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Semi-parametric Air Shower Shape Reconstruction with Information Field Theory

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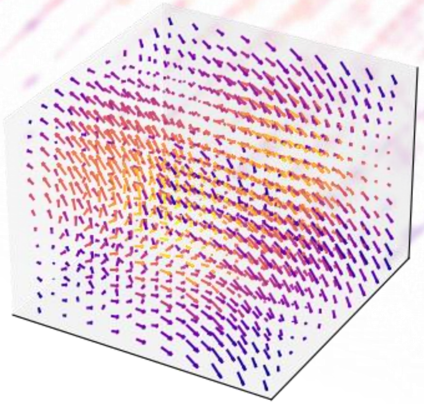
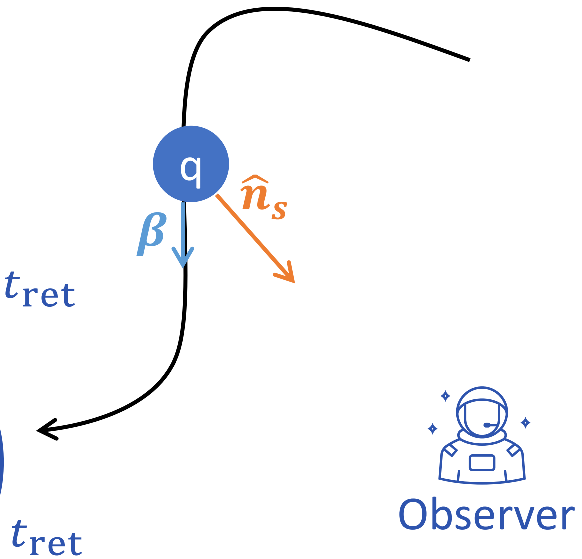


NIFTy

Liénard–Wiechert potential

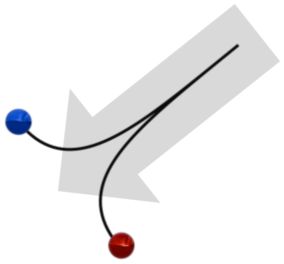
- $A^{\mu}(\boldsymbol{x}_{\text{obs}}, t_{\text{obs}}) = \int \frac{j^{\mu}}{n_{\text{eff}}(\boldsymbol{x}_{\text{obs}},\boldsymbol{x}')|\boldsymbol{x}_{\text{obs}}-\boldsymbol{x}'|} \delta\left(t' - t_{\text{obs}} + \frac{n_{\text{eff}}(\boldsymbol{x}_{\text{obs}},\boldsymbol{x}')}{c} |\boldsymbol{x}_{\text{obs}} - \boldsymbol{x}'|\right) \mathrm{d}^4 x'$

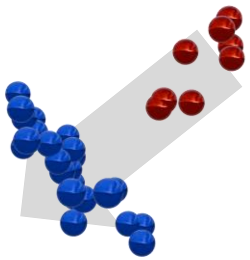
- Reproduces Liénard-Wiechert potential for point charges:



$$\varphi(\boldsymbol{x}_{\text{obs}}, t_{\text{obs}}) = \left(\frac{q}{n_{\text{eff}}(1 - n_{\text{eff}}\widehat{\boldsymbol{n}}_{\boldsymbol{s}} \cdot \boldsymbol{\beta})|\boldsymbol{x}_{\text{obs}} - \boldsymbol{r}_{\boldsymbol{s}}|}\right)_{t_{\text{ret}}}$$

$$A^{i}(\boldsymbol{x}_{\text{obs}}, t_{\text{obs}}) = \left(\frac{q\boldsymbol{\beta}}{n_{\text{eff}}(1 - n_{\text{eff}}\widehat{\boldsymbol{n}}_{\boldsymbol{s}} \cdot \boldsymbol{\beta})|\boldsymbol{x}_{\text{obs}} - \boldsymbol{r}_{\boldsymbol{s}}|}\right)_{t_{\text{ret}}}$$





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Differentiable Programming with JAX

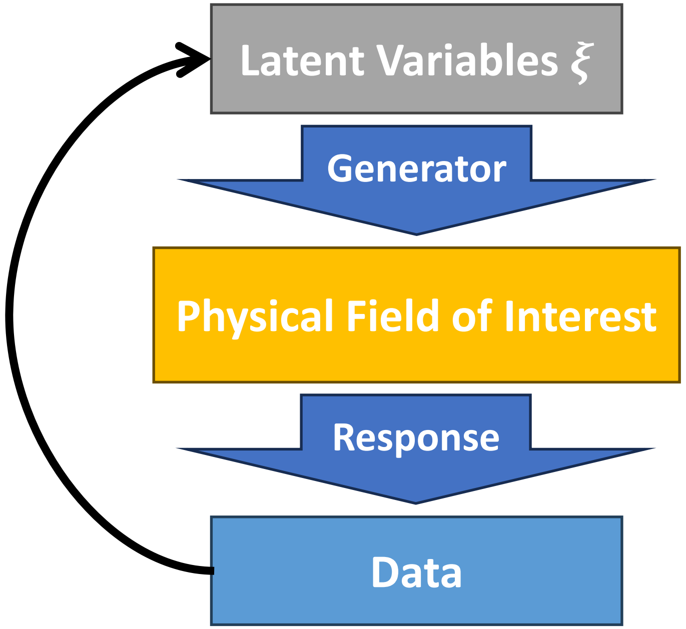
- Python library for high-performance numerical computing
- Numpy-like interface
- Runs on CPU and GPU
- Automatic vectorization
- Autograd: Differentiable python code
- Just-In-Time compilation: Speed-up of 1,000x possible

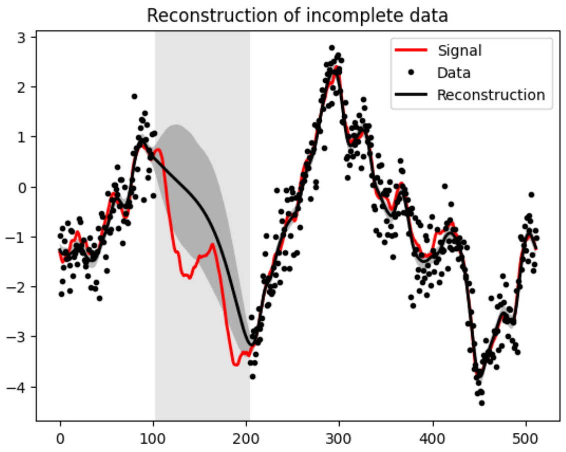
→ Key component of this analysis

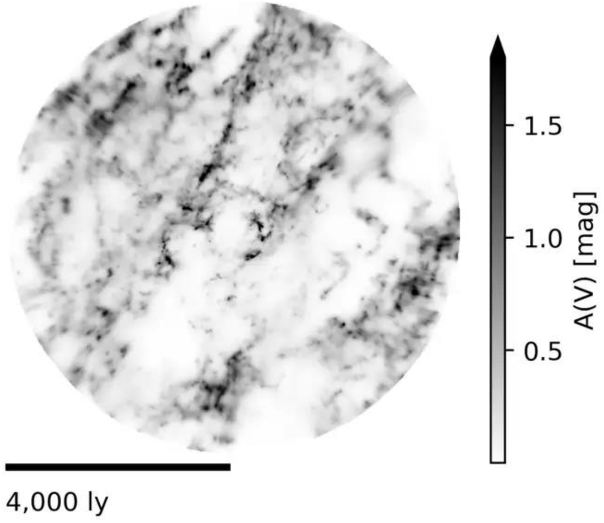
Information Field Theory

- Bayesian framework for large numbers of degrees of freedom
- Continuous fields ↔ discrete representations
- Statistical fit with variational inference
  → Approximate posterior
- Learn correlation structures

Inference with NIFTY



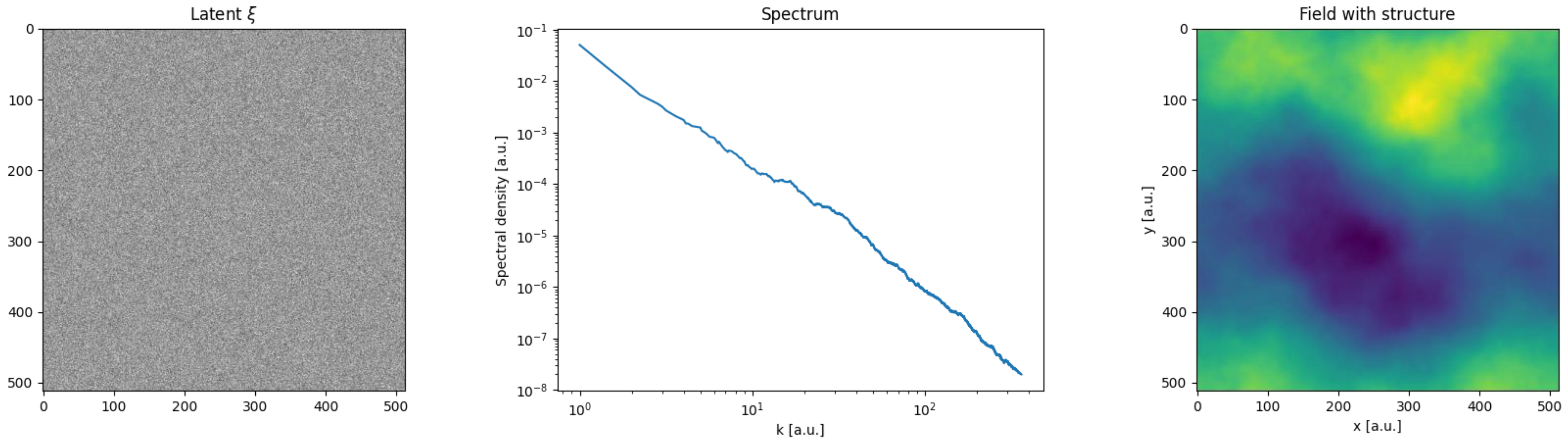




https://arxiv.org/abs/2308.01295

Modeling structures

- Latent variables ξ: Zero-centered, unit-width Gaussians
- Impose correlation structure: Neighbors talk to each other
  - Convolve ξ with spectrum → spectrum can be inferred as well
  - Different spectra for subspaces
- Include other physical priors at this stage

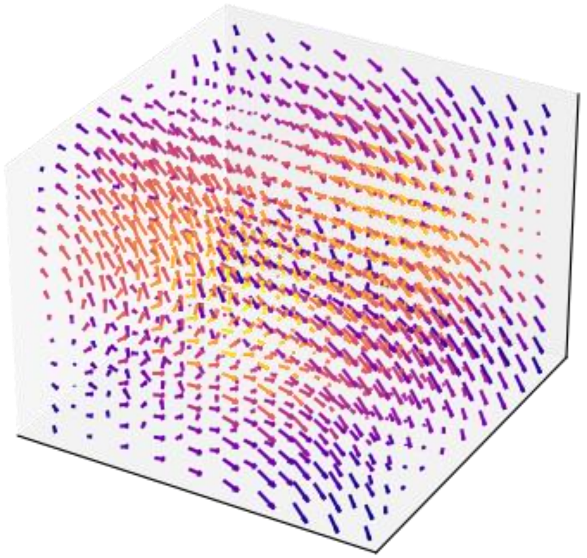


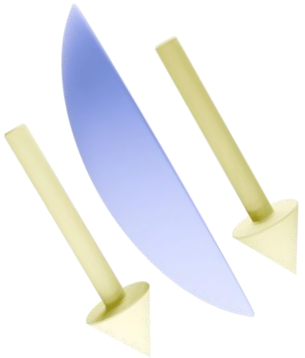
Shower model

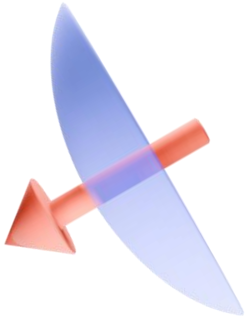
- Model as binned voxels:
  - q: Charge in space, shape (T, X, Y, Z)
  - $\boldsymbol{\beta}$: Drift velocities, shape (T, X, Y, Z, 3)
  - ρ: Electron density, shape (T)

  } non-parametric

  - exploiting e.g., radial symmetry possible
  - Scalar parameters
- Drift current: $q\boldsymbol{\beta}$
- Excess current: $q\rho\boldsymbol{c}$







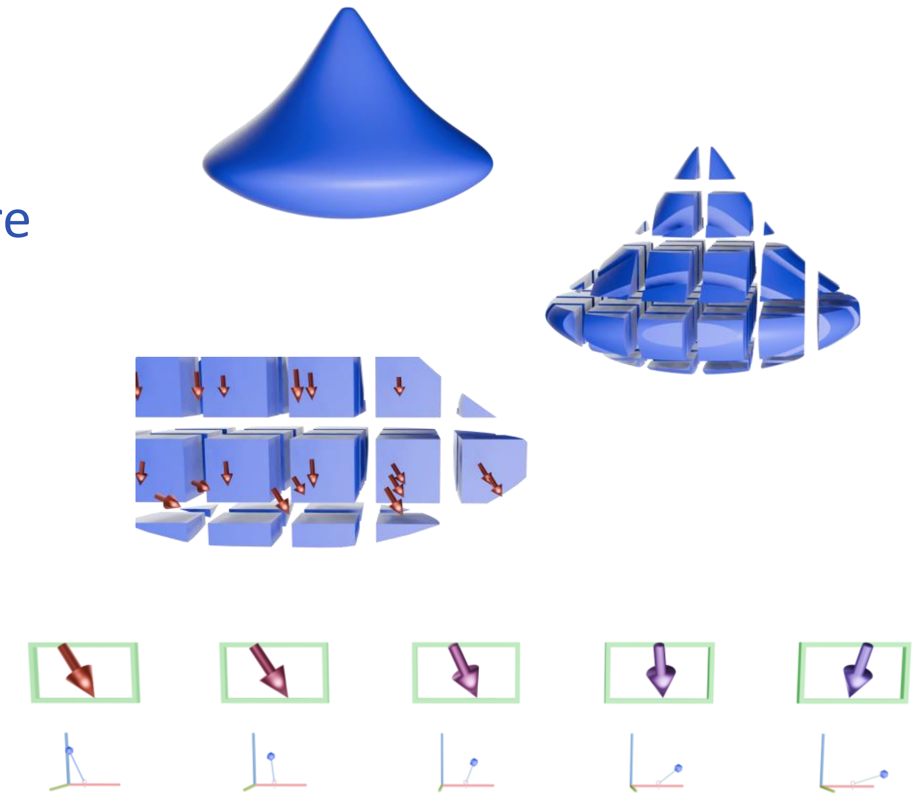
Forward Process

Shower frame:

- Model shower as a cuboid moving through atmosphere
- Divide cuboid into space-time voxels
- Voxels contents: superposition of point sources
- Bin observed $\boldsymbol{A}$ in time
- Subsample t_{ret}

Observer frame:

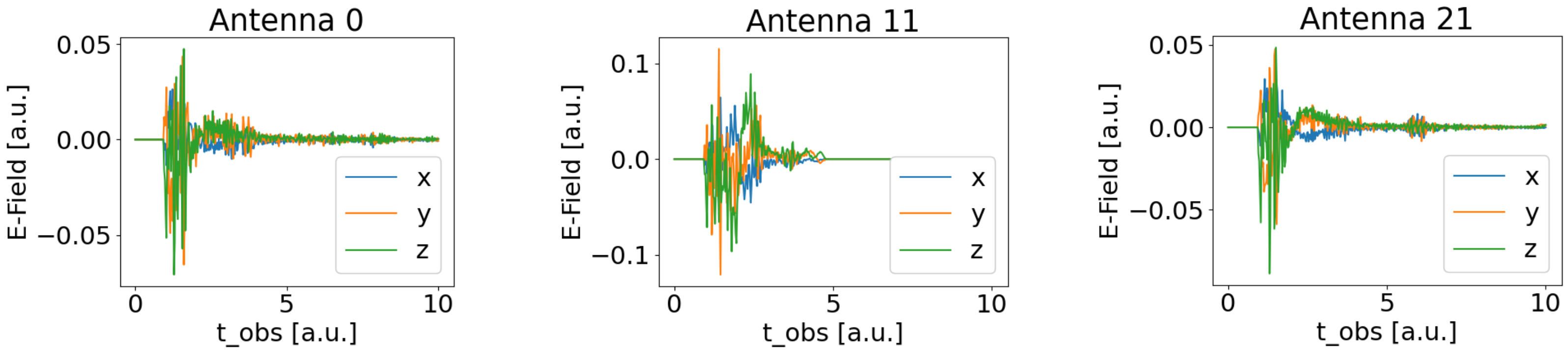
- $f(t_{\mathrm{obs}}) = \int f(t_{\mathrm{shower}}) \left|\frac{\mathrm{d}t_{\mathrm{obs}}}{\mathrm{d}t_{\mathrm{shower}}}\right| \mathrm{d}t_{\mathrm{shower}}$
- Calculate $\boldsymbol{E}$ numerically



In short: draw j^{μ} and calculate $\boldsymbol{E}$ for the observer

$\underbrace{\text{draw } j^{\mu}}_{\text{Generator}}$ and $\underbrace{\text{calculate } \boldsymbol{E}}_{\text{Response}}$

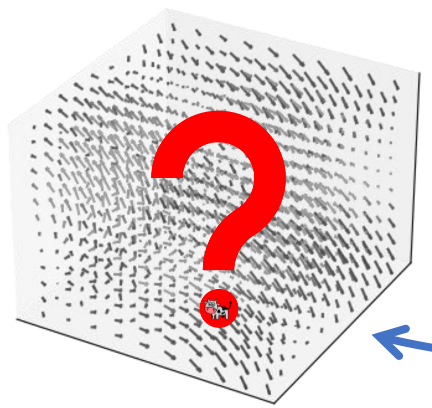
Testing the framework



Toy Model!

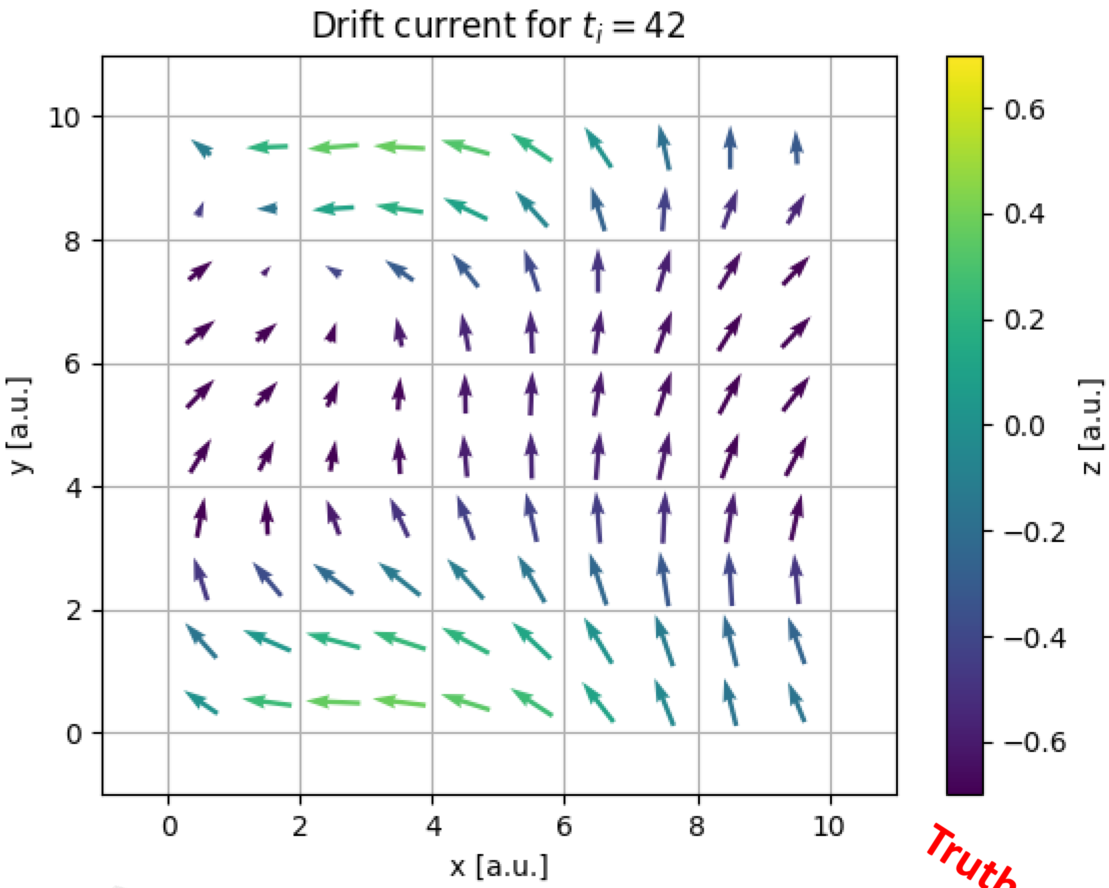
given these traces

- Filled the cuboid with random structure
- Used grid of 24 antennas
- Self-consistency check:
  →do we get out what we put in?

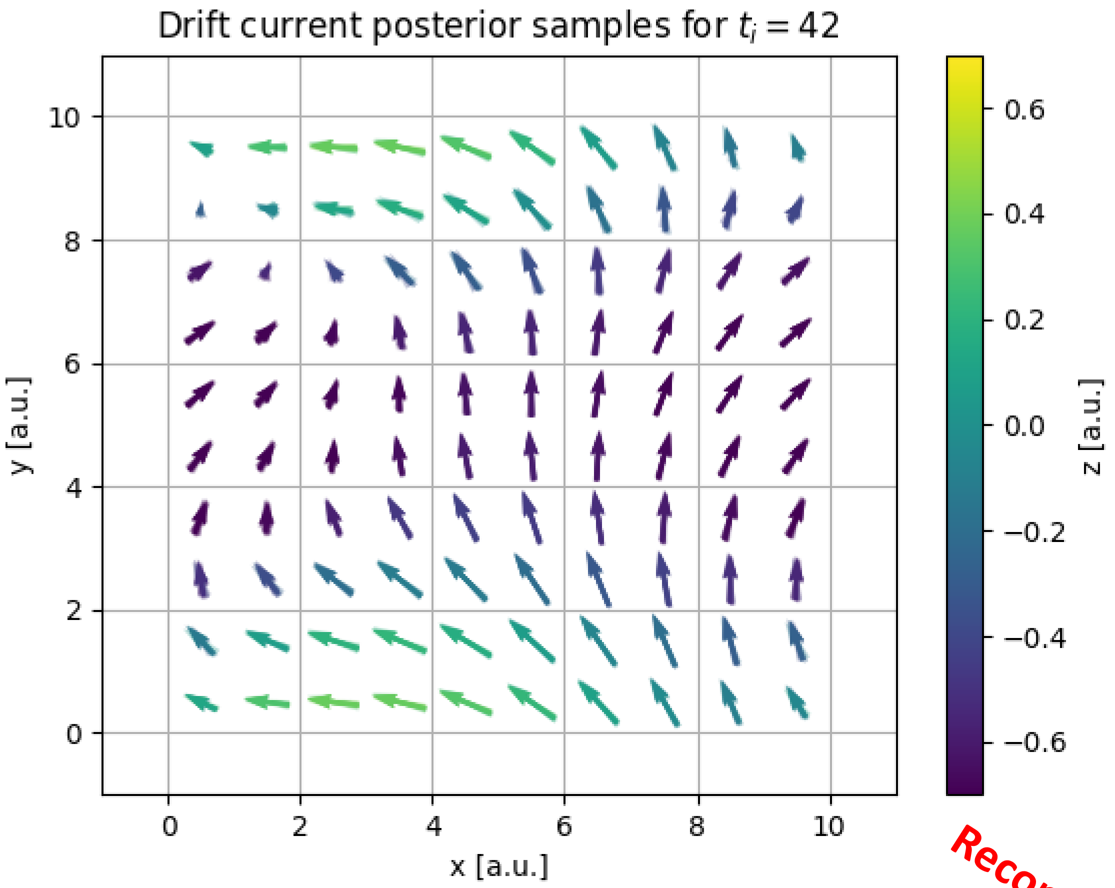


what does the shower look like?

Preliminary Results $q\beta$

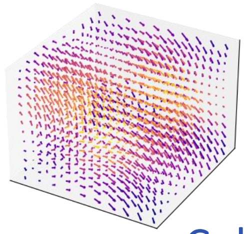


Truth



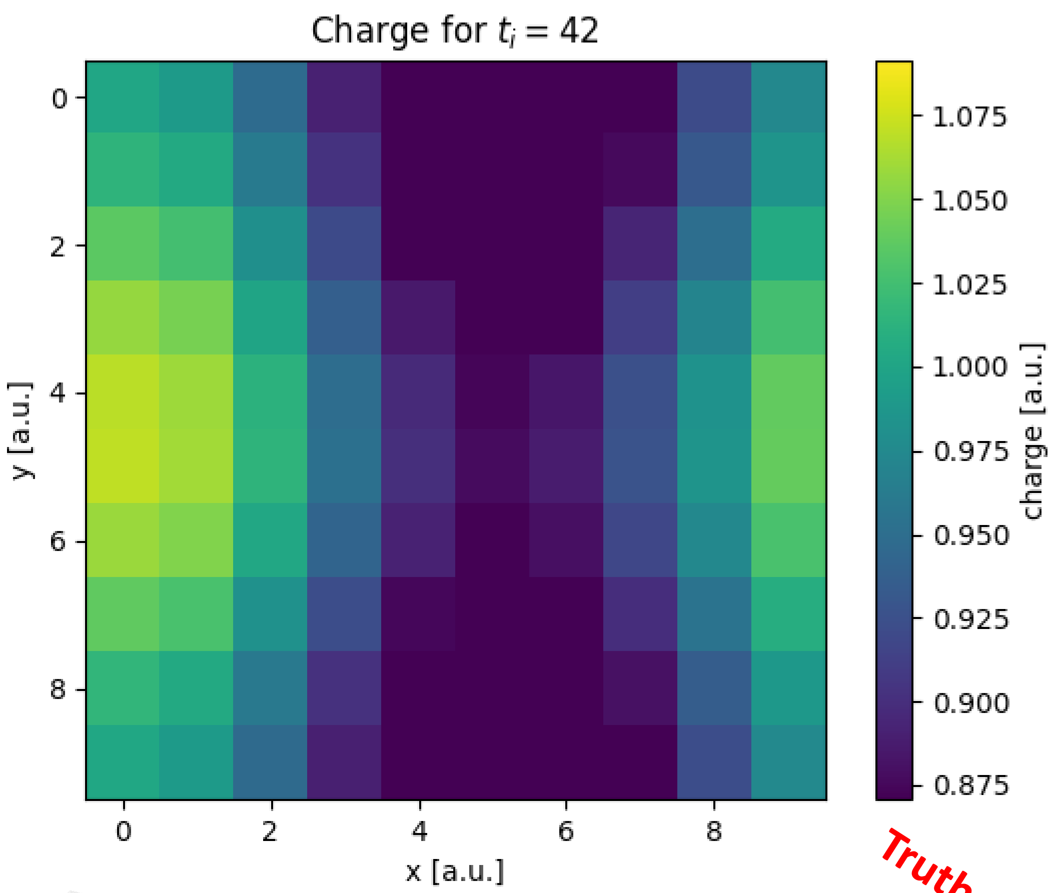
Reconstruction

Reconstruction includes uncertainties!

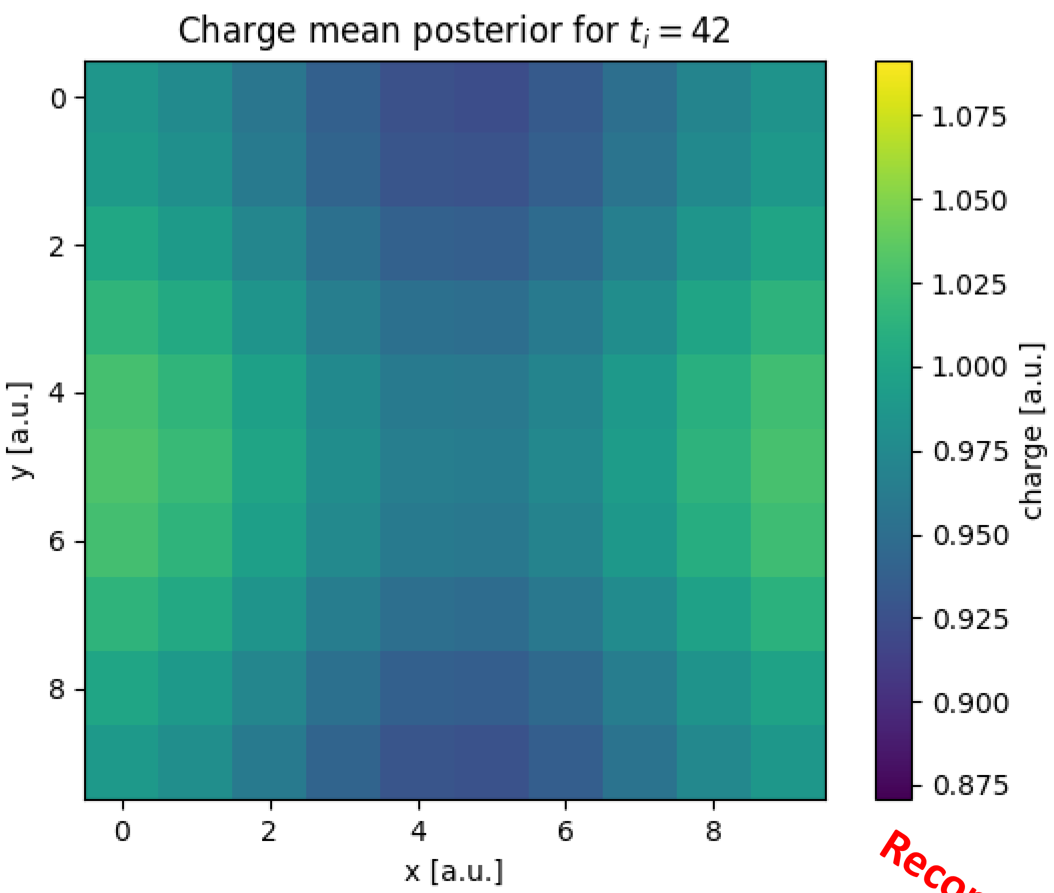


Cuboid slice at one point in time

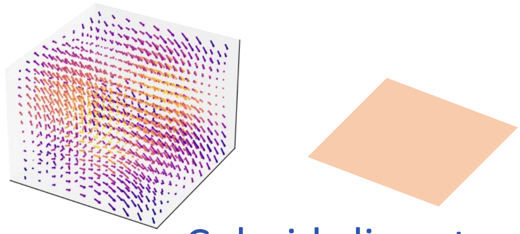
Preliminary Results q



Truth



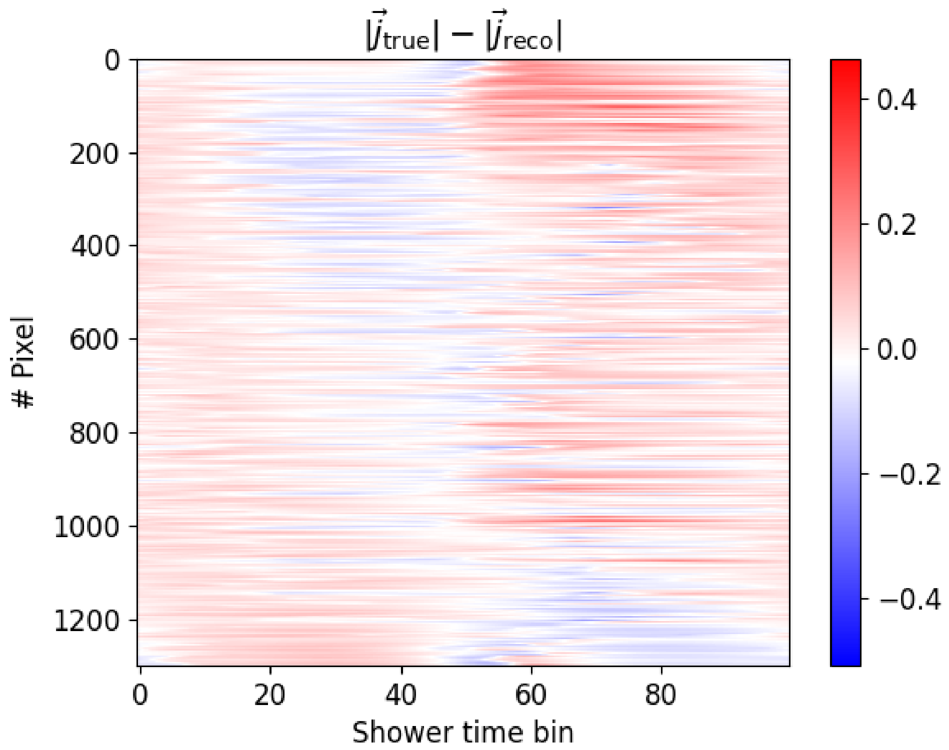
Reconstruction

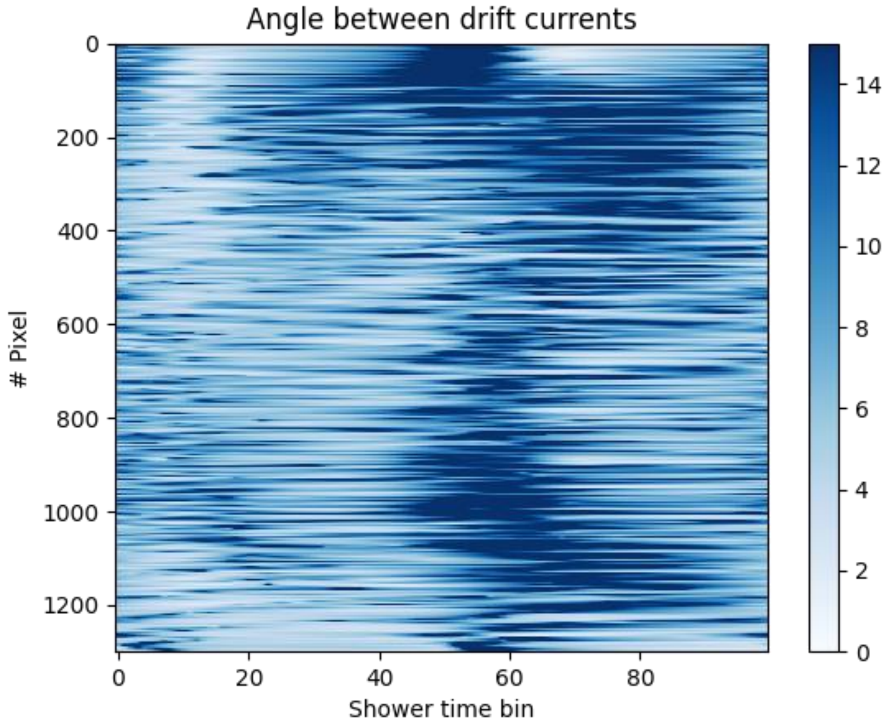


Cuboid slice at one point in time

Preliminary Results

- Overall reconstruction similar to truth
- Expected to improve with more stringent priors





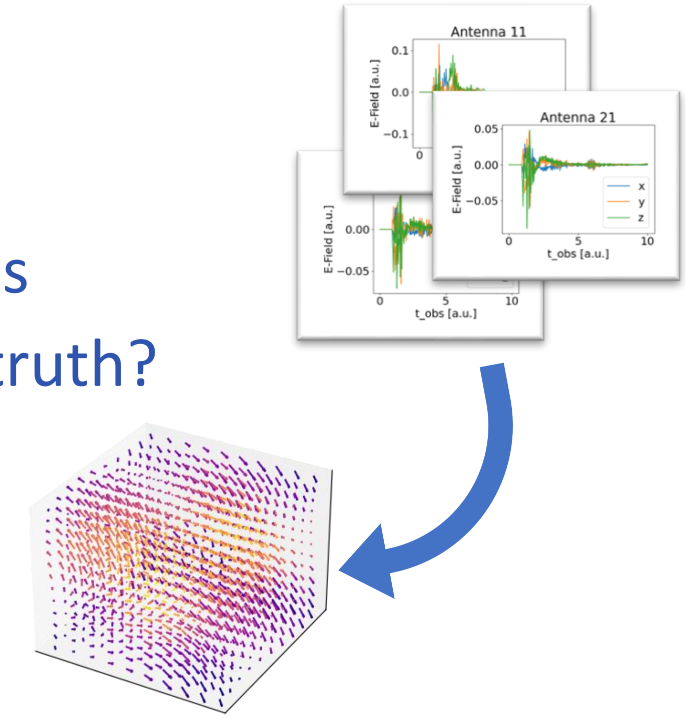
Currently investigating!

Summary

- Working prototype of a macroscopic air shower imaging algorithm
- Use of Information Field Theory to fit many voxels at once
- Sample posterior for uncertainty estimation

Next up:

- Expand parametrization → include physical assumptions
- Check self-consistency: How close is the output to the truth?
- Test physical scenarios: How flexible is the framework?
- How degenerate is the solution space?



- Application to simulated showers