Radio wavefront shape of cosmic ray air showers

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for the LOFAR Key Science Project Cosmic Rays

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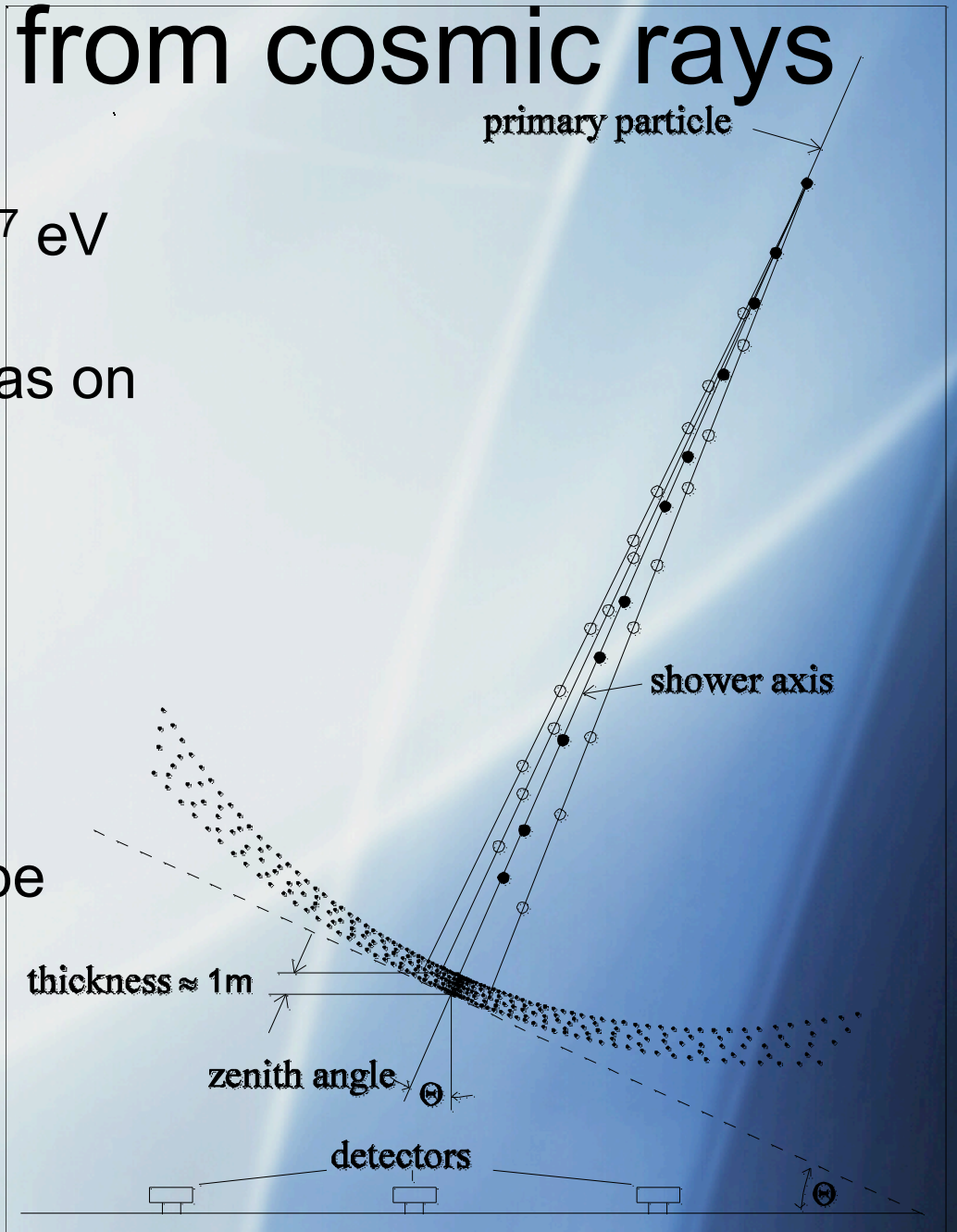
Radio pulses from cosmic rays

Short (10 ns) pulses from cosmic-ray particles > ~ 10^{17} eV

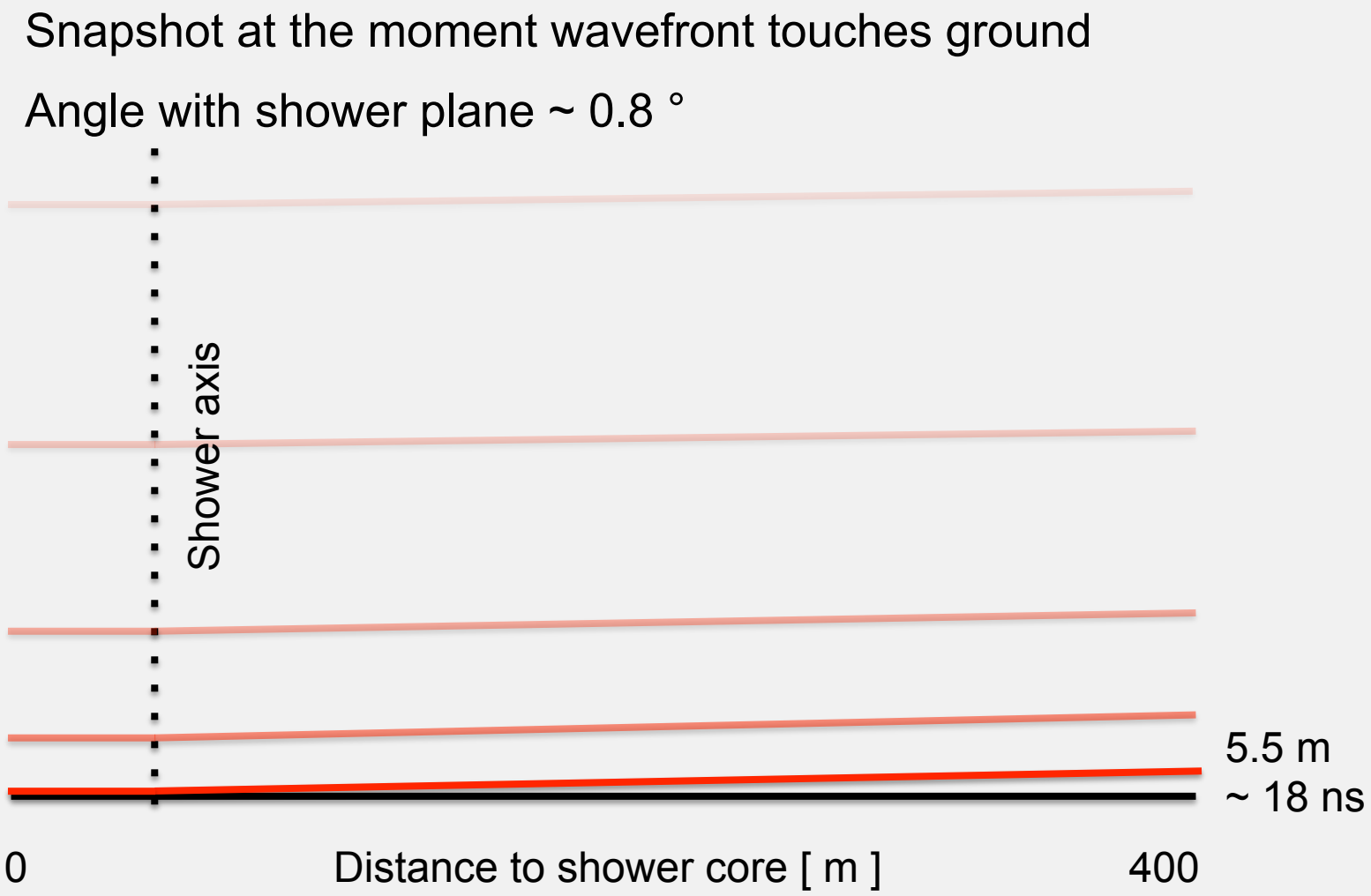
In 200 - 400 LOFAR antennas on the ground, we measure:

- Lateral distribution of
  - Signal power
  - Signal arrival time
    - ➢ Wavefront shape
  - Spectrum / pulse shape
  - Polarization

- Wavefront shape measurements



Wavefront at actual aspect ratio



Arrival times for a cosmic ray

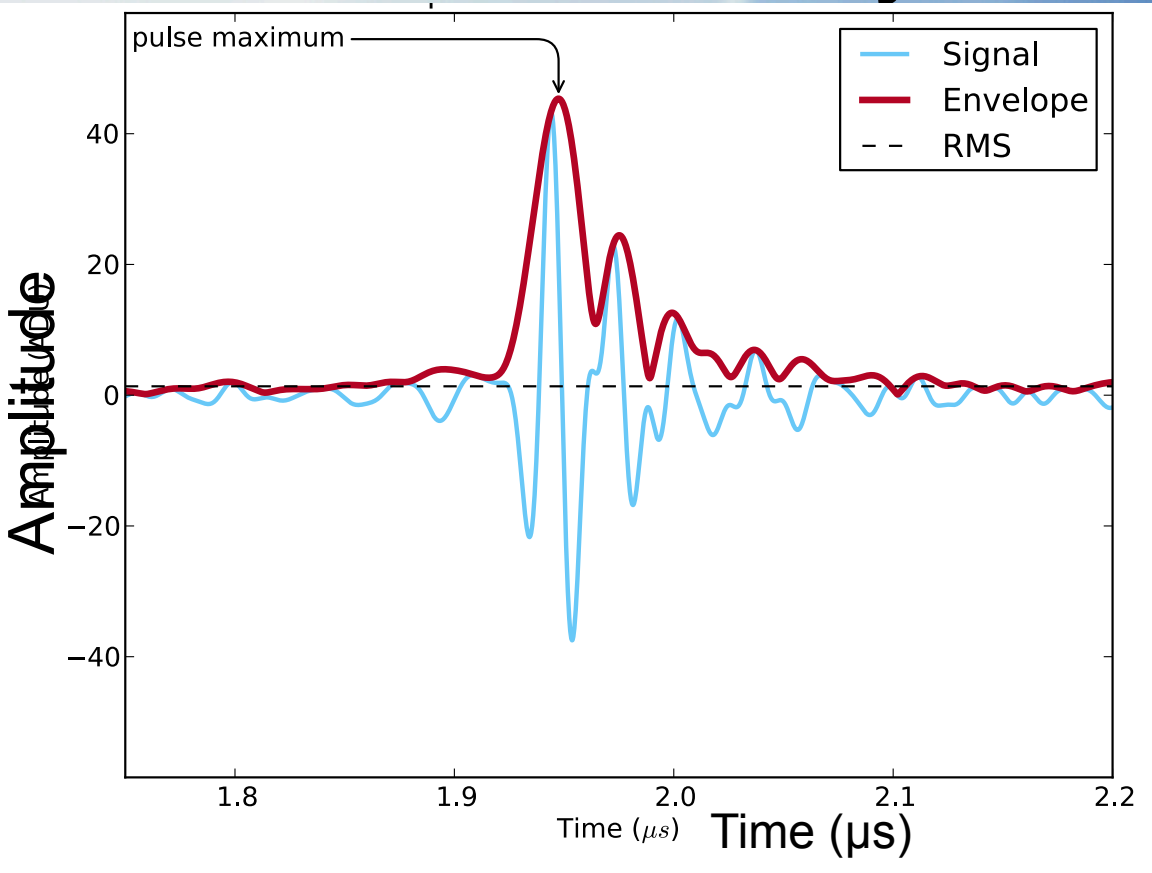
Measuring arrival time of pulse in individual antennas:

- Time series signal

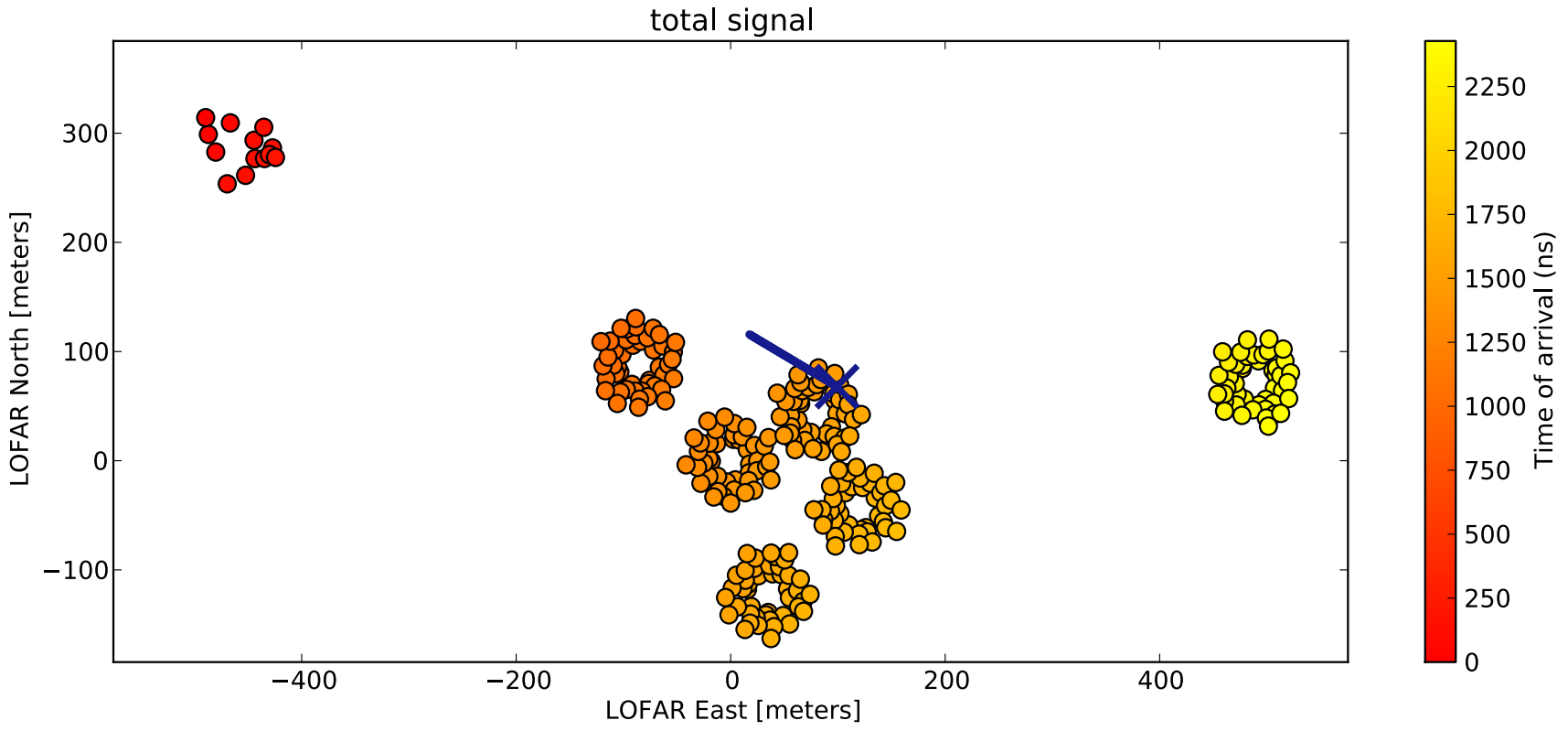
Apply Hilbert transform to get *Hilbert envelope*

- Envelope maximum is ‘the arrival time’

$$\sigma_t = \frac{12.7}{SNR} \text{ ns} < 5 \text{ ns!}$$

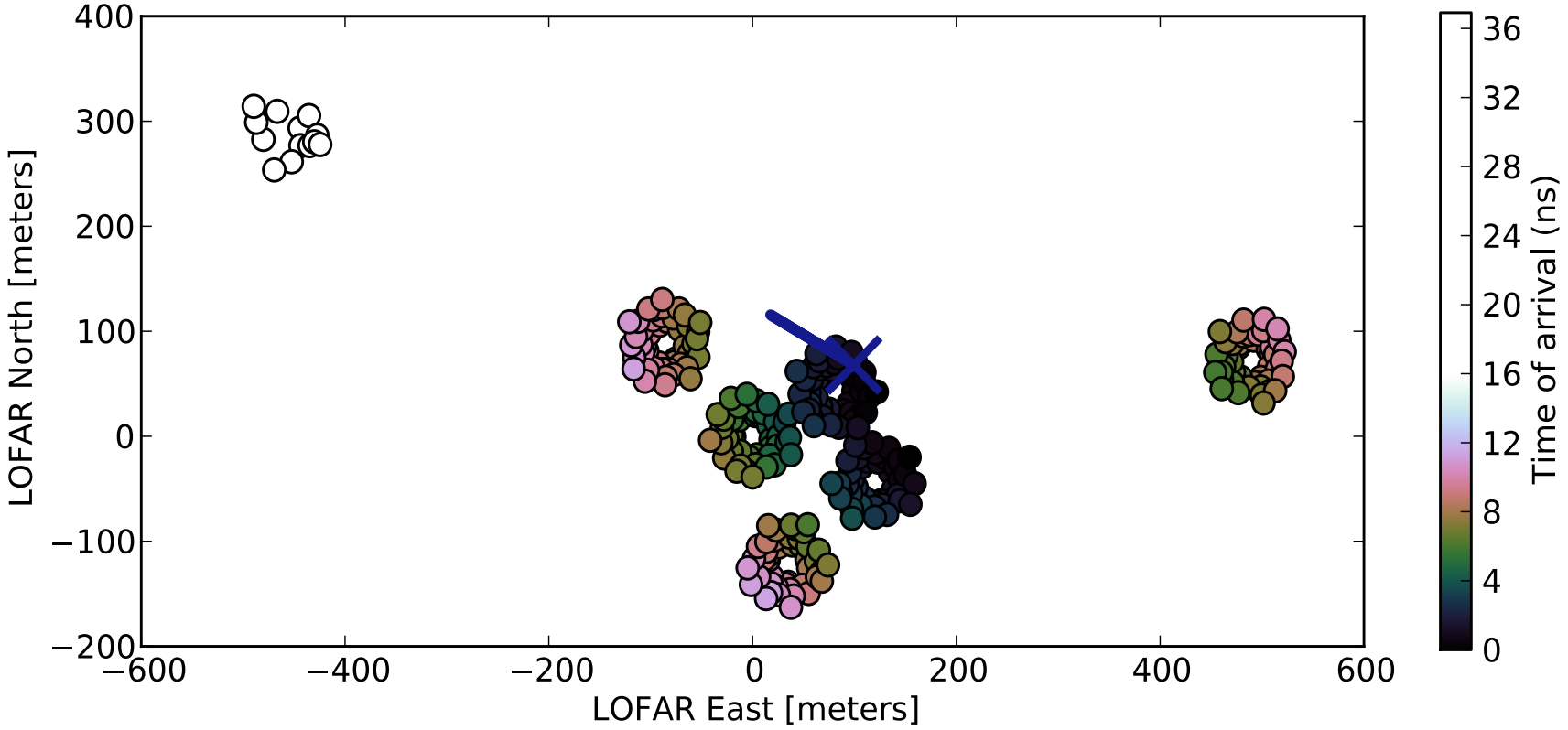


Arrival times for a cosmic ray



Arrival times after subtracting plane-wave solution

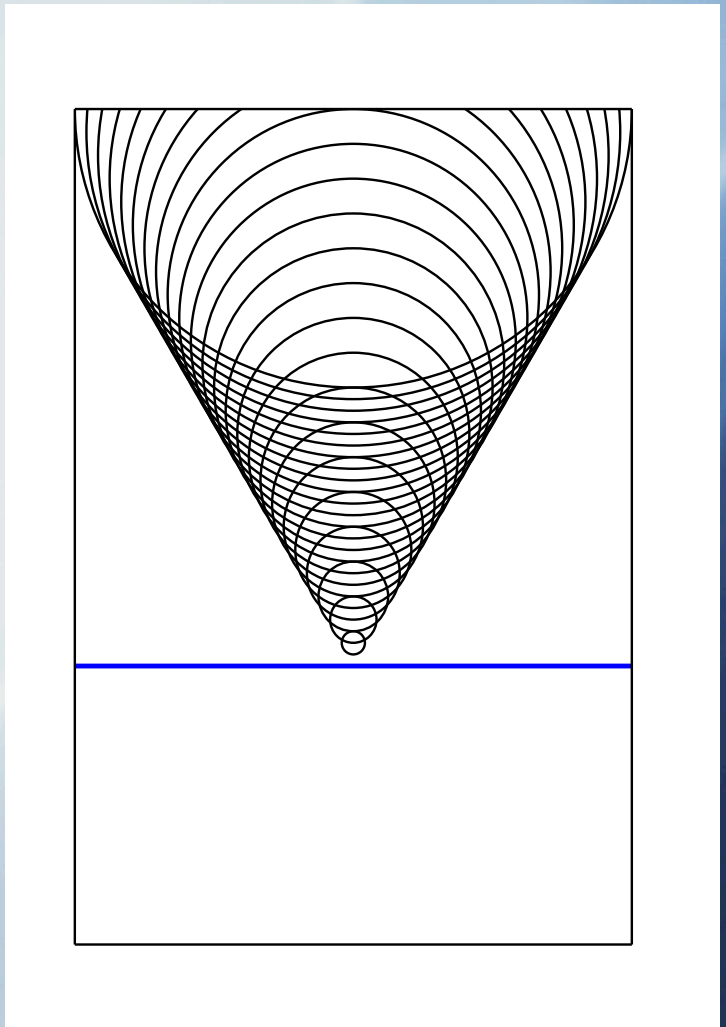
Corstanje et al., to be submitted to Astroparticle Physics



Toy model for wavefront shape

- A point source moving at $v = c$
- Emitting radiation for a limited time
- Medium has refractive index n
- Waves propagate at $v = c/n$

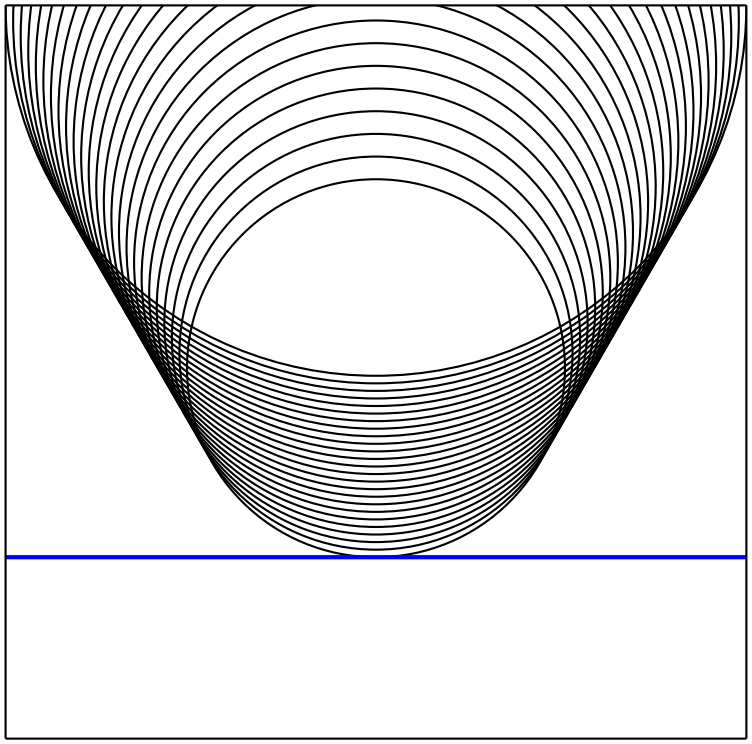
- Emission all the way to the ground: **conical** shape



Toy model for wavefront shape

- A point source moving at $v = c$
- Emitting radiation for a limited time
- Medium has refractive index n
- Waves propagate at $v = c/n$

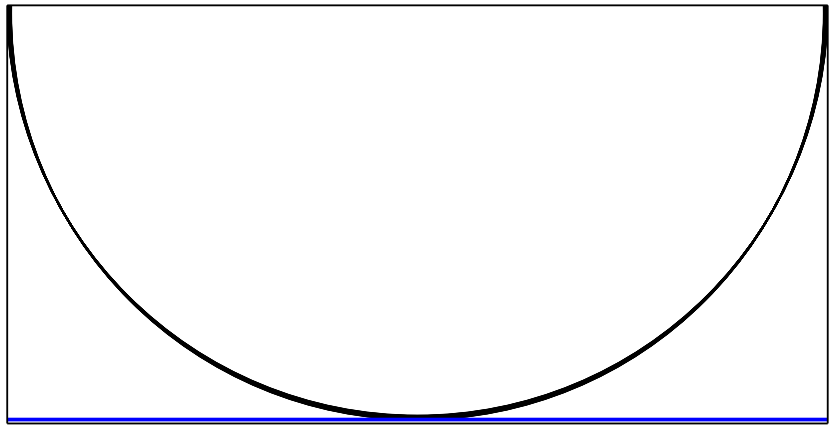
- Emission stops before ground: **hyperbolic**(-like) shape



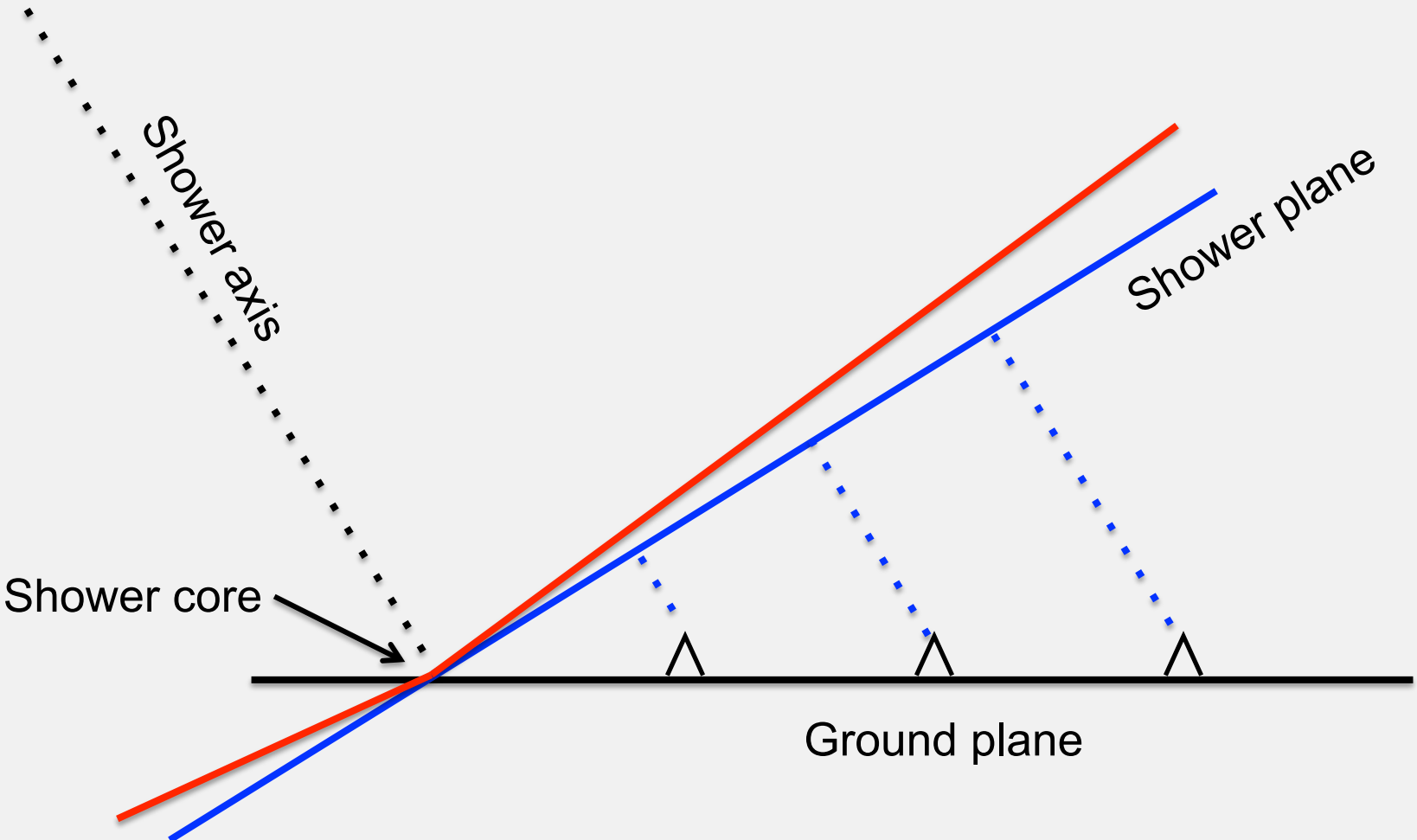
Toy model for wavefront shape

- A point source moving at $v = c$
- Emitting radiation for a limited time
- Medium has refractive index n
- Waves propagate at $v = c/n$

- Emission only very far from ground: **spherical** shape



Shower plane projection



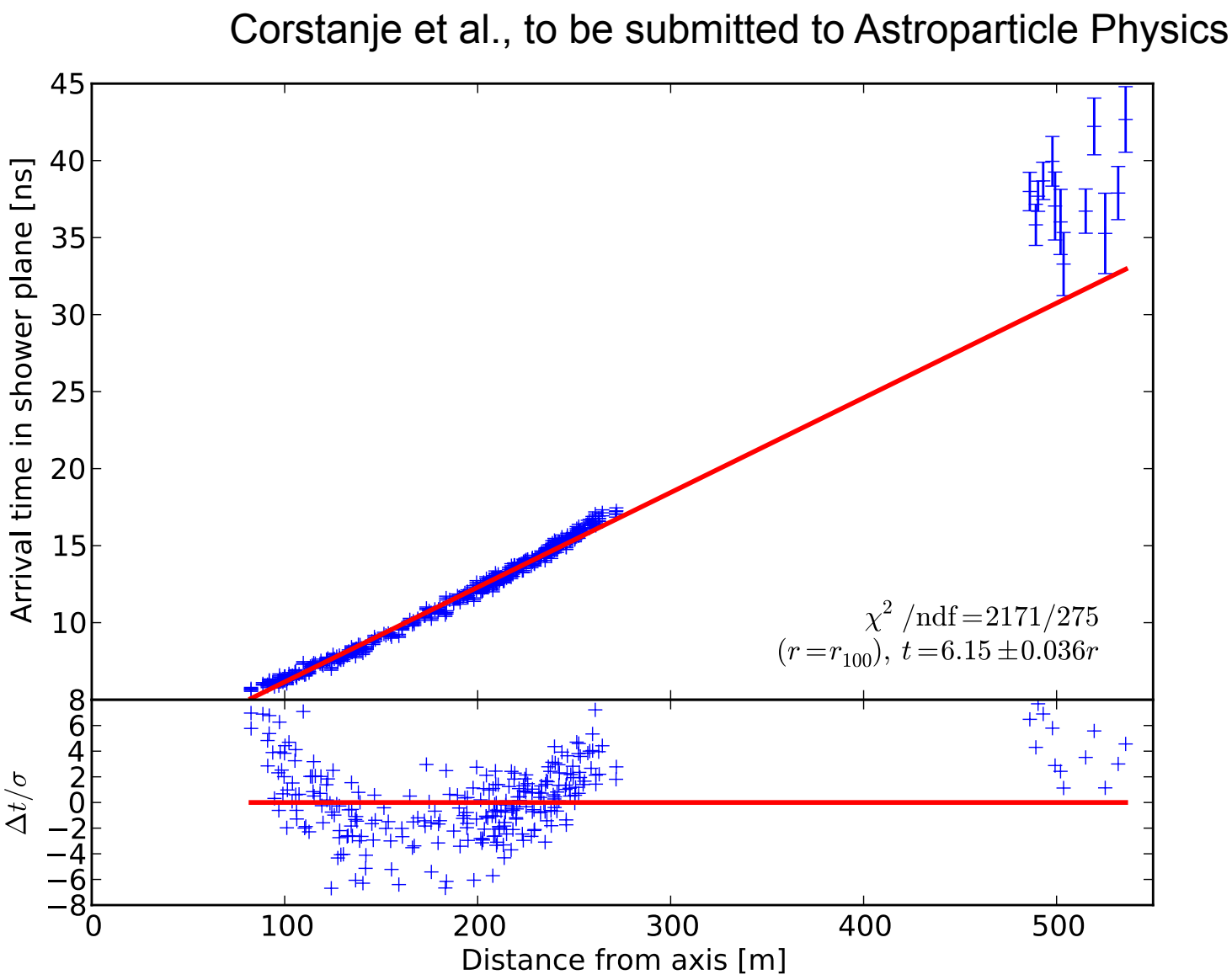
Shower plane

- Project antennas into shower plane
  - Shower axis position
  - Shower axis direction
  - Unknown: free **fit parameters**

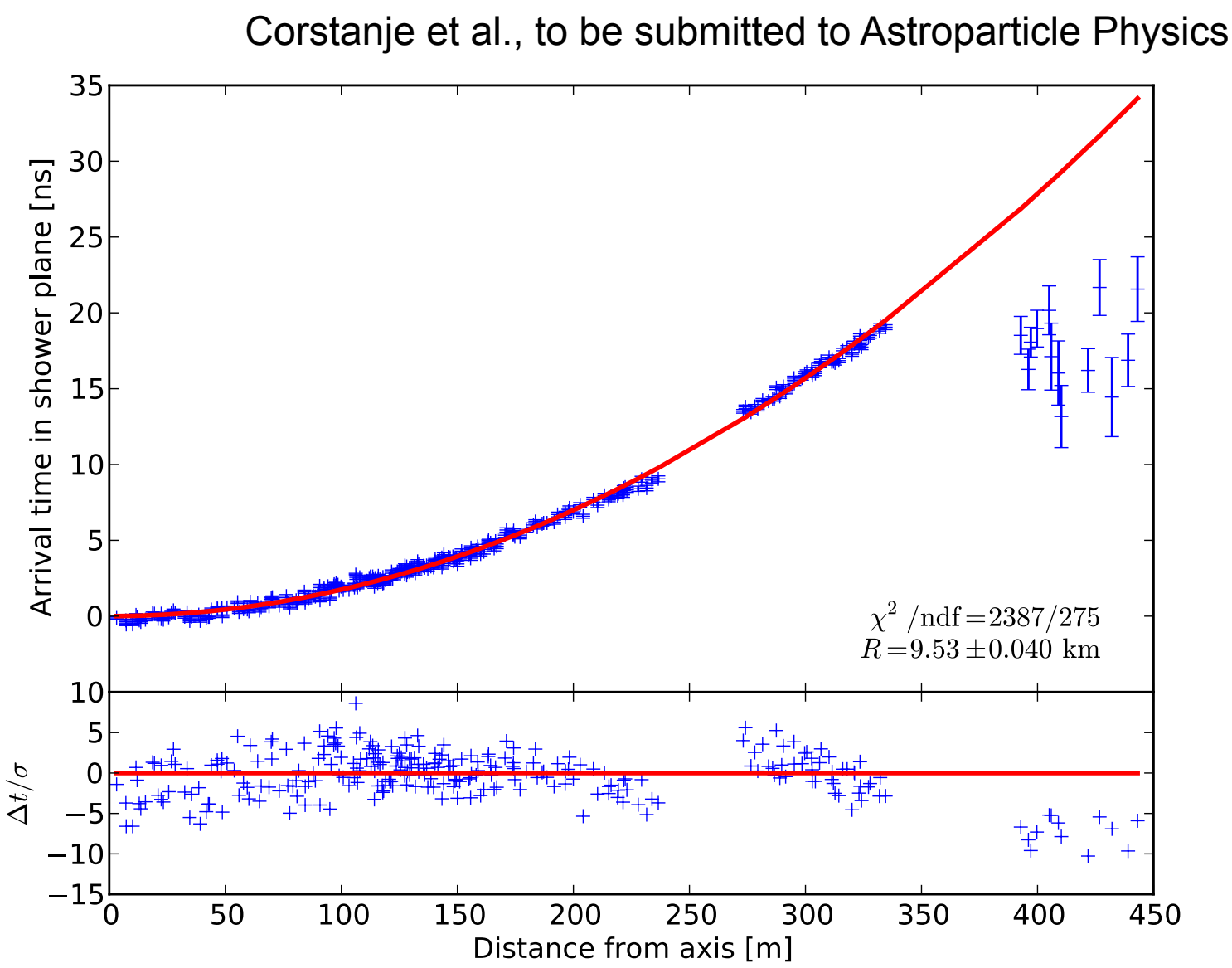
- Wavefront: arrival times as function of distance from shower axis

- Nested fitting (**7** params):
- Optimize shower **core position**
  - Optimize axis **direction**
    - Optimize **curve-fit**

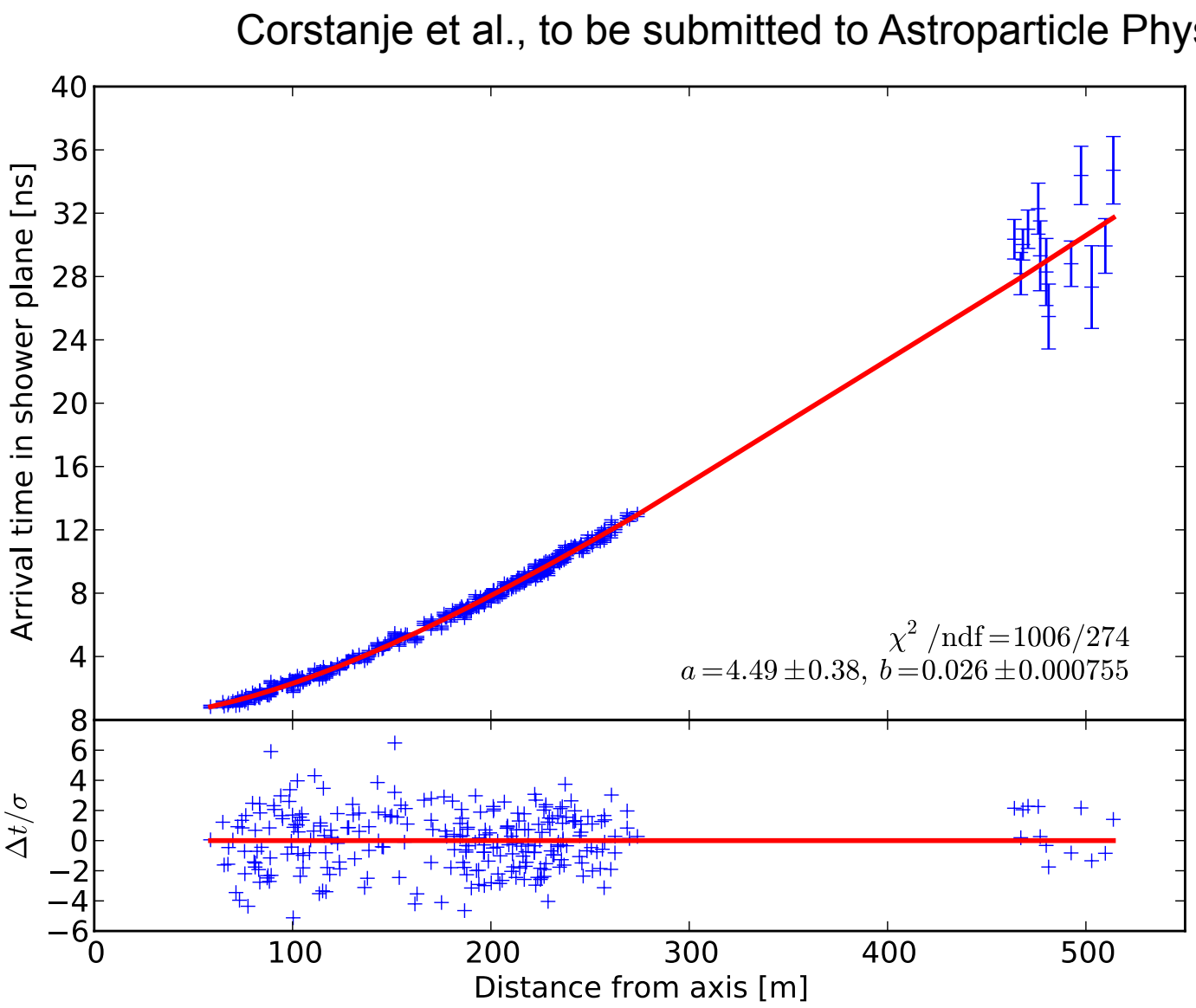
Best-fitting conical shape



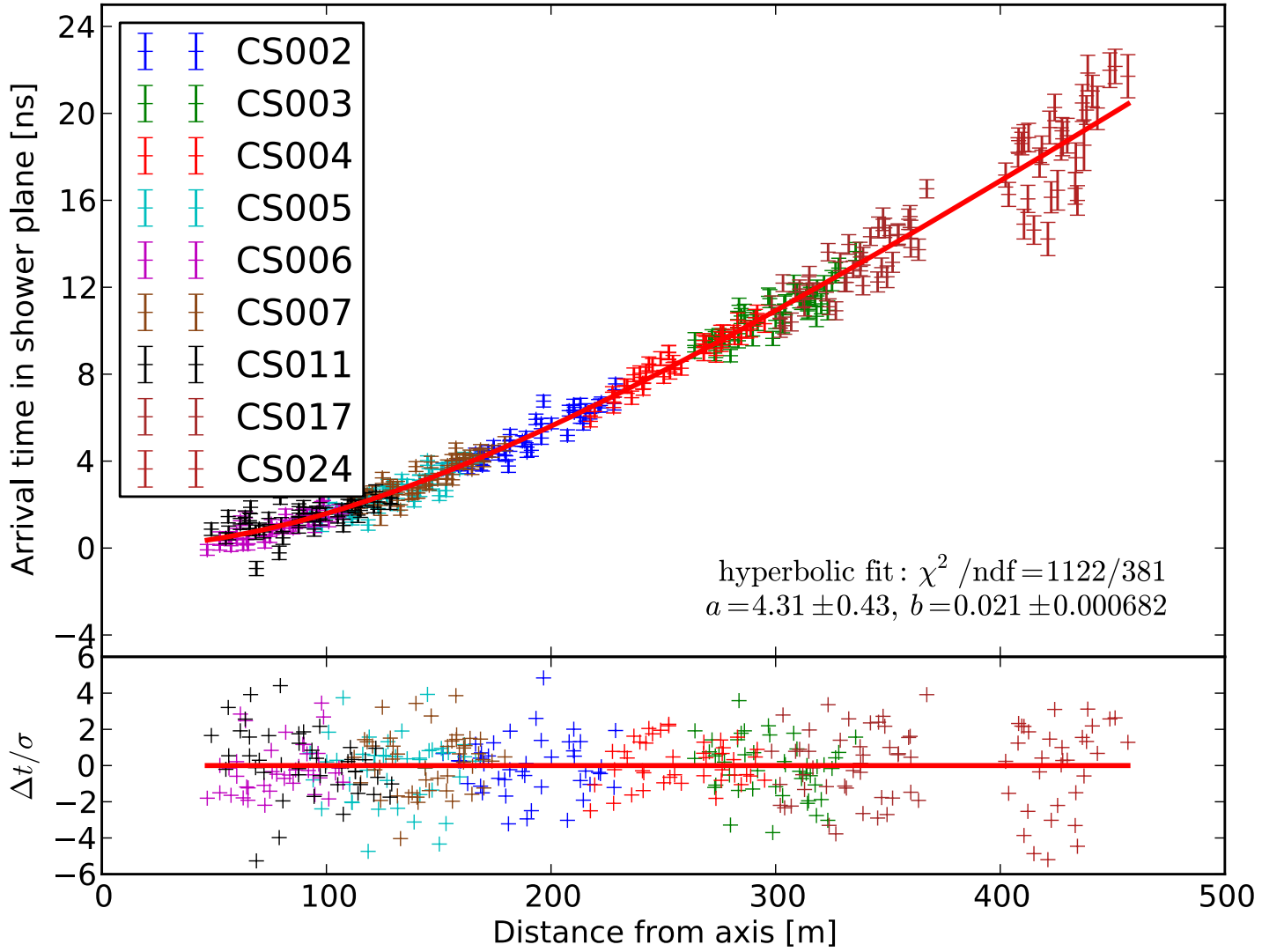
Best-fitting spherical shape



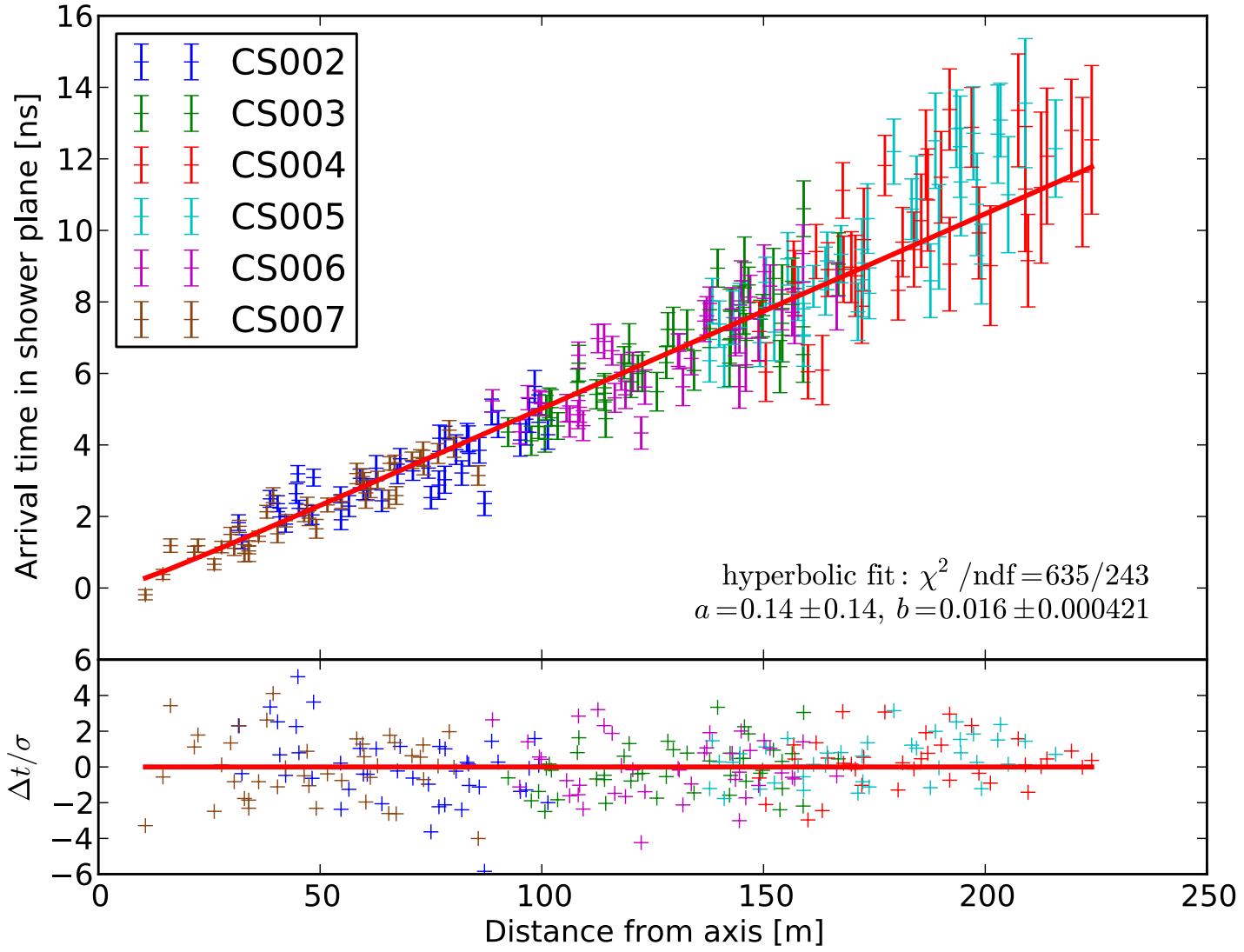
Best-fitting hyperbolic shape



Another example



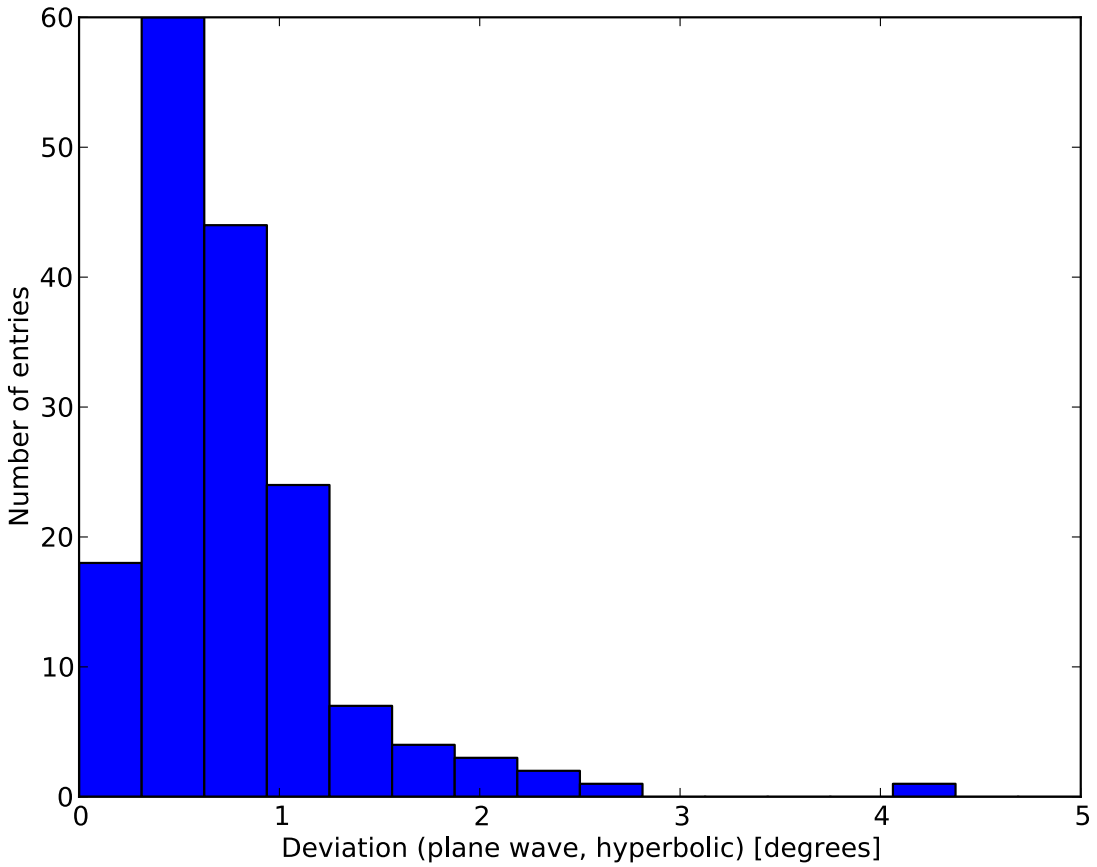
Conical-shaped example



Improved angular resolution

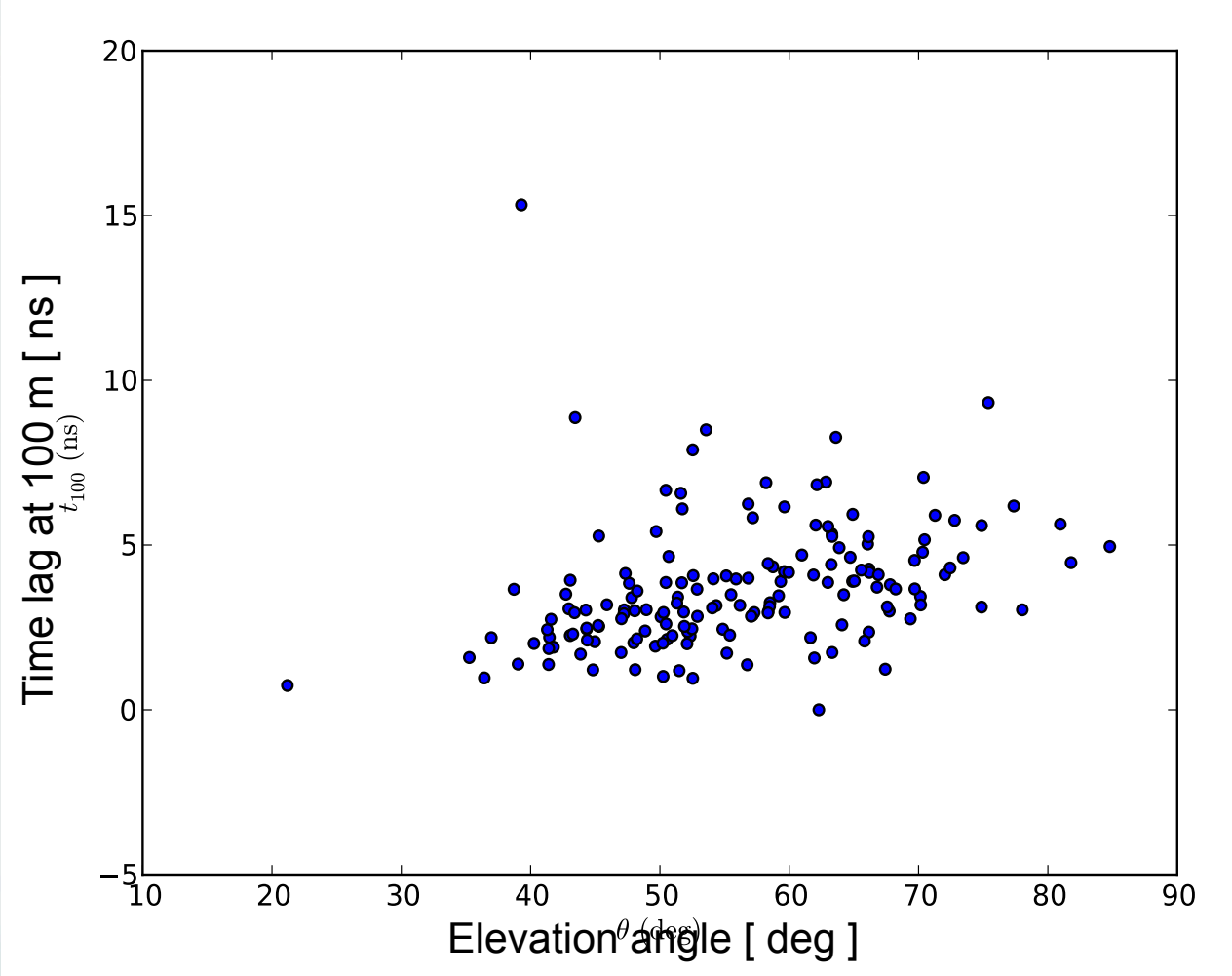
Corstanje et al., to be submitted to Astroparticle Physics

- Using hyperbolic wavefront improves directional accuracy
- About 1 degree difference
- Difference with conical shape ~ 0.1 degree



Elevation angle dependence

- Time lag at 100 m from shower axis of best-fitting hyperboloid
- Weak correlation with elevation angle
- Uncertainty in shower core position



Conclusions and outlook

- Wavefront timing measured with accuracy better than 1 ns per antenna
- A hyperboloid clearly fits best; no significant structure in residuals
  - Significant spread between events, well resolved

- Arrival direction more accurately fitted using hyperboloid wavefront (to ~ 0.1 deg)
- Compare with simulations to get more accurate shower core position, and correlate with Xmax and particle type