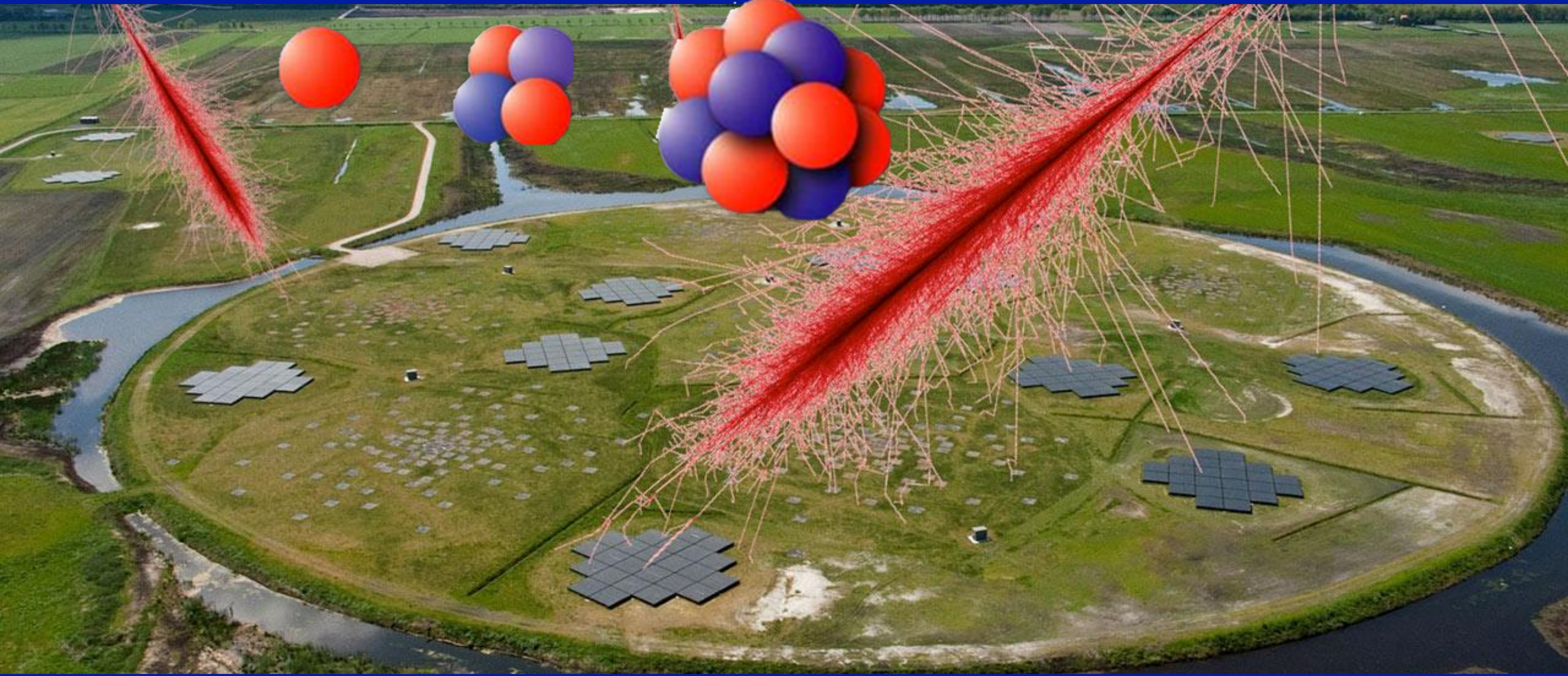
Improving the accuracy of cosmic-ray composition measurements with LOFAR



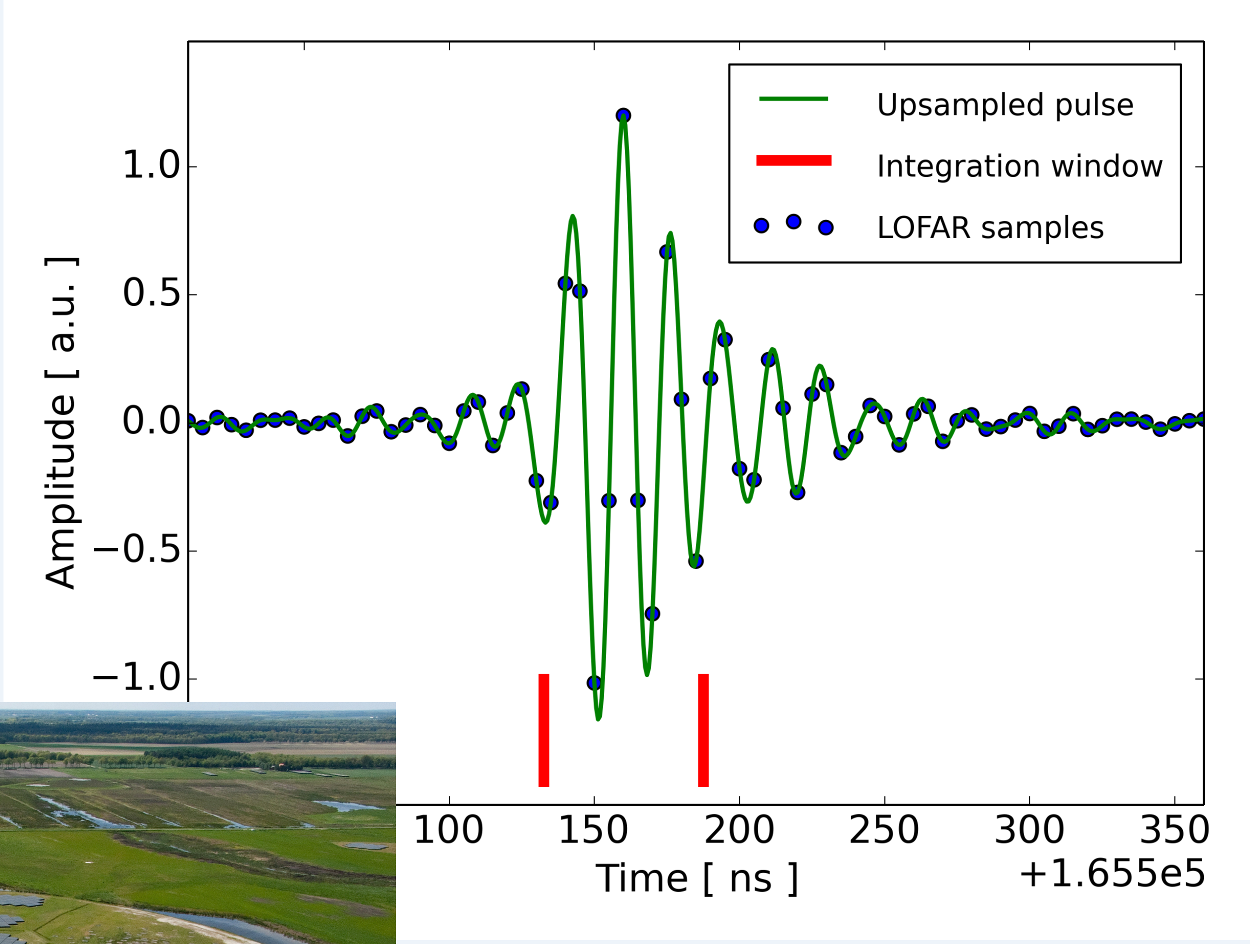
Arthur Corstanje, Radboud University Nijmegen
for the LOFAR Cosmic Rays Key science project

The Broad Impact of Low Frequency Observing, June 23, 2017

Measuring pulses at LOFAR

Measure pulse intensity in every LBA antenna

30-80 MHz bandpass filter

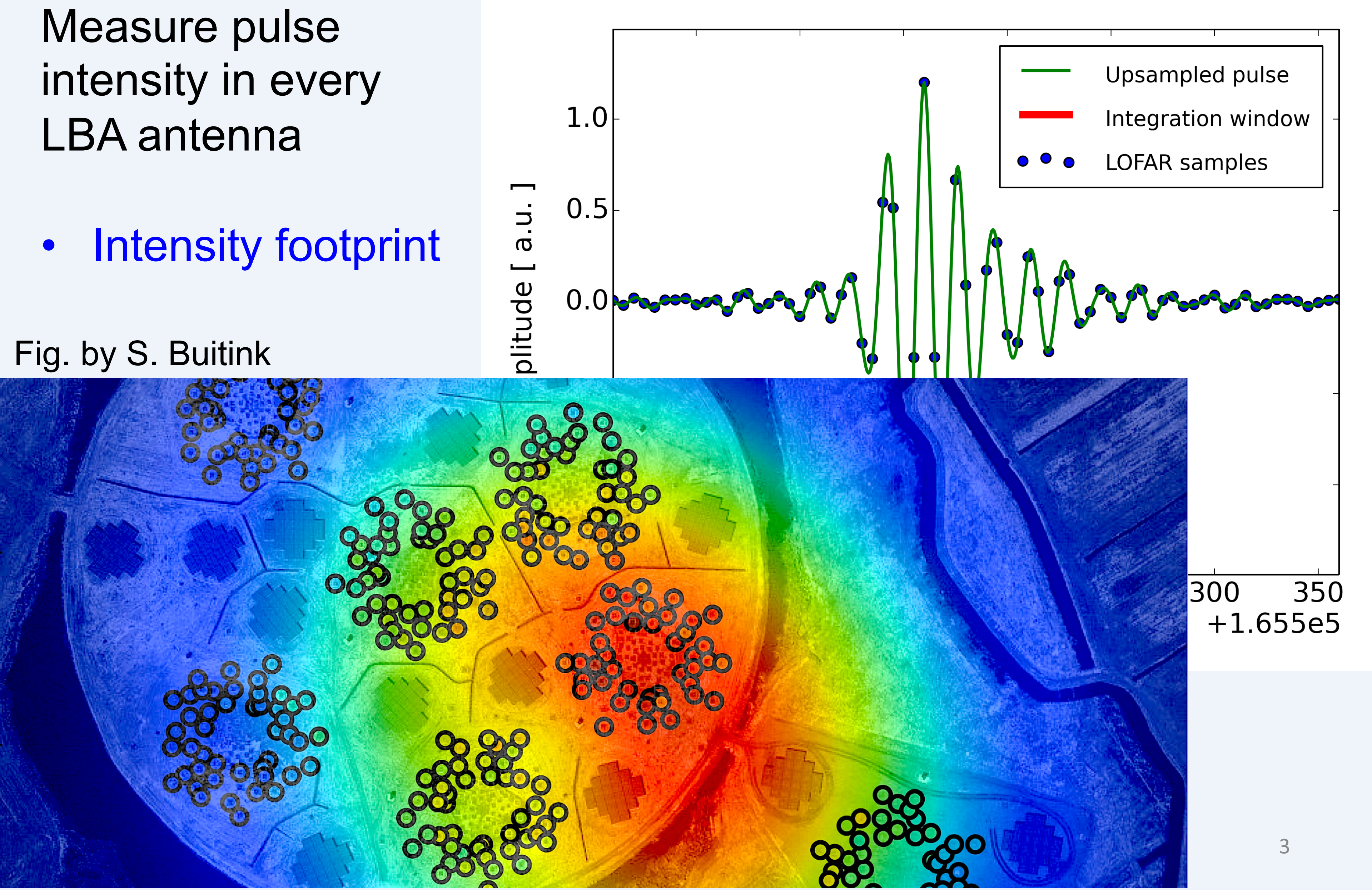


Measuring pulses at LOFAR

Measure pulse intensity in every LBA antenna

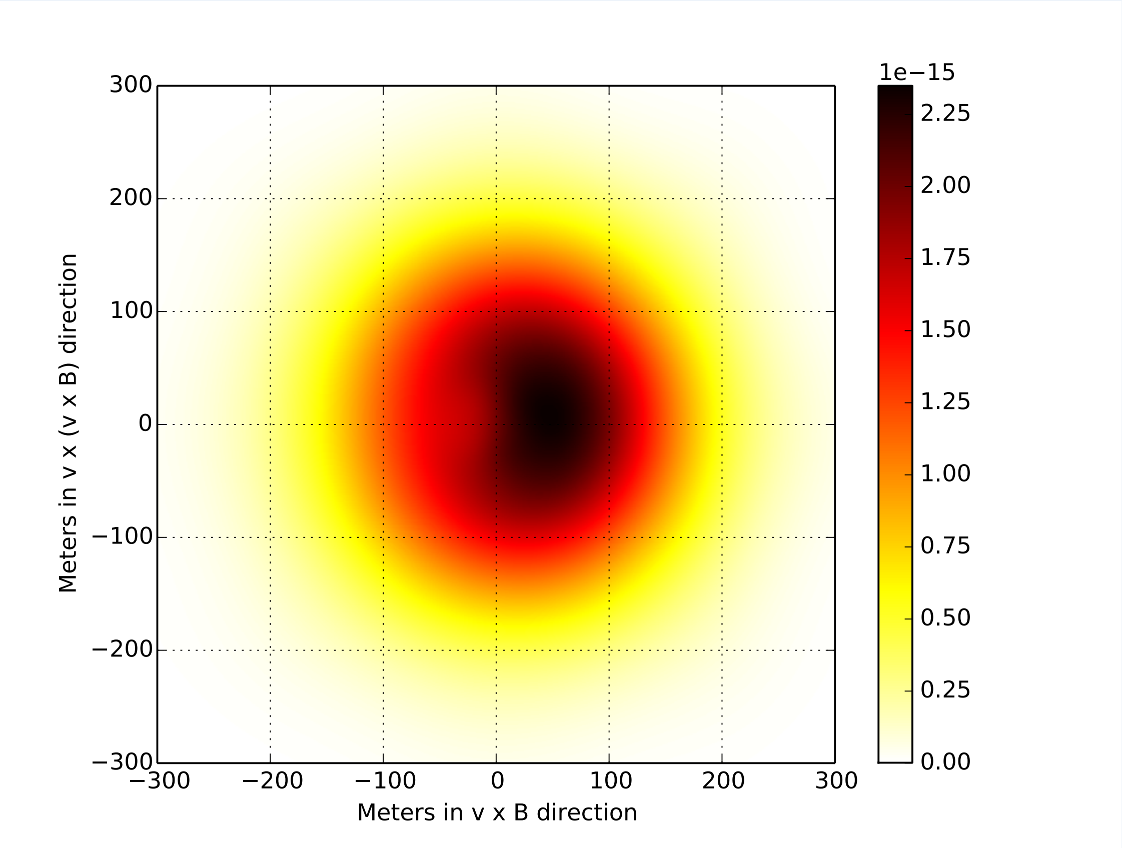
- Intensity footprint

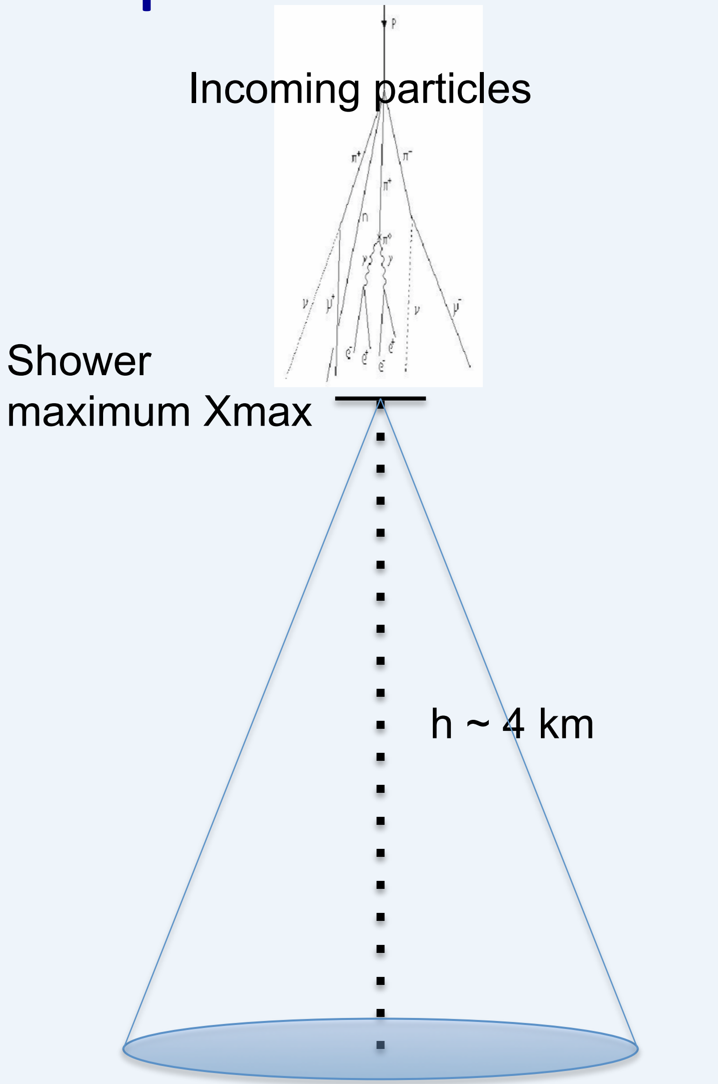
Fig. by S. Buitink



Simulating intensity footprints (CoREAS)

Xmax = 630 g/cm^2

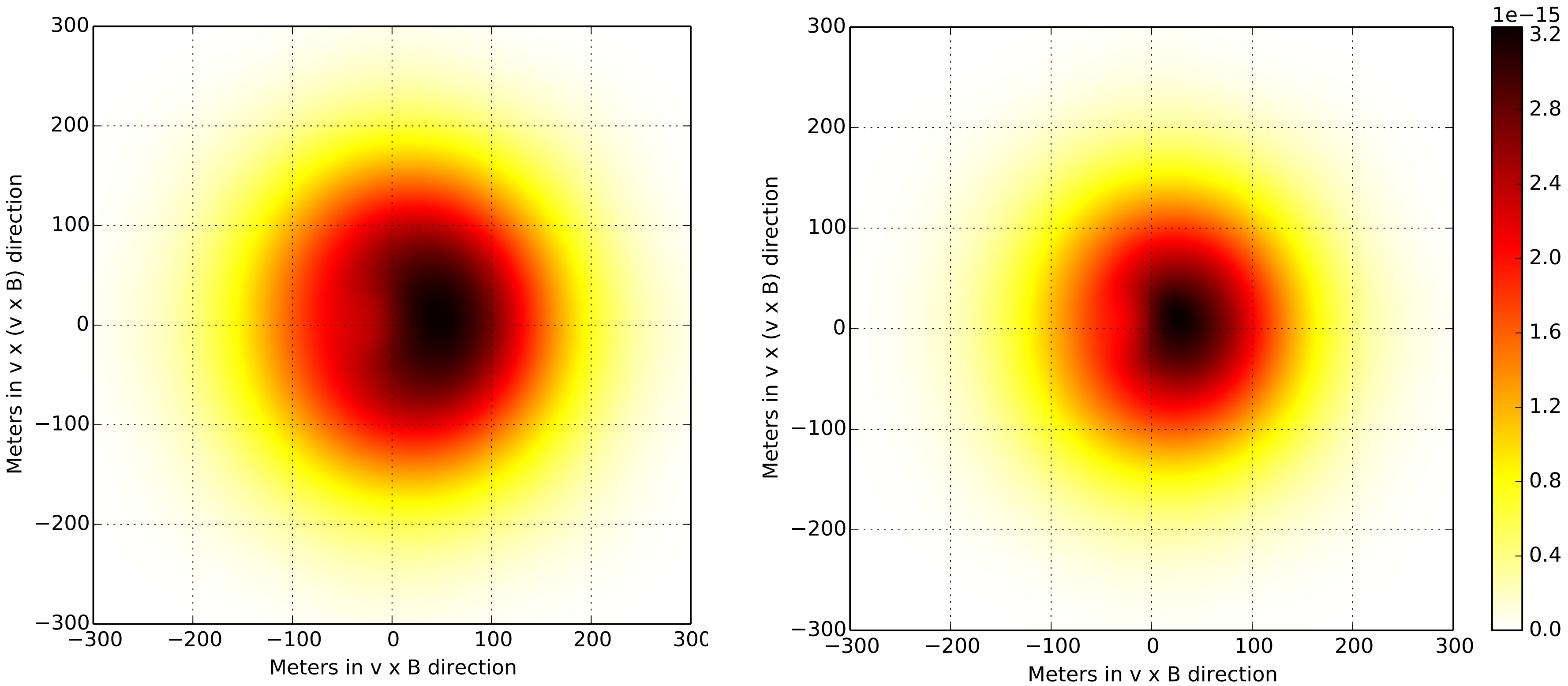




CoREAS simulated footprints: not circular symmetric

Footprint at low frequencies, 30 – 80 MHz

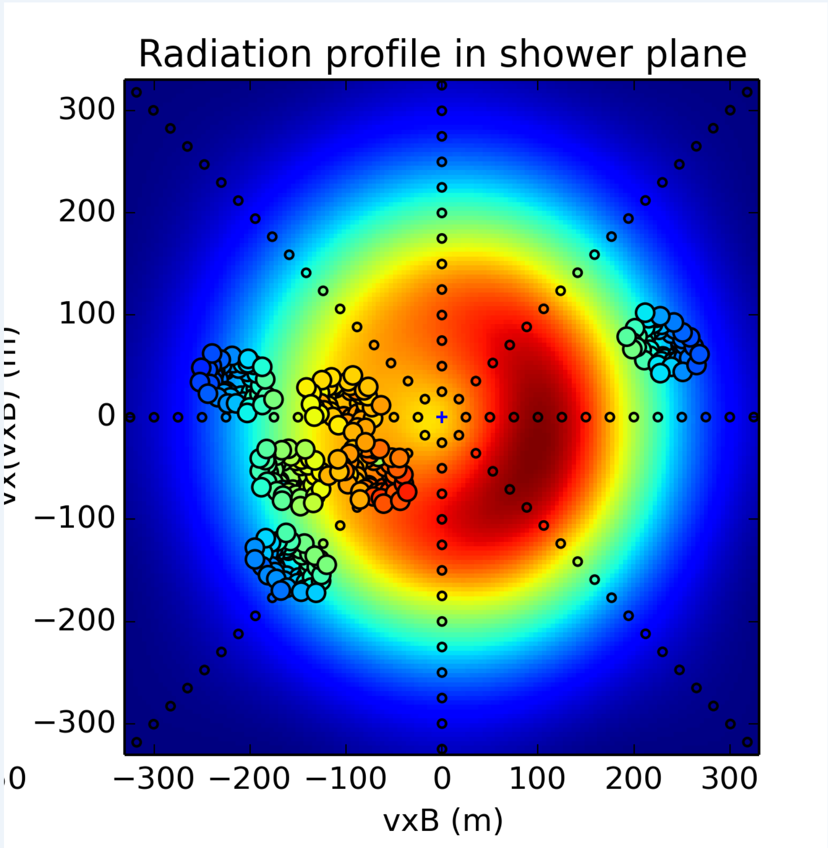
Xmax = 630 g/cm^2 Xmax = 700 g/cm^2



Smaller footprint when Xmax is closer to the ground although not a pure scaling

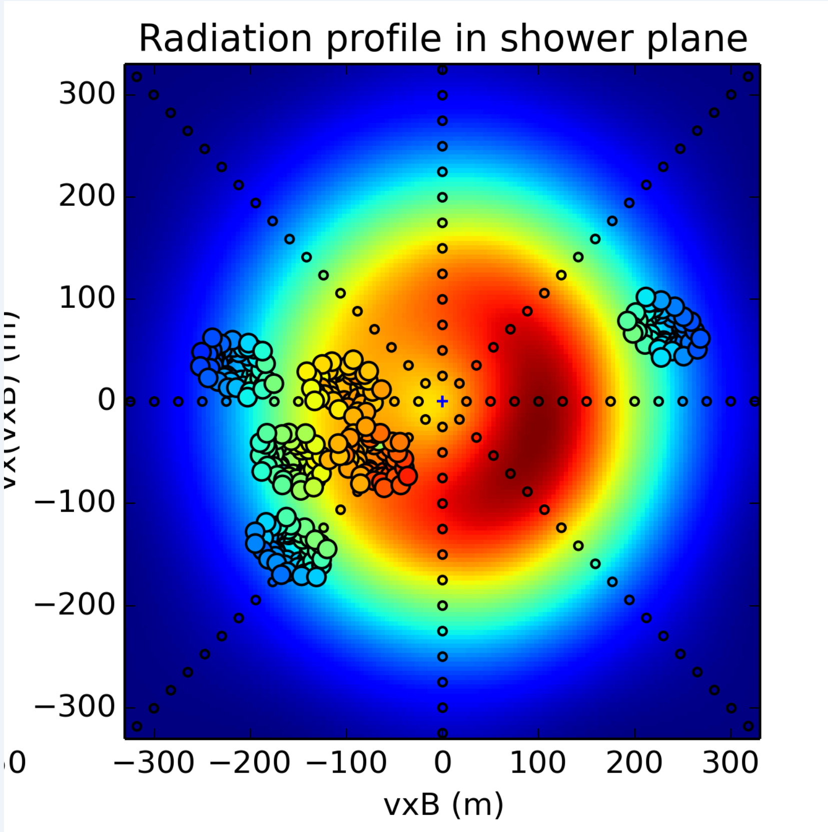
Matching simulated footprints to LOFAR data

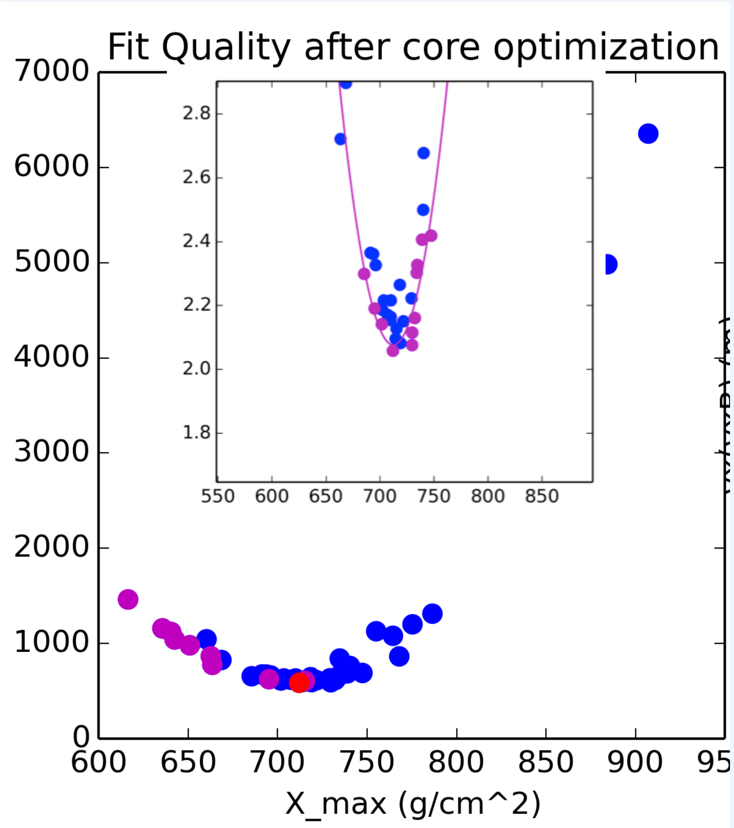
- Simulate 40 showers: 25 proton, 15 iron
- Core position and intensity scaling factor as free parameters
- Also fitting simulated particles to particle measurements



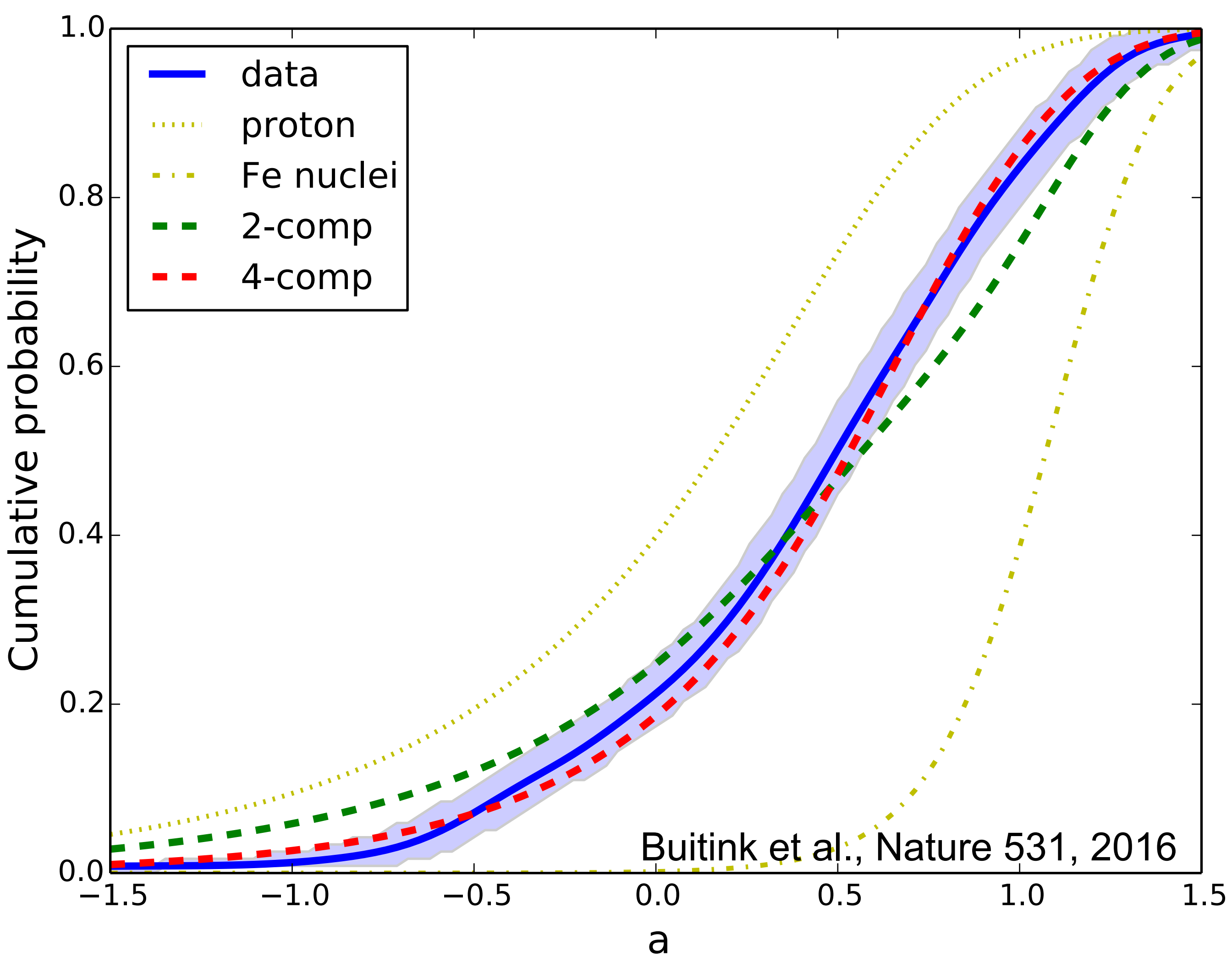
Matching simulated footprints to LOFAR data

- Simulate 40 showers: 25 proton, 15 iron
- Chi-squared as function of simulated Xmax: optimum
- State-of-the-art resolution of < 20 g/cm^2





Cumulative distribution of Xmax at LOFAR: Cosmic-ray composition fit > 10^{17} eV, 114 showers



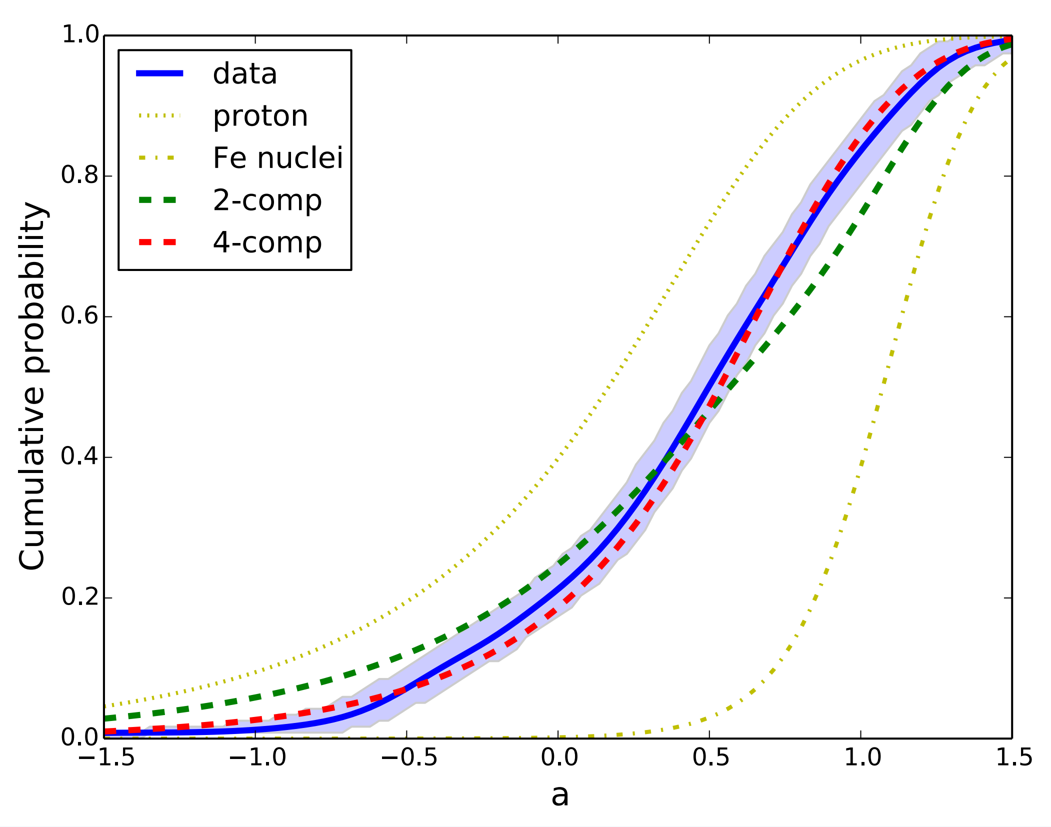
Parameter a:
a=0 is average Xmax for protons

a=1 is average Xmax for iron

Light elements:
p+He fraction > 40%
(99 % confidence)
But can be 40-95 %

4-component fit
p, He, C/N/O, Fe

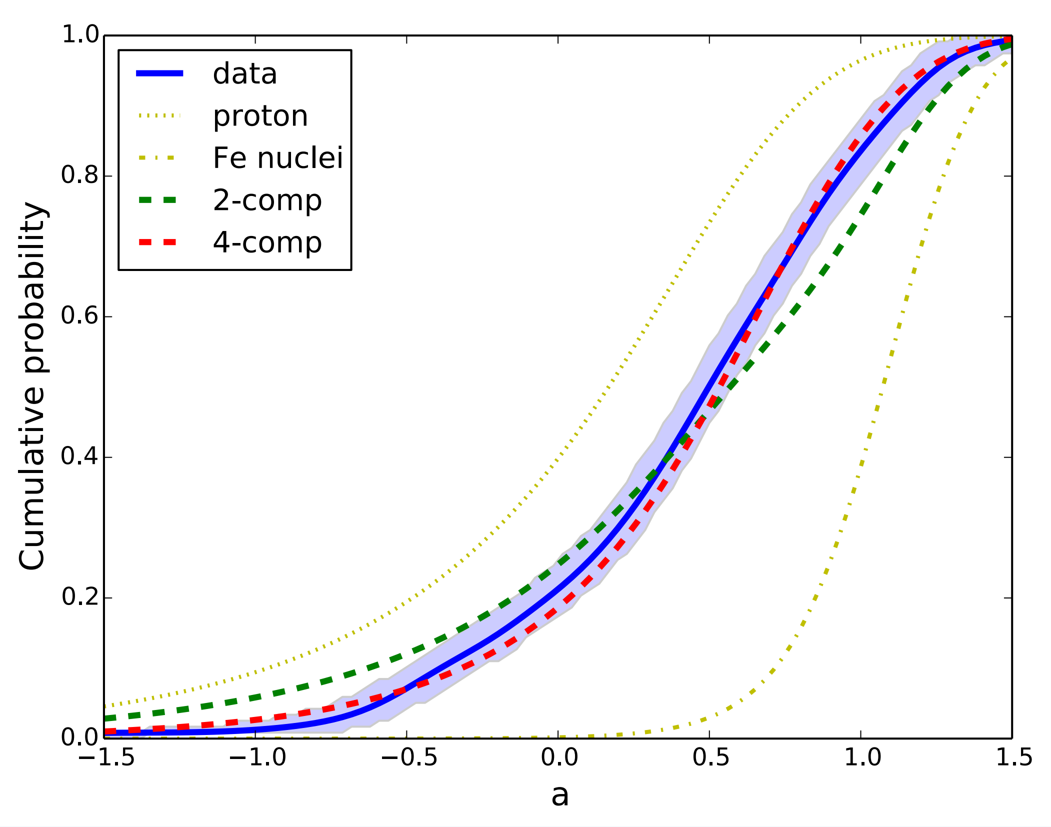
Cumulative distribution of Xmax at LOFAR: Room for further improvement



Buitink et al., Nature 531, 2016

- Better constraints of the light element (p+He) fraction, for stronger tests of CR origin & propagation models
- Cannot resolve protons vs helium yet
- Fit a multi-component mixture with better limits (e.g. rule out iron?)

Cumulative distribution of Xmax at LOFAR: How to improve previous results

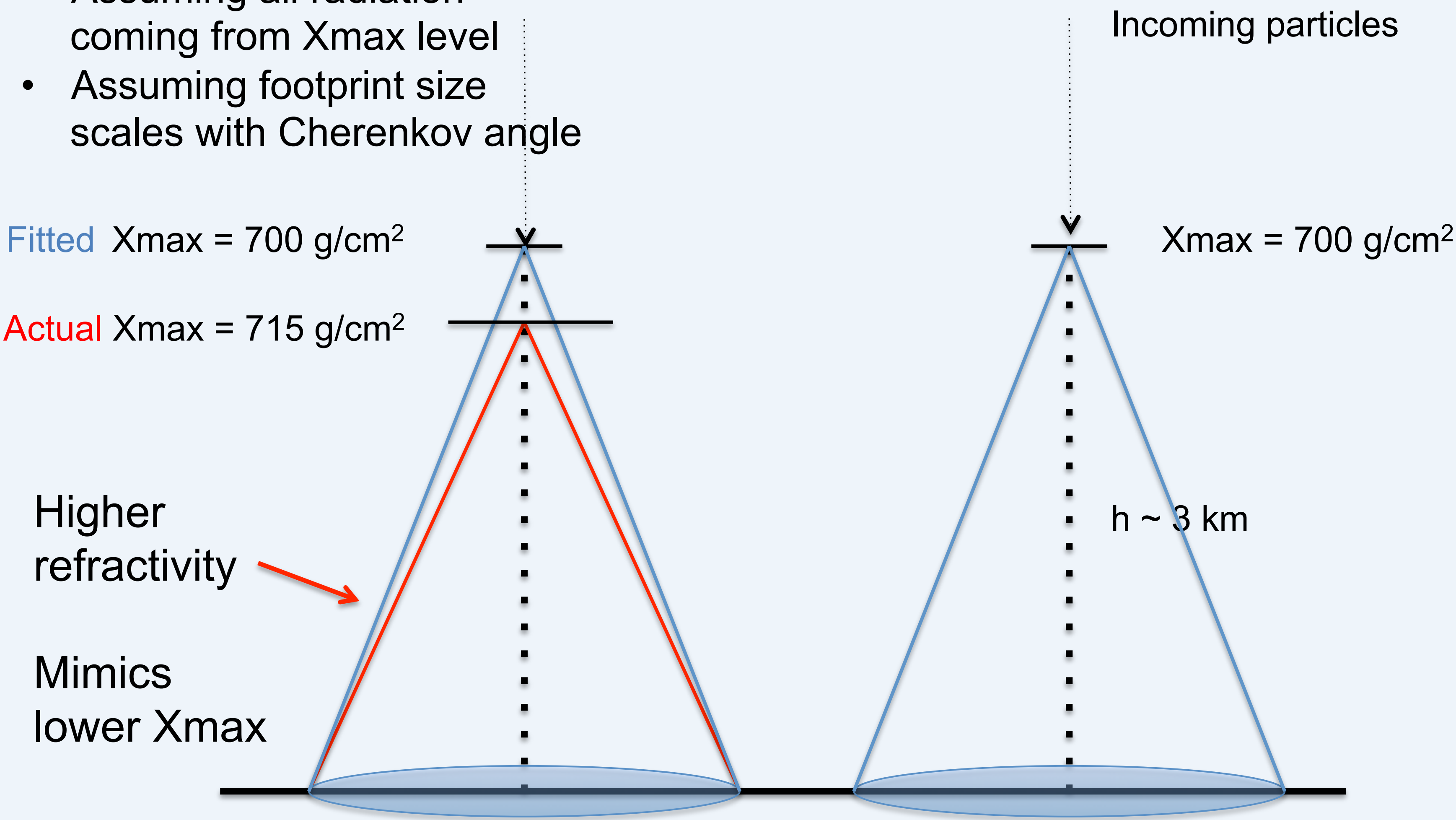


Buitink et al., Nature 531, 2016

- To reduce uncertainty margins (blue shaded area):
  - More measured showers, ~ 300 instead of 114
  - Reduce systematic errors: account for atmospheric variations
- Simulations including local atmosphere profiles will be run over the coming months

The effect of variations in refractive index (simplified)

- Assuming all radiation coming from Xmax level
- Assuming footprint size scales with Cherenkov angle



Simulating the effect of varying refractivity on Xmax measurements

- Use a fitting method as in composition analysis:

Ensemble 1: Normal N

50 simulated showers

Ensemble 2: 10% higher N

50 simulated showers

take one as ‘test shower’

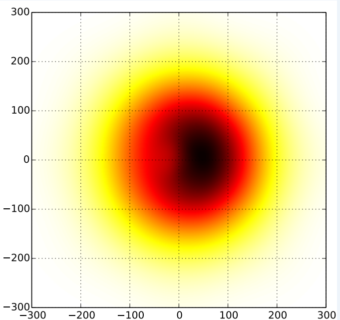
(mock data)

Fit 49 showers to the test shower

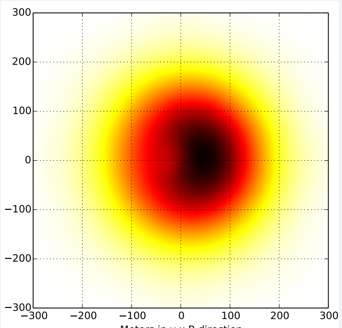
(intensity footprints)

- Make plot of fit quality versus Xmax
- Minimum indicates best-fitting Xmax

Average offset over all ‘test’ showers



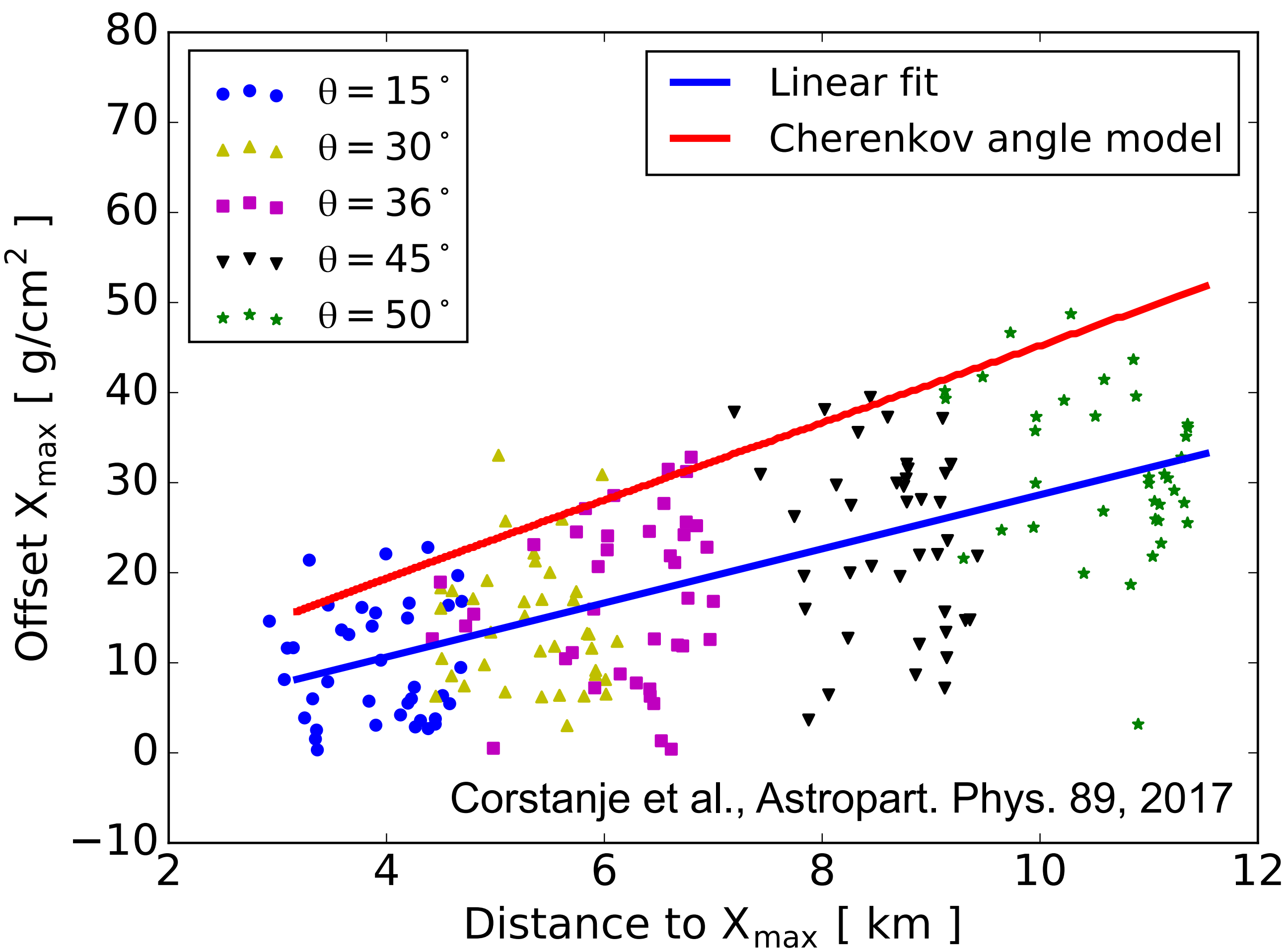
x 50



x 50

Results for 30-80 MHz (LOFAR)

Xmax syst. error for 10 % increase in N



In the atmosphere above LOFAR:
~ 4 % variation realistic

- Syst. uncertainty of 4 to 11 g/cm^2

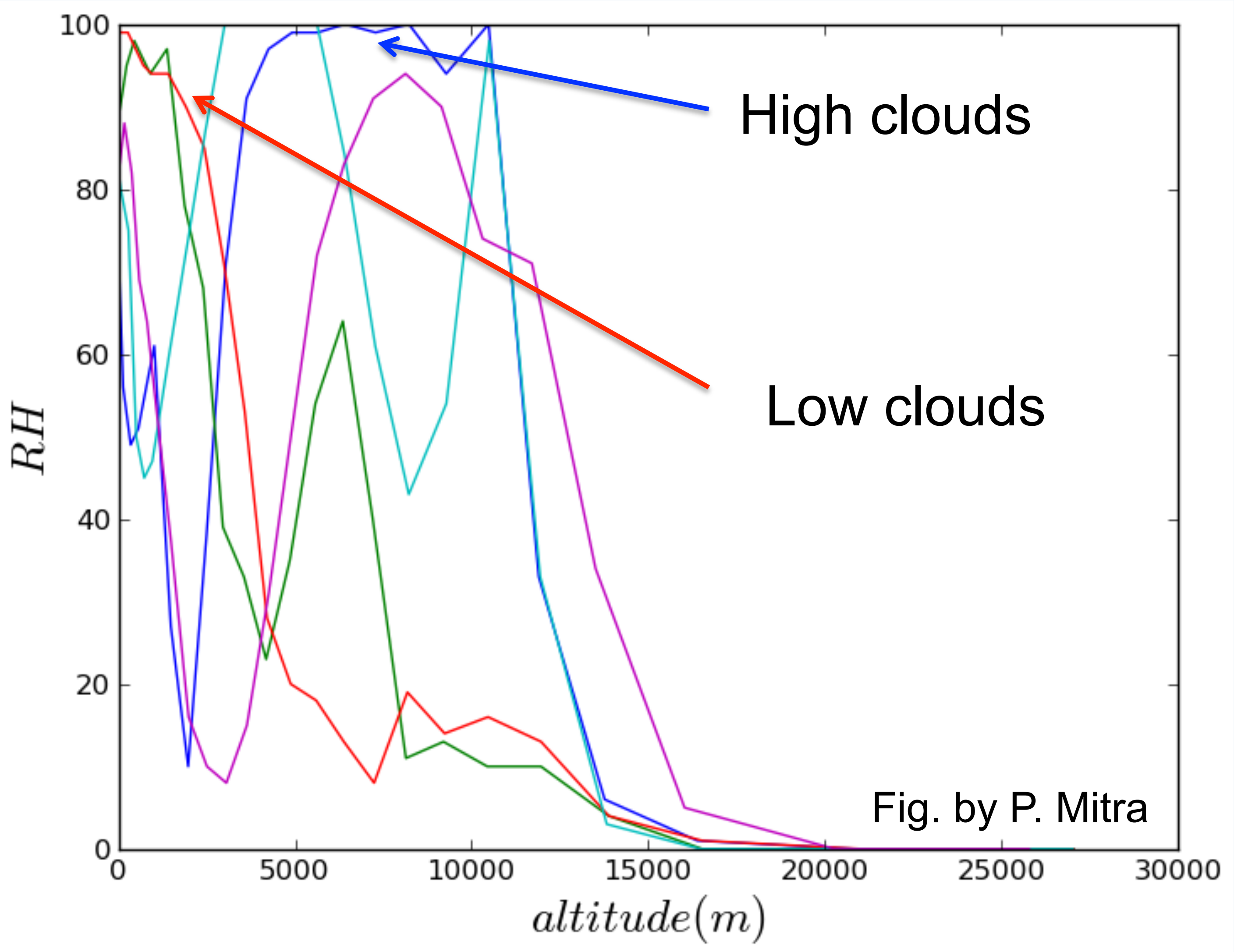
Significant effect especially for inclined air showers

Comparable to syst. uncertainty from hadronic interactions 10-15 g/cm^2

Atmospheric information from GDAS

- Global Data Assimilation System: database of atmospheric data used for weather forecasting
- 1°x1°, 3 hour grid
- Altitude profiles of temperature, pressure, humidity.
- These give the density and refractive index for use in the simulations

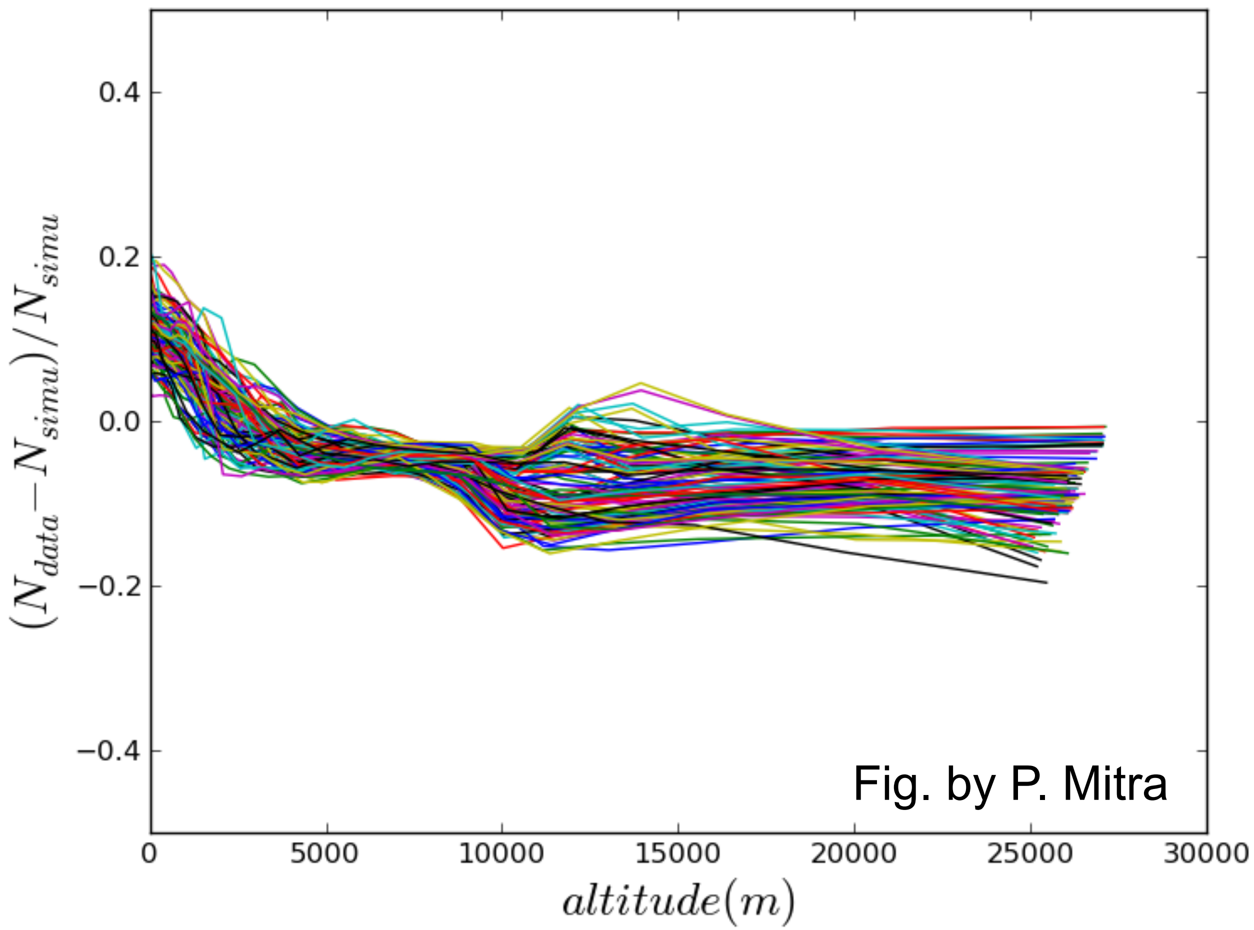
Atmospheric information from GDAS



5 different air showers

Humidity can vary a lot at LOFAR (as we know…)

Refractivity profiles for 100 events



Relative variations on the order of 3 to 5 % at 3 to 8 km altitude

Translates to about 10 g/cm^2 in Xmax

Summary

- Strong component of light particles: > 40 % p+He (2016 publication on 114 air showers)
- Simulated syst. uncertainty due to atmospheric variations: 4 to 11 g/cm^2
- Ongoing efforts to improve accuracy
  - More data, about 300 showers
  - Include local atmospheric profiles to reduce systematics
  - Simulation study to be run over the next few months
- Measuring well-constrained mixed composition for stronger tests of cosmic-ray propagation models
- Uncertainty on hadronic interaction models at high energy will be limiting factor for high-statistics runs; may be possible to test in the future