Friedrich-Alexander-Universität
Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Reconstruction methods for radio detection of air showers with LOFAR

Karen Terveer
Oct 4th, 2023

LOFAR

- Low-Frequency Array (LOFAR) is large telescope array with stations across Europe
- Core located in the Netherlands

- 52 stations total
- Each station consists of Low Band Antennas (LBA) and High Band Antennas (HBA)
- additionally, particle detectors (LORA) at the core,
  (triggering, direction reconstruction)

- Various key science projects

Ultra high-energy cosmic rays

- Cosmic ray produces air shower in atmosphere
- Two effects: Askaryan effect and geomagnetic emission cause radio frequency emission that can be measured with antennas

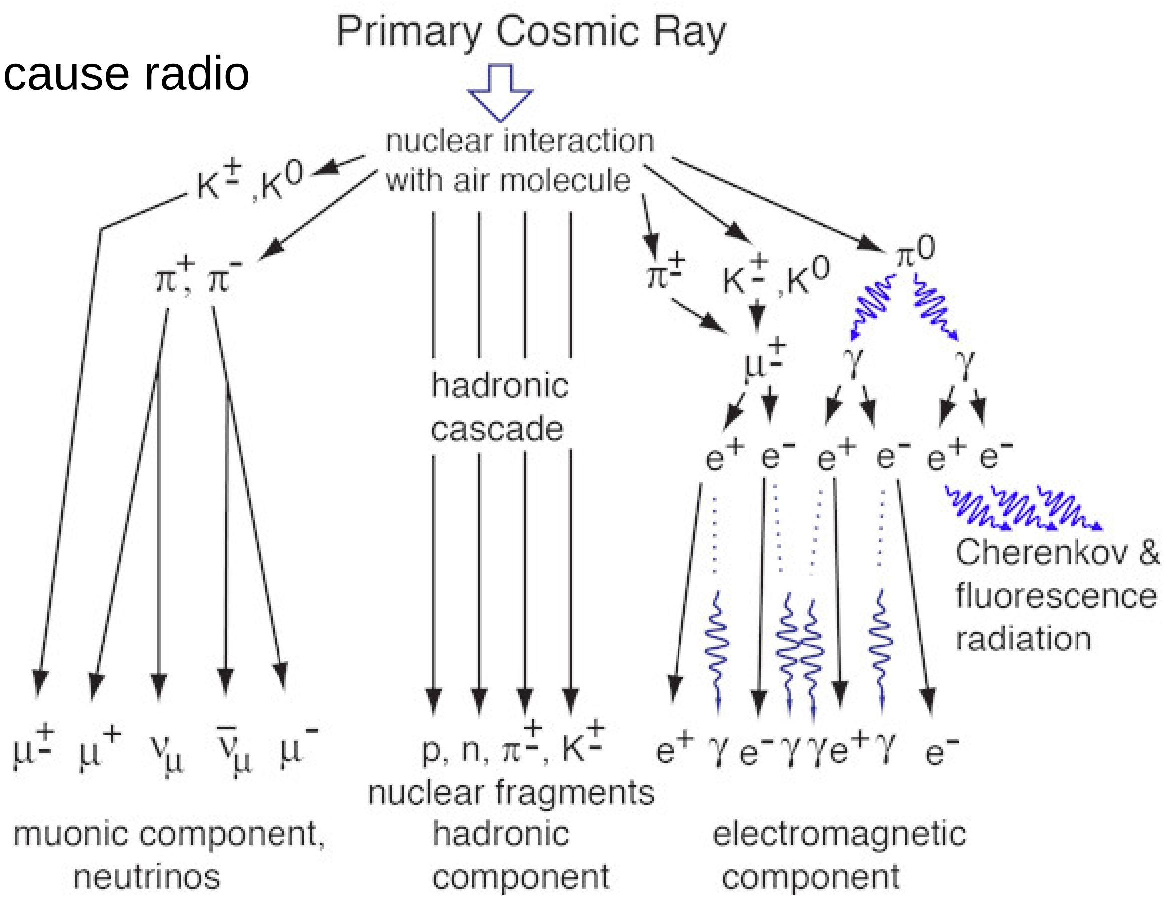
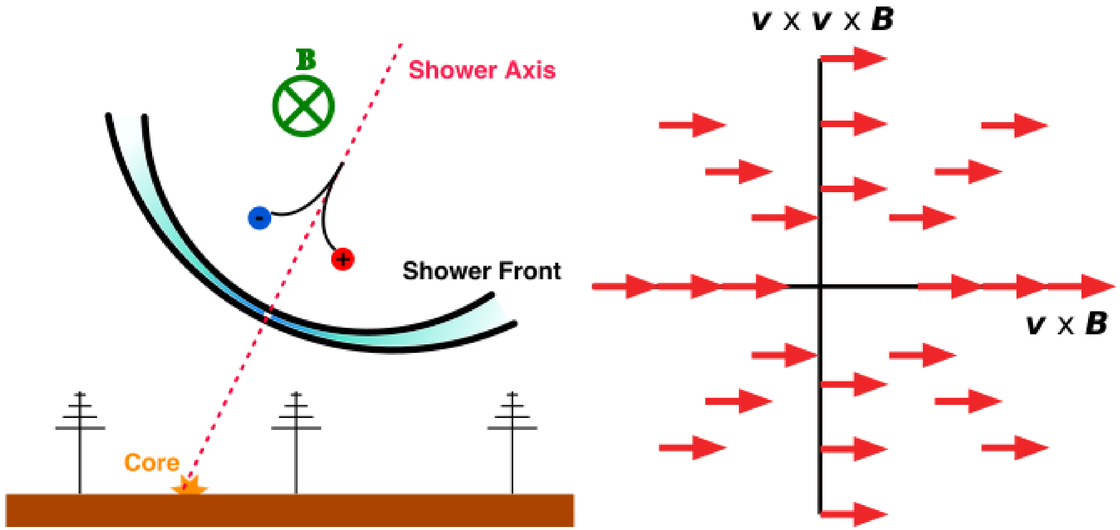


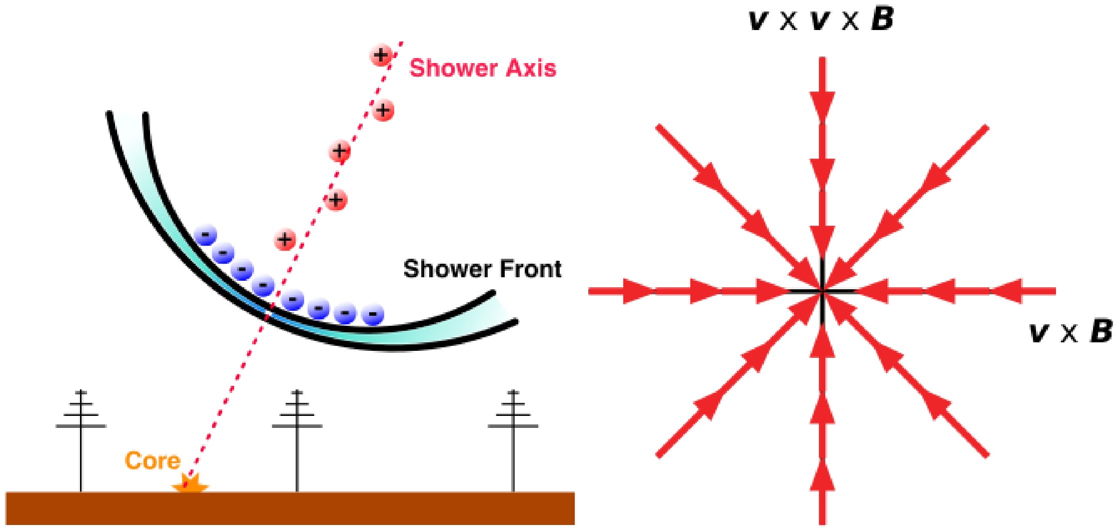
Image: http://hyperphysics.phy-astr.gsu.edu/

- Cosmic ray produces air shower in atmosphere
- Two effects: Askaryan effect and geomagnetic emission cause radio frequency emission that can be measured with antennas

https://arxiv.org/abs/1601.07426



Geomagnetic emission



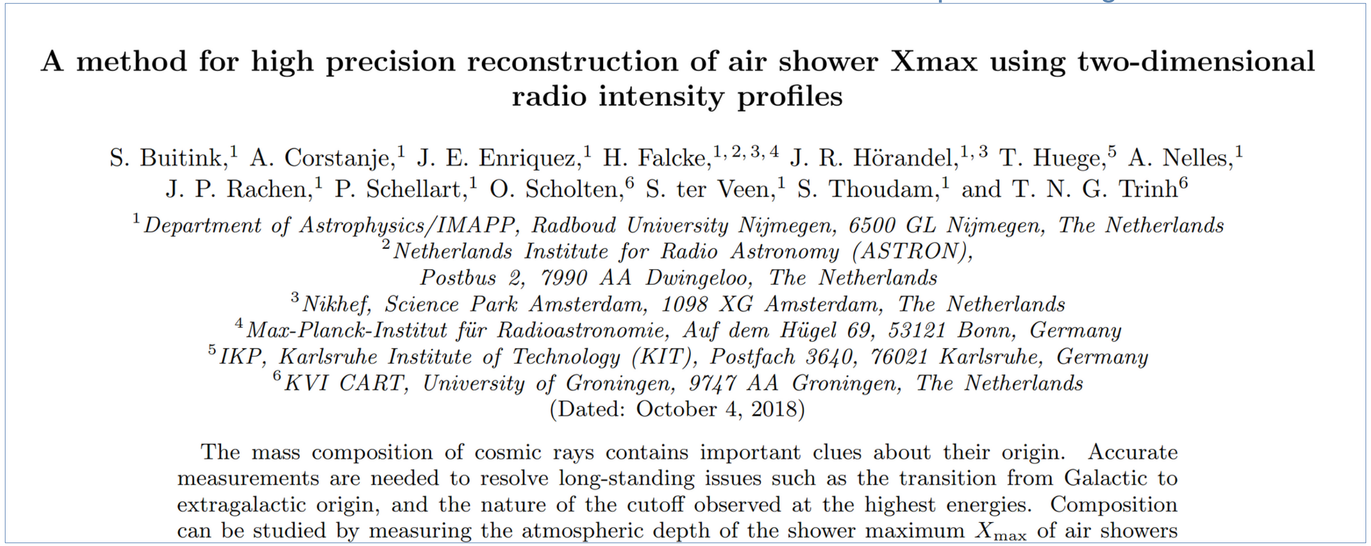
Askaryan effect

- Cosmic ray produces air shower in atmosphere
- Two effects: Askaryan effect and geomagnetic emission cause radio frequency emission that can be measured with antennas

- From antenna measurement, air shower can be reconstructed.
  - important quantity: Xmax

- Reconstruction method used thus far:

https://arxiv.org/abs/1408.7001



A method for high precision reconstruction of air shower Xmax using two-dimensional radio intensity profiles

S. Buitink,[1] A. Corstanje,[1] J. E. Enriquez,[1] H. Falcke,[1,2,3,4] J. R. Hörandel,[1,3] T. Huege,[5] A. Nelles,[1] J. P. Rachen,[1] P. Schellart,[1] O. Scholten,[6] S. ter Veen,[1] S. Thoudam,[1] and T. N. G. Trinh[6]

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(Dated: October 4, 2018)

The mass composition of cosmic rays contains important clues about their origin. Accurate measurements are needed to resolve long-standing issues such as the transition from Galactic to extragalactic origin, and the nature of the cutoff observed at the highest energies. Composition can be studied by measuring the atmospheric depth of the shower maximum X_{max} of air showers

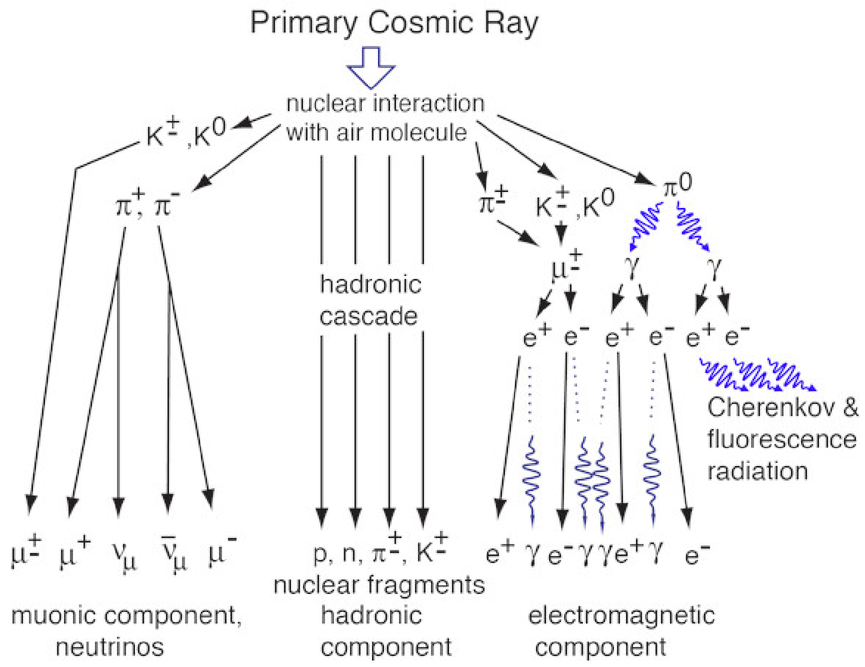
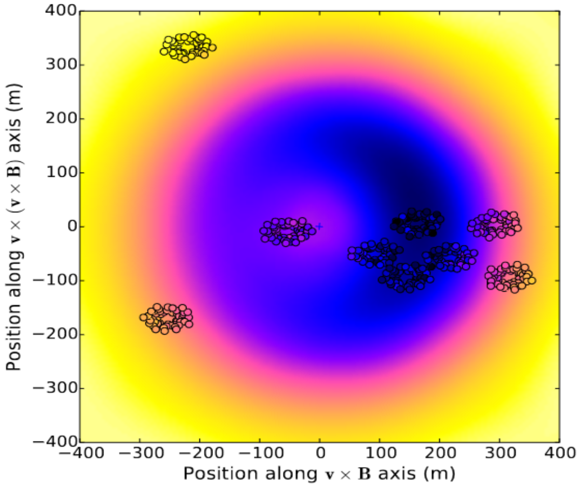


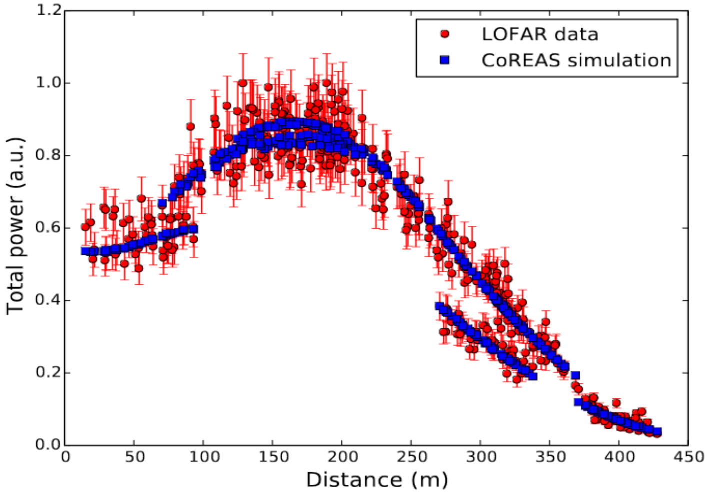
Image: http://hyperphysics.phy-astr.gsu.edu/

- Data is fit to air shower simulations from CoREAS by minimising the χ^2:

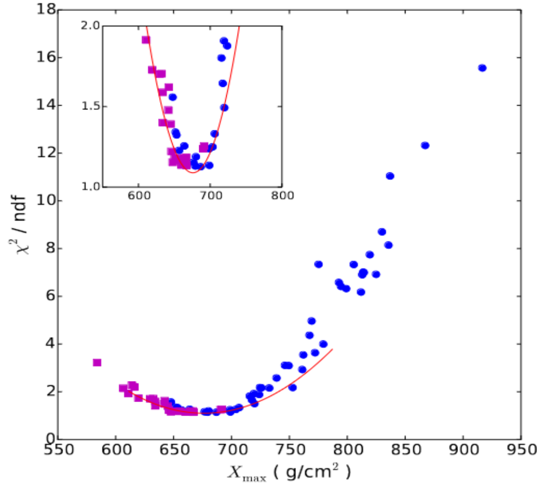
$$\chi^2 = \sum_{\text{antennas}} \left(\frac{P_{\text{ant}} - f_r^2 P_{\text{sim}}(x_{\text{ant}} - x_0, y_{\text{ant}} - y_0)}{\sigma_{\text{ant}}} \right)^2 + \sum_{\substack{\text{particle}\\ \text{detectors}}} \left(\frac{d_{\text{det}} - f_p d_{\text{sim}}(x_{\text{det}} - x_0, y_{\text{det}} - y_0)}{\sigma_{\text{det}}} \right)^2 \quad (1)$$



Simulated radio map

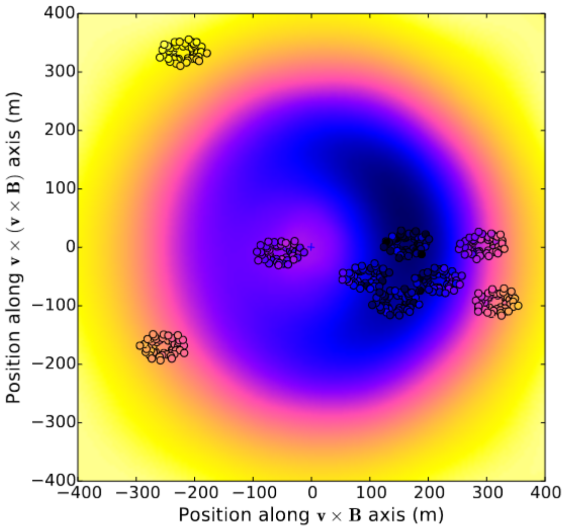


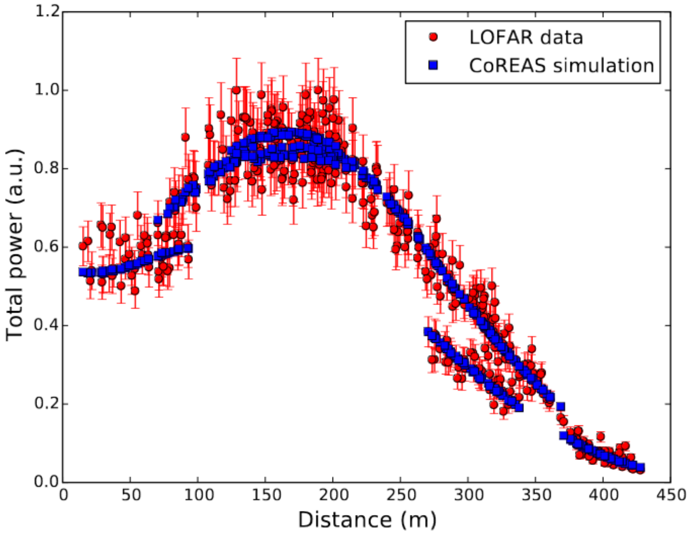
One-dimensional distribution functions

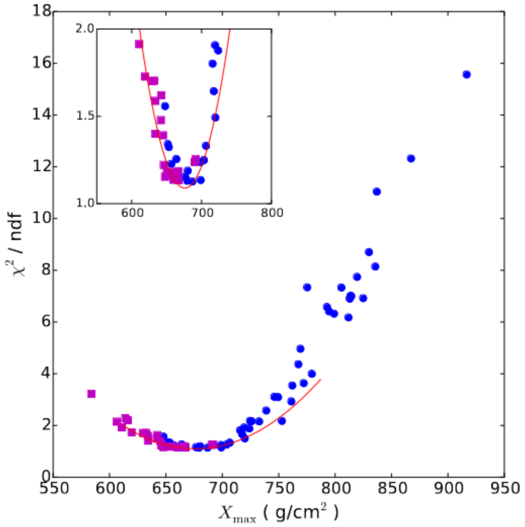


Reduced χ^2 as function of Xmax

Xmax reconstruction







- Uncertainties on Xmax 17 g/cm²
- Con: CoREAS simulations needed, which are very slow

“Information field theory (IFT) is information theory, logic under uncertainty, applied to fields.”

- Probabilistic (Bayesian) theory to reconstruct signals exploiting prior knowledge, i.e. on correlations.

Some basics:

- Prior: probability distribution function of the signal *P(s)*, prior model
- Posterior: Likelihood for signal to be *s* given the data *d*: *P(s|d)*
- Noise: any discrepancies between the model and data must be noise: *P(d|s)=P(N=d-model)*

Bayes Theorem:

$$P(s|d) = \frac{P(d, s)}{P(d)} = \frac{P(d|s)\, P(s)}{P(d)}$$

https://arxiv.org/abs/2102.00258

Full toolbox of methods:

- classical approximation (= Maximum a posteriori)
- effective action (= Variational Bayes)
- Feynman diagrams
- Renormalization
- …

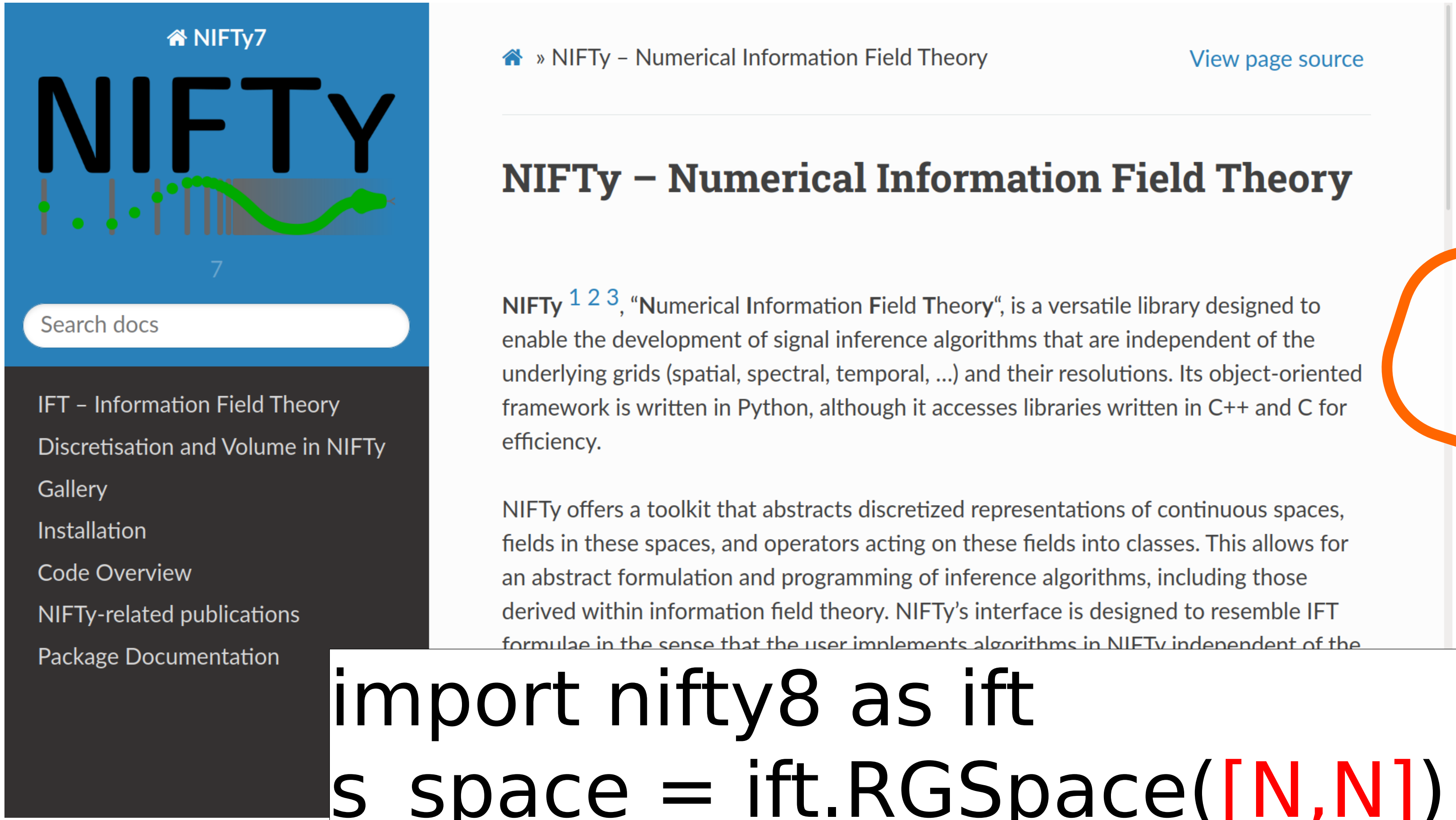
Information field theory

Needed for reconstructing electric field pulses:

- Model for prior distribution of the electric field E (signal)
- Model of the detector response (to connect the data to the signal, measured voltages U to electric field)
- Model of the noise N

→ From that knowledge, the most likely signal can be reconstructed from given data (maximise the posterior $P(E|U)$).

→ **NIFTy**


NIFTy7

NIFTy

7

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IFT – Information Field Theory
Discretisation and Volume in NIFTy
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Installation
Code Overview
NIFTy-related publications
Package Documentation

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NIFTy – Numerical Information Field Theory

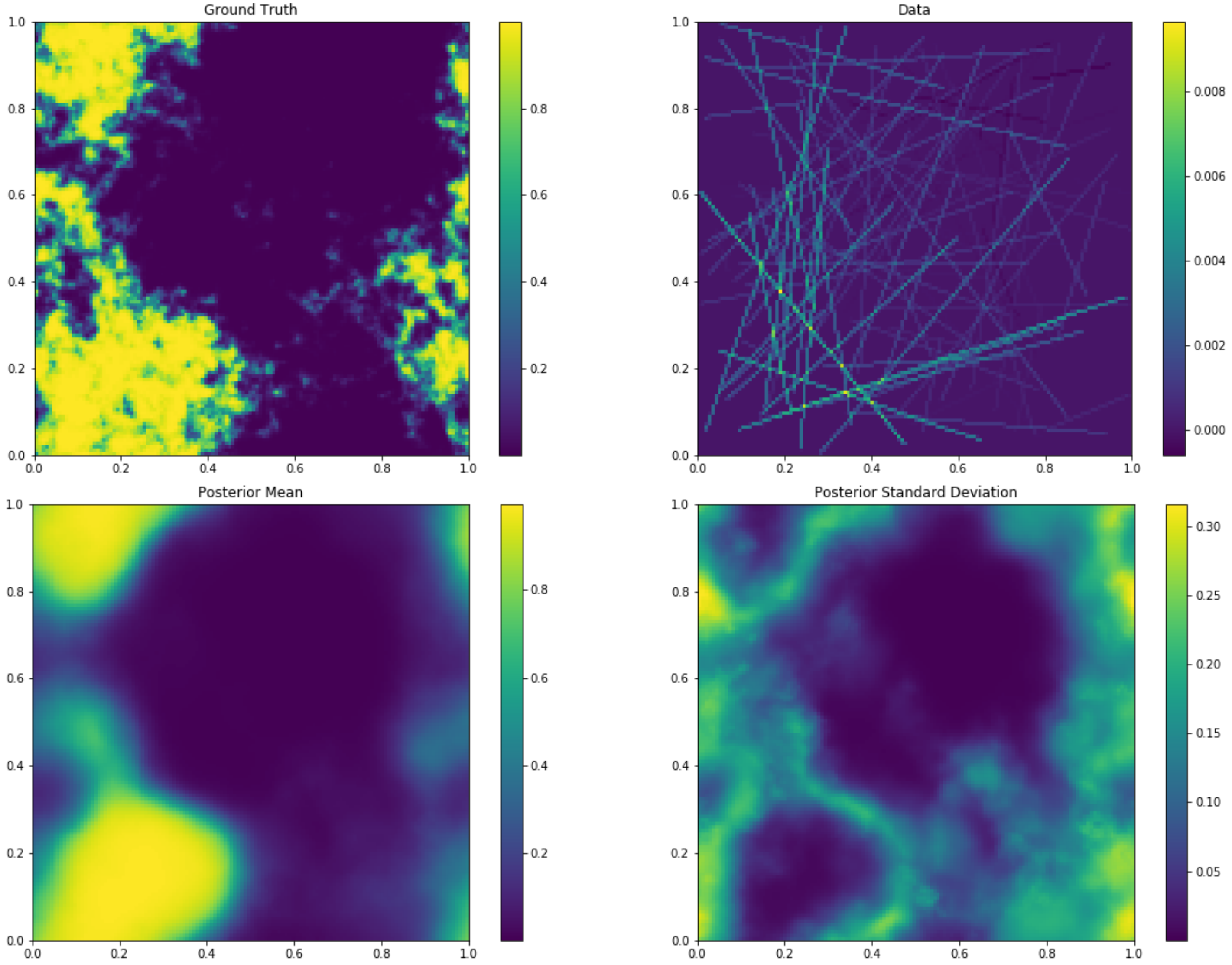
NIFTy [1] [2] [3], "**N**umerical **I**nformation **F**ield **T**heory", is a versatile library designed to enable the development of signal inference algorithms that are independent of the underlying grids (spatial, spectral, temporal, …) and their resolutions. Its object-oriented framework is written in Python, although it accesses libraries written in C++ and C for efficiency.

NIFTy offers a toolkit that abstracts discretized representations of continuous spaces, fields in these spaces, and operators acting on these fields into classes. This allows for an abstract formulation and programming of inference algorithms, including those derived within information field theory. NIFTy's interface is designed to resemble IFT formulae in the sense that the user implements algorithms in NIFTy independent of the …

Differentiable Probabilistic Programming in Python

```
import nifty8 as ift
s_space = ift.RGSpace([N,N])
```

NIFTy – Numerical Information Field Theory



Summary

- Air showers produce radio signals
- Current reconstruction methods can reconstruct single parameters of the shower
- Information Field Theory could be used to reconstruct shower as a whole