Interferometry with the Auger Engineering Radio Array

By: Pim van Dillen

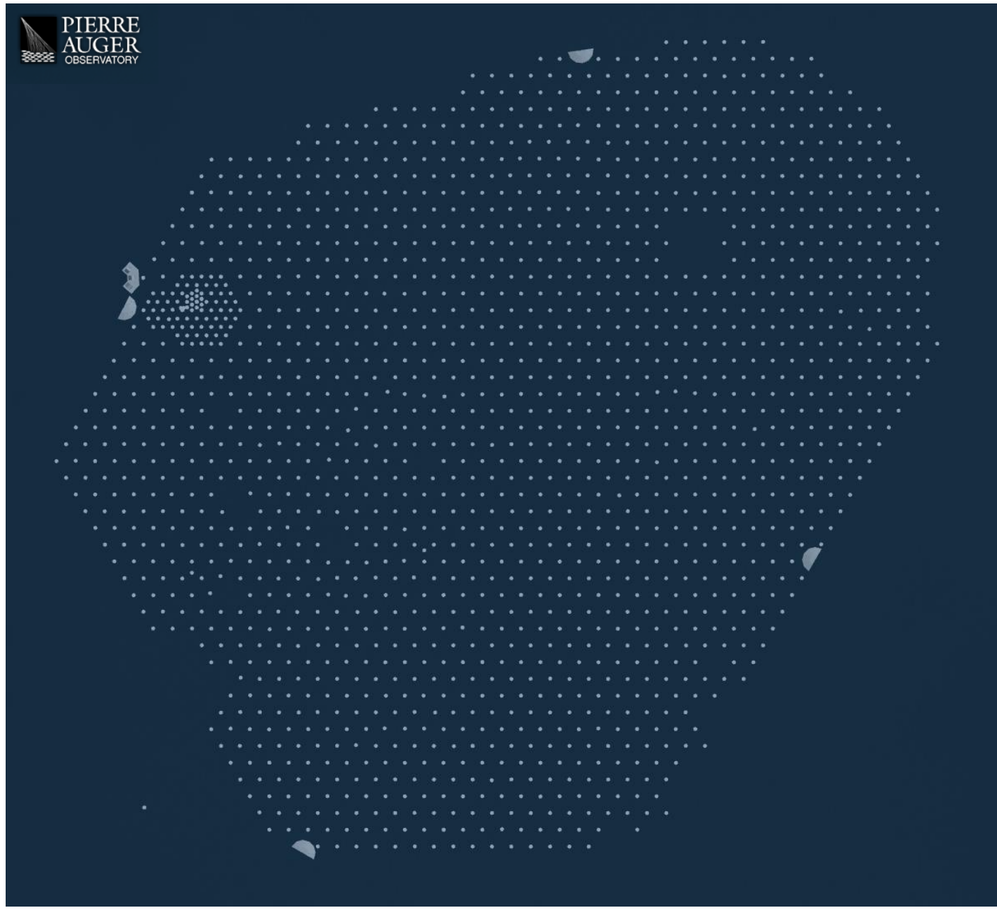
Funded by the European Union

European Research Council
Established by the European Commission

Radboud University

Auger Engineering Radio Array (AERA)

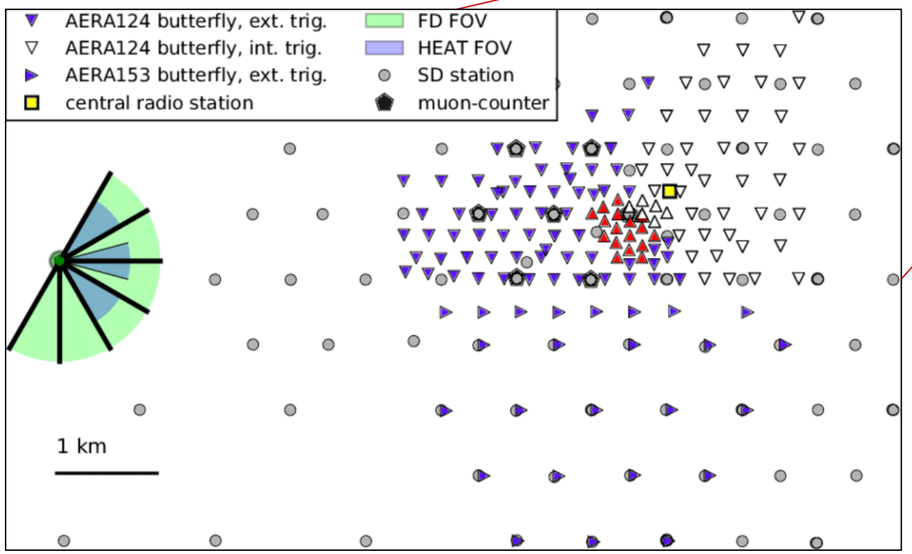
- Pierre Auger Observatory



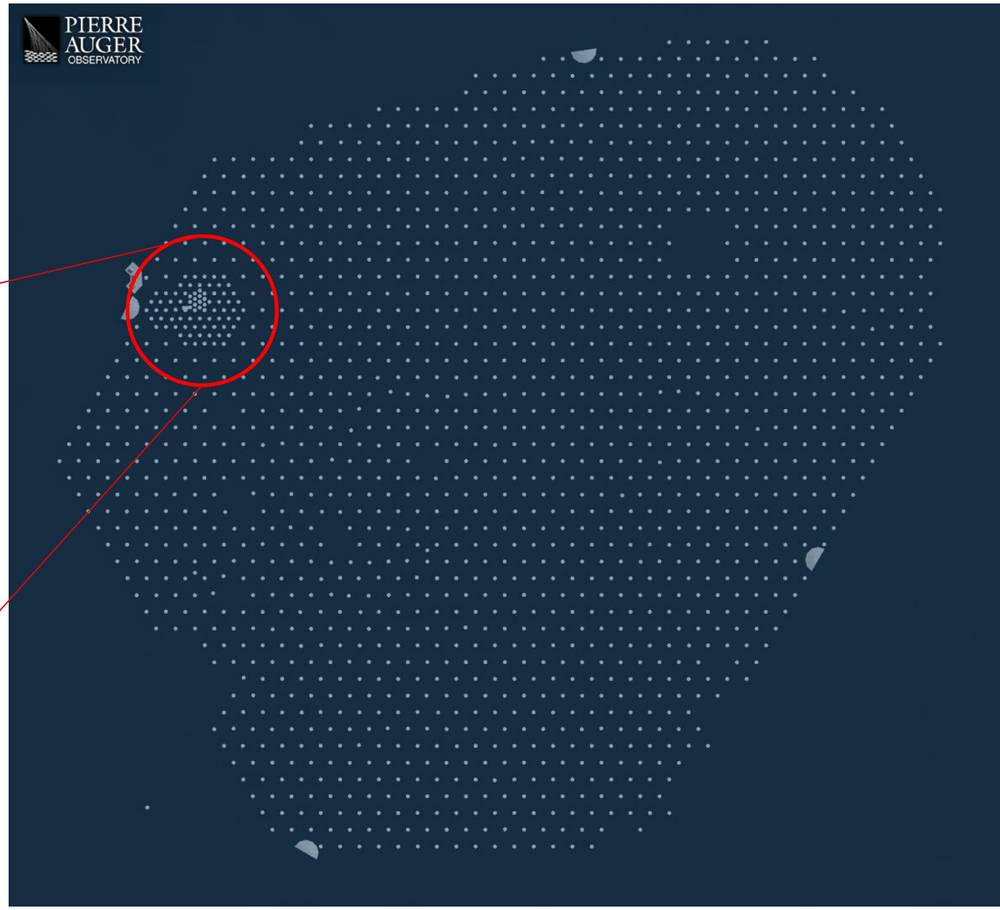
https://opendata.auger.org/display.php

Auger Engineering Radio Array (AERA)

- Pierre Auger Observatory
- Radio detector



DOI:10.1051/epjconf/201713501006

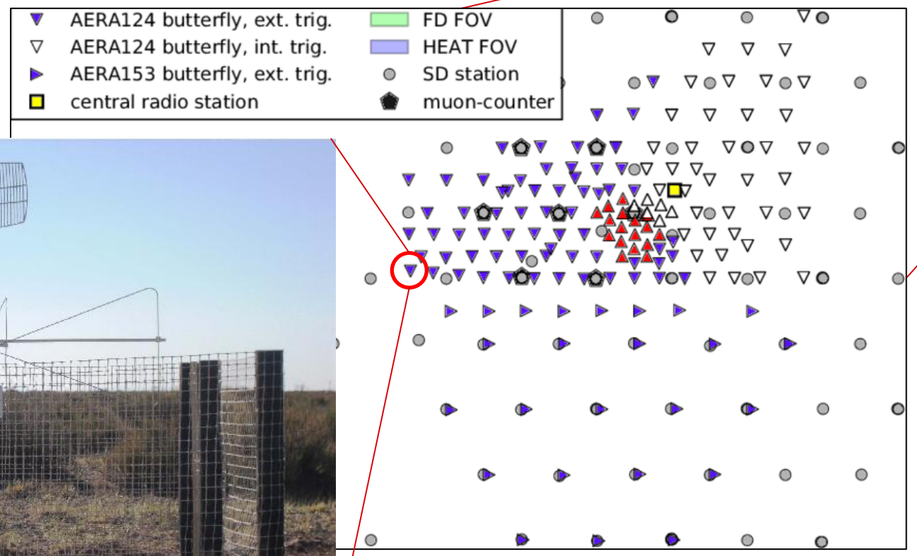


https://opendata.auger.org/display.php

Auger Engineering Radio Array (AERA)

- Pierre Auger Observatory
- Radio detector
- Butterfly antenna

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



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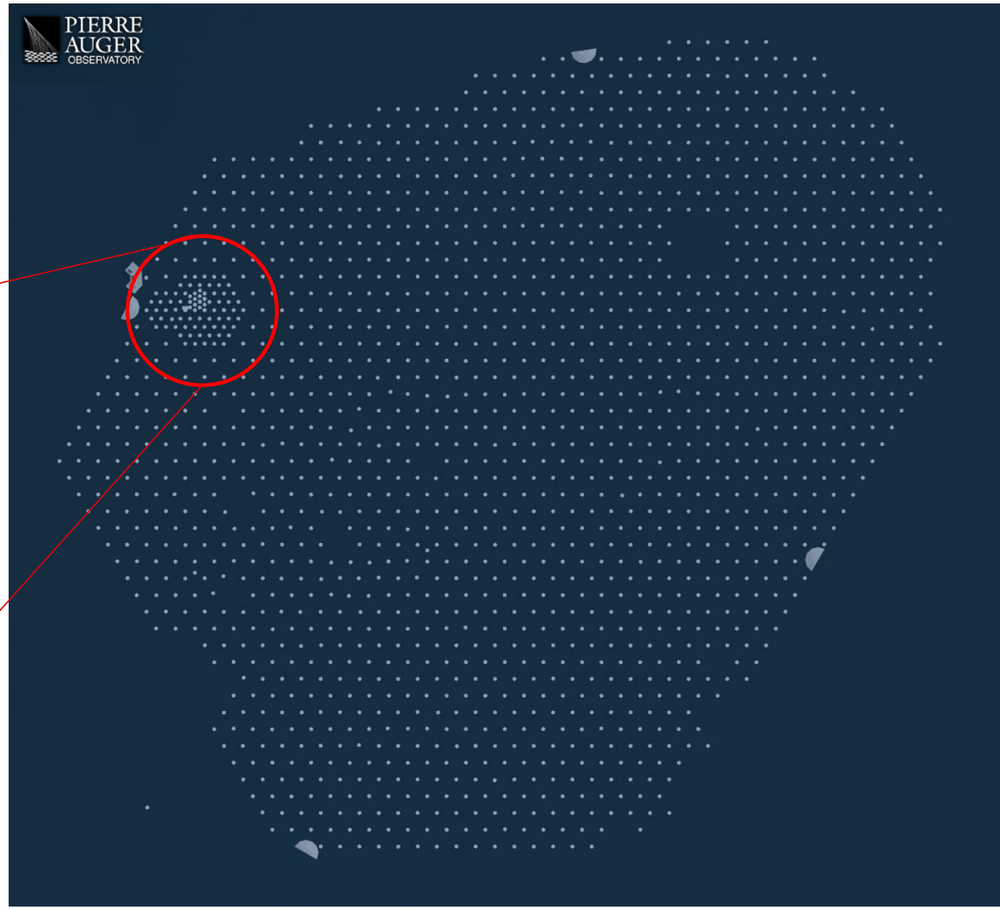
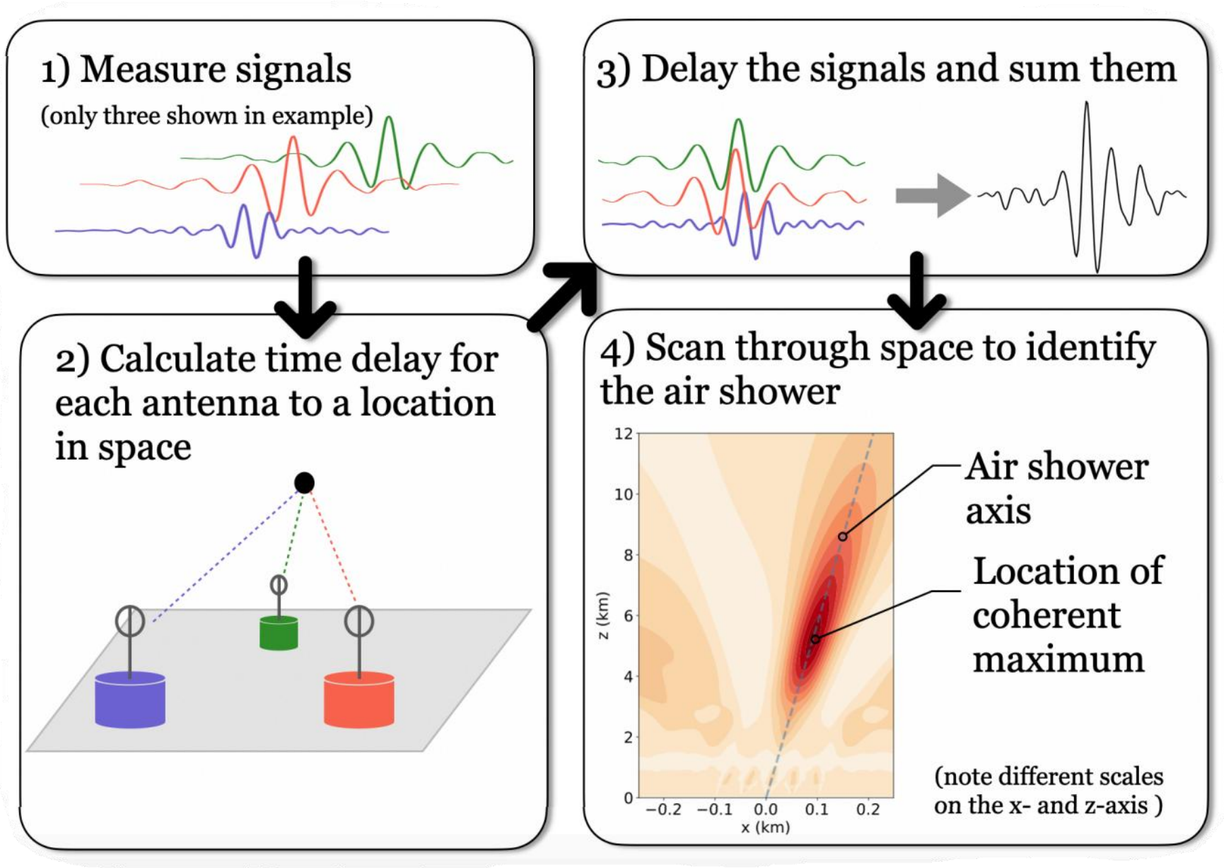


https://opendata.auger.org/display.php

Radio Interferometry Technique (RIT)

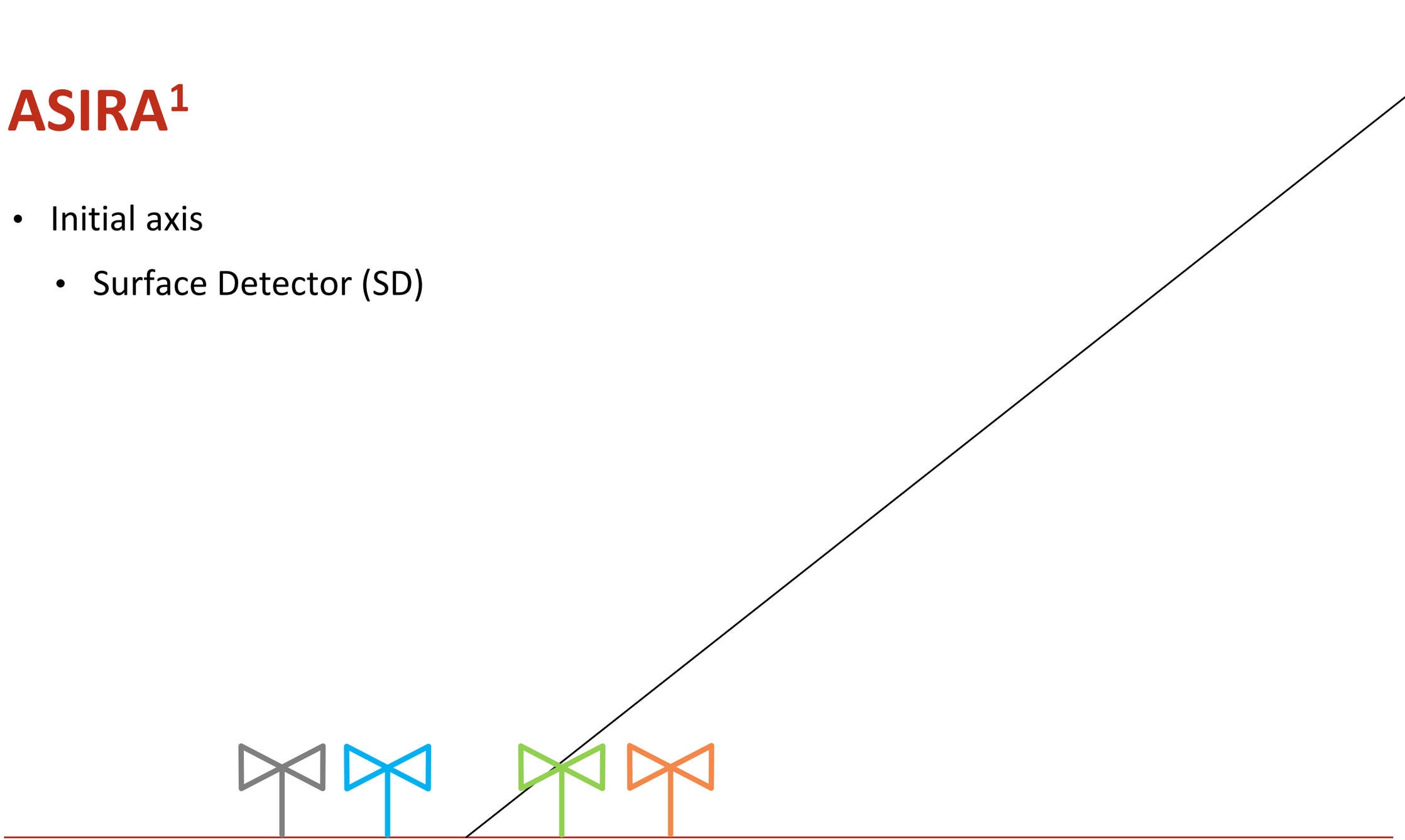
- Use relative time differences in arrival time



DOI: 10.22323/1.444.0380

ASIRA[1]

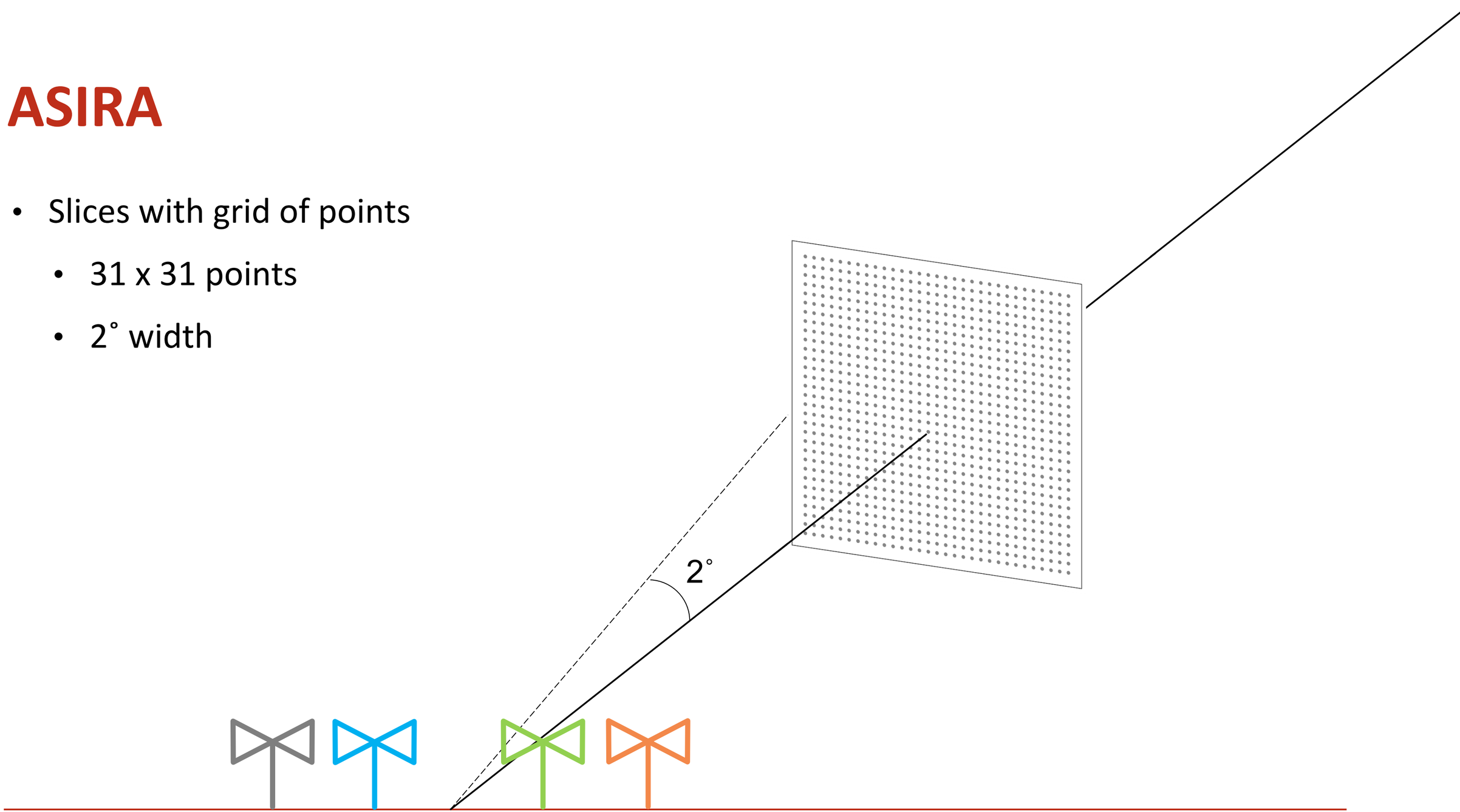
- Initial axis
  - Surface Detector (SD)



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

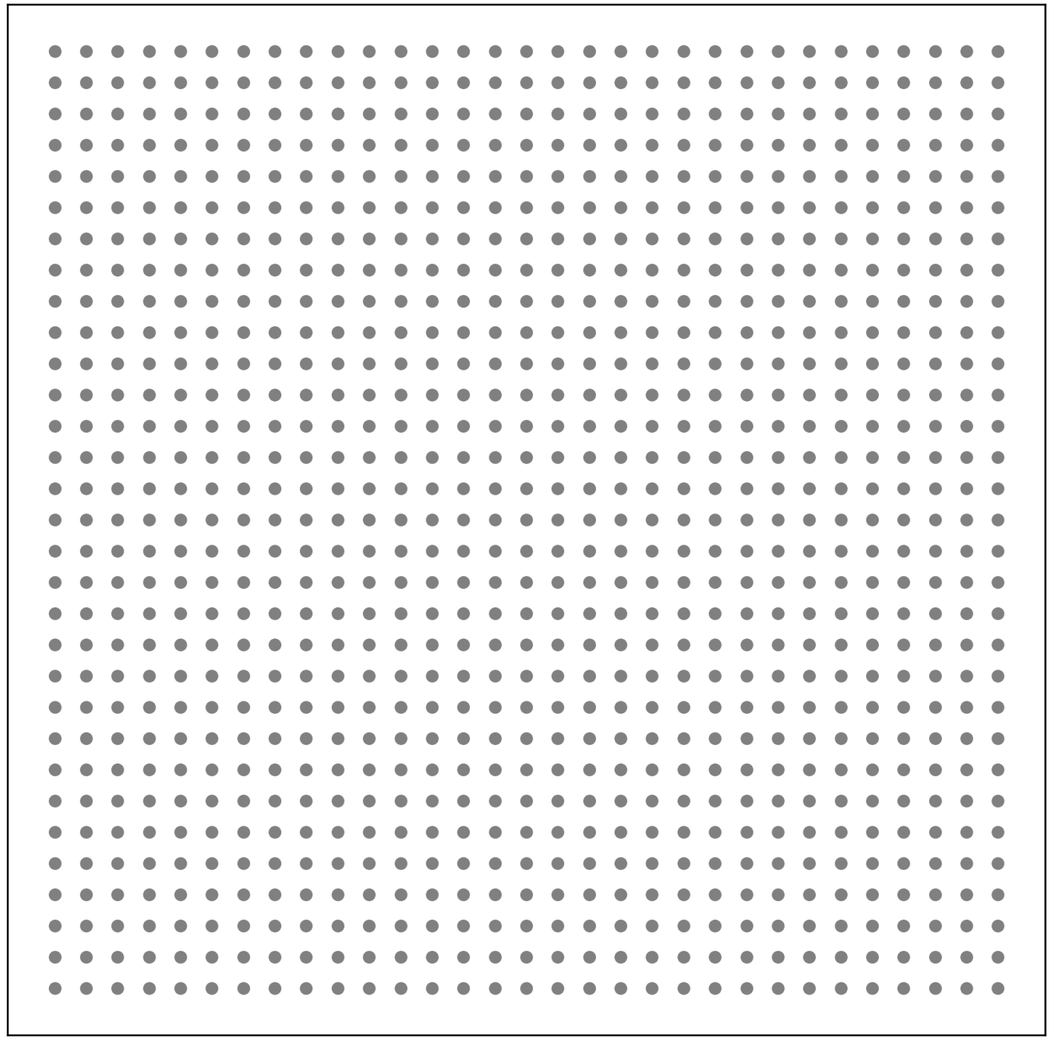
ASIRA

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



ASIRA

- Determine intensity for every point



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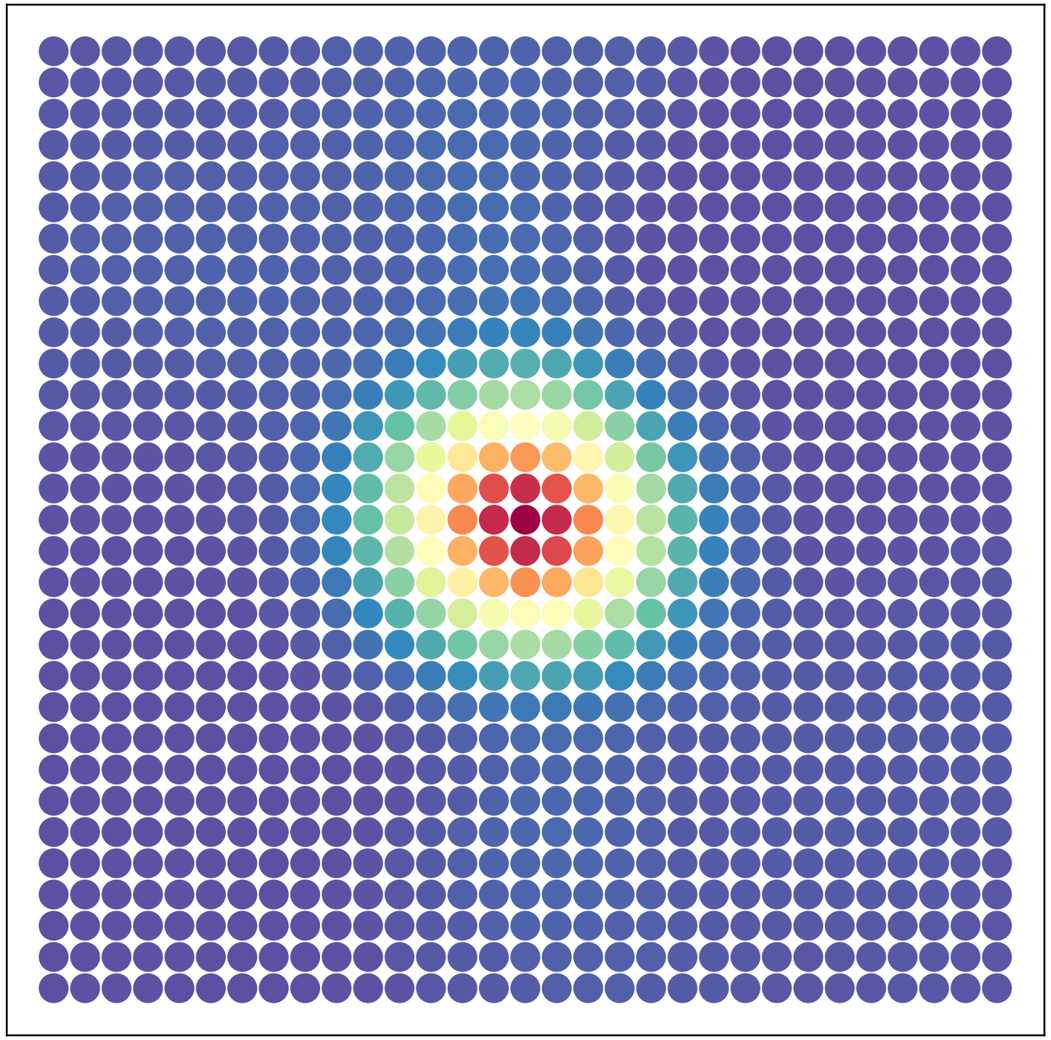
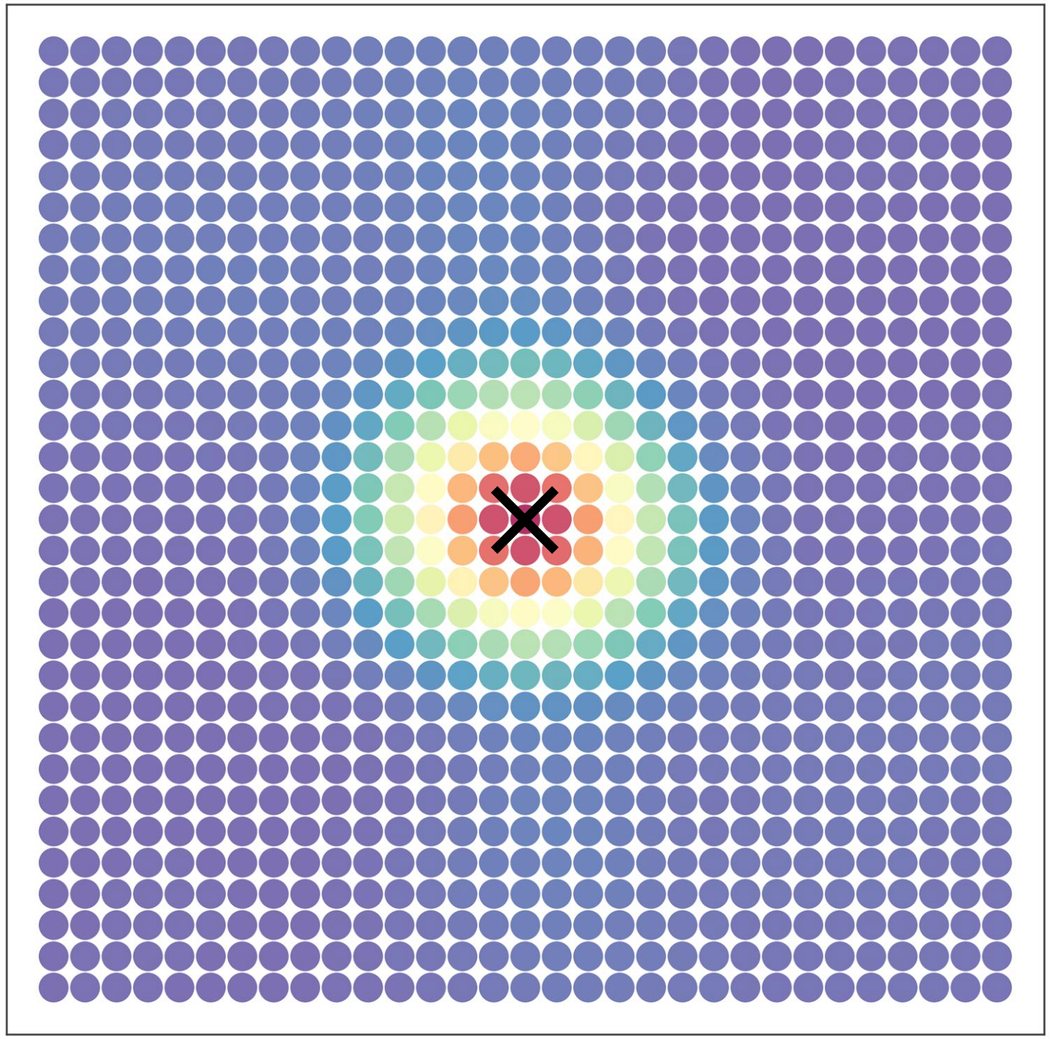


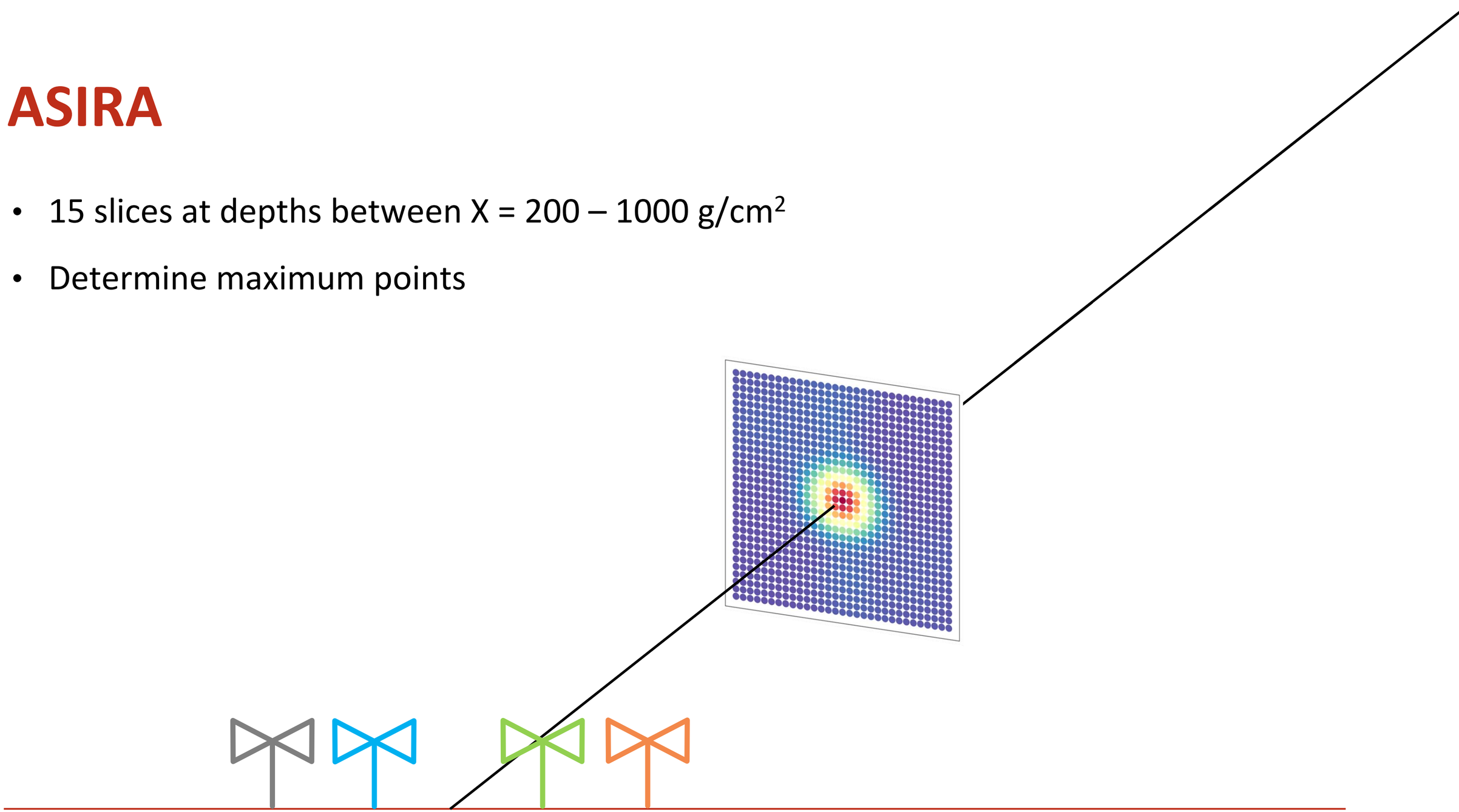
ASIRA

- Determine intensity for every point
- Locate maximum



ASIRA

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



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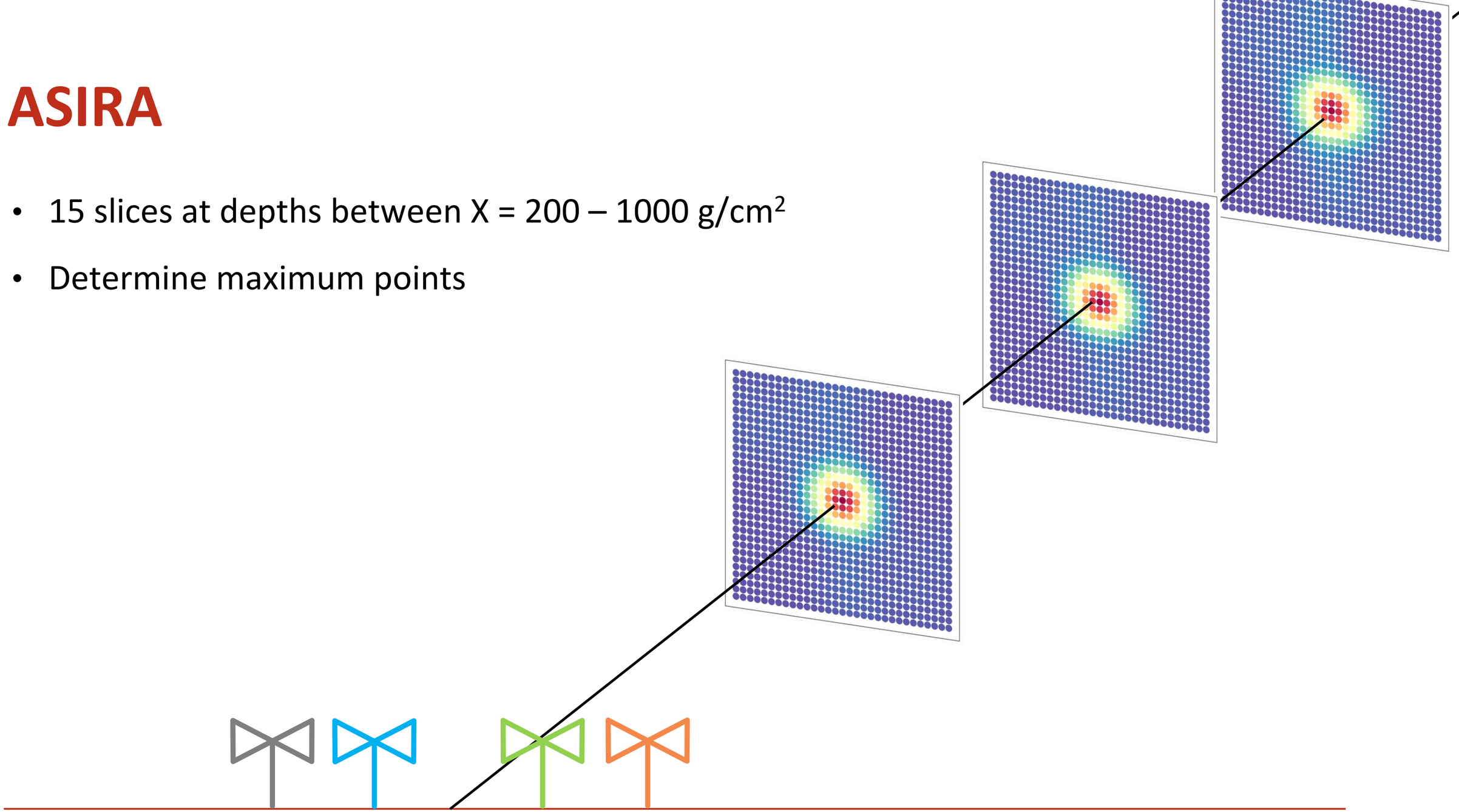

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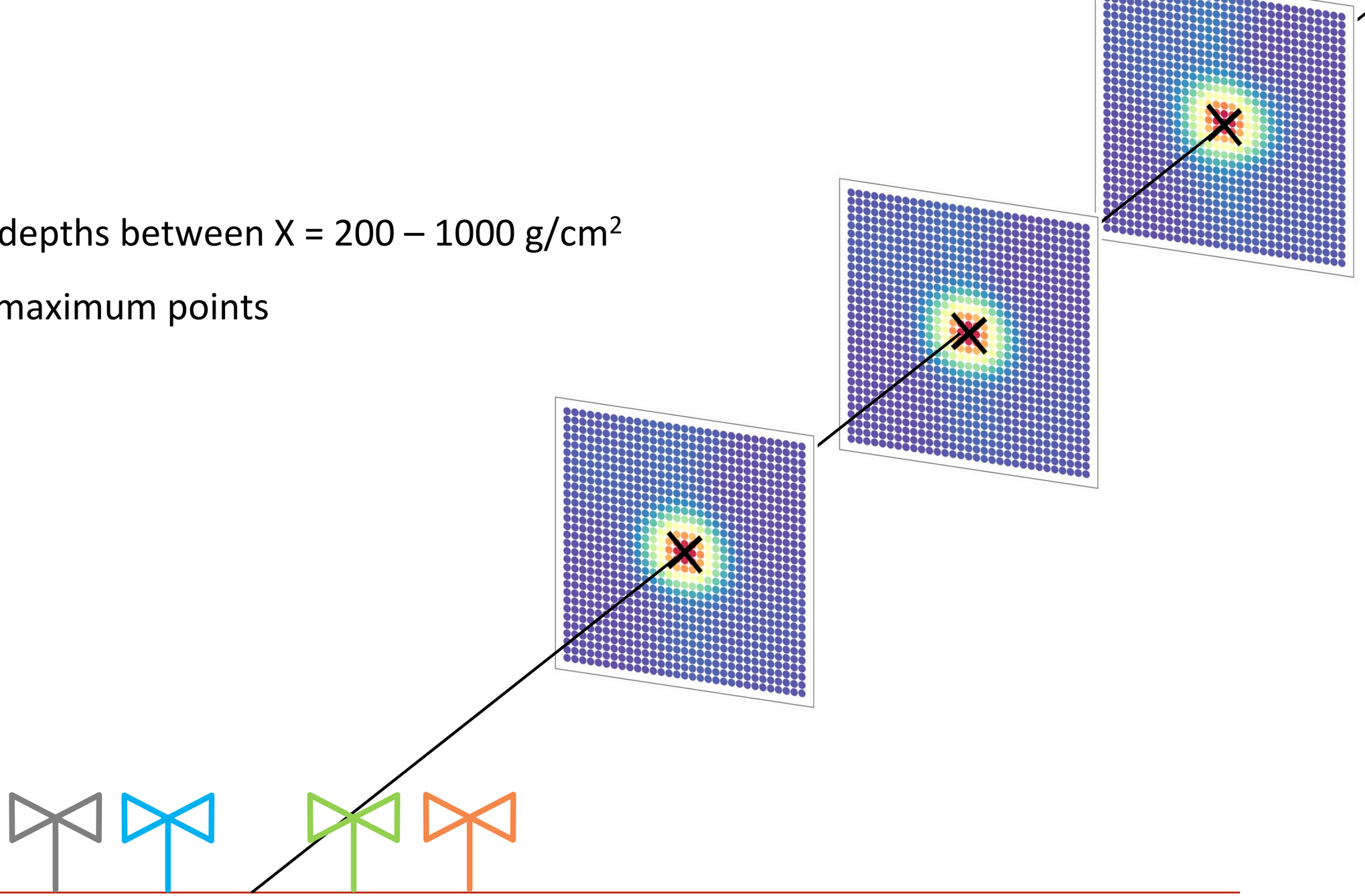
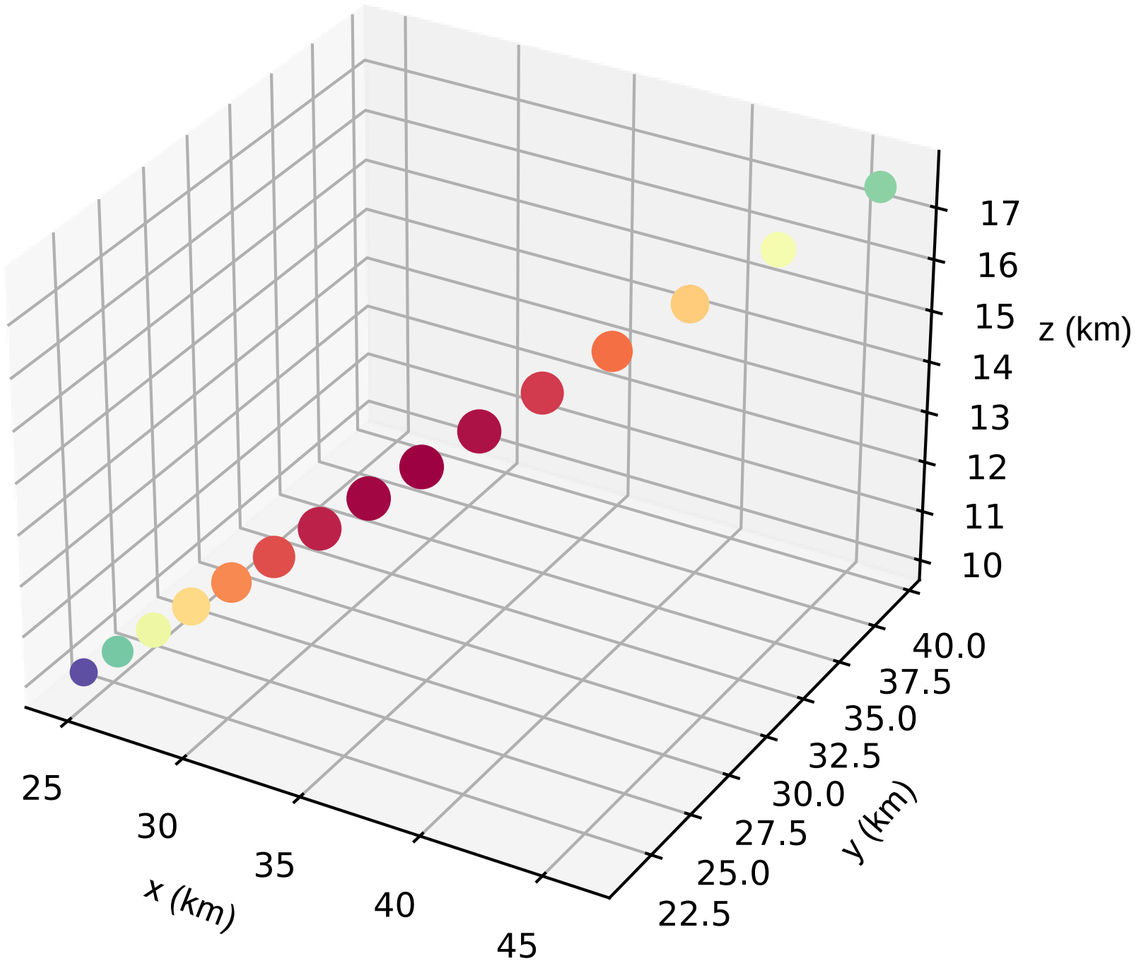


ASIRA

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



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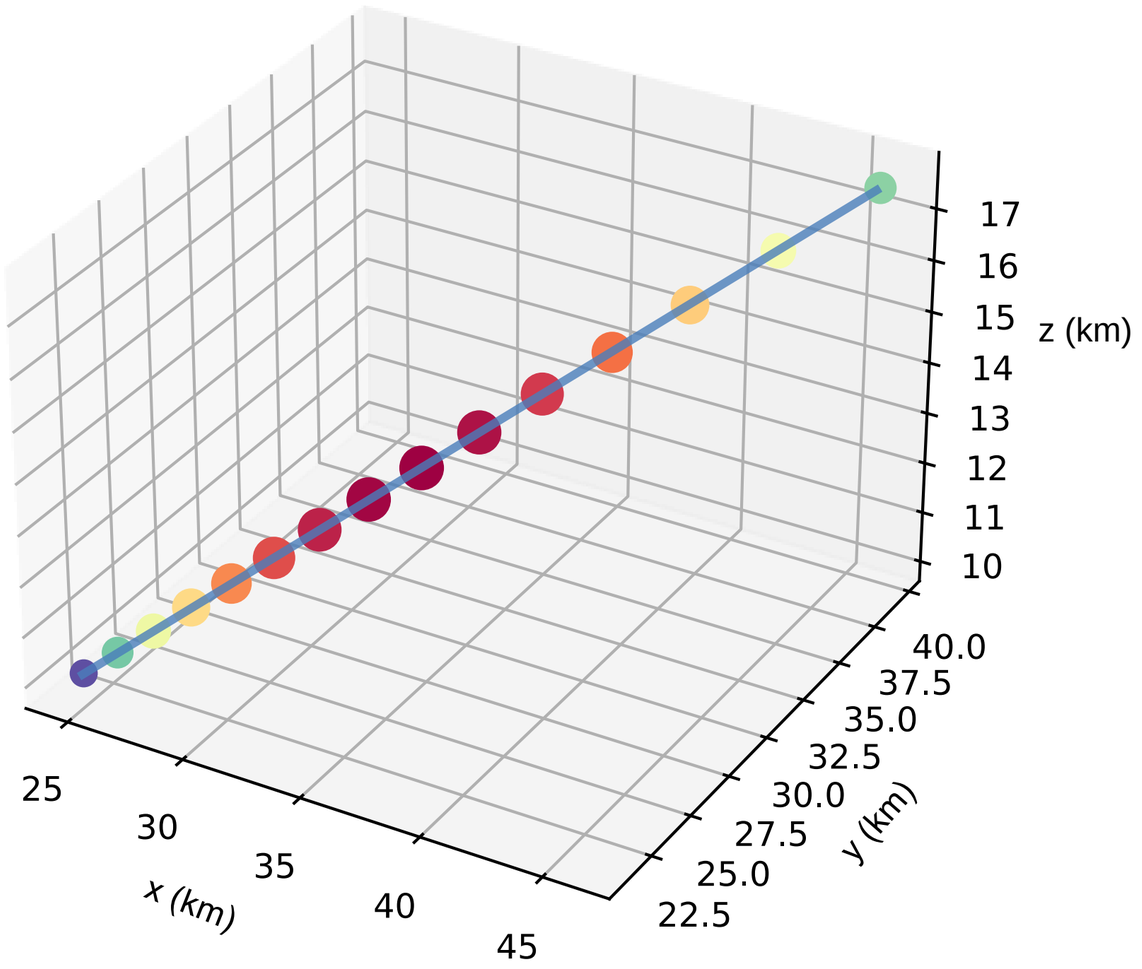
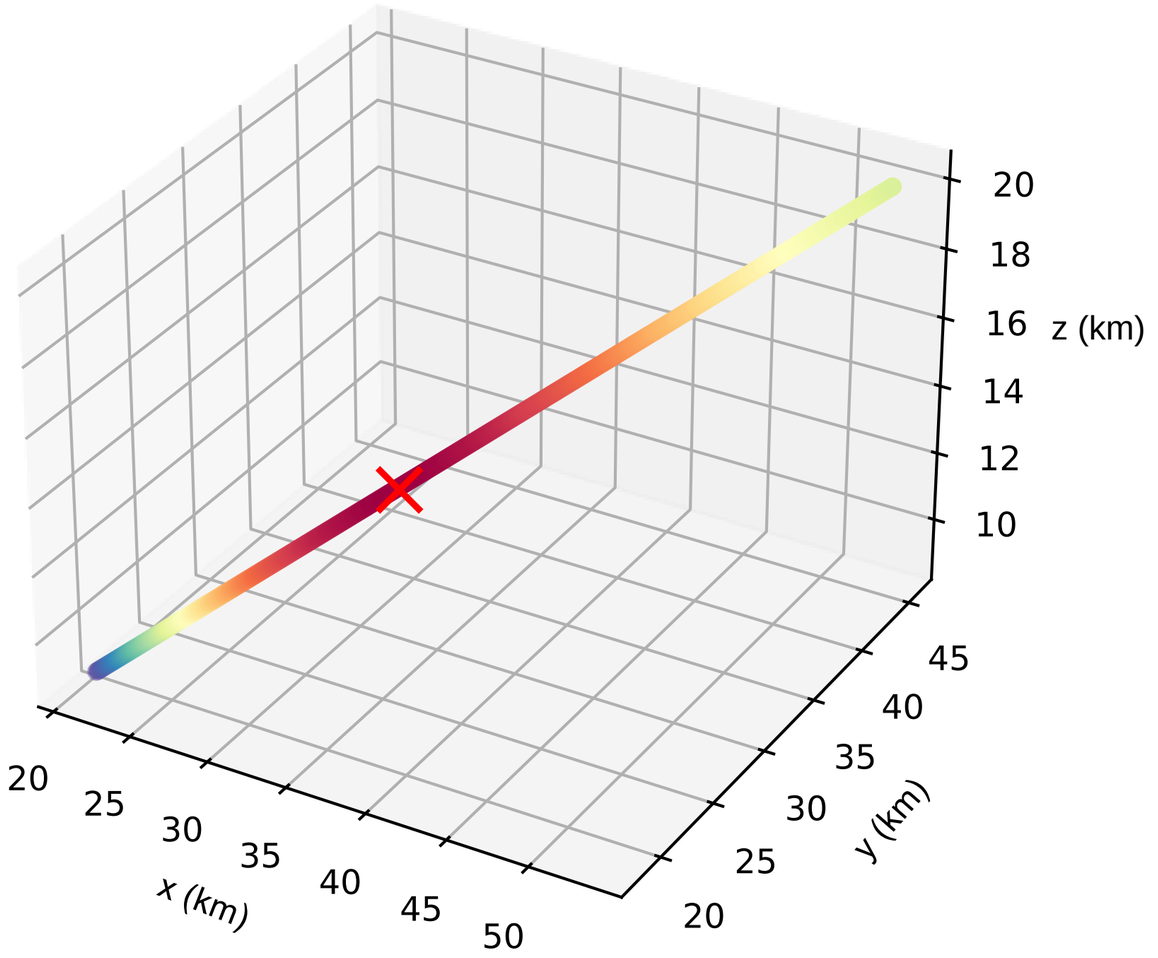


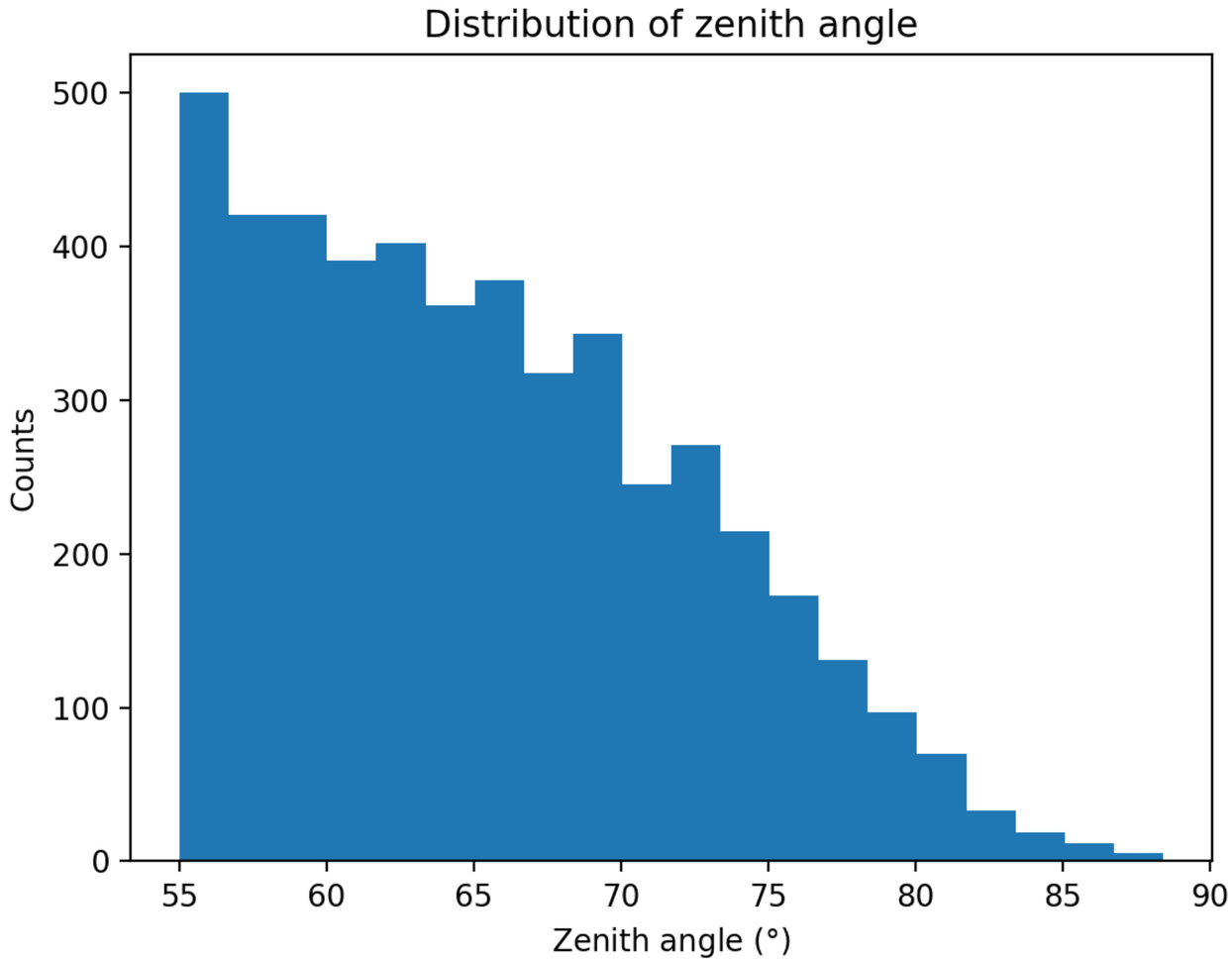
ASIRA

- **Depth of radiation maximum (X_{RIT})**
  - Find maximum intensity along shower axis



Dataset

- Inclined air showers
- Measured with SD as well as AERA
- 5148 events



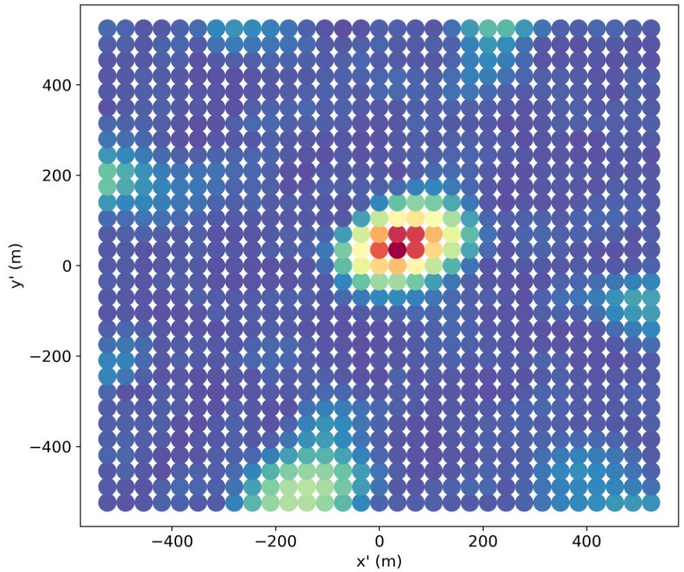
Dataset created by Marvin Gottowik & Felix Rhien

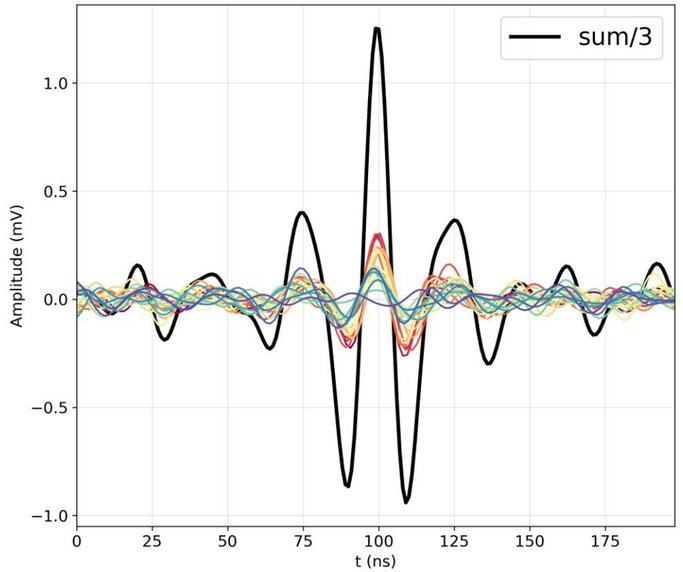
Selection methods

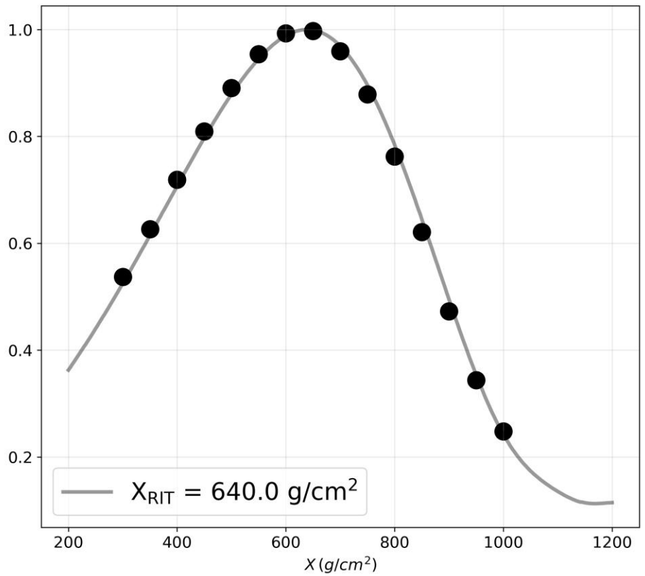
- Seperate usefull events from useless events
- Criteria:
  - Information of late shower development
  - High contrast in slice
  - Good fit through axis points
  - Footprint fully contained
  - No thunderstorm conditions

Results

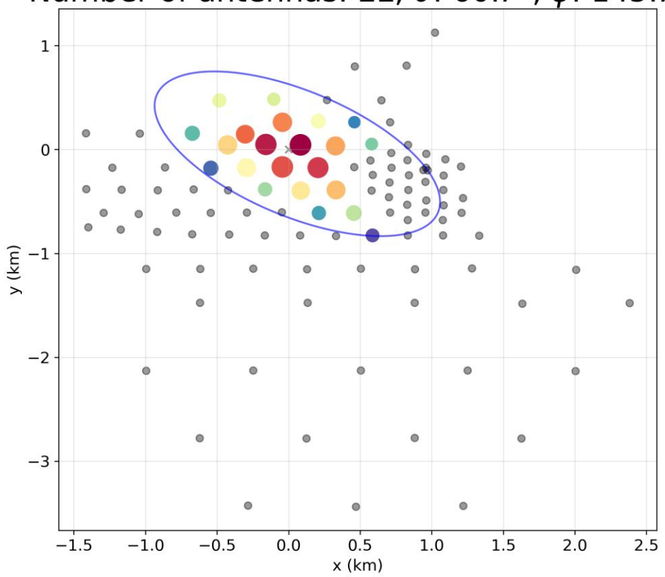
- 665 events
- Reconstructed:
  - Shower axis
  - Core
  - X_{RIT}





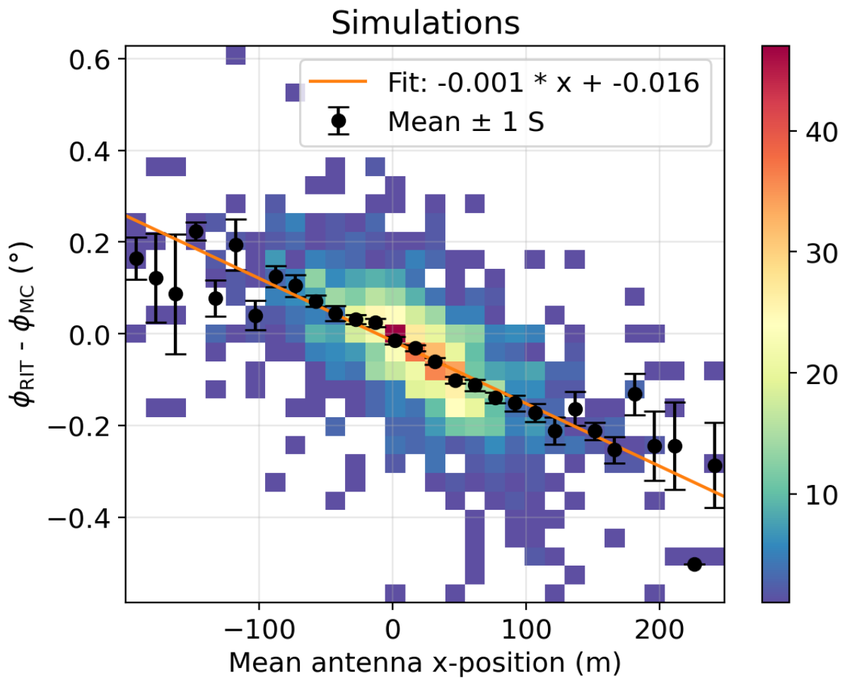


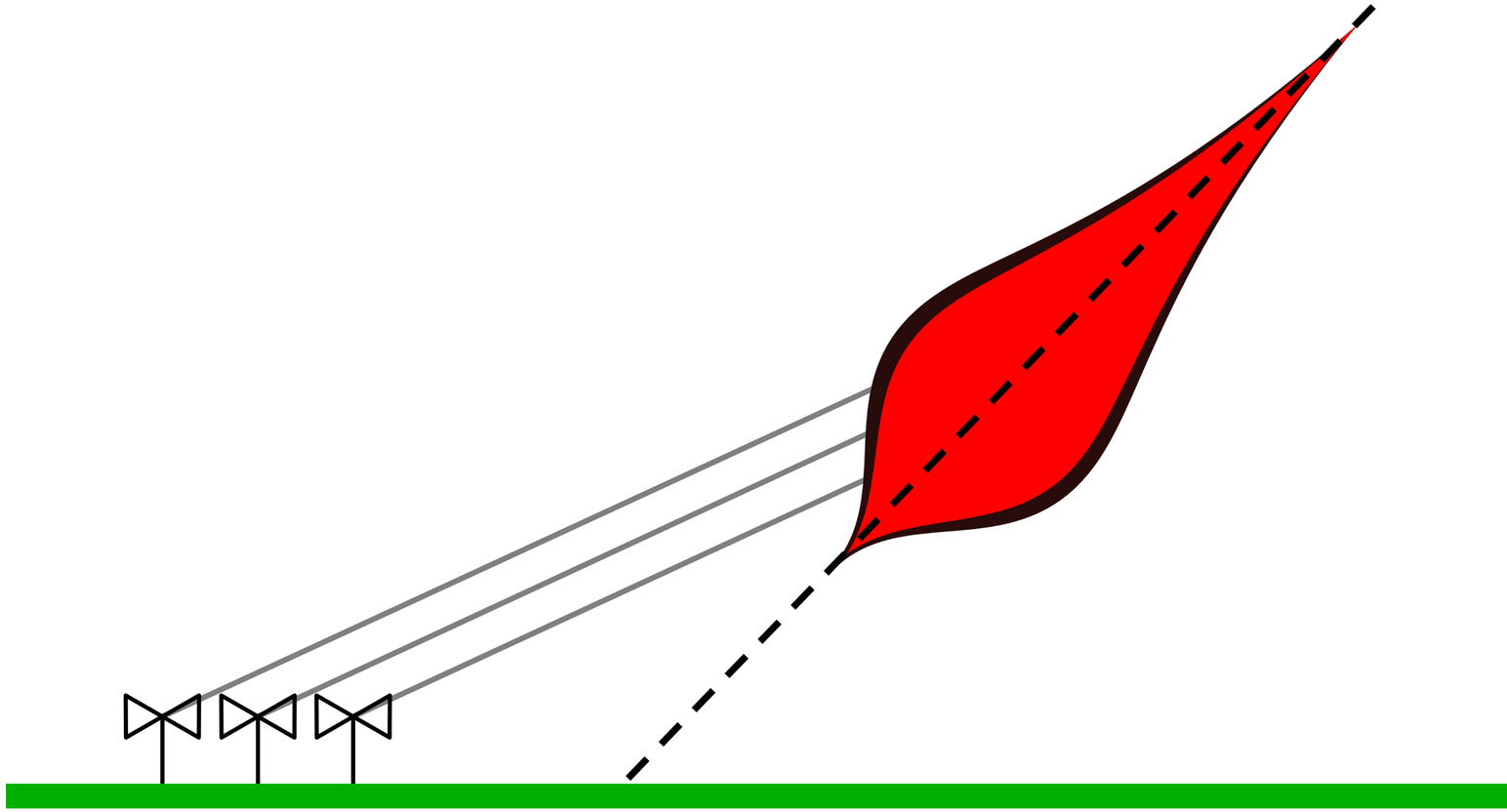
Number of antennas: 22; θ: 60.7°, ϕ: 145.7°



Bias

- Slight bias depending on antenna position





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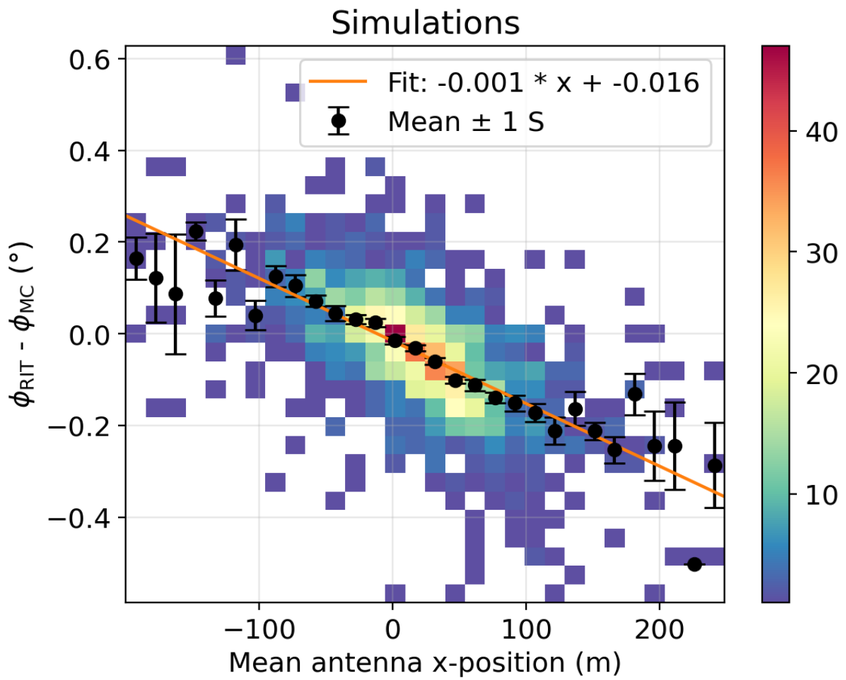
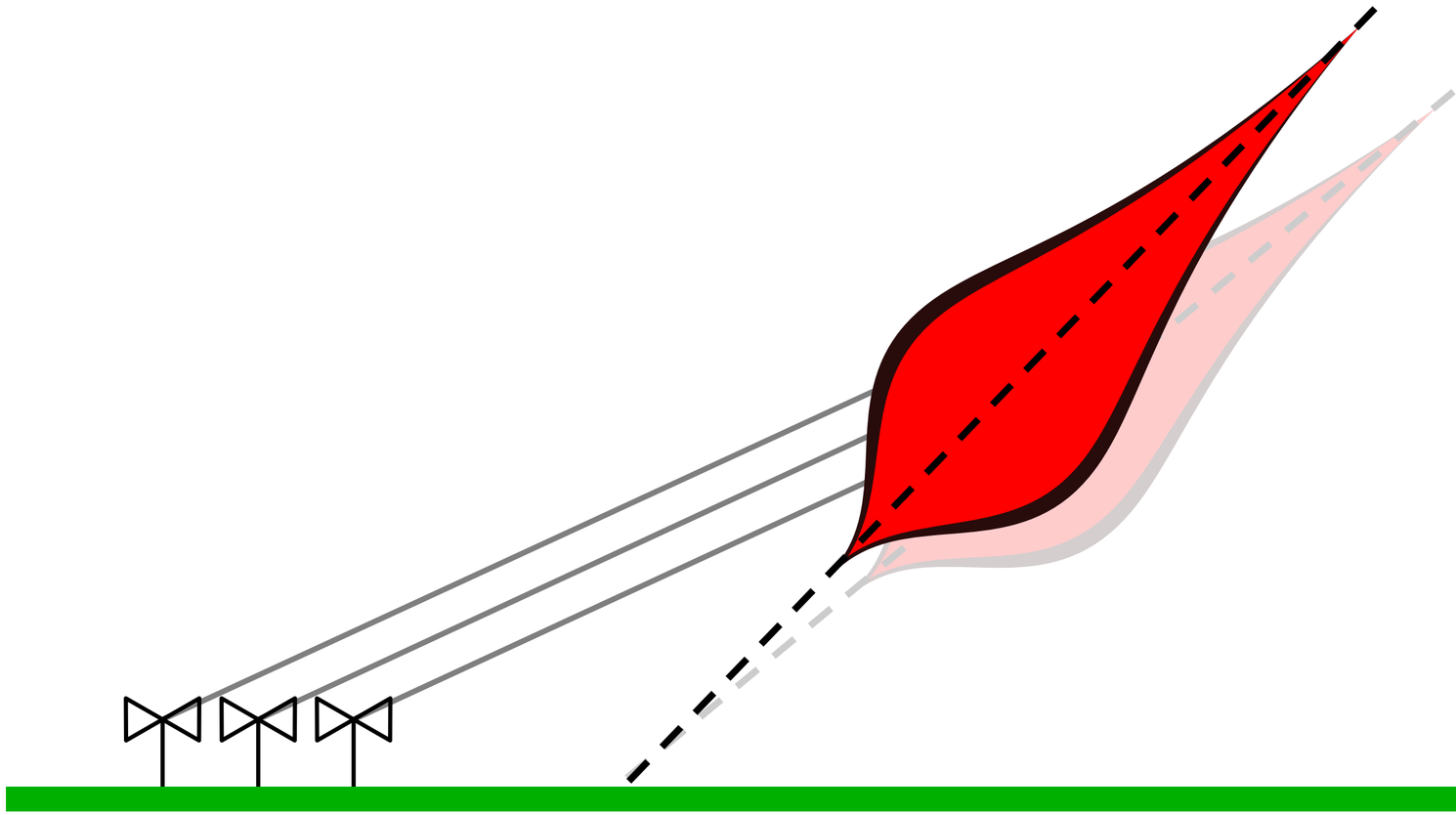
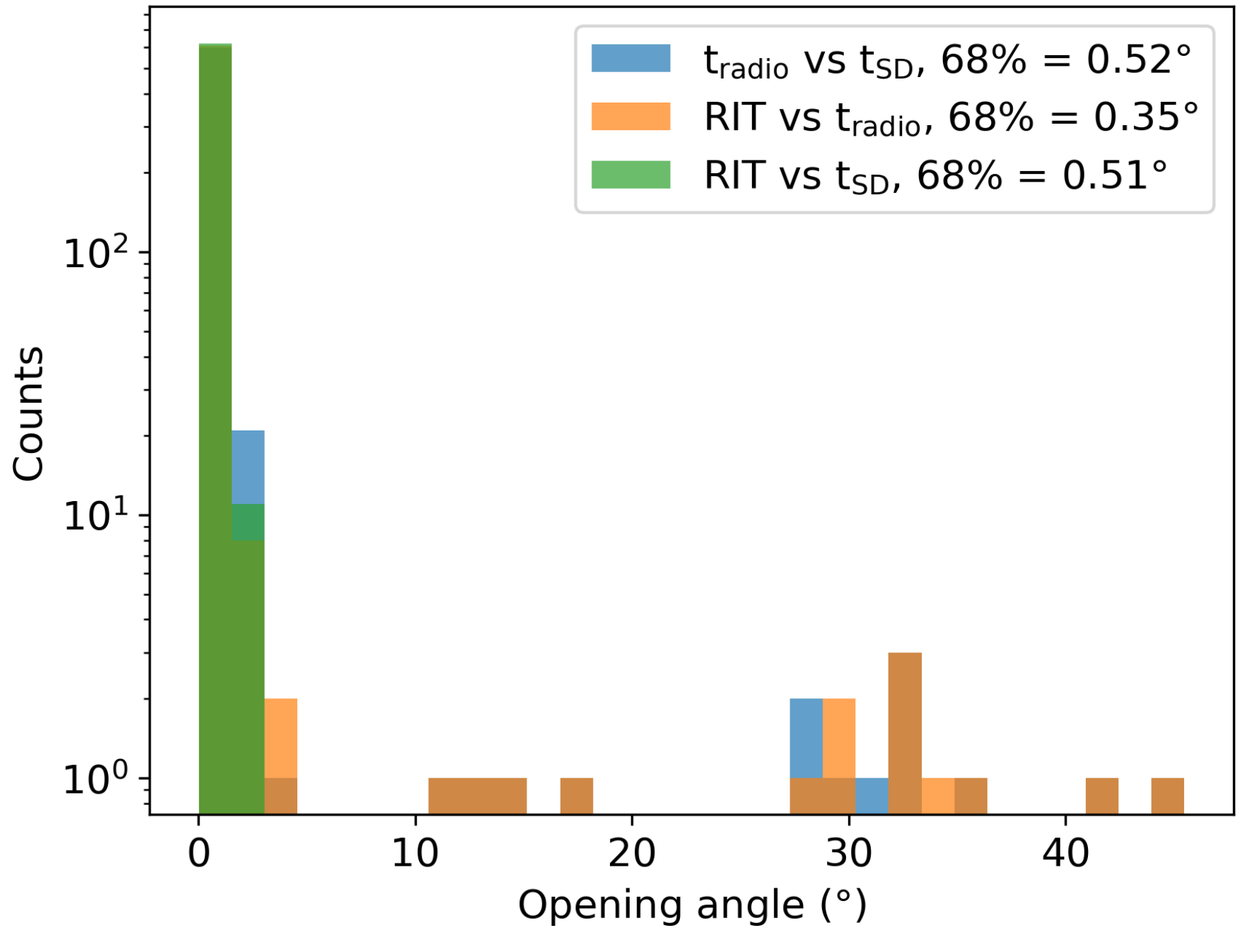




Results – Opening angle

- Opening angle between different reconstructions



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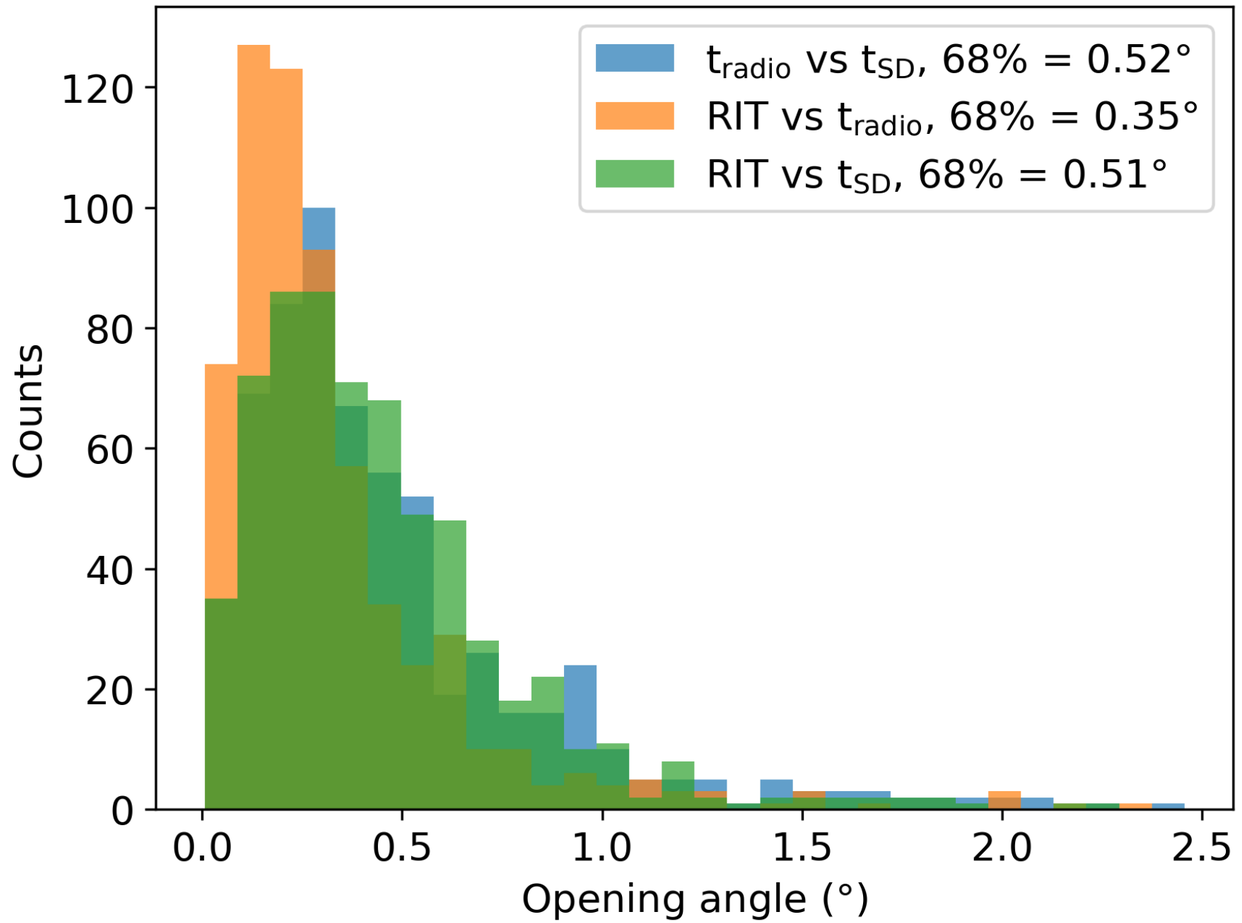
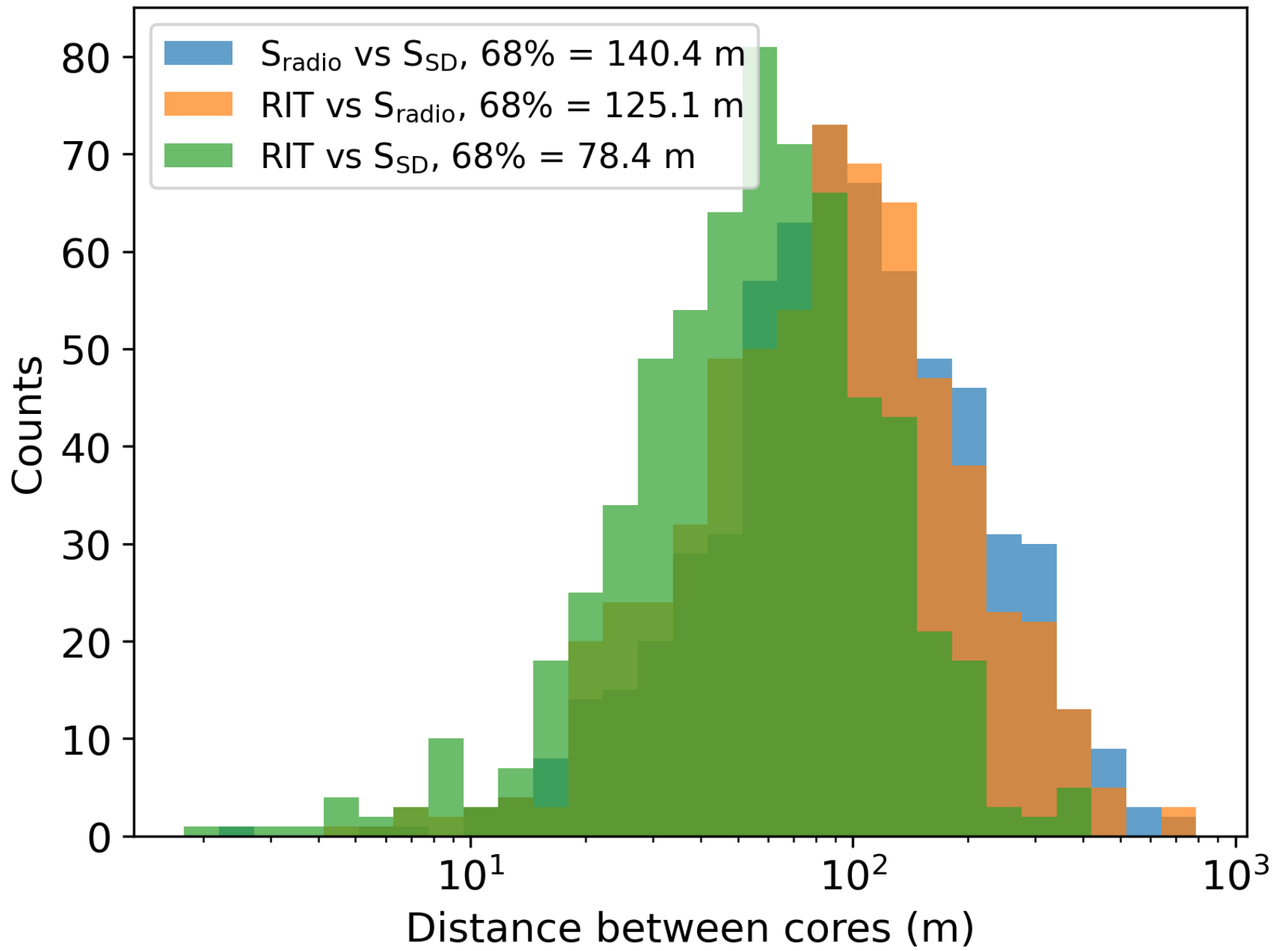


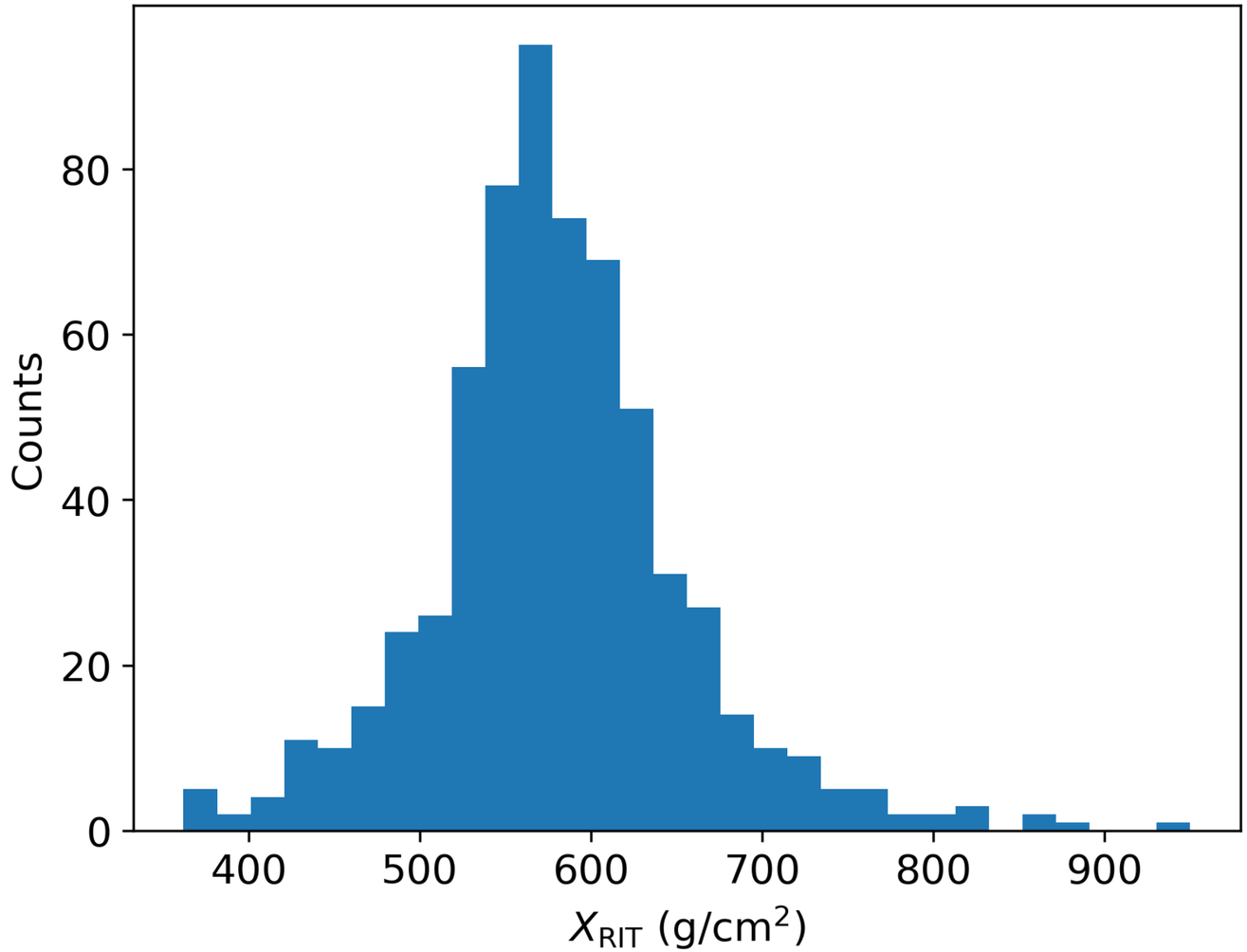
Results – Core

- Distance between cores of different reconstructions
- Shower plane



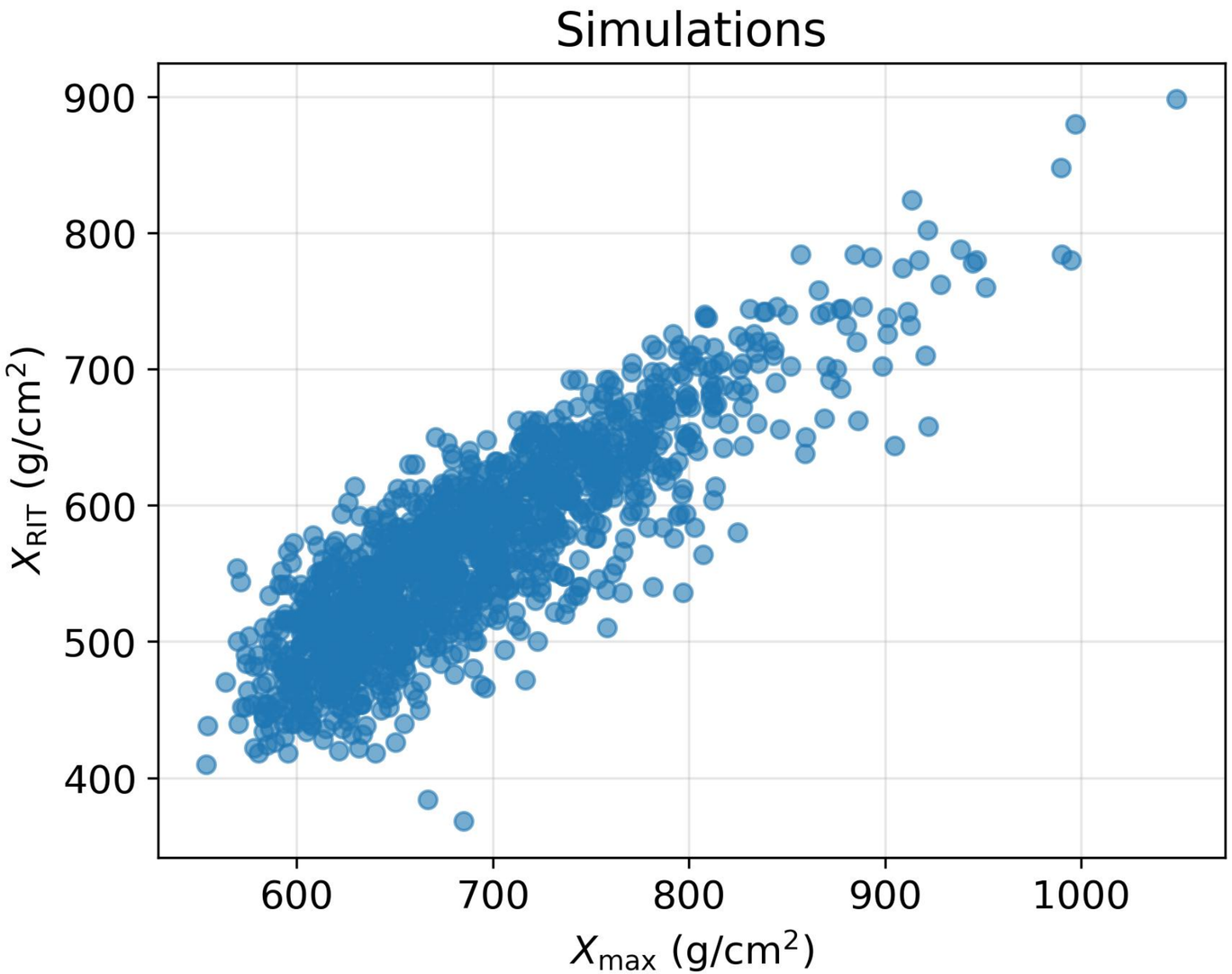
Results – X_{RIT}

- Depth of radiation maximum
- Not the same as X_{max}
  - Conversion needed



Results – X_{RIT}

- Conversion based on simulations
- No trivial relationship
- Dependent on:
  - Zenith angle
  - Antenna layout



Conclusion

- Interferometry for the first time applied to large dataset
- Good results
- X_{max} measurements possible
  - Composition studies

Outlook

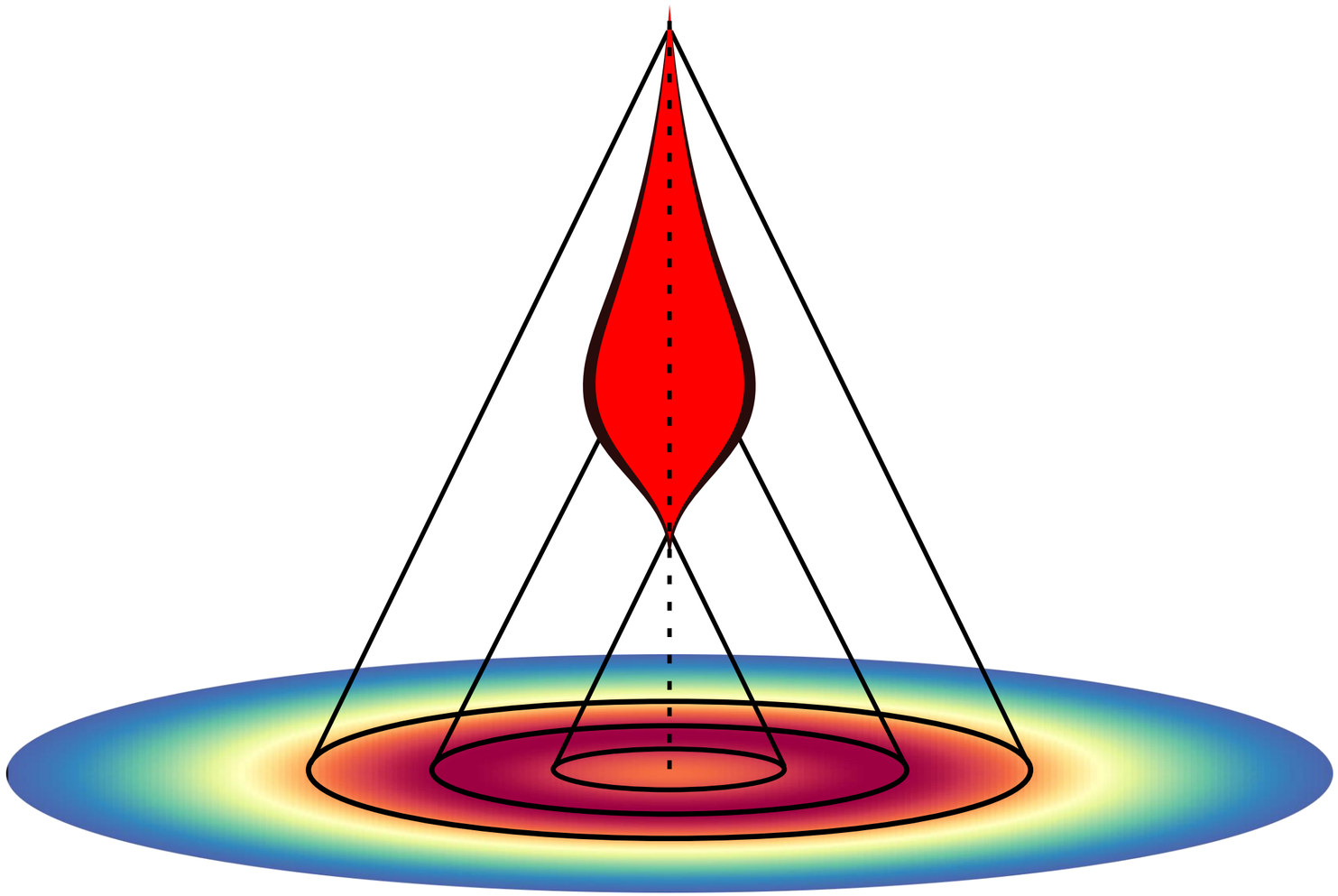
- Can be used on whole array because of AugerPrime upgrade
- What should be done to enable interferometry:
  - Install beacon for time synchronisation below 1 ns
  - GPS survey to get position accuracy below 30 cm
- New tool to help unravel the mysteries of the most energetic cosmic rays!

Questions?

BACKUP

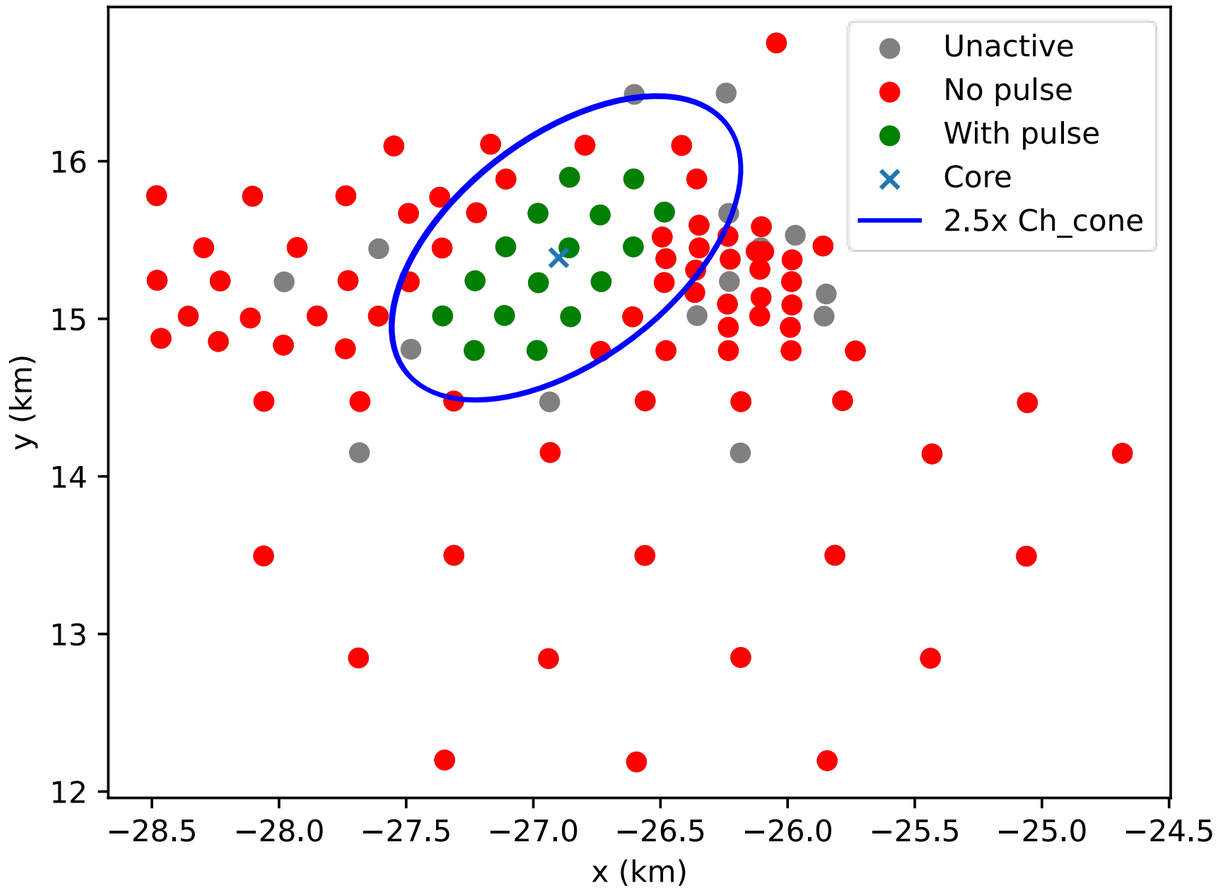
Radio Emission

- Coherent radiation
  - Frequencies < 100MHz
- **Cherenkov cone**



Antenna selection

- Also information in antennas without pulse
- Only use antennas with sufficient shower signal



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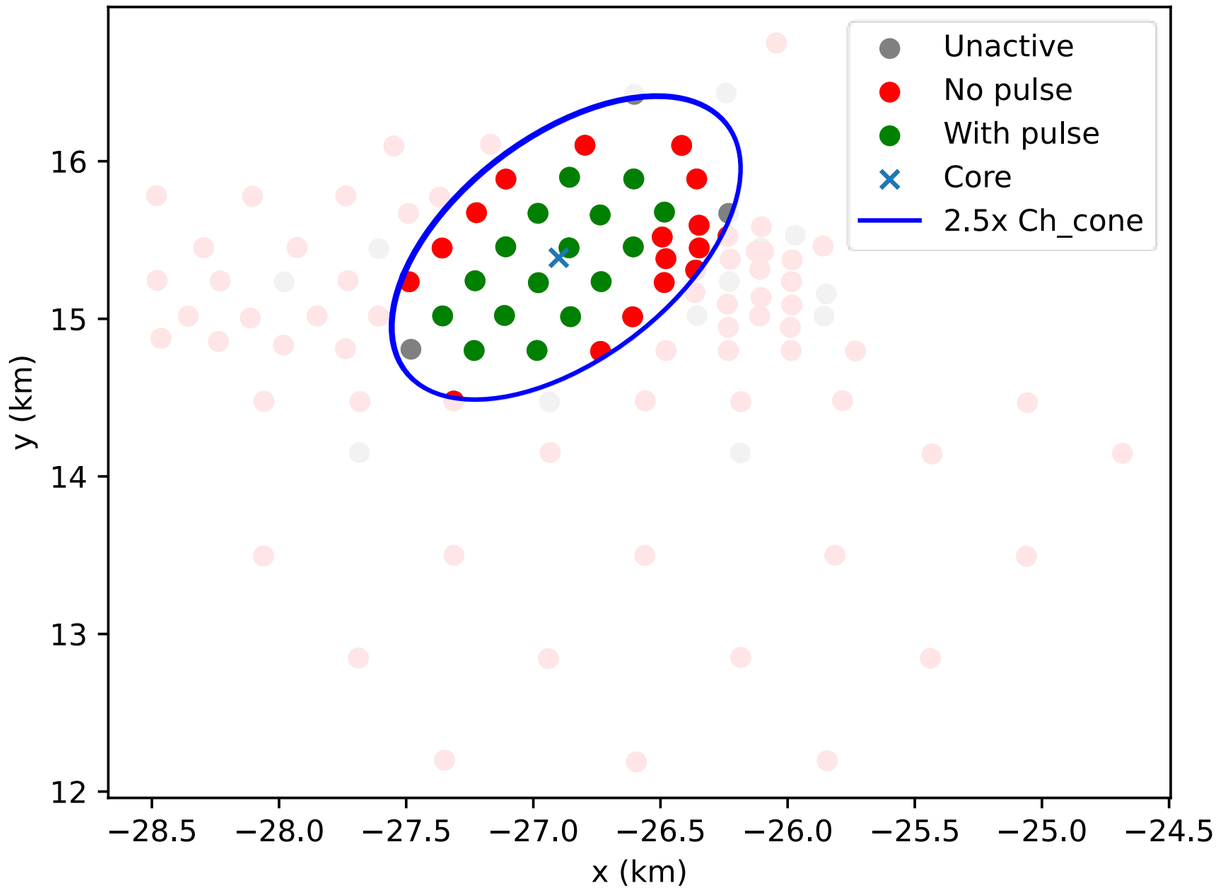
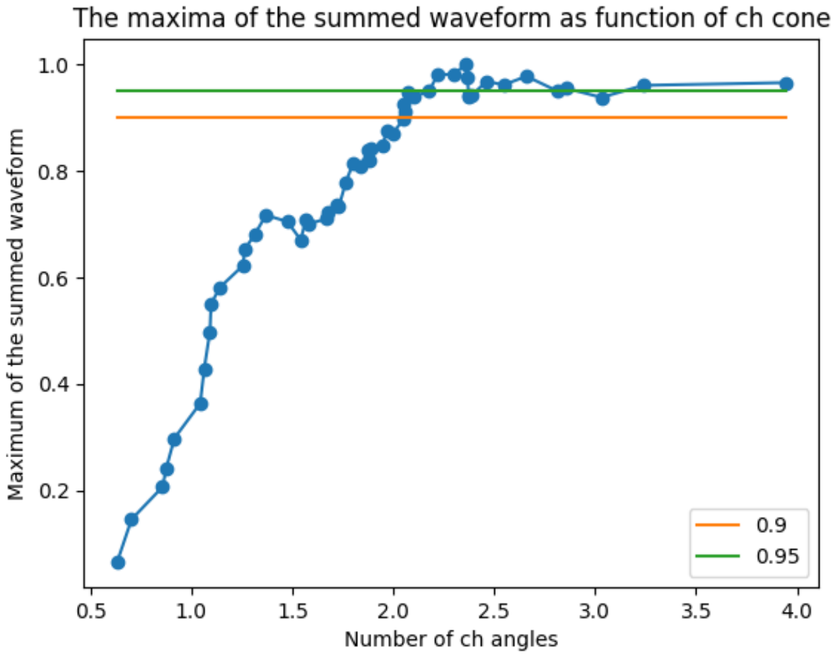
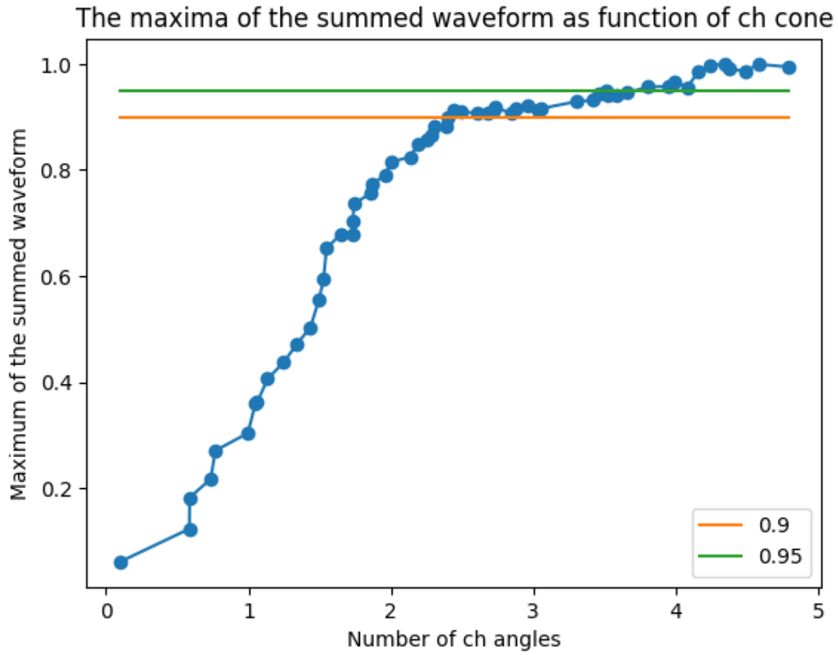
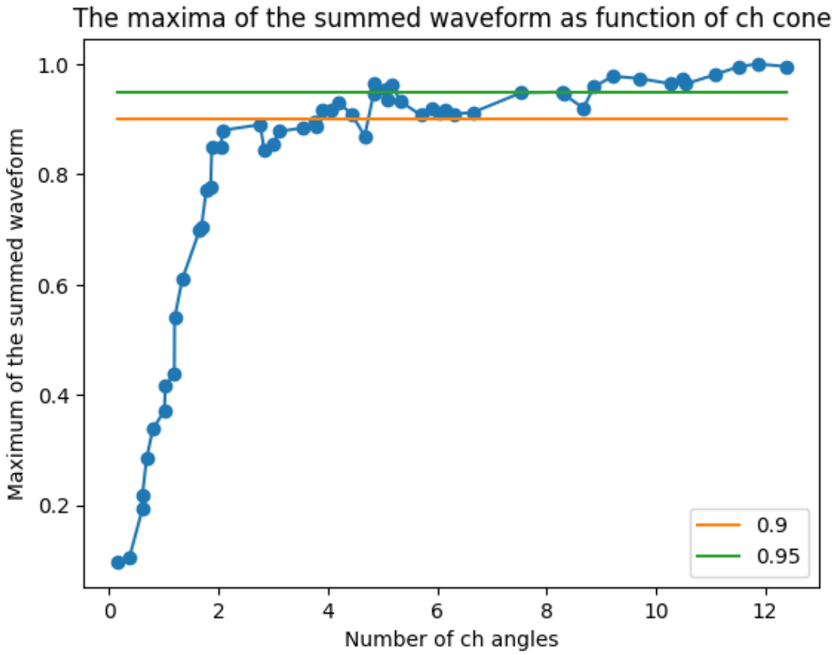


Antenna selection

- **Contribution to the summed waveform peak**



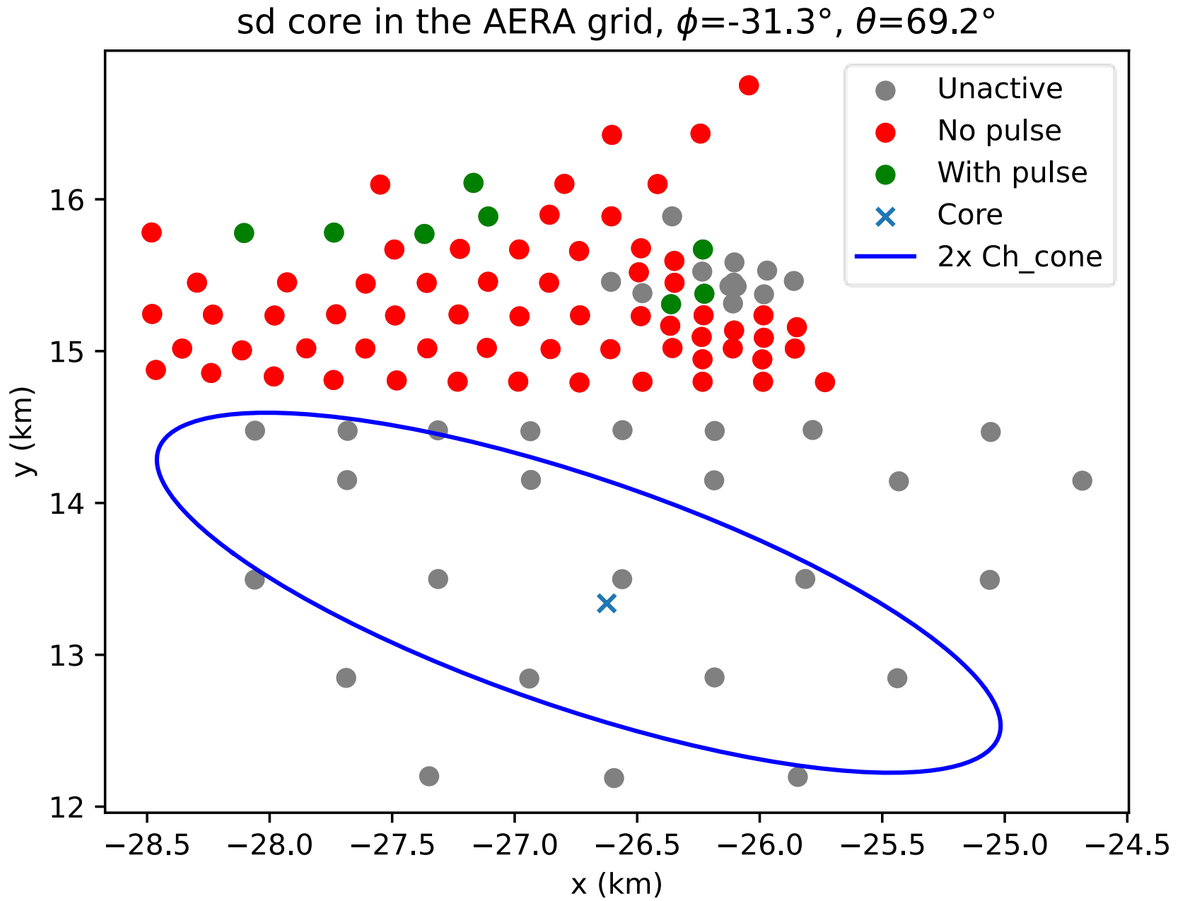




Selection methods

- Seperate usefull events from useless events

- **Antenna in 2x Cherenkov cone**
- Mean slice intensity
- Intensity residual
- Core in antennas



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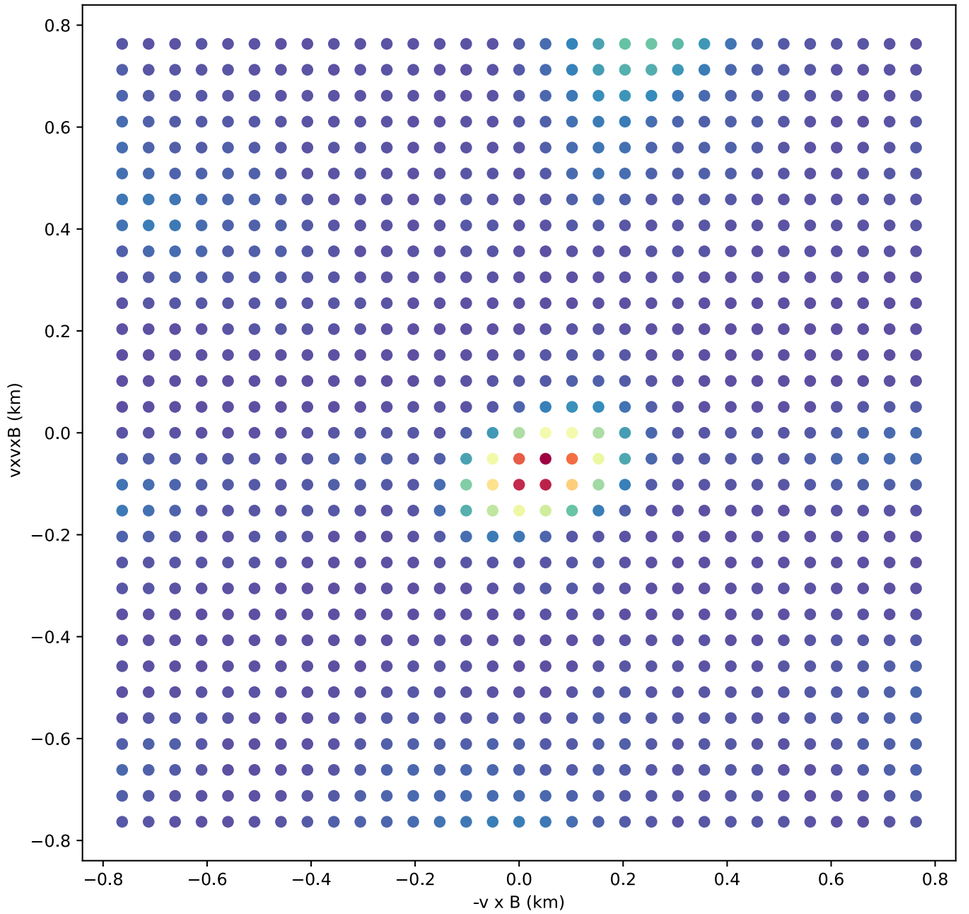

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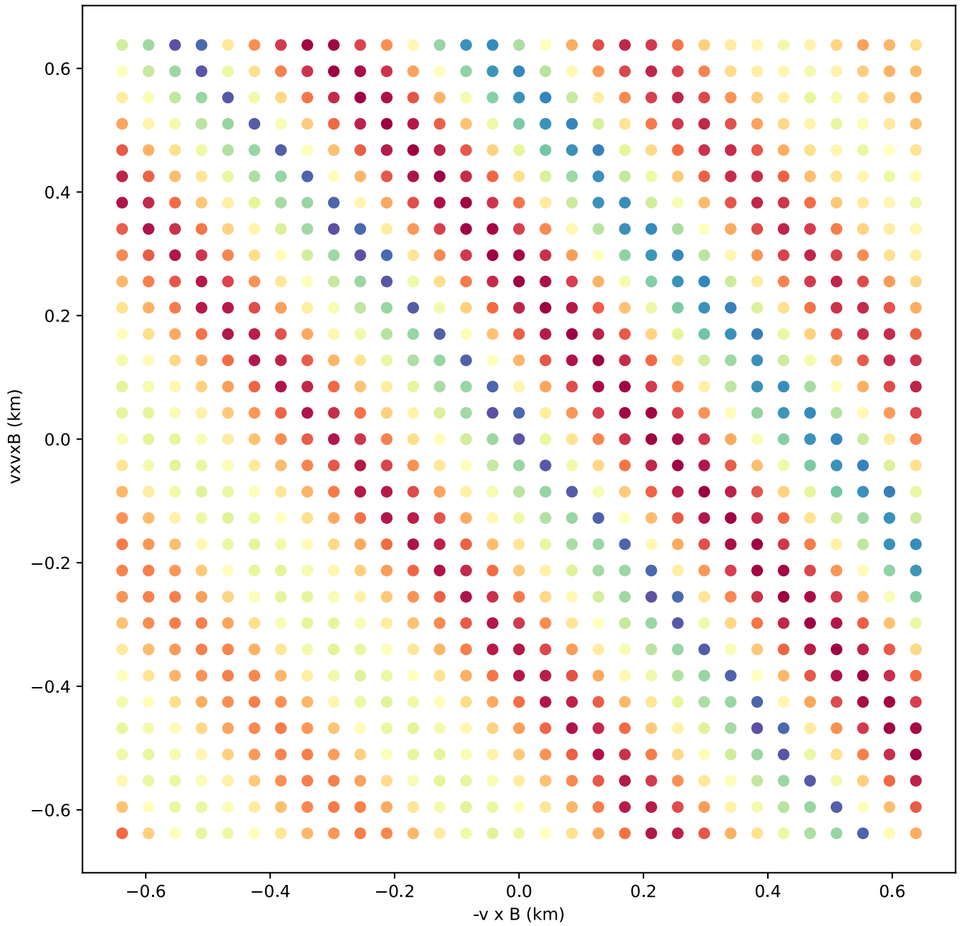

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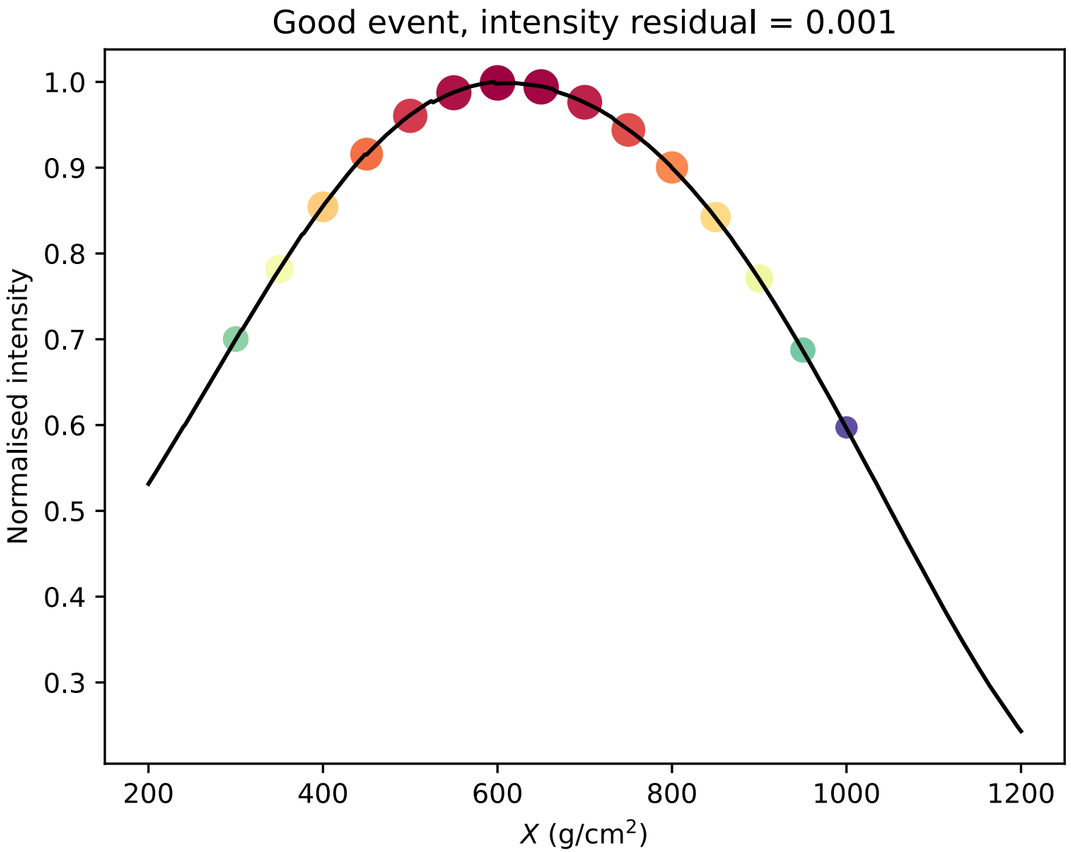

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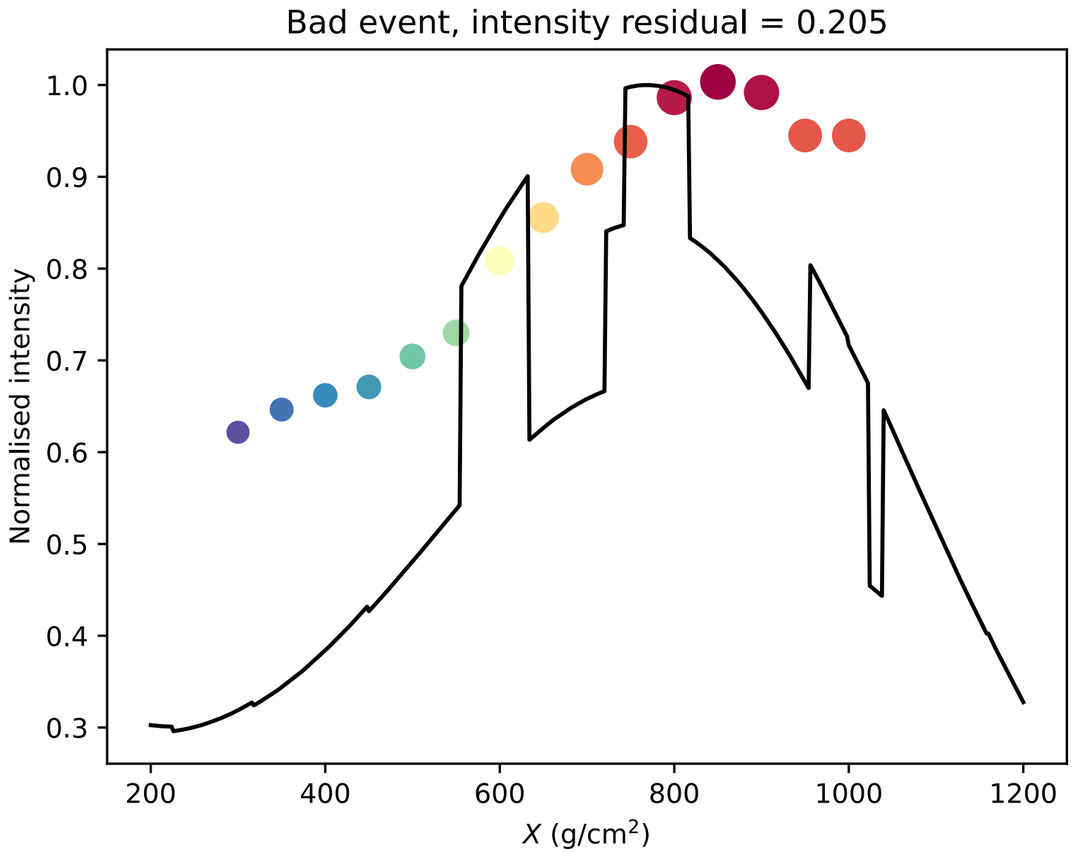

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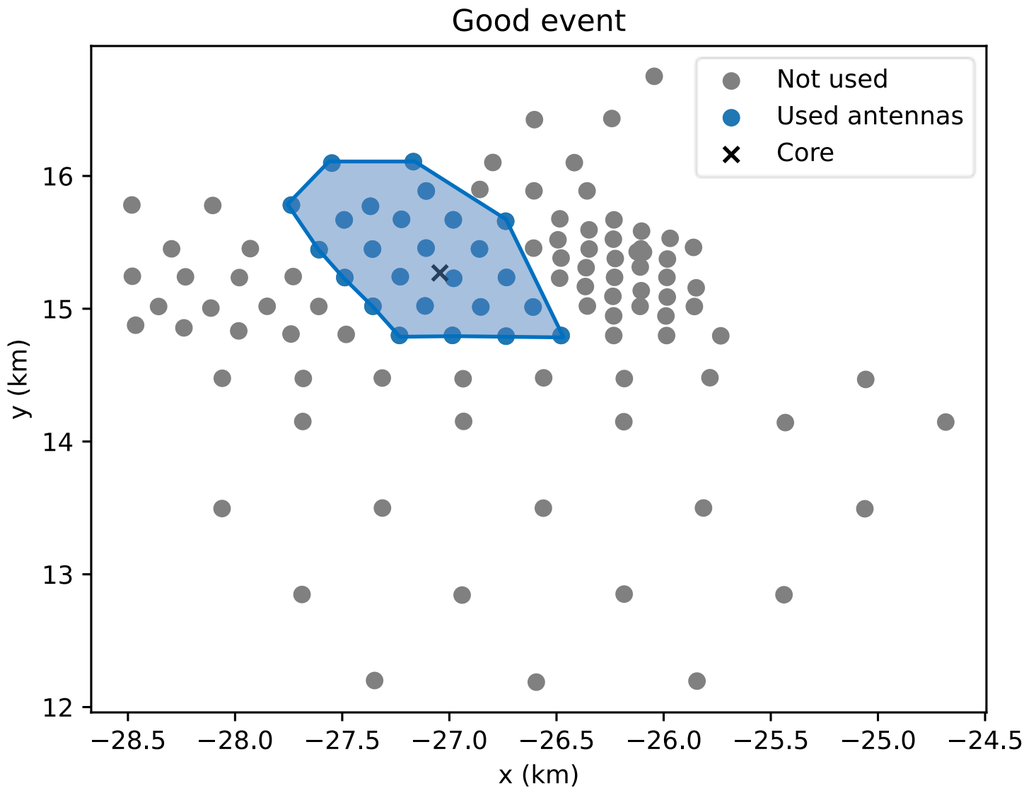
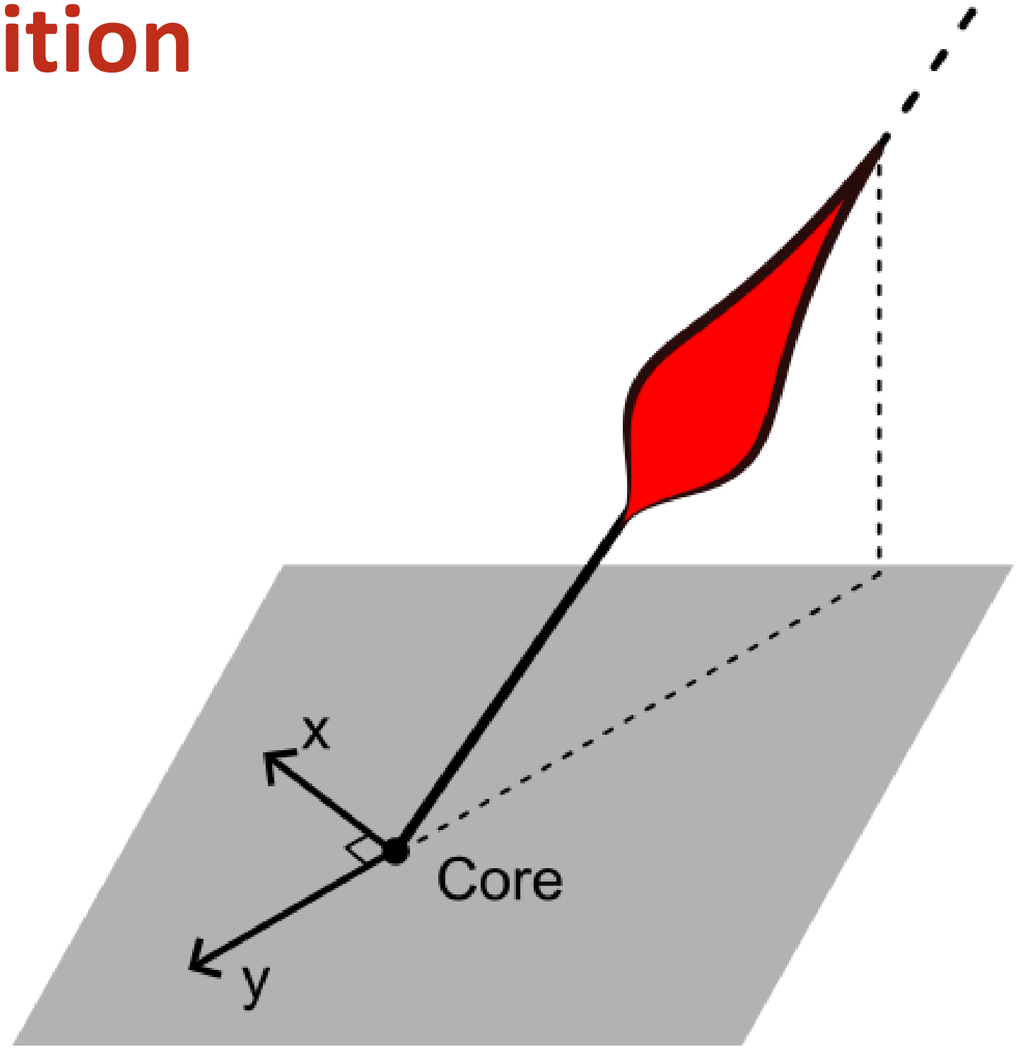


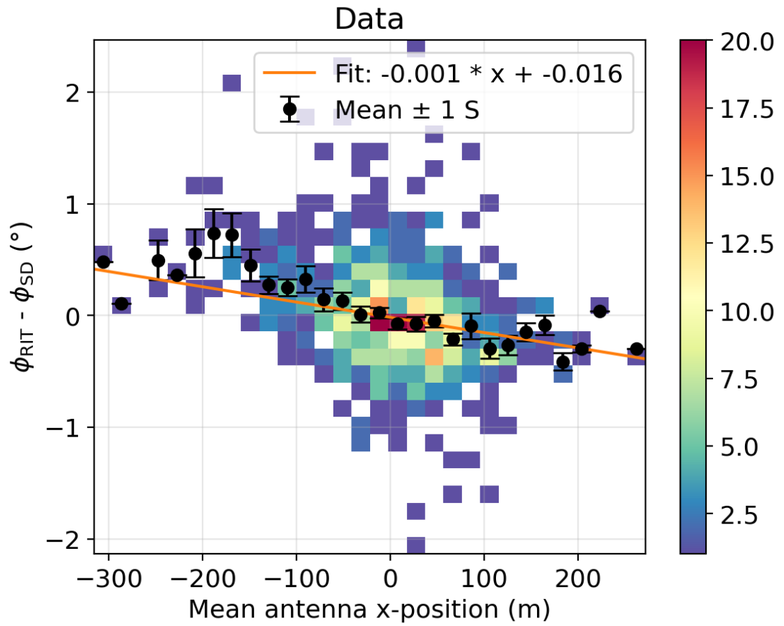
Biases – Mean antenna position

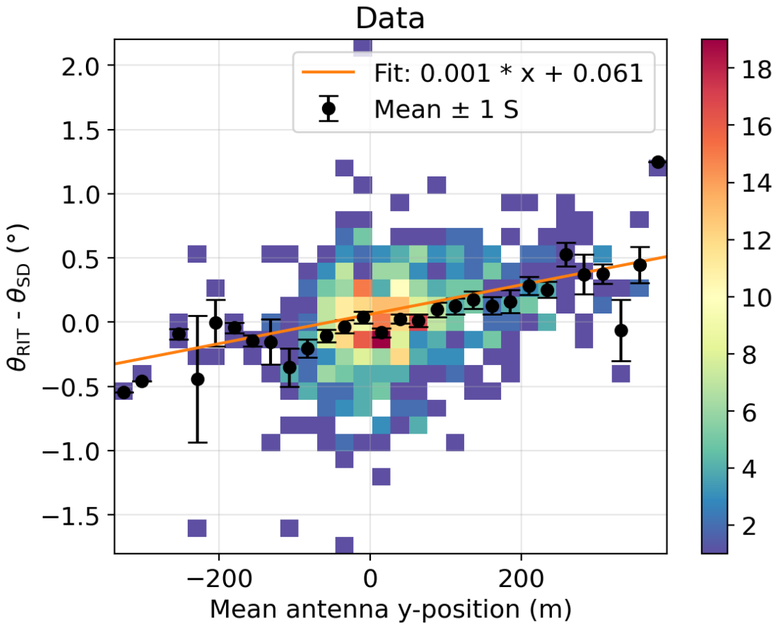
- Center of mass/barycenter

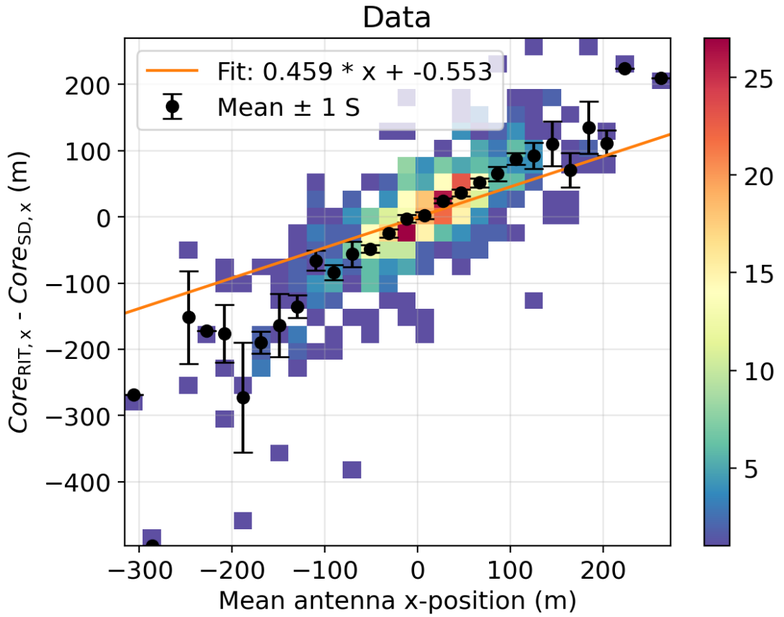


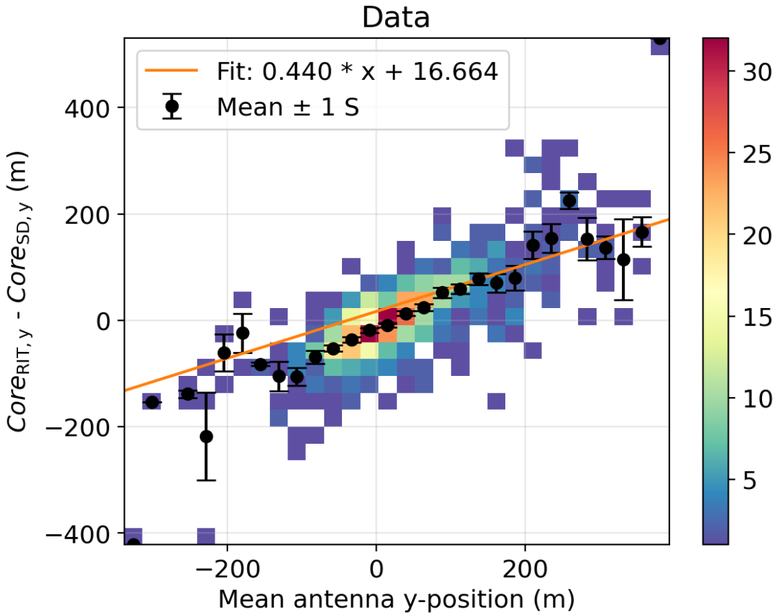
Bias – Data

- Linear fit based on simulations



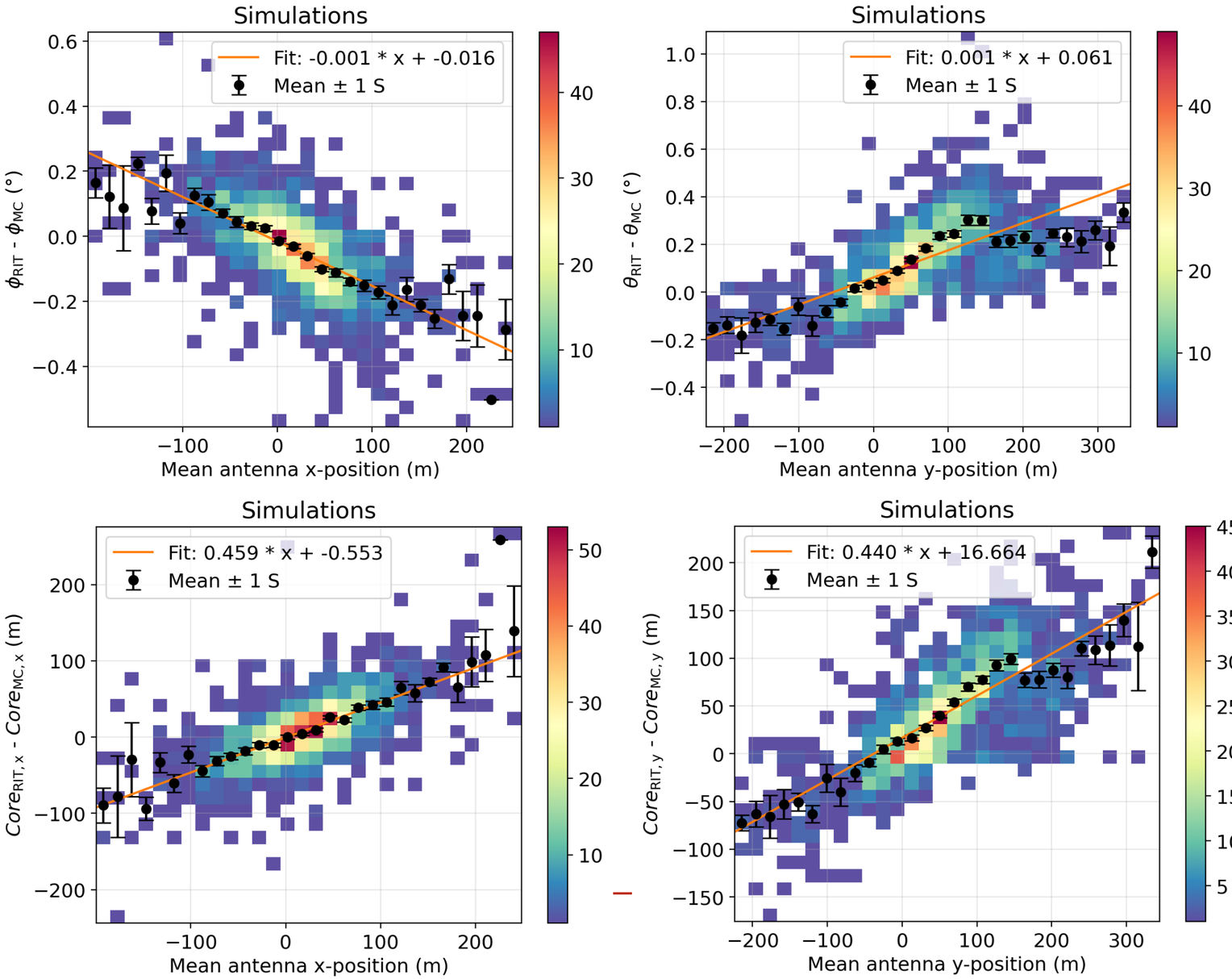






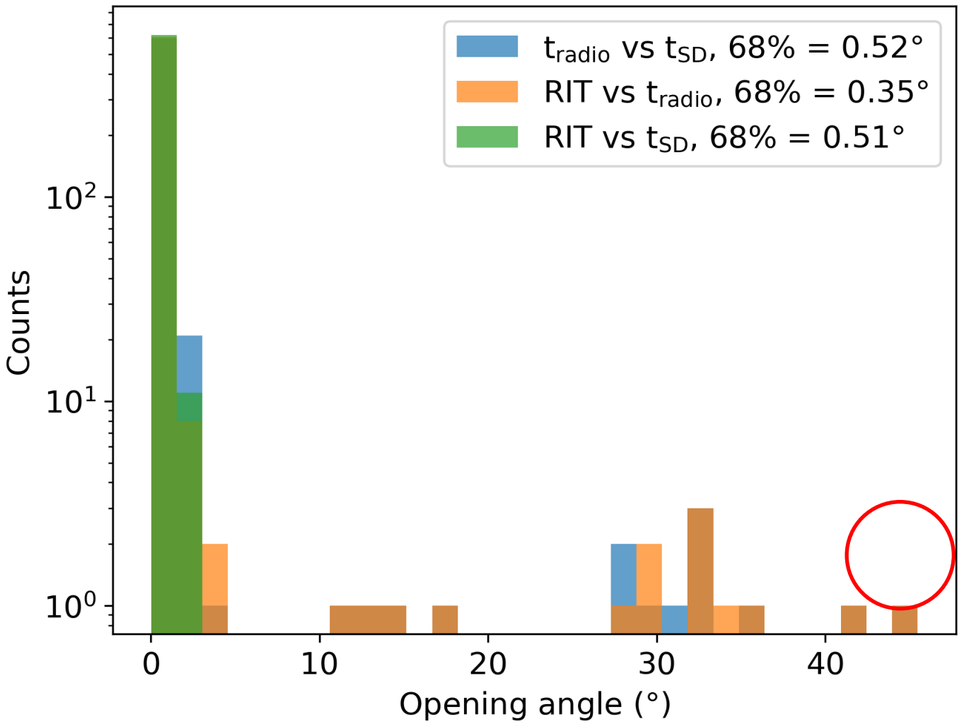
Bias – Simulations

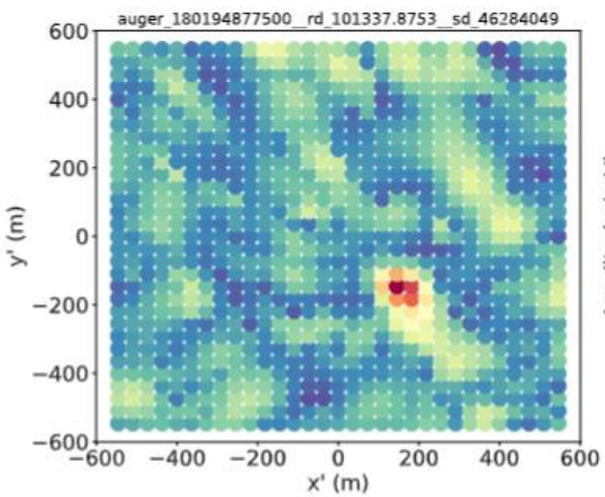
- Correct with linear relation

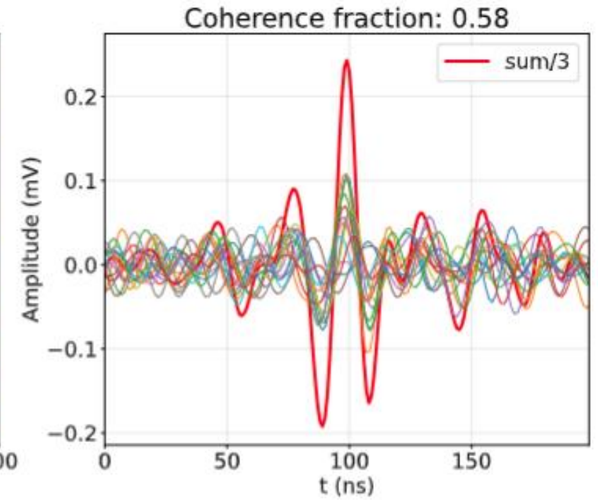


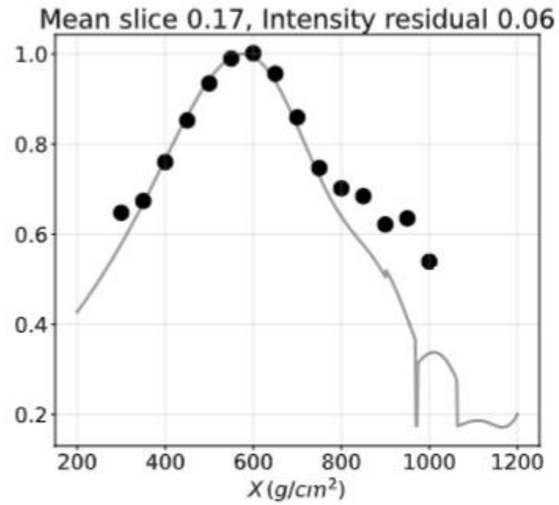
Outlier

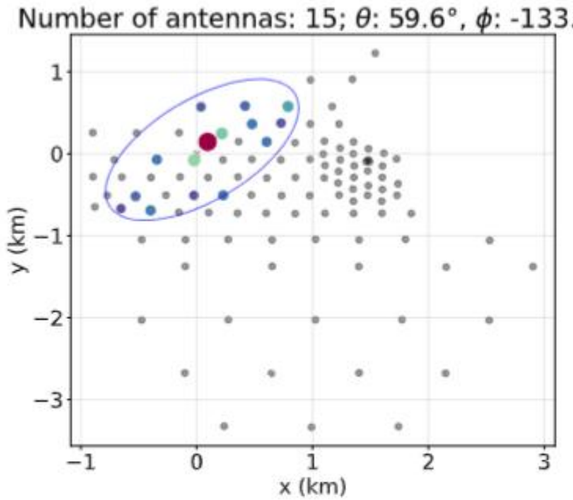
- Only 4 antennas used in RD reconstruction
- RD vs RIT: 44.5˚
- SD vs RIT 1.4˚





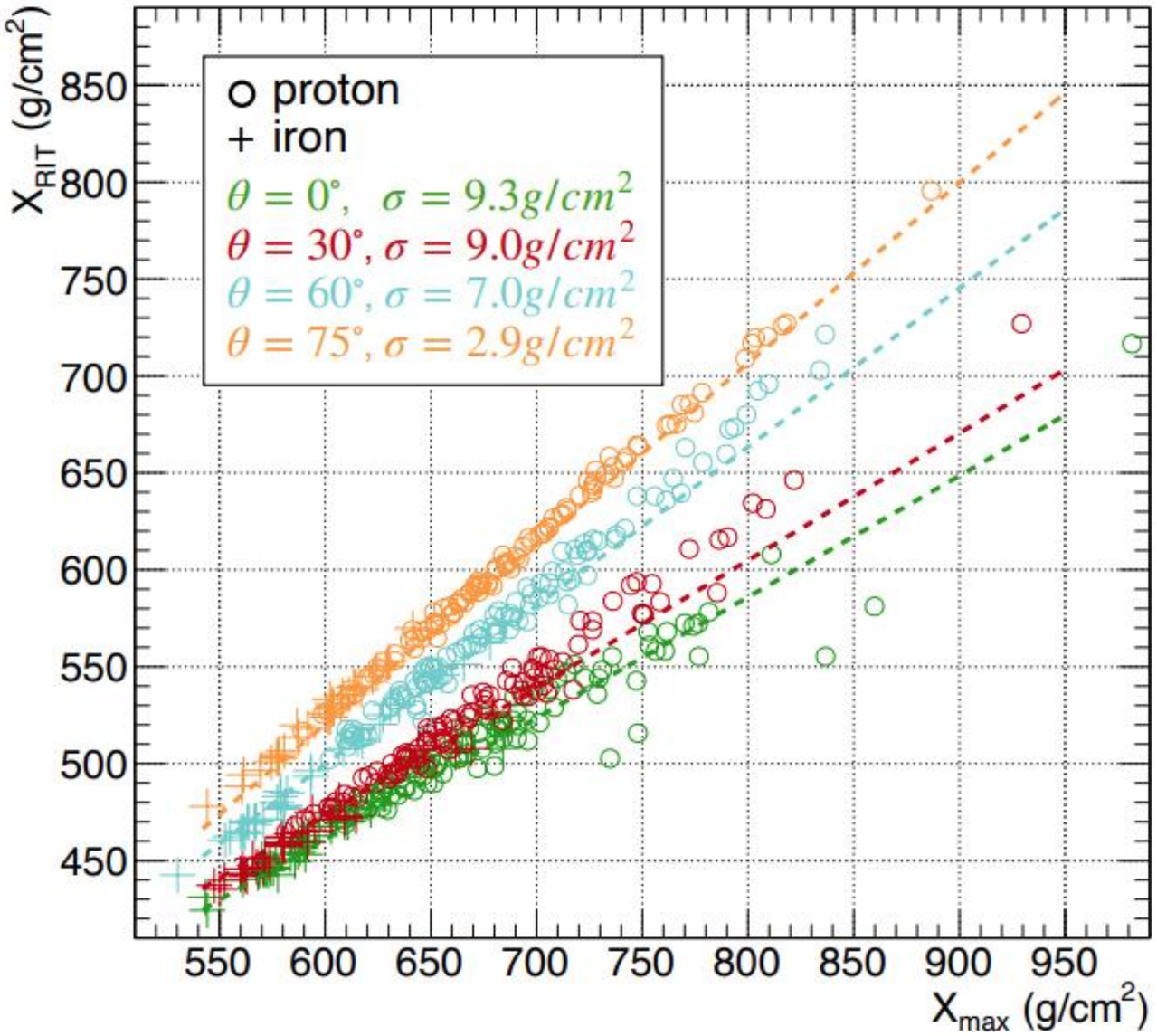






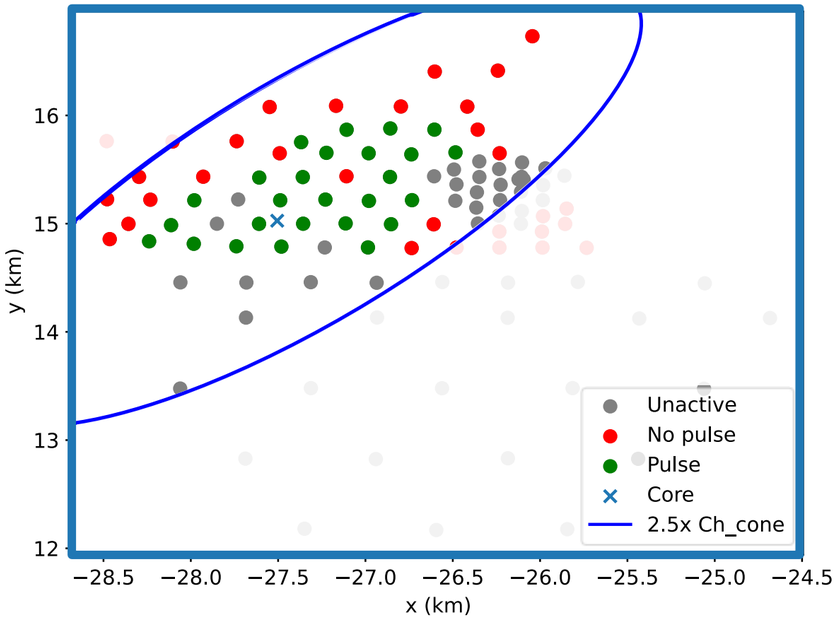
X_{RIT} to X_{max}

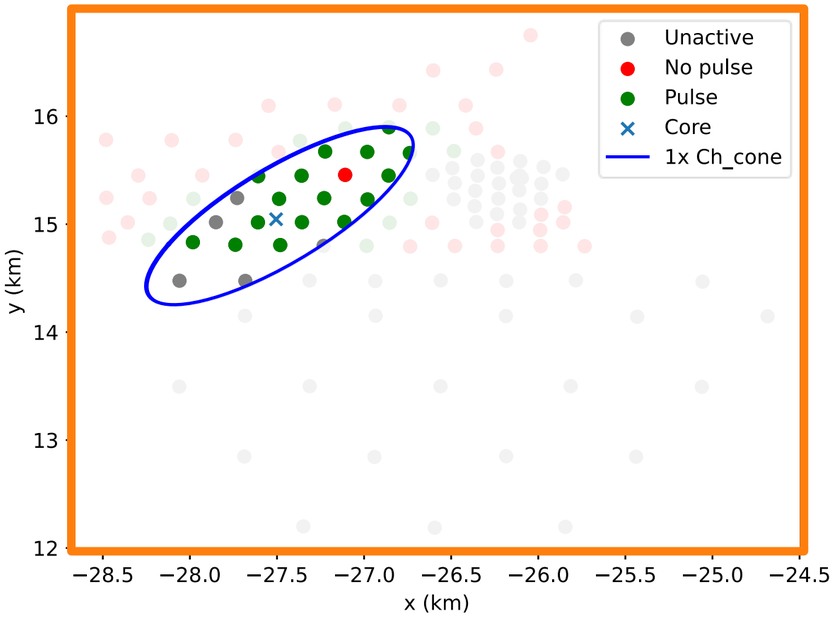
- Zenith dependence

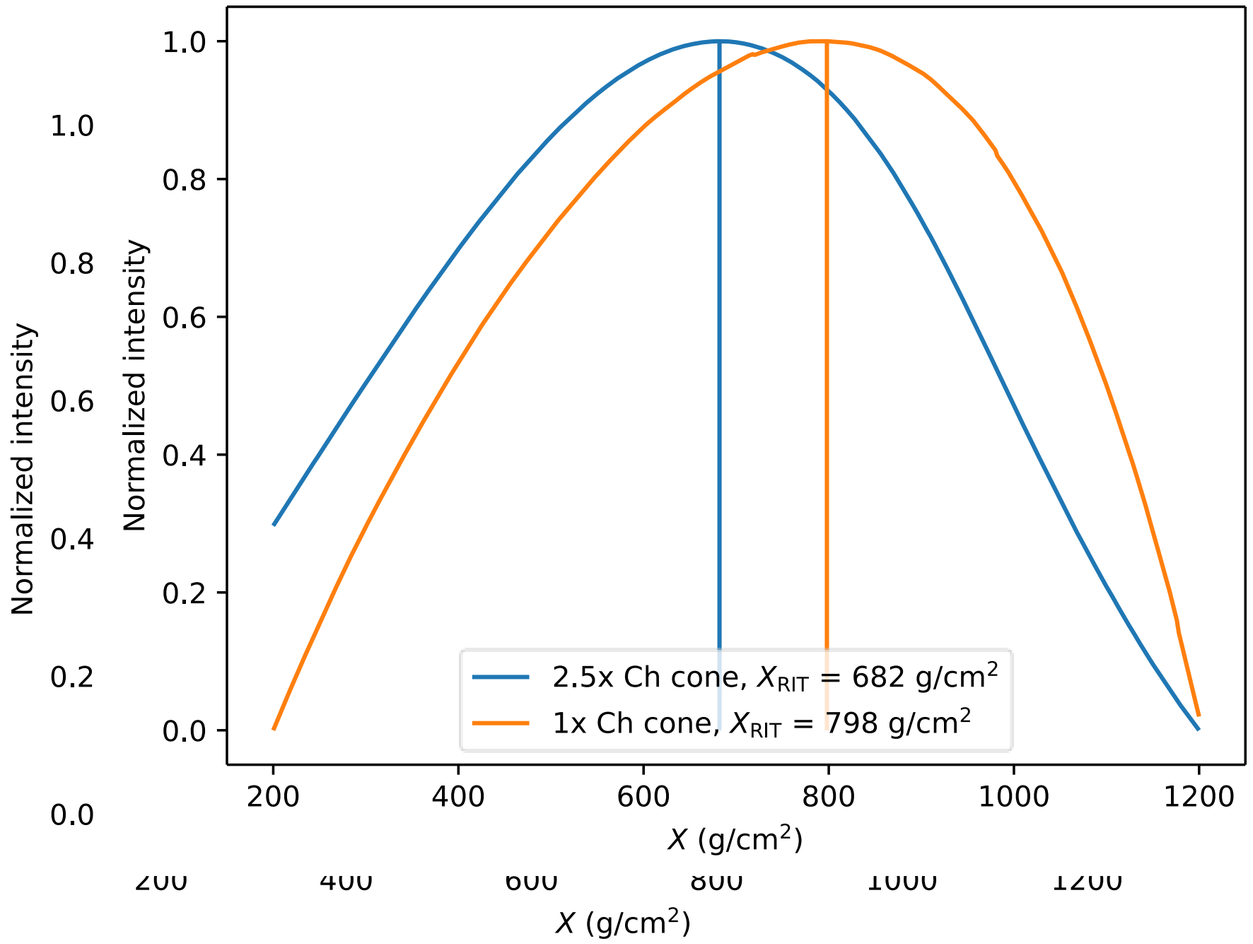


https://doi.org/10.48550/arXiv.2006.10348

X_{RIT}


Unactive
No pulse
Pulse
Core
2.5x Ch_cone
y (km)
x (km)


Unactive
No pulse
Pulse
Core
1x Ch_cone
y (km)
x (km)


Normalized intensity
2.5x Ch cone, X_{RIT} = 682 g/cm^2
1x Ch cone, X_{RIT} = 798 g/cm^2
X (g/cm^2)