Radio detection and interferometry at the Pierre Auger Observatory

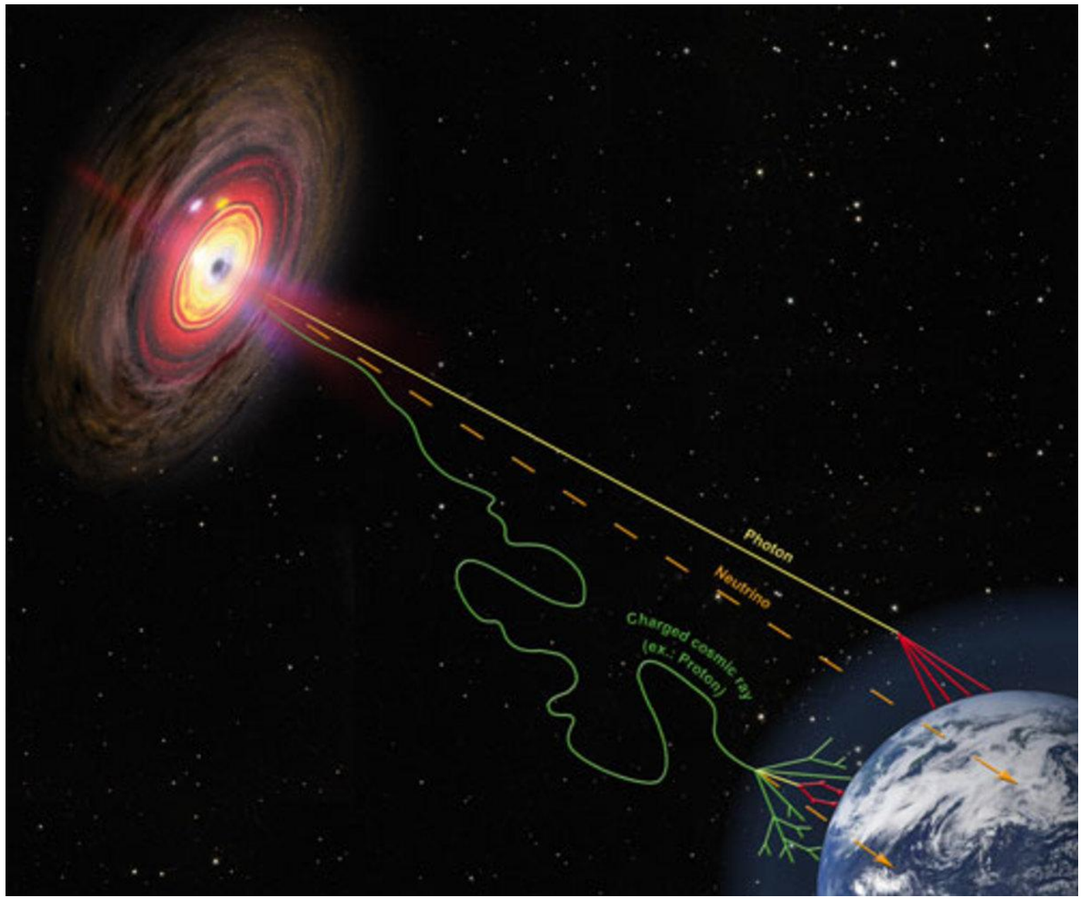
By: Pim van Dillen

Figure: https://vr.mephi.ru/en/eas

Funded by the European Union

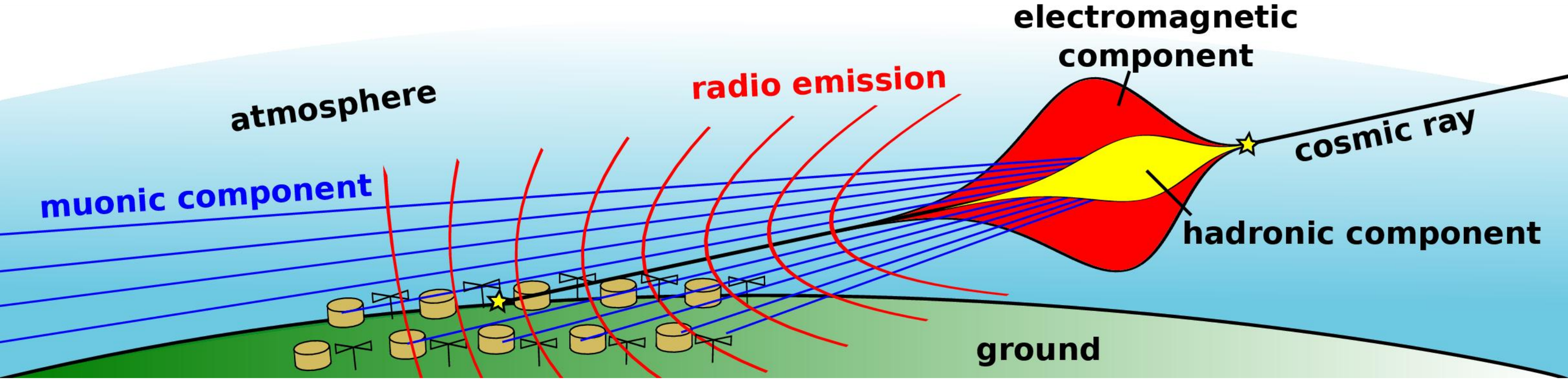
Cosmic rays

- Ultra-high-energy cosmic rays (UHECRs)
  - > 1 EeV (10^{18} eV)
- Sources unknown



Extensive Air showers

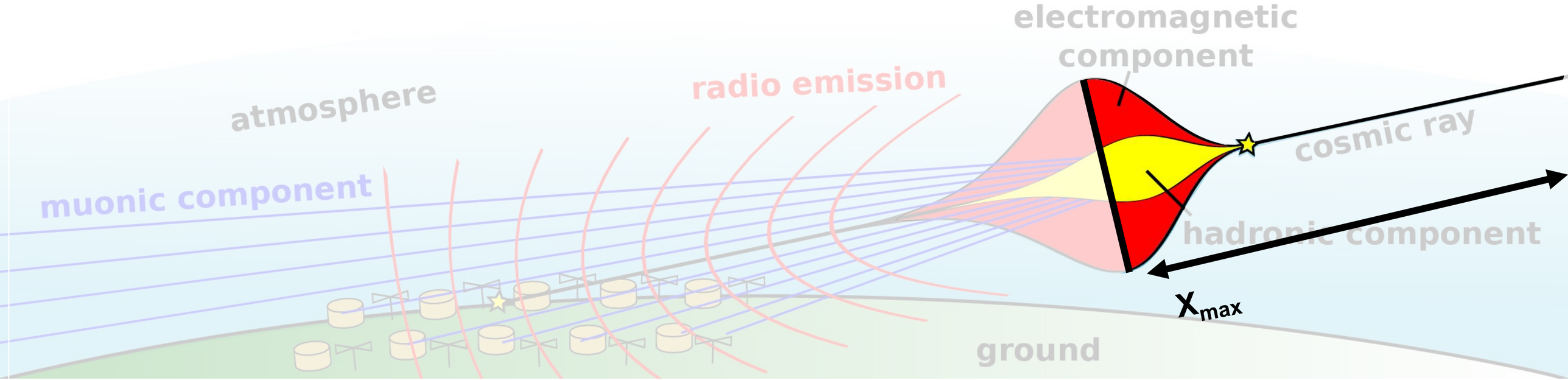
- Reconstruct:
  - Energy
  - Direction
  - Composition



DOI: 10.1051/epjconf/201920815001

Extensive Air showers

- Composition
  - **Depth of shower maximum (X_{max})**
  - Muons



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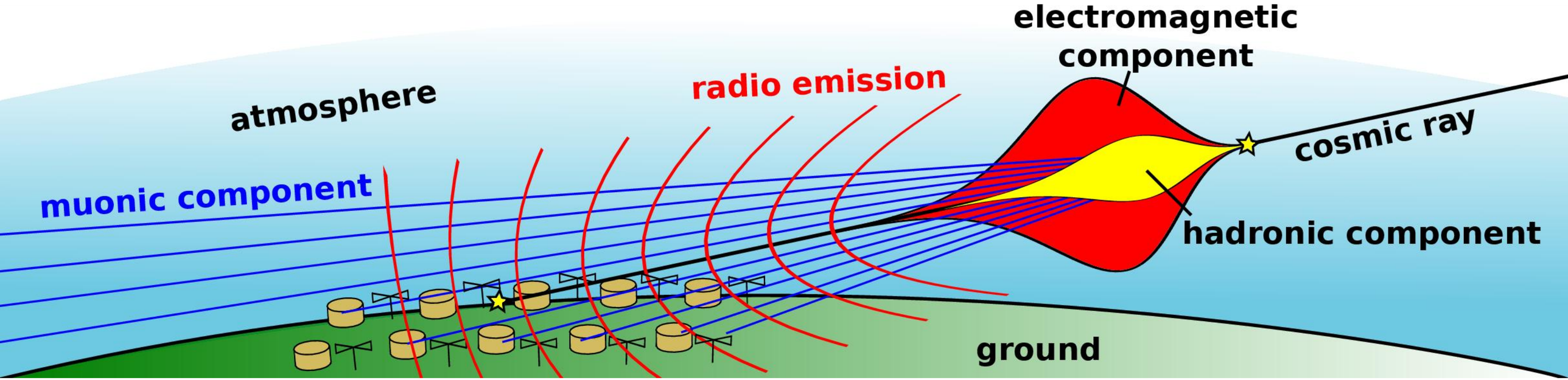
Extensive Air showers

- Composition
  - Depth of shower maximum (X_{max})
  - **Muons**



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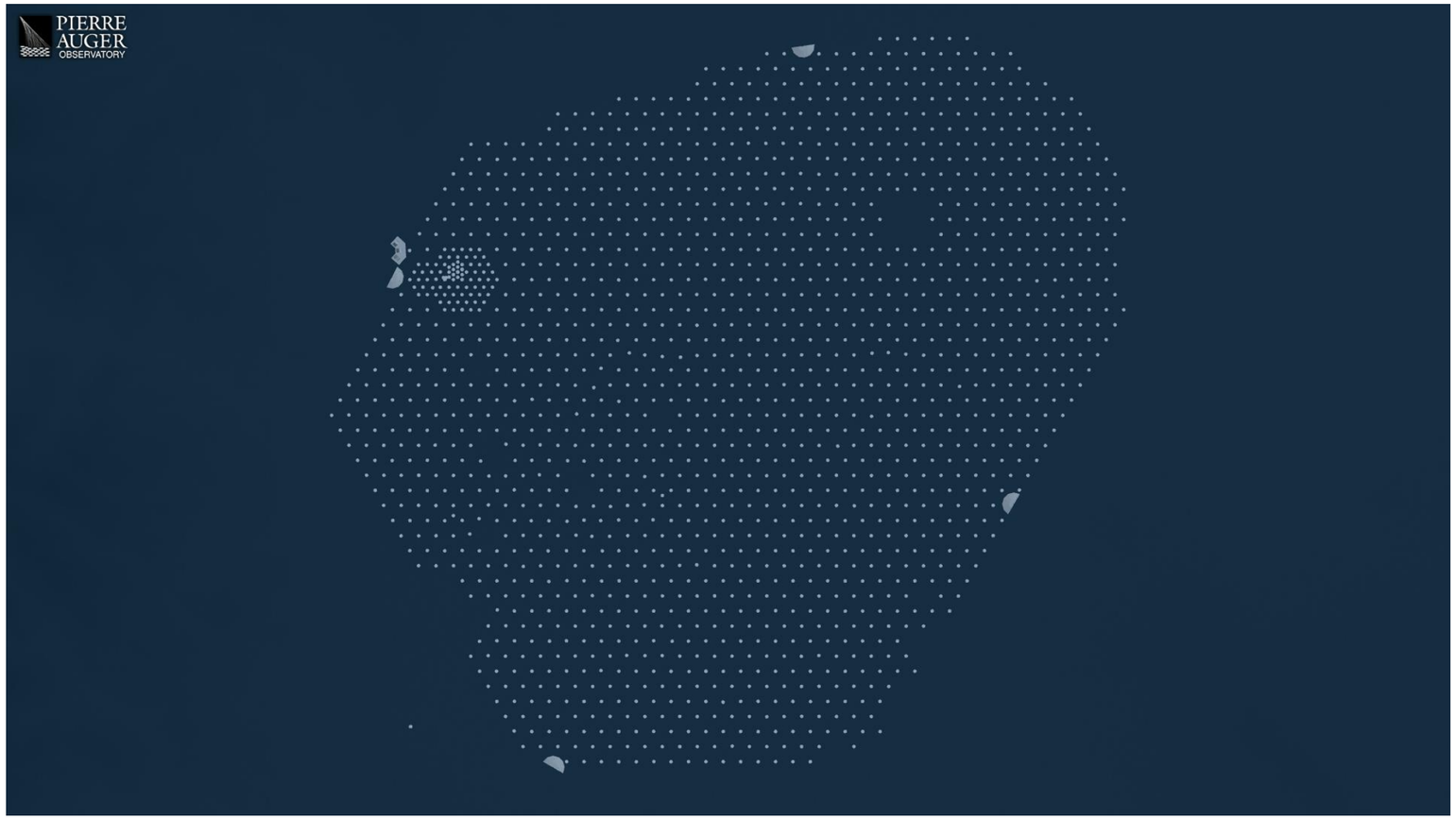
Pierre Auger Observatory

- Malargüe, Argentina
- 3000 km^2
- Hybrid detector
  - Surface Detector (SD)
  - Fluorescence Detector (FD)



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

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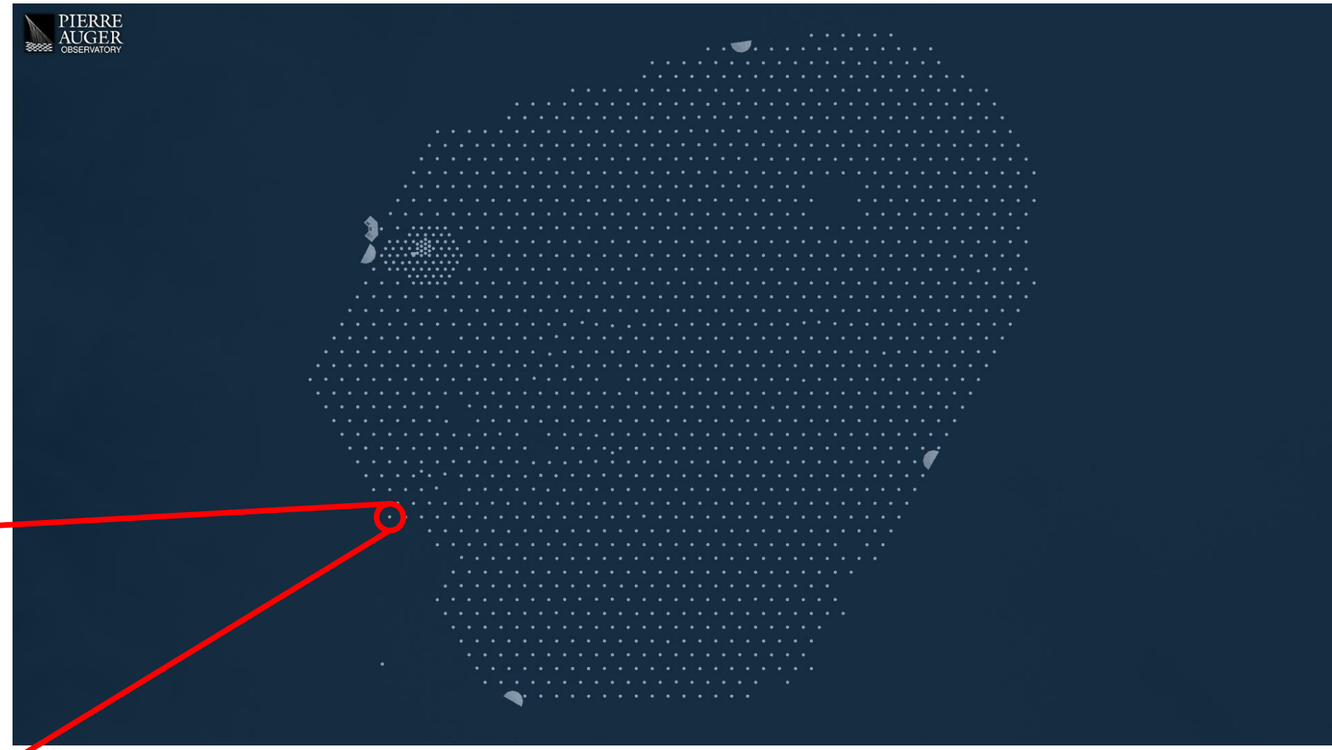

https://cerncourier.com/a/augerprime-looks-to-the-highest-energies/

Pierre Auger Observatory

- Malargüe, Argentina
- 3000 km^2
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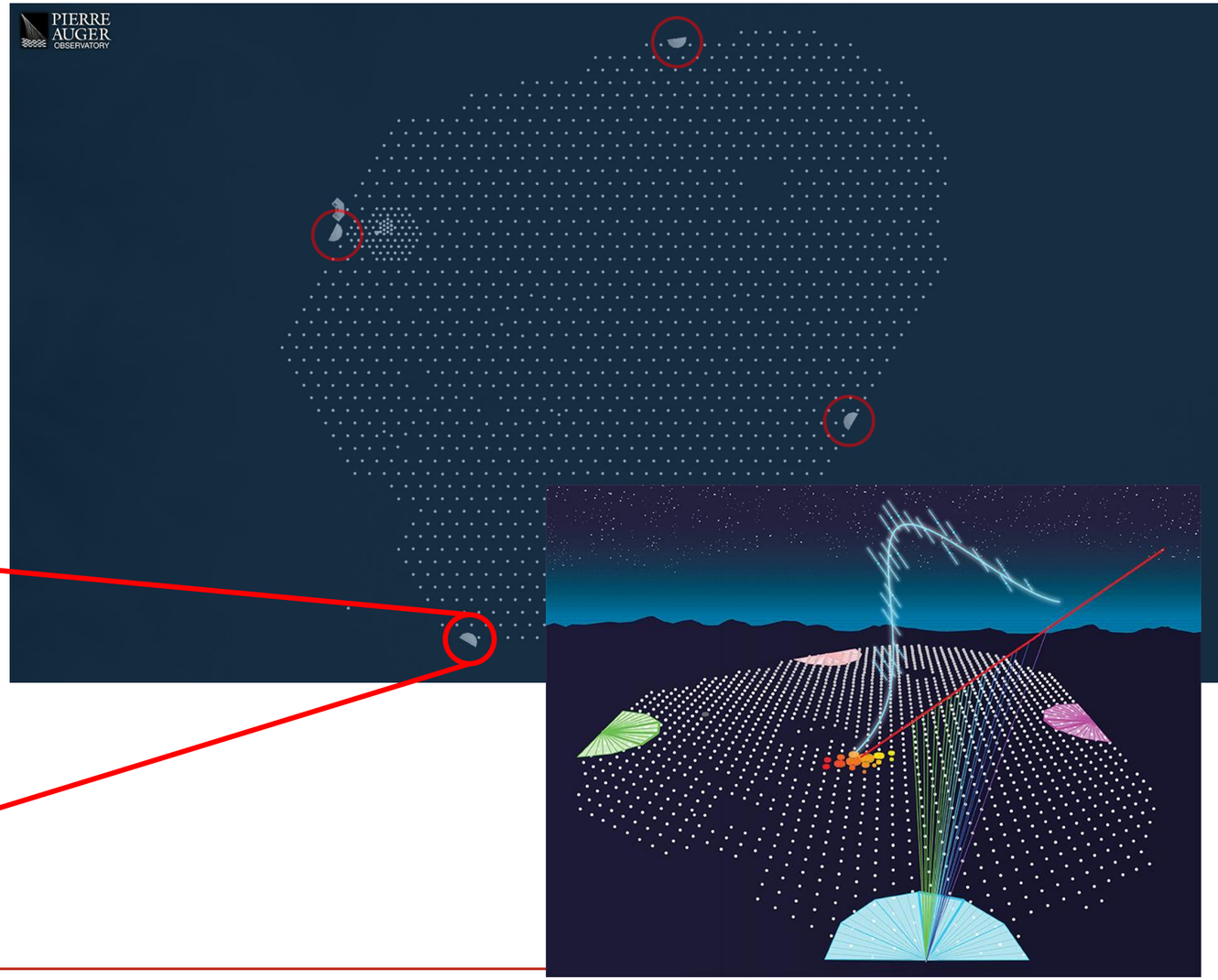
  - Surface Detector (SD)
  - **Fluorescence Detector (FD)**

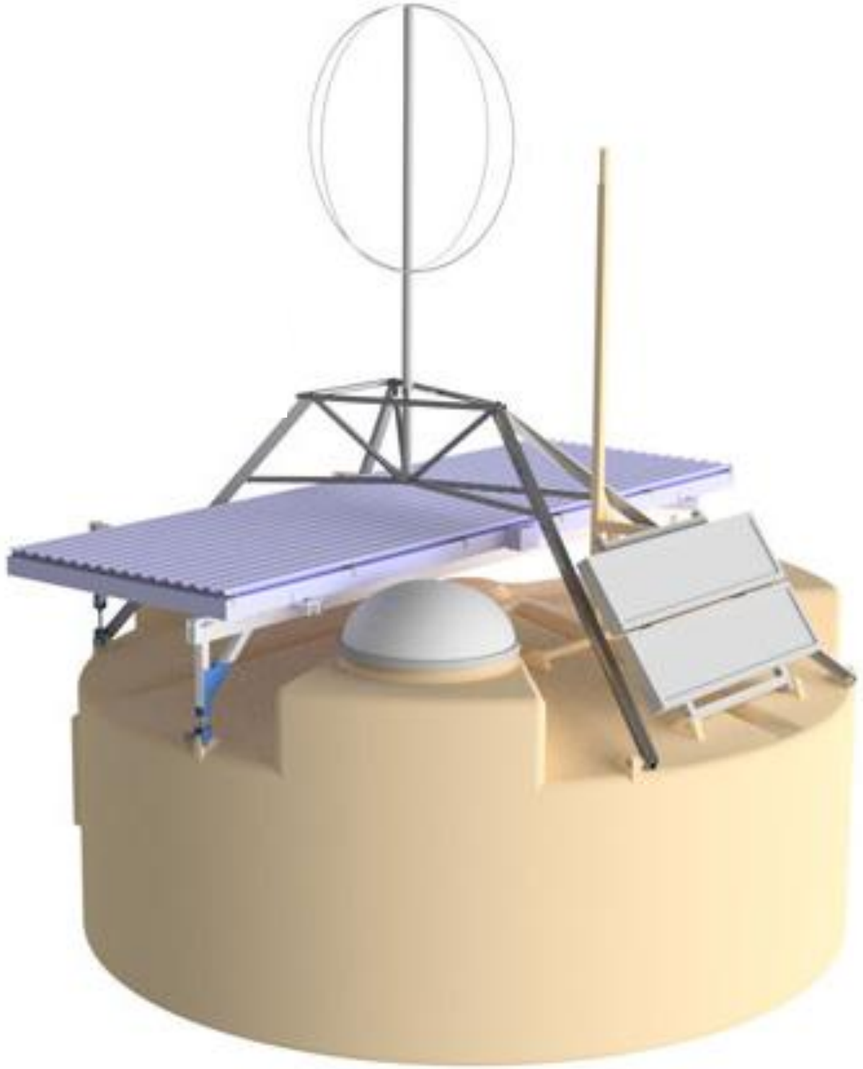
https://doi.org/10.1016/j.nima.2015.06.058



Phys. Rev. Lett. 117, 192001 (2016)

AugerPrime

- Upgrade of the Surface Detector
  - **Surface Scintillator Detector (SSD)**
  - Radio Detector (RD)



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

AugerPrime

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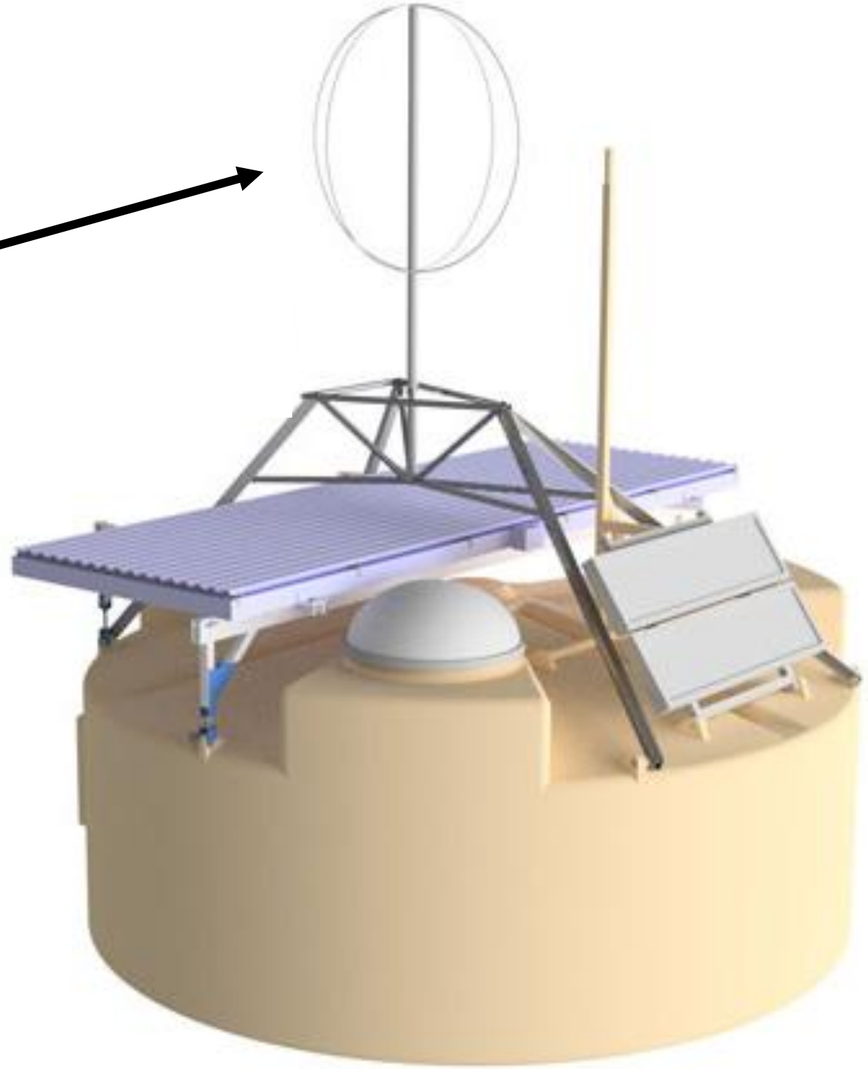
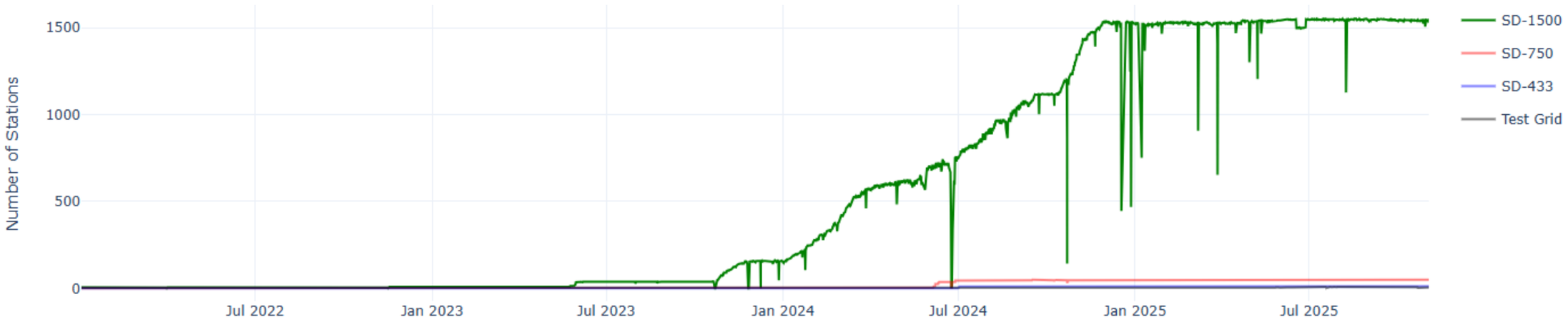


https://www.auger.org/observatory/augerprime

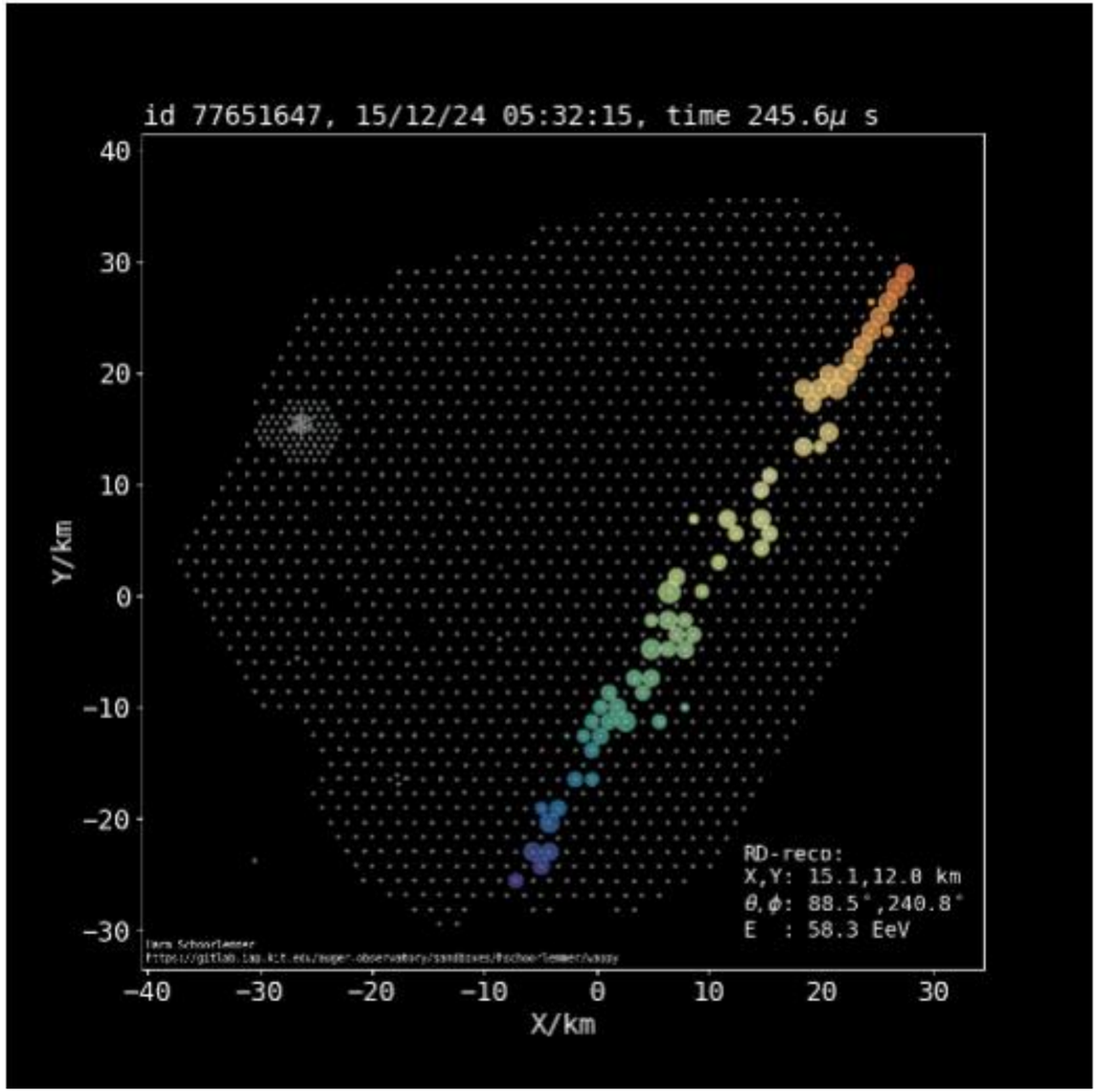
Deployment

- Started: **Begin 2024**
- Finished: **28-11-2024**



Events

- Very inclined events
- Lots of stations triggered



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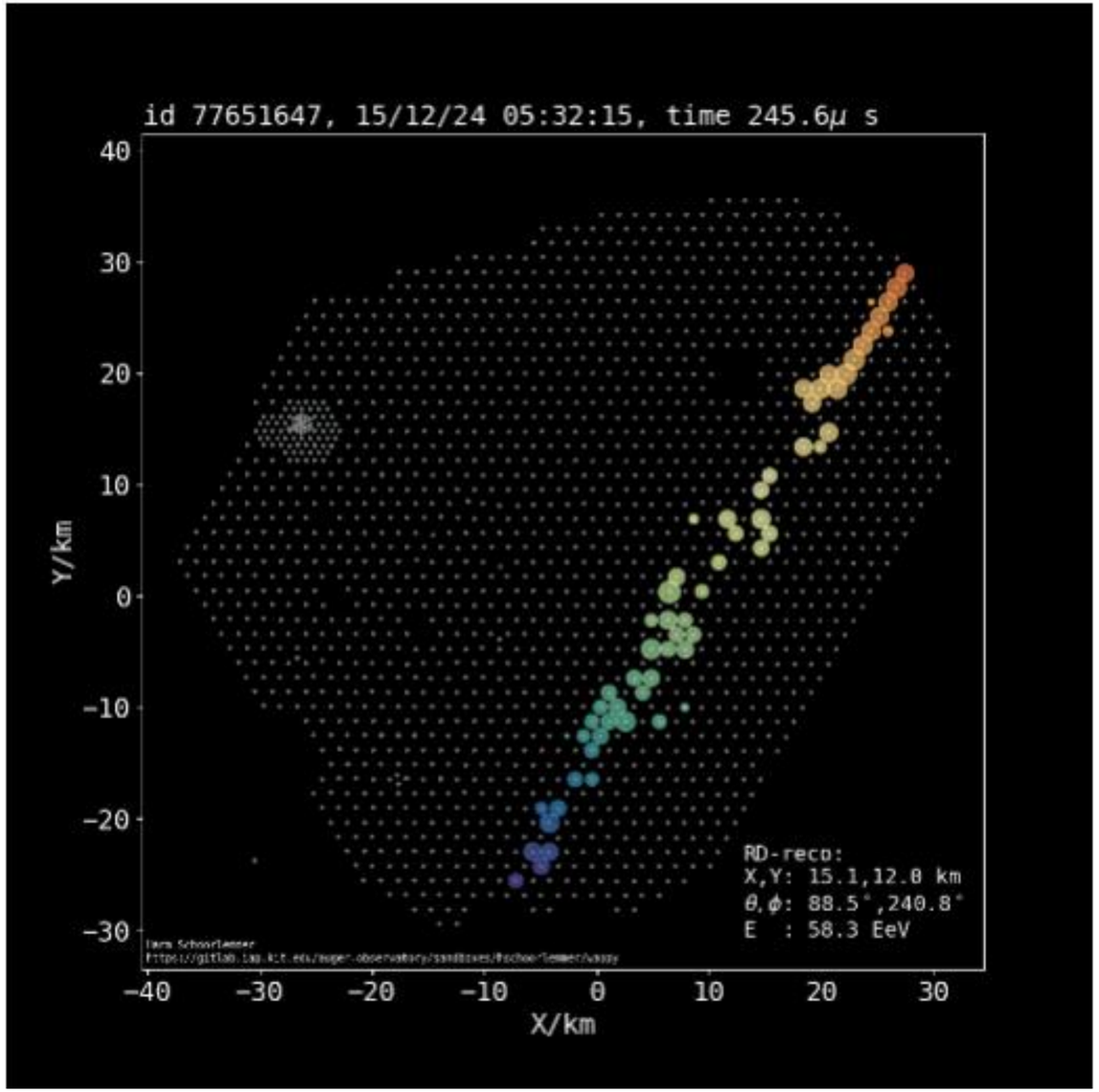
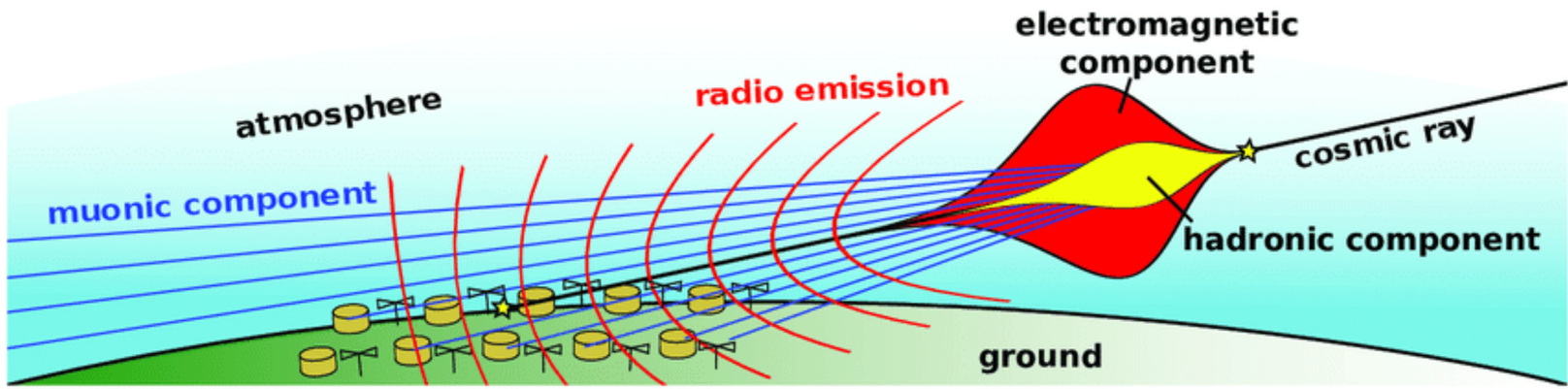


Why radio interferometry?

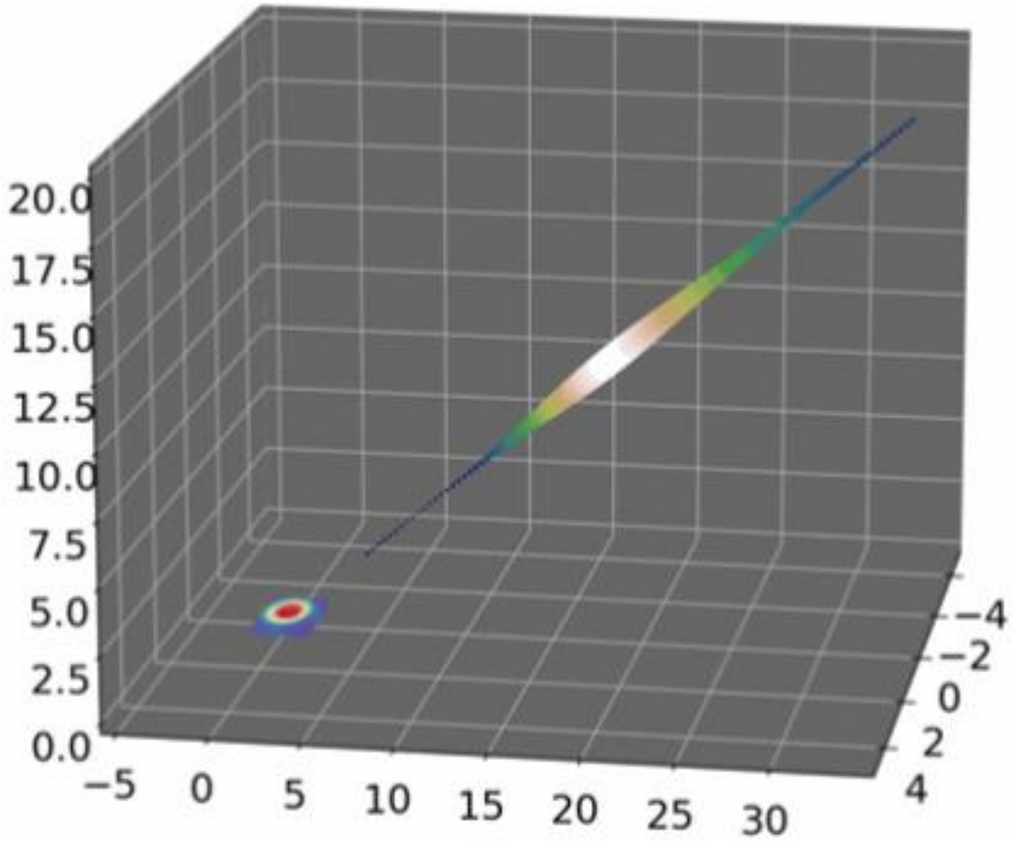
Why radio interferometry?

- Direct measurement of the electromagnetic component
  - Decoupled of SD measurement
  - Independent energy measurement
- Muon puzzle
- Almost 100% duty cycle
  - FD only ≈ 15%
- More sensitive to neutrals
  - Photons
  - Neutrinos



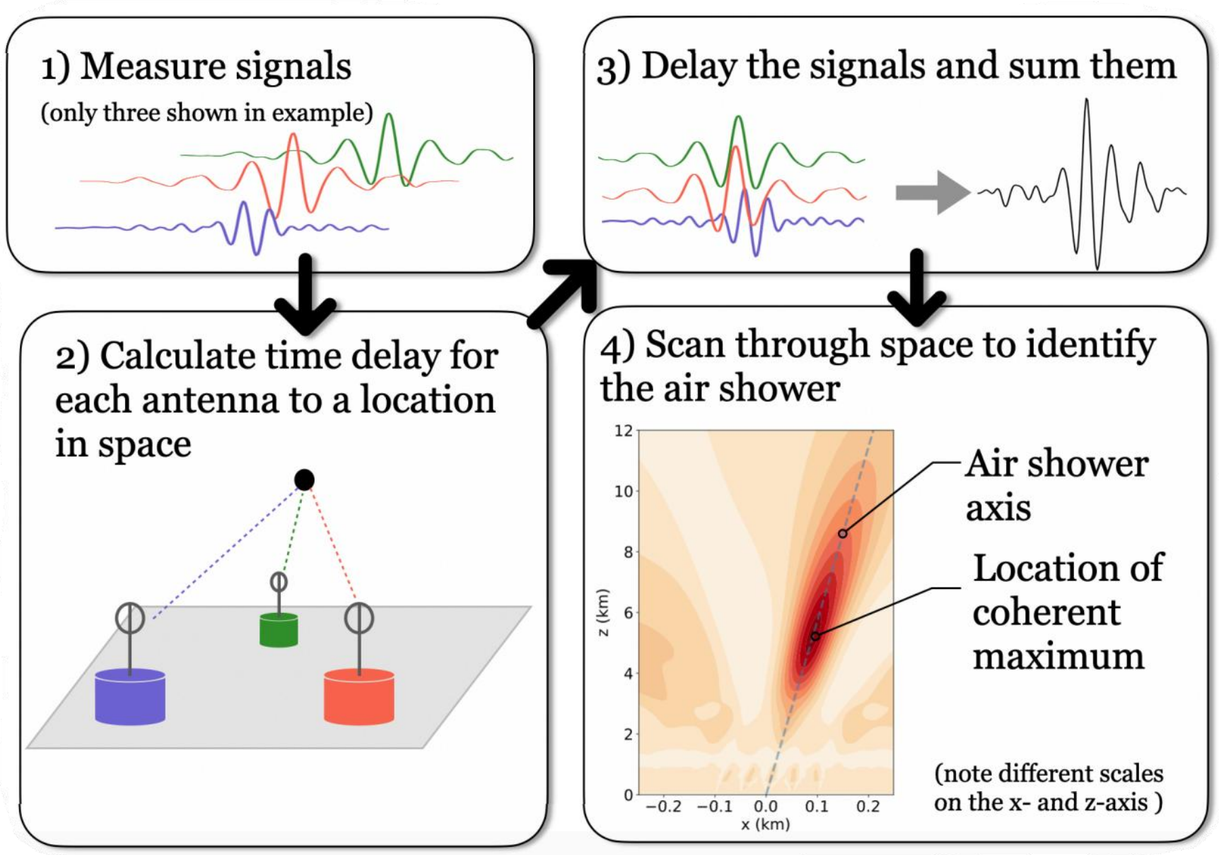
Why radio interferometry?

- Full 3D mapping of the Air Shower's emission region
- Excellent directional accuracy
- Reconstruction of X_{max}
  - Composition measurement
- Lowering detection threshold



Radio Interferometry Technique (RIT)

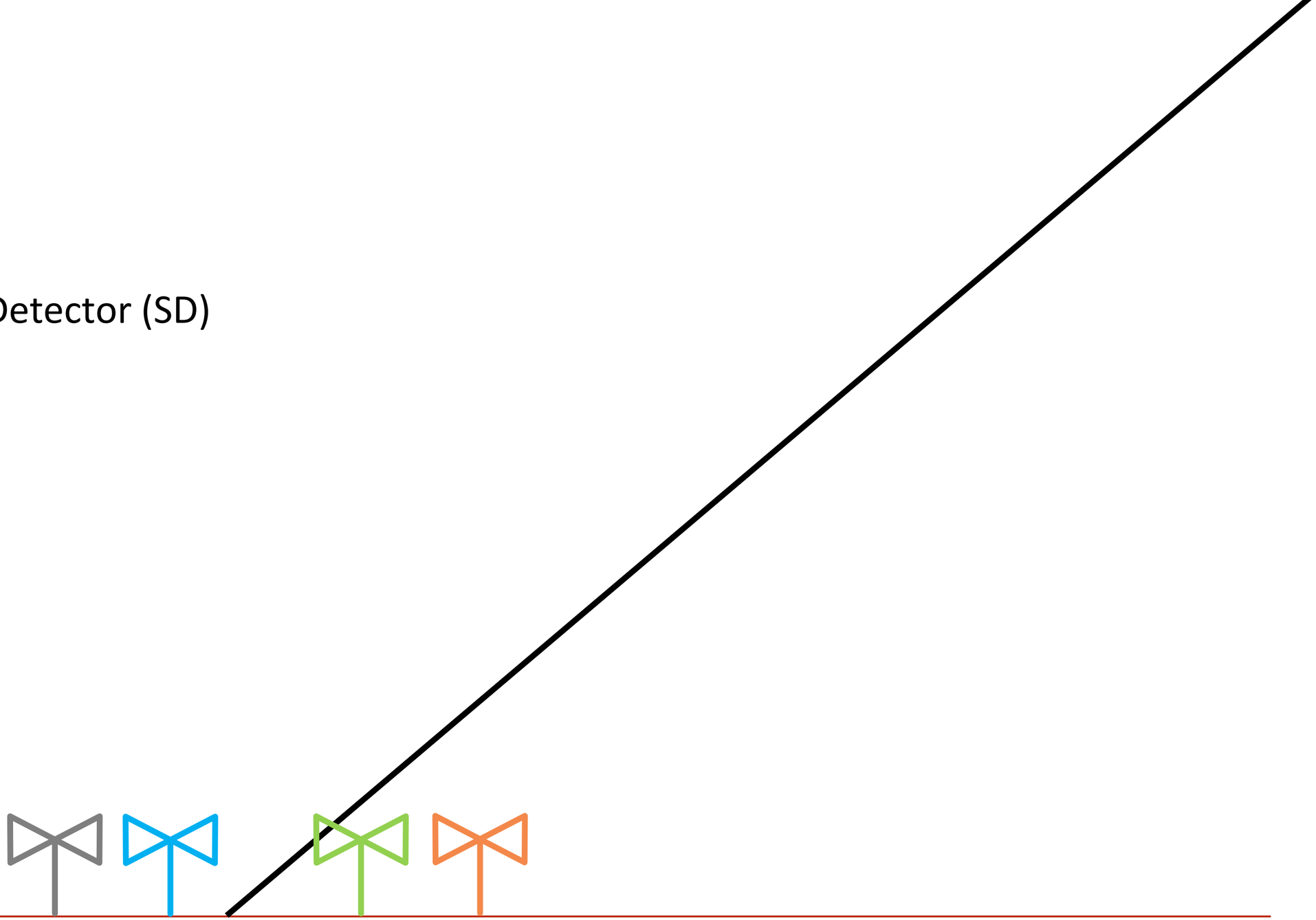
- Use the relative time differences in arrival time
- Very accurate timing of the signal needed
  - Time synchronisation **< 1 ns**
  - Positional accuracy **< 30 cm**



DOI: 10.22323/1.444.0380

ASIRA[1]

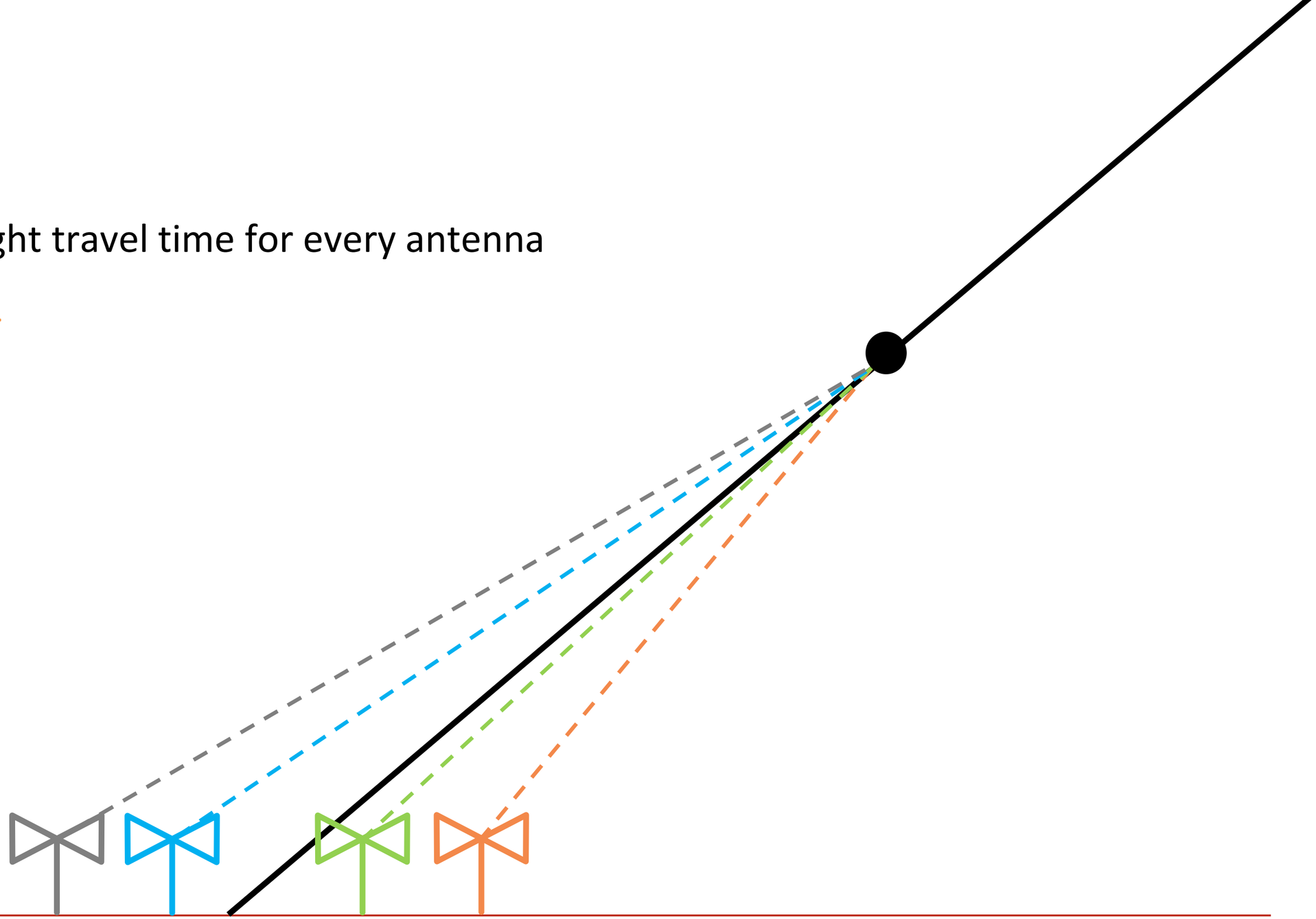
- Initial axis
  - Surface Detector (SD)



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

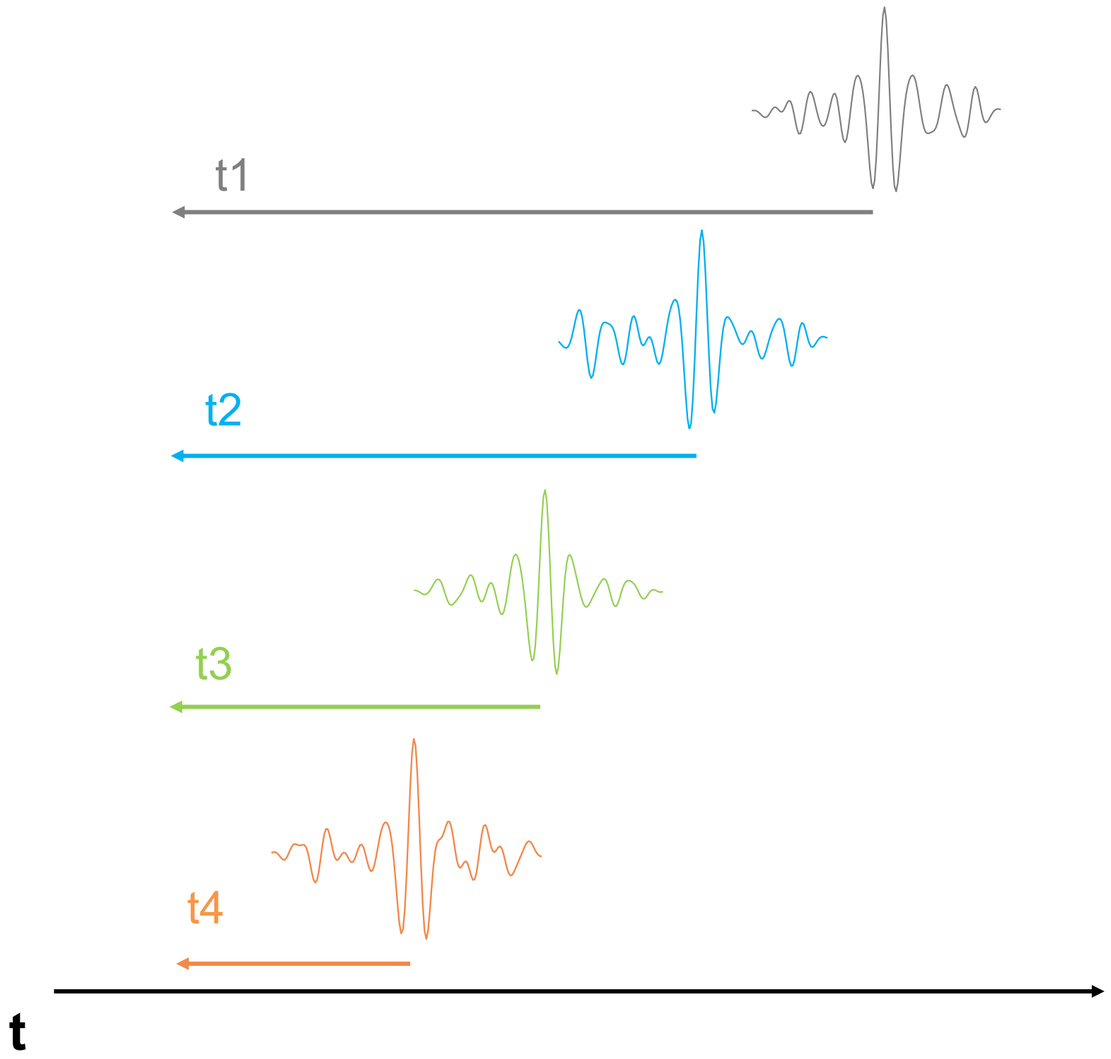
ASIRA

- Calculate light travel time for every antenna
- t1, t2, t3, t4



ASIRA

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



ASIRA

- **Subtract travel time from waveforms**
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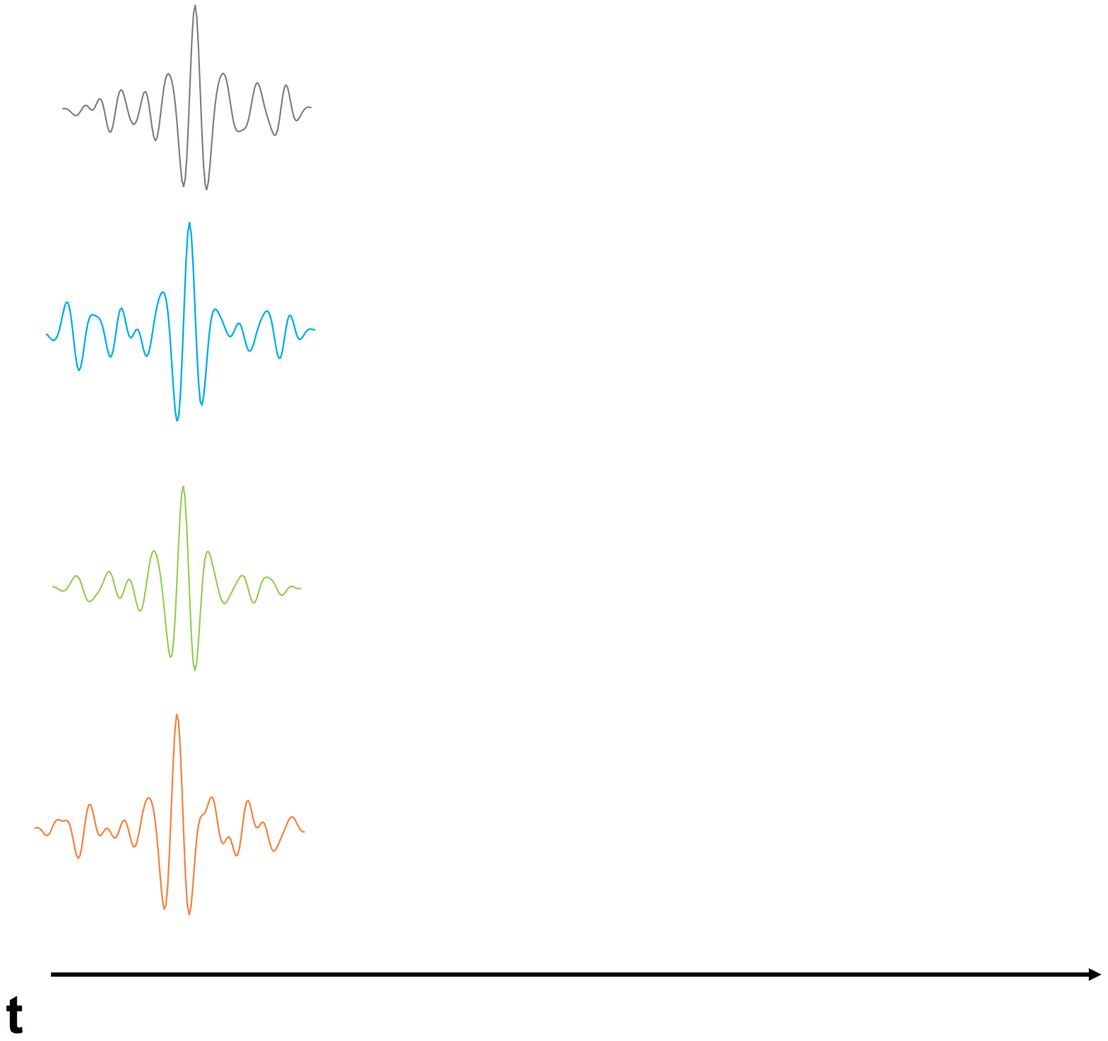

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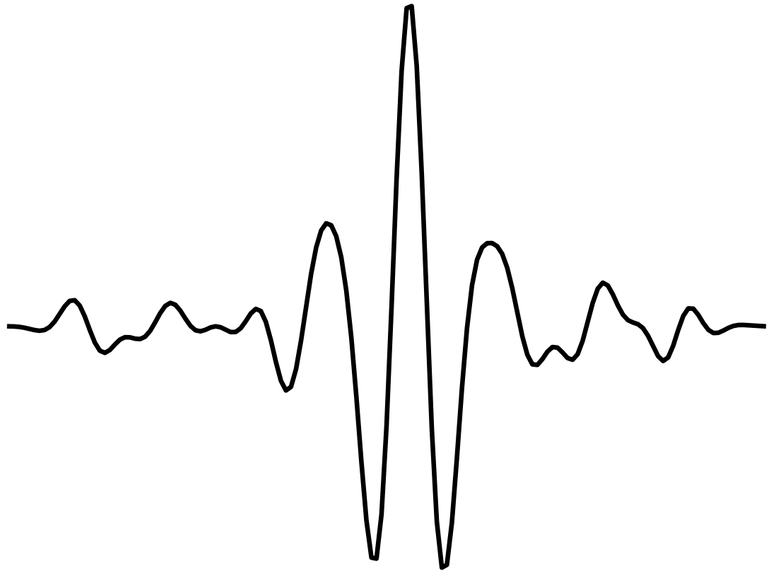

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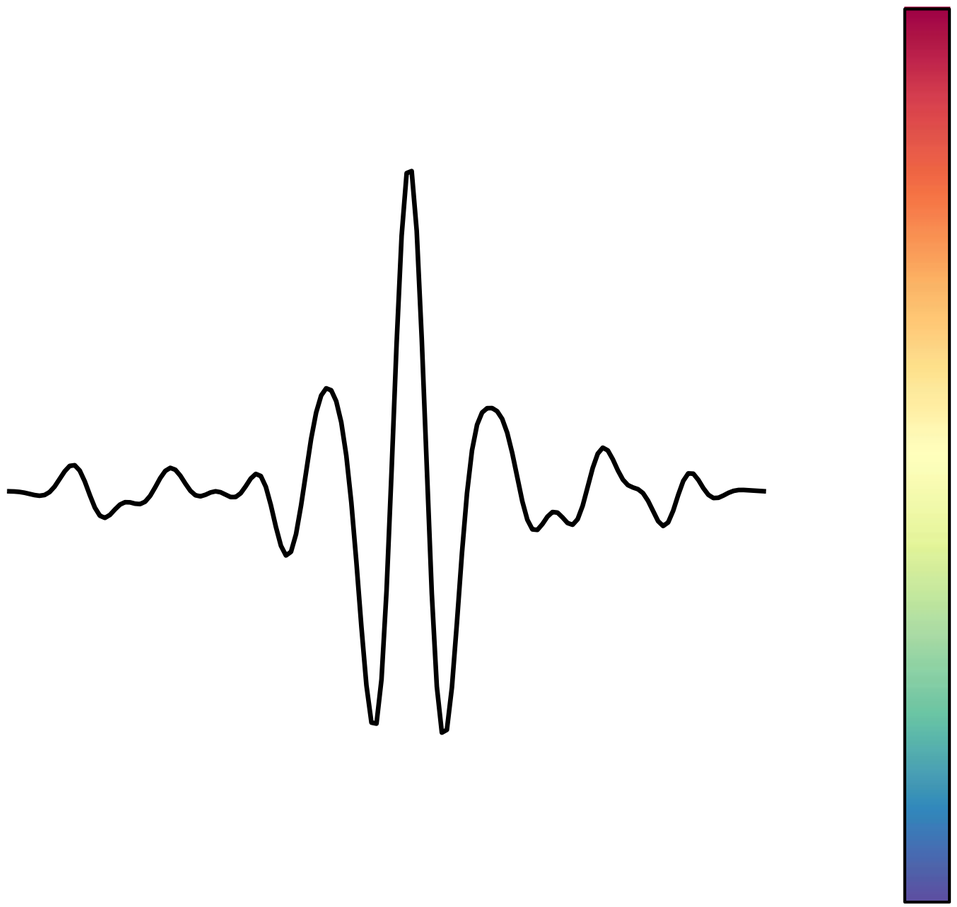

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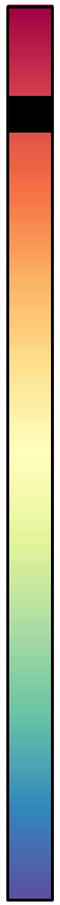
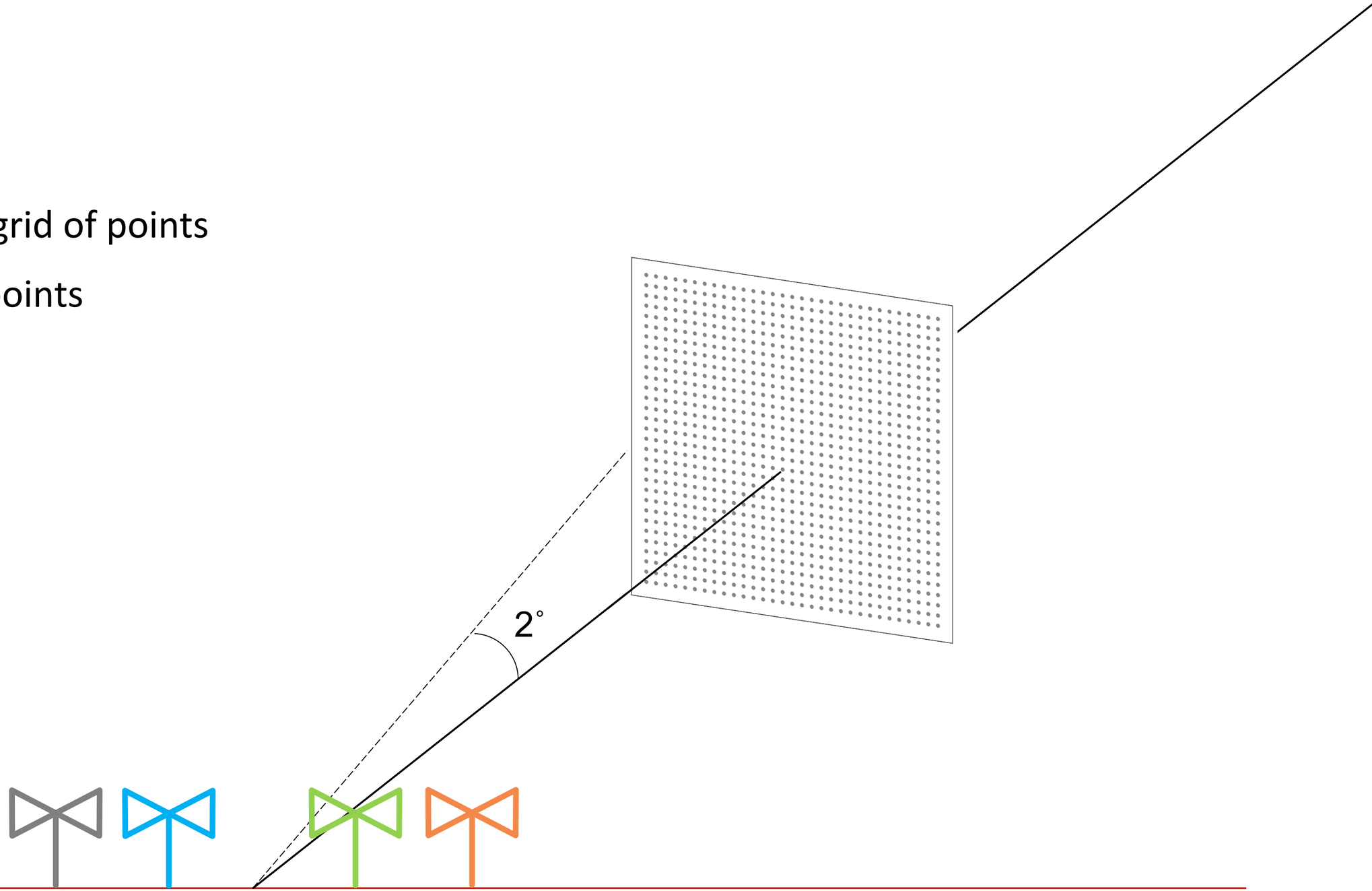


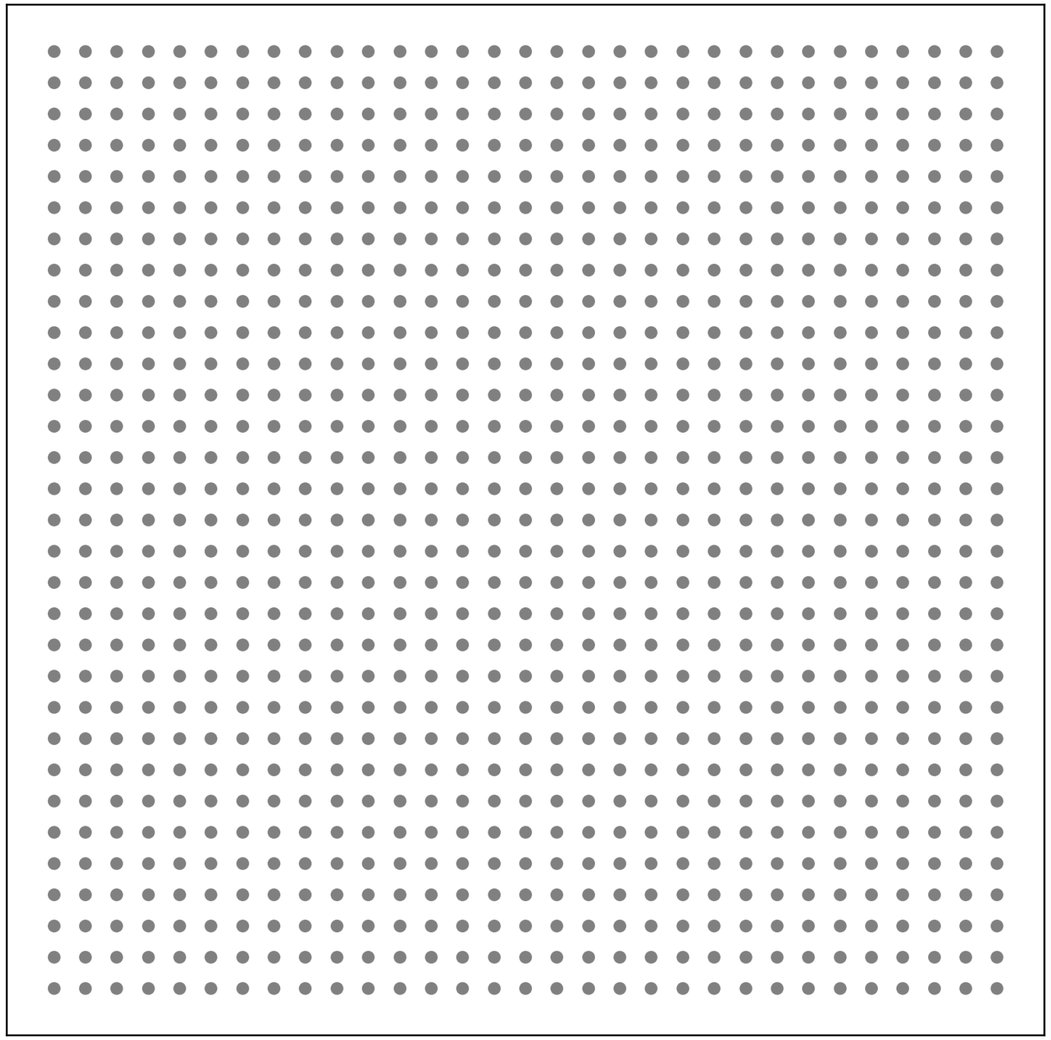
ASIRA

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



ASIRA

- Determine intensity for every point



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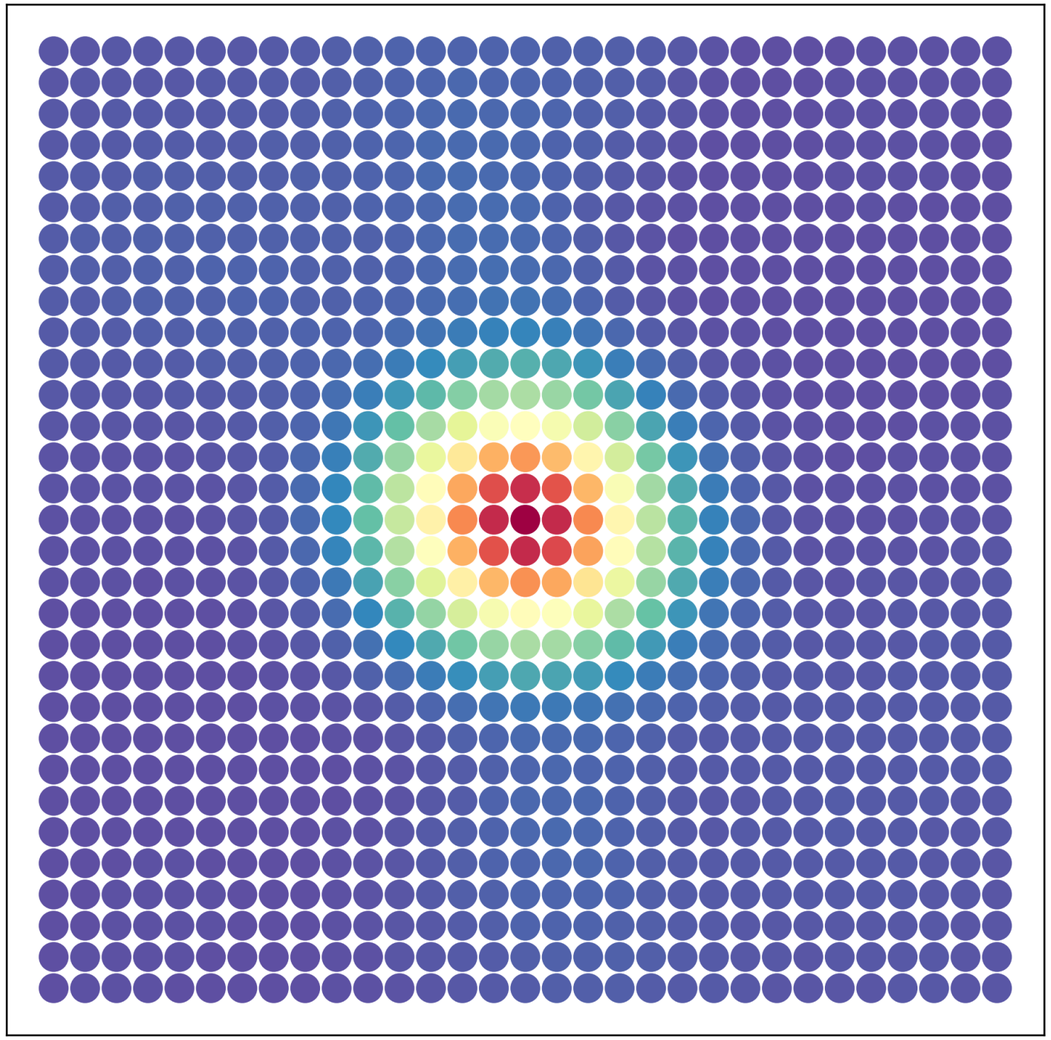
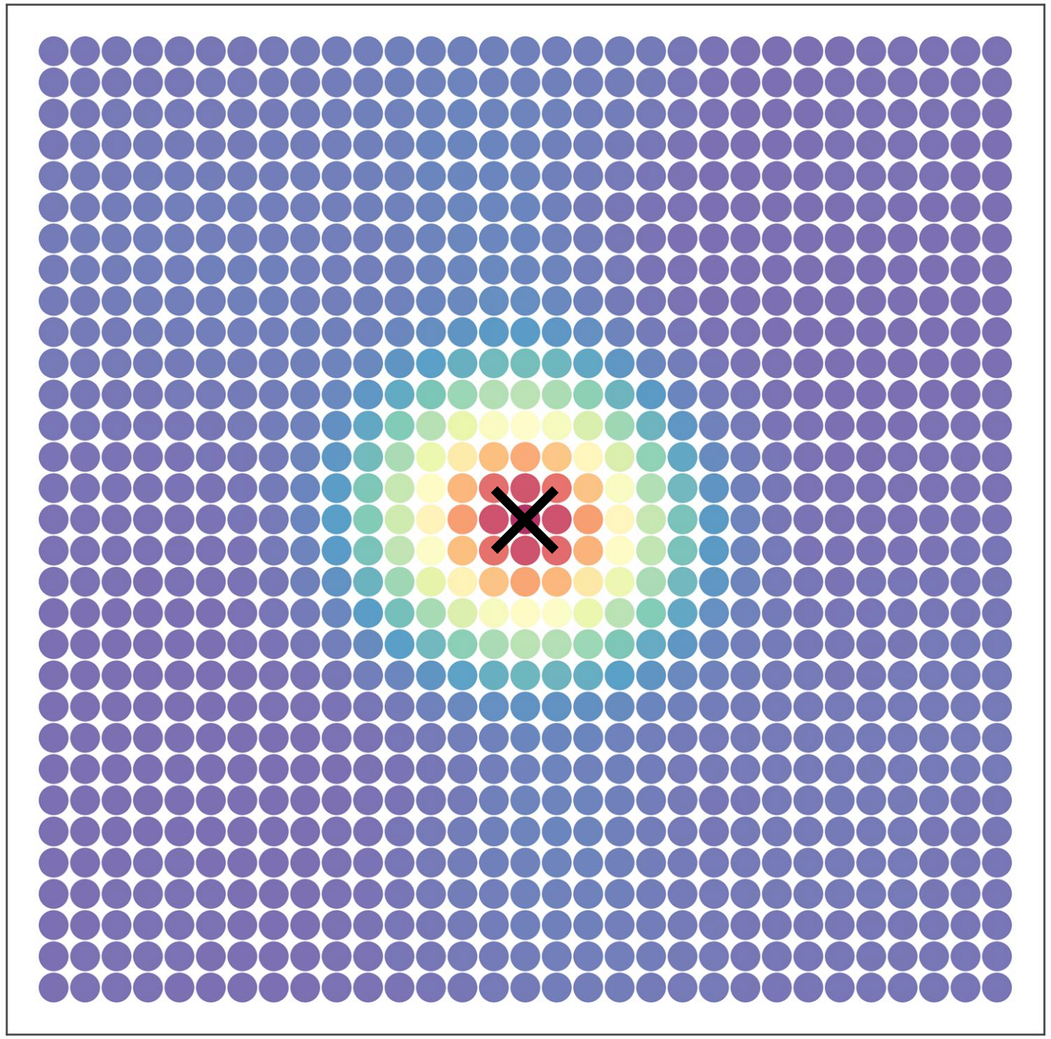


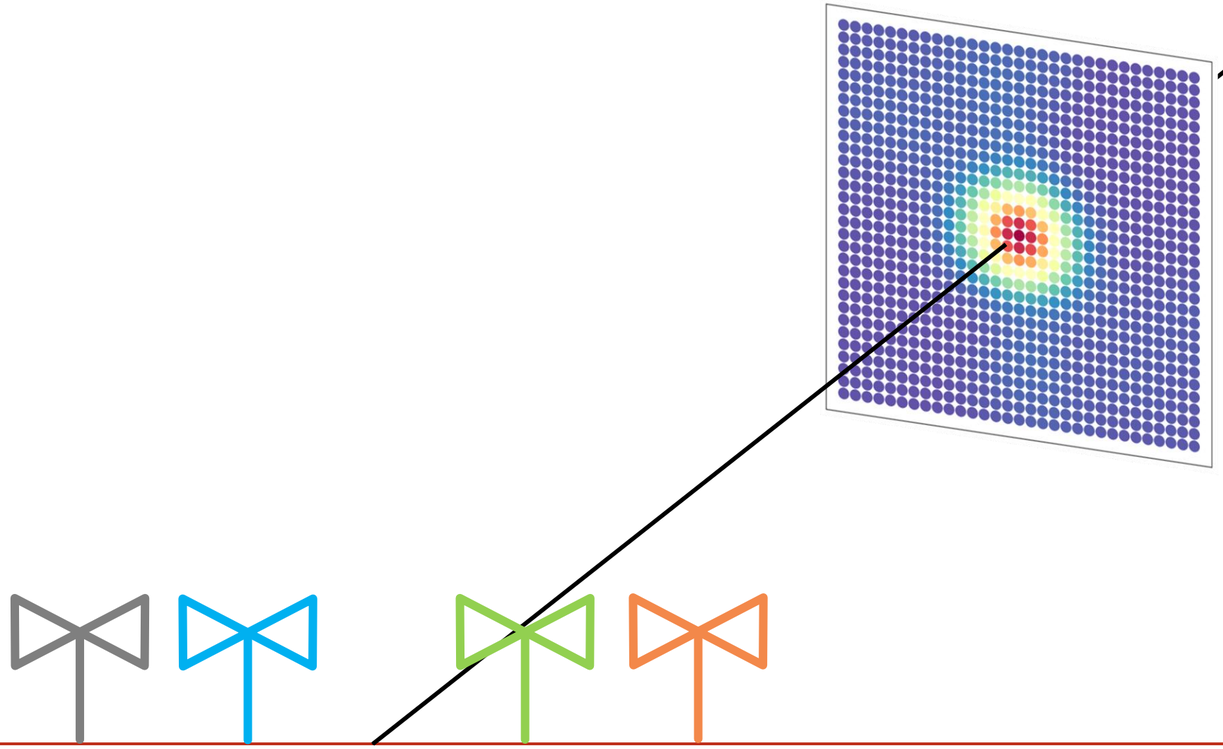
ASIRA

- 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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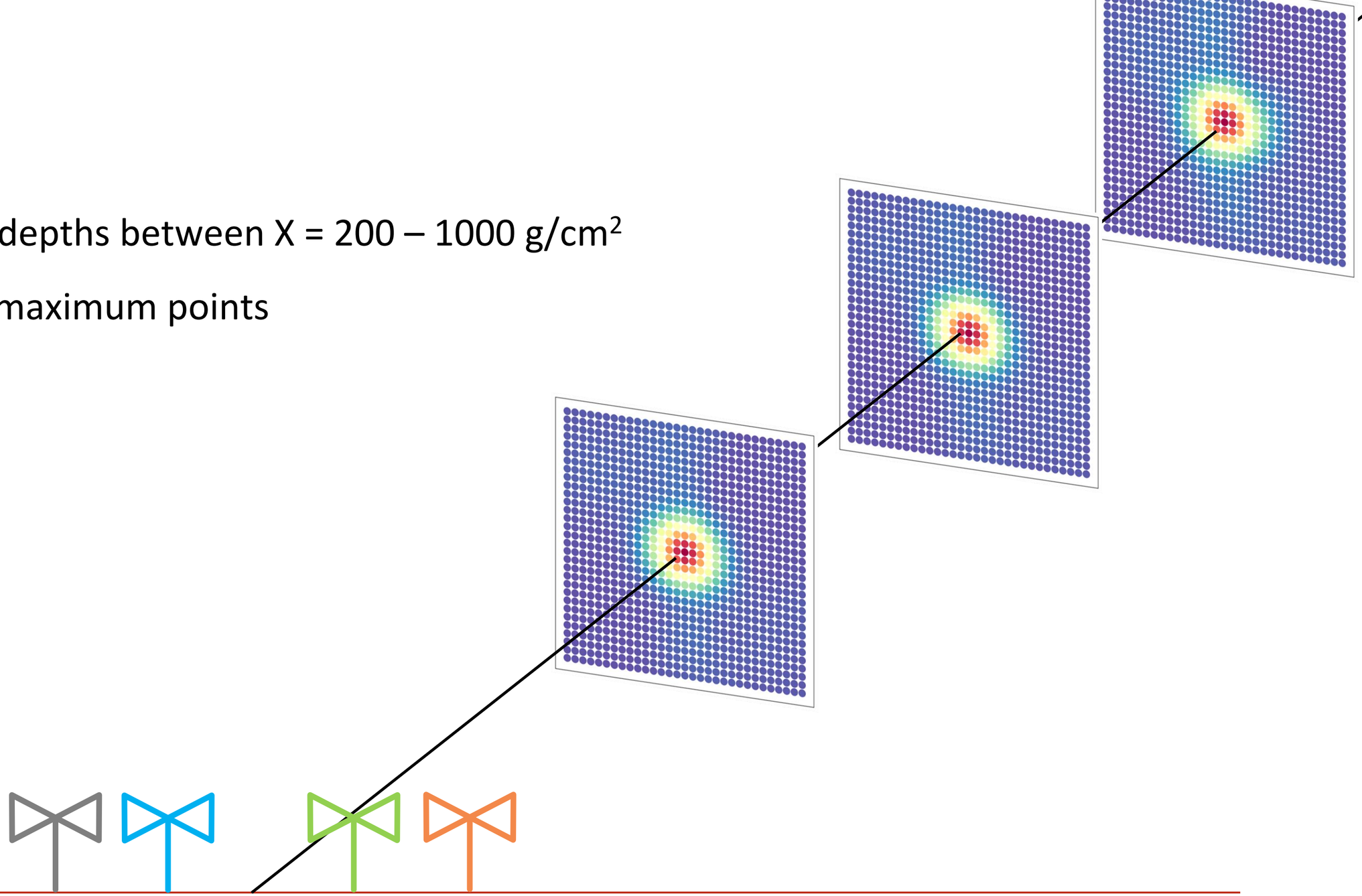

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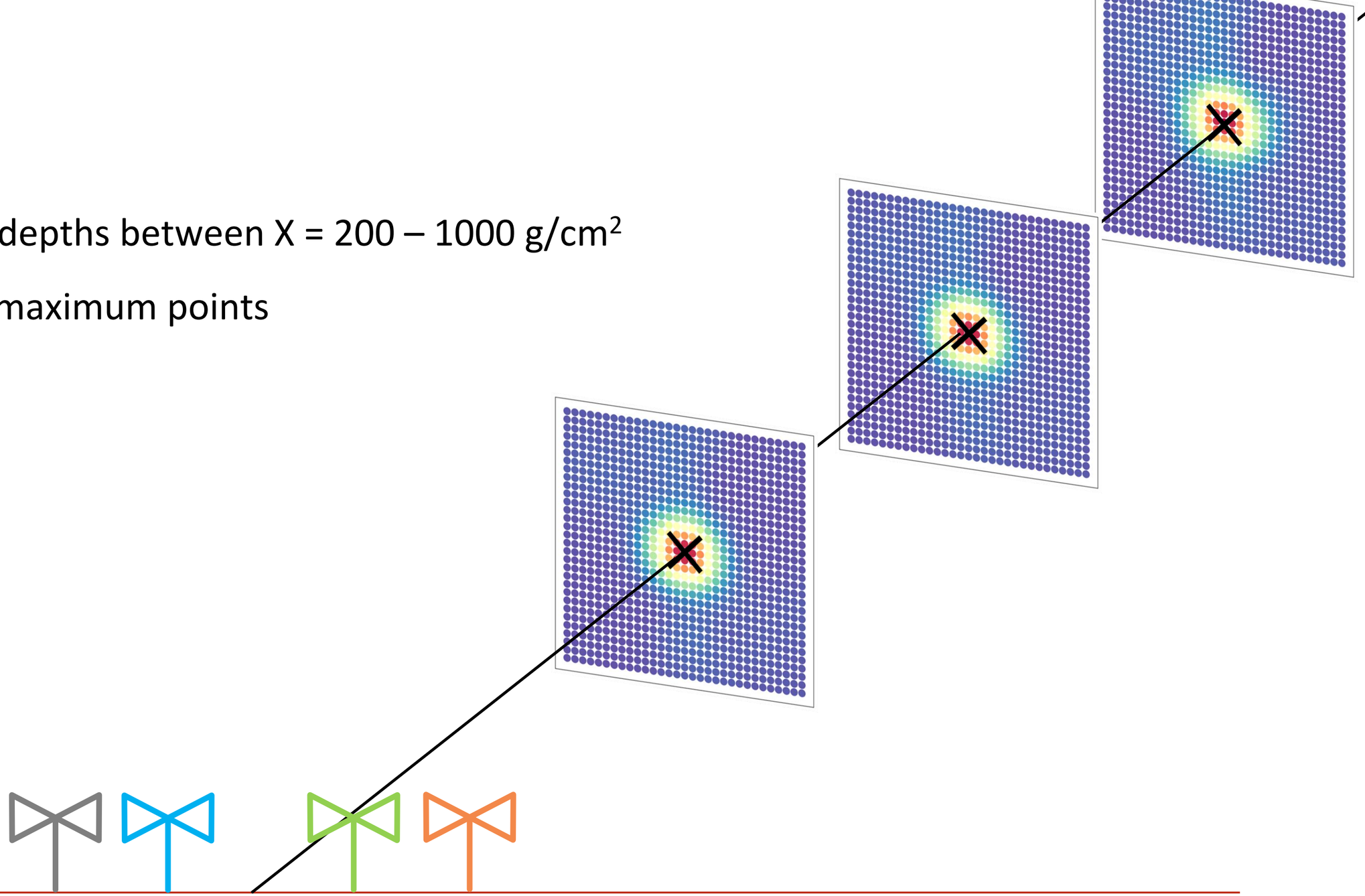
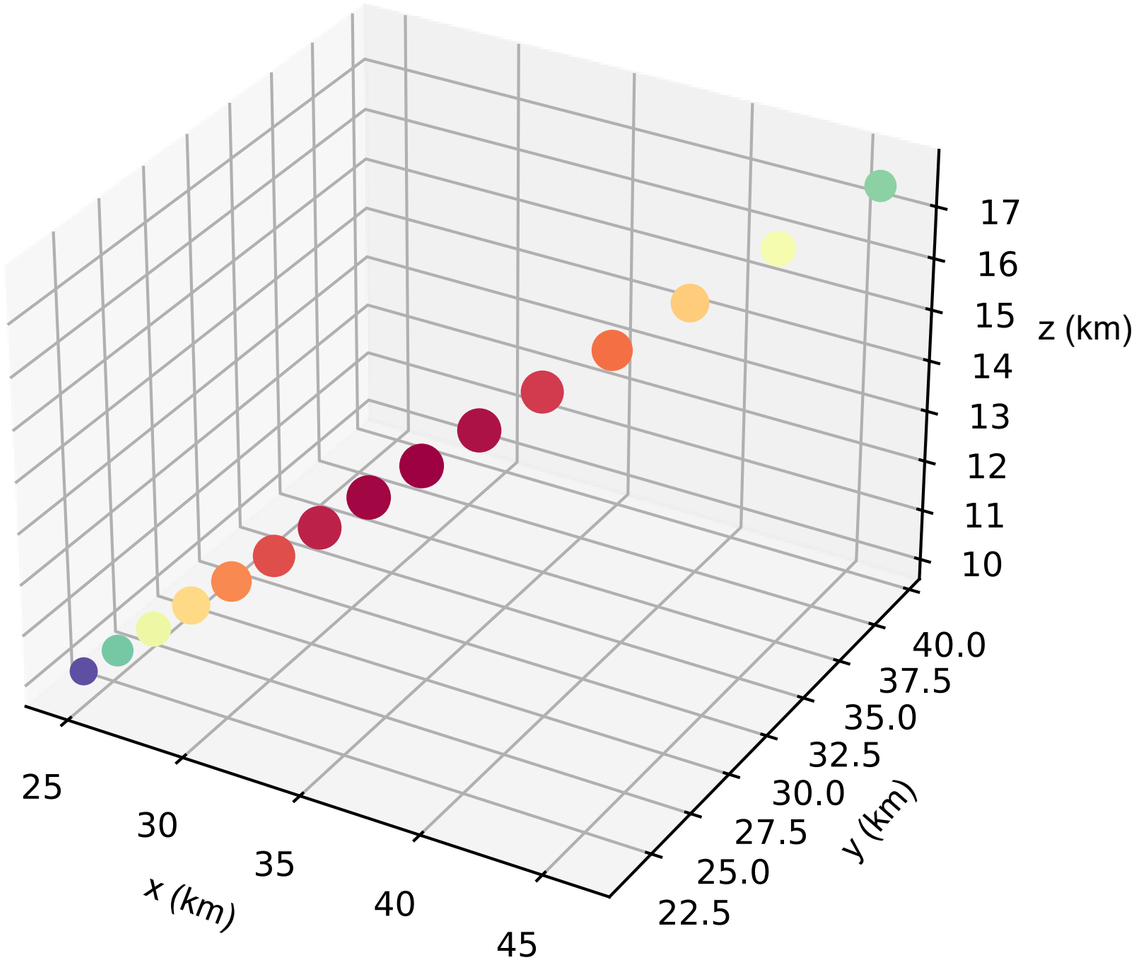


ASIRA

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



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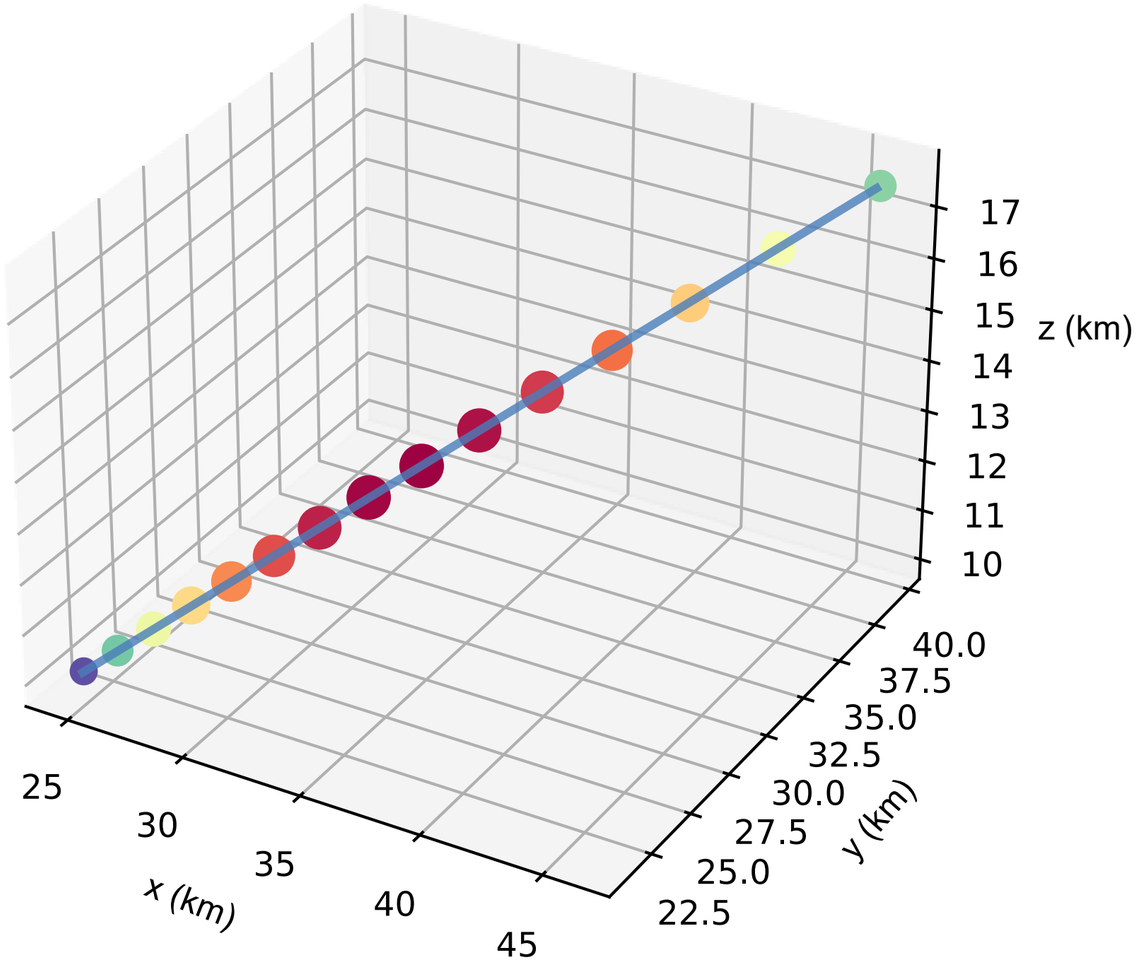
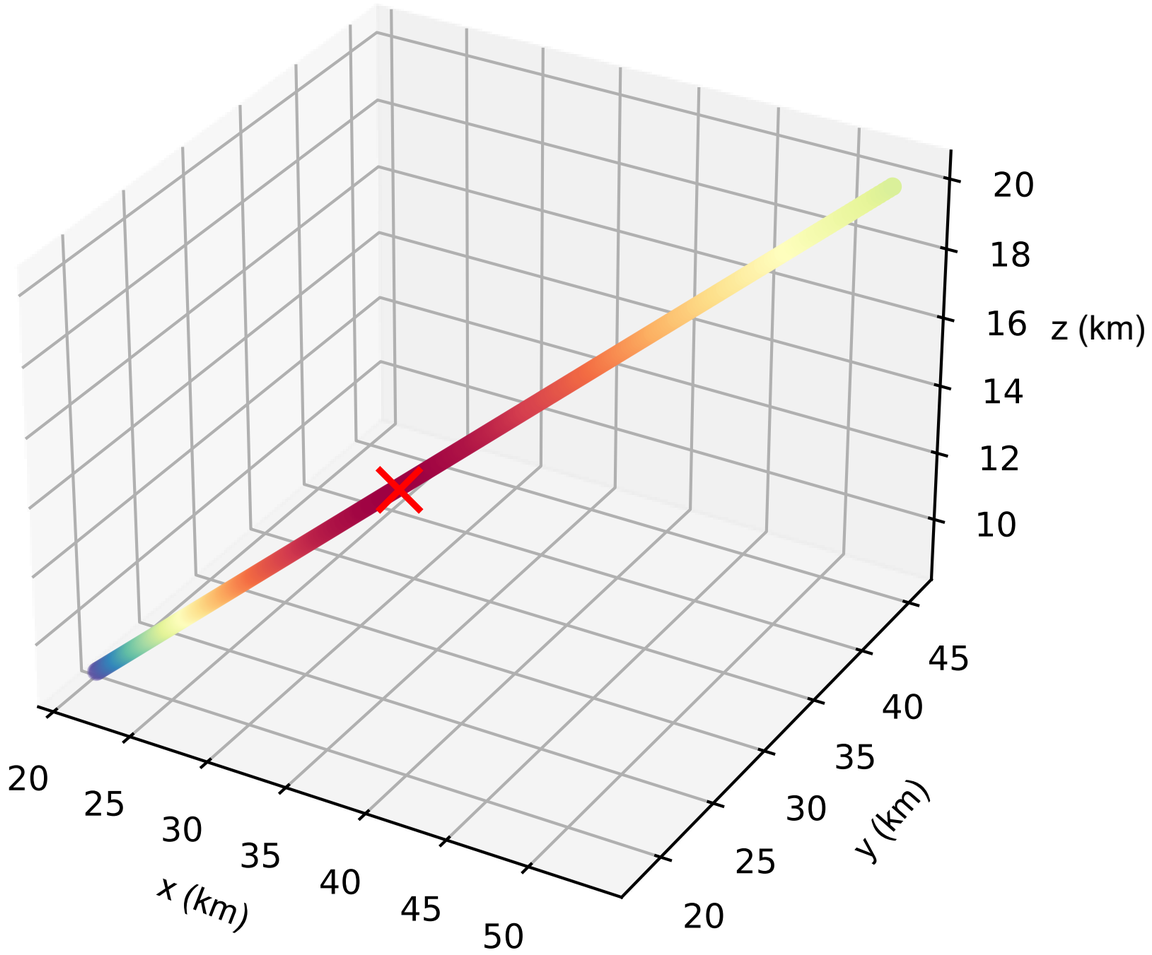


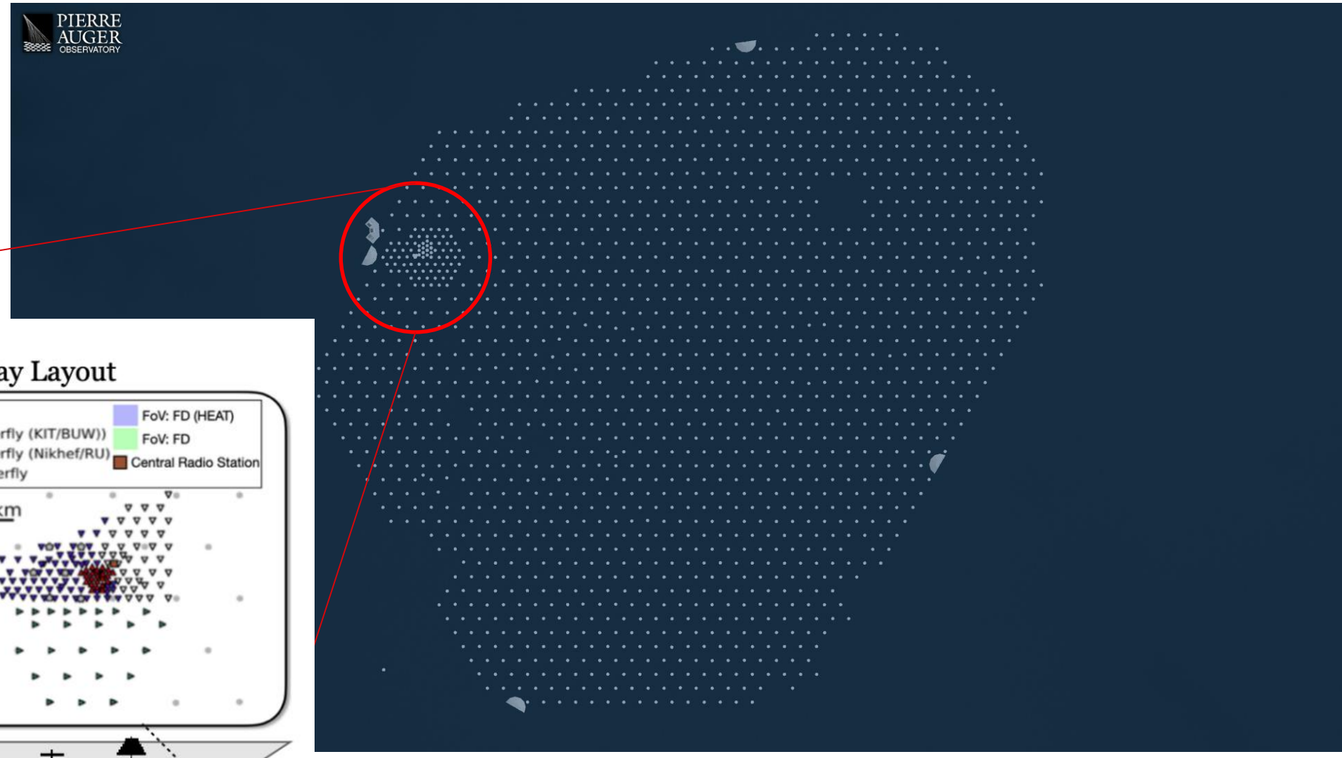
ASIRA

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

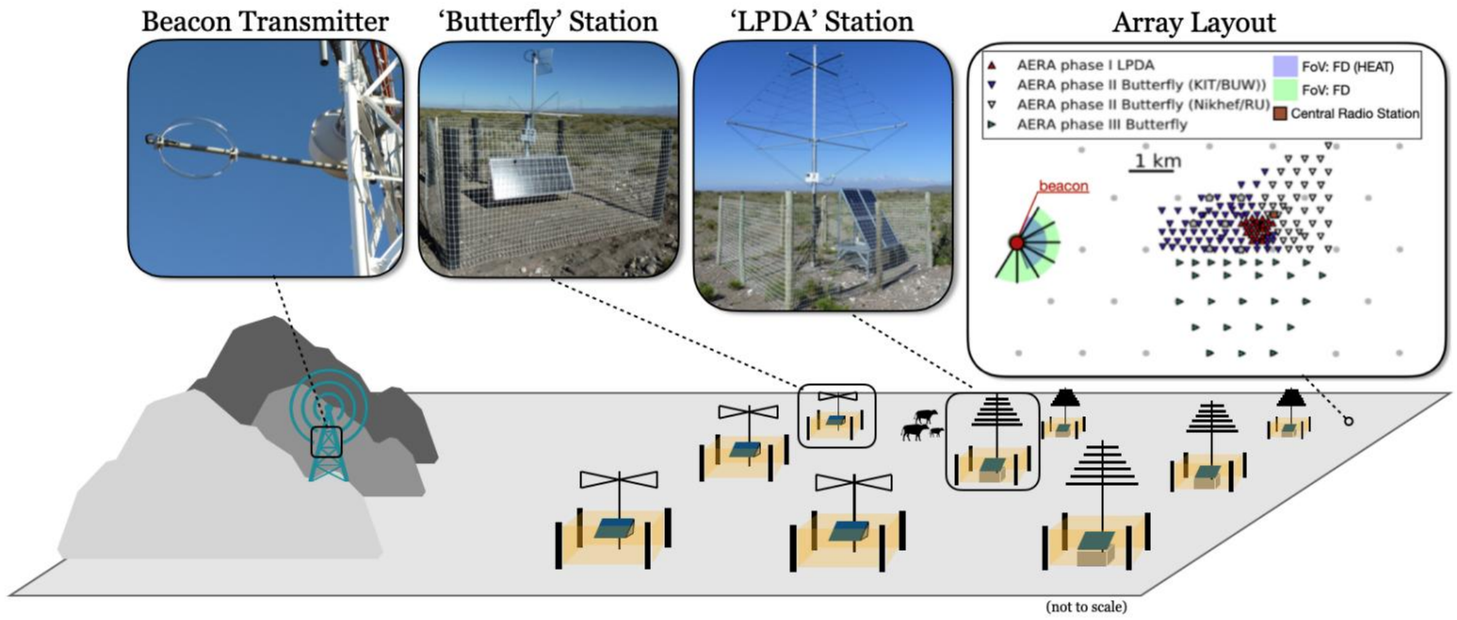


Auger Engineering Radio Array (AERA)

- Differential GPS measurements
- Beacon for time synchronisation



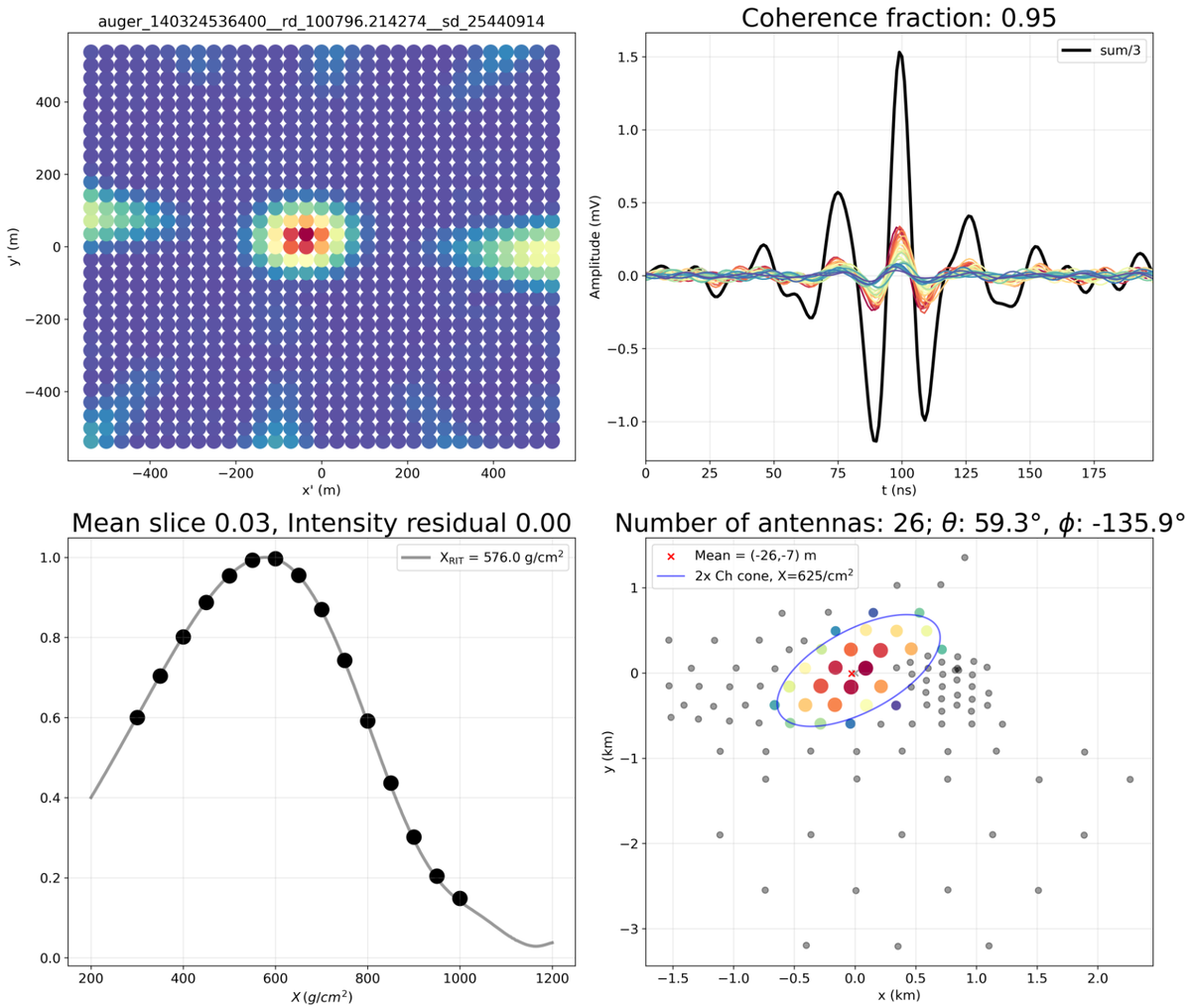
https://opendata.auger.org/display.php



DOI:10.1051/epjconf/201713501006

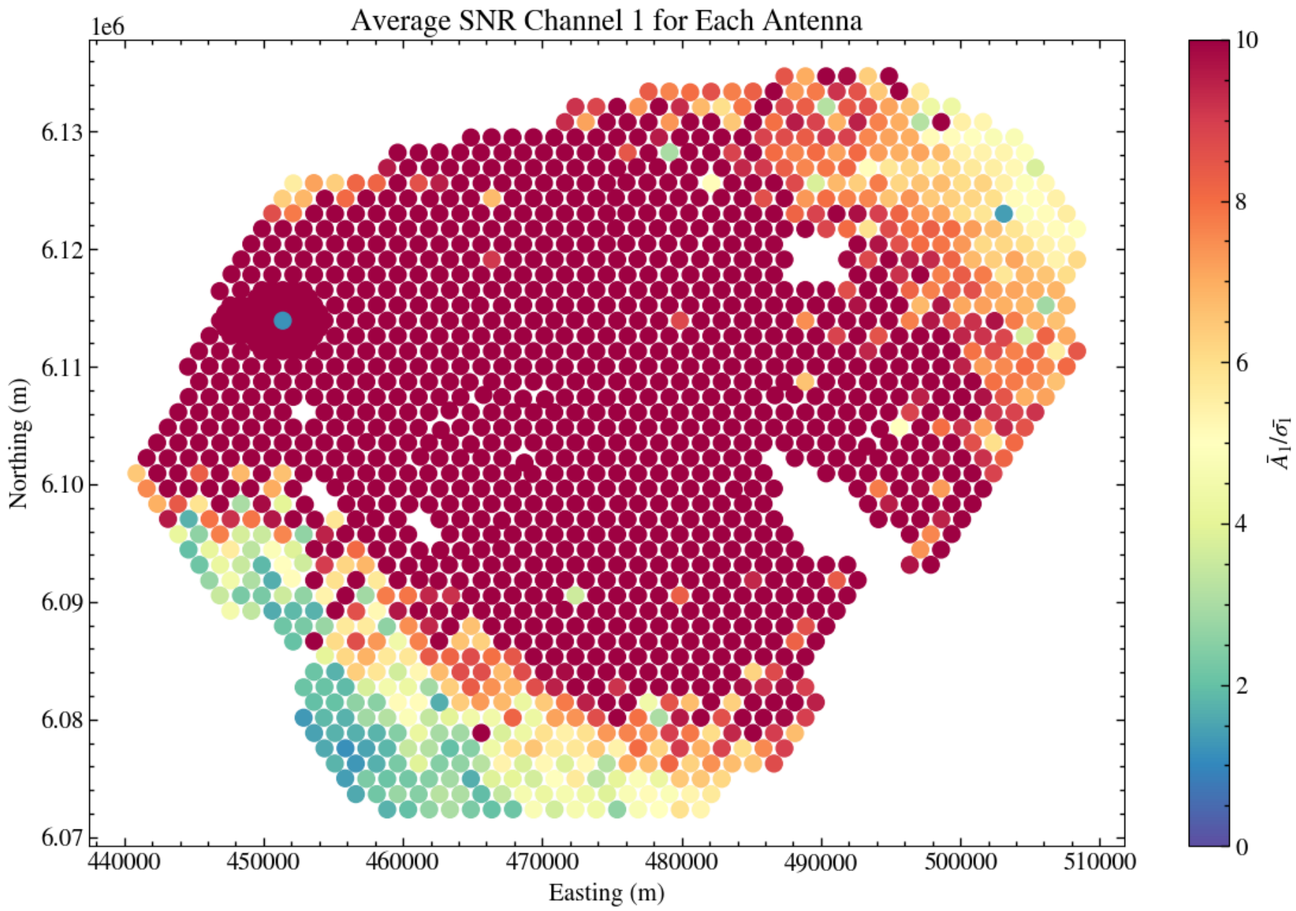
Auger Engineering Radio Array (AERA)

- Interferometry already tested on large dataset
- Promising results!



Interferometry with RD

- Beacon(s) for time synchronisation **< 1 ns**
- Differential GPS for antenna positions **< 30 cm**



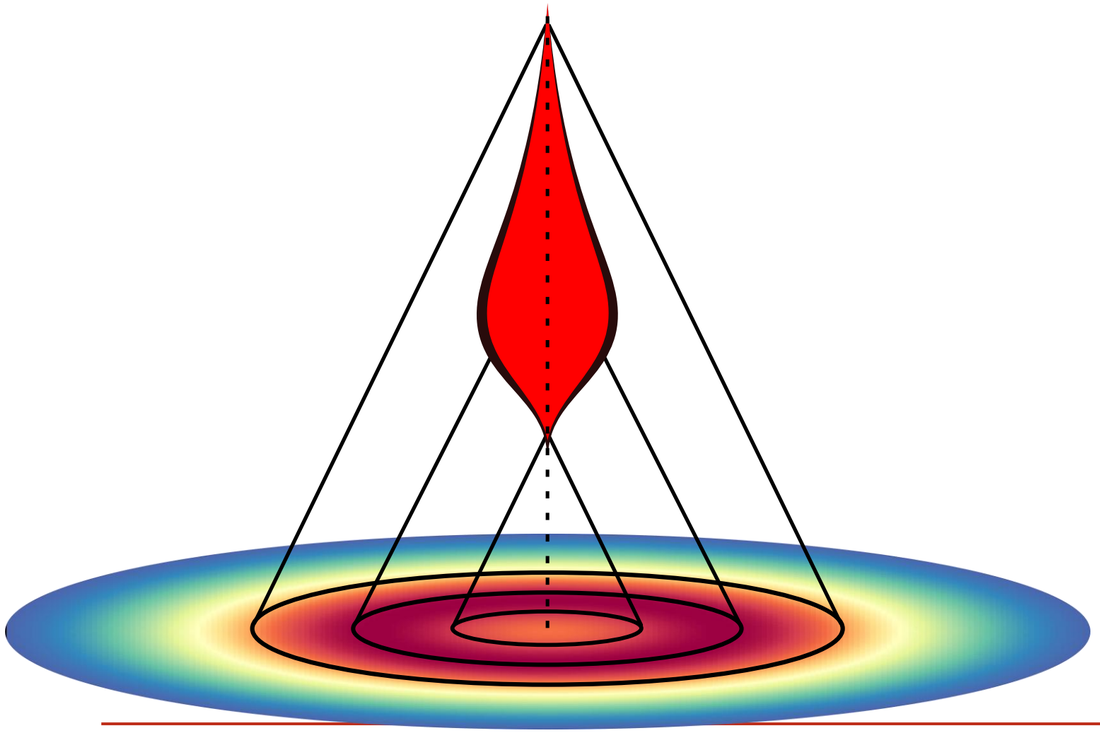
Conclusion

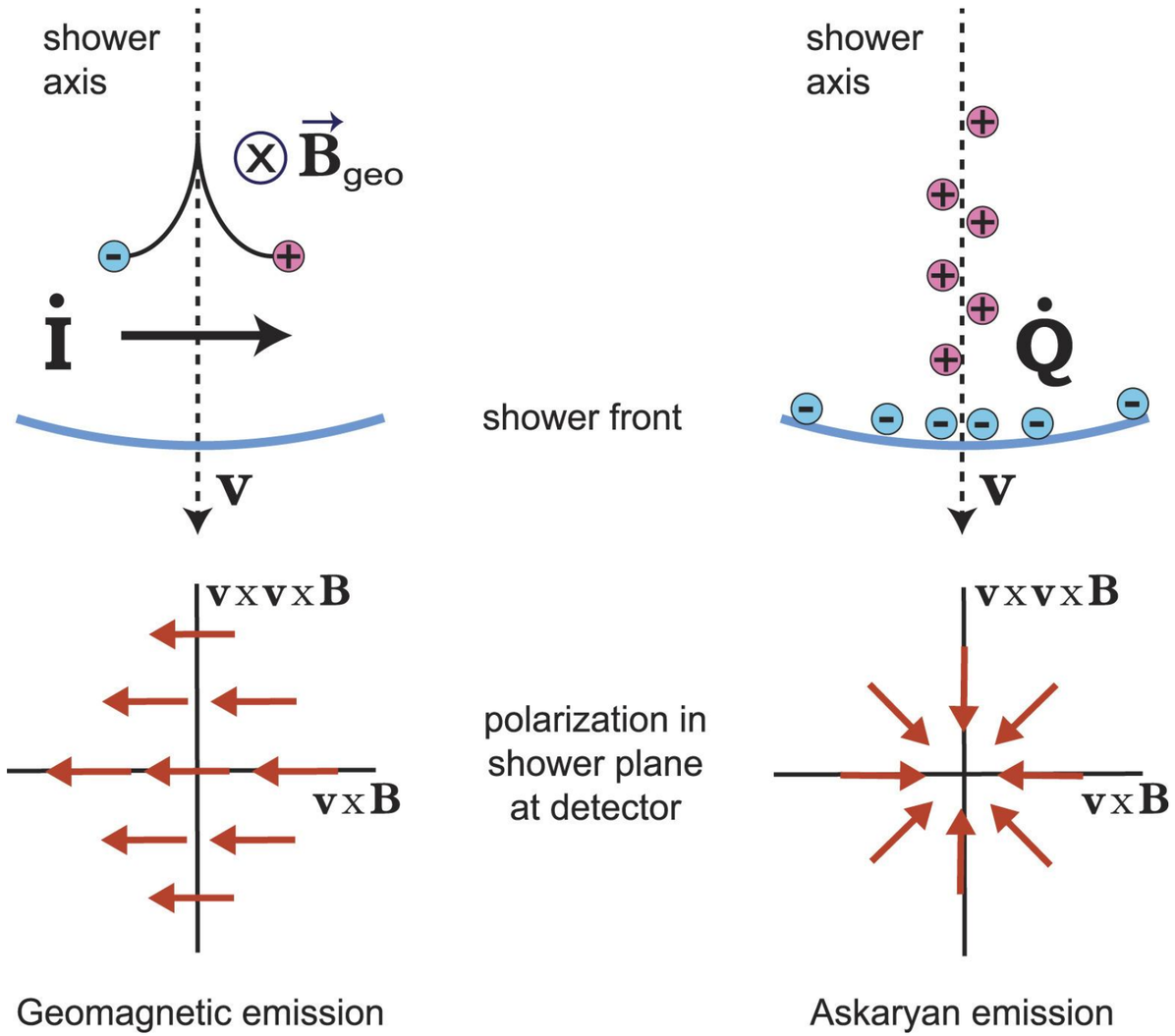
- Radio
  - Enabled radio detection for full array
  - Reconstruct air shower parameters independently of surface detector
  - Increase sensitivity for neutral particles
- Interferometry
  - Full 3D mapping of air shower is possible
  - Full array is being prepared
- Combining methods will help in unravelling the mysteries of the most energetic cosmic rays!

BACKUP

Radio Emission

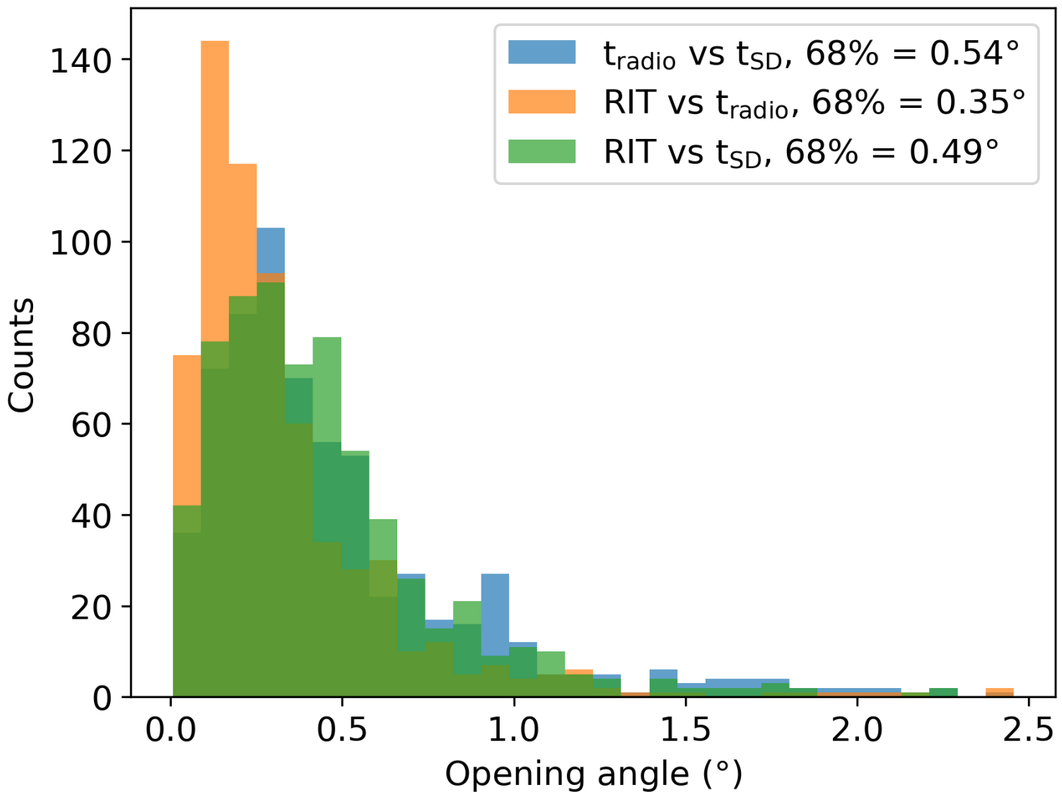
- Coherent radiation
  - Frequencies < 100MHz
- Cherenkov cone

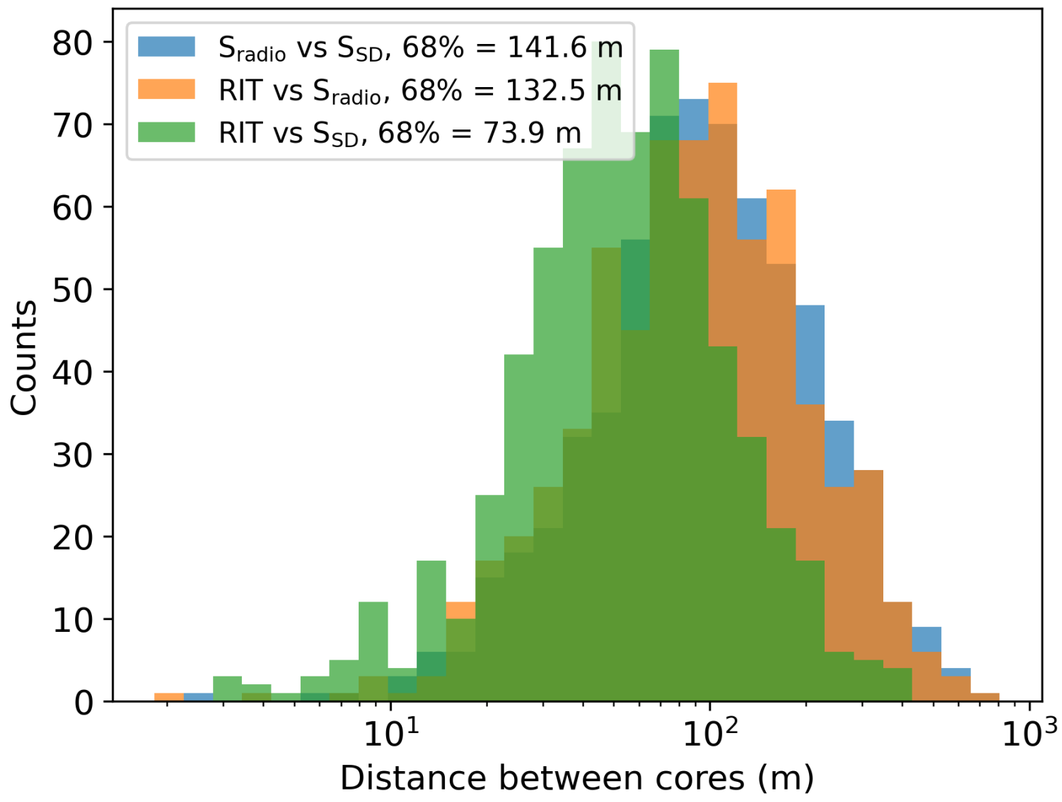




AERA – Data

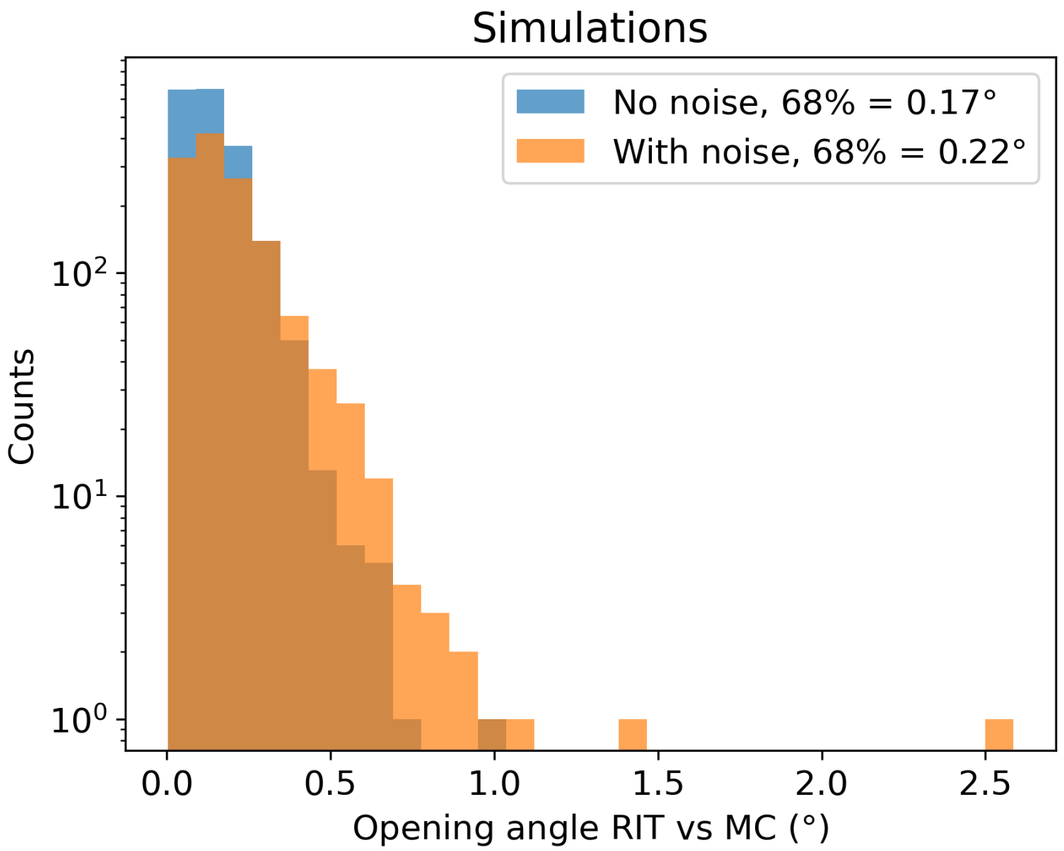
- Comparable with SD and RD reconstructions
- **663 events**

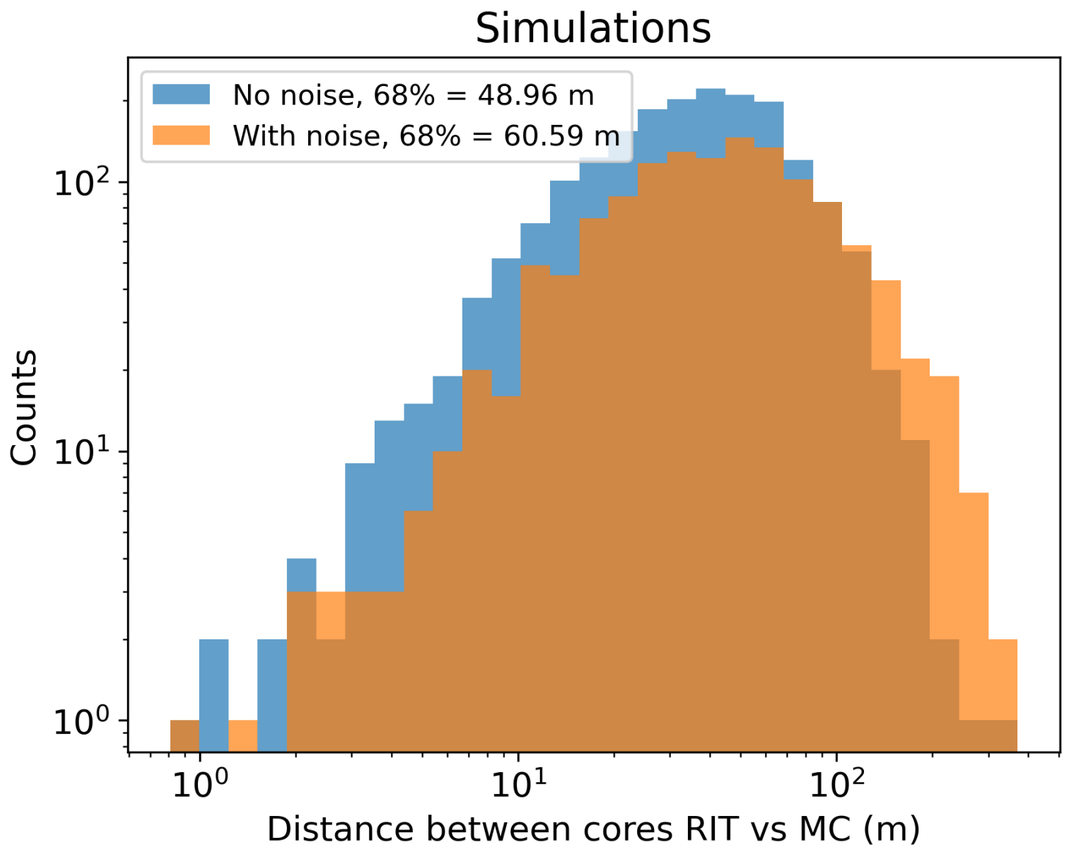




AERA – Simulations

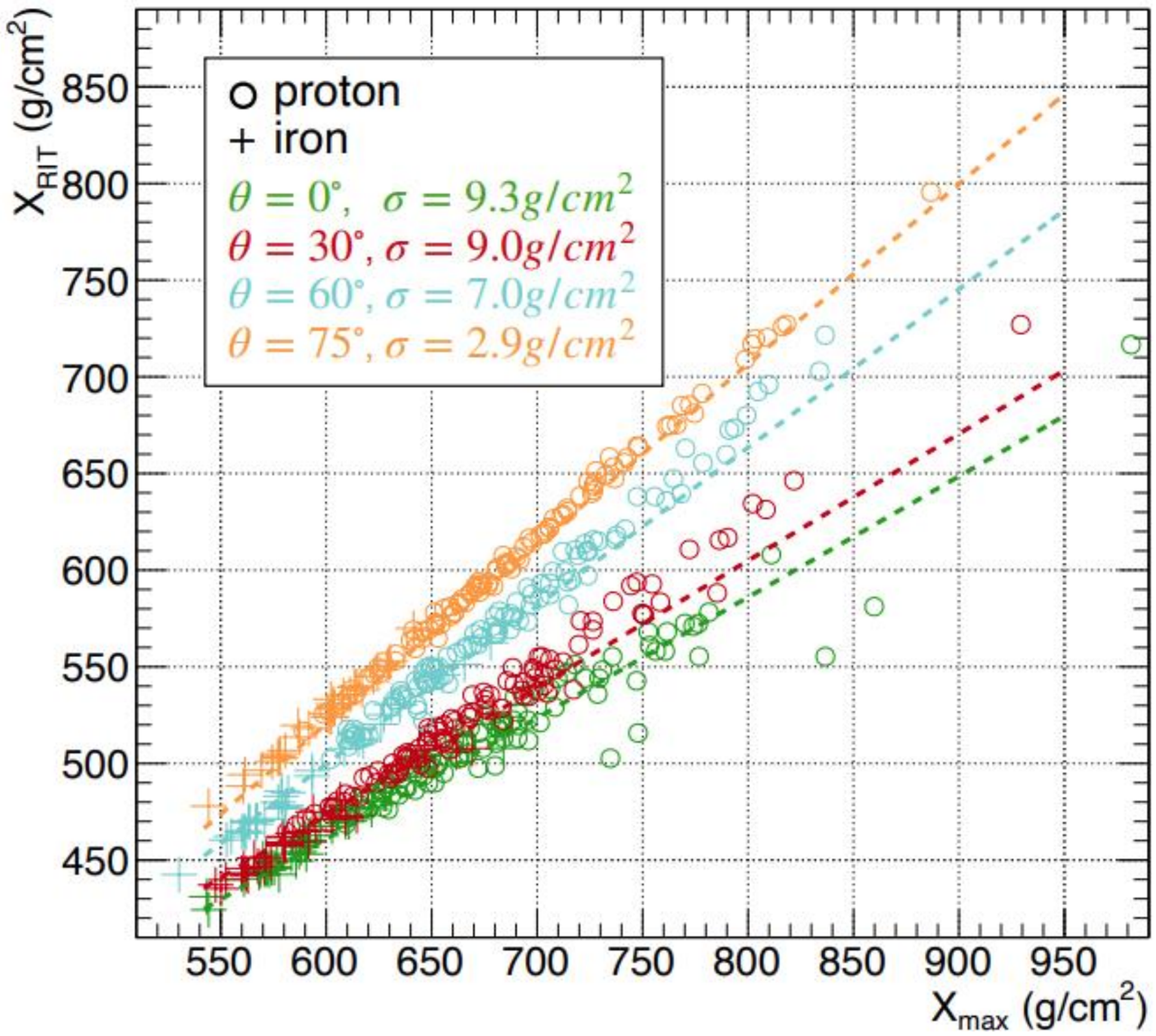
- **1915 events**





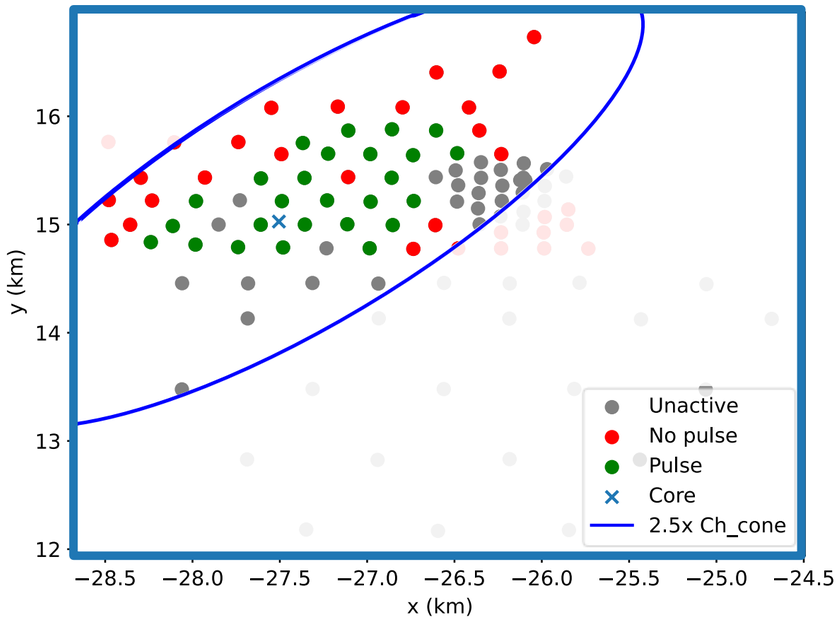
X_{RIT} to X_{max}

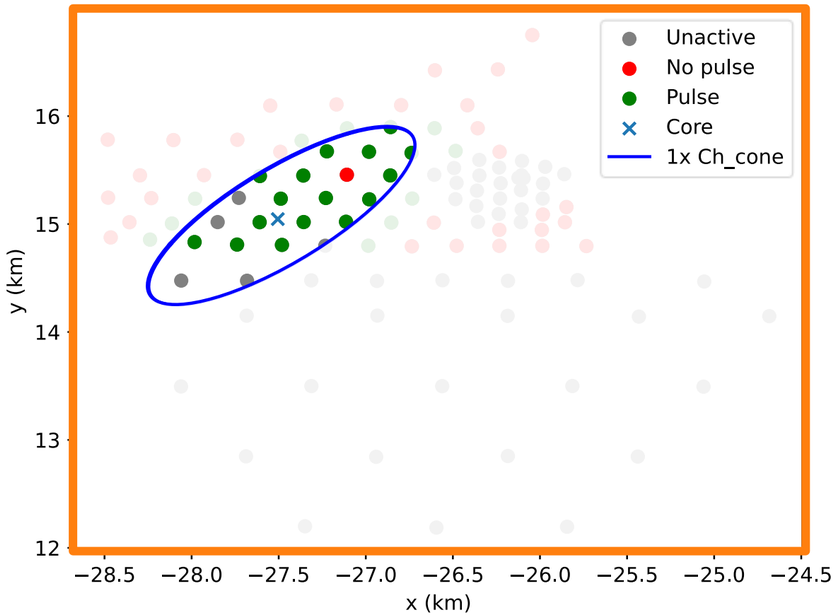
- Zenith dependence

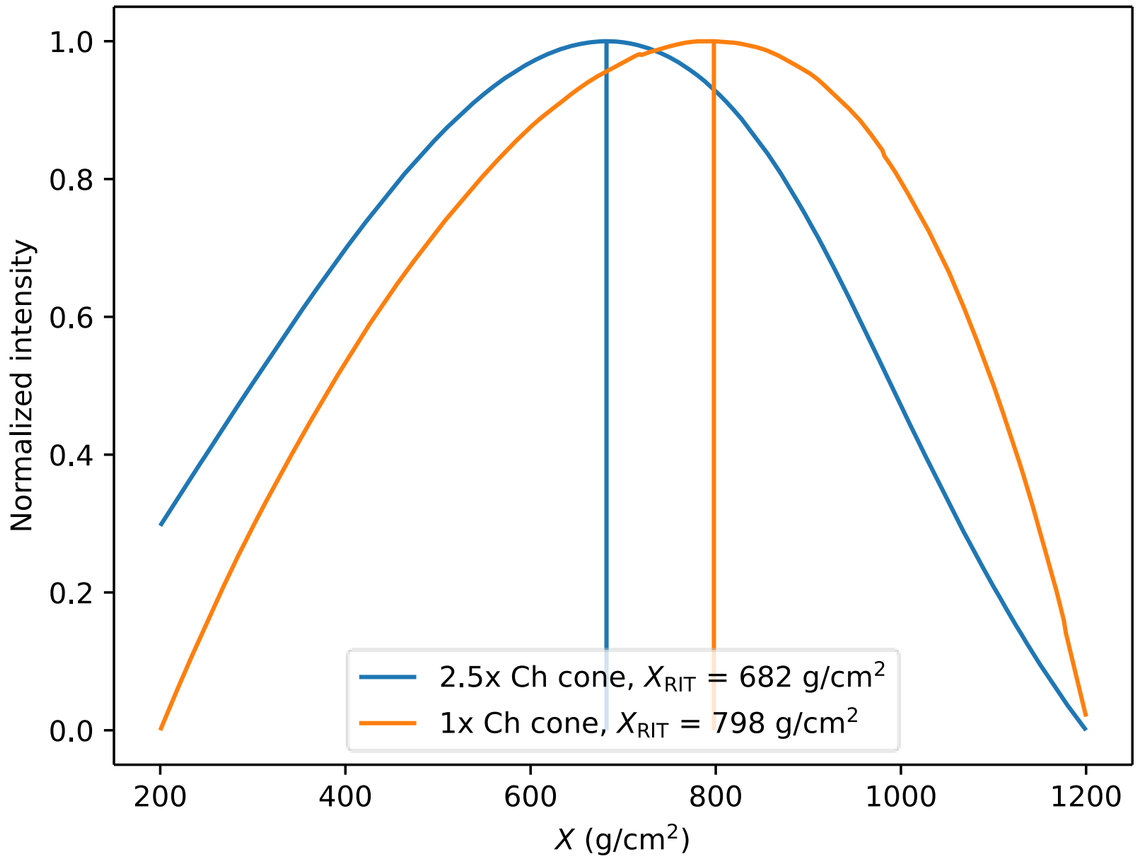


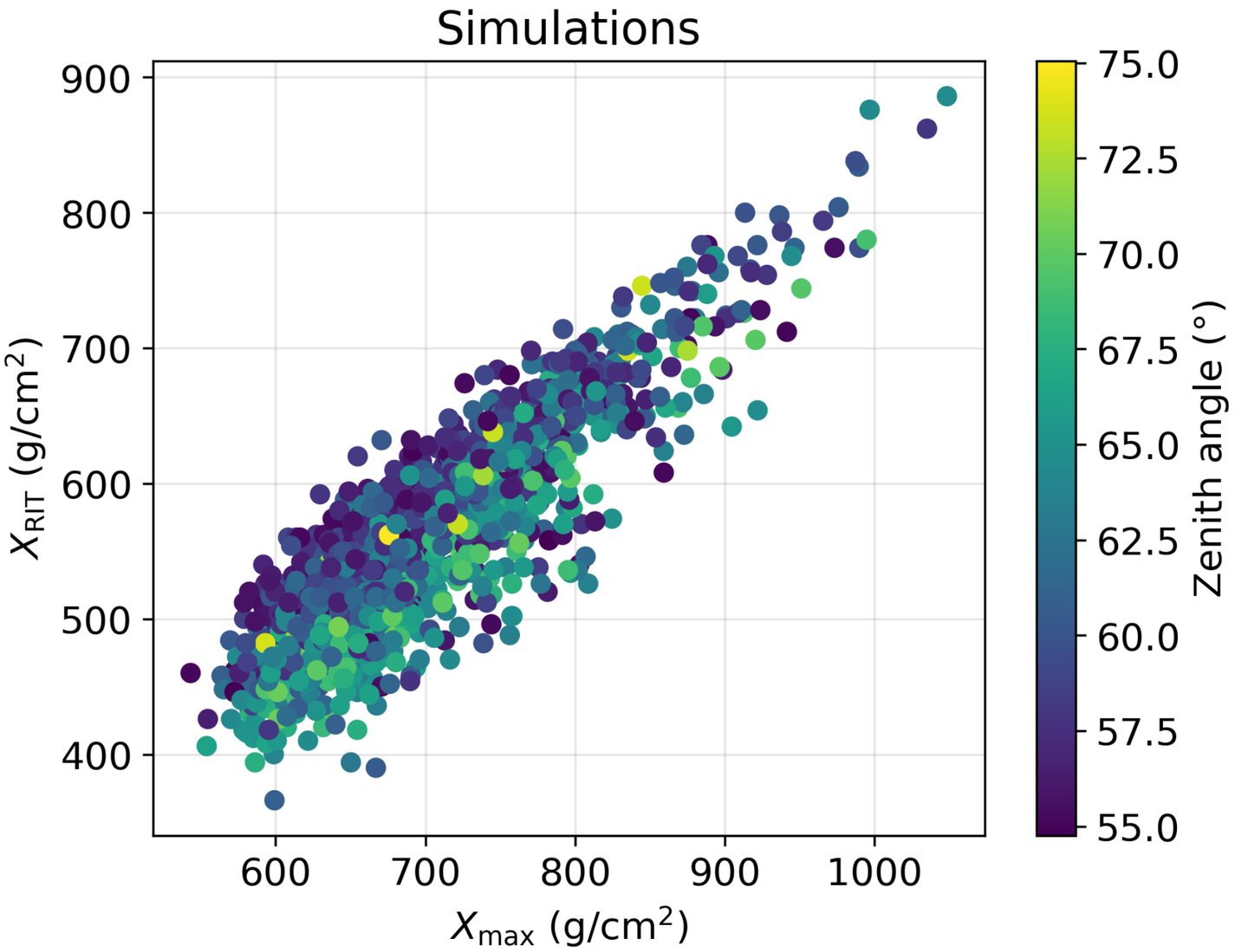
https://doi.org/10.48550/arXiv.2006.10348

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)

X_{RIT} to X_{max}

- No noise