Interferometic Measurements with hexagonal Antenna Arrays

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HIRSAP Meeting, November 2020

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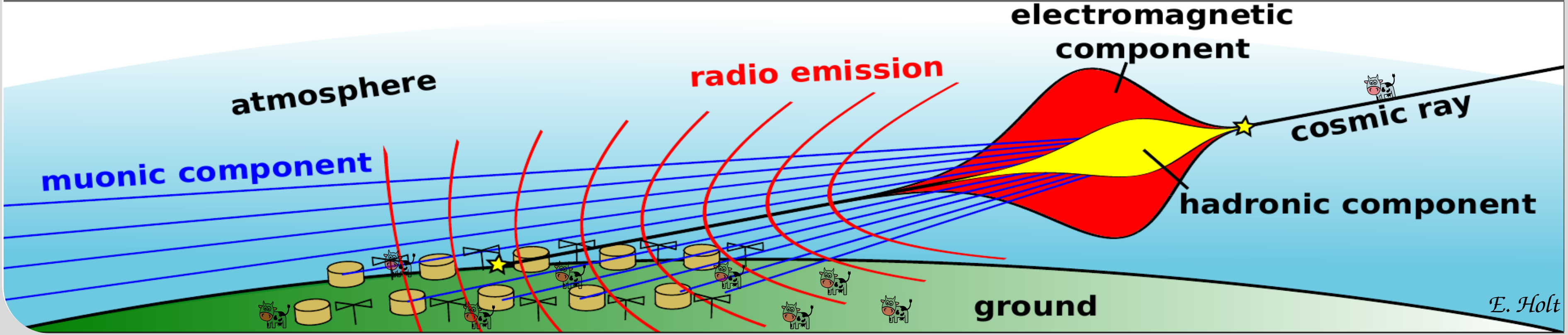
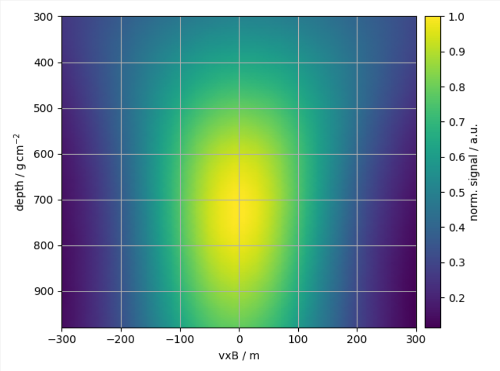


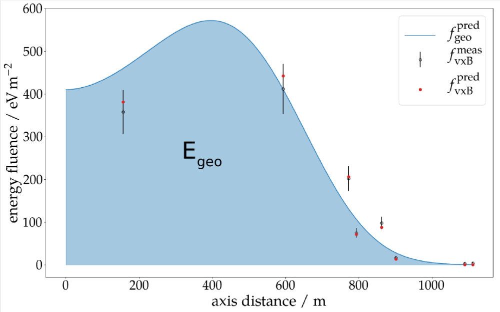
Recap, Recent Work, and Plans

Interferometric Reconstruction



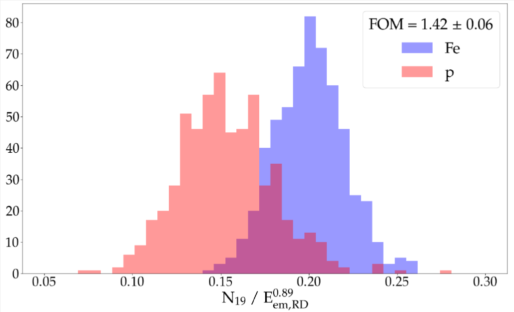
- For Auger: GAP 2020-54
- More general:
This talk, SAL in prep

Reconstruction of inclined Air Shower



- My first HIRSAP talks
- POS(ICRC2019)294
- Still improving; SAL in prep

Performance of the Auger Radio Detector



- RD Science Case Report
- OCM2 Talk
- ICRC2021
- NIM paper

Last year:

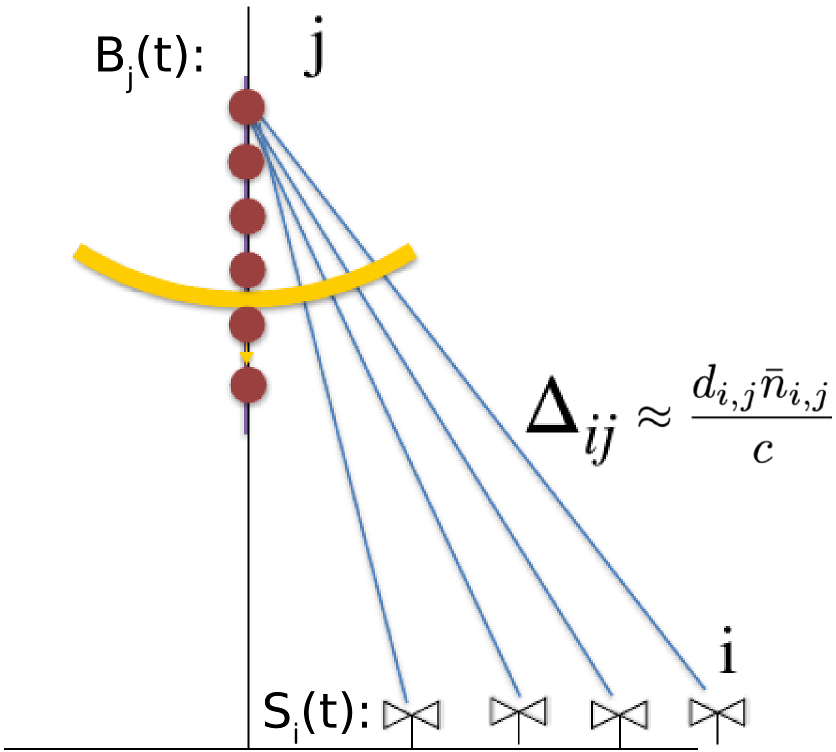
- Refractive displacement of radio-emission footprint https://doi.org/10.1140/epjc/s10052-020-8216-z
- Emission depth on the radiation; Contribution of low energetic electrons to radio signal

Radio Interferometric Technique (In a nutshell)

arXiv:2006.10348v1

- Determine coherent signal *B* by interfering all measured signals S_i:

$$B_j(t) = \sum_i^j S_i(t - \Delta_{i,j})$$



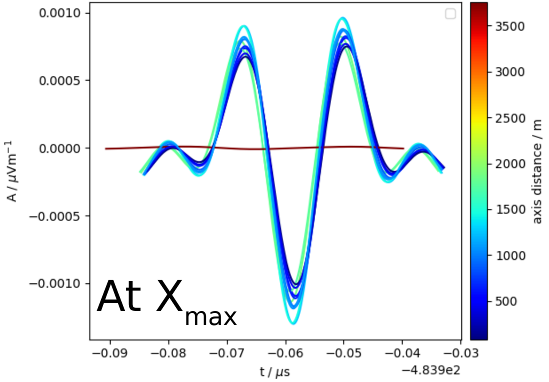
Illustrations from H. Schoorlemmer

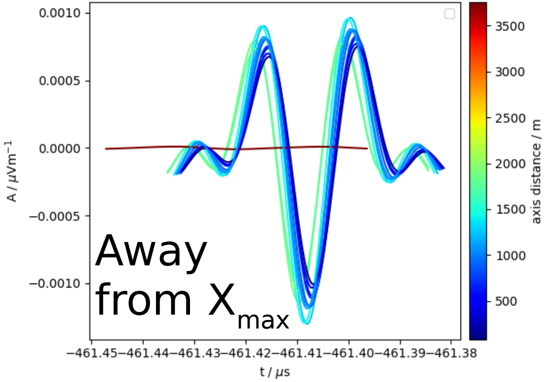
Radio Interferometric Technique (In a nutshell)

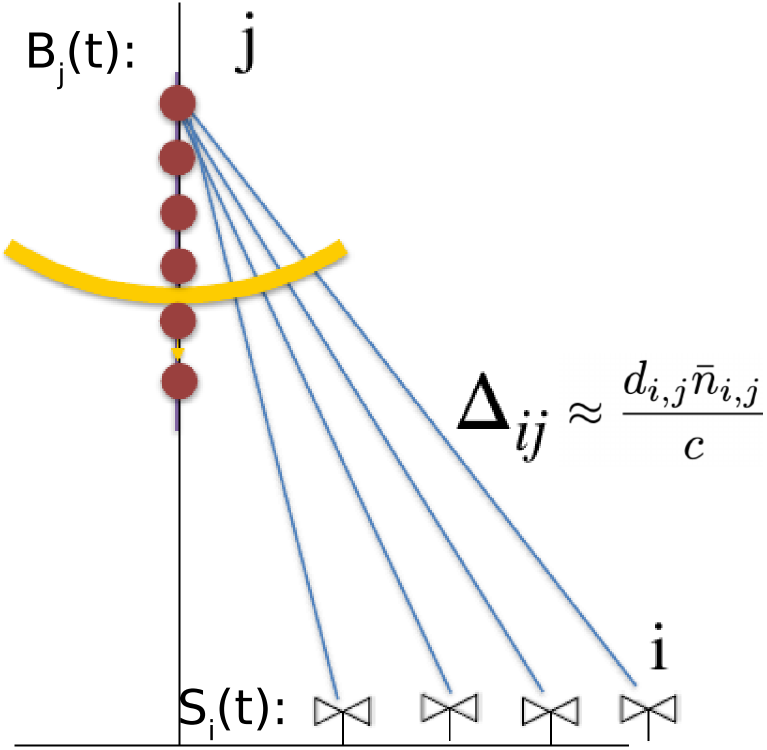
- Determine coherent signal *B* by interfering all measured signals S_i:

$$B_j(t) = \sum_i^j S_i(t - \Delta_{i,j})$$

Time shifted signals $S_i(t-\Delta_{i,j})$:

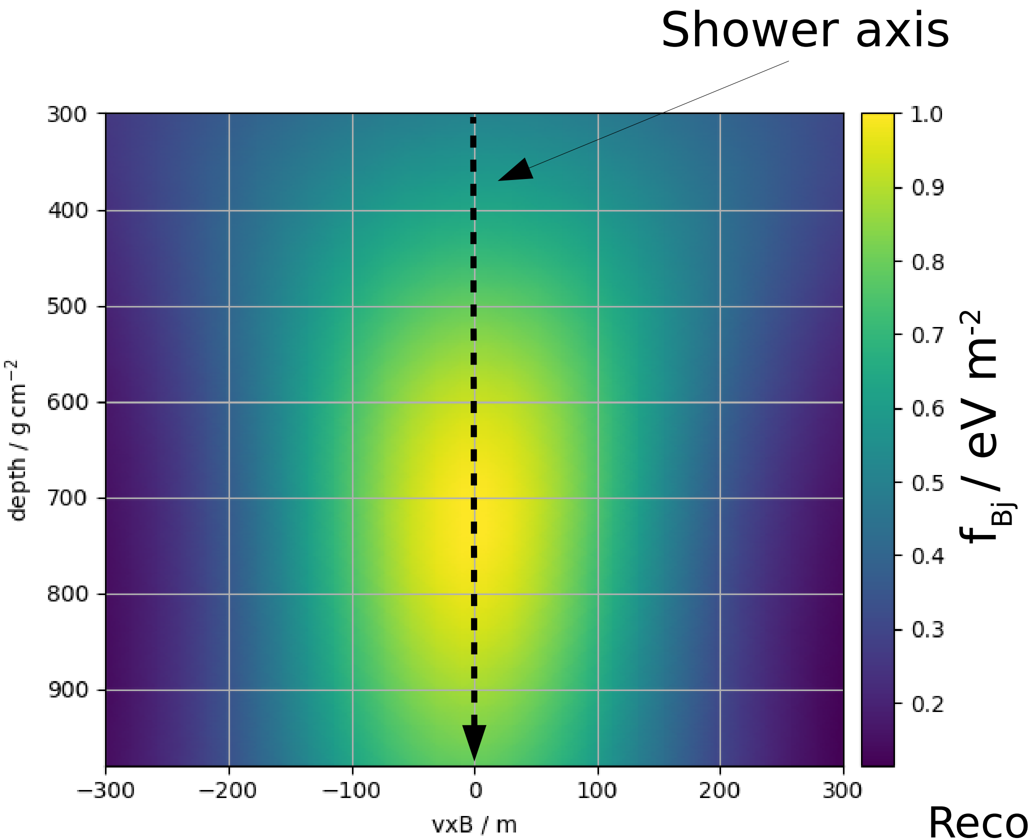


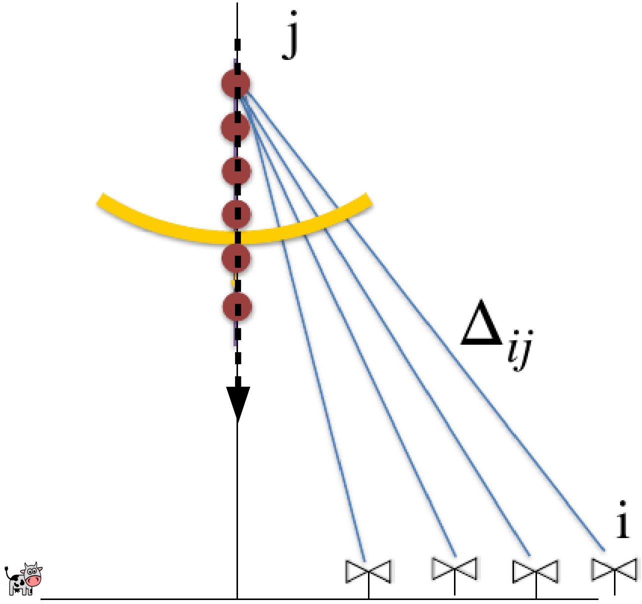




Illustrations from H. Schoorlemmer

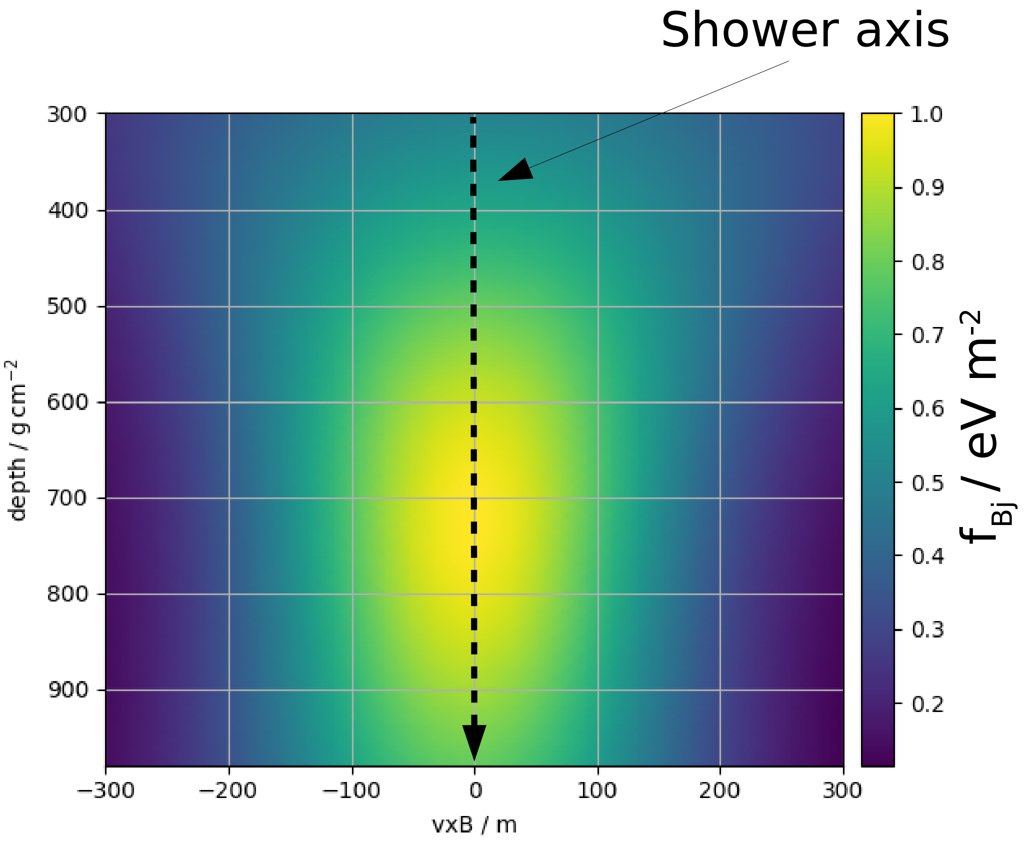
Radio Interferometric Technique



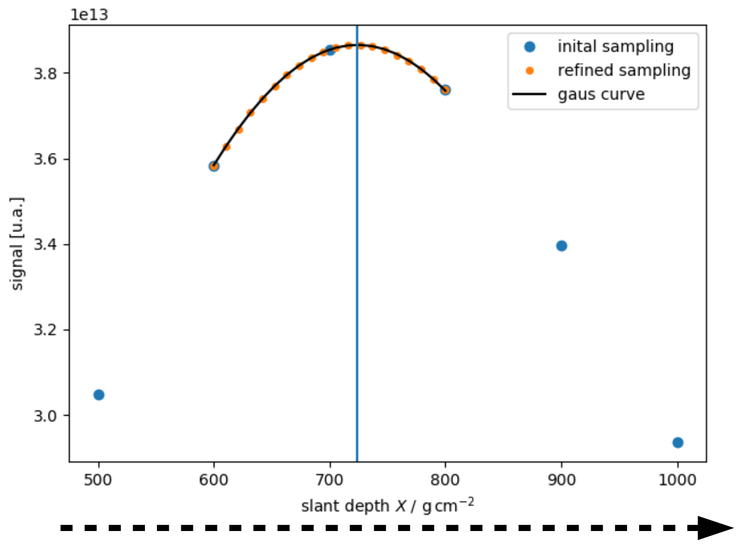


Reconstruct shower geometry: axis & X_{max}

X_{max} Reconstruction



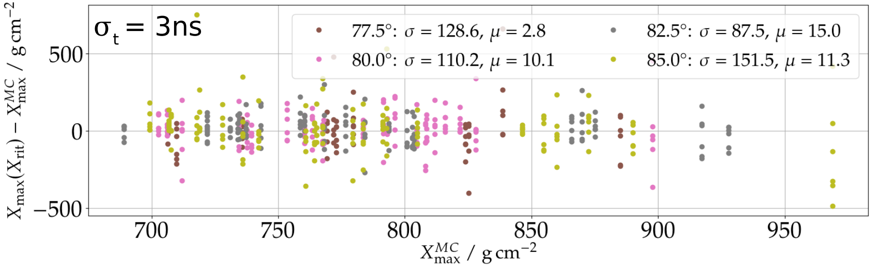
- Scan signal along axis → Longitudinal shower profiles → X_{RIT}



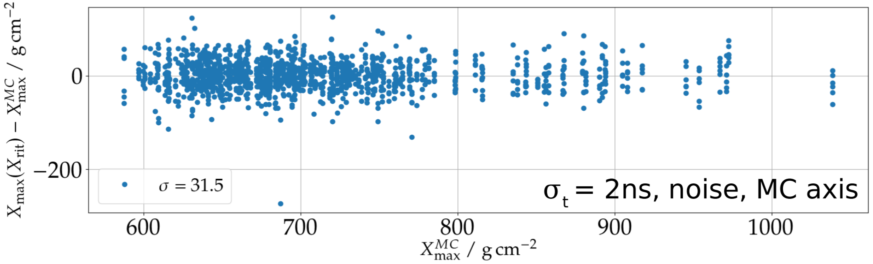
RIT for Auger

- Evaluated for Auger Radio Detectors
  - In principle applicable: requires dense array & good time synchronization
  - Impact of time jitter depends on detector layout / station multiplicity

RIT for RD



RIT for AERA

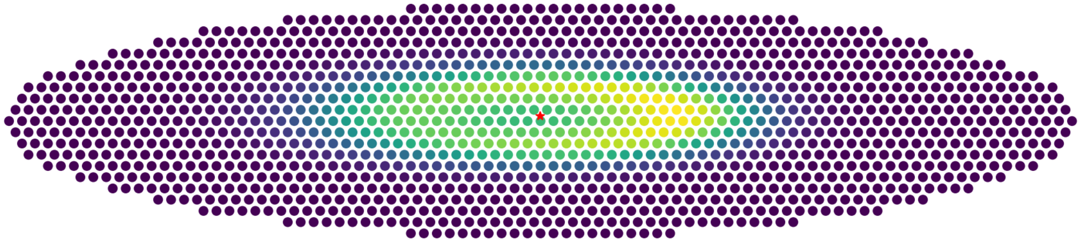


RD: time synchronization to inaccurate

- Now: Formulate some general rules for the application of RIT
  - Station multiplicity vs. time jitter

Study dependency on station multiplicity

- 50 very dense 77.5° showers, random core around central station

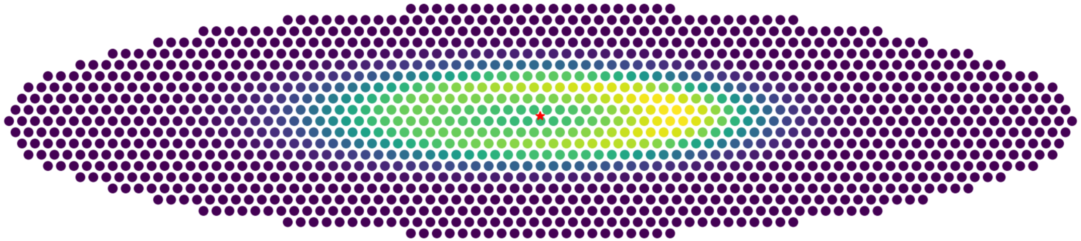


250m spacing

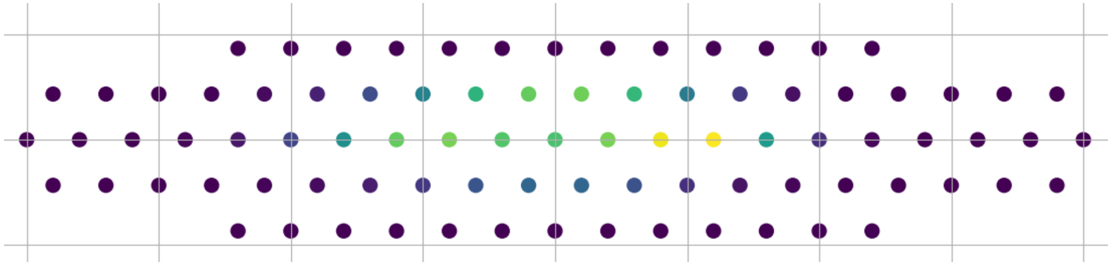
Study dependency on station multiplicity

No triggers!

- 50 very dense 77.5° showers, random core around central station



250m spacing



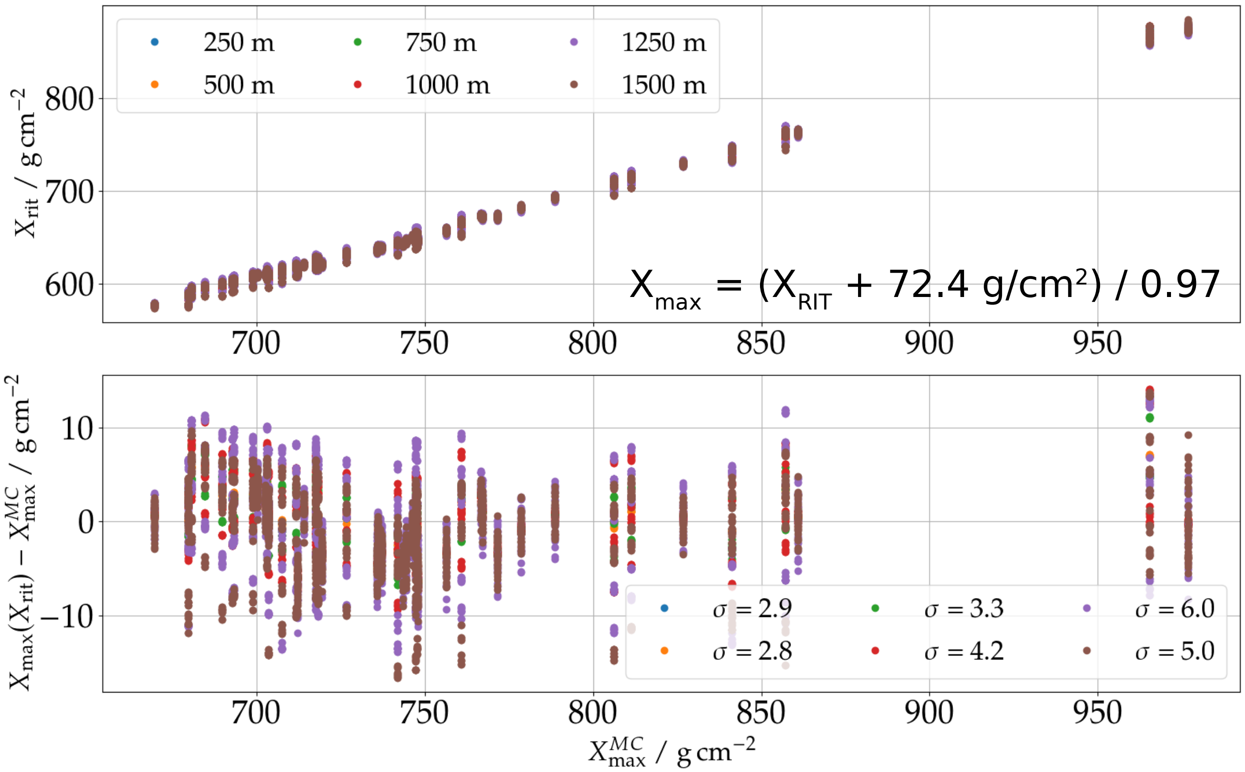
1000m spacing

Spacing	# stations
250m	1349
500m	341
750m	153
1000m	87
1250m	55
1500m	37

X_{max} Reconstruction

MC axis, no noise, no time jitter

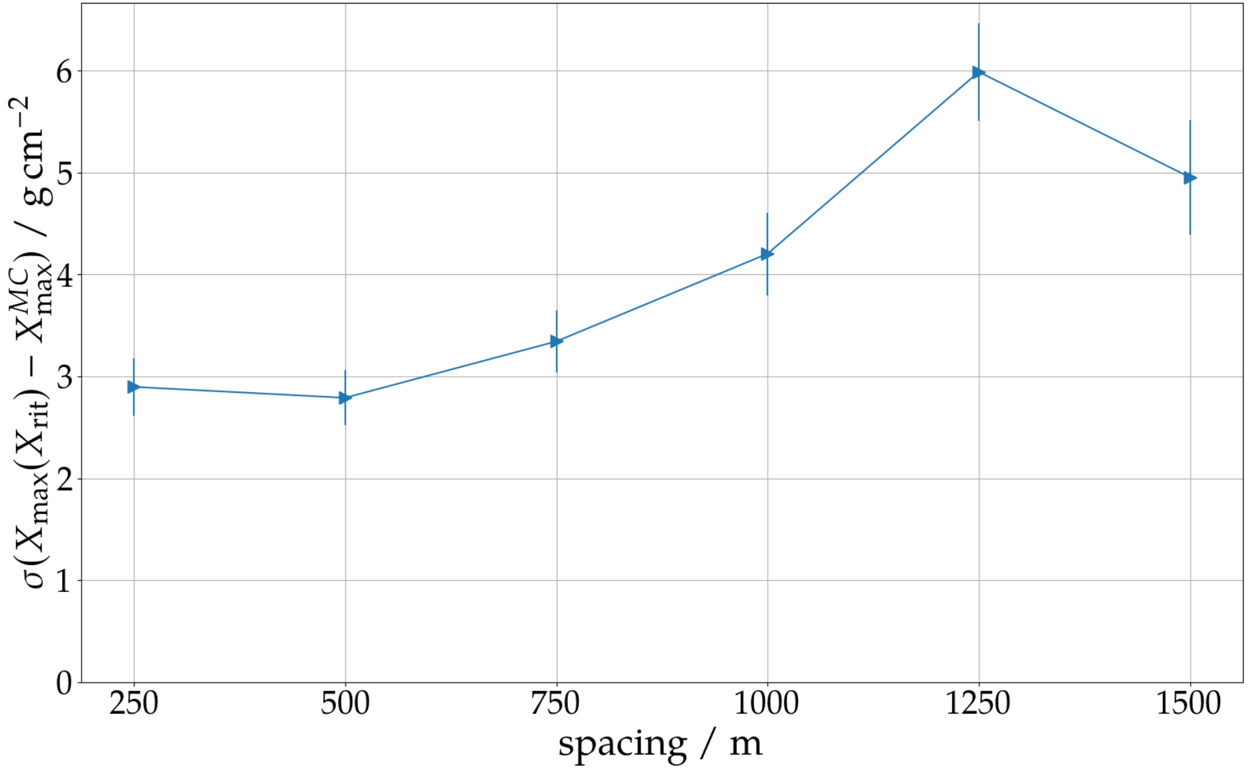
- Use one calibration for all spacings
  - Minor bias
- Dense regular grid is better than star-shape pattern
- No significant correlation bt. N_{stat} and σ_{Xmax}



Resolution

MC axis!

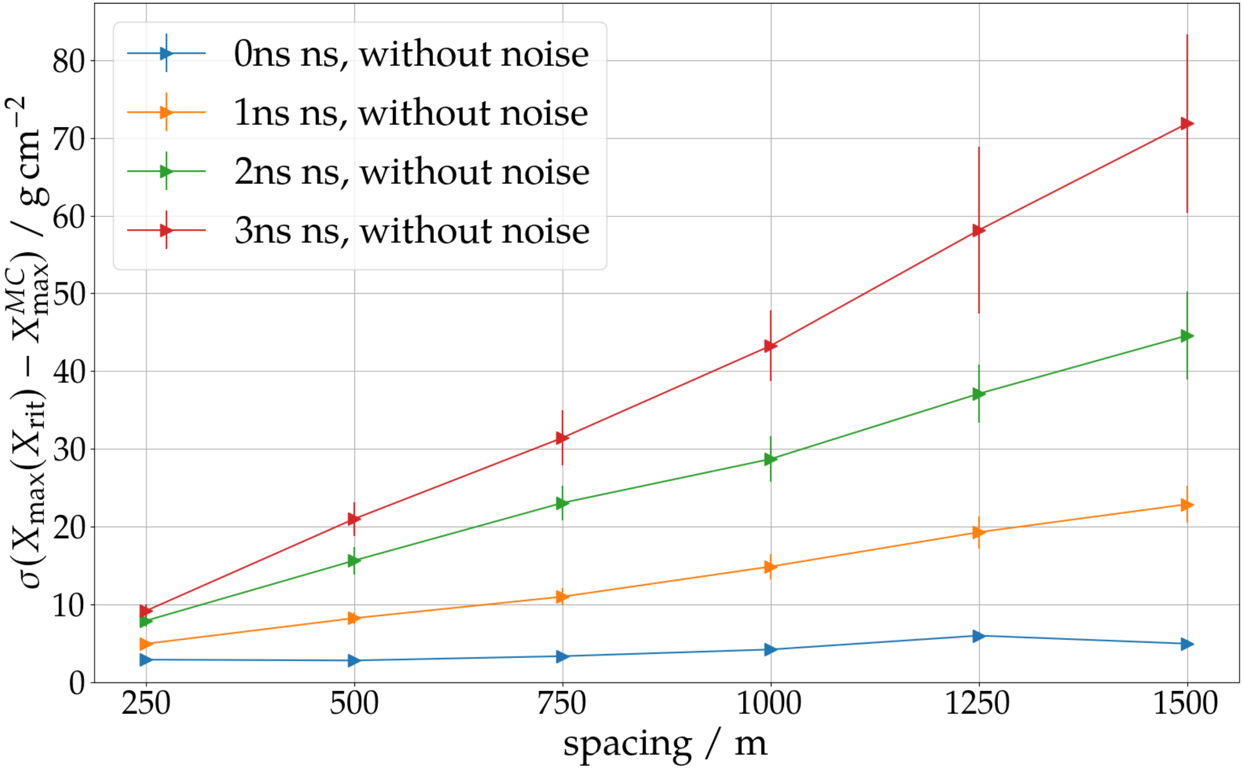
- Perfect time sync:
  - No (significant) trend



Resolution

MC axis!

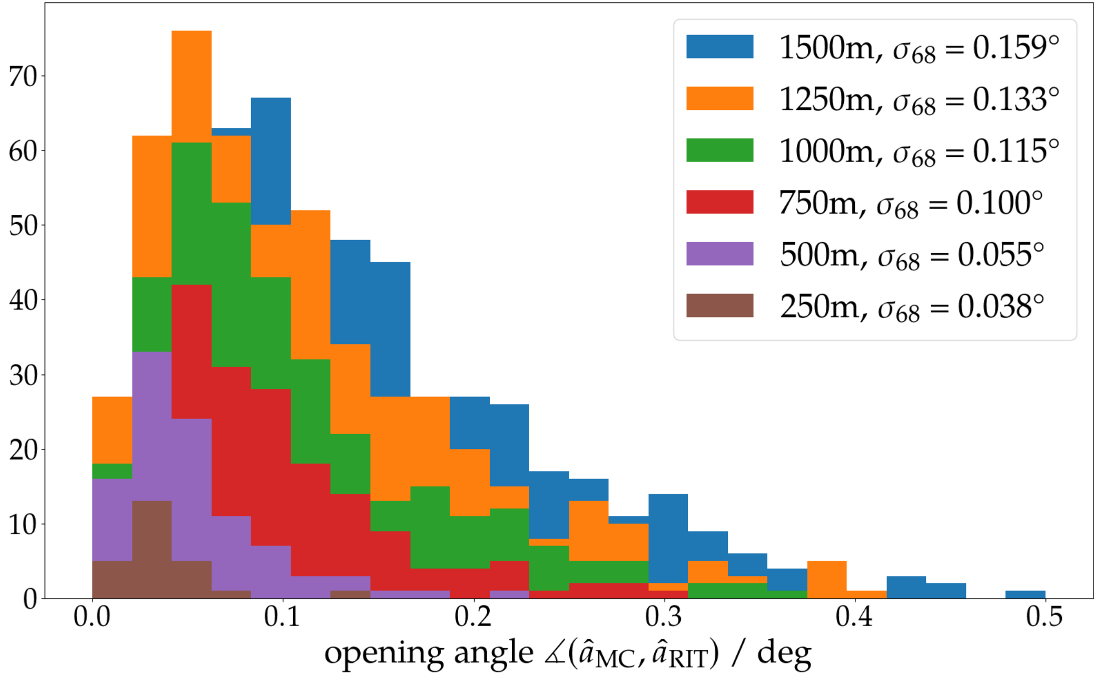
- Perfect time sync:
  - No (significant) trend
- With time jitter:
  - Significant trend



Axis Reconstruction

- Depends on arrival direction ($\varphi = 0$) is worse case scenario
- Dependencies
  - spacing
  - time jitter
- With selection
  - based on X_{max} gauss fit goodness
  - efficiency depends on spacing

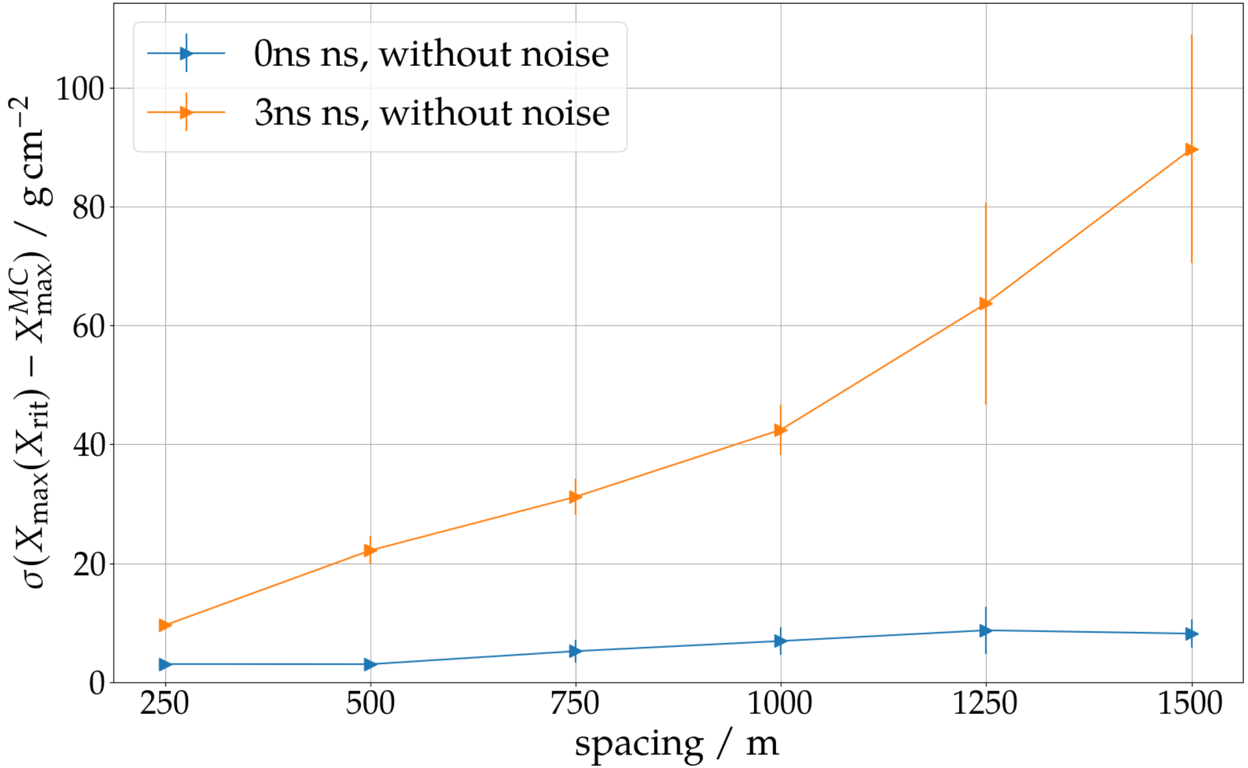
$\varphi = 30°, \sigma_t = 3\text{ns}$



Resolution

Reconstructed axis!

- Similar result as with MC axis
  - But smaller reconstruction efficiency



Summary

- Impact of time jitter scales with station multiplicity
  - Better time synchronization needed for higher frequencies
- For accurate axis reconstruction
  - Dense sampling improves reconstruction / makes it more reliable
  - Mild effect by time jitter
- For higher frequency bands:
  - Need better time synchronization
  - Need higher station density: rely on sufficiently sampled (sharper) Cherenkov Cone
- Atmosphere: Uncertainty in refractivity model has NO impact on rec. $X_{max,}$
  - similar uncertainty from density profile as FD: 2 - 4 g/cm^2

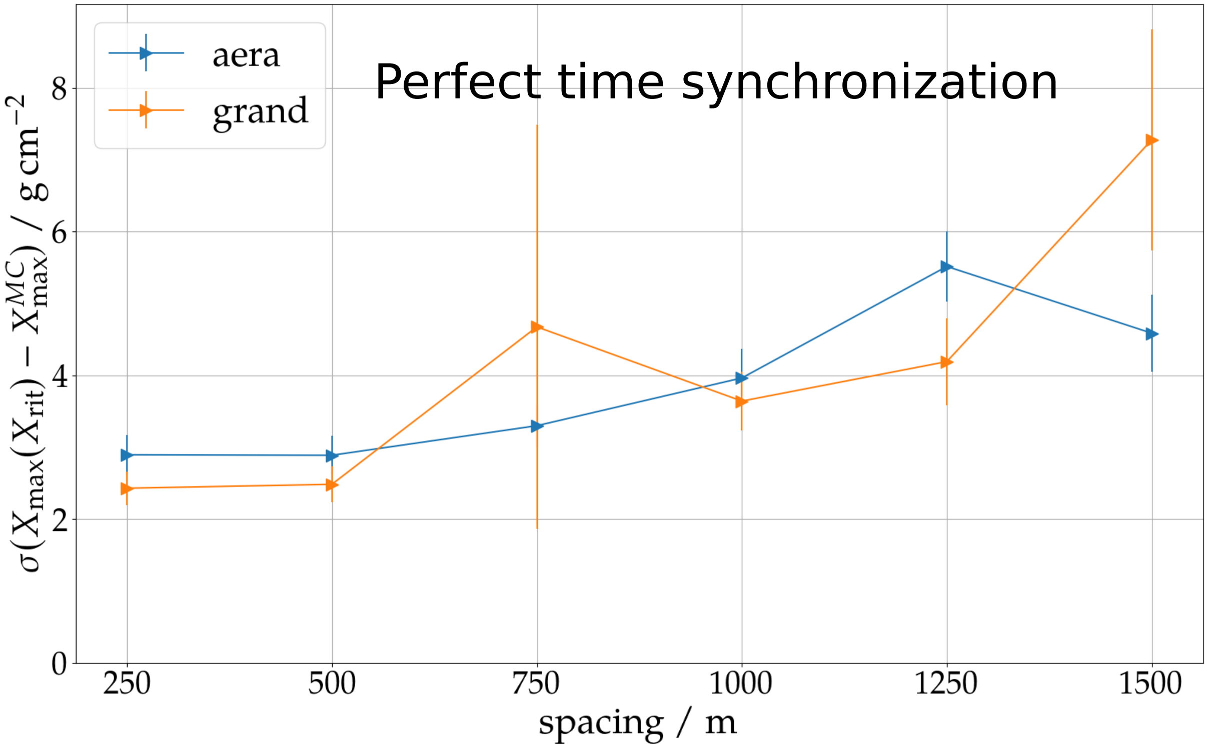
Outlook

- Generalization to other zenith angle (toy model)?

Frequency bands

MC axis!

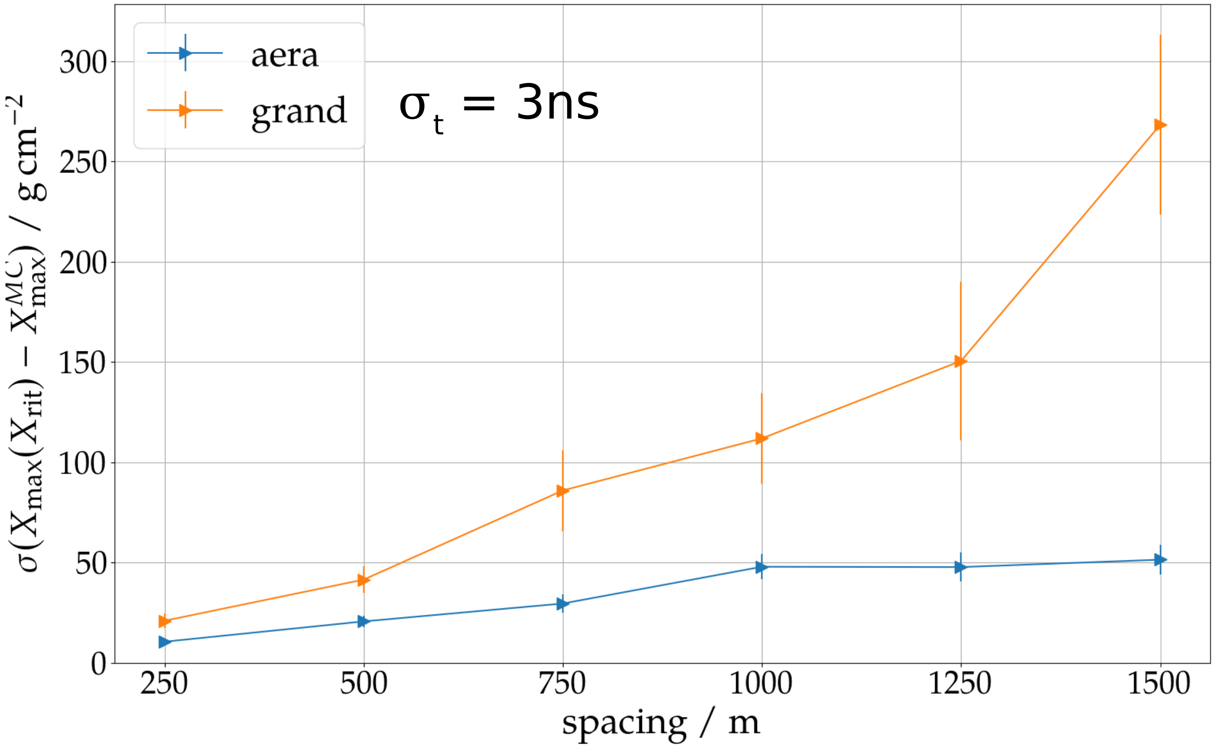
- AERA: 30 – 80 MHz
- Grand: 50 – 200 MHz



Frequency bands

MC axis!

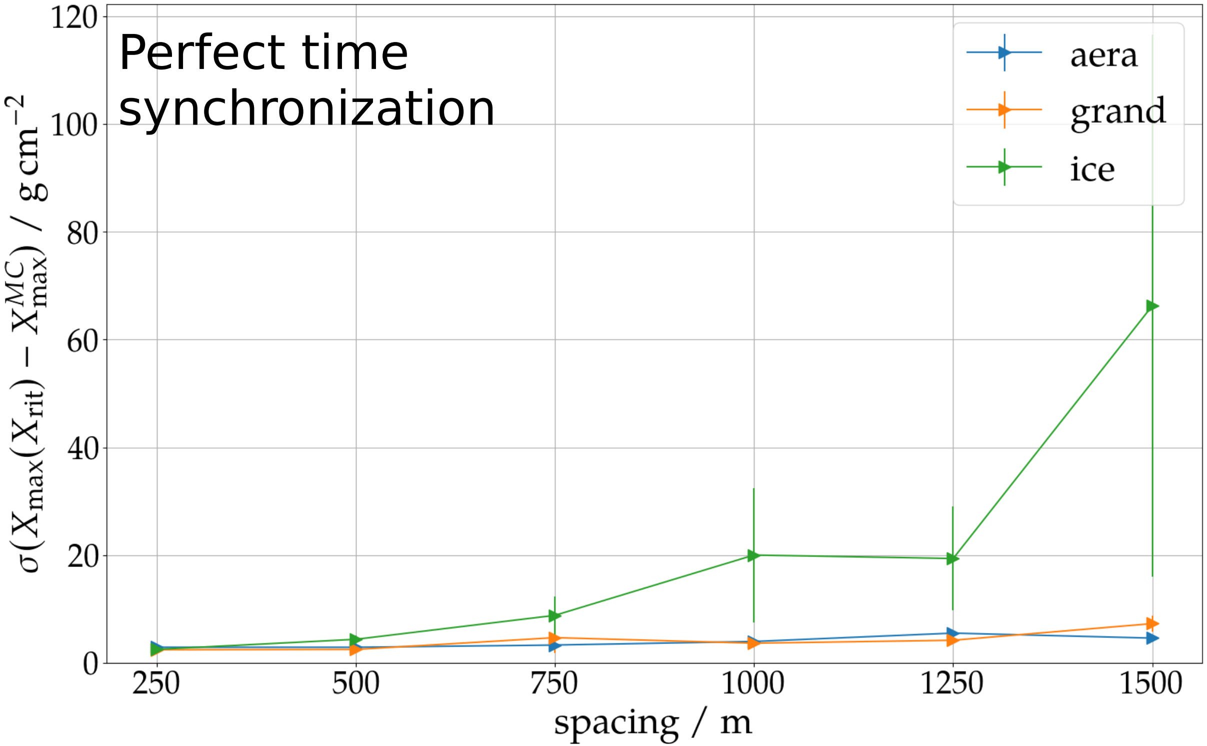
- AERA: 30 – 80 MHz
- Grand: 50 – 200 MHz
- For higher frequencies a better time synchronization is needed (expected!)



Frequency bands

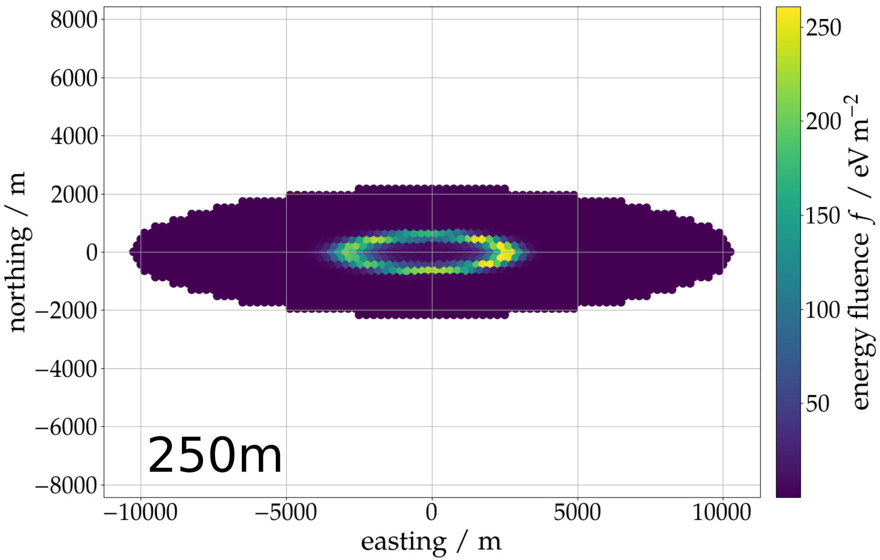
MC axis!

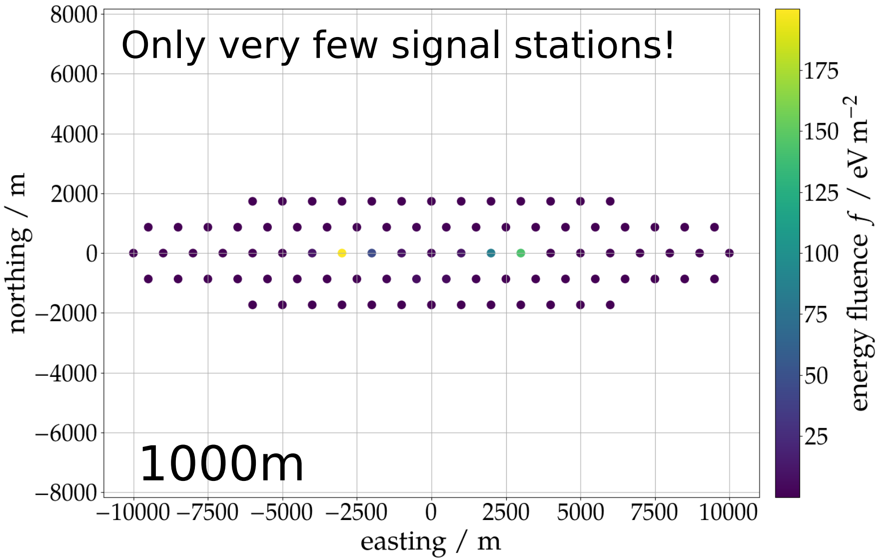
- AERA: 30 – 80 MHz
- Grand: 50 – 200 MHz
- For higher frequencies a better time synchronization is needed (expected!)
- IceTop: 150 – 350 MHz
  - A few strong outliers



Footprint for IceTop

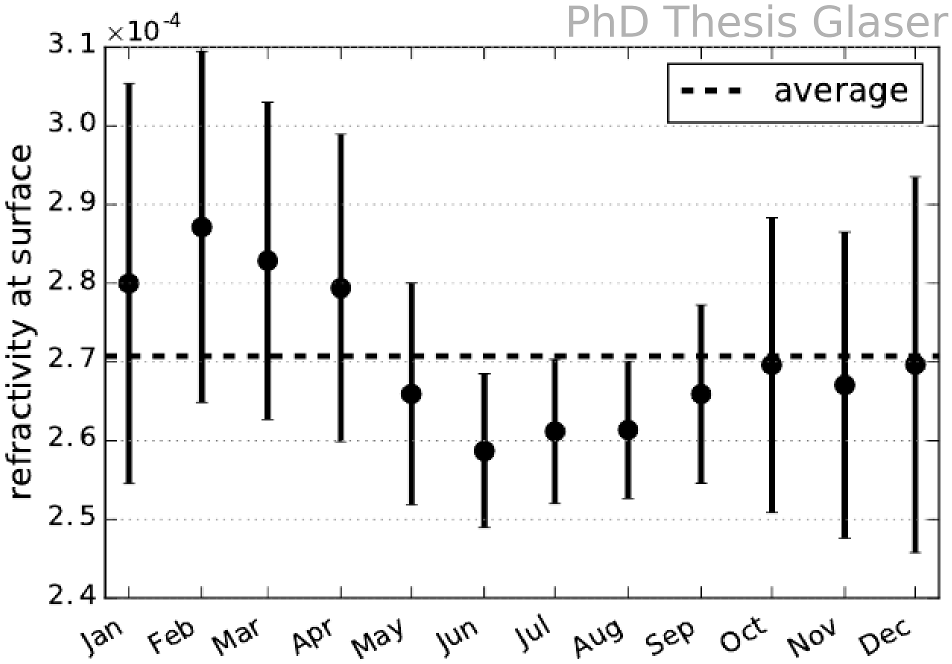
- For higher frequencies: You need to sample the Cherenkov ring
  - Need denser spacing





Atmosphere and Refractivity

$N = (n - 1) \cdot 10^6$



Monthly-averaged refractivity at the surface at the Pierre Auger Observatory.

Select refractivity at sea level according to atmospheric model

	N_{0m}	N_{1400m}
Oct	312	269
Feb	330	286
Jun	301	259

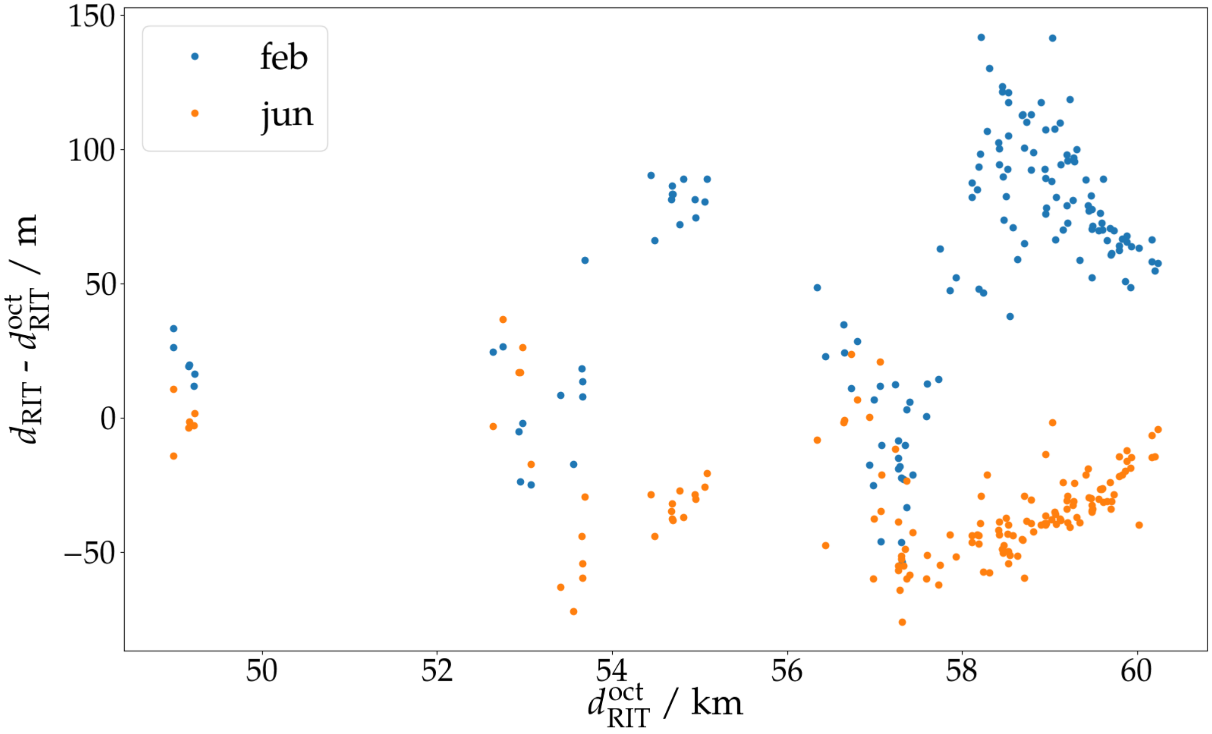
Used in simulation

"Chosen by eye"

Use wrong models for reconstruction

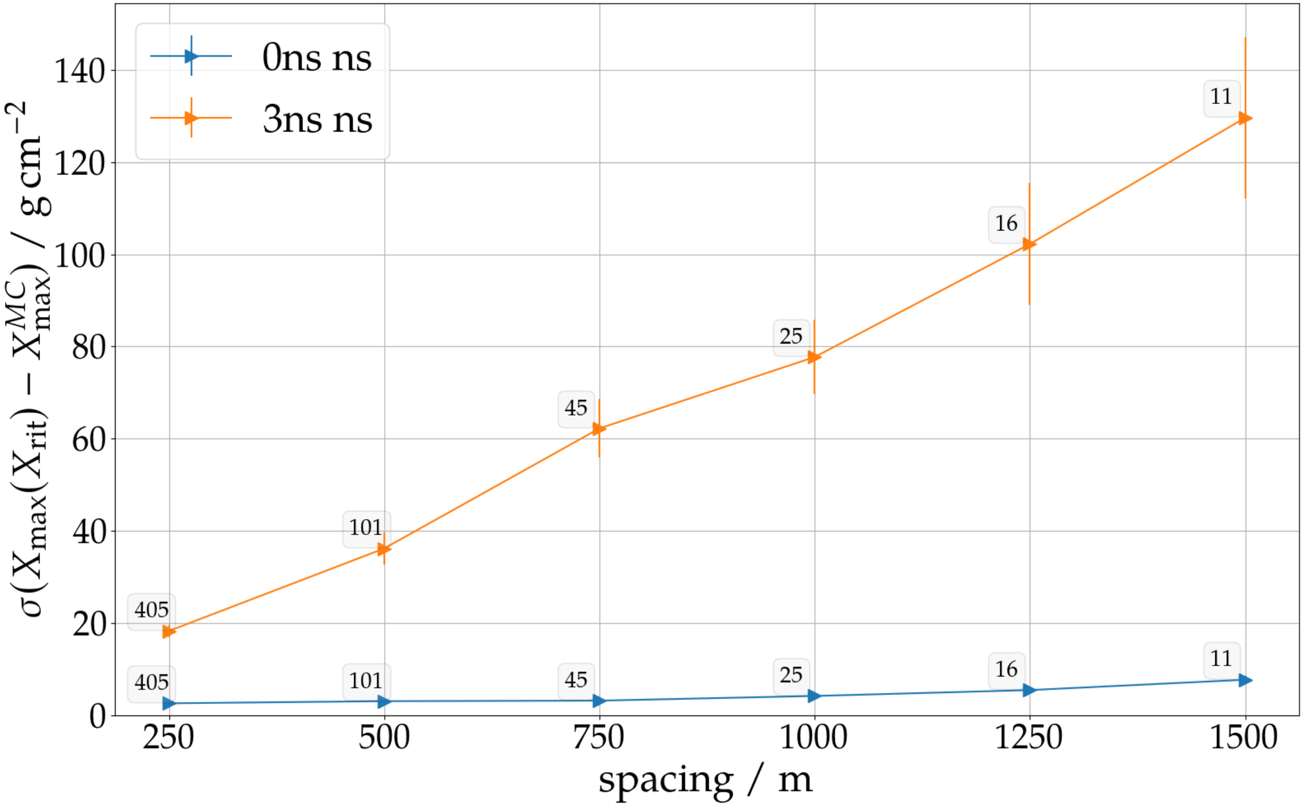
Atmosphere and Refractivity

- Simulated with oct atmosphere reconstructed with feb/jun
- Reconstruct the same position of maximum
- X_{max} Reconstruction: Similar uncertainty due to density profile as FD
  - 2 – 4 g/cm2



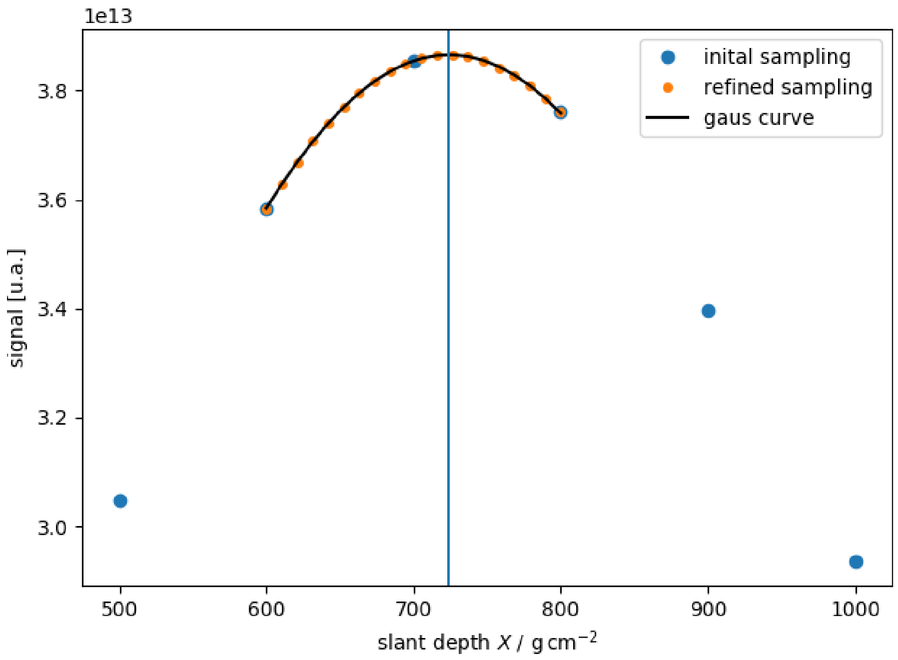
Radio Trigger: $A_{max} > 100\mu V$

- $N_{sig} / N_{all} \sim 1 / 3.5$
- MC axis
- No noise
- Similar results:
  - 0ns: no trend
  - 3ns: significant trend

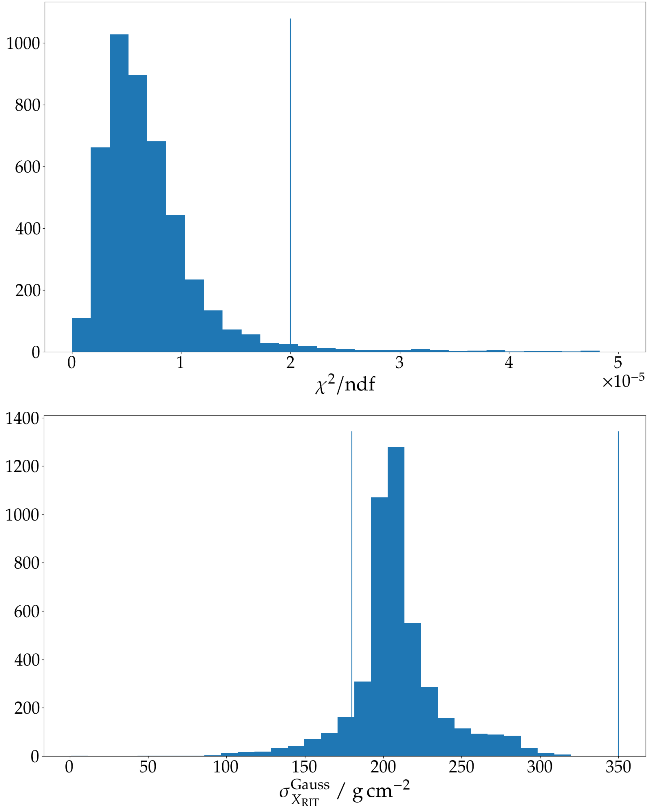


Selection

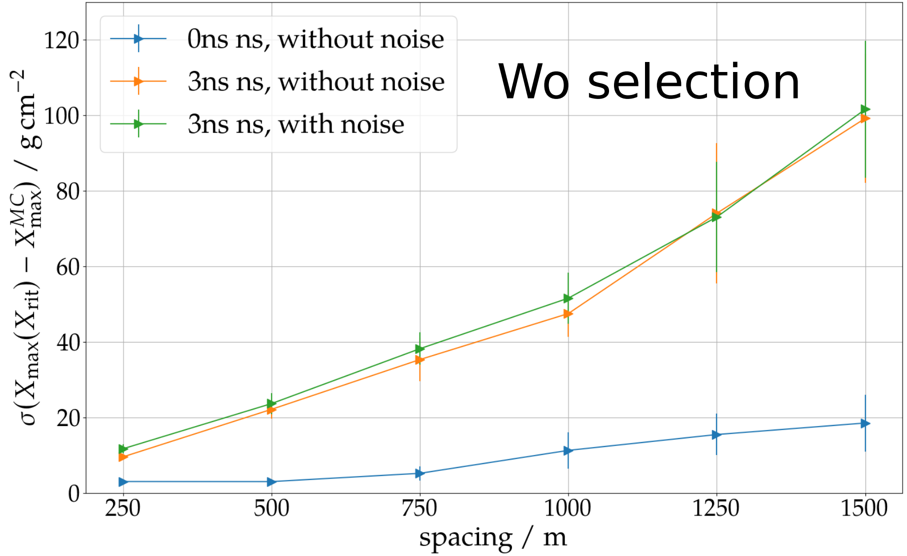
- Selection based on Gaus fit: Chi2, σ_{gaus}

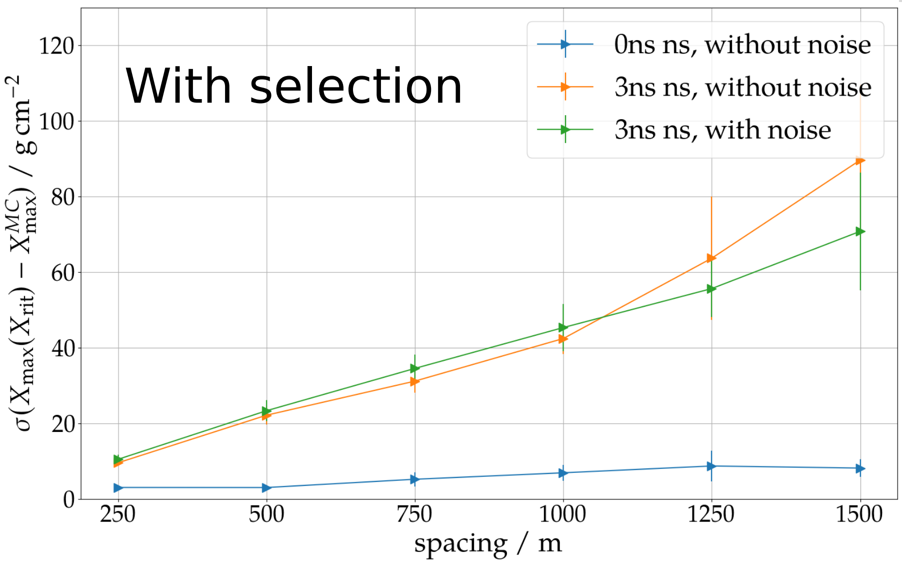


rec. axis, σ_t = 0ns



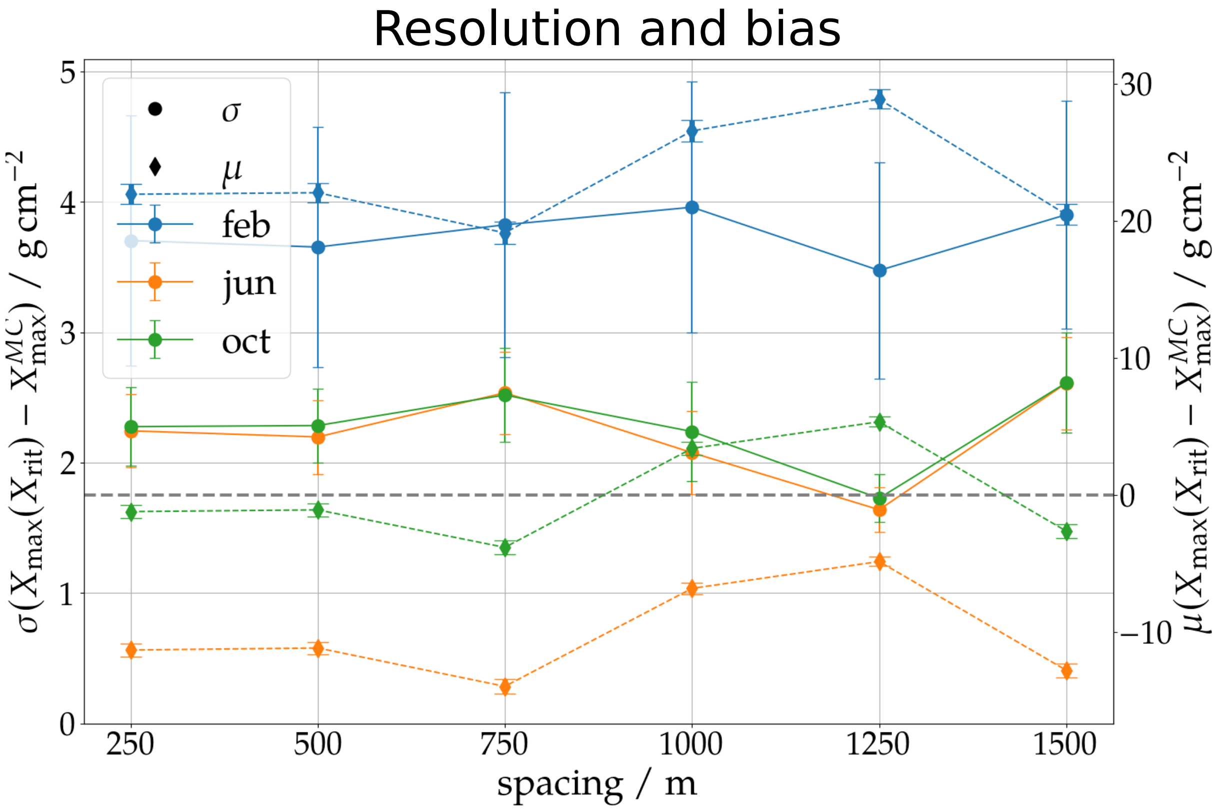
Reconstruction with noise





Atmosphere and Refractivity

- Introduces bias in reconstruction
  - Due to density not refractivity profile
- $\Delta X_{max} \sim 30$ g/cm²
- Combined:
  $\sigma = 14$ g/cm²
- Zenith angle dependency?

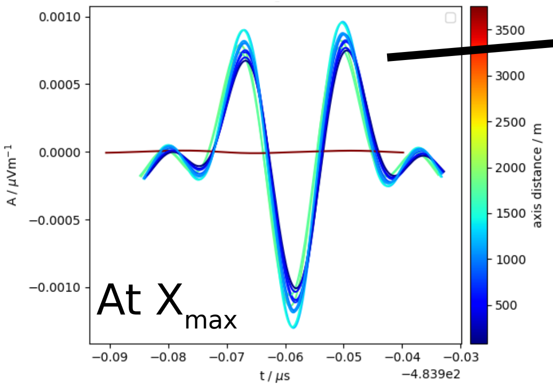


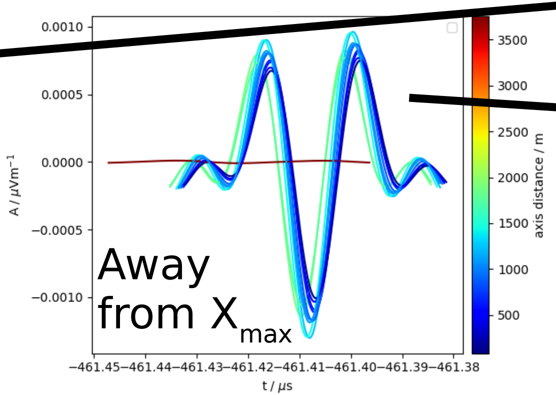
Radio Interferometric Technique (In a nutshell)

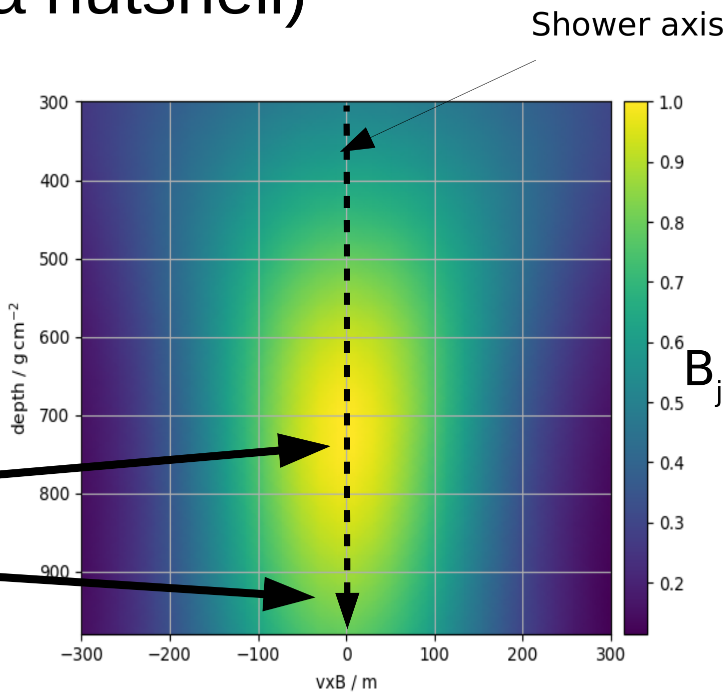
- Determine coherent signal *B* at position *j* by interfering all measured, time shifted signals S_i:

$$B_j(t) = \sum_i^j S_i(t - \Delta_{i,j})$$

$S_i(t-\Delta_{i,j})$:





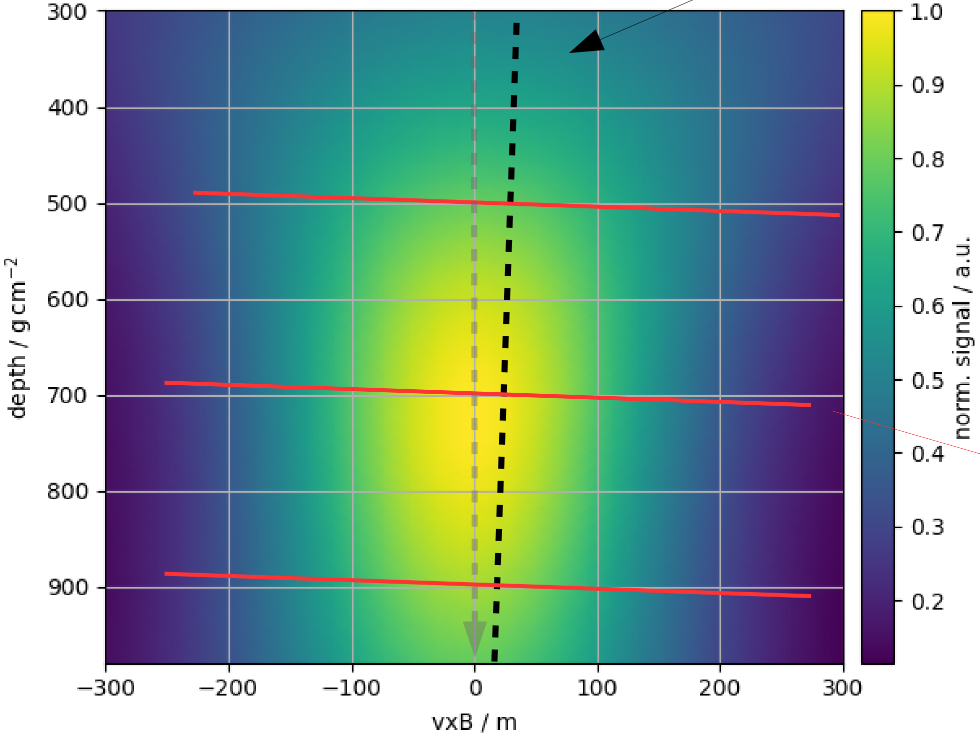


Reconstruct geometry:
- Shower axis
- X_{max}

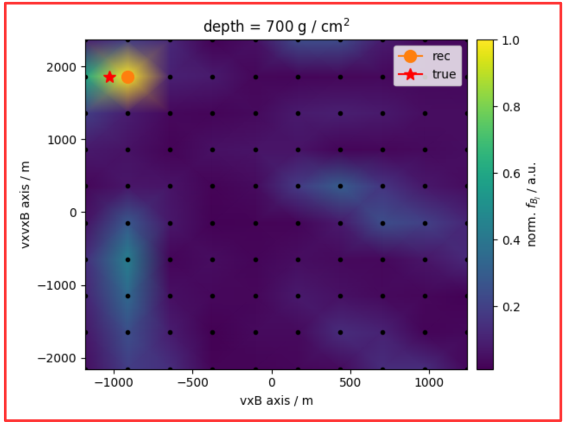
Reconstruct shower axis

"Lines are drawn by eye"

Initial shower axis



- Smear MC axis (0.5°) and MC core (100m) before reconstruction
- Sample slices
  - (perpendicular to axis)



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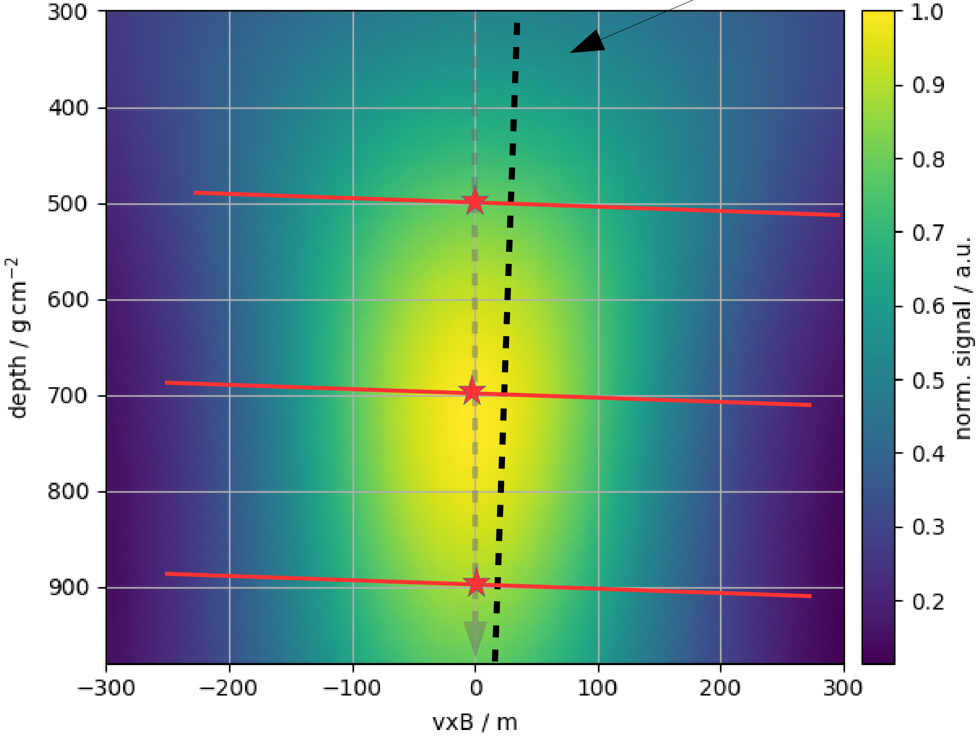

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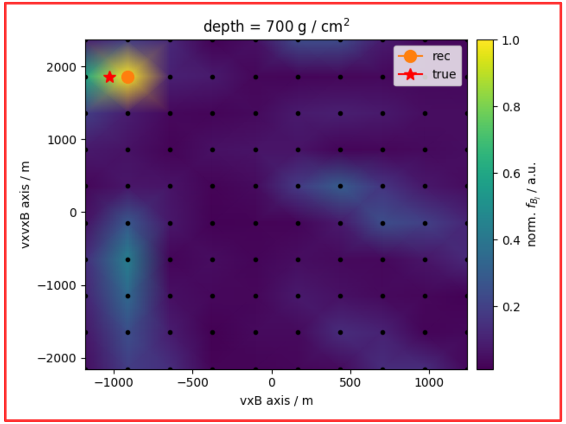
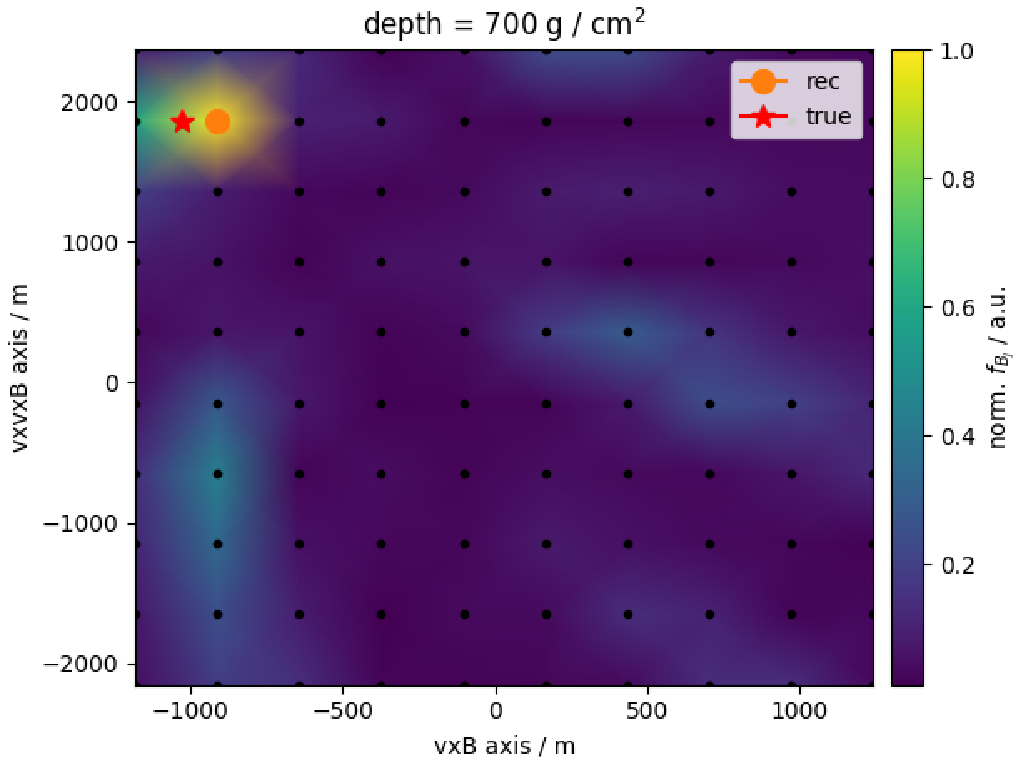
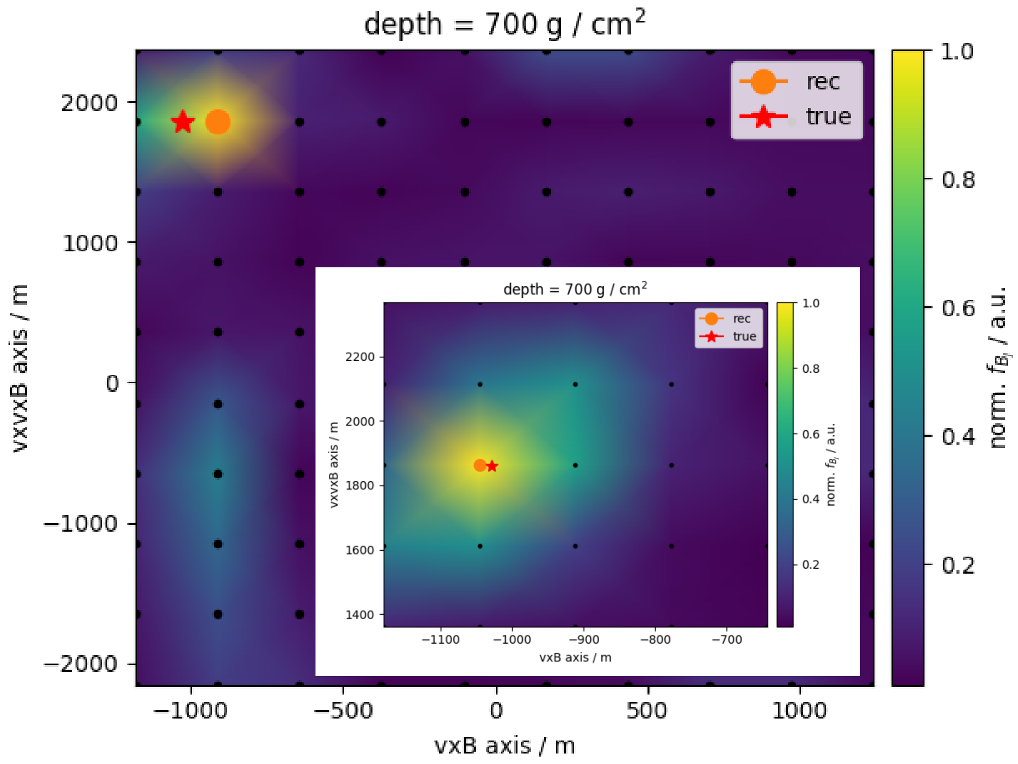


Shower axis reconstruction



- Search for maximum on rectangular grid

Shower axis reconstruction



- Search for maximum on rectangular grid
- Zoom in on maximum
  - Repeat several times

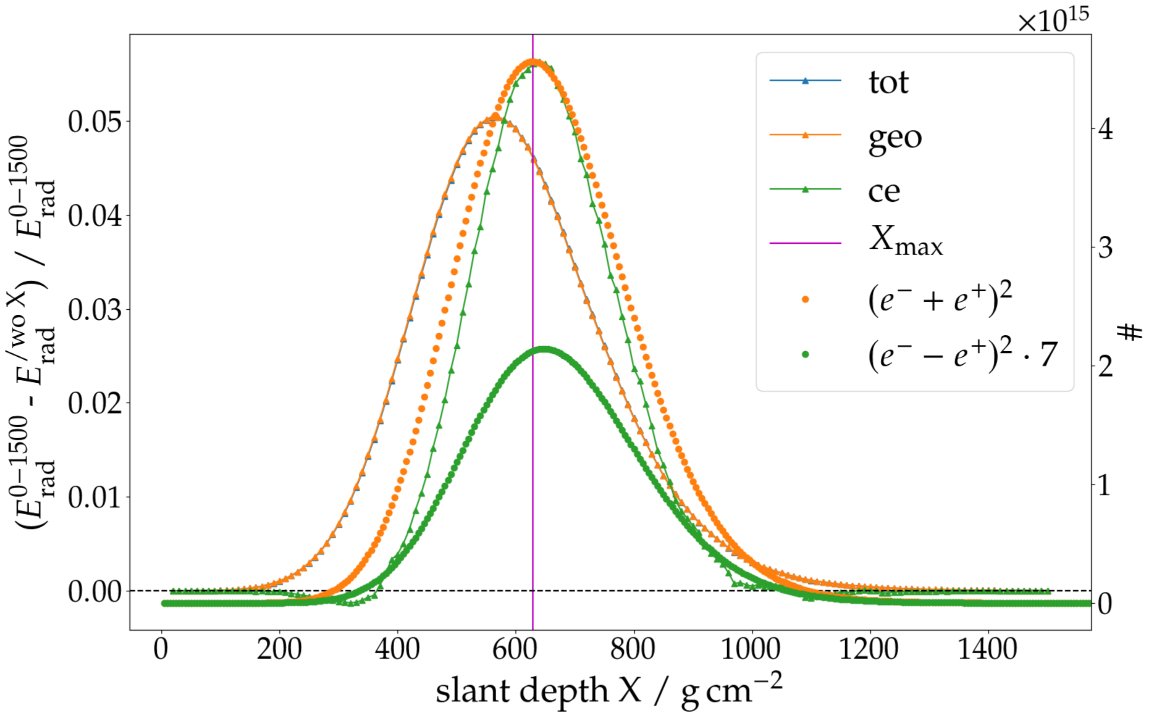
Atmosphere and Refractivity

The yearly fluctuations of the air refractivity at the site of the Pierre Auger Observatory are 7%, and are only 4% and 3% at the LOFAR and Tunka sites, respectively.

PhD Thesis Glaser

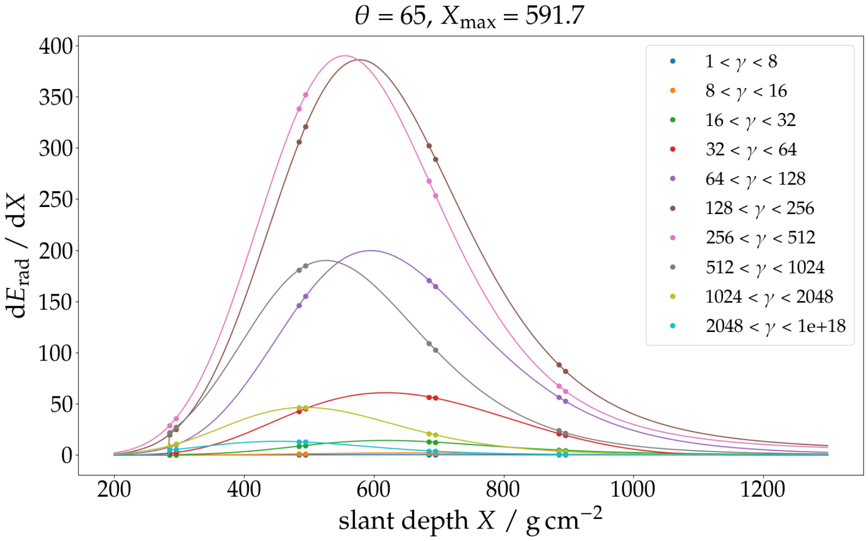
Where is the Radio Emission coming from?

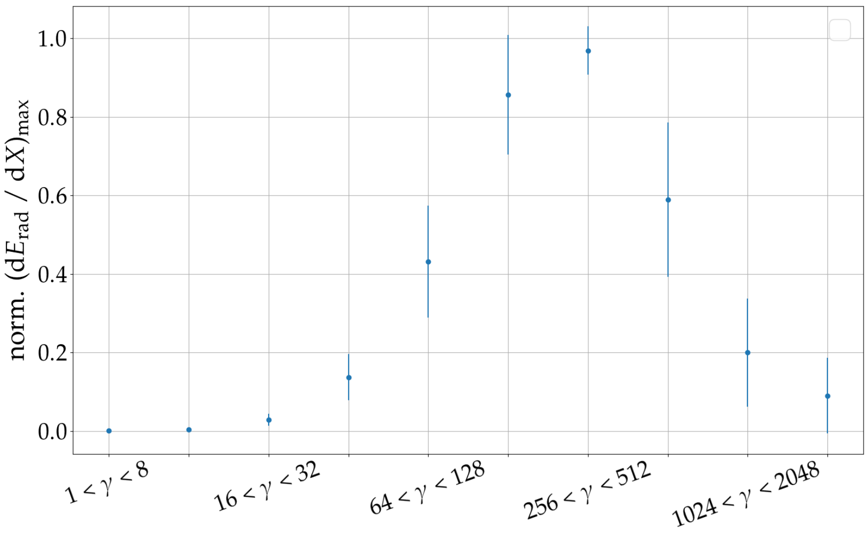
- Sliced Simulations
  - Isolate radiation from all particles in a certain slide
- Proper handling of the coherence
- Charge-Excess in later than particles (and geomagnetic emission)
  - Contradiction with lit.



Where is the Radio Emission coming from?

- Inconsistent treatment of coherence!





Where is the Radio Emission coming from?