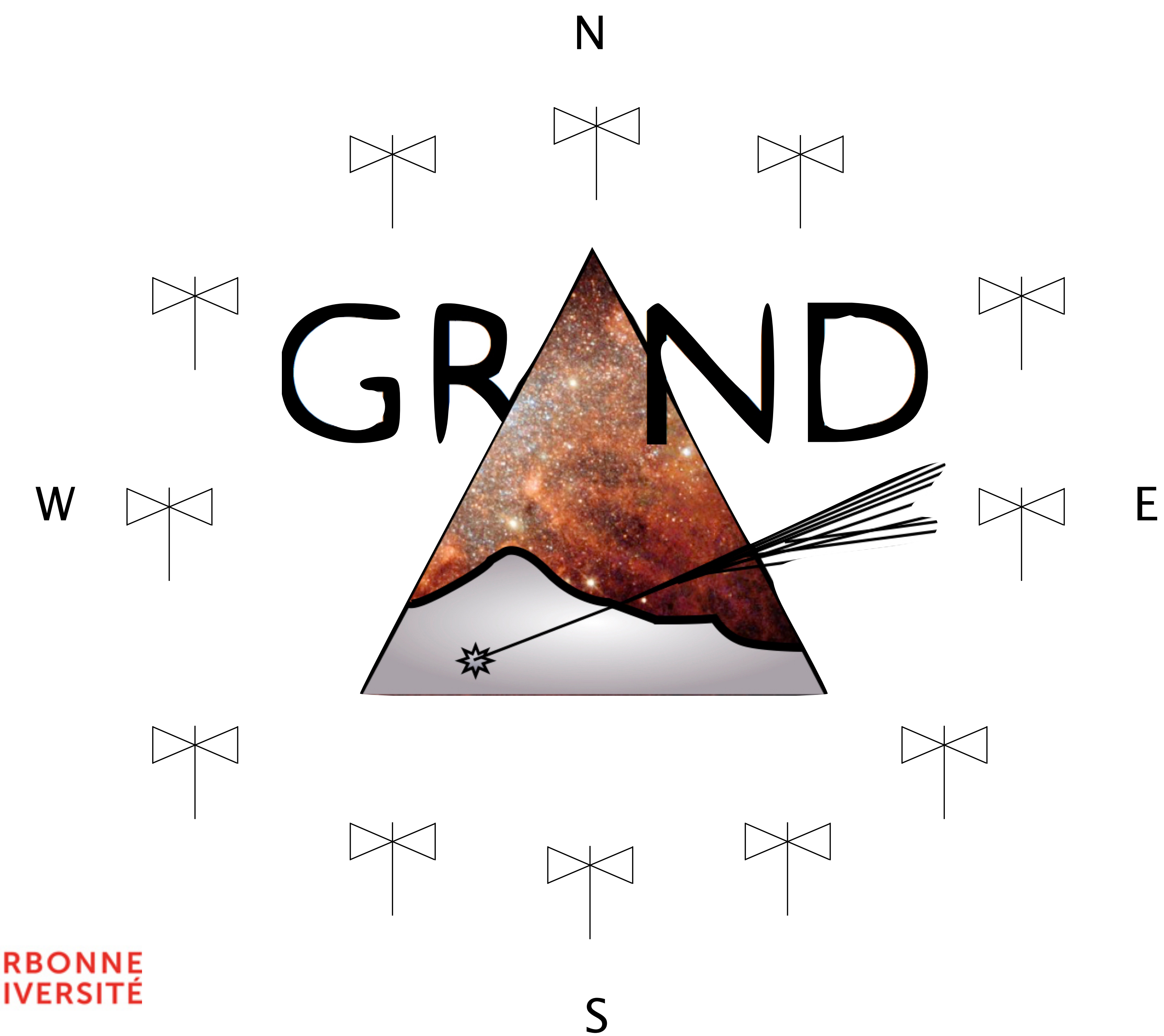
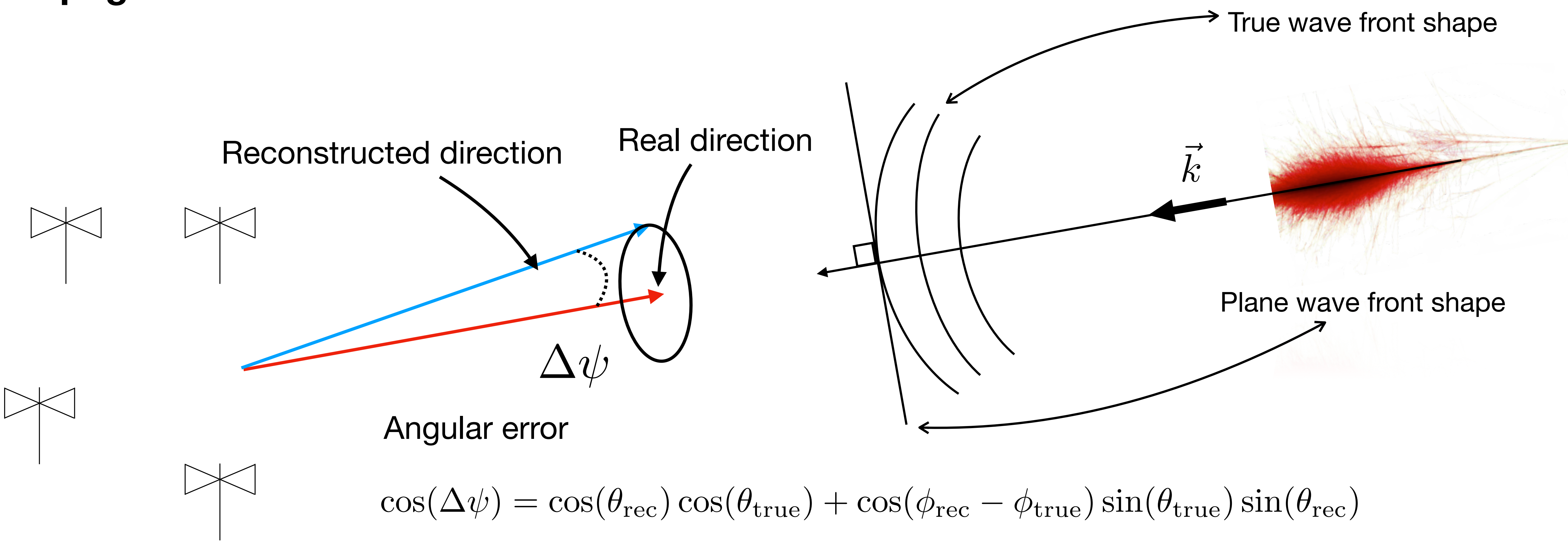
GRAND angular reconstruction status

Valentin Decoene (IAP) & Olivier Martineau (LPNHE)



Determine direction form antennas trigger times

Propagation model relies on wave front model



$$\cos(\Delta\psi) = \cos(\theta_{\rm rec})\cos(\theta_{\rm true}) + \cos(\phi_{\rm rec} - \phi_{\rm true})\sin(\theta_{\rm true})\sin(\theta_{\rm rec})$$

Antennas array:
- **Voltages traces**
- **Antennas positions**
- **Times**

Reconstruction

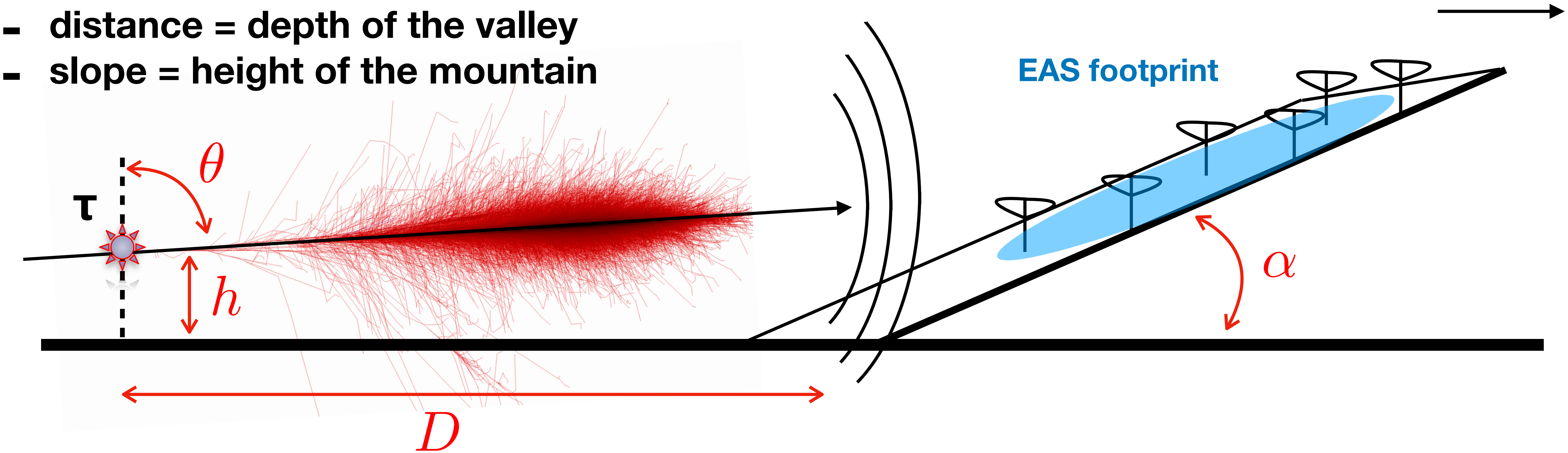
Extensive Air Shower:
- **Direction** $\vec{k} = f(\theta, \phi)$
- **Energy**
- **Xmax**

Simulation set up: Toy Model set up

Simulations done for the study of the impact of topographies on ν detection rates

"Effect of topography on the detection of neutrino-induced air showers" **VD** et al. arXiv 1903.10466

A simplified topography with two parameters:
- **distance = depth of the valley**
- **slope = height of the mountain**



Full simulation chain :
- **Neutrino induced tau decay (DANTON)**
- **Shower propagation + electric field computation (ZHAires)**
- **Antenna response computation : voltage response (NEC) / filtering (50-200MHz) / noise adding (gaussian) / sampling (1ns)**

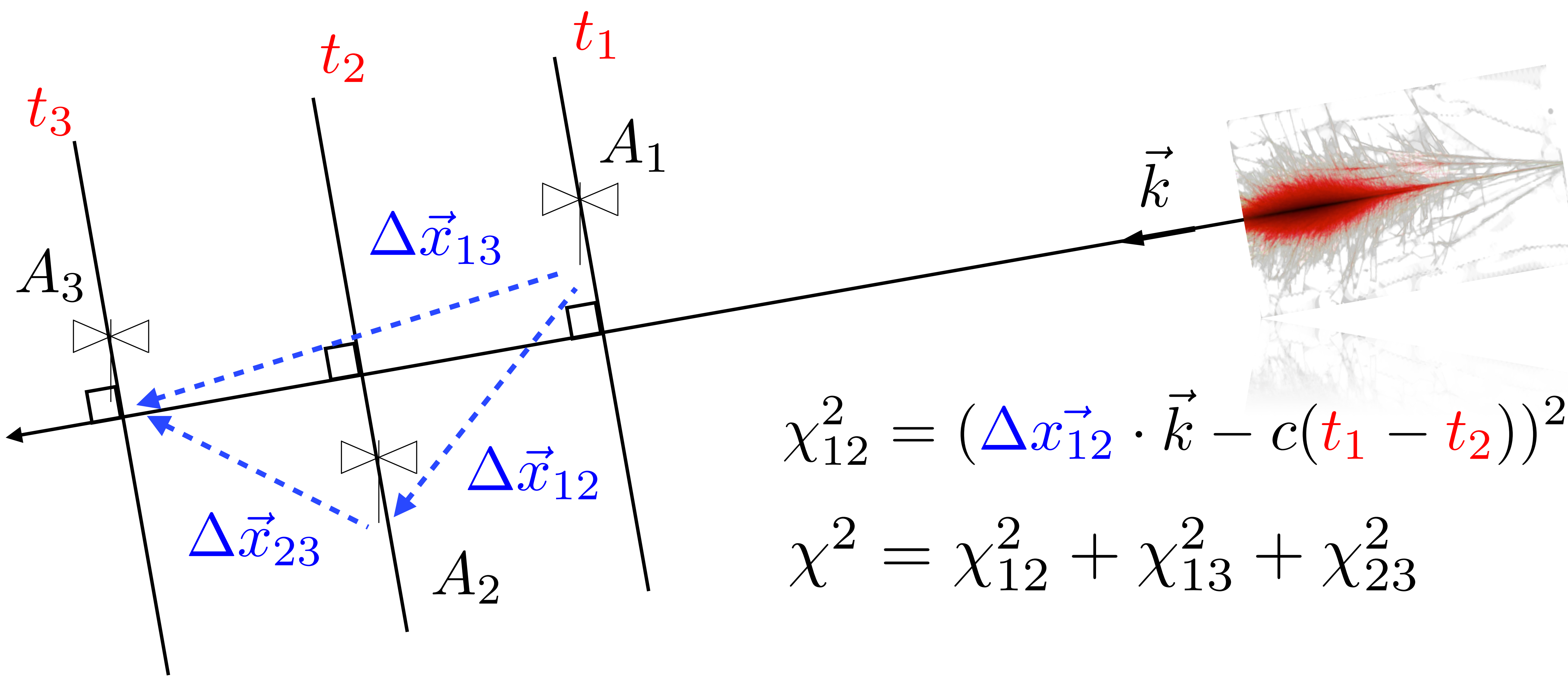
Why using these simulation ?
- **Already done**
- **Good statistics (≈10 000)**
- **Few parameters to play with**

⚠ **Symmetries -> mirror effects reconstruction errors**

Plane wave reconstruction: first approach

see IAP workshop august 2018

- **Wave front model : plane**
- **Pure timing comparison**



$$\chi^2_{12} = (\Delta\vec{x_{12}} \cdot \vec{k} - c(t_1 - t_2))^2$$

$$\chi^2 = \chi^2_{12} + \chi^2_{13} + \chi^2_{23}$$

Free parameter $\vec{k} = f(\theta, \phi)$

minimisation → $$\chi^2 = \sum_{\mathrm{i}} \sum_{\mathrm{j}} (\Delta\vec{x_{\mathrm{ij}}} \cdot \vec{k} - c(t_{\mathrm{i}} - t_{\mathrm{j}}))^2$$

Plane wave reconstruction: summary

Set of 3 550 simulations of 10^{10}GeV primary neutrinos

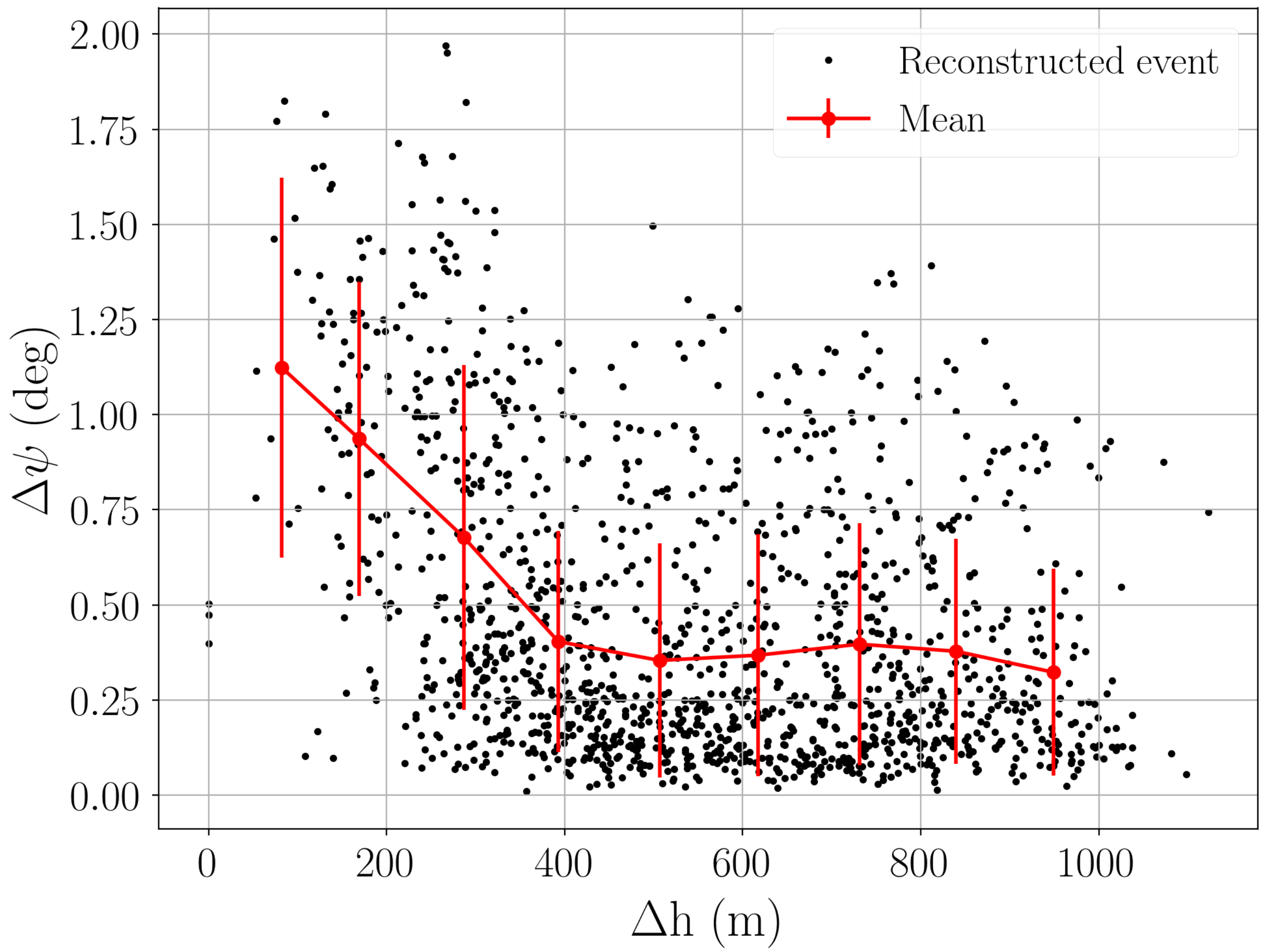
1606 showers detected with aggressive trigger conditions (5 antennas > 2 x noise level)
1370 with more than 10 antennas

Peaktime from Hilbert envelope + GPS jitter (gaussian, σ = 5ns)

Mean angular error ≈ 0.5° reachable

$$< \chi^2/\text{ndf} >>> 1000$$

➡ **Wave front is not plane**



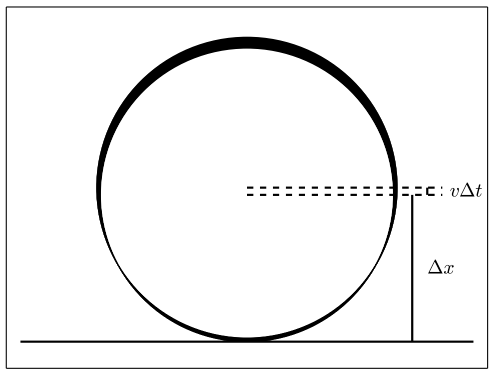
Mean slope between triggered antennas

- **Strong effect of topography on resolution : antennas height -> handle on zenith reconstruction**
- **Resolution sufficient for UHECR reconstruction (direction)**
- **Better resolution needed for neutrino astronomy !**

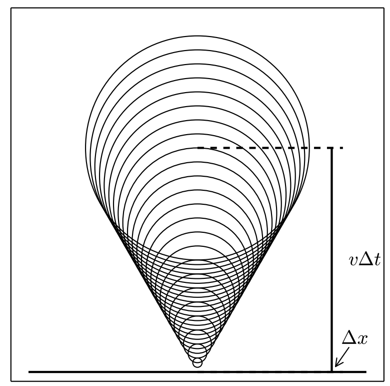
GRAND White Paper, GRAND coll. (**VD**) arXiv:1810.09994v1

The emission source determines the wave front shape

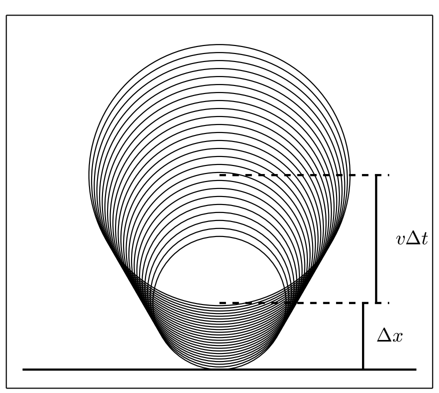
Point source emission
spherical

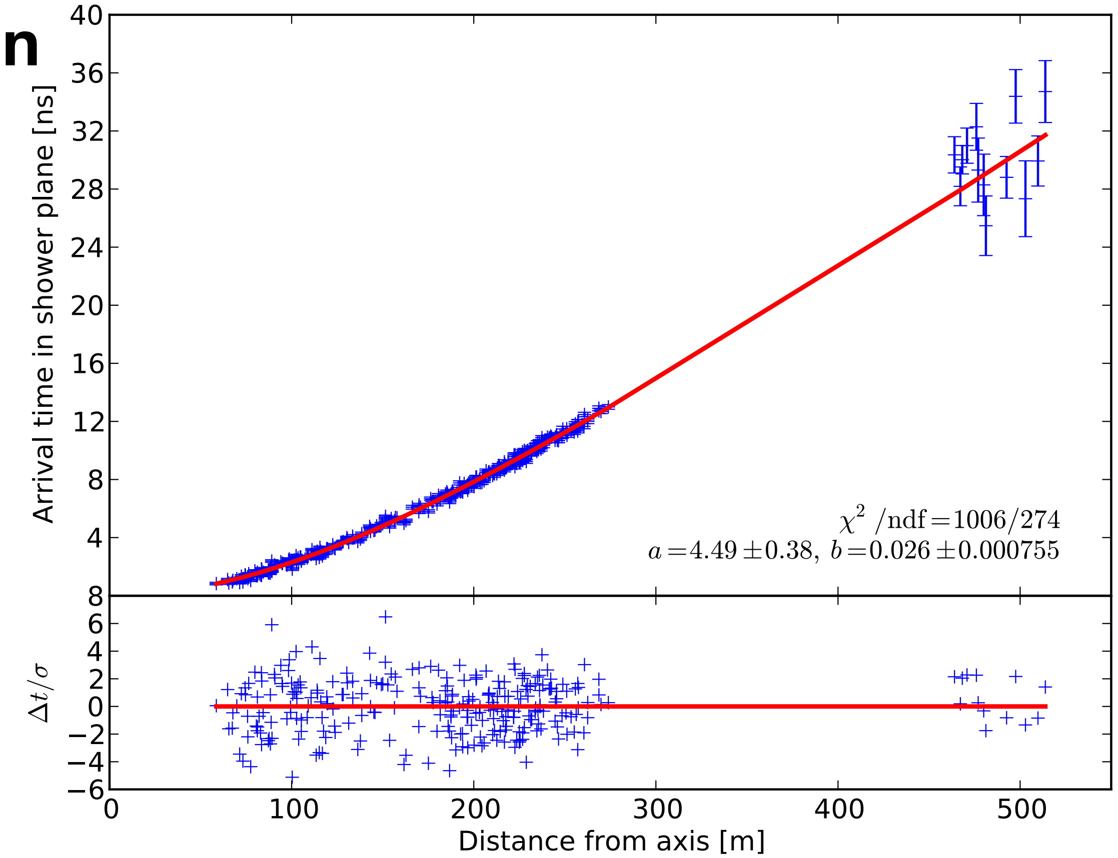


moving source emission
conical



Slow moving source emission
hyperbolic



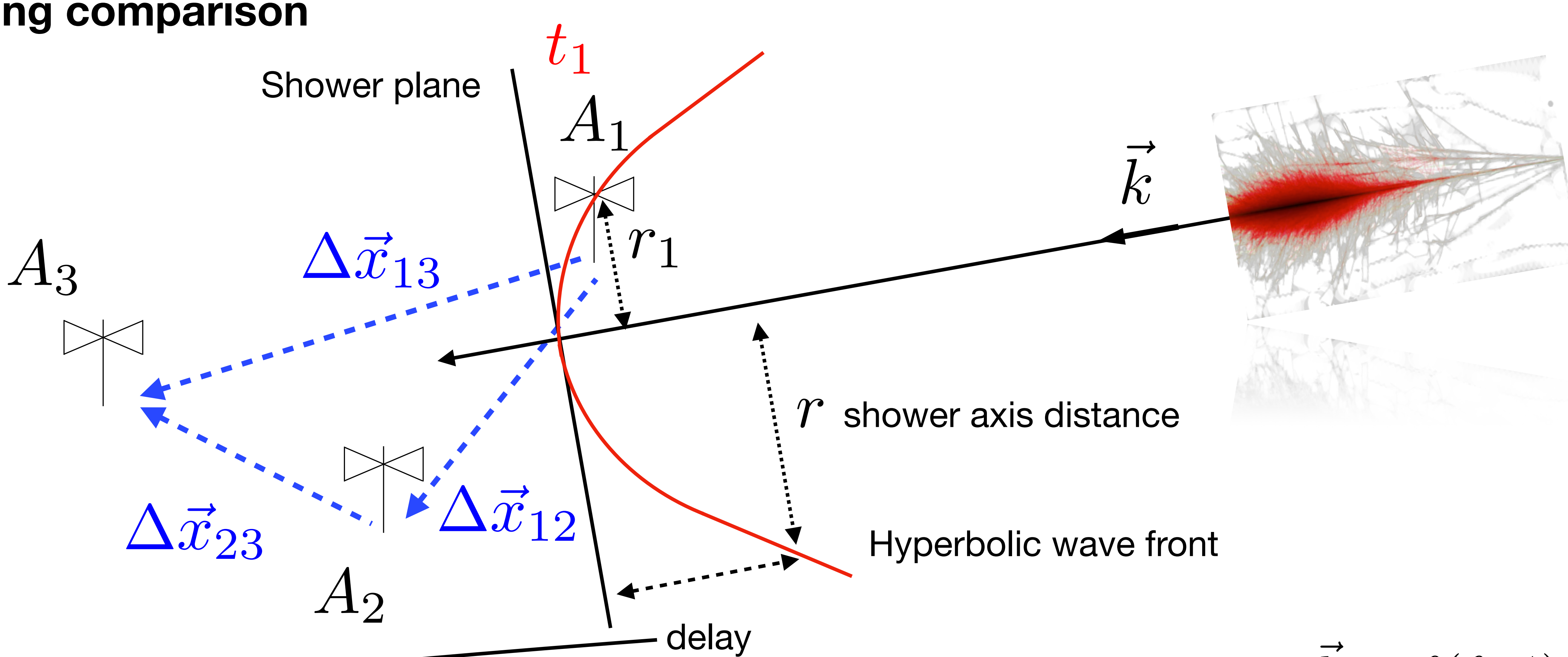


The shape of the radio wavefront of extensive air showers as measured with LOFAR. A. Corstanje et al. 2014.

Hyperbolic wave front shapes measured by LOFAR

Hyperbolic wave front shape

- **Wave front model : hyperbolic**
- **Pure timing comparison**



$$f_i^{\mathrm{WS}}(r_i, a, b) = \sqrt{a^2 + b^2 r_i^2} - a$$

Free parameter

$$\vec{k} = f(\theta, \phi)$$

$$(a, b)$$

$$\chi_{ij} = c\Delta t_{ij} - \vec{k} \cdot \Delta\vec{x}_{ij} - f_{ij}^{\mathrm{WS}}(r_i, r_j, a, b)$$

minimisation

$$f_{ij}^{\mathrm{WS}}(r_i, r_j, a, b) = f_i^{\mathrm{WS}}(r_i, a, b) - f_j^{\mathrm{WS}}(r_j, a, b)$$

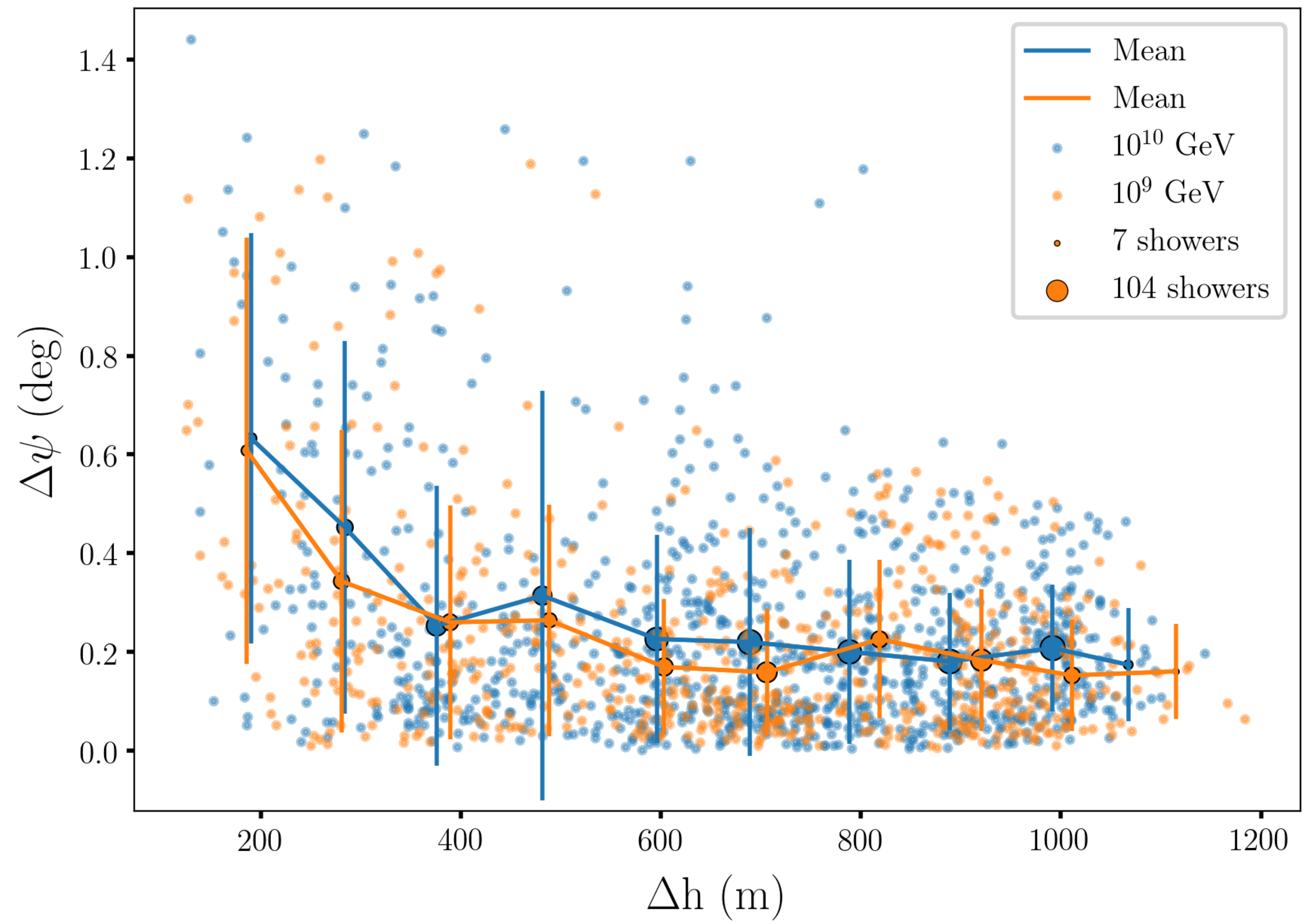
Hyperbolic wave front shape: LOFAR type

Set of 10 000 simulations of 10^{10} GeV and 10^9 GeV primary neutrinos

Hyperbolic parameters fixed from LOFAR measurements

$$(\mathrm{a}, \mathrm{b}) = (4.49\,\mathrm{m}, 0.026)$$

Mean angular error ≈ 0.2° reachable



GPS precision = 5ns

No noise

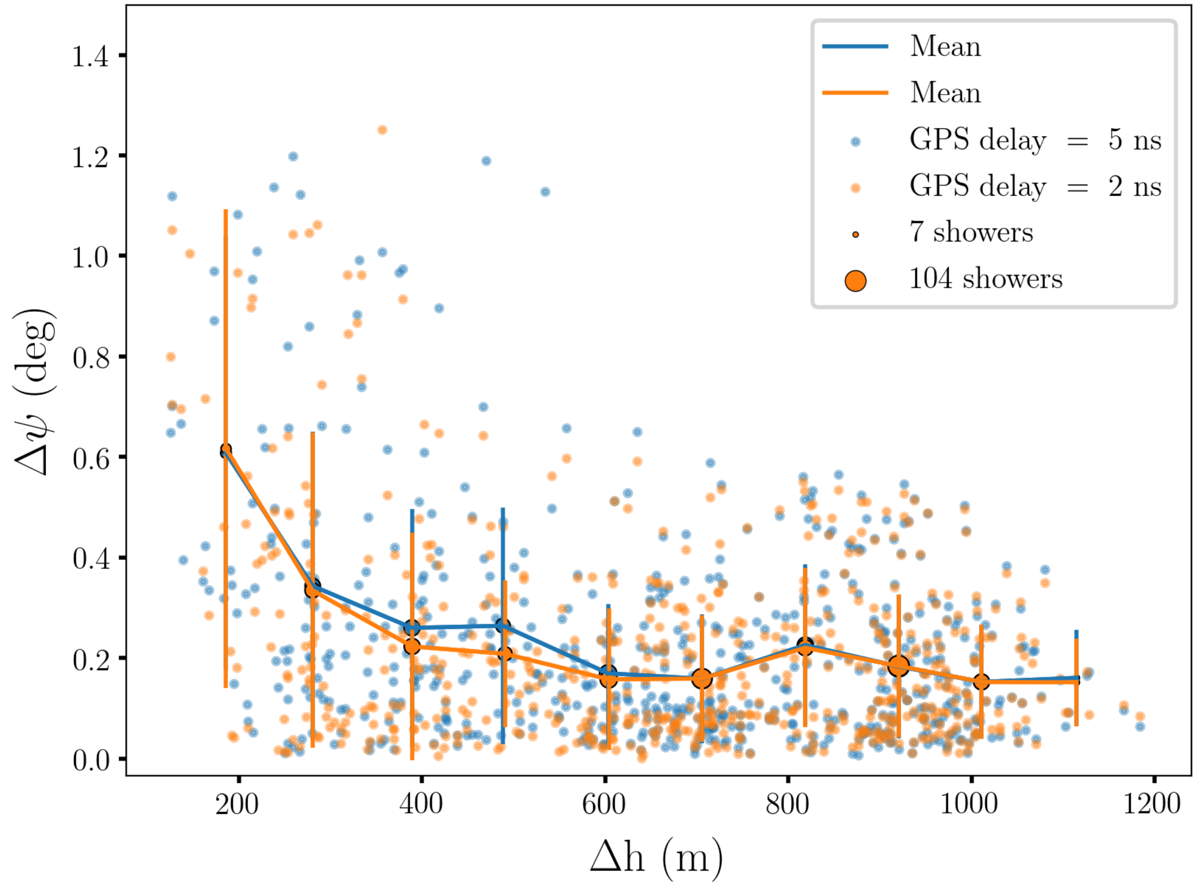
Aggressive trigger conditions (2x noise level)

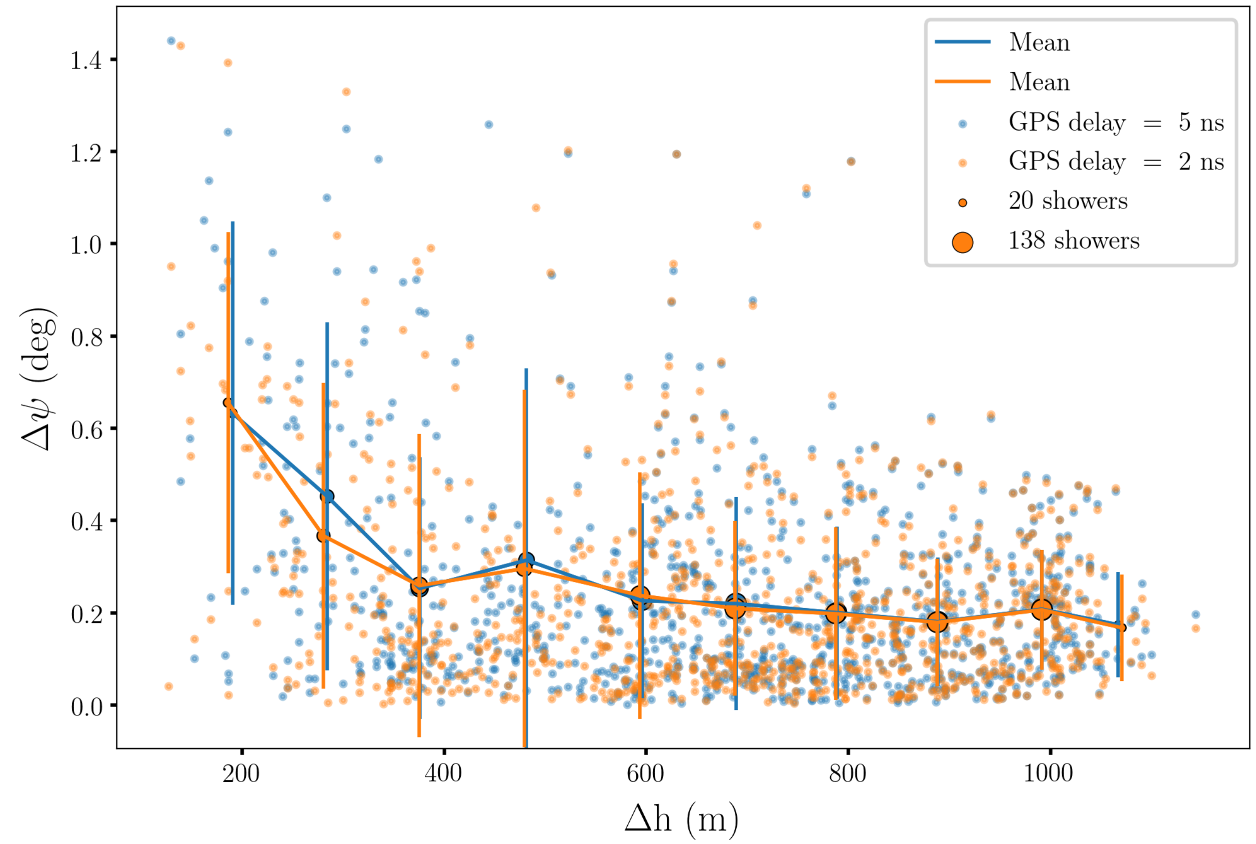
Overall similar results for both energies (slightly better for 10^9 GeV)

Hyperbolic wave front shape: LOFAR type

Testing effect of GPS precision on resolution

10^9 GeV **10^{10} GeV**





GPS precision = 5ns or 2ns → Same resolution

No noise

Aggressive trigger conditions

- **GPS precision and noise are not a limiting factor on resolution in this wave front model**

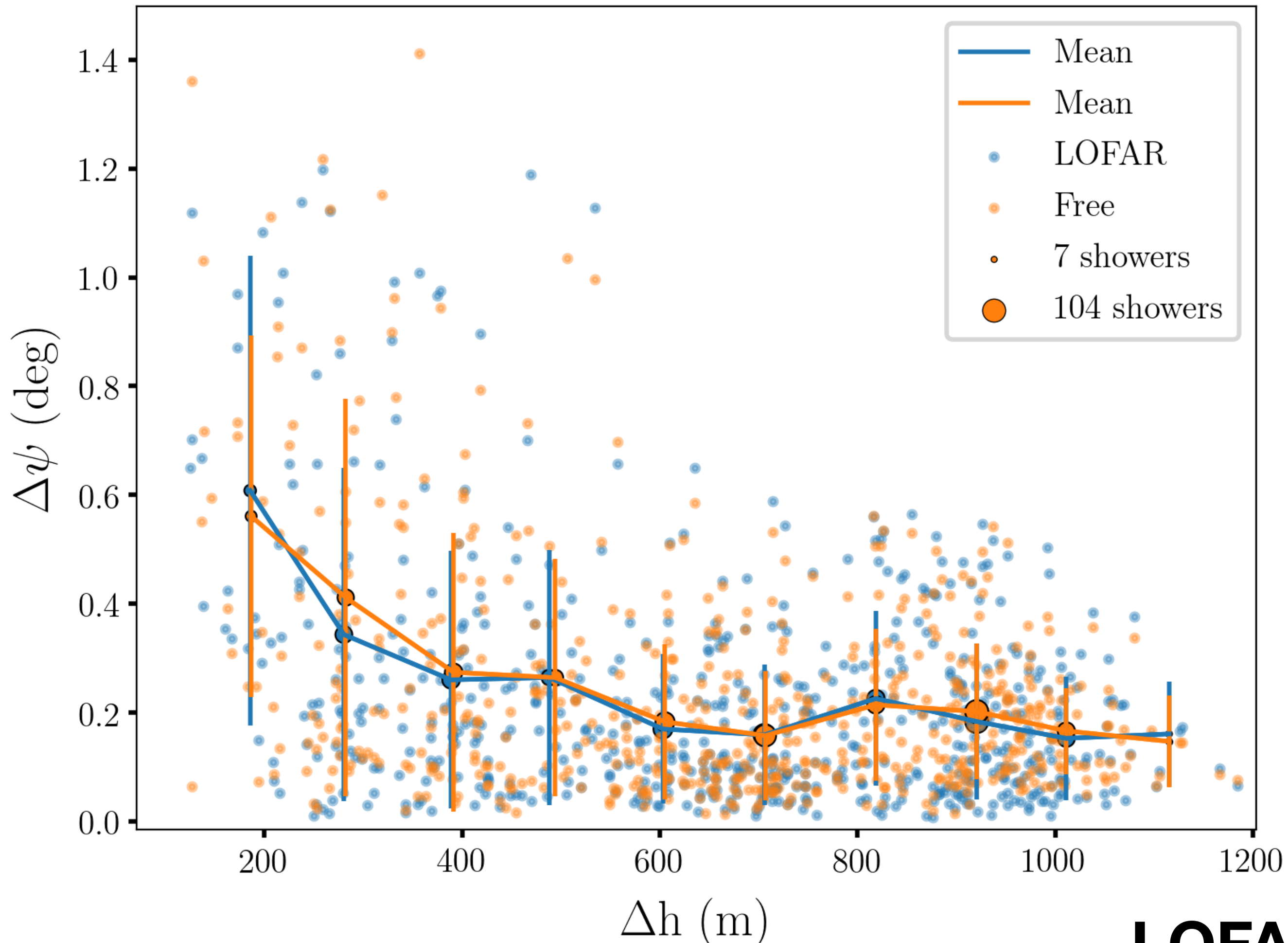
Hyperbolic wave front shape: free parameters

- **LOFAR:** $< \chi^2/\mathrm{ndf} > \approx 10$ **Can it be improved ?**

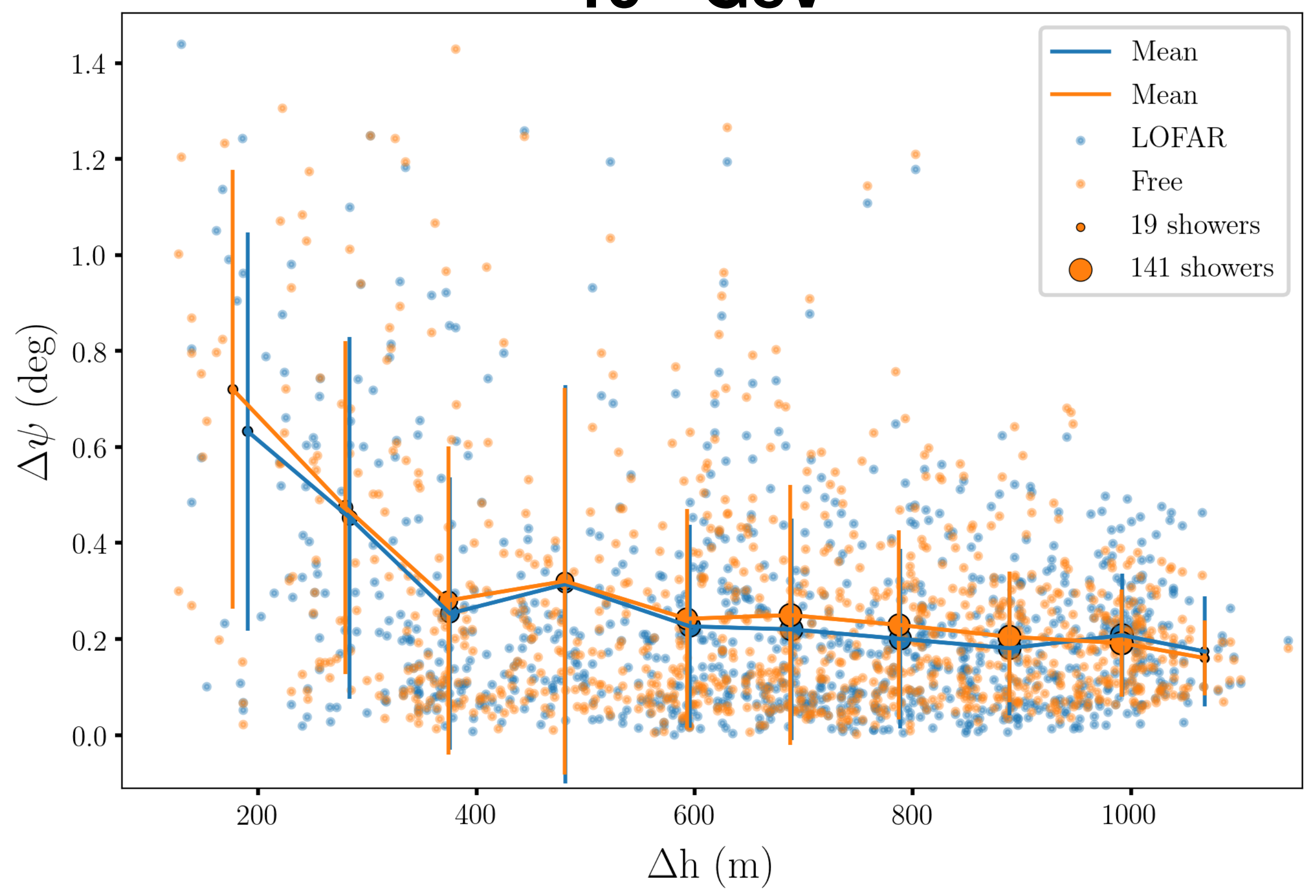
→ **Hyperbolic parameters set free and determined during the minimisation**

$$f_i^{\mathrm{WS}}(r_i, a, b) = \sqrt{a^2 + b^2 r_i^2} - a$$

10^9 GeV



10^{10} GeV



LOFAR type / Free

GPS delay = 5ns

No noise

Aggressive trigger conditions

- **Free:** $< \chi^2/\mathrm{ndf} > \approx 5$ **But no significant improvement in the reconstruction**

Better result with hyperbolic reconstruction than plane reconstruction

From ≈ 0.5° to 0.2°

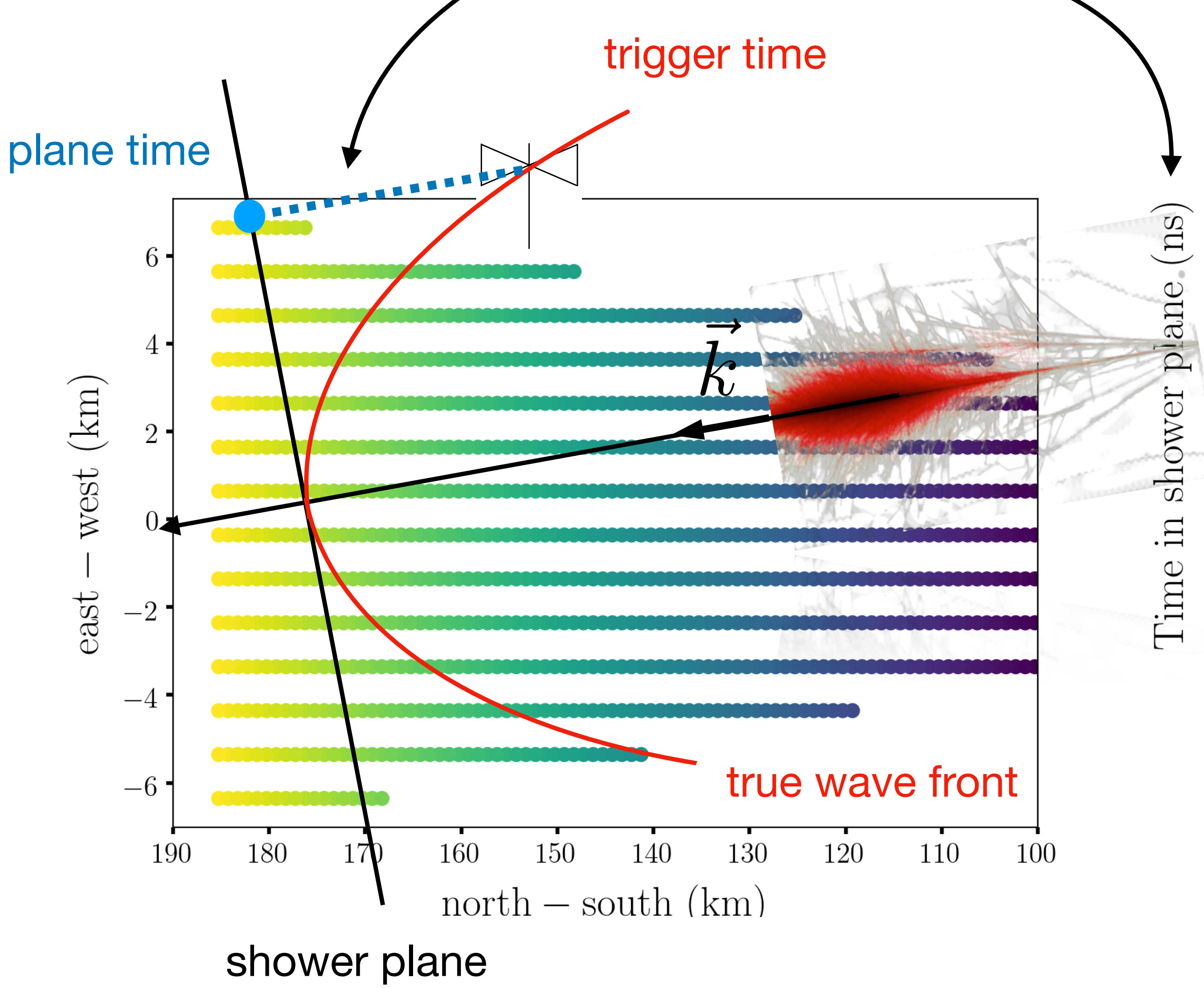
The normalised chisq is not as good as expected if the wave front model was correct

In addition GPS precision and noise don't impact the reconstruction

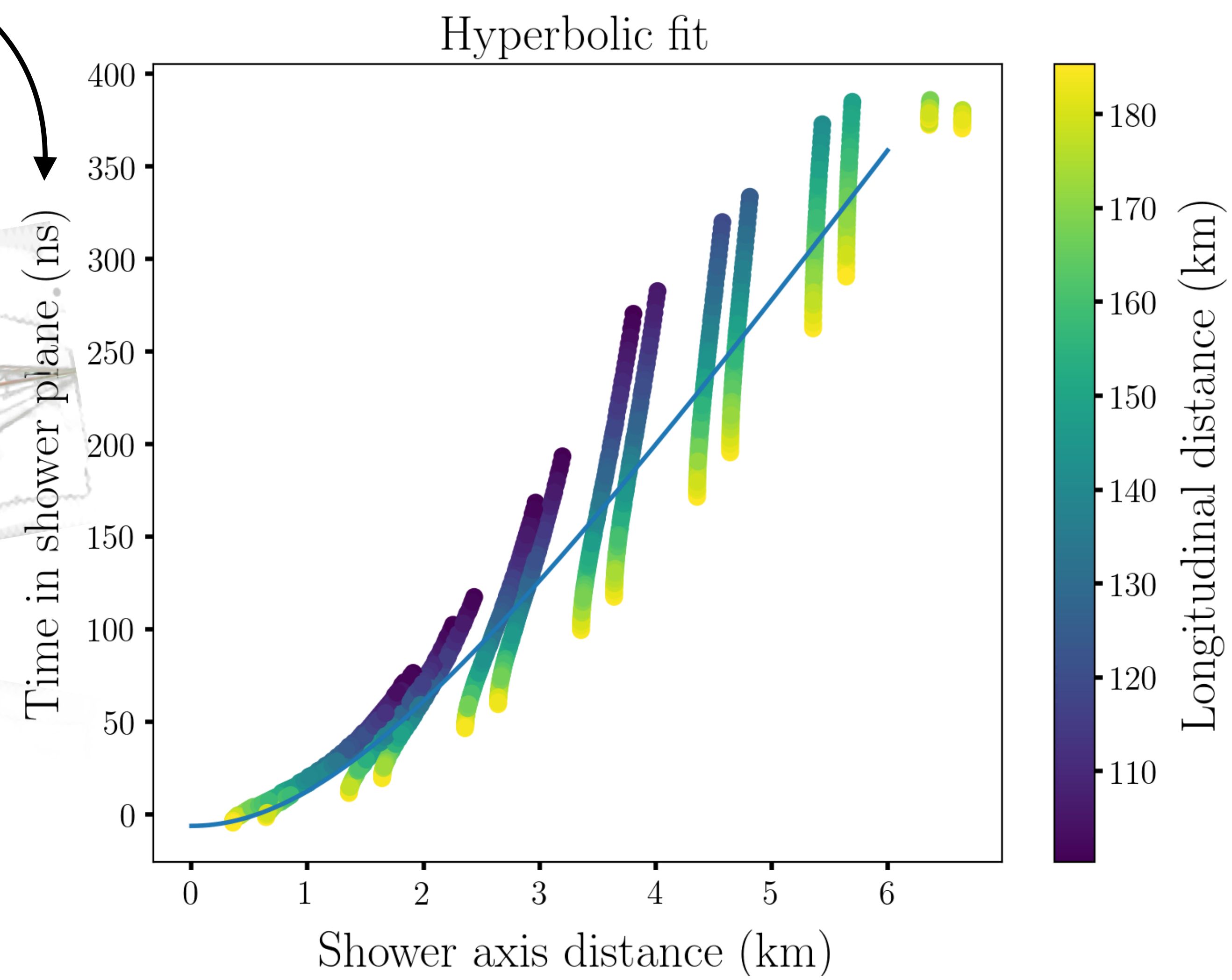
This suggests that other systematic effects are not taken into account.

→ Need for a detailed wave front study.

Time in shower plane = trigger time - plane time



$$cdt - \vec{k} \cdot d\vec{x} - \sqrt{a^2 + b^2 r^2} + a$$

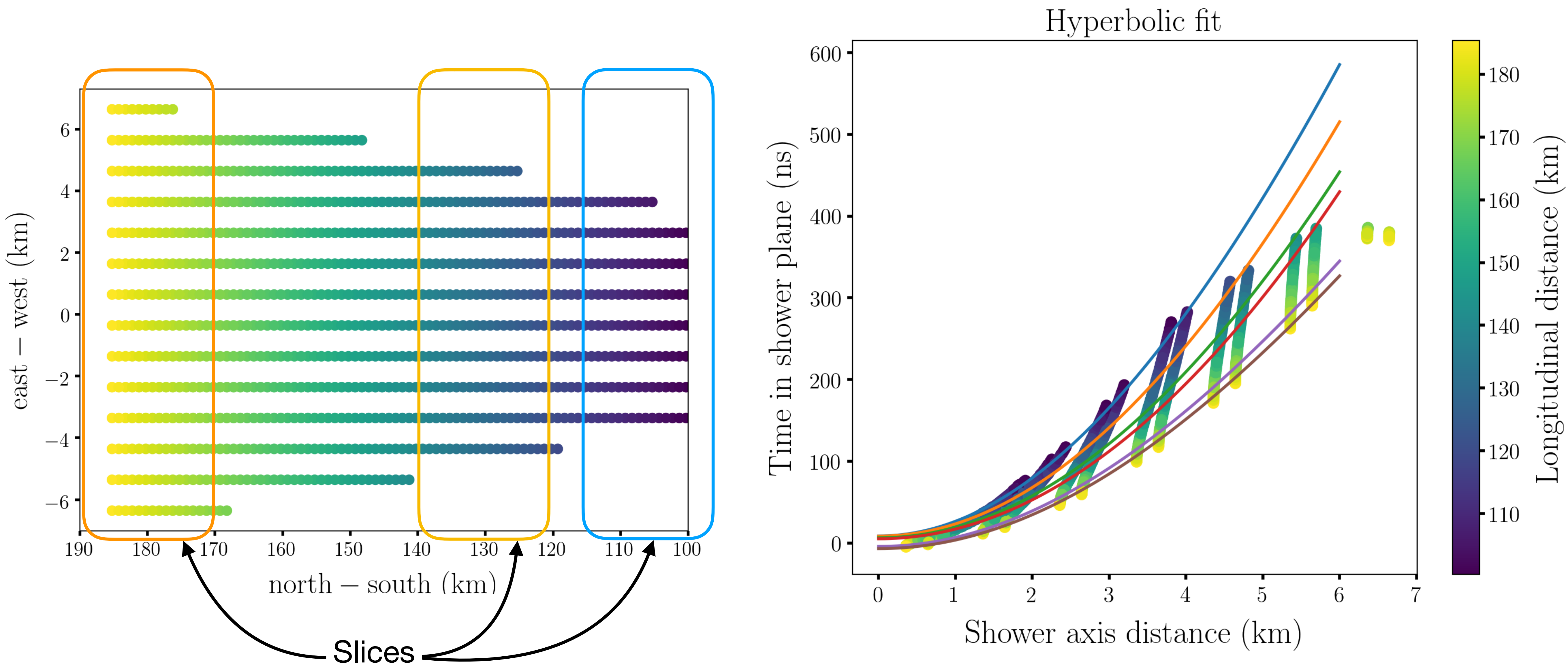


Toy Model configuration

No noise

data can't be fitted with one single analytical function because the wave front evolves with time (ageing)

To fit different wave front parameters for each propagation distances -> slicing



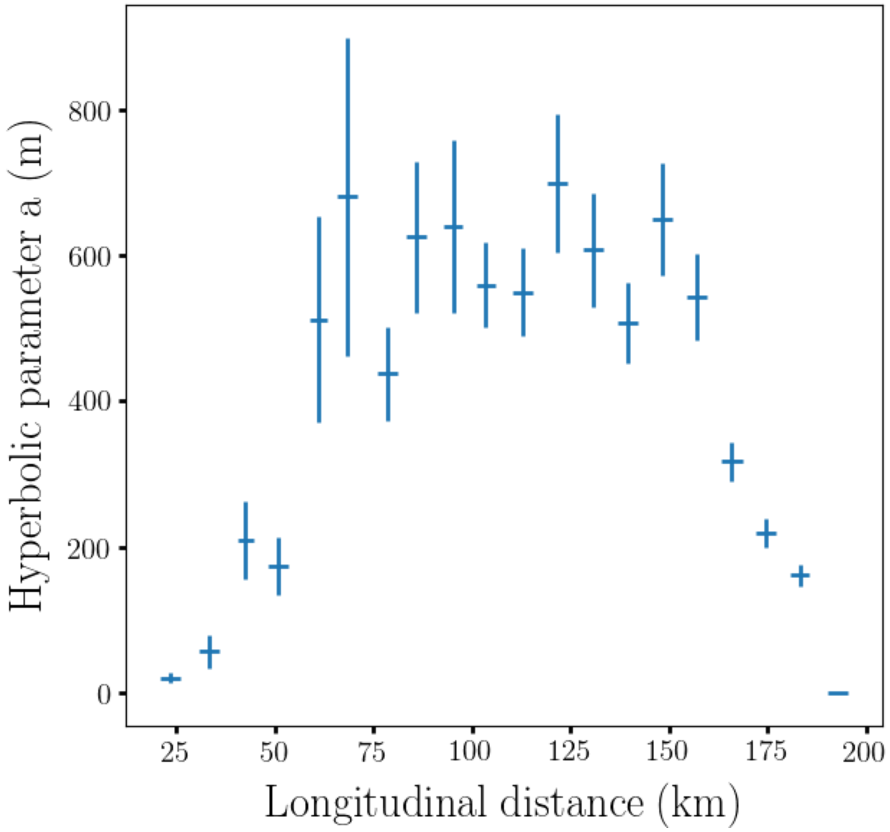
- **Each slice correspond to a propagation distance -> shower age**
- **For each slice an independent fit is perform (using the correct direction)**

The best parameters (a, b) for each shower age (and each wave front model) are computed

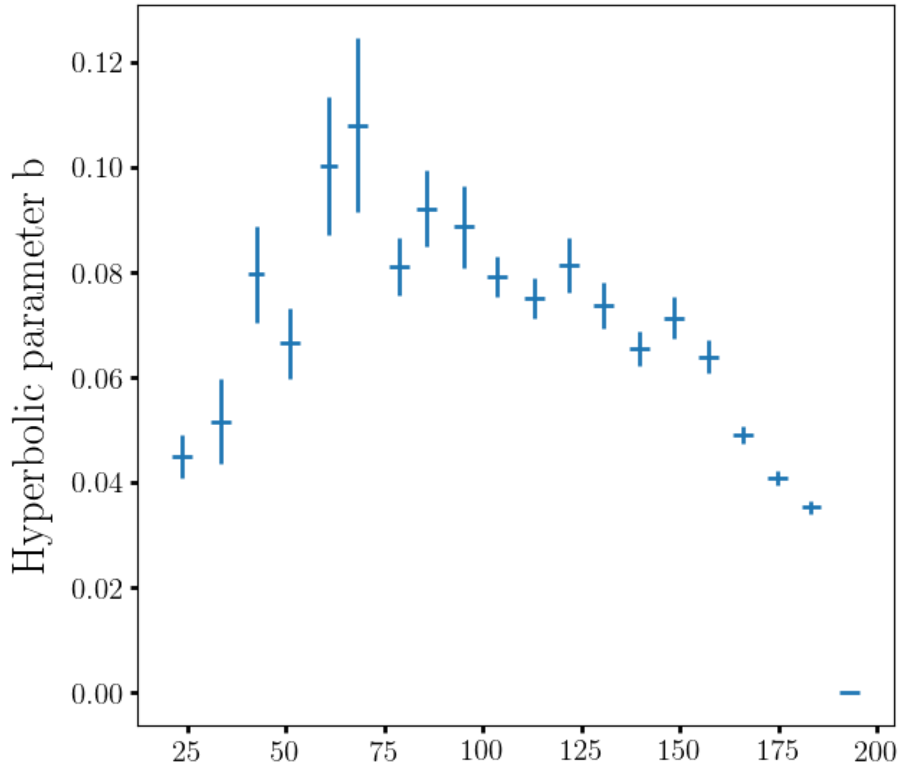
Wave front shape study: parameters ageing

Hyperbolic model

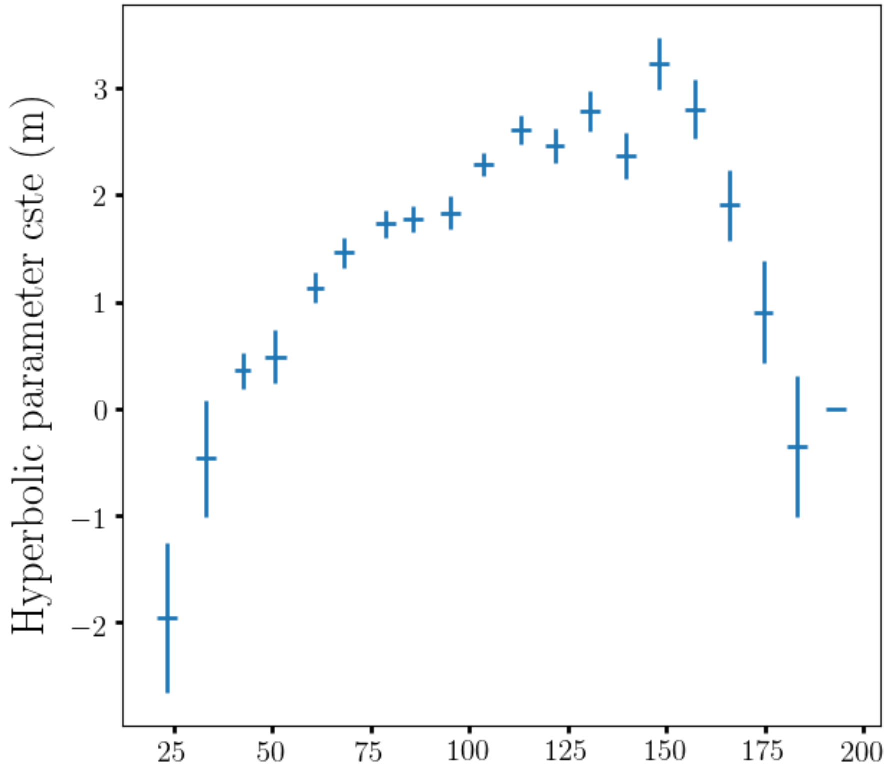
simulations stacking



Spherical curvature



Conical angle

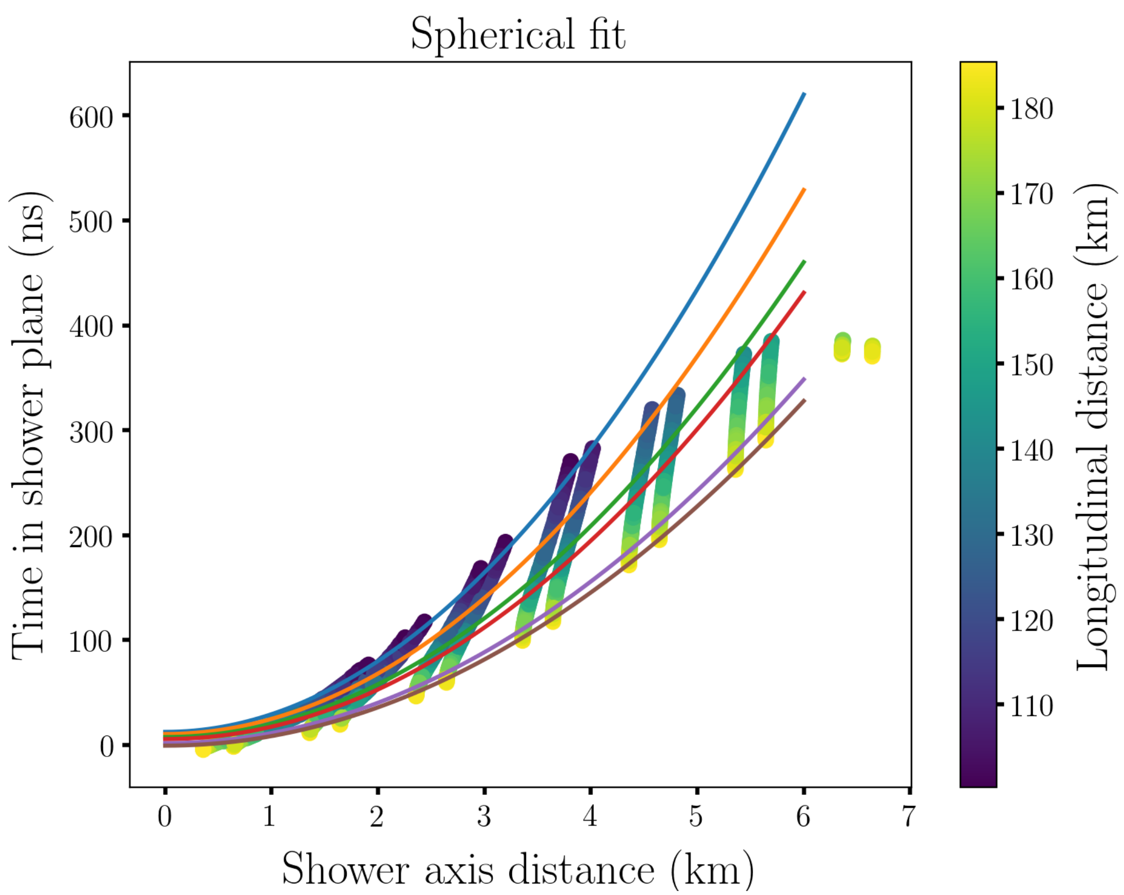


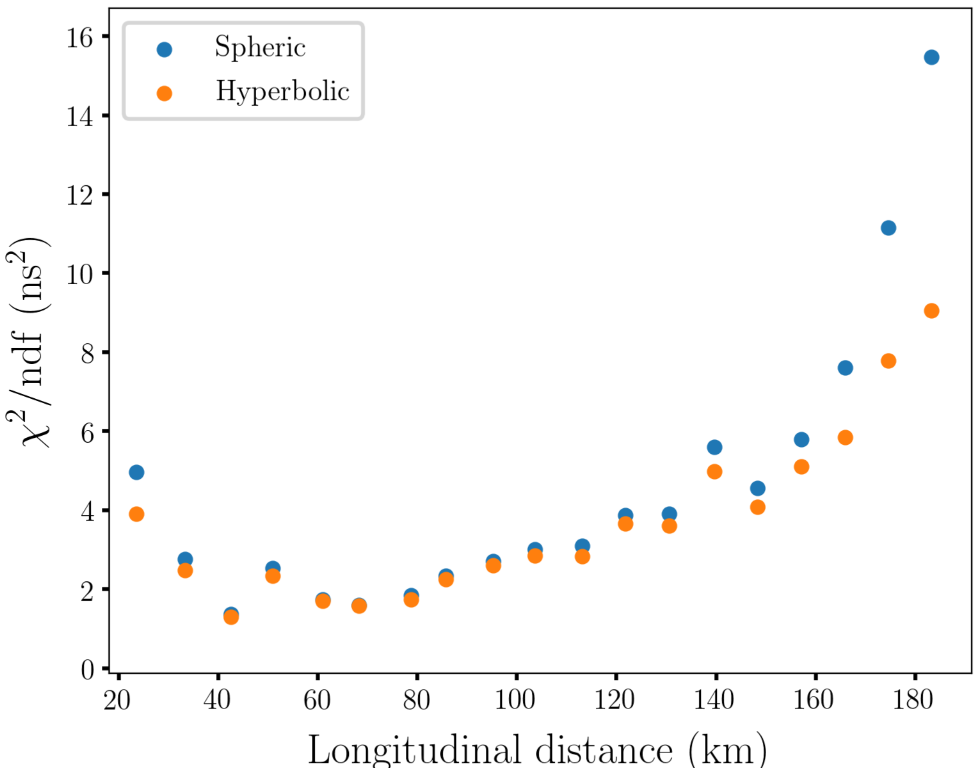
Refractive index correction

Here $a \approx rb$ **for** $\sqrt{a^2 + b^2 r^2} - a \longrightarrow \approx \sqrt{R^2 + r^2} - R$

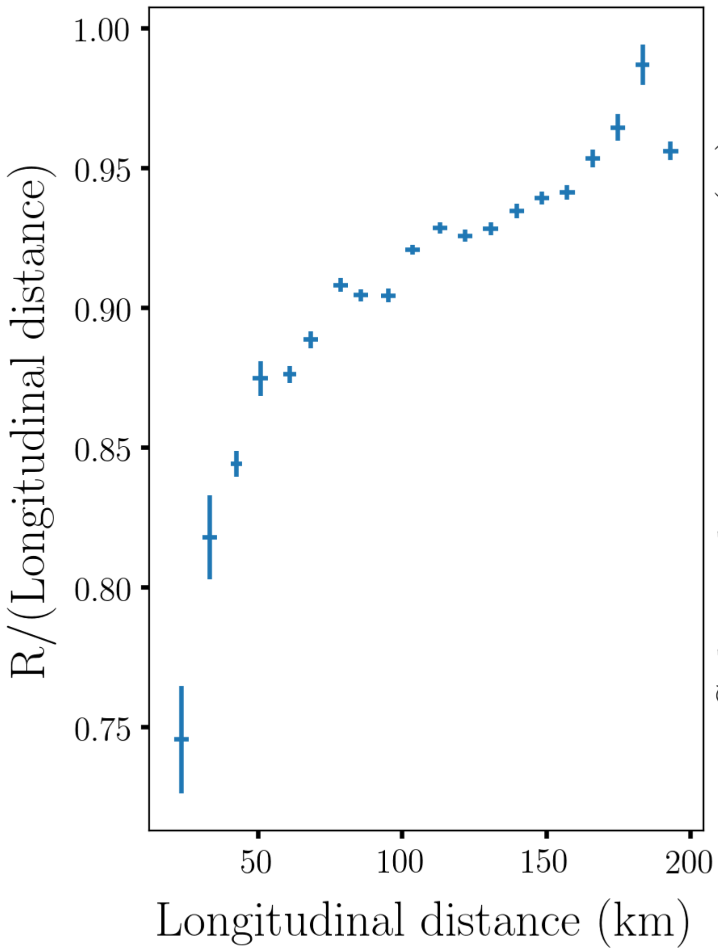
Parameters fitted are compatible with a spherical model

Slicing can be also applied to spherical model

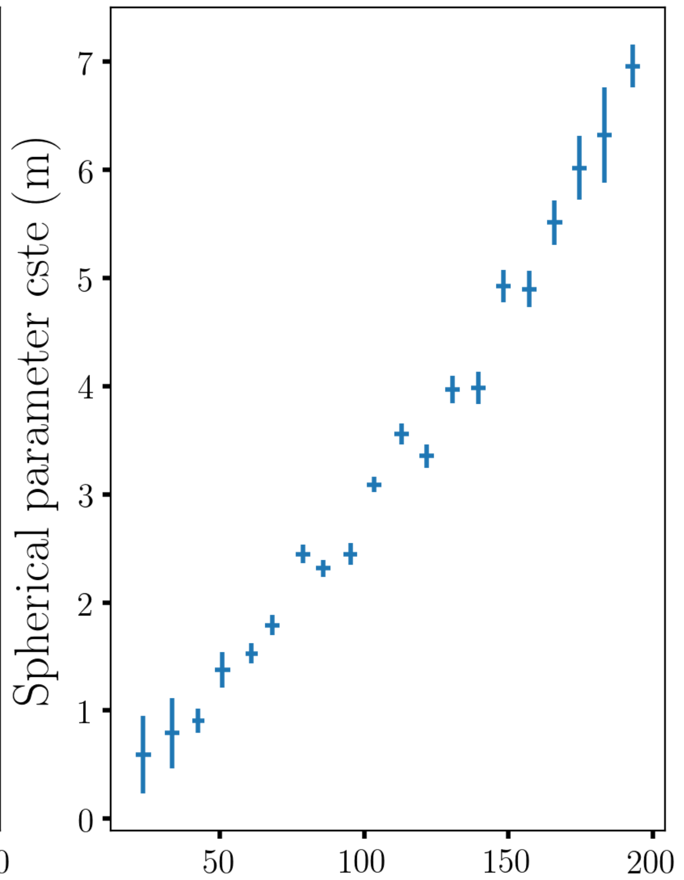




simulations stacking



Spherical curvature



Refractive index correction

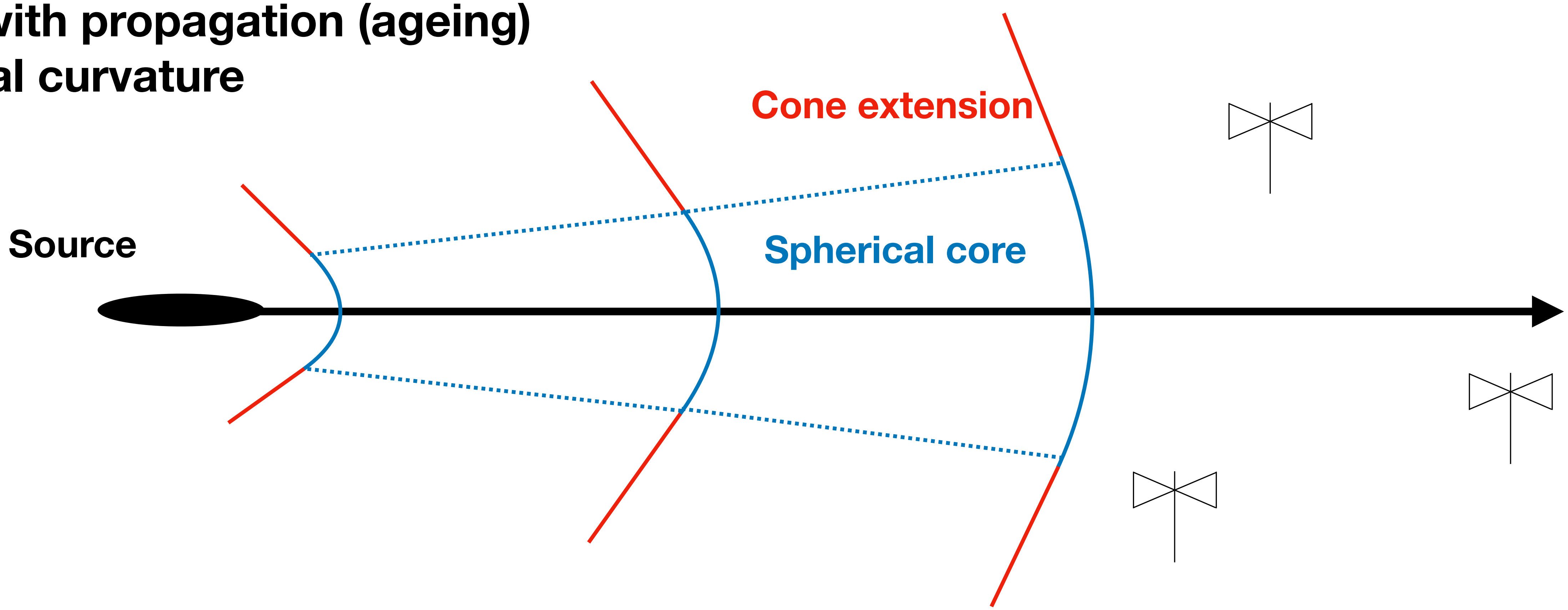
Curvature not linear with longitudinal distance -> not a point source emission

- **Spherical fit close to hyperbolic**

Hyperbolic fit remains better at large distances

The new wave front shape picture

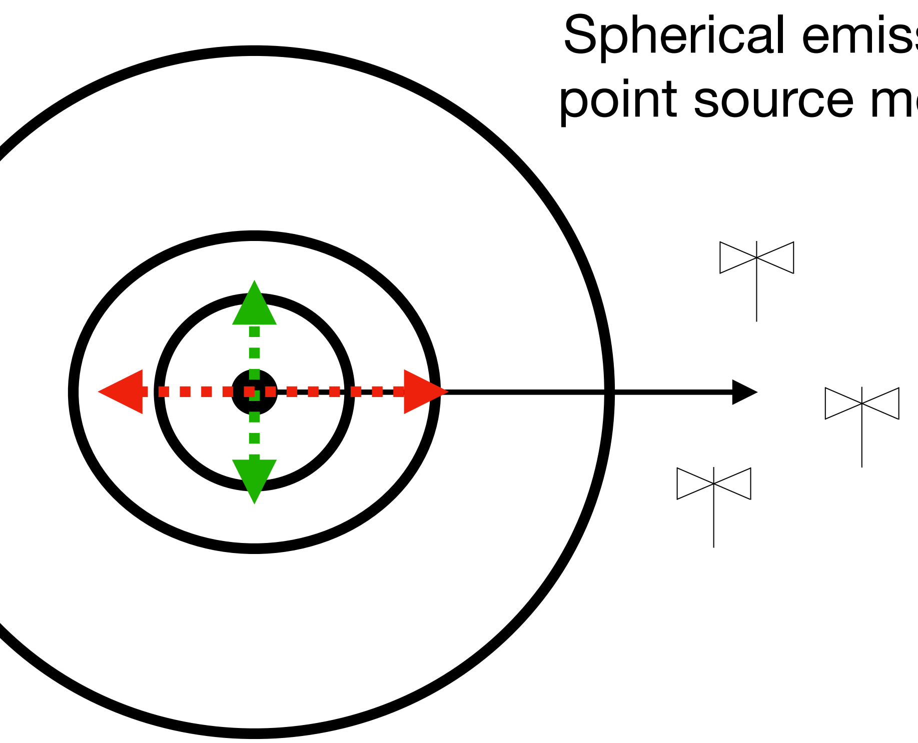
Wave front shape :
- **Hyperbolic**
- **Evolve with propagation (ageing)**
- **Spherical curvature**

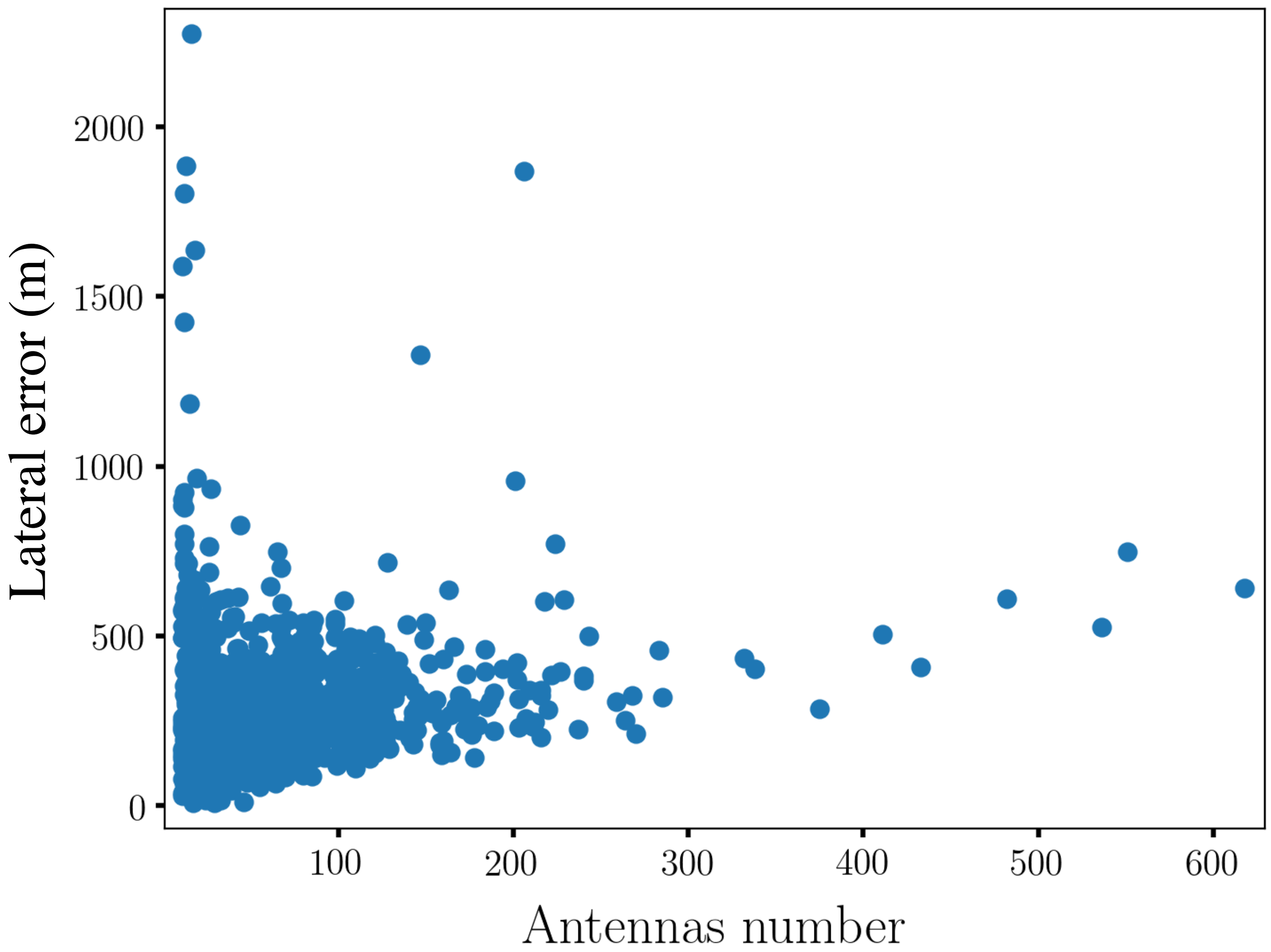


But 2 problems :
- **Many parameters to fit and big parameters space (a, b)**
- **Need to compute shower axis distance (r)**

We need spherical reconstruction to have a first estimate of shower axis position

Wave front shape is not point source like -> spherical reconstruction using a point source model lead to great error along the axis.
But the curvature and the large array allows a good handle on the lateral position of the shower axis.





Error on the lateral position from the shower axis
Error on the position along the shower axis

Position of the shower axis can be reasonably reconstructed with a point source model

Iterative reconstruction:

Loop

- Plane wave reconstruction -> direction estimate
- Spherical reconstruction -> position anchor for the direction

→ Shower axis distances for antennas

- Hyperbolic reconstruction using direction estimate and shower axis distances

Slicing reconstruction

Parametrising reconstruction parameters -> emission physic

Hybrid reconstruction:

Mixing timing information with amplitude information

- Amplitude -> shower core
- Polarisation -> axis distance

Conclusion

Standard hyperbolic reconstruction allows to reach 0.2° of angular resolution

Errors are above GPS precision and Noise effects

Wave front study shows the models are not adapted for the reconstruction

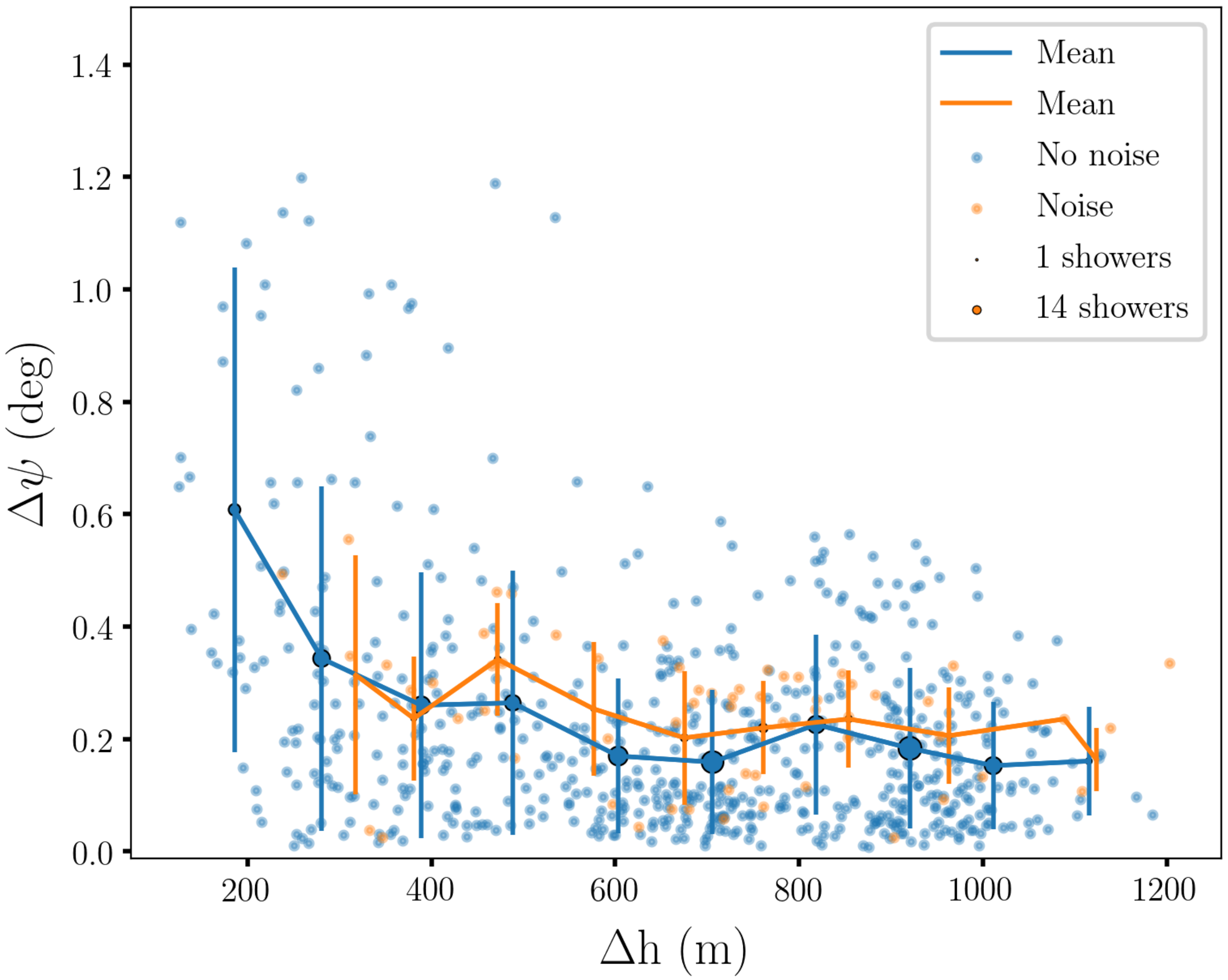
Ageing effects

Iterative reconstruction and slicing reconstruction should increase the angular resolution and allows to reach below 0.1° where GPS precision and noise effect would start to lead.

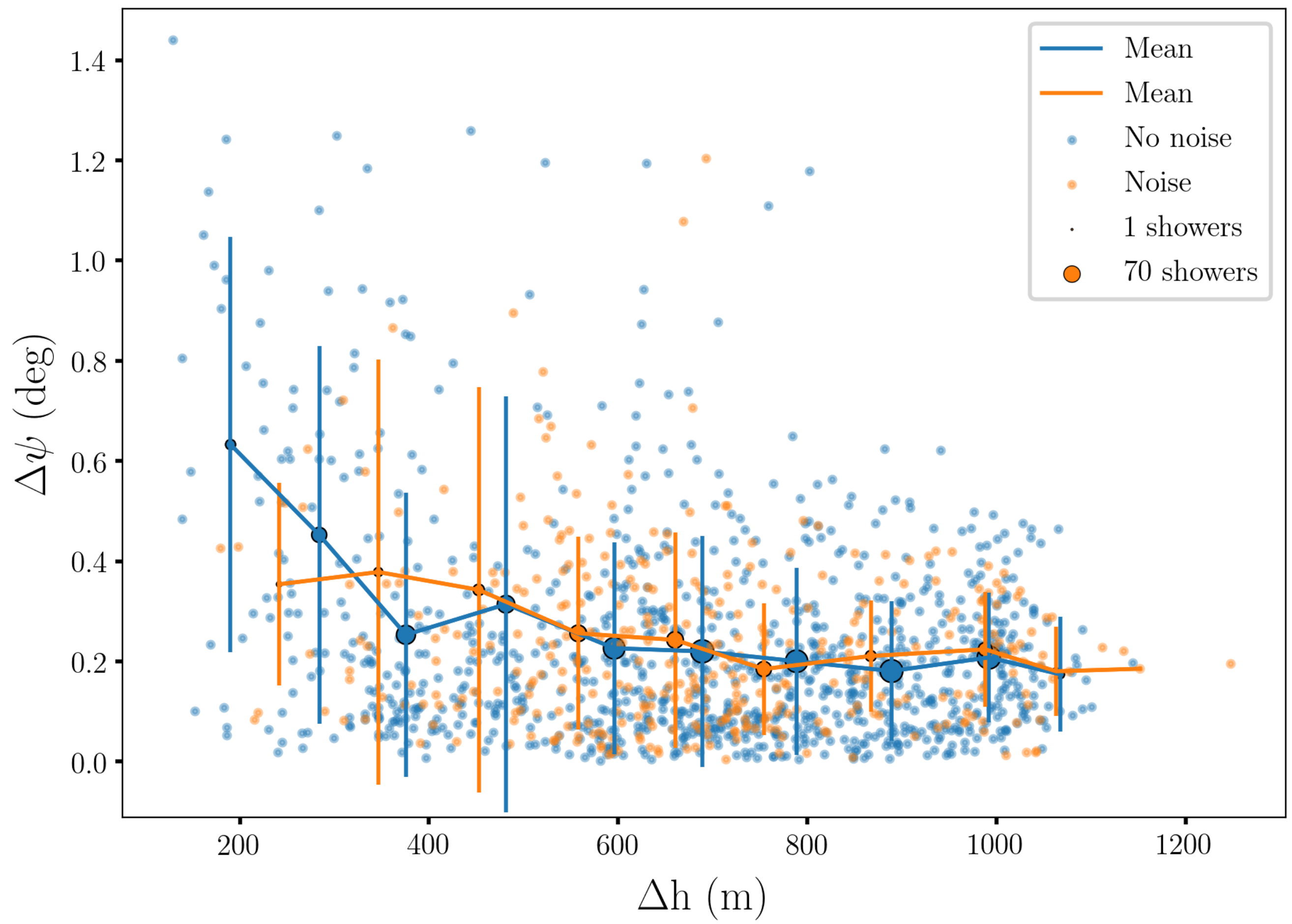
Hyperbolic wave front shape: LOFAR type

Noise comparison

10^9 GeV



10^{10} GeV



GPS delay = 5ns

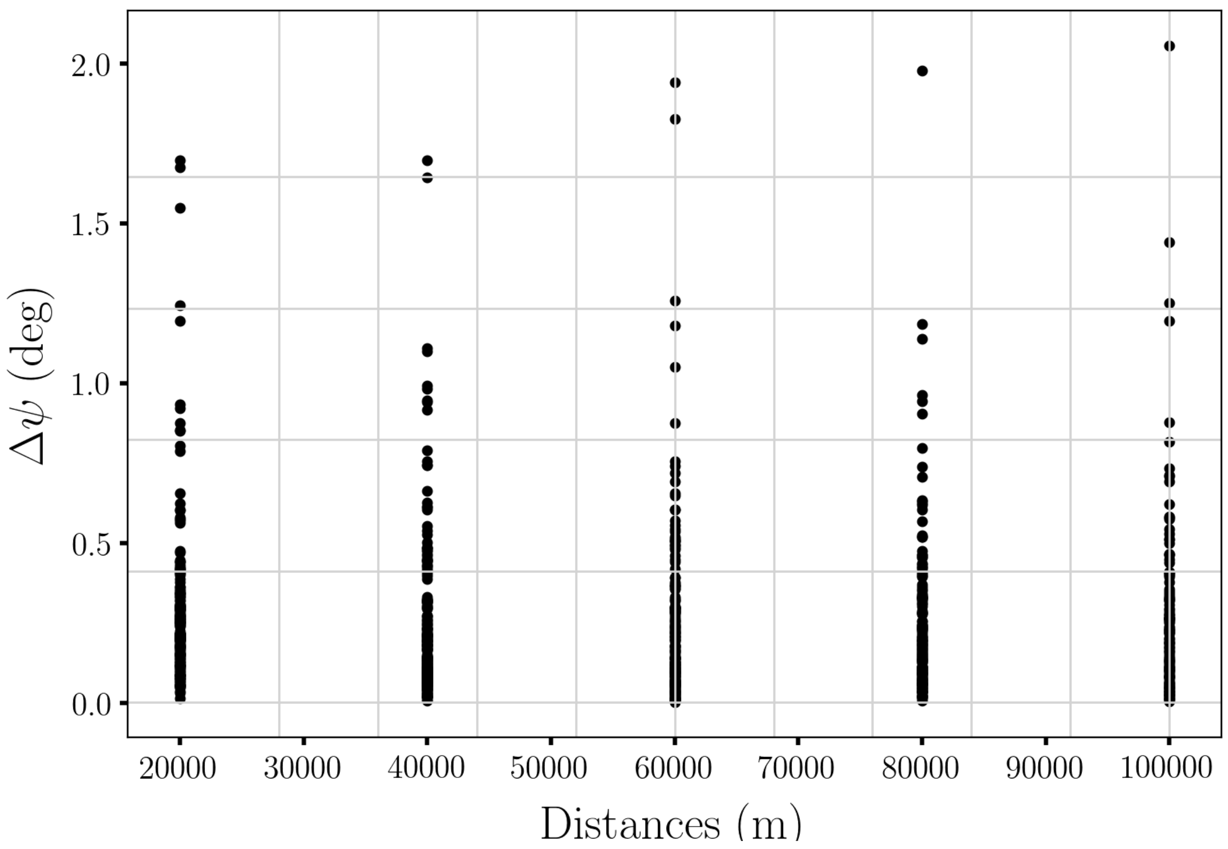
No noise / noise (Gaussian, mean = 15 µV) + sampling (1ns)

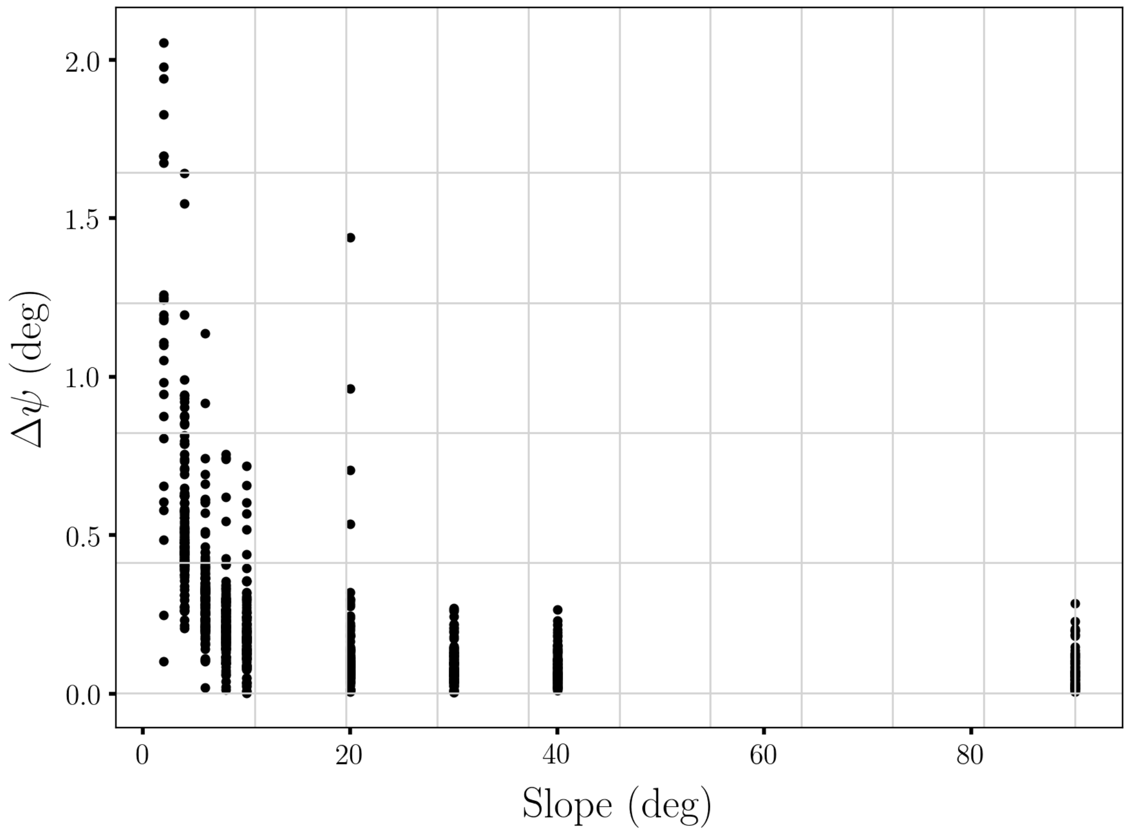
Threshold value = 100 µV

Noise reduce resolution but can be limited by increasing the threshold level (events cost)

Hyperbolic wave front shape: array configuration

Impact of Toy Model parameters on the reconstruction

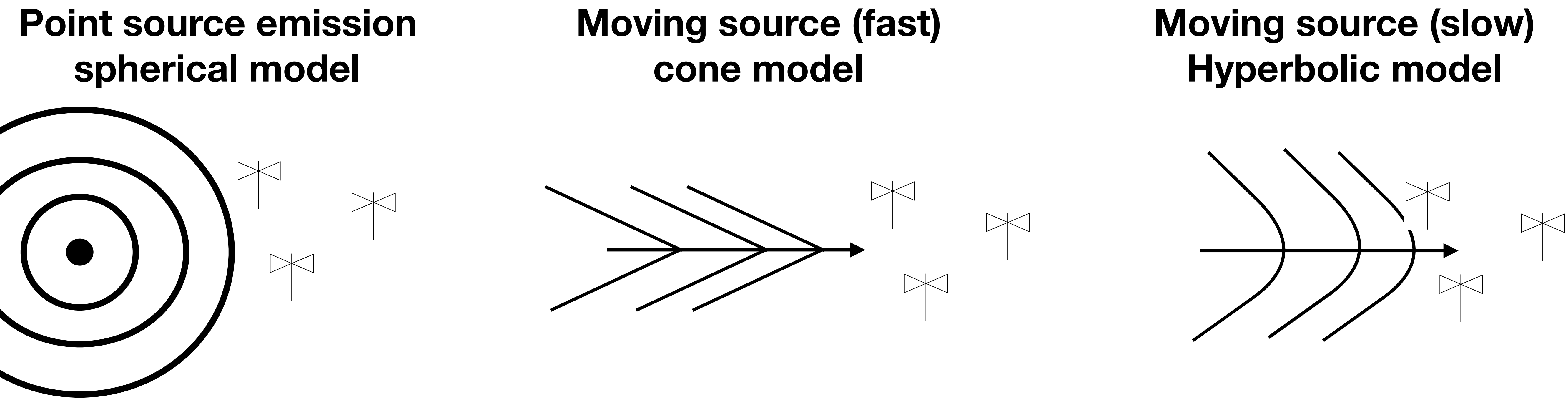


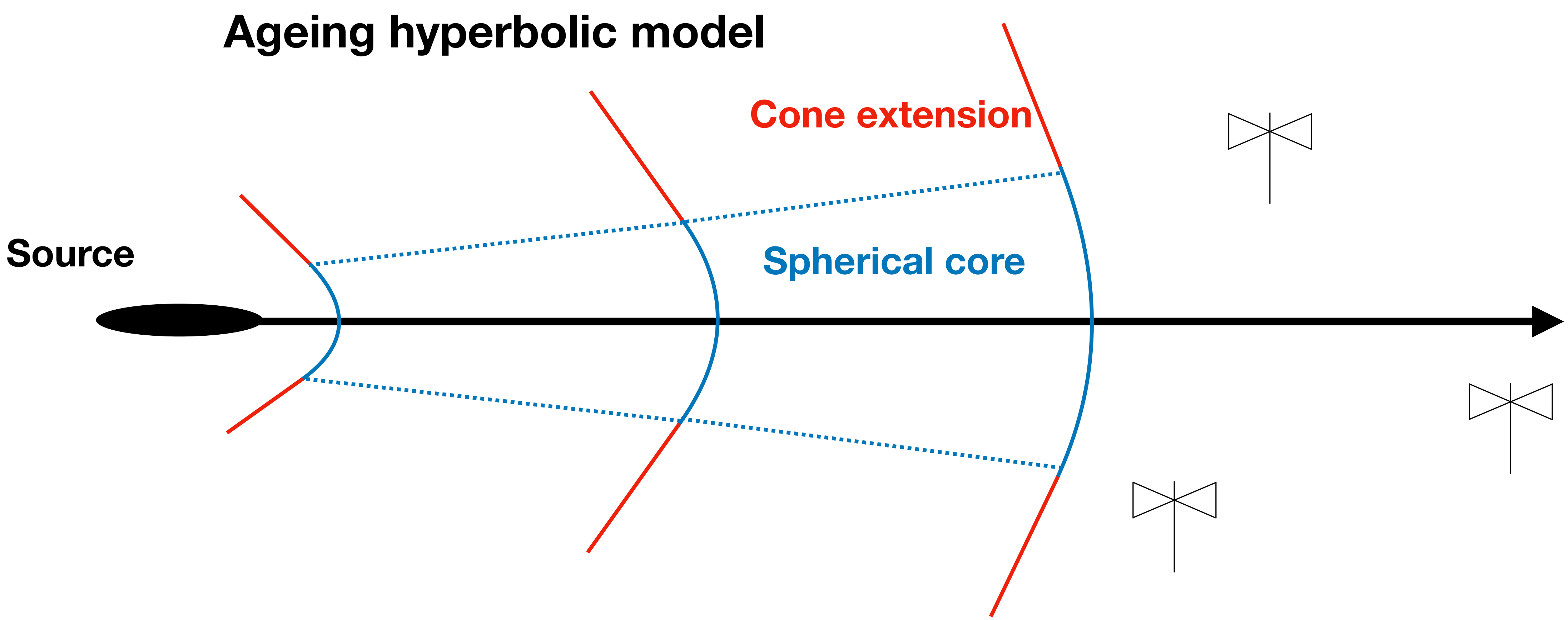


Distance -> no effect

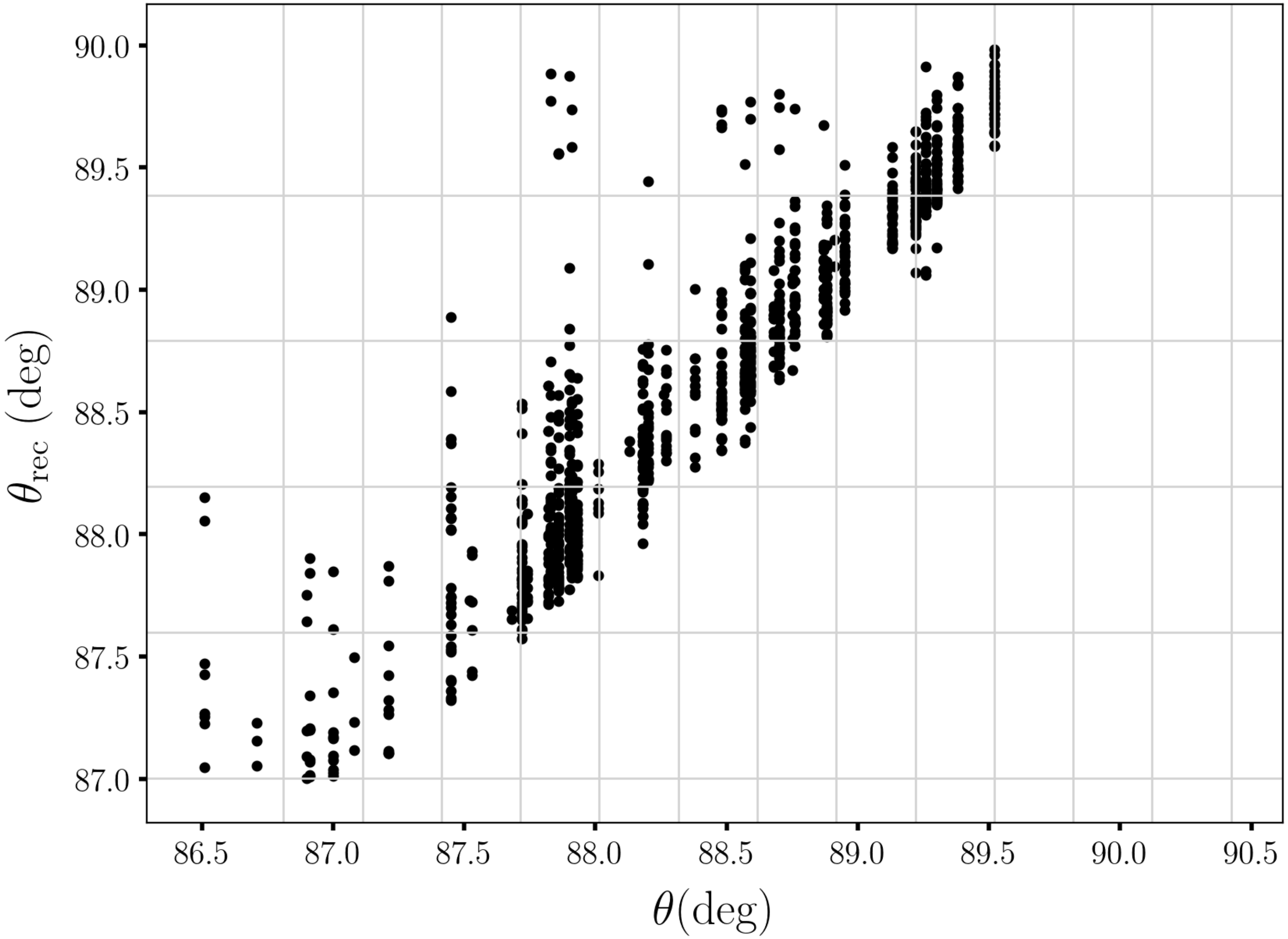
Slope -> important effect

Wave front shape study: ageing model

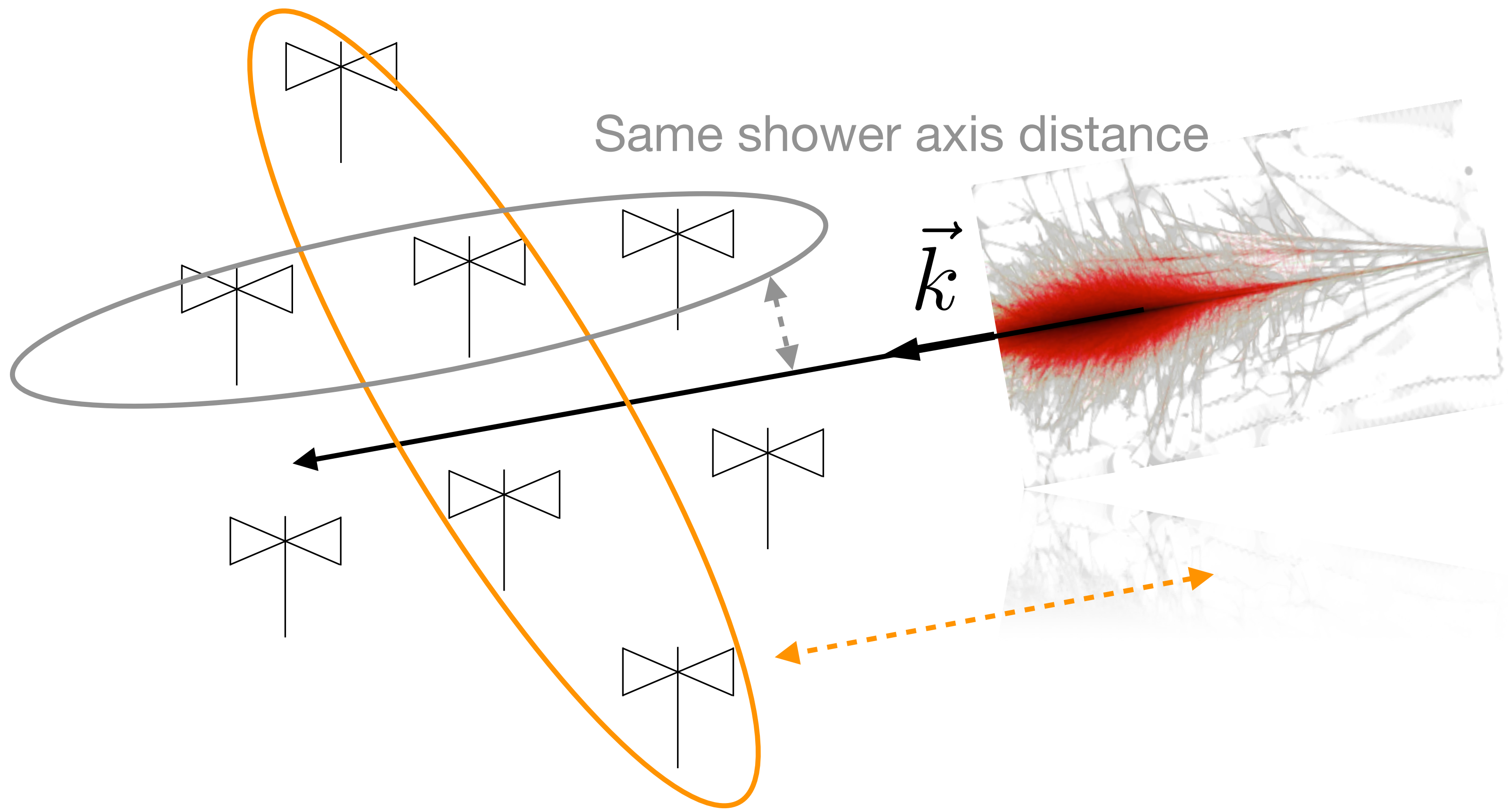




Hyperbolic wave front shape: limitation



Symmetries effects -> main limiting factor
Toy Model configurations issue


Same shower axis distance
$\vec{k}$
Slice at same propagation distance
from the source