Radio interferometric technique applied to air showers

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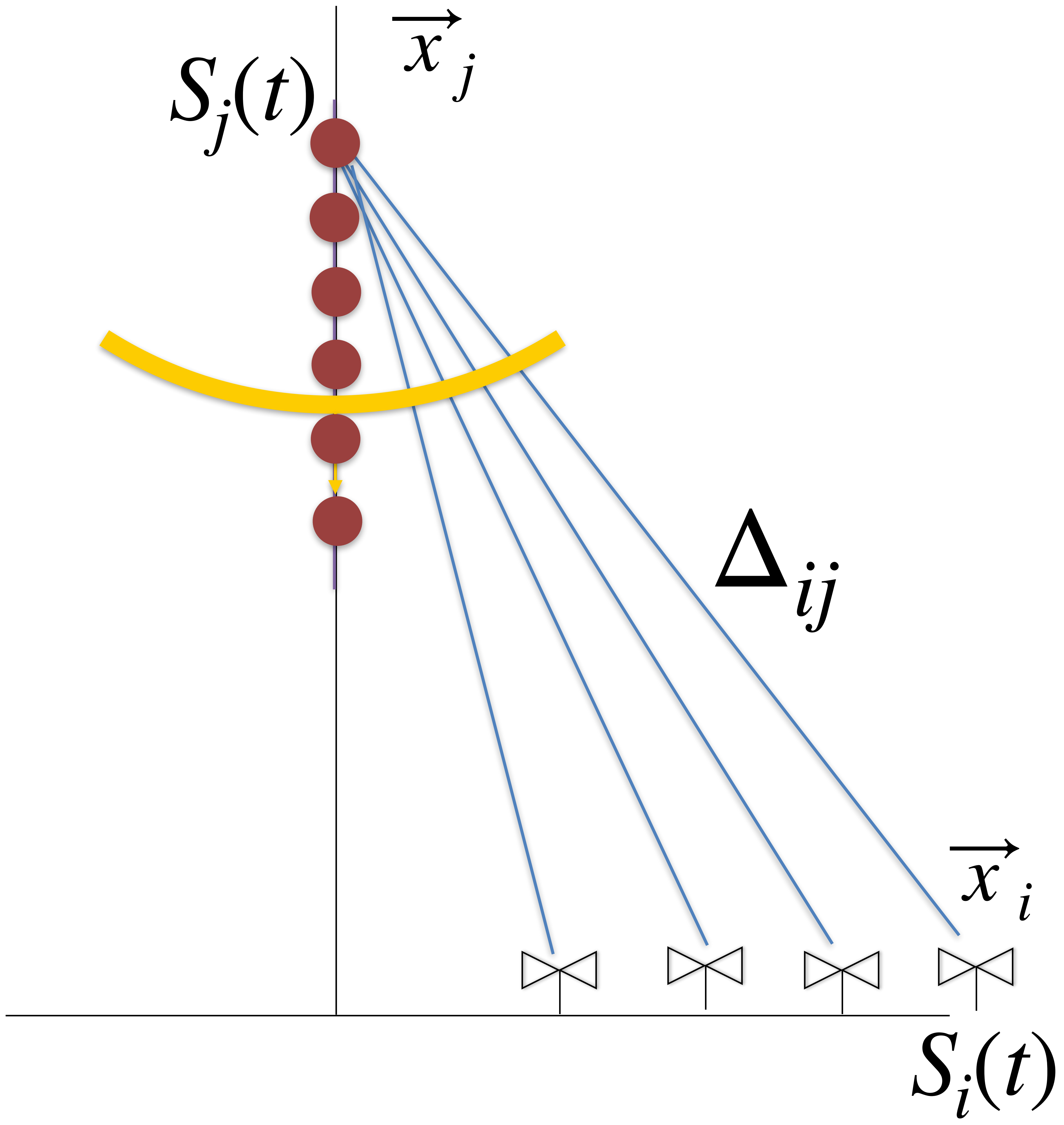
Concept



Calculate light travel time from antennas to locations in space

$$\Delta_{ij} = \frac{|\vec{x}_j - \vec{x}_i|n}{c}$$

Sum the waveforms from all antennas together with proper delays:

$$S_j(t) = \sum_i^N S_i(t + \Delta_{ij})$$

Evaluate the signal strength of $S_j(t)$ throughout space & time: Radio Interferometric Maps

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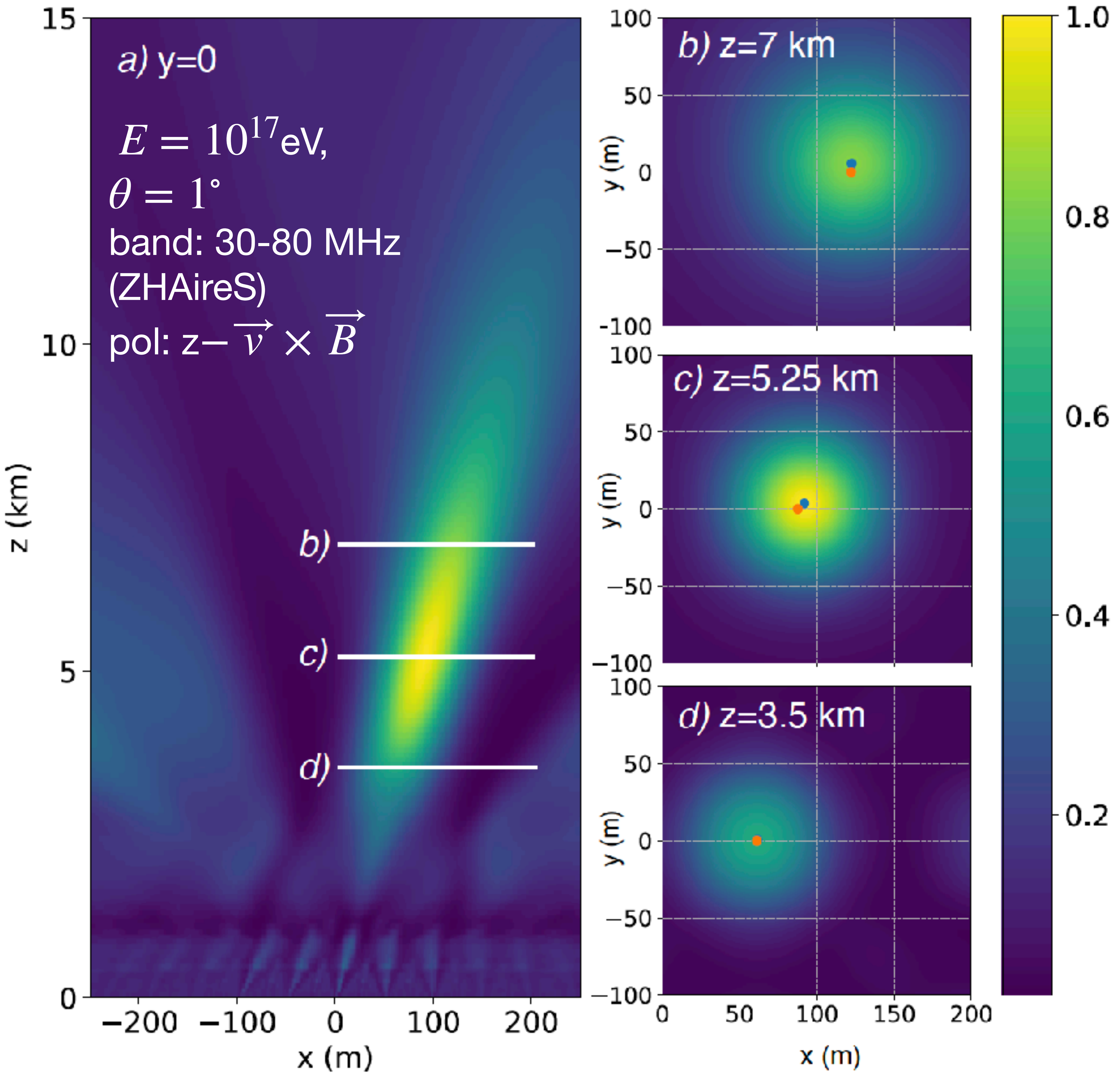

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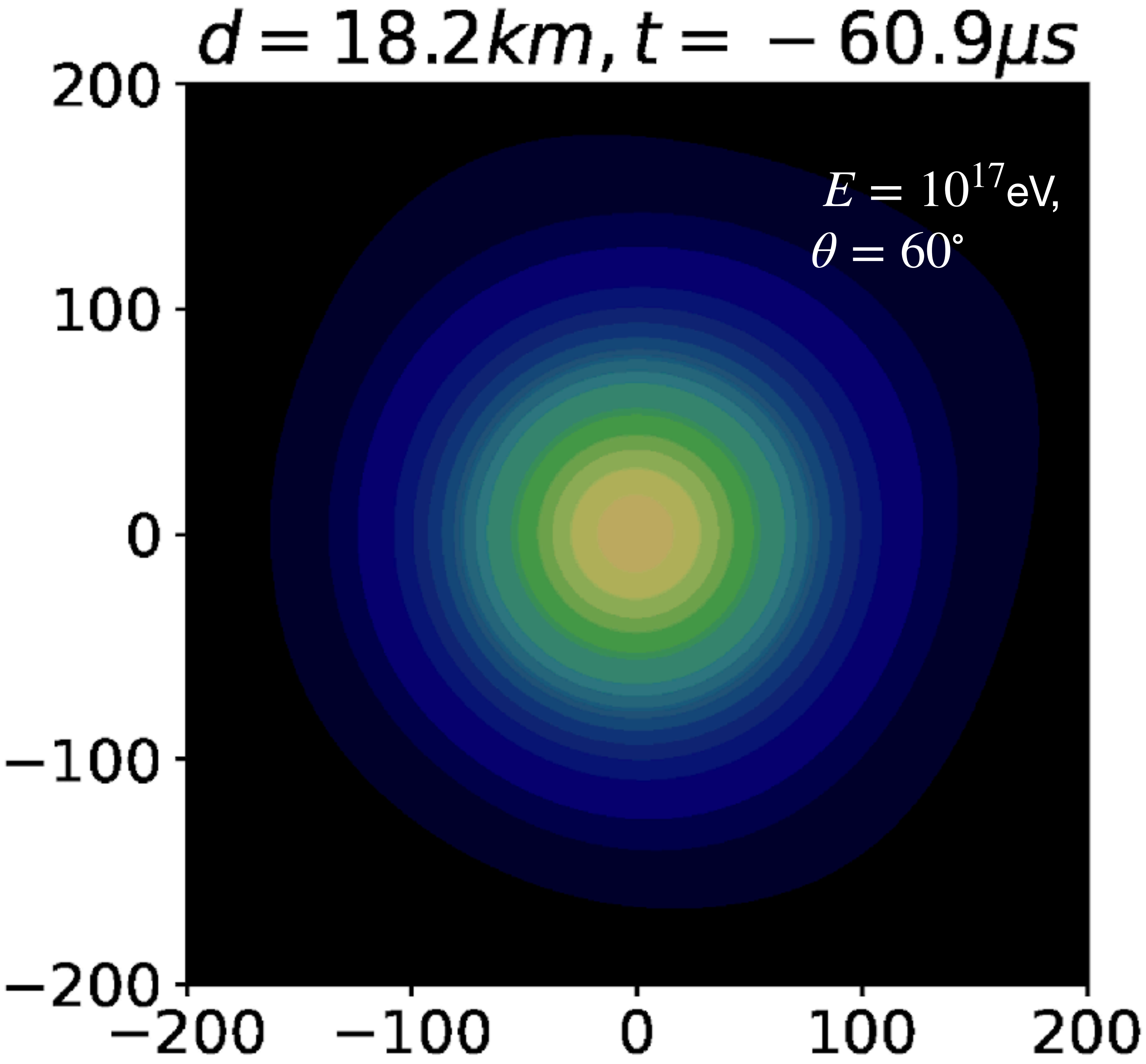
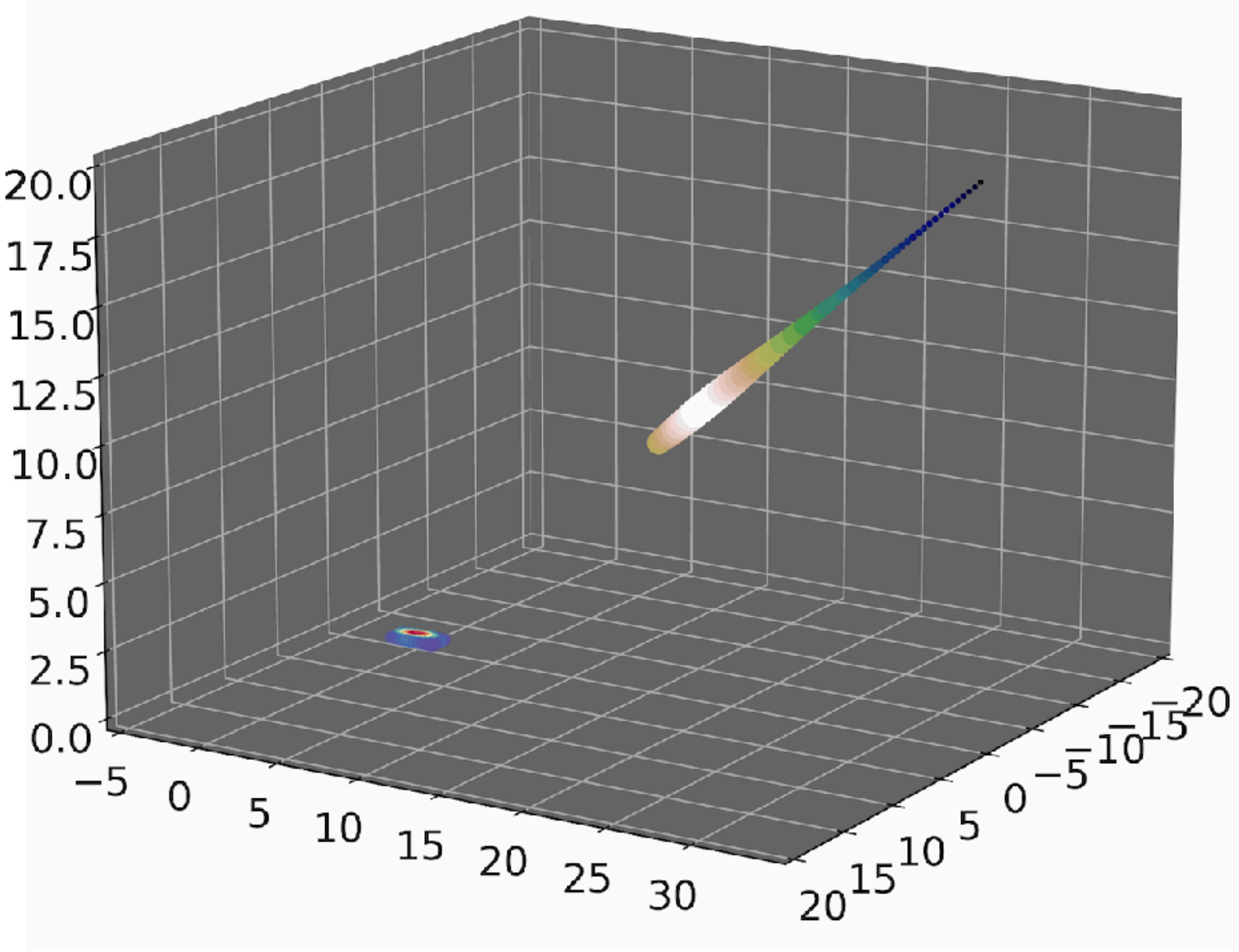
Tracking of air shower (4D)



Shower plane (m)



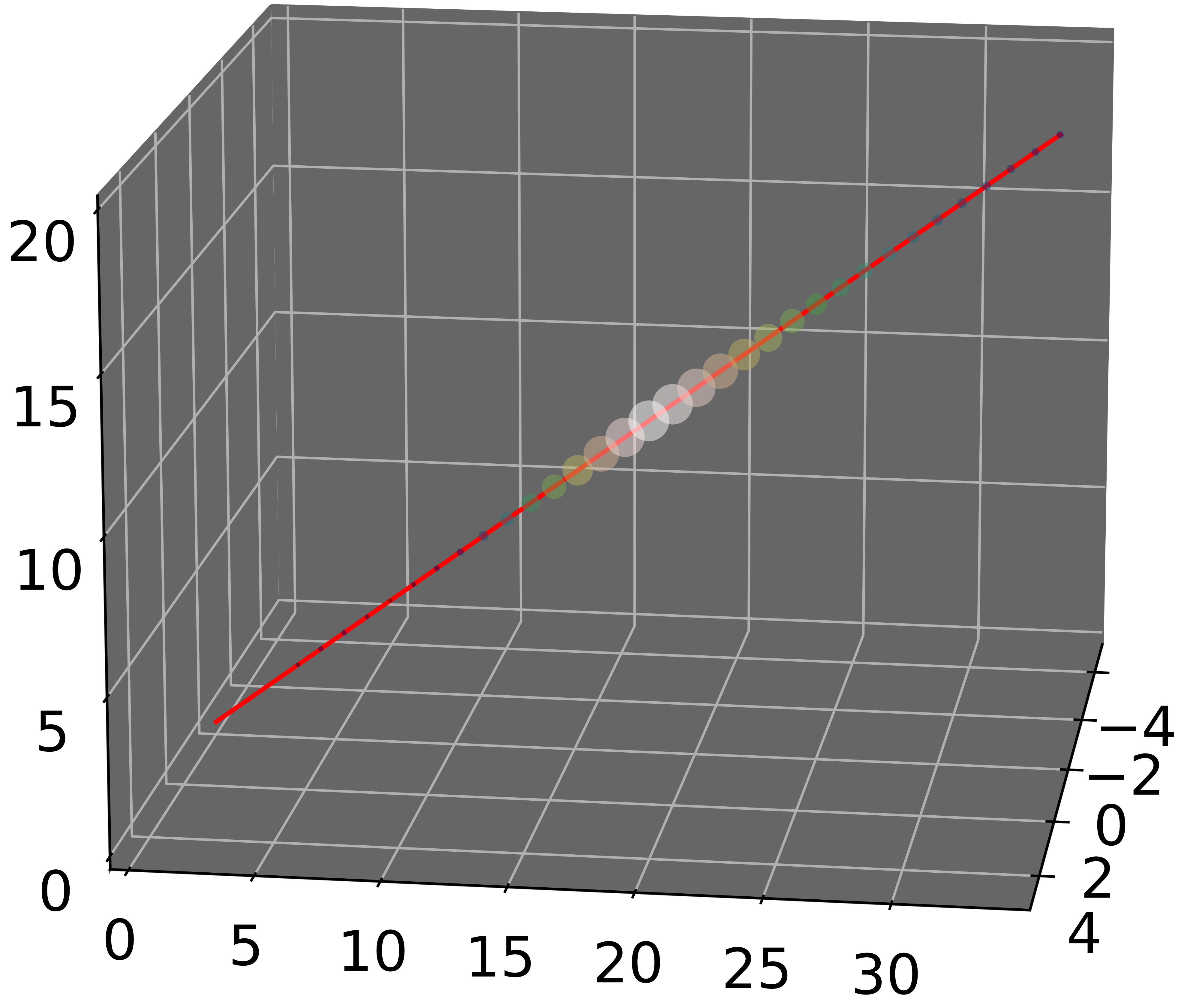
Shower track (km)

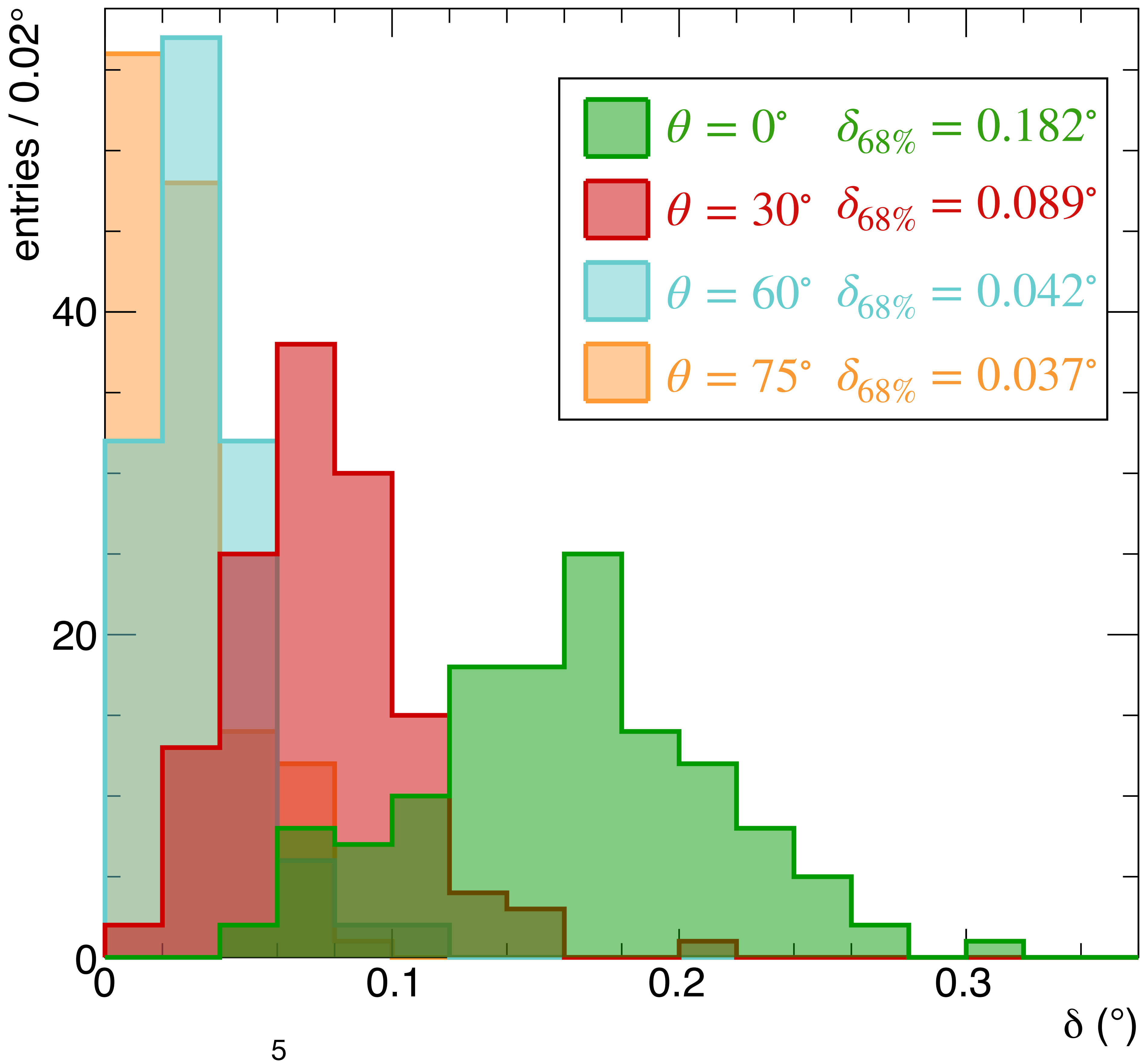
Direction reconstruction of the air shower

Fit straight track to the locations of maxima in slices along the shower axis*: (x_0, y_0, θ, ϕ)

Results on a set of randomised core locations and proton (100) / iron (30) mixture

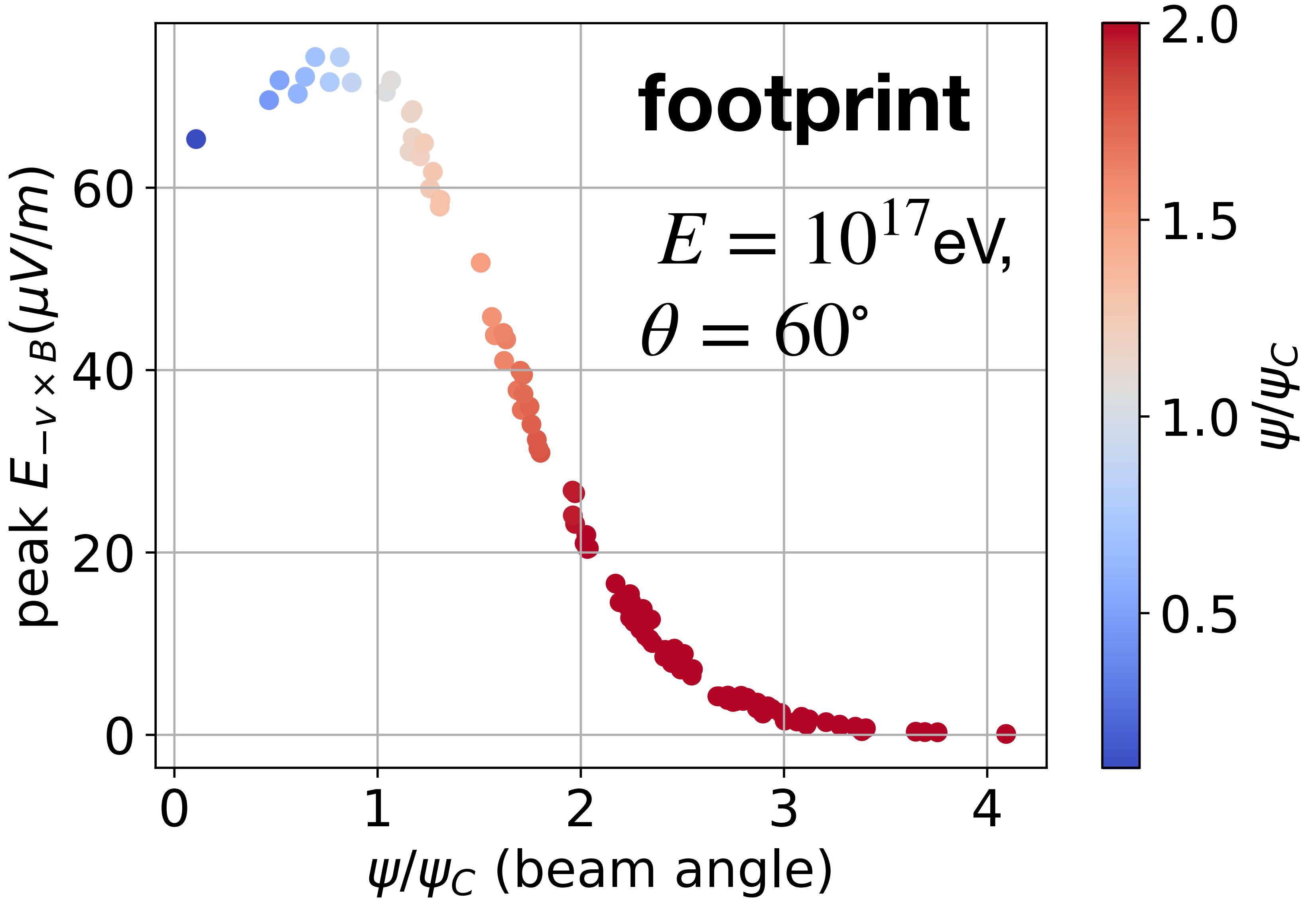
***No need for:**
"Wavefront models"
"deriving peak-times"
"early-late effects"

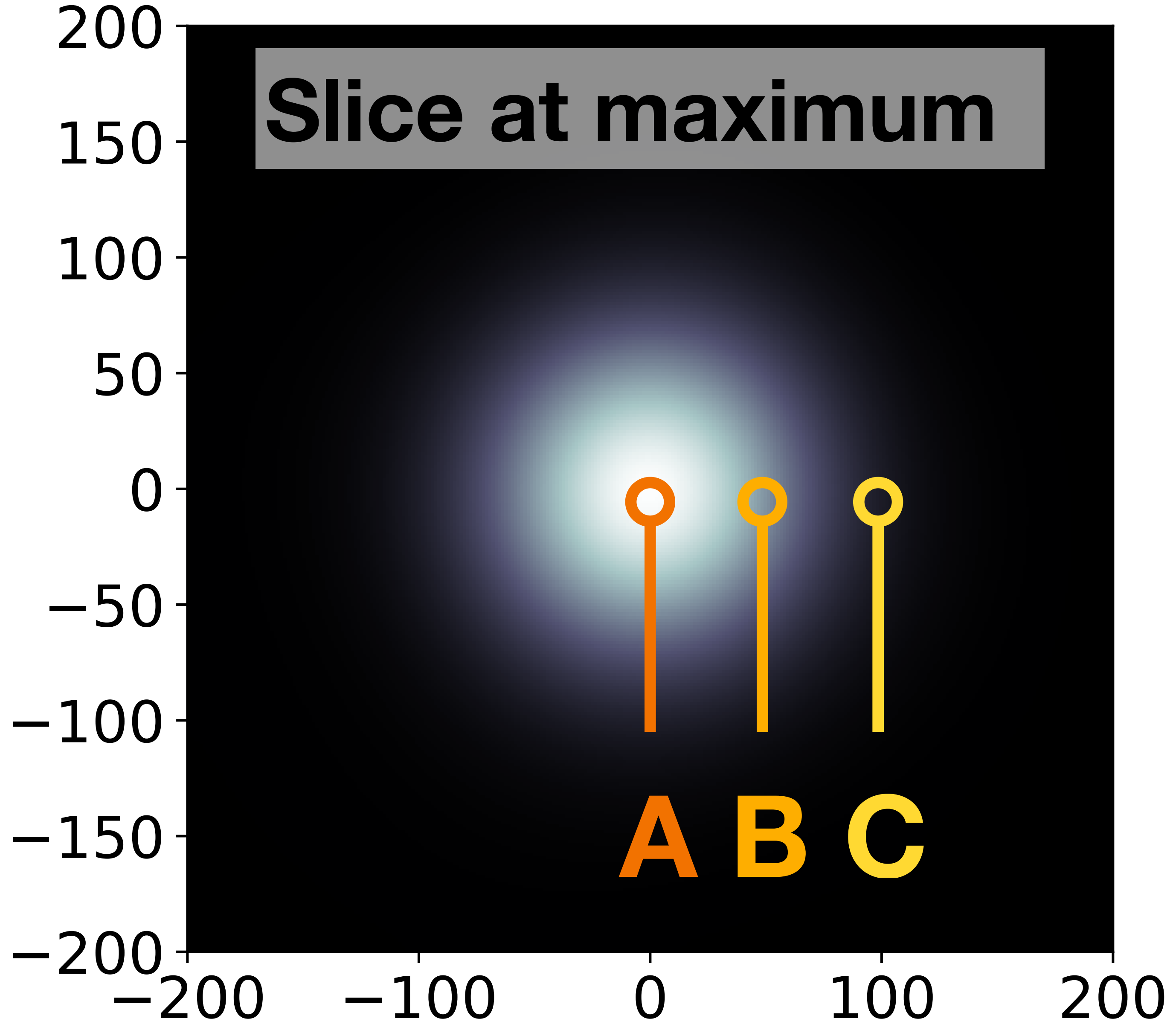


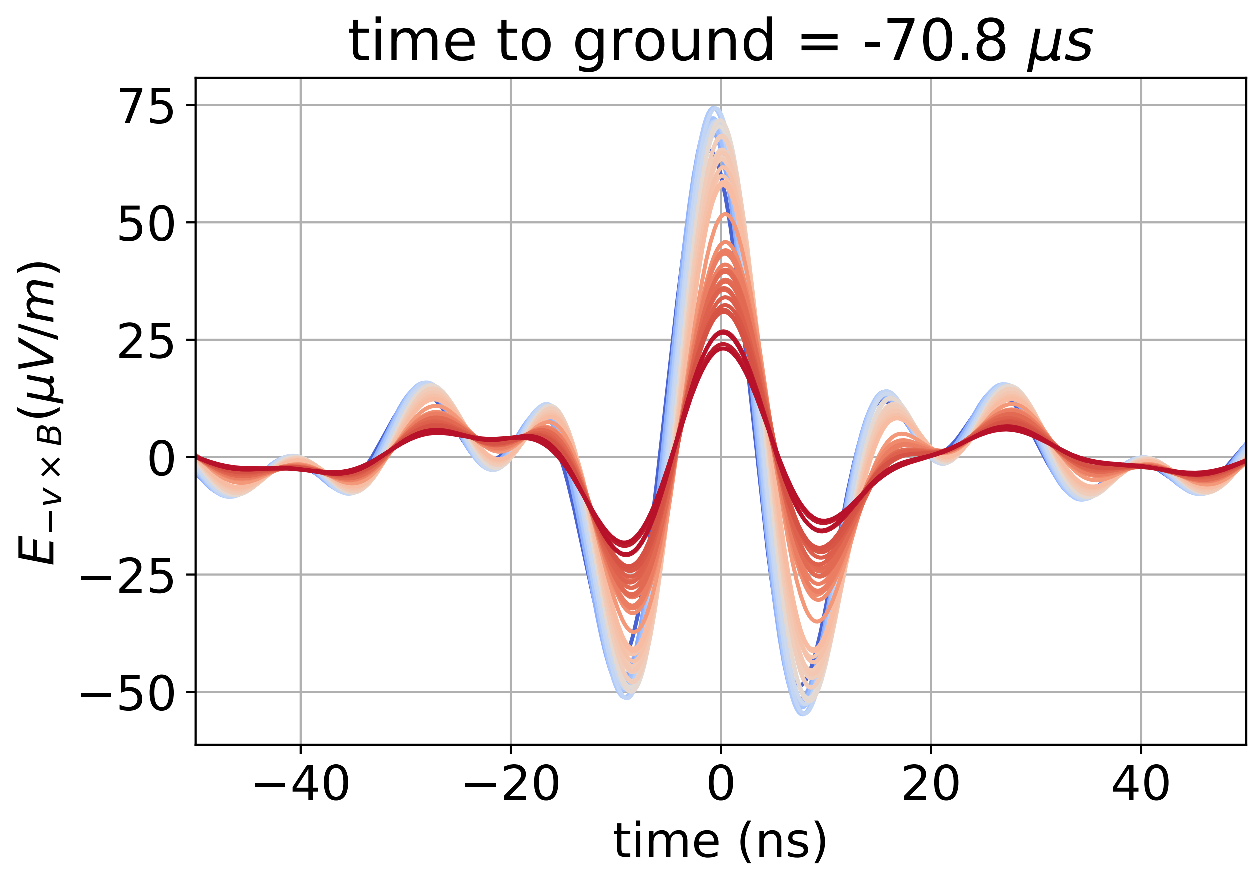


Good accuracy, improves with zenith angle

How does it work?

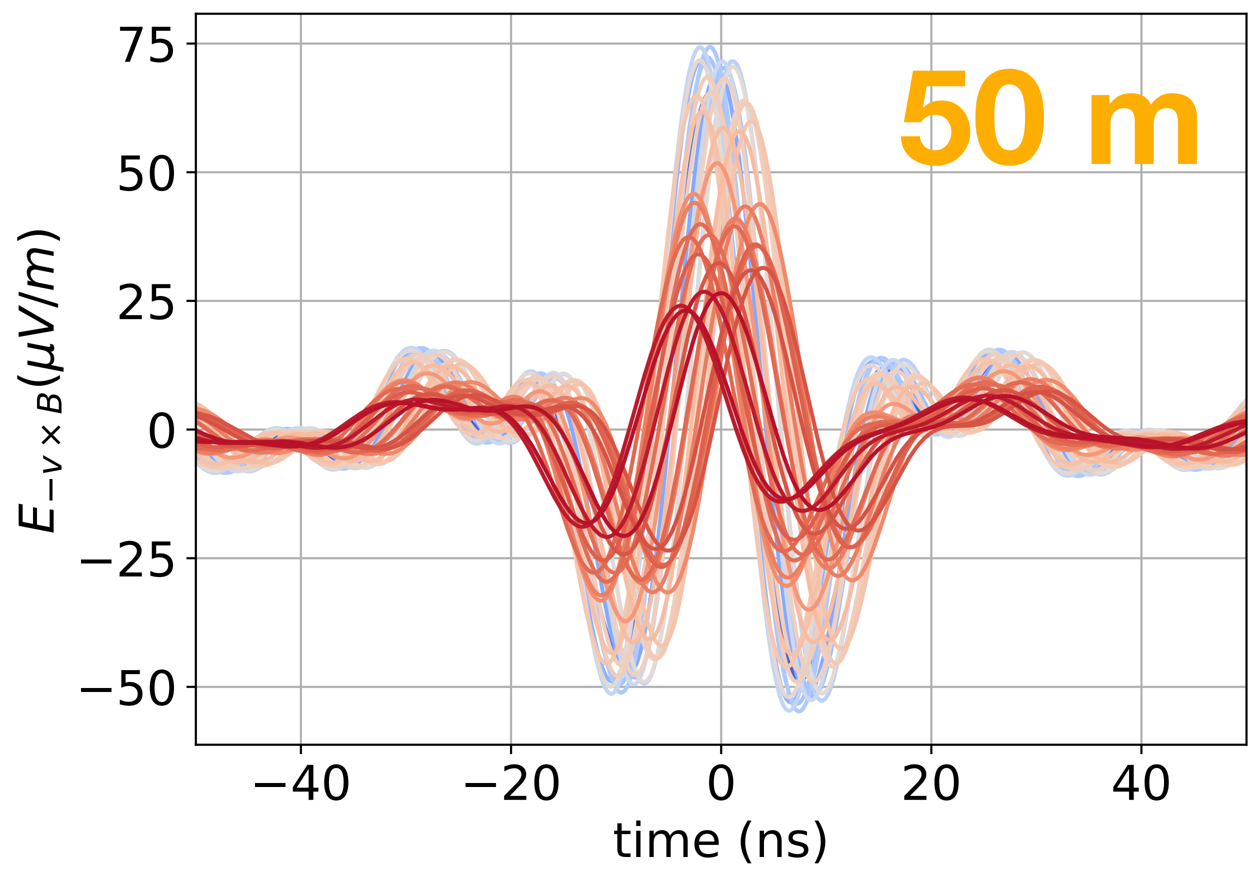






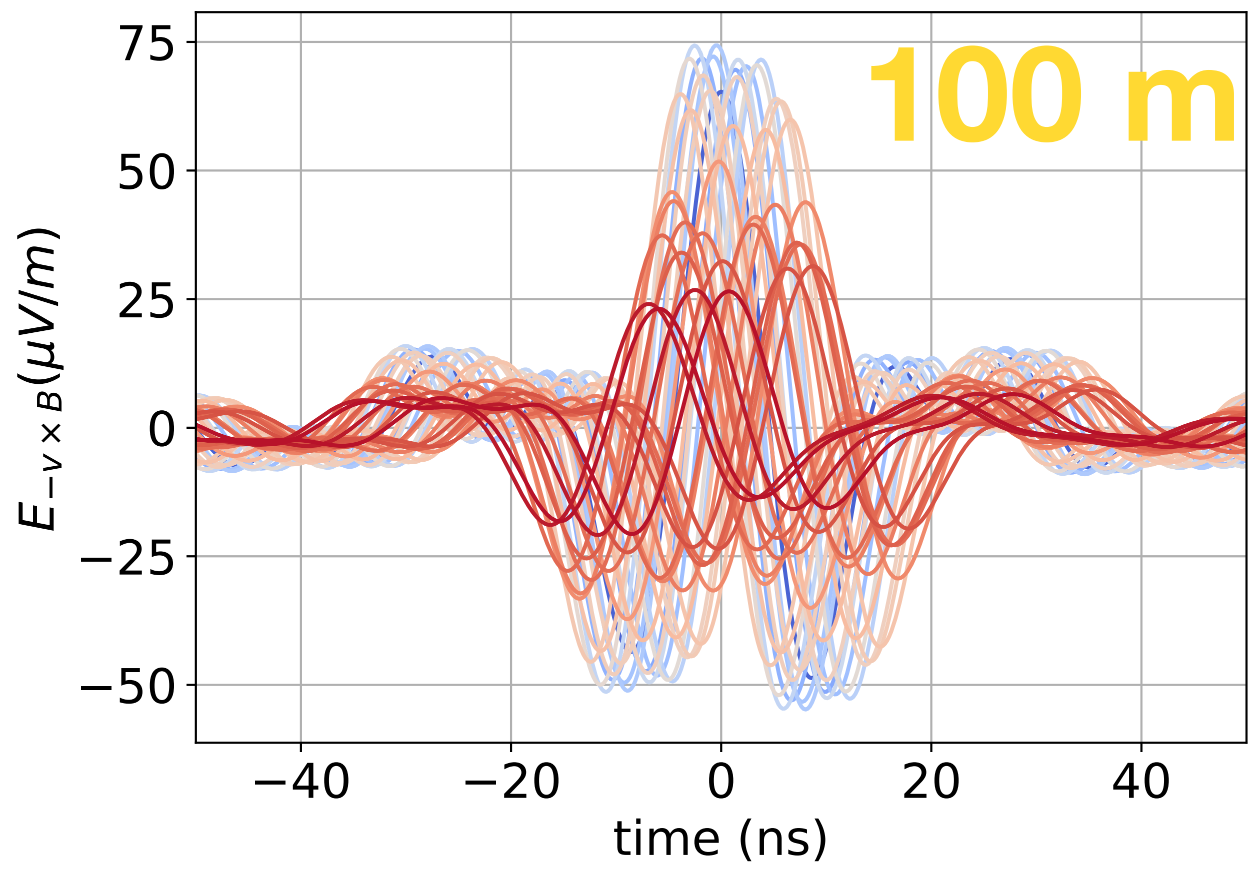
A)

Coherence from most antennas in footprint



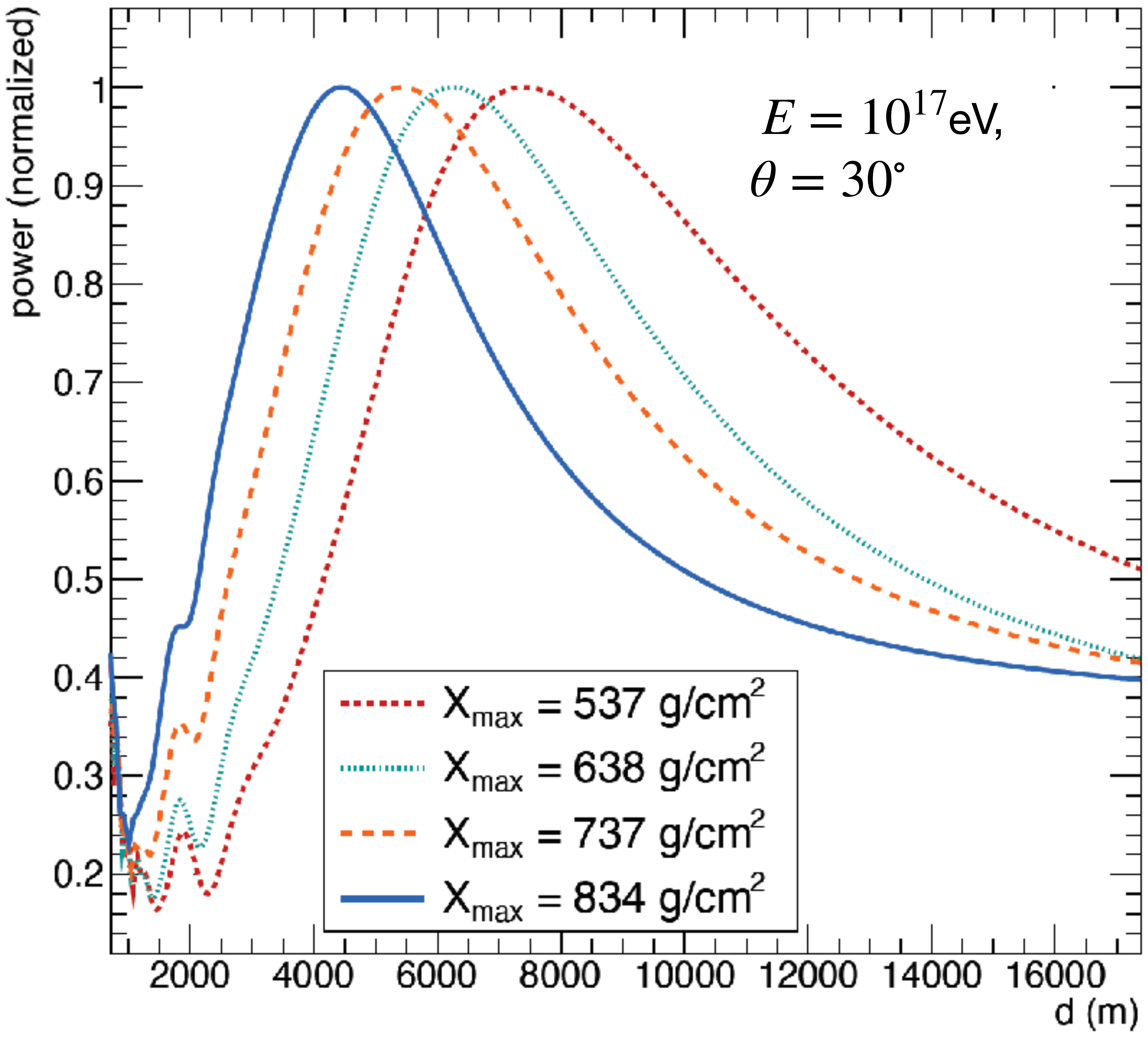
B) C)

rapid loss of coherence among all antennas



Reconstruction of air shower depth

Use reconstructed axis, and obtain depth of maximum along the axis



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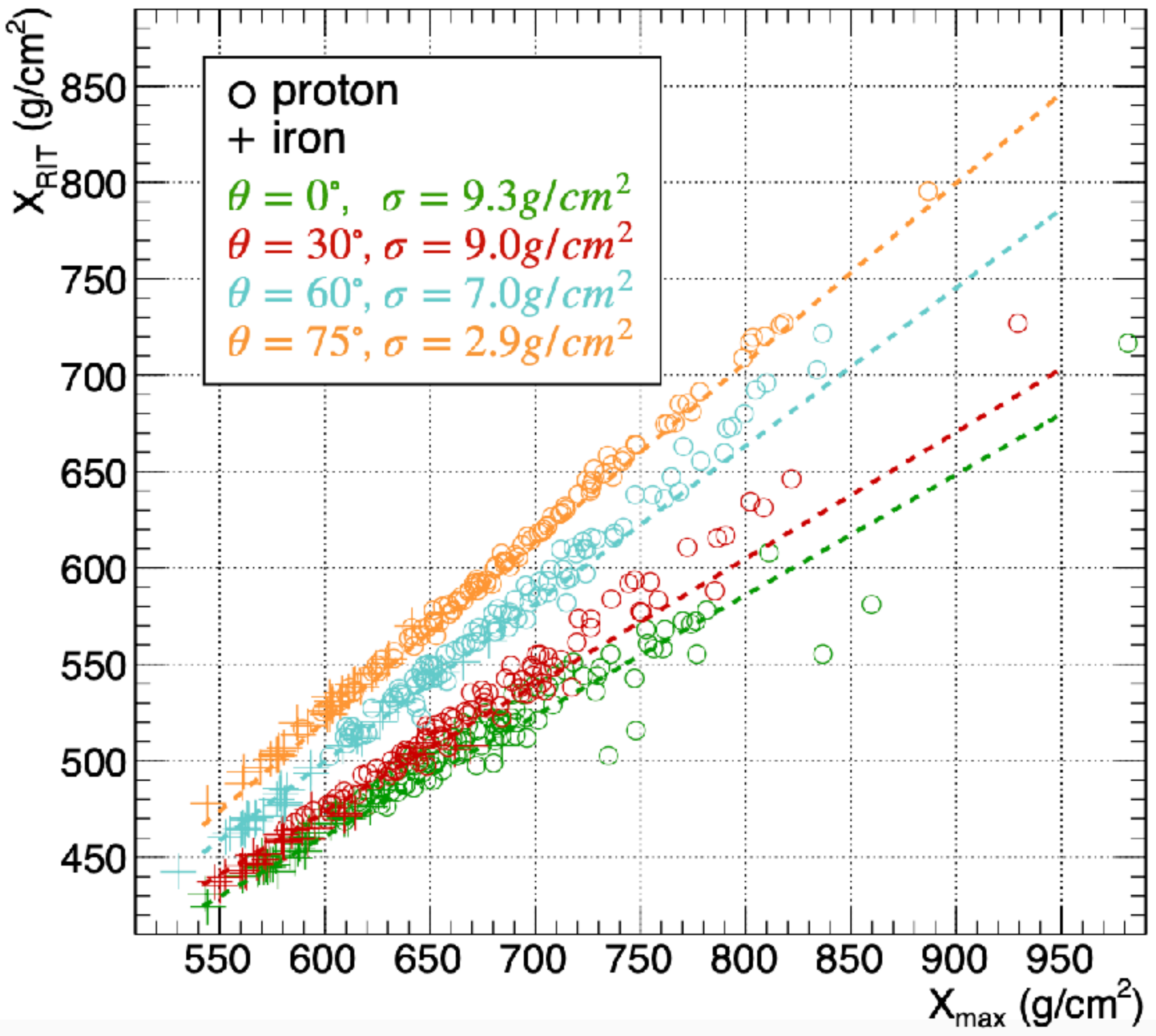
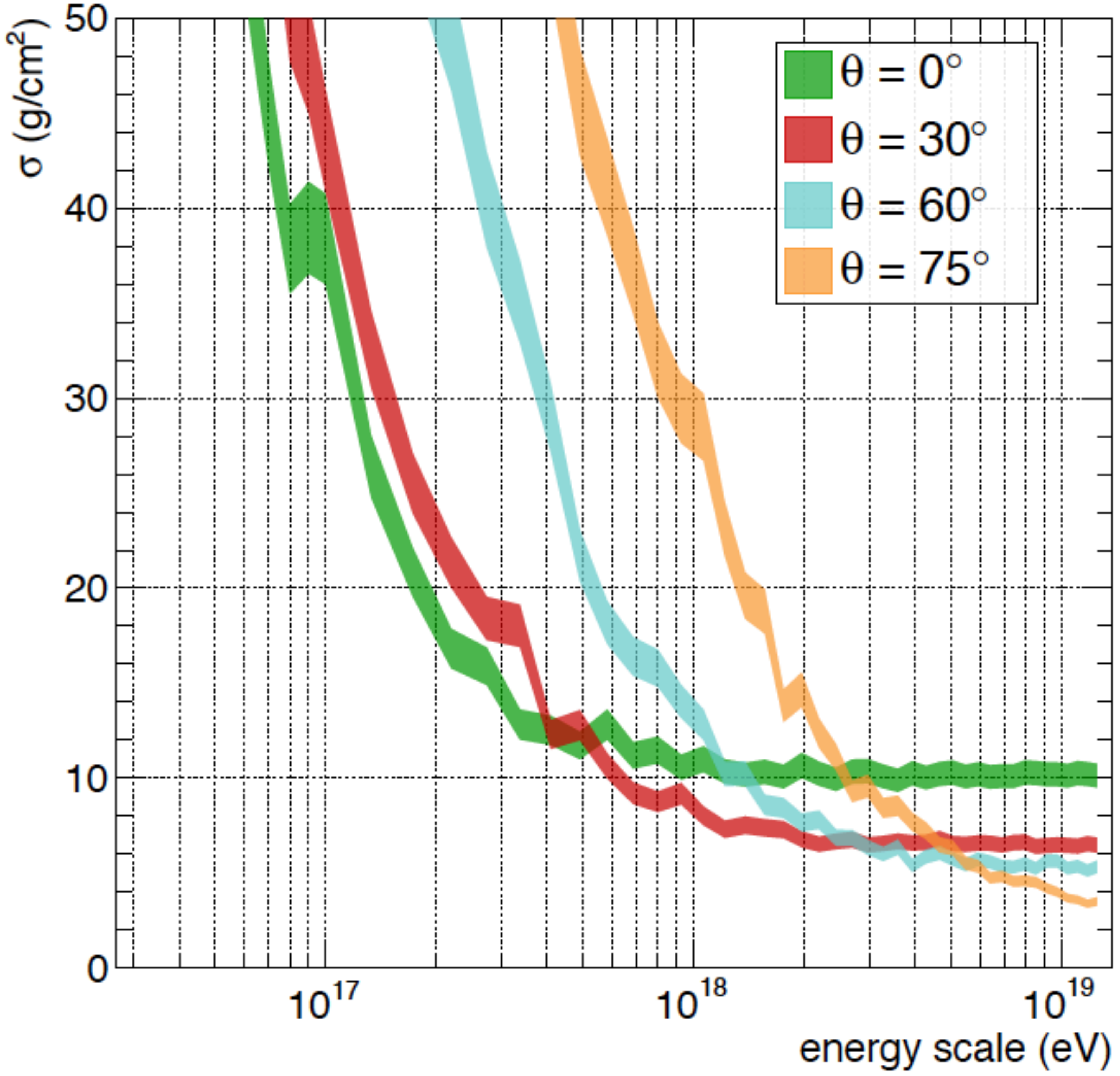
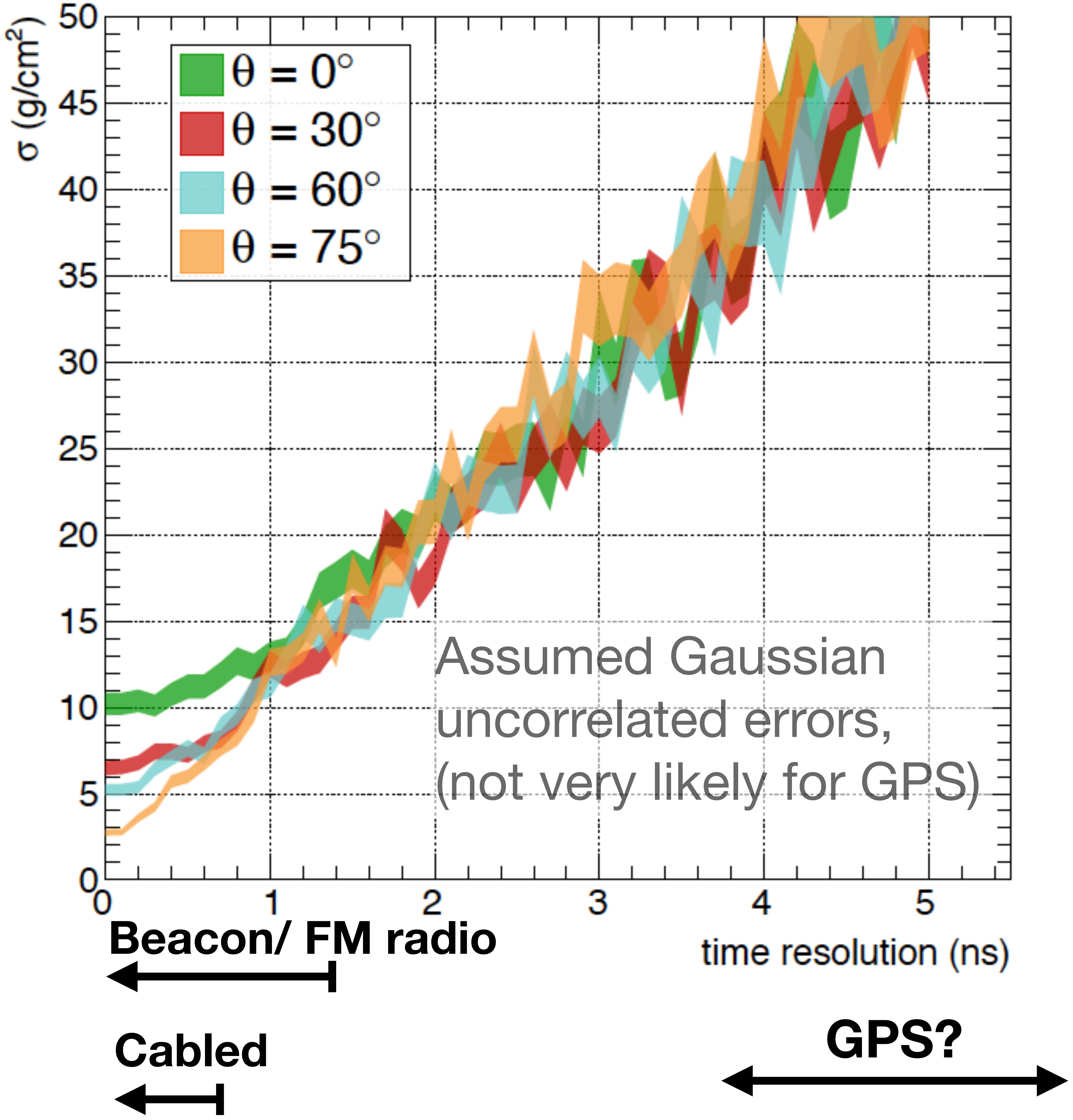


Influence of noise*

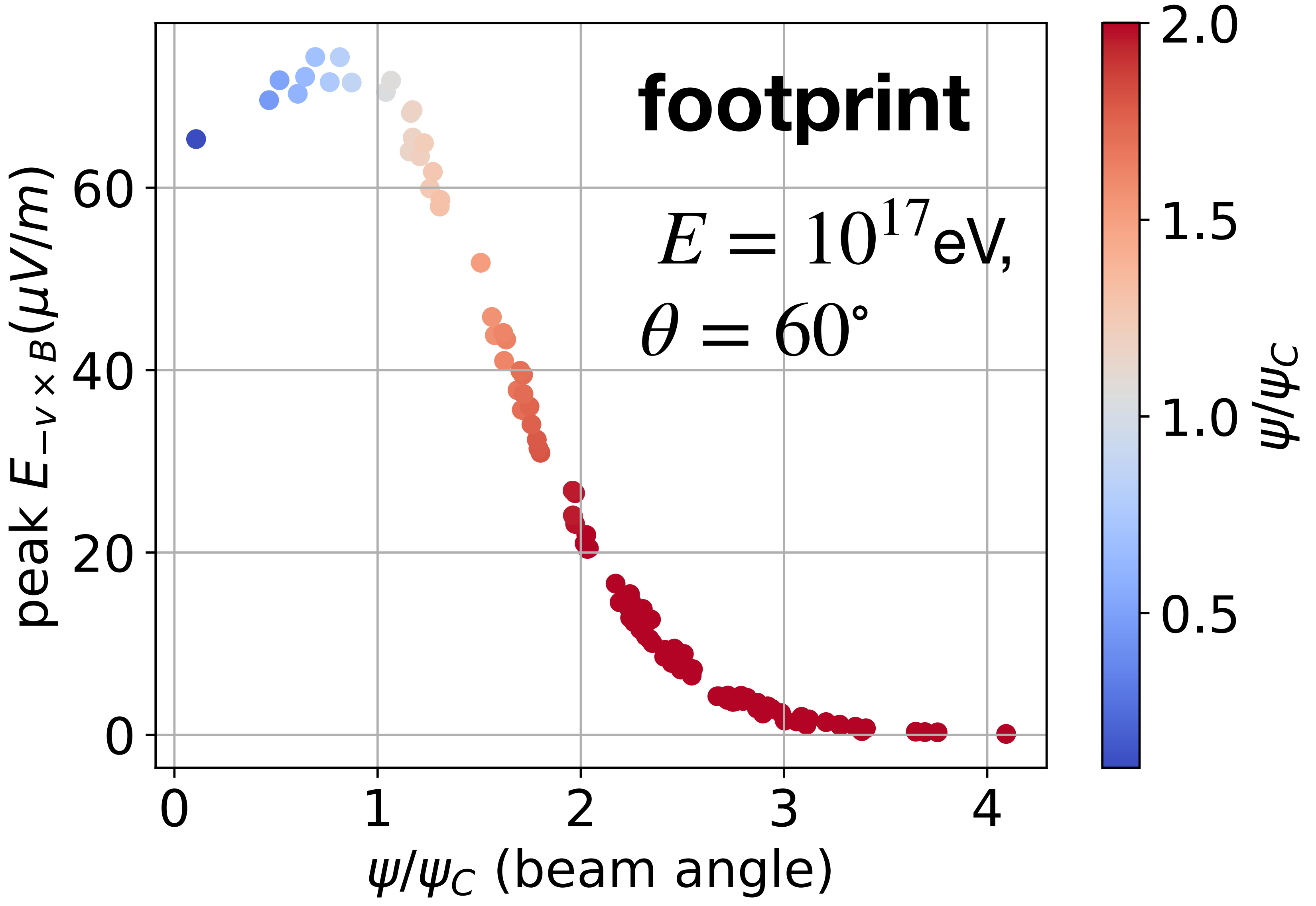


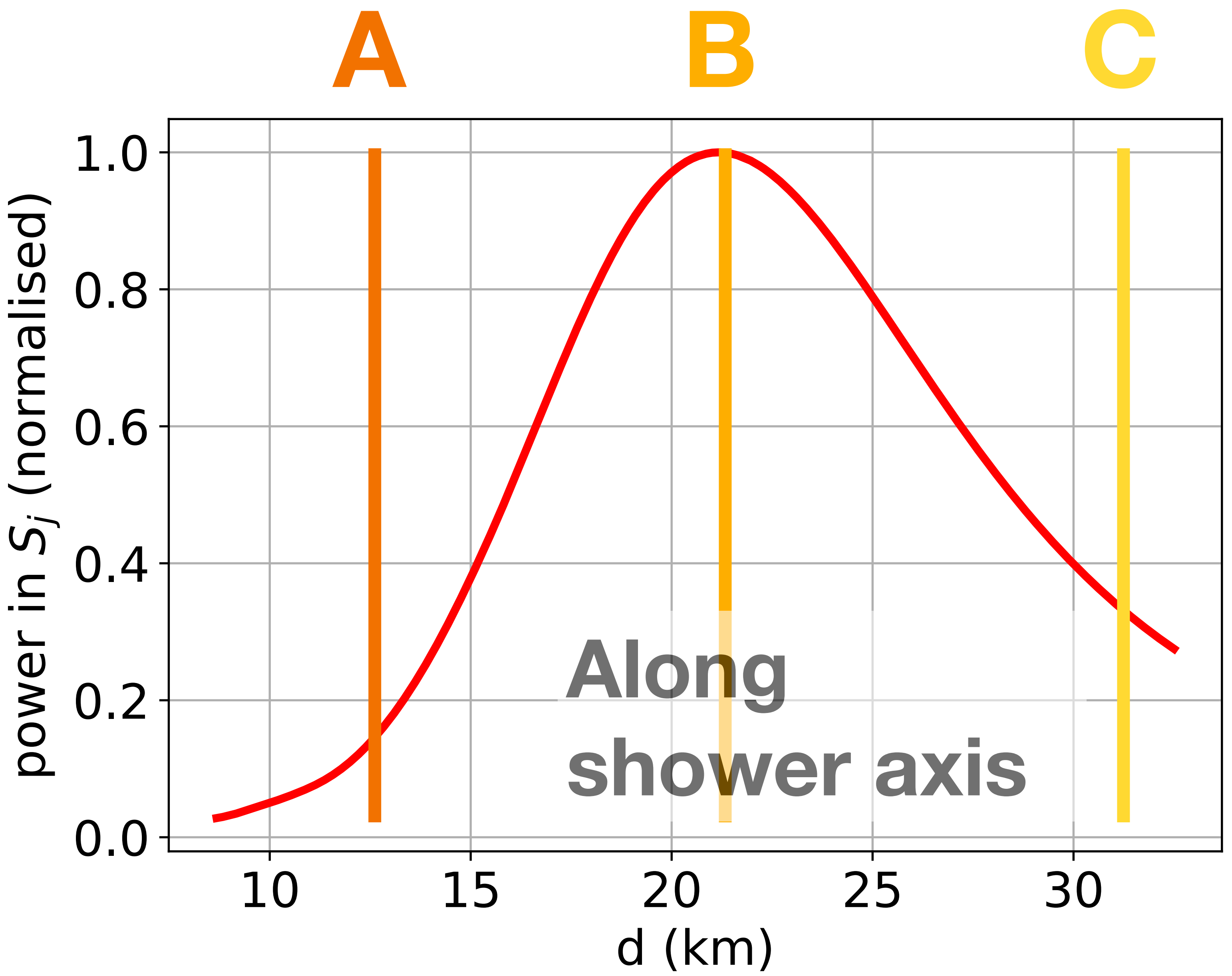
*This figure depends on the array layout

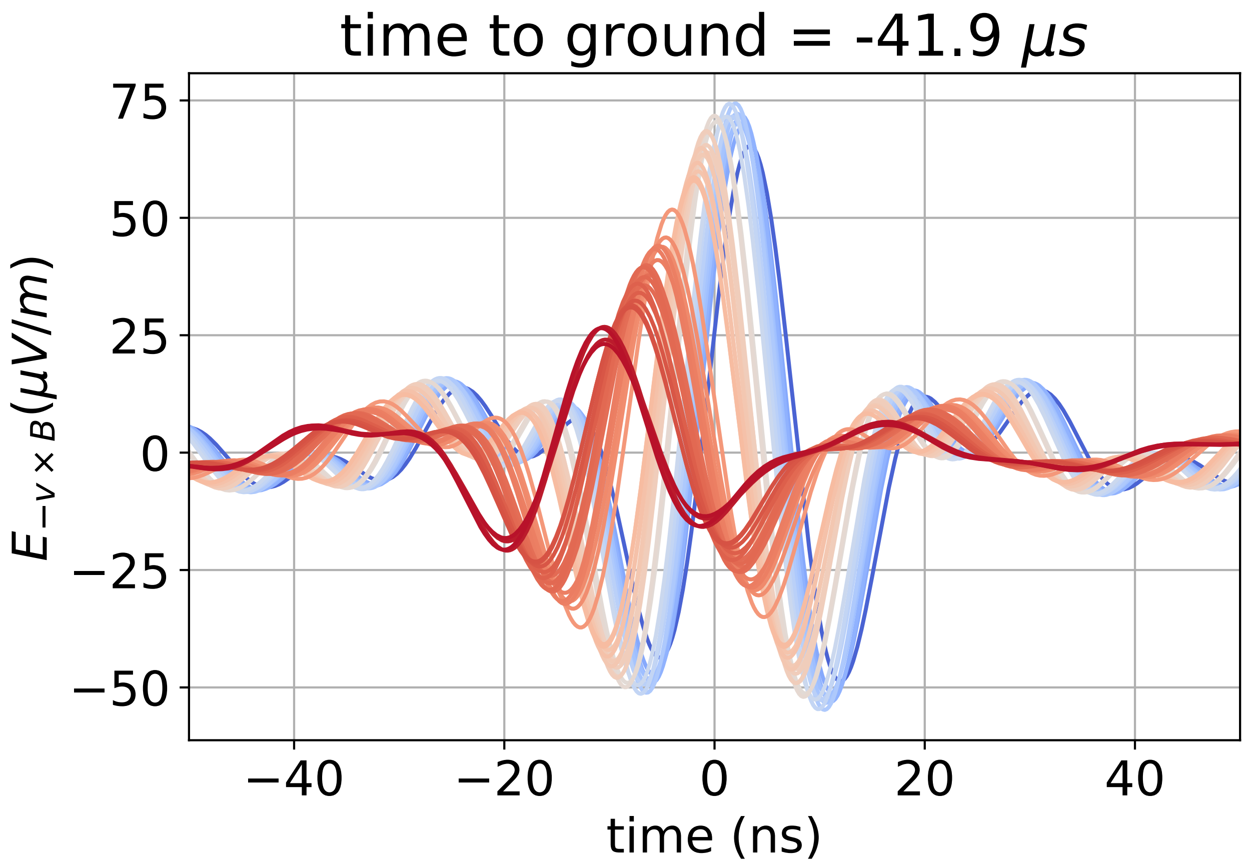
Influence of timing errors*



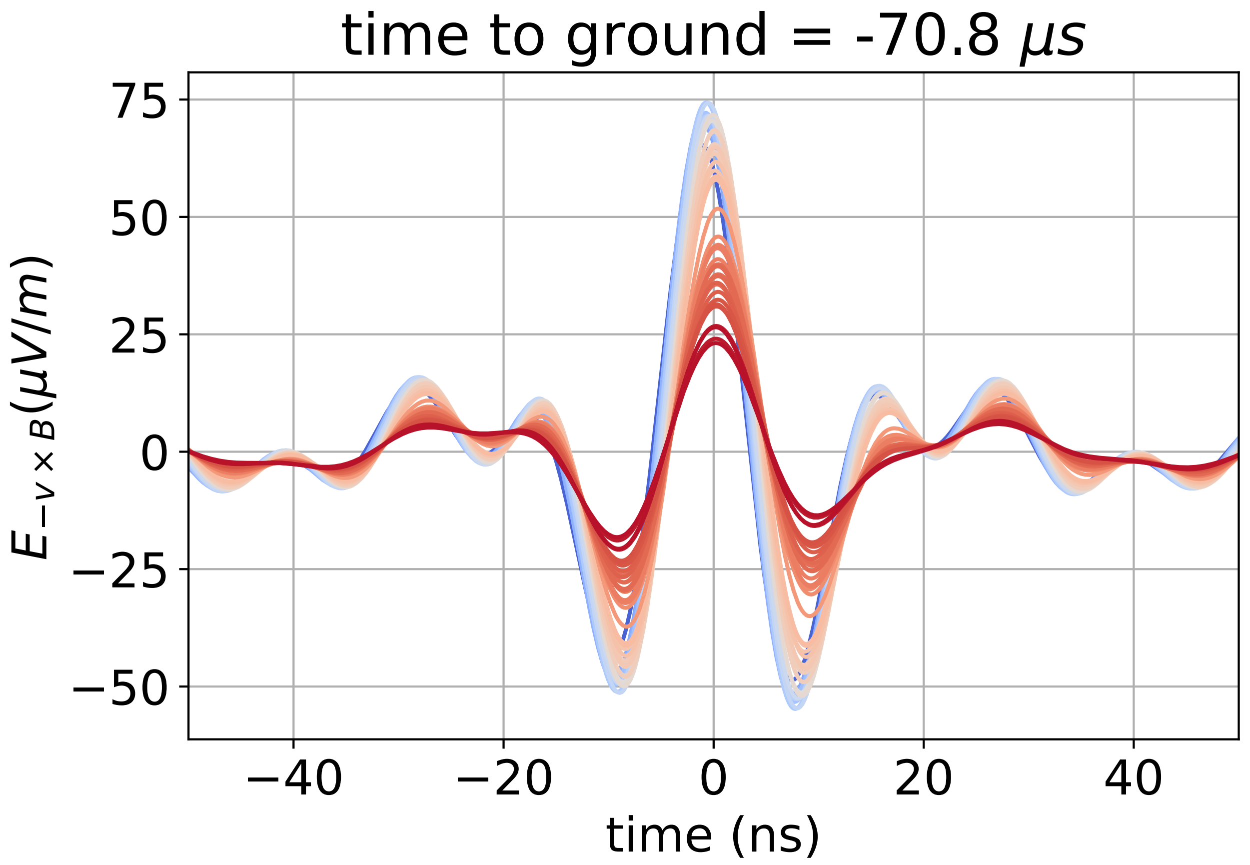
How does it work?



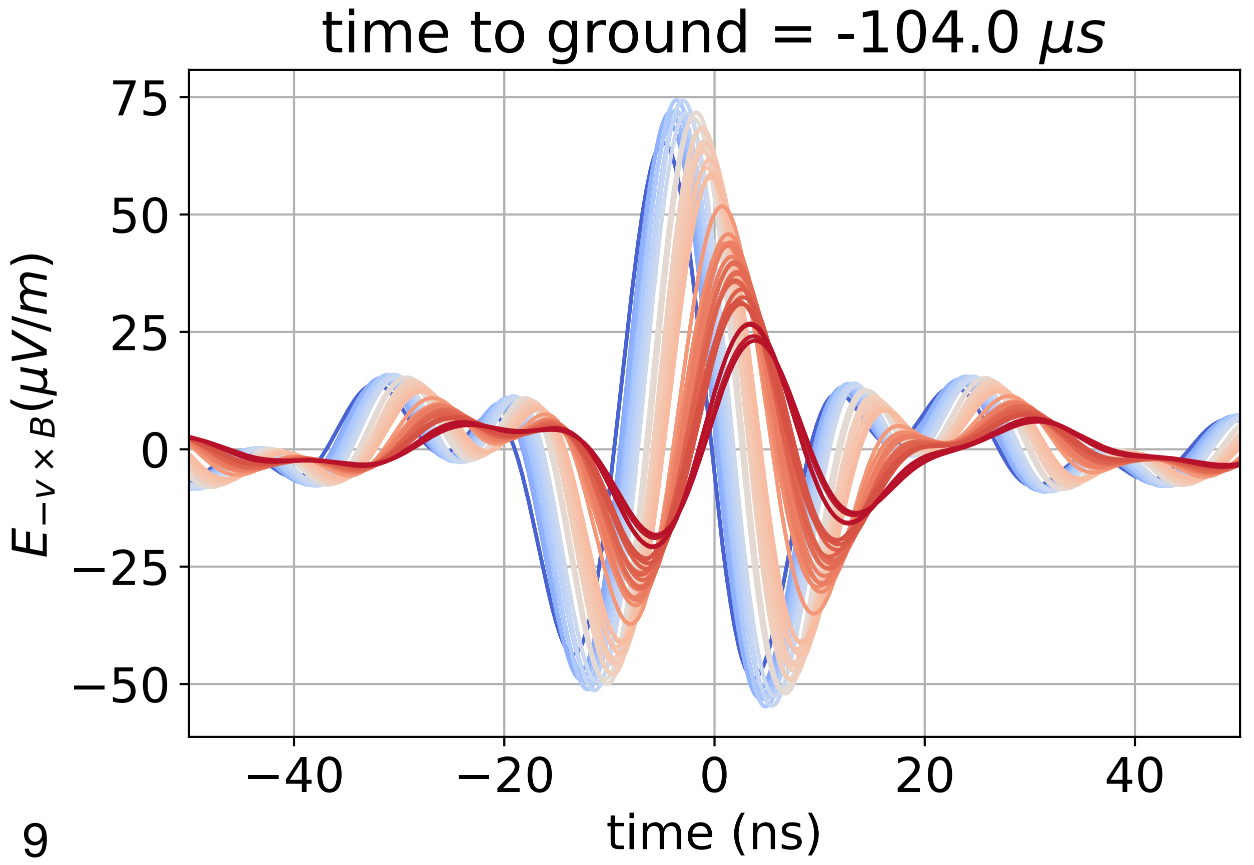




A) **Coherence from antennas inside & near the Cherenkov cone**



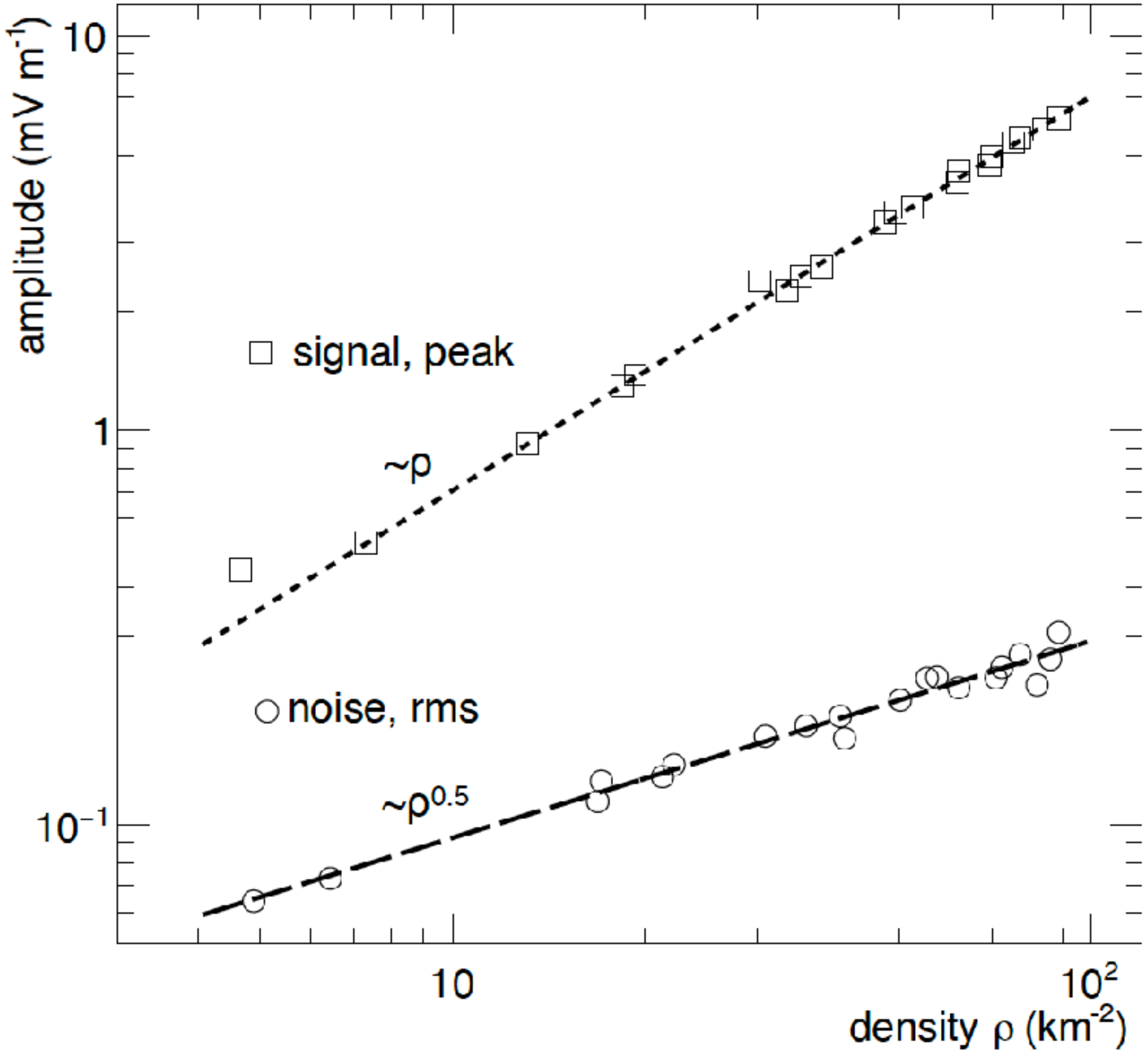
B) **Coherence from most antennas in footprint**



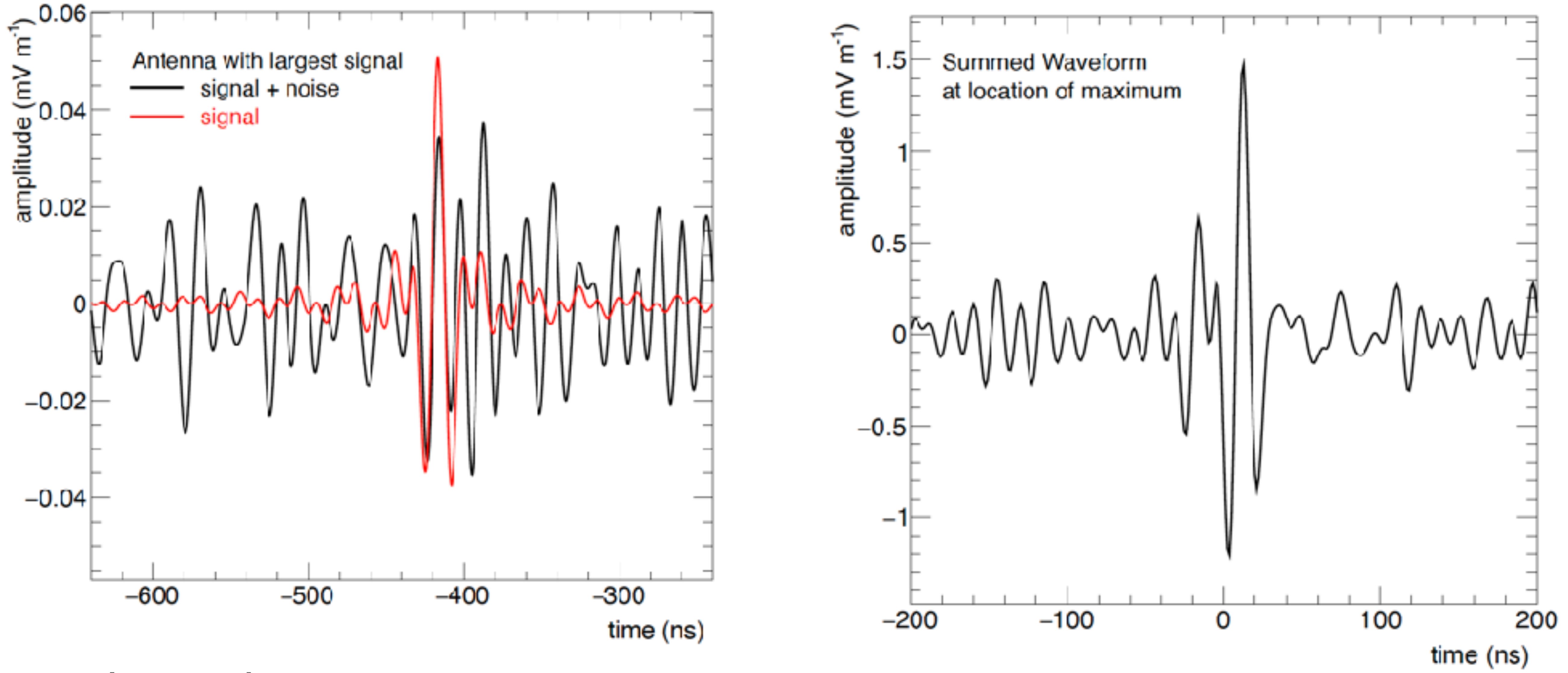
C) **Coherence from most antennas outside & near the Cherenkov cone**

Scaling with antenna density

Signal to noise ratio in coherent sum scales as $\rho^{0.5}$ (antenna density)



"Over dense" radio telescopes (like LOFAR/OVRO-LWA/SKA) can lower the radio detection threshold significantly by using an external particle trigger.



(poor) **example: 22 antennas per km²**

Summary

The radio interferometric technique can be use to accurately reconstruct air shower geometry (core, direction, shower depth).

In “radio telescope arrays”, it can be applied to air showers at significantly lower energy than is set by the local station threshold.

The accuracy for inclined events might significantly boost the performance of arrays like AugerPrime & GRAND.

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Back-up

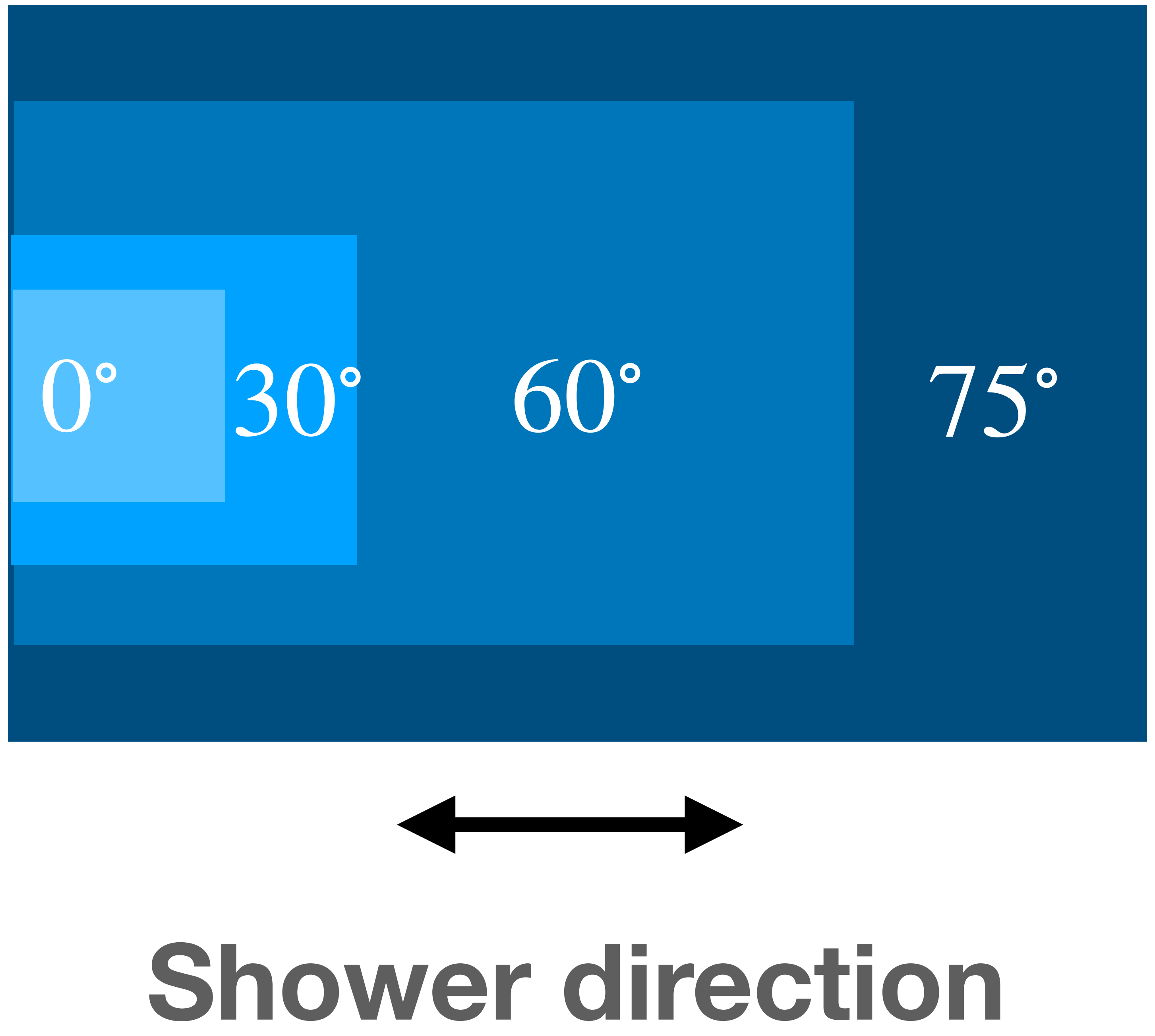
Back-up: Used Array Layouts

We calculated with ZHAireS the radio emission of sets of proton and iron induced air showers at different zenith angles. A rectangular array of antennas was used in which we increased the grid-spacing of the grid unit as a function of the zenith angle of the shower (See Table 1). In this way, the number of antennas in the radio-footprint on the ground was kept roughly constant (typically between 25-40) in the different zenith angle sets.

Table 1 Array properties.

zenith angle	Antenna density (km^{-2})
0°	400
30°	204
60°	22
75°	2.7

scaling of rectangular grid unit



"Similar density angular space"

Back-up: Beacon/ TV or Radio signal (statistical)

$$p_\Theta(\theta) = \frac{e^{-\frac{s^2}{2\sigma^2}}}{2\pi} + \sqrt{\frac{1}{2\pi}}\,\frac{s}{\sigma}\,e^{-\left(\frac{s^2}{2\sigma^2}\sin^2\theta\right)}\,\frac{1+\operatorname{erf}\left(\frac{s\cos\theta}{\sqrt{2}\sigma}\right)}{2}\cos\theta, \qquad (2.9\text{-}24)$$

for $\pi < \theta \leq \pi$, zero otherwise. The function erf$(\cdot)$ is the standard error function,

$$\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}\,dt. \qquad (2.9\text{-}25)$$

$$\Delta t = \frac{\Delta\theta}{2\pi f} \approx \frac{\sqrt{\sigma_\theta^2}}{2\pi f}$$

Even at modest signal to noise ratio, already sub-nanosecond accuracy