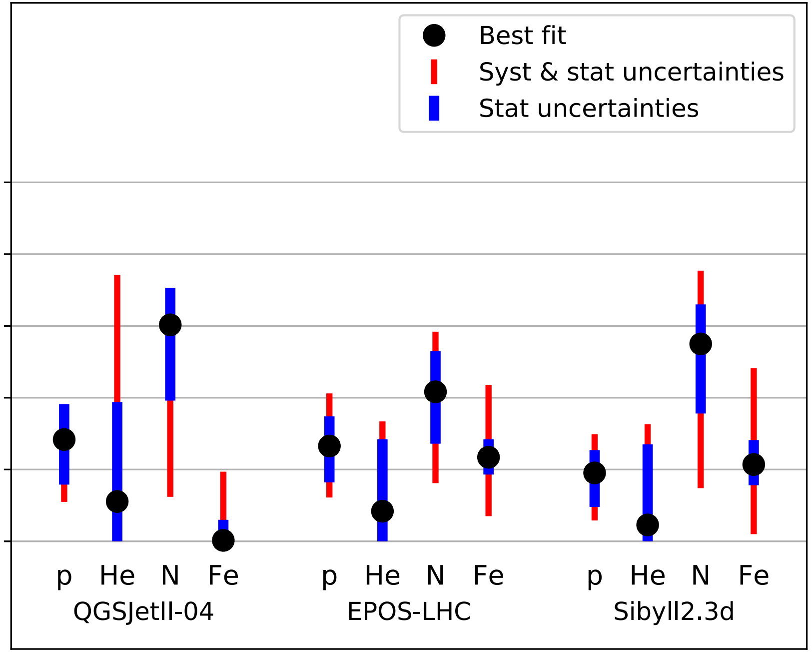

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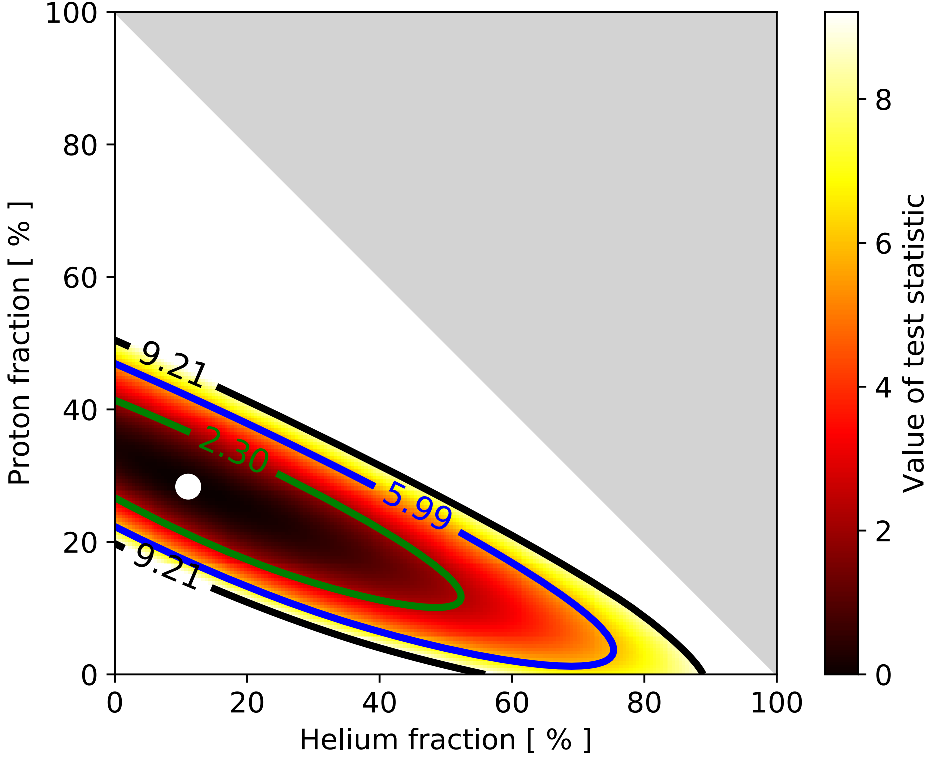
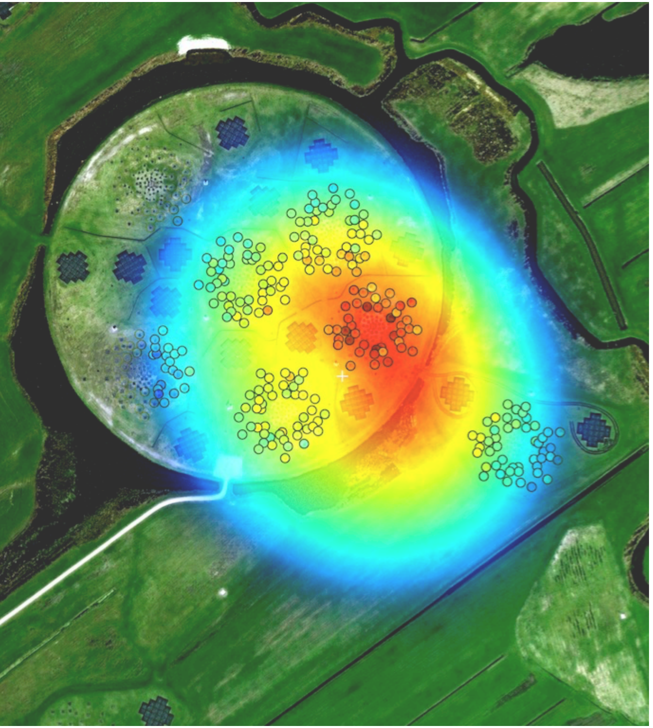



Likelihood when interchanging protons and helium
(contours for one-sigma, 95% and 99% C.L.)

Lower proton fraction implies (much) higher helium fraction

Ability to distinguish protons and helium is limited: overlapping $X_{\max}$ distributions, dataset size, systematics

# Summary



LOFAR has measured the shower maximum $X_{max}$ at a resolution of **19 g/cm²** and systematic uncertainty of **7 to 9 g/cm²**

Average $X_{max}$ versus energy differs from the Auger result, while consistent with TALE and others; tension is currently unexplained

Mass composition analysis confirms significant light-mass component, C/N/O dominant
Conclusions about trend with energy require a larger dataset (factor 2 to 3)