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Electric Field Reconstruction with Information Field Theory

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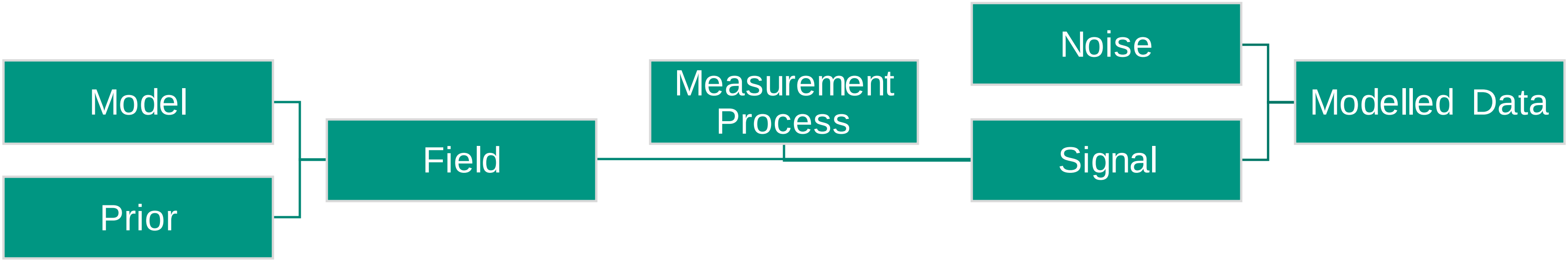
Information Field Theory – In Practice

- Define Measurement Process
- Define Field model
  - Set adequate priors
- Define Noise

→ IFT model – ready for variational inference



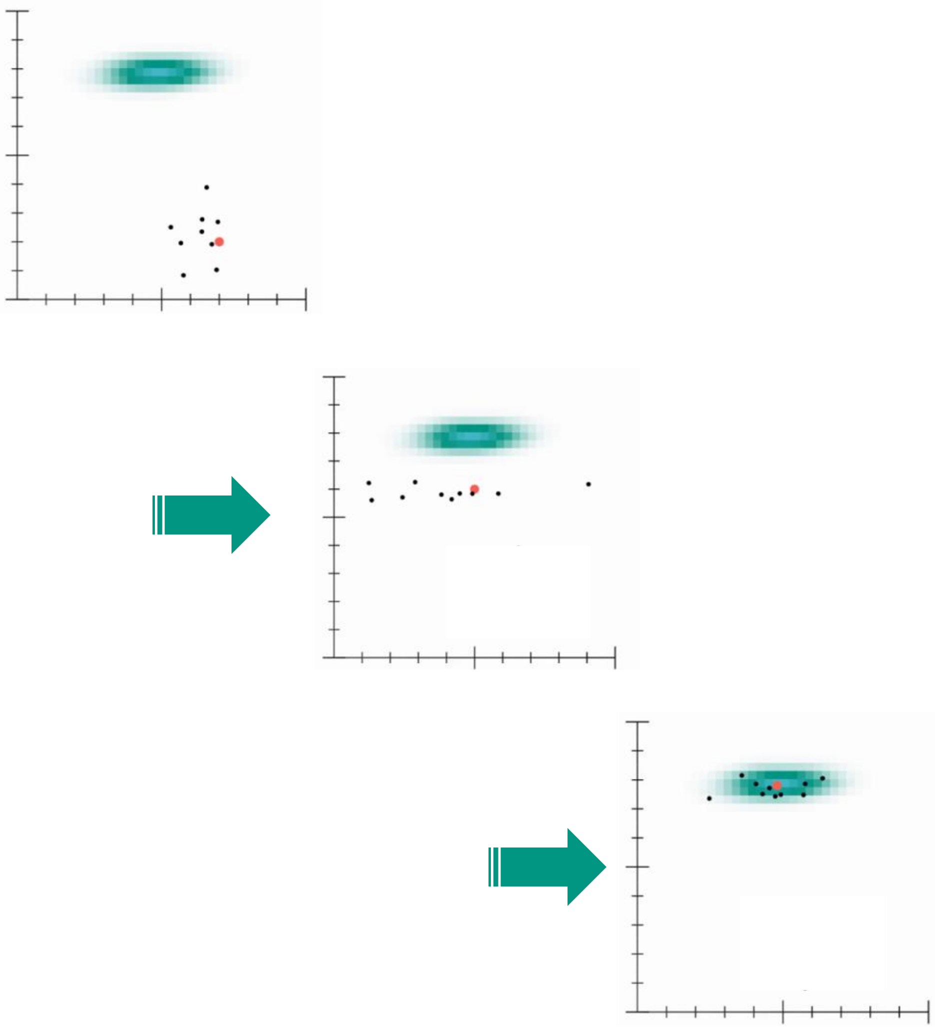
Information Field Theory: Metric Gaussian Variational Inference

- Bayes Theorem: $P(\theta|d) = \frac{P(d|\theta)P(\theta)}{P(d)}$

- Variational Inference:
  - Approximate posterior with known distribution

- Iteratively:
  - Draw samples
  - Approximate covariance
  - Minimize distance between distributions

➔ Samples from Posterior



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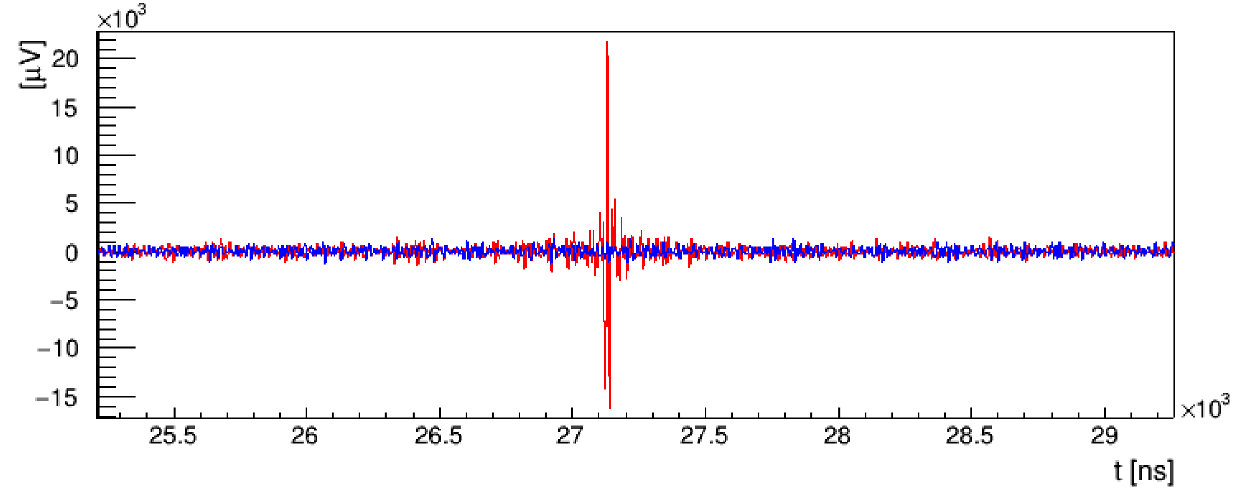
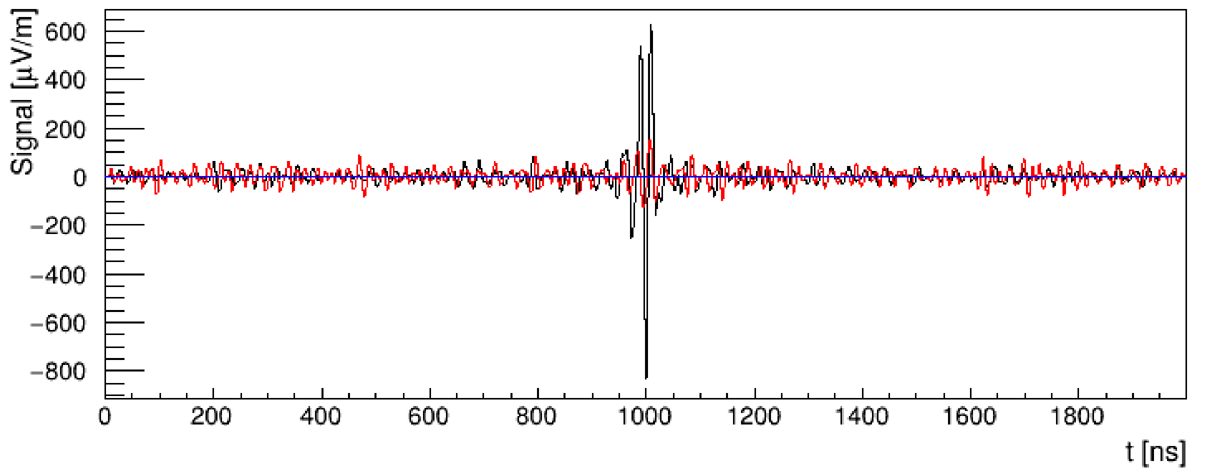
“Classical” reconstruction

- Preprocessing (ADC → V)
- Reconstruction of electric field
  - Assume far field: $E_r = 0$
  - Solve: $\begin{pmatrix} V_1 \\ V_2 \end{pmatrix}(f) = \begin{pmatrix} H_\theta^1 & H_\varphi^1 \\ H_\theta^2 & H_\varphi^2 \end{pmatrix}_f \begin{pmatrix} E_\theta \\ E_\varphi \end{pmatrix}(f)$
- Calculate energy fluence
  - $\Phi_{\text{signal}} = \Phi_{\text{pulse}} - \Phi_{\text{noise}}$
- Energy / directional analysis are separate





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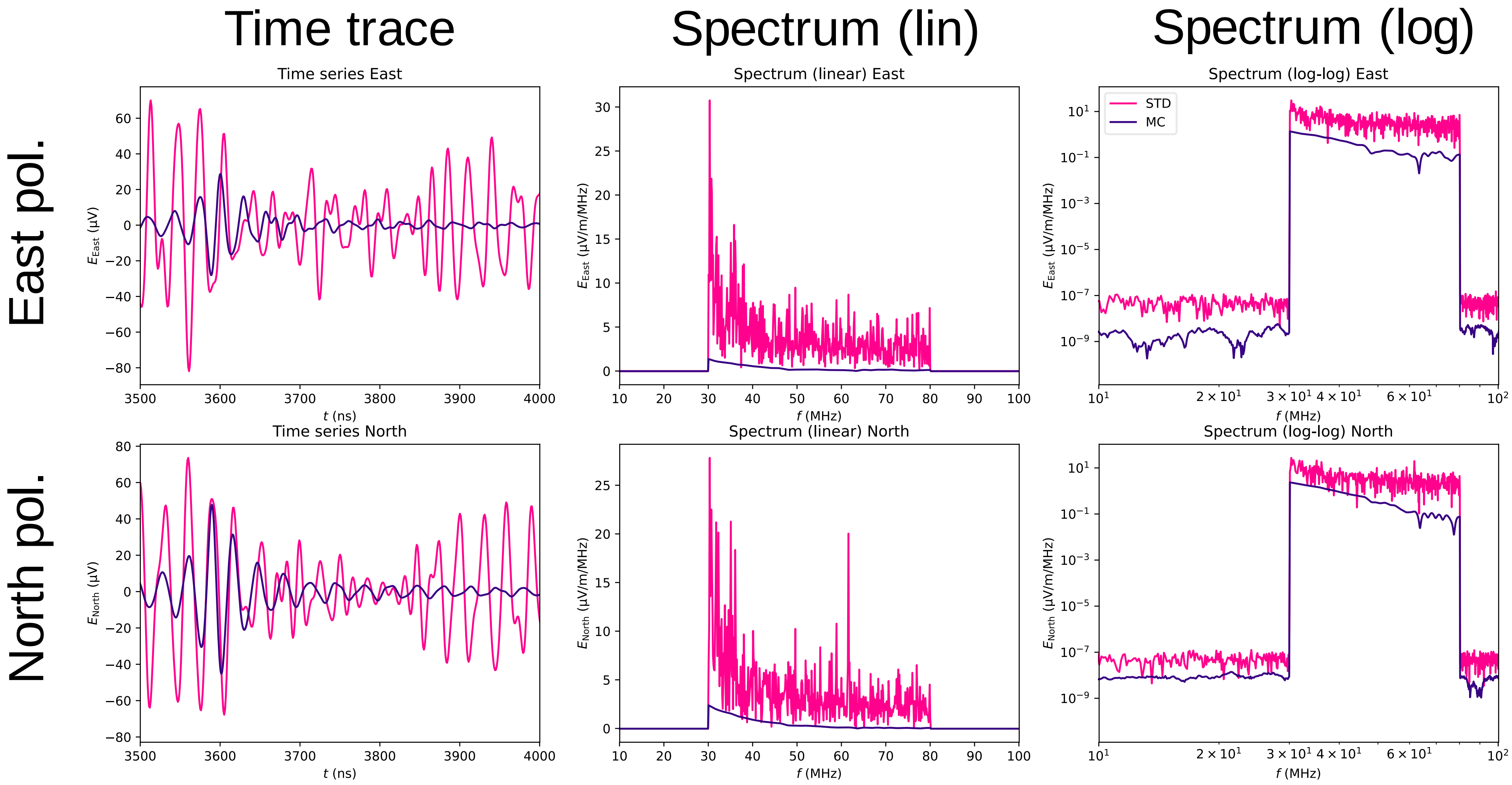
The Problem



Time trace
Spectrum (lin)
Spectrum (log)
East pol.
North pol.
Time series East
Spectrum (linear) East
Spectrum (log-log) East
Time series North
Spectrum (linear) North
Spectrum (log-log) North
STD
MC
t (ns)
f (MHz)

Forward Model

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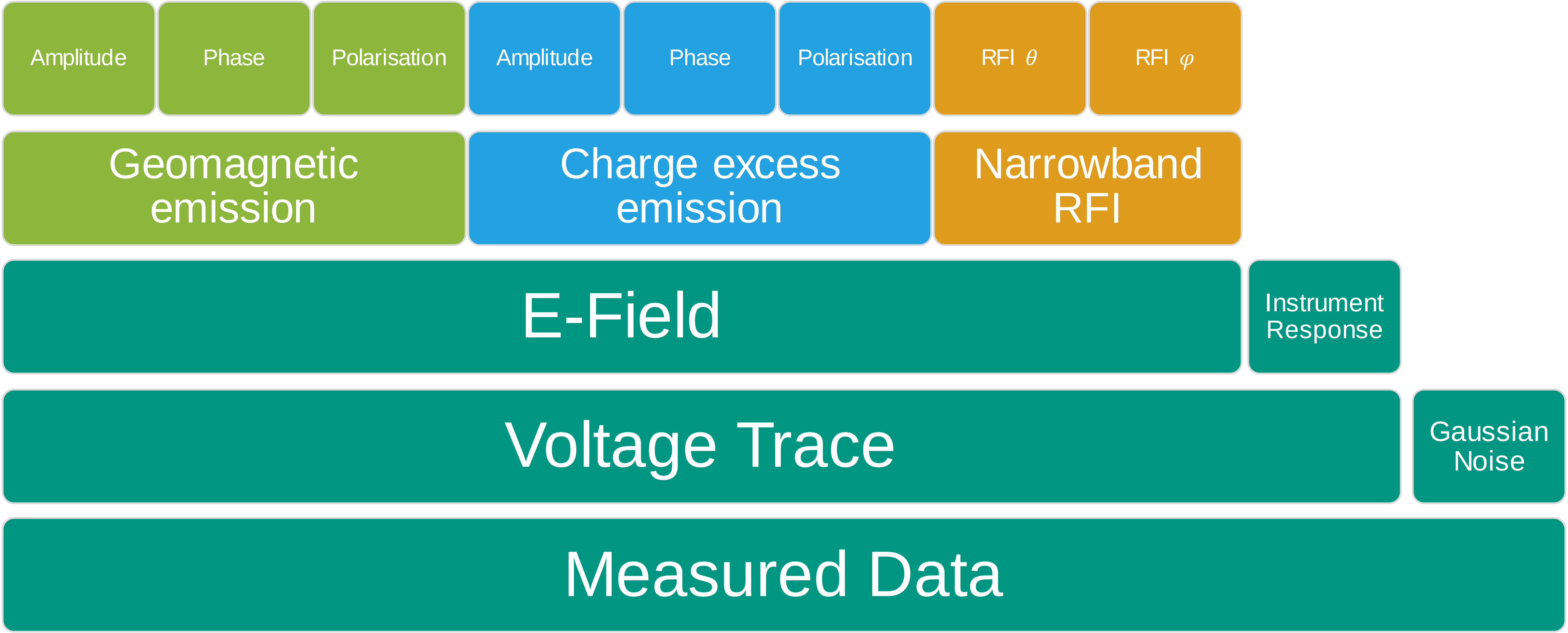
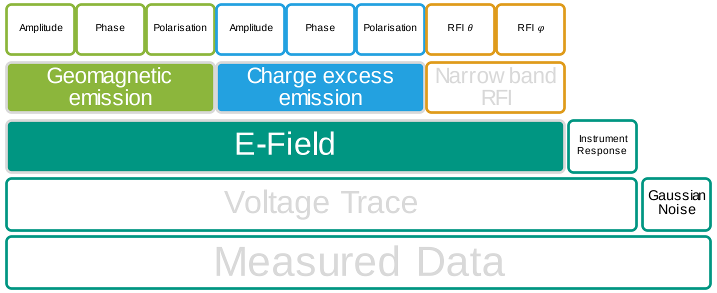




E-Field Model

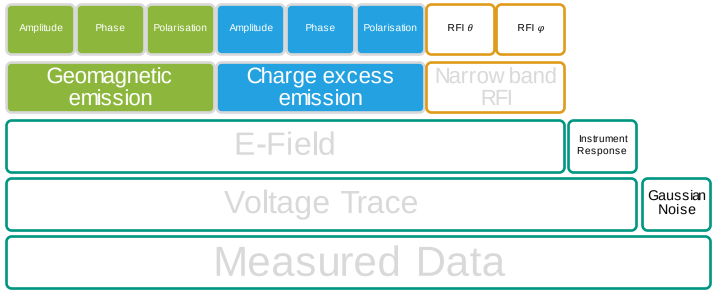
- Previous work from Welling et al. (JCAP, 2021)

- Far field approximation
- Split into geomagnetic, charge excess and RFI

$$\begin{aligned}\vec{E}(f) = \quad & \left(\mathcal{E}_{geo}(f)\cos\boxed{\psi_{geo}} + \mathcal{E}_{CE}(f)\cos\boxed{\psi_{CE}} + R_\theta\right)\hat{\theta} \\ & + \left(\mathcal{E}_{geo}(f)\sin\psi_{geo} + \mathcal{E}_{CE}(f)\sin\psi_{CE} + R_\phi\right)\hat{\phi}\end{aligned}$$

- Split into amplitude and phase

$$\mathcal{E}(f) = |\mathcal{E}|(f)e^{i\phi(f)}$$



Signal Model

- Geomagnetic emission

$$\left|\mathcal{E}_{\mathrm{geo}}\right|(f) = \boxed{A}\cdot 10^{m_f^{\mathrm{geo}}(f-f_0)+m_{f2}^{\mathrm{geo}}(f-f_0)^2} + \int OU\left(f,\boxed{\xi_{\mathrm{geo}}}\right)df$$

$A, m_f^{\mathrm{geo}}, m_{f,2}^{\mathrm{geo}}$ parametrised in $\boxed{r, d_{\max}}$

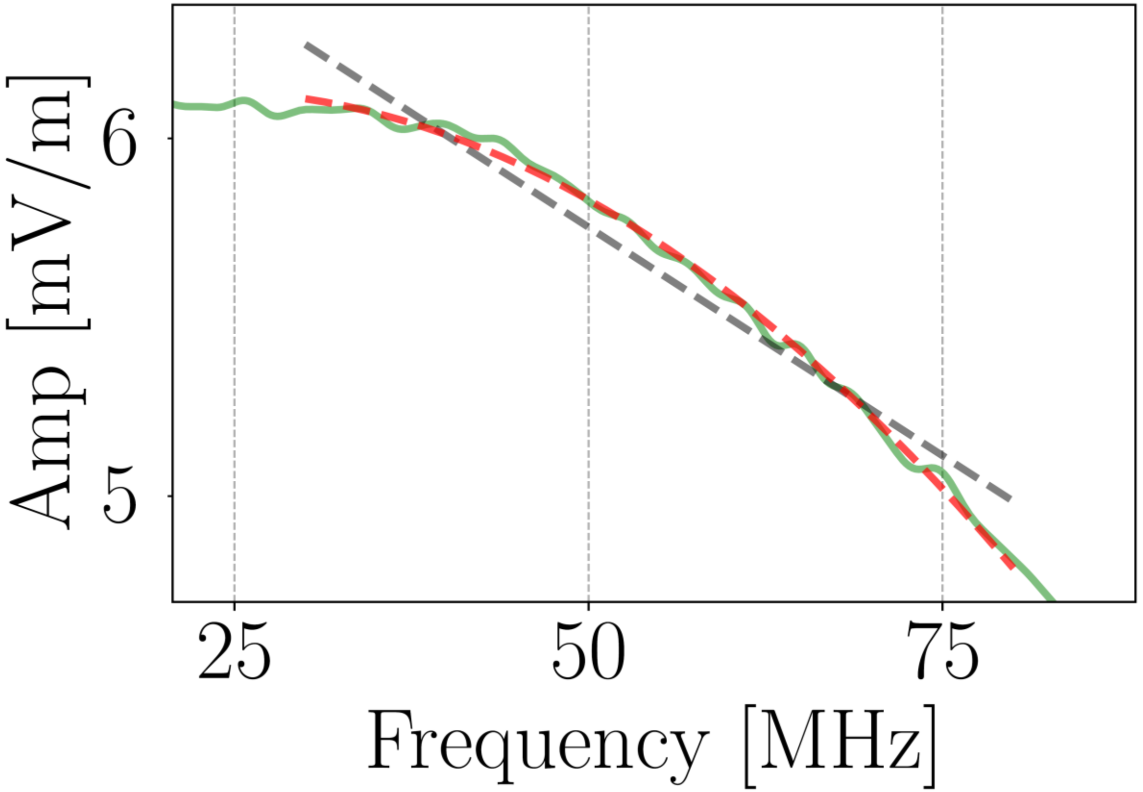
$f_0 = 55$ MHz

OU – Ornstein-Uhlenbeck process

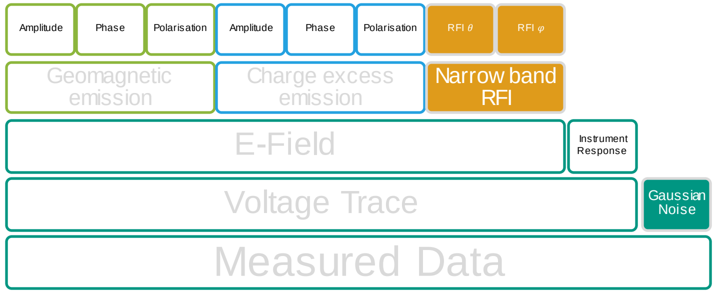
$$\phi_{\mathrm{geo}} = \boxed{\phi_m^{\mathrm{geo}}}f + \boxed{\phi_0^{\mathrm{geo}}}$$

- CE similarly

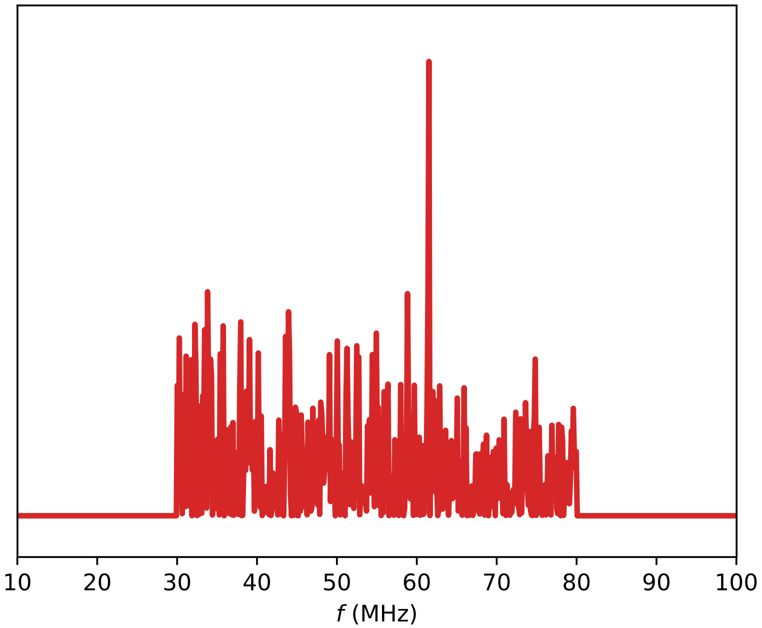
Martinelli et al. (ARENA, 2022)



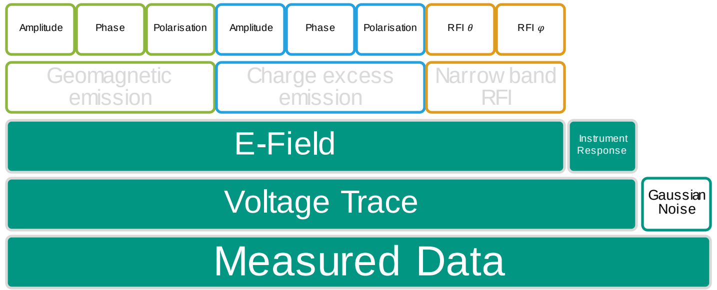
Noise Model



- Narrowband RFI
  - Part of the “signal” model
  - Modelled separately per **antenna** polarisation
  - $R_{\theta,\varphi} = \Gamma^{-1}(\alpha, s, \boxed{\xi_{\theta,\varphi}}) \cdot e^{i\boxed{\phi_{RFI,\theta,\varphi}}}$



- Measurement noise/Broadband RFI
  - $n \hookleftarrow \mathcal{G}(0, \Sigma_{V,\mathrm{meas}})$
  - $\Sigma_{V,\mathrm{meas}} = \mathrm{diag}(s_{\mathrm{V,meas}})$



Measurement Model

- Forward fold antenna response $$\vec{V}(f) = \widetilde{H}(f) \circ \vec{E}(f)$$
- Fourier transform $$\vec{V}(t) = \mathrm{RFFT}^{-1}(\vec{V}(f))$$
- Measurement equation $$d_i = \vec{V}\left(\vec{E}(t_i)\right) + n_i$$
- Likelihood $$P(\vec{d}_i|\vec{E}) = \mathcal{G}(\vec{d}_i - \vec{V}, s_n)$$

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Simulations

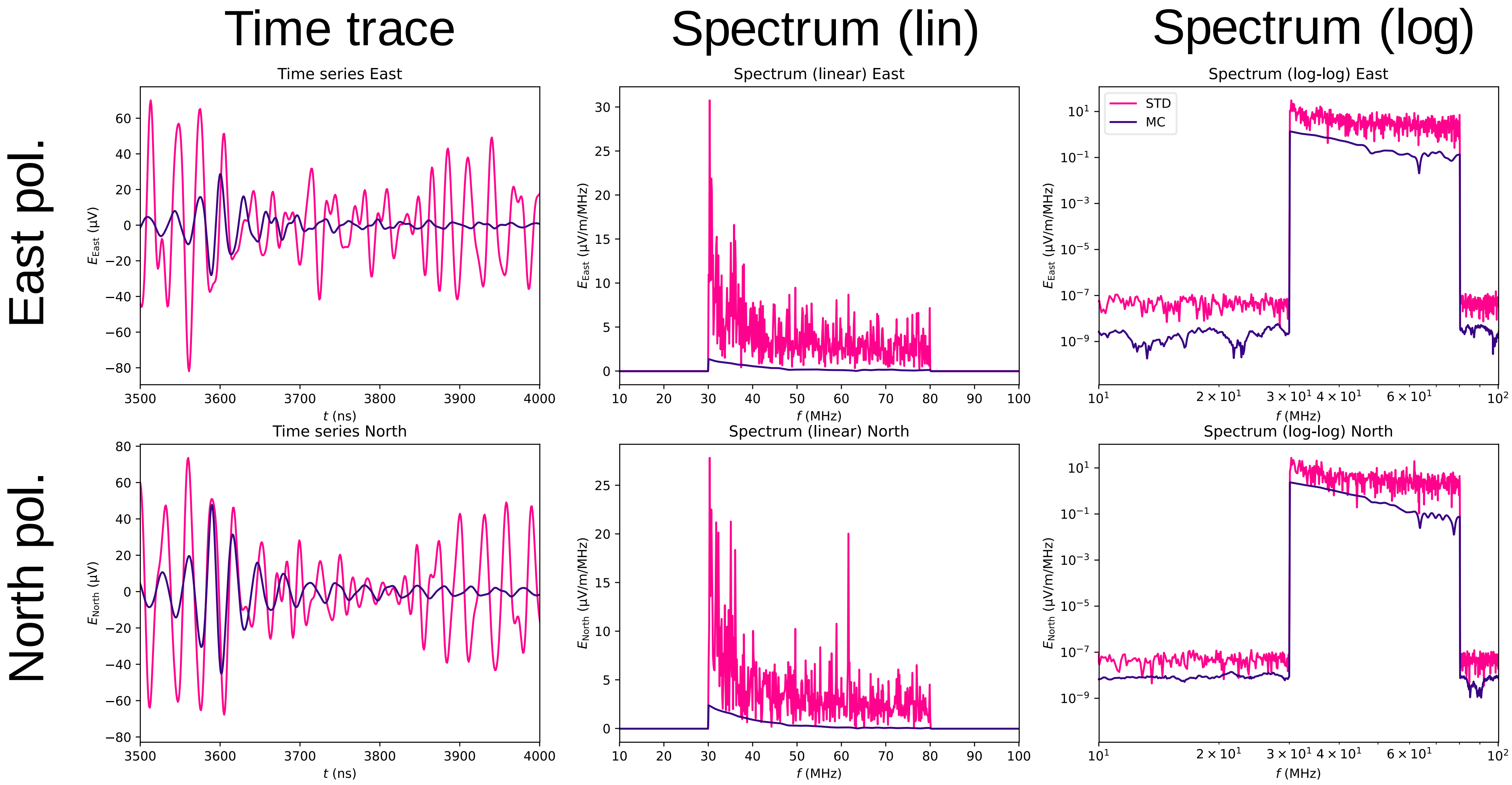
- Library of CoREAS simulations

- Primaries: Proton, Helium, Nitrogen, Iron
- Energy: $10^{18.4}\mathrm{eV}$ - $10^{20.1}\mathrm{eV}$
- Zenith angle: $65°$ - $85°$

- IFT Reconstruction: ≈ 800 showers
- Standard Reconstruction: 4000 showers

- Detector simulation for Pierre Auger Observatory
- Measured noise

Reconstruction Example
E-Field: Standard



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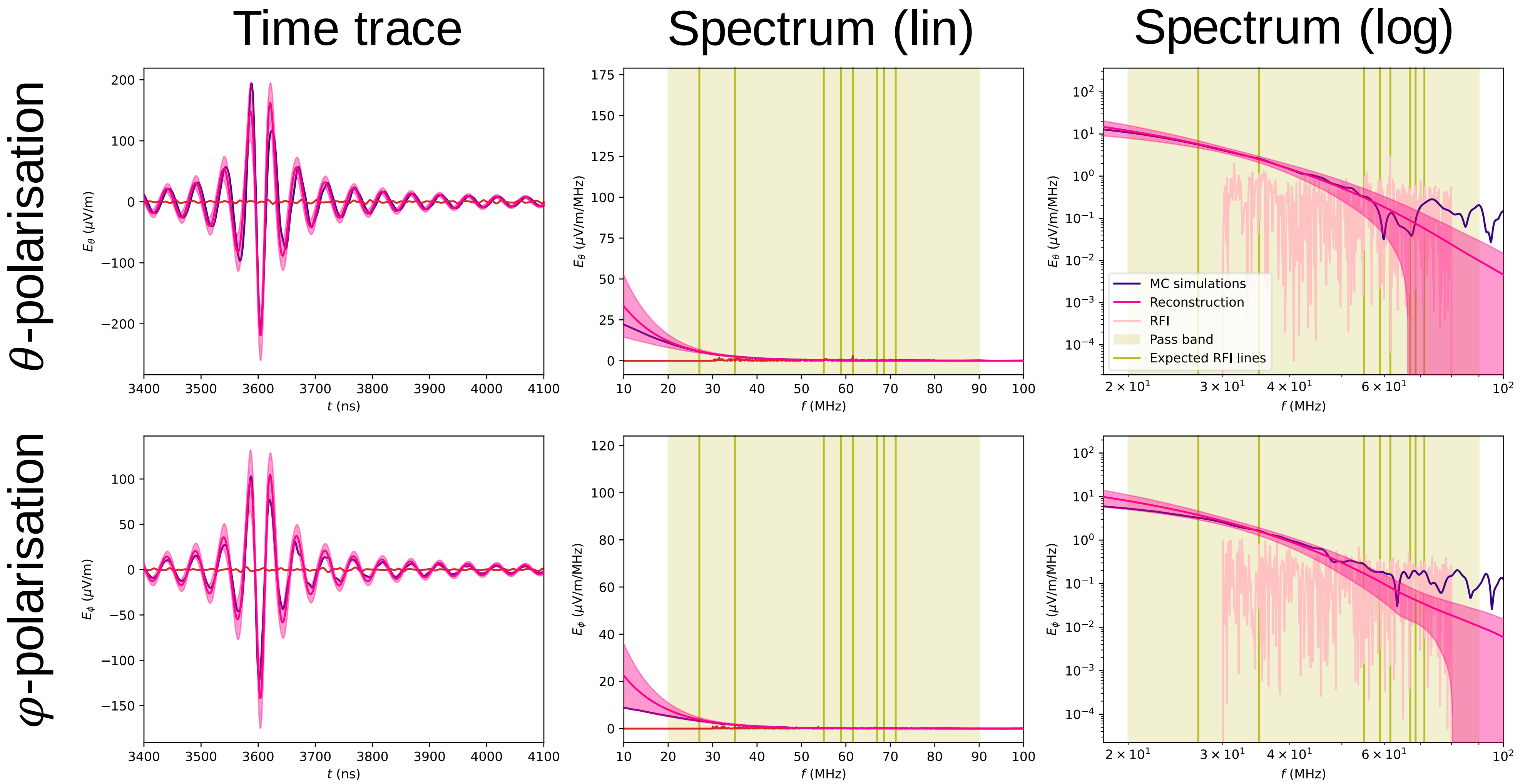
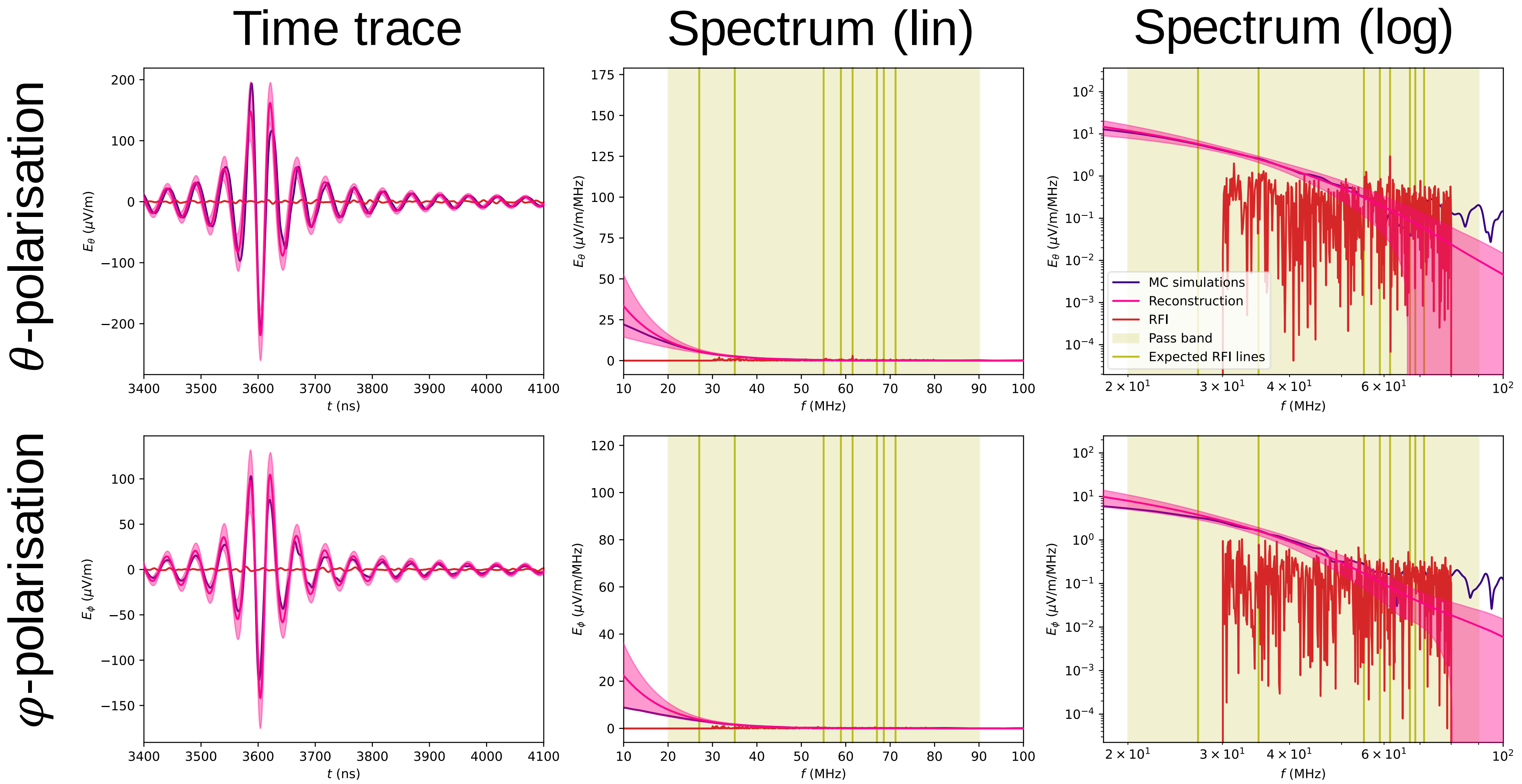
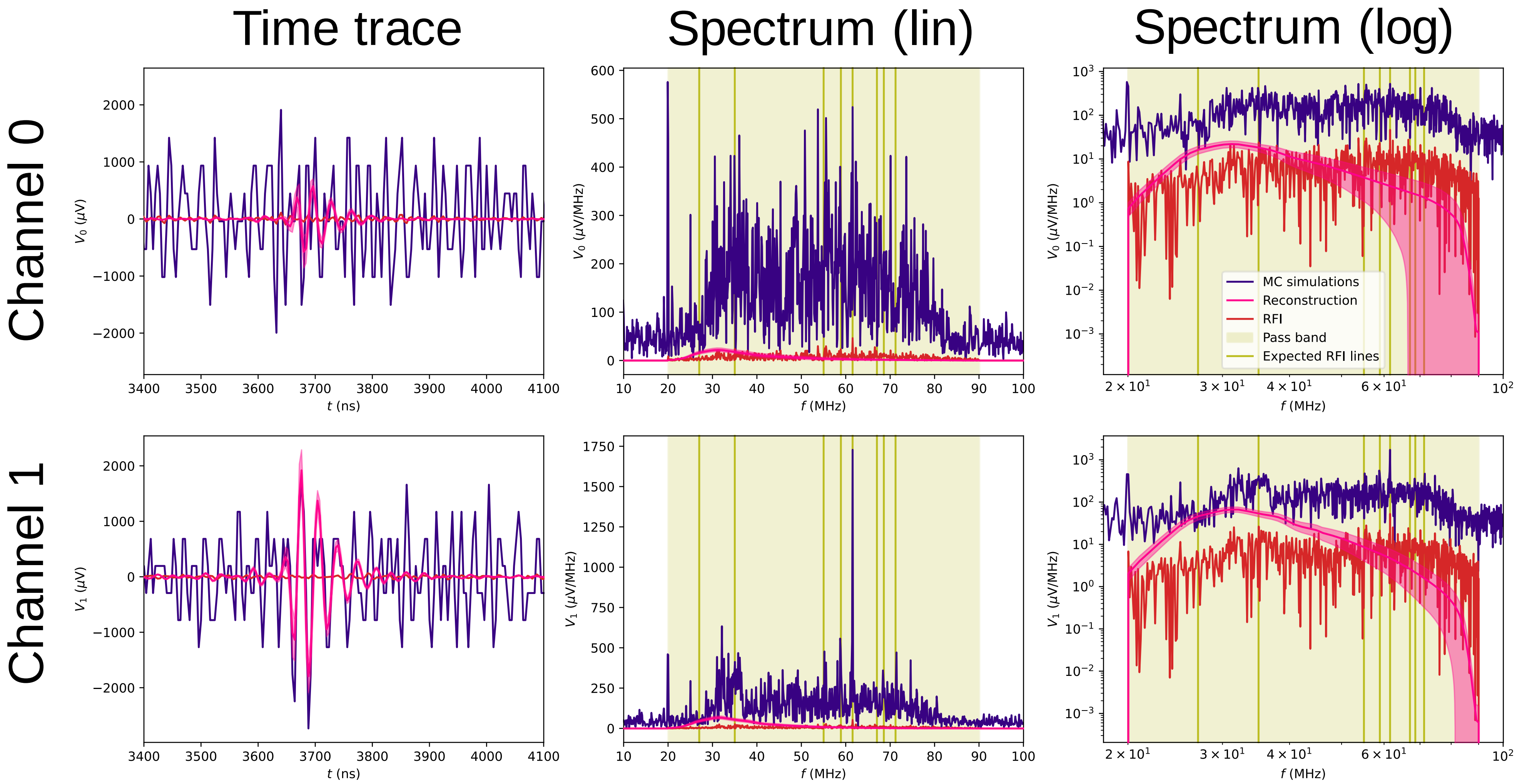
Reconstruction Example
E-Field: IFT



Reconstruction Example
E-Field: IFT



Reconstruction Example
Voltage: IFT



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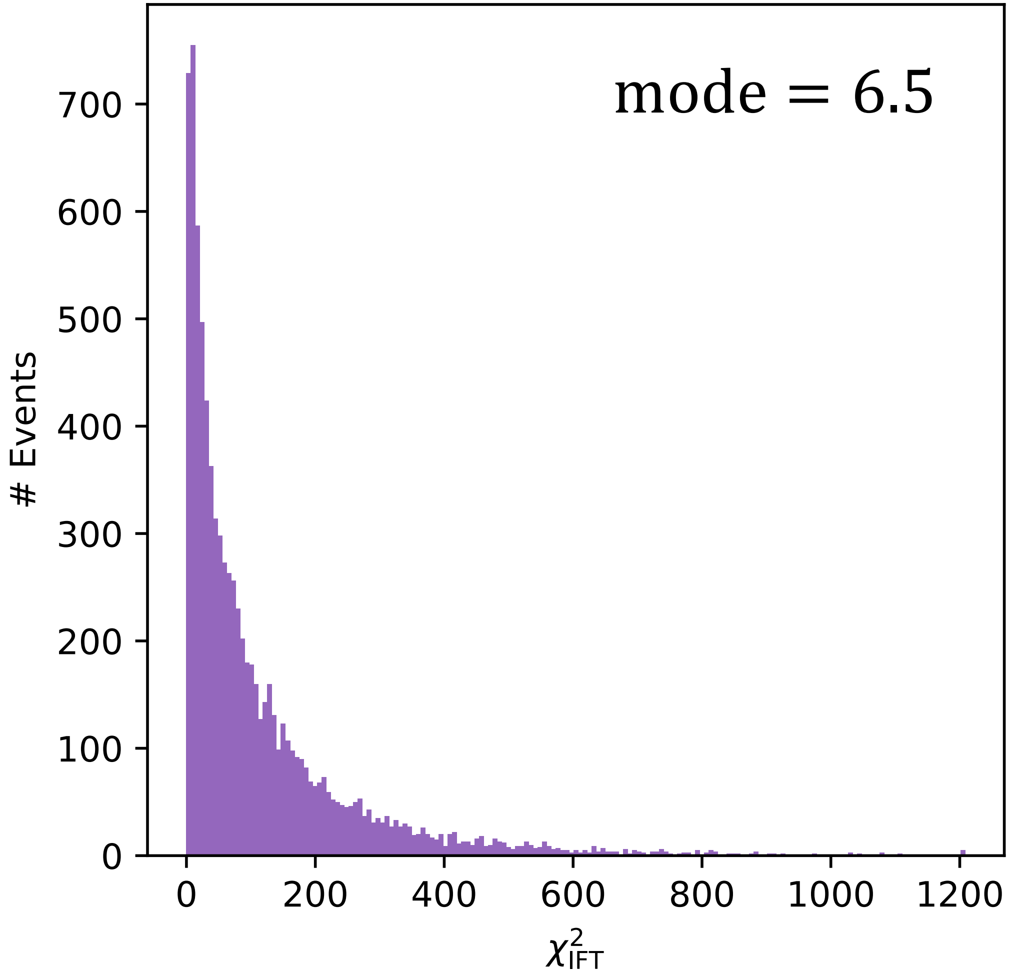
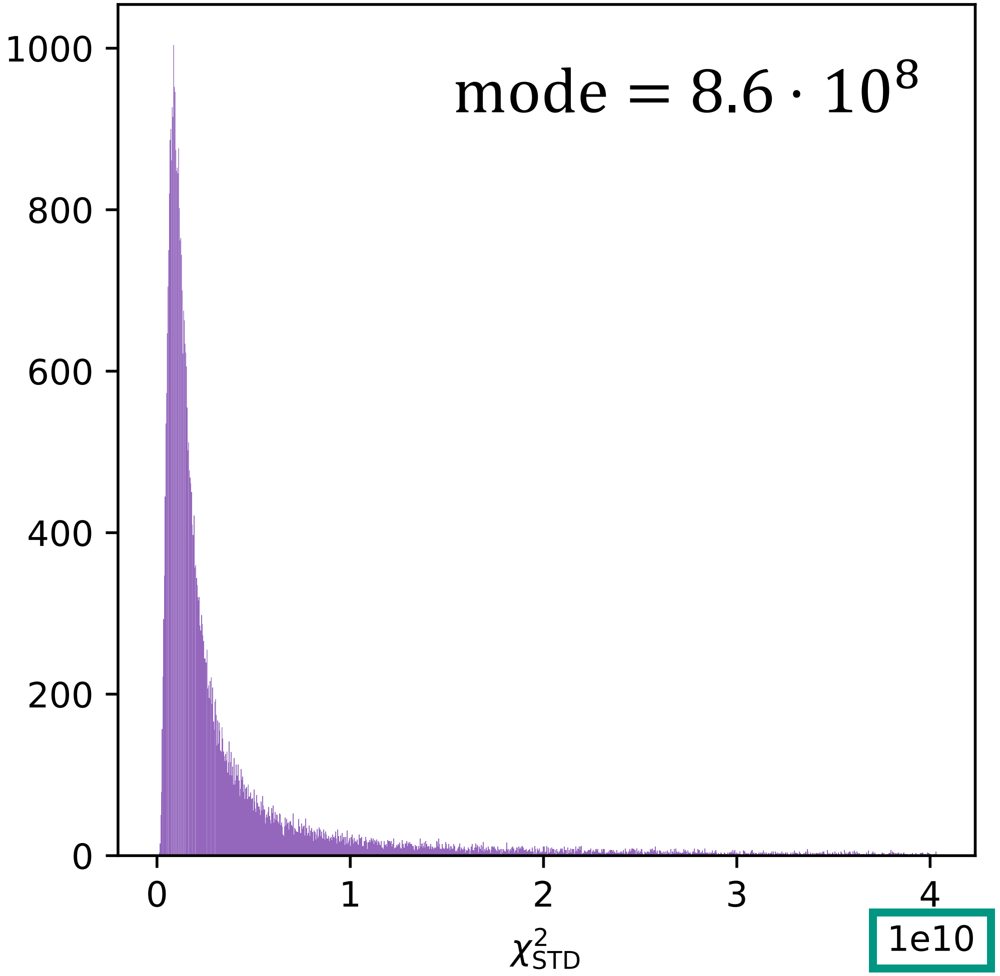
χ^2-distribution improvements

IFT Reconstruction

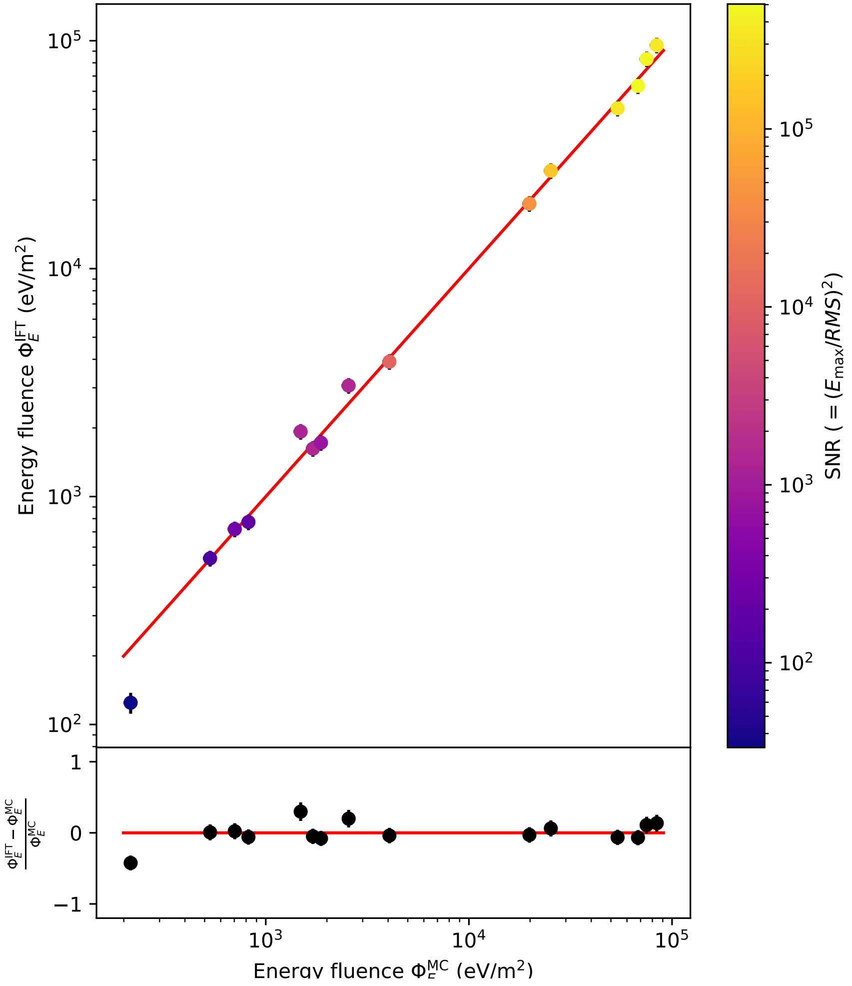


Standard reconstruction

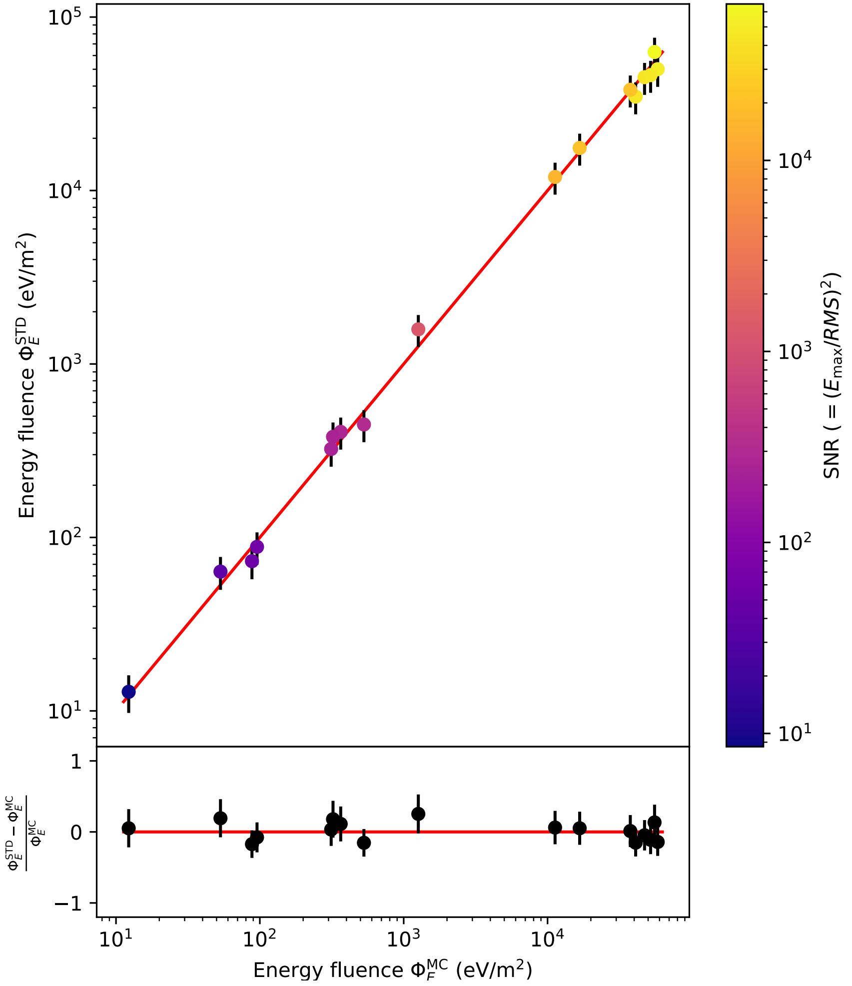


Fluence comparison: Single Events

IFT Reconstruction

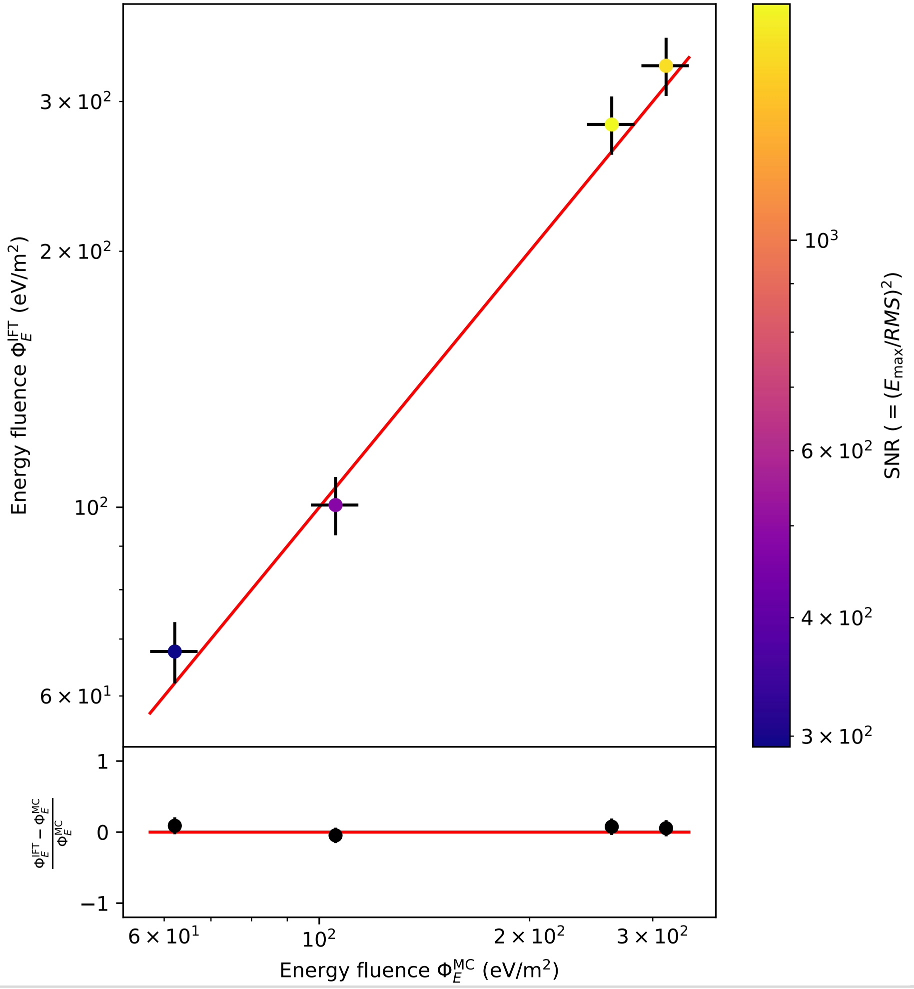


Standard reconstruction

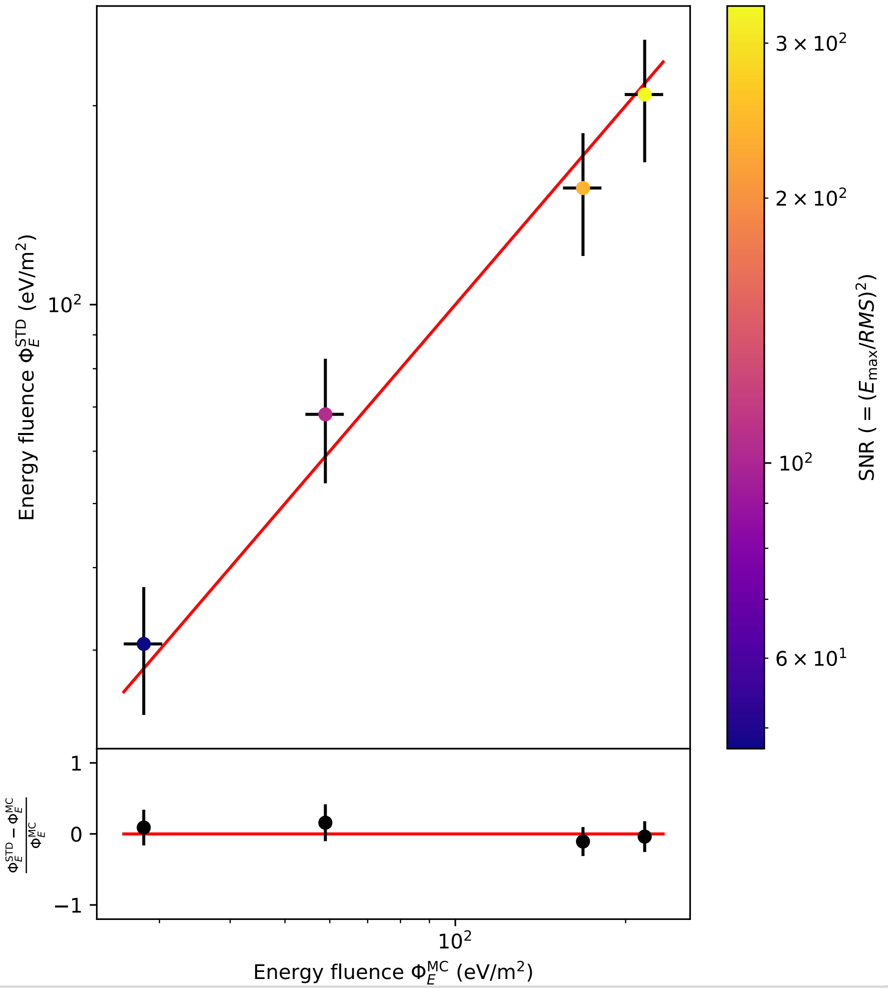


Fluence comparison: Single Events

IFT Reconstruction



Standard reconstruction



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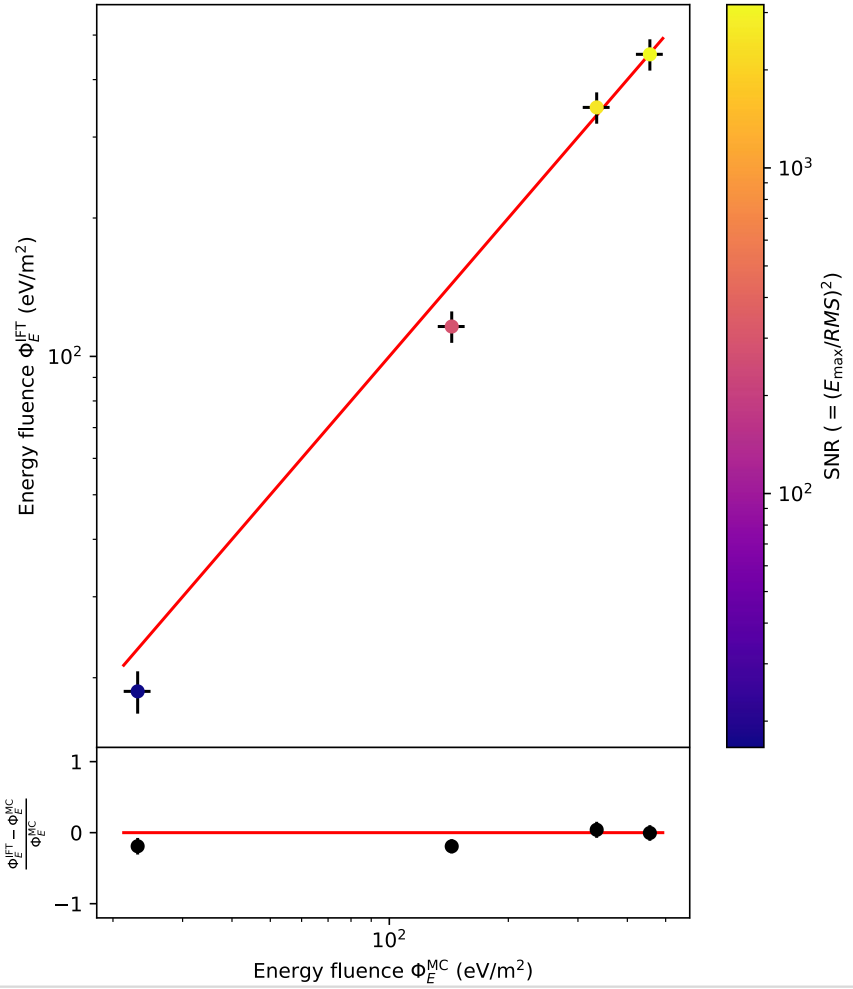
Fluence comparison: Single Events

IFT Reconstruction



Standard reconstruction

Not reconstructable

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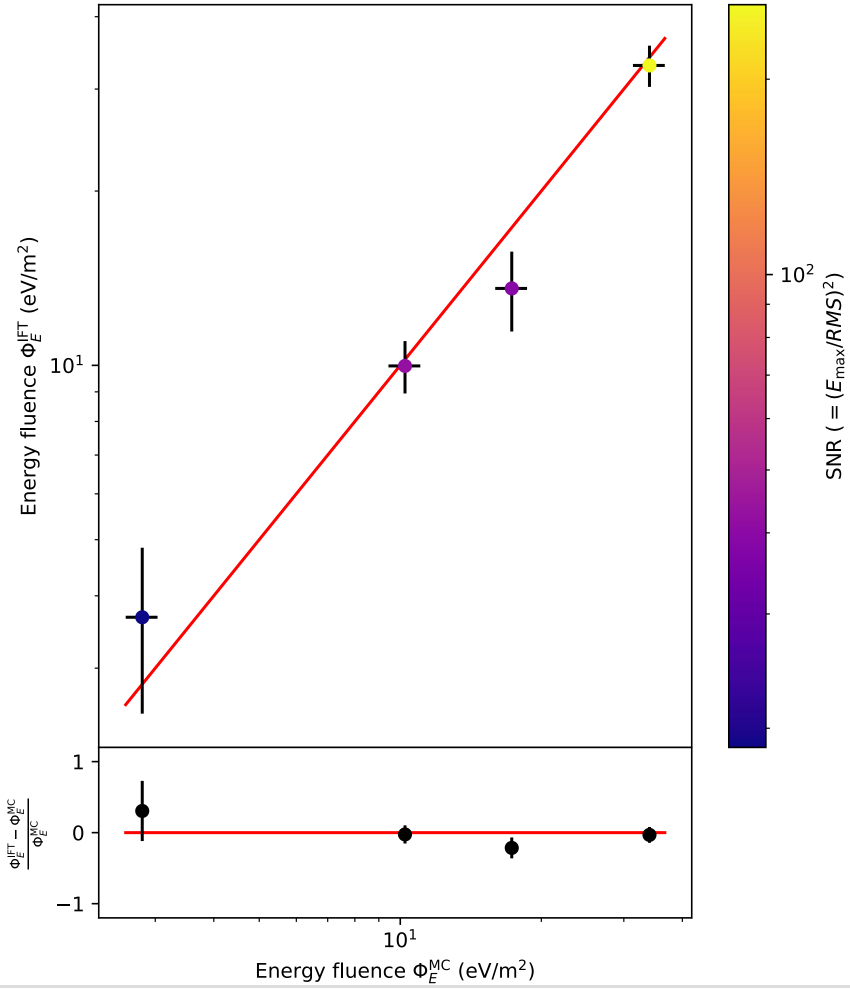
Fluence comparison: Single Events

IFT Reconstruction

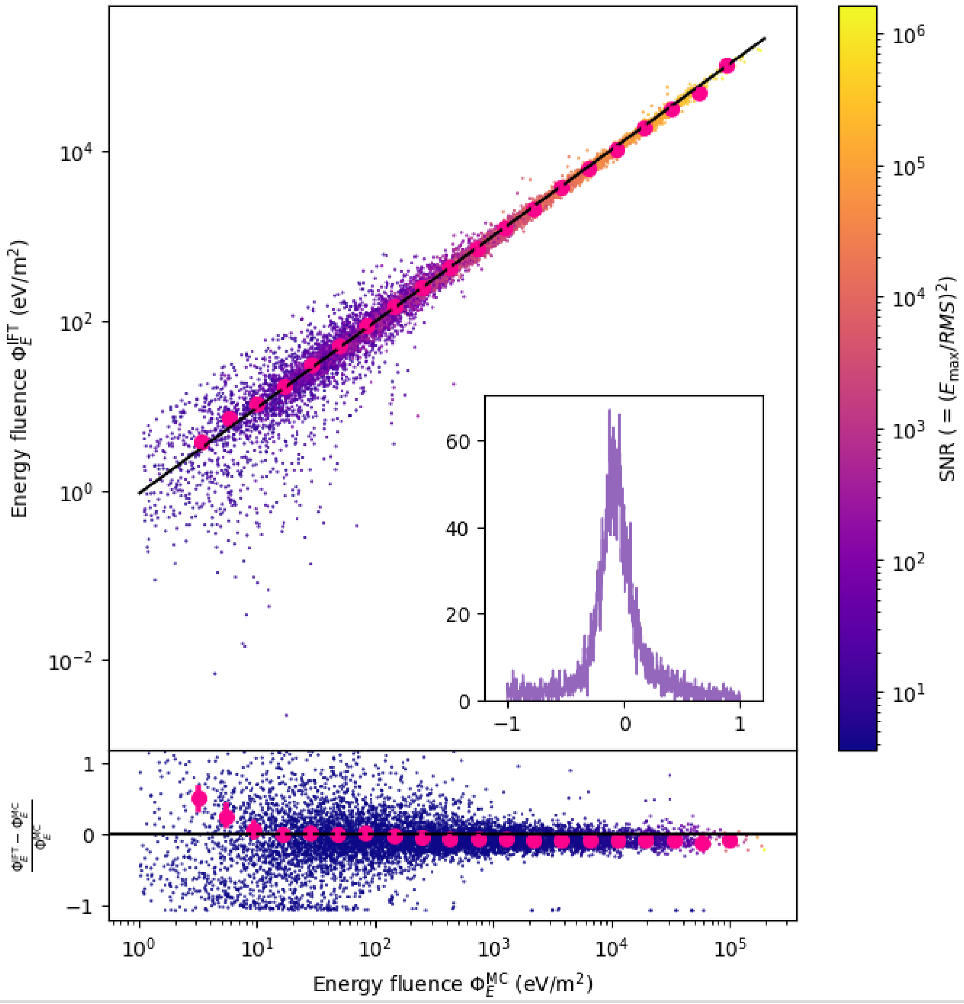


Standard reconstruction

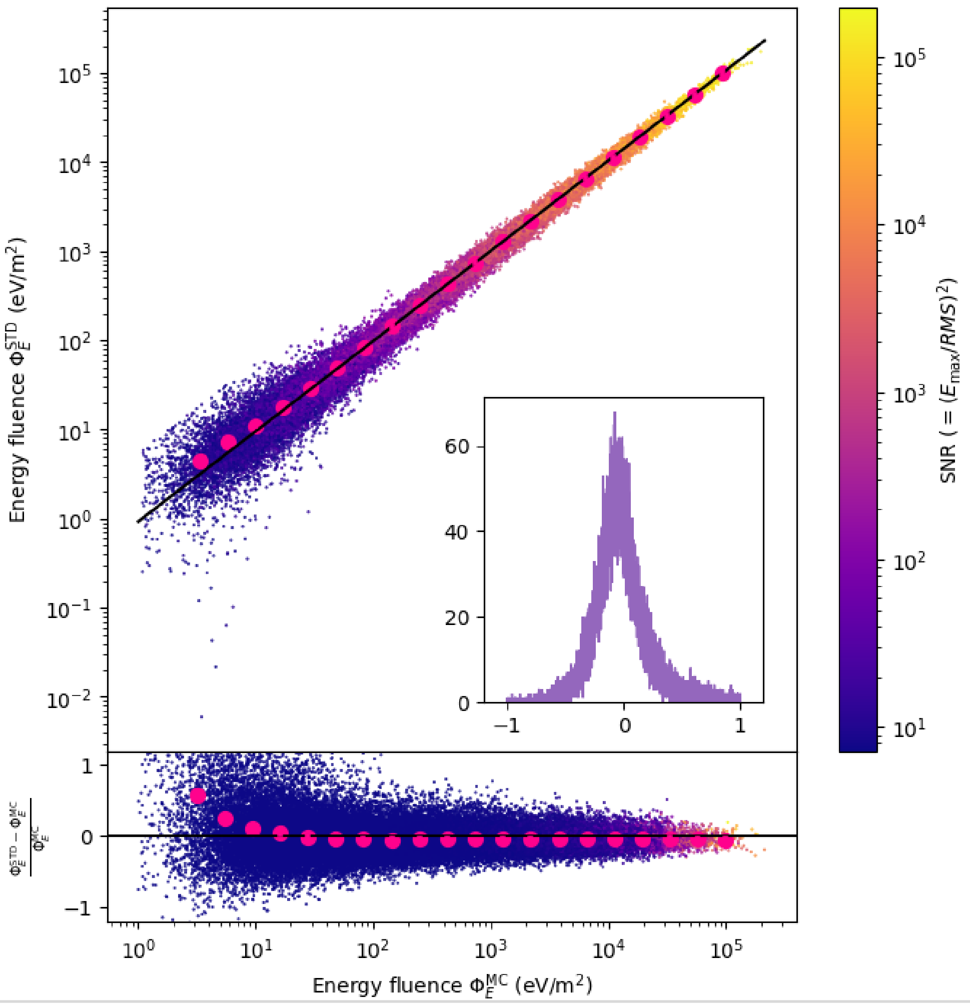
Not reconstructable

Fluence comparison: All Data

IFT Reconstruction



Standard reconstruction



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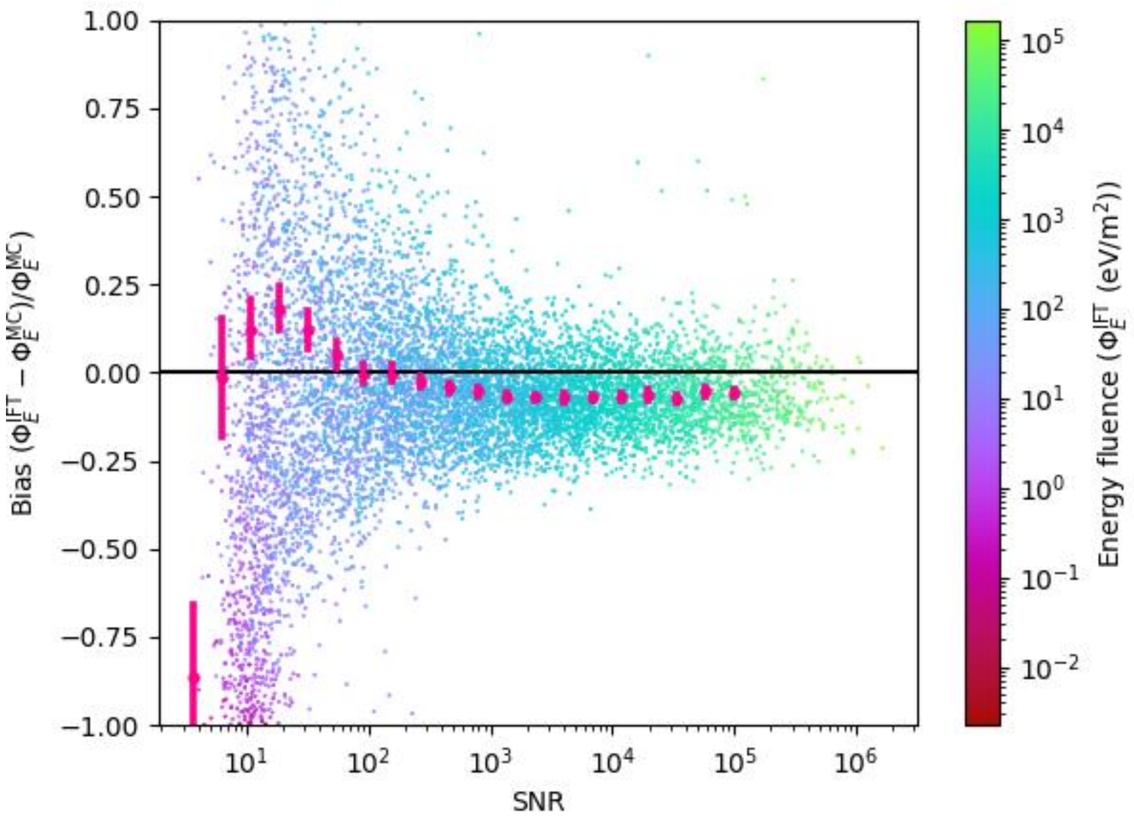
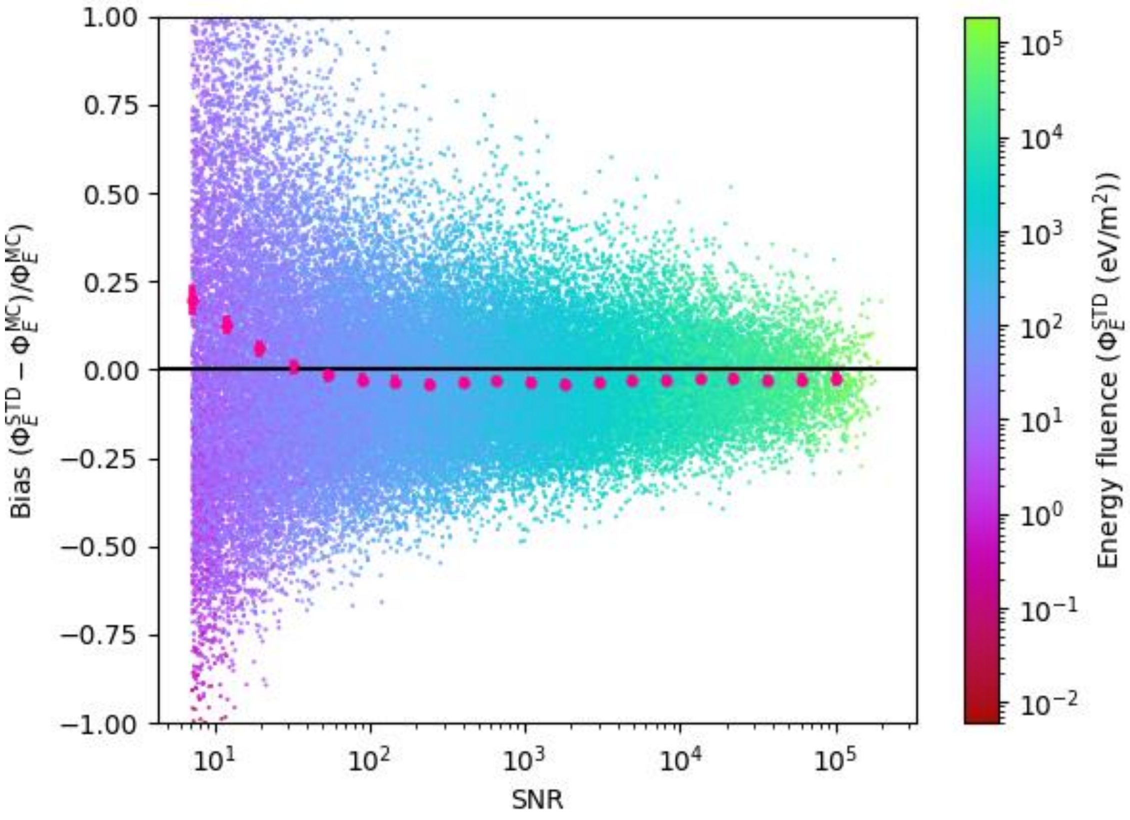
SNR – Bias comparison

IFT Reconstruction



Standard reconstruction



Summary

- First physics-based model for IFT reconstruction of E-Field

- Has been successfully tested on MC simulations

- Improved E-Field reconstruction
  - Better χ^2 distribution
  - (Slightly) less biased fluence calculation

- No direct improvement to current reconstruction

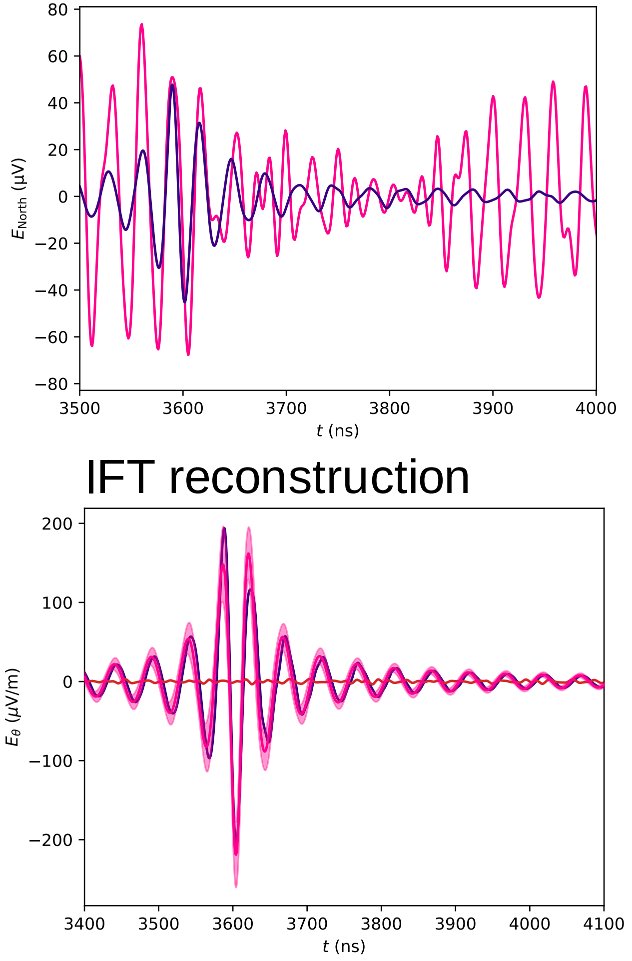
- Computation-heavy

Outlook

- Improved noise model
- Reconstruct all stations at once
  - E-Field model as shown
  - Add model for LDF
    - Amplitude
    - Pulse shape
- Add data from other detectors
  - Surface array (WCD and scintillators)

Standard reconstruction

IFT reconstruction



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