Friedrich-Alexander-Universität
Erlangen-Nürnberg

LOFAR

Erlangen Centre for Astroparticle Physics

Holistic air shower reconstruction for LOFAR using Information Field Theory

Work in the context of the Cosmic Ray Key Science Project

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Radio2024 Erlangen
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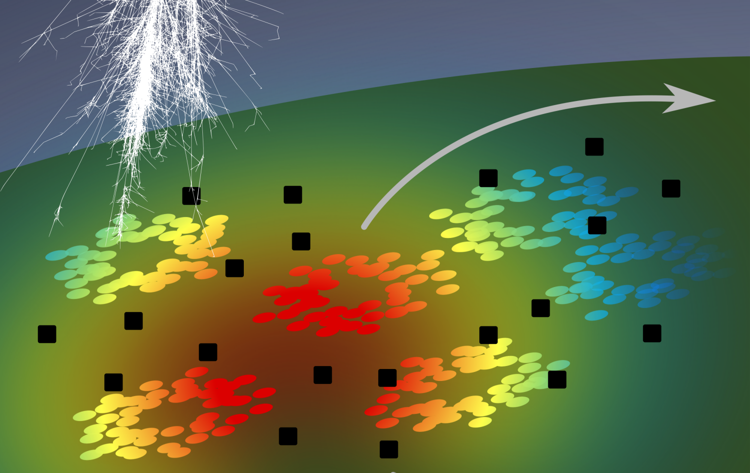
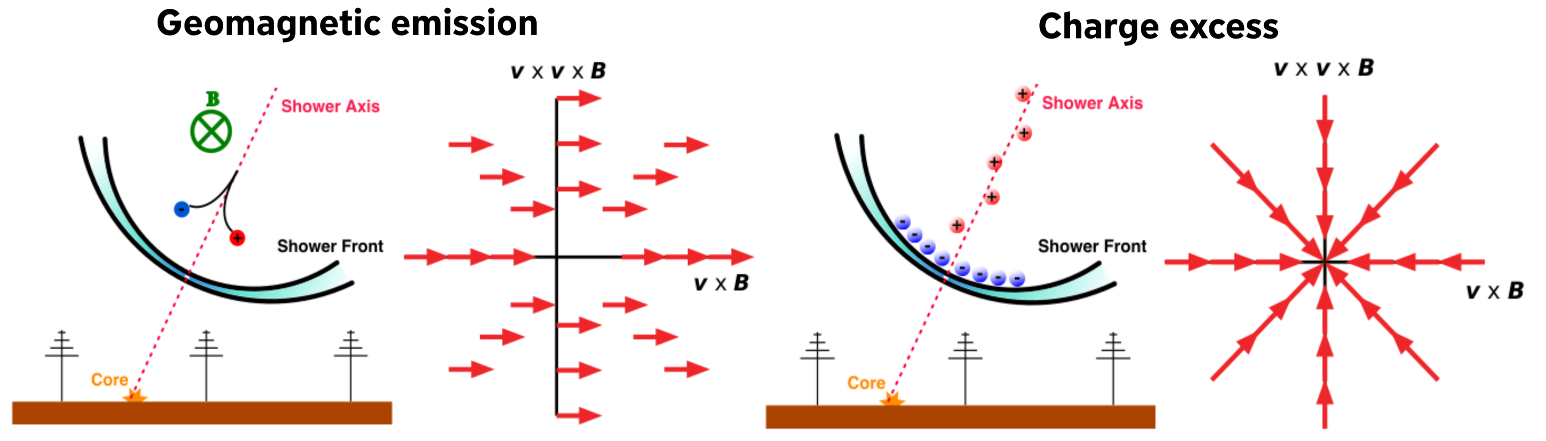
gefördert von
ERUM-Data

Air shower detection with LOFAR

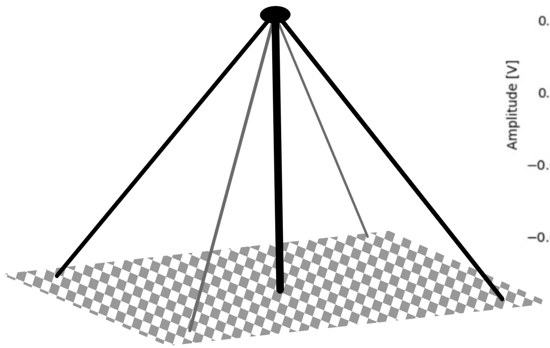
The LOw-Frequency-ARray

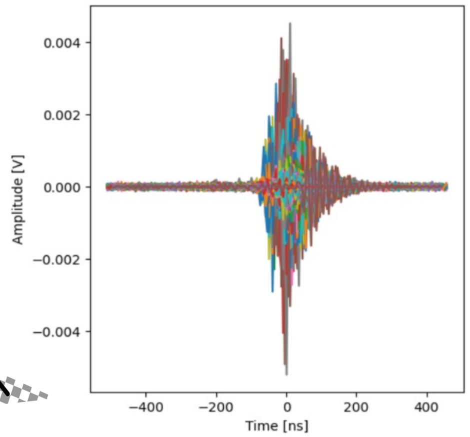




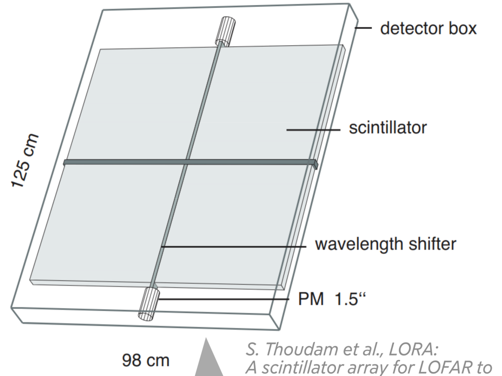
T. Huege, Phys. Rep. 620, 1 (2016)

LOFAR LBA





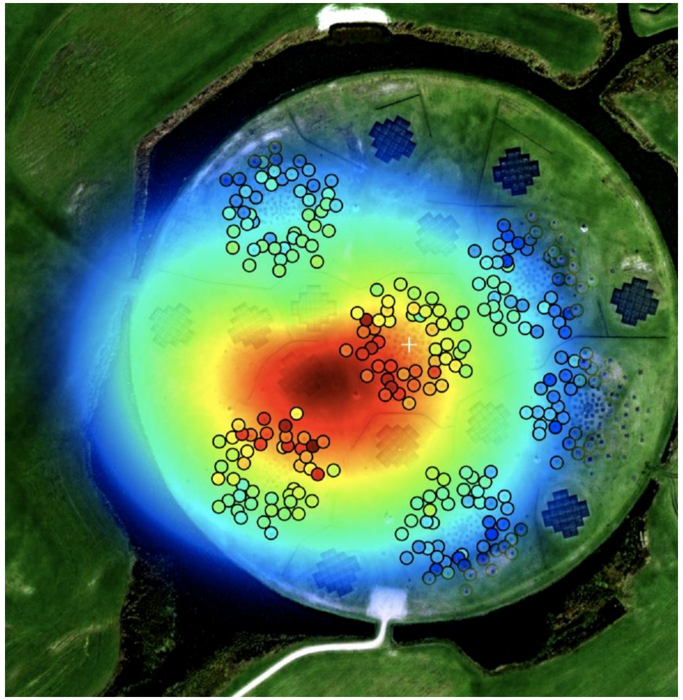
LORA



S. Thoudam et al., LORA: A scintillator array for LOFAR to measure extensive air showers

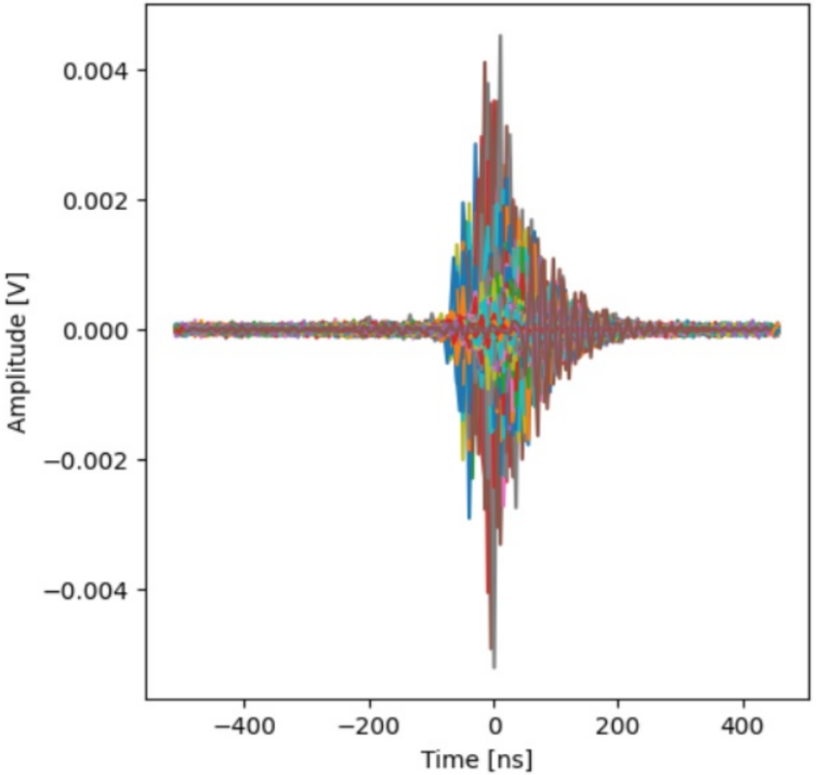
Radio detection of air showers

Radio footprint can be observed by antenna array:

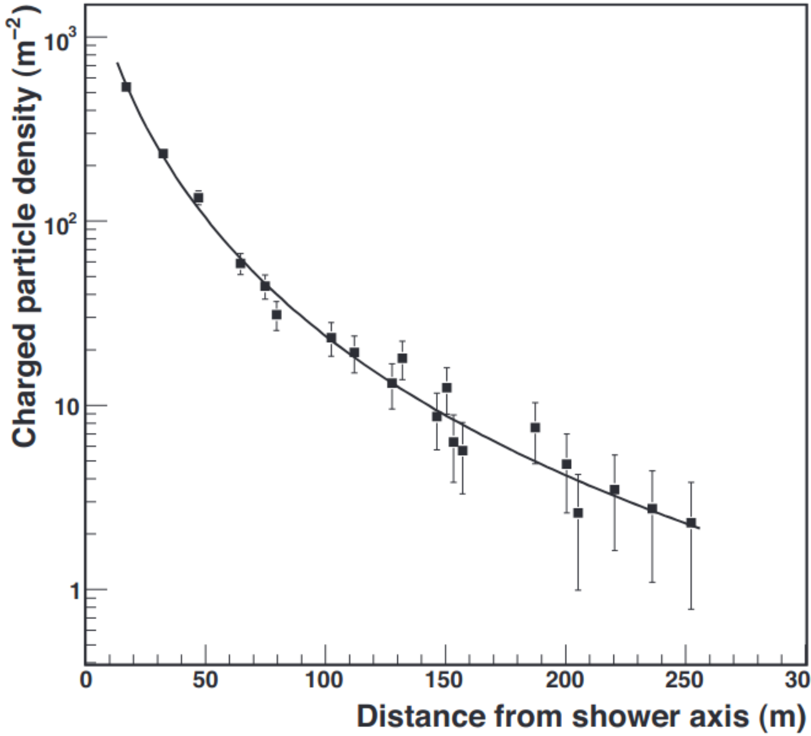


A. Corstanje

Time traces from all antennas:

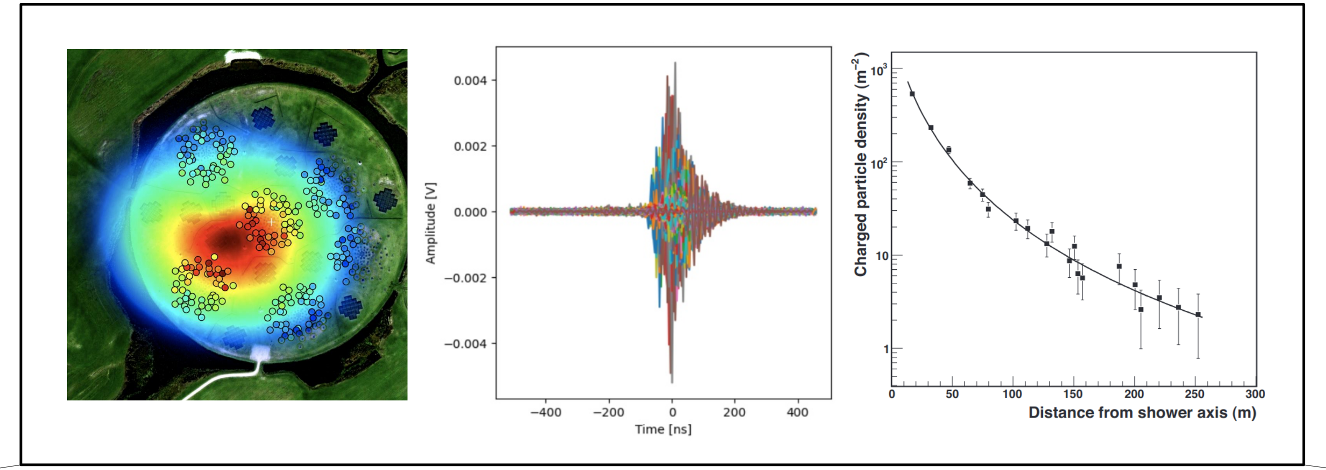


Additional information from particle detectors (LORA):



S. Thoudam et al., LORA: A scintillator array for LOFAR to measure extensive air showers

Radio detection of air showers



Current analyses usually only use all this information separately, sequentially, or brute force simulation which is very resource hungry

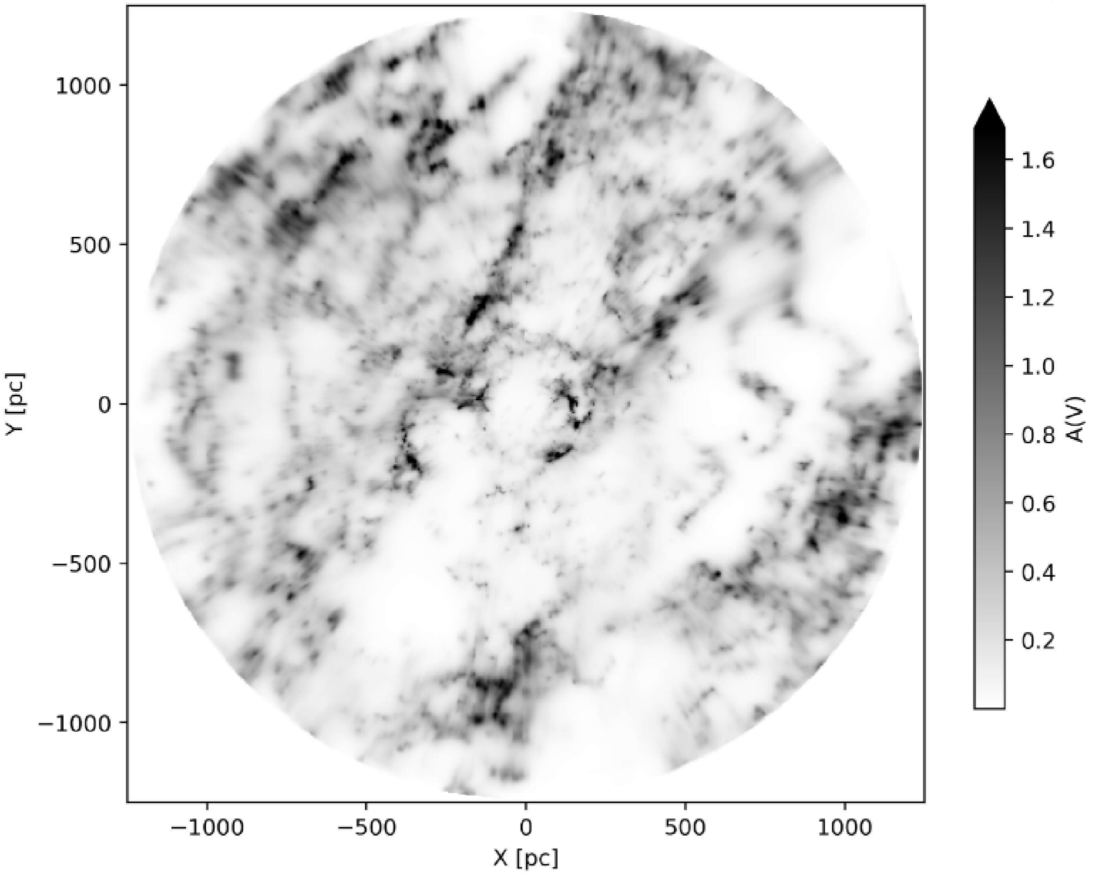
How could one combine all information and get the most out of the data?

Information Field Theory

- Framework for inferring and reconstructing spatially or temporally distributed physical fields from incomplete or noisy data
- Python software nifty8: https://gitlab.mpcdf.mpg.de/ift/nifty

- Key Concept: In IFT, physical field is treated as random field
  → it has a probabilistic structure that can be modeled, even when direct observations are sparse or noisy

G. Edenhofer et al., A&A 685 (2024)



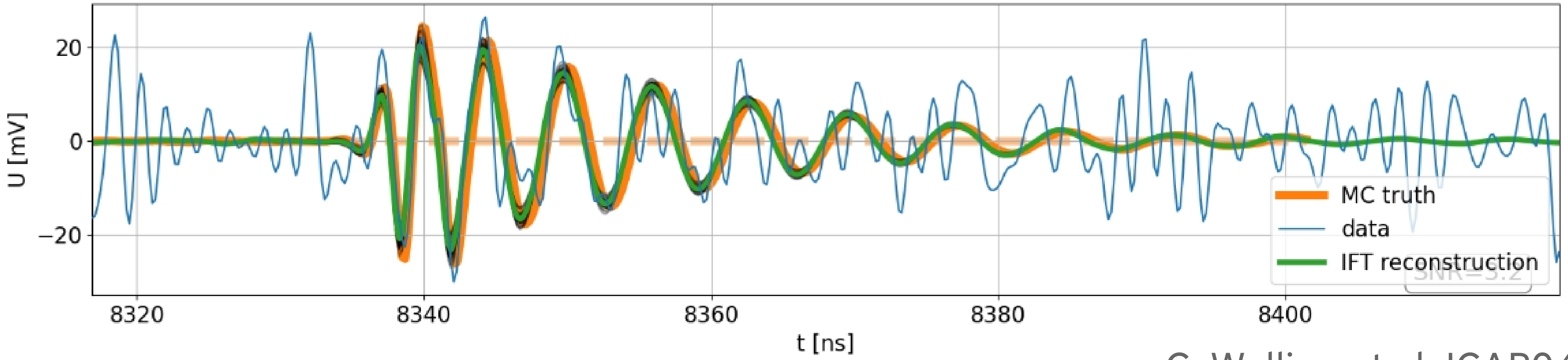
3D interactive version here: https://faun.rc.fas.harvard.edu/czucker/Paper_Figures/3D_Dust_Edenhofer2023.html

Information Field Theory

- Inherently Bayesian
  → uses prior knowledge about the field
  → updates this knowledge based on observed data

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

- By treating fields probabilistically, IFT can provide uncertainty quantification



C. Welling et al JCAP04(2021)071

Holistic air shower reconstruction

Idea 1

- Observing the same field **s** with two different measurement devices & reconstructing together is possible by multiplying likelihoods!

$$d_1 = R_1 s + n_1$$

$$d_2 = R_2 s + n_2$$

$$\mathcal{P}(s|d_1, d_2) \propto \mathcal{P}(d_1, d_2|s)\mathcal{P}(s) = \mathcal{P}(d_1|s)\mathcal{P}(d_2|s)\mathcal{P}(s)$$

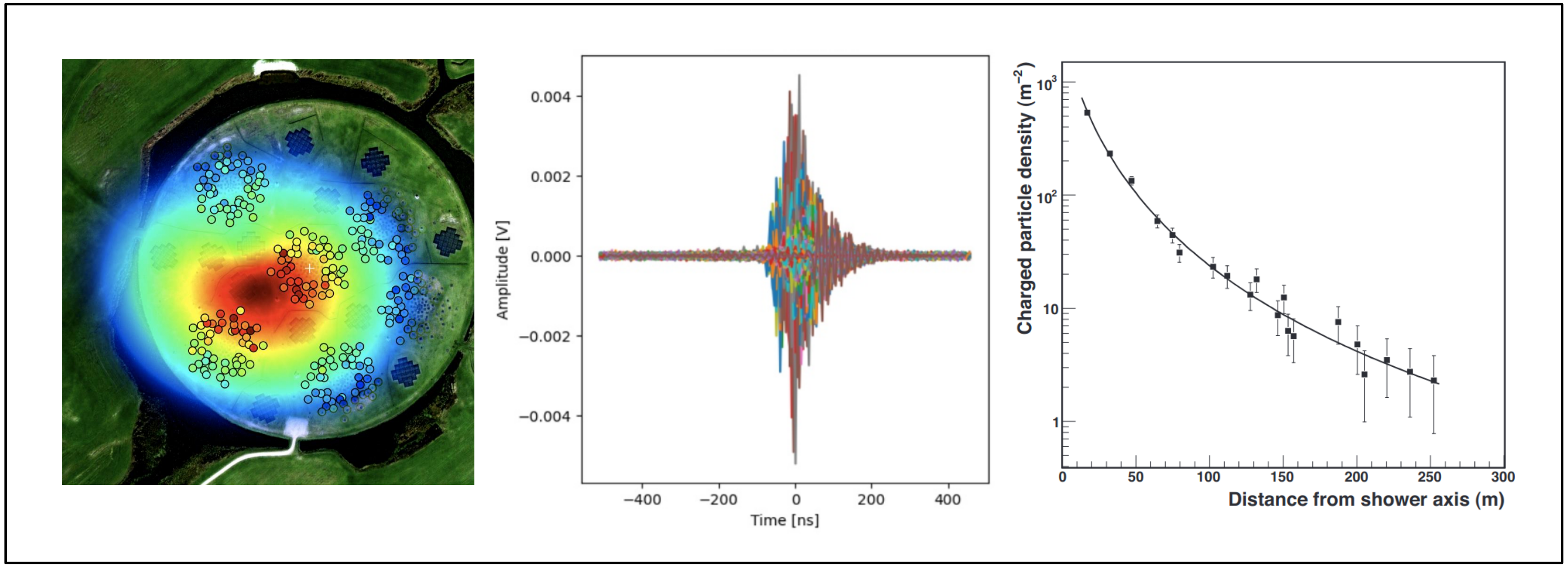
- But for very different measurement devices (particle and radio) it can be hard to find a common description for field **s**

Holistic air shower reconstruction

Idea 2

- Find a parameterized model that relates to physical properties (CR energy, X_{max}, θ, ϕ,…) for each measurement device
- Optimise the parameters simultanously using IFT

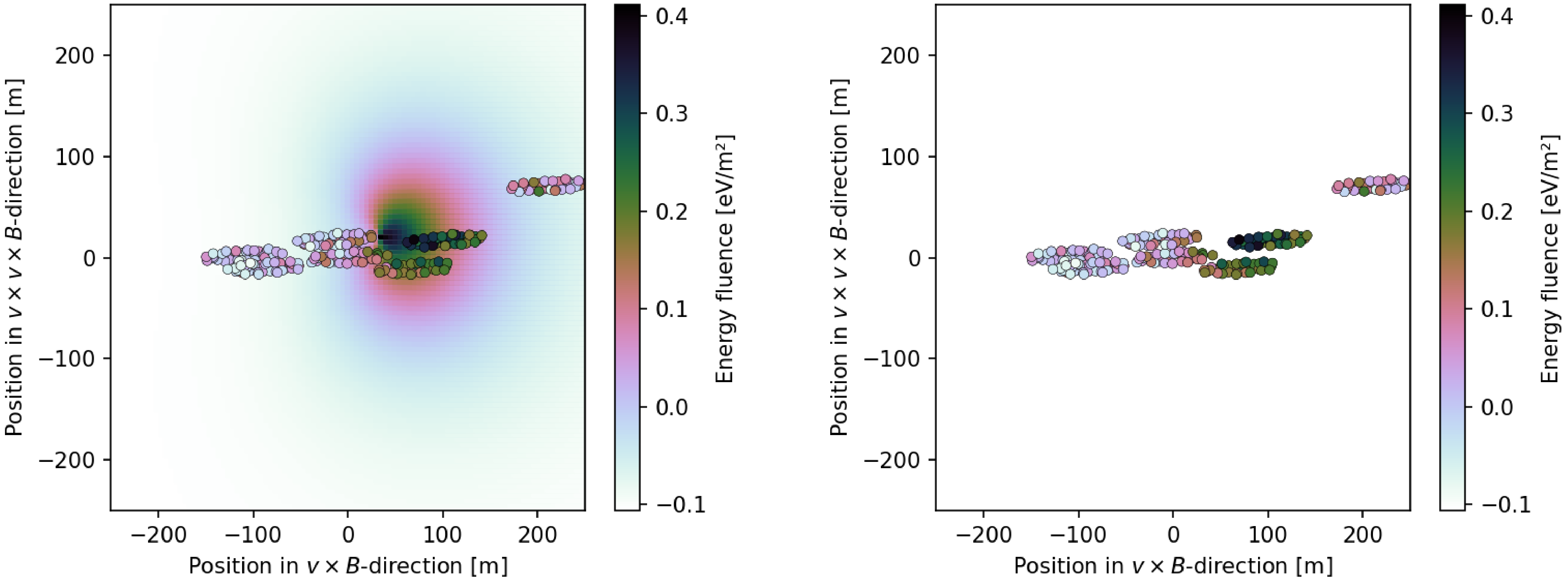
- Current status: building and testing the models separately



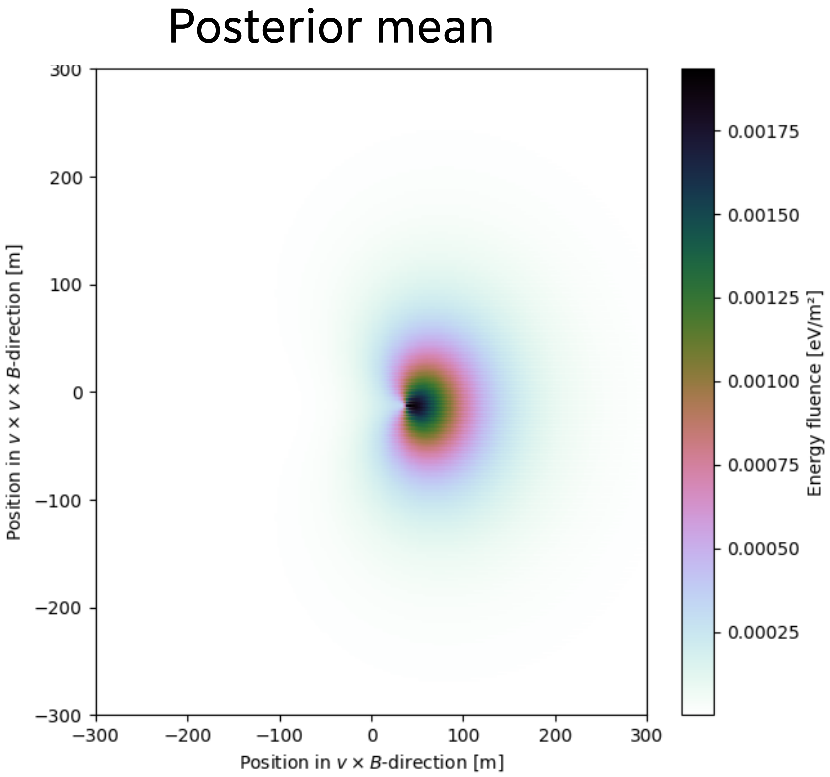
Radio footprint reconstruction

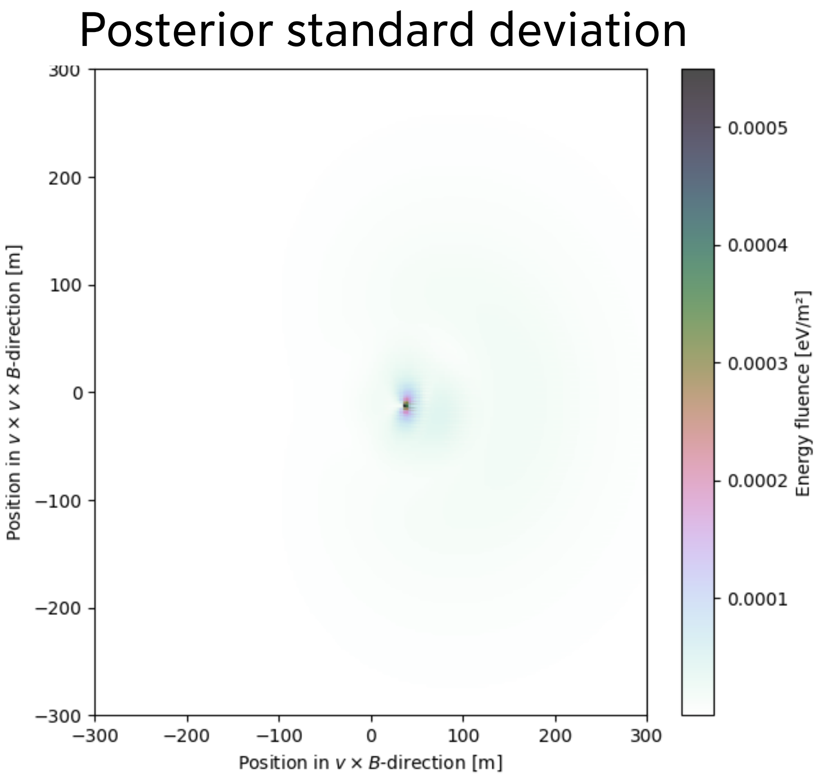
Background: ground truth

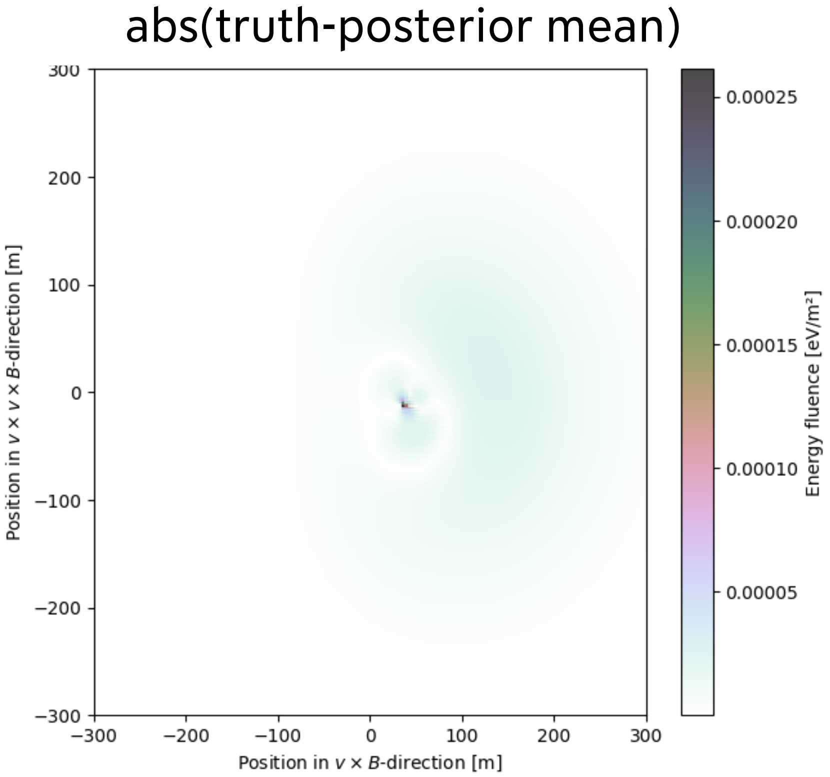
Dots: sampled mock data + noise

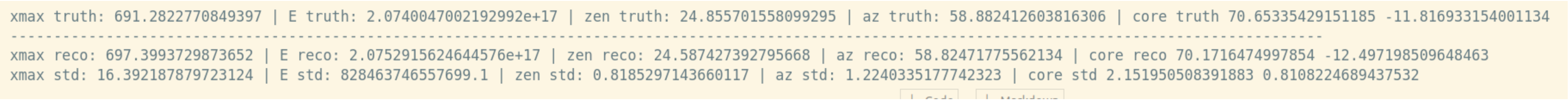


A good reconstruction





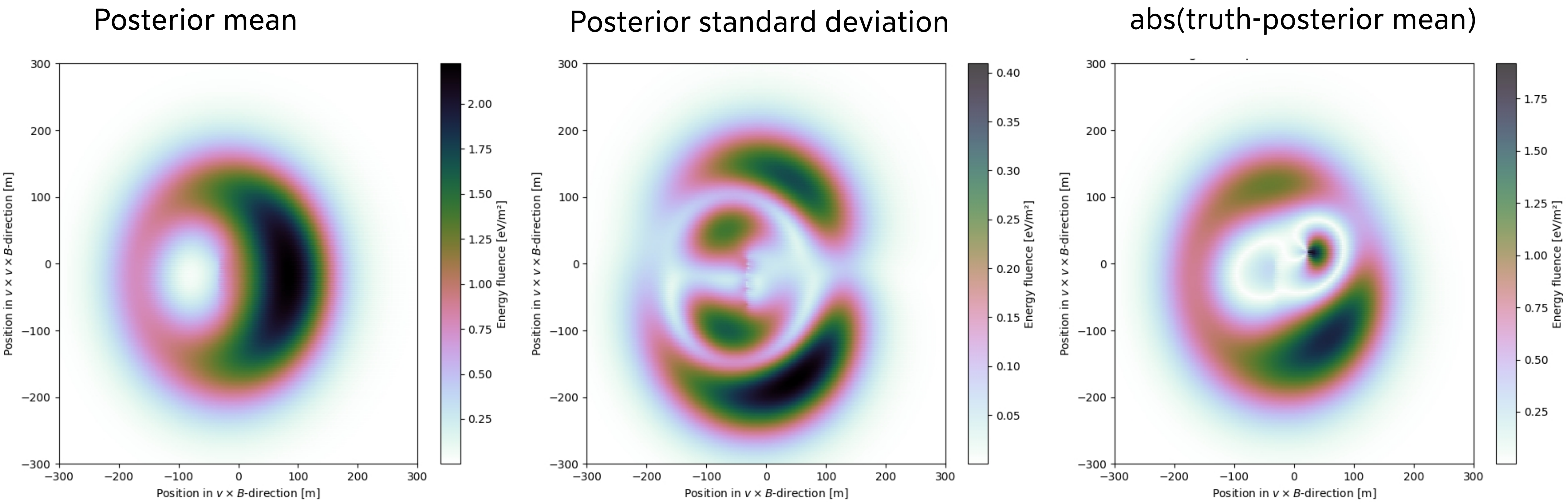




```
xmax truth: 691.2822770849397 | E truth: 2.0740047002192992e+17 | zen truth: 24.855701558099295 | az truth: 58.882412603816306 | core truth 70.65335429151185 -11.816933154001134
-----------------------------------------------------------------------------------------------------------------------------------------------------------
xmax reco: 697.3993729873652 | E reco: 2.0752915624644576e+17 | zen reco: 24.587427392795668 | az reco: 58.82471775562134 | core reco 70.1716474997854 -12.497198509648463
xmax std: 16.392187879723124 | E std: 828463746557699.1 | zen std: 0.8185297143660117 | az std: 1.2240335177742323 | core std 2.151950508391883 0.8108224689437532
```

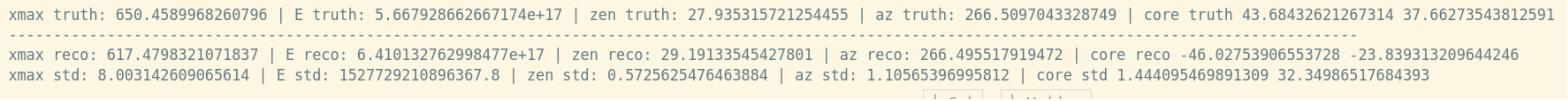
A bad reconstruction

When the core does not reconstruct well


Posterior mean

Posterior standard deviation

abs(truth-posterior mean)


```
xmax truth: 650.4589968260796 | E truth: 5.667928662667174e+17 | zen truth: 27.935315721254455 | az truth: 266.5097043328749 | core truth 43.68432621267314 37.66273543812591
------------------------------------------------------------------------------------------------------------------------------------------------------
xmax reco: 617.4798321071837 | E reco: 6.410132762998477e+17 | zen reco: 29.19133545427801 | az reco: 266.495517919472 | core reco -46.02753906553728 -23.839313209644246
xmax std: 8.003142609065614 | E std: 1527729210896367.8 | zen std: 0.5725625476463884 | az std: 1.10565396995812 | core std 1.444095469891309 32.34986517684393
```

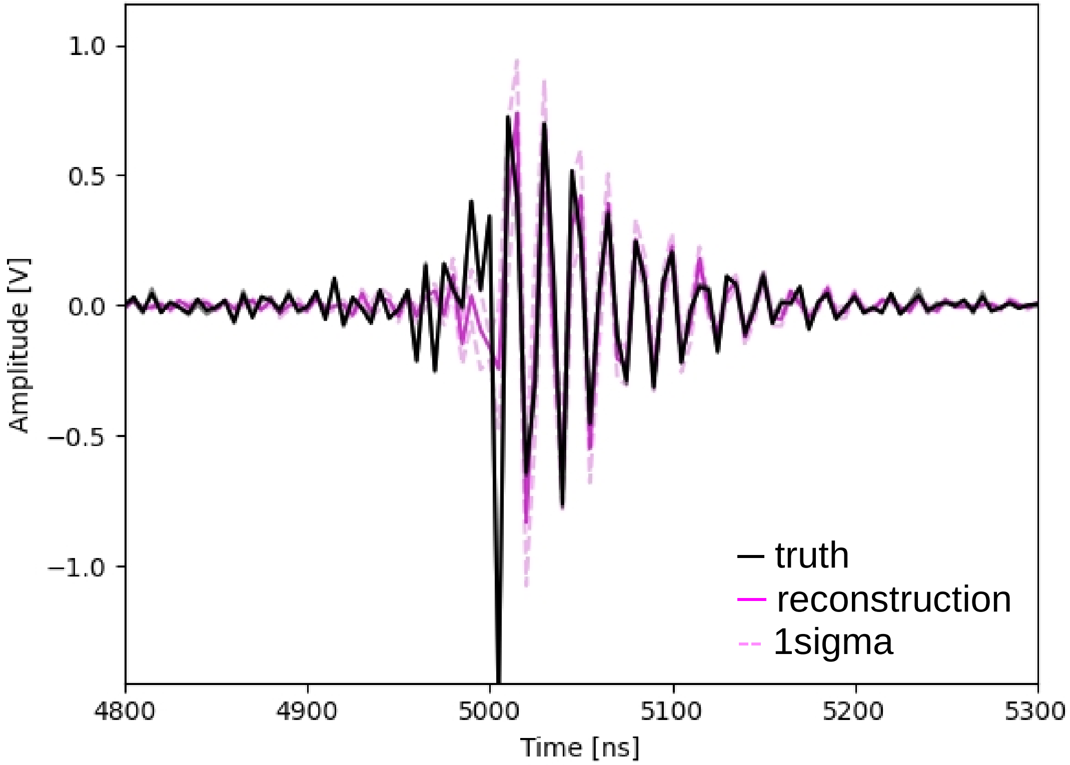
E-Field/trace reconstruction

- LOFAR antenna is very resonant → reconstructing a frequency spectrum for the lower and higher end of LBA bandwith with noise present is challenging
- E-Field parameterization depends on
  - θ, ϕ,
  - The ratio of geomagnetic and charge excess contributions
  - The antenna position relative to the shower core

$$S(\nu) = A \cdot 10^{b_T(\nu - \nu_0)}$$

$$b_T = \frac{1}{v_+ - v_-} \log_{10}\left[\frac{10^{b_G(v_+ - v_0)} + f\left(\Phi_{\mathrm{obs}}\right) R \cdot 10^{b_C(v_+ - v_0)}}{10^{b_G(v_- - v_0)} + f\left(\Phi_{\mathrm{obs}}\right) R \cdot 10^{b_C C(v_- - v_0)}}\right]$$

S. Jansen, PhD thesis, 2016



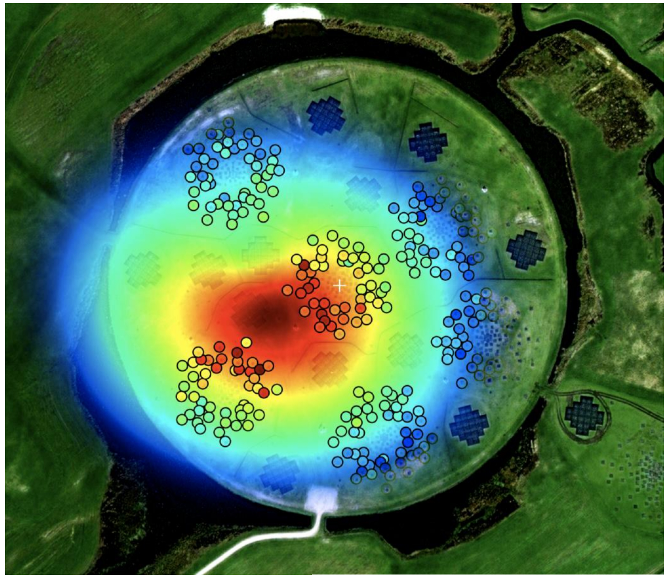
Future: Combine E-Field and LDF

- The current challenges are be due to limited information and degeneracies in the parameterizations!
- Combining E-Field and LDF reconstruction and (in the future) adding particle data is expected to greatly improve the performance

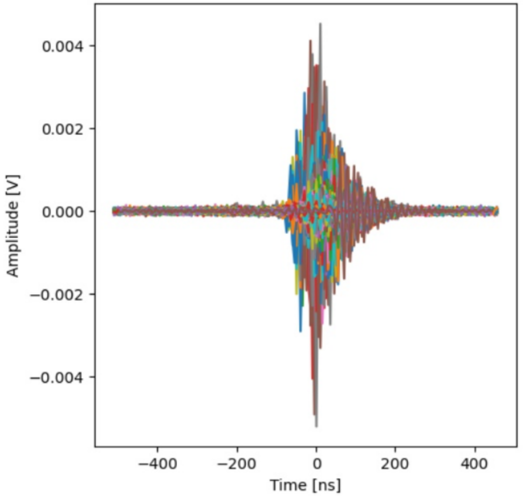
- **End goal:** Plug data in, press "magic button" and get full reconstruction

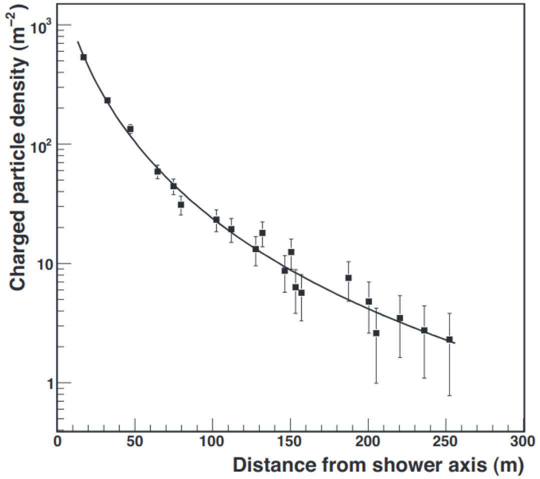
Summary

- Cosmic ray induced air showers produce radio emission that can be measured by detectors like LOFAR
- Reconstructing air shower parameters using all available information is a challenging task
- Information Field Theory is a possible solution



Thank you!

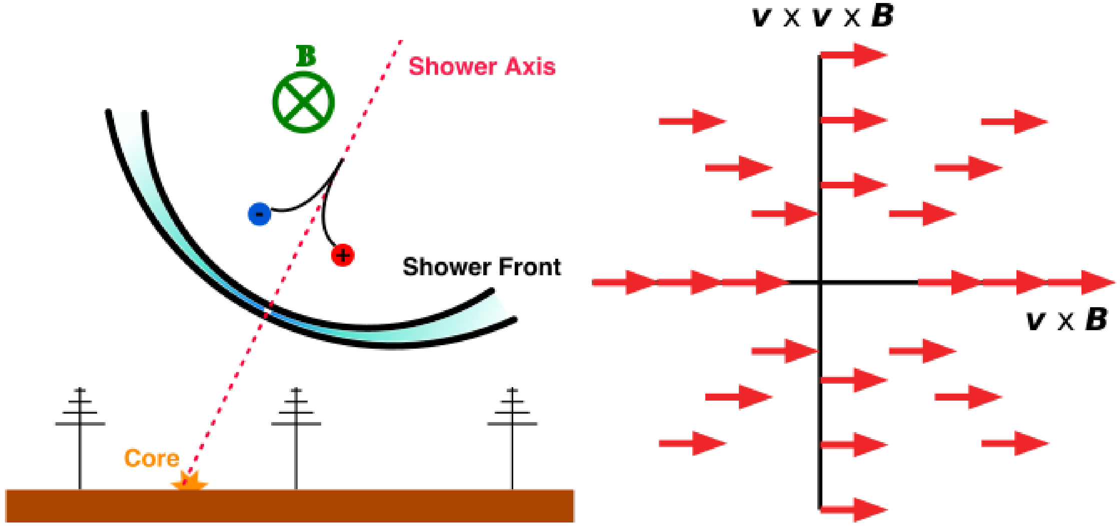




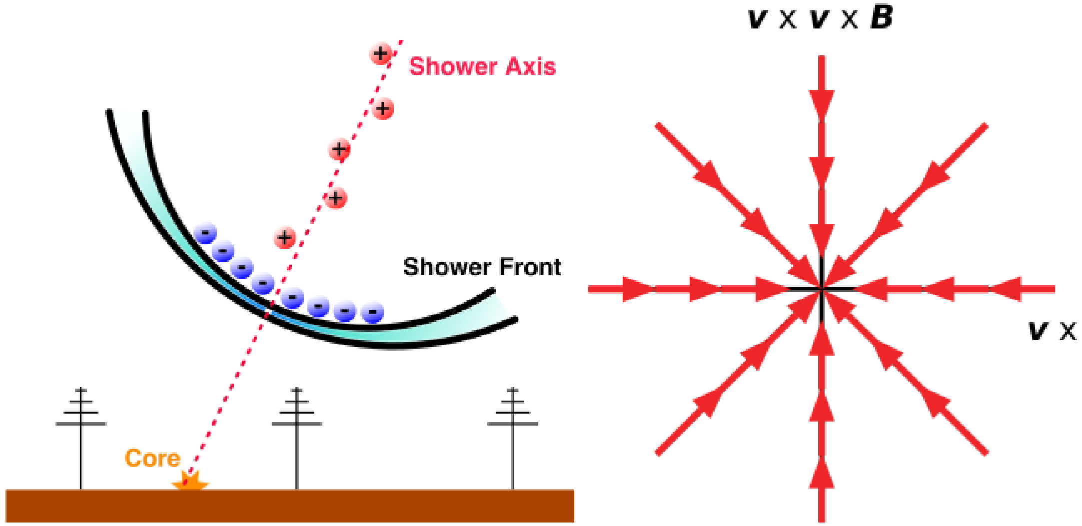
Radio emission from air showers

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

T. Huege, Phys. Rep. 620, 1 (2016)

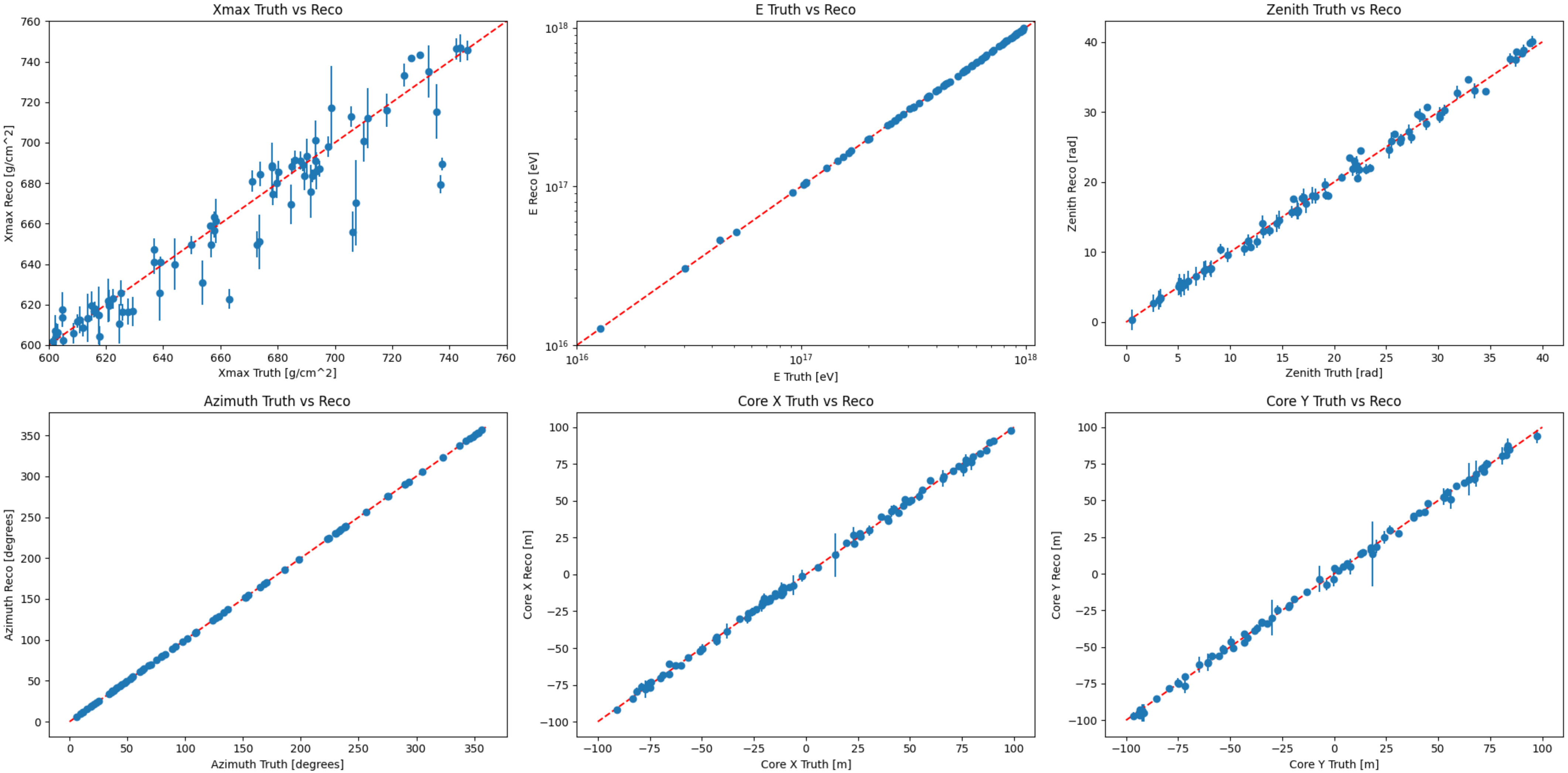


Geomagnetic emission



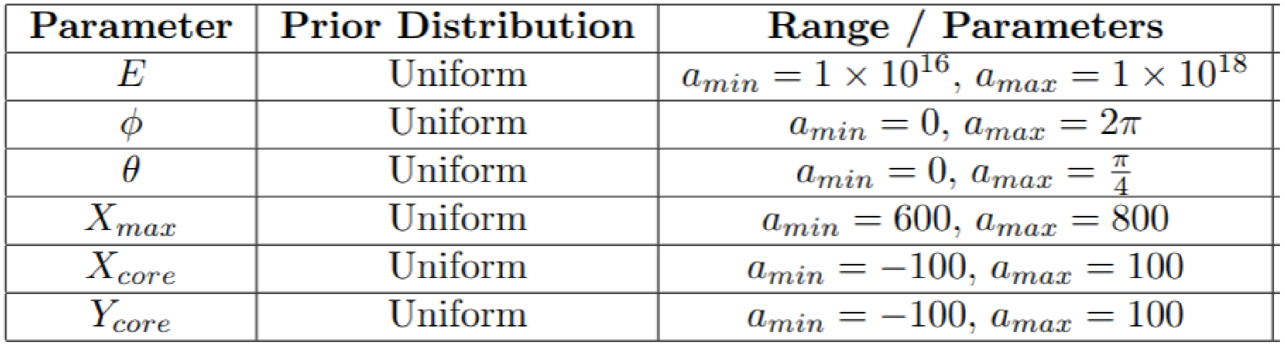
Askaryan effect

~ 100 reconstructions
for abs(core_truth-core_reco) < 10 m

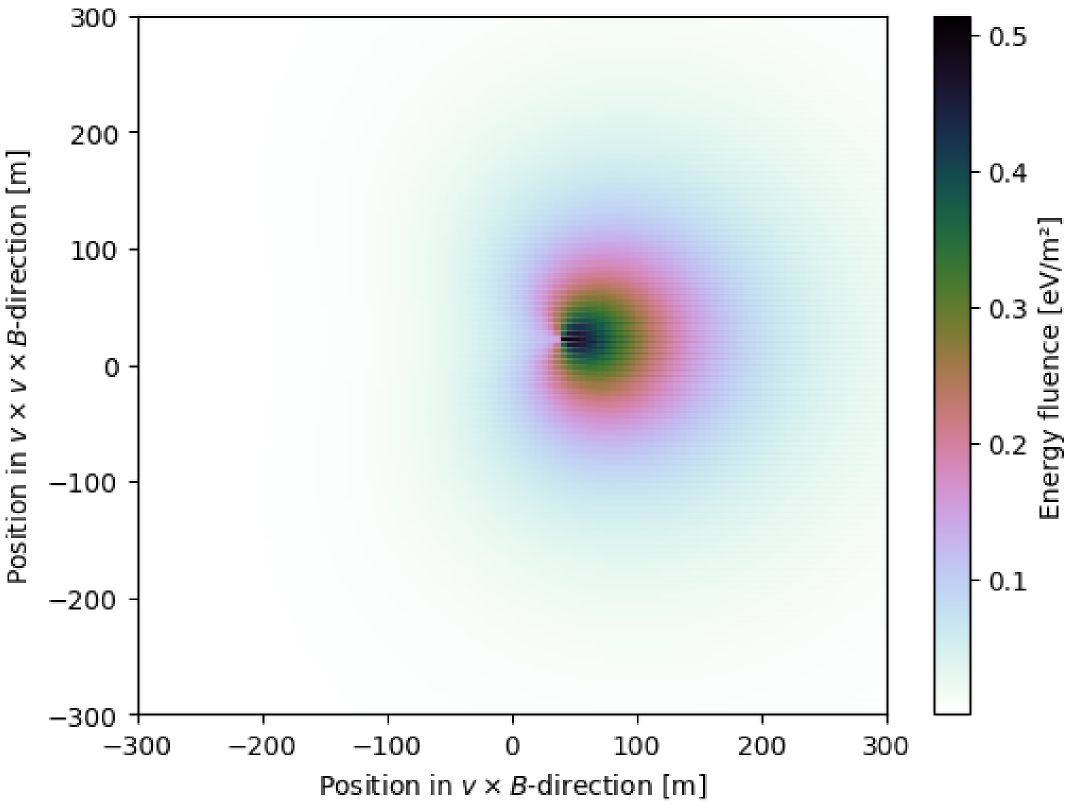


LDF parameterization

- LDF model based on emission mechanisms (geomagnetic and charge excess)
- https://github.com/cg-laser/geoceLDF
- Parameters: Xmax, E, zenith, azimuth, core (X,Y)



Parameter	Prior Distribution	Range / Parameters
E	Uniform	$a_{min} = 1 \times 10^{16}$, $a_{max} = 1 \times 10^{18}$
ϕ	Uniform	$a_{min} = 0$, $a_{max} = 2\pi$
θ	Uniform	$a_{min} = 0$, $a_{max} = \frac{\pi}{4}$
X_{max}	Uniform	$a_{min} = 600$, $a_{max} = 800$
X_{core}	Uniform	$a_{min} = -100$, $a_{max} = 100$
Y_{core}	Uniform	$a_{min} = -100$, $a_{max} = 100$



Air shower detection with LOFAR

The LOw-Frequency-ARray