Template synthesis approach for radio emission from extensive air showers

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WE NEED A FASTER WAY TO SIMULATE RADIO EMISSION TO HANDLE INCREASED DATA RATES

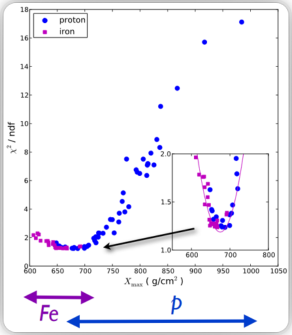


Figure: The LOFAR method for reconstructing X_{max} requires a dedicated set of simulations.

- For every observed event, we need a dedicated set of simulations.
- Microscopic simulation codes (eg. CORSIKA) require significant computing time.

WE CAN SYNTHESISE THE RADIO EMISSION USING FULL MICROSCOPIC SIMULATIONS AS TEMPLATES

Following the work of David Butler, our goal is to implement a robust and efficient method for synthesising the radio emission from EAS.

- The method uses a full MC simulation as the starting point (called the **template**).
- Employing semi-analytical relations, the radiation from the template is transformed to reproduce the signal from a shower with different parameters (such as primary energy and X_{max}).
- This method will be applicable to any experiment detecting cosmic rays with radio emission.

We call this method **template synthesis**.

TEMPLATE SYNTHESIS WORKS FOR VERTICAL COSMIC RAY AIR SHOWERS

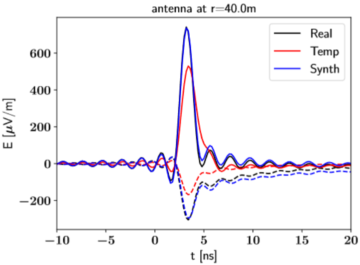


Figure: Previous synthesis result from David.

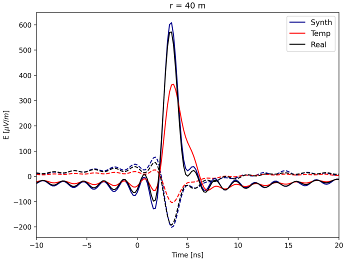


Figure: Our current synthesis result with the same showers.

Furthermore, we have implemented a more robust fitting method as well as quantified the reconstruction quality using different metrics.

THE REST OF THE TALK

1. Exploiting air shower universality
2. Atmospheric slicing and the template synthesis method
3. Gauging the reconstruction quality
4. Conclusion

WE CAN USE AIR SHOWER UNIVERSALITY TO SYNTHESISE THE RADIO EMISSION

Exploiting air shower universality

We characterise the longitudinal evolution of the air shower using the Gaisser-Hillas function.

$$N(X) = N_{max} \cdot \left(\frac{X - X_1}{X_{max} - X_1} \right)^{\frac{X_{max} - X_1}{\alpha + \beta X + \gamma X^2}} \cdot \exp\left(\frac{X_{max} - X}{\alpha + \beta X + \gamma X^2} \right) \quad (1)$$

The parameters α, β and γ are universal within 5-10%. We refer to these variations as shower-to-shower fluctuations.

The others are the shower maximum X_{max}, the number of particles at the maximum N_{max} and the depth of first interaction X_1. If we normalise these out, all the showers should look equal.

WE LOOK AT THE EMISSION COMING FROM DIFFERENT SLICES OF THE ATMOSPHERE SEPARATELY

Atmospheric slicing and the template synthesis method

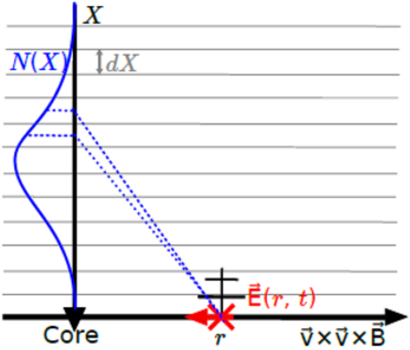


Figure: Slicing of the atmosphere.

- We divide the atmosphere into slices of constant atm. depth of **5** g/cm^2.
- Then we consider the radio emission coming from each slice separately and rescale it with respect to the shower parameters.

WE PARAMETERISE THE AMPLITUDE SPECTRA PER SLICE

Atmospheric slicing and the template synthesis method

For each slice and antenna position, we can look at the amplitude frequency spectrum of the radiation, normalised by the number of particles in the slice. We parameterise it as

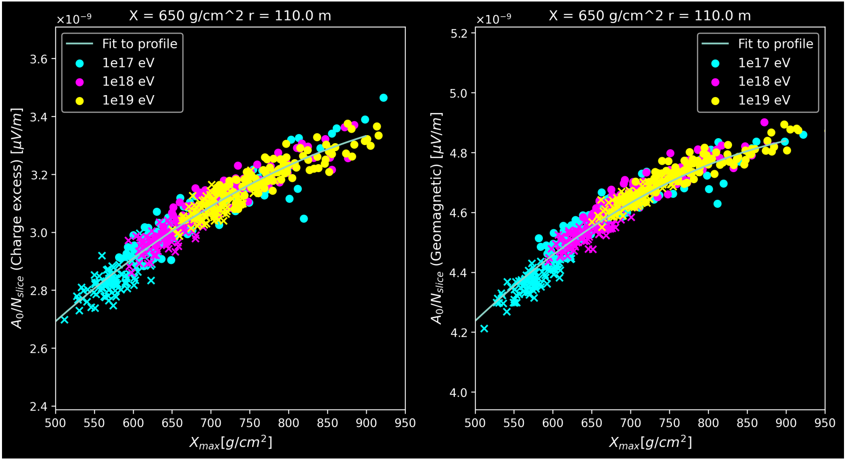
$$\tilde{A}_{\text{slice}}(f) = \frac{A_0}{N_{\text{slice}}} \cdot \exp(b \cdot f + c \cdot f^2) + d \, , \qquad (2)$$

where f denotes frequency in MHz and

$$\sqrt{d} = \max\left[10^{-9} \cdot \left(\frac{X}{400\,\text{g/cm}^2} - 1.5\right) \cdot \exp\left(1 - \frac{r}{400\,\text{m}}\right), 0\right]$$

Here d represents the noise floor. We refer to the parameters A_0, b and c as the spectral parameters.

THE THREE SPECTRAL PARAMETERS HAVE A PARABOLIC DEPENDENCE ON X_{max}, INDEPENDENT OF ENERGY



$$\frac{\mathbf{A_0}}{\mathbf{N_{slice}}} \cdot \exp(b \cdot f + c \cdot f^2) + d$$

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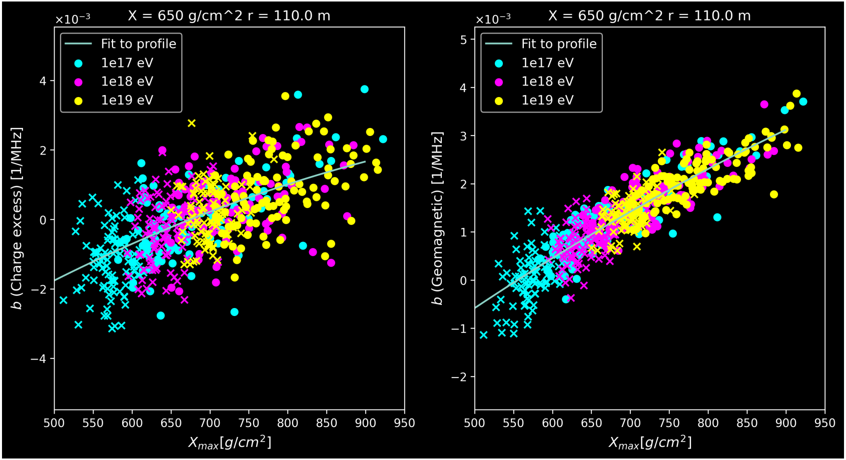

$$\frac{A_0}{N_{\text{slice}}} \cdot \exp(\mathbf{b} \cdot f + c \cdot f^2) + d$$

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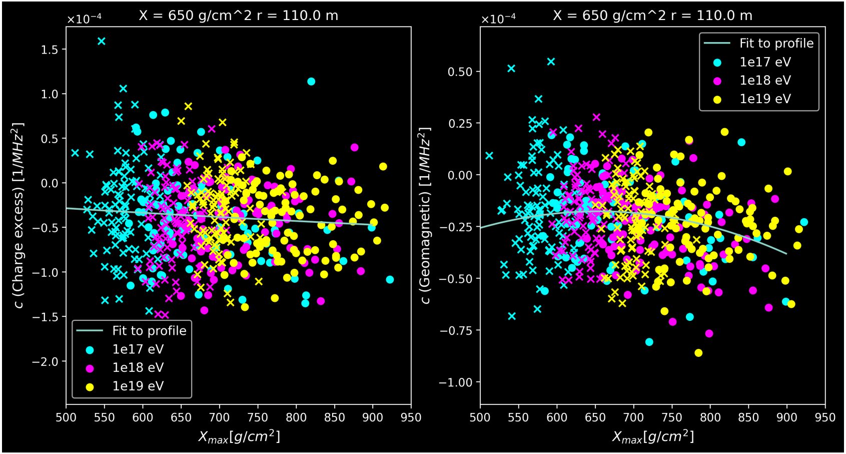


$$\frac{A_0}{N_{\text{slice}}} \cdot \exp(b \cdot f + \mathbf{c} \cdot f^2) + d$$

THE SPECTRAL PARAMETERS CAN BE EXTRACTED FROM THE QUADRATIC FITS FOR ANY SHOWER

Atmospheric slicing and the template synthesis method

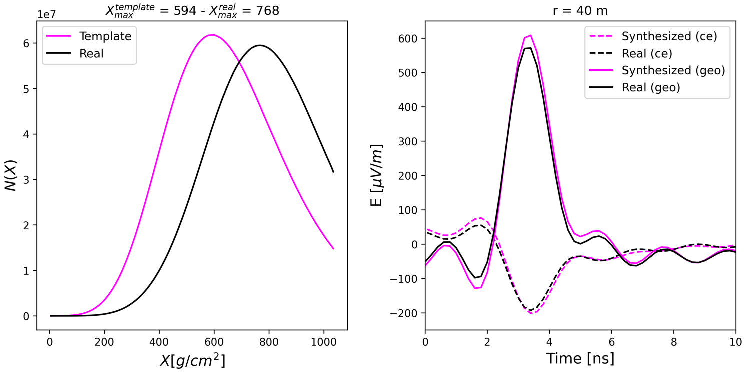
Using the obtained dependencies of the spectral parameters on X_{max}, we can now synthesise the amplitude spectra of a shower with arbitrary X_{max}.

- We have these fitted functions for every combination of slice and antenna.
- The parameter values both depend on the slicing and the frequency range in which the signal is fitted.

THE SIGNAL IN THE ANTENNA IS OBTAINED BY SUMMING OVER ALL THE SLICES

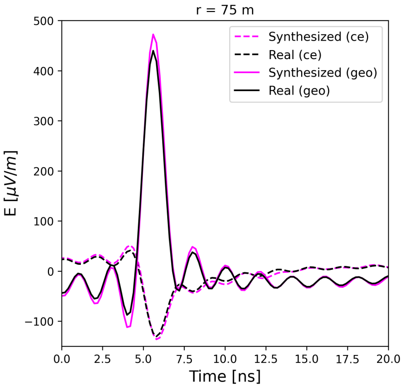
Atmospheric slicing and the template synthesis method

Synthesis of 10^{17} eV proton shower using another 10^{17} eV proton shower. The signals are filtered in the range $[20, 500]$ MHz.



THE SIGNAL IN THE ANTENNA IS OBTAINED BY SUMMING OVER ALL THE SLICES

Atmospheric slicing and the template synthesis method



WE APPLIED DIFFERENT SCORING FUNCTIONS TO GAUGE THE RECONSTRUCTION QUALITY

Gauging the reconstruction quality

$$F(E) \propto \Delta t \cdot \sum E^2 \qquad (3)$$

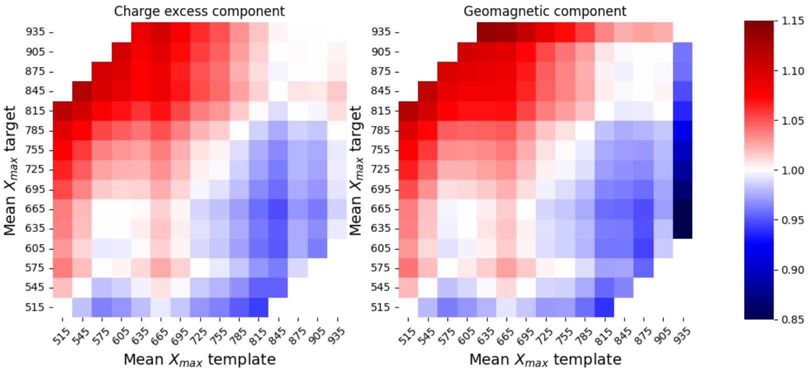


Figure: Ratio of energy fluence in synthesised and real signal in the antenna at 110m from the shower axis.

WE APPLIED DIFFERENT SCORING FUNCTIONS TO GAUGE THE RECONSTRUCTION QUALITY

Gauging the reconstruction quality

$$F(E) = max(E) \quad (4)$$

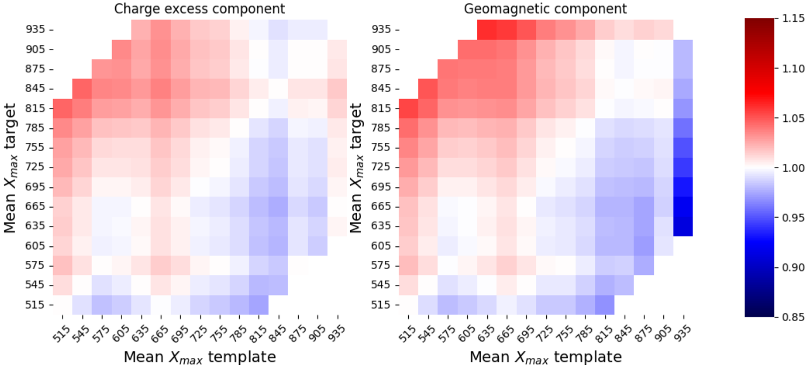
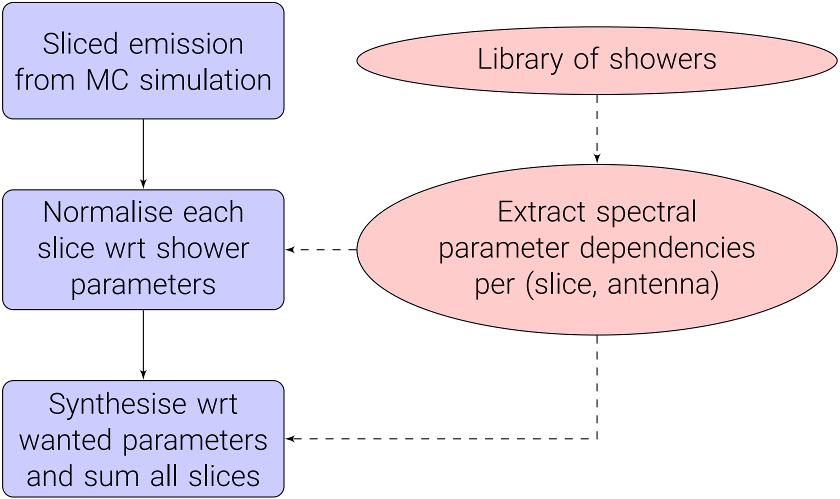


Figure: Ratio of max amplitude in synthesised and real signal in the antenna at 110m from the shower axis.

REVIEW OF THE SPECTRAL RESCALING METHOD

Conclusion



WE ACHIEVE A RECONSTRUCTION QUALITY COMPARABLE TO THE SHOWER-TO-SHOWER FLUCTUATIONS

Conclusion

- We have demonstrated the template synthesis method for vertical cosmic ray air showers.
- We also showed that each emission component separately is correctly synthesised, with a fluence ratio < 12% and a peak amplitude ratio < 7%.
- This reconstruction accuracy is close to the shower-to-shower fluctuation limit, by which template synthesis is bound.

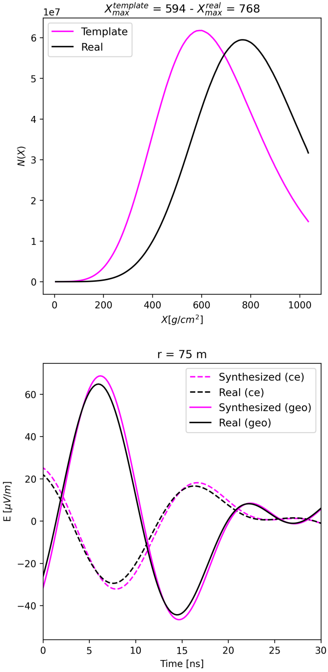
WE HAVE A LONG ROAD AHEAD BEFORE THIS METHOD CAN BE FULLY INTEGRATED INTO THE ANALYSIS PIPELINE

In the future, we want to

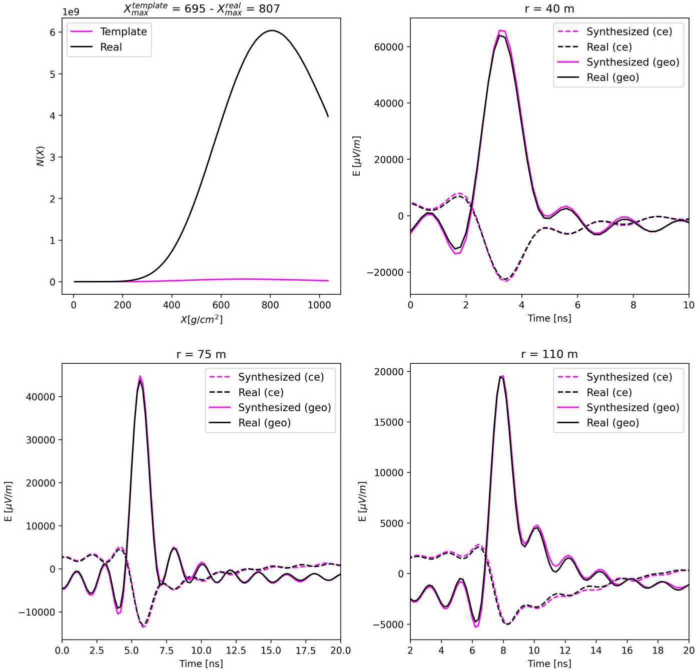
1. expand our method to other geometries.
2. build a robust software package that implements this method and distribute it.
3. integrate the method into the LOFAR pipeline in order to investigate the performance in an experimental setup.

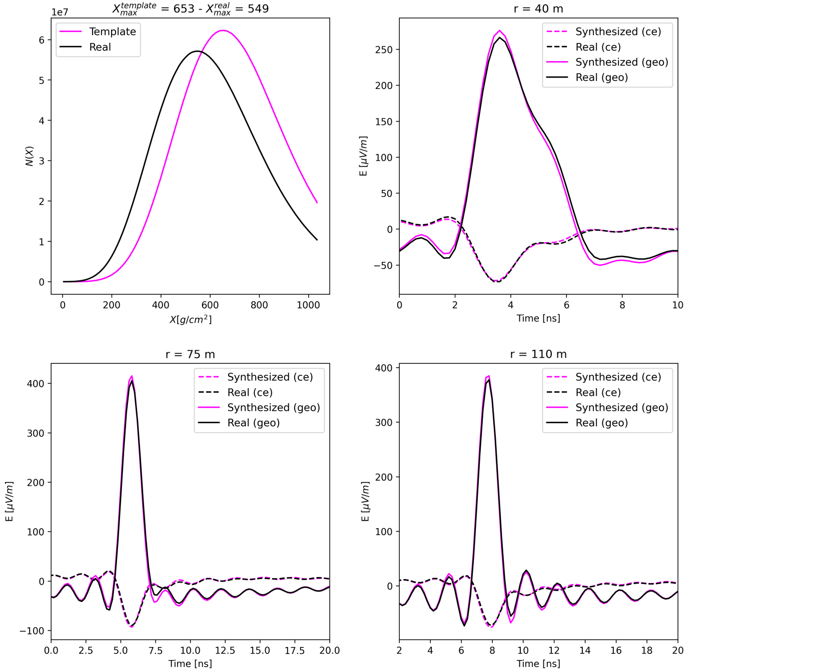
We also want to explore the possibility of reconstructing other shower parameters, such as L and R, with LOFAR and also SKA.

Thank you!



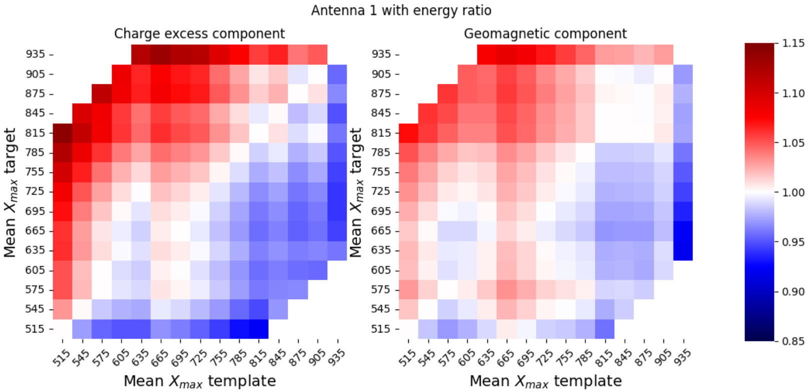
$X_{max}^{template}$ = 594 - X_{max}^{real} = 768
1e7
Template
Real
N(X)
$X[g/cm^2]$
r = 40 m
r = 75 m
r = 110 m
Synthesized (ce)
Real (ce)
Synthesized (geo)
Real (geo)
E [$\mu V/m$]
Time [ns]


$X_{max}^{template}$ = 695 - X_{max}^{real} = 807
1e9
Template
Real
N(X)
X[g/cm^2]
r = 40 m
r = 75 m
r = 110 m
Synthesized (ce)
Real (ce)
Synthesized (geo)
Real (geo)
E [μV/m]
Time [ns]



$X_{max}^{template}$ = 653 - X_{max}^{real} = 549
1e7
Template
Real
N(X)
X[g/cm^2]
r = 40 m
Synthesized (ce)
Real (ce)
Synthesized (geo)
Real (geo)
E [$\mu V/m$]
Time [ns]
r = 75 m
Synthesized (ce)
Real (ce)
Synthesized (geo)
Real (geo)
E [$\mu V/m$]
Time [ns]
r = 110 m
Synthesized (ce)
Real (ce)
Synthesized (geo)
Real (geo)
E [$\mu V/m$]
Time [ns]

OTHER QUALITY RESULTS



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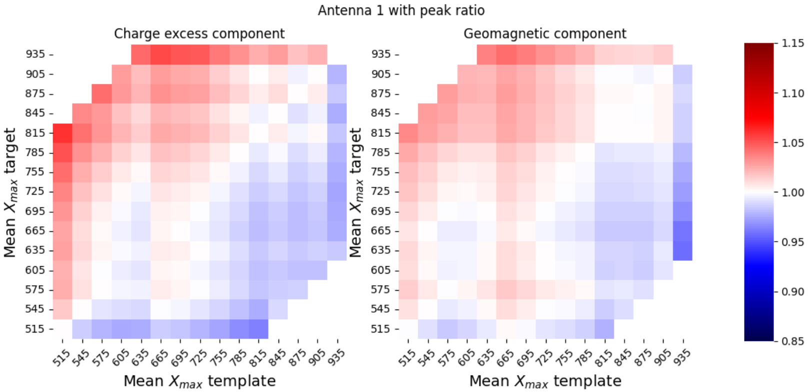
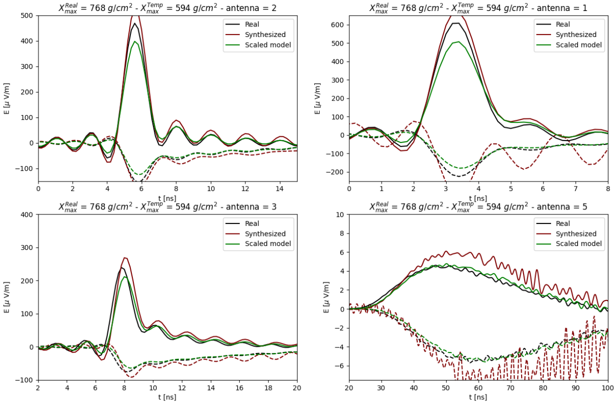
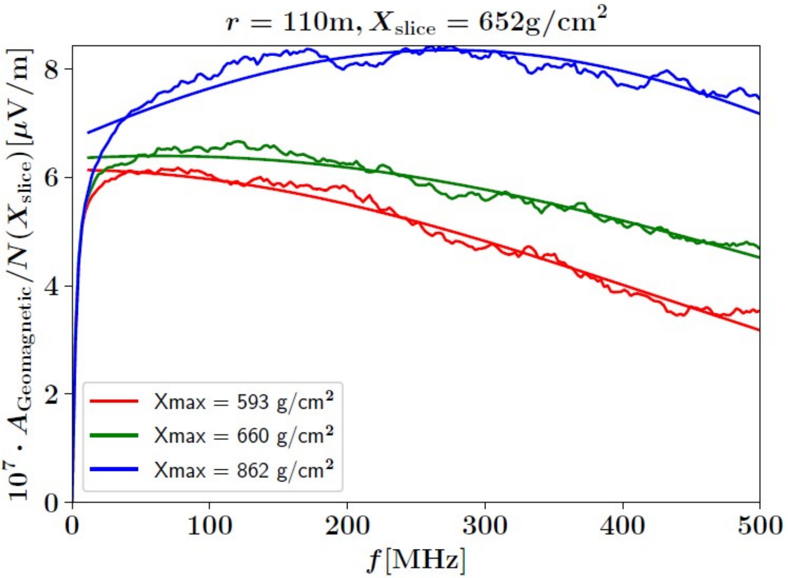


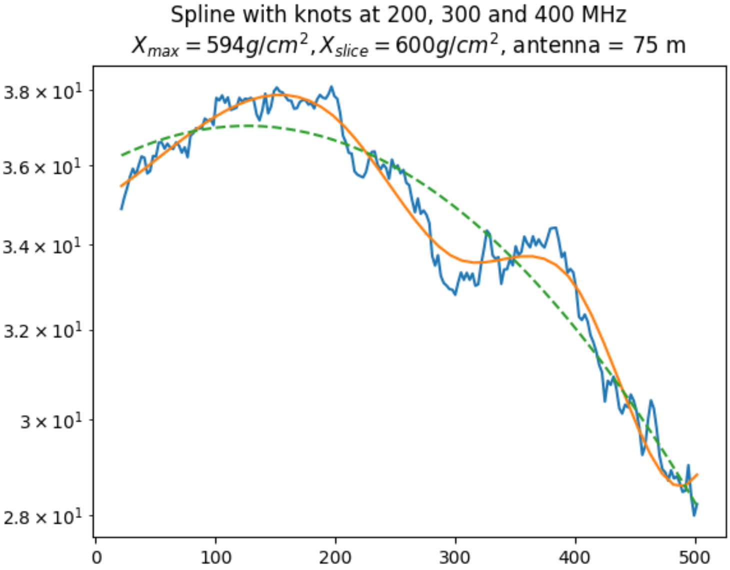
RESCALING WITH ONLY THE NUMBER OF PARTICLES DOES NOT WORK



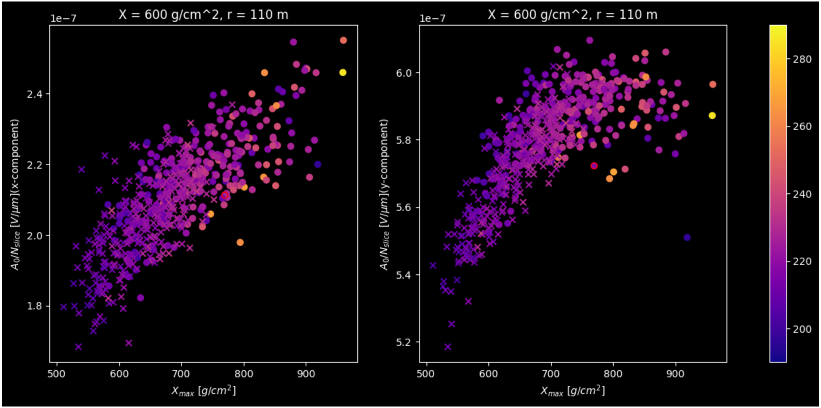
THE AMPLITUDE SPECTRUM FITS SHOW A CLEAR HIERARCHY WITH XMAX



FREQUENCY RANGE OVER WHICH WE FIT THE AMPLITUDE SPECTRUM DOES MATTER



THE SCATTER IN THE SPECTRAL PARAMETERS APPEARS TO BE DEPENDENT ON L



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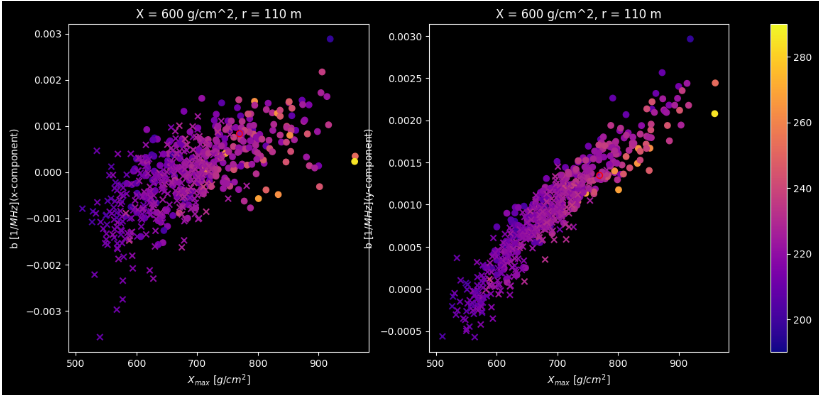
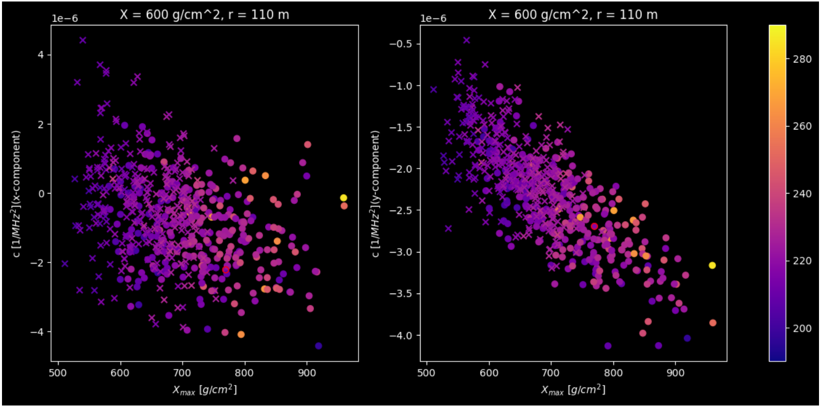
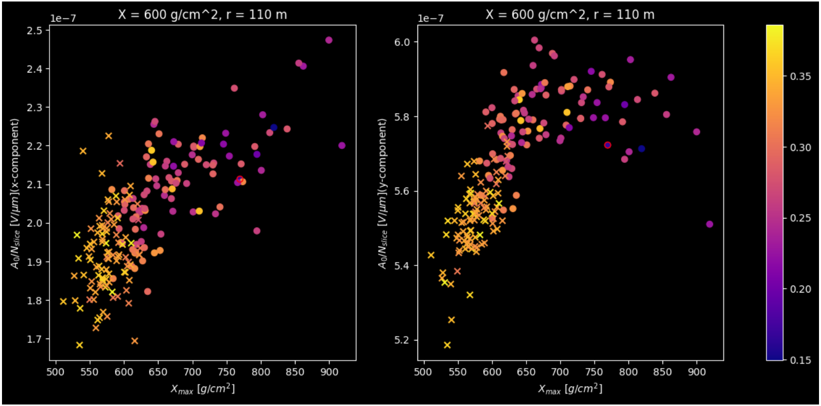


THE SCATTER IN THE SPECTRAL PARAMETERS APPEARS TO BE DEPENDENT ON L



SOME DEPENDENCE ON R IS ALSO OBSERVED



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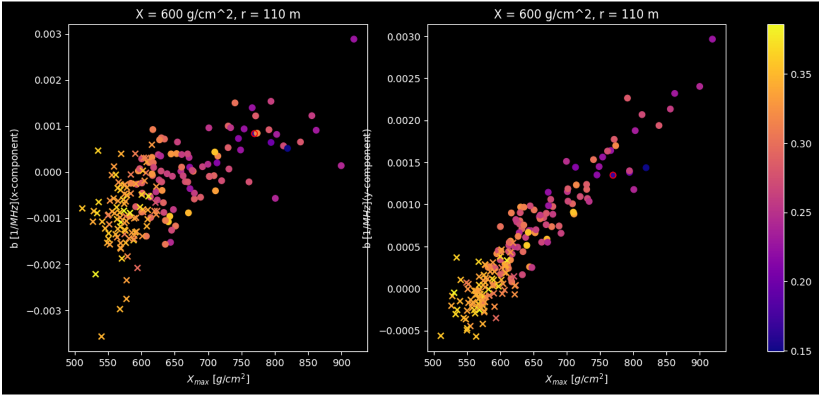

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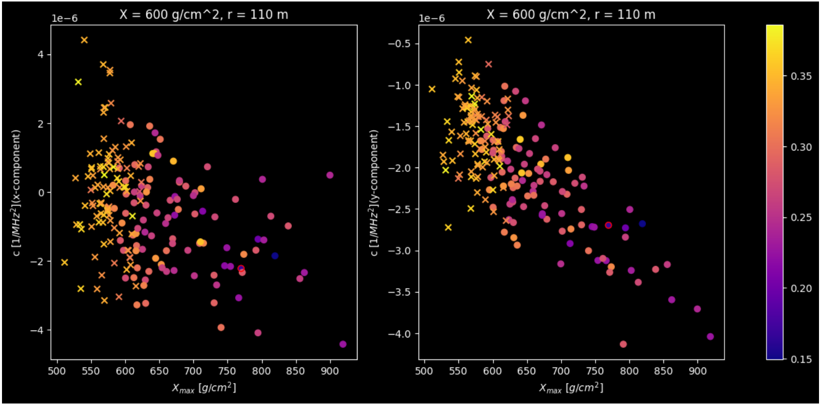
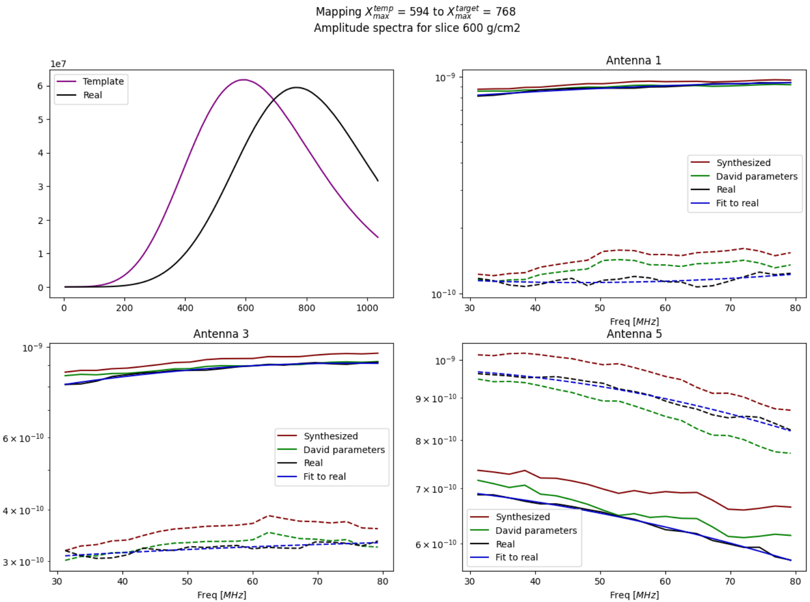
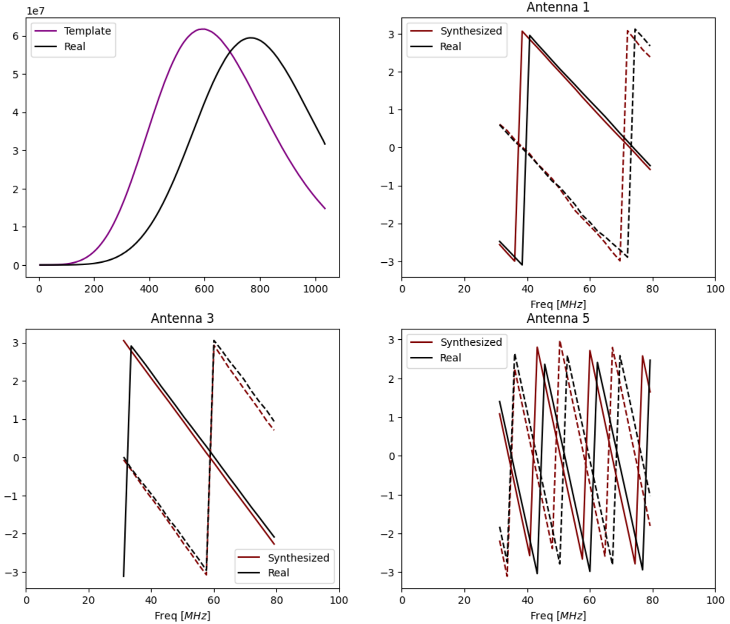


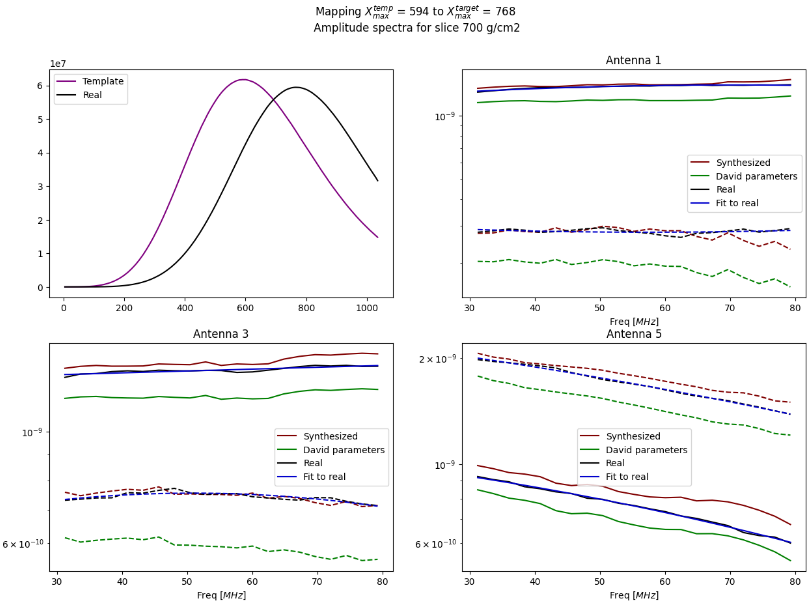
SYNTHESIS OF EMISSION PER SLICE

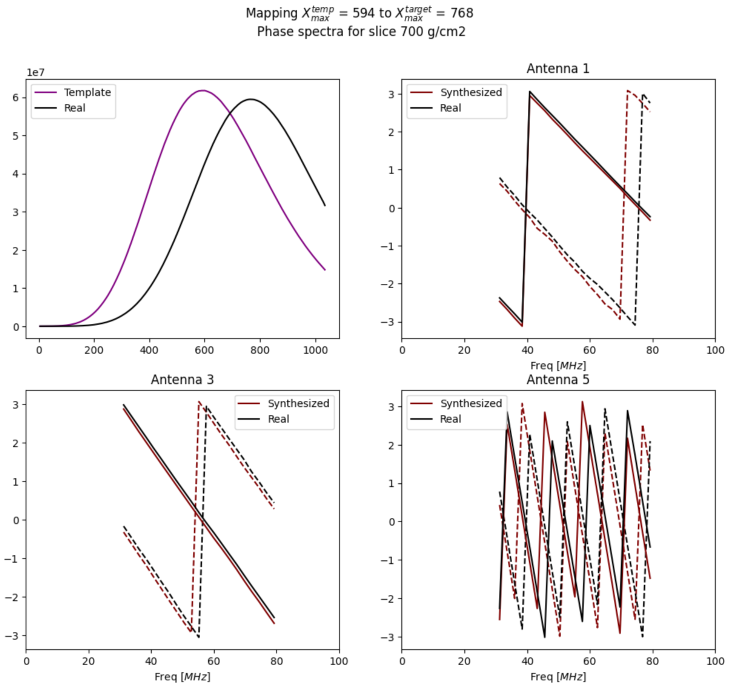


Mapping X_{max}^{temp} = 594 to X_{max}^{target} = 768
Phase spectra for slice 600 g/cm2



SYNTHESIS OF EMISSION PER SLICE




Mapping $X_{max}^{temp} = 594$ to $X_{max}^{target} = 768$
Phase spectra for slice 700 g/cm2
1e7
Template
Real
Antenna 1
Synthesized
Real
Freq [MHz]
Antenna 3
Synthesized
Real
Freq [MHz]
Antenna 5
Synthesized
Real
Freq [MHz]