Funded by the European Union

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PIERRE AUGER OBSERVATORY

Radio interferometric air shower reconstruction at the Pierre Auger Observatory

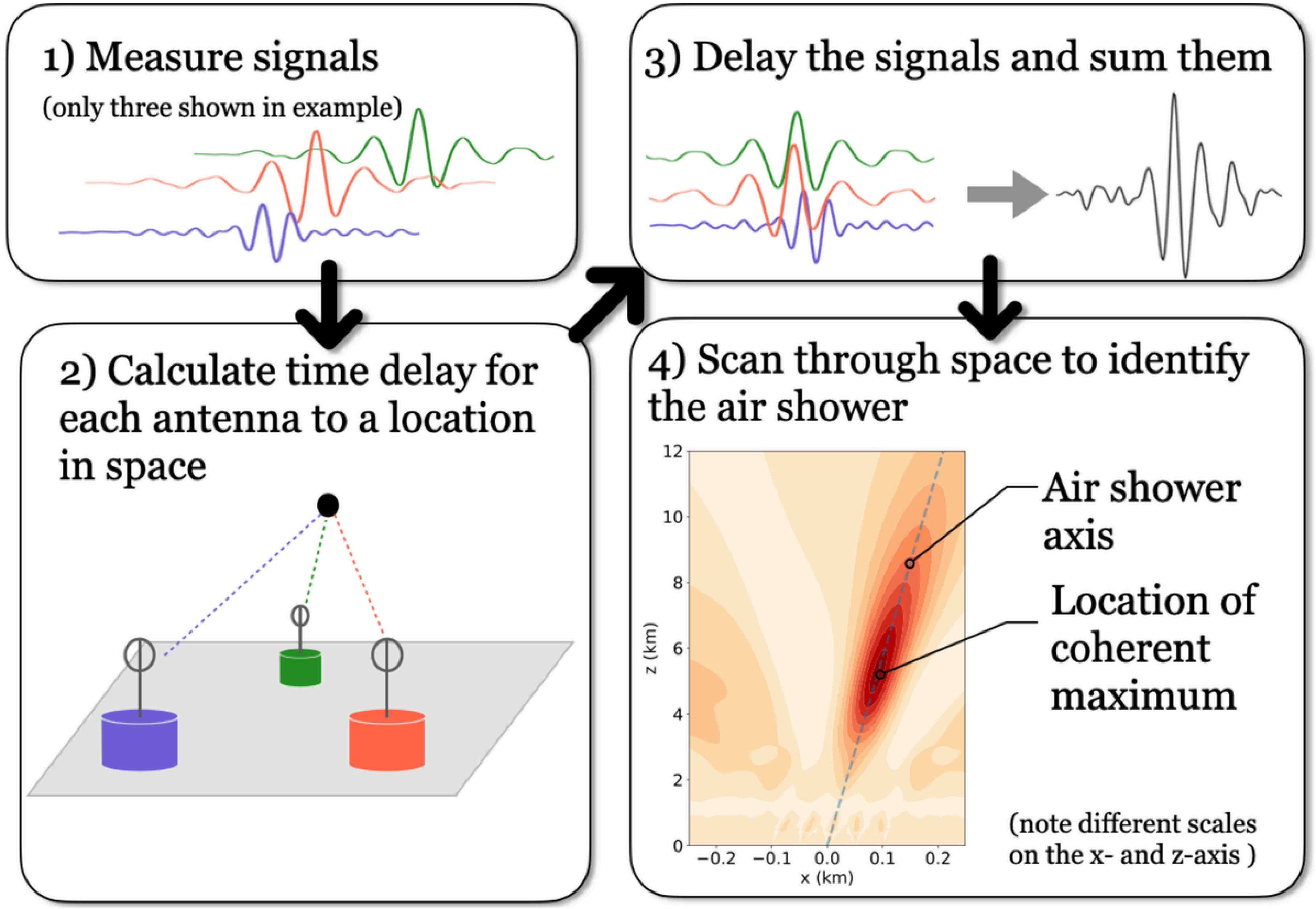
Pim van Dillen, for the Pierre Auger Collaboration

Nikhef

Radboud University

Radio Interferometry Technique (RIT)

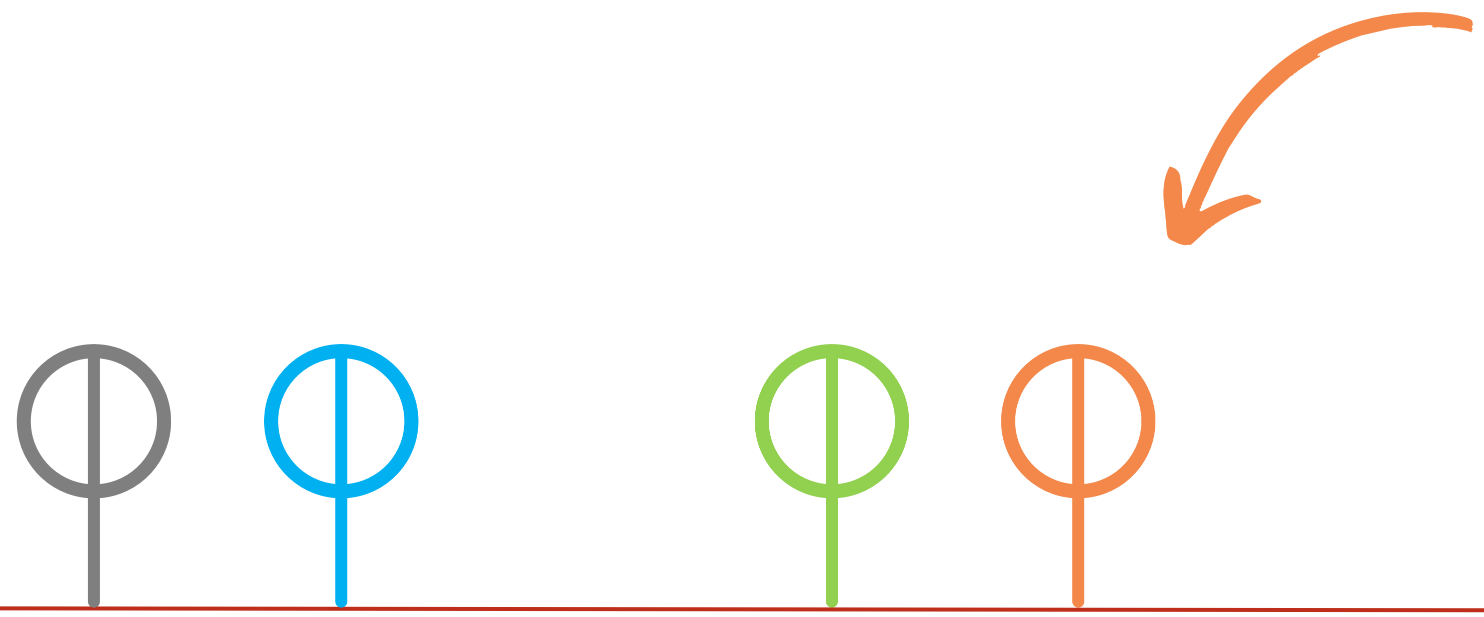
- Reconstruct air showers initiated by ultra-high-energy cosmic rays
- Combine the individual waveforms by exploiting the relative time difference
- Very accurate timing of the signal needed $\sim$ **1 ns**
  - Clock synchronisation
  - Positional accuracy (< 30 cm)

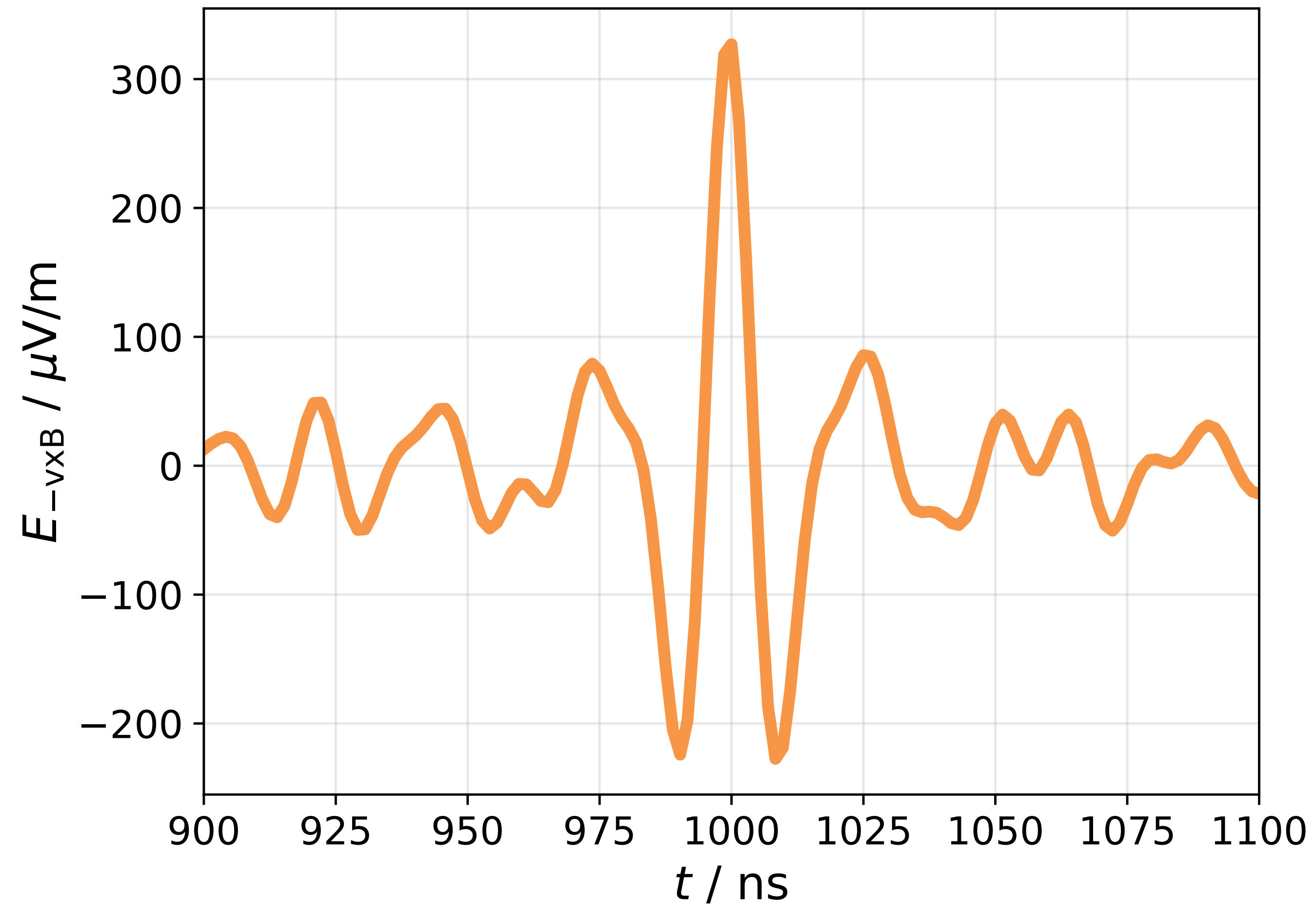


DOI: 10.22323/1.444.0380

Air Shower Interferometric Reconstruction Algorithm[1]

- Input:
  - Single waveform:
    - Projection on **-vxB**
  - Initial guess:
    - Surface detector reconstruction





[1] *Air Shower Interferometric Reconstruction Algorithm:* https://gitlab.com/harmscho/asira

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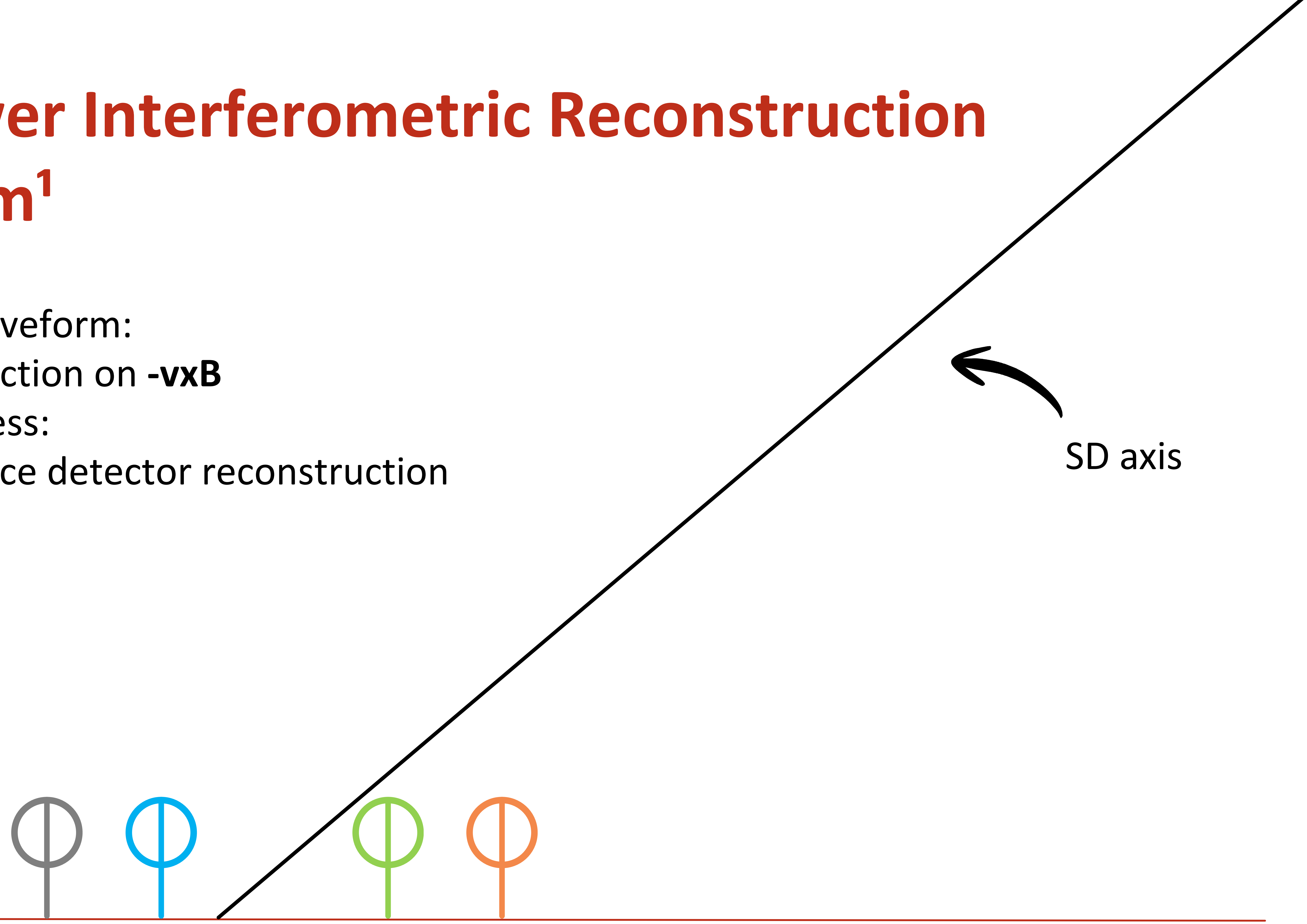

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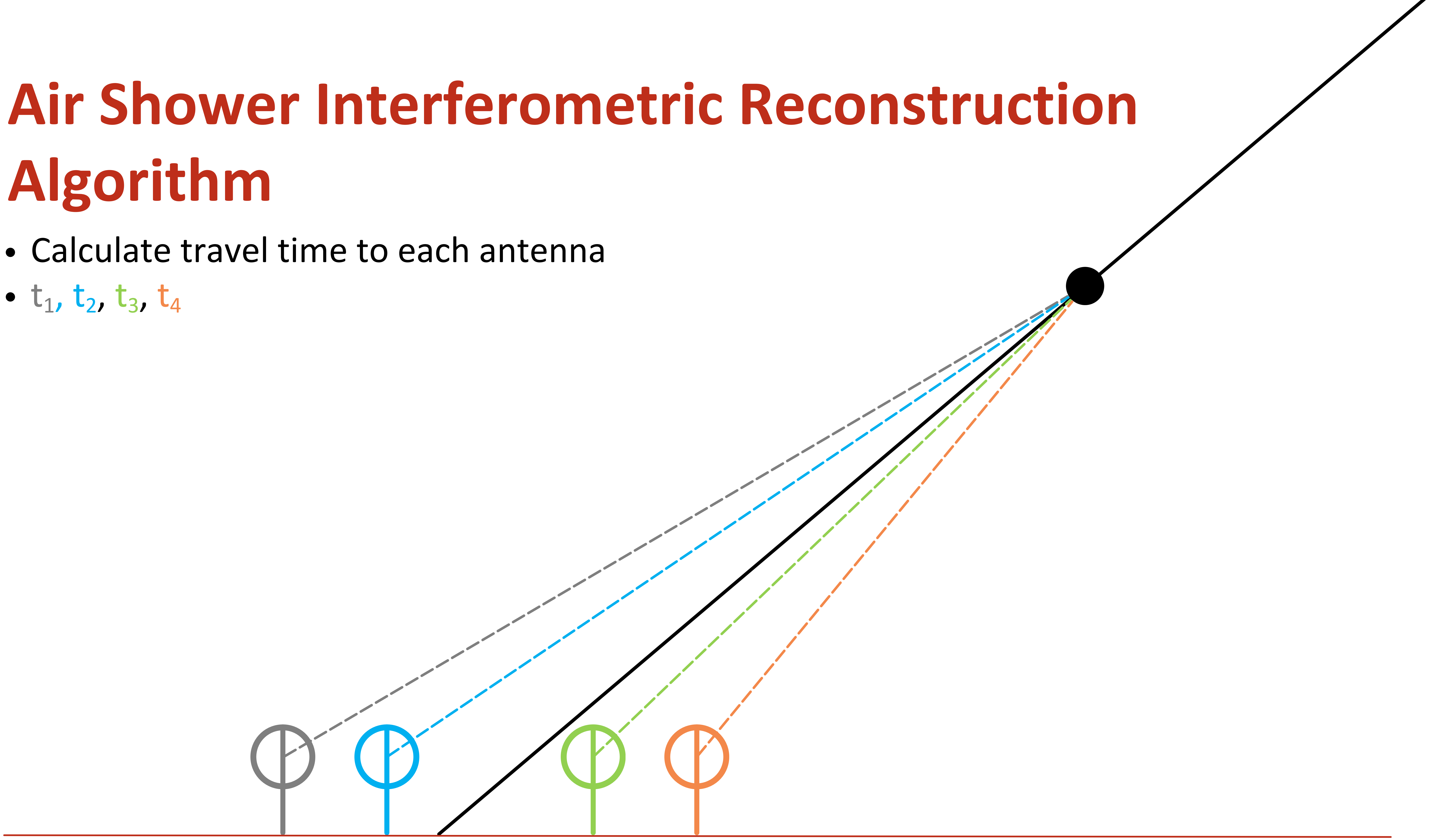
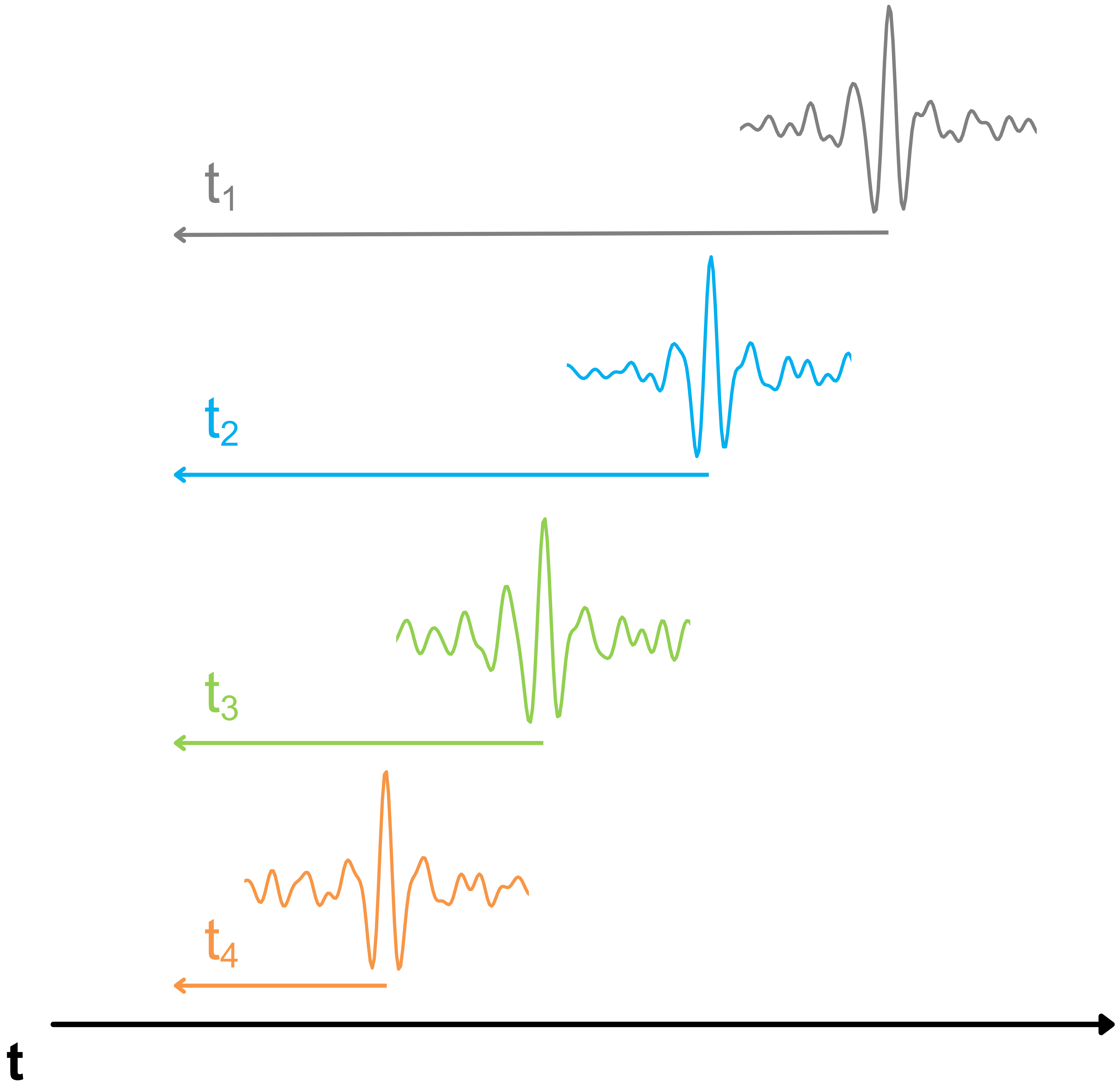
Air Shower Interferometric Reconstruction Algorithm

- Calculate travel time to each antenna
- t_1, t_2, t_3, t_4



Air Shower Interferometric Reconstruction Algorithm

- Subtract travel time from waveforms
- Add them up
- Integrate



Air Shower Interferometric Reconstruction Algorithm

- **Subtract travel time from waveforms**
- Add them up
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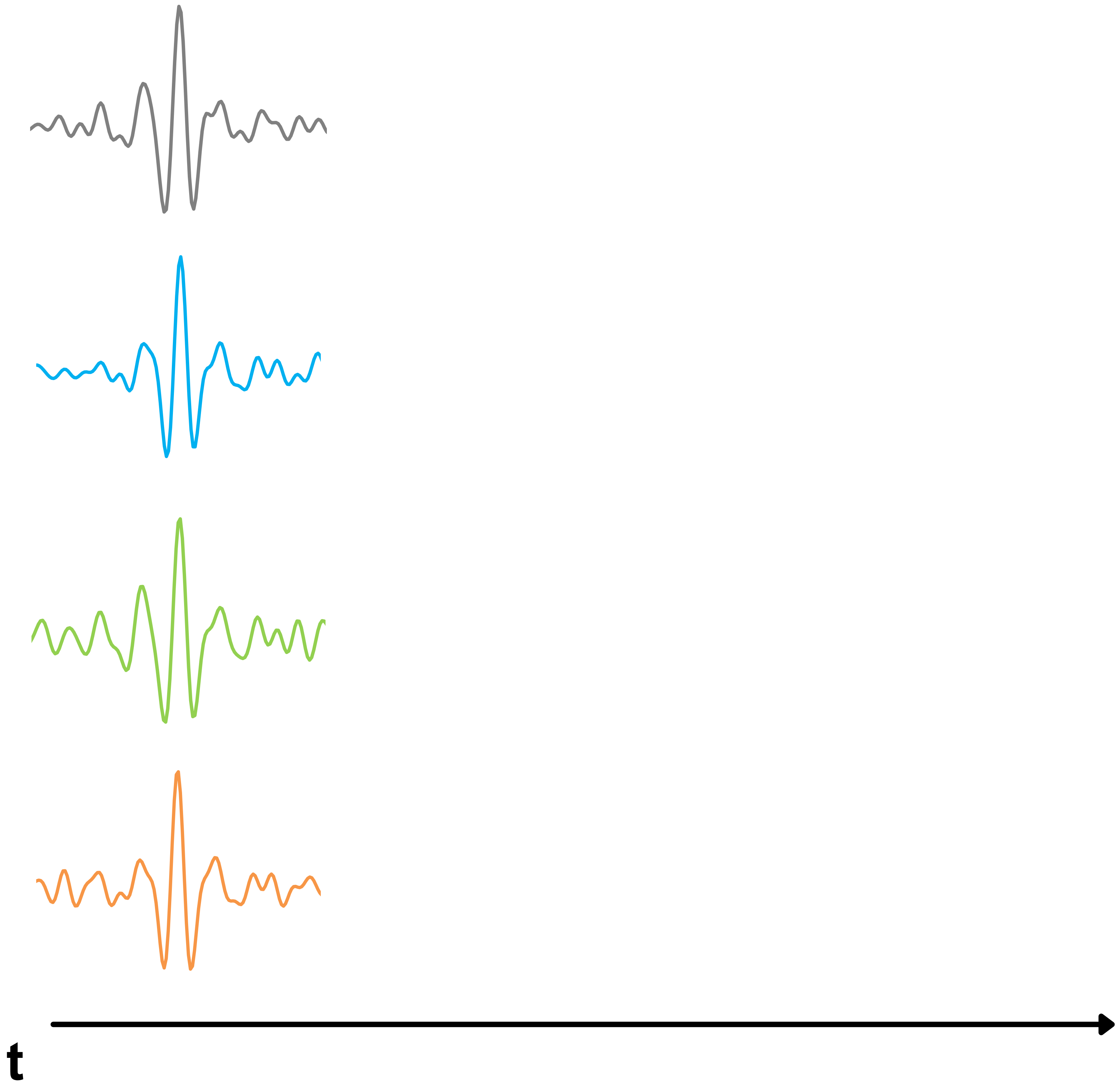

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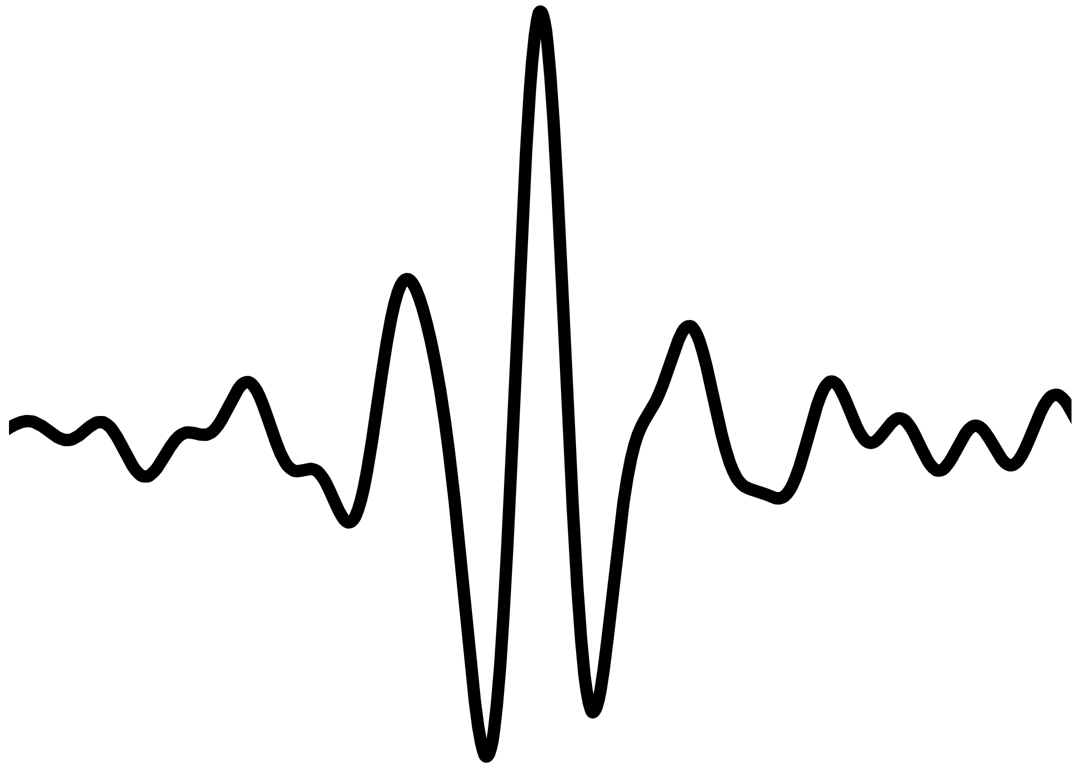

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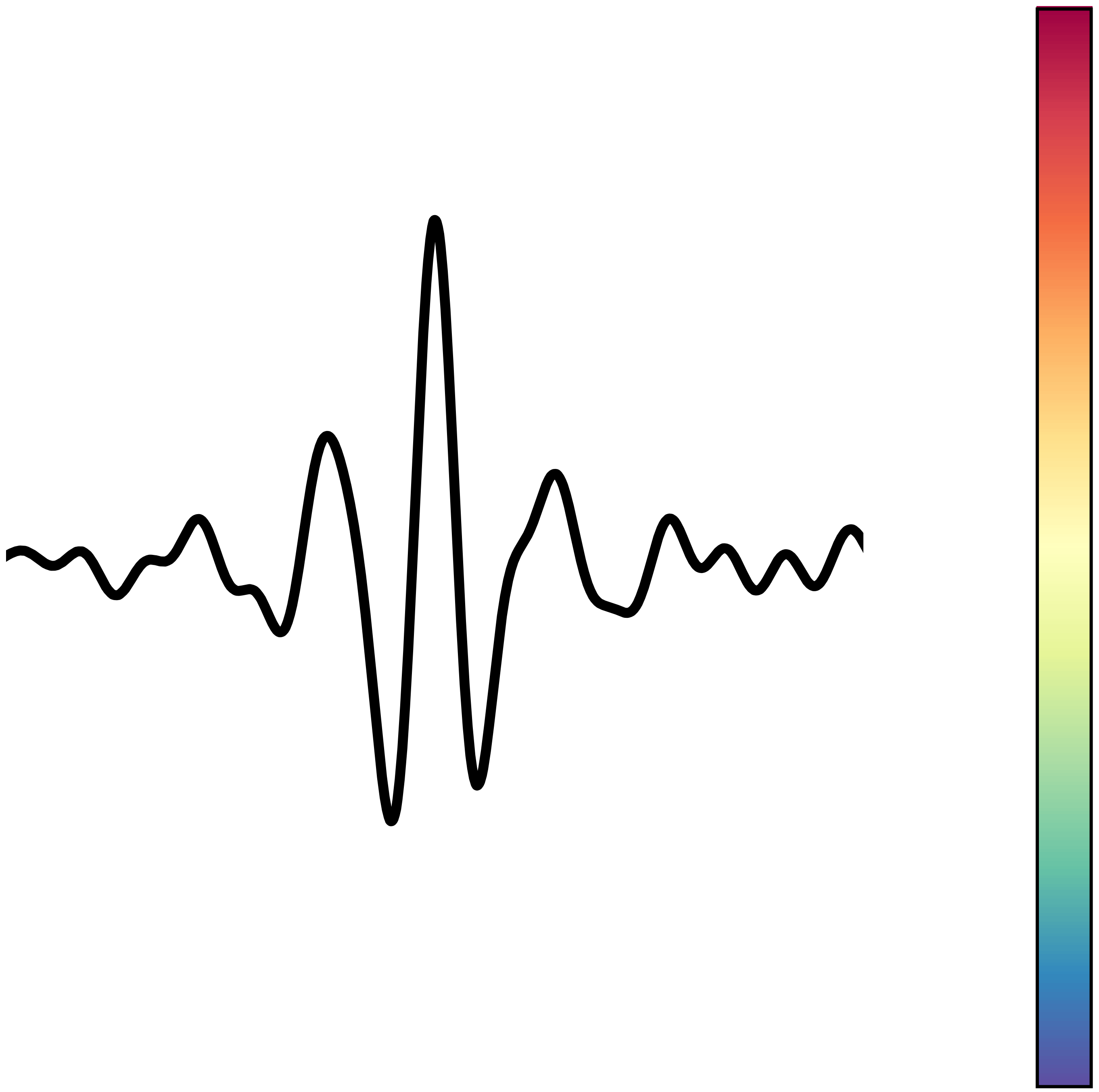

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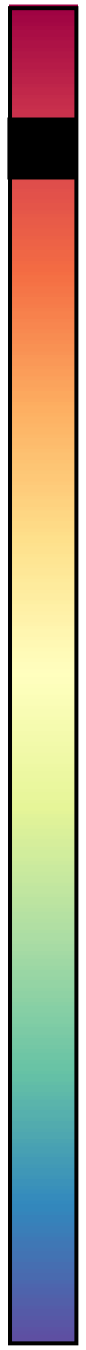
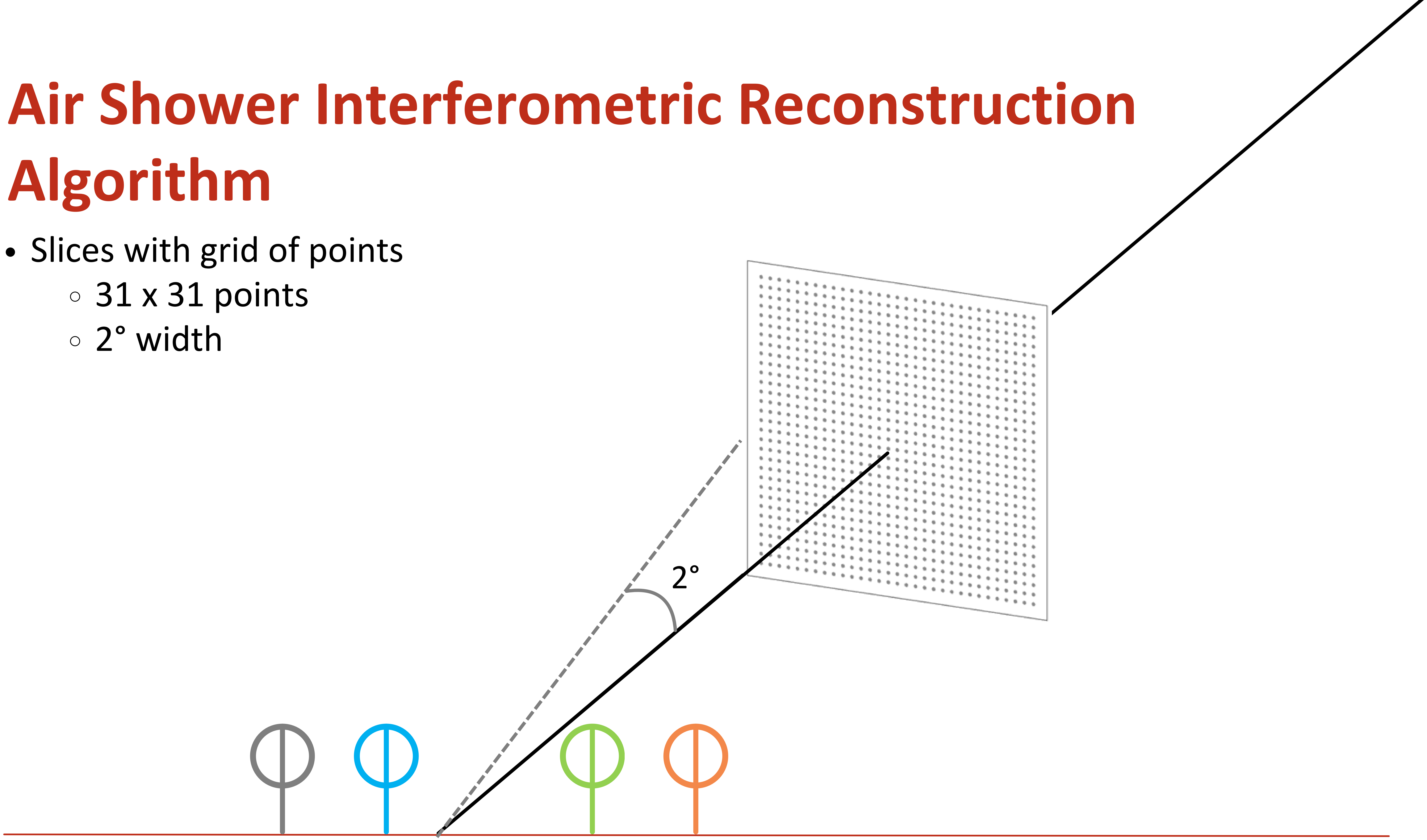


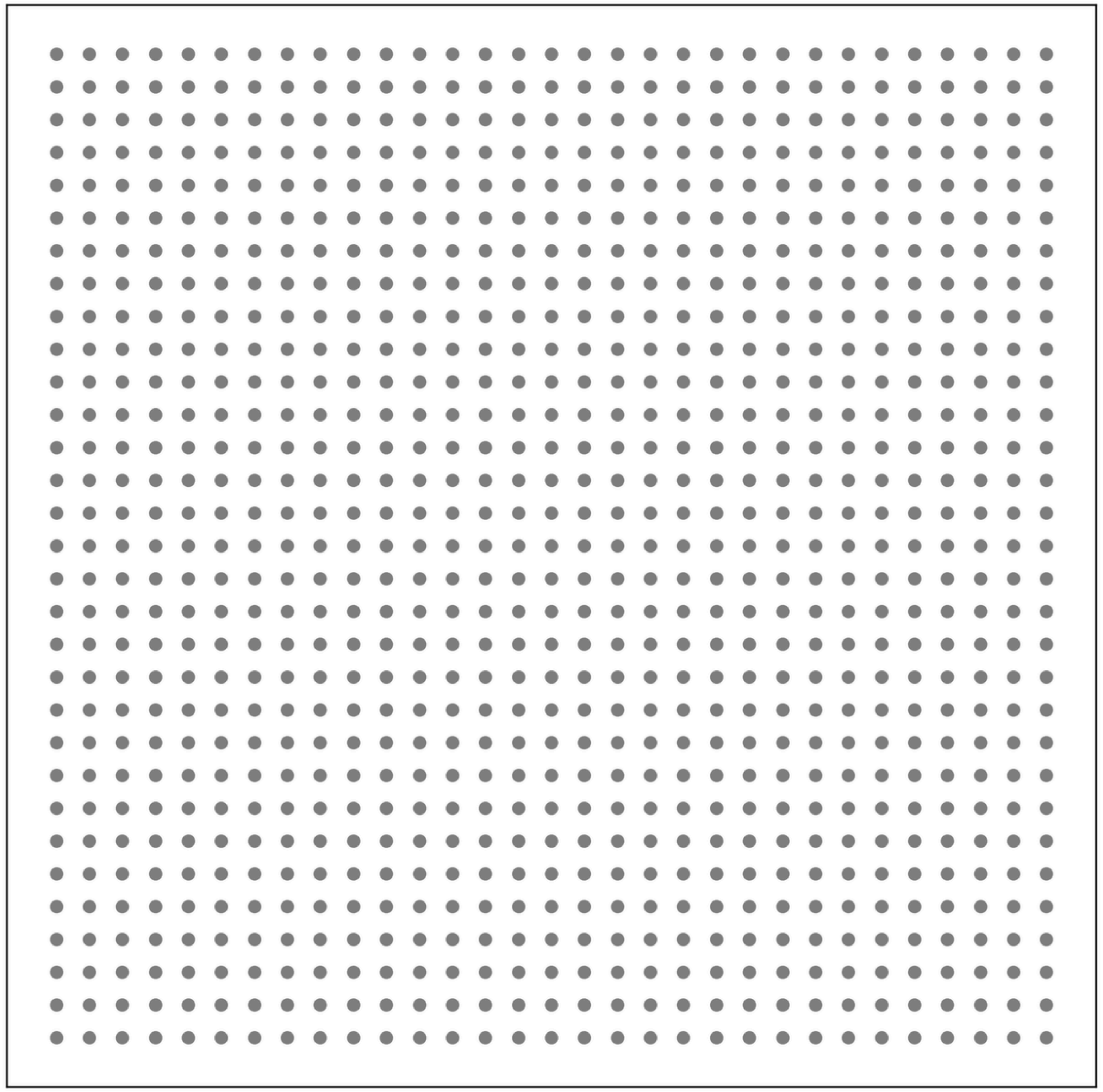
Air Shower Interferometric Reconstruction Algorithm

- Slices with grid of points
  - 31 x 31 points
  - 2° width



Air Shower Interferometric Reconstruction Algorithm

- Determine intensity for every point



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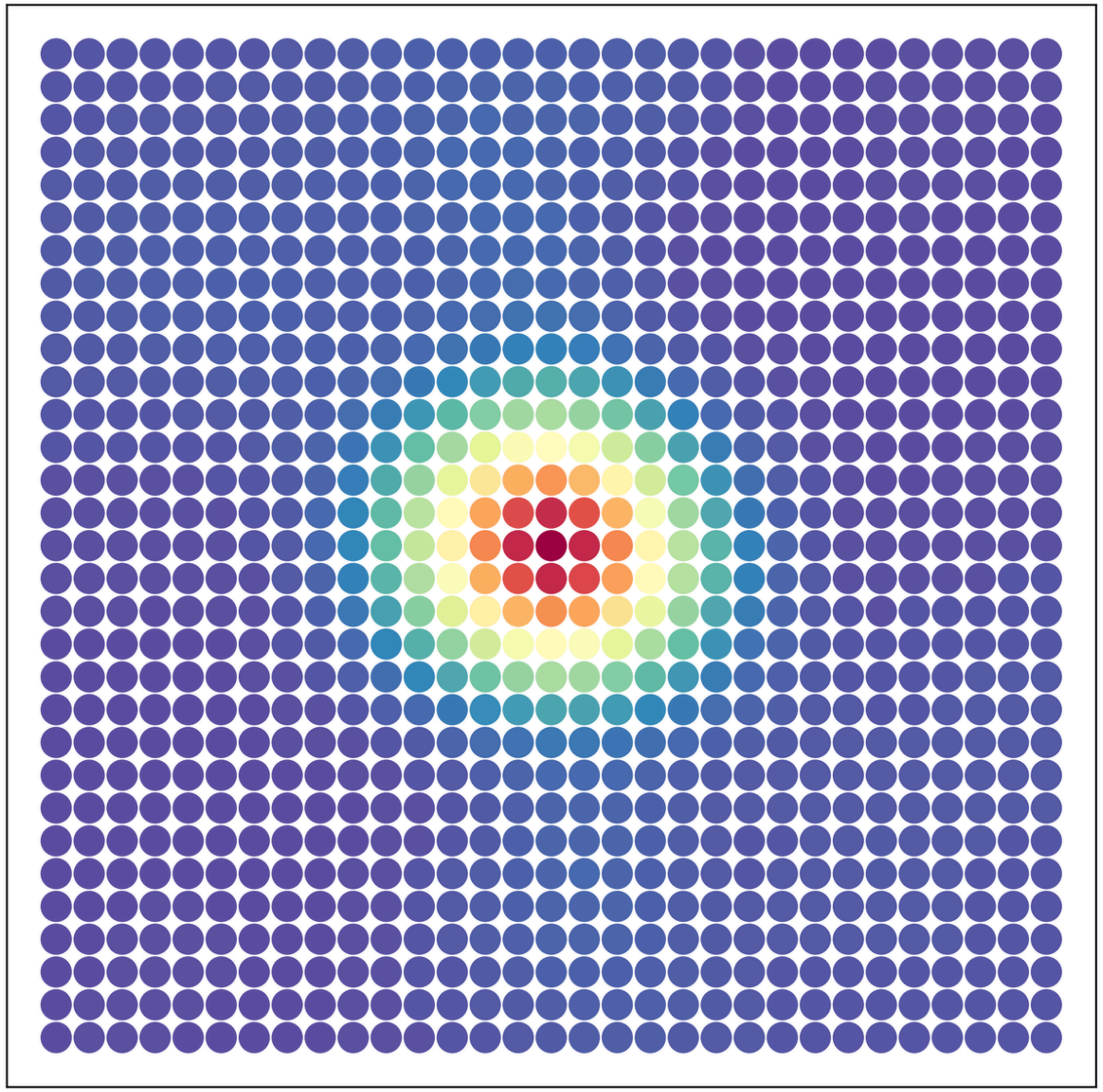
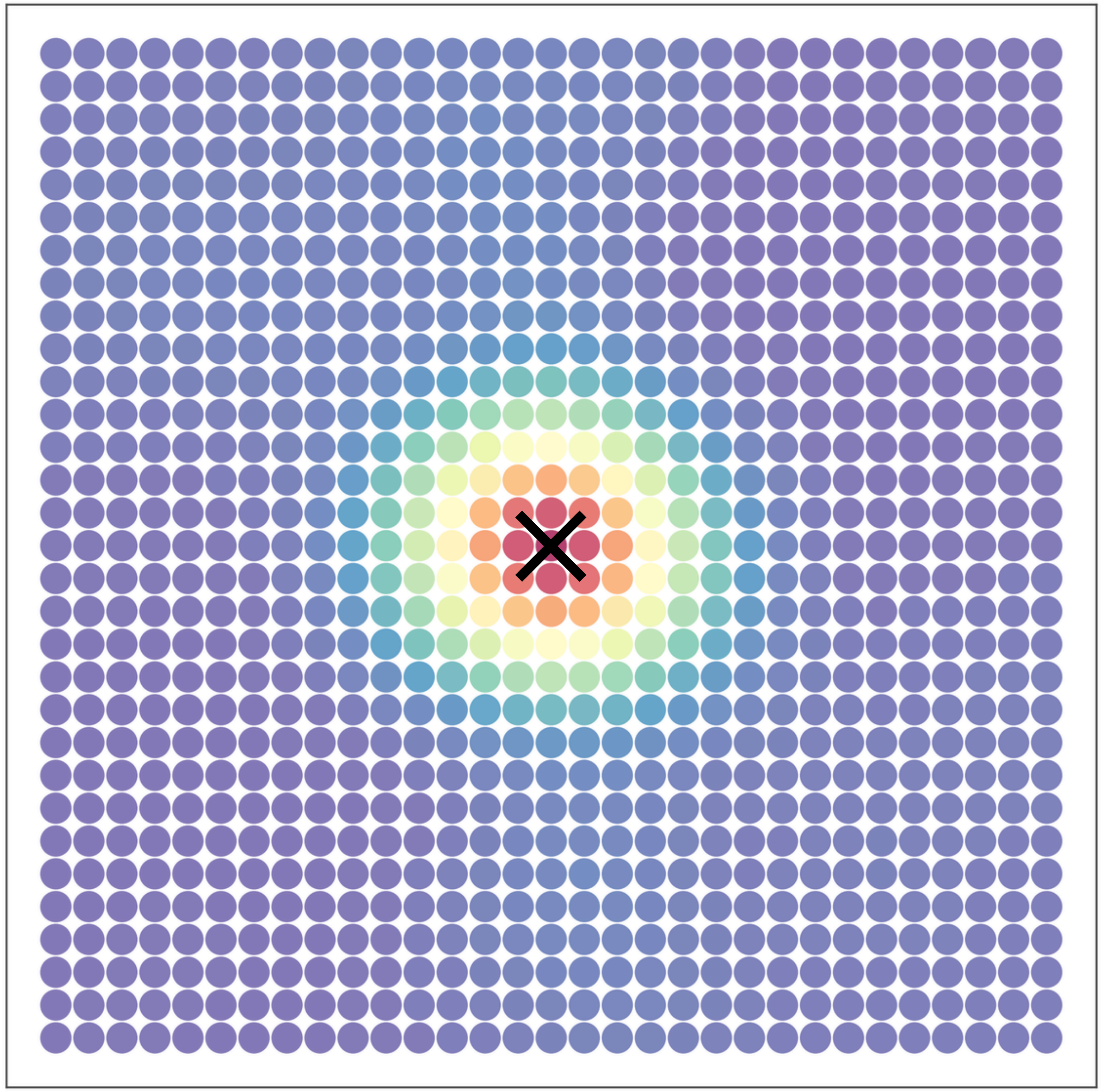


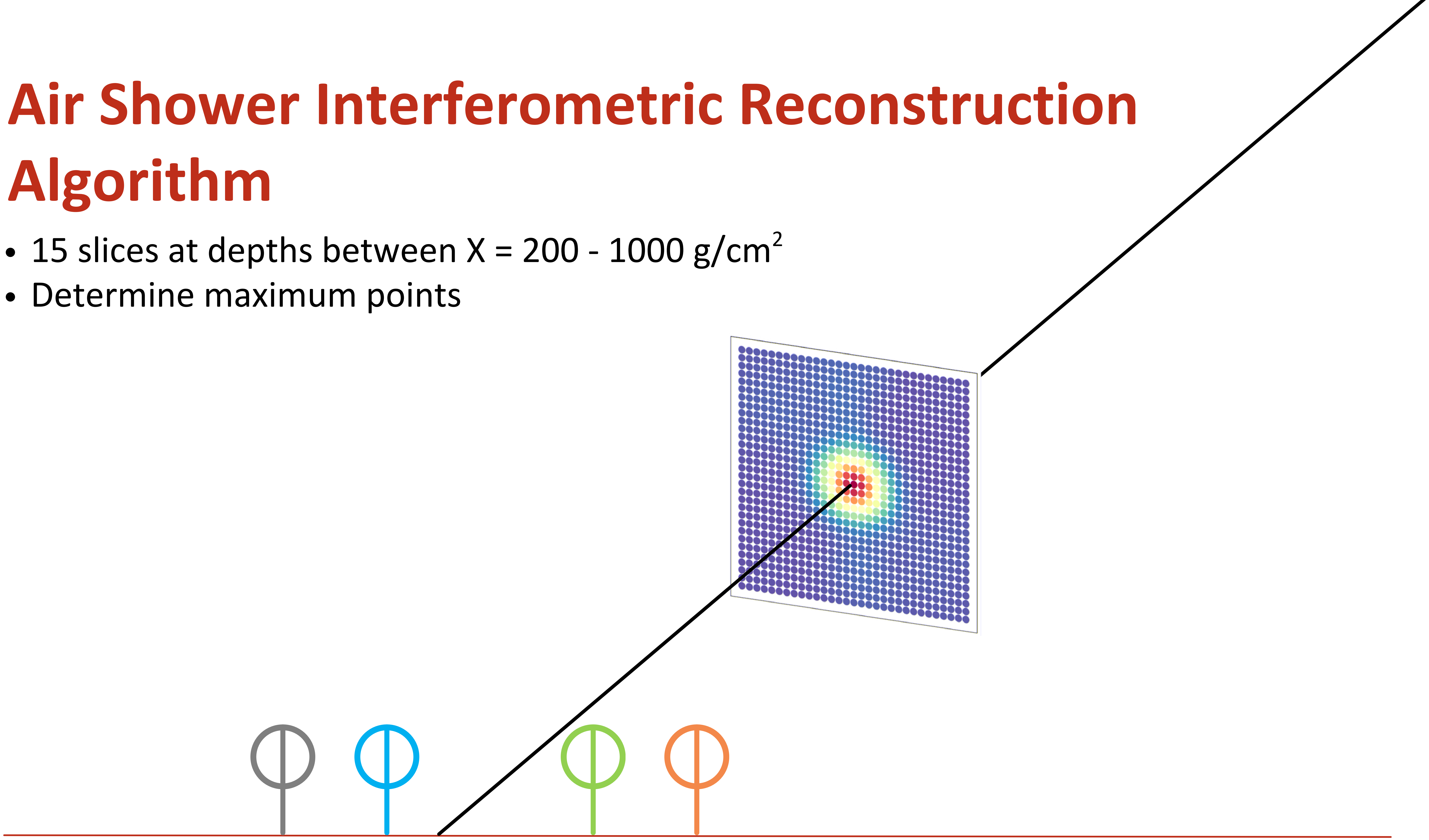
Air Shower Interferometric Reconstruction Algorithm

- Determine intensity for every point
- Locate maximum



Air Shower Interferometric Reconstruction Algorithm

- 15 slices at depths between X = 200 - 1000 g/cm^2
- Determine maximum points



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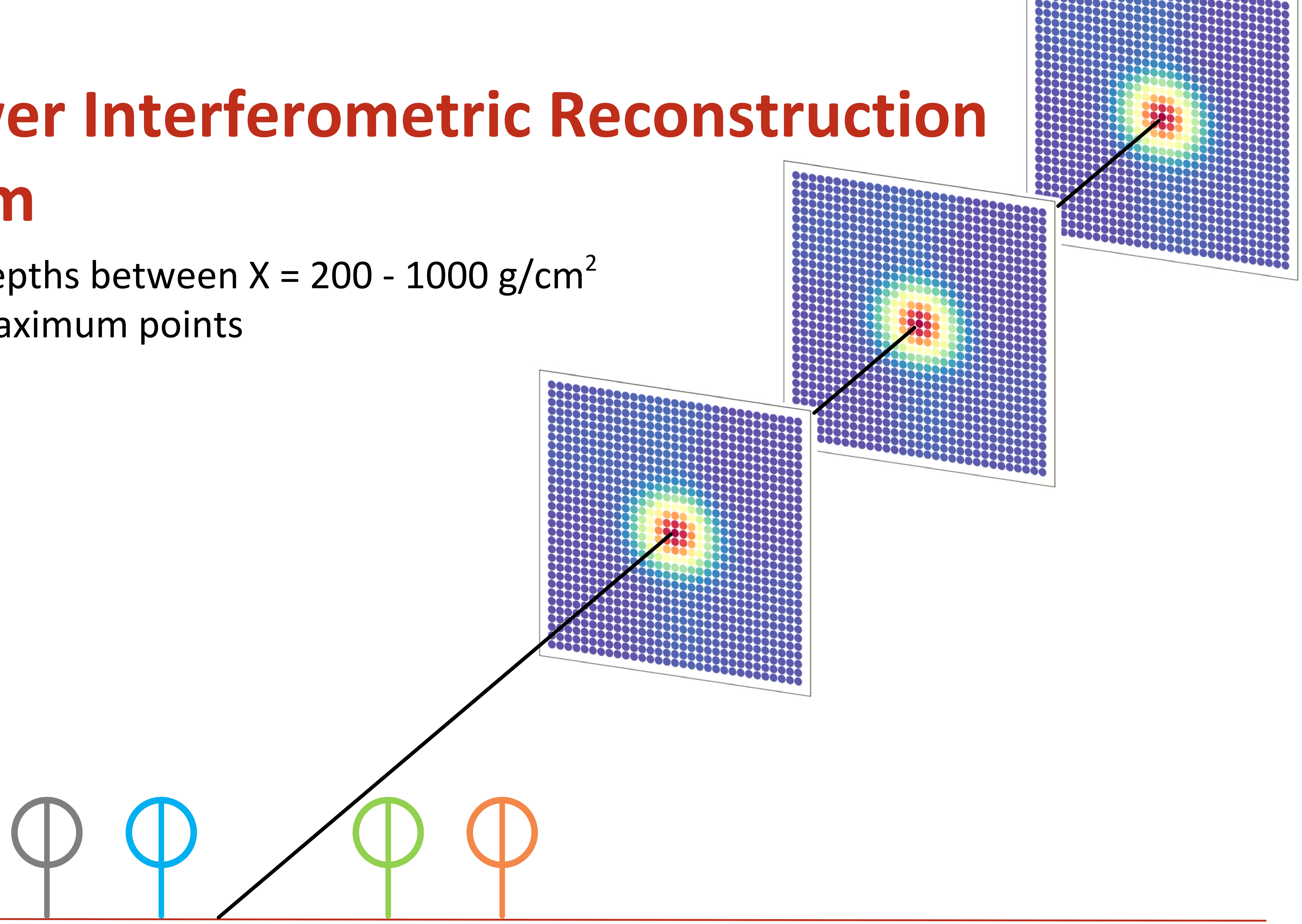

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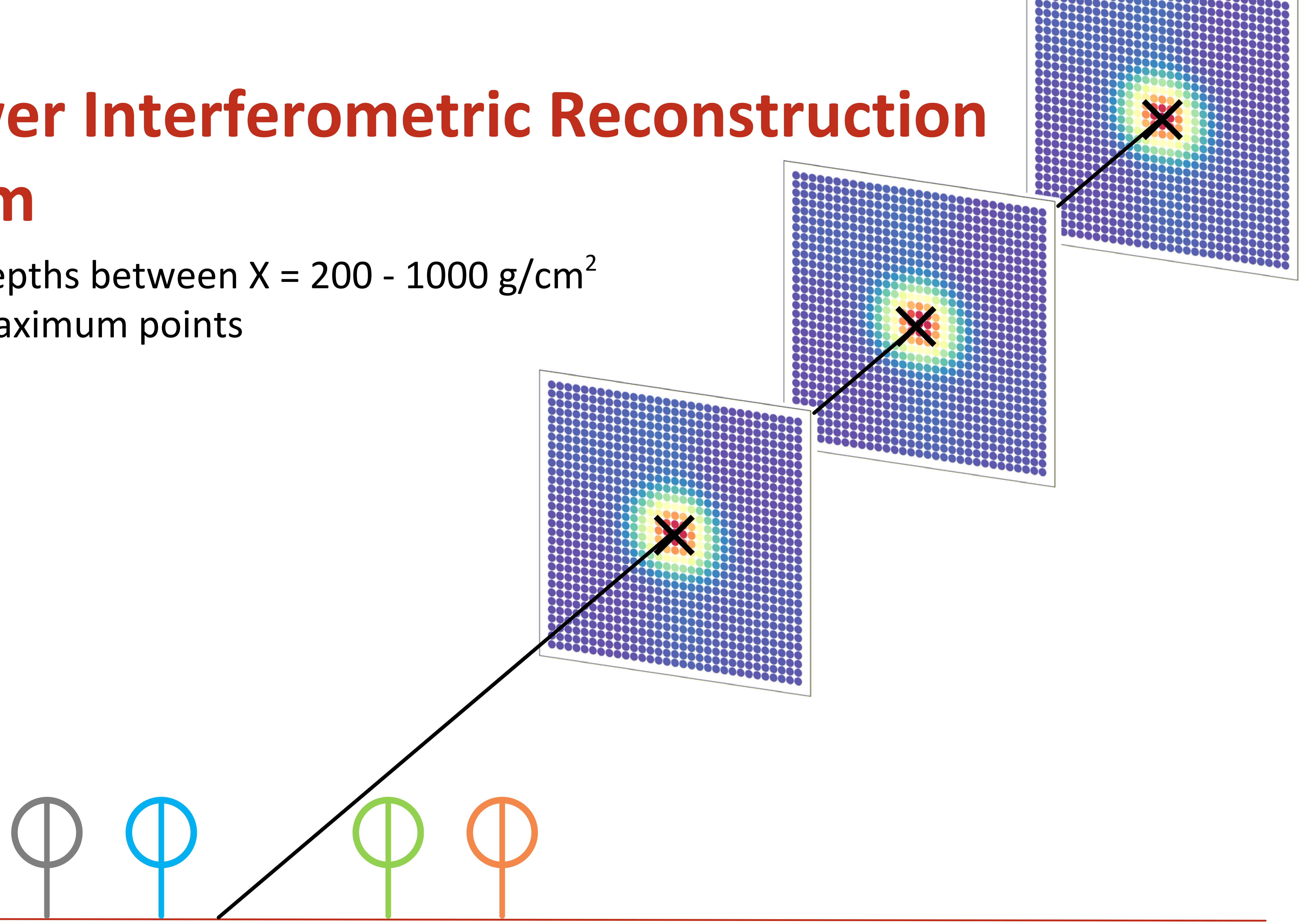
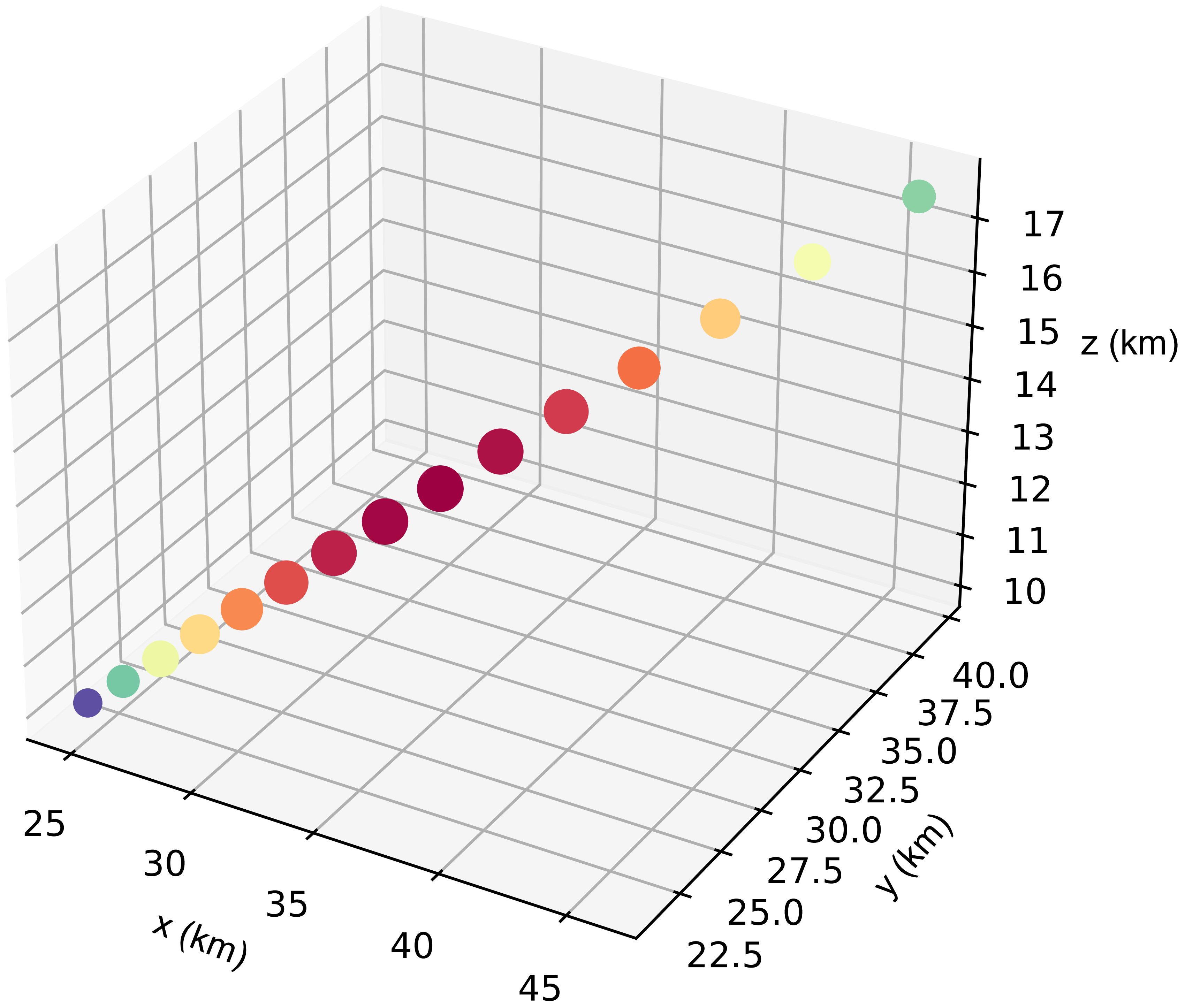


Air Shower Interferometric Reconstruction Algorithm

- Fit axis through points
- Free parameters:
  - Zenith angle
  - Azimuth angle
  - Core position (x,y)



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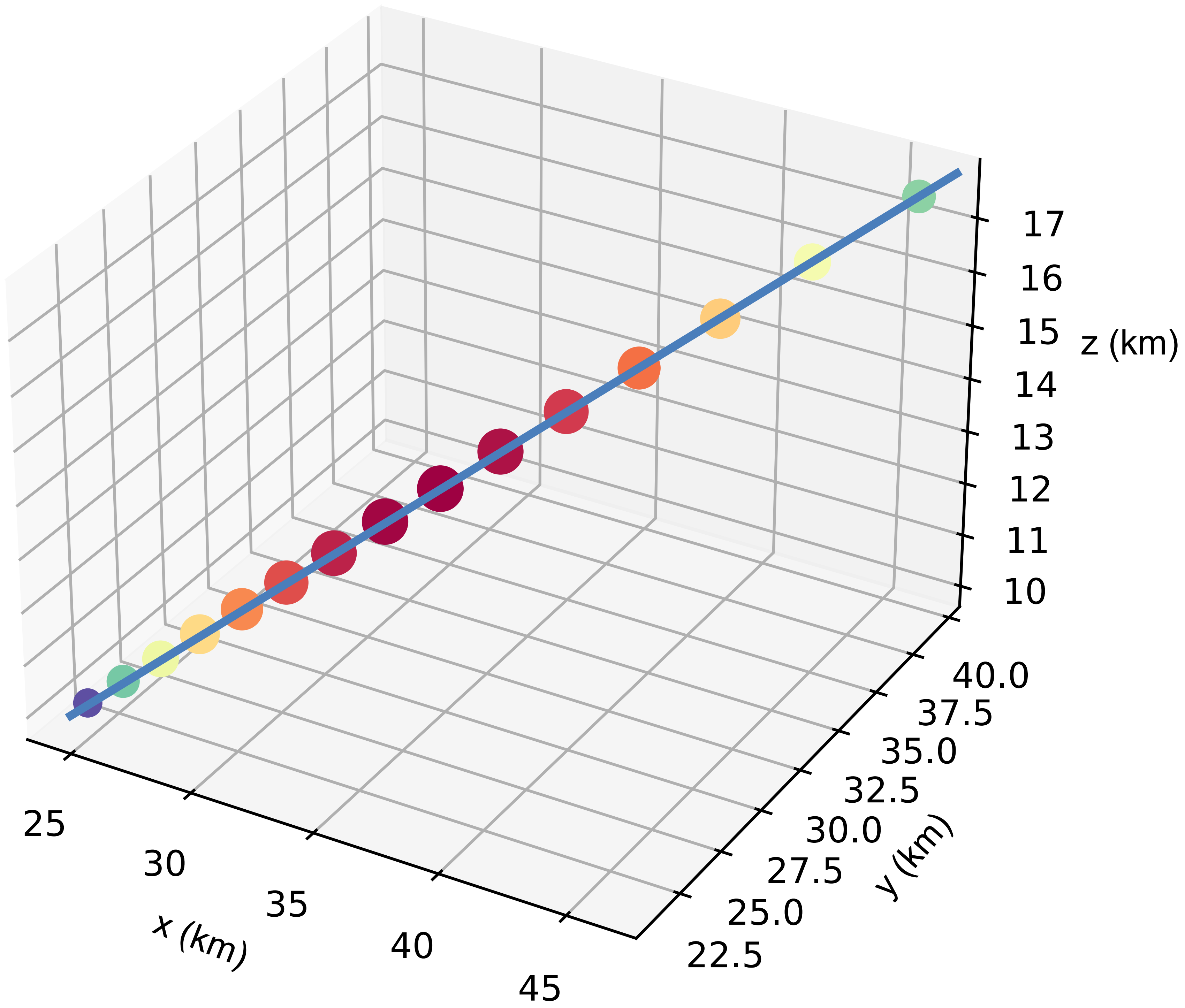
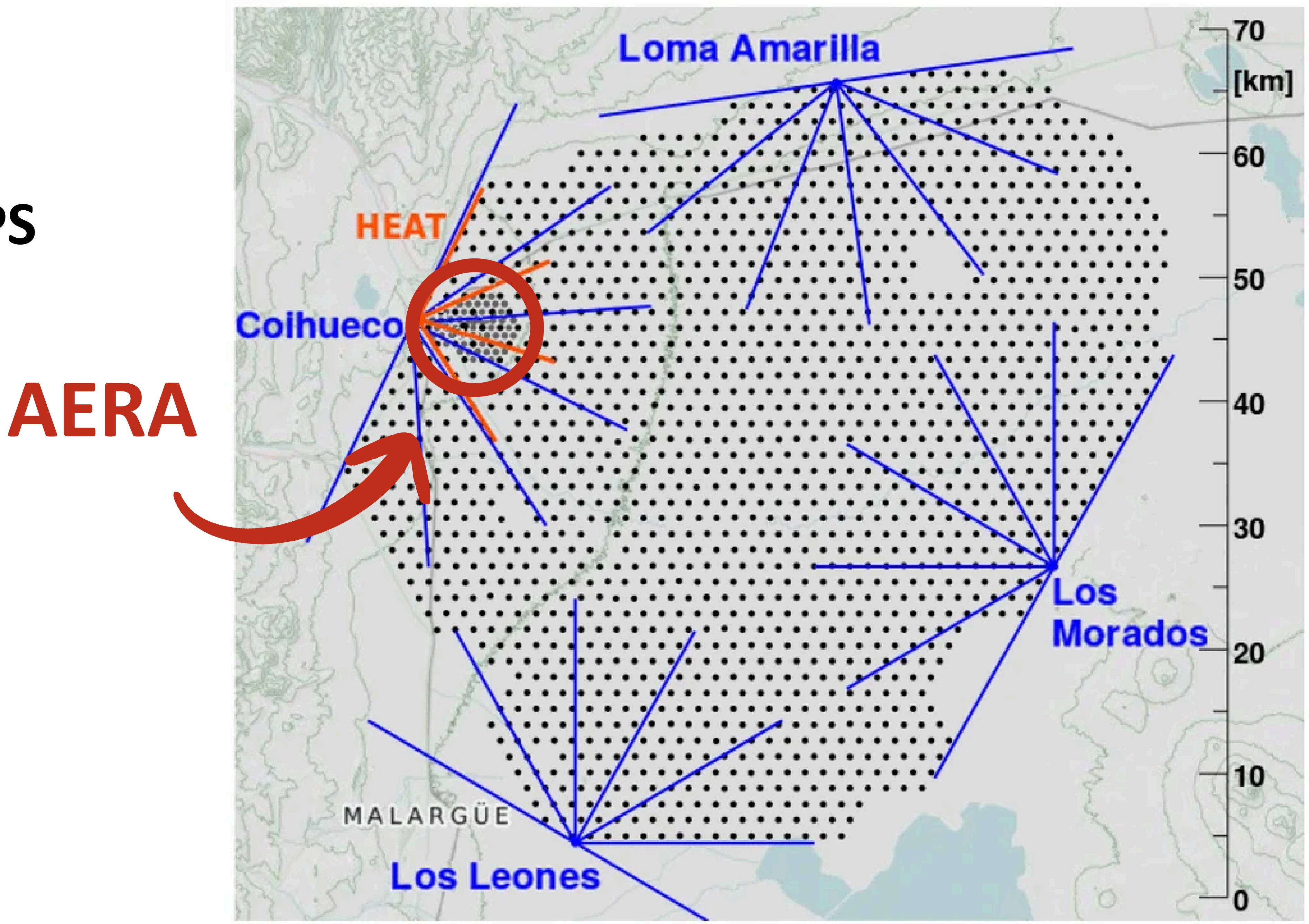


Auger Engineering Radio Array (AERA)

- Apply to measured data with the Auger Engineering Radio Array
- Triggers on Surface Detector
- **1 ns** timing accuracy:
  - Clock synchronisation: **Beacon**
  - Positional accuracy: **Differential GPS**



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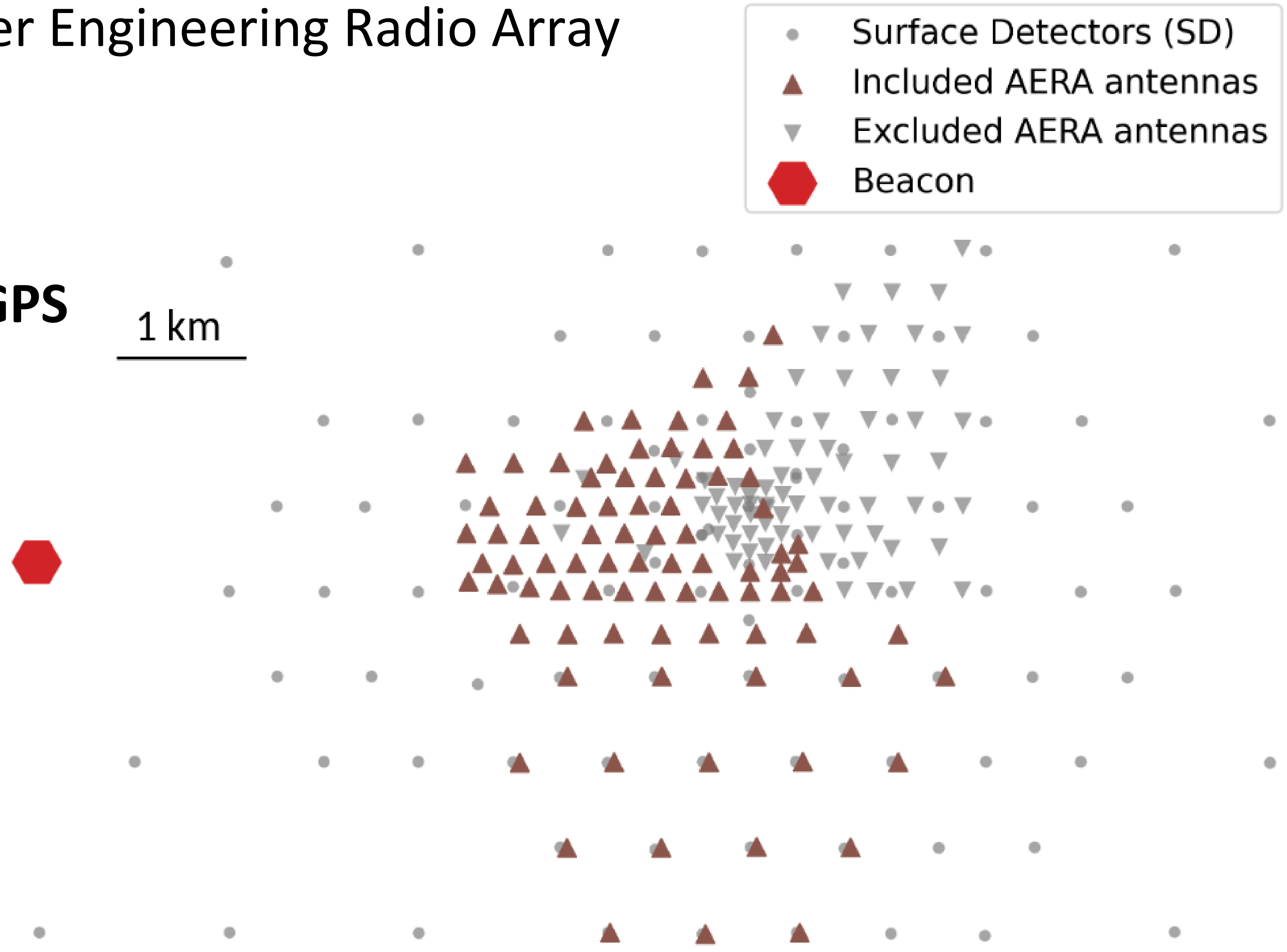

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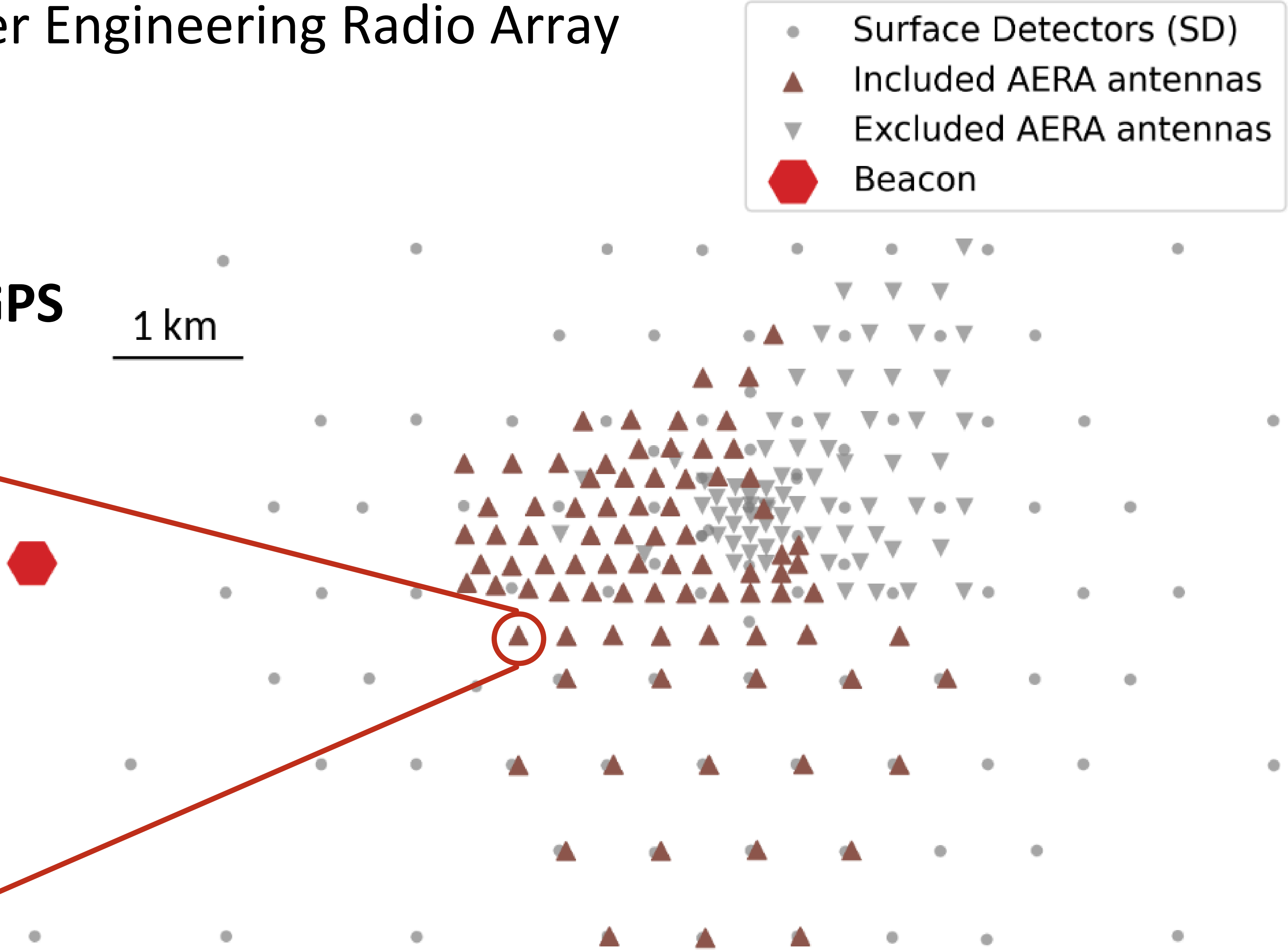
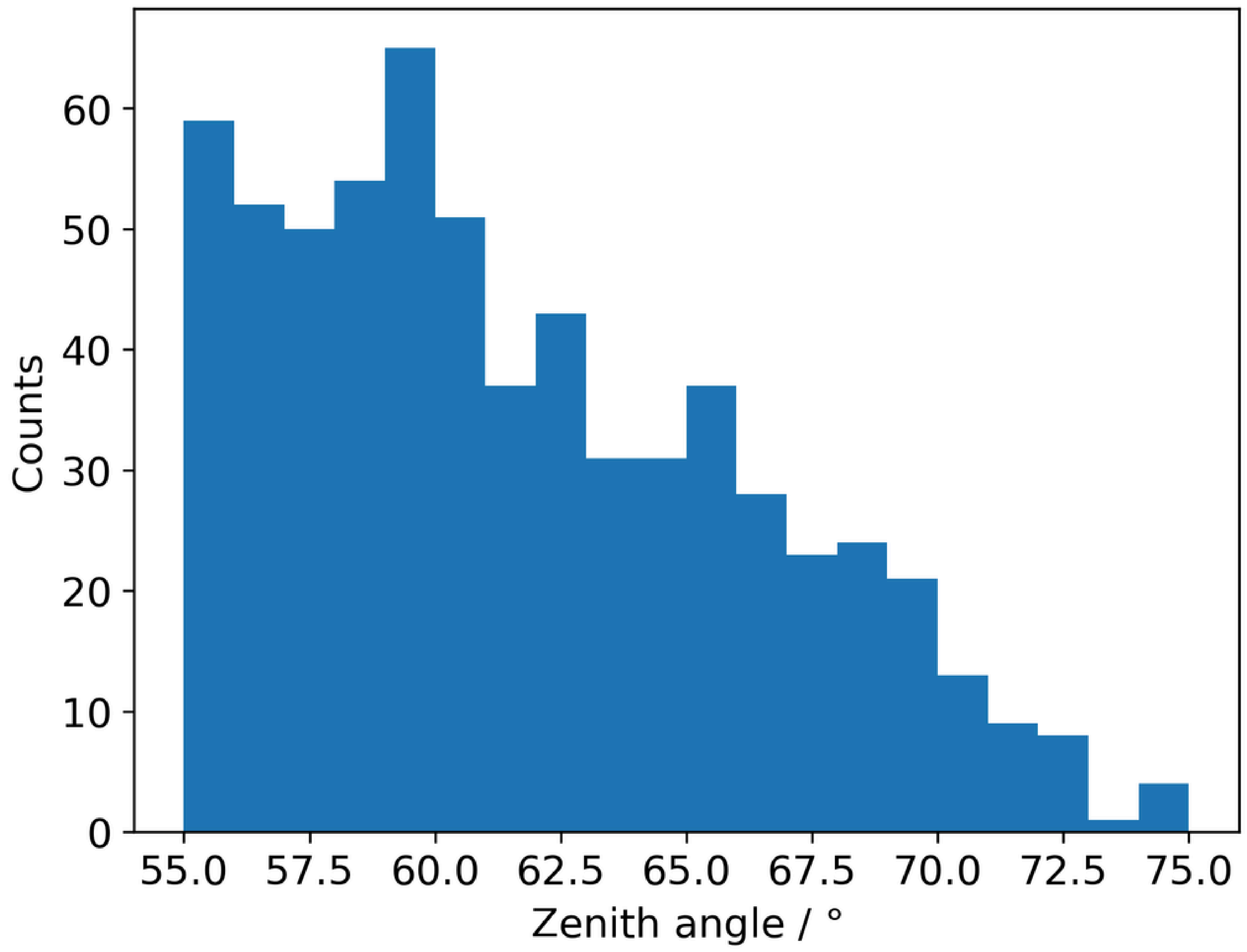


https://api.semanticscholar.org/CorpusID:166218997

AERA dataset

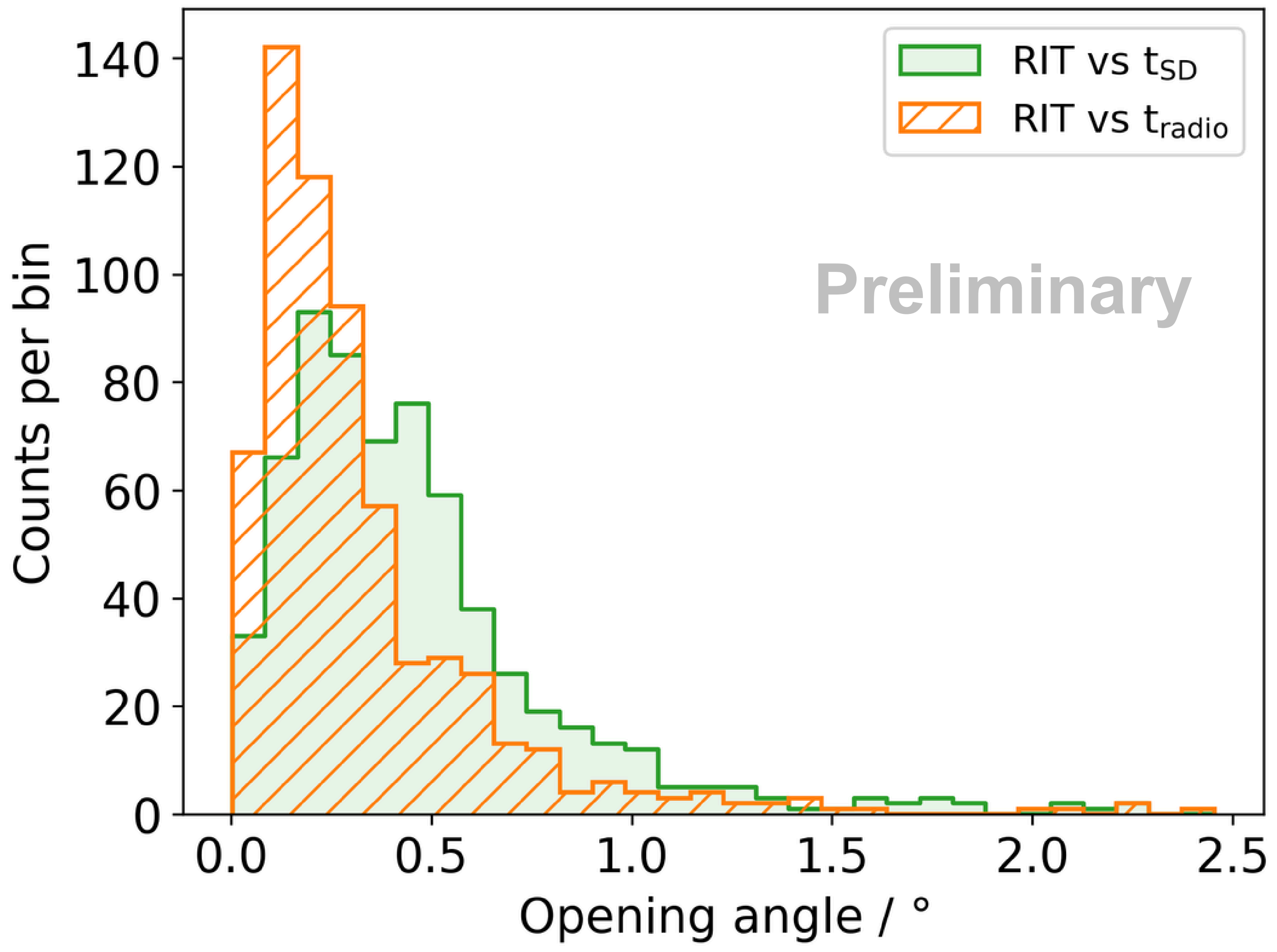
- Inclined air showers
- Measured with surface detector as well as AERA
- 4847 events without thunderstorm conditions
- After quality cuts:
    - 641 events
    - Biggest cut (85%): containment of footprint
    - *See backup for other cuts*

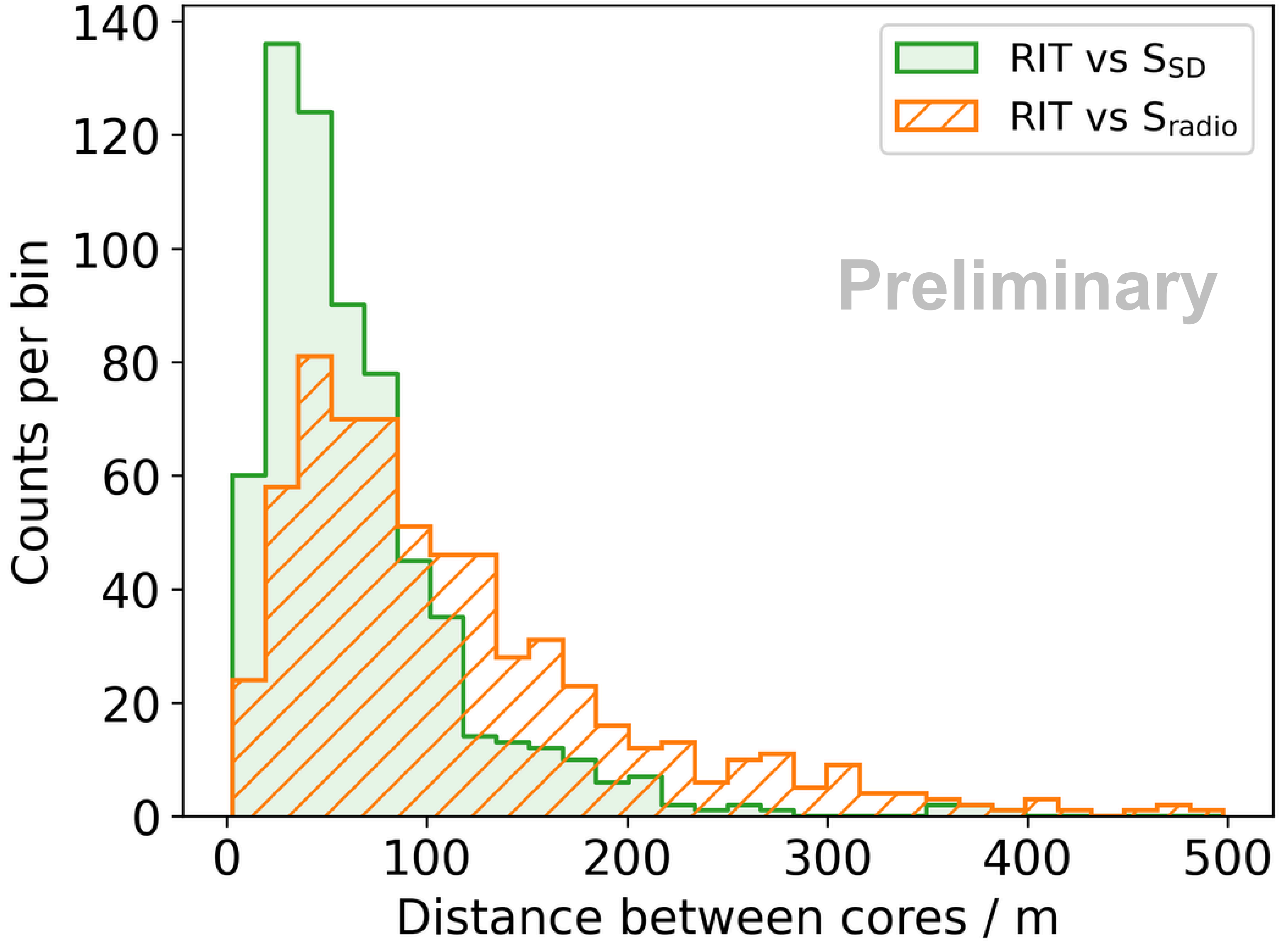


Dataset created by Marvin Gottowik & Felix Rhien

Results – Data

- Correct for interferometric bias (*see backup*)
- Comparable with surface detector and conventional radio reconstructions



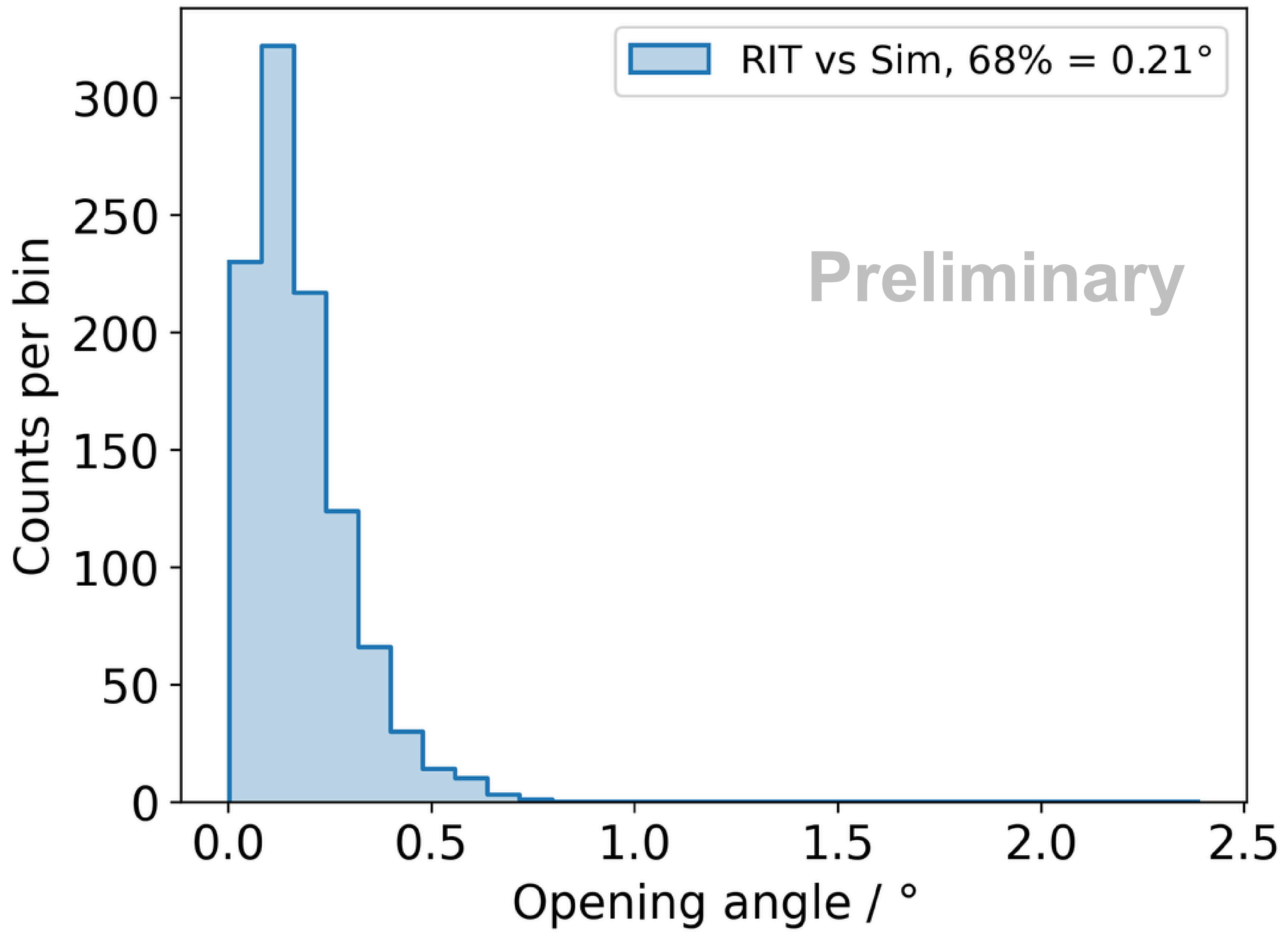


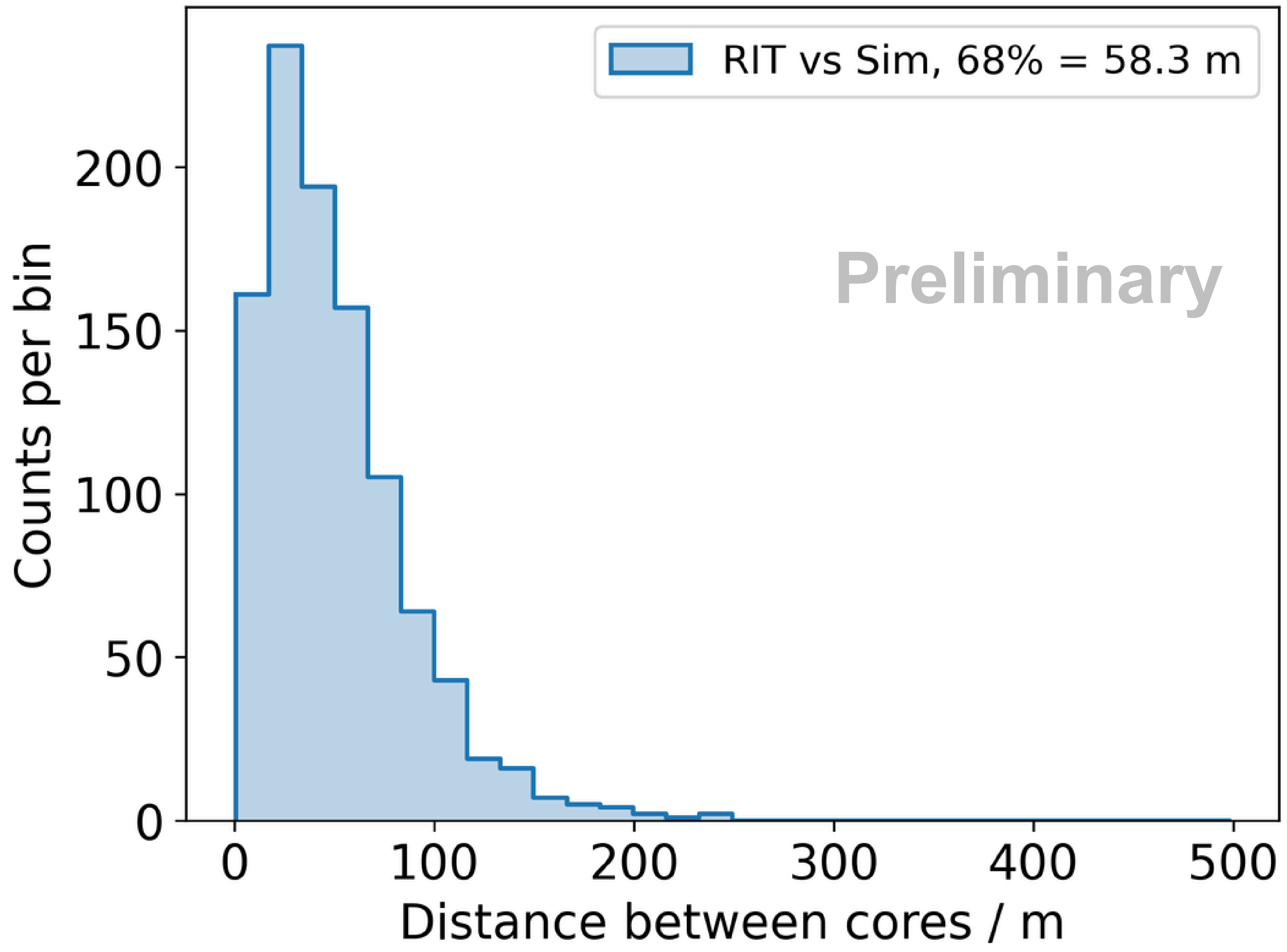
Results – Simulations

- Correct for interferometric bias (*see backup*)
- Reconstruction on simulations close to Monte-Carlo truth

Simulation set
- *Core*: Randomly distributed
- *Particles*: H, He, N, Fe
- *Azimuth*: Uniform
- *Zenith*: 55 - 85° ($\sin^2\theta$)
- *Energy*: $10^{17.2}$ - 10^{19} eV (E^{-1})

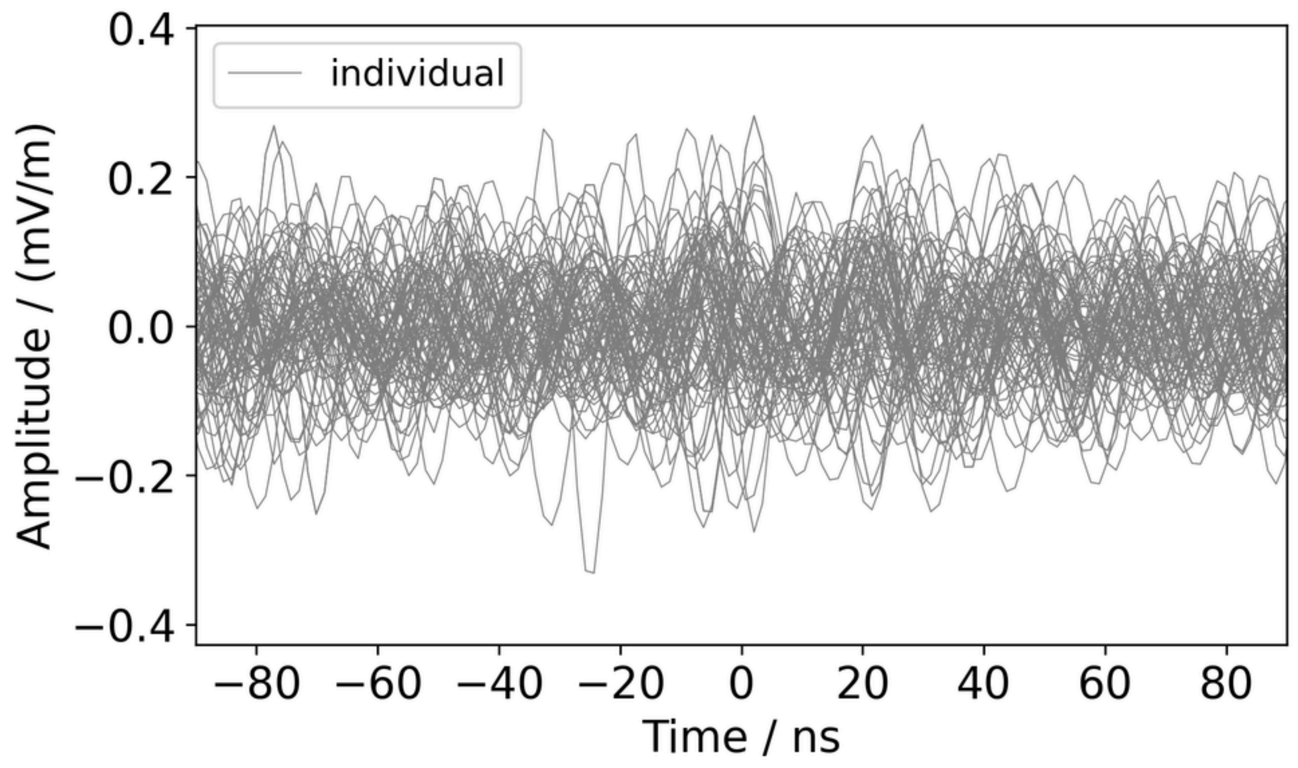
Same antenna selection as for data set
Same quality cuts as for data set





Low energy application

- Use interferometry to ‘dig up’ the signal out of the noise
- New dataset: Very inclined events with a lot of antennas
- Selection for RIT:
    - **SNR > 7 (max/std) of the summed waveform**



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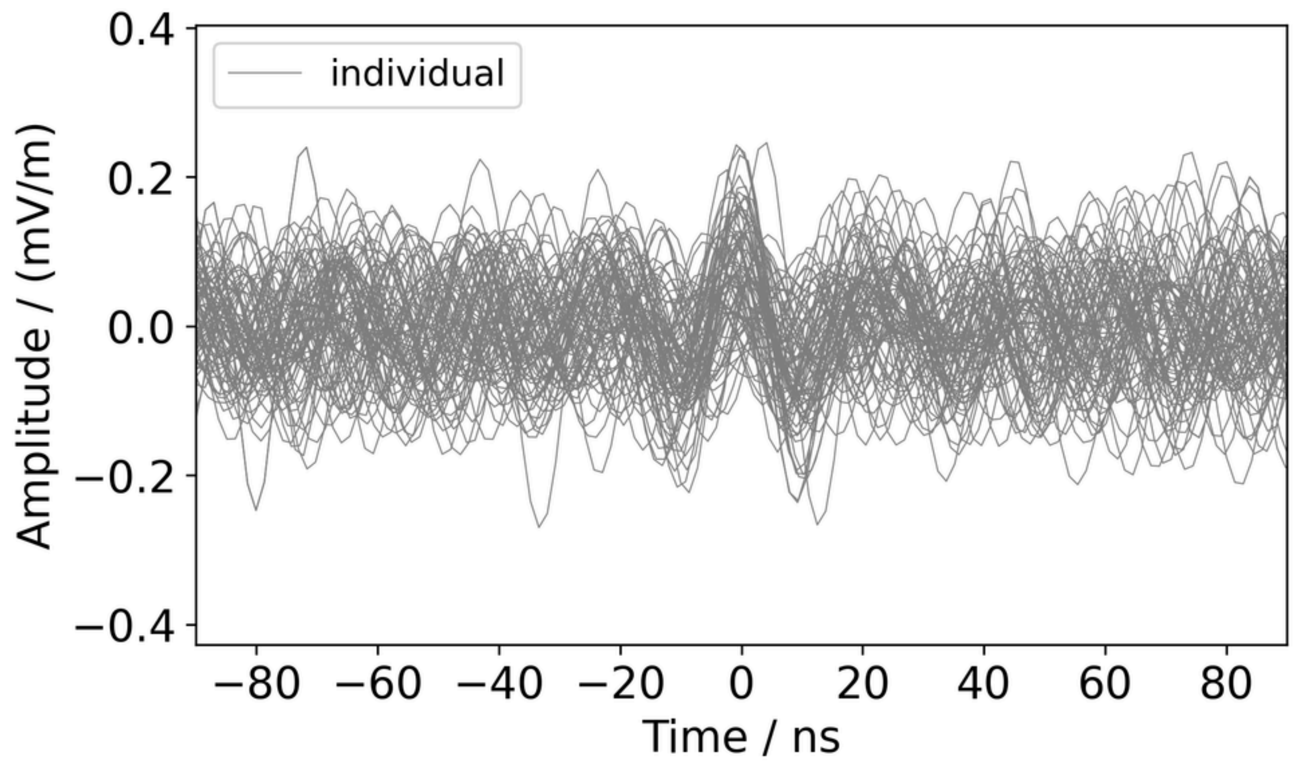

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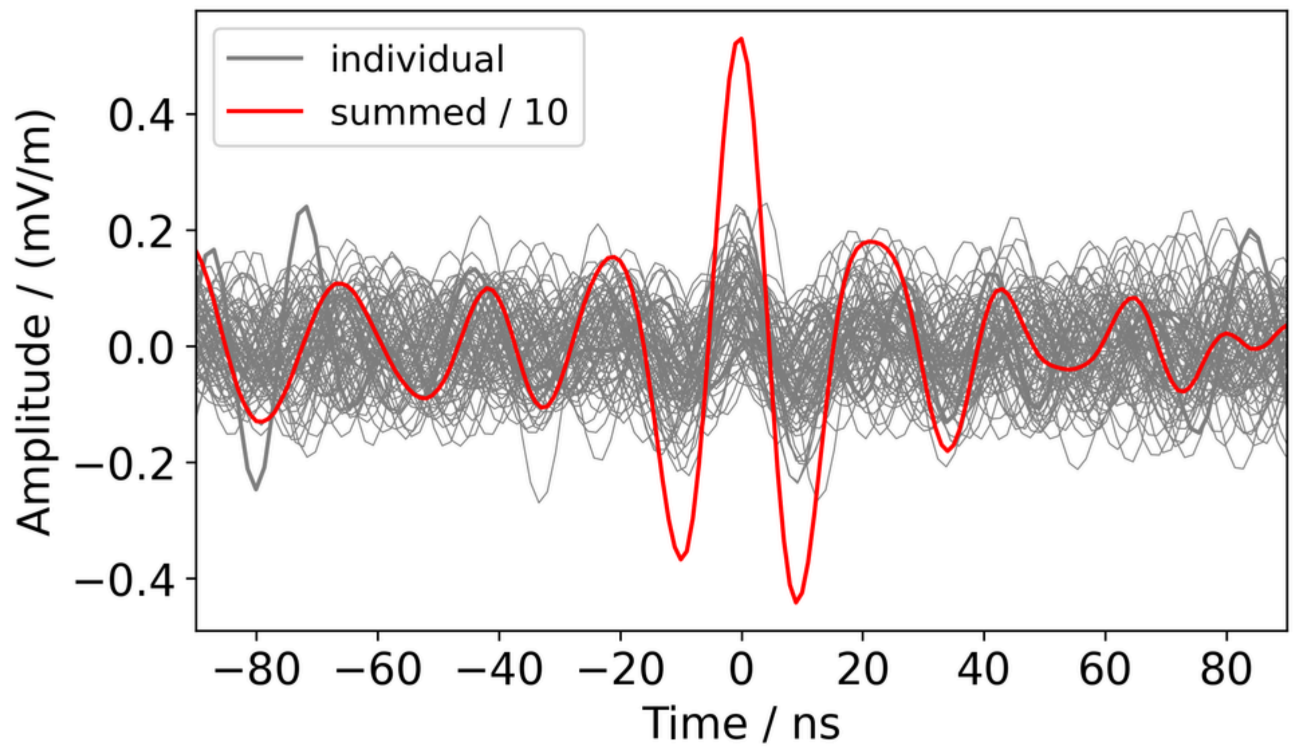

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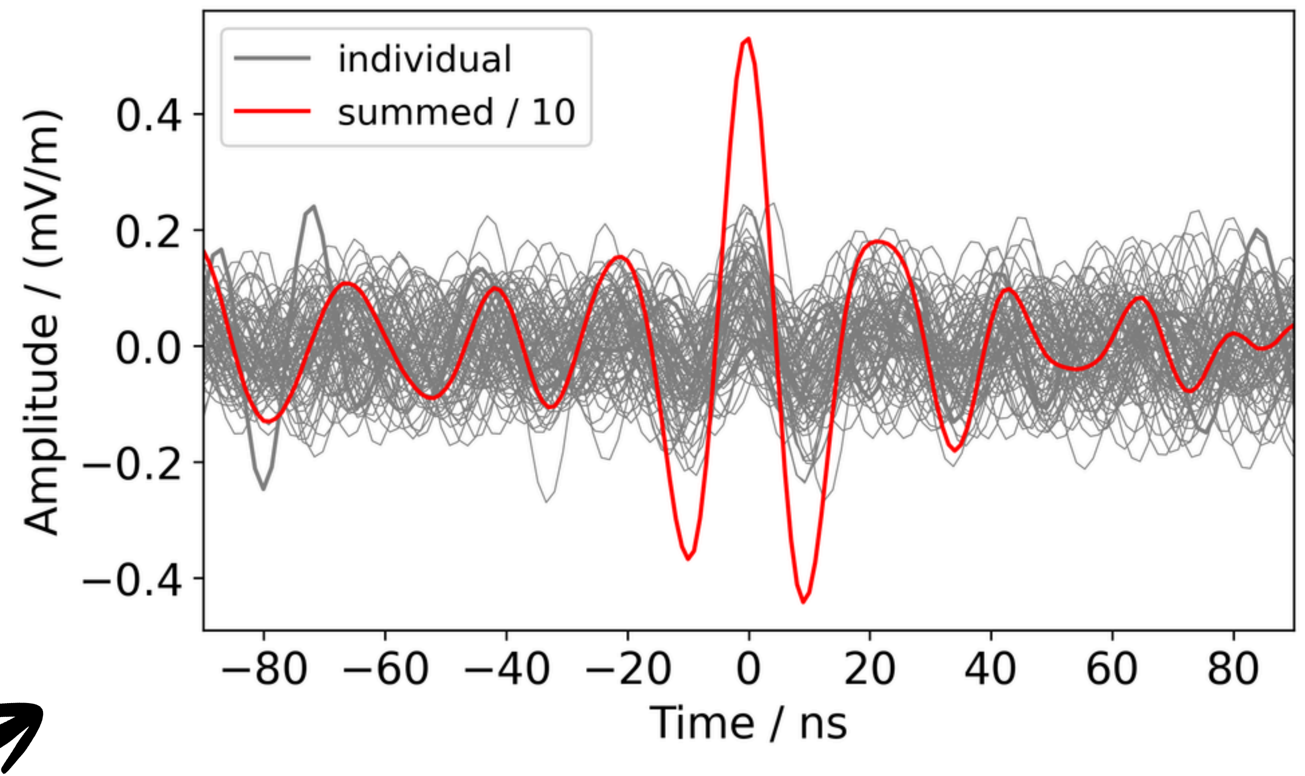
Events: 194
- RD reco: 17
- RIT reco: 57

Data



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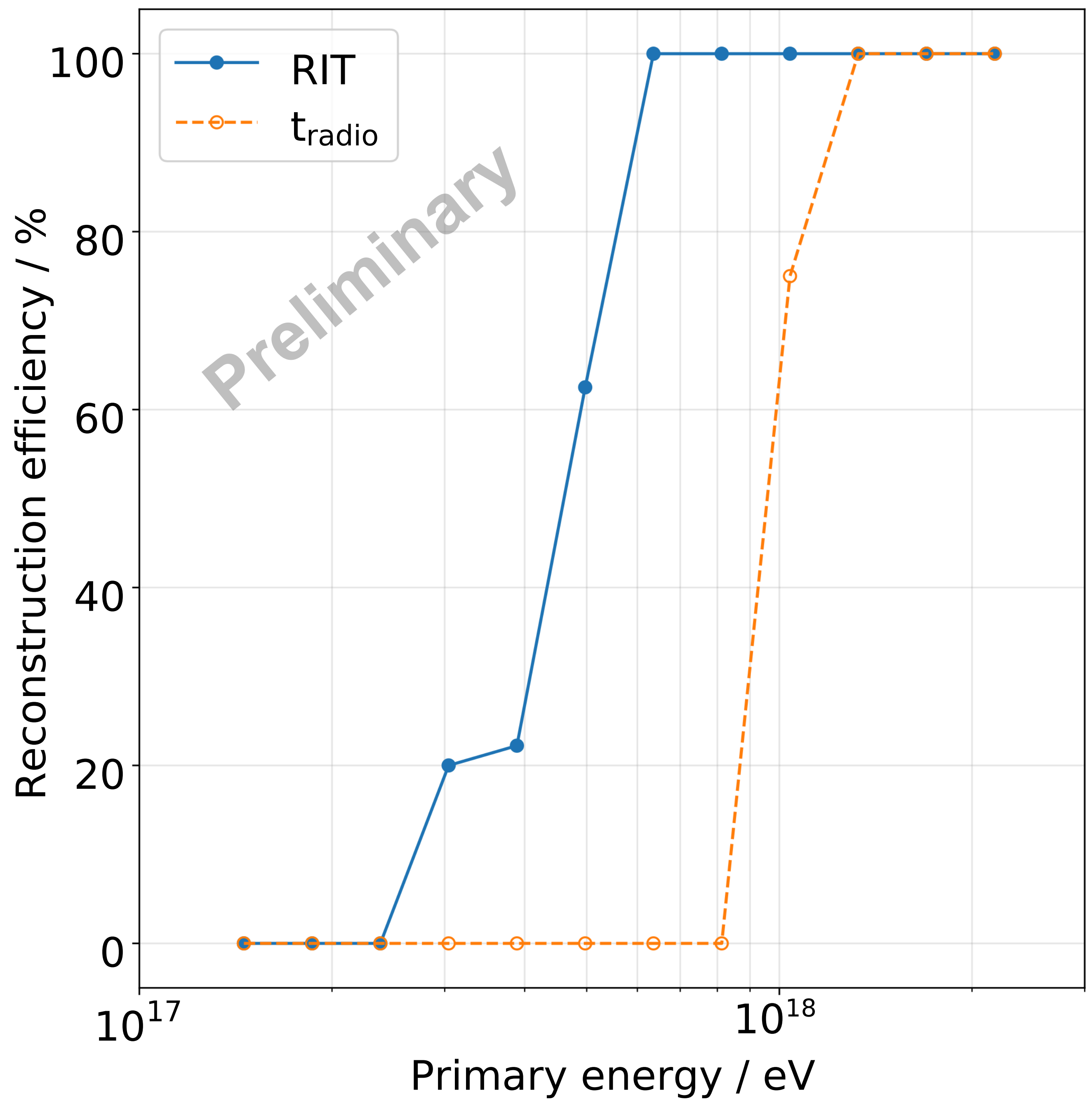

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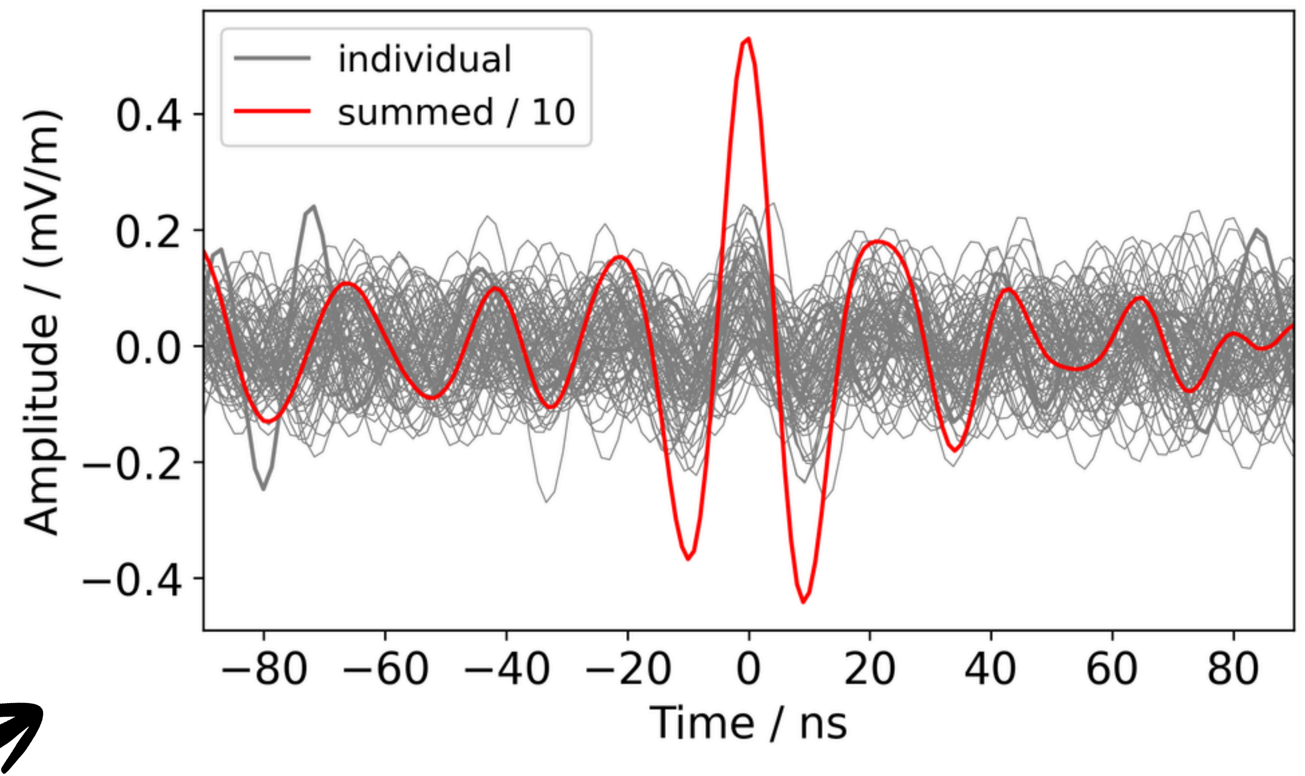
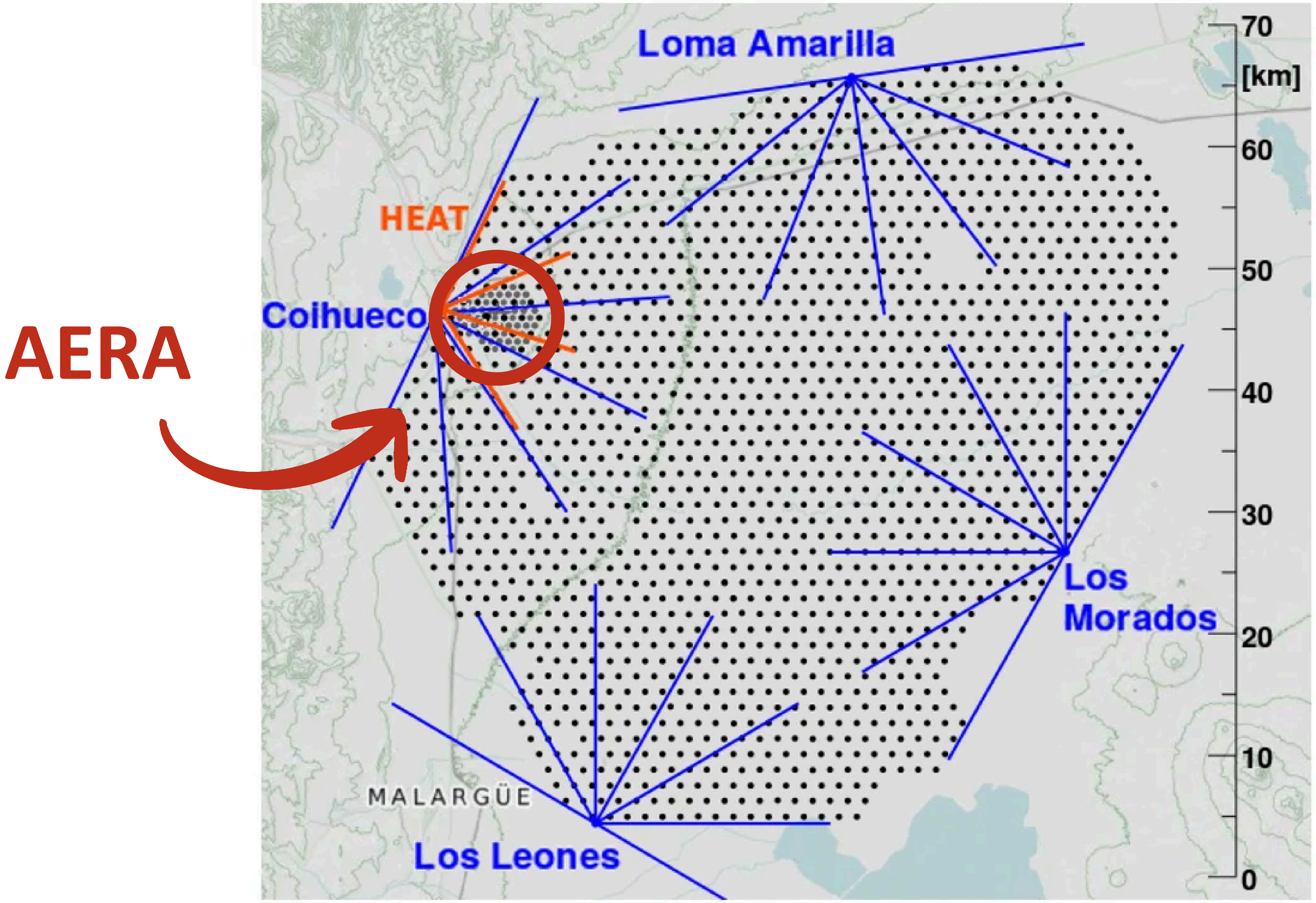


Interferometry with AugerPrime

- Next step: expand to the full 3000 km^2 array ($\sim$ 1660 detectors)
- Same **1 ns** accuracy needed:
    - Clock synchronisation
    - Positional accuracy (< 30 cm)



DOI:10.3390/universe10080327

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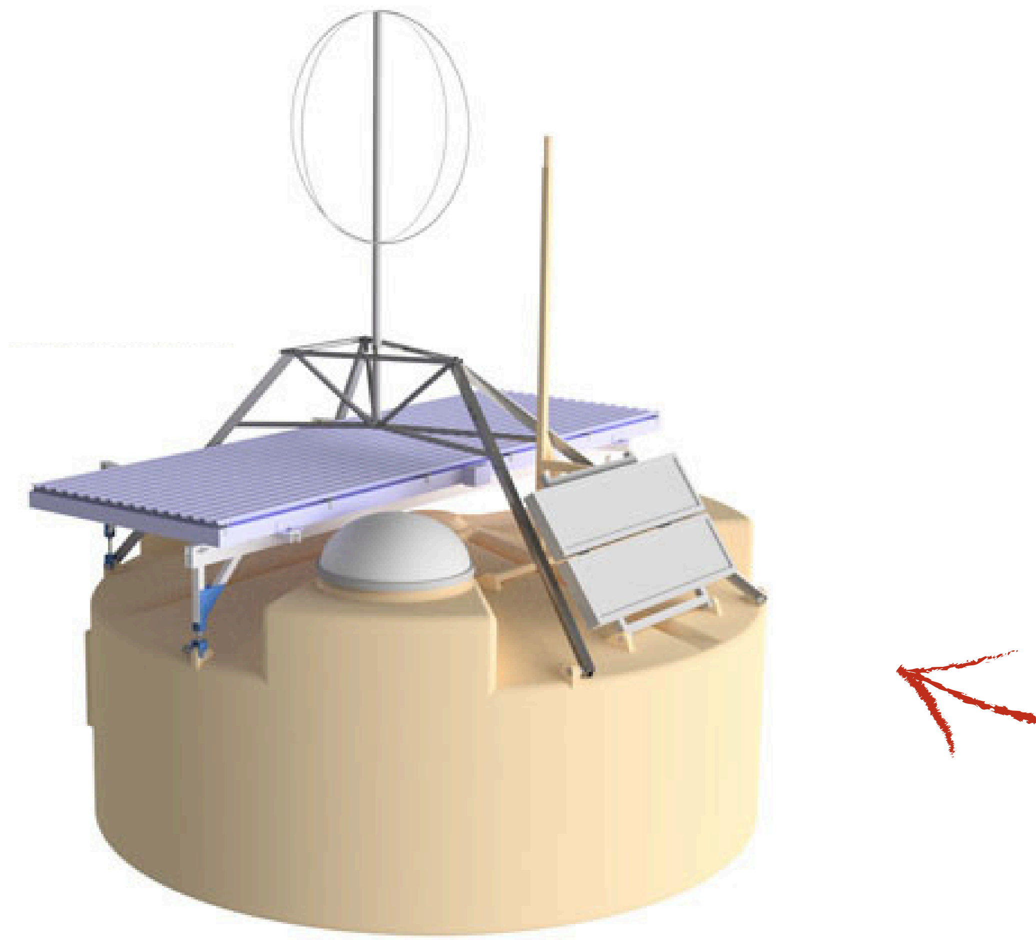
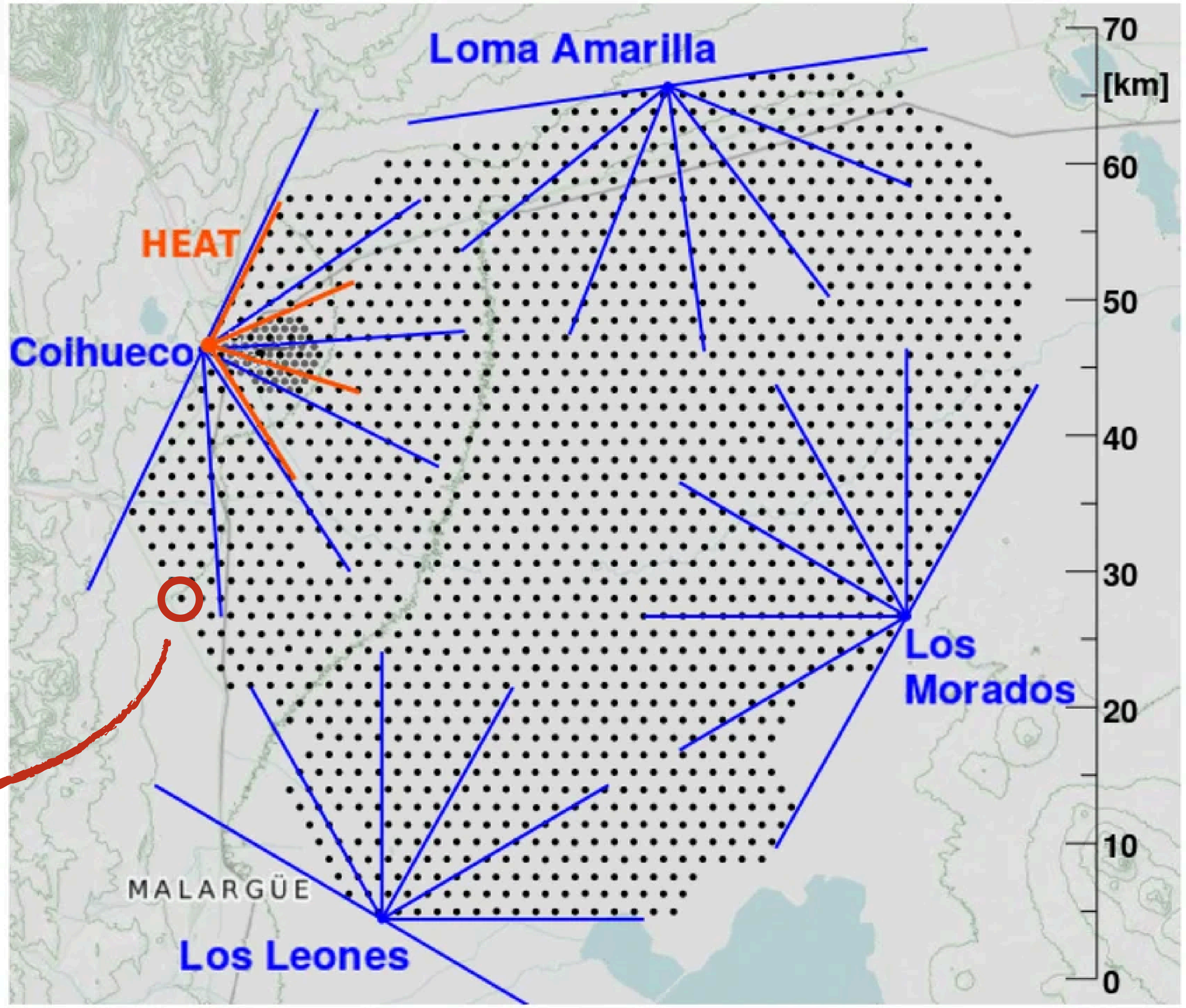


https://www.auger.org/observatory/augerprime



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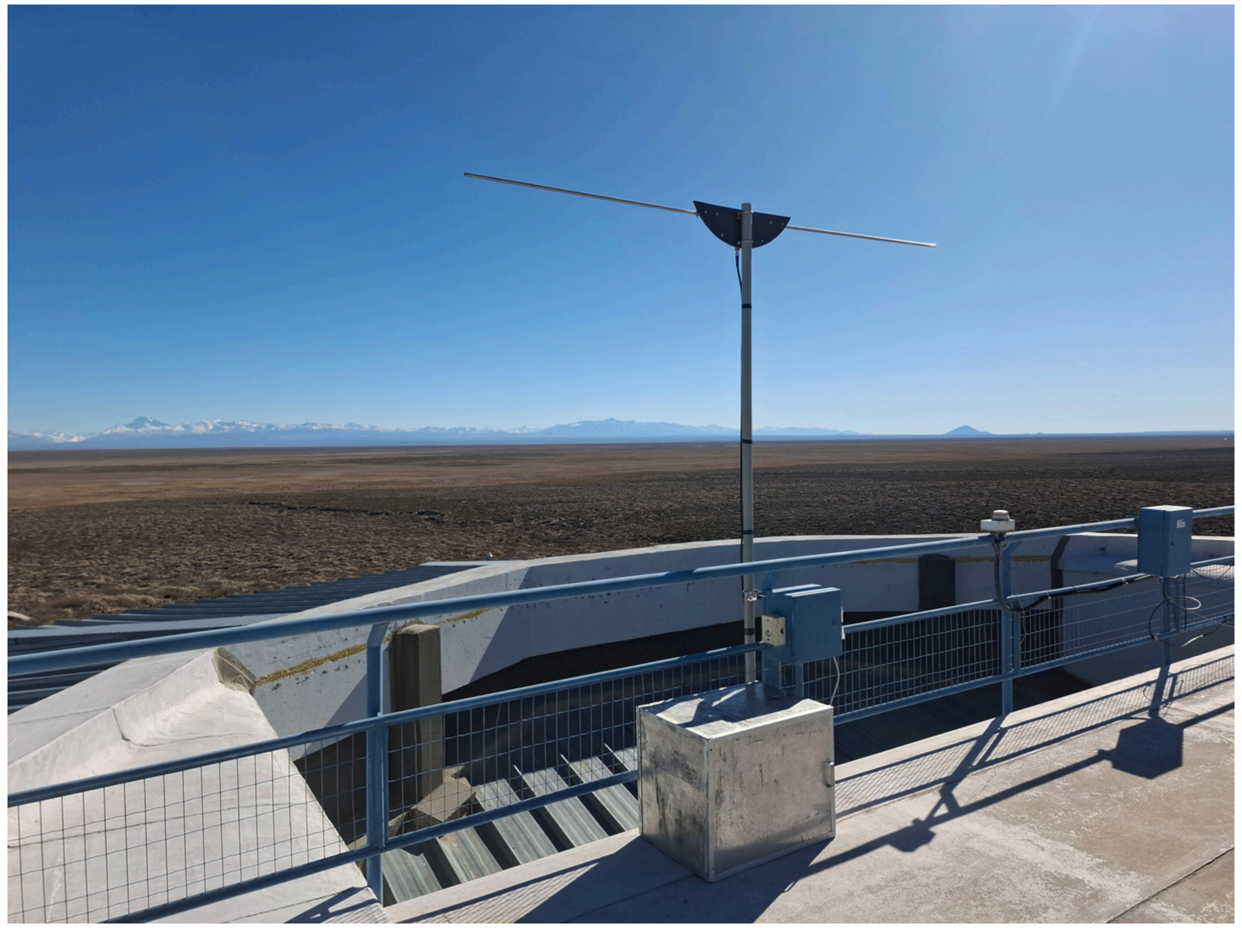
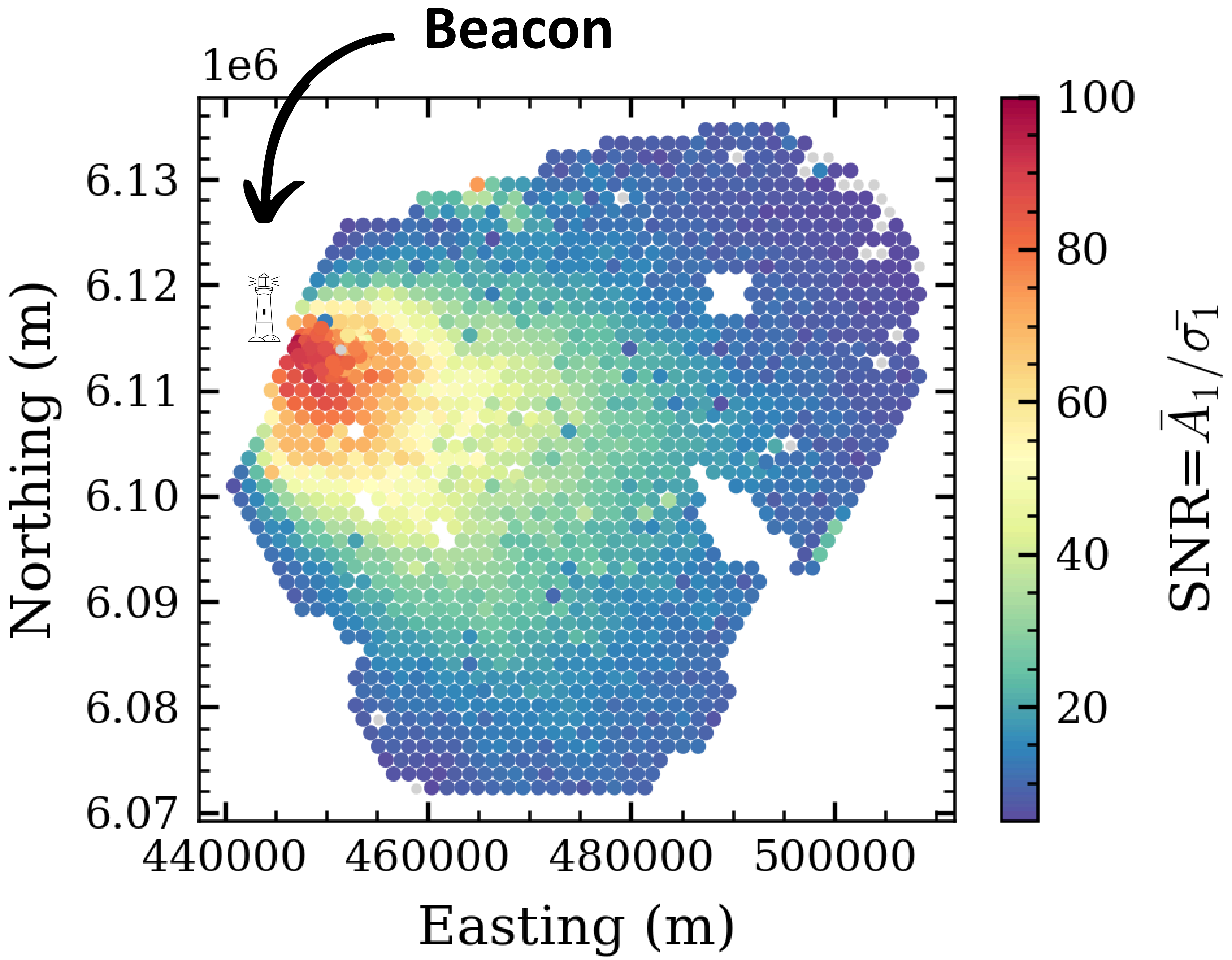
Interferometry with AugerPrime

- **Clock synchronisation**
- Beacons
    - 50 MHz
- Synchronise based on 1 frequency



Credit: Andres Travaini



Interferometry with AugerPrime

- **Positional accuracy (< 30 cm)**
- Differential GPS survey
  - Few centimeter accuracy
  - ∼ 6-12 months

Summary

- Interferometric reconstruction was performed on a large AERA dataset
    - Results comparable with existing reconstructions
    - Successful reconstruction of low energy events
    - Collaboration wide paper in preparation
- Next step: Expand to AugerPrime
    - Preparations being made → Beacons + DGPS survey

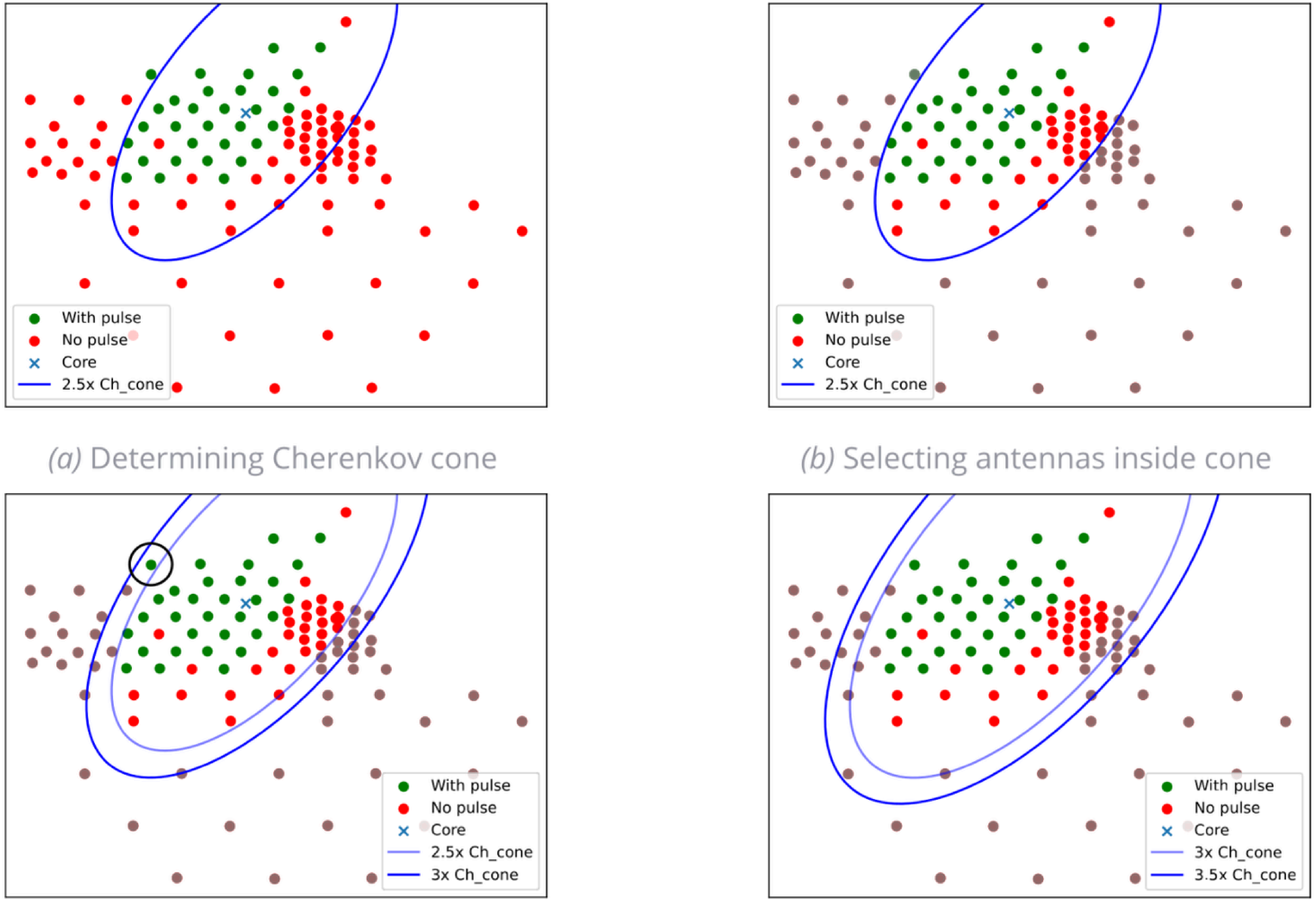
Email: pim.vandillen@ru.nl

P. van Dillen is funded by the European Union. Views and opinions expressed are how- ever those of the author(s) only and do not necessarily re- flect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. This work is supported by ERC grant (CR-INTERFEROMETRY 101170979).

BACKUP

Antenna selection

- Axis and core by SD reconstruction
- All antennas within 2.5x Cherenkov cone (at reference depth of 625 g/cm^2) are selected
- Antennas 'with pulse'; SNR >= 10 (quadratic), close to the 2.5x Cherenkov cone are included as well



(a) Determining Cherenkov cone

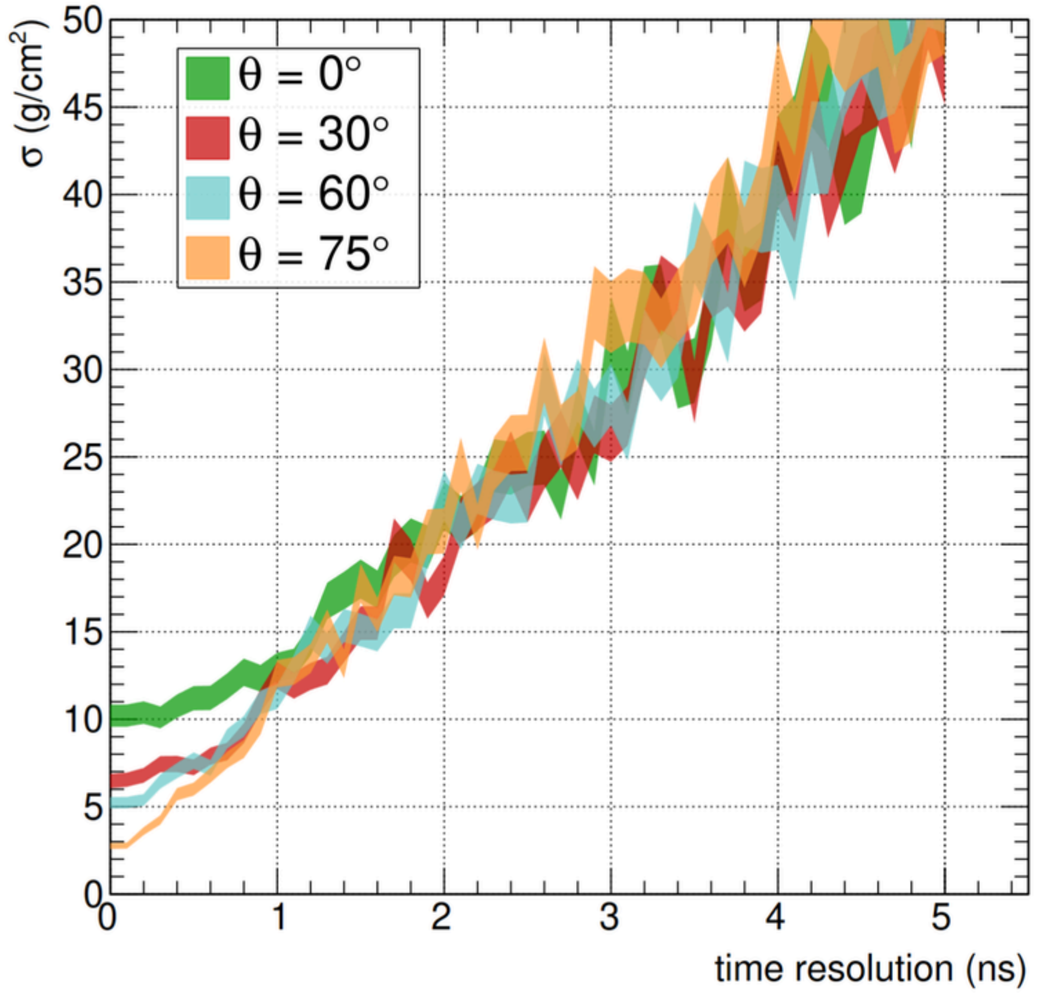
(b) Selecting antennas inside cone

(c) Add extra antennas with pulse

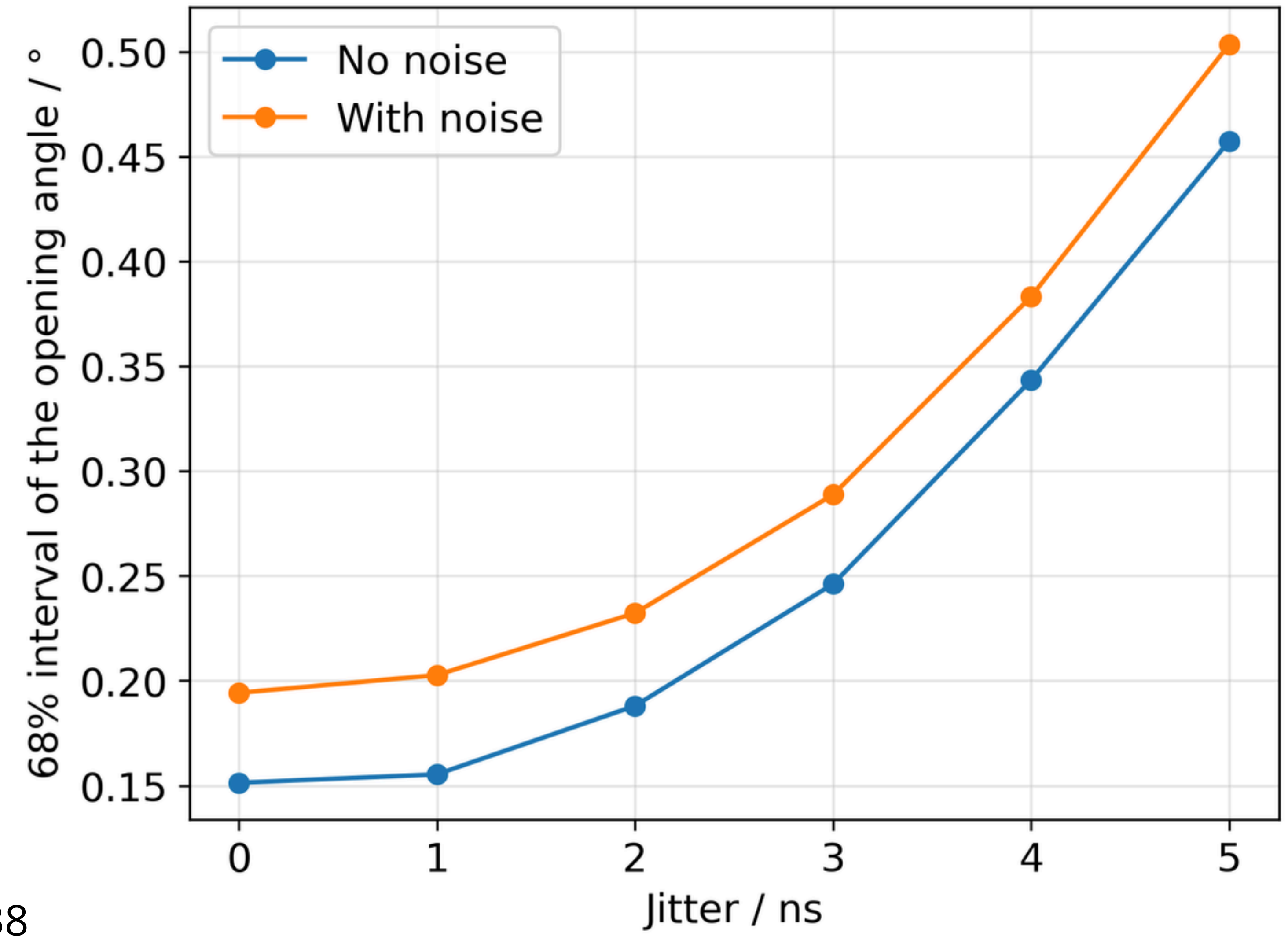
(d) Terminate if no new antennas with pulse

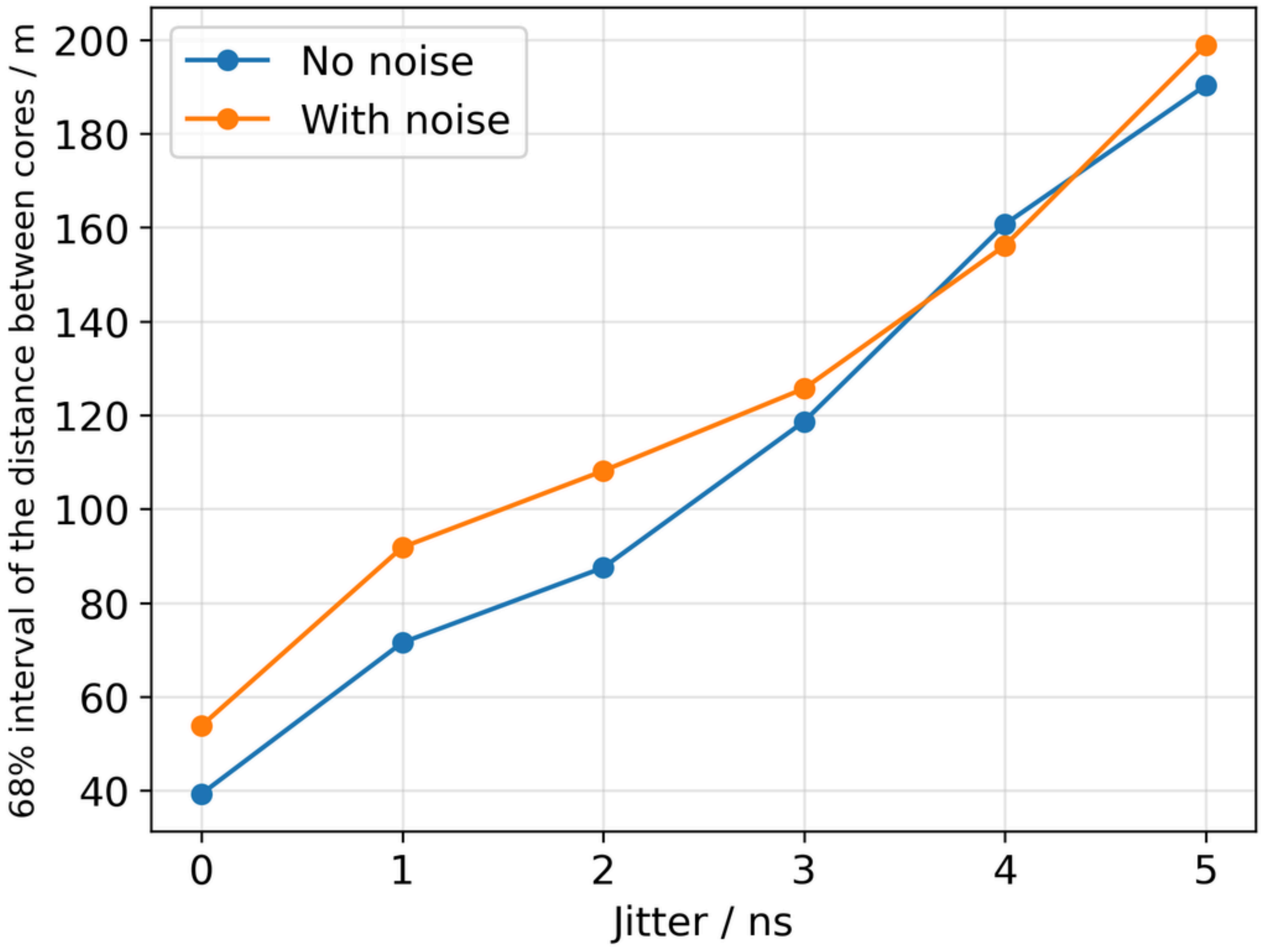
Timing jitter

- AERA simulation set both with and without noise
- Gaussian jitter



https://doi.org/10.48550/arXiv.2006.10348

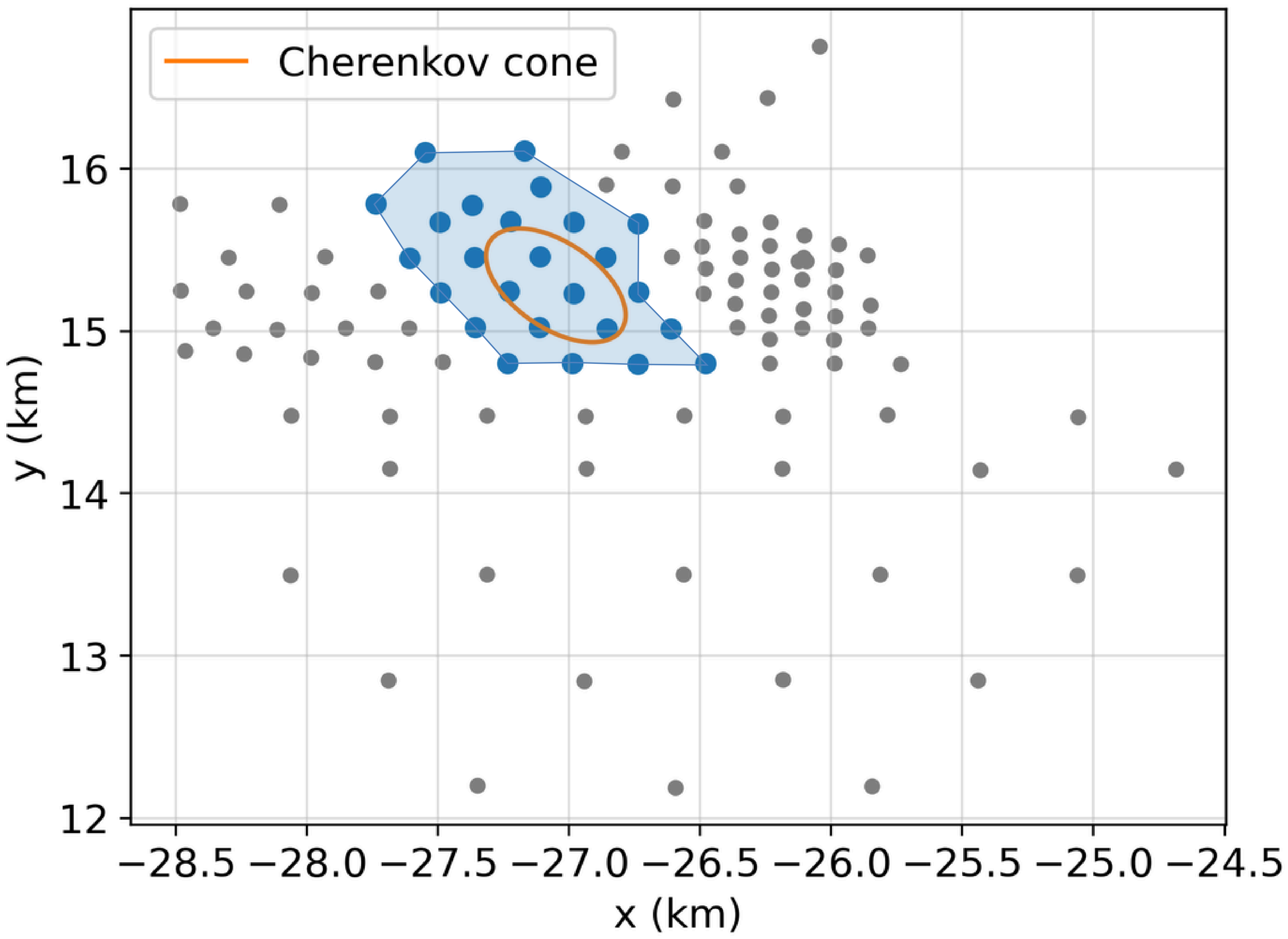




AERA dataset - Cuts

- Select usefull events
  - No thunderstorm flag (6%)
  - **Full containment of radio footprint (85%)**
  - High contrast in slice (13%)
    - At least for 6 slices
  - Good fit through axis points (2%)

The percentage (...%) shows the fraction of events that are discarded due to the cut



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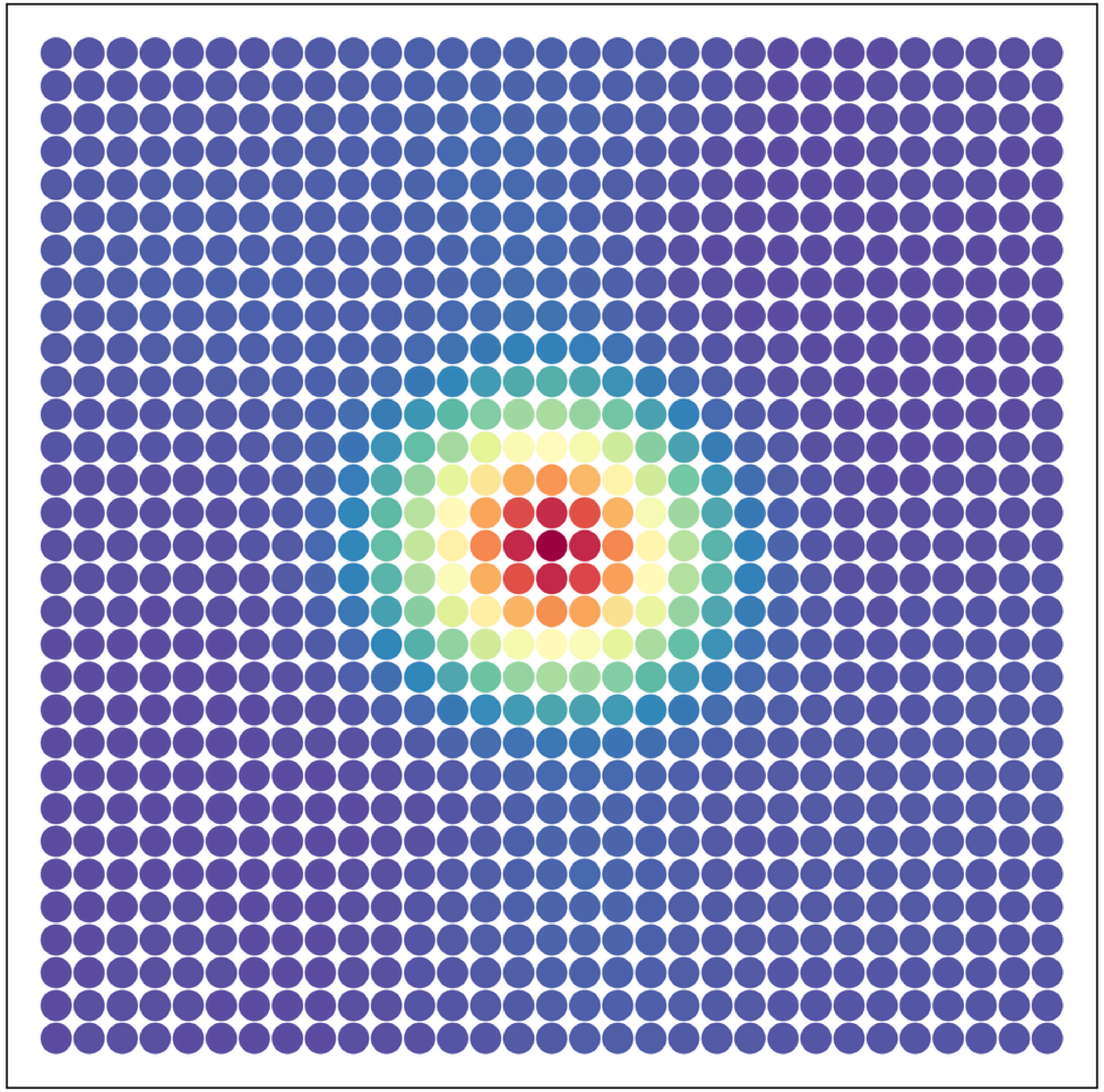

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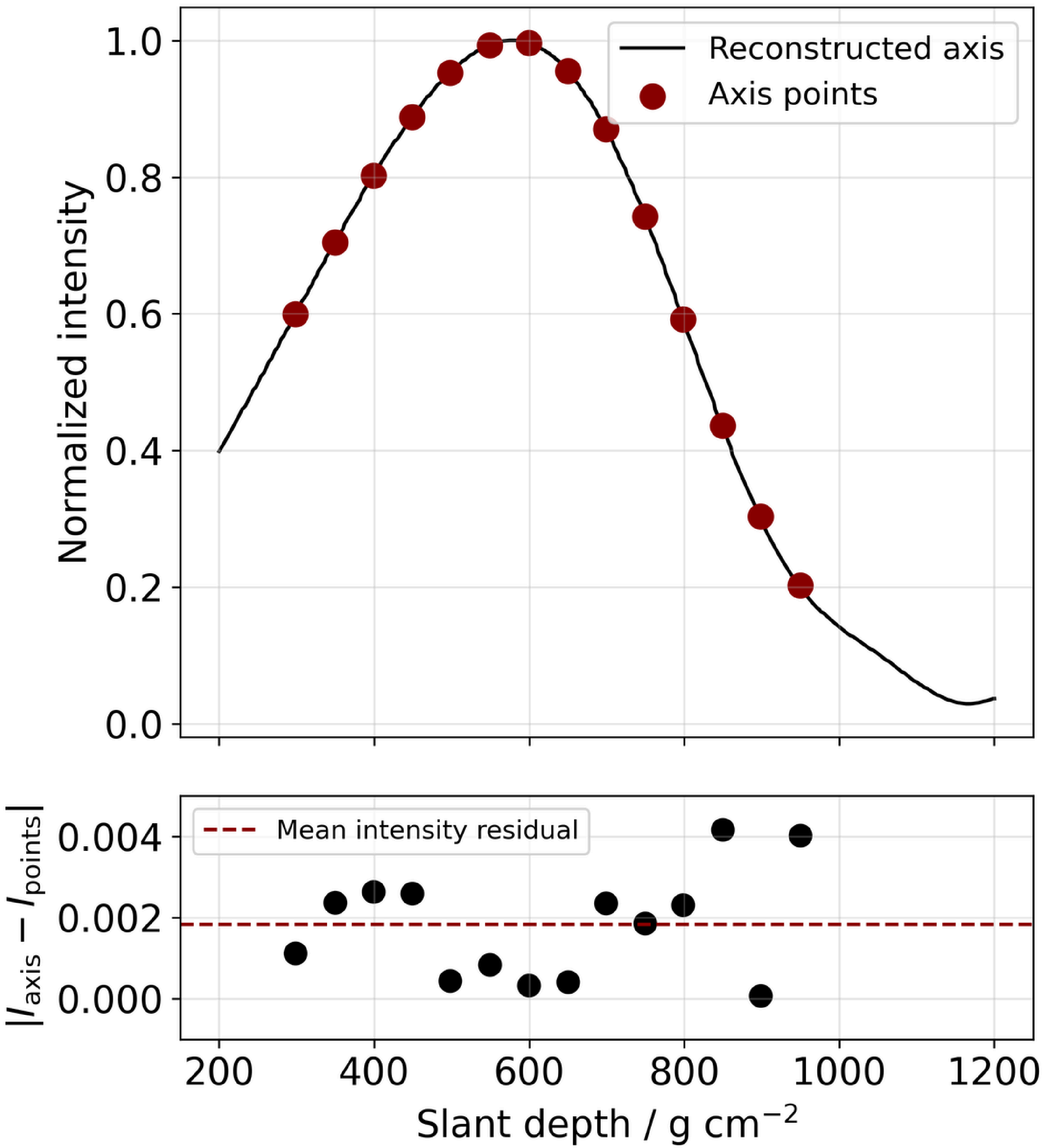
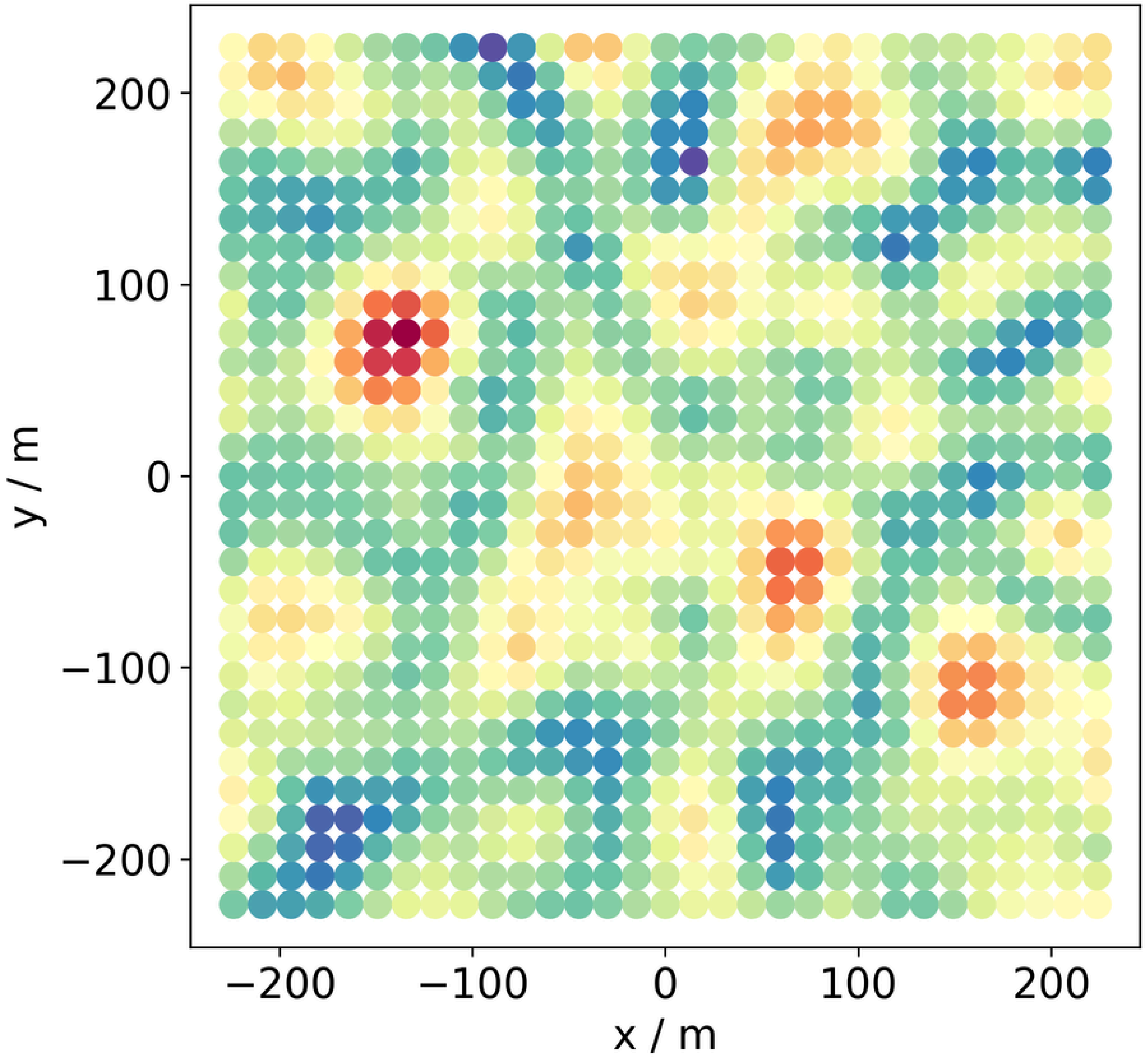
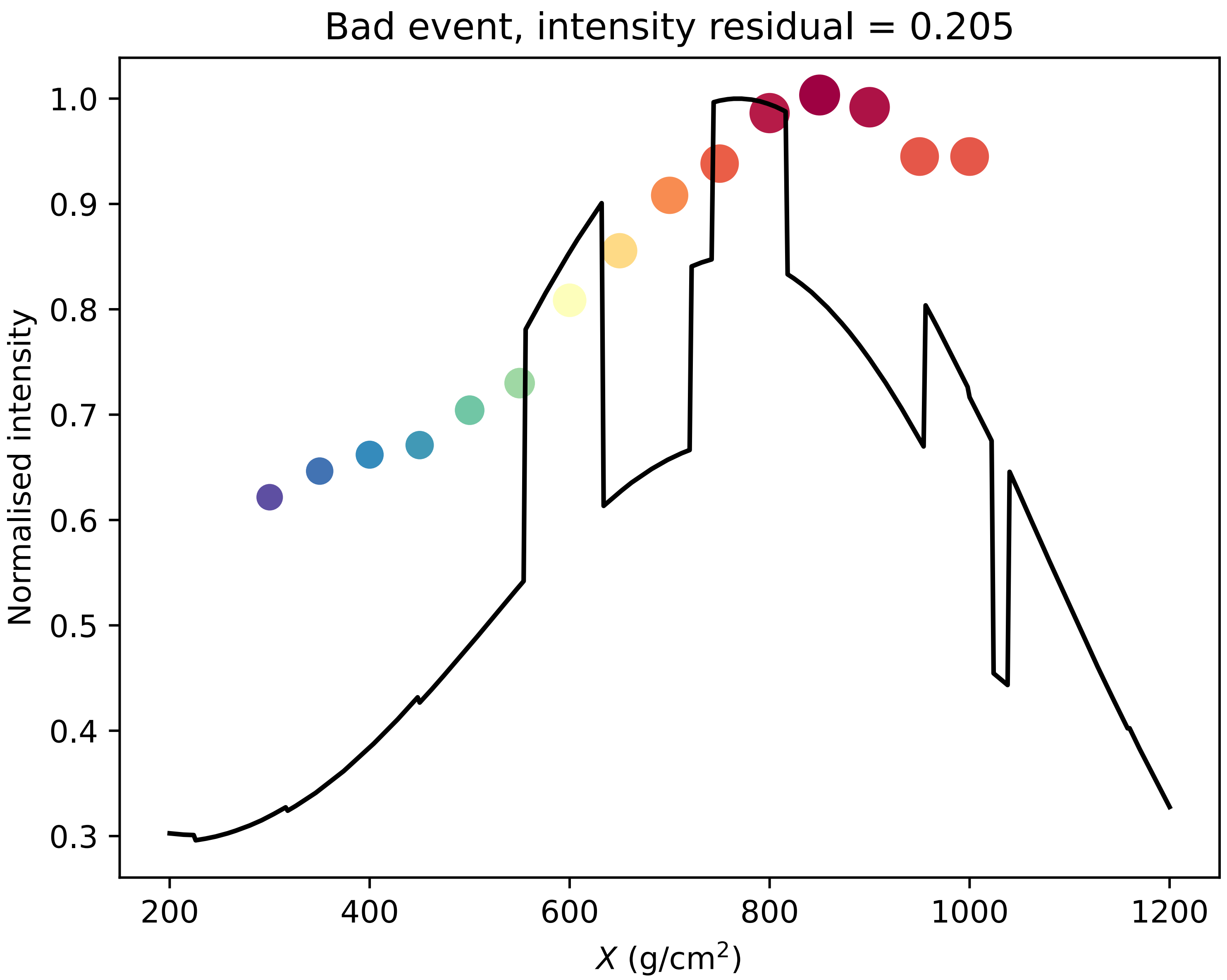


AERA dataset - Cuts, bad examples

- High contrast in slice
- Good fit through axis points

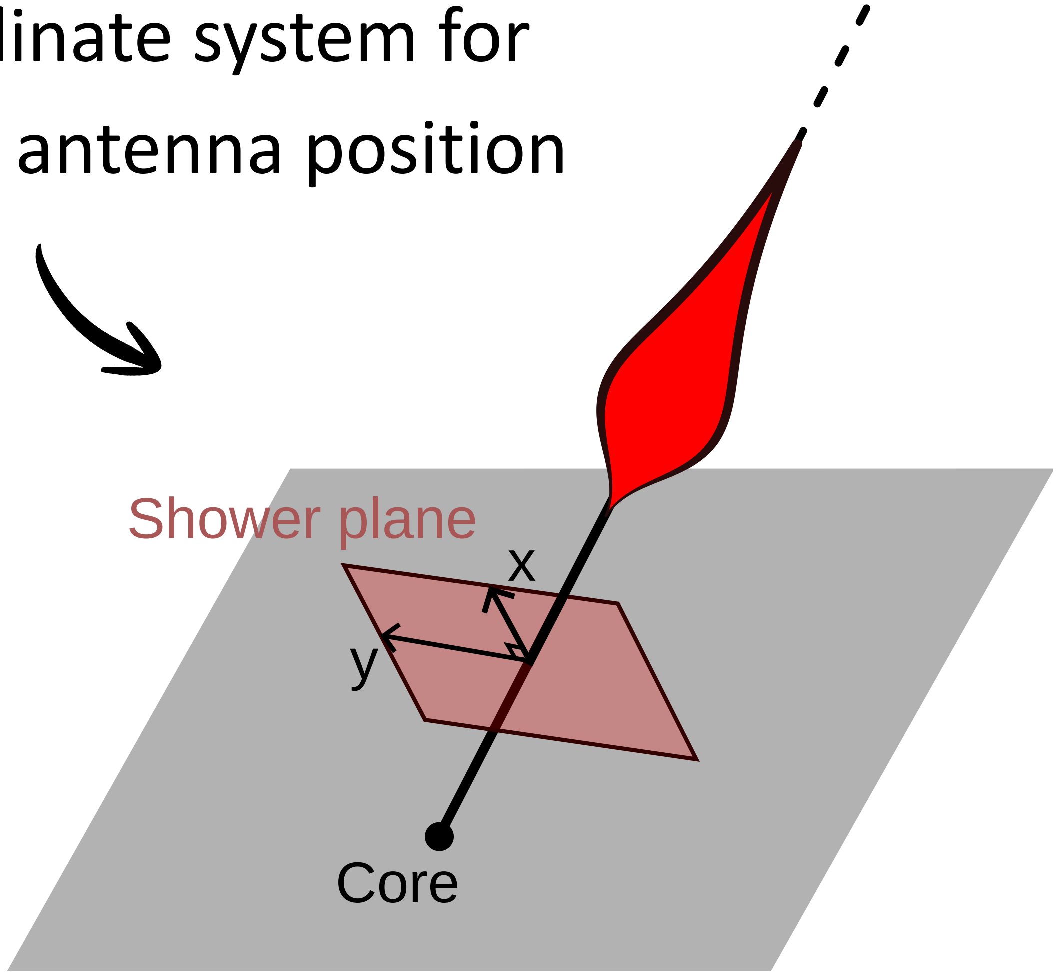


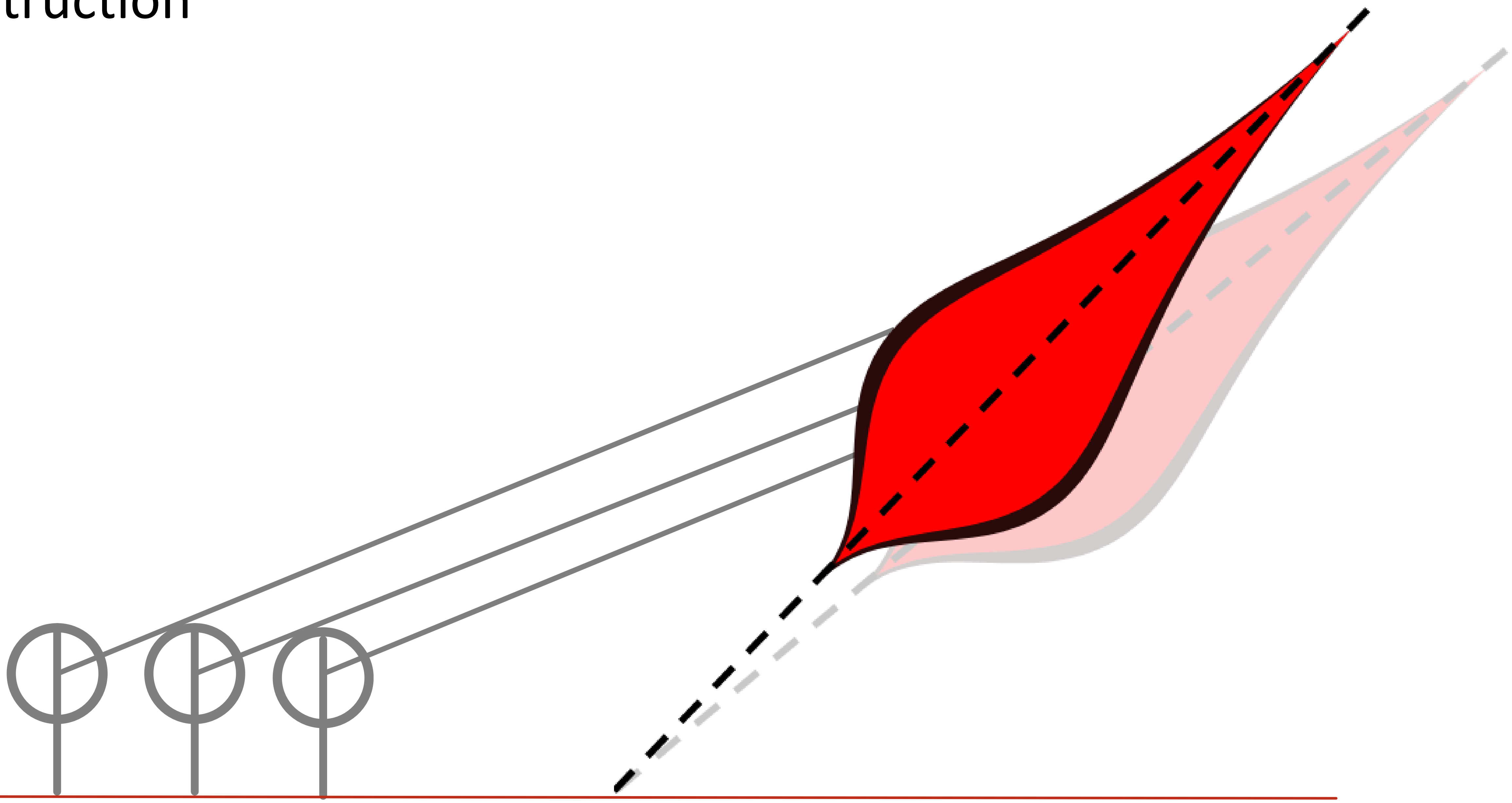


Biases

- Air shower projected differently due to interferometric method
- Depending on the *mean antenna position/barycenter/centre-of-mass* of the antenna
- Shower 'pushed' away from actual shower axis
- Both bias in core as angle reconstruction

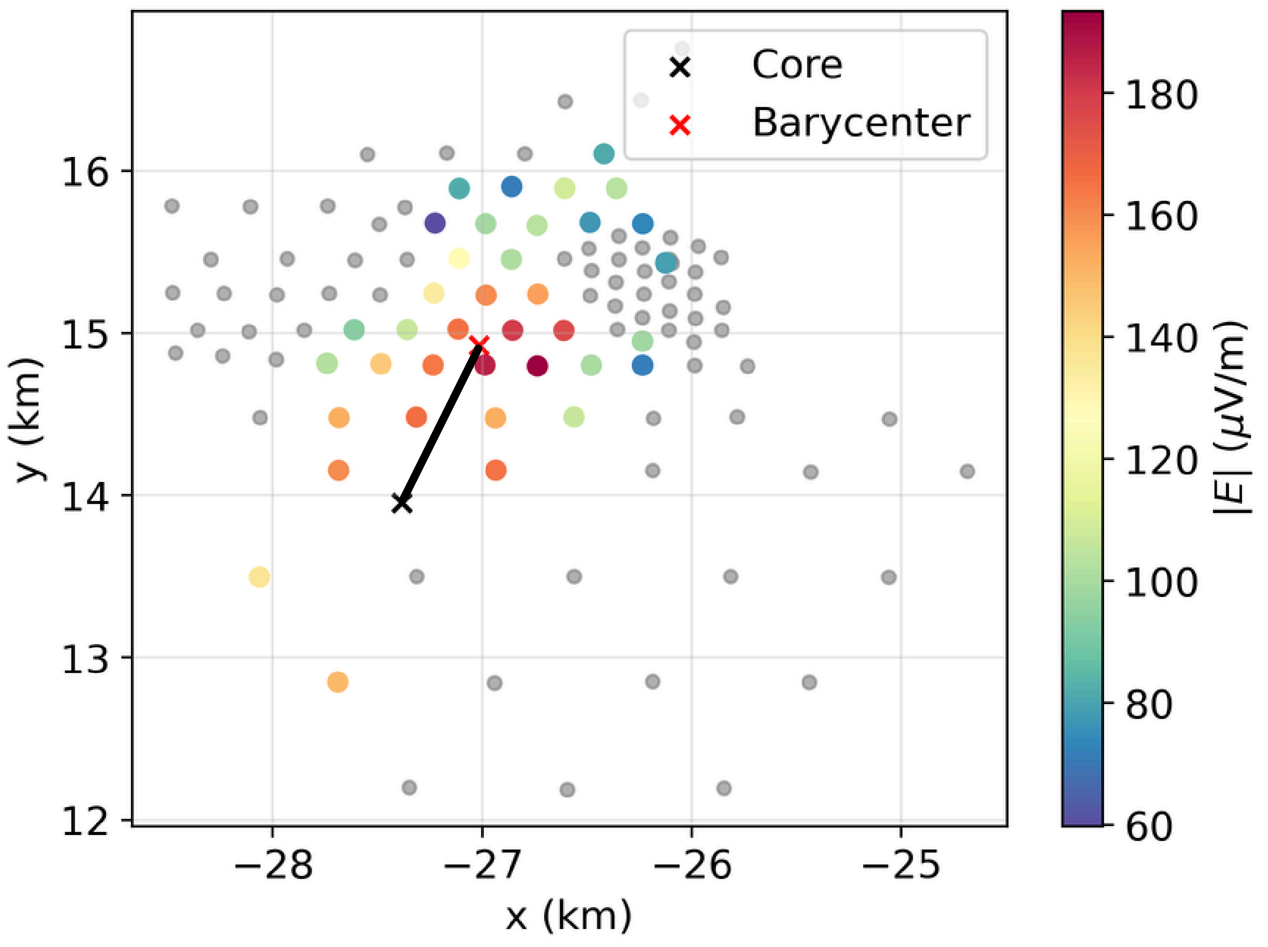
Coordinate system for mean antenna position

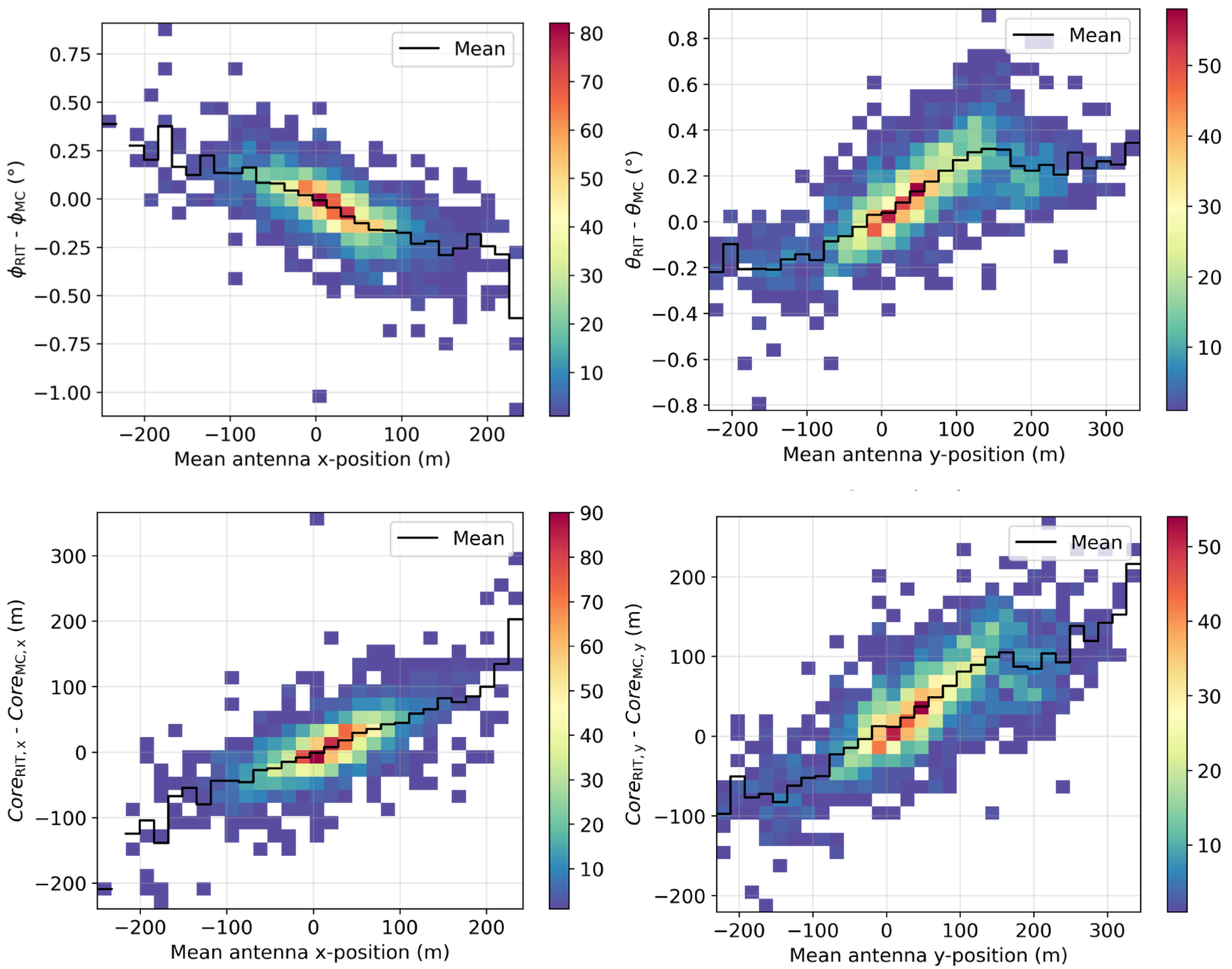




Biases – Simulations

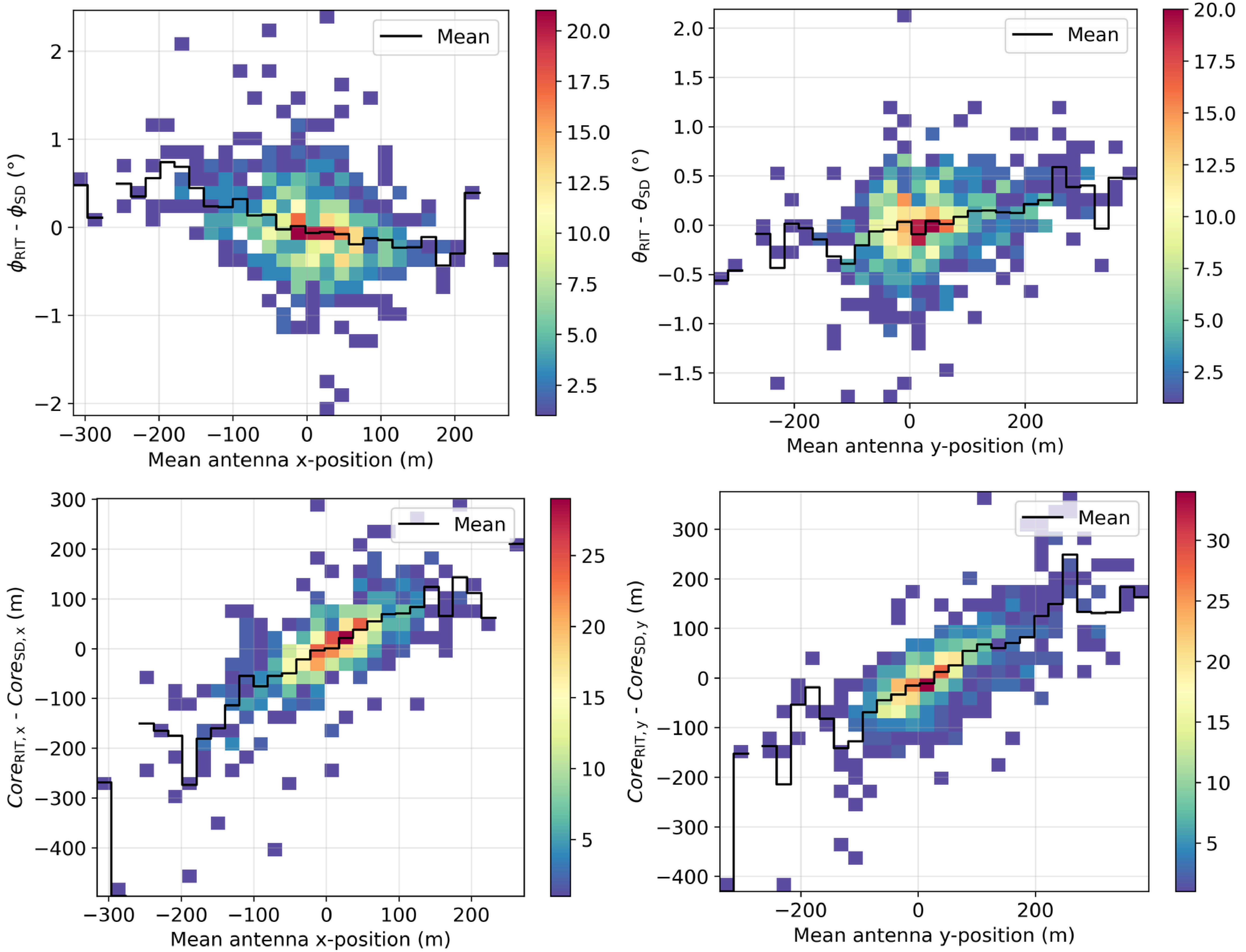
- Compared to MC





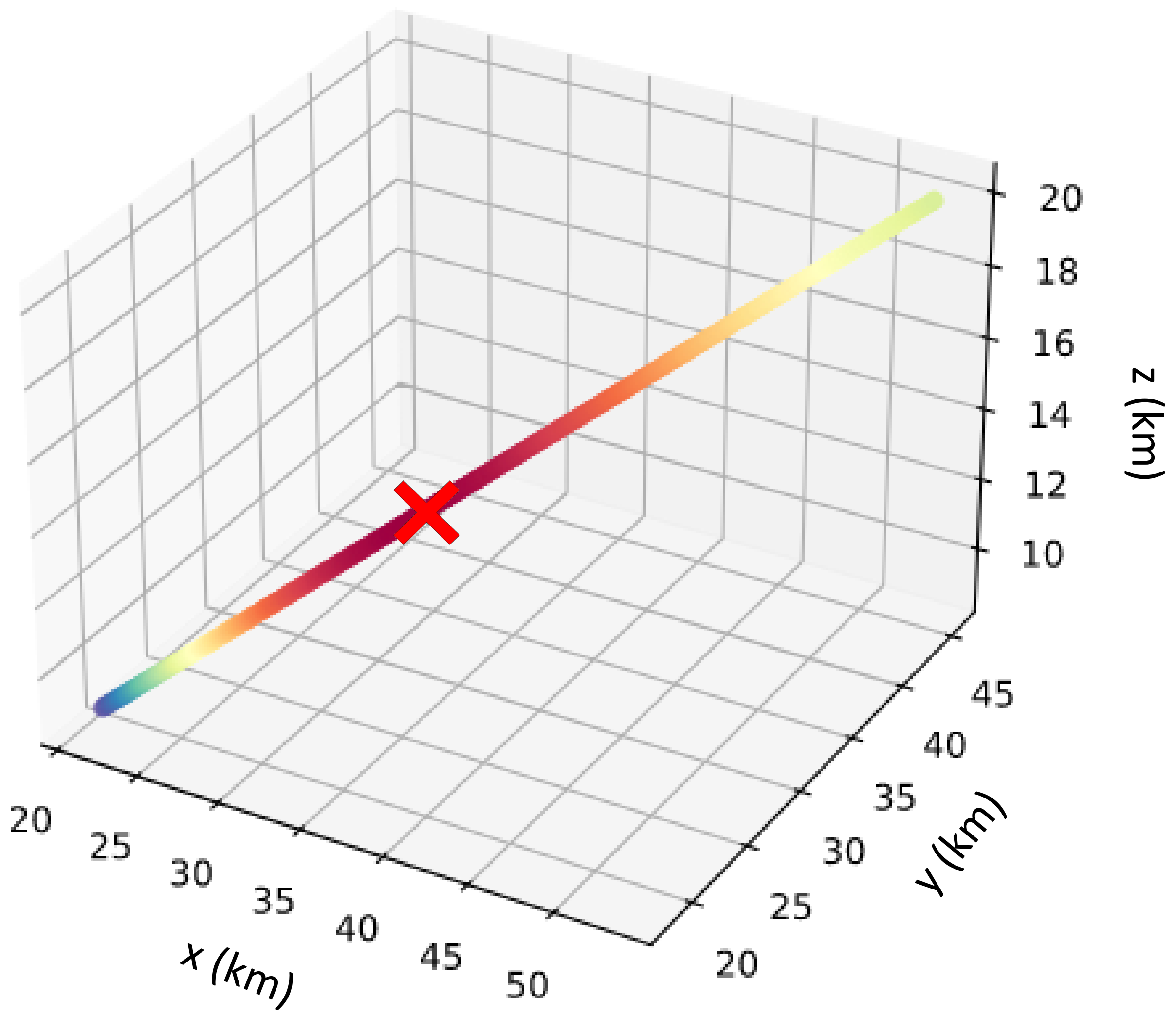
Biases – Data

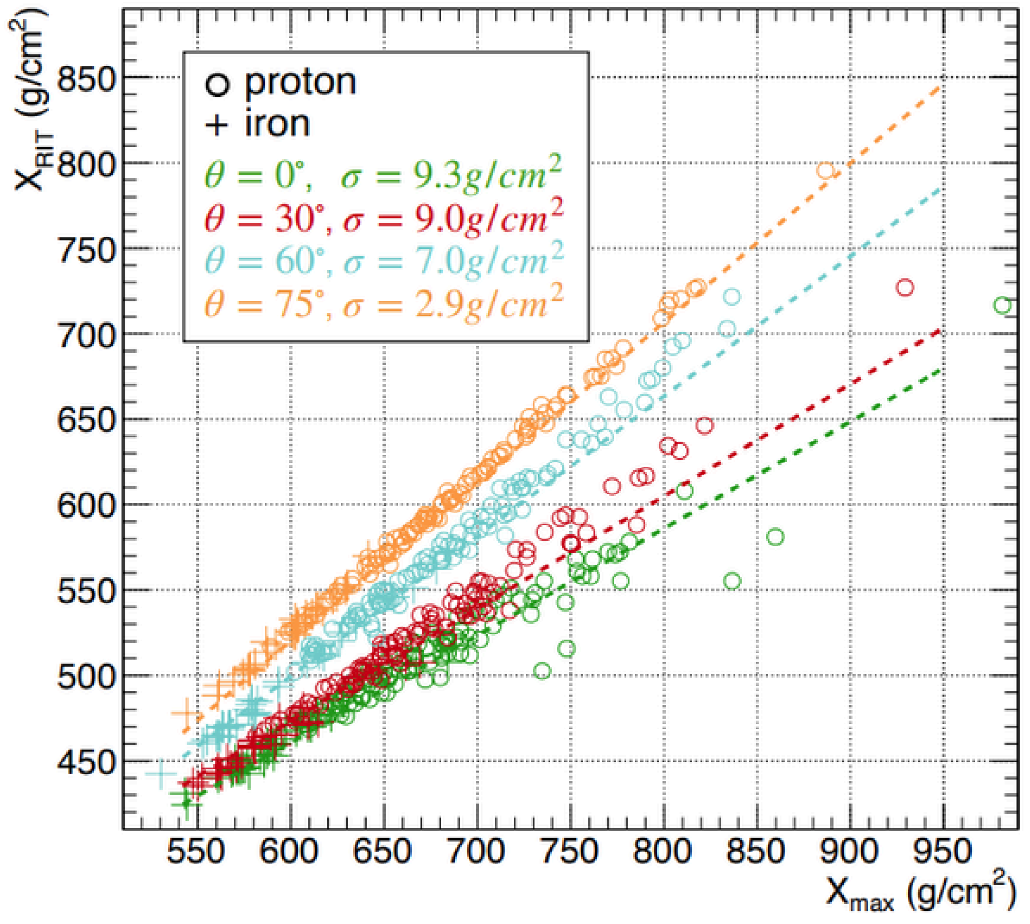
- Compared to SD



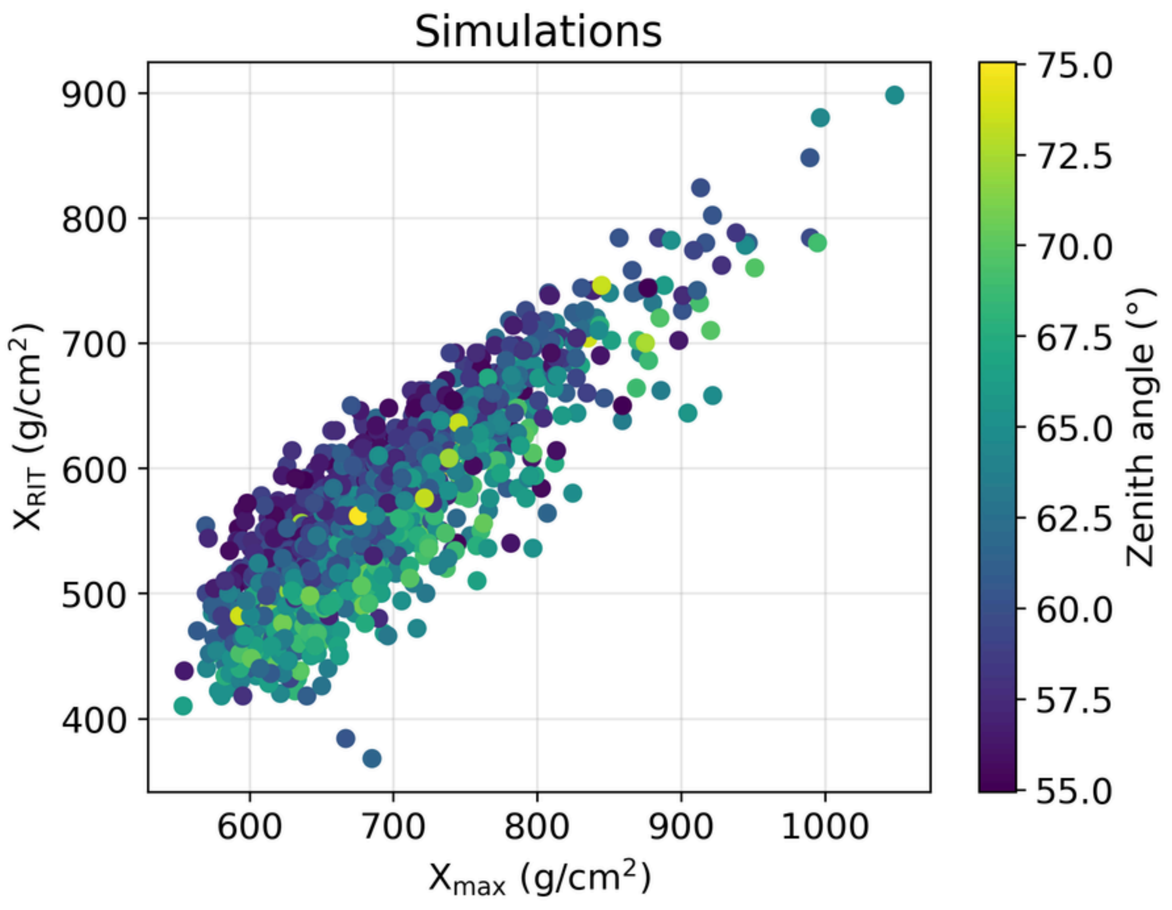
X_{max} reconstruction

- Get X_{RIT} from reconstruction
  - Not the same as X_{max}!
- Conversion dependent on:
  - Zenith angle
  - Antenna layout
- Difficult for AERA
  - Irregular grid



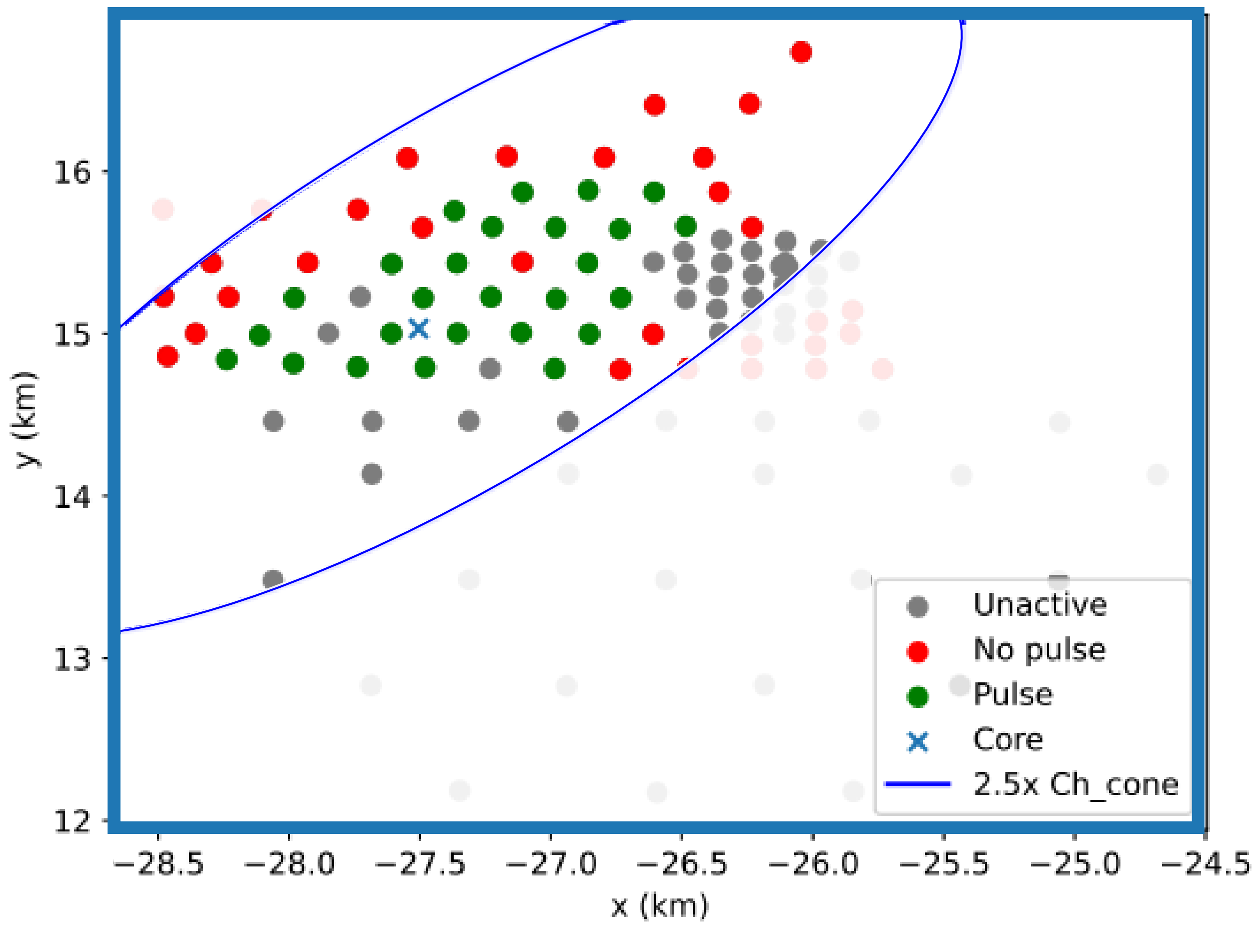


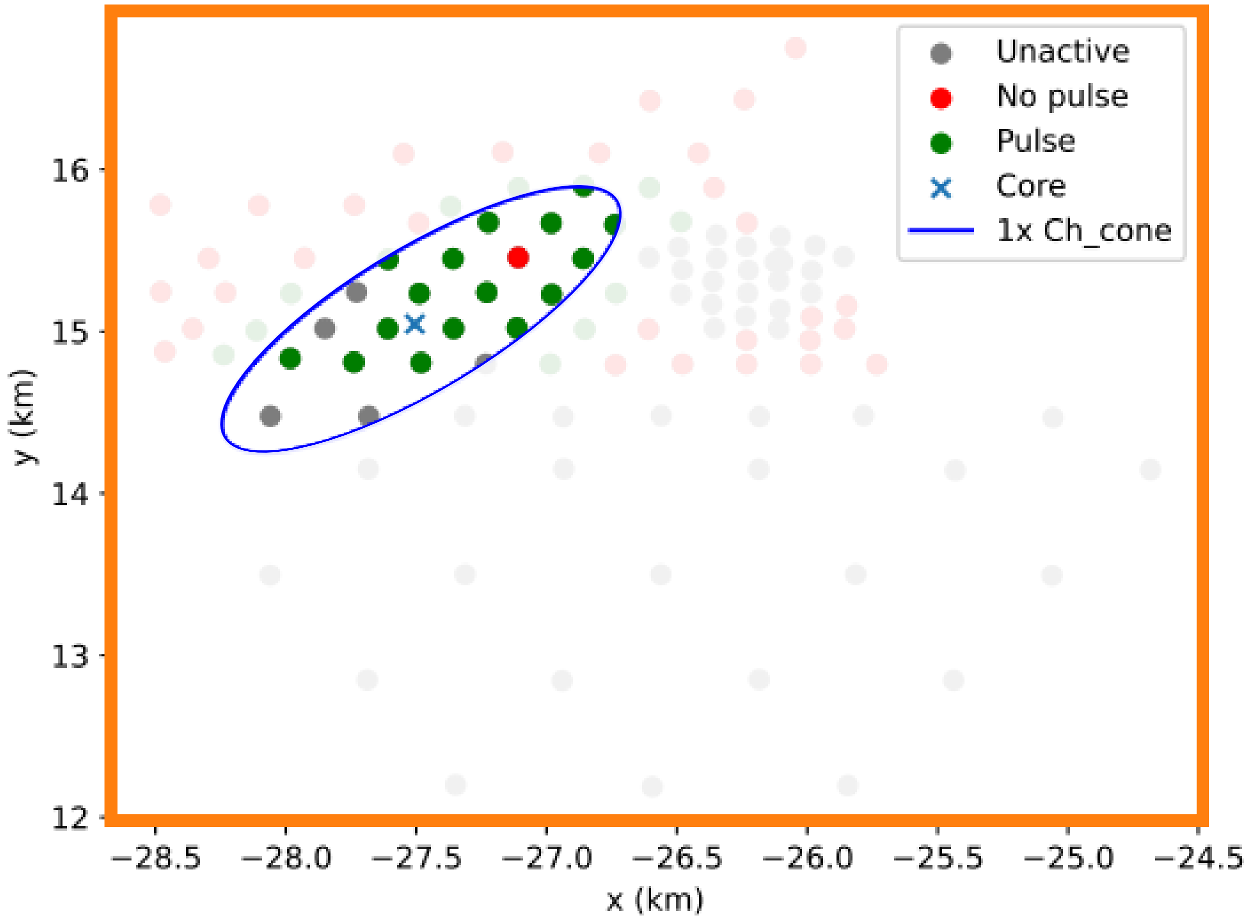
https://doi.org/10.48550/arXiv.2006.10348

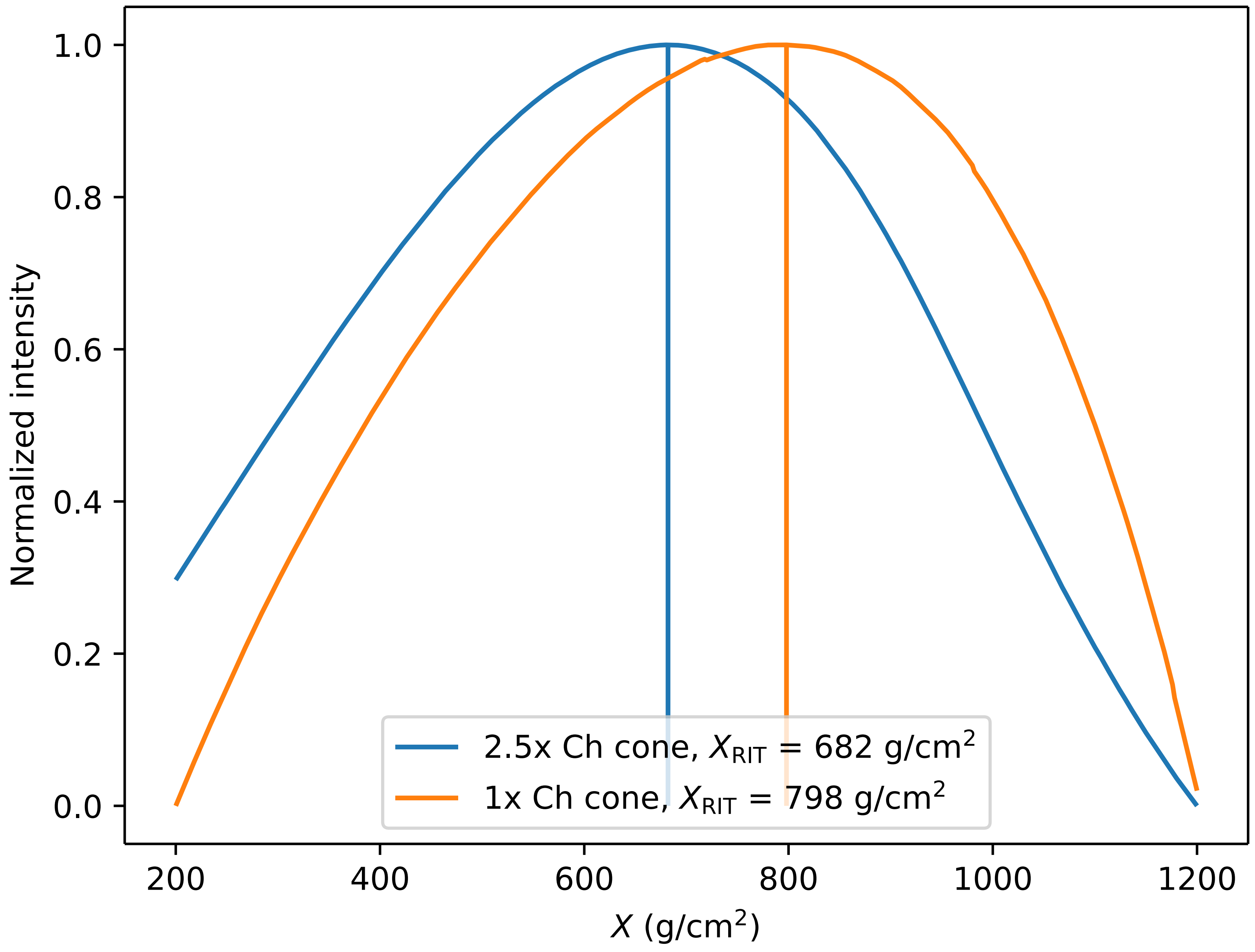


X_{RIT}

Reconstructed profile highly dependent on antenna layout/ antennas included in reconstruction







Low energy application

Event selection

- Zenith angle: $75^\circ < \theta < 82^\circ$
- Energy: $\sim$1 EeV
- SD quality: $\frac{\sigma_{19}}{N_{19}} < 0.5$
- Stations: > 60 (in 2x Cherenkov cone @750 g/cm²)