Karlsruher Institut für Technologie

Towards Cosmic Ray Air Shower Imaging using Radio Measurements

Keito Watanabe, Tim Huege

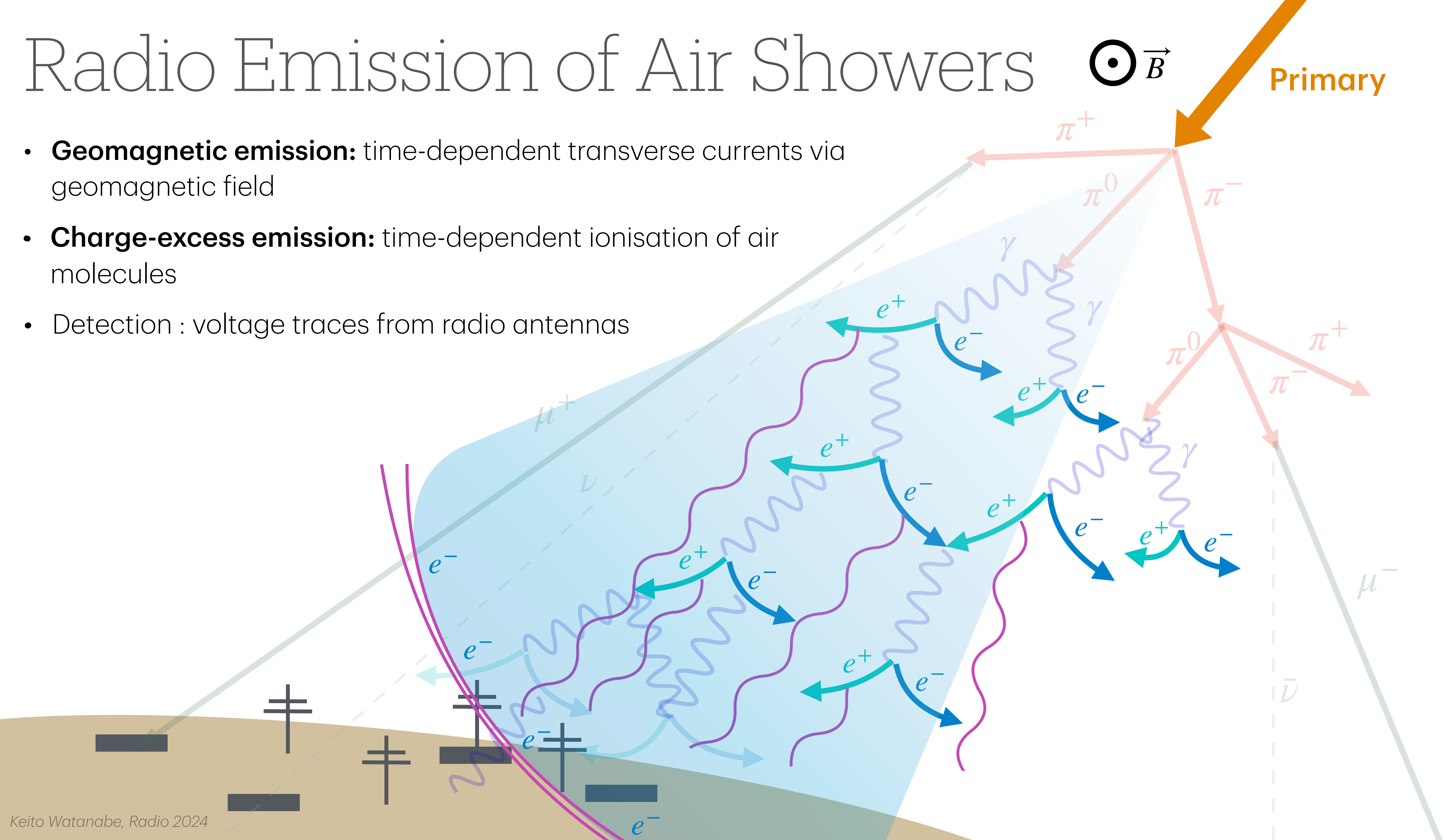
Radio 2024, 12.11.2024

Extensive Air Showers

- Cascade of particles through **hadronic** and **electromagnetic** processes
- Generated by **high energy cosmic rays**
- Primary (energy, direction, mass) : obtained via <u>reconstruction</u> from surface & fluorescence detectors

Radio Emission of Air Showers

- **Geomagnetic emission:** time-dependent transverse currents via geomagnetic field
- **Charge-excess emission:** time-dependent ionisation of air molecules
- Detection : voltage traces from radio antennas



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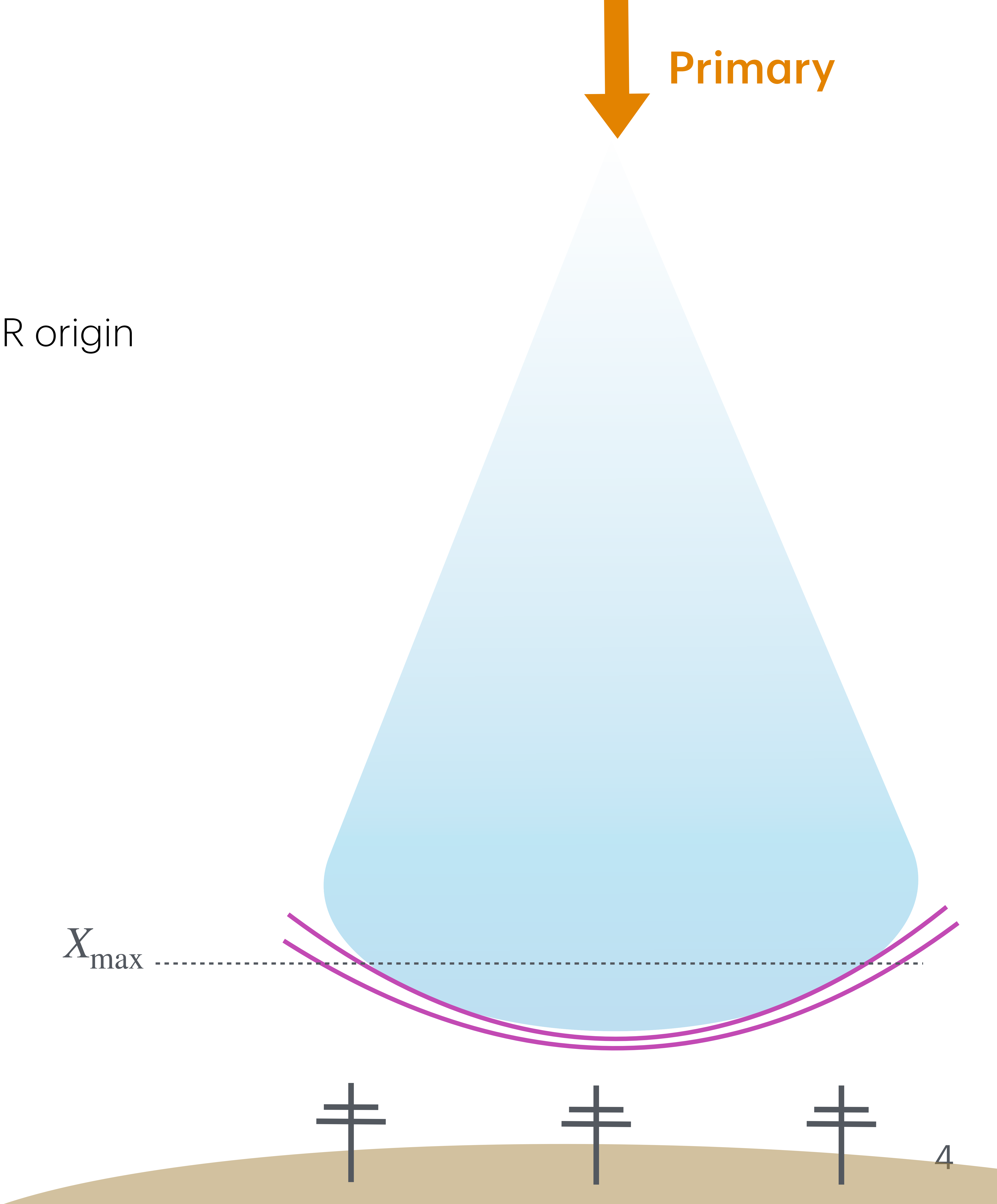
All information of primary cosmic ray (energy, direction, mass) encoded in traces

→ complementary approach to traditional detection methods

X_{max} Reconstruction

X_{max} : atmospheric depth of shower maximum ($\mathrm{g\ cm^{-2}}$)

- Proxy for primary mass → crucial piece to understand UHECR origin



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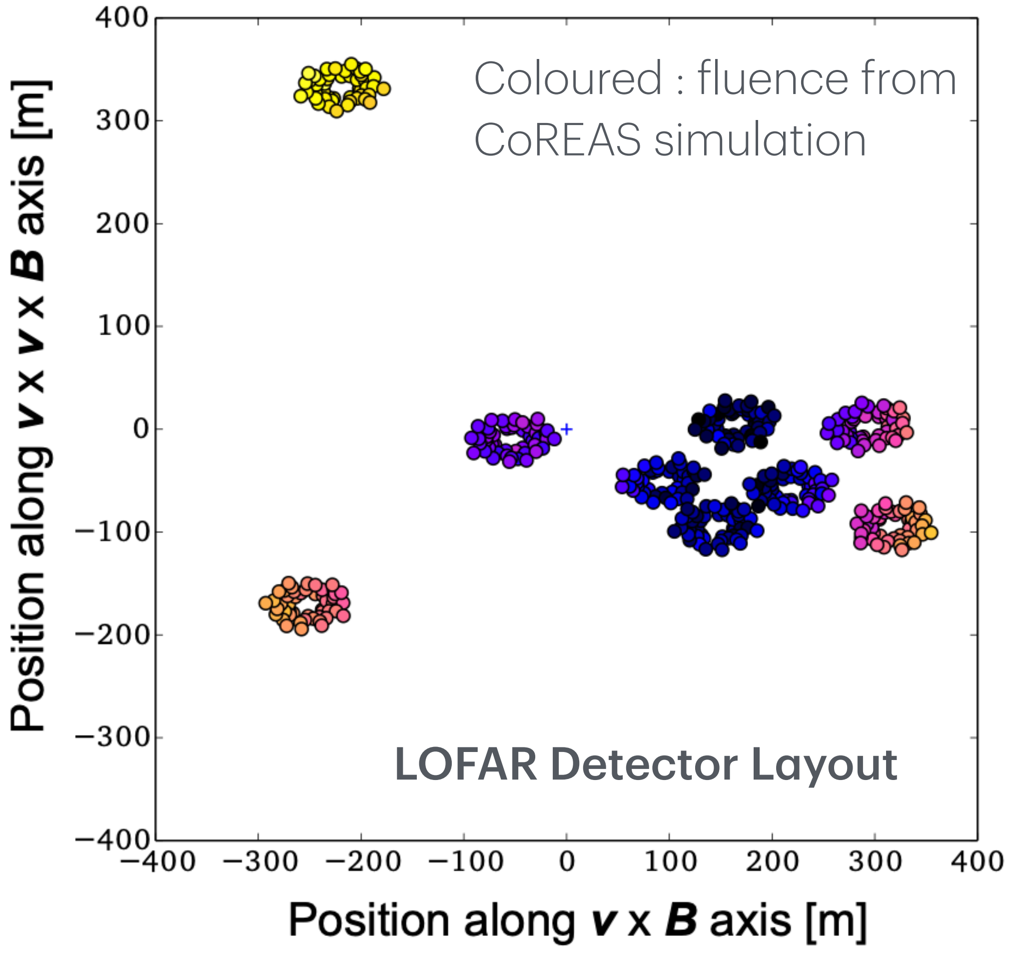
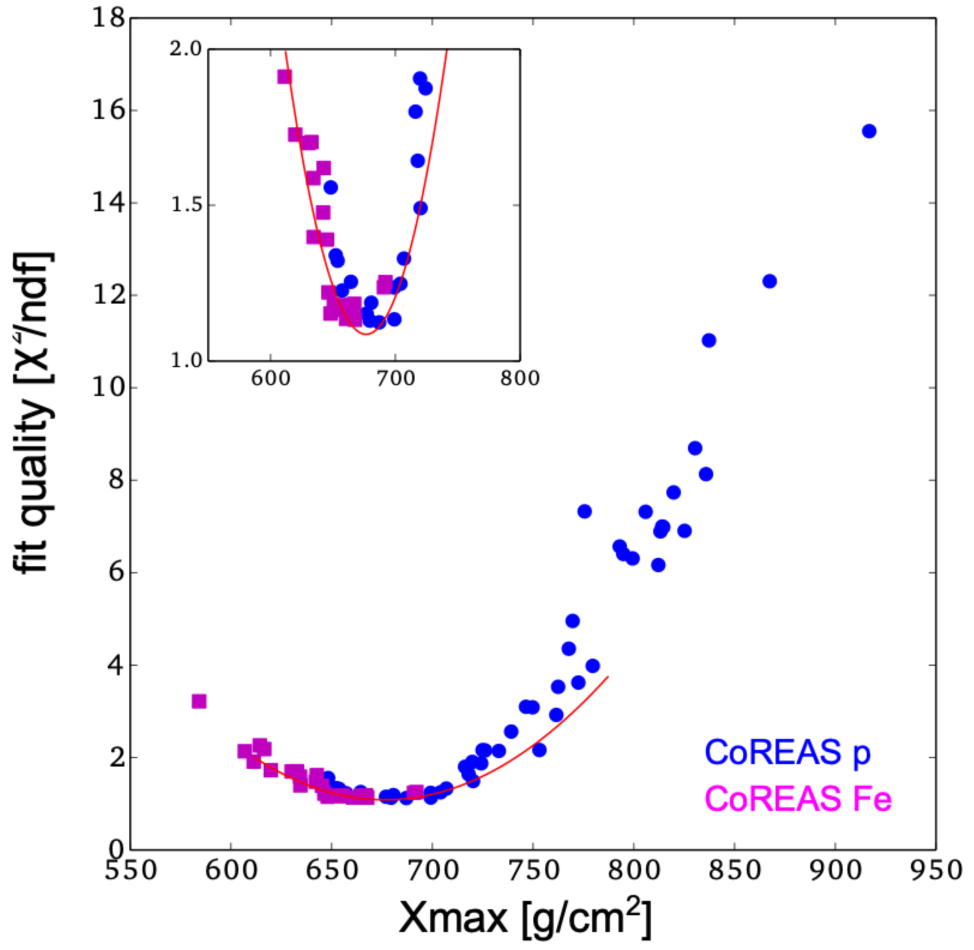
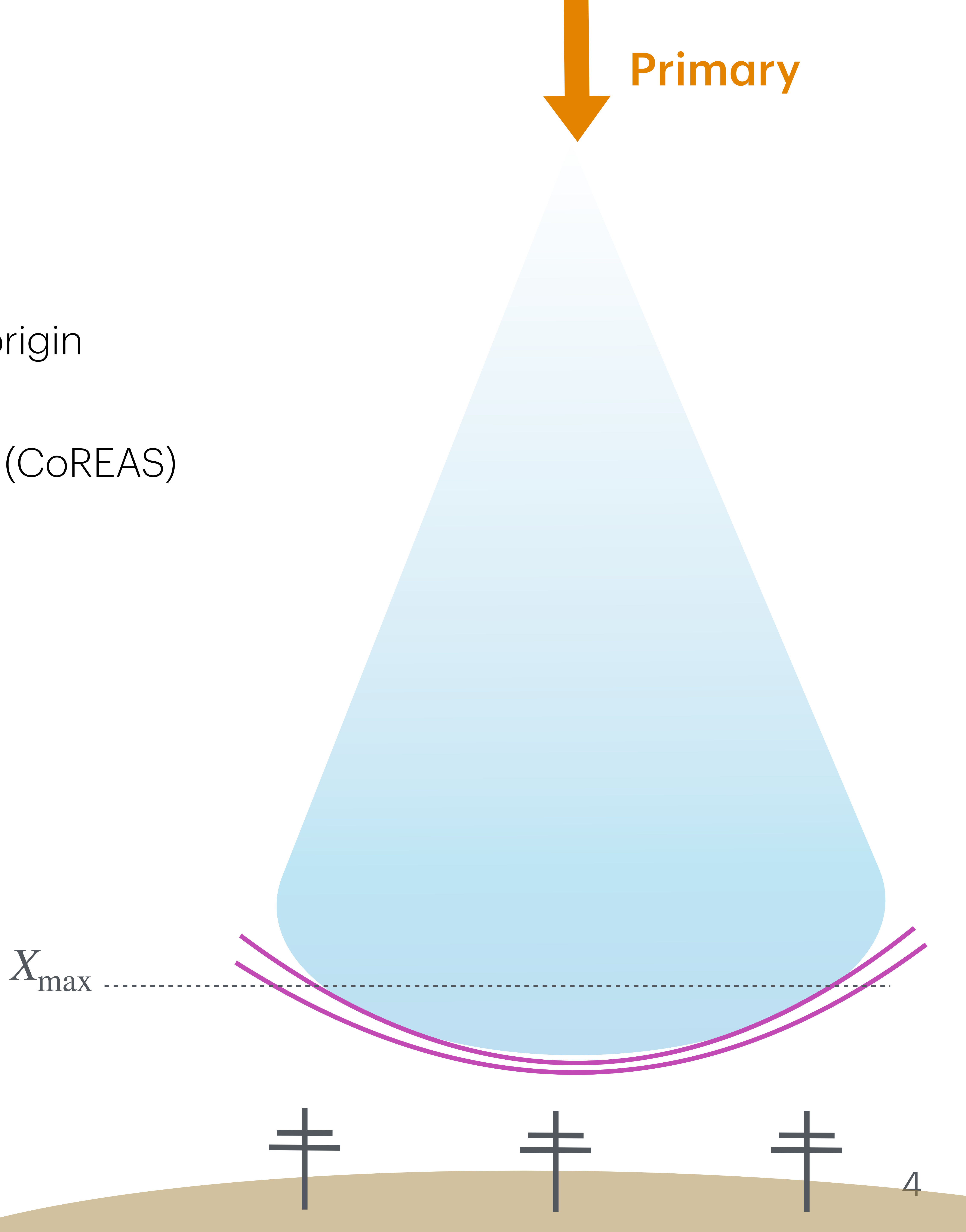
Current: through fit quality of measurements with MC simulations (CoREAS)





S. Buitink et al. Phys.Rev.D 90 (2014) 082003



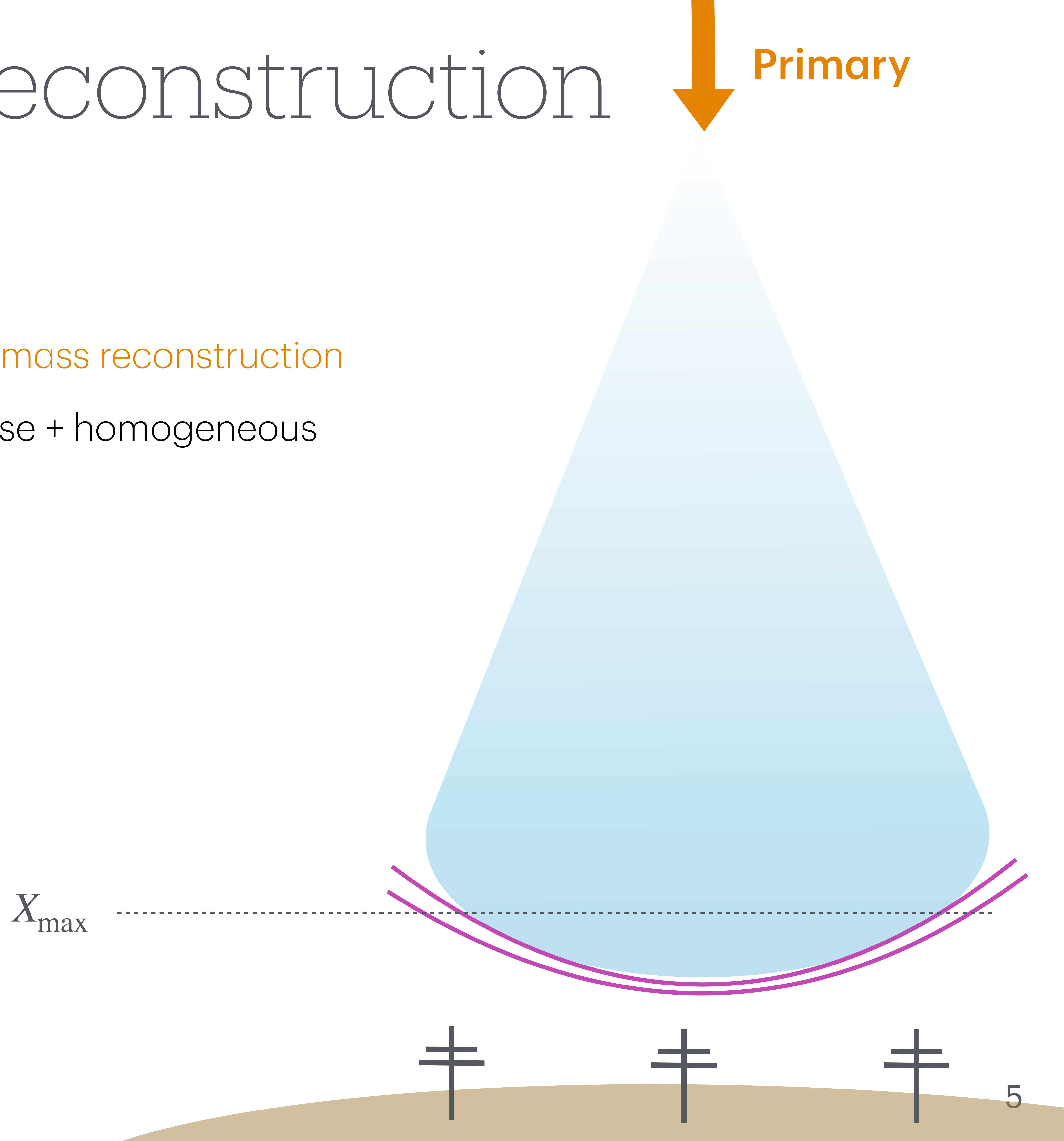
- Only energy deposited (fluence) used → not all information utilised

⟹ can we extract more information for the primary mass ?

~~X_{max}~~ Shower Profile Reconstruction

Goal: reconstruct the **full air shower profile**

- Extract **more profile parameters** → more accurate mass reconstruction
- Leverage *extremely precise measurements* from dense + homogeneous antenna layout of **Square Kilometre Array**
- <u>All information already available through traces!</u>



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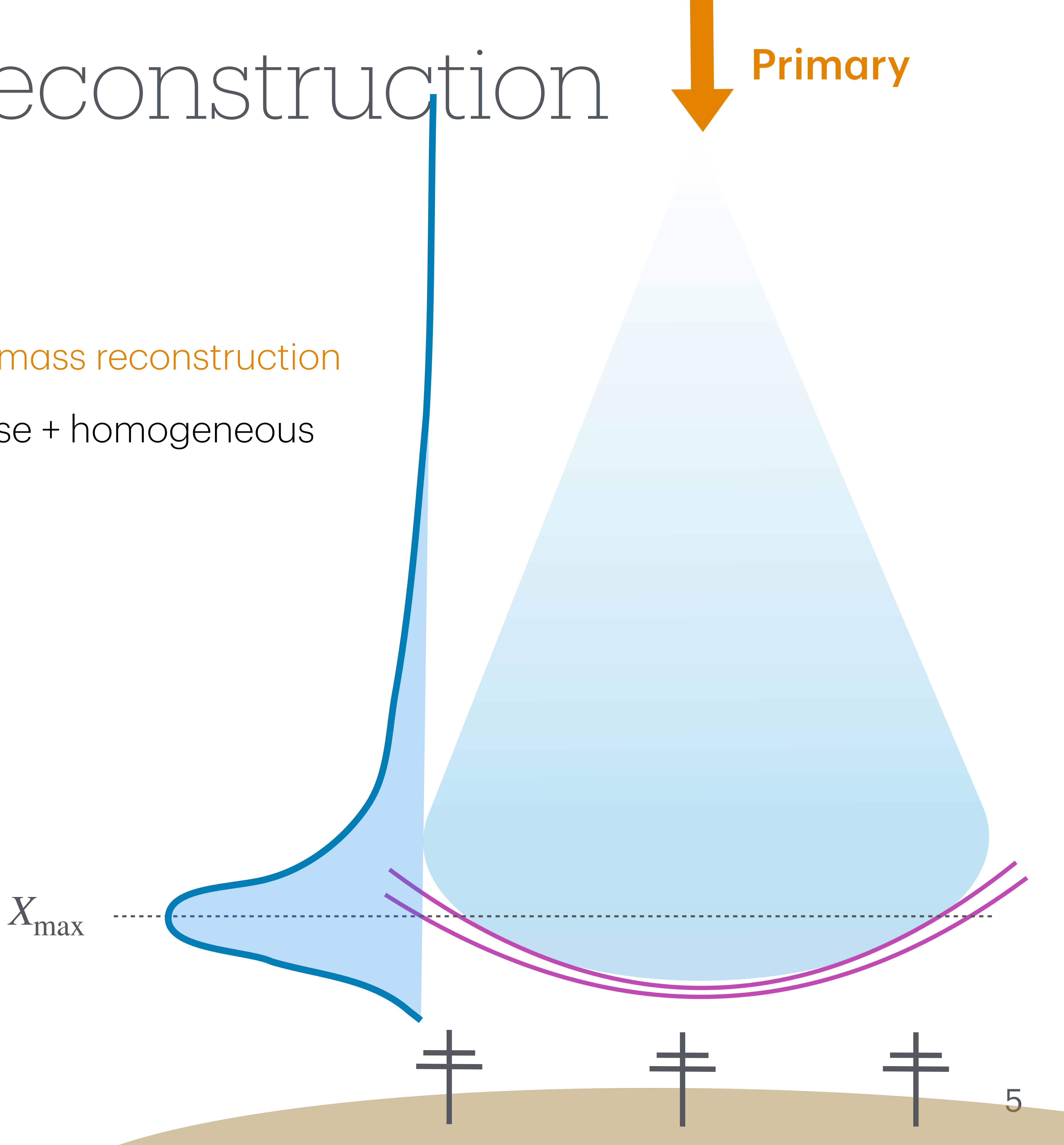

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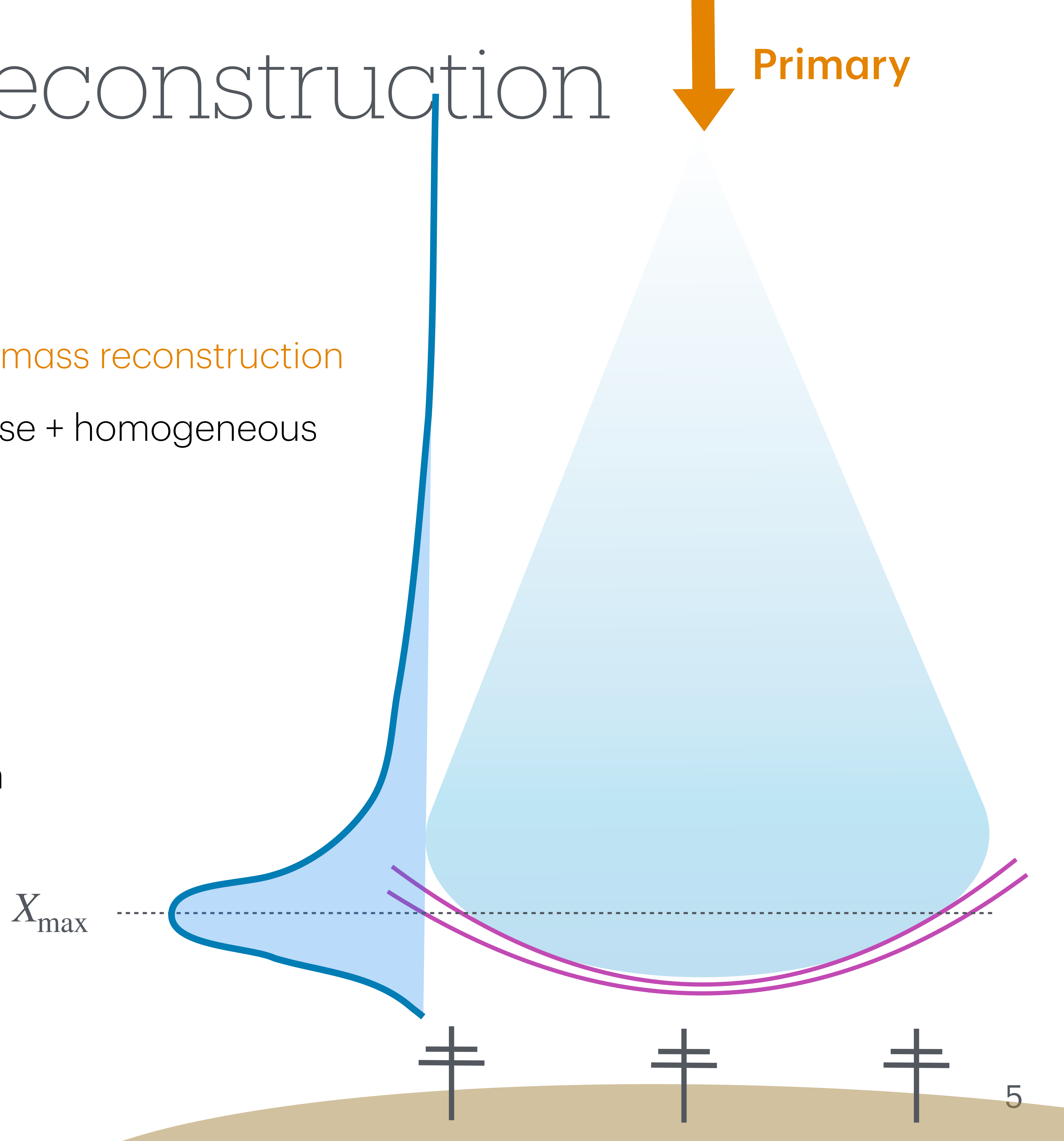
Challenges:

- Spatial & time-dependent processes → **4-D problem**
- Trace = field → **many d.o.f. ($> O(10^3)$)**



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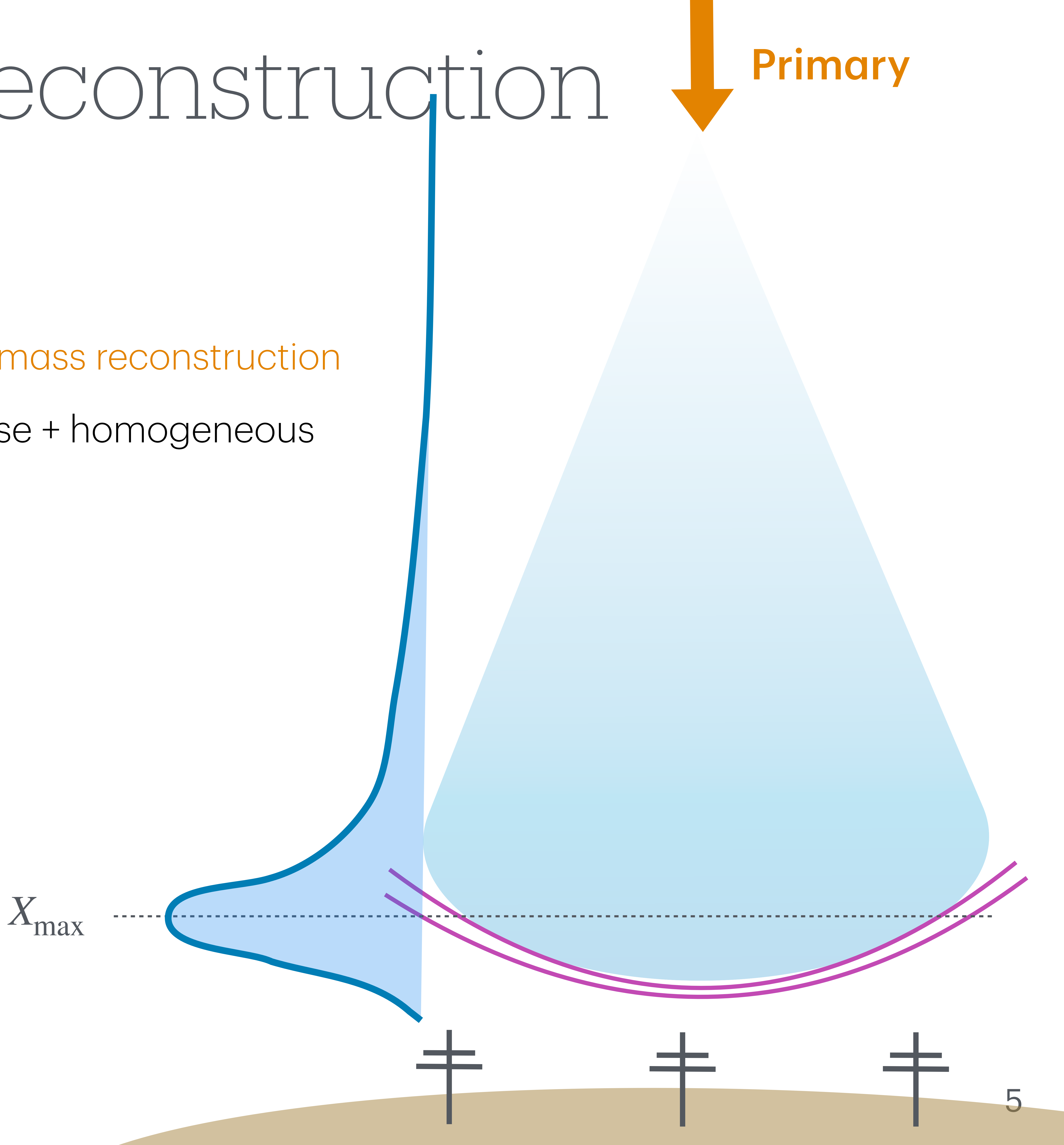
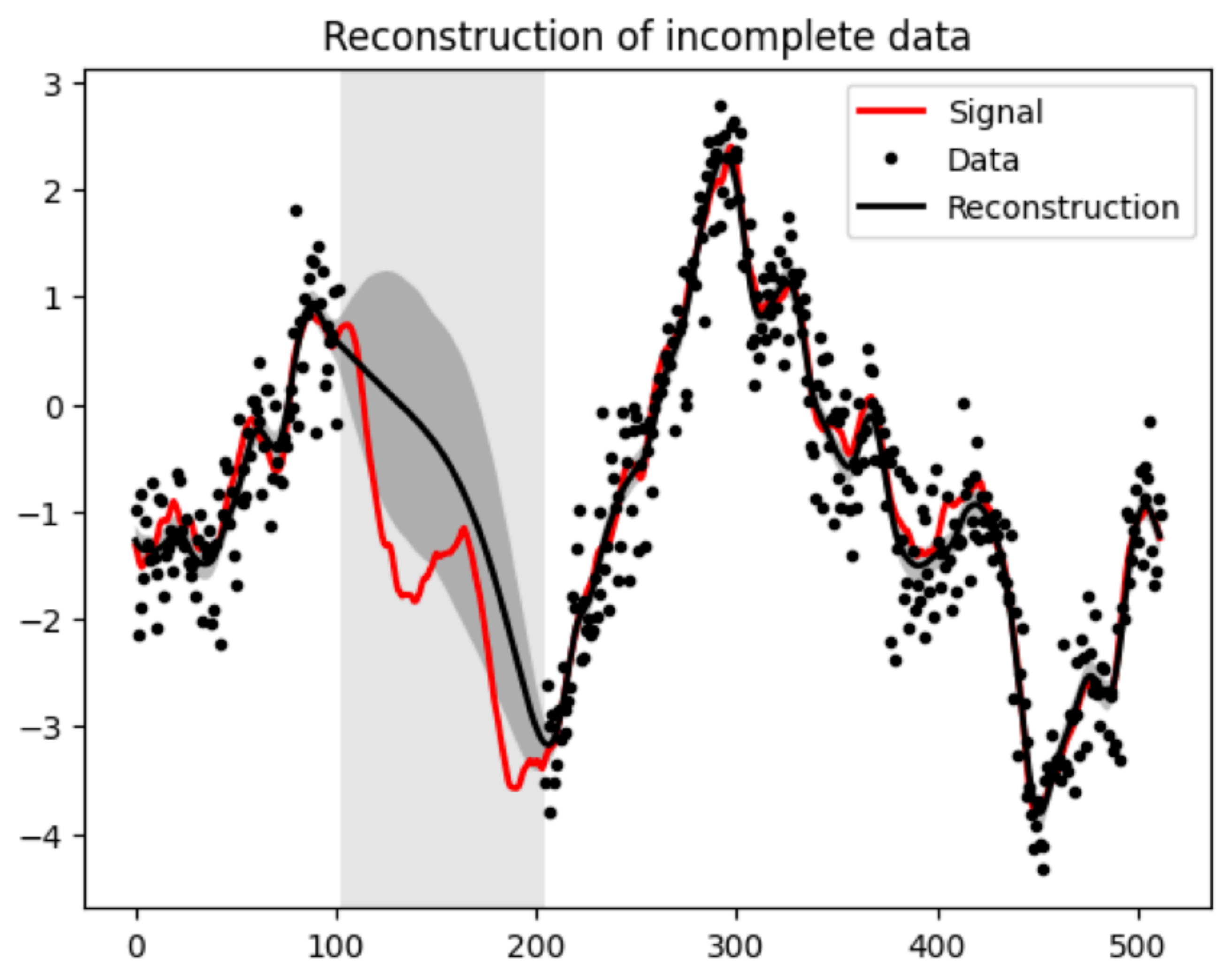
Solution: Information Field Theory!



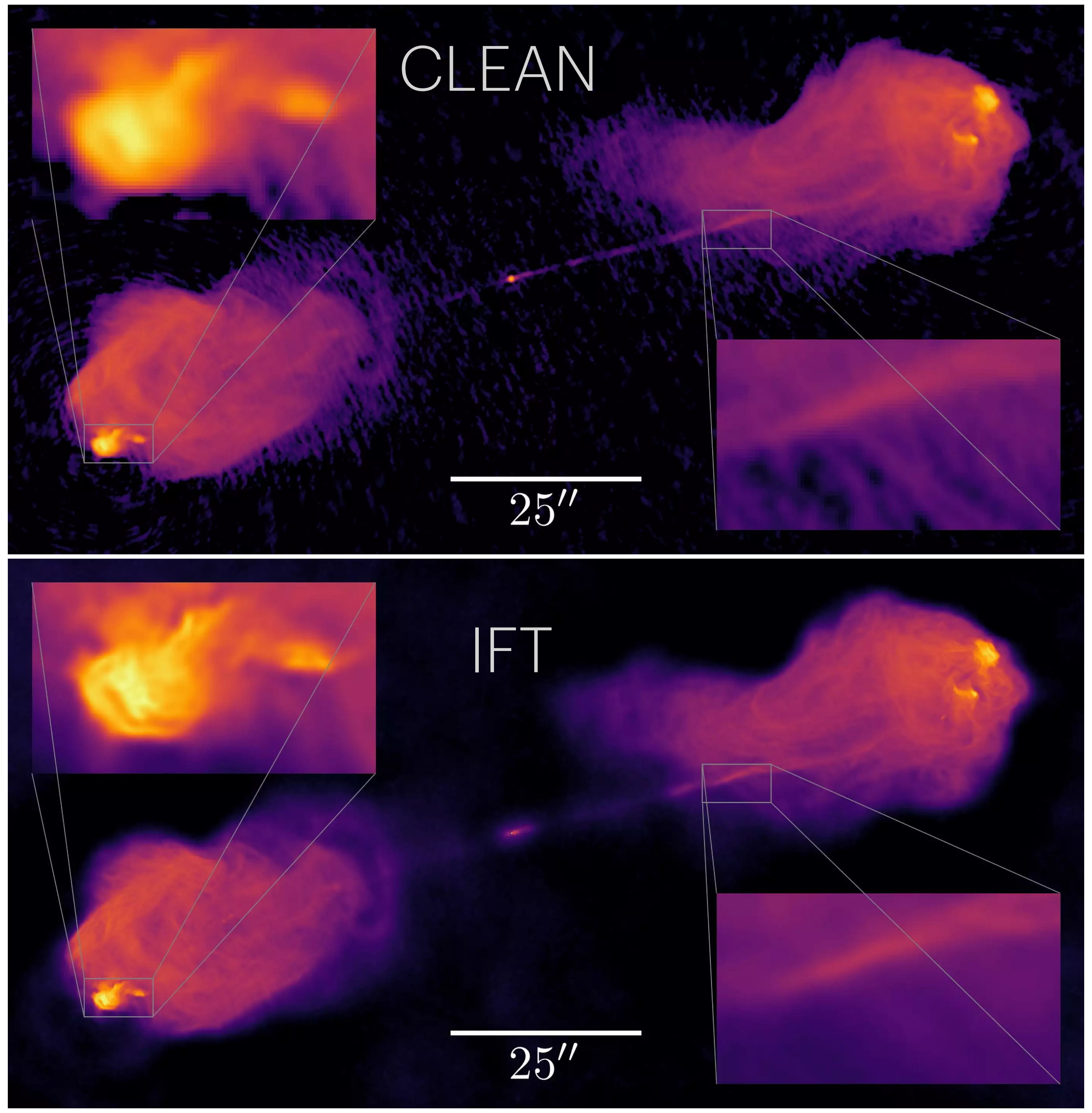
Information Field Theory (IFT)

- Bayesian framework applied on field-like structures
- Easy-to-use Pythonic interface with NIFTy
- **Requirements**: fast & invertible forward model
- More information on MPA/Ensslin/IFT

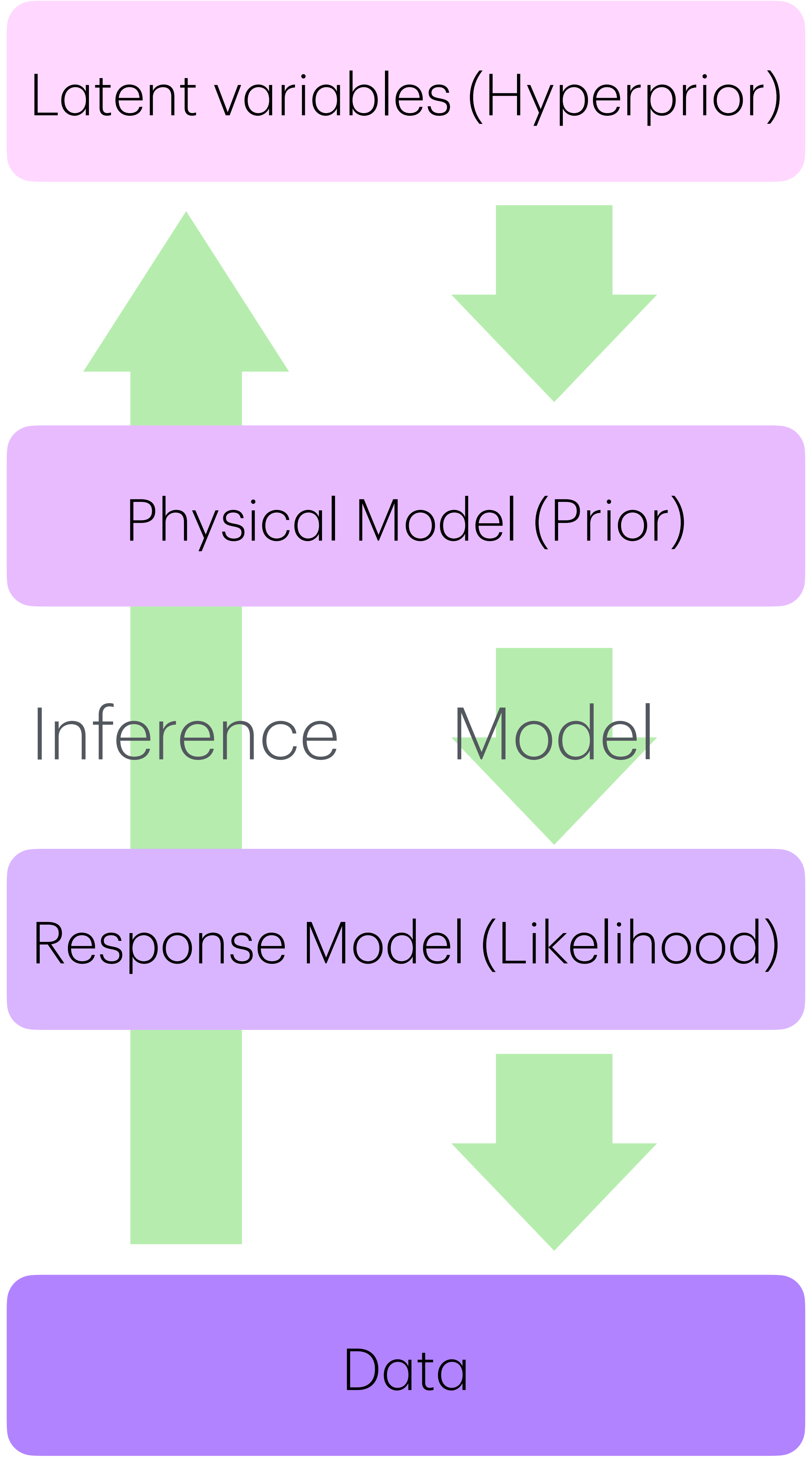


M. Straub, ARENA 2024

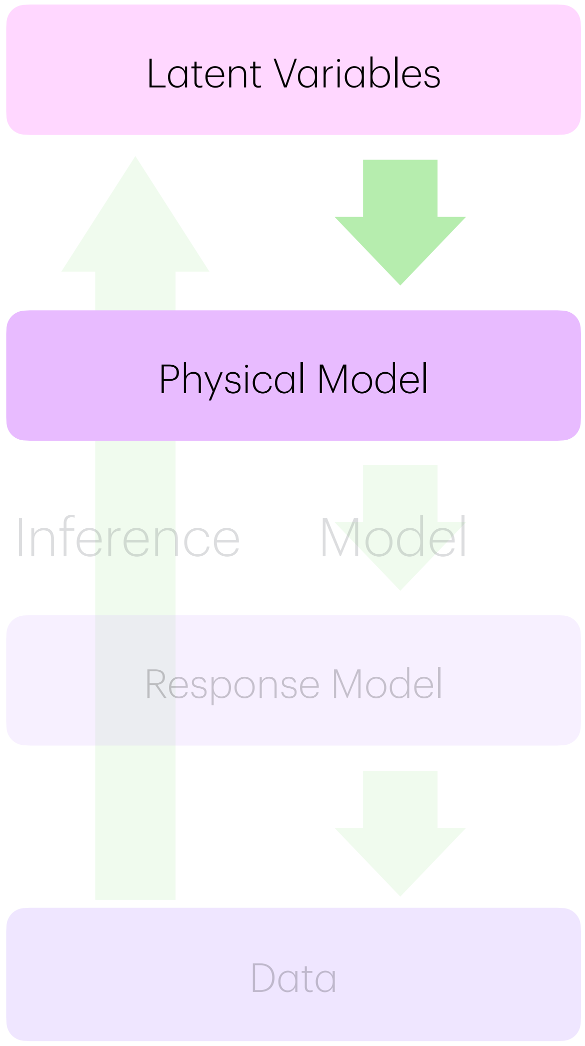
MPA; NRAO/Klasse Richard A.



Reconstruction of Cygnus A



Shower Profile Model



1. Sample **shower parameters (** $X_{\max}, N_{\max}$) from prior distributions

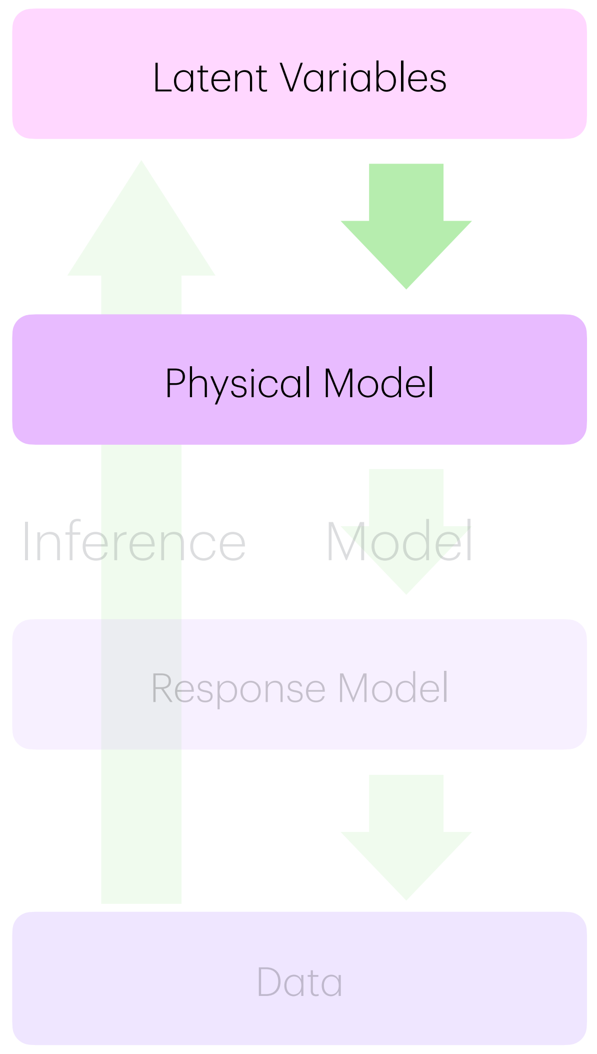
$$X_{\max} \sim \mathrm{Uniform}(\min(X_{\max}), \max(X_{\max}))$$

$$N_{\max} \sim \mathrm{LogNormal}(\mu_{N_{\max}}, \sigma_{N_{\max}})$$

$X_{\max}$: atmospheric depth at shower maximum

$N_{\max}$: number of particles at $X_{\max}$

Shower Profile Model



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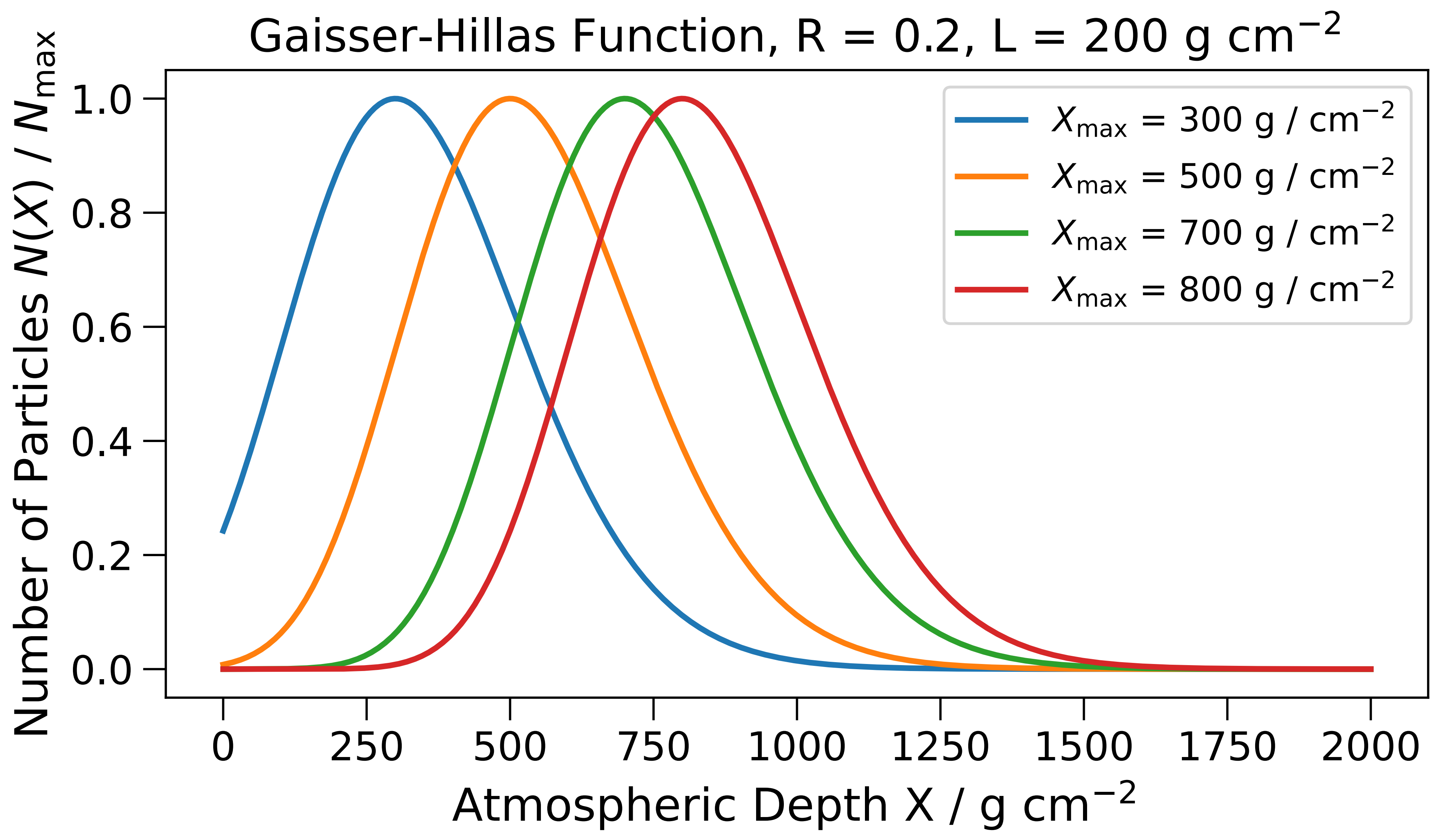


2. Describe **spatial evolution of shower** using **Gaisser-Hillas function:**

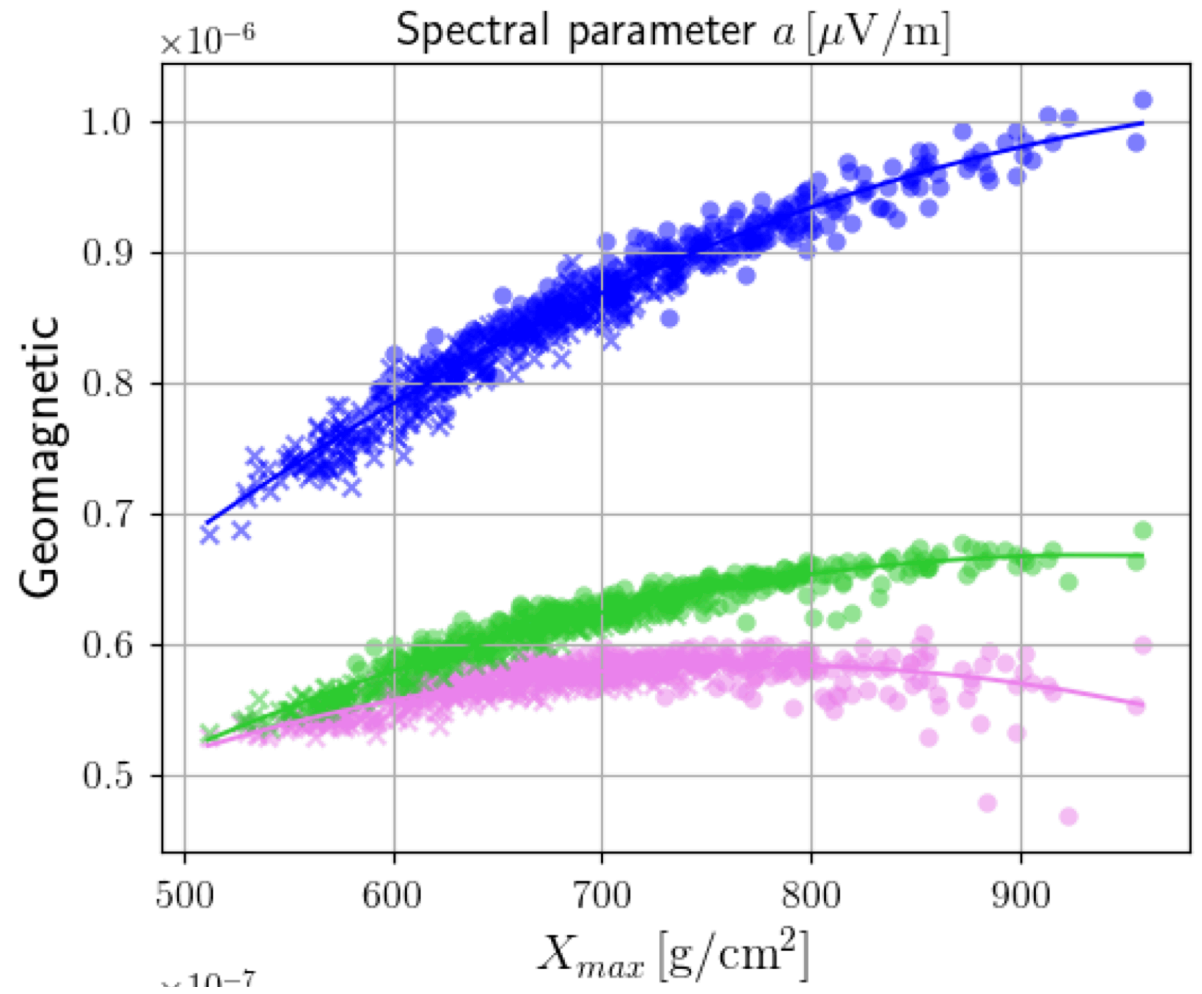
$$N(X) = N_{\max} \exp\left(\frac{X_{\max} - X}{L \cdot R}\right) \left(1 + \frac{R \cdot (X - X_{\max})}{L}\right)^{R^{-2}}$$

NB: We only consider 1-D spatial evolution for now and fix L, R parameters

Radio Emission Model

Template Synthesis (Desmet+ 2024)

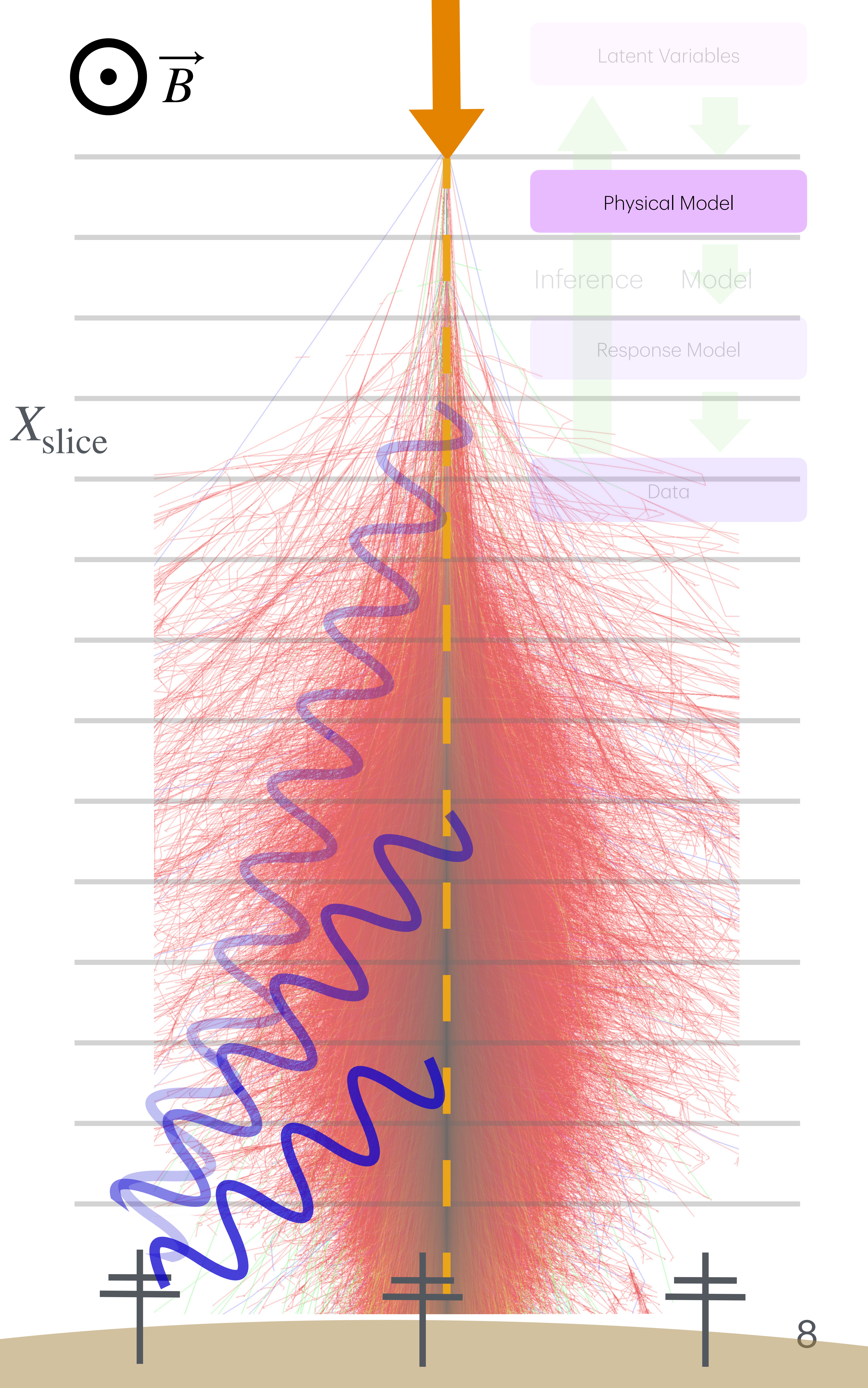
1. Parametrise relations between showers using MC simulations for each **atmospheric slice** X_{slice} & antennas



Spectral Parameter a computed from MC simulations at X_{slice}, $X_{\max}$ and $\vec{r}_{\mathrm{ant}}$

$d_{\mathrm{core}} = 75\,\mathrm{m}$ **[50, 200] MHz**

Desmet et al. 2024, Astroparticle Physics, 157, 102923



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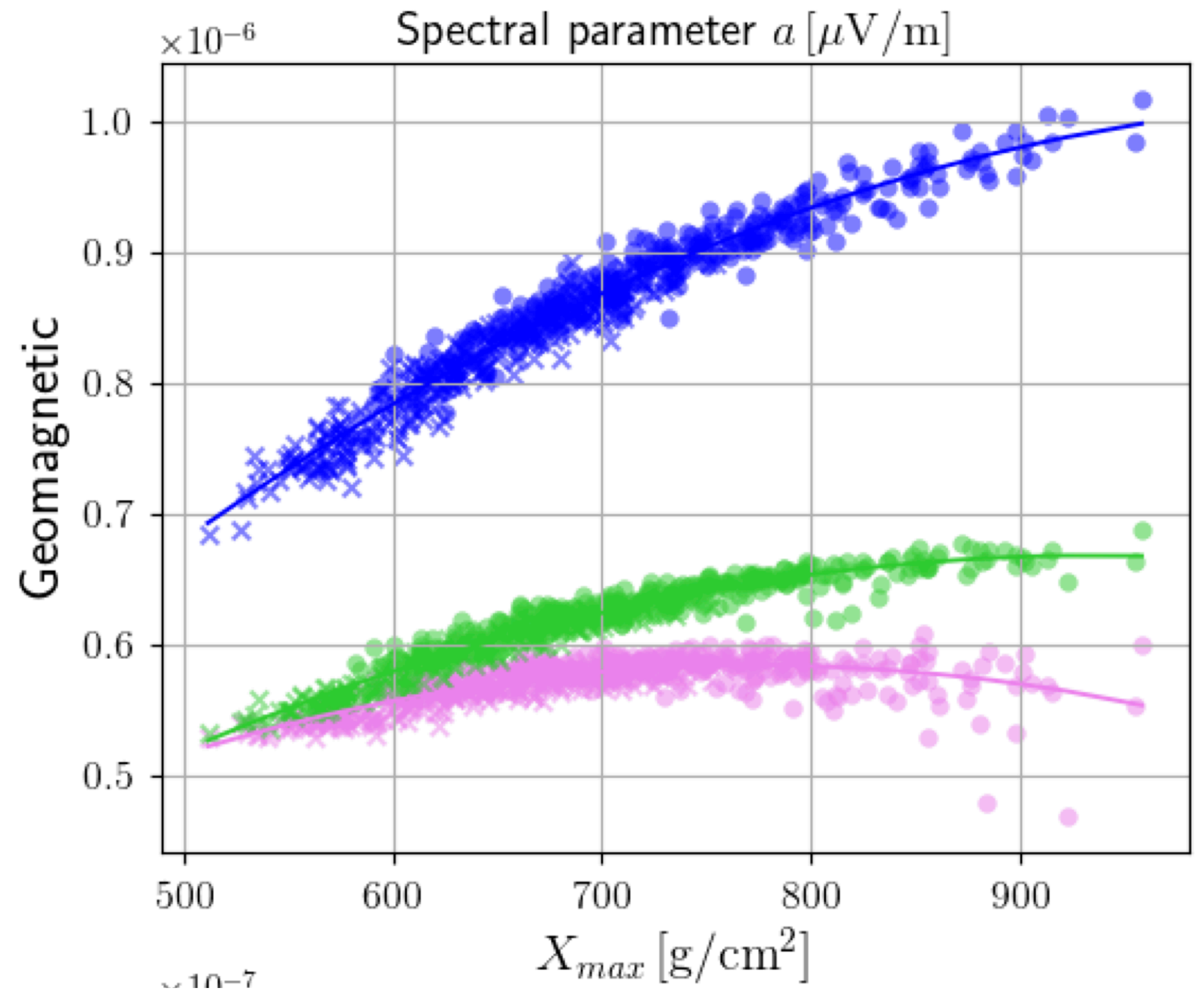
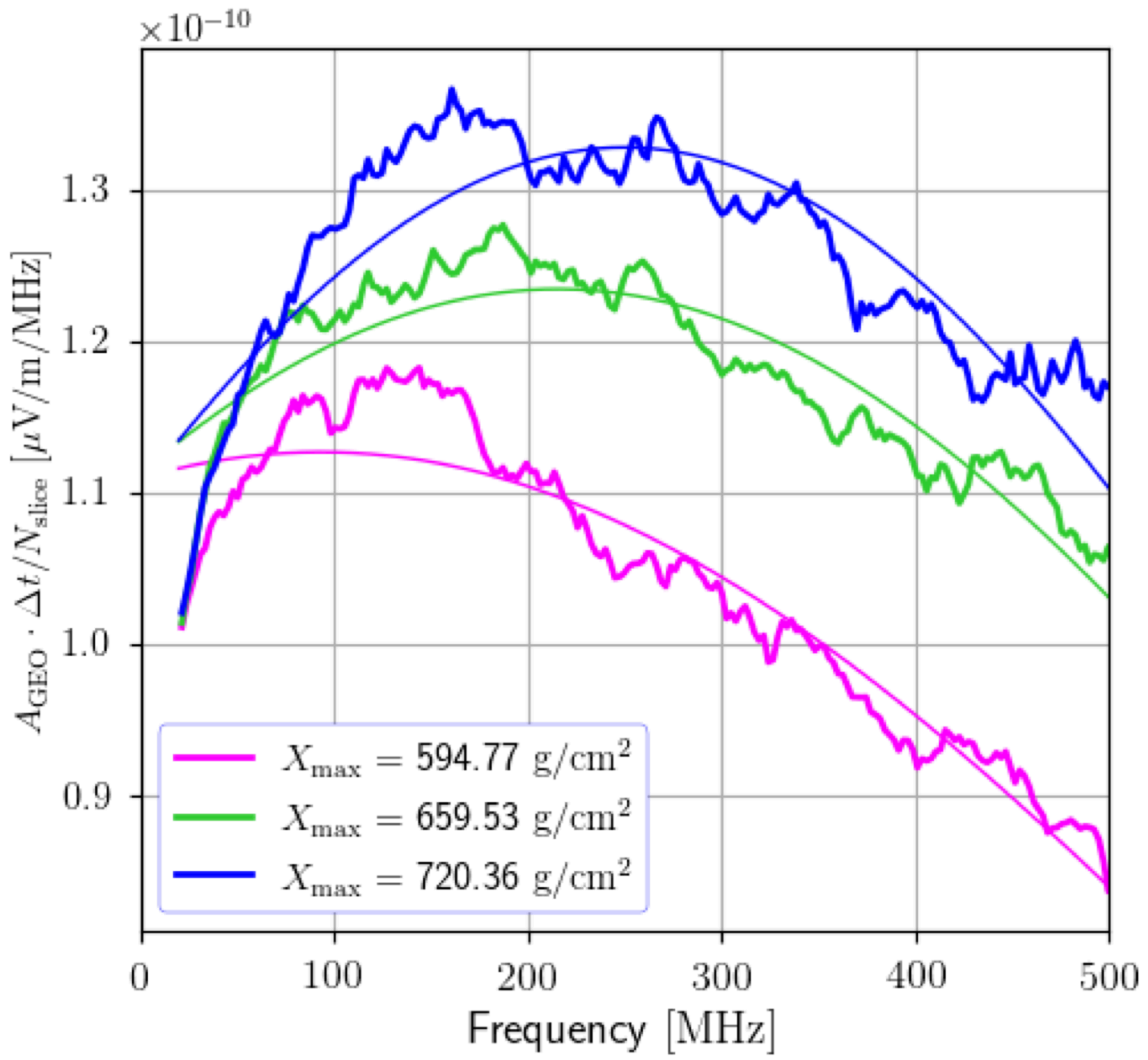


Spectral Parameter a computed from MC simulations at X_{slice}, $X_{\max}$ and $\vec{r}_{\text{ant}}$

$d_{\text{core}} = 75$ m **[50, 200] MHz**

Amplitude spectrum computed from spectral parameters at $X_{\text{slice}} = 600 \text{ g cm}^{-2}$



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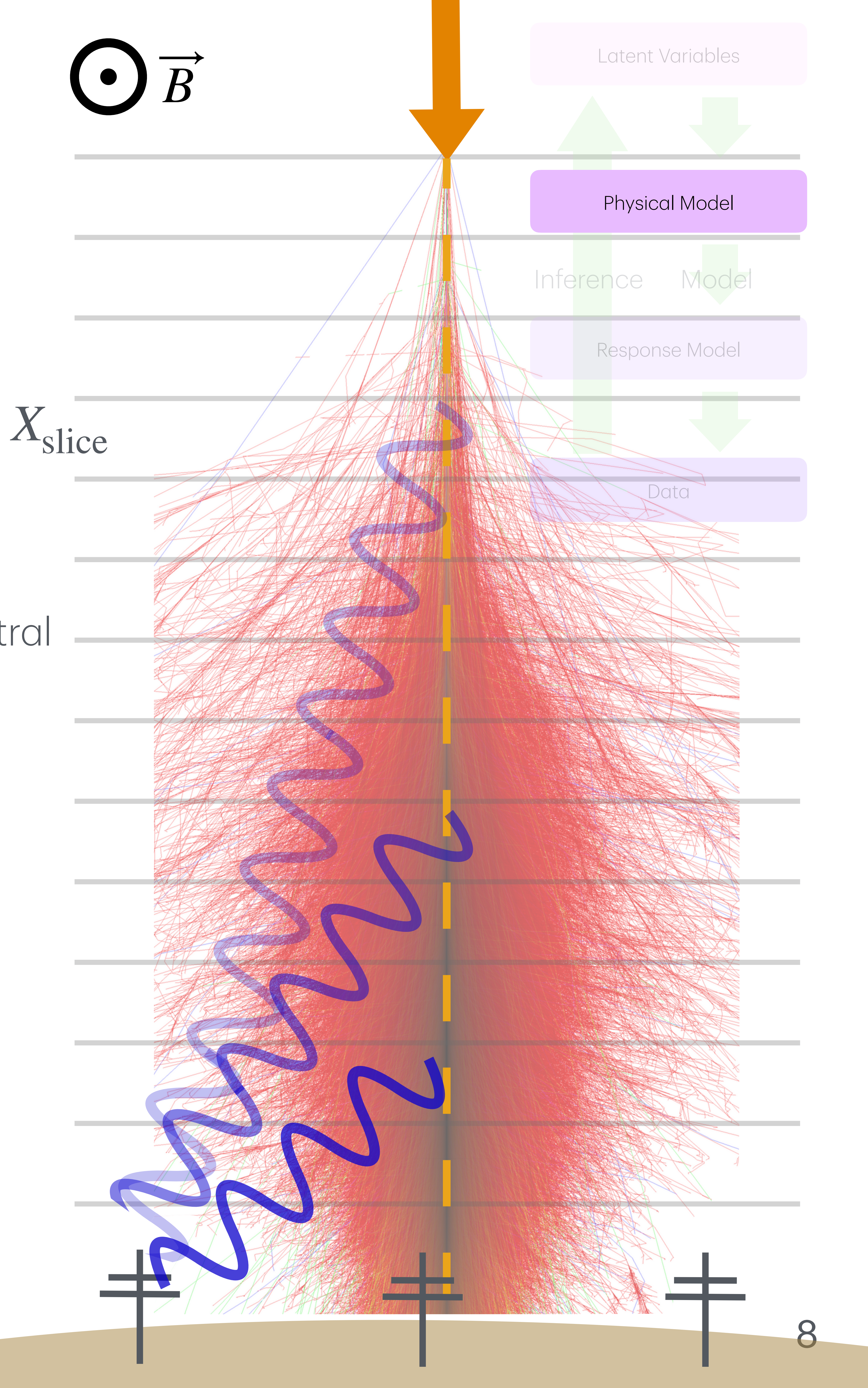

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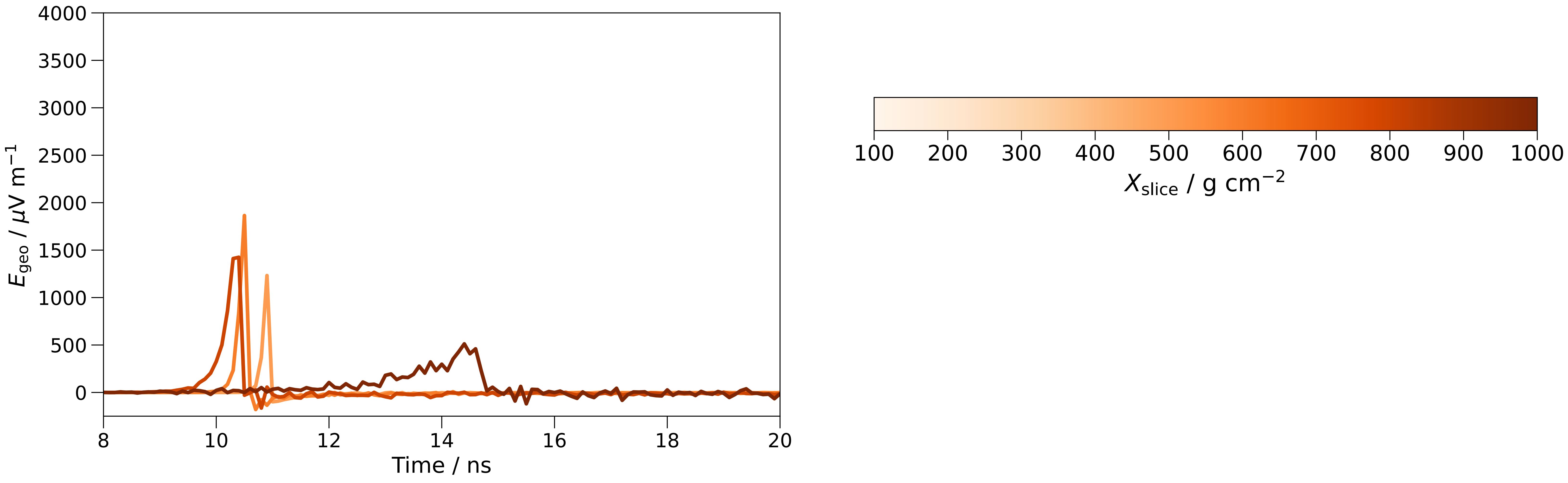
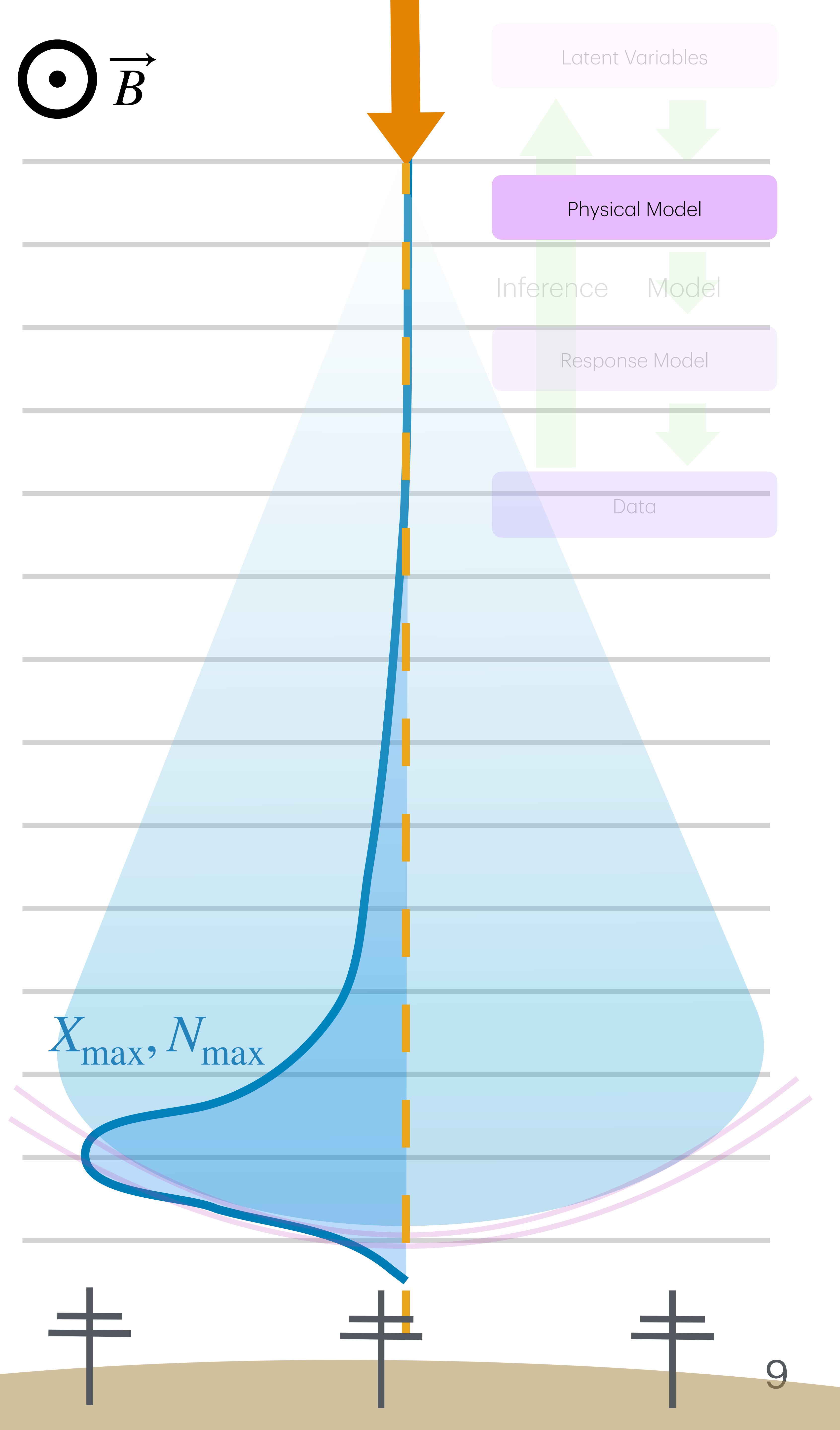
2. Calculate amplitude spectrum from **simulated traces** of an **origin shower** for each slice & antenna



Electric field traces of origin shower

$d_{core} = 75\,\mathrm{m}$ **[30, 80] MHz**



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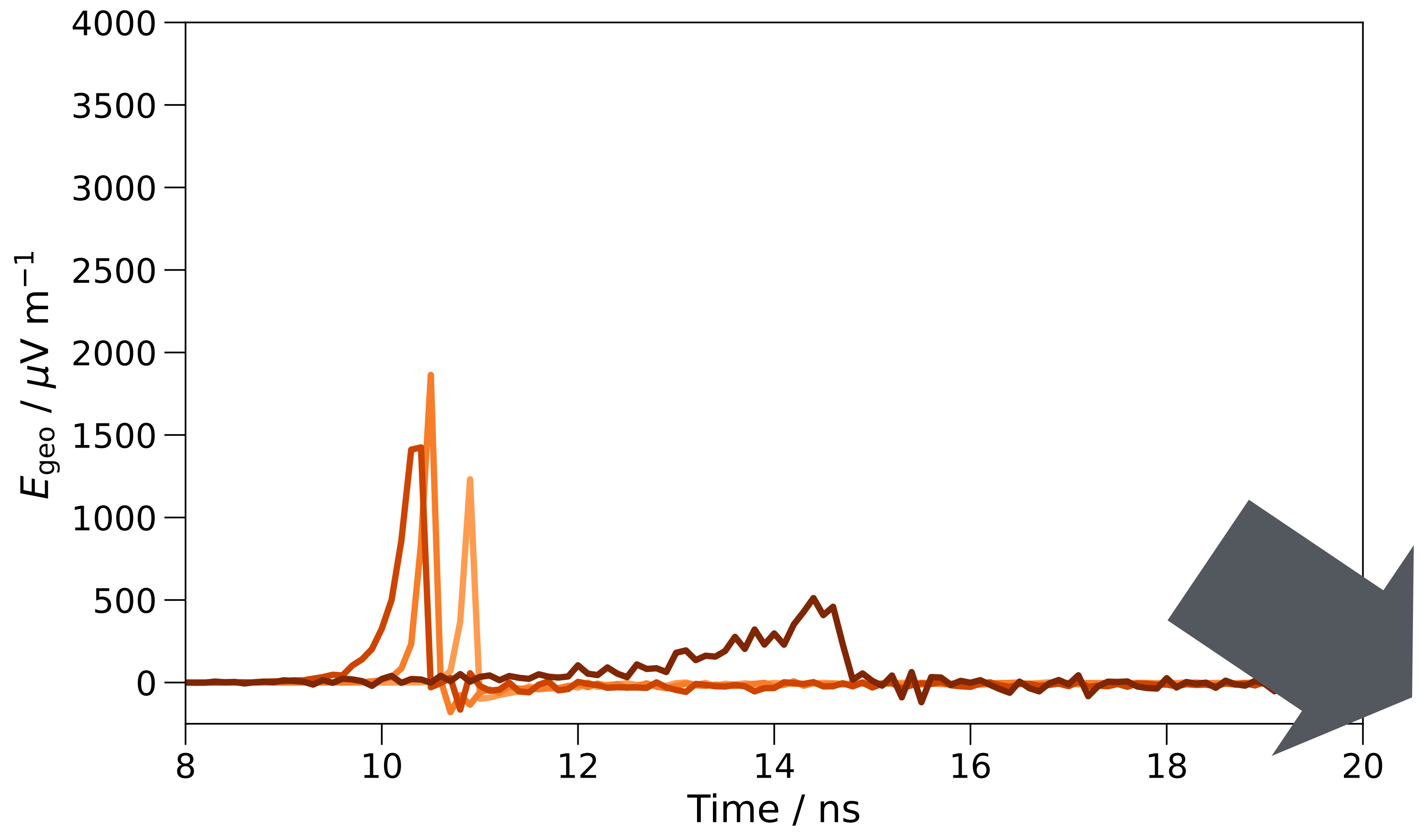

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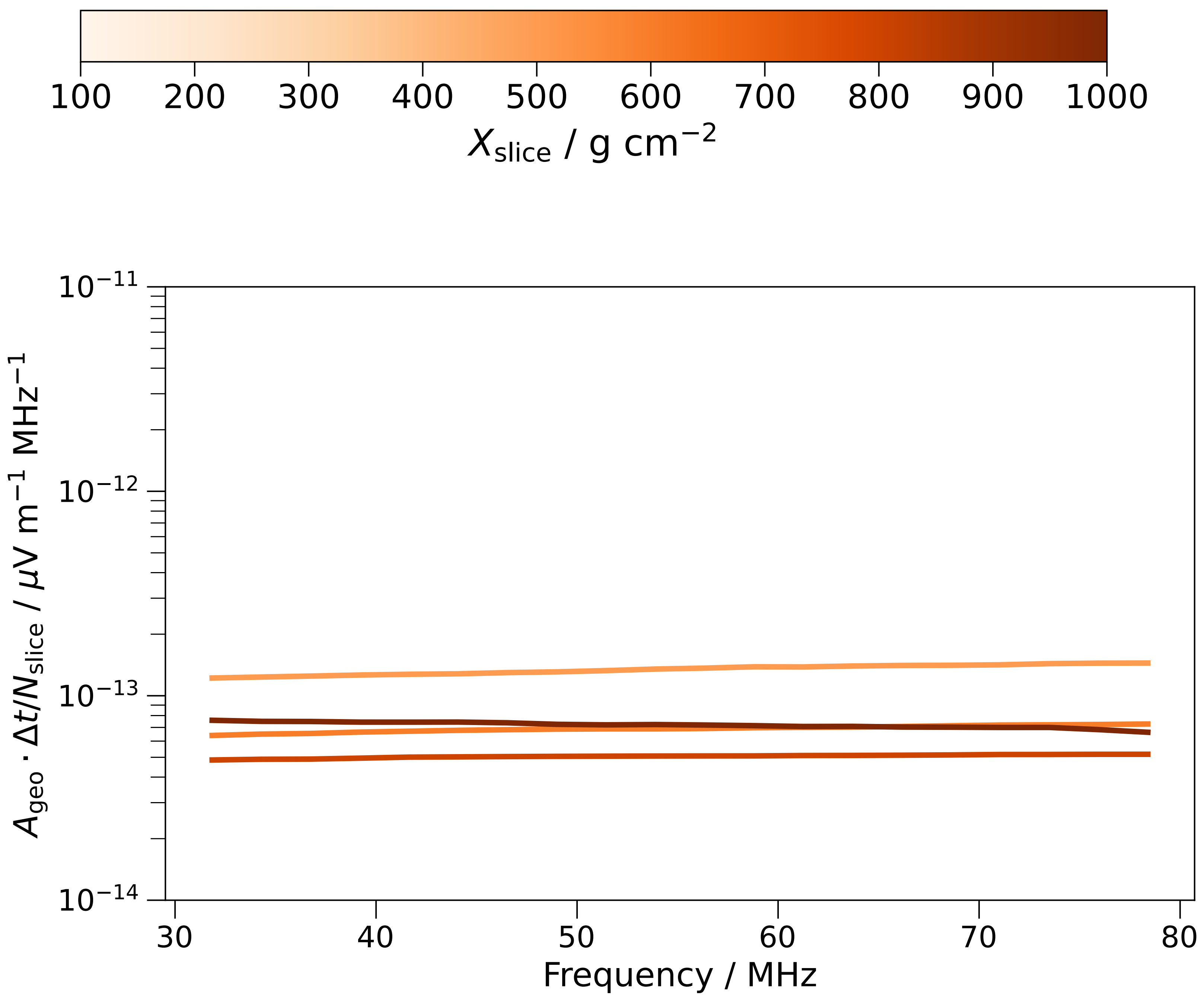

Amplitude spectrum

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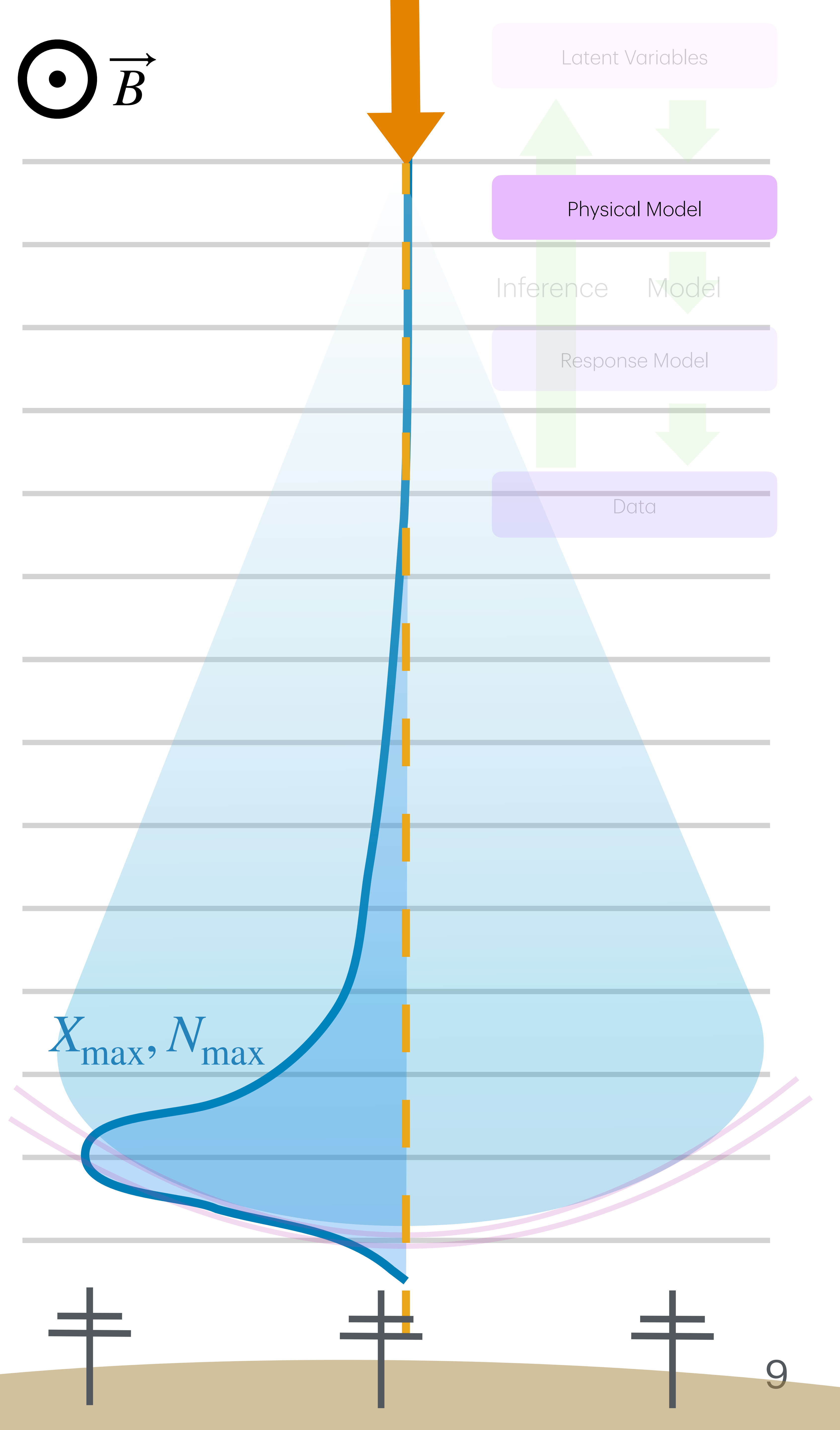
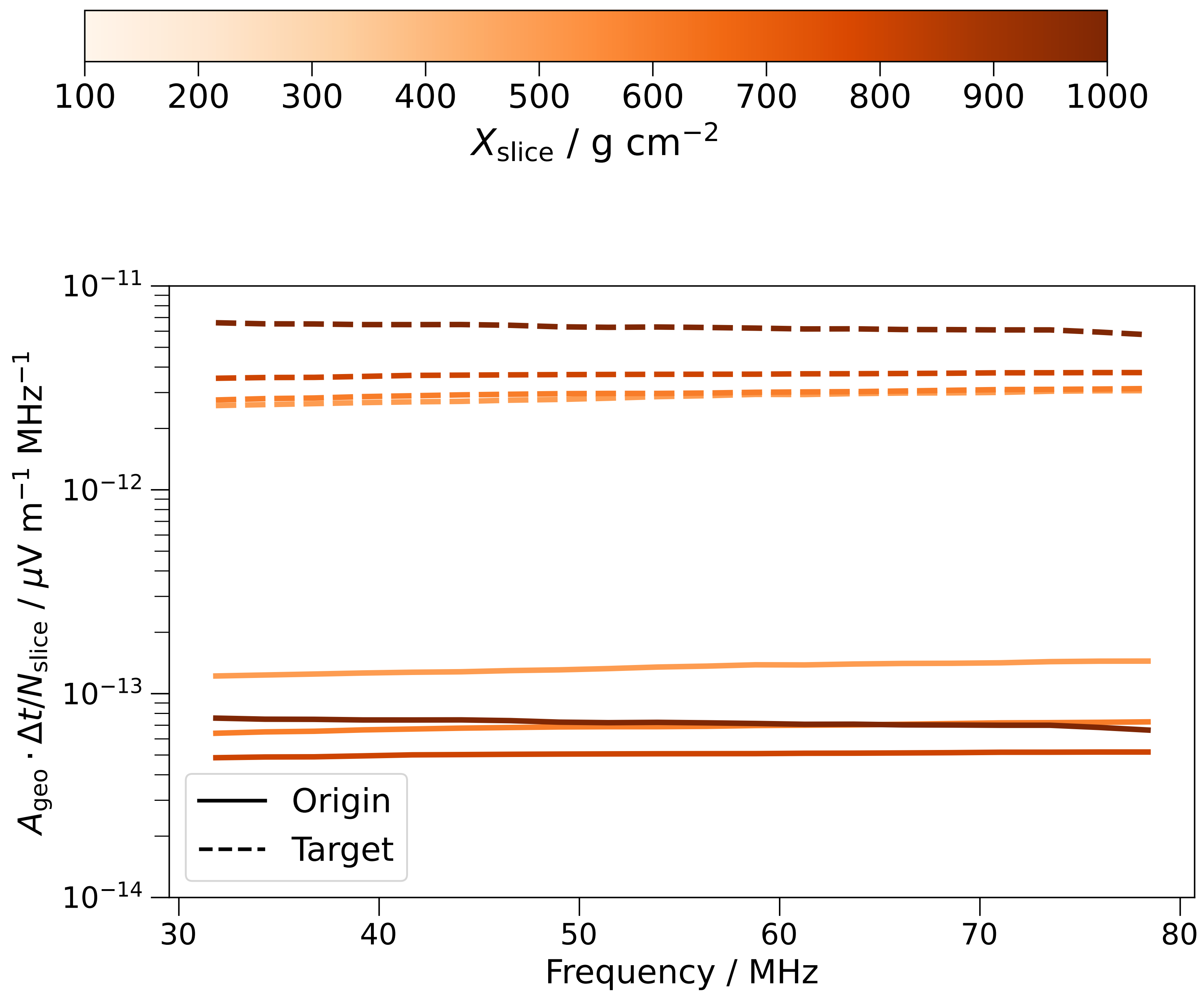


Radio Emission Model

Template Synthesis (Desmet+ 2024)

3. Synthesise emission from **target shower** using relations with origin shower



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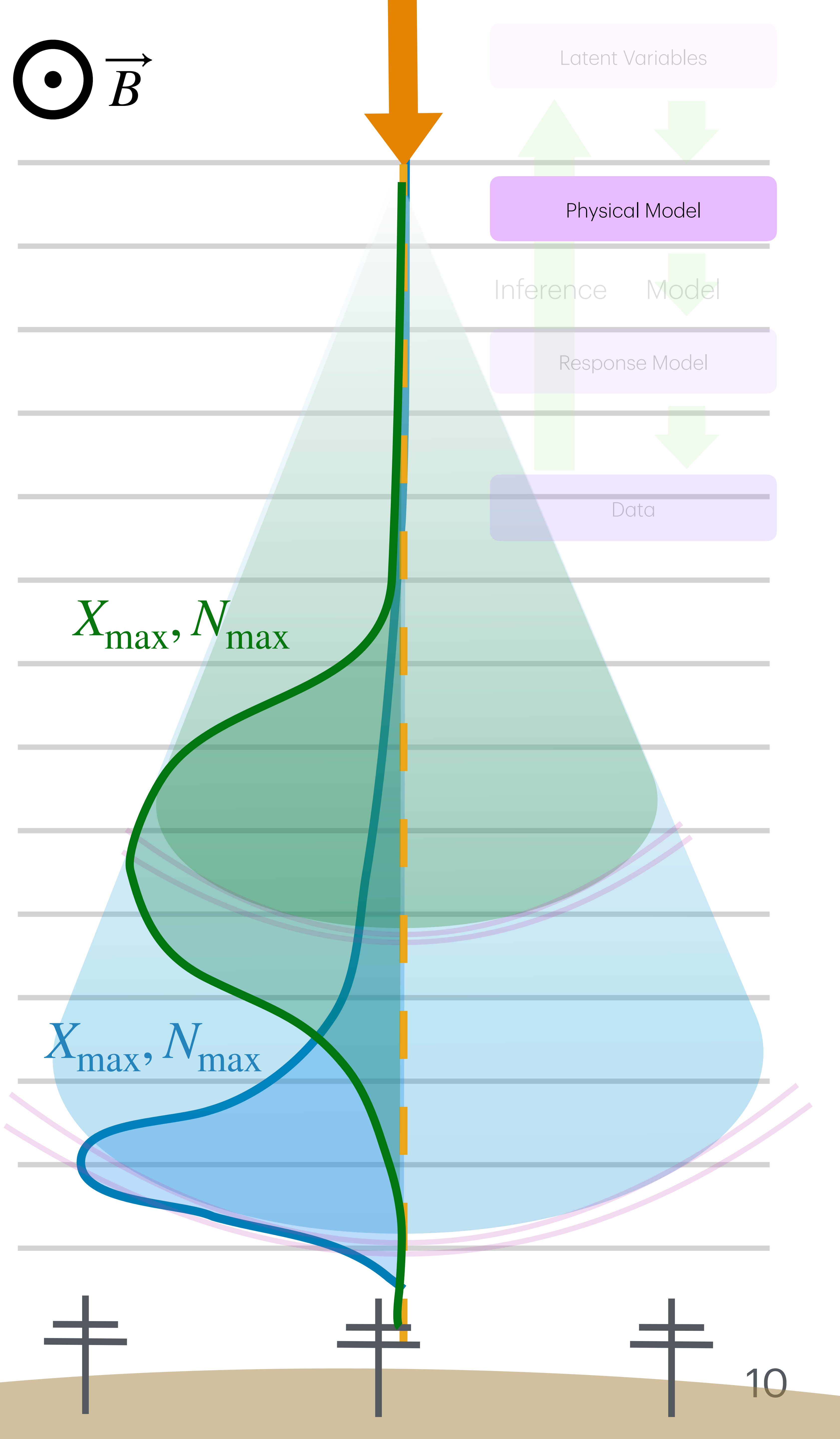

Solid: Origin Shower
Dashed: Target Shower

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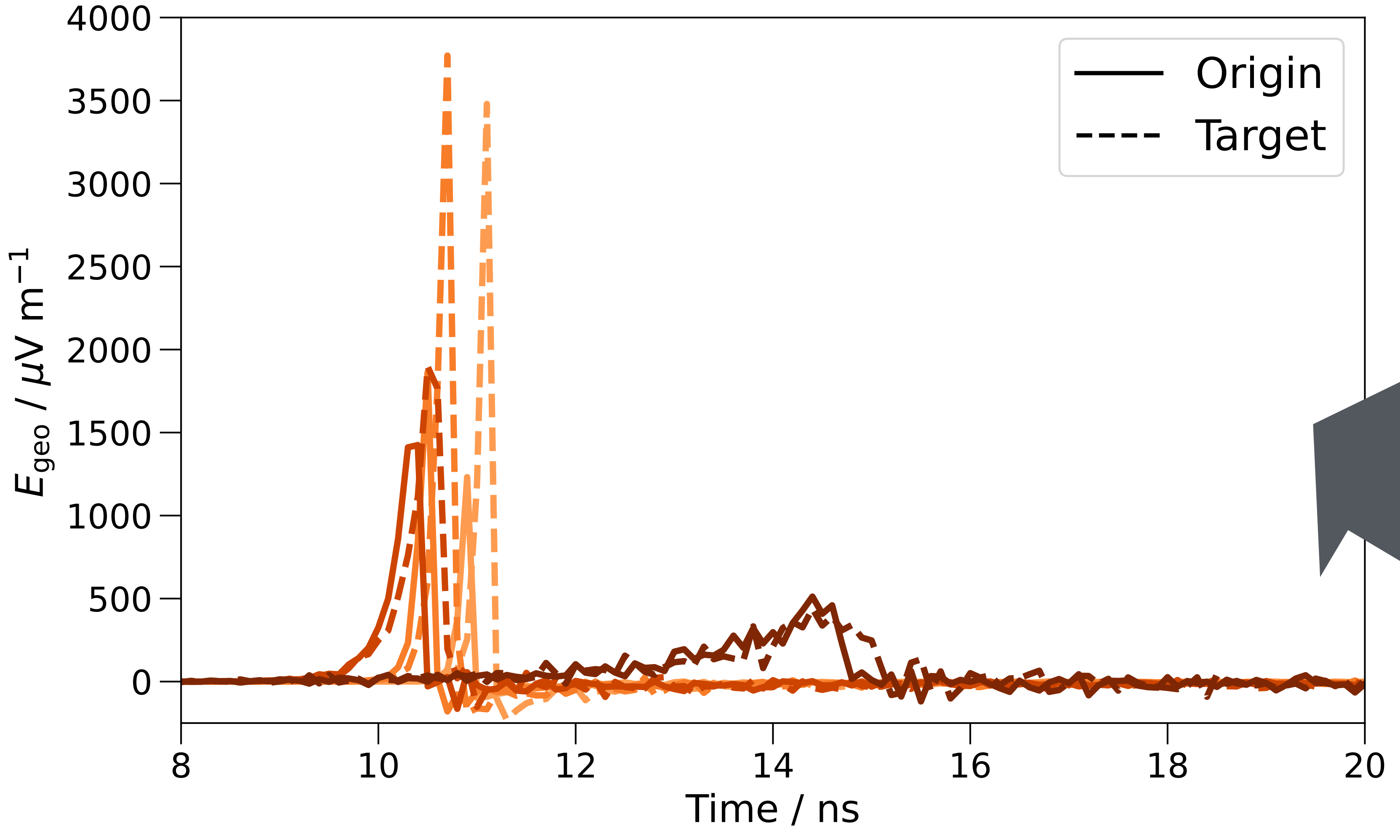

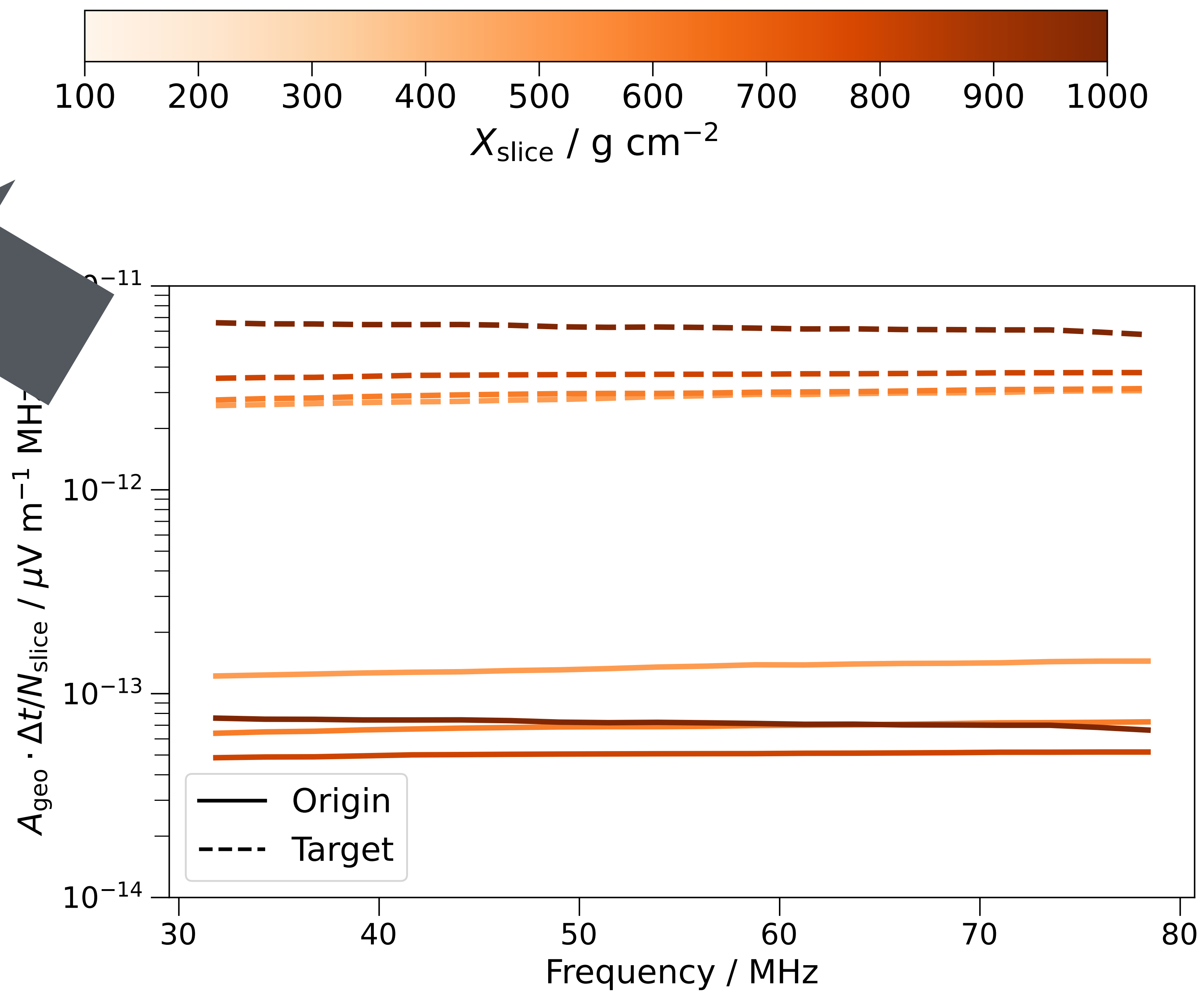

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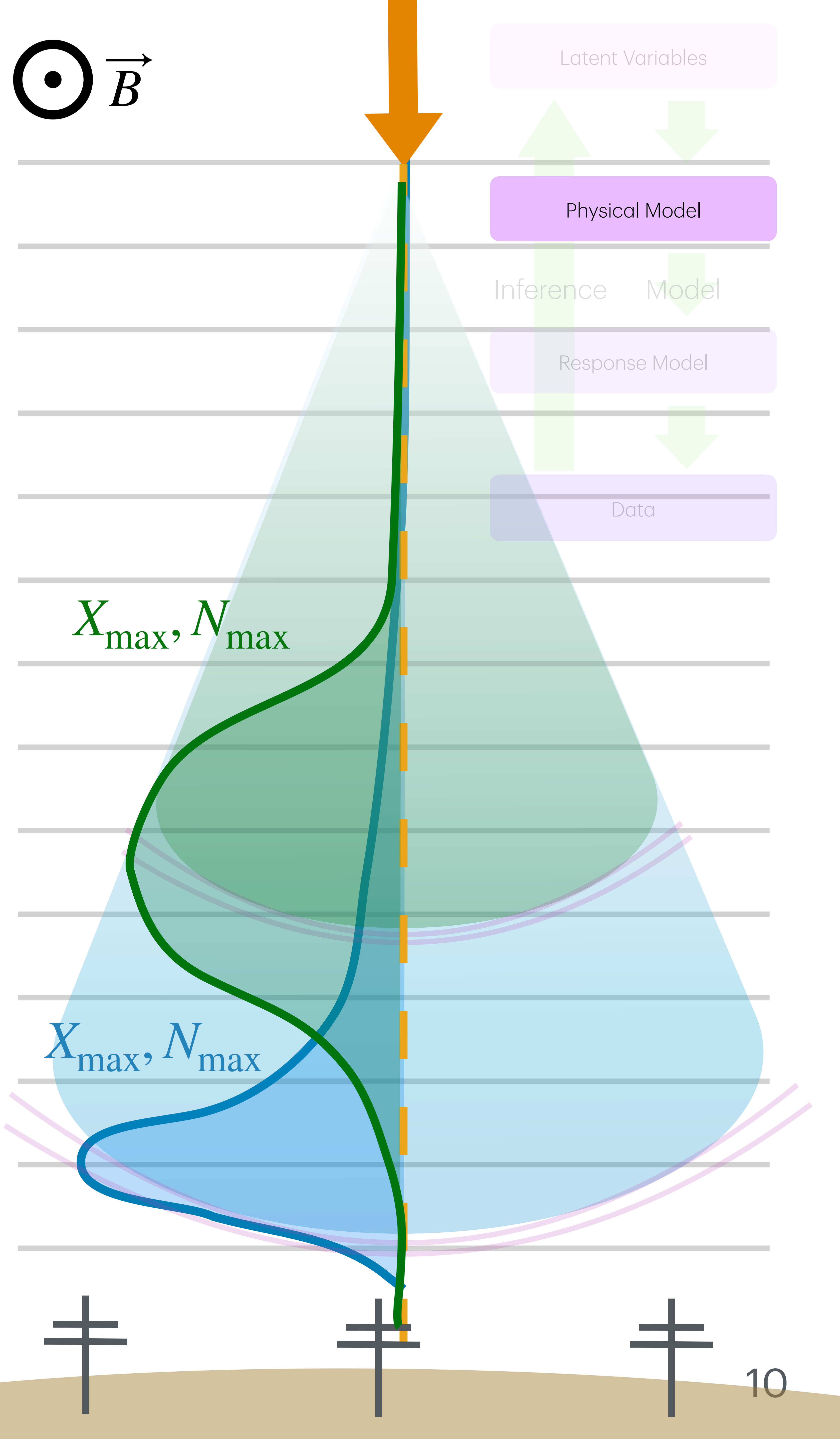
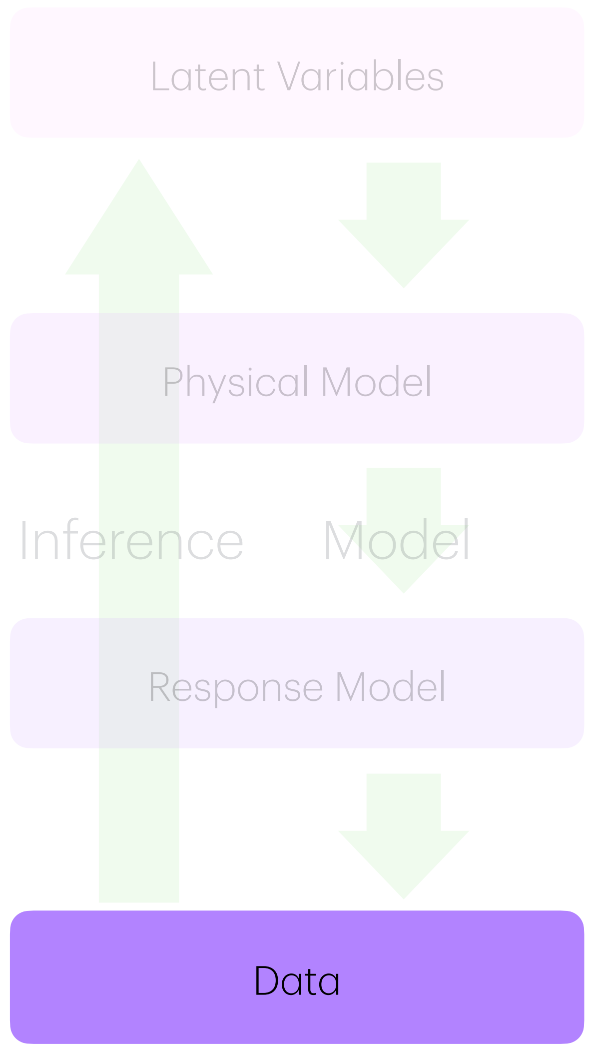
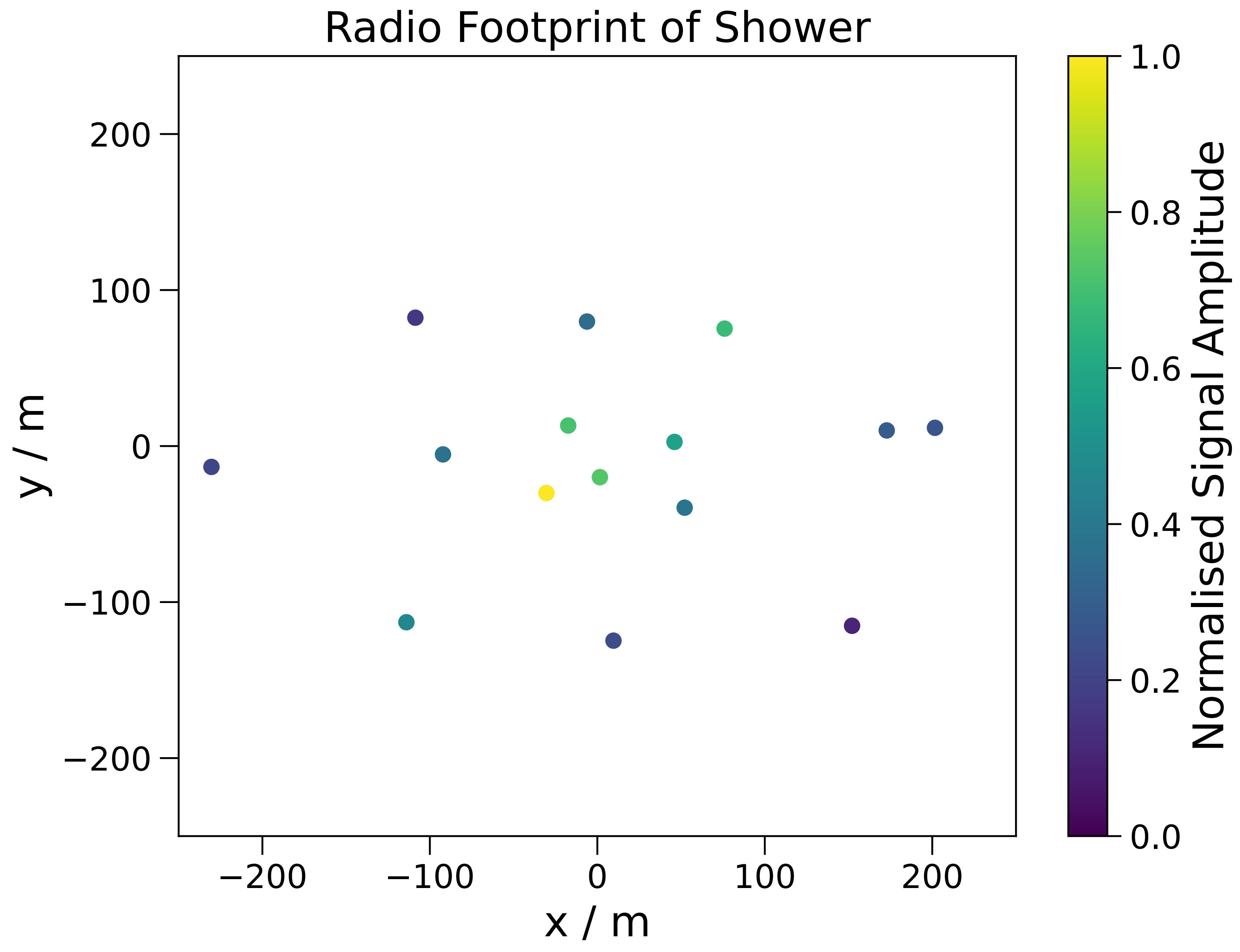


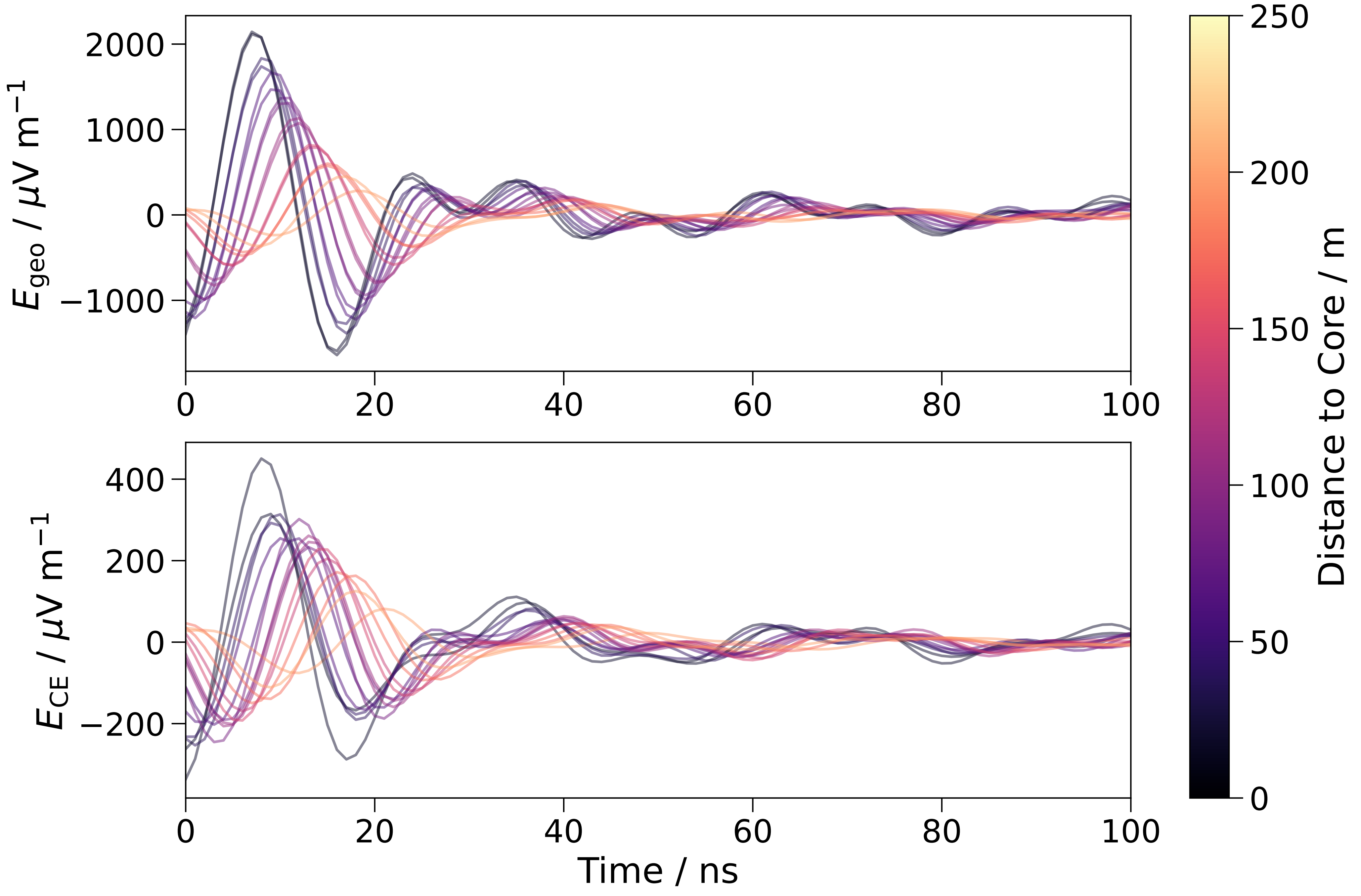
Verification with Synthetic Data



- **Synthetic data** in **[30, 80] MHz** band, **16 antennas** following star-shape pattern with $\Delta t = 1$ ns
- **Noise** added through covariance matrix:
  - **3%** of maximum amplitude from **all** antennas (calibration uncertainty)
  - **5%** of maximum amplitude from **each** antenna (antenna-to-antenna uncertainty)



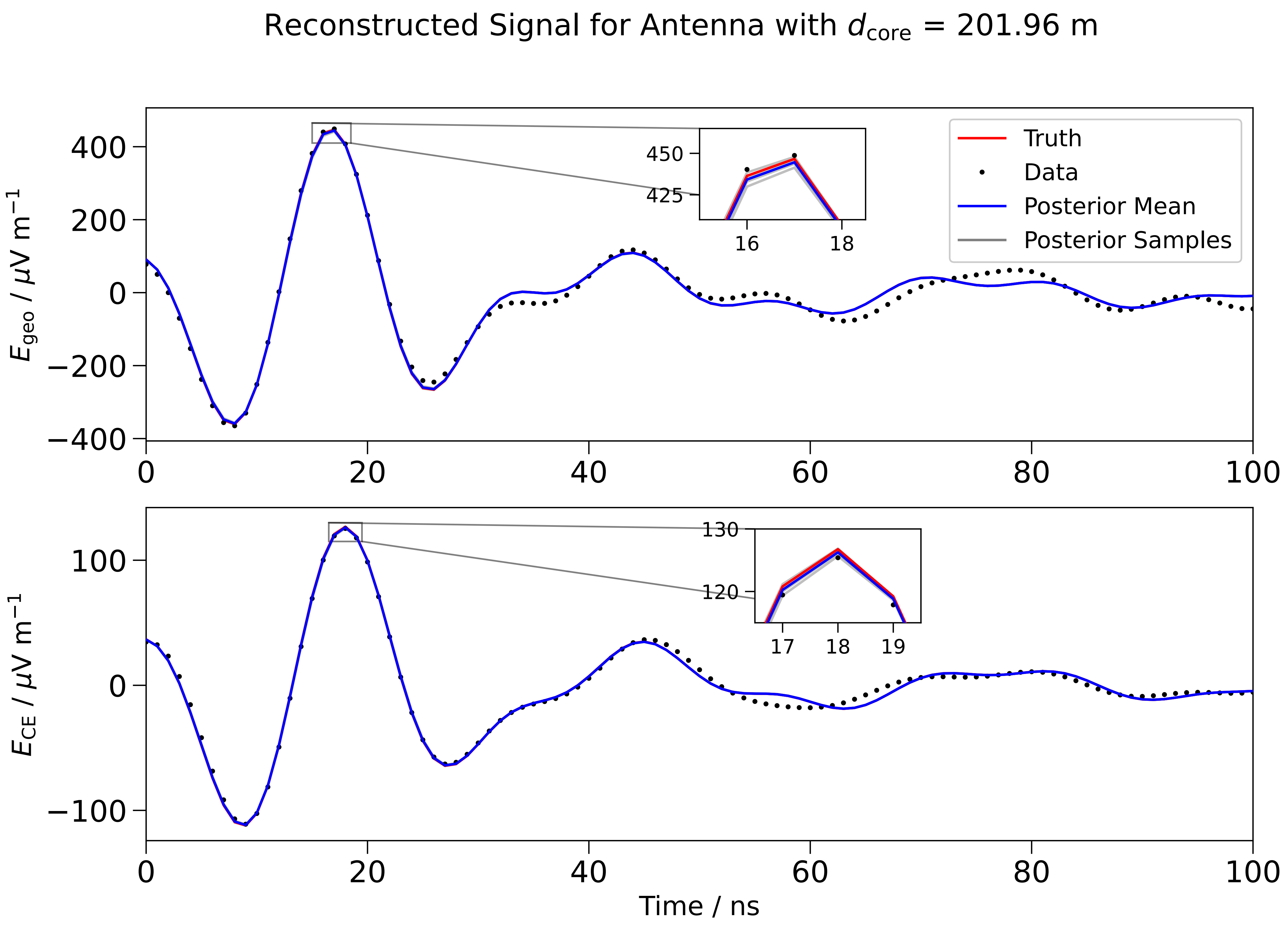
Radio Footprint of Shower

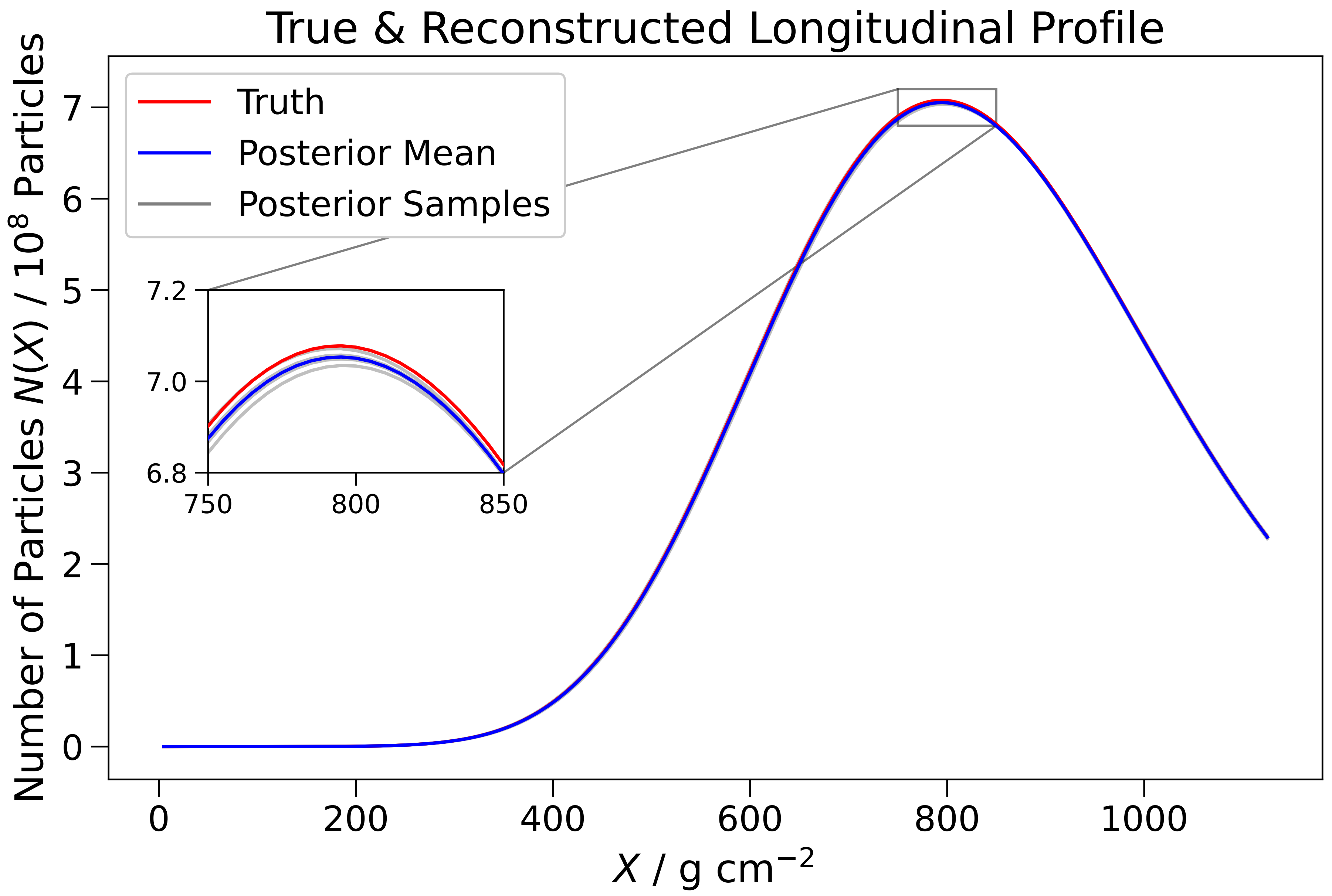


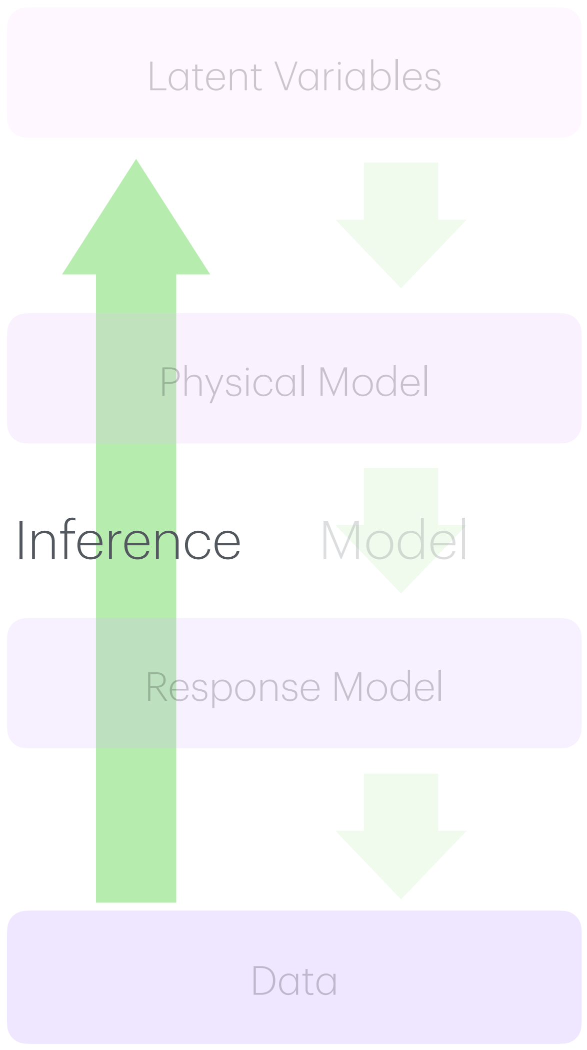
Electric Field Traces of Shower

Verification with Synthetic Data

- Shower parameters reconstruct well as expected
- Can also reconstruct shower profile / traces from shower parameters







	Truth	Reconstructed	Δ
X_{max} / g cm^{-2}	794.2	794.6 ±1.4	-0.38
N_{max} / 10^8	7.078	7.056± 0.016	0.025

Keito Watanabe, Radio 2024

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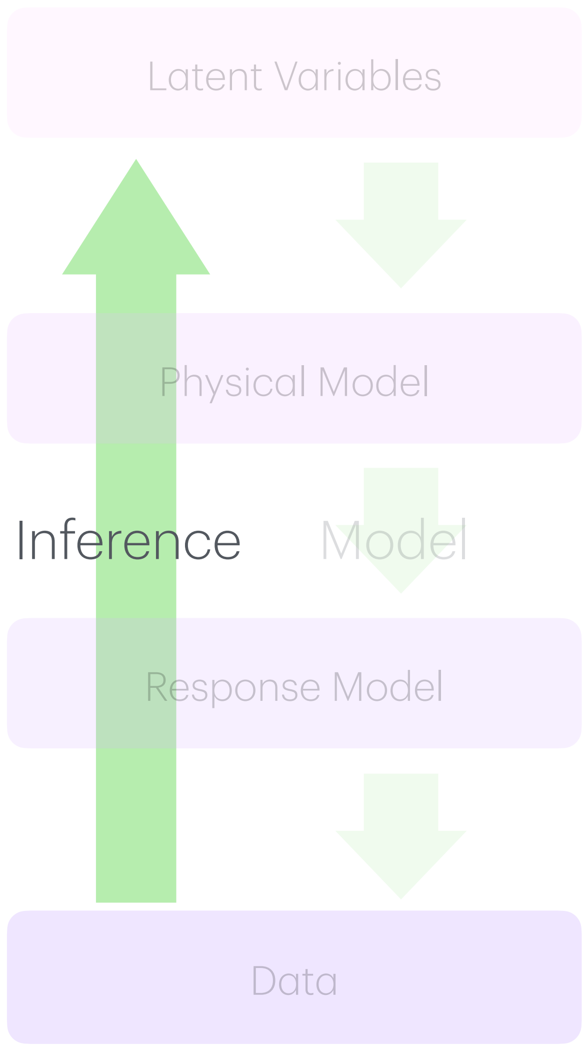
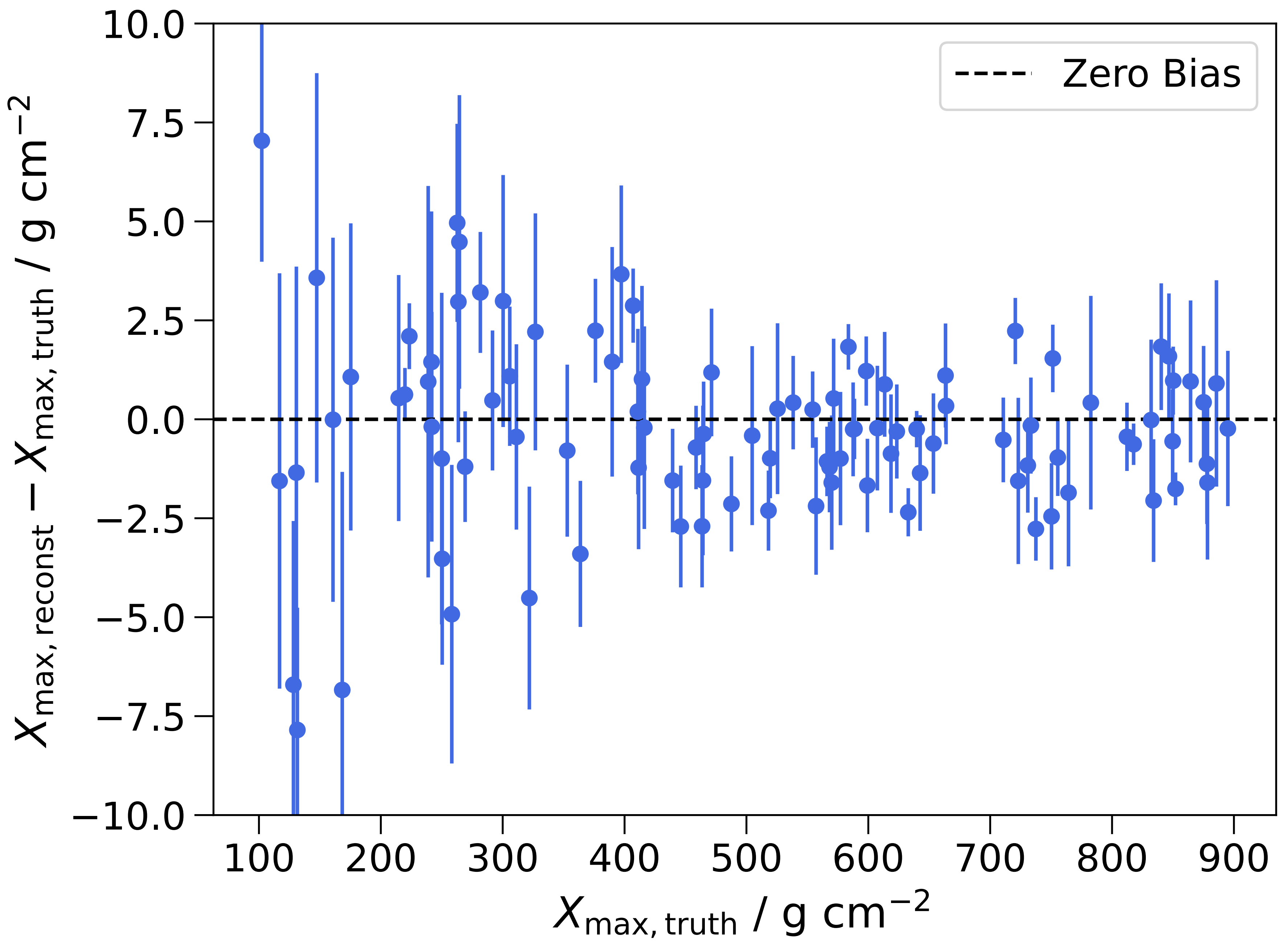
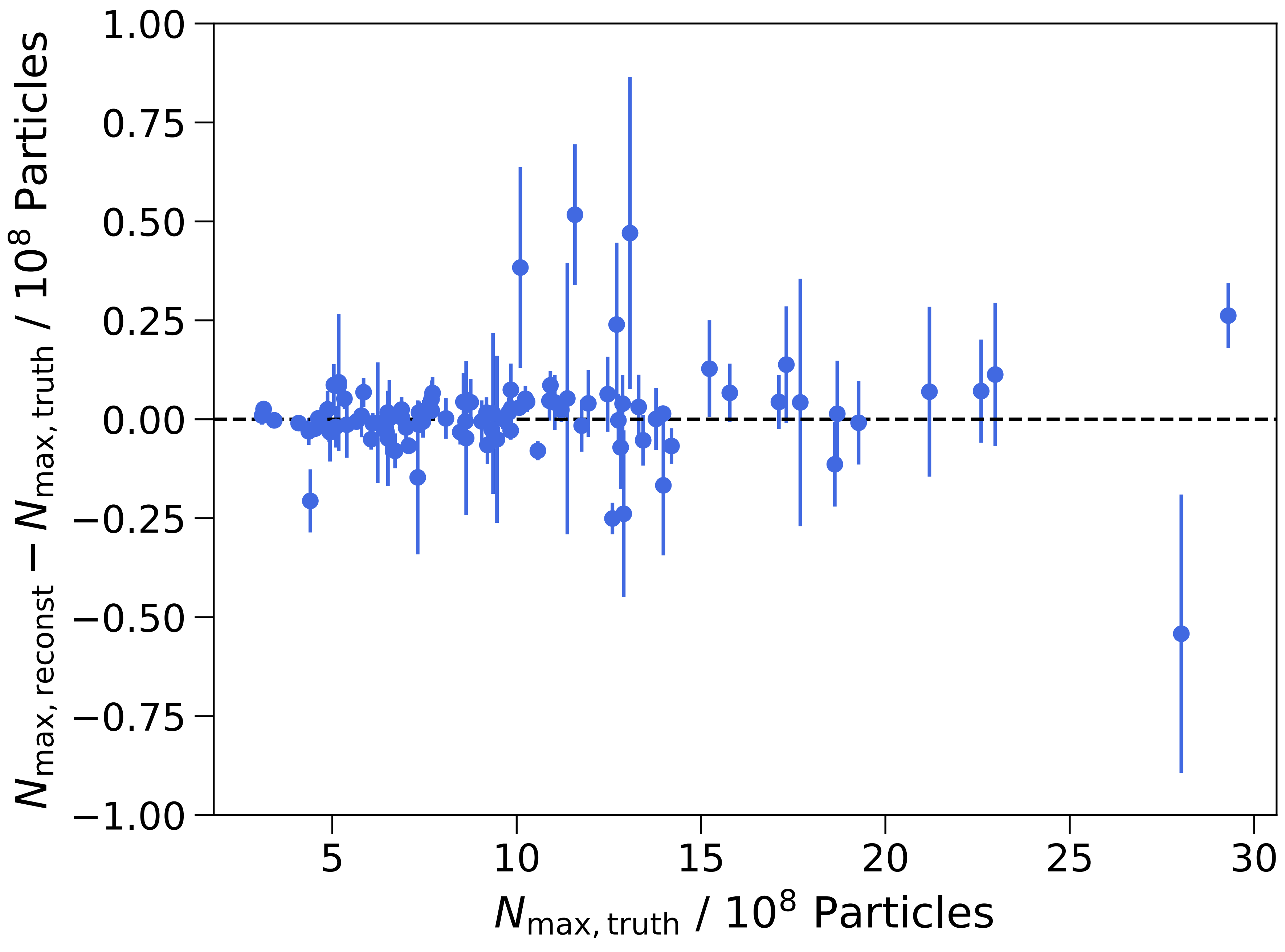


- Testing reconstruction bias with 100 synthetically generated showers

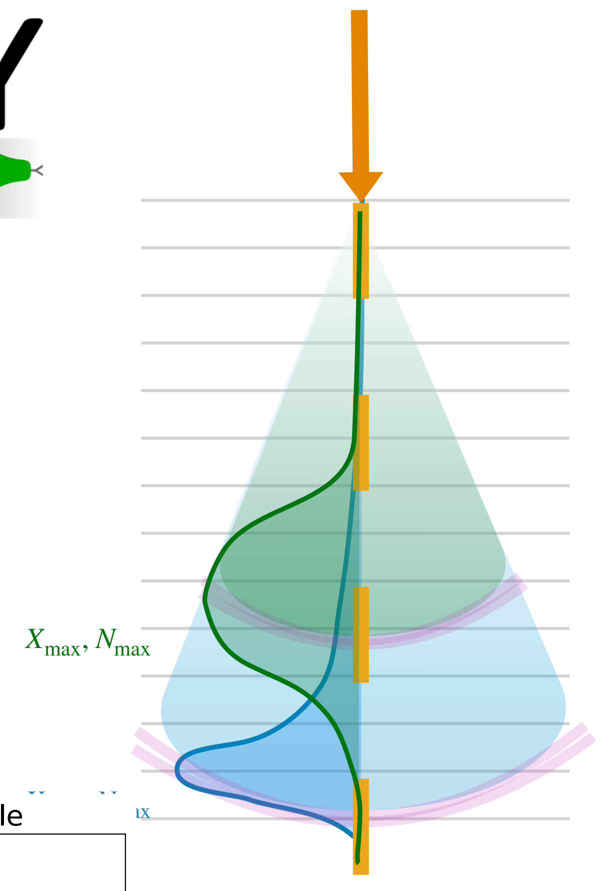




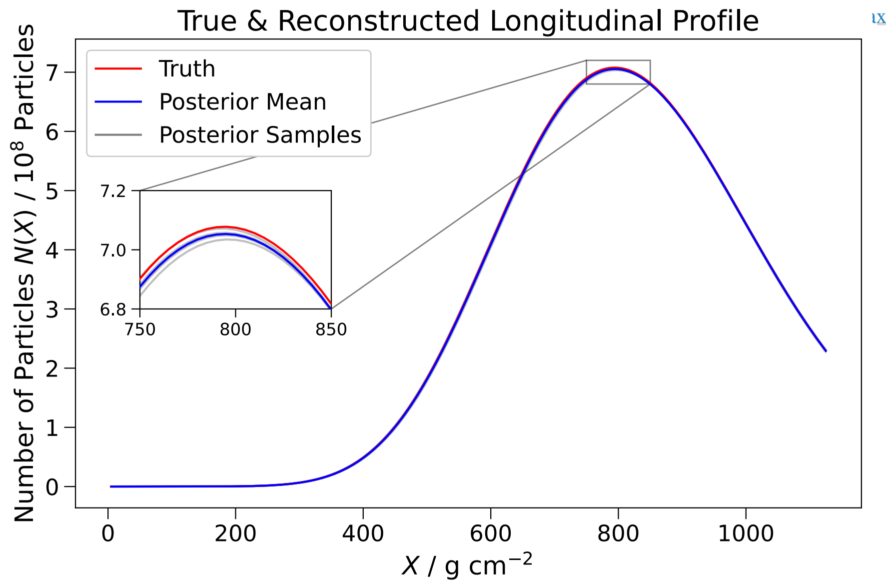
X_{max} reconstruction bias of $\lesssim 8$ g cm^{-2}, comparable with classical reconstruction methods

$\Longrightarrow$ but need to include antenna response & realistic noise model for further interpretation (see K. Terveer's talk)

Conclusion & Outlook

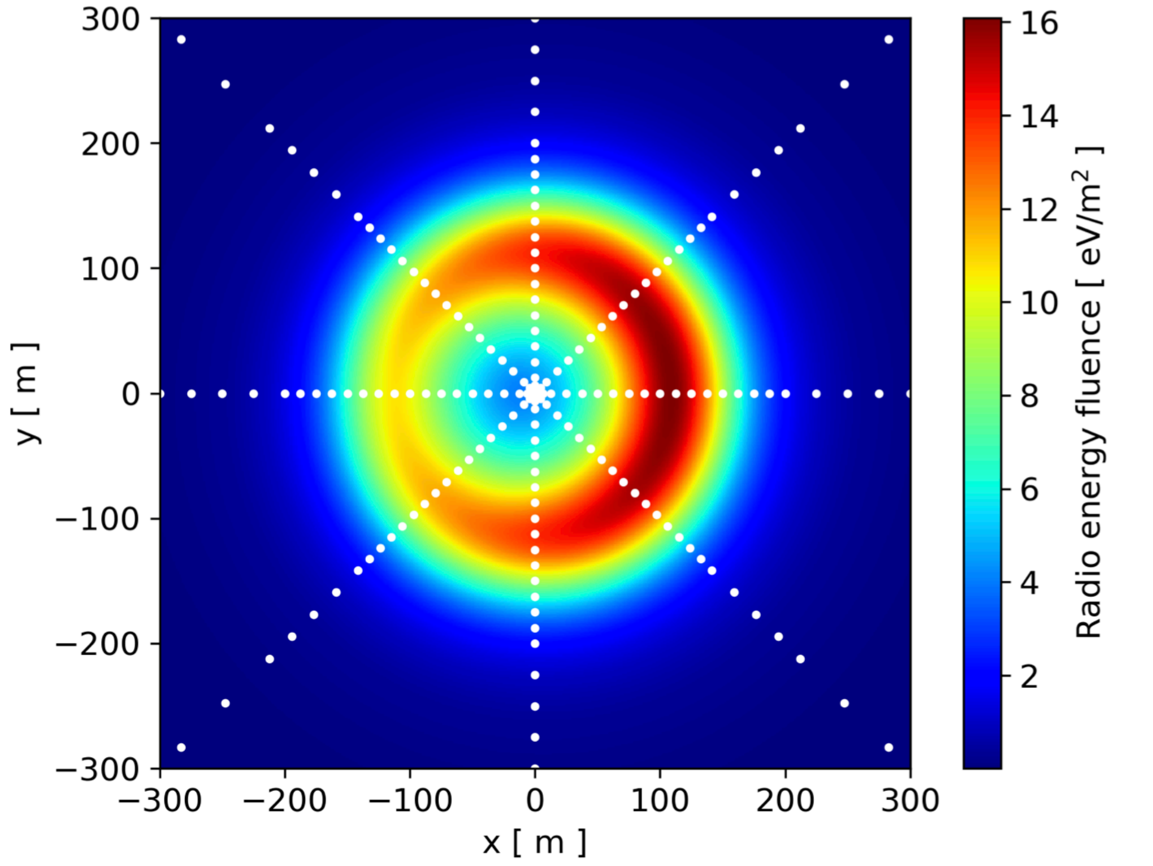


- **Goal:** use **Information Field Theory** for reconstruction of shower profile
- Utilised fast-forward model for radio emission: **template synthesis**
- Preliminary results show accurate reconstruction of X_{max} and N_{max}



Outlook

- Generalise for arbitrary antenna positions (Fourier interpolation)
- Include antenna response & realistic noise model
- Apply to realistic simulated data & to LOFAR data
- Reconstruct full shower profile instead of shower parameters



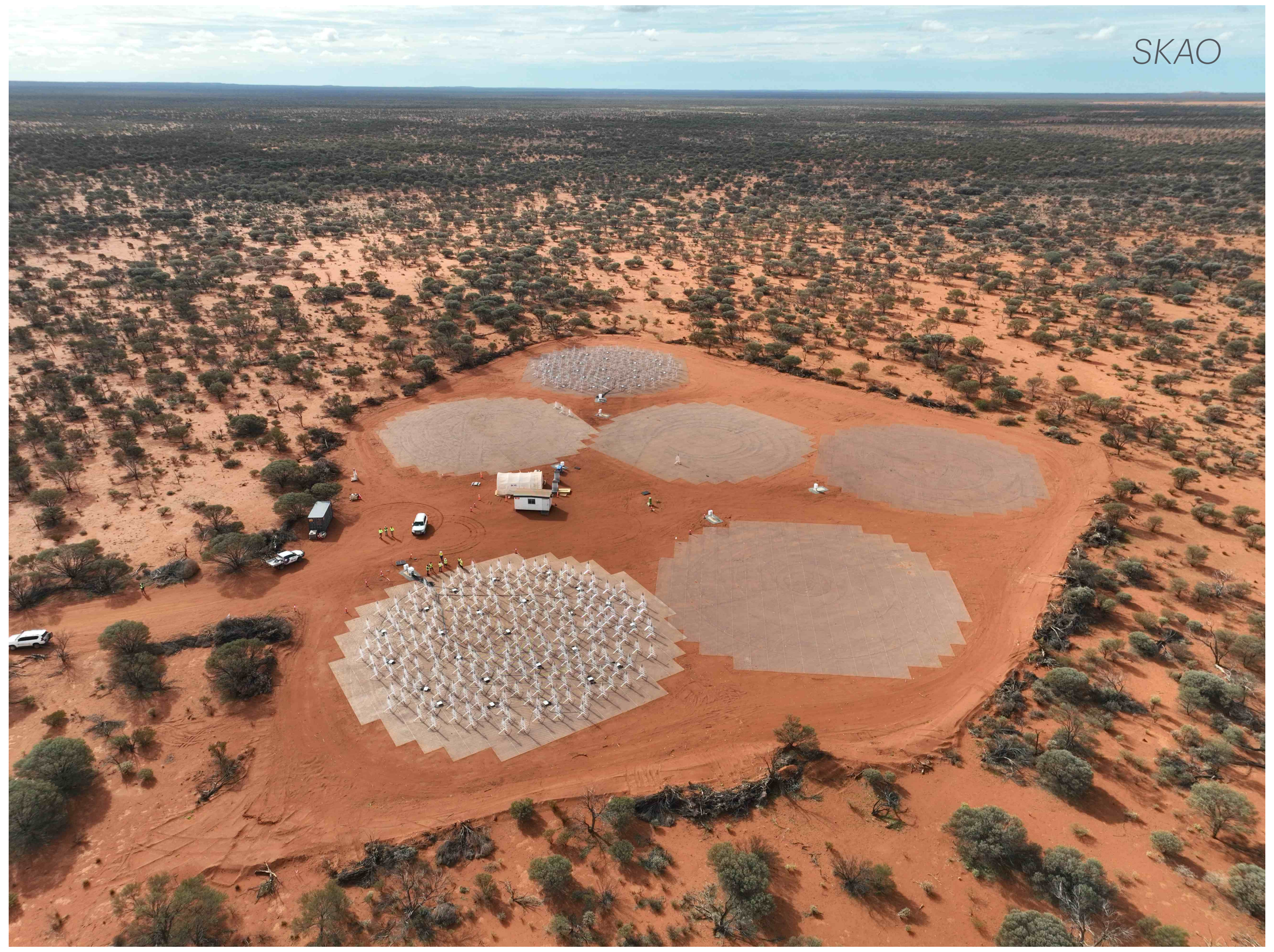
A. Corstanje et al. 2023 JINST 18 P09005

Backup Slides

Square Kilometre Array

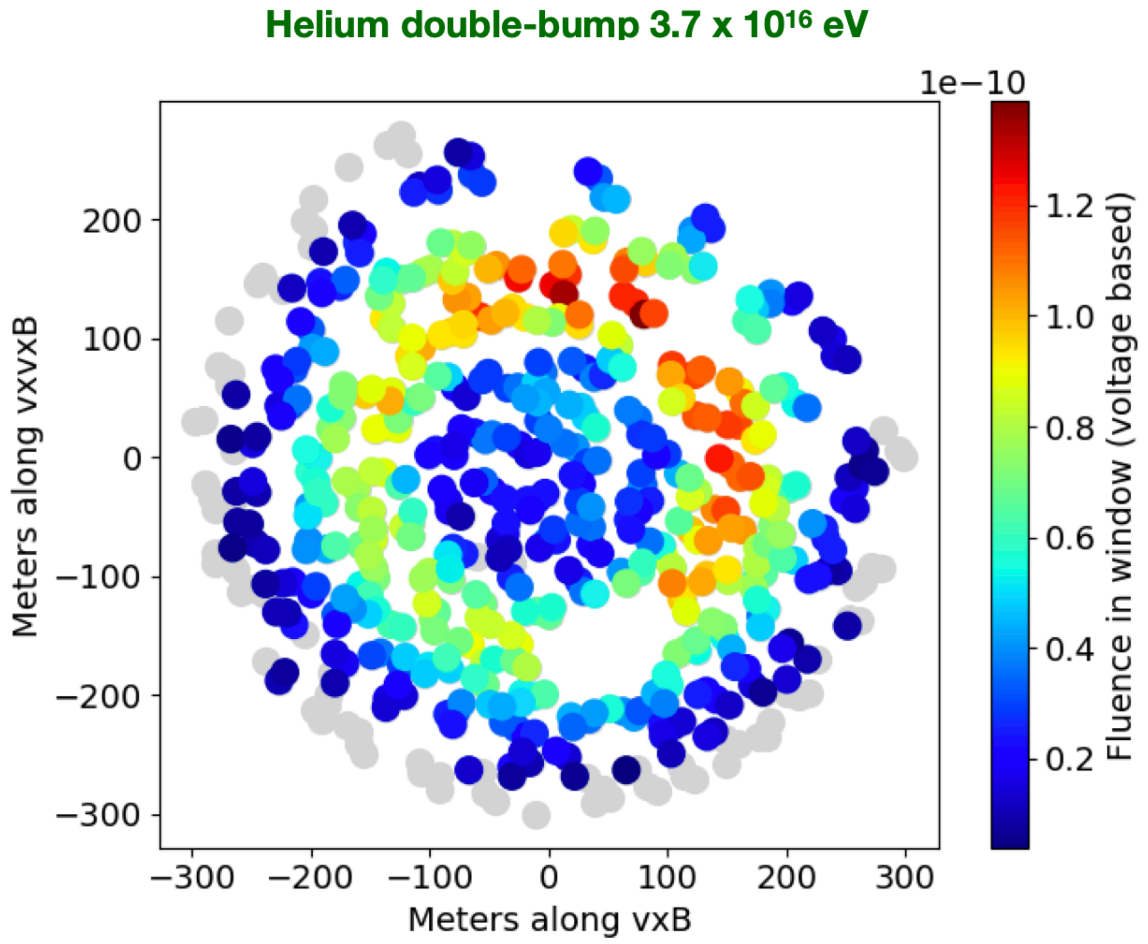
Reconstruction of full air shower profile possible with Square Kilometre Array (SKA)

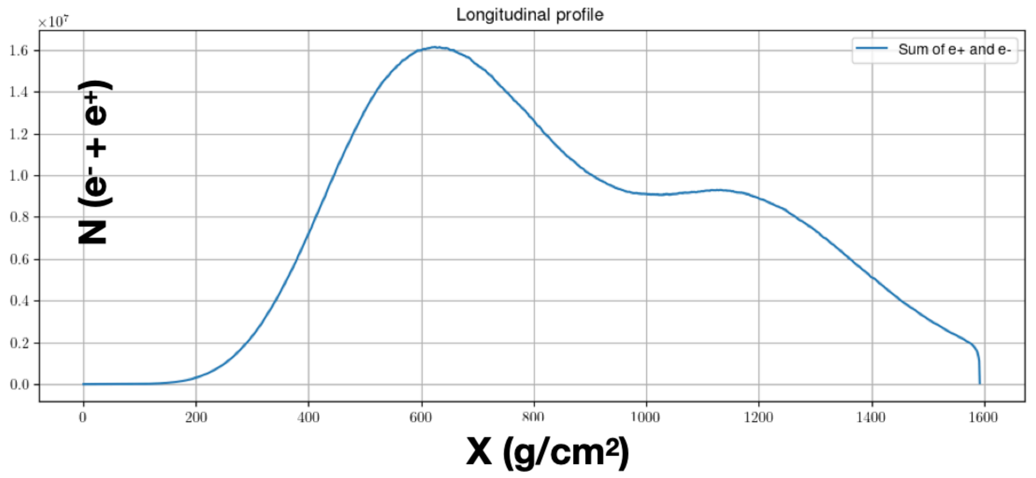
- **~ 60,000** antennas planned within ~ 1 km^2
- Planned bandwidth from **50 - 350 MHz**
- X_{max} reconstruction with SKA simulations show resolution of **6-8** $\mathbf{g\ cm^{-2}}$ (LOFAR: 20 $\mathbf{g\ cm^{-2}}$)
- Also possible to reconstruct L, R parameters, double-bump showers & possibly PeV gamma-rays



The first 2 complete stations with 512 antennas, deployed at Murchison Radio-astronomy Observatory

SKALA : SKA log-periodic antenna





Full simulation including:
Antenna response
Galactic + instrumental noise

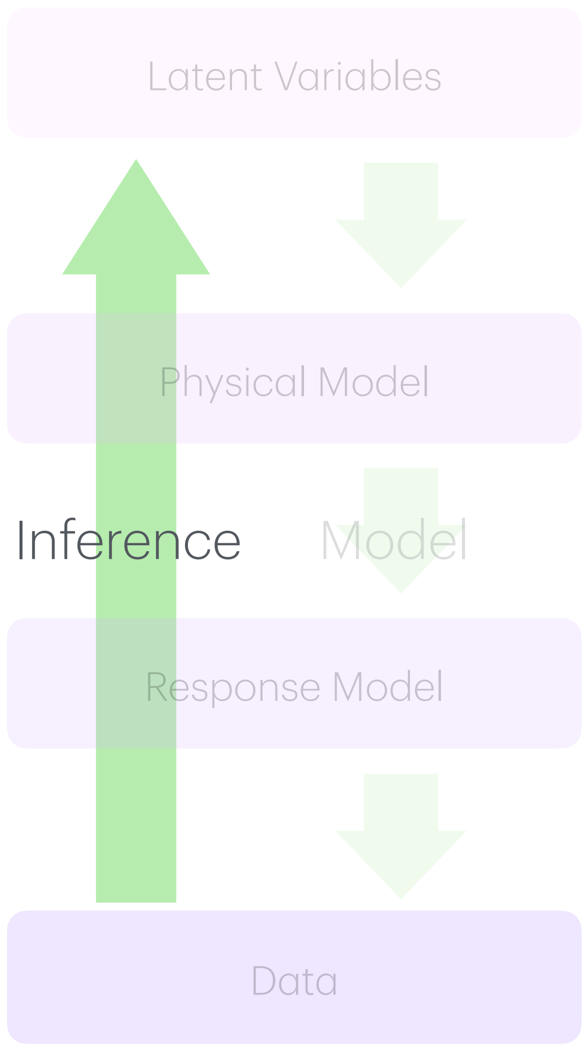
Antenna decimation factor 64
SNR increase 8

S. Buitink, ARENA 2024

Cosmic Rays

- **Highly energetic particles** (nuclei, γ-rays, neutrinos) that are from astrophysical origin
- Sources of the highest energy particles are still **not yet known**!
- **Indirectly** measured through **air showers** at highest energies

Verification with Synthetic Data



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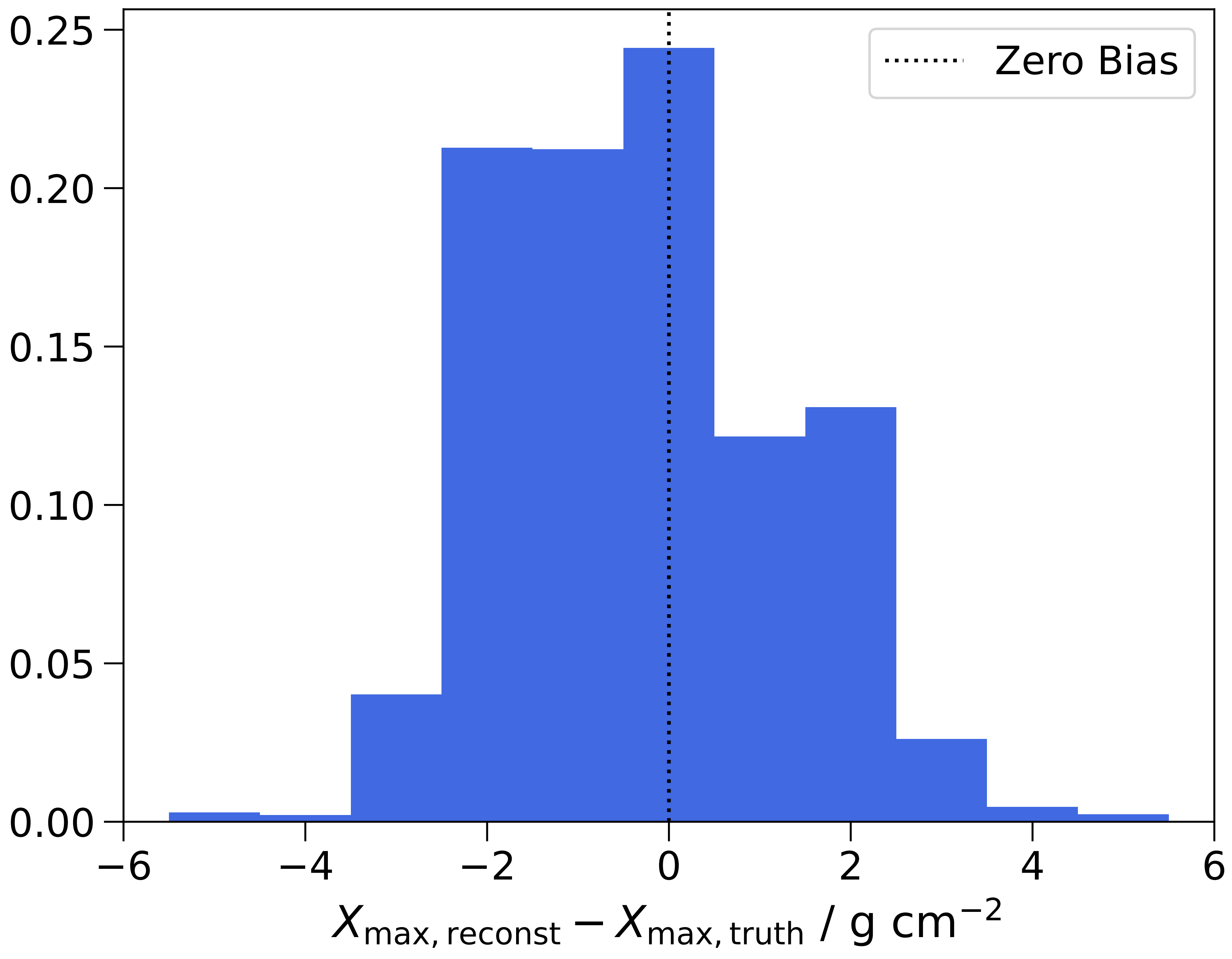

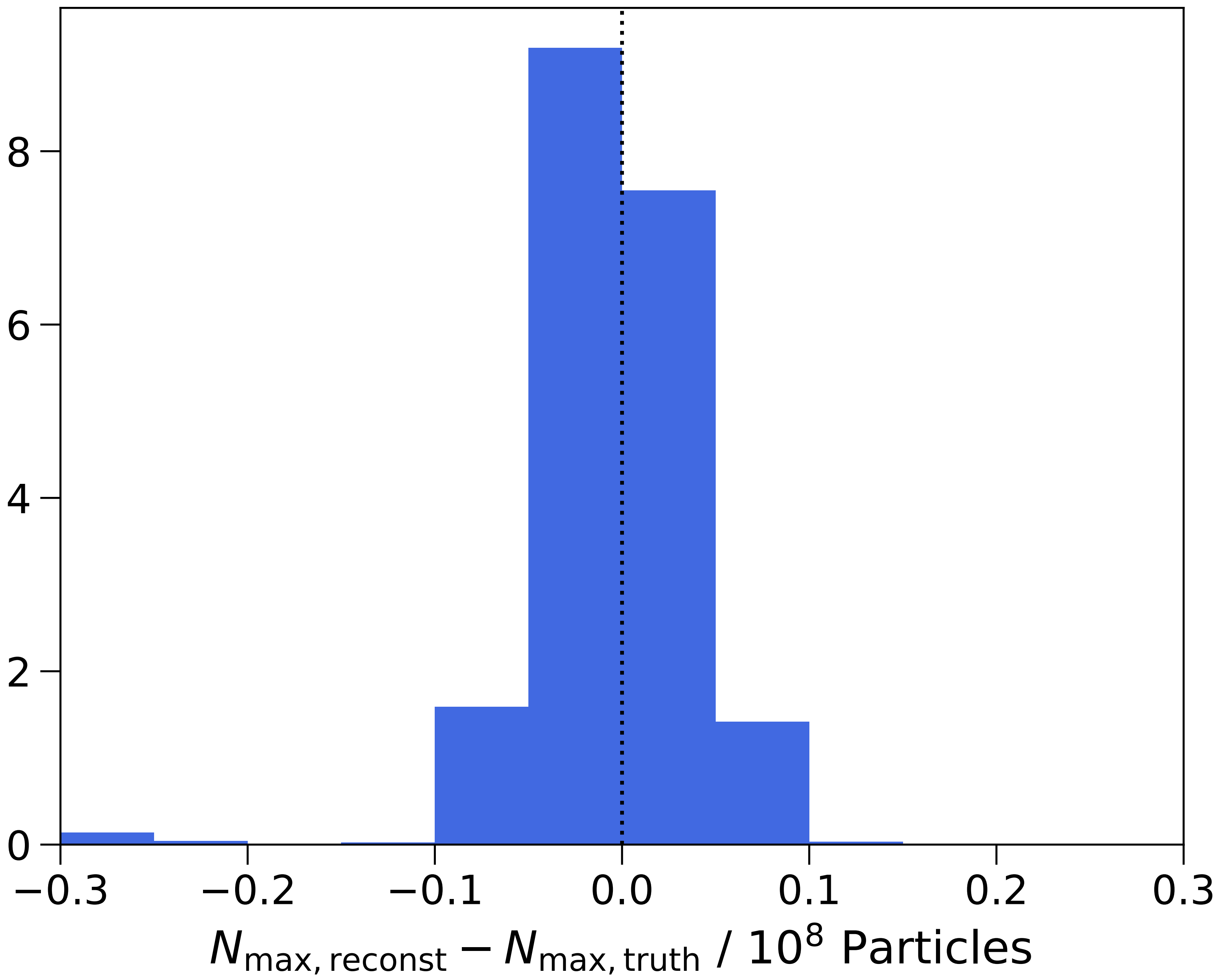

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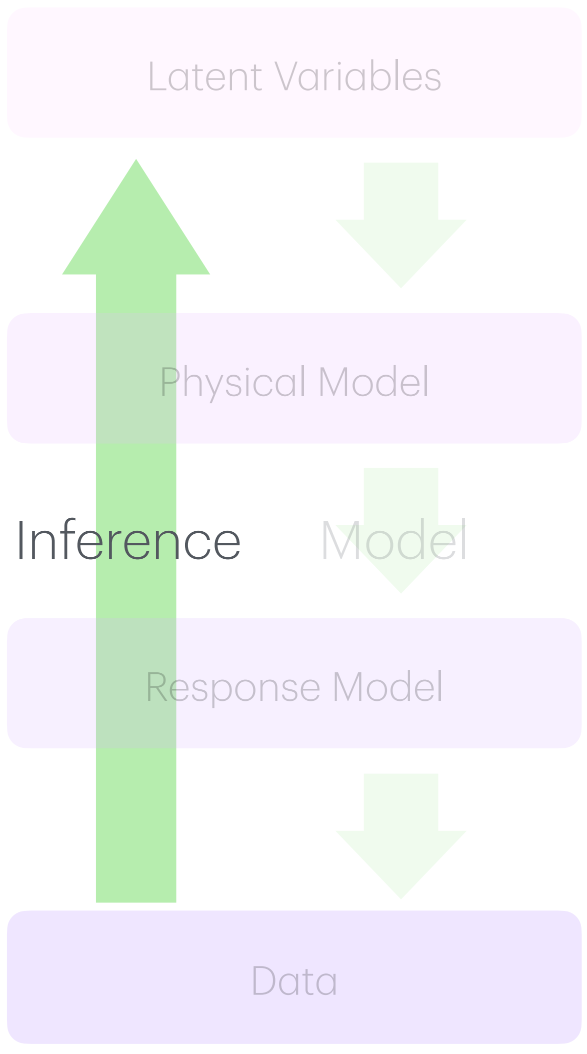
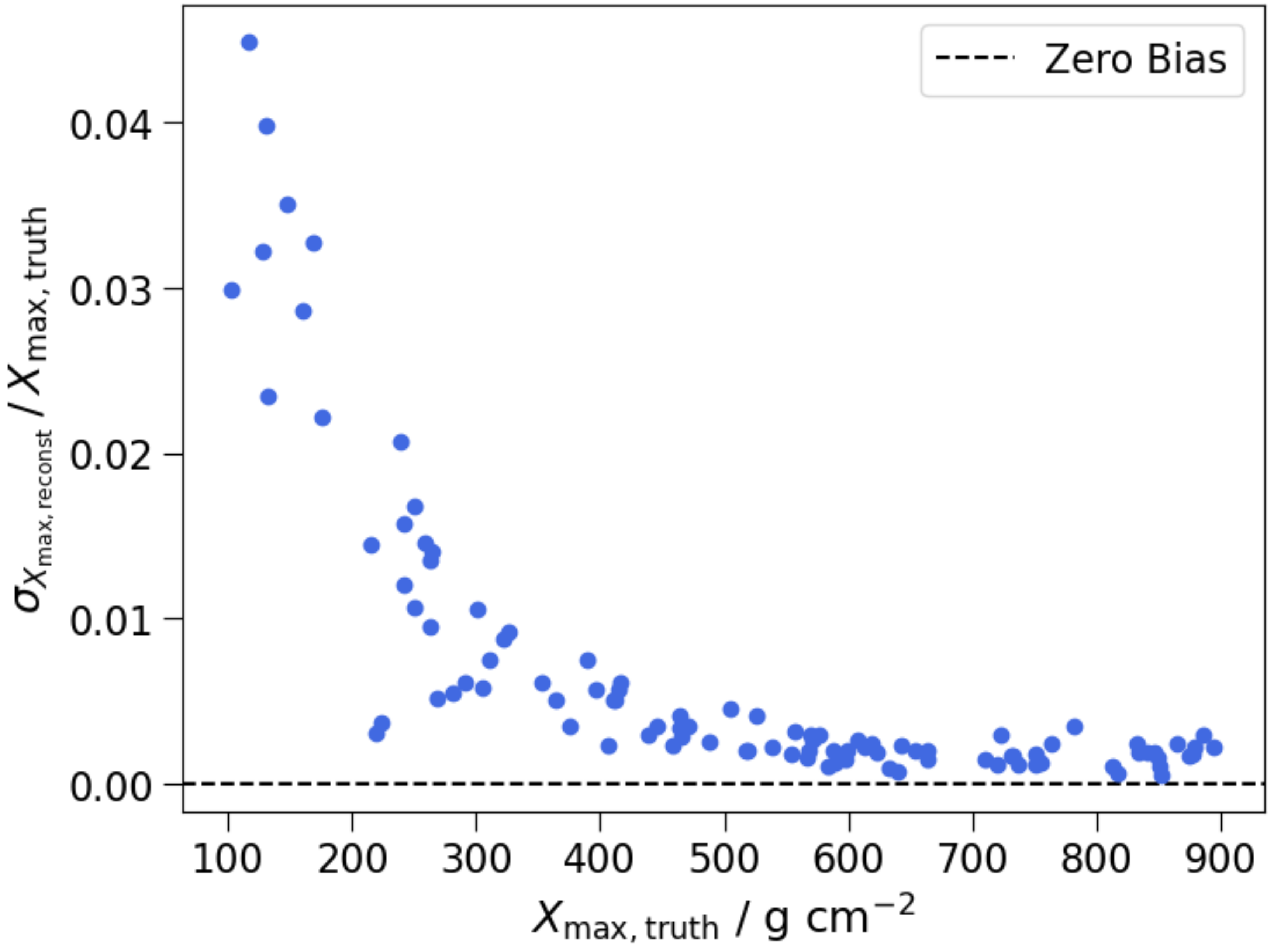
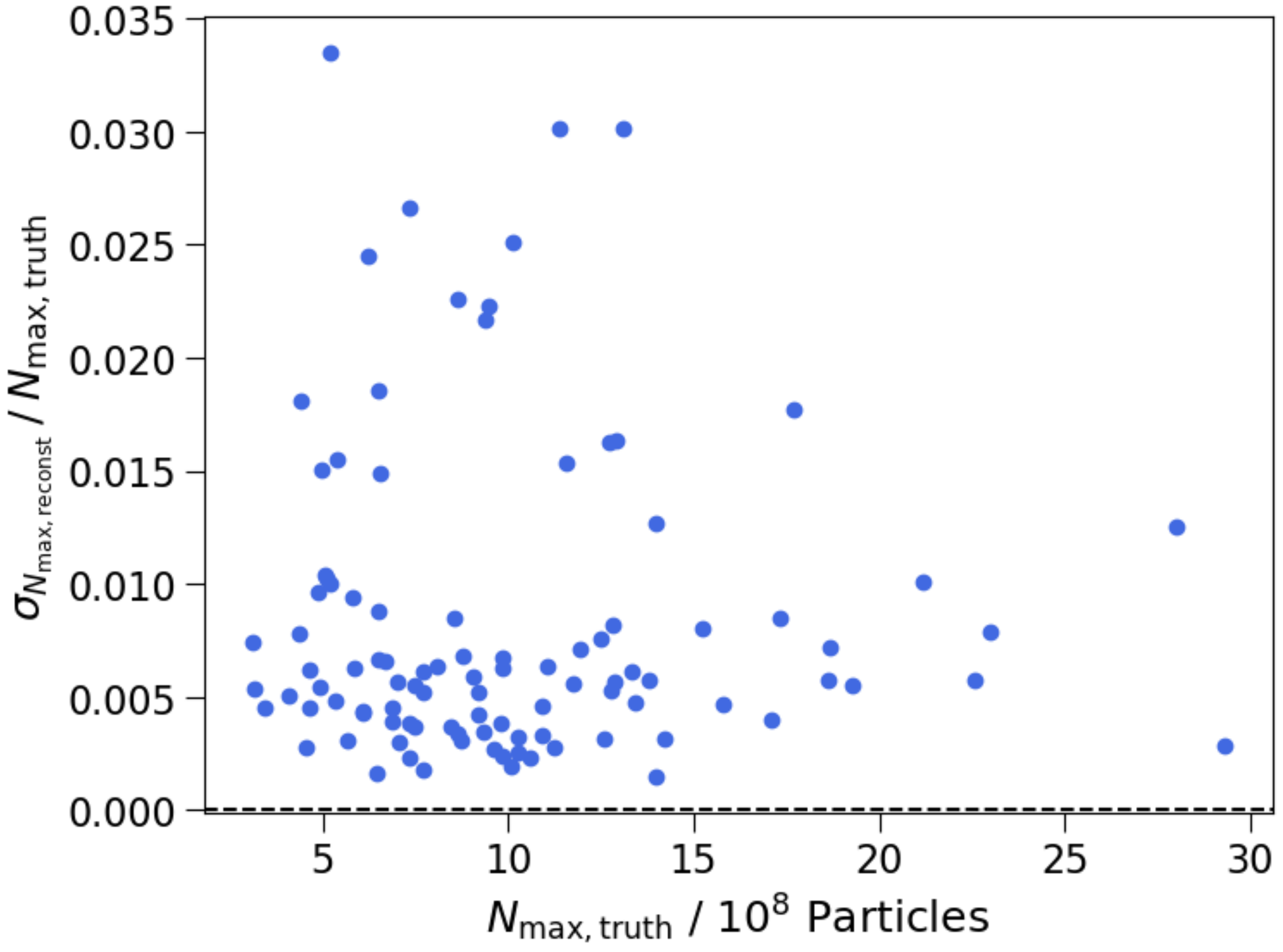


- Reconstruction Efficiency with 100 synthetically generated showers

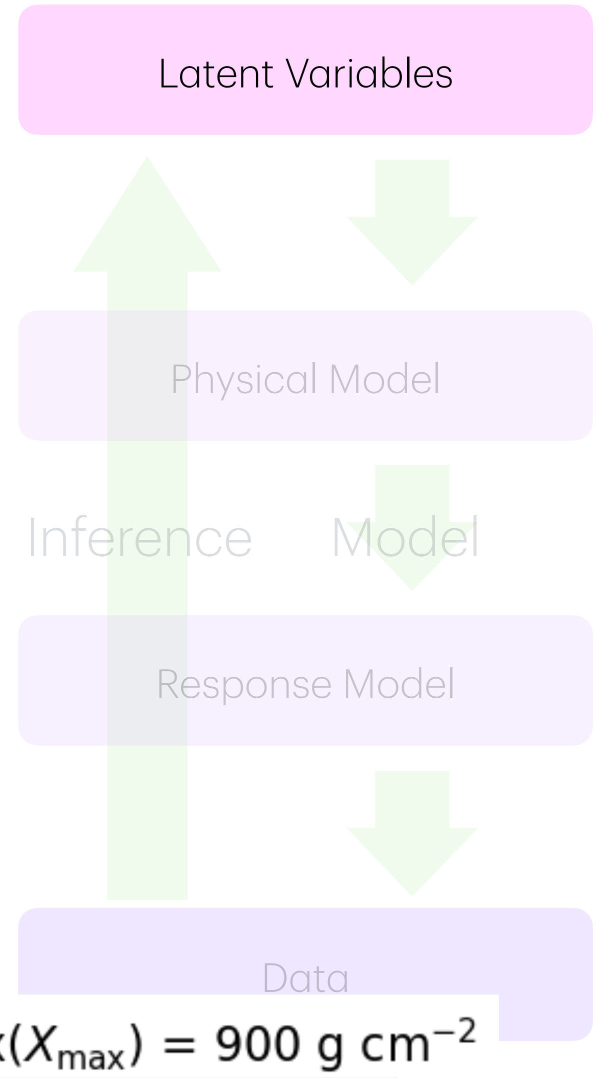




X_{max} reconstruction efficiency increases with lower X_{max}, but still < 4%

$\Longrightarrow$ but need to include antenna response & realistic noise model for further interpretation!

Prior Model



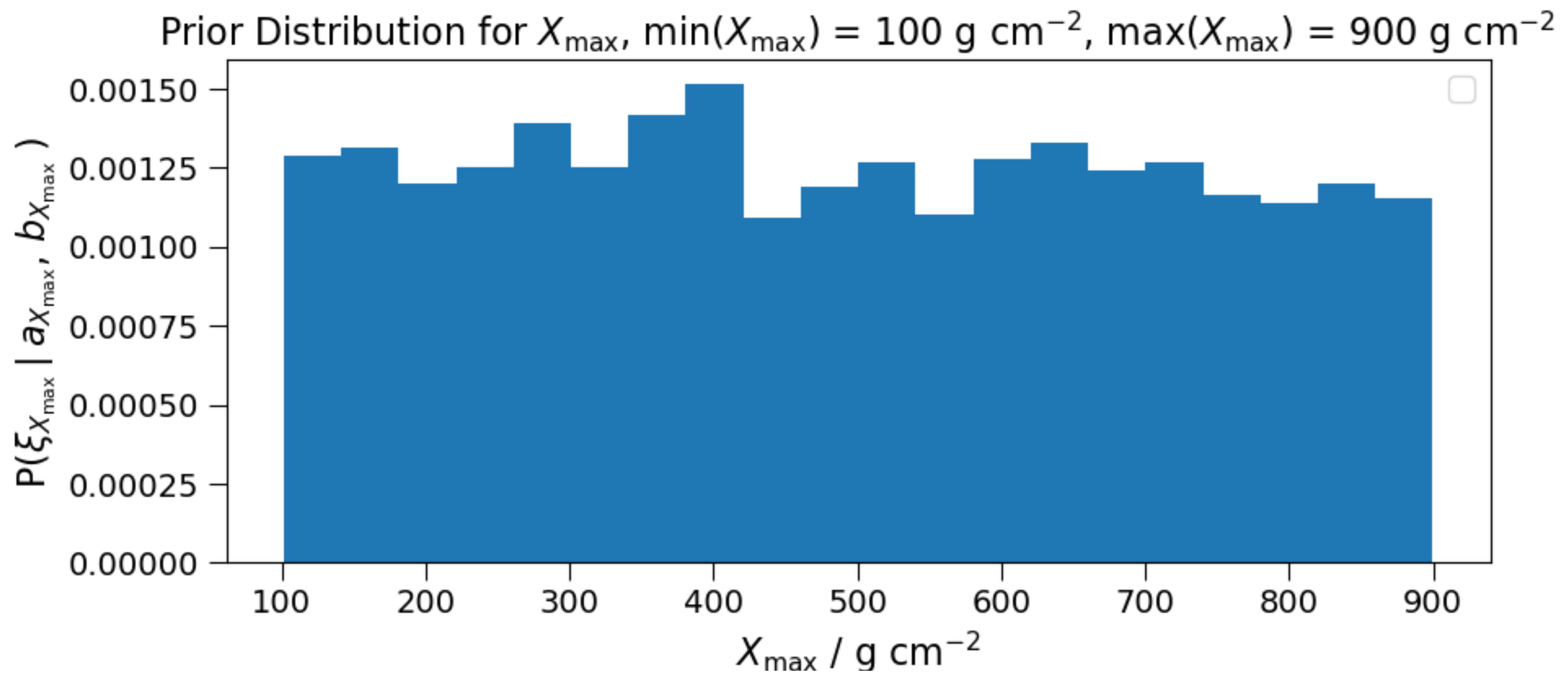
- Distribution to sample physical observables for reconstruction
- Sample each latent parameter ξ as unit Gaussian → transform to $X_{\max}$, $N_{\max}$

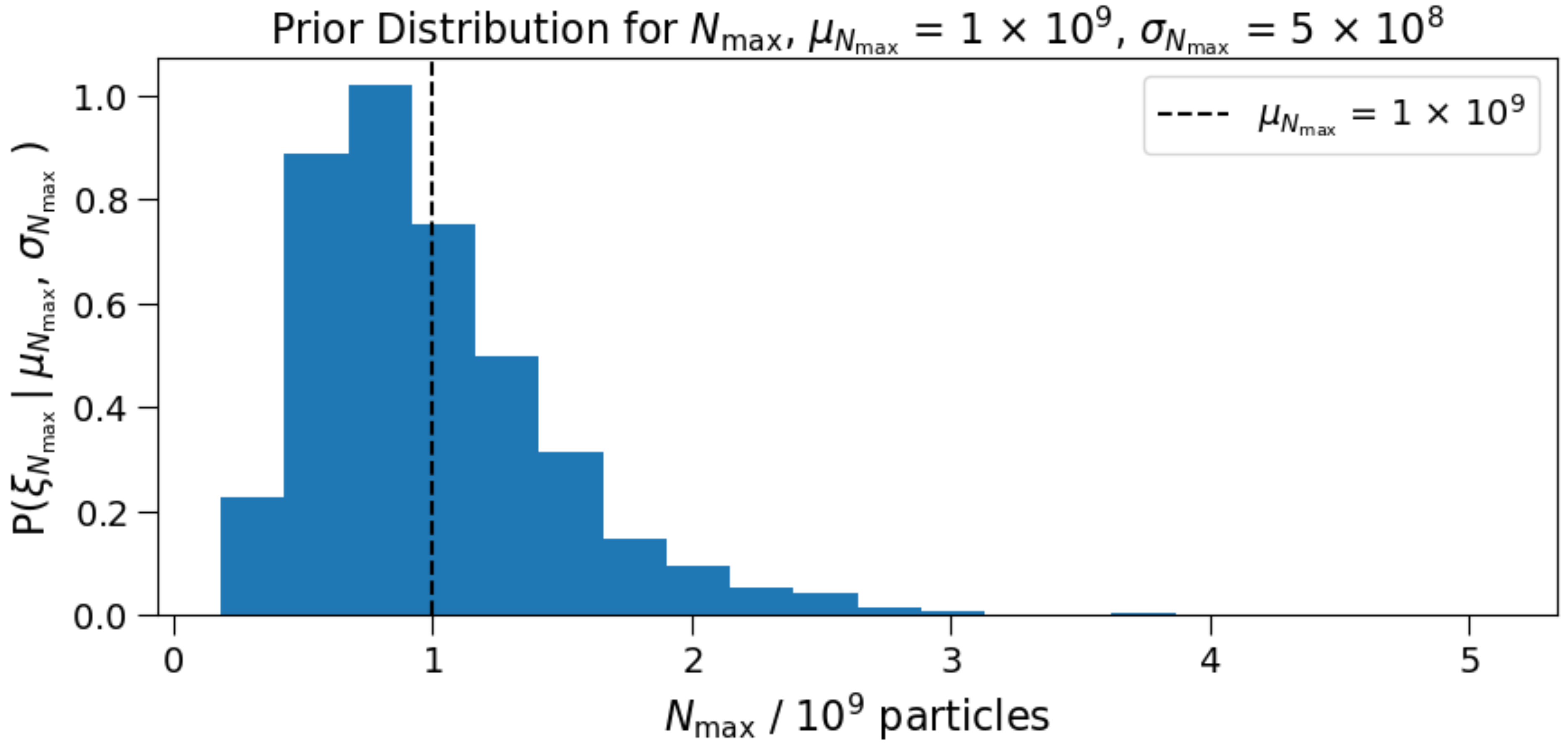
$$\xi_{X_{\max}} \sim \mathcal{N}(0,1) \qquad X_{\max} \sim P(\xi_{X_{\max}} \mid \min(X_{\max}), \max(X_{\max}))$$

$$\xi_{N_{\max}} \sim \mathcal{N}(0,1) \qquad N_{\max} \sim P(\xi_{N_{\max}} \mid \mu_{N_{\max}}, \sigma_{N_{\max}})$$

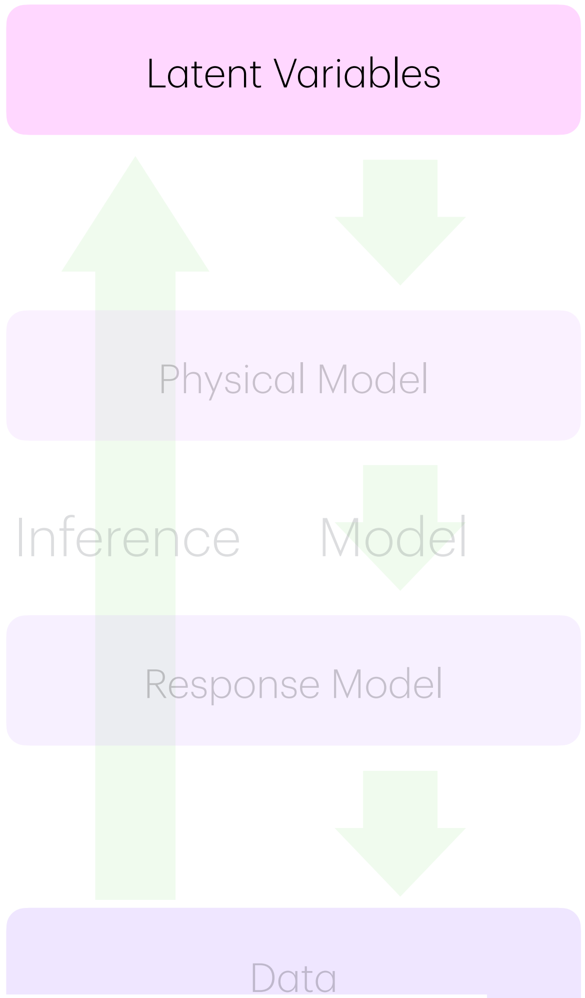
$X_{\max}$: atmospheric depth at shower maximum

$N_{\max}$: number of particles at $X_{\max}$





Prior Model



- Distribution to sample physical observables for reconstruction

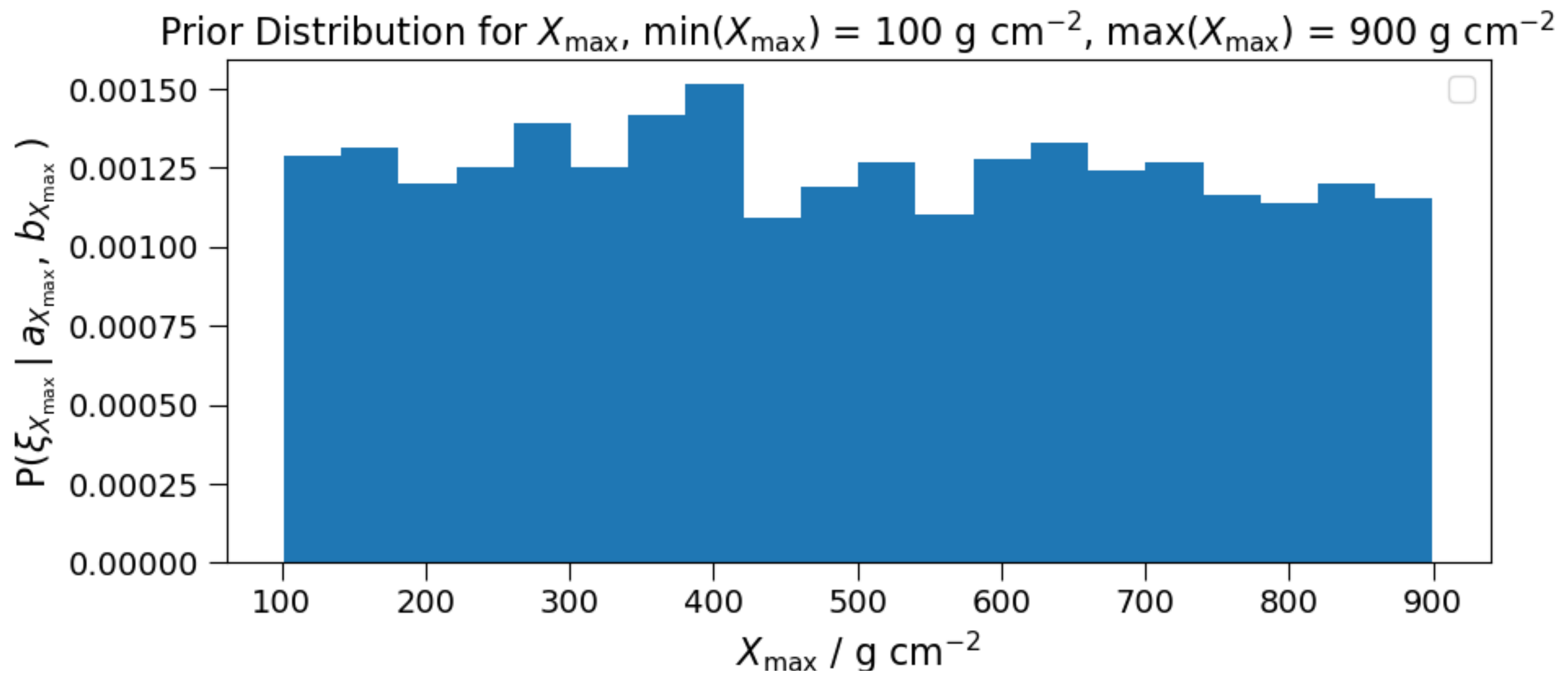
- Sample each latent parameter ξ as unit Gaussian → transform to $X_{\max}$, $N_{\max}$

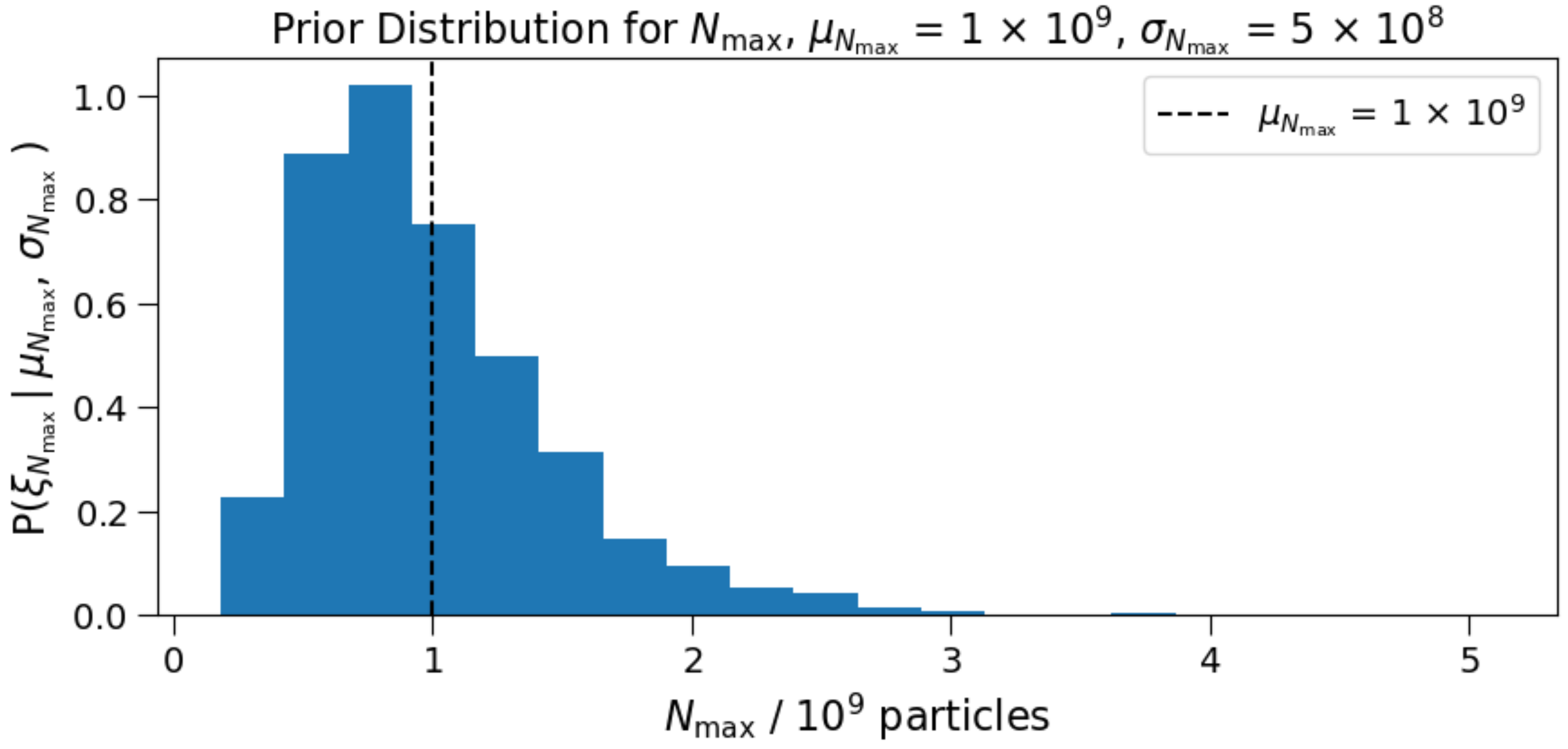
$$\xi_{X_{\max}} \sim \mathcal{N}(0,1) \quad \Rightarrow \quad X_{\max} \sim P(\xi_{X_{\max}} \mid \min(X_{\max}), \max(X_{\max}))$$

$$\xi_{N_{\max}} \sim \mathcal{N}(0,1) \quad \Rightarrow \quad N_{\max} \sim P(\xi_{N_{\max}} \mid \mu_{N_{\max}}, \sigma_{N_{\max}})$$

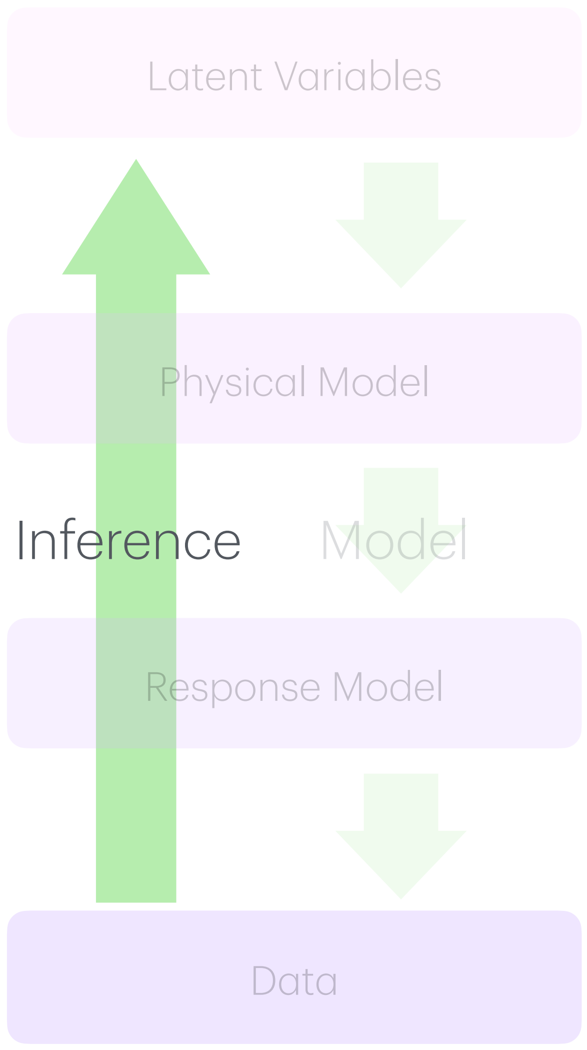
$X_{\max}$: atmospheric depth at shower maximum

$N_{\max}$: number of particles at $X_{\max}$

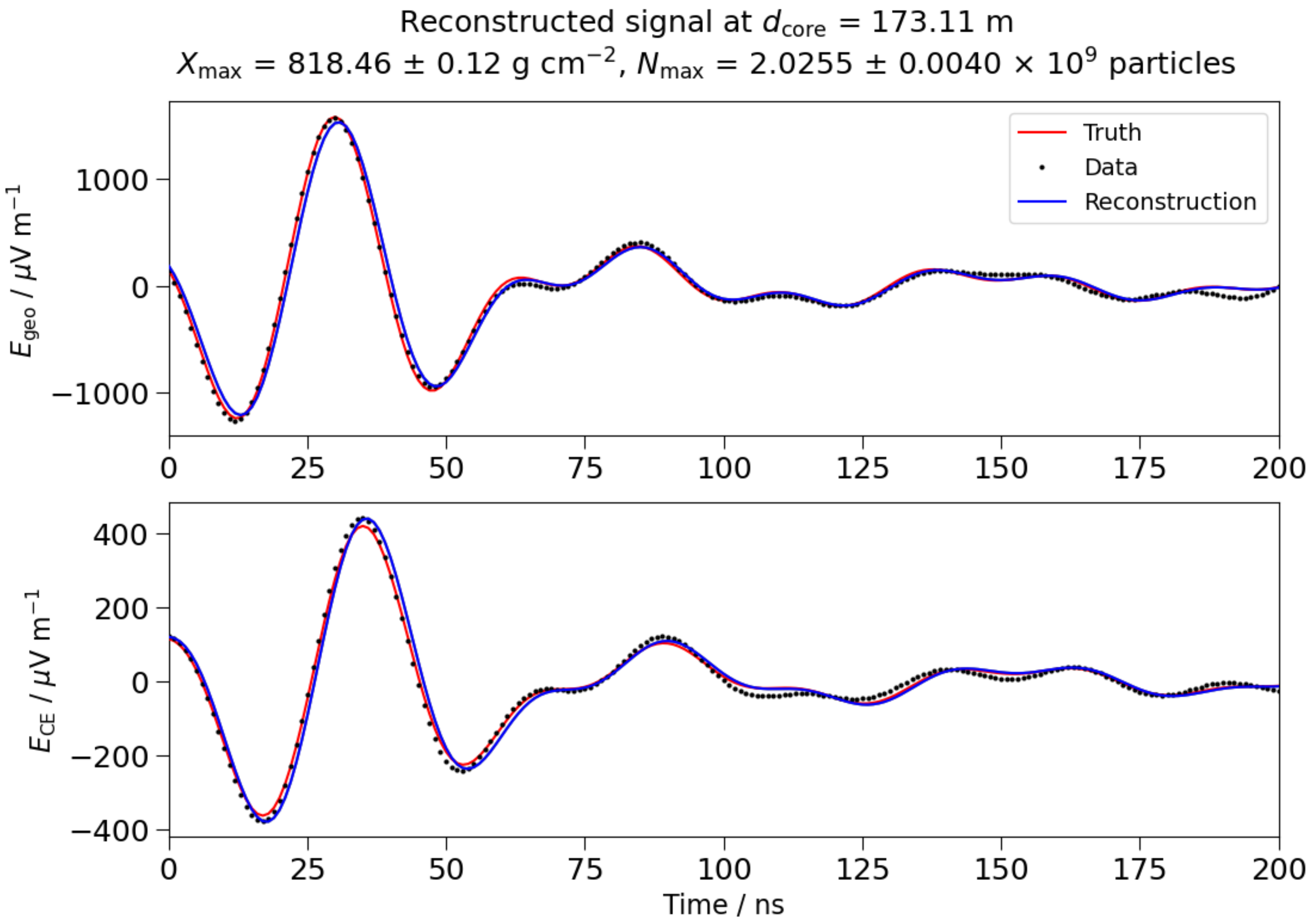


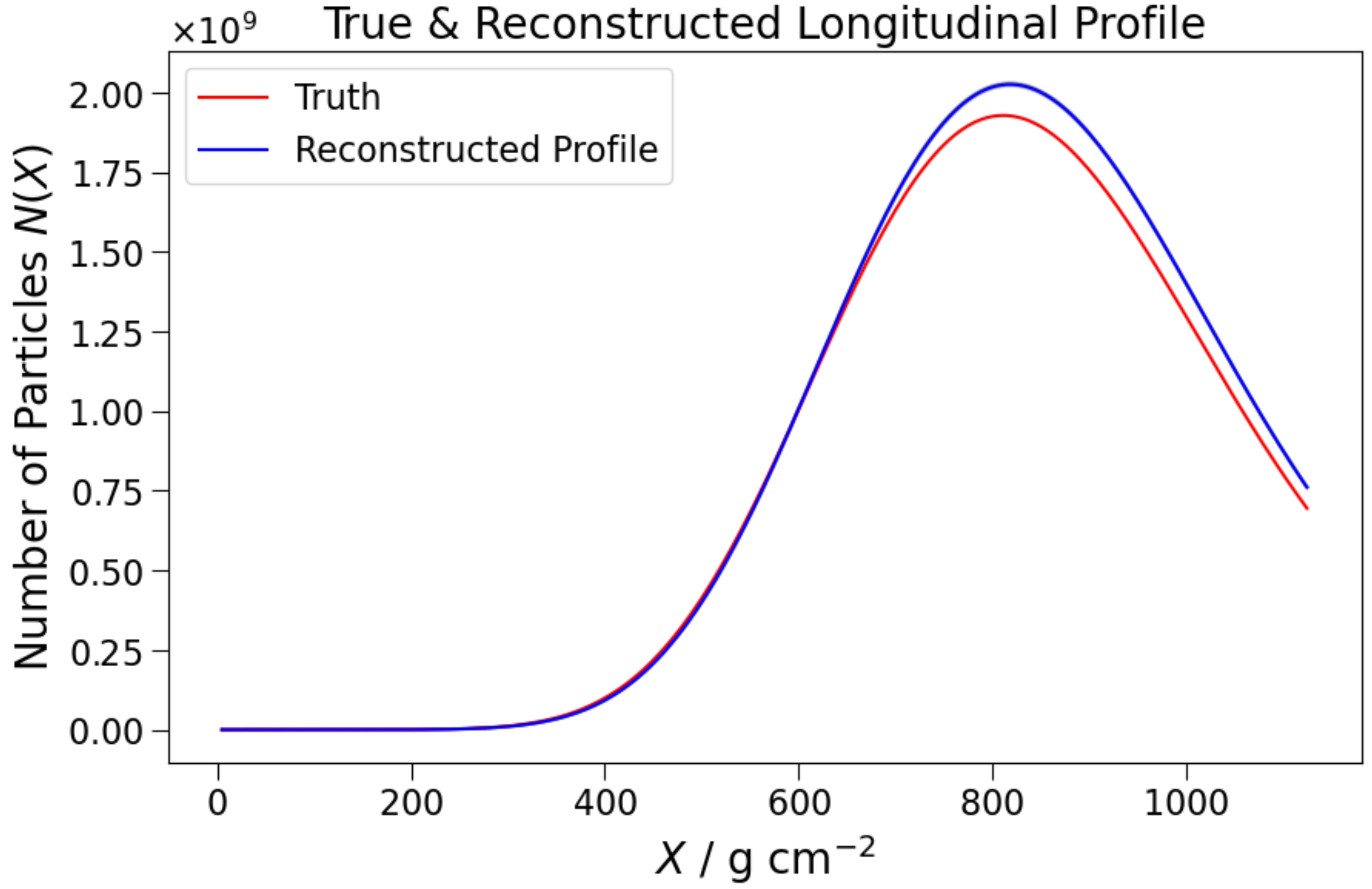


Application to Simulated Data



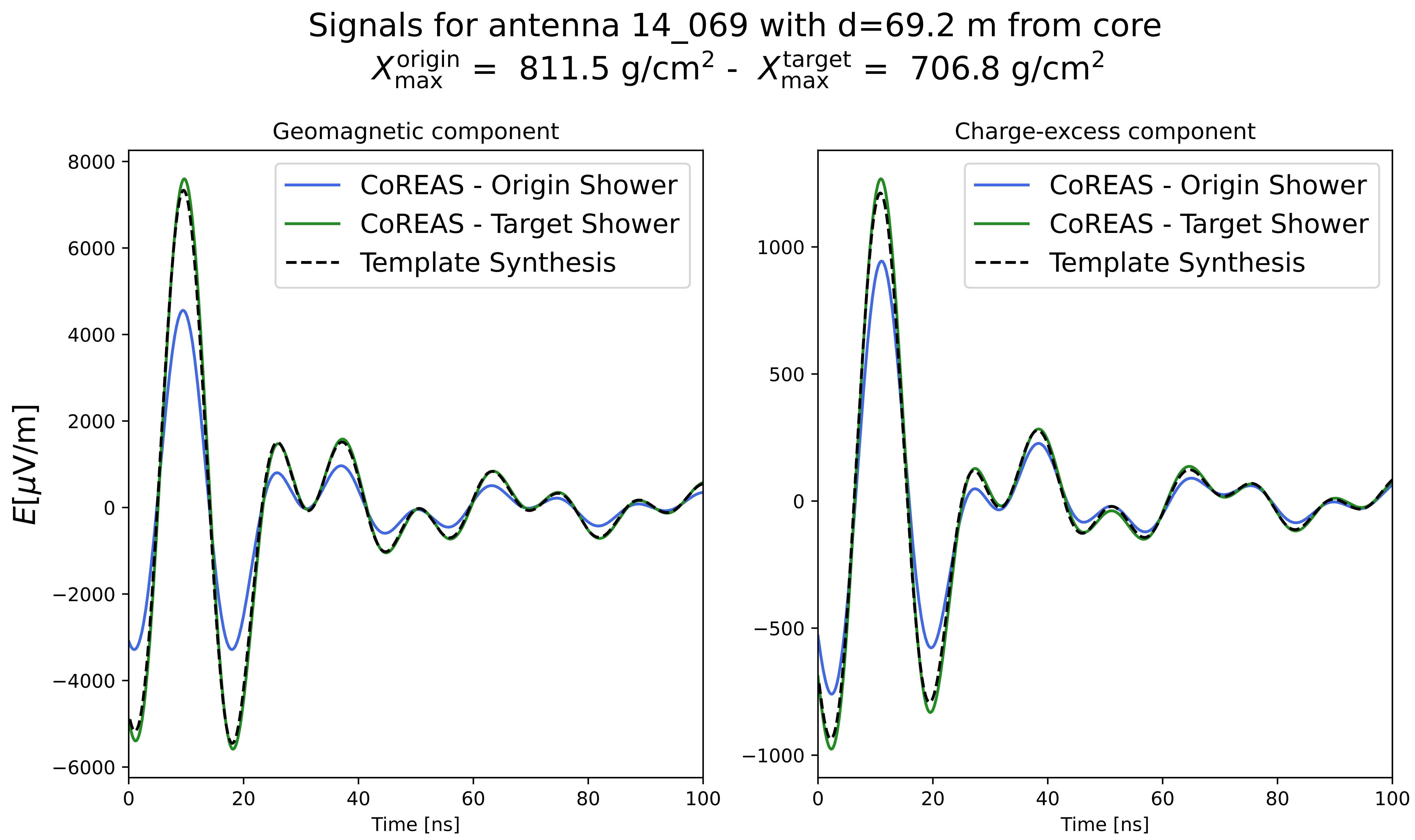
- **Simulated Data** using coREAS simulations
- Accurate X_{max} reconstruction with bias of $< 10\ \mathrm{g\ cm^{-2}}$

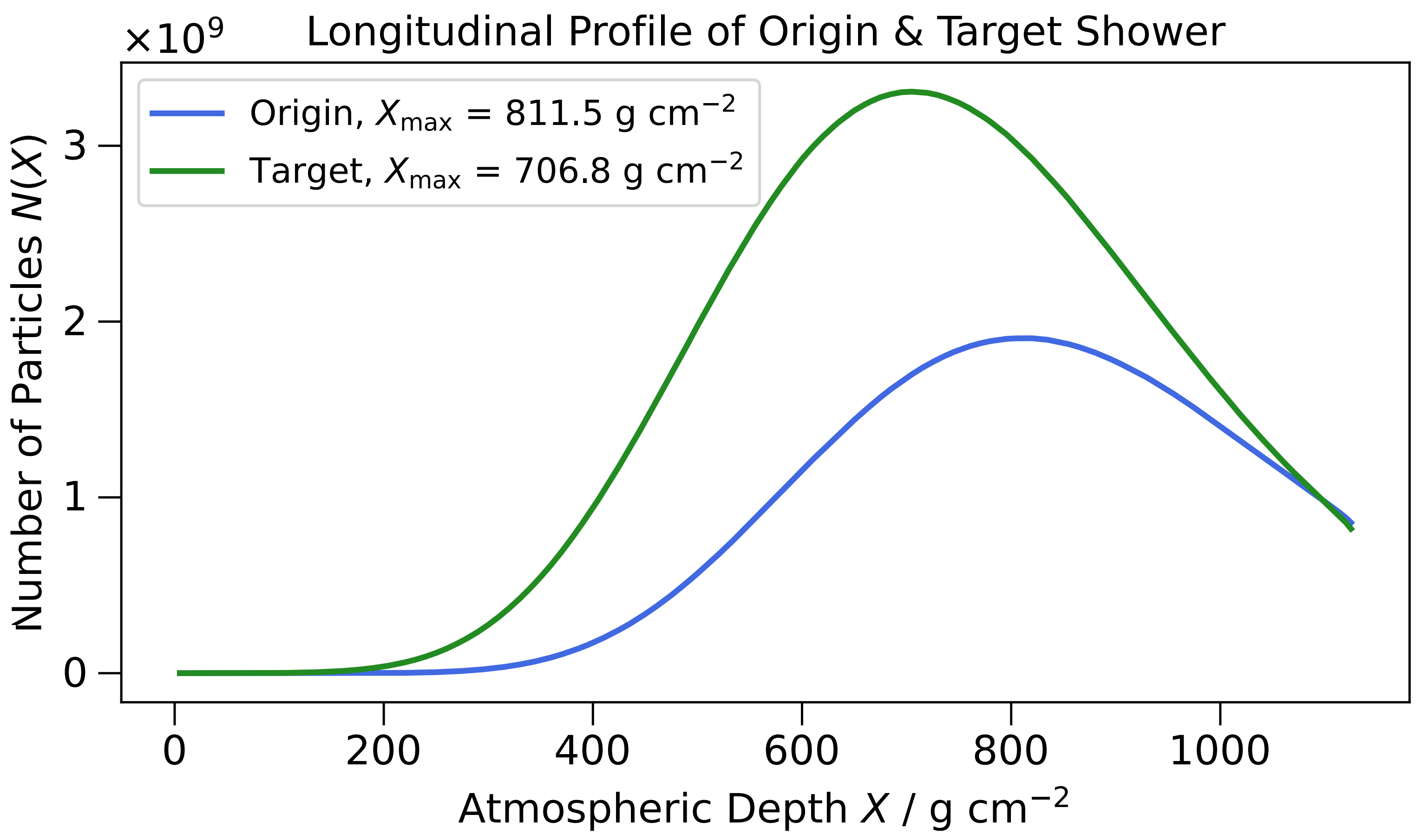


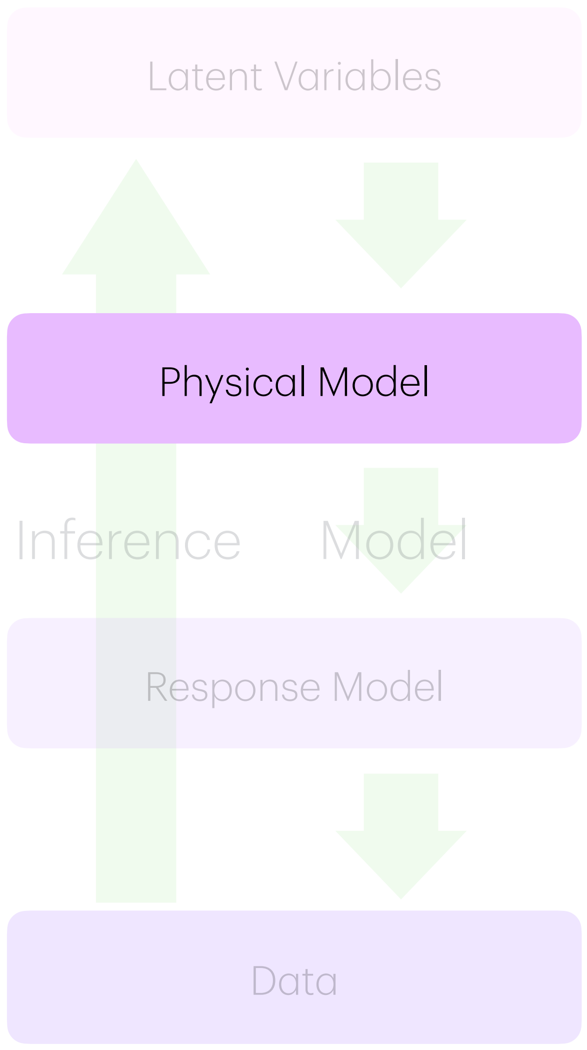


Template Synthesis

Verification





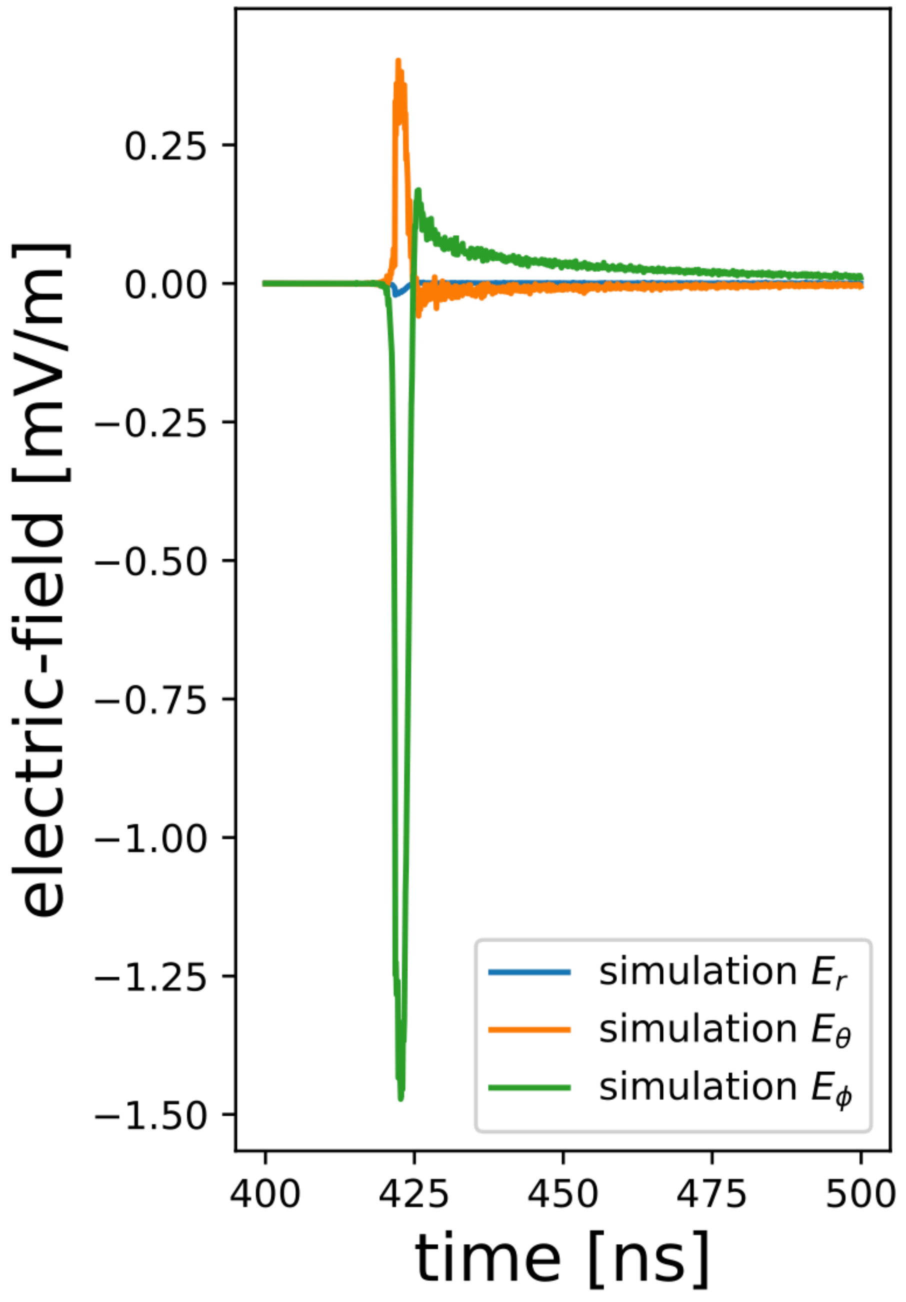


- Frequency band of 30 - 80 MHz
- Template synthesis match simulated results $\lesssim 5\%$!
- **<1 s** per synthesis → viable physical model for IFT reconstruction

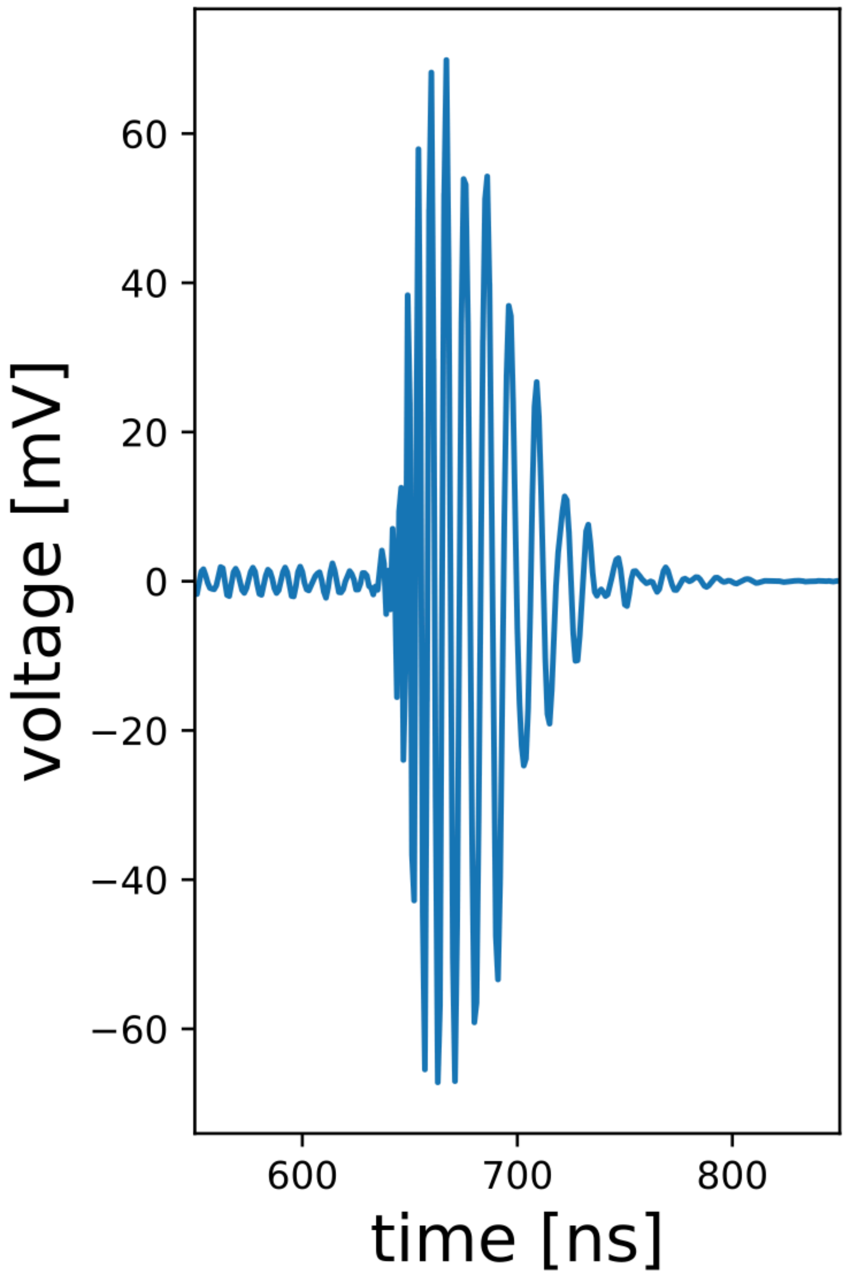
Electric field trace at single antenna from all slices for simulated target shower and synthesised target shower

Instrumental Response

Idea: Transform electric field trace → voltage trace through antenna response

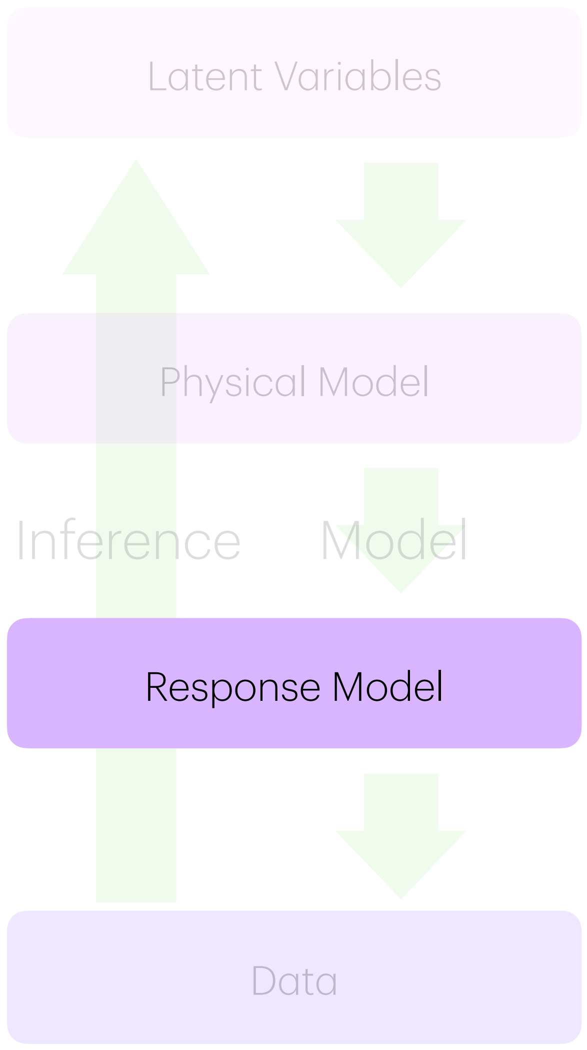


Antenna Response

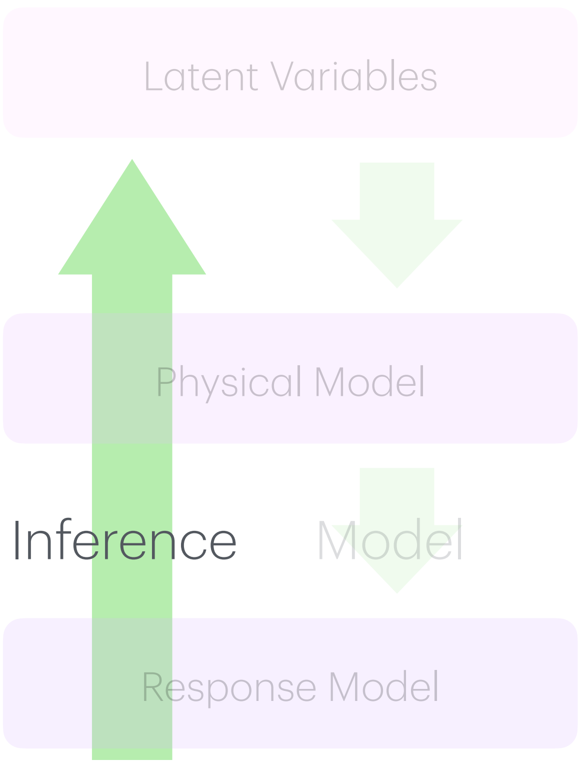


Glaser et al., Eur. Phys.Jour. C (2019) 79: 464

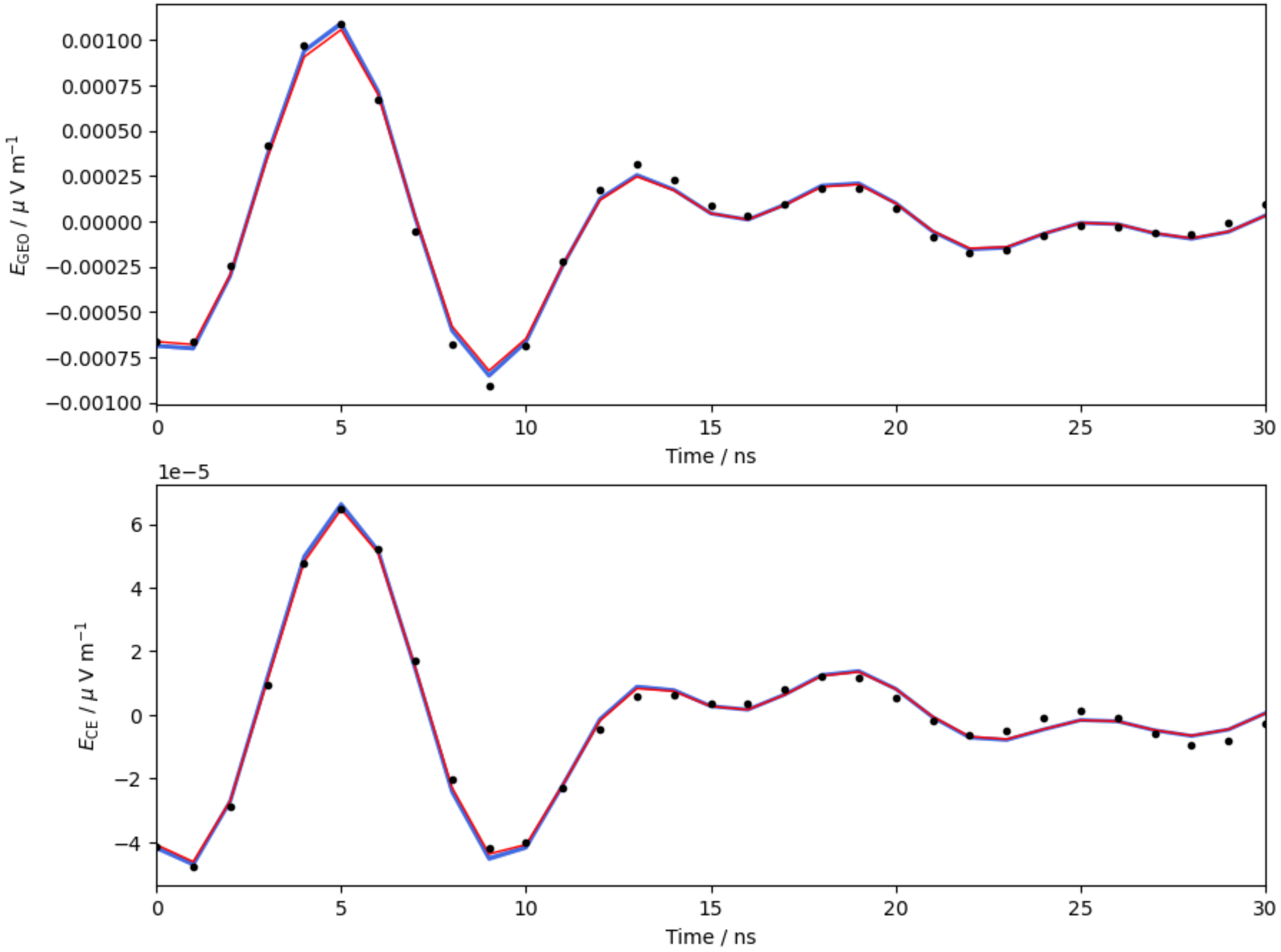
Currently not implemented! → use electric field traces for now

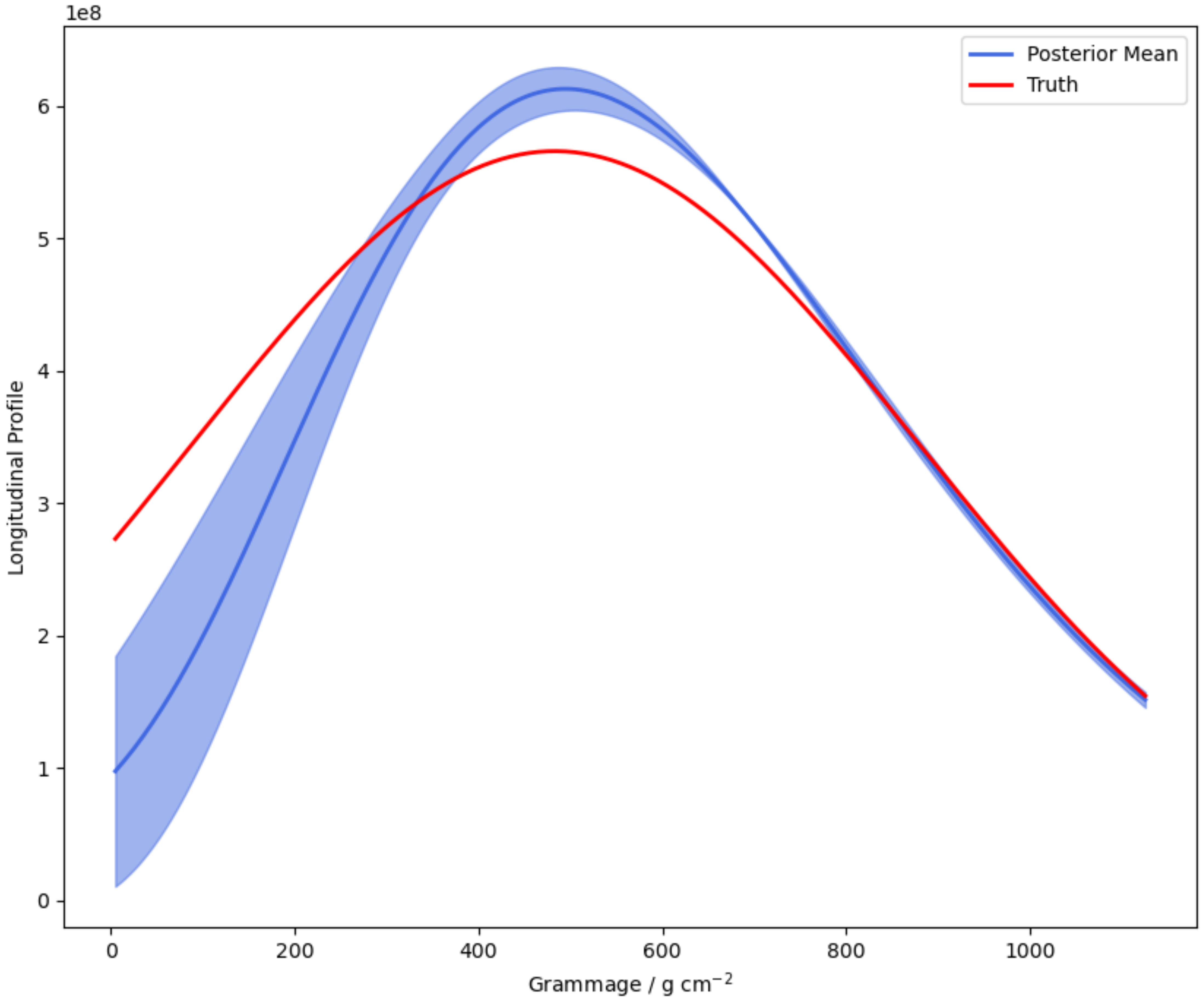


Reconstruction of Longitudinal Profile



- Use the whole profile as a prior instead of using Xmax





Keito Watanabe, Radio 2024