Friedrich-Alexander-Universität
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Cosmic Ray detection with LOFAR

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LOFAR

- LOw-Frequency ARray (LOFAR) is a large telescope array with stations across Europe
- Core located in the Netherlands

- 52 stations total
- Each core station consists of 96 Low Band Antennas (LBA, 30-80 MHz) and 48 High Band Antennas (HBA, 110-240 MHz)
- Additionally, particle detectors (LORA) at the core,
  (triggering, direction reconstruction)

- Dense instrumentation, ~150 LBA per km^2 in core

Images: ASTRON

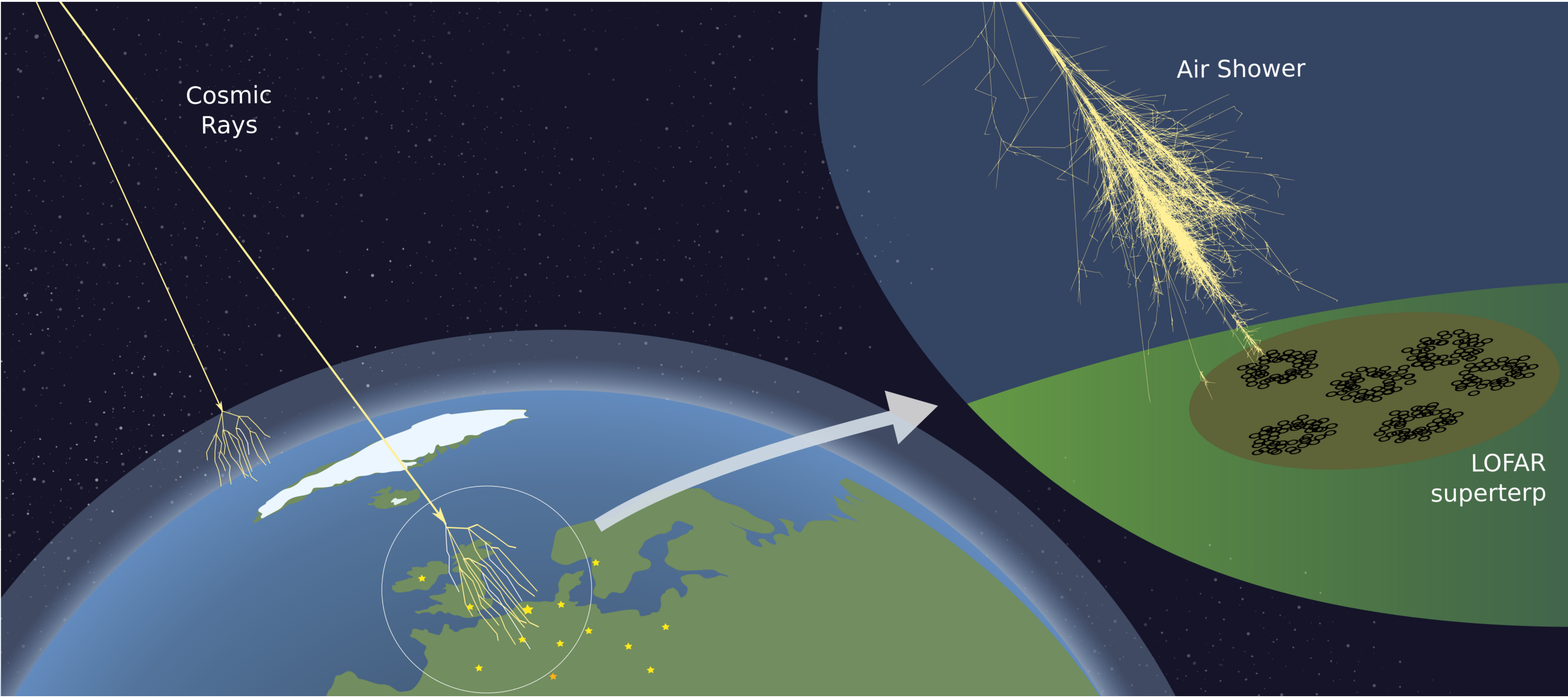
LOFAR

- Shared observatory!
  - Various different key science projects (KSP) utilise the stations

- First LOFAR cosmic ray detection in 2012
- Many papers published since, with more to come

Images: ASTRON

LOFAR

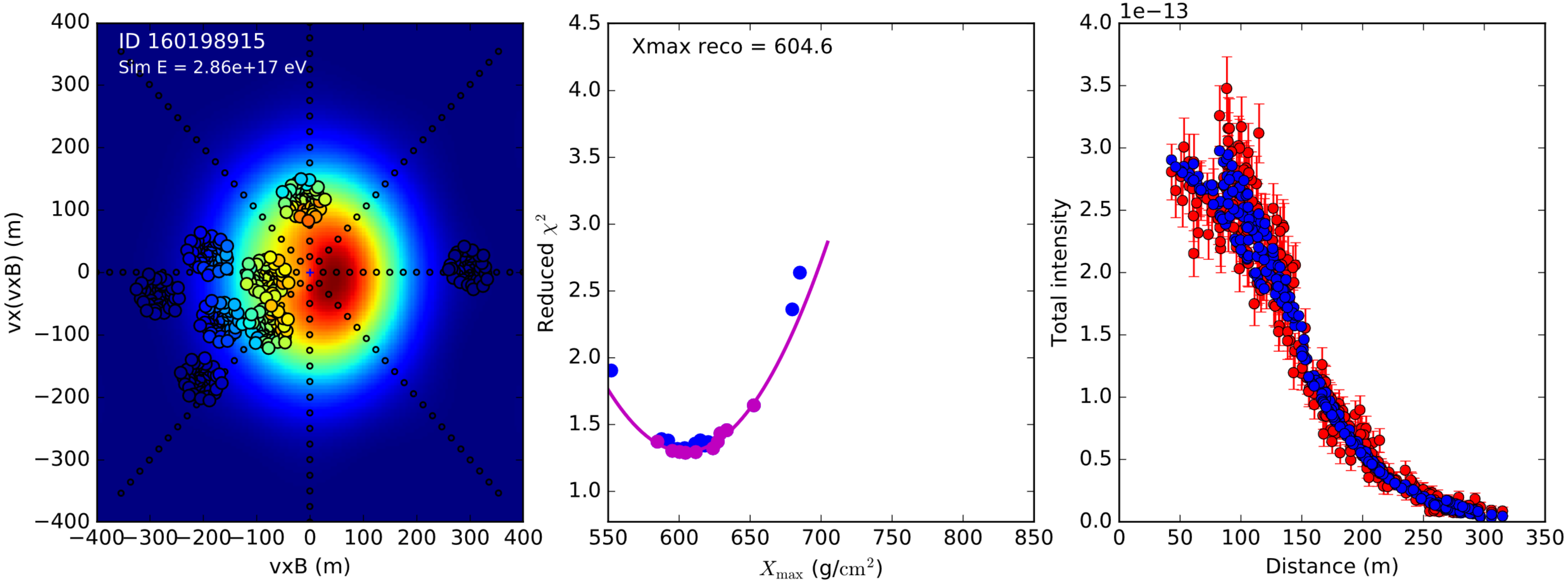


LOFAR

The LOFAR method

- Radio footprint can be observed by antenna array
- Compared to CoREAS simulations to reconstruct X_{max}
- X_{max} uncertainty of 7-9 g/cm²

$$\chi^2_{\text{radio}} = \sum_{\text{antennas}} \left(\frac{P_{\text{ant}} - f_r^2 P_{\text{sim}}(x_{\text{ant}} - x_0, y_{\text{ant}} - y_0)}{\sigma_{\text{ant}}} \right)^2$$



A. Corstanje et al., PhysRevD.103.102006

LOFAR

The LOFAR method

- Radio footprint can be observed by antenna array
- Compared to simulations to reconstruct reconstruct X_{max}
- X_{max} uncertainty of 7-9 g/cm²

	Syst. uncertainty	Added stat. unc.
Choice of hadronic interaction model	$5\,\mathrm{g/cm^2}$	
Remaining atmospheric uncertainty	$\sim 1\,\mathrm{g/cm^2}$	$\sim 2\,\mathrm{g/cm^2}$
Five-layer atmosphere CORSIKA	$2\,\mathrm{g/cm^2}$	$4\,\mathrm{g/cm^2}$
Possible residual bias	$3.3\,\mathrm{g/cm^2}$	
Curve fit for χ^2 optimum	$\leq 1\,\mathrm{g/cm^2}$	
Total, added in quadrature	$7\,\mathrm{g/cm^2}$	

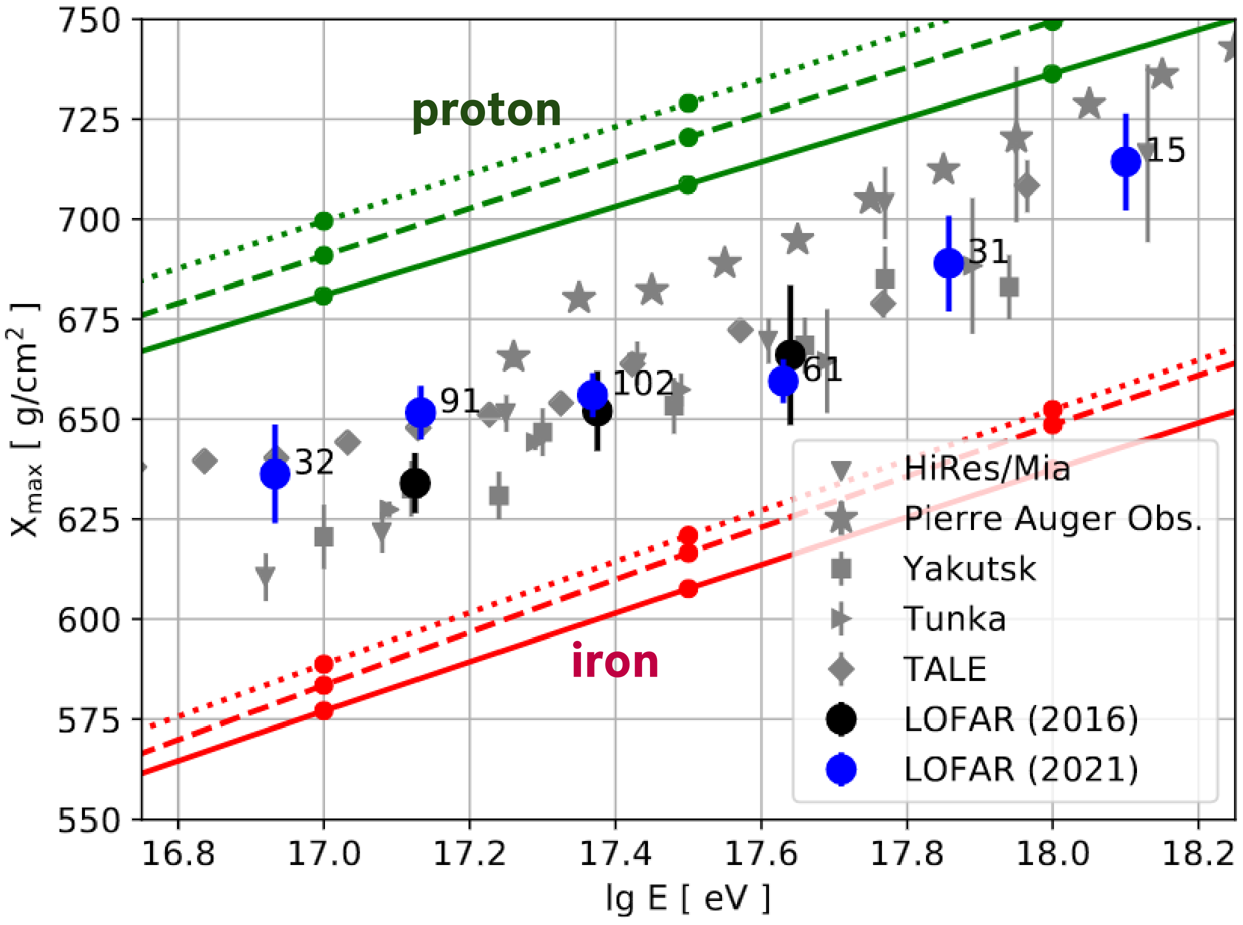
A. Corstanje et al., PhysRevD.103.102006

LOFAR

Mass composition

- Combine energy reconstruction via fluence (*K. Mulrey et al JCAP11(2020)017*) with X_{max} reconstruction for mass composition
- Agrees reasonably well with other experiments
- Slightly heavier mass composition as compared to Auger

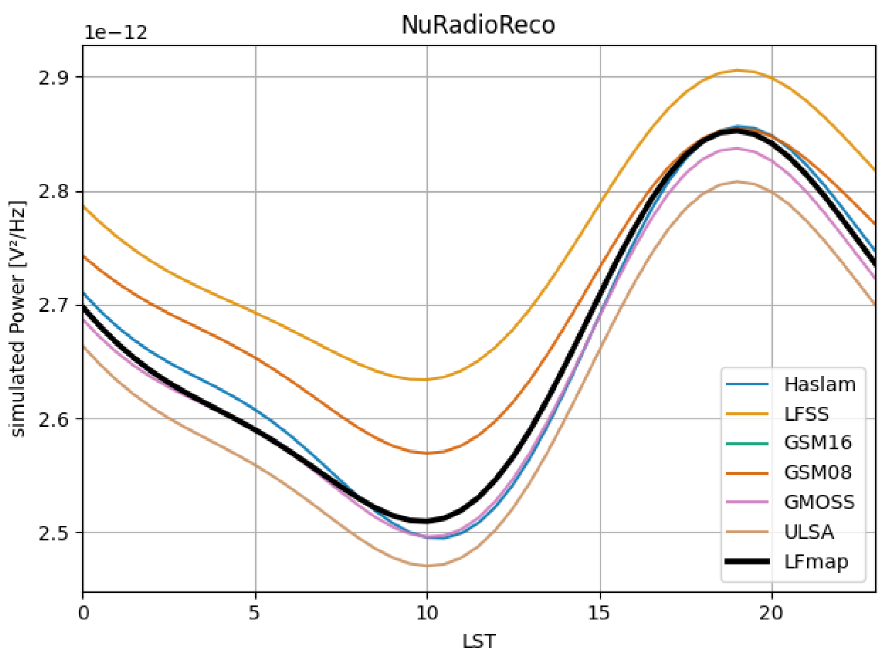
A. Corstanje et al., PhysRevD.103.102006



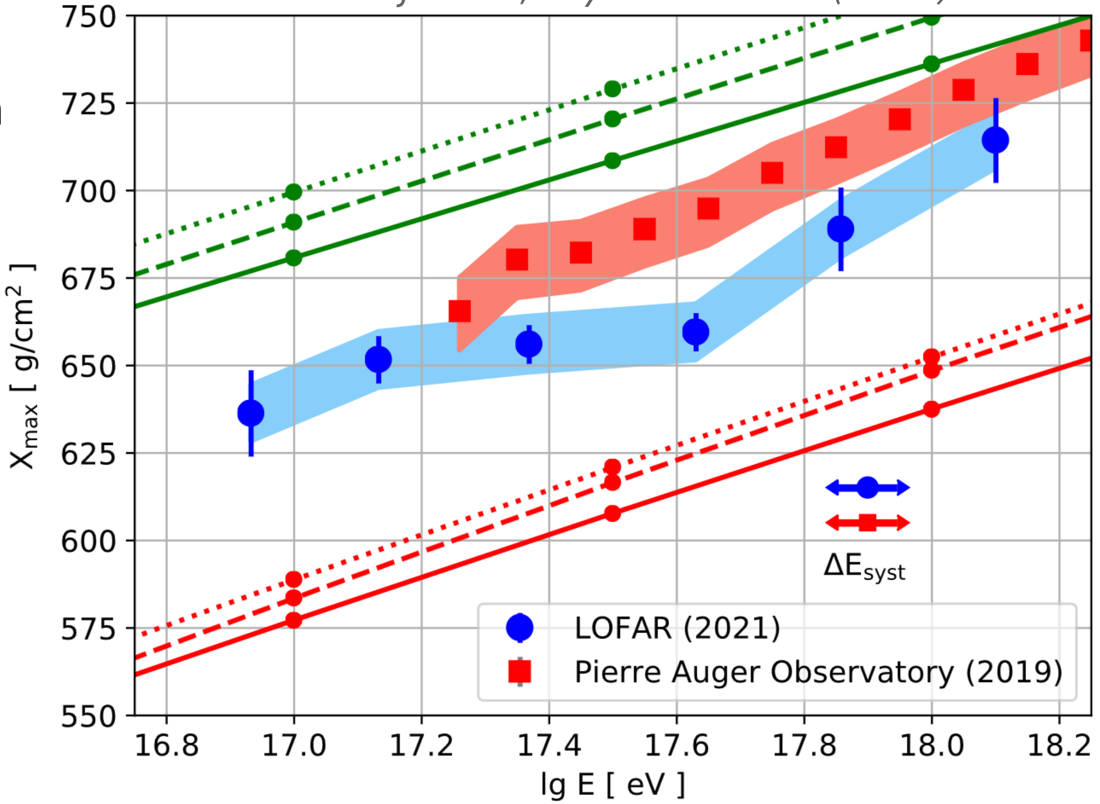
Calibration

Current work in the LOFAR Cosmic Ray KSP

- Discrepancies between LOFAR and Auger mass composition
  - Joint Auger/LOFAR working group has performed cross checks, so far no possible source found
    → Revisit antenna calibration as possible source
- Antennas calibrated via Galaxy
    → compare different models for galactic radio emission



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



Software

Current work in the LOFAR Cosmic Ray KSP

C. Glaser, A. Nelles, I. Plaisier, C. Welling et al., Eur. Phys. J. C (2019) 79: 464

We recently moved to NuRadioReco!

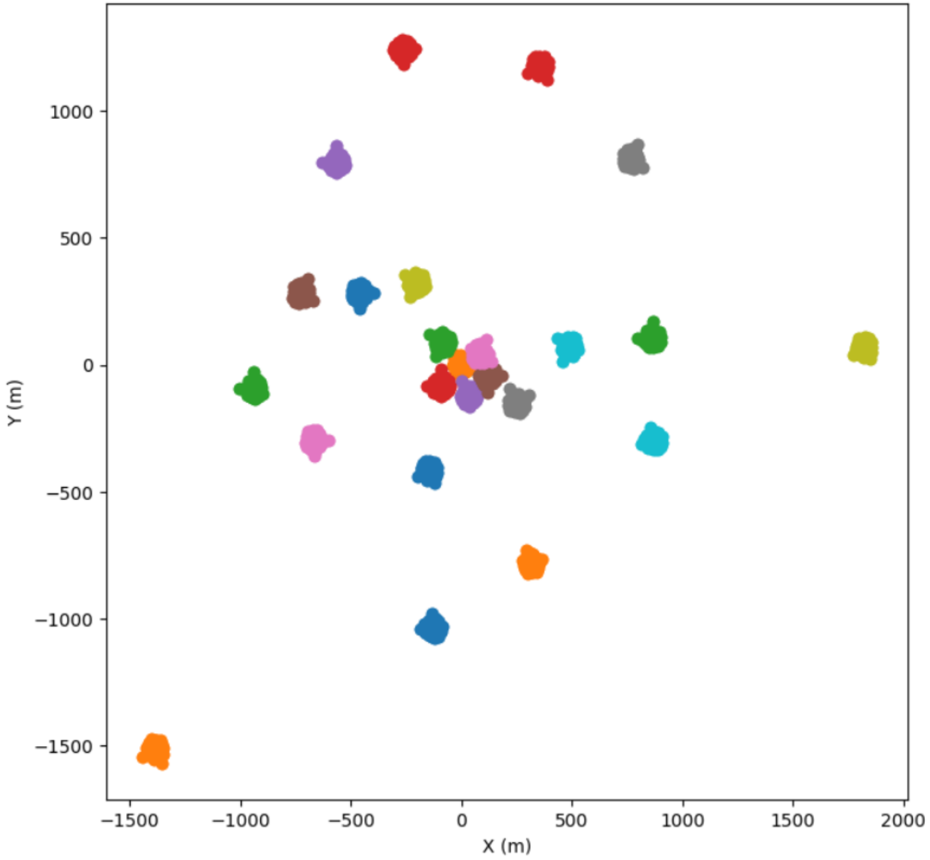
```
from NuRadioReco.detector import detector

# Load Detector description
det = detector.Detector(
    'LOFAR/LOFAR.json',
    source='json',
    antenna_by_depth=False
)
```

- LOFAR pipeline is now running on NRR
- We can use NuRadio modules, write our own and will use NRR for future analyses

Interested in using NuRadioReco?

Talk to us!

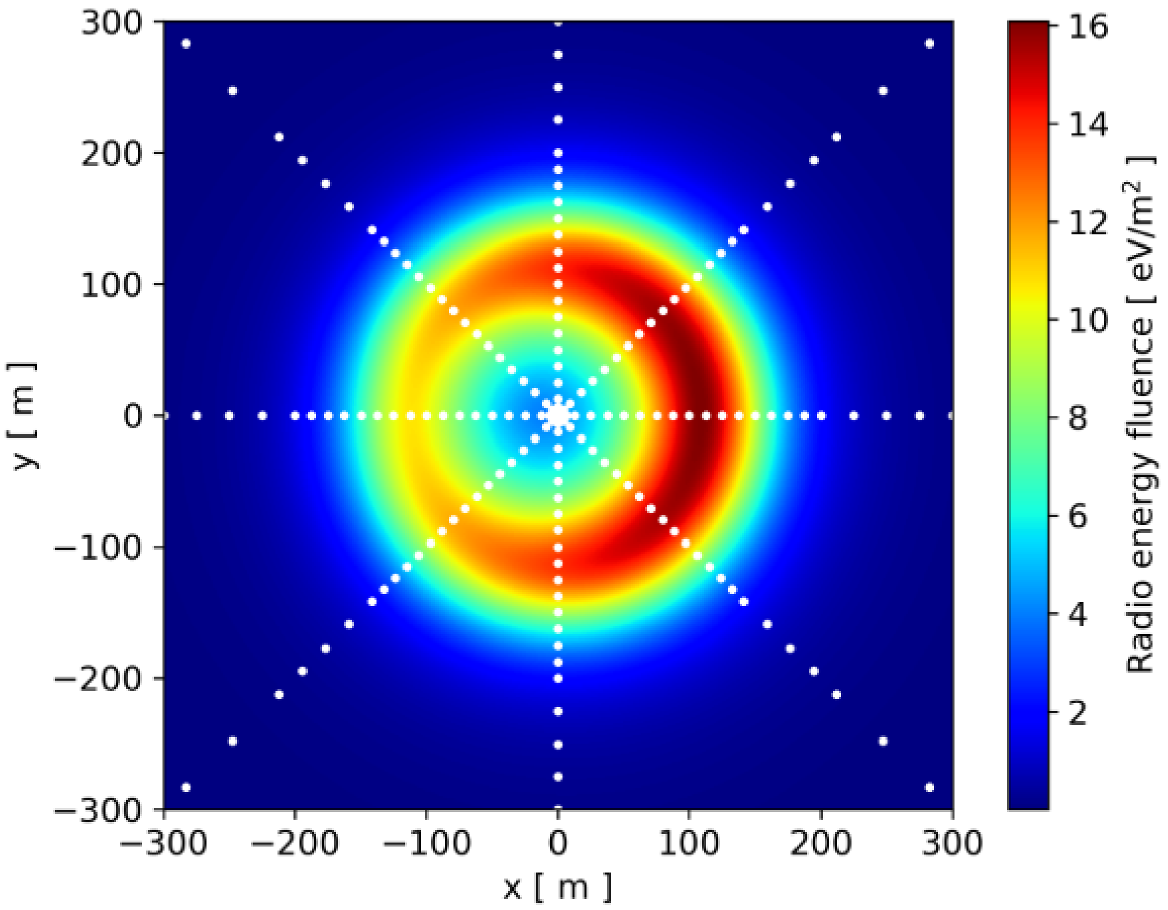


Interpolation

Current work in the LOFAR Cosmic Ray KSP

A. Corstanje et al 2023 JINST 18 P09005

- Detailed simulations needed for reconstruction are time-consuming, especially for future endavours such as SKA (60,000 antennas)
- New interpolation algorithm uses Fourier series and cubic splines
- Simulating 200 antennas suffices for precise analysis in SKA era, reducing computational costs
- Soon available on NuRadioReco



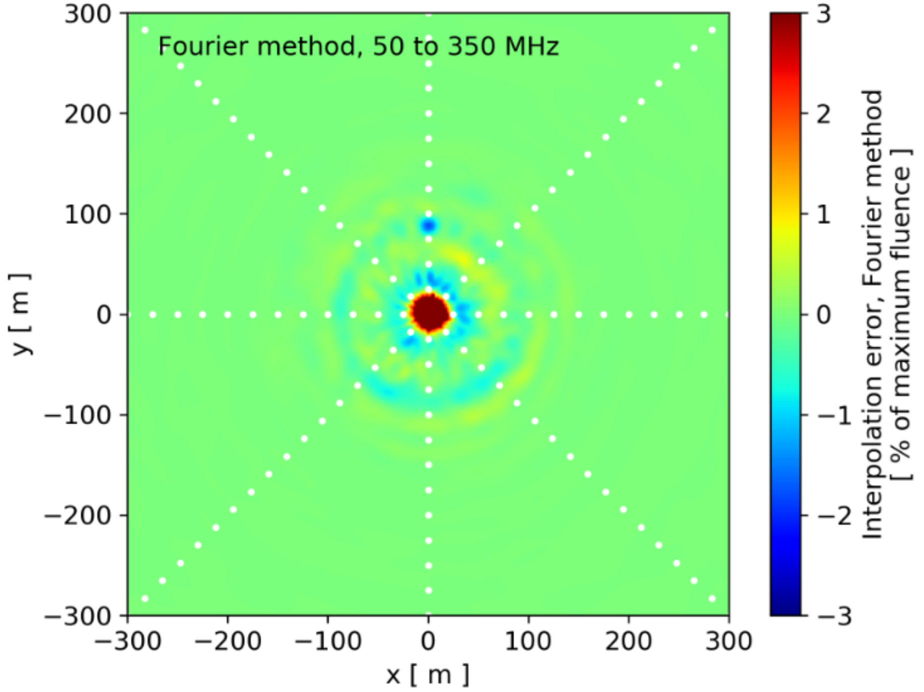
Interpolation

Current work in the LOFAR Cosmic Ray KSP

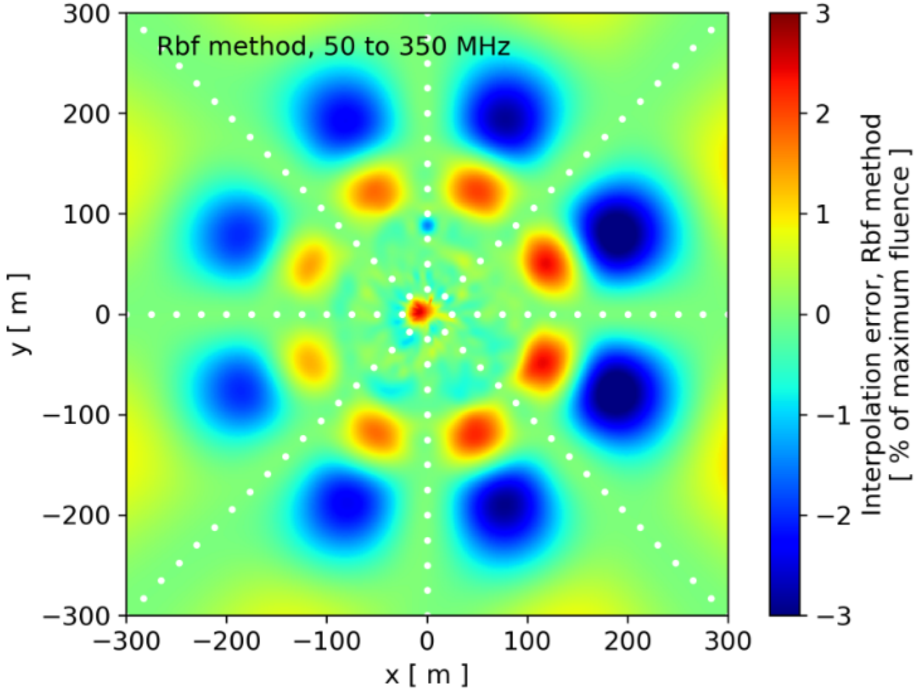
A. Corstanje et al 2023 JINST 18 P09005

- Previous method used radial basis functions, errors of the order of 3% of the max. fluence
- New method has smaller errors (For LOFAR frequency range below 1%)

NEW



OLD



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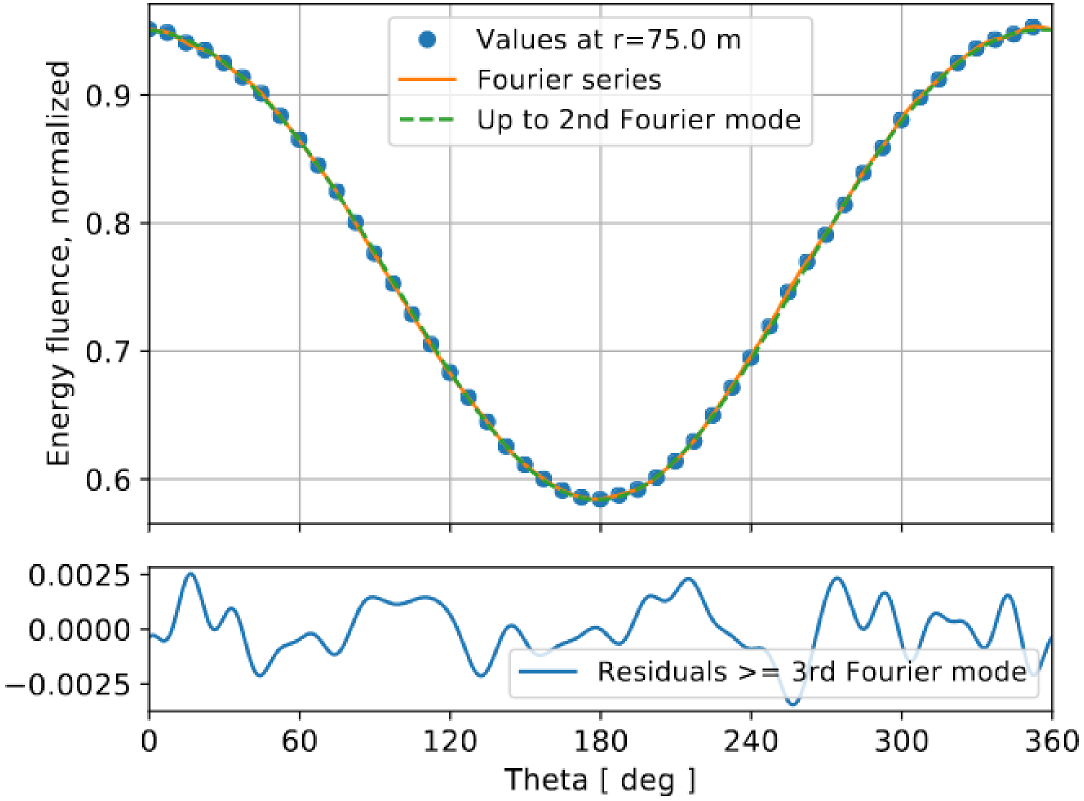

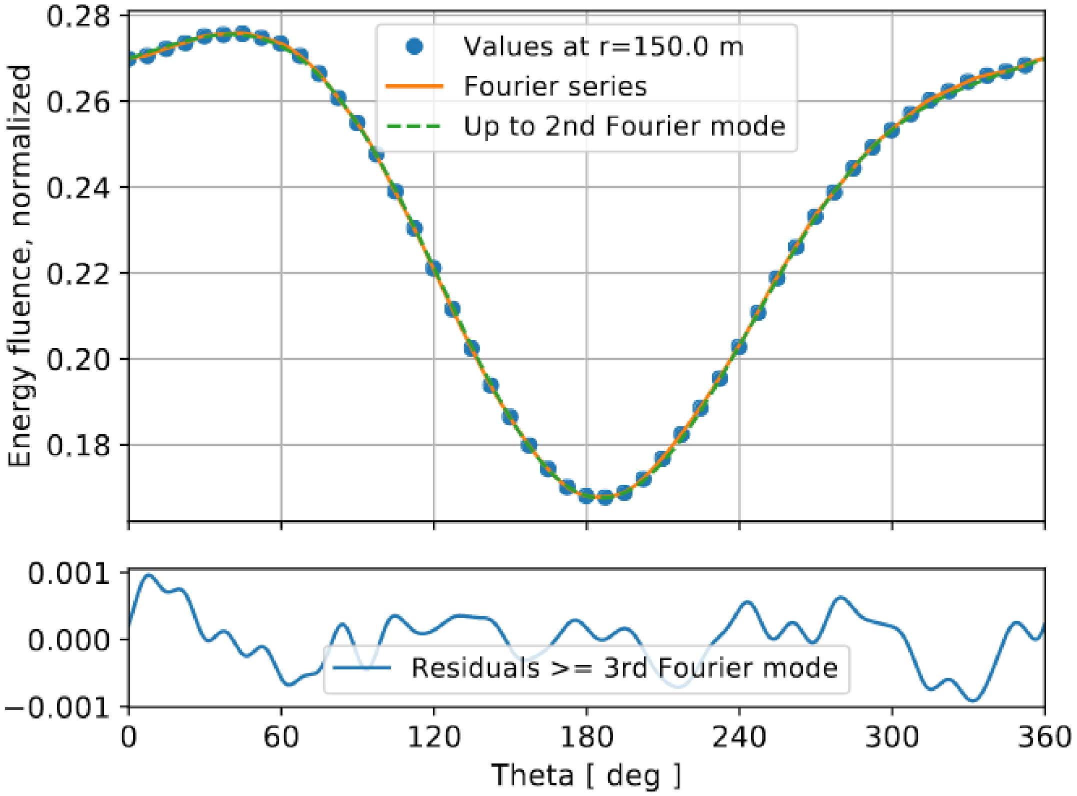

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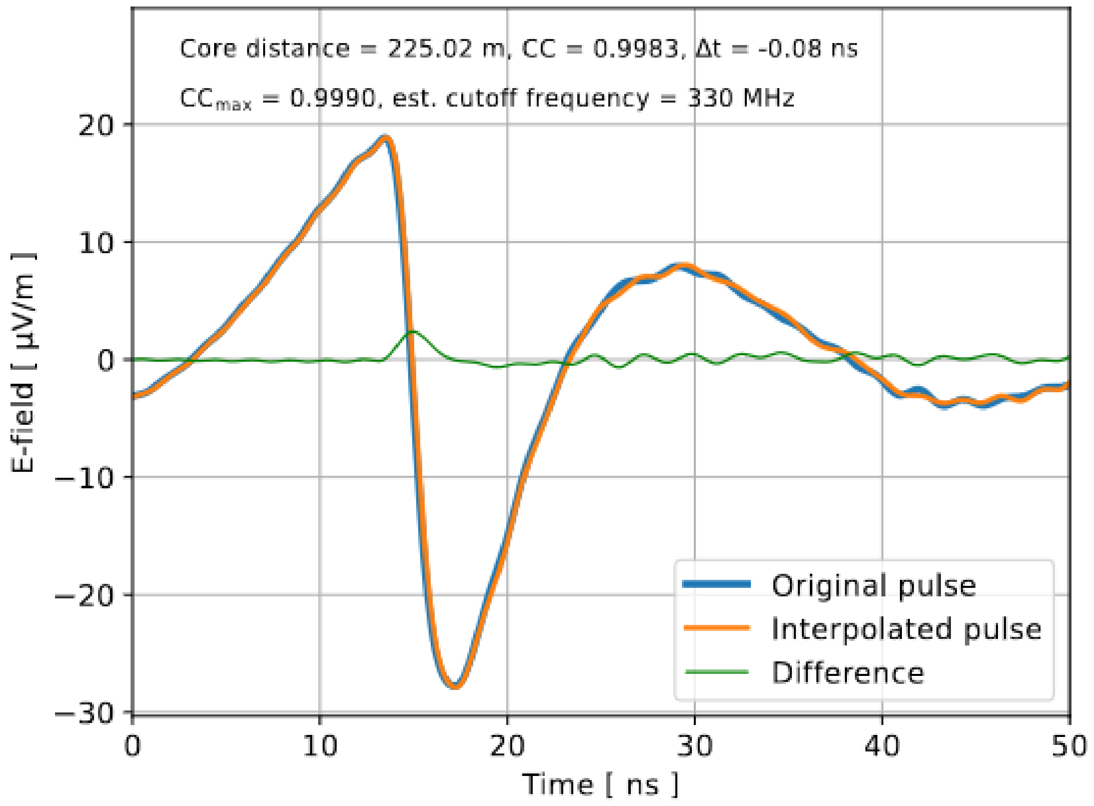

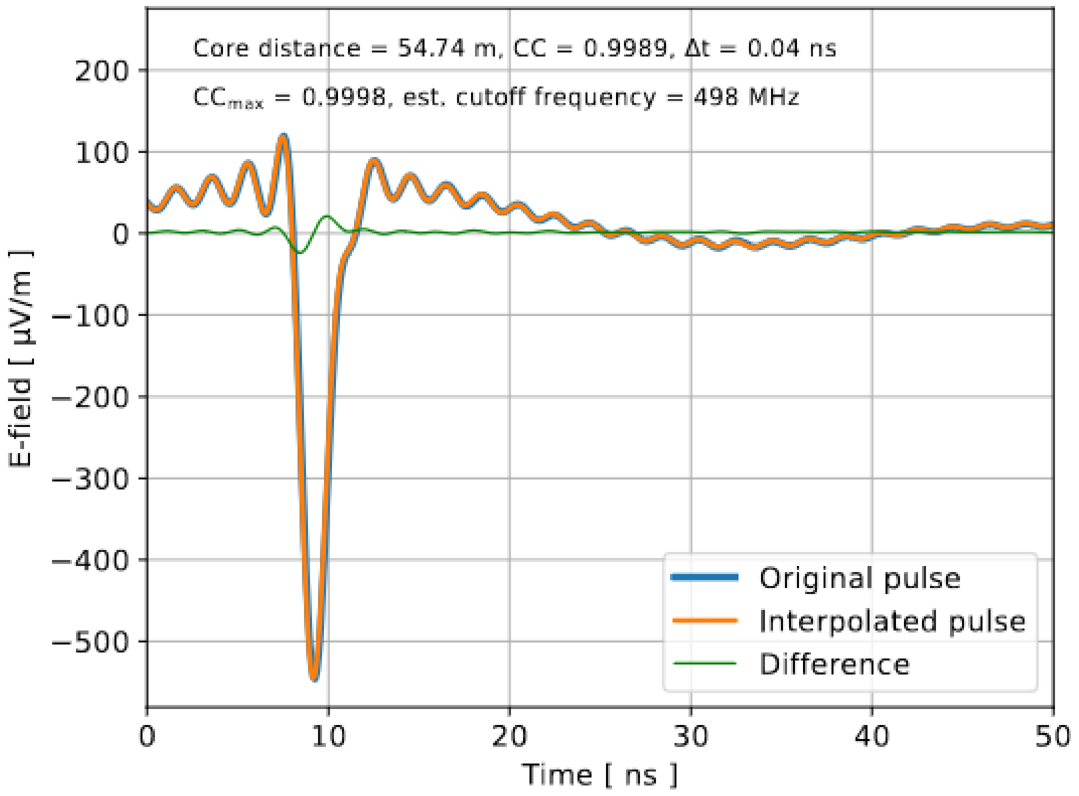

Machine learning

Current work in the LOFAR Cosmic Ray KSP

more on this: Master's Thesis, Luuk van Zuijlen

- Current reconstruction is very dependent on simulations
- For future, machine learning trained on simulations could be an option

1) Make simulations (300.000)

These already exist!

2) Characterize signal by **features**

3) Train model (FCNN) on features to predict **targets**

Targets: *Xmax, L, R, core position, energy*

4) Study results

- **L, R,** relate to the rise and fall of the longitudinal profile

Gaisser-Hillas formula:

$$N_c^{\mathrm{G-H}}(X_\mathrm{z}) = N_\mathrm{max} \times \left(\frac{X_\mathrm{z} - X_0}{X_\mathrm{max} - X_0} \right)^{\frac{X_\mathrm{max} - X_0}{\Lambda}} e^{\frac{X_\mathrm{max} - X_\mathrm{z}}{\Lambda}}$$

R,L Formula:

$$N_c^{\mathrm{R-L}}(X_\mathrm{z}) = N_\mathrm{max} \times \left(1 - \frac{R}{L}(X_\mathrm{max} - X_\mathrm{z}) \right)^{R^{-2}} e^{\frac{X_\mathrm{max} - X_\mathrm{z}}{RL}}$$

Machine learning

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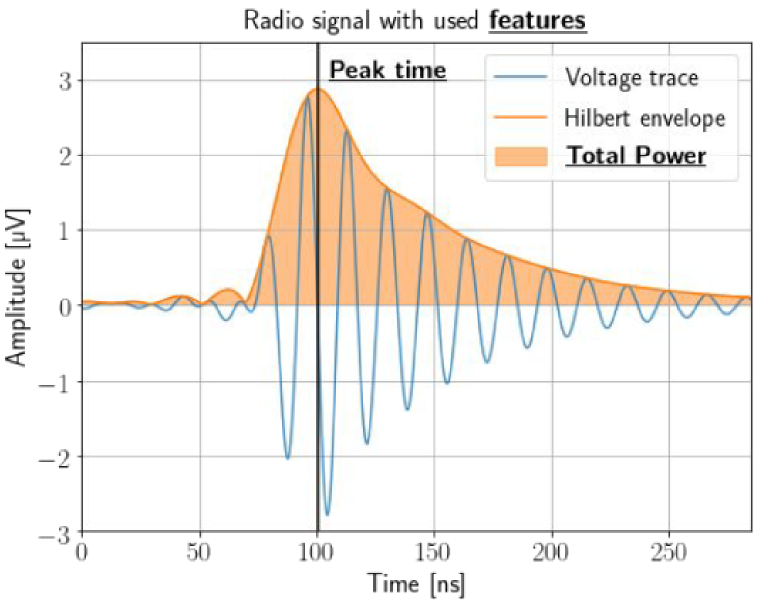
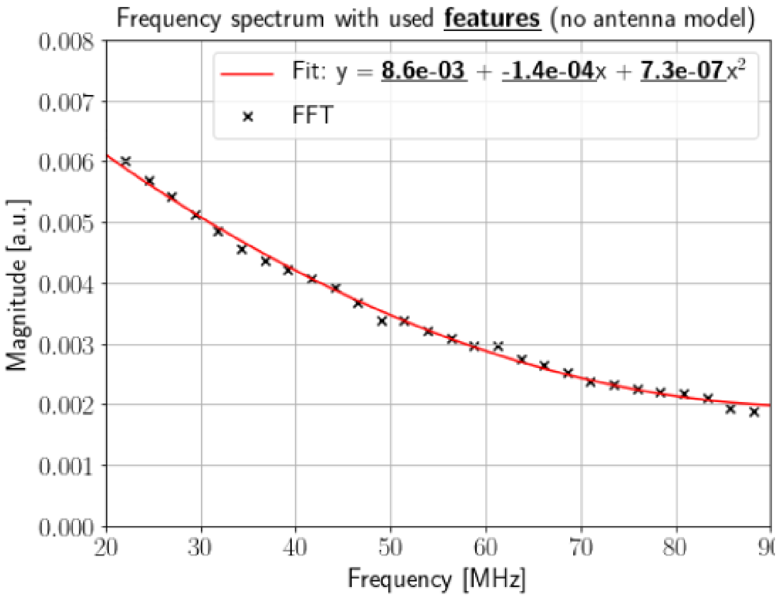
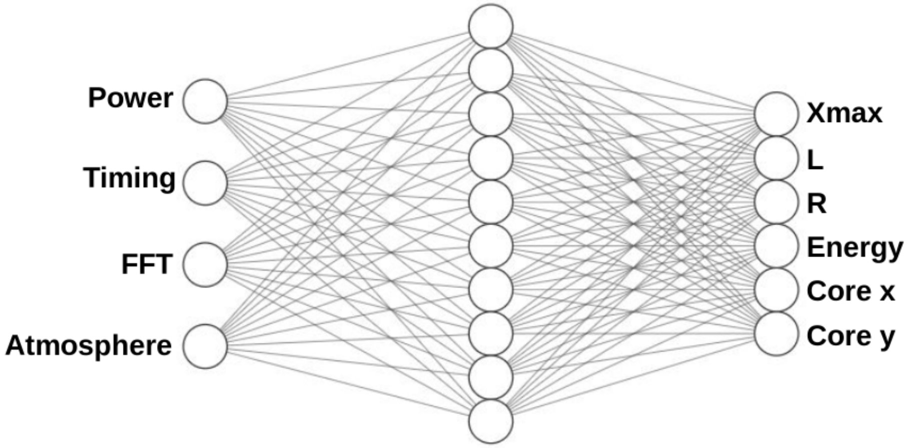




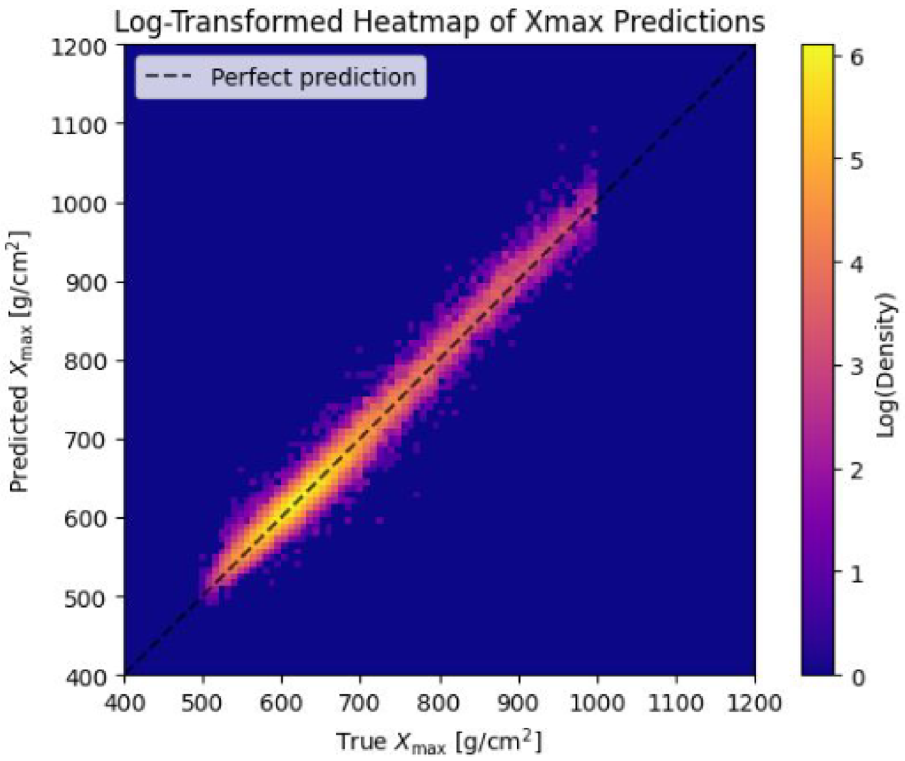


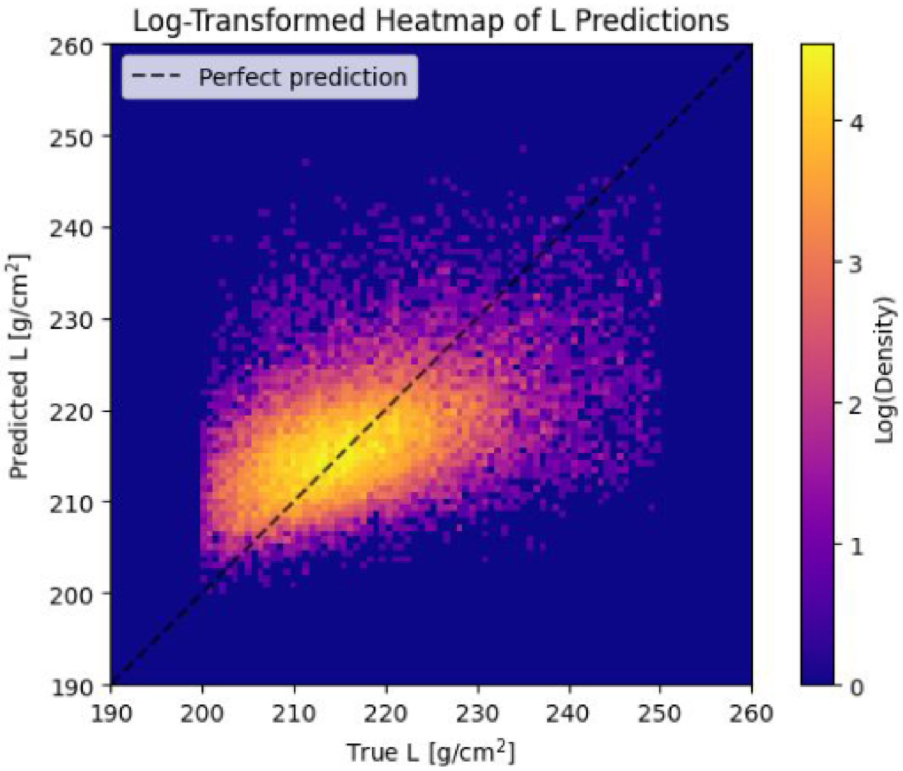
7 hidden layers
4 million learnable parameters
3 hours training time

Machine learning

Current work in the LOFAR Cosmic Ray KSP

more on this: Master's Thesis, Luuk van Zuijlen





- Xmax MAE = 17 g/cm2 → 3.4%
- L MAE = 6.1 g/cm2 → 12%

- R MAE = 0.022 → 11%
- Log(E) MAE = 0.25 → 1.5%
- Core resolution = 3.4 m ± 2.4 m

Holistic air shower reconstruction

My future work

- Again: Current reconstruction is very dependent on simulations

- **Goal of my work:** Holistic air shower reconstruction
  - Use all parameters at once (signal power, timing, polarisation, …) to reconstruct meaningful shower properties
  - to be used for all LOFAR events while quantifying uncertainties
  - Utilising **Information Field Theory** (*T. A. Enβlin, ANNALEN DER PHYSIK (2019), 531, 1800127*)

Summary

Lots of exciting work is happening in the LOFAR Cosmic Ray KSP!

- We joined NuRadioReco
- We have a new and improved interpolator
- In addition to conventional methods, we are also testing machine learning for reconstruction
- We are revisiting the Galactic calibration

- This year LOFAR enters the next phase, LOFAR2.0
- While upgrades to station hardware are built, full dataset of phase 1 can be evaluated
- “LOFAR1.0” data and analysis will be published

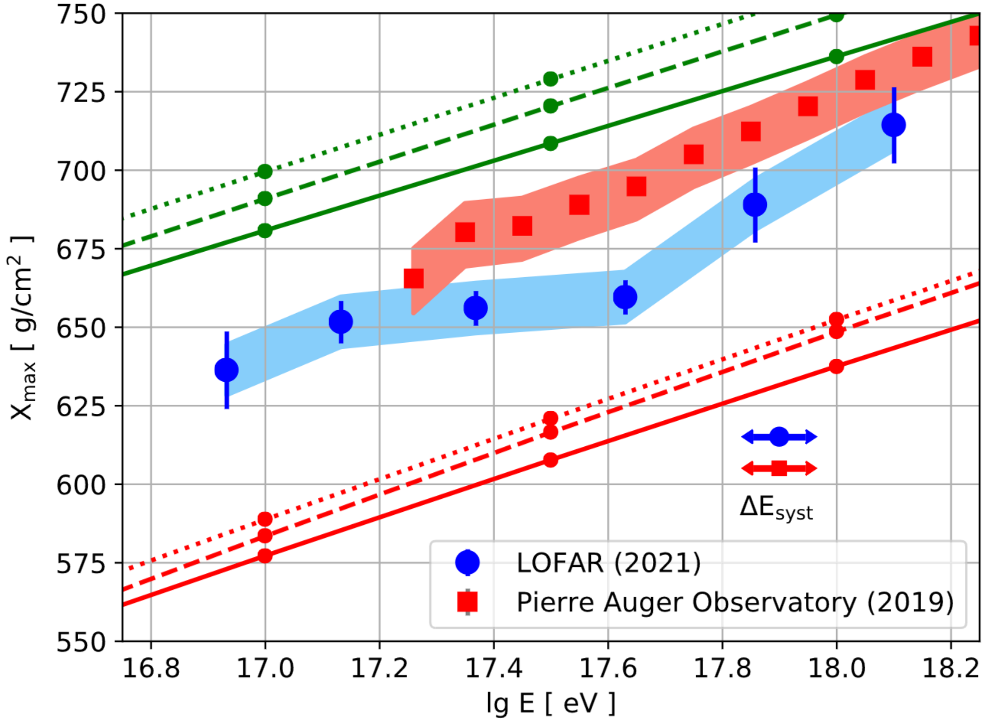
stay tuned!

Auger/LOFAR cross-checks

Current work in the LOFAR Cosmic Ray KSP

- Split data in 2 or more bins, in zenith angle, azimuth, core, etc. Issue: statistical errors become too large, can only see very big effects
  - No problems found
- Use entire distributions: are there unaccounted selection effects?
  - k-sample Anderson-Darling test:
  - see if 2 or more samples are drawings from the same distribution or not
  - Split in zen, az, core (x, y), core uncertainty, radio chi^2, # stations
  - No significant differences in either LOFAR or AERA data
- Hypothesis test: are LOFAR and Auger-FD or AERA compatible up to
- a single overall shift in Xmax, or in energy?

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

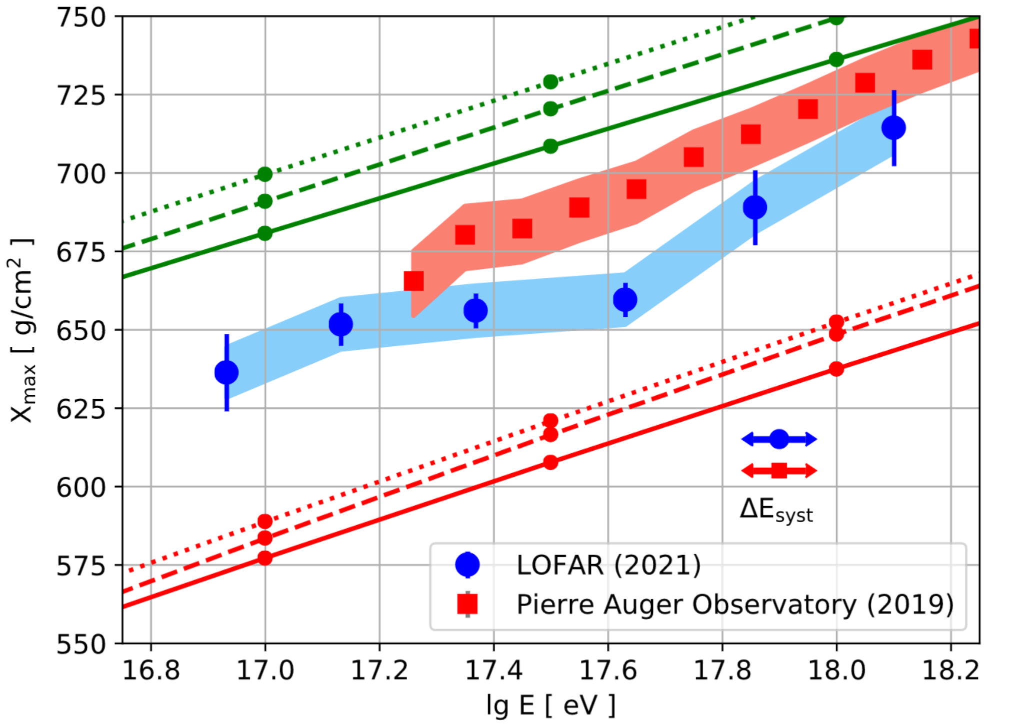


Auger/LOFAR cross-checks

Current work in the LOFAR Cosmic Ray KSP

- Hypothesis test: are LOFAR and Auger-FD or AERA compatible up to a single overall shift in Xmax, or in energy?
- Distributions of LOFAR, Auger-FD and AERA are compatible
- LOFAR would require an Xmax shift upward of 21 +/- 6 g/cm2 to be compatible with the other two
- Or, an energy shift downward of roughly 40 %

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



Interpolation

Current work in the LOFAR Cosmic Ray KSP

A. Corstanje et al 2023 JINST 18 P09005

Pulse energy footprint:

- Uses FFT to express pulse energy variation along a circle with fixed radius as a Fourier series
- Represents Fourier components with cos and sin amplitudes at each radius
- Interpolates components radially using cubic splines

$$\hat{f}(r,\theta) = \sum_{k=0}^{n/2} c_k(r)\cos(k\,\theta) + s_k(r)\sin(k\,\theta)$$

Pulse time series:

- Linear combination of nearby signals not suitable for approximating E-Field due to nonlinear changes in pulse arrival times, polarization, and shape
- Interpolation in the spectral domain is used for accurate full pulse interpolation

$$F(\nu) = \mathcal{F}(E(t)) = |F(\nu)|\exp(\mathrm{i}\,\phi(\nu))$$