Timing calibration and Radio wavefront shape of cosmic ray air showers

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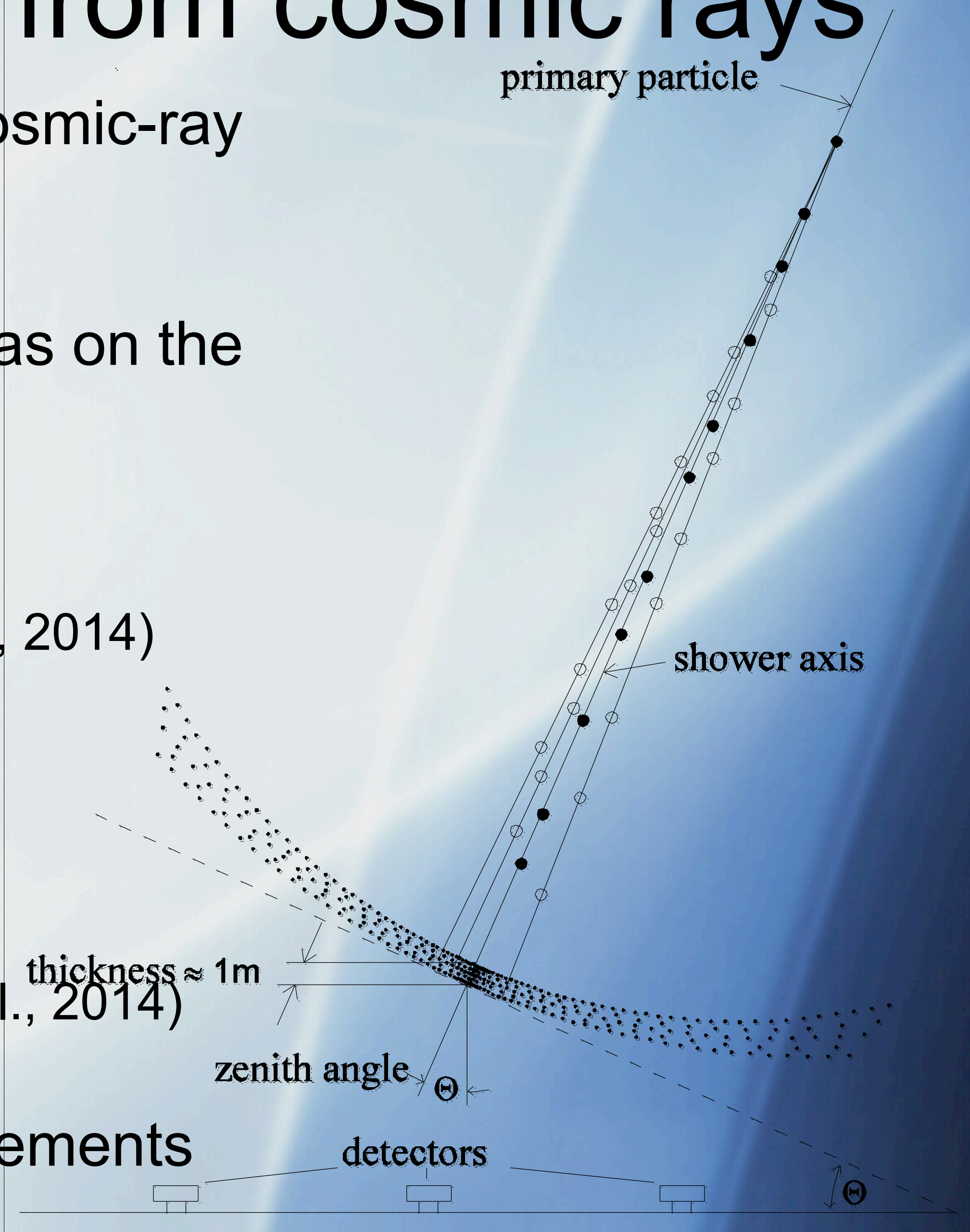
Radio pulses from cosmic rays

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 (Nelles et al., 2014)
  - Signal arrival time (Corstanje et al., 2015)
    - Wavefront shape
  - Spectrum / pulse shape (Rossetto et al., in prep.)
  - Polarization (Schellart et al., 2014)
- Wavefront shape measurements



Arrival times for a cosmic ray

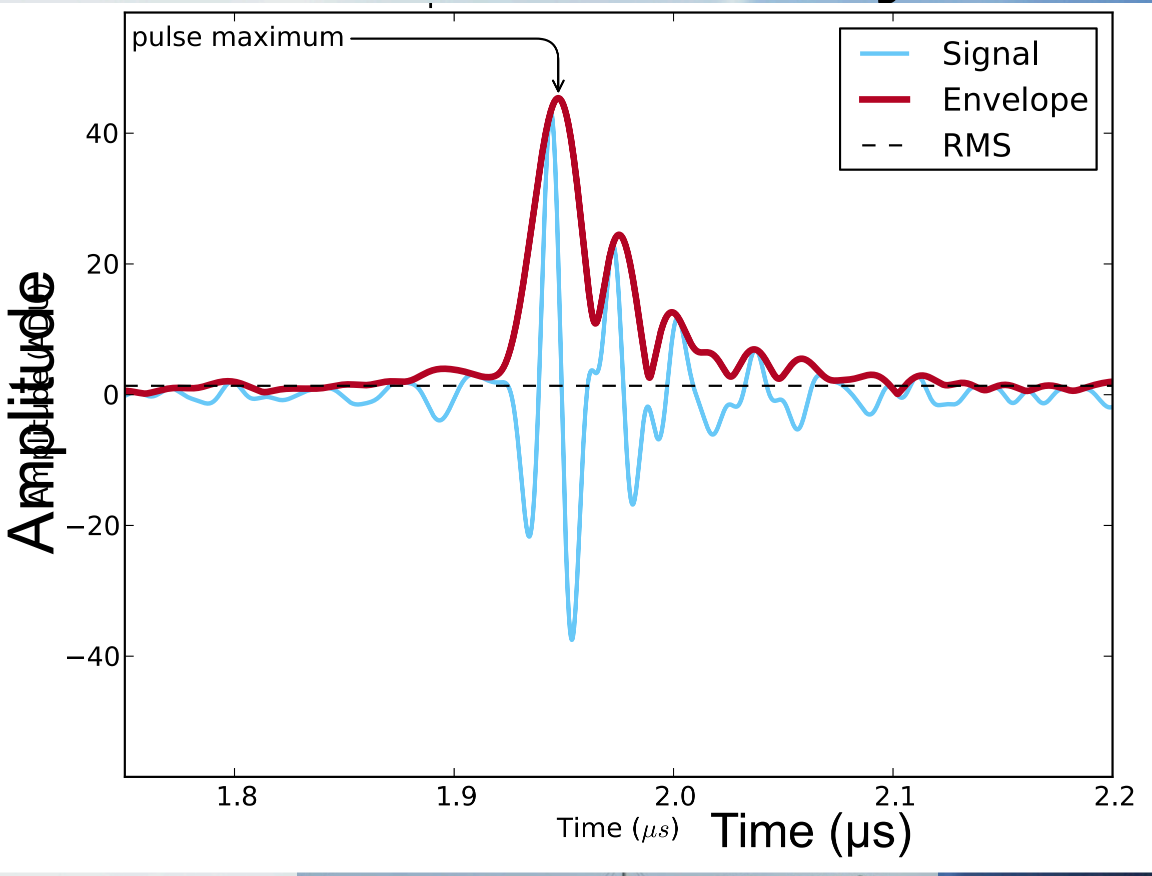
Measuring arrival time of pulse in individual antennas:

- Time series signal

Apply Hilbert transform to get *Hilbert envelope*

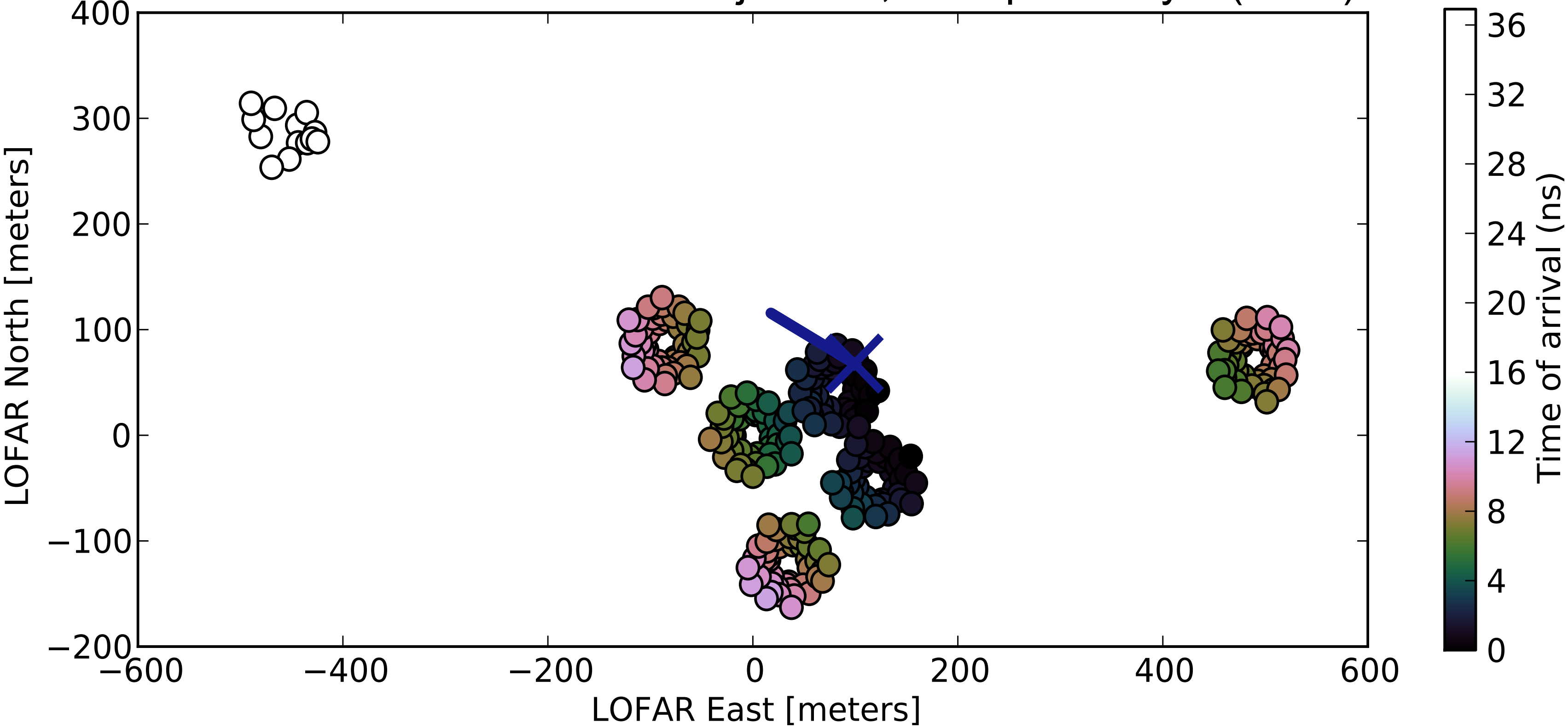
- Envelope maximum is ‘the arrival time’

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

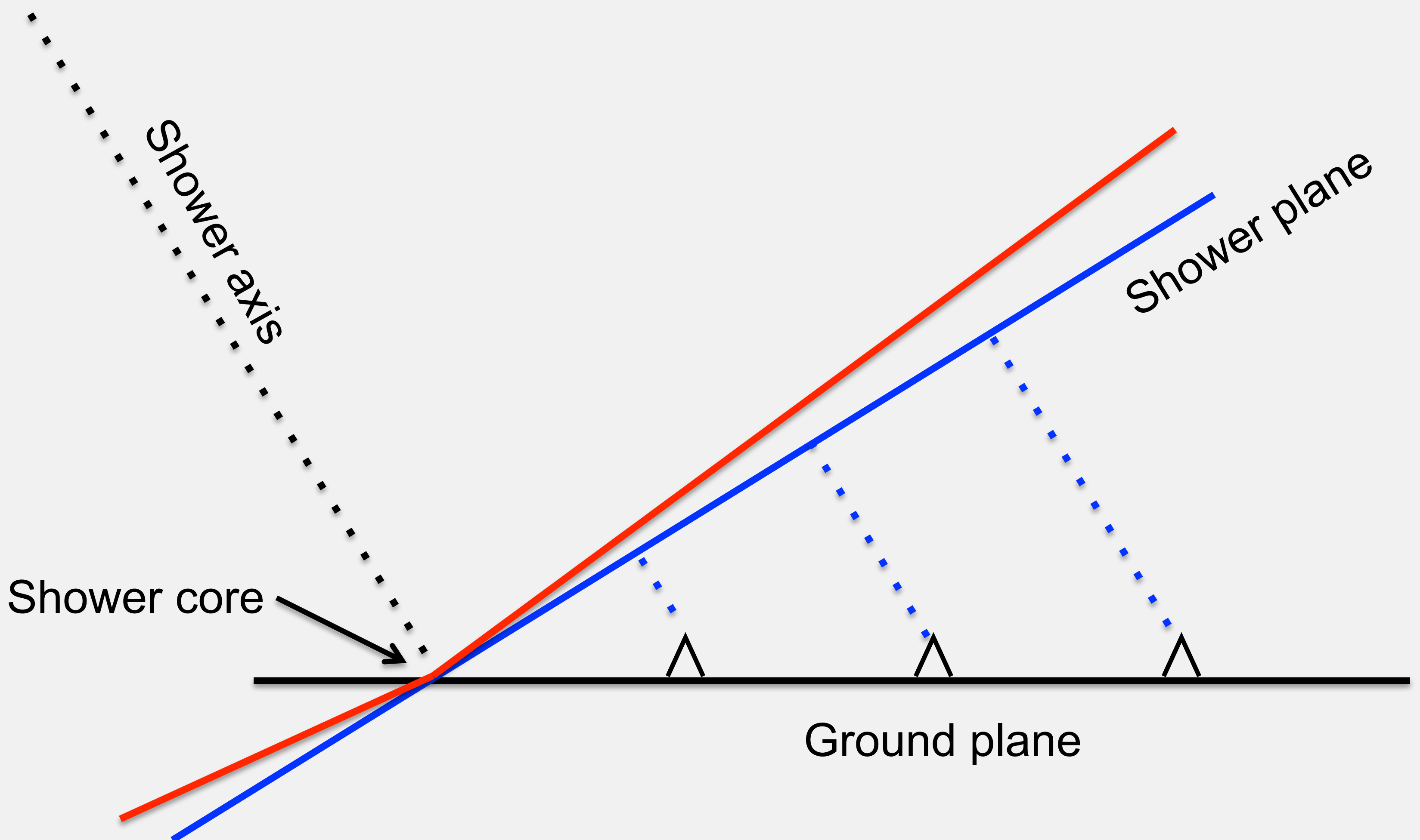


Arrival times after subtracting plane-wave solution

Corstanje et al., Astropart. Phys. (2015)



Shower plane projection



Shower plane

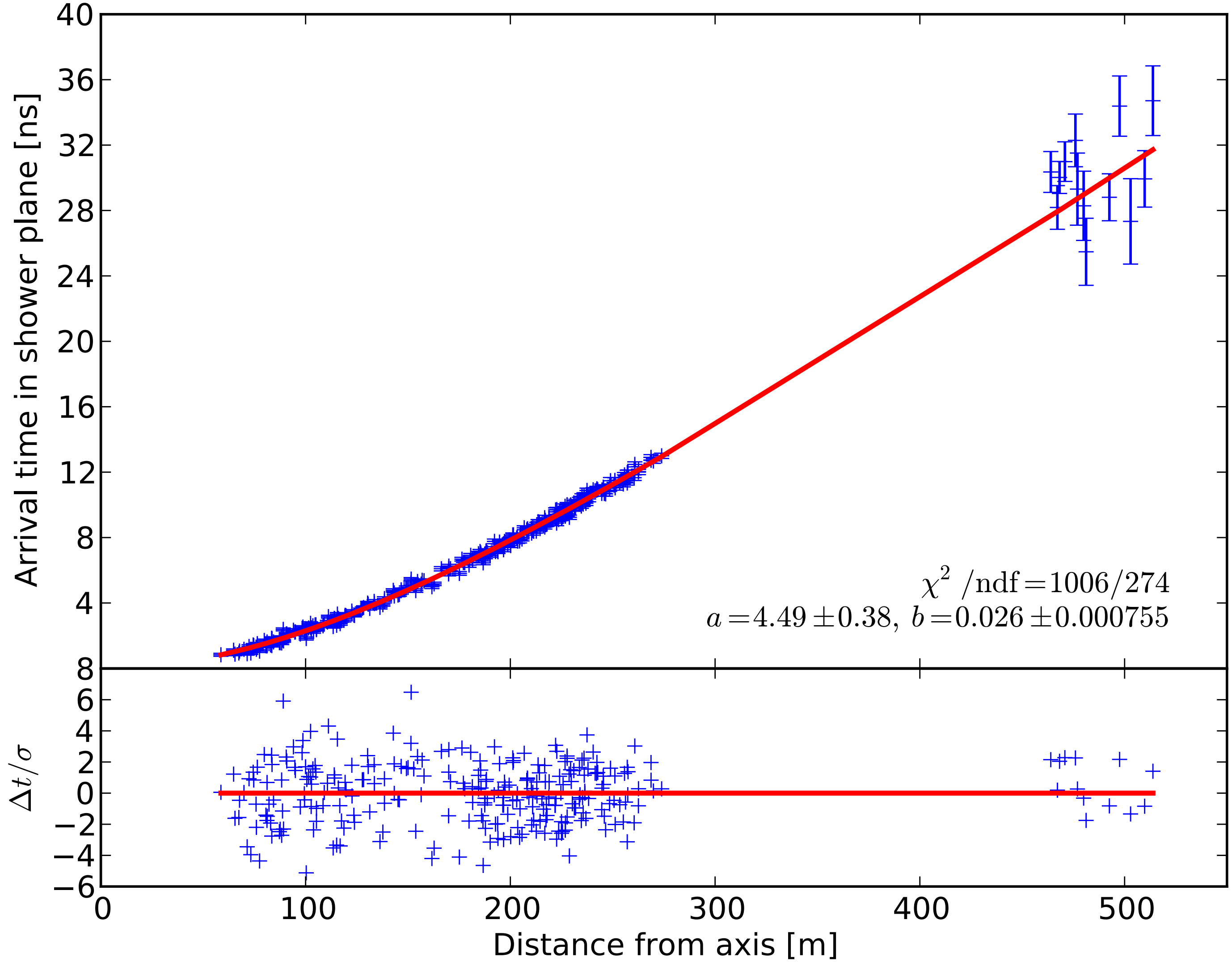
- Project antennas into shower plane
  - Shower axis position: fixed using power-LDF (parametrization by Nelles et al., 2014)
  - Shower axis direction unknown to desired accuracy: **free fit parameters**

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

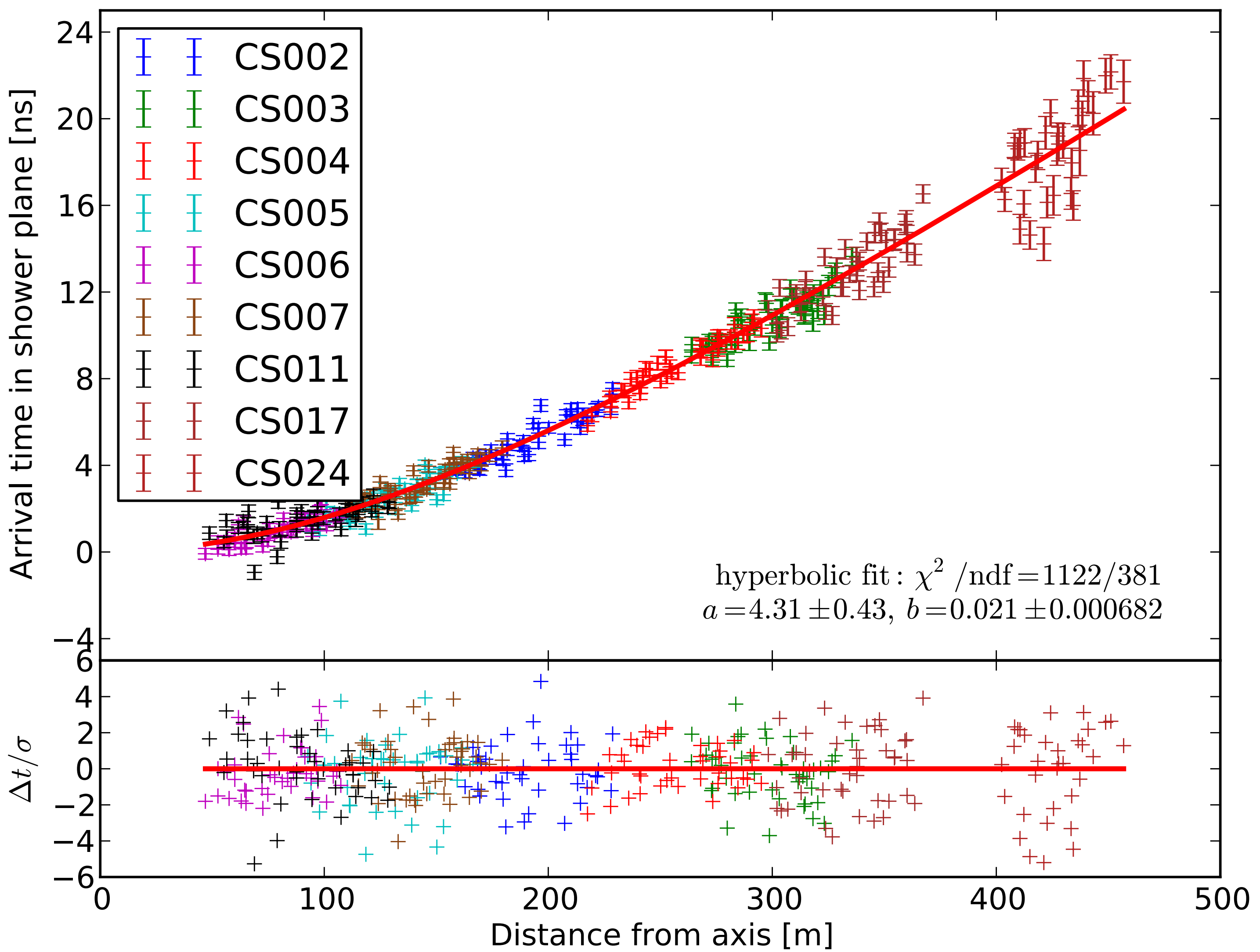
- Nested fitting (**5** parameters):
  - Optimize shower axis **direction** (2)
    - Optimize **curve-fit** (3)

Best-fitting hyperbolic shape

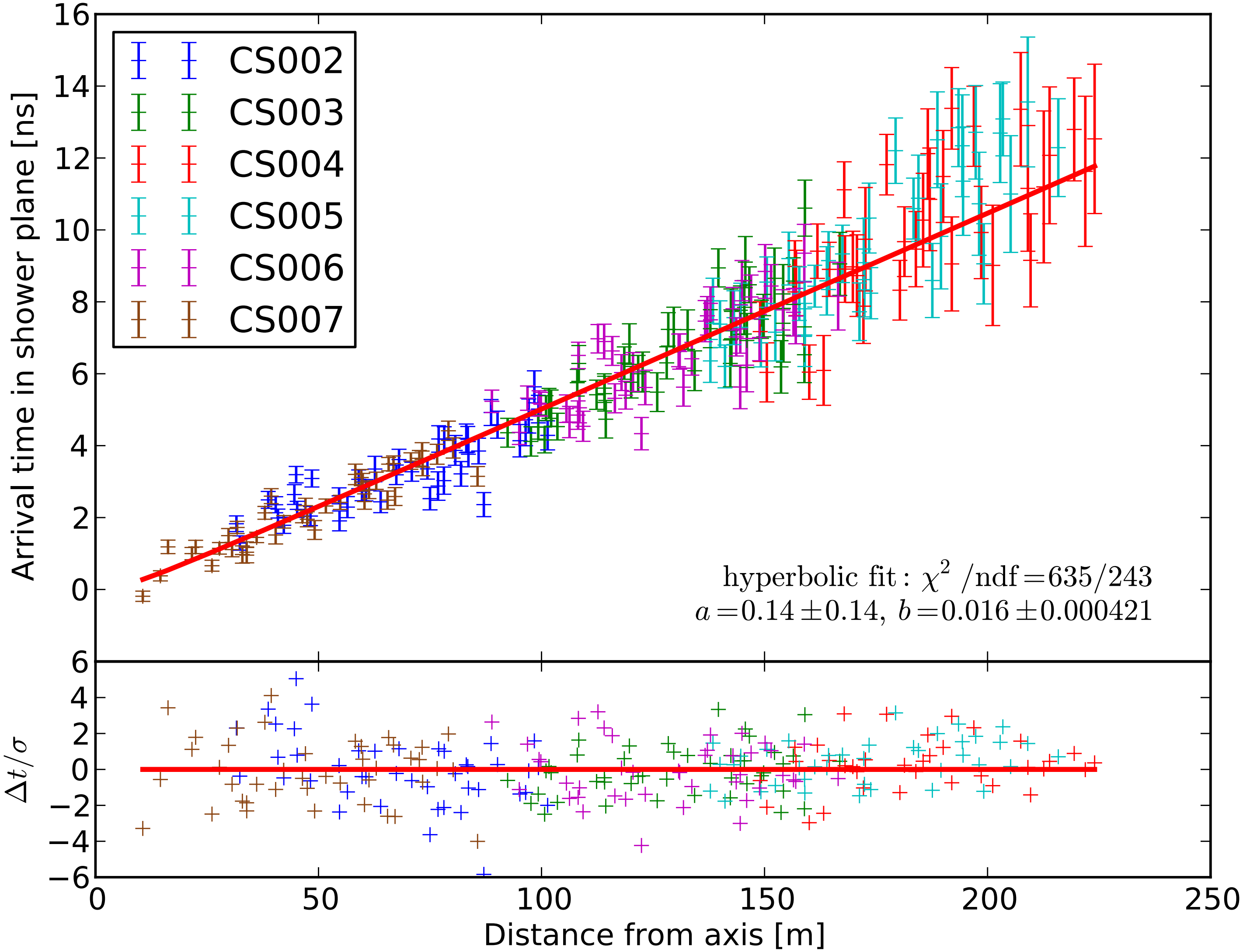
Corstanje et al., Astropart. Phys. (2015)



Another example



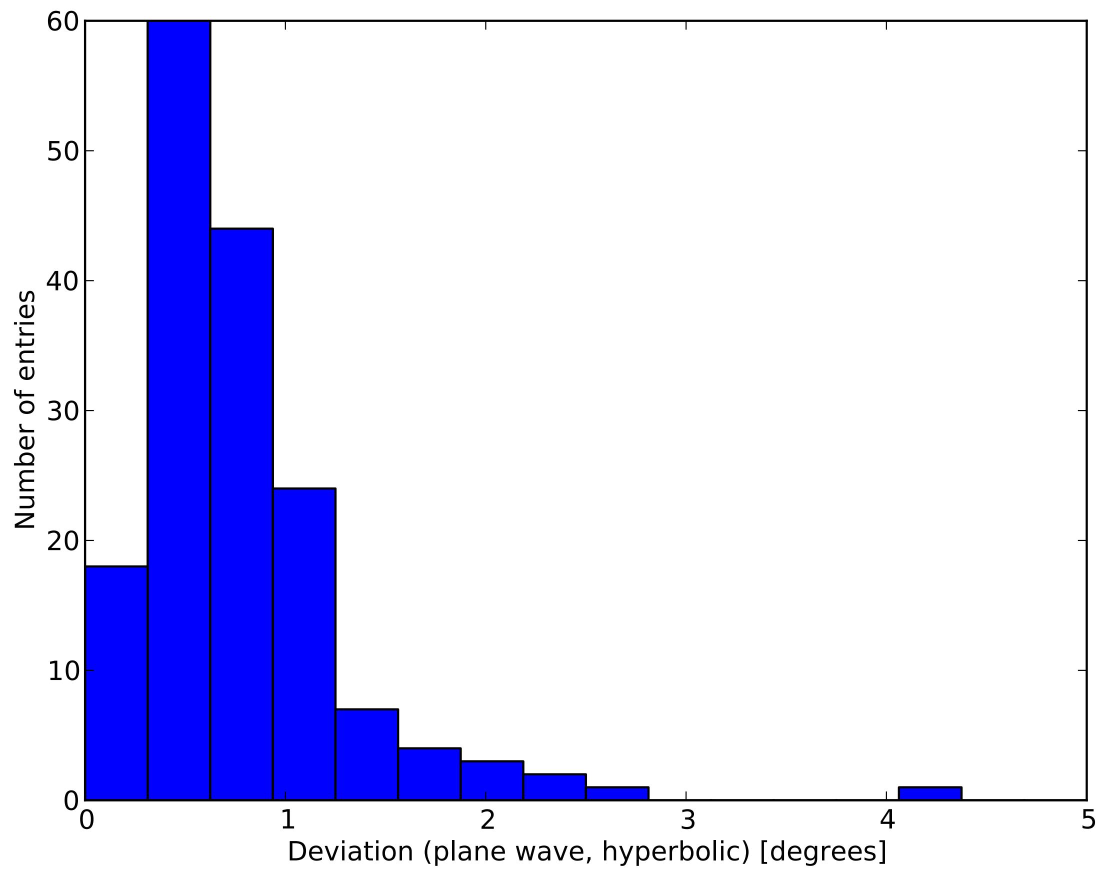
Conical-shaped example



Improved angular resolution

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

Corstanje et al., Astropart. Phys. (2015)



Comparing with simulations

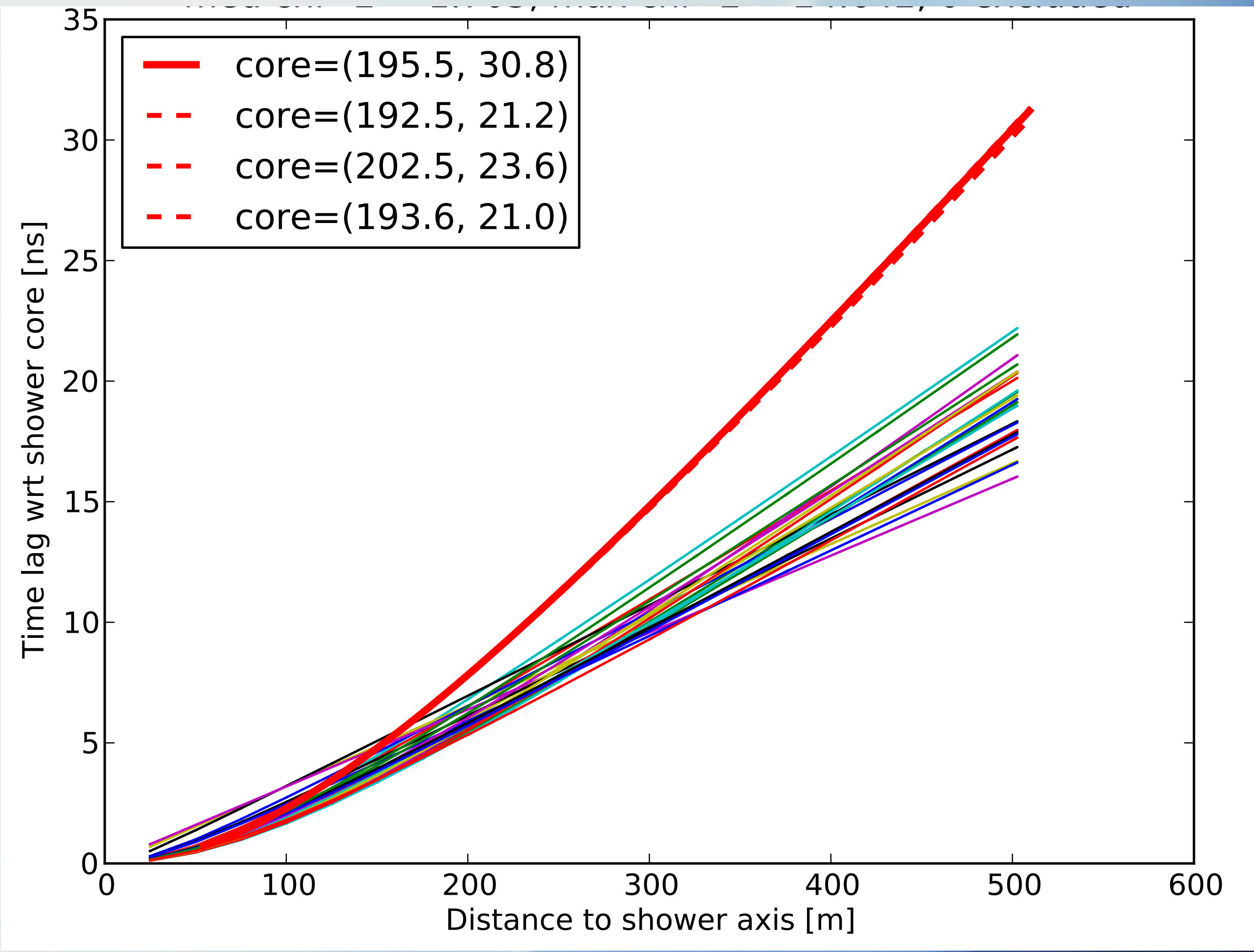
- Monte Carlo simulations of particles and radio emission, CoREAS.
- 25 proton showers, 15 iron showers
- Do pulse timing in the same way, in a

  30 - 80 MHz bandpass window
- Look at wavefronts, processed from pulse times with the same code

Proton simulations vs LOFAR data

Measured wavefront is steeper than any of the simulations!

Uncertainty from core position is negligible



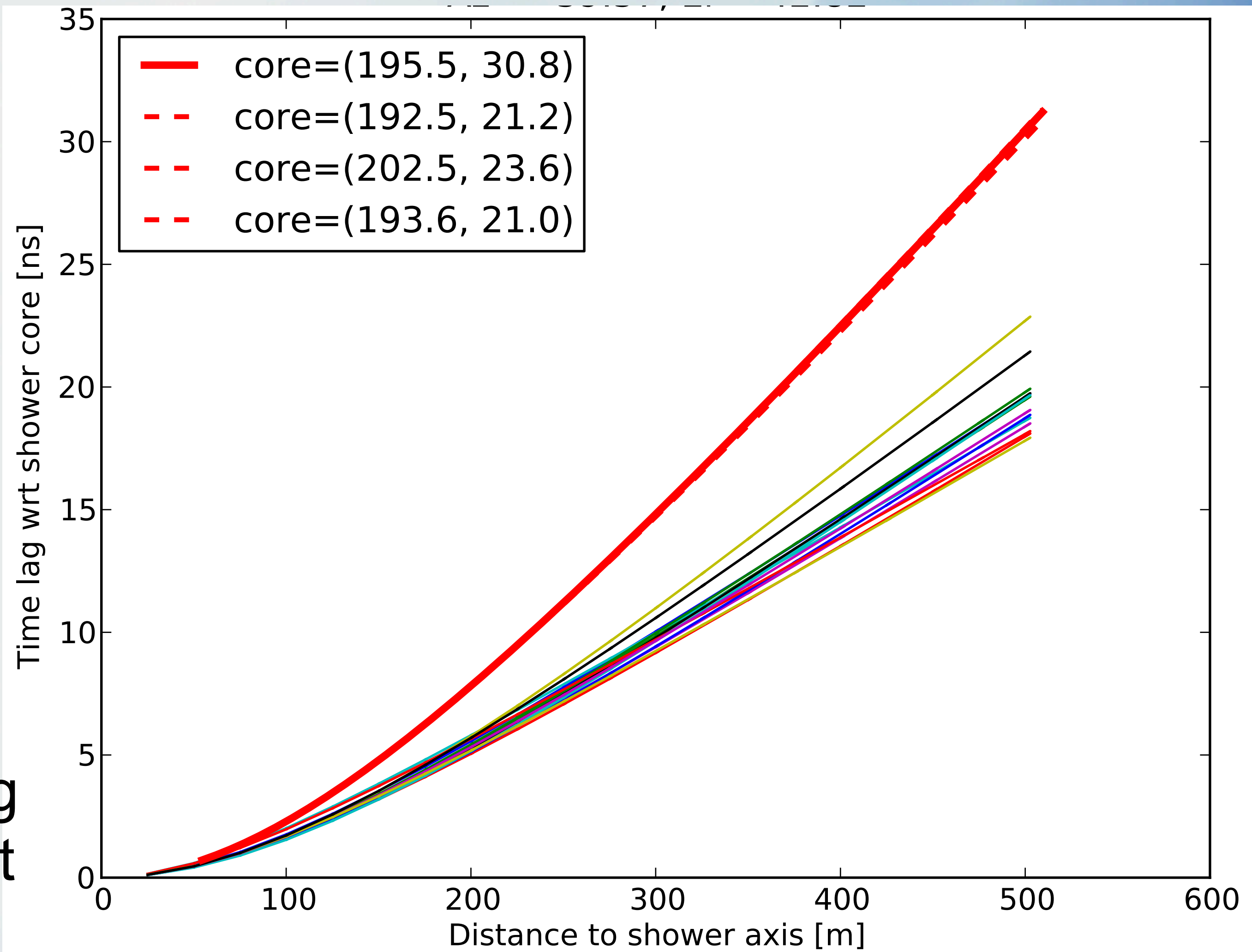
Iron simulations vs LOFAR data

Same deviation

Cause?
Antenna or filter characteristics?

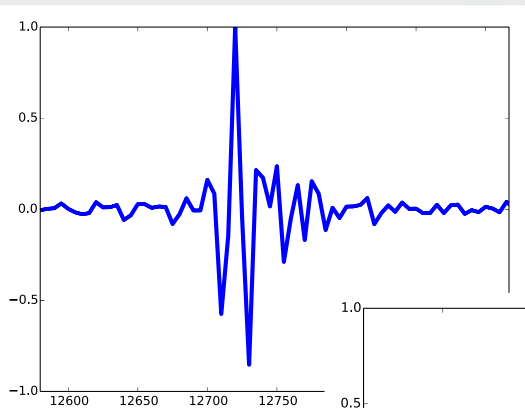
Or gap in understanding radio emission?

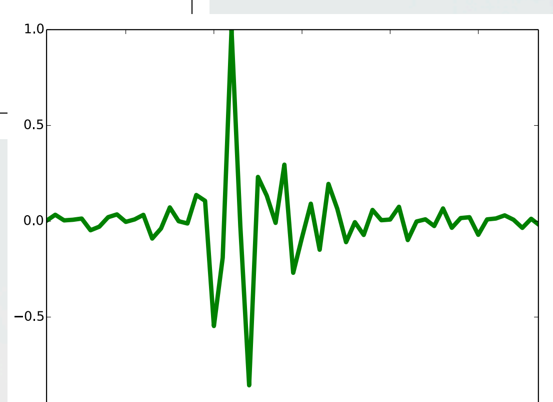
→ Alternative timing method cancels out dispersion

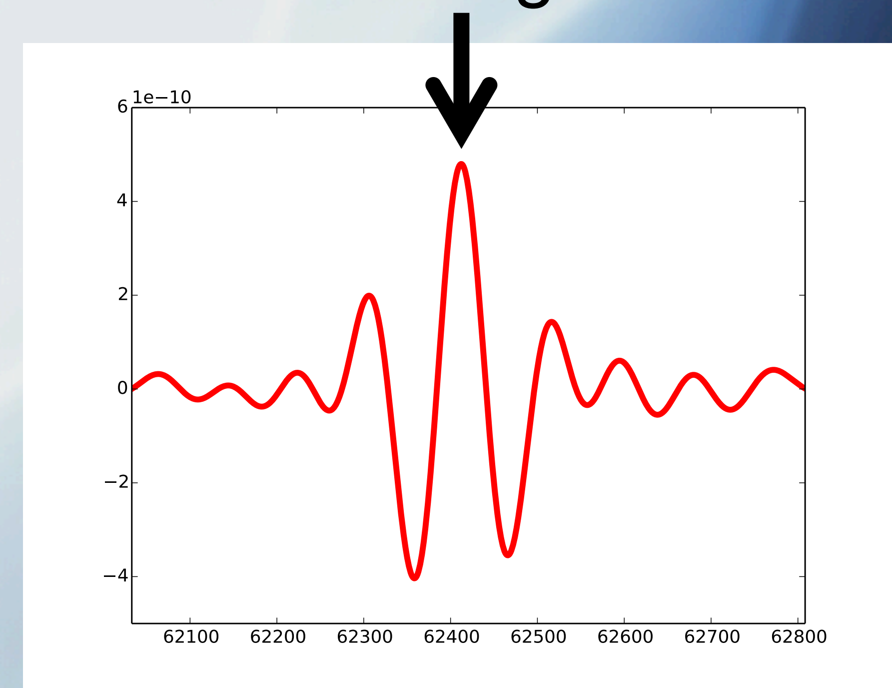


Cross-correlation timing

- Alternative way of measuring pulse times
- For antenna “1” and “2”, take FFT of time series to obtain complex spectra X_1 and X_2
- Crosscorrelation is then: $\mathrm{IFFT}(X_1 X_2^*)$
- Positive maximum defines relative timing



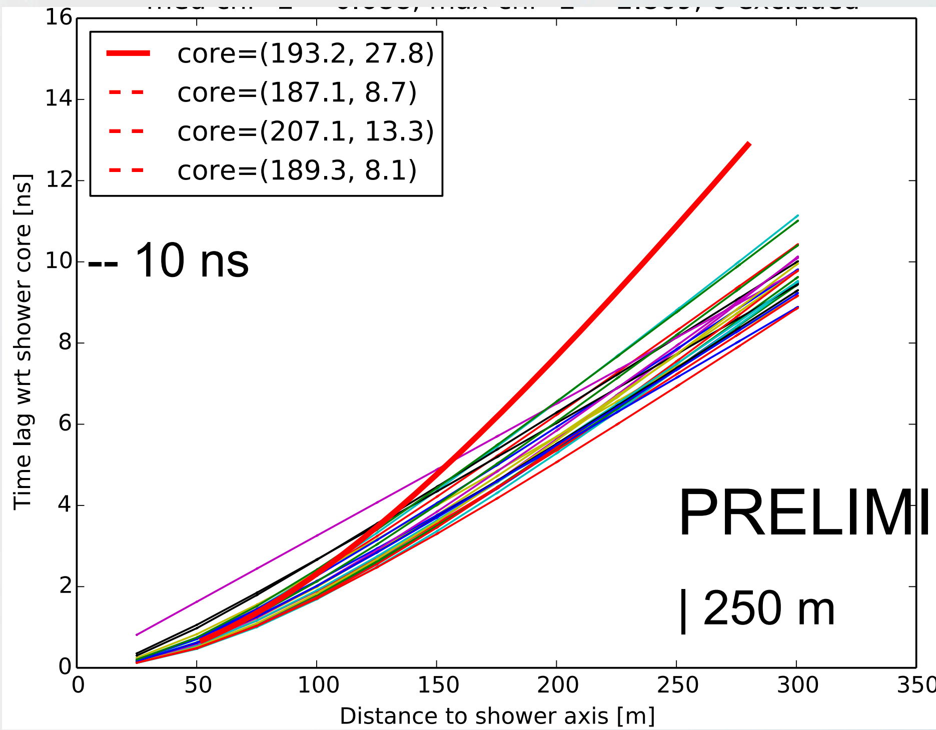




Comparing timing methods

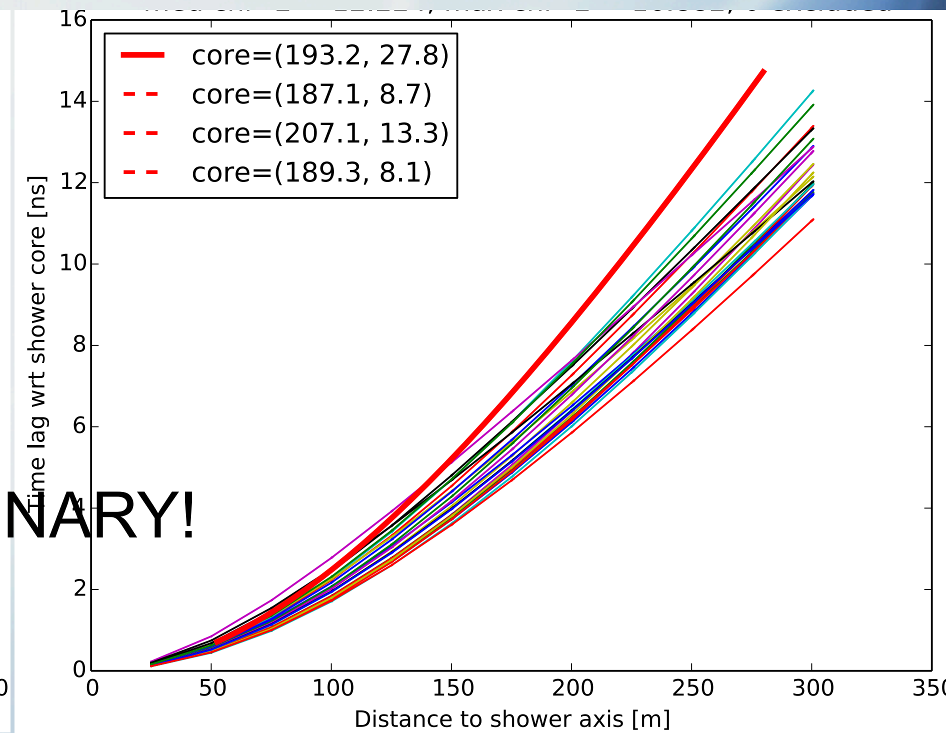
- Wavefronts steeper with cross-correlation timing
- Both measured and simulated wavefronts

Hilbert envelope timing



PRELIMINARY!

Cross-correlation timing

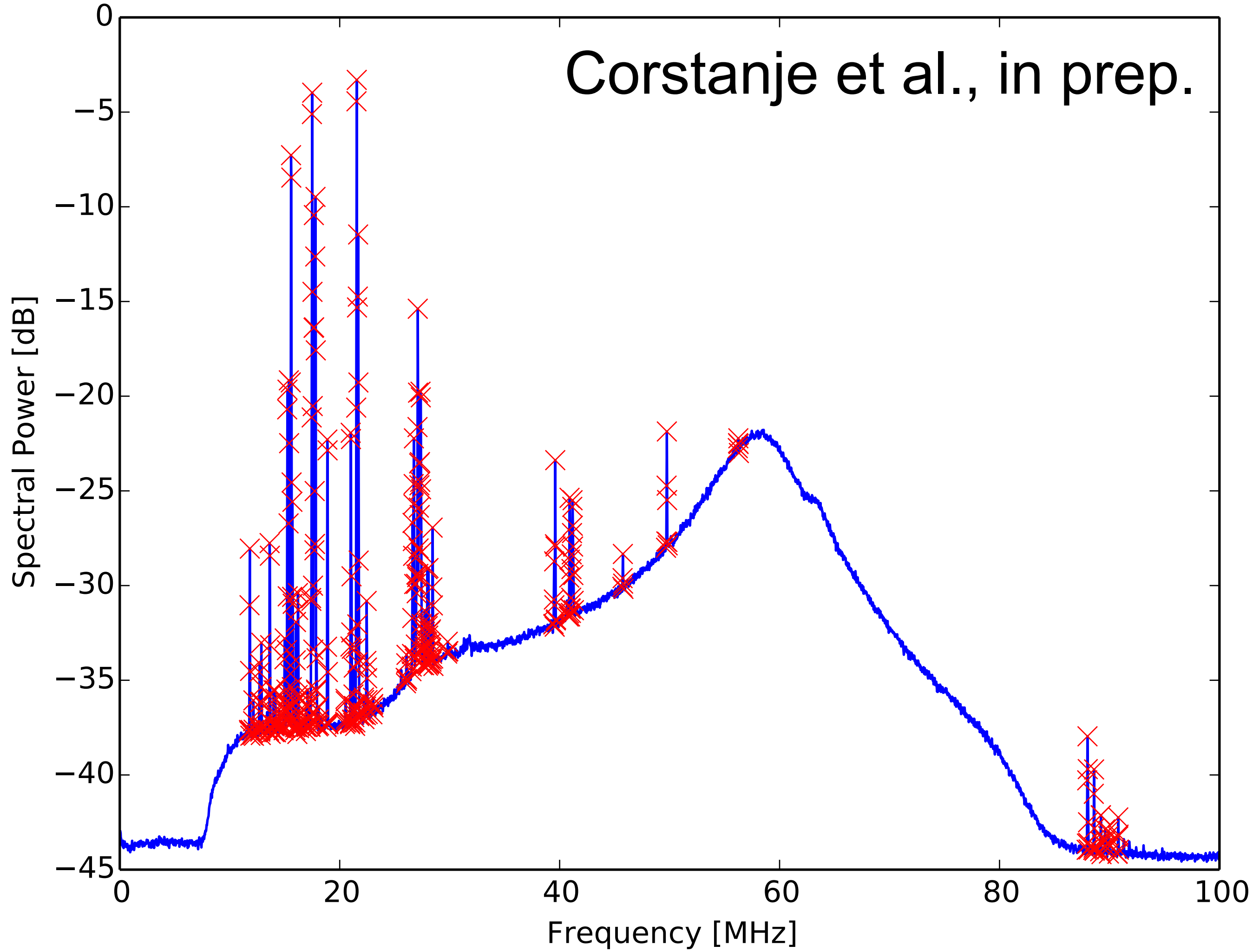


Timing calibration using radio transmitter phases

- Use phases of narrowband radio signals from a known transmitter (Smilde)
- Relative phases per baseline from FFT of time series
- average over ~ 50 blocks of 8000 samples (2 ms!)
- Compare measured phases with calculated phases from source position
- Use GPS location converted to ITRF

- Gives calibration delays per antenna pair, modulo ~ 11 ns for each frequency

LOFAR LBA spectrum



Calibration timing signal per antenna (one polarization)

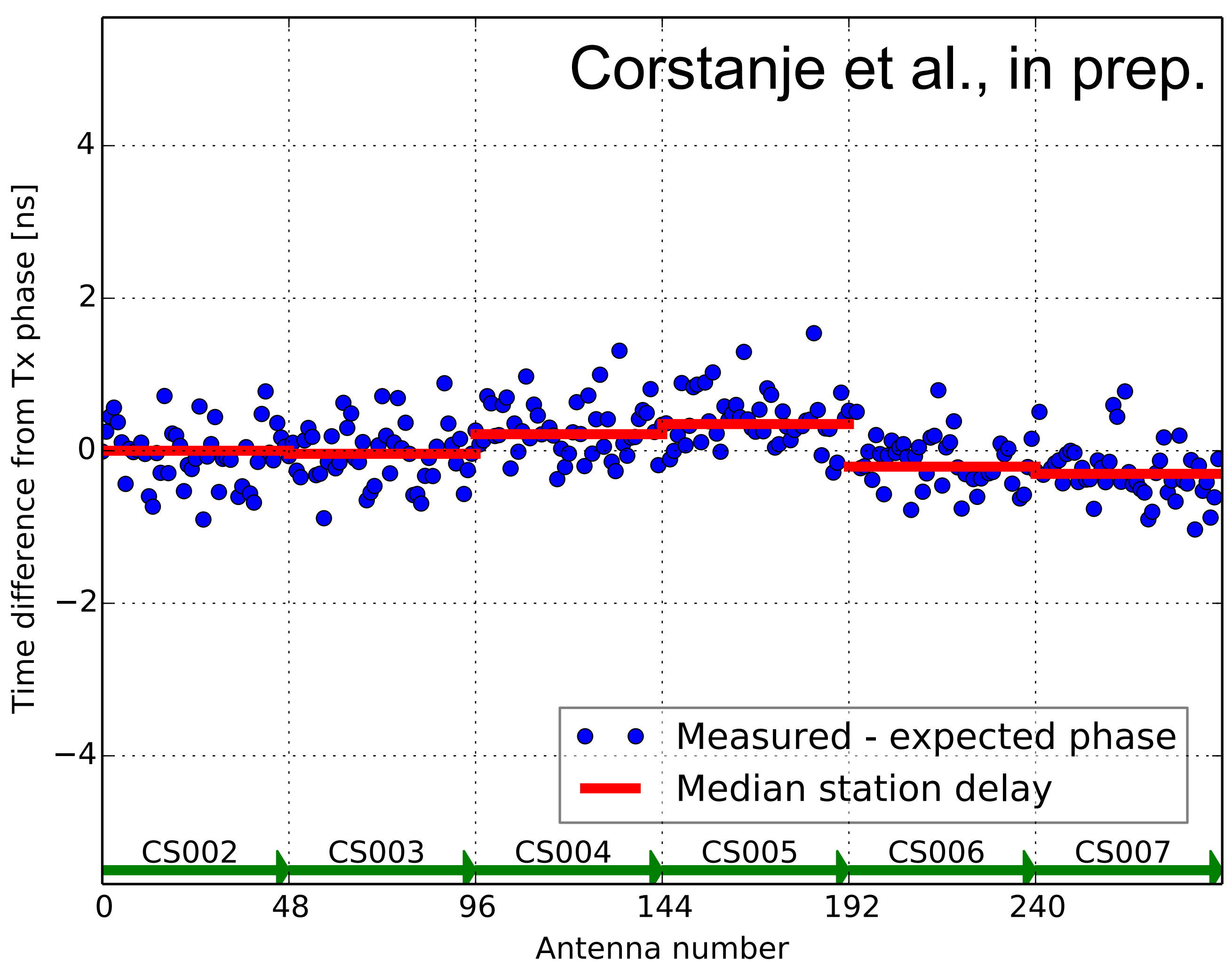
Stable calibration

Small diff wrt Caltables

Sigma ~ 0.4 ns (per station)

- Includes all systematics!

Median gives inter-station clock offset



Differential measurements

- − Measuring at the edge of the band (filter) and a signal coming from the horizon
- − Signal propagation effects not completely known

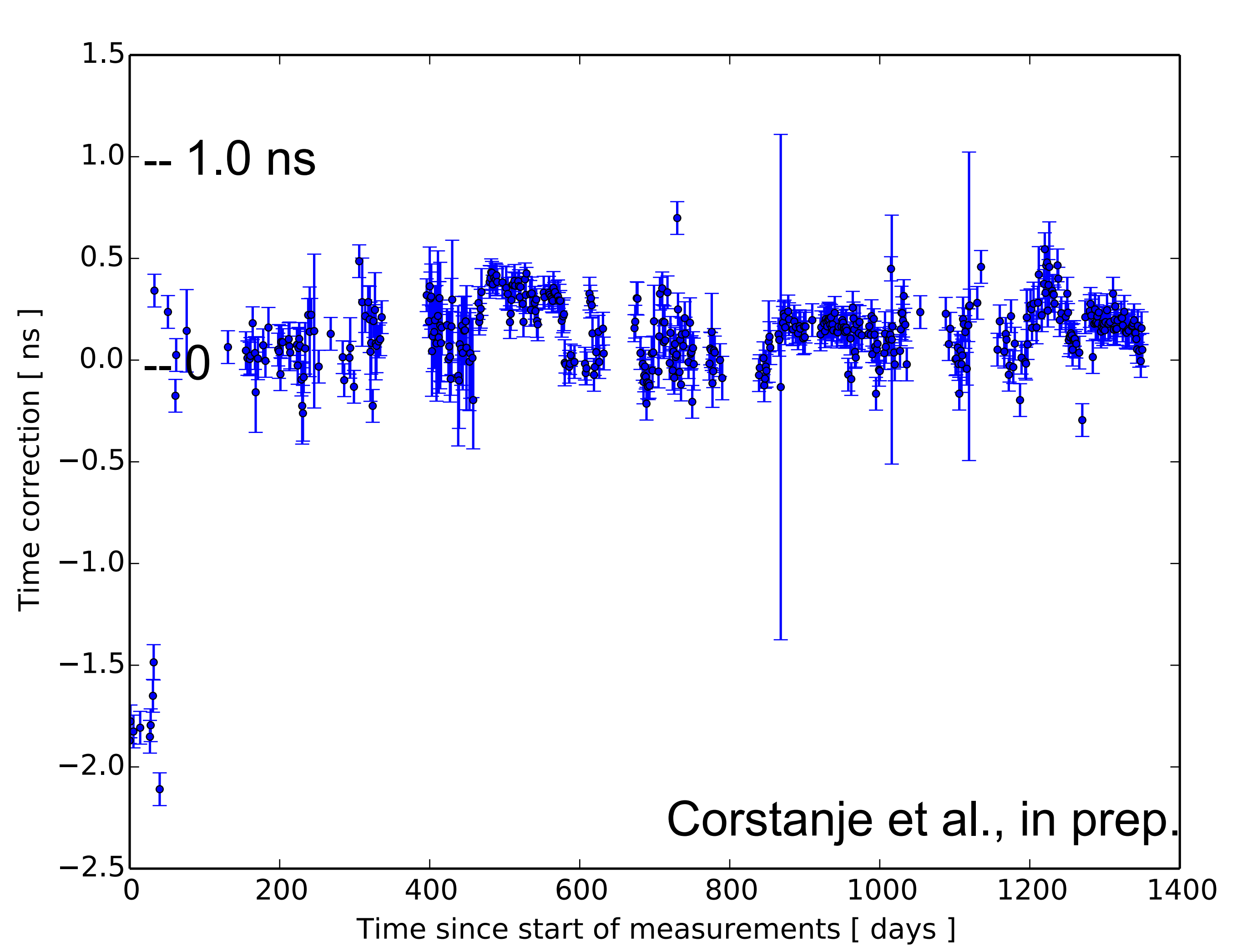
- + Phase difference between channels takes out the common filter characteristic at this frequency
- + Given a starting (cross)calibration, e.g. astronomical: can take difference between observations to observe trends, drifting, glitches etc.

Calibration timing offsets per antenna: variations over time

Mostly stable calibration

Timing variations up to +/- 0.3 ns

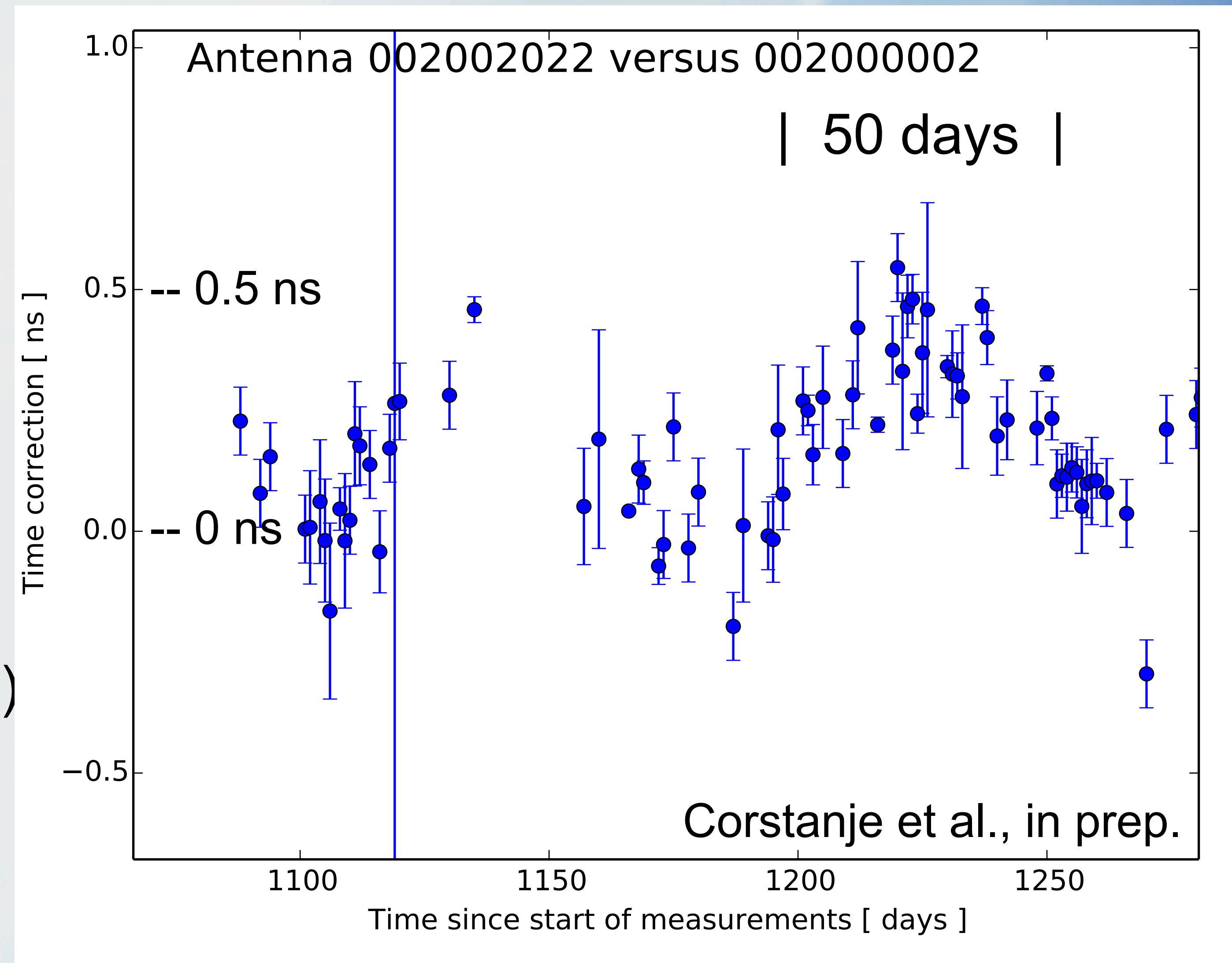
Sigma ~ 0.08 ns in a 24-hr bin (>= 5 data points)



Calibration timing signal per antenna: variations over time

Slow drifting,
About 0.6 ns
peak-peak

Sigma ~ 0.08 ns
in a 24-hr bin
(>= 5 data points)

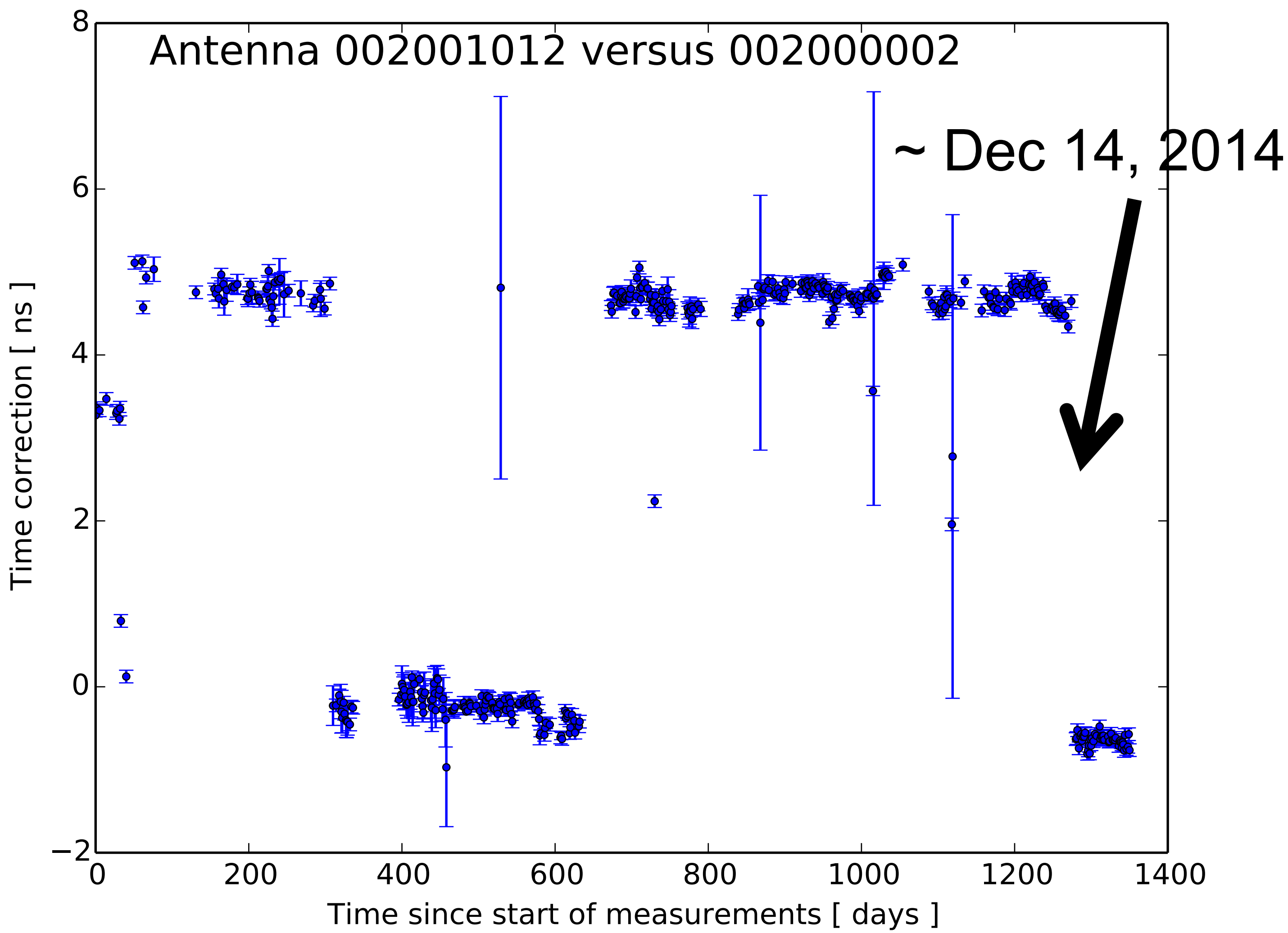


Conclusions and outlook

- Wavefront timing measured with accuracy better than 1 ns per antenna for strong showers
- A hyperboloid fits best; no structure in residuals
- Simulation comparison shows that measured wavefronts are steeper, cause unknown
- Cross-correlation timing: mismatch still there, but rules out phase component of filters (dispersion)

- Timing calibration using FM radio works well, sigma ~ 0.4 ns per antenna, ~ 0.1 ns inter-station
- Only 2 ms of data, piggybacked, a few minutes end-to-end, radio signal always present
- Monitoring clock drifts with sigma ~ 0.08 ns

5 ns glitch…


Antenna 002001012 versus 002000002
~ Dec 14, 2014
Time correction [ns]
Time since start of measurements [days]
8
6
4
2
0
−2
0
200
400
600
800
1000
1200
1400