Karlsruher Institut für Technologie

Reconstructing the Longitudinal Profile of Air Showers

Using an IFT-based Algorithm for Radio Data

Keito Watanabe, Tim Huege

Astroparticle School 2024, 14.10.2024

Extensive Air Showers

- Cascade of particles through **hadronic** and **electromagnetic** processes
- Generated from (ultra-)high-energy cosmic rays
- Primary (energy, direction, shower profile) : obtained via hybrid measurement (scintillation + fluorescence yield)

Radio Emission of Air Showers

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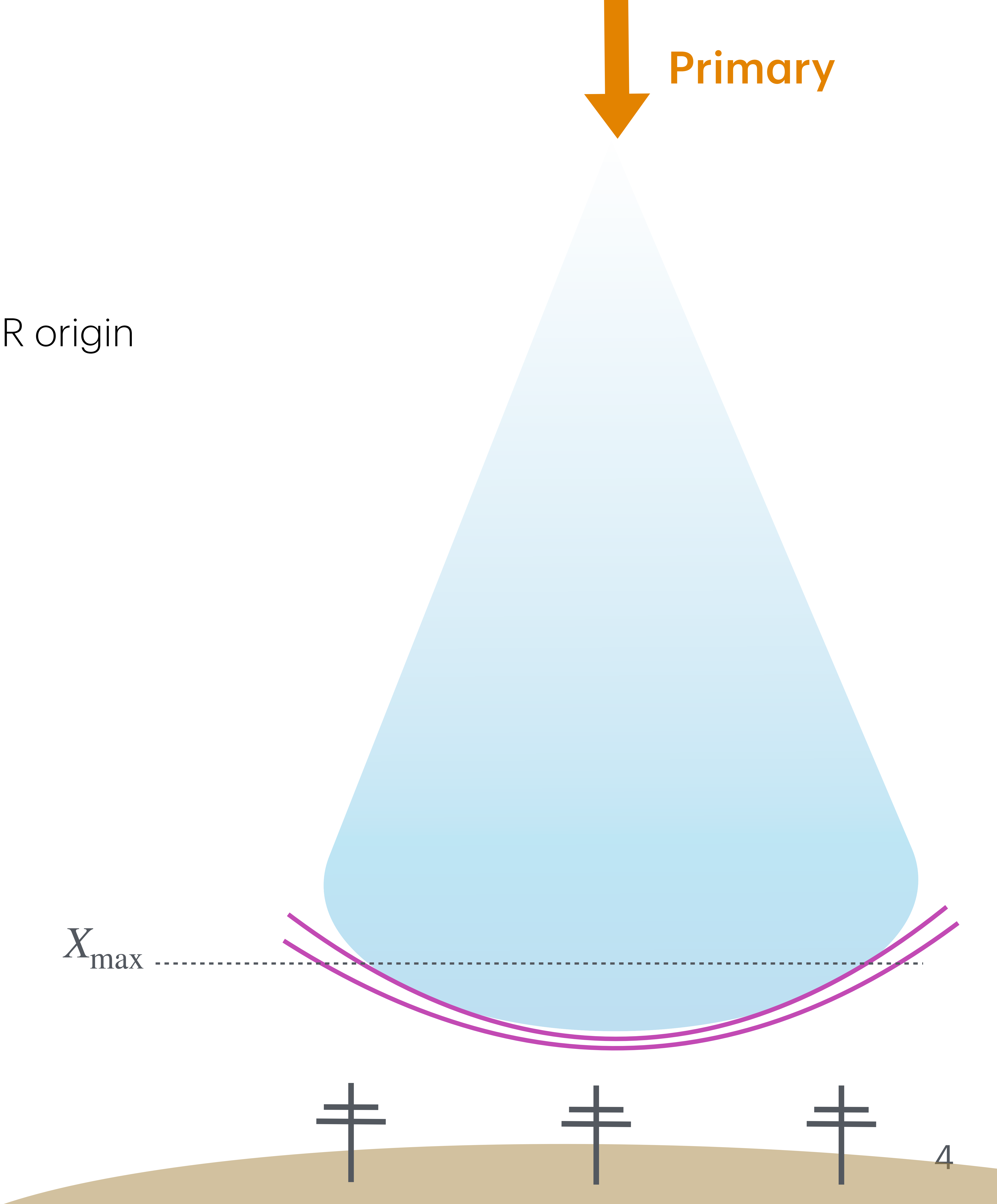
All information of primary (energy, direction, shower profile) encoded in traces

→ complementary approach to hybrid detection

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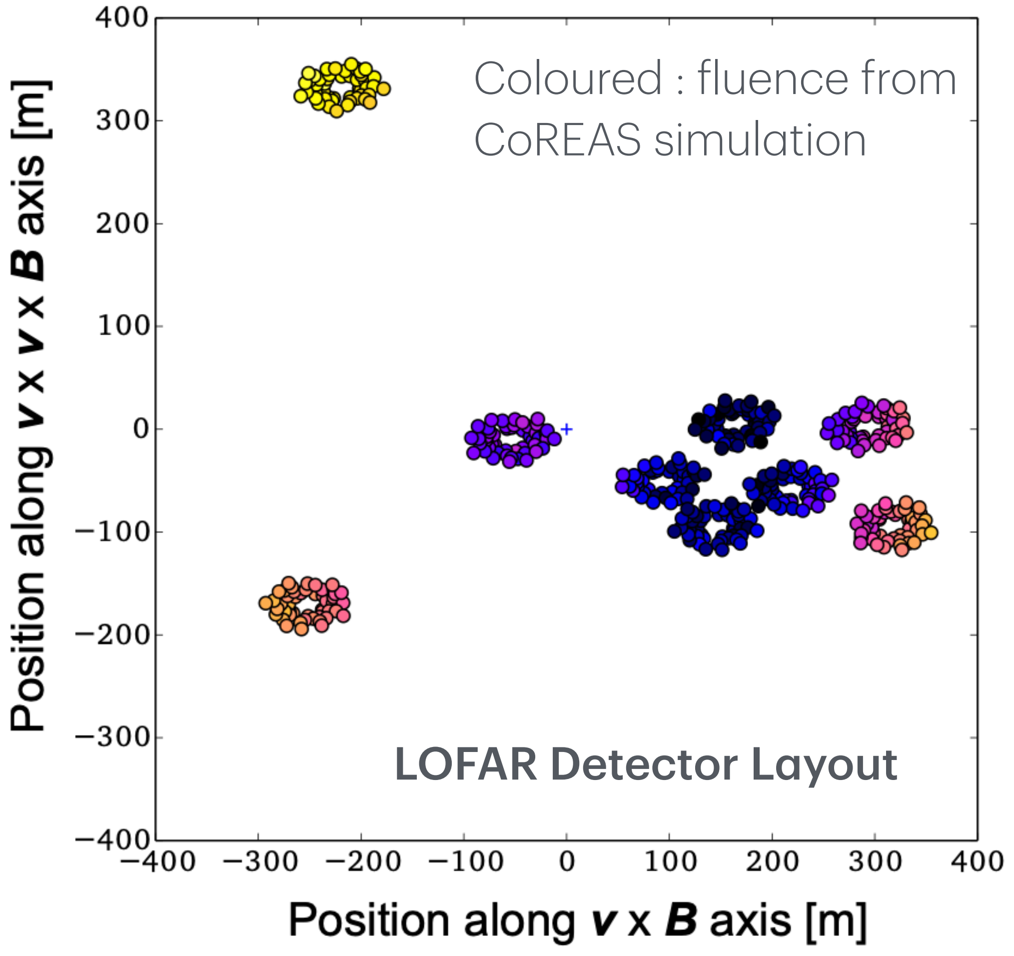
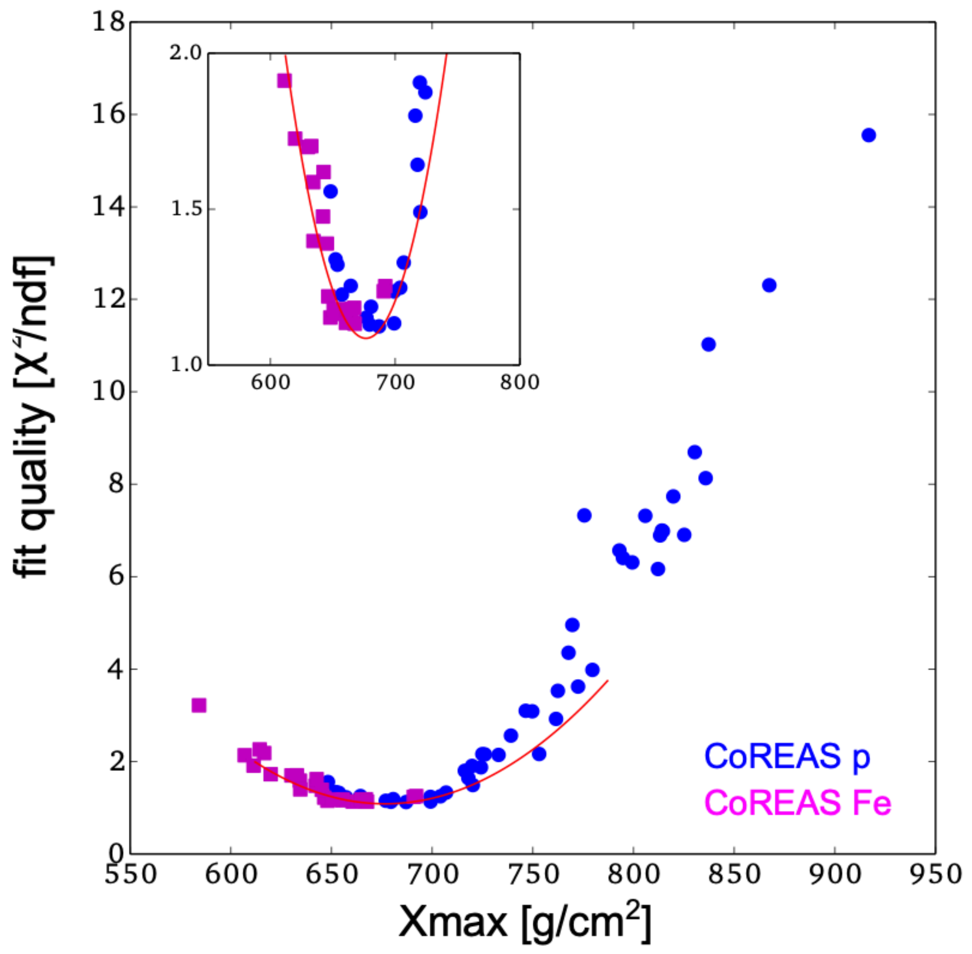
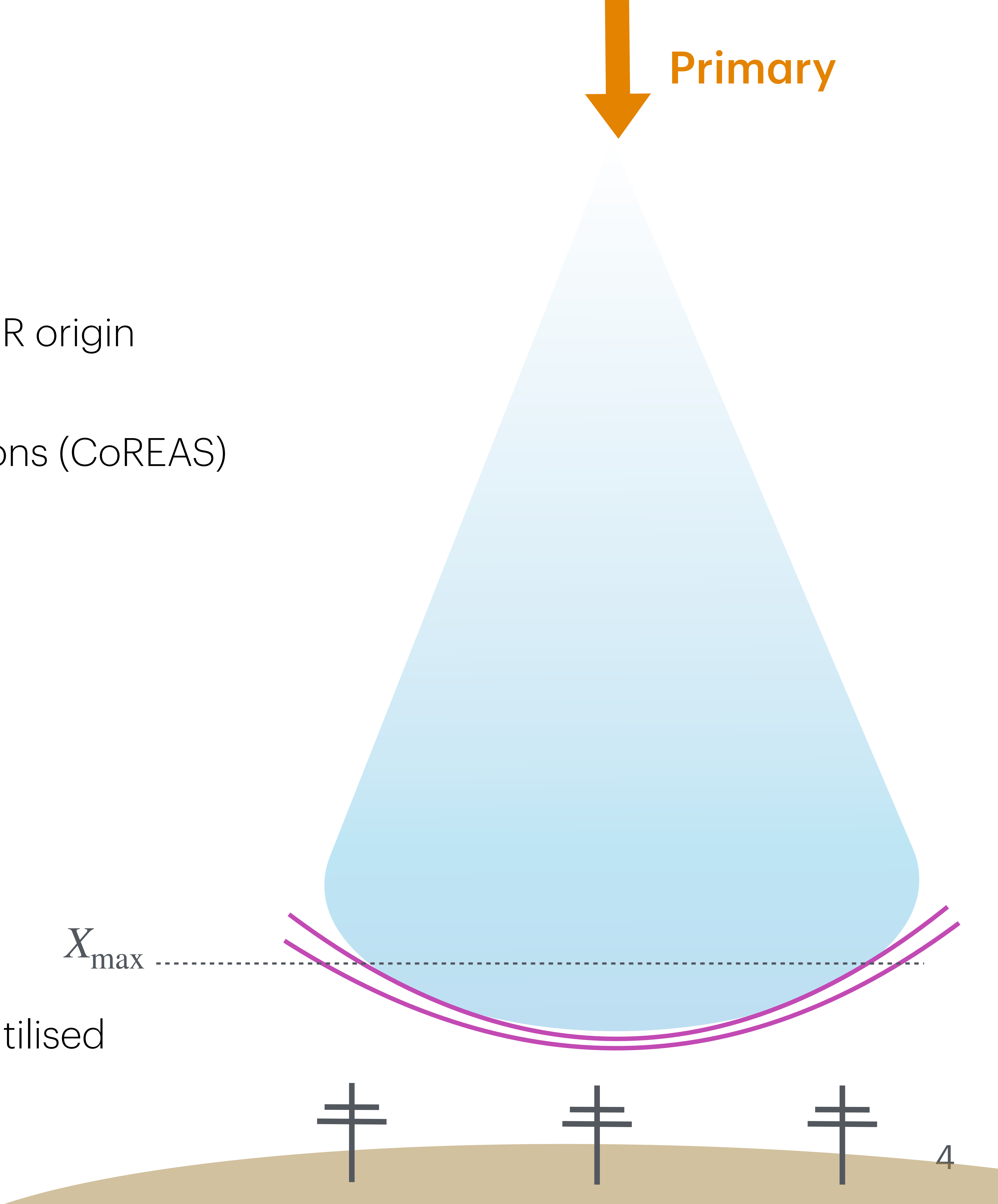
Current: through fit quality of measurements with MC simulations (CoREAS)





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

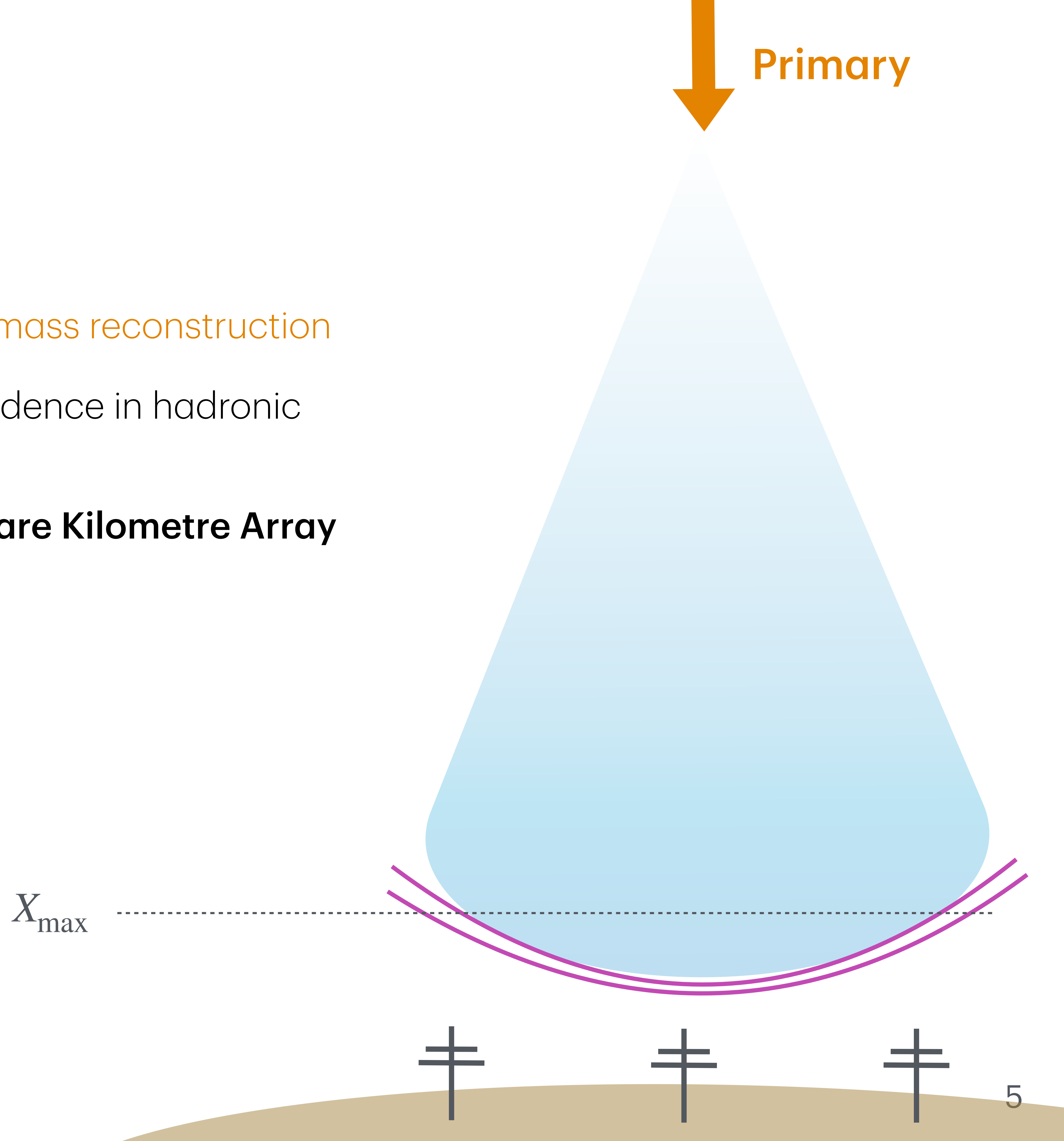


- Only energy deposited (fluence) used → not all information utilised
- Full shower profile cannot be reconstructed

X_{max} Reconstruction

Goal: reconstruct the full air shower profile

- Extract **more profile parameters** → more accurate mass reconstruction
- Identification of **substructures** → can resolve dependence in hadronic interaction models
- Leverage *extremely precise measurements* from **Square Kilometre Array**
- All information already available through traces!



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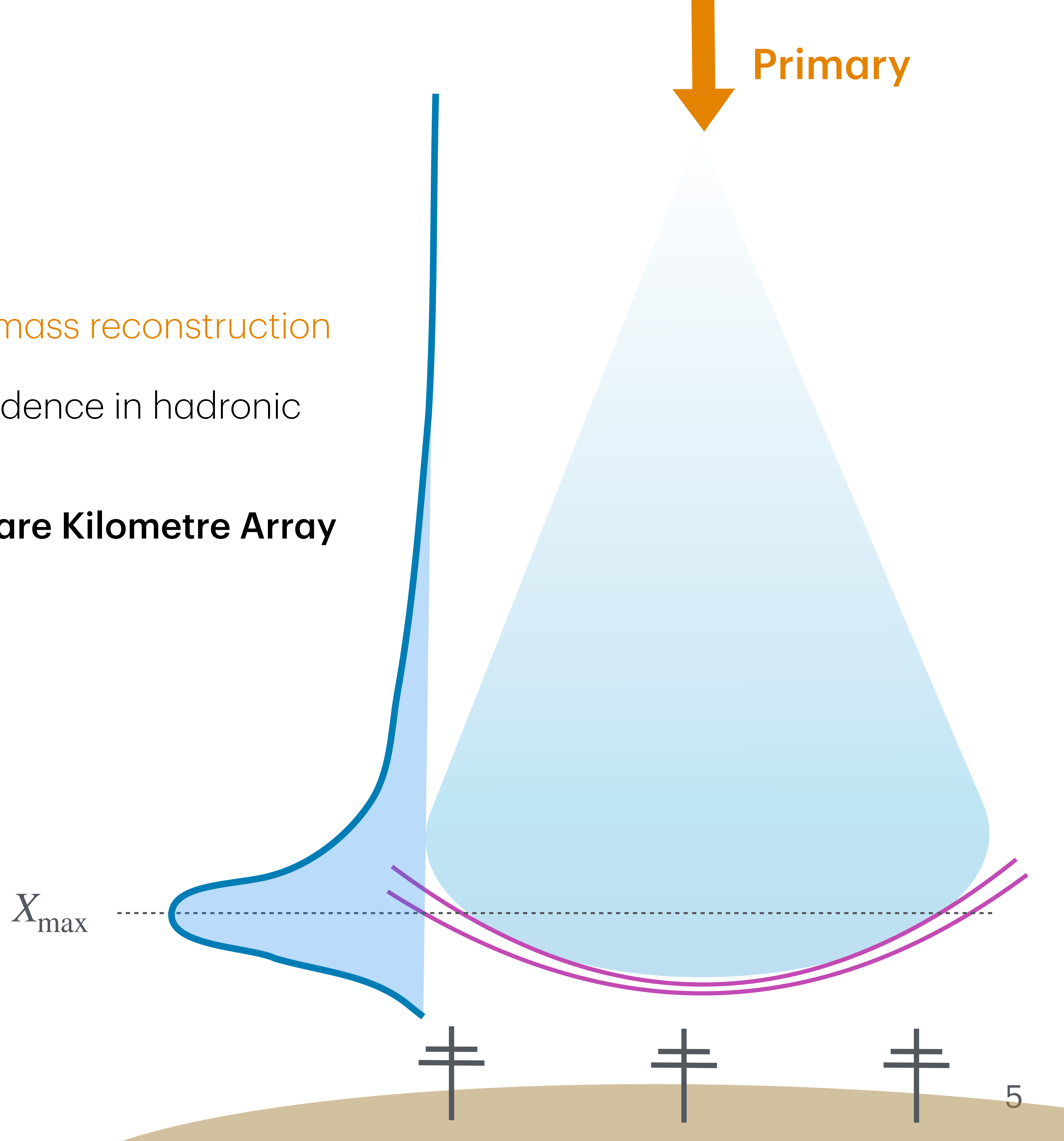

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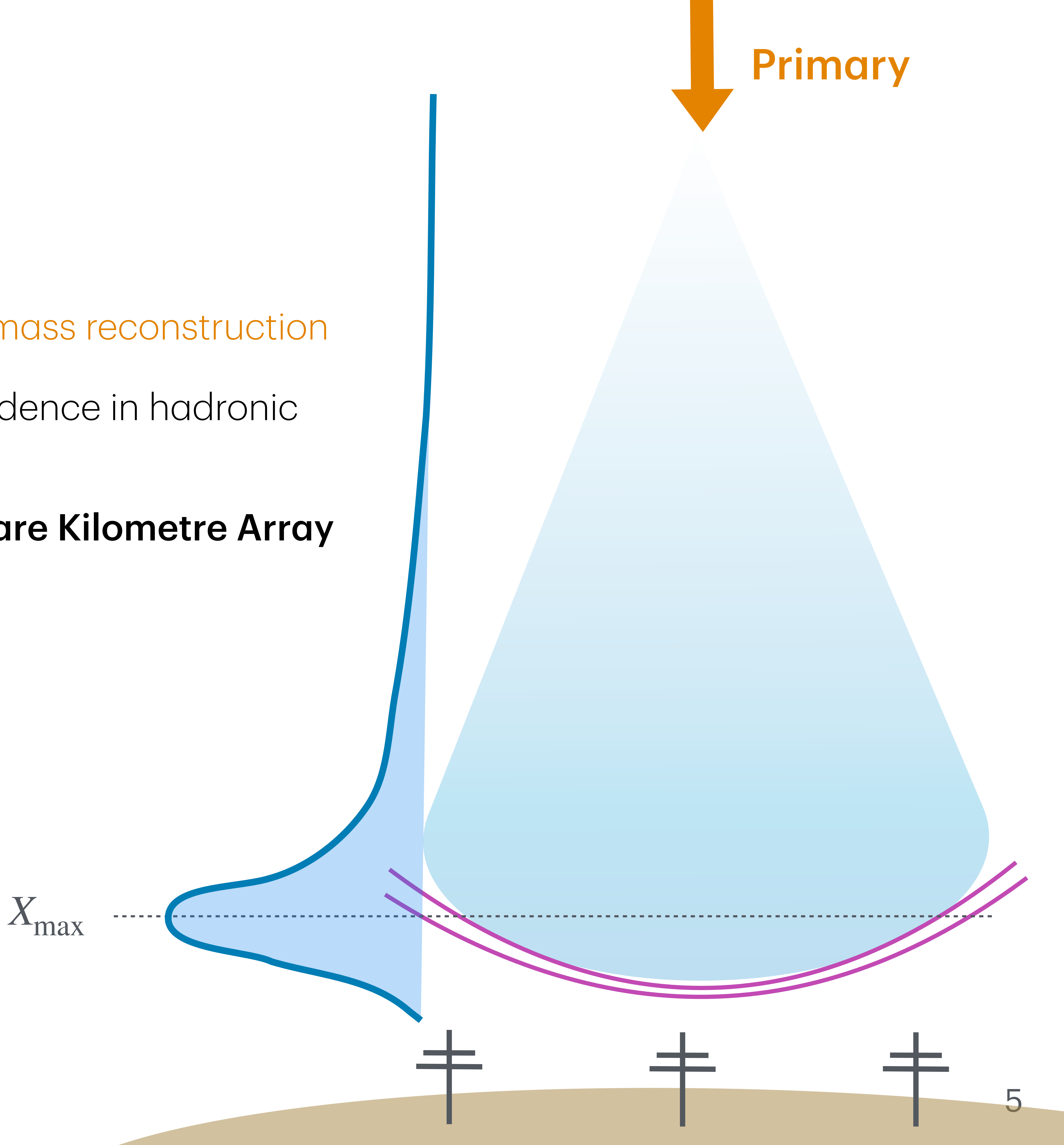
Challenges:

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



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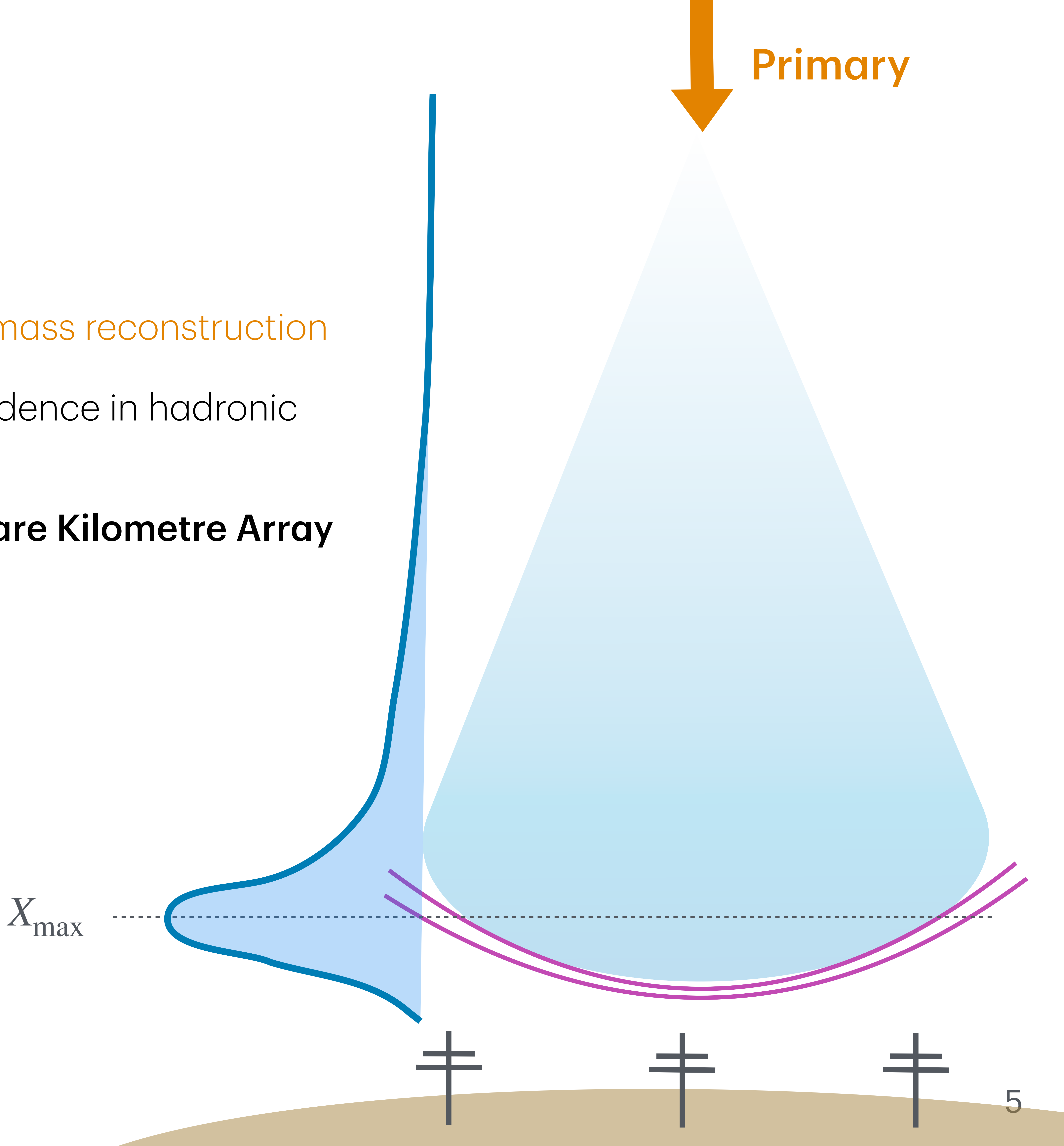
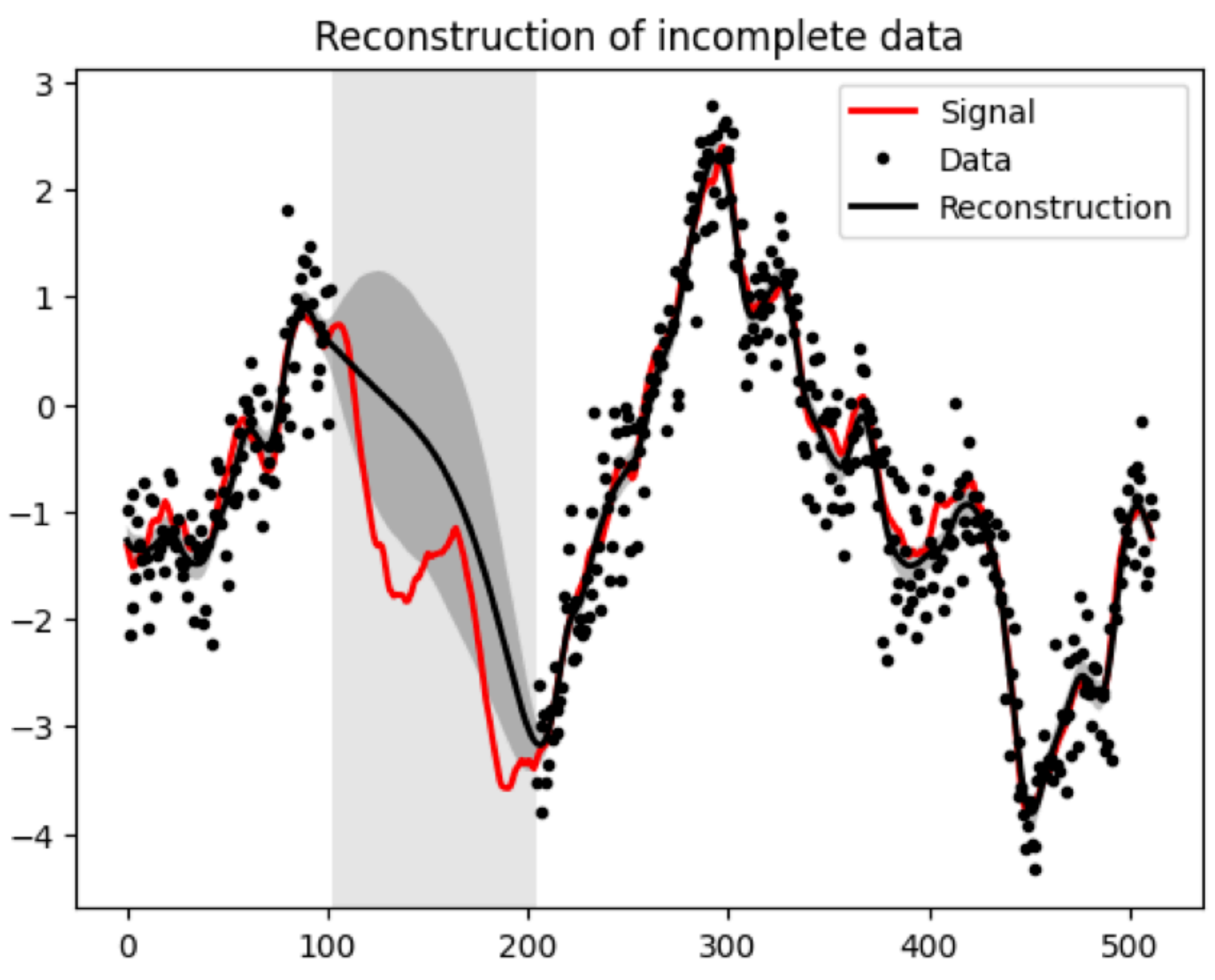
Solution: Information Field Theory!



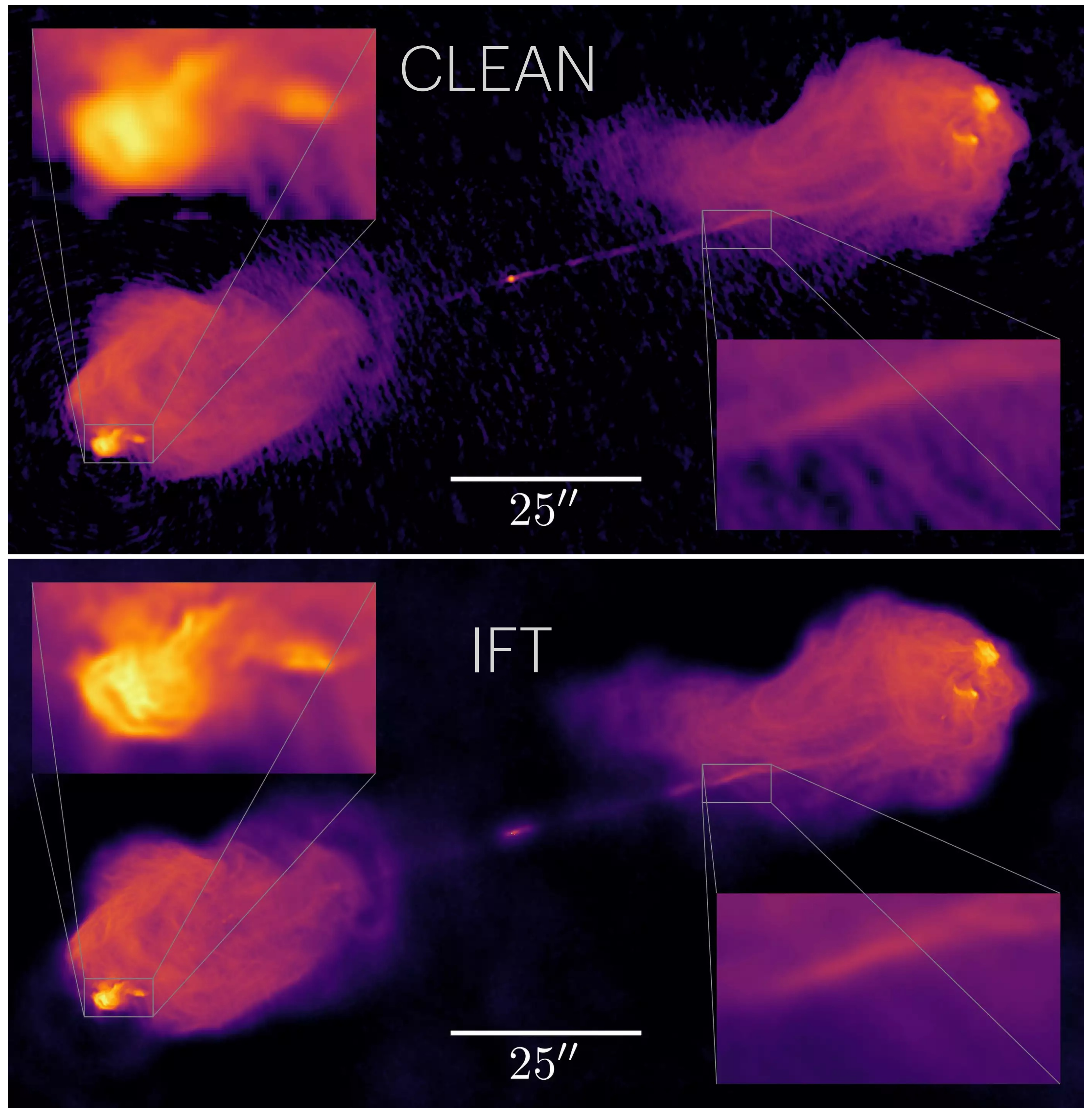
Information Field Theory (IFT)

- 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](), also talk by M. Jetti

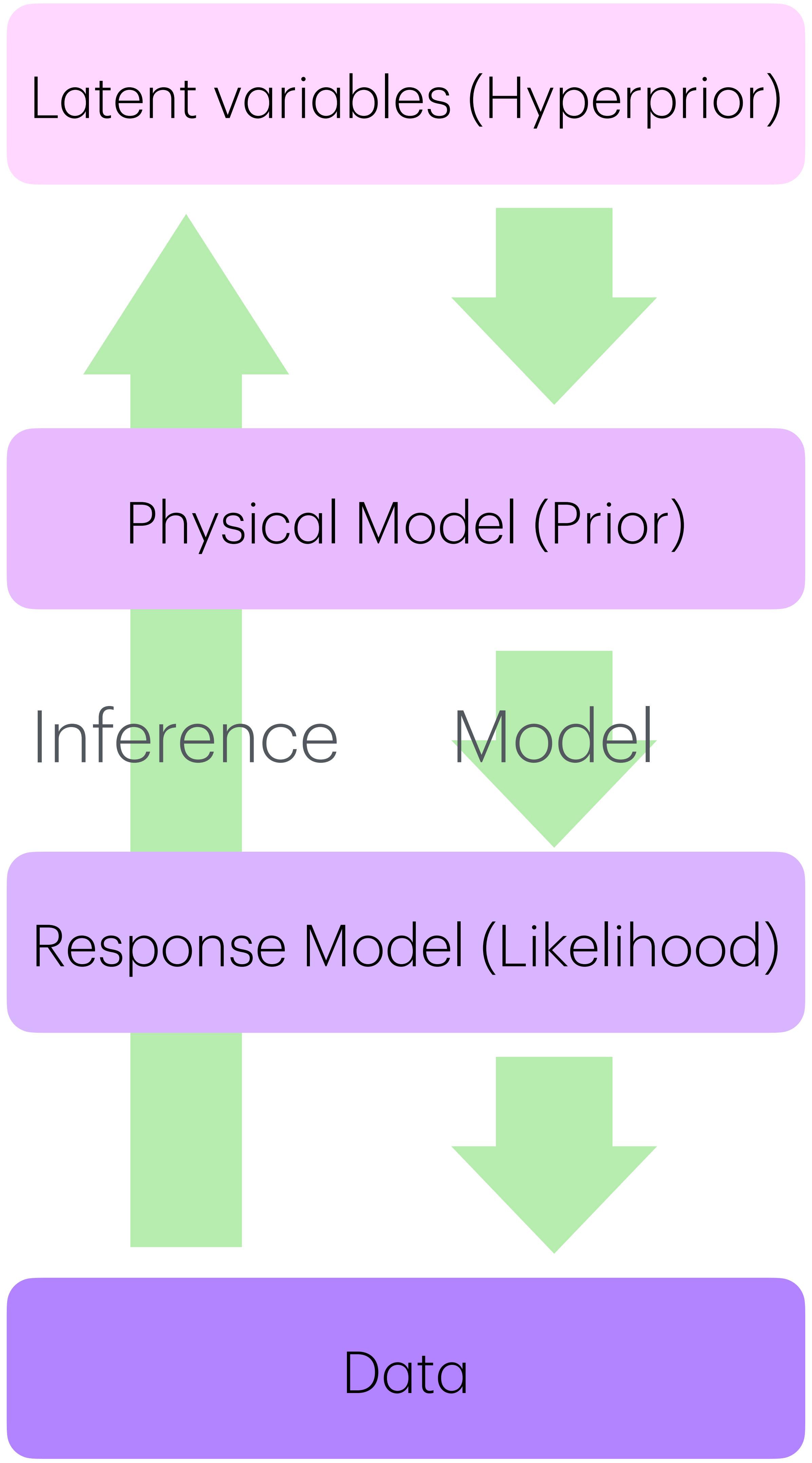


M. Straub, ARENA 2024

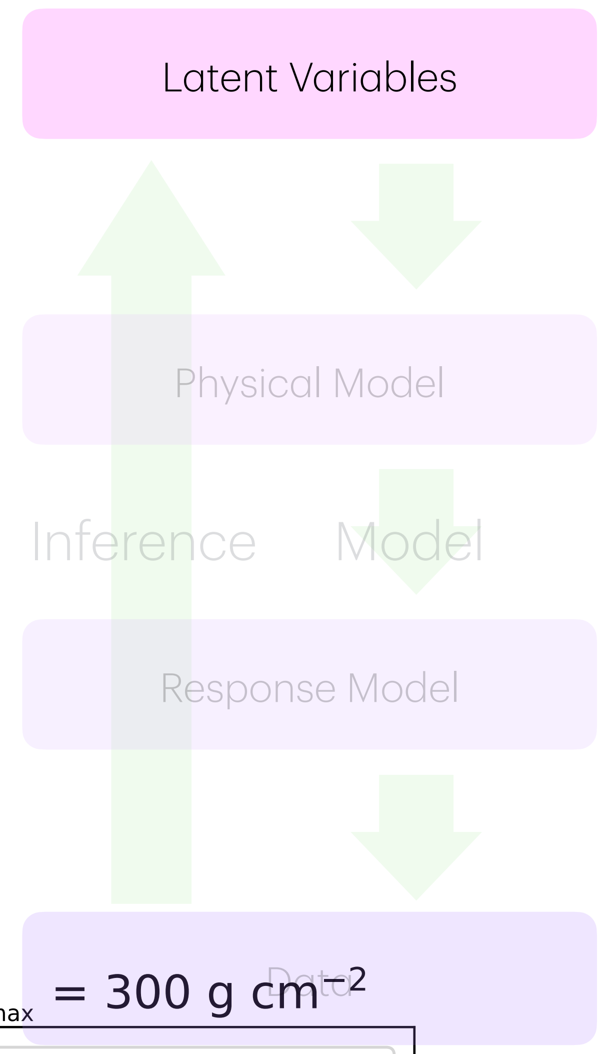
MPA; NRAO/Klasse Richard A.



Reconstruction of Cygnus A



Prior Model



- Distribution to sample physical observables for reconstruction

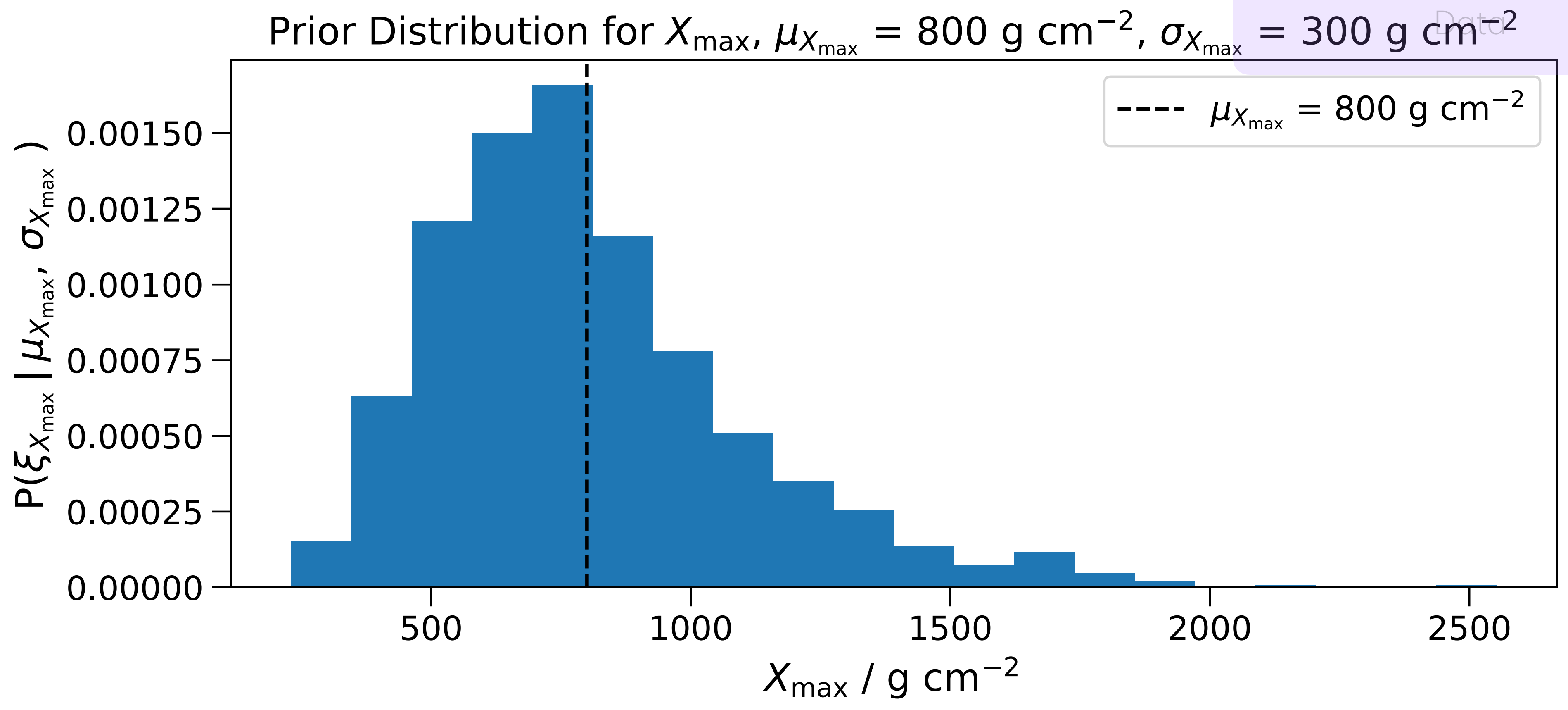
- Sample each latent parameter ξ as unit Gaussian → transform to $X_{\max}, N_{\max}$ via log-normal distribution

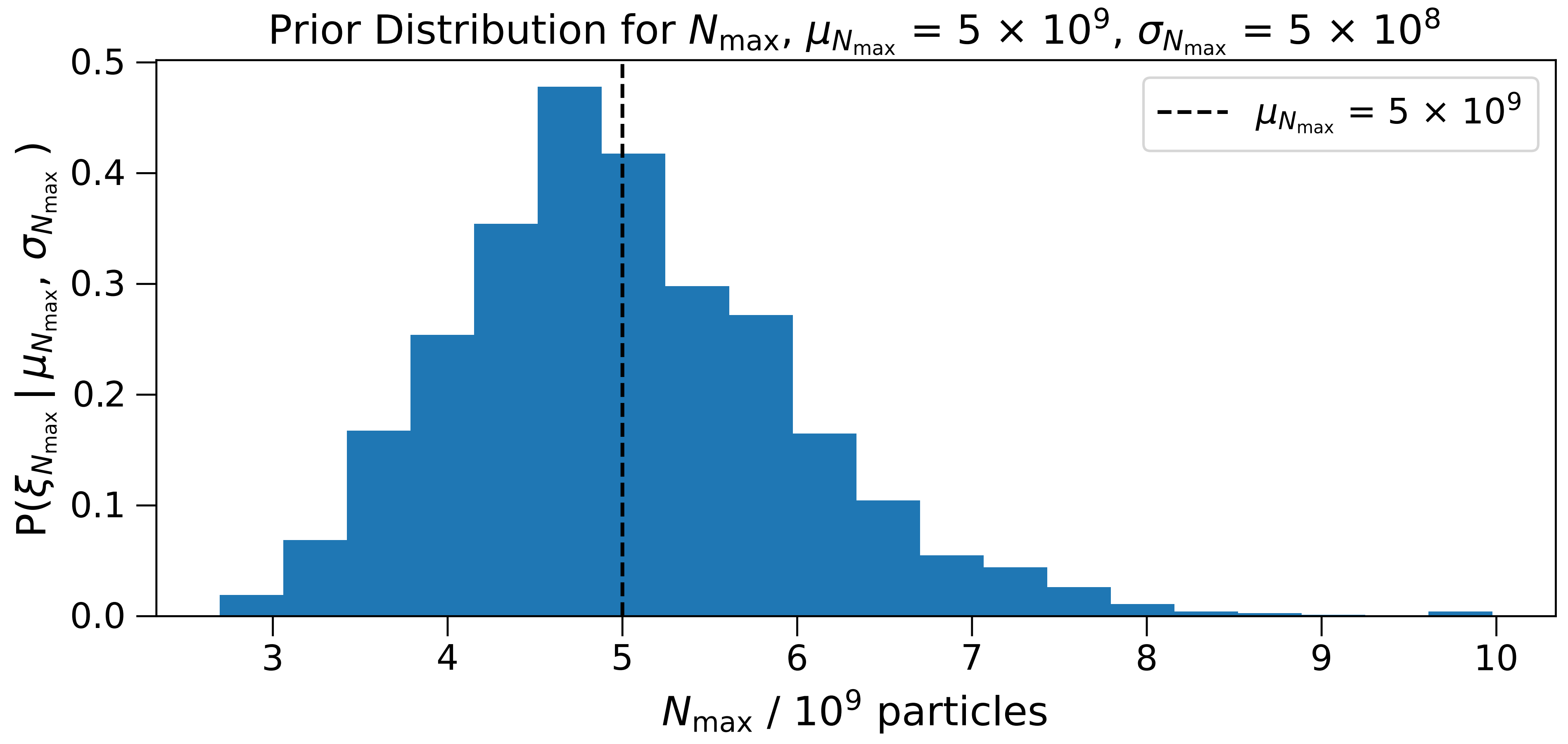
$$\xi_{X_{\max}} \sim \mathcal{N}(0,1) \qquad X_{\max} = P(\xi_{X_{\max}} \mid \mu_{X_{\max}}, \sigma_{X_{\max}})$$

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

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

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





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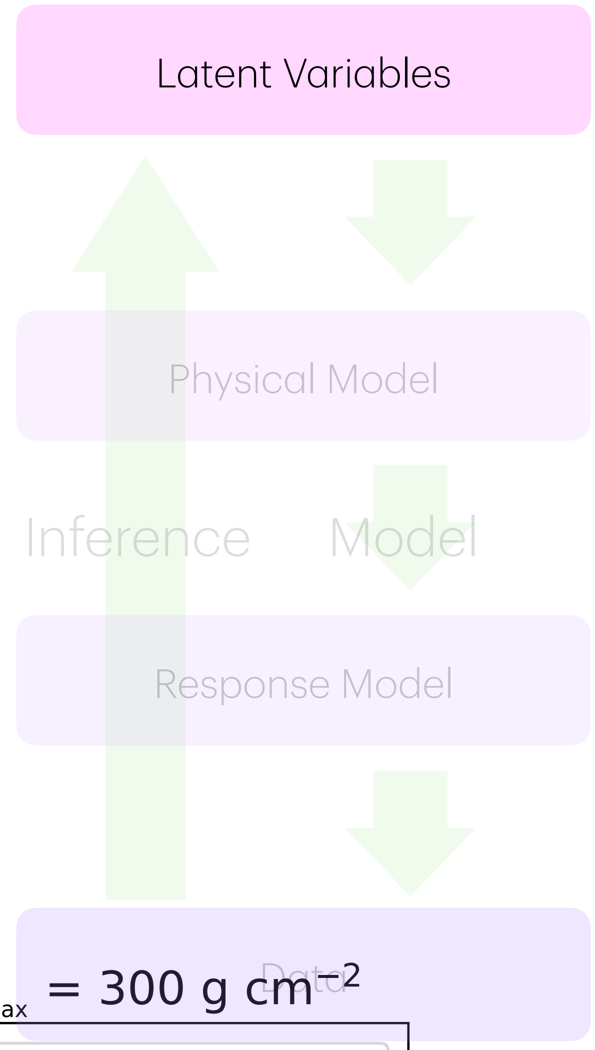

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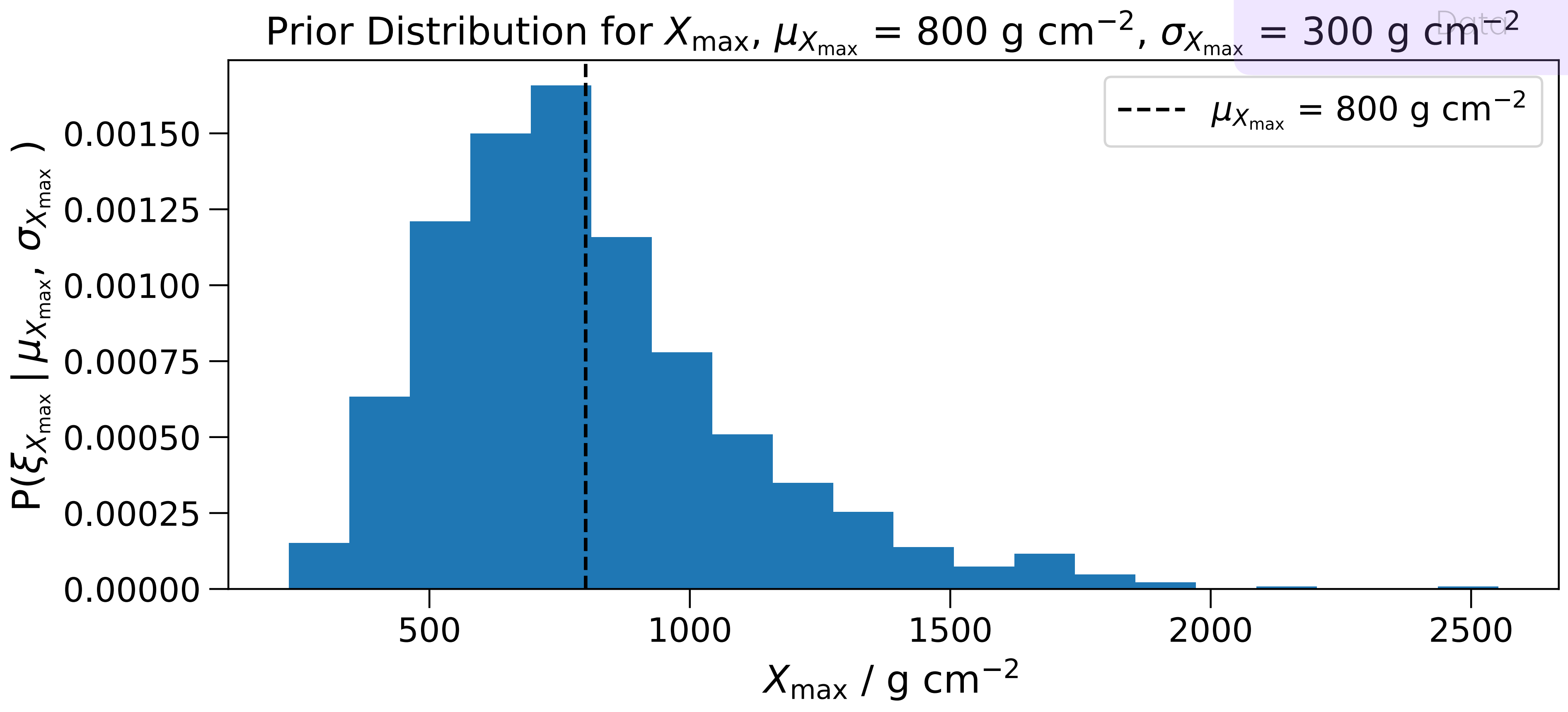
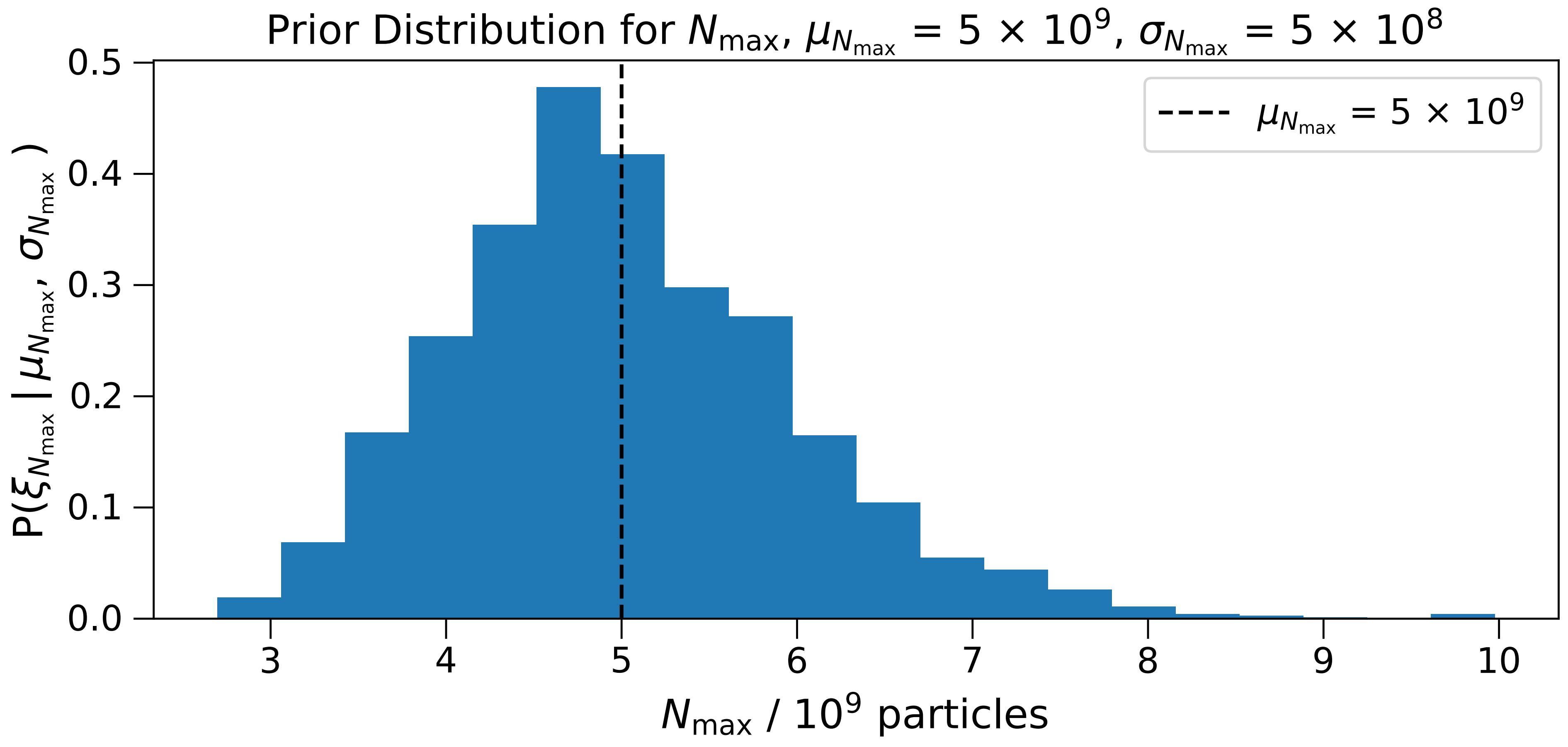
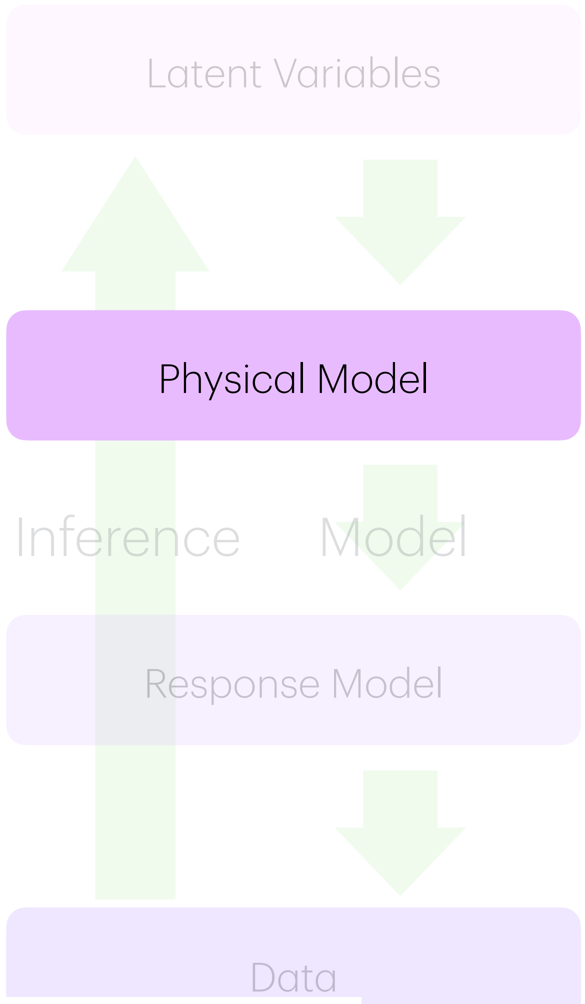




Longitudinal Profile of Air Shower



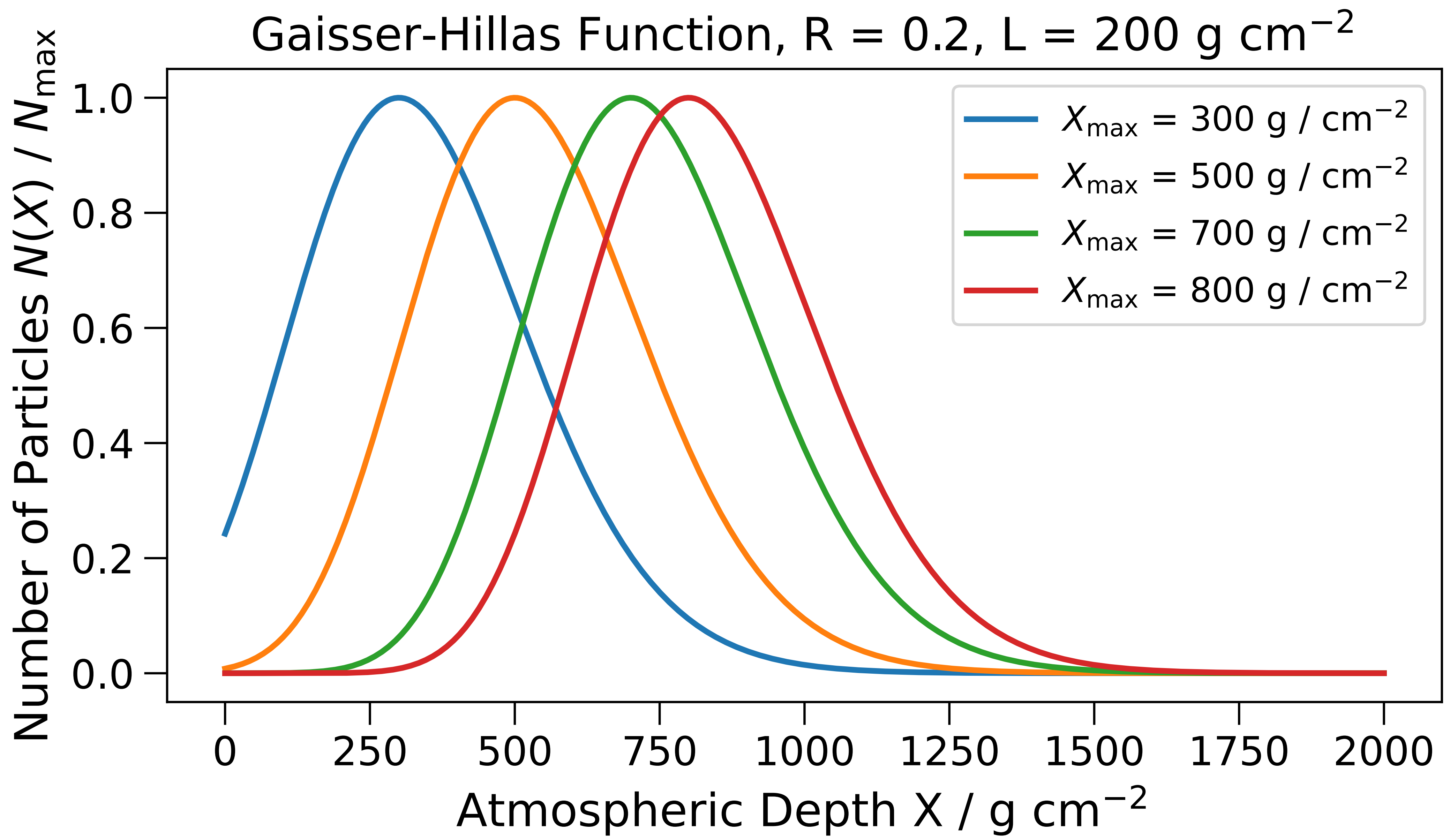
Gaisser-Hillas Function (R-L formulation)

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

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

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

R, L : shape parameters (fixed for now)

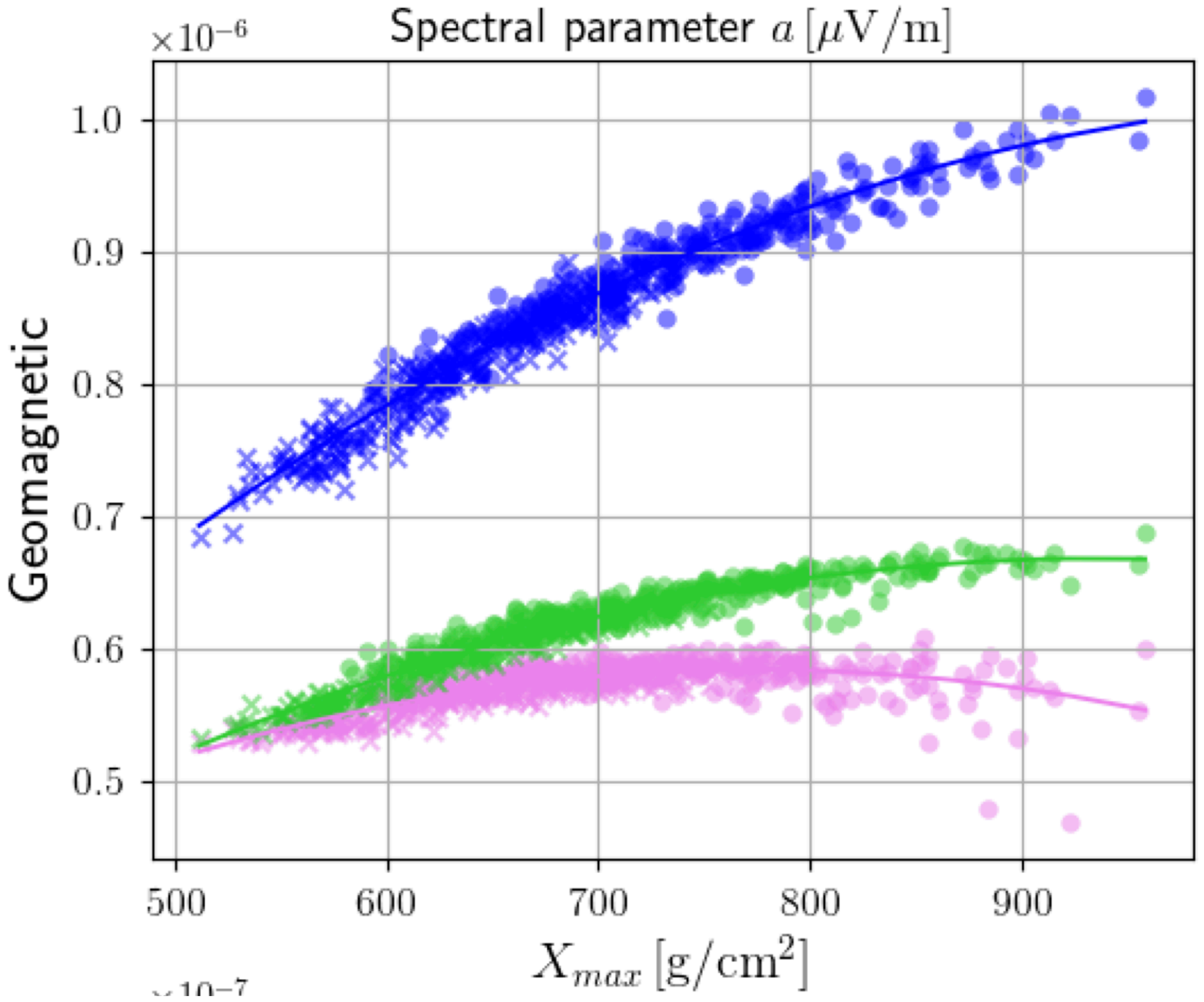


- Only consider longitudinal profile (1-D case) in this work (4-D case → P. Laub)

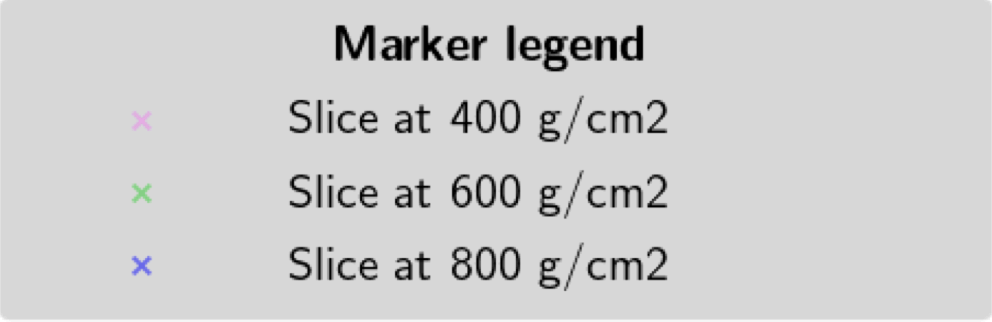
Template Synthesis

Fast-forward model for radio emission (Desmet+ 2024)

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



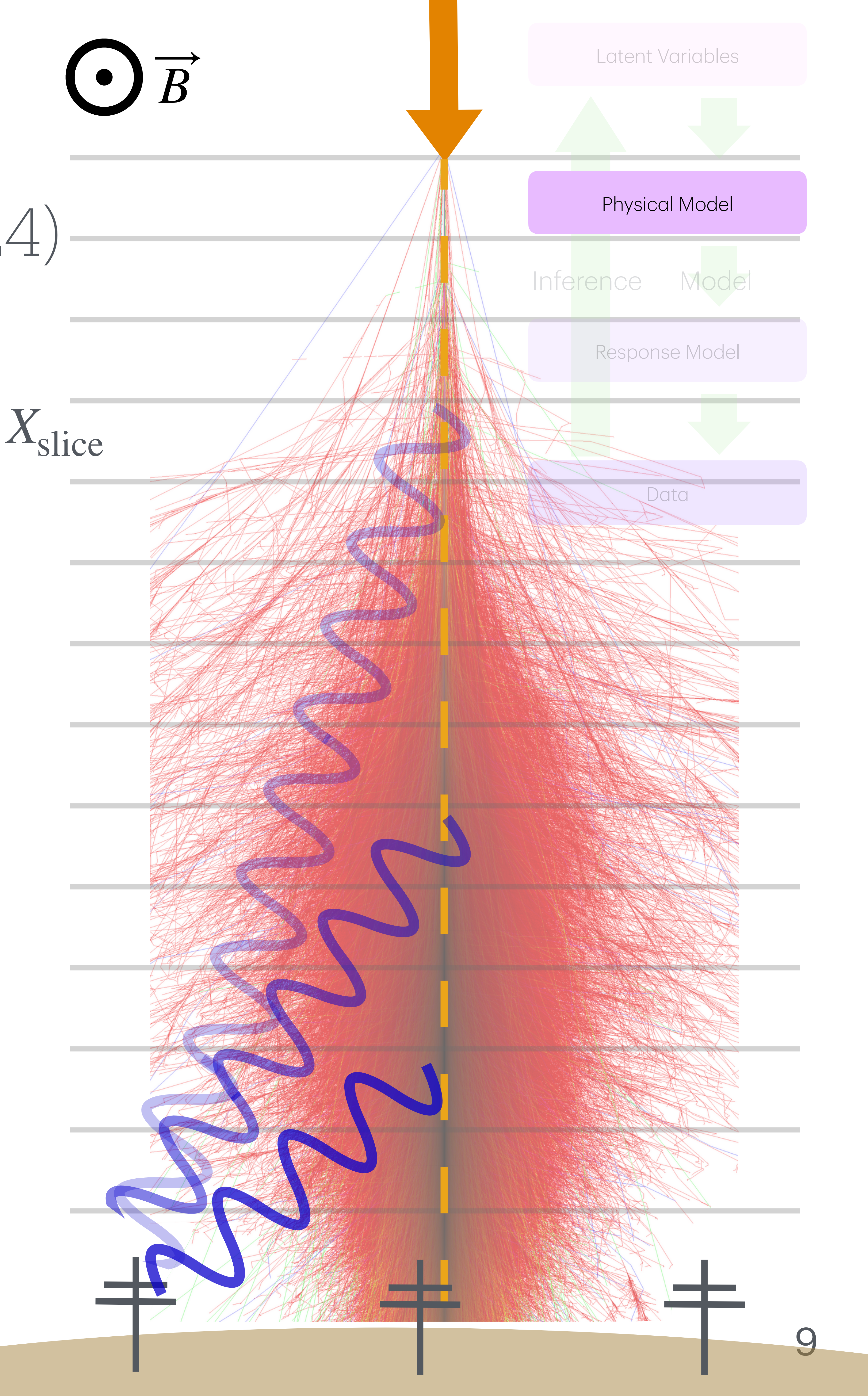
$$a = a(\vec{r}_{\text{ant}}, X_{\text{max}}, X_{\text{slice}})$$



[20, 500] MHz

$d_{\text{core}} = 75\,\text{m}$

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



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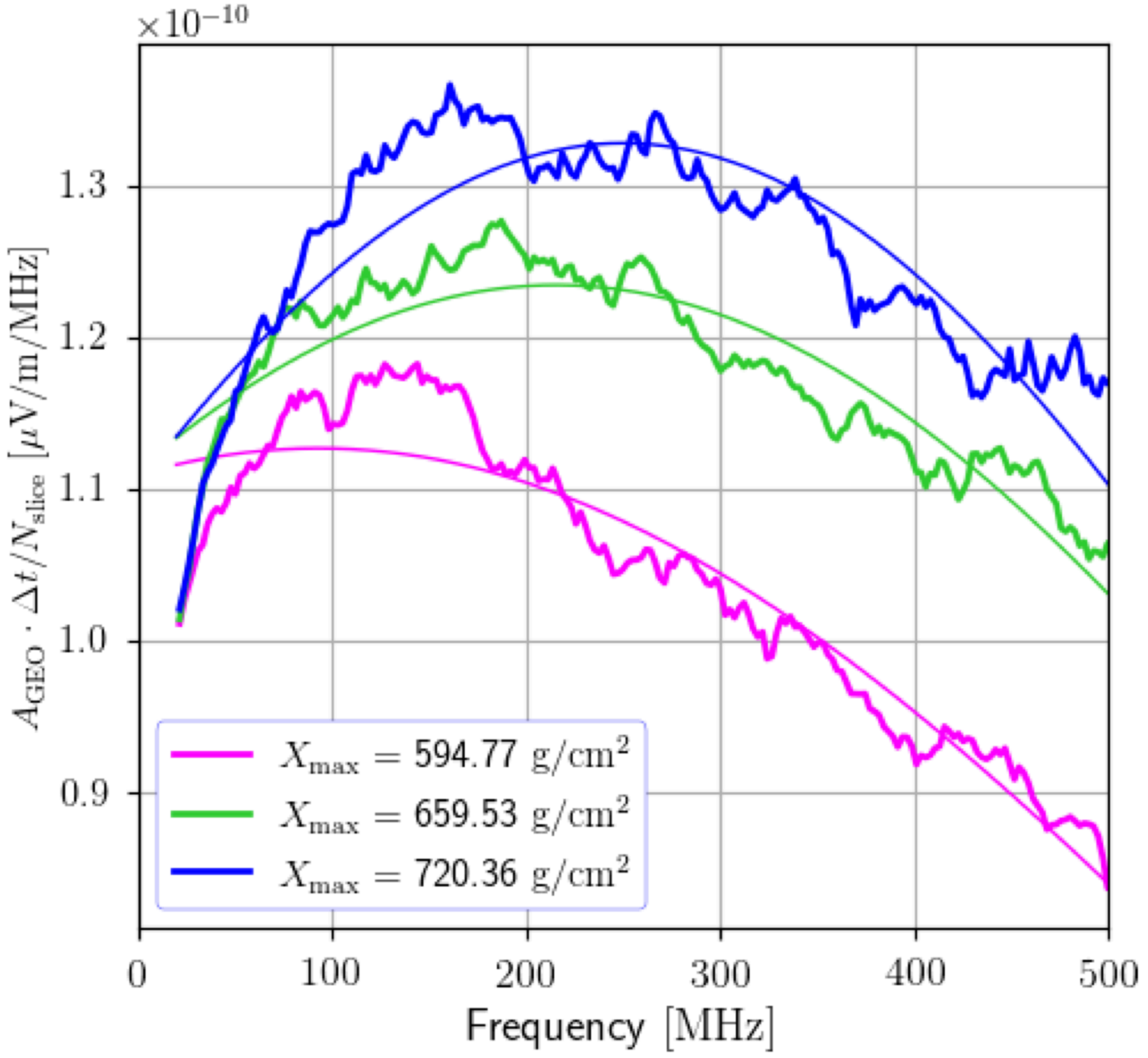

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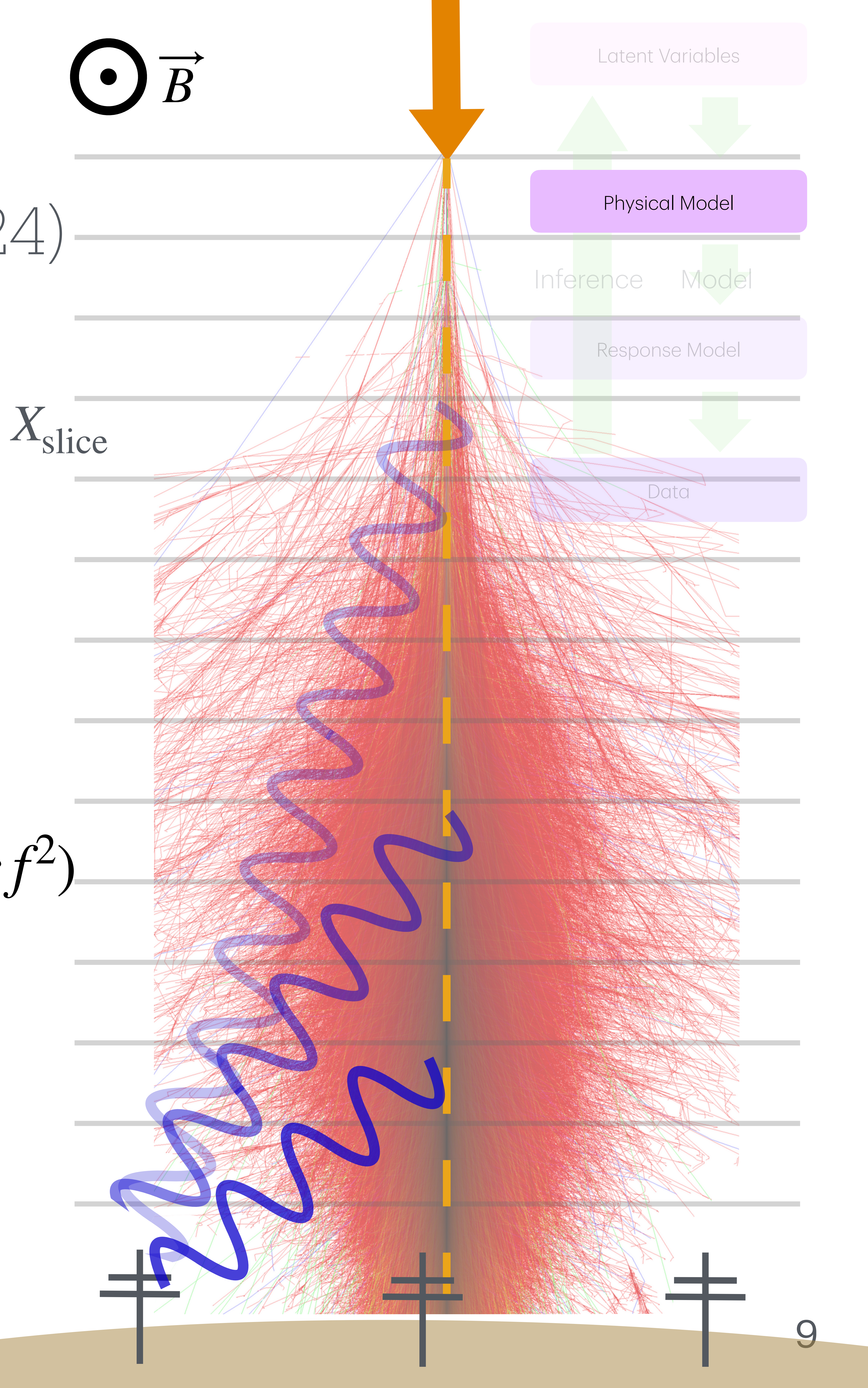
$$A(f, \vec{r}_{\text{ant}}, X_{\text{slice}}, X_{\text{max}}) = a\, N_{\text{slice}} \exp(bf + cf^2)$$

$X_{\text{slice}} = 600\,\text{g}\,\text{cm}^{-2}$

$d_{\text{core}} = 75\,\text{m}$



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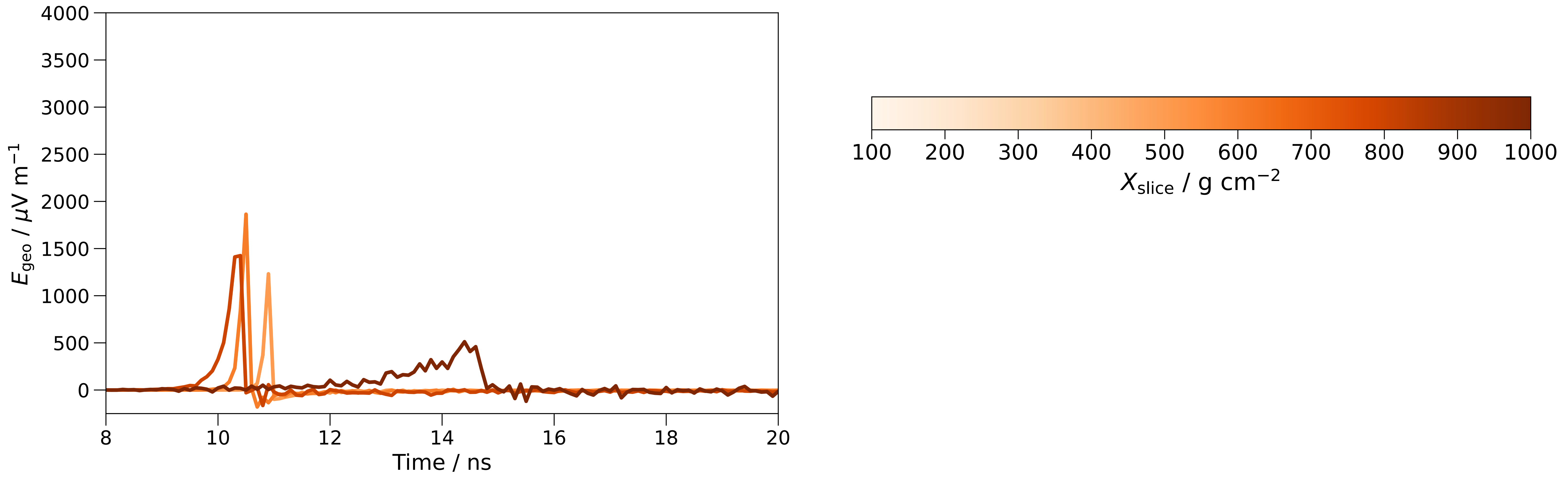
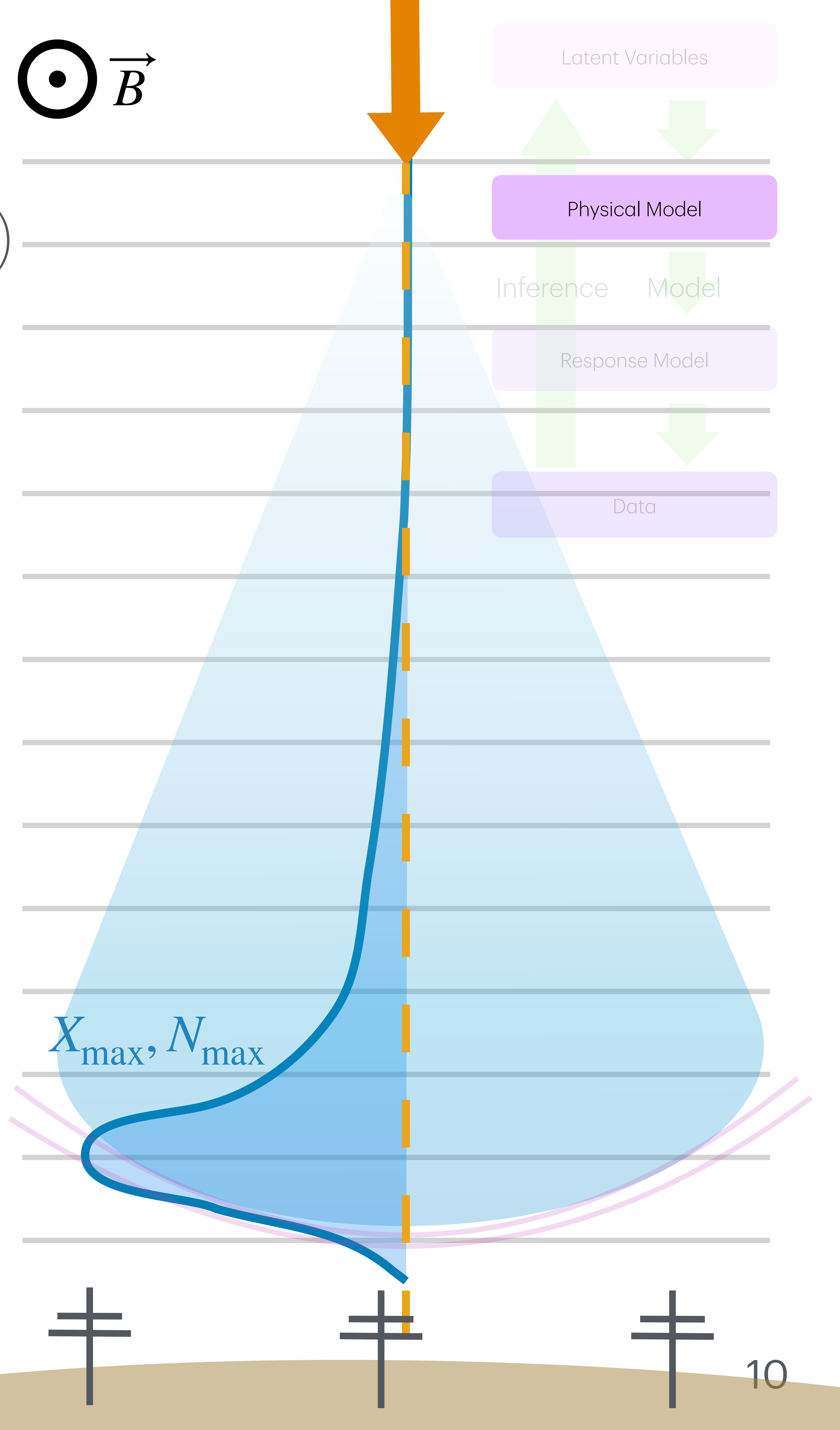
2. Calculate amplitude spectrum from **simulated traces** of **origin shower** for each slice & antenna



Electric field traces of origin shower

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



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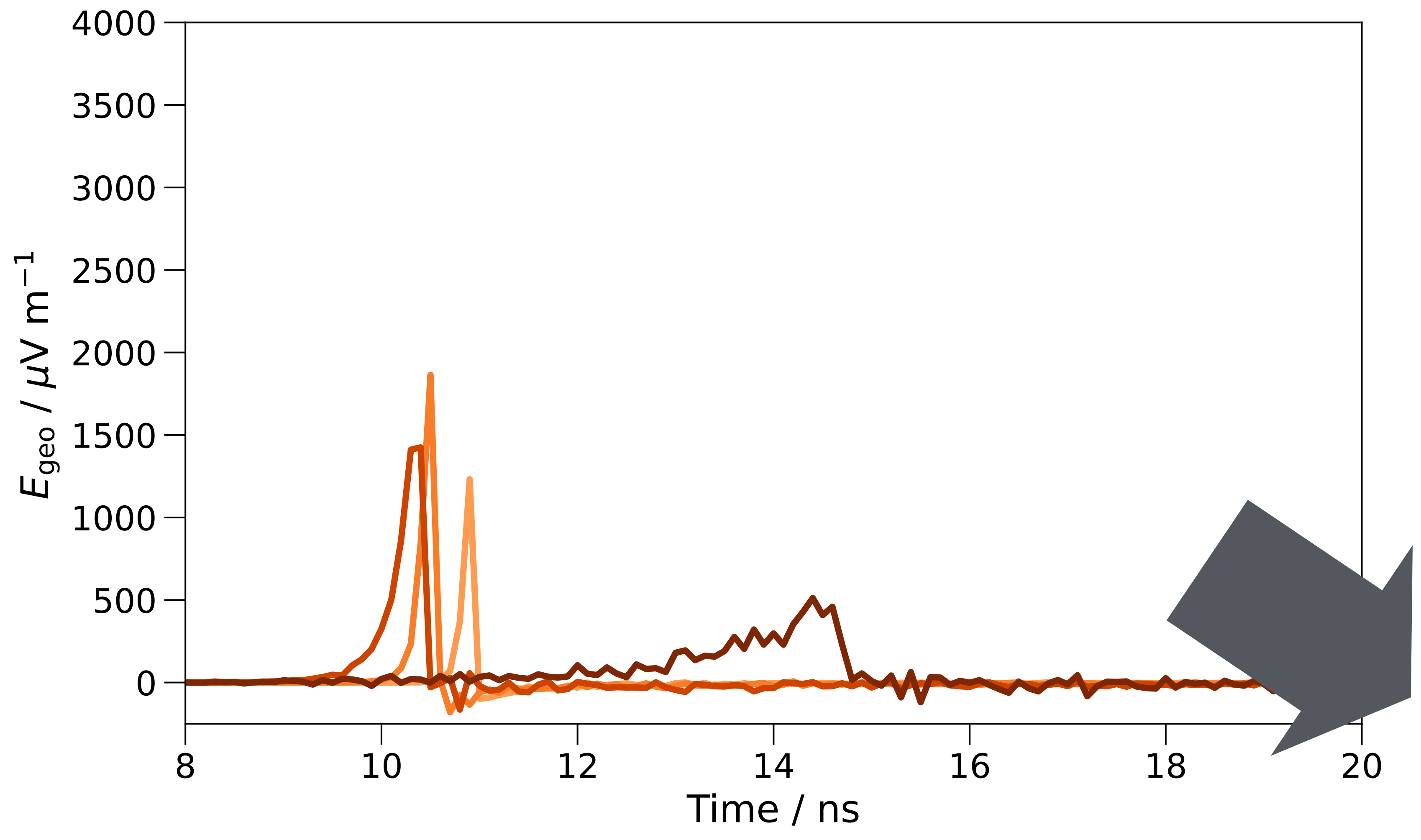

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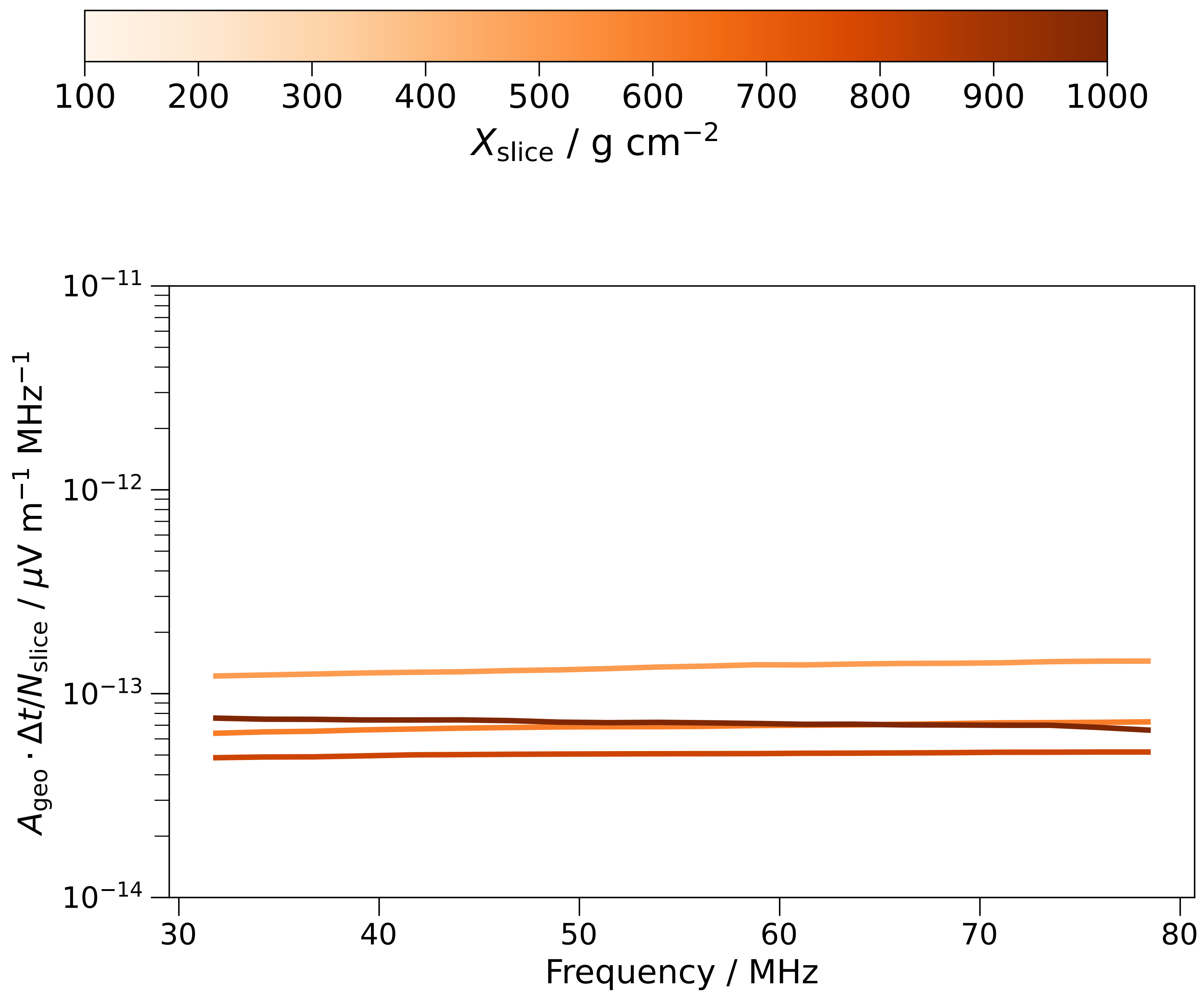

Amplitude spectrum

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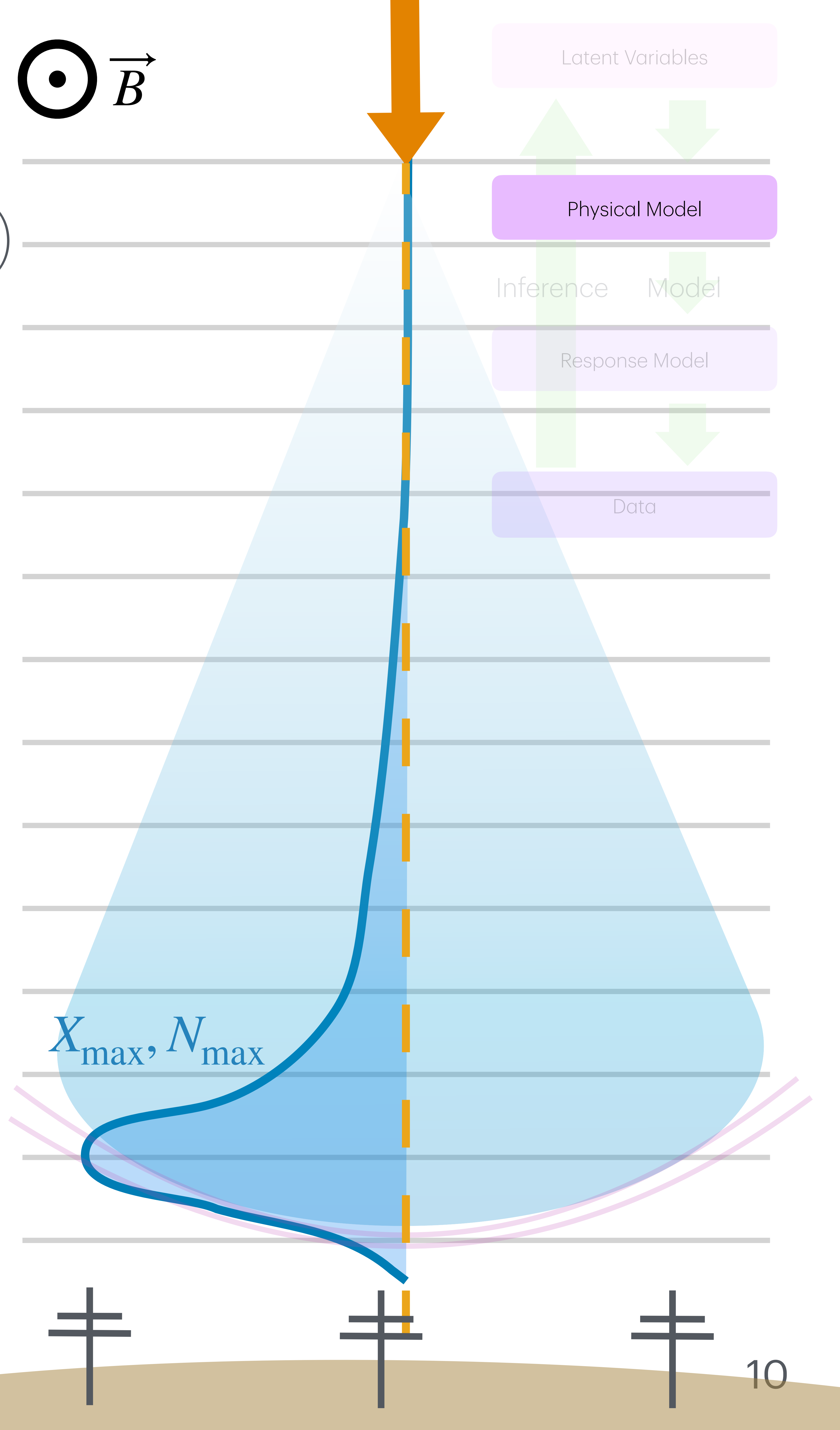

Template Synthesis

Fast-forward model for radio emission (Desmet+ 2024)

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

Solid: Origin Shower
Dashed: Target Shower

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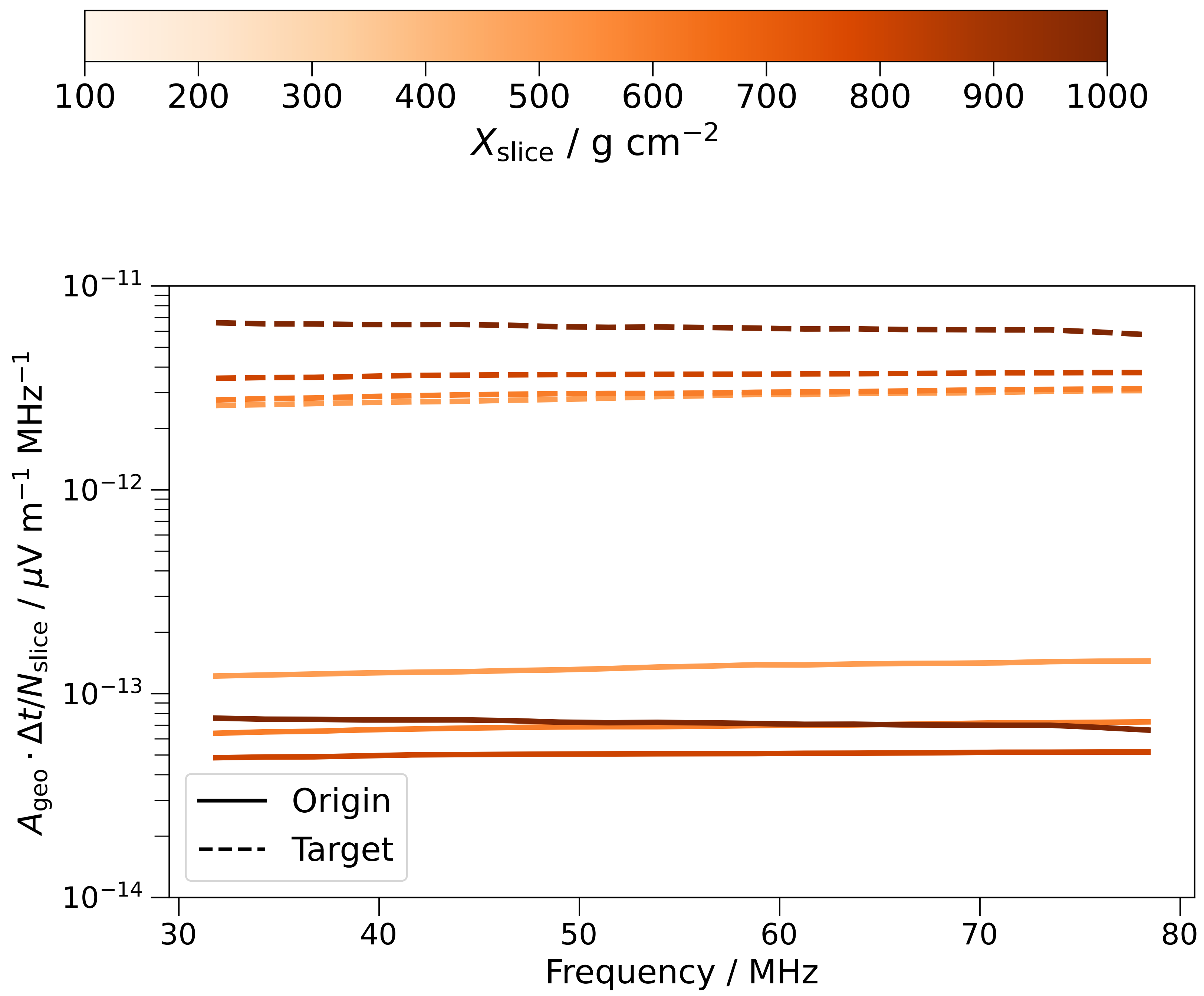

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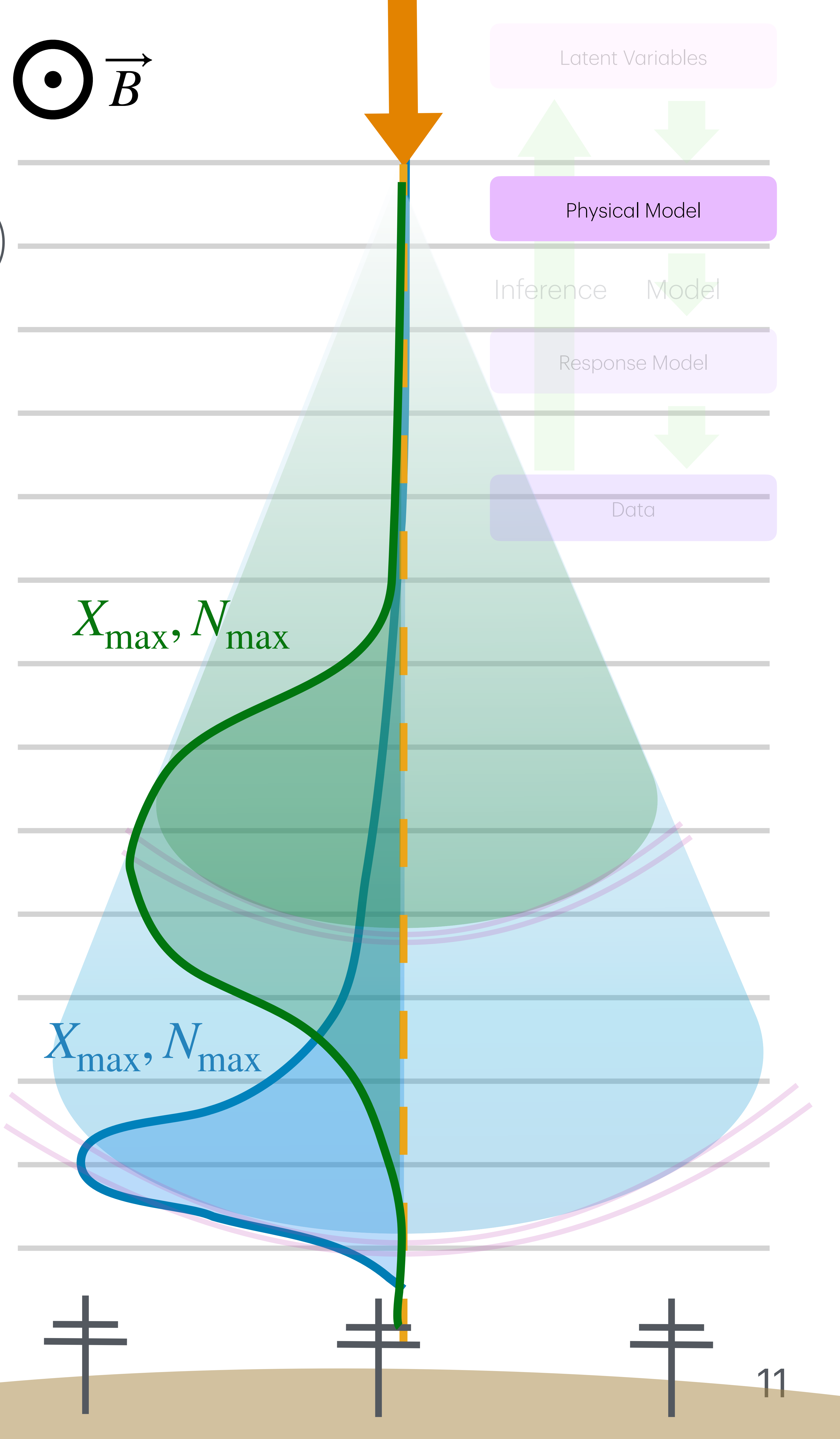

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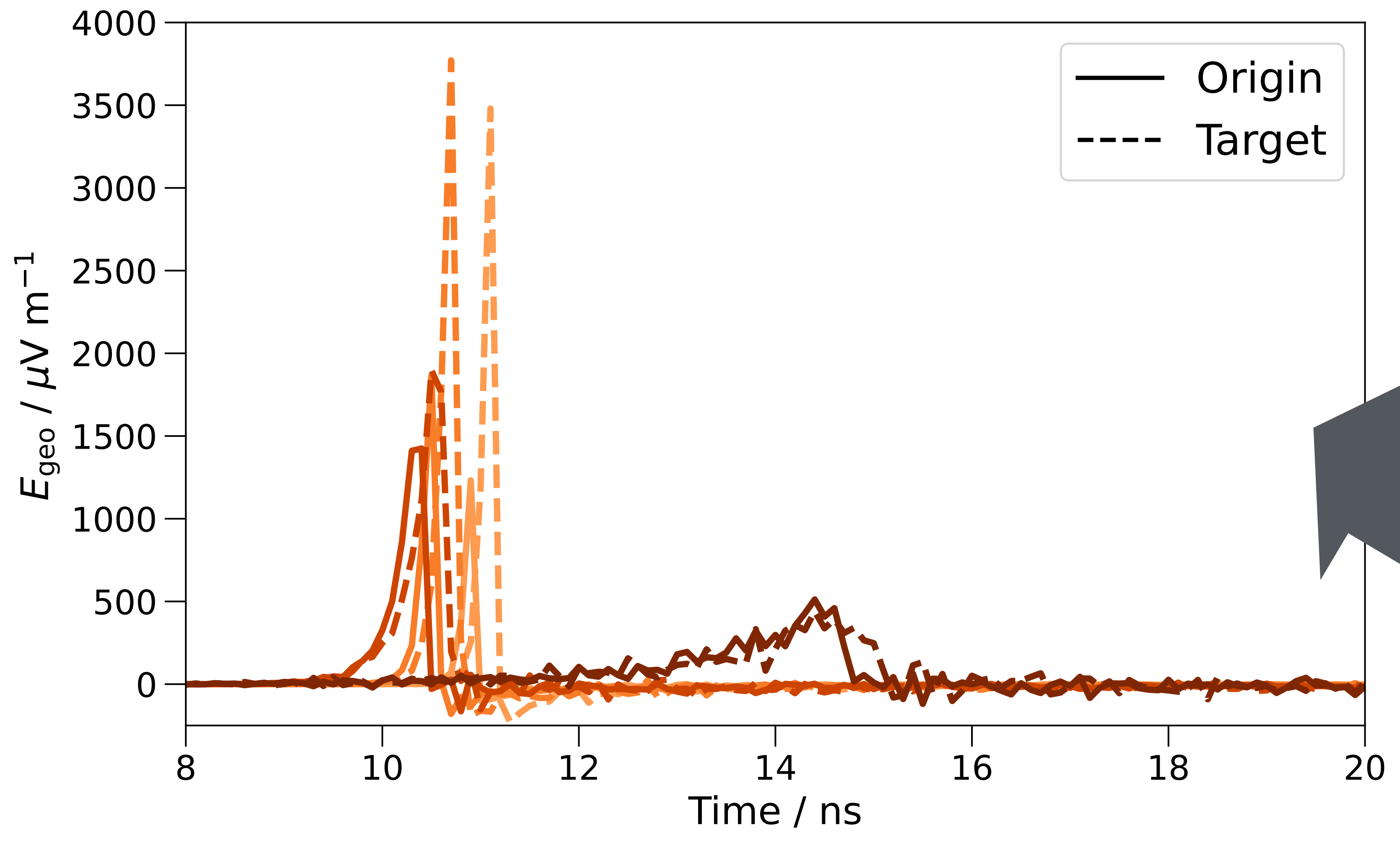

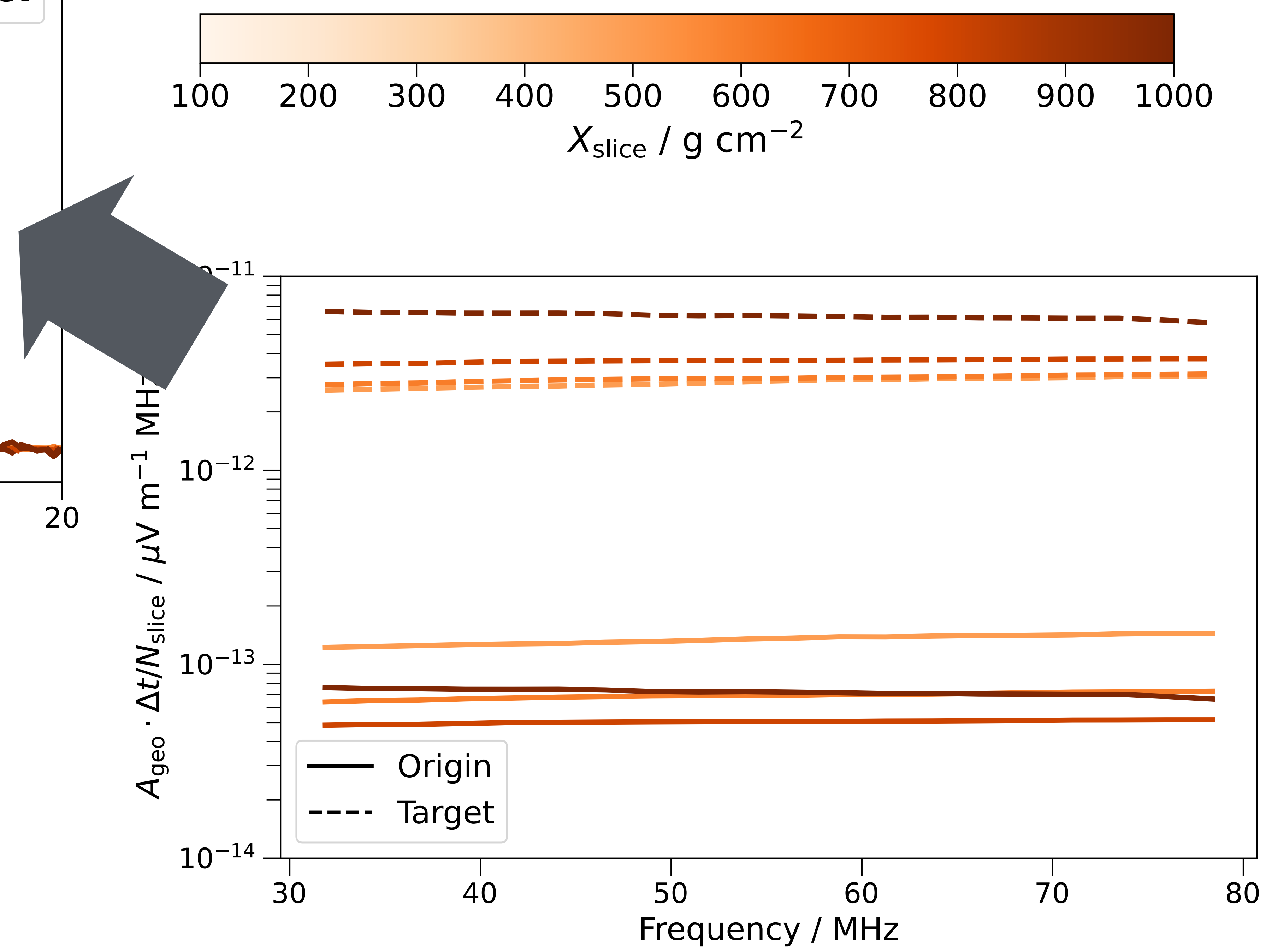

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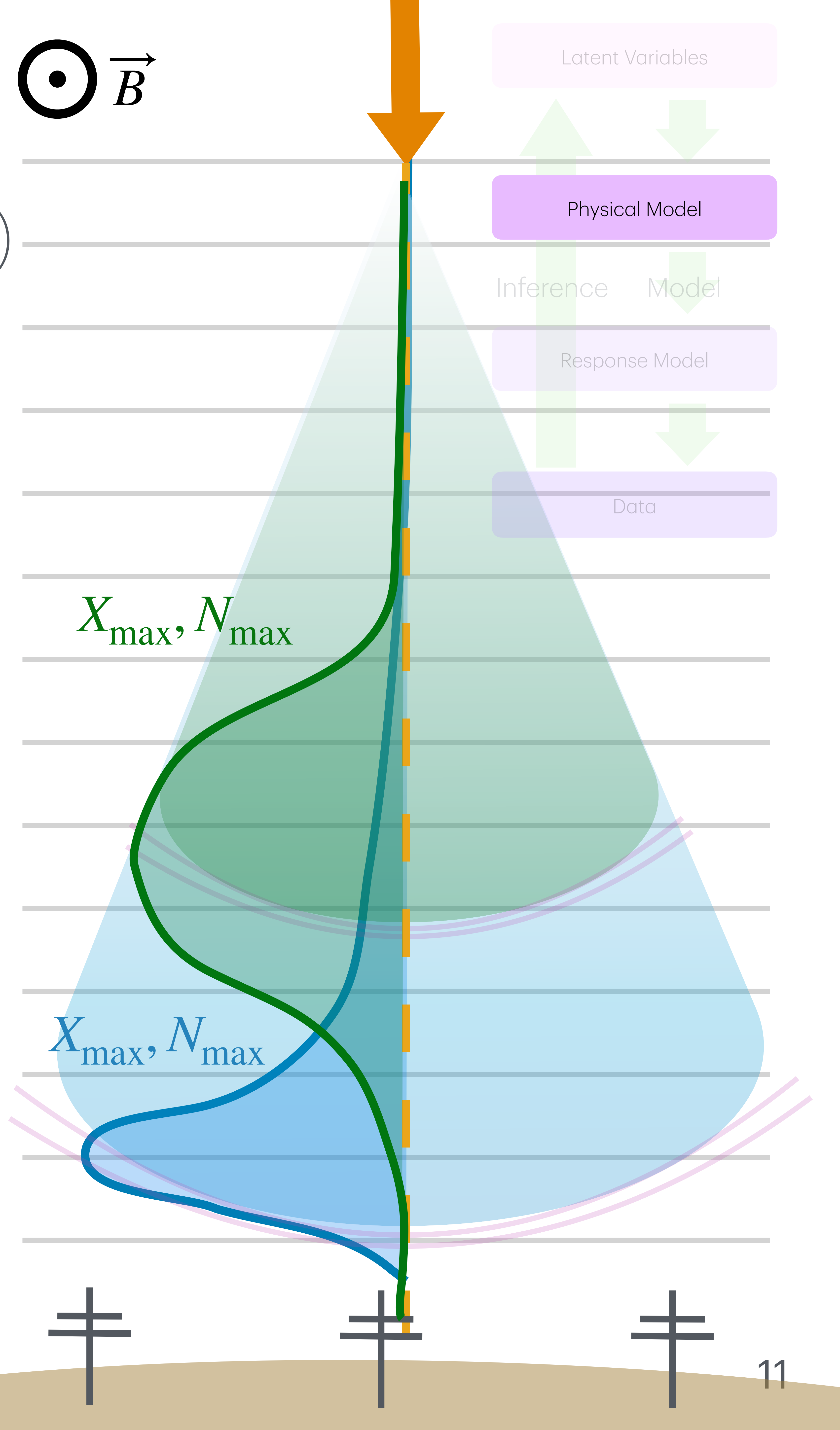
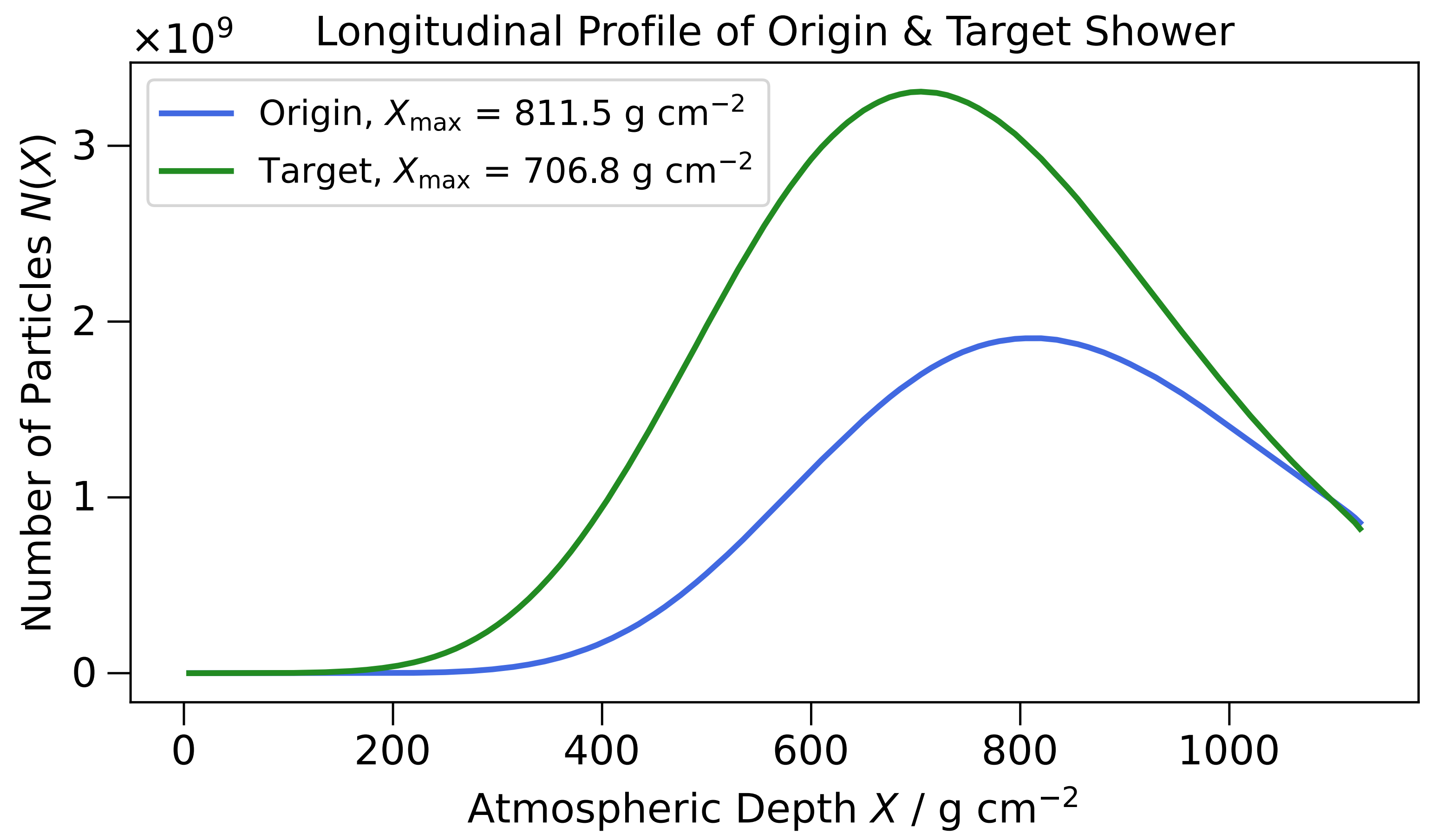
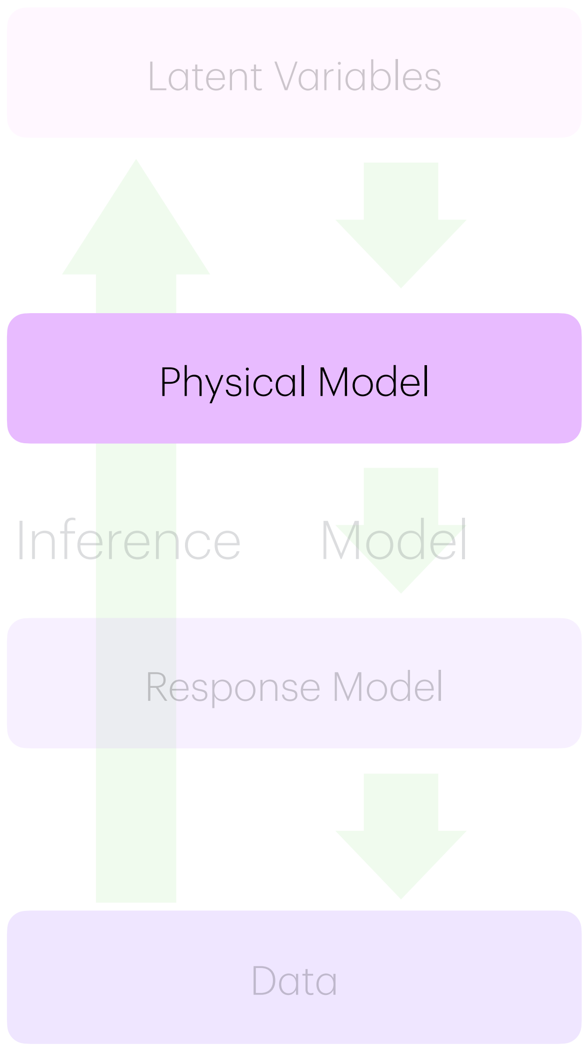
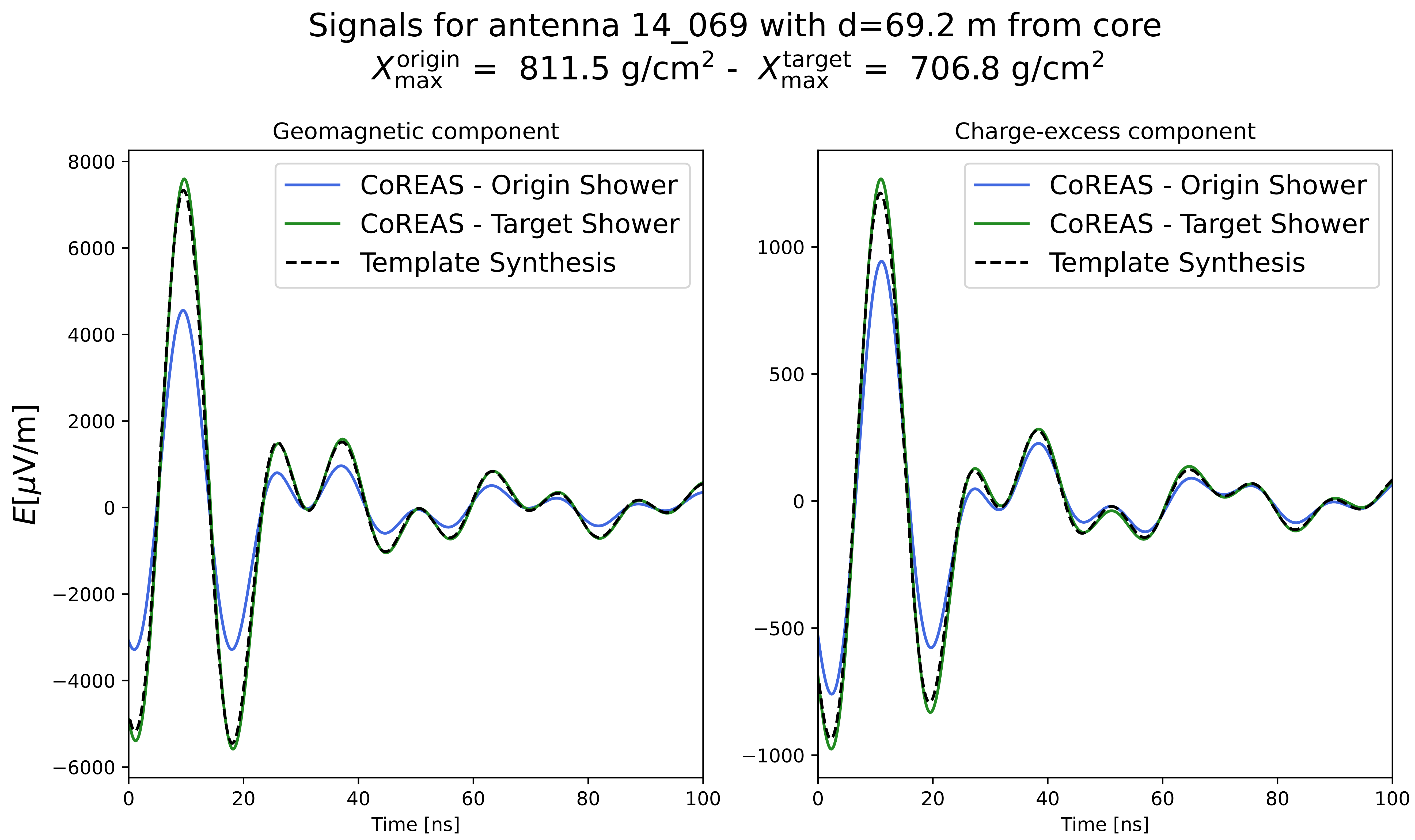


Template Synthesis

Verification



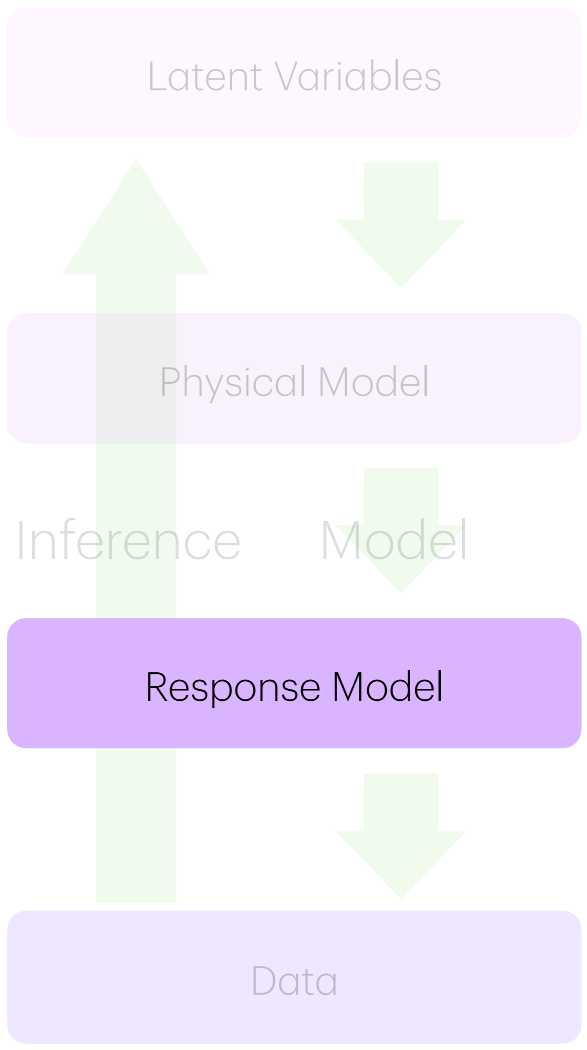




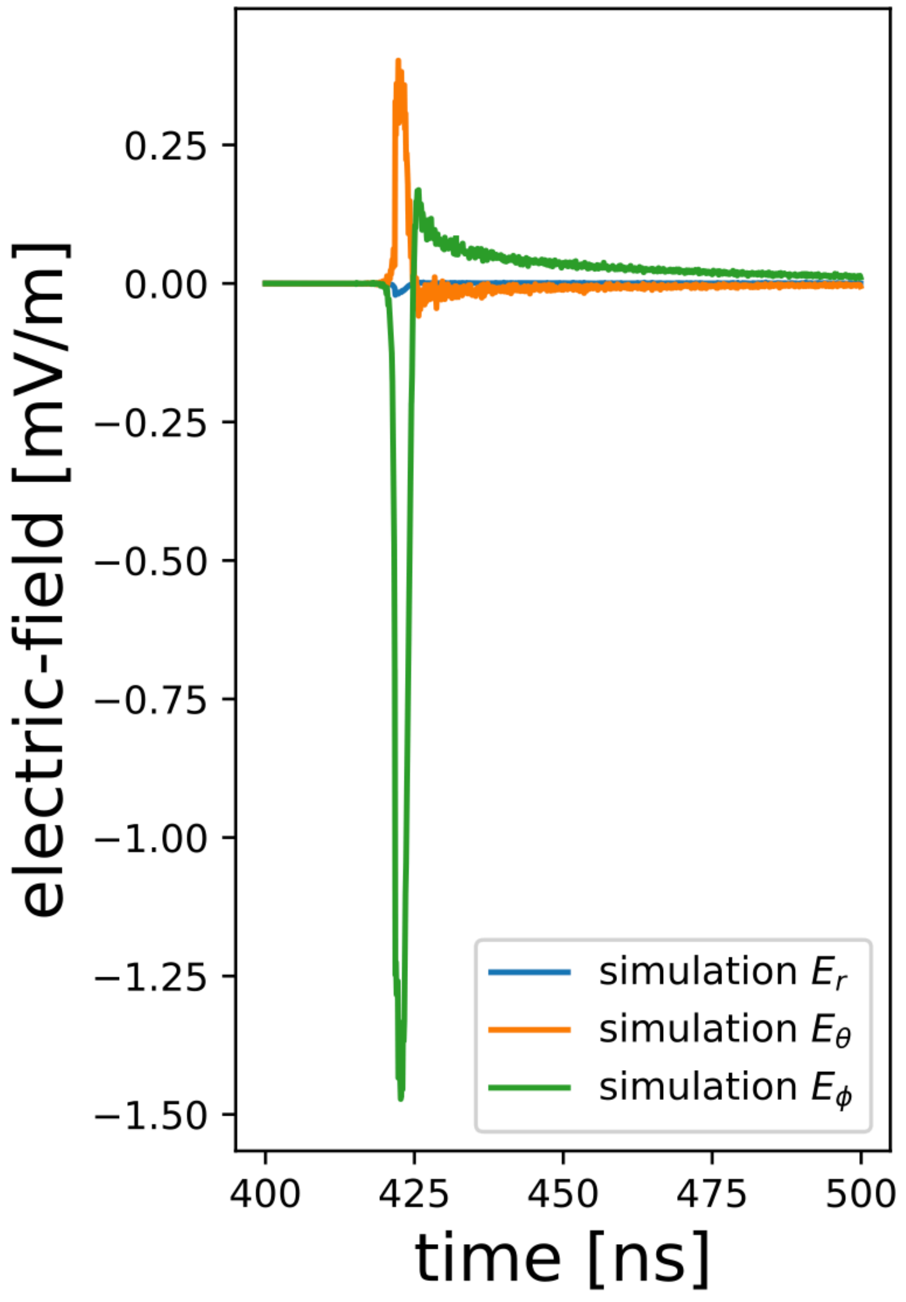
- Frequency band of 30 - 80 MHz
- Template synthesis match simulated results $\lesssim 5\%$!
- **< 1 s** per synthesis → viable physical model for IFT reconstruction

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

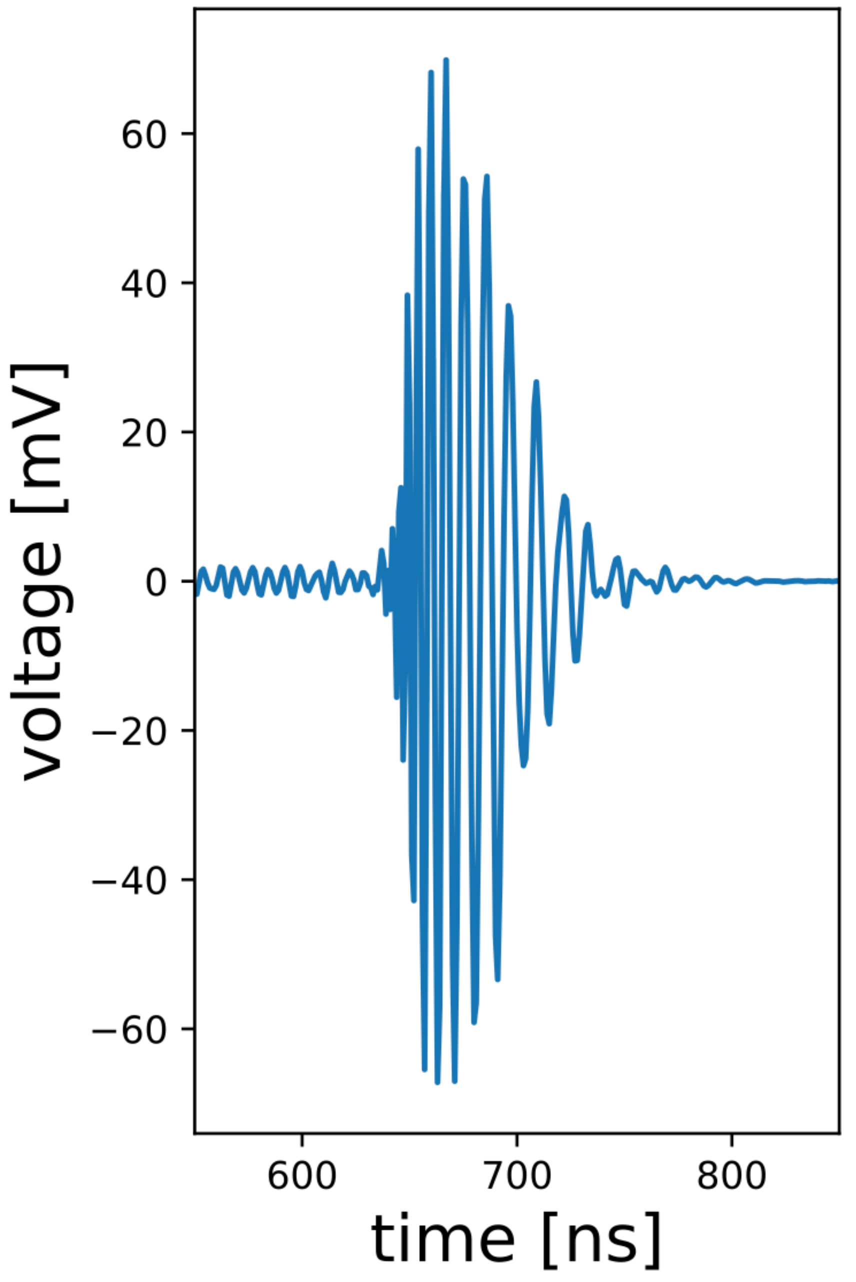
Instrumental Response



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



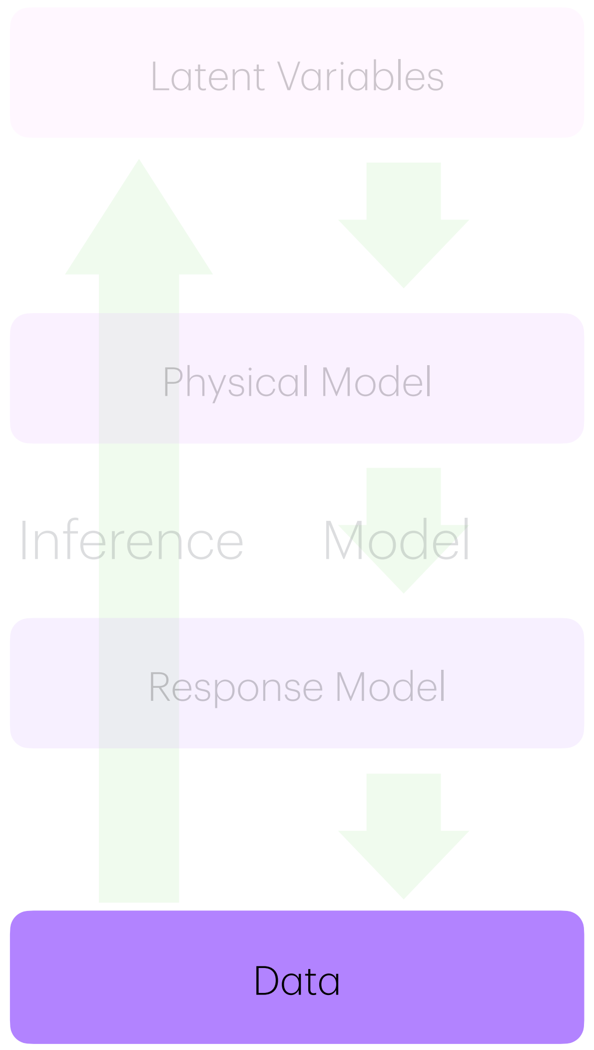
Antenna Response



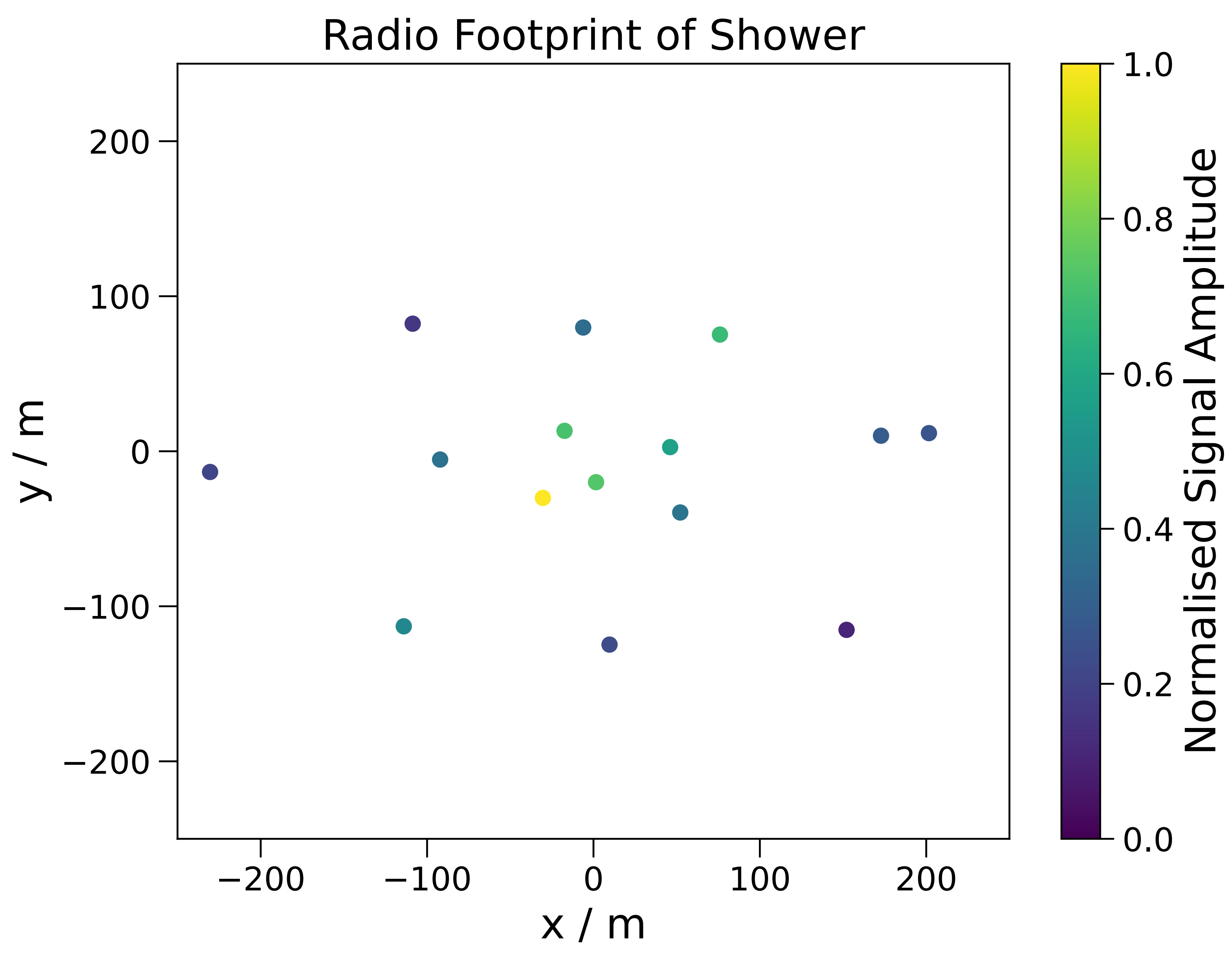
Glaser et al., Eur. Phys.Jour. C (2019) 79: 464

Currently not implemented! → use electric field traces for now

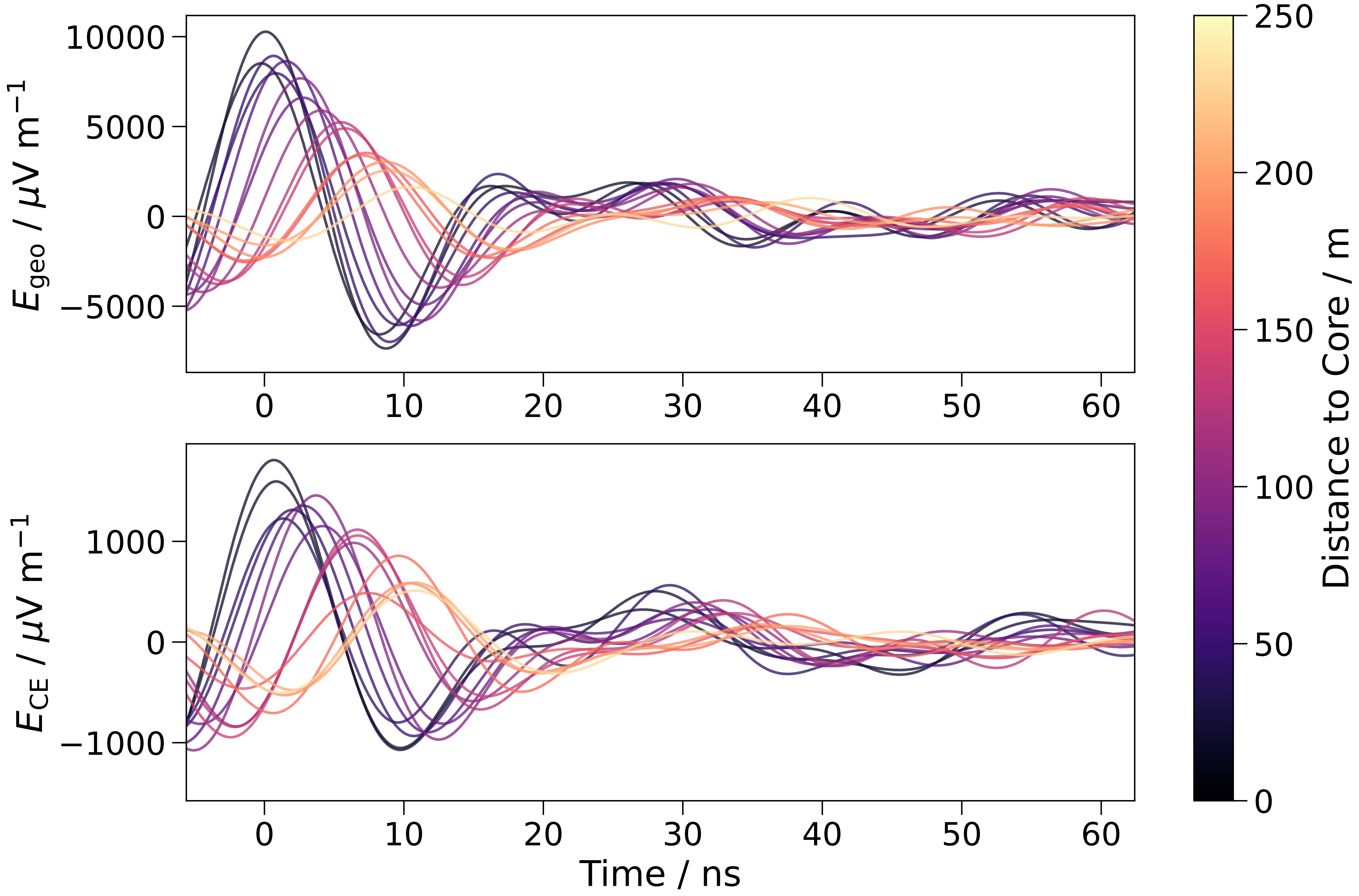
(Data)



- **Synthesised data** from model in **[30, 80] MHz** band, **15 antennas**
- **Noise** added through covariance matrix:
  - 30% of maximum amplitude from **all** antennas (calibration uncertainty)
  - 50% of maximum amplitude from **each** antenna (antenna-to-antenna uncertainty)



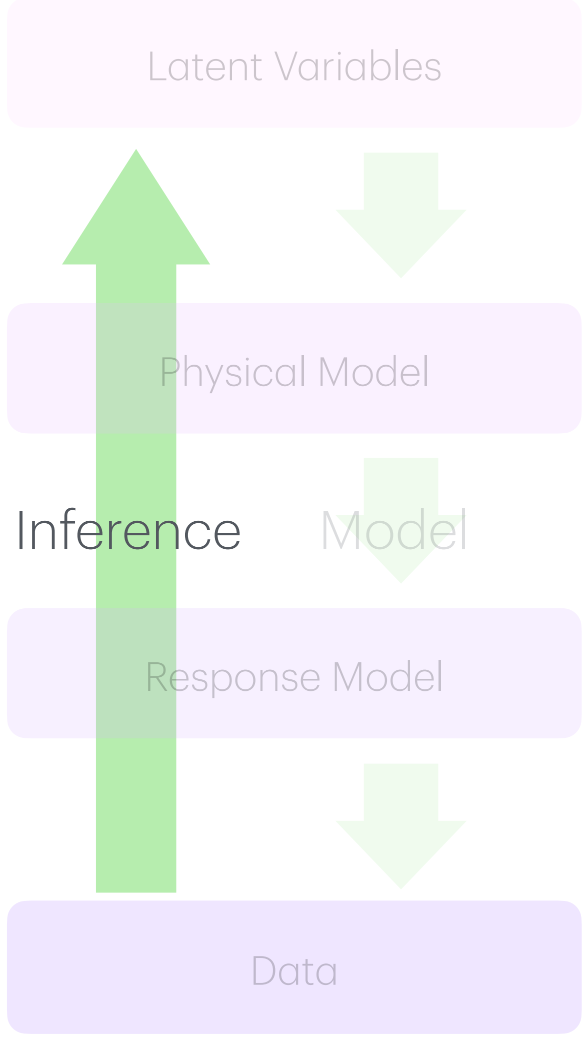
Radio Footprint of Shower

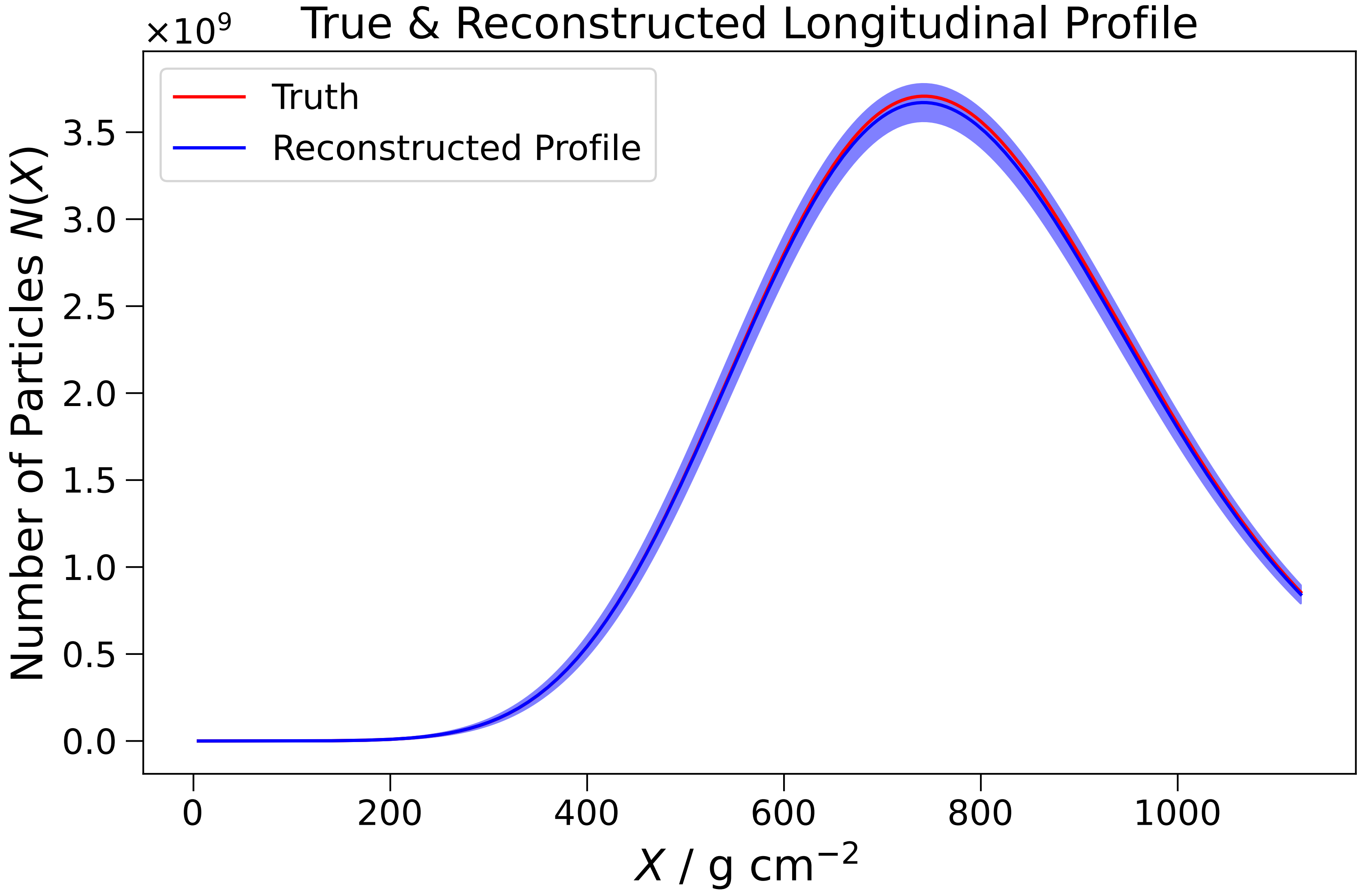


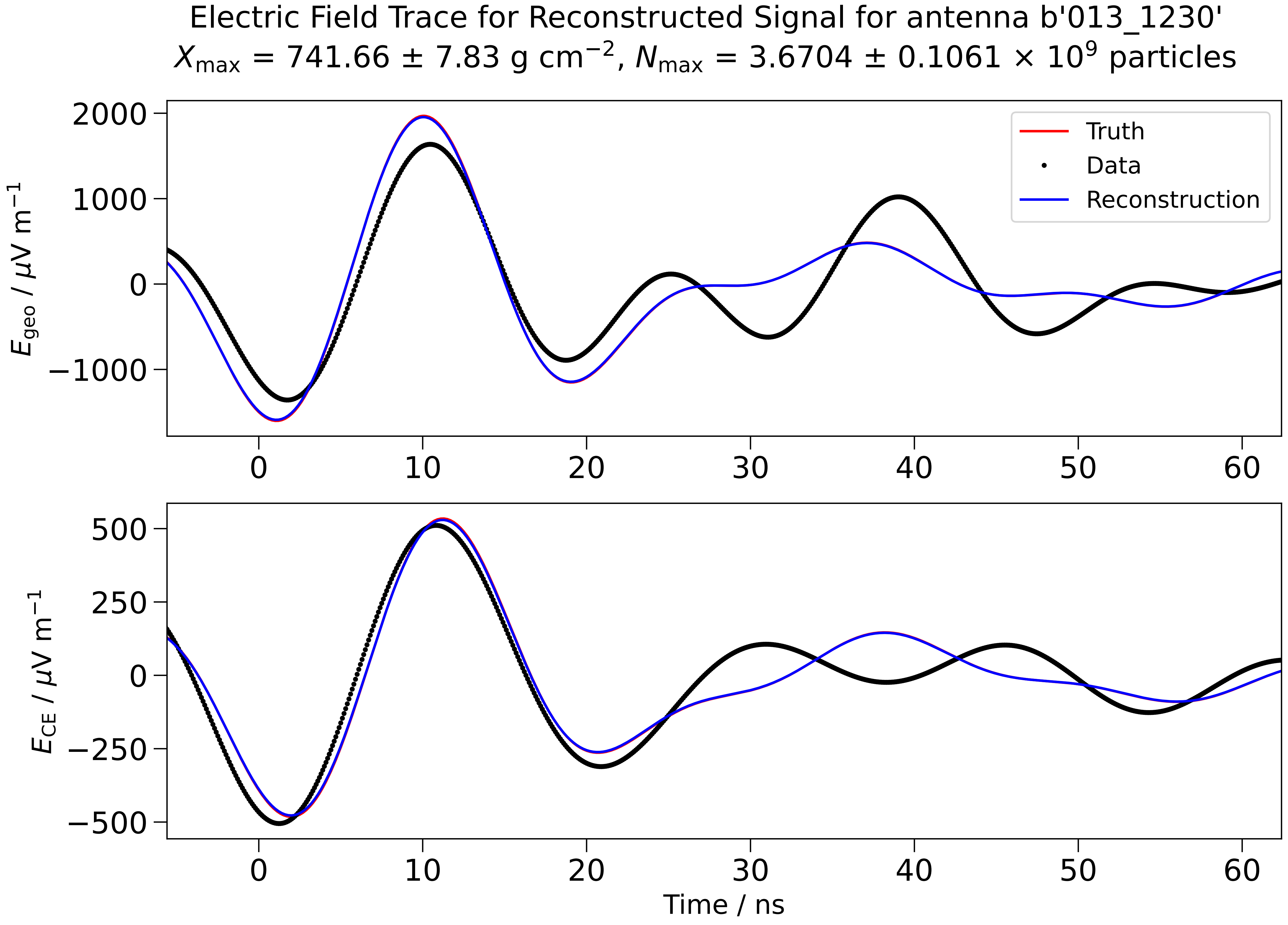
Electric Field Traces of Shower

Preliminary Results

- X_{max} and N_{max} accurately reconstructed as expected

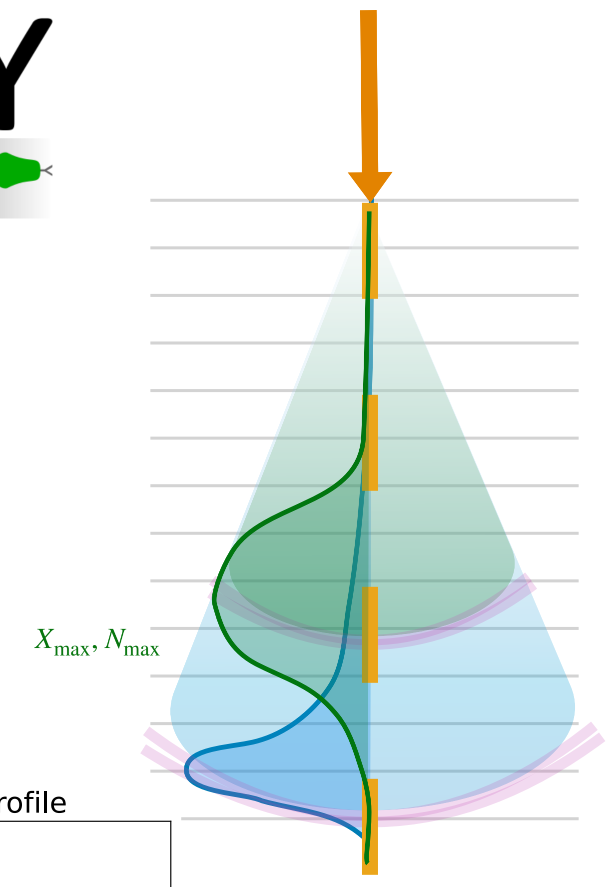




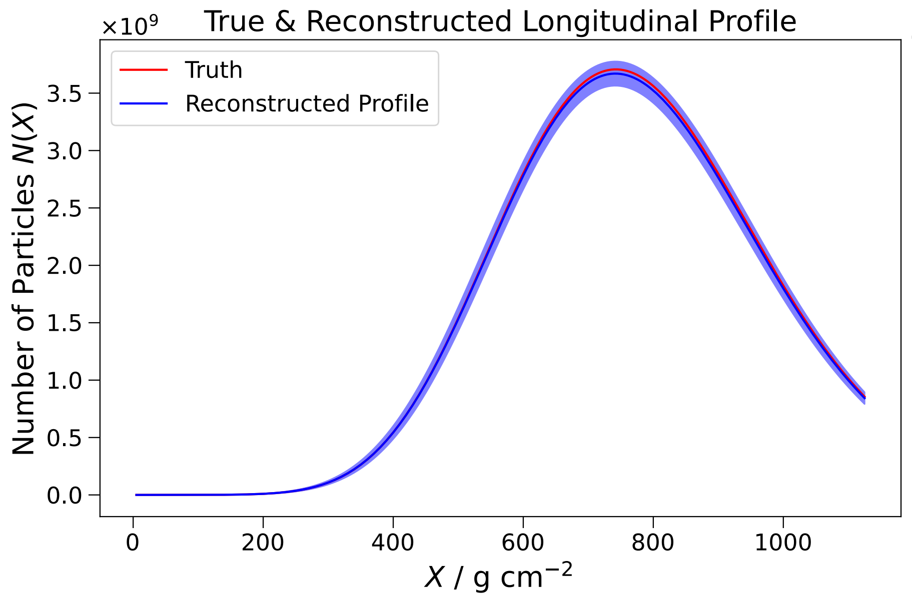


	Truth	Reconstructed	Δ
X_{max} / g cm^{-2}	742.3	741.7 ± 7.8	0.72
N_{max} / 10^9	3.71	3.67± 0.11	0.04

Conclusion & Outlook

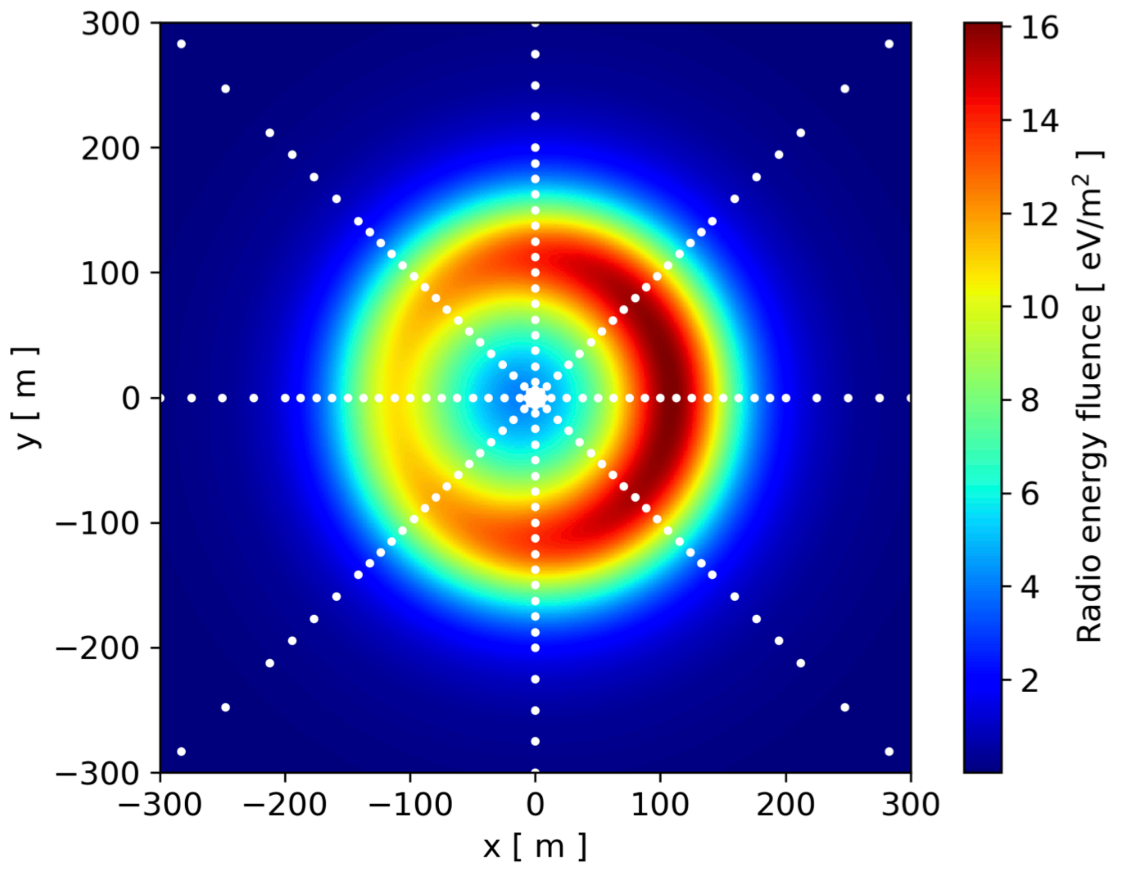


- **Goal:** use **Information Field Theory** for 1-D reconstruction of longitudinal profile
- Utilised fast-forward model for radio emission: **template synthesis**
- Preliminary results show accurate reconstruction of X_{max} and N_{max}



Outlook

- Generalise for arbitrary antenna positions (Fourier interpolation)
- Include antenna response & noise model
- Apply to realistic simulated data & later to LOFAR data



A. Corstanje et al. 2023 JINST 18 P09005

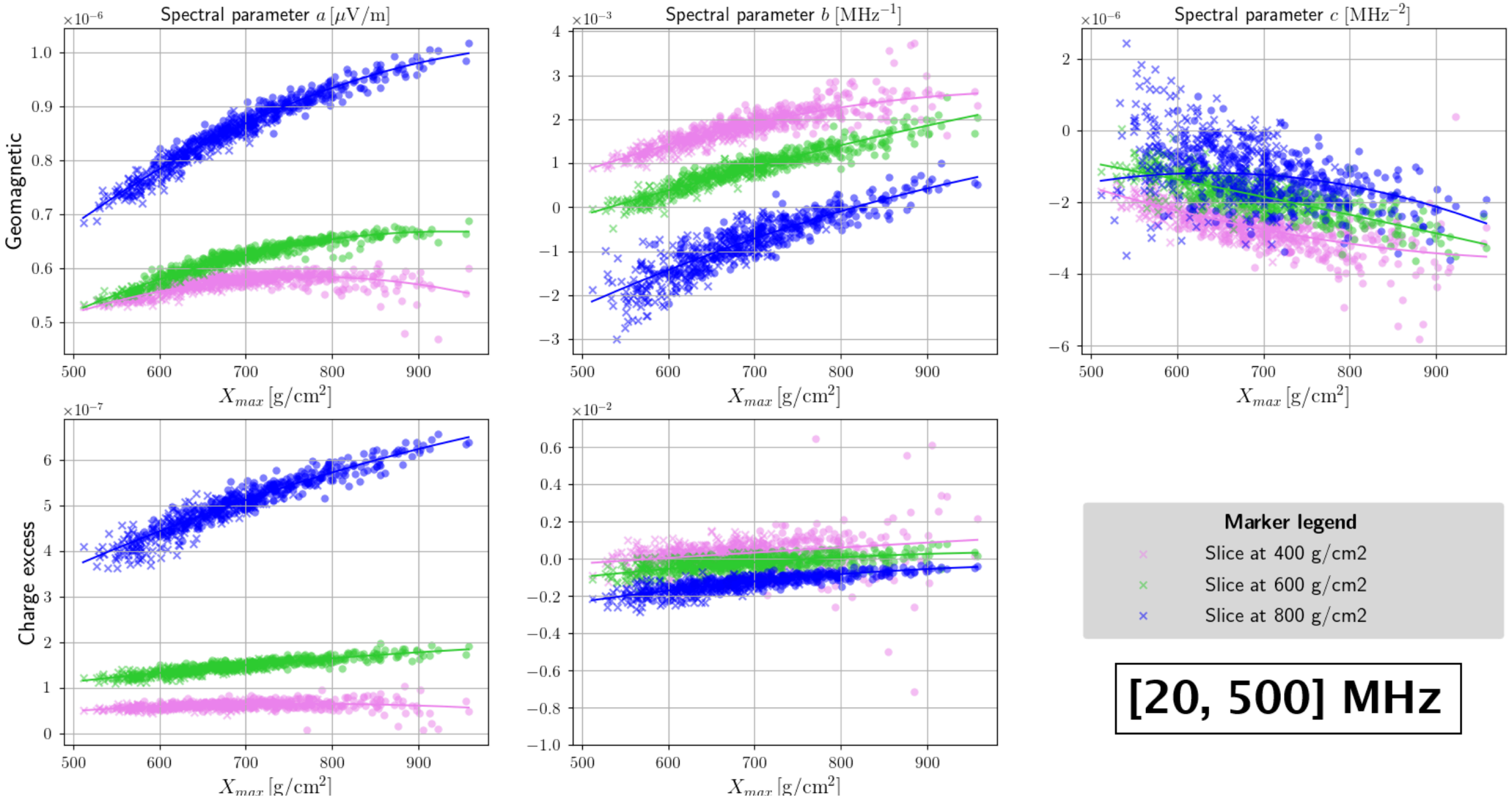
Backup Slides

Template Synthesis Spectral Relations for all parameters

$$\tilde{A}_{geo}(f, \Delta X_{max}) = \left(a_{geo} \cdot \frac{N_{slice} \cdot \sin(\alpha_{GEO})}{d_{slice} \cdot \rho_{slice}} \right) \cdot \exp\left(b_{geo} \cdot (f - f_0) + c_{geo} \cdot (f - f_0)^2 \right)$$

HIGHLIGHTS FROM THE PAPER

$$\tilde{A}_{ce}(f, \Delta X_{max}) = \left(a_{ce} \cdot \frac{N_{slice} \cdot \sin(\theta_{Cherenkov})}{d_{slice}} \right) \cdot \exp\left(b_{ce} \cdot (f - f_0) \right)$$

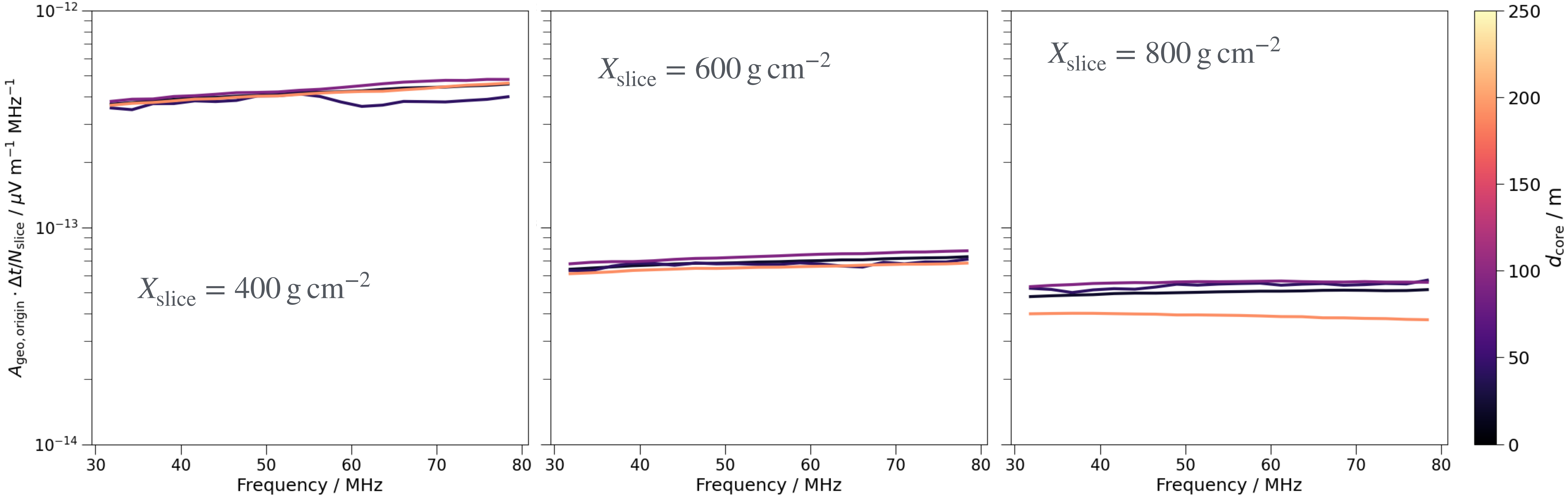


[20, 500] MHz

M. Desmet, ARENA2024

Template Synthesis

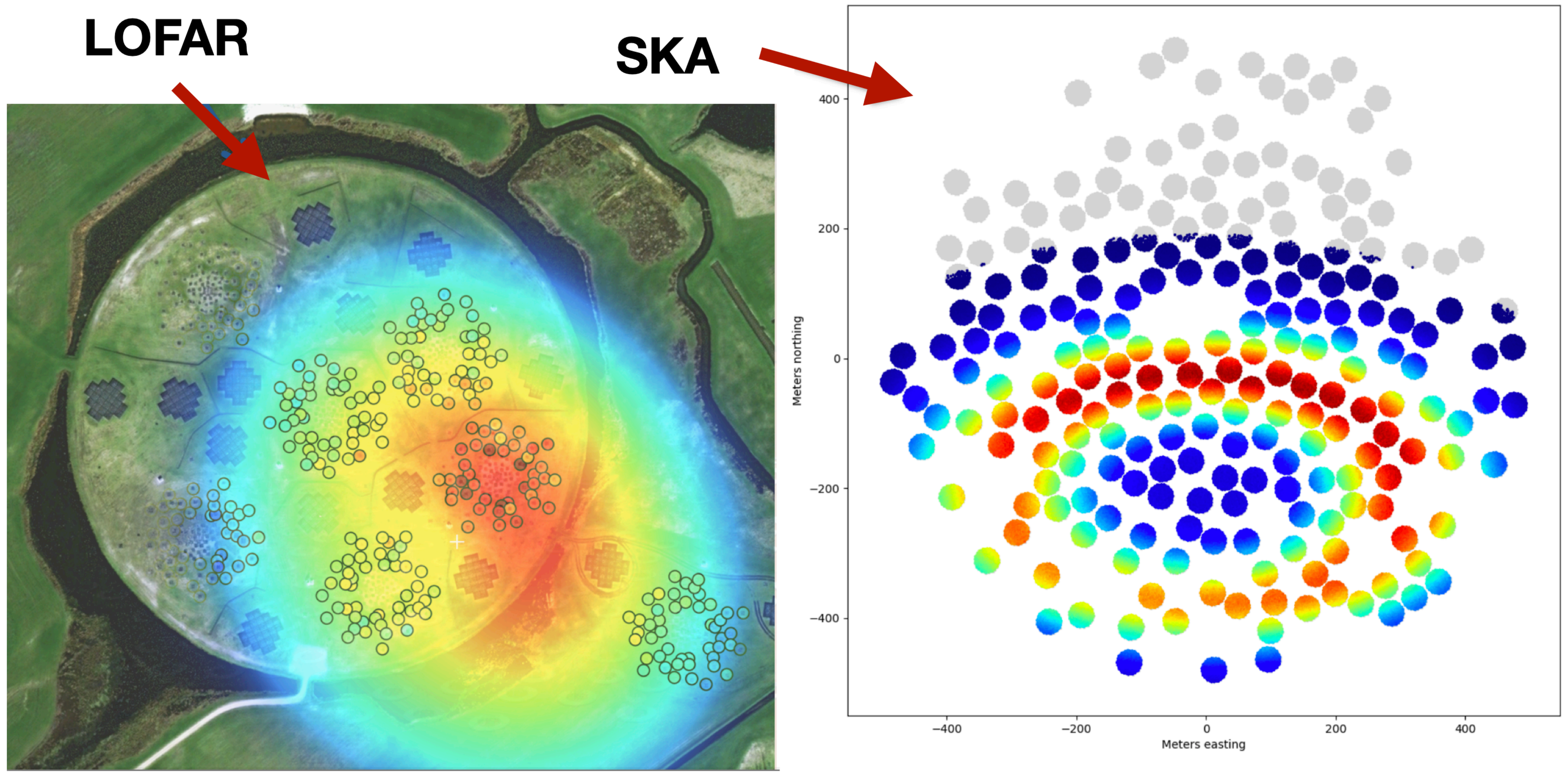
Antenna distance dependence of origin amplitude spectrum at different atmospheric slice



Square Kilometre Array

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

- **~ 60,000** antennas planned within ~ 1 km^2
- Wide frequency 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 (→ P. Laub)



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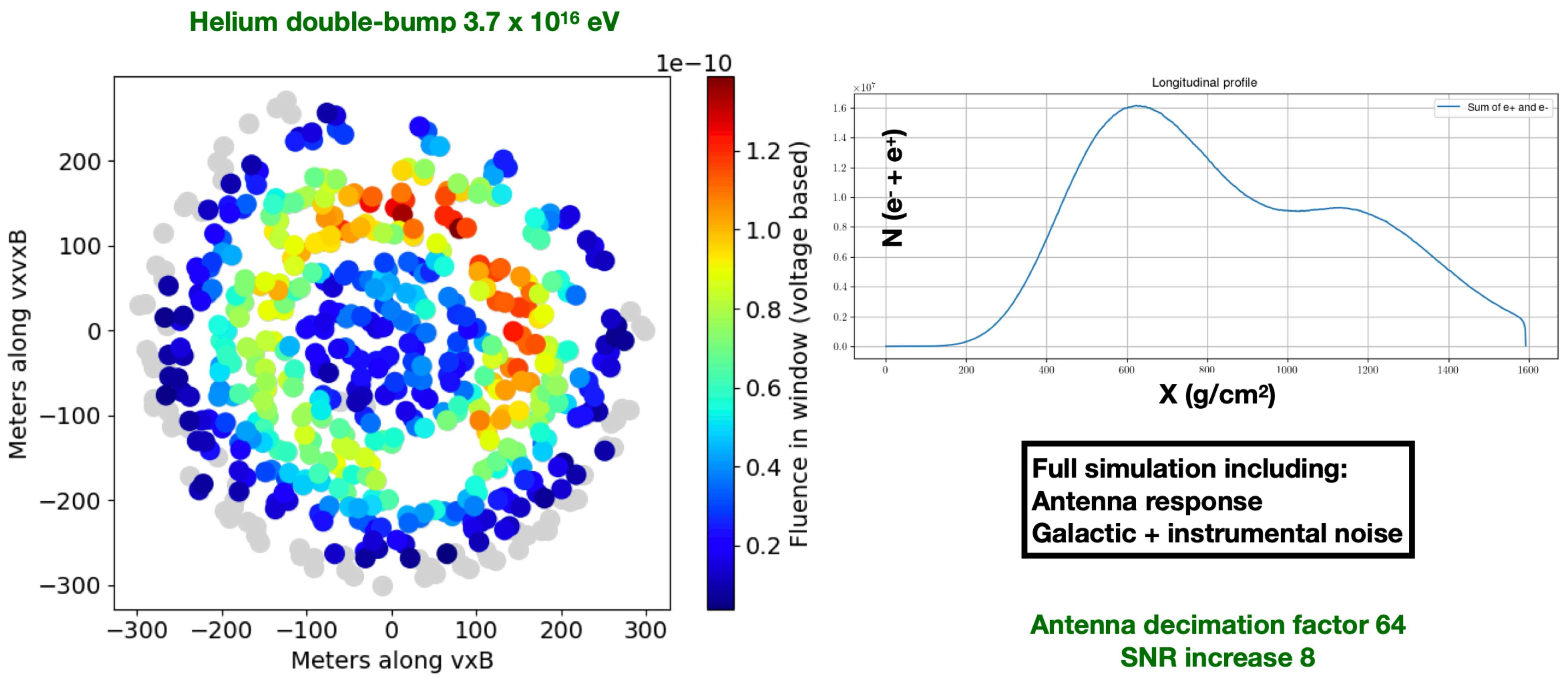

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