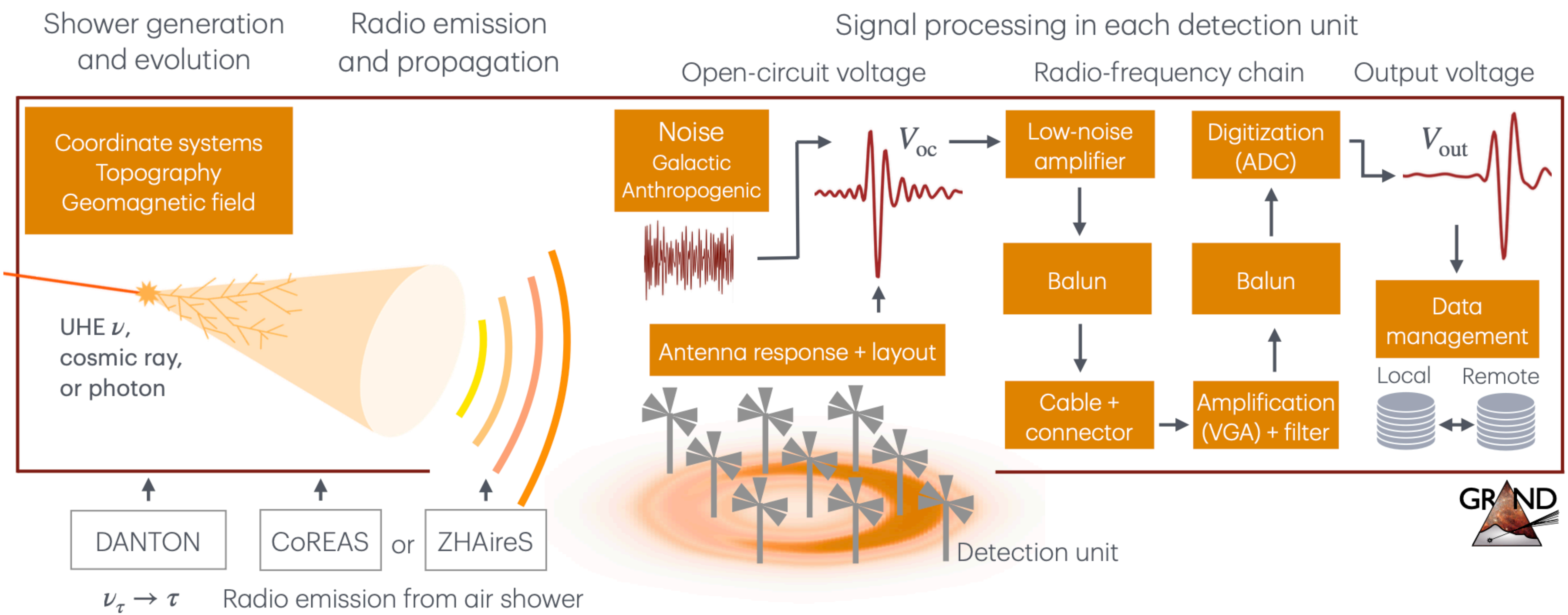
E-Field Reconstruction with Truncated Likelihood Ratio Estimation

Thomas McKinley - SFSU

For the GRAND Collaboration

GRANDlib Simulation Pipeline



[1] Grandlib: A simulation pipeline for the giant radio array for neutrino detection (grand). Computer Physics Communications, 308:109461, March 2025.

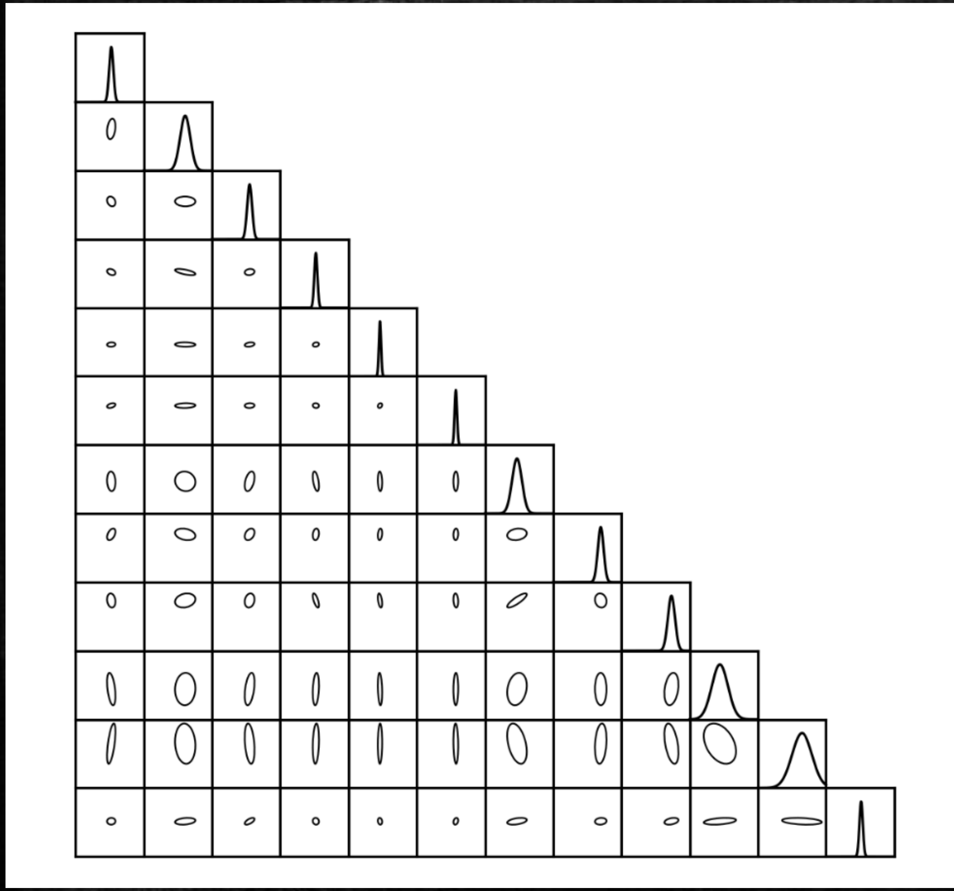
Electric Field Reconstruction for GRAND

- Use Simulation-Based Inference to detect UHECR signals in the heavily contaminated data from background noise.
- From read-out voltage, we can recreate the input electric field amplitude using the GRANDlib simulation pipeline.
- Based on realistic GRANDlib simulations. We can train a neural network through SBI to retrieve actual signals from the noisy data.

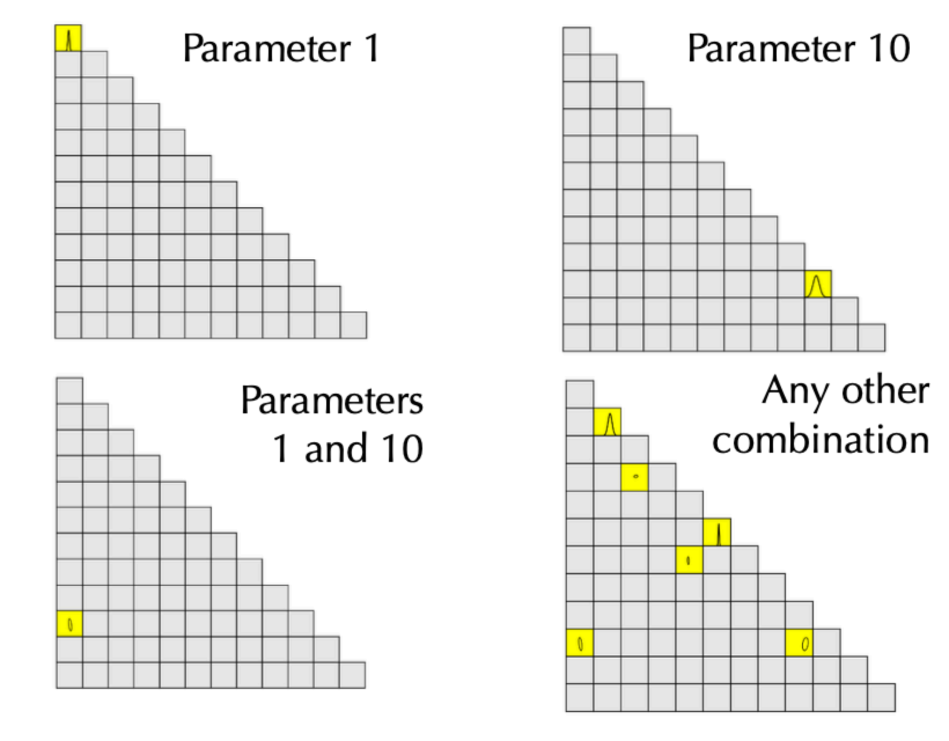
Swyft and Marginal Inference

Swyft through marginalization allows us to cherry-pick the parameters of interest.

Standard MCMC



Swyft



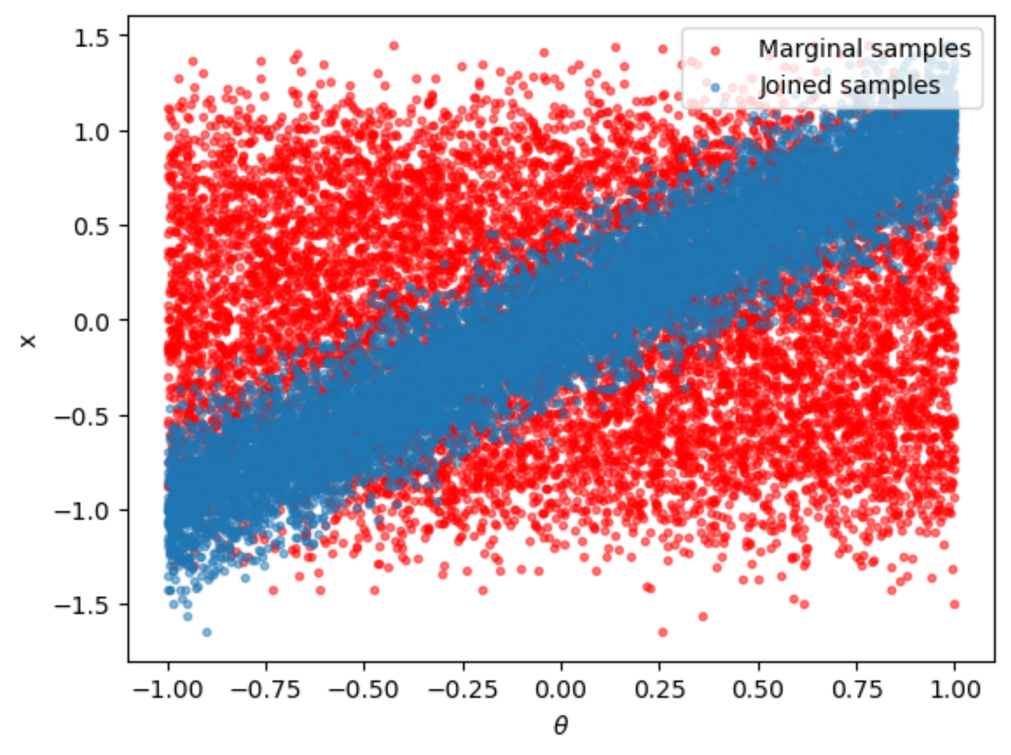
Credit for image and inspiration of the following slides is given to Christoph Weniger.

NRE Algorithm

Swyft uses Neural Ratio Estimation (NRE) for SBI.

$$r(x;\theta) \equiv \frac{p(x|\theta)}{p(x)} = \frac{p(\theta|x)}{p(\theta)} = \frac{p(x,\theta)}{p(x)p(\theta)}$$

$$x = \theta + \sigma$$



Generate training data:

Y = 1: Matching

$$p(x,\theta|Y=0) = p(x,\theta)$$

Y = 0: Scrambled (Marginal)

$$p(x,\theta|Y=1) = p(x)p(\theta)$$

Credit: Noemi Anau Montel, Alex Cole, Benjamin Kurt Miller, Christoph Weniger

NRE Cont

Initialize neural net:

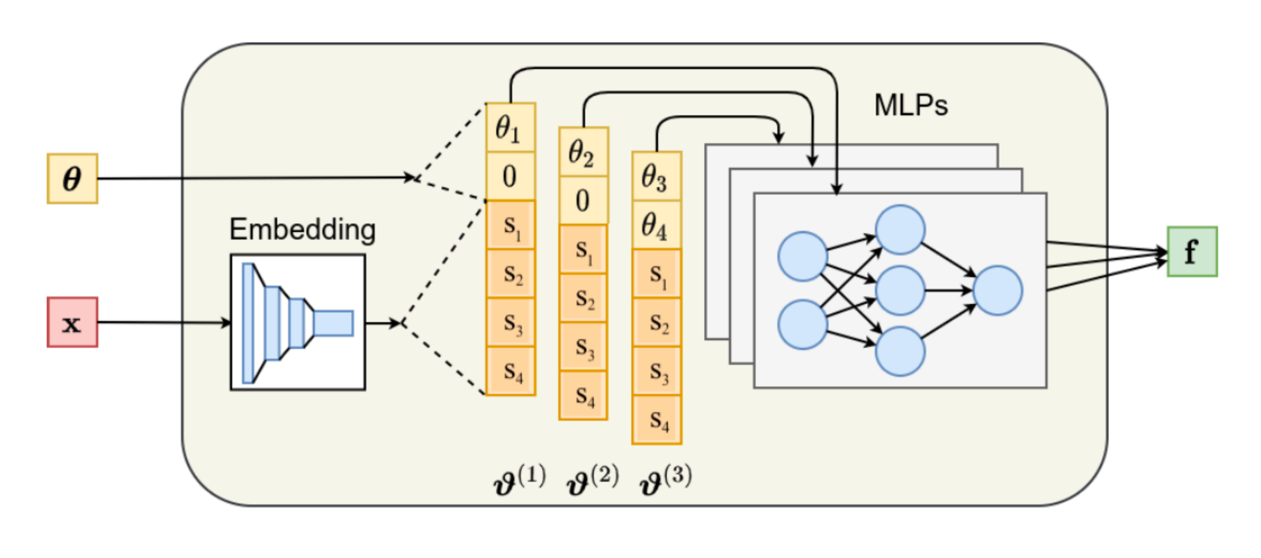
$$f_\phi(x, \theta)$$

$$\mathcal{L}(\phi) = \sum_{i \in B} \ln\sigma(f_\phi(x_i, \theta_i)) + \ln\sigma(-f_\phi(x_i, \theta_{P(i)}))$$

After Training:

$$f_\phi(x, \theta) \approx \ln r(x; \theta) = \ln \frac{p(\theta|x)}{p(\theta)}$$

Sample Swyft Network



[2] Benjamin Kurt Miller, Alex Cole, Christoph Weniger, Francesco Nattino, Ou Ku, and Meiert W. Grootes. swyft: Truncated marginal neural ratio estimation in python. Journal of Open Source Software, 7(75):4205, 2022.

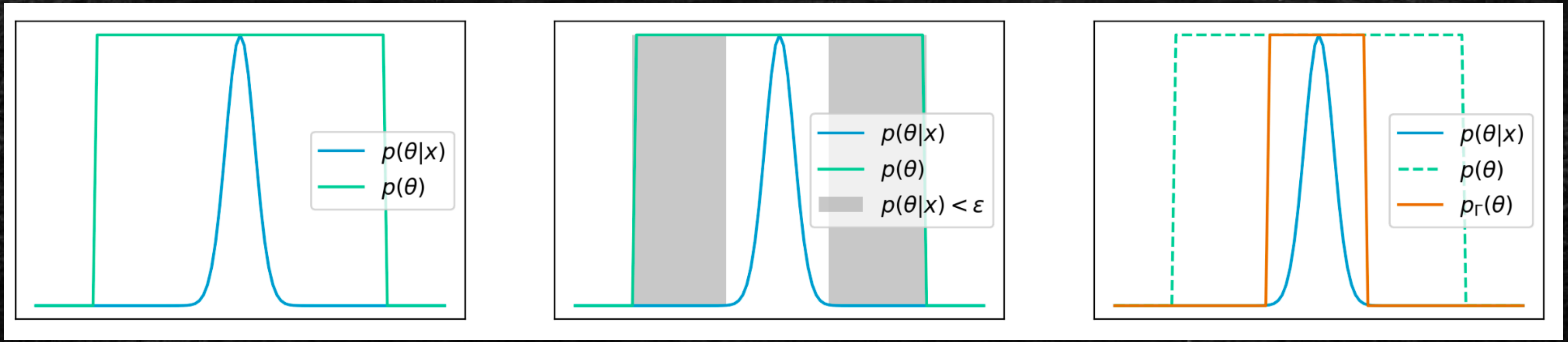
TMNRE

Use a truncated version of the prior for proposal function for marginal estimation.

$$p(x|\theta_1) = \int d\theta_2 ... d\theta_N p(x|\theta)\tilde{p}(\theta_2, ..., \theta_N)$$

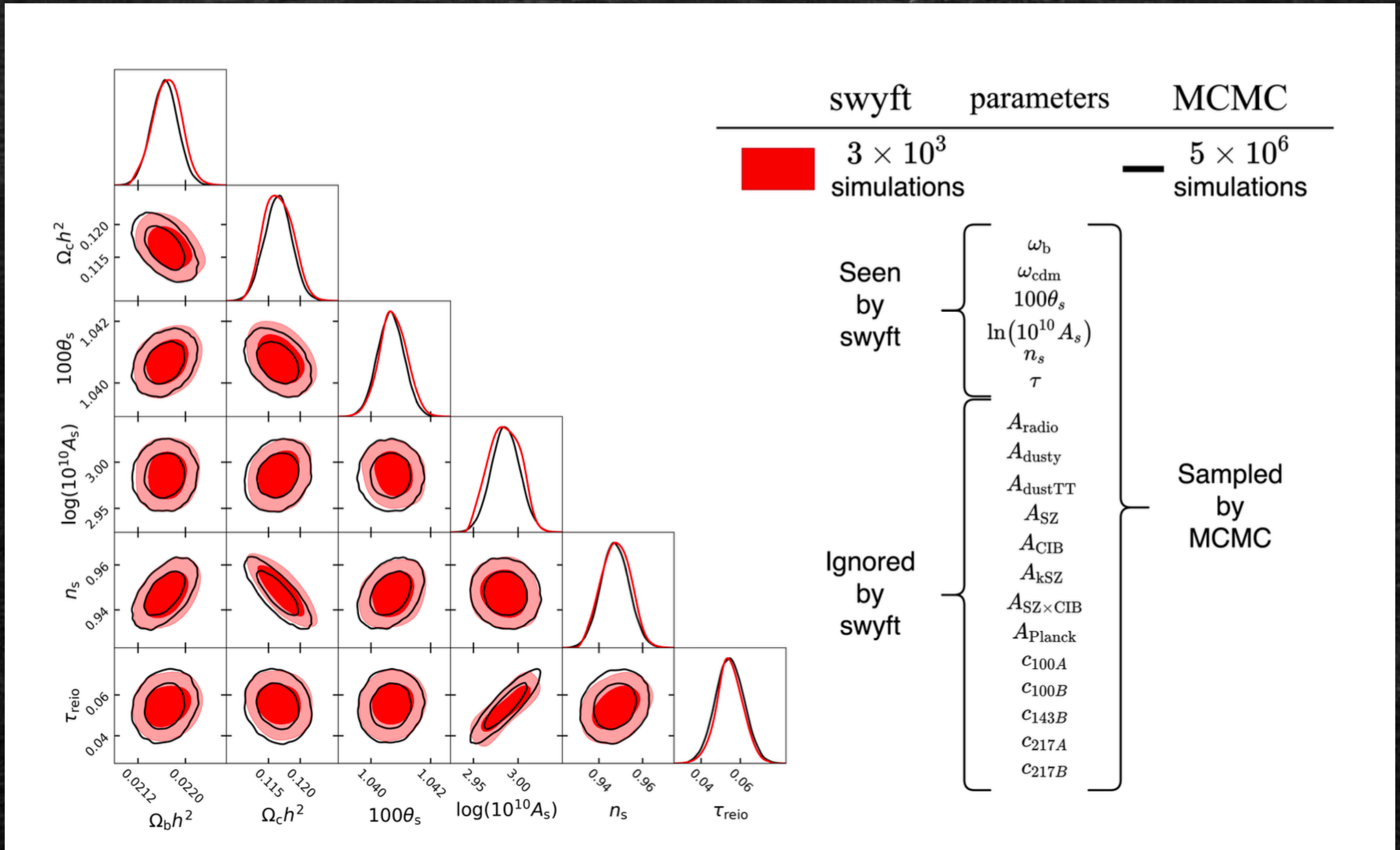
Indicator function for allowed truncation within Gamma.

$$\tilde{p}(\theta) = \frac{1}{Z}\mathbb{I}(\theta \in \Gamma)p(\theta)$$



[2] Benjamin Kurt Miller, Alex Cole, Christoph Weniger, Francesco Nattino, Ou Ku, and Meiert W. Grootes. swyft: Truncated marginal neural ratio estimation in python. Journal of Open Source Software, 7(75):4205, 2022.

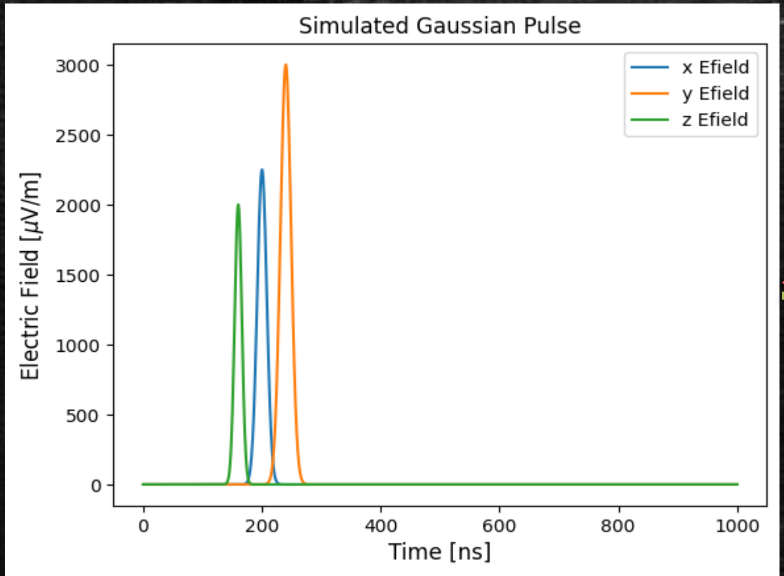
Why Swyft? Cosmological Parameter Example

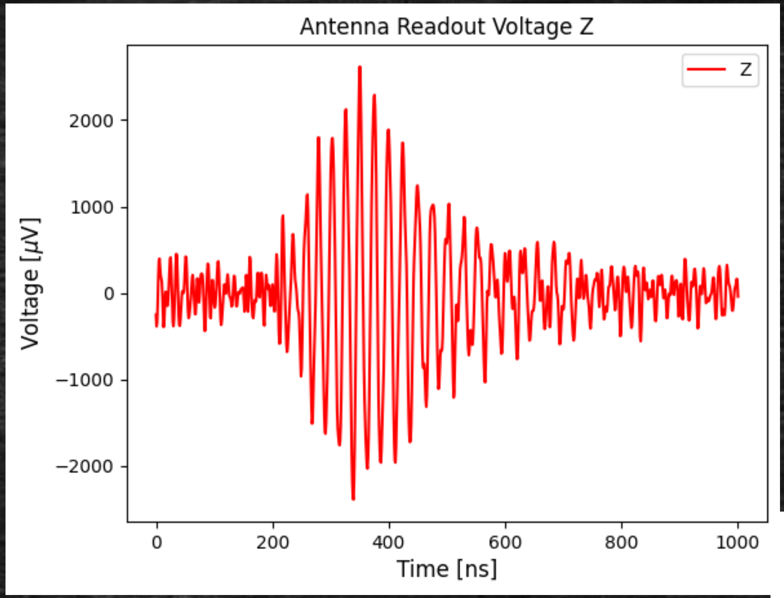


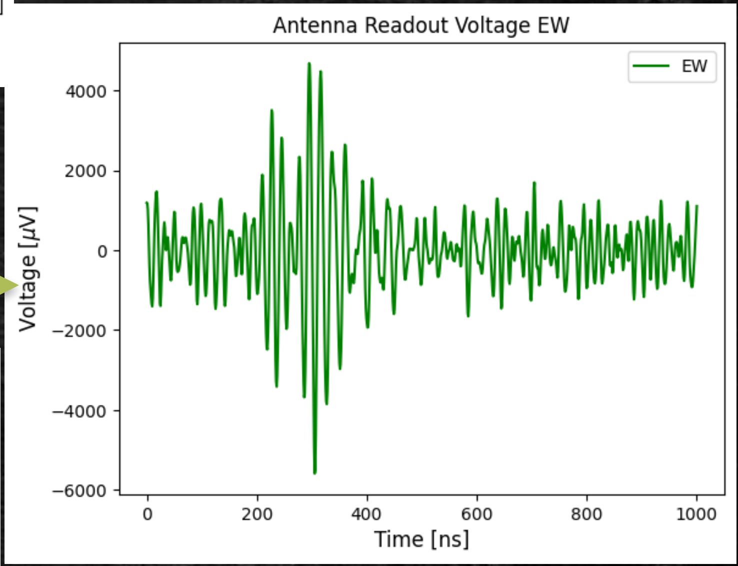
[2] Benjamin Kurt Miller, Alex Cole, Christoph Weniger, Francesco Nattino, Ou Ku, and Meiert W. Grootes. swyft: Truncated marginal neural ratio estimation in python. Journal of Open Source Software, 7(75):4205, 2022.

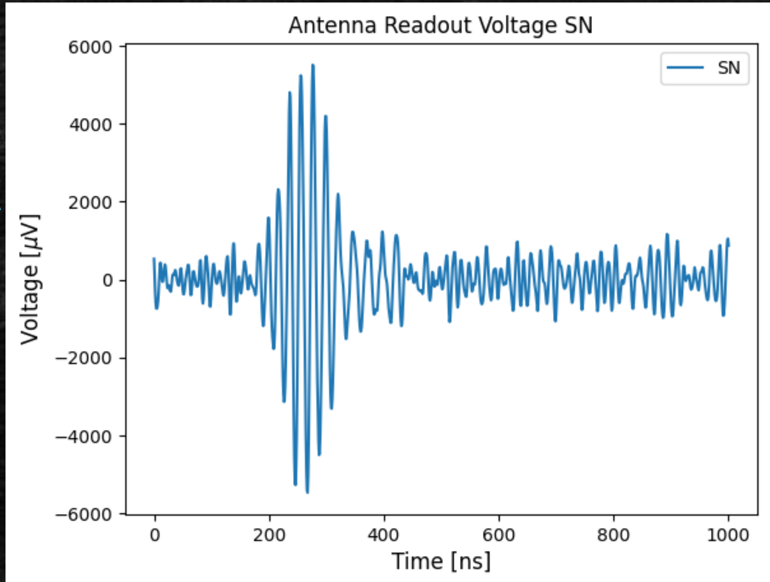
Voltage Simulator

9 primary parameters:
Amplitude, Sigma, Mu for each direction.









RF Chain! Coordinate transformation,
9 secondary parameters!

Swyft Implementation

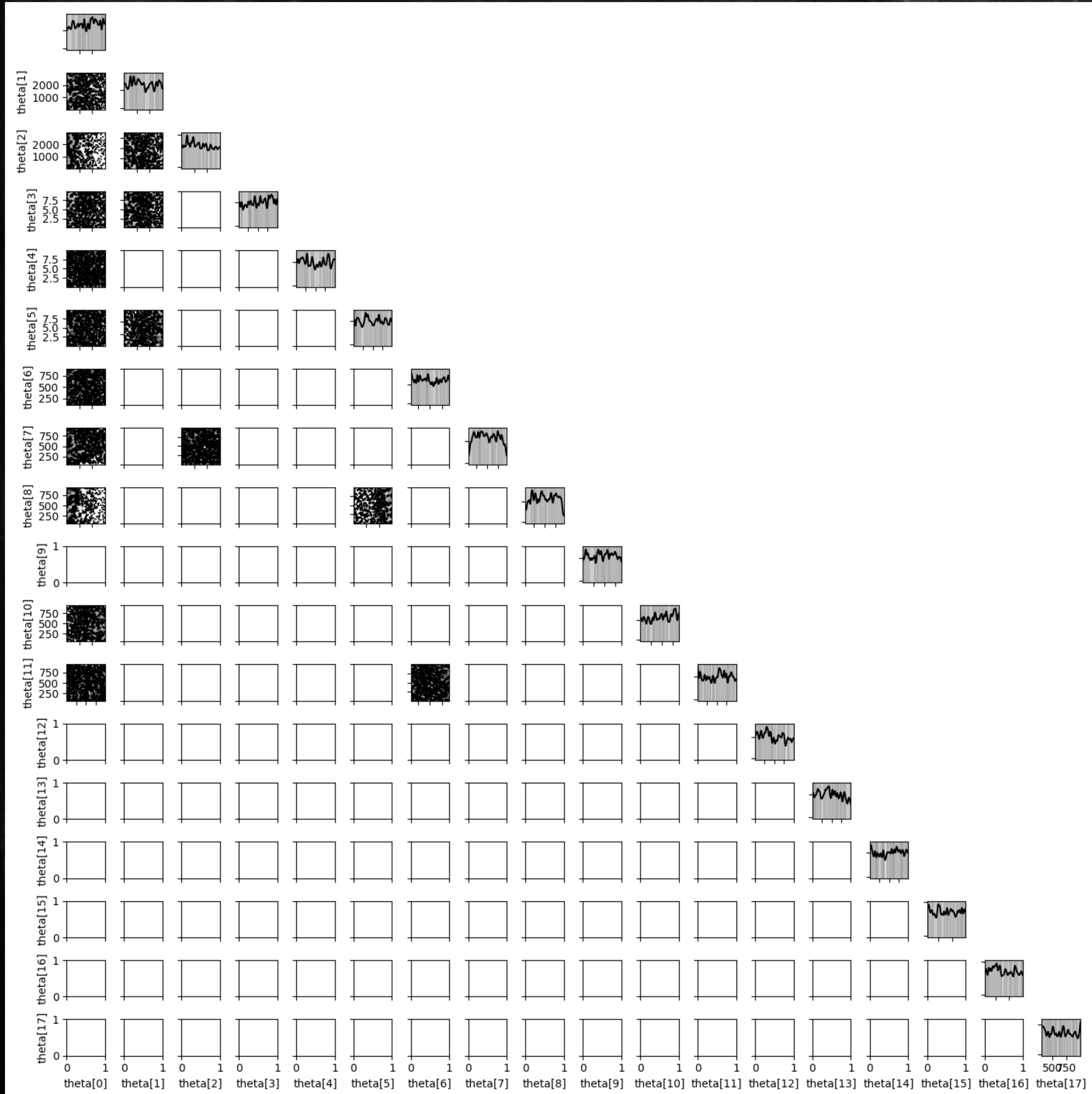
Our Swyft network was constructed following the tutorials.

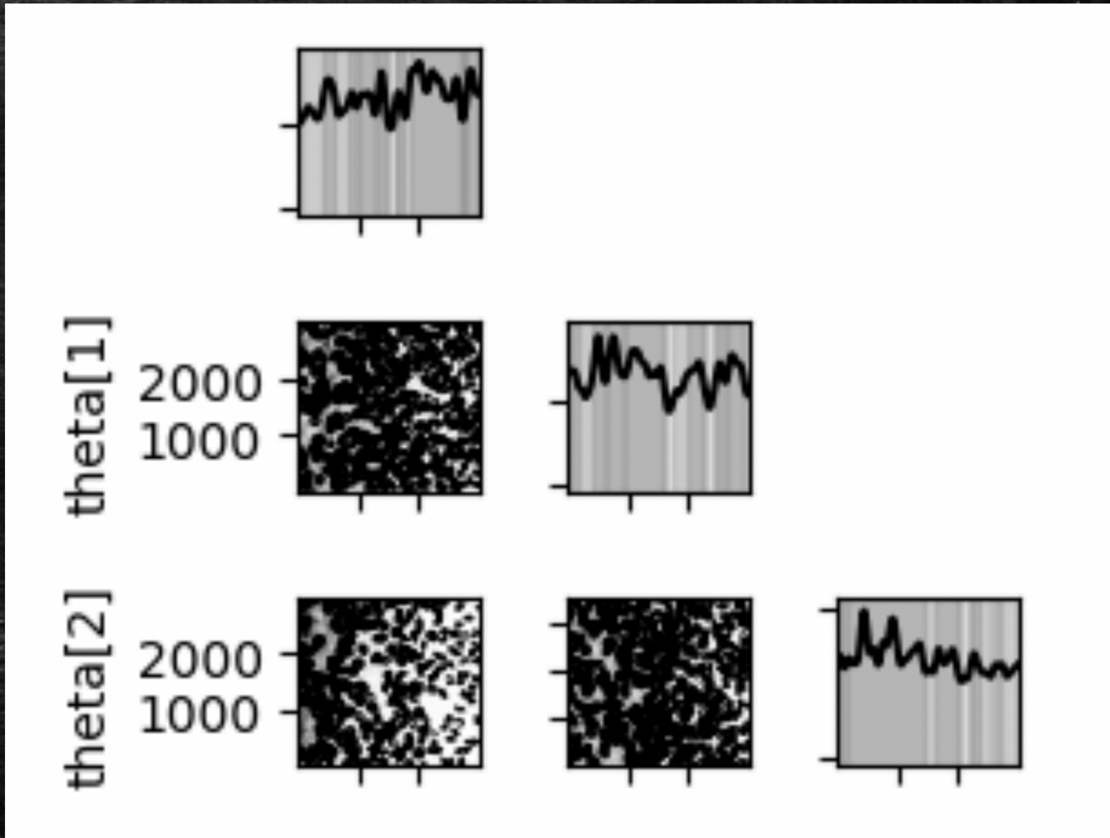
1. We generate the training data, x, and draw θ_i .
2. We establish an inference network to estimate ratios of the form:

$$r(x;\theta_i) = \frac{p(x,\theta_i)}{p(x)p(\theta_i)}$$

3. Data has dimensions of the number of time-bins by 3.
4. Training commences.
5. We finally evaluate our inference network by comparing to the prior sample of the drawn θ_i's.

SWYFT and E-field Reconstruction





Giant Radio Array for Neutrino Detection

Future Goals

- Get network working! Truncation!
- Gaussian pulse is a rough approximation for electric field. Plan to use physically motivated simulators that better approximate real EM Showers.
- Directly implement our eventual working network into the GRANDlib pipeline.