LOFAR key science project Cosmic Rays

Precission measurements of the radio emission from extensive air showers

Measurement of the particle type with LOFAR

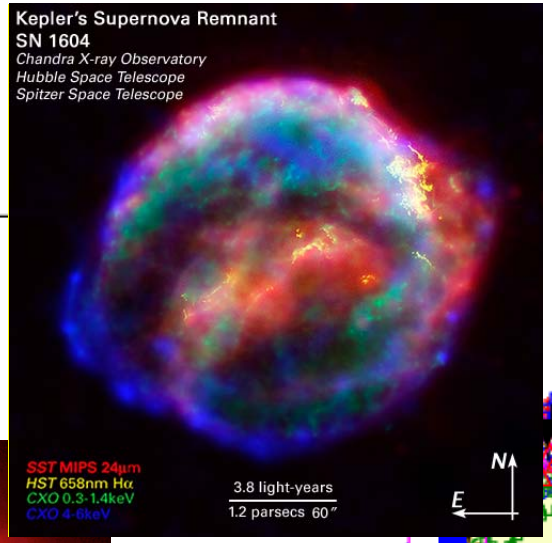
S. Buitink, A. Corstanje, J.E. Enriquez, H. Falcke, W. Frieswijk, J.R. Hörandel, A. Nelles, J.P. Rachen, L. Rossetto, S. Thoudam, P. Schellart, O. Scholten, S. ter Veen, T.N.G. Trinh

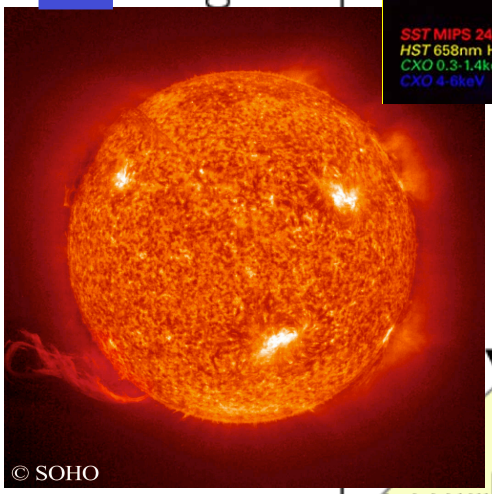
Jörg R. Hörandel Radboud University Nijmegen/Nikhef http://particle.astro.ru.nl

extragalactic cosmic rays

galactic cosmic rays

solar particles





knee

2nd knee

ankle

LOFAR

AERA

LOPES

galactic

JRH, Adv. Space Res. 41 (2008) 442

TRACER

KASCADE

Pierre Auger

-Grande

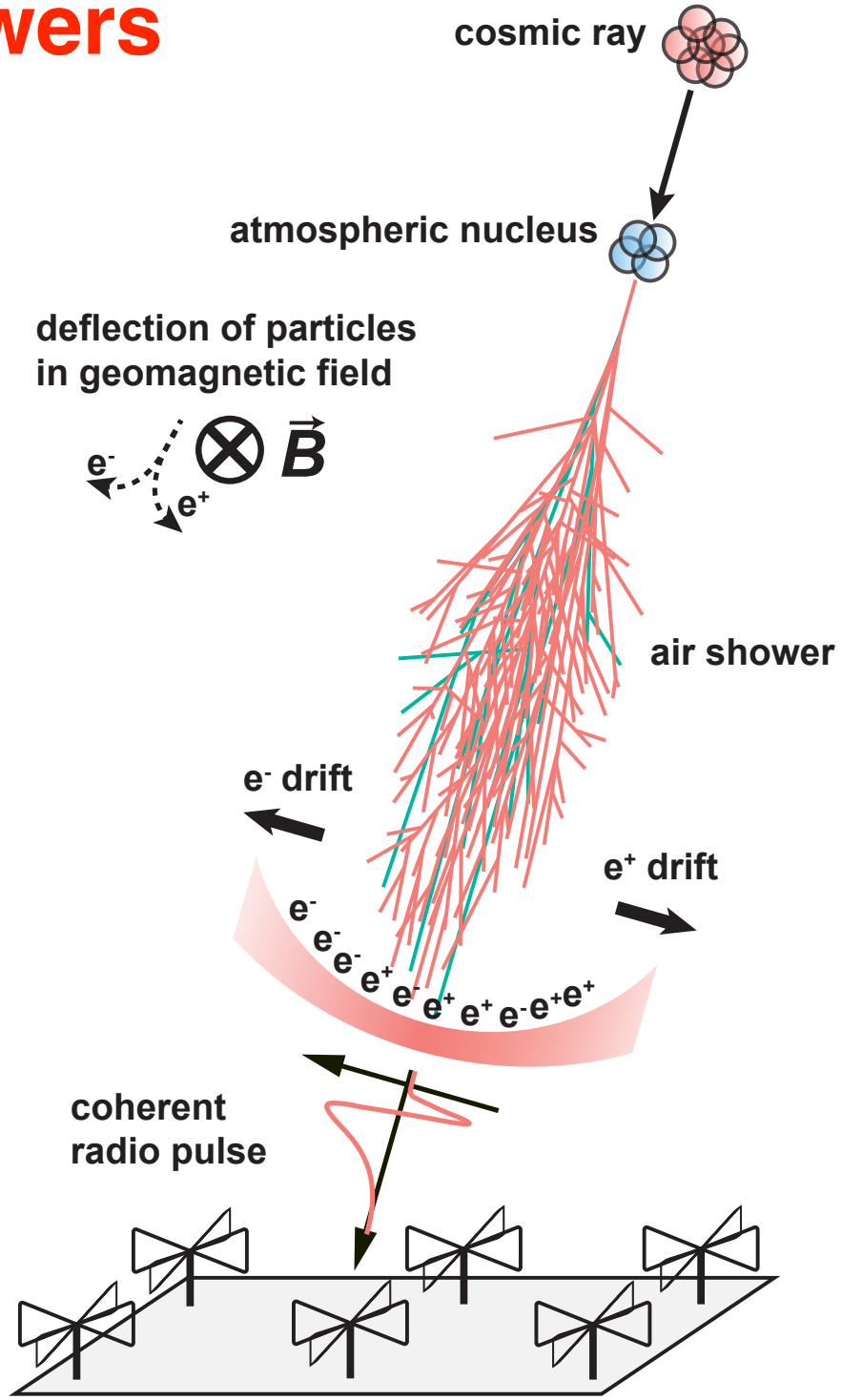
Radio Emission in Air Showers

- **Mainly: Charge separation in geomagnetic field**

$$\vec{E} \propto \vec{v} \times \vec{B}$$

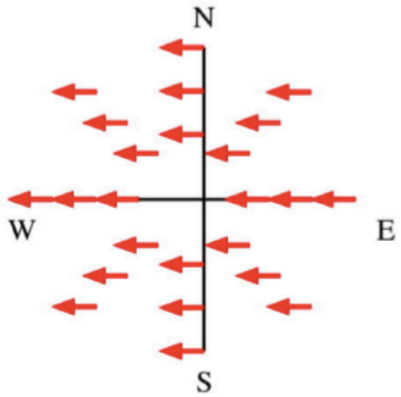
Theory predicts additional mechanisms:

- **excess of electrons in shower: charge excess**
- **superposition of emission due to Cherenkov effects in atmosphere**

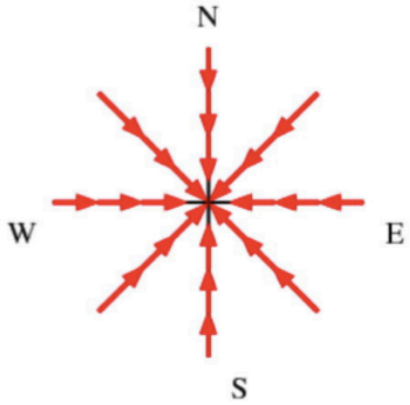


polarization of radio signal

geomagnetic effect

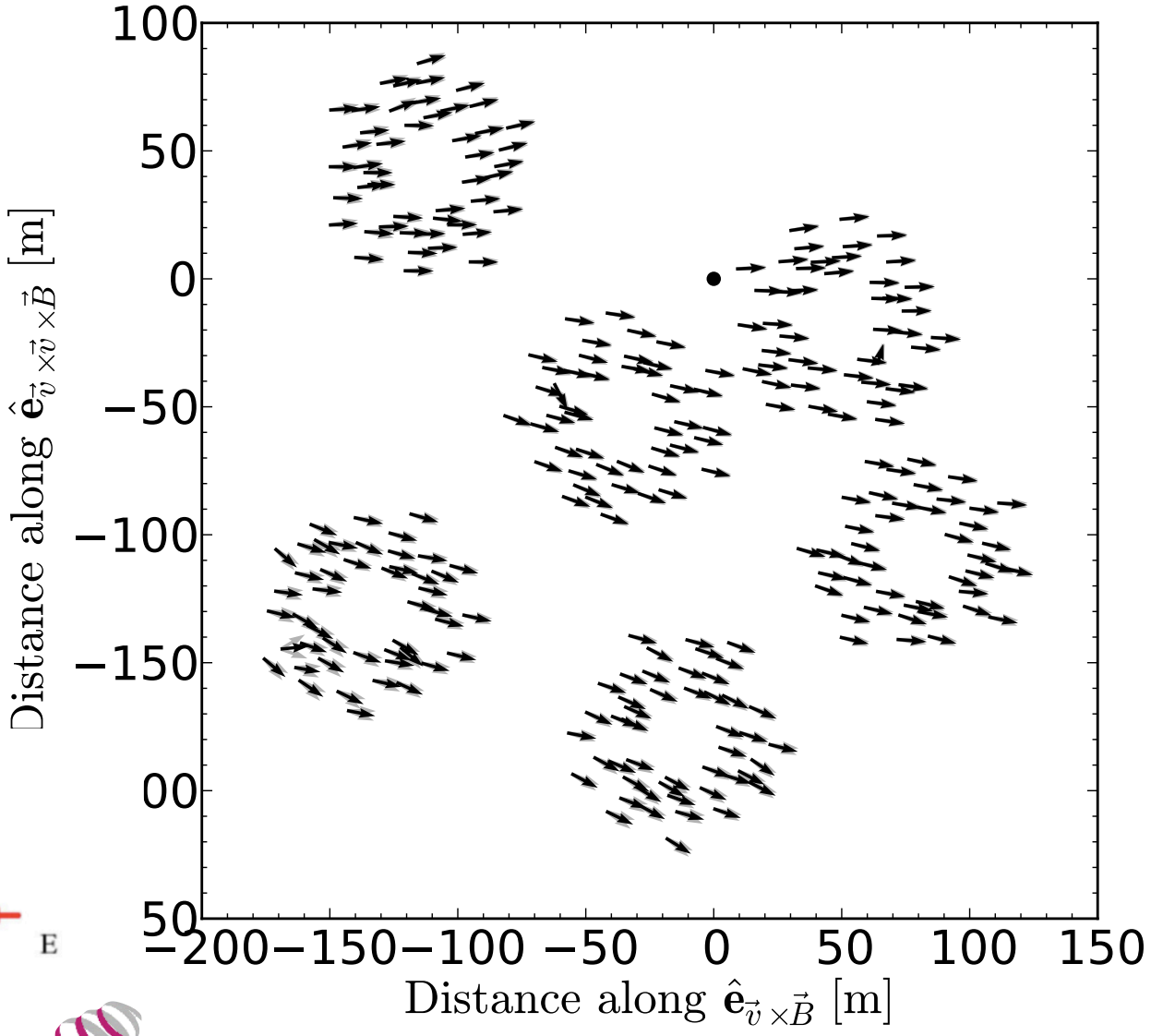


charge excess

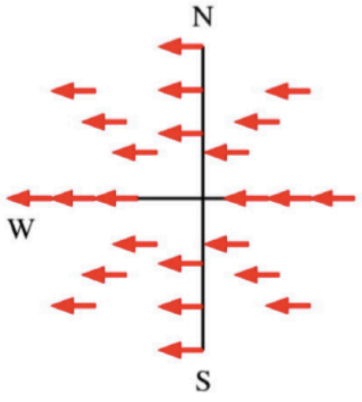


Polarization footprint

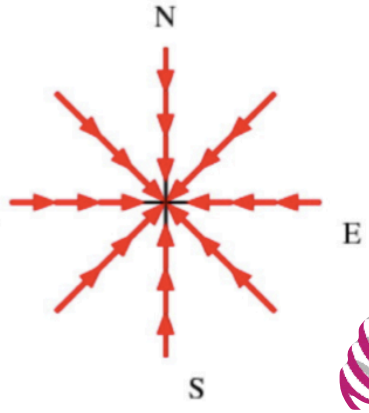
of an individual air shower



geomagnetic



Askaryan



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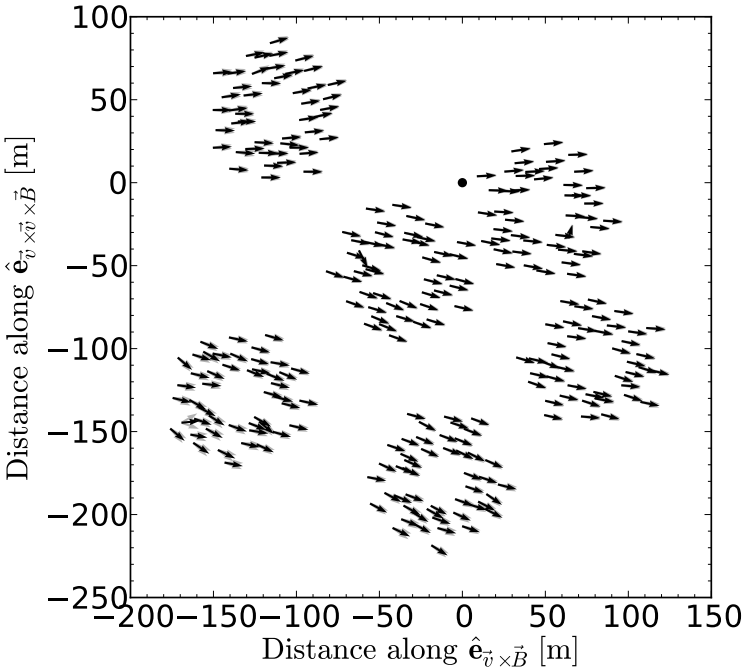
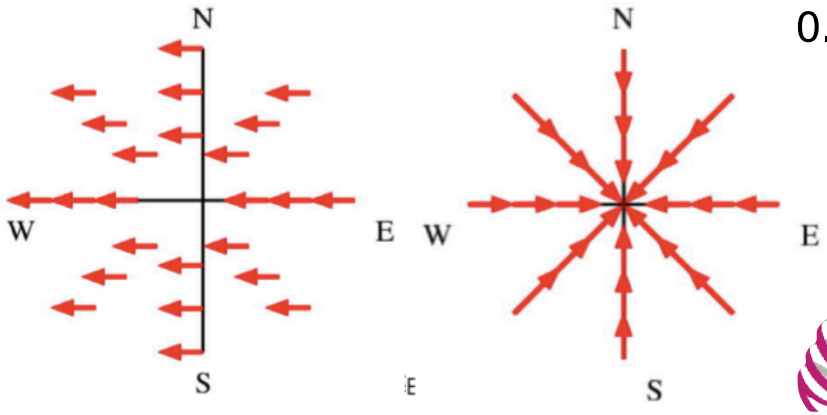
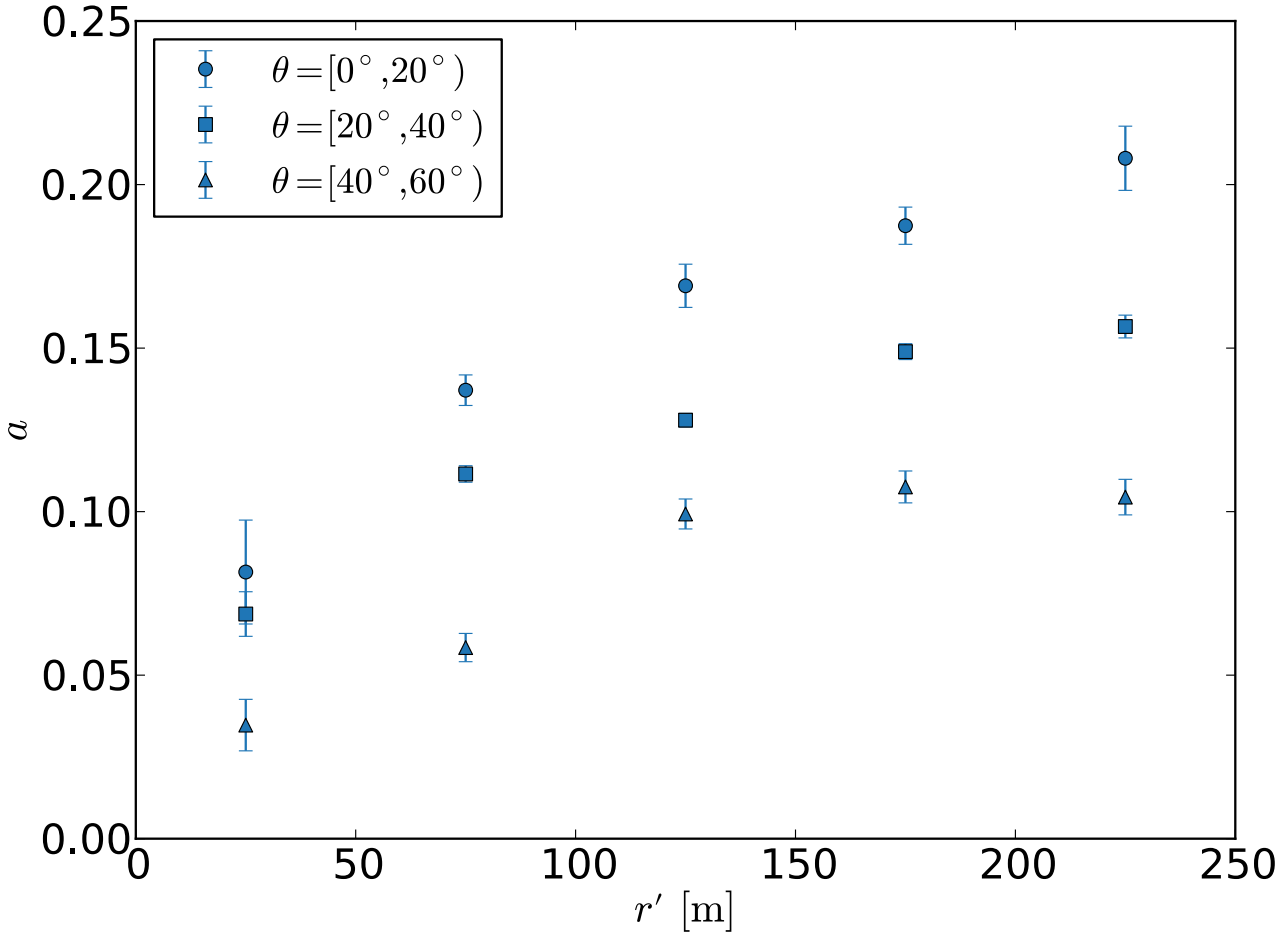
P. Schellart et al., JCAP 10 (2014) 014

Charge excess fraction



geomagnetic **Askaryan**

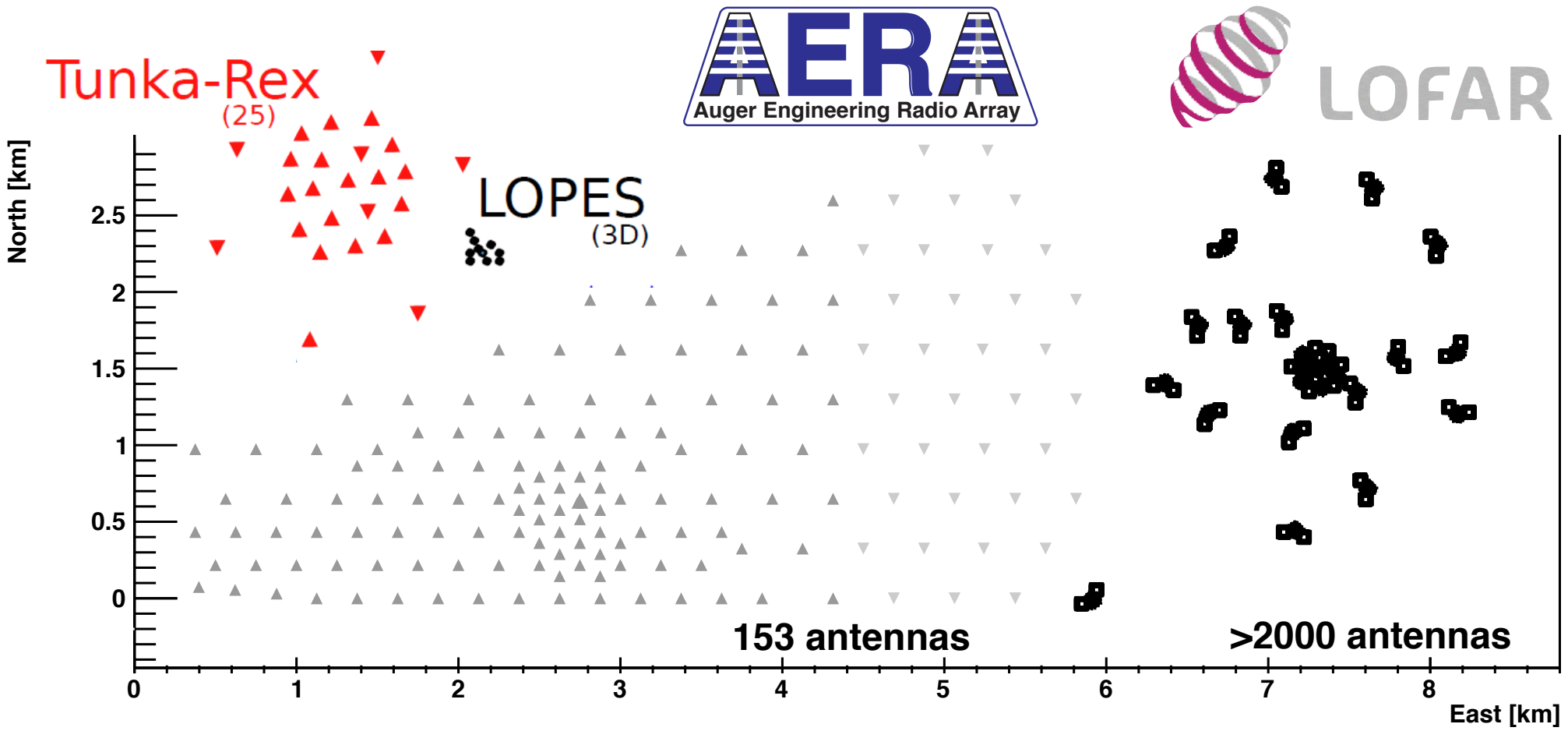




LOFAR

P. Schellart et al., JCAP 10 (2014) 014

Large-scale radio detectors to measure extensive air showers

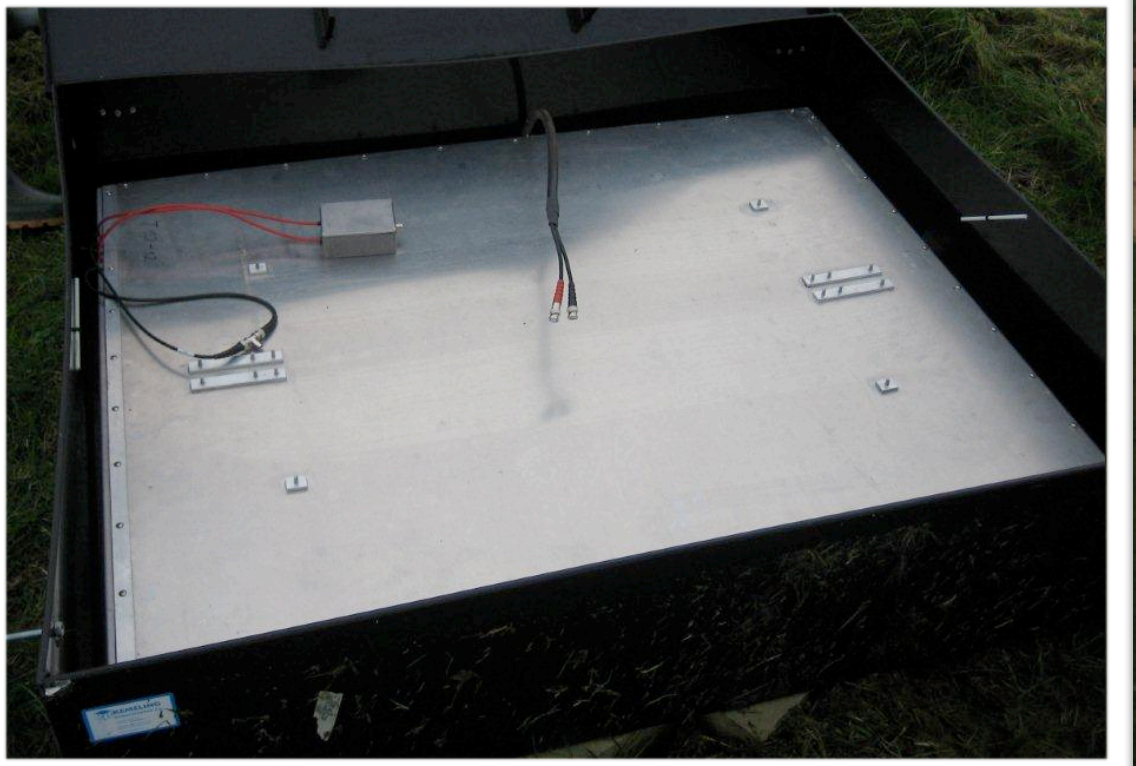


LOFAR Radboud Air Shower Array - LORA

20 scintillator units
(~1 m^2 each)
read out by
wavelength shifter bar
and PMT
in LOFAR core

→ provide

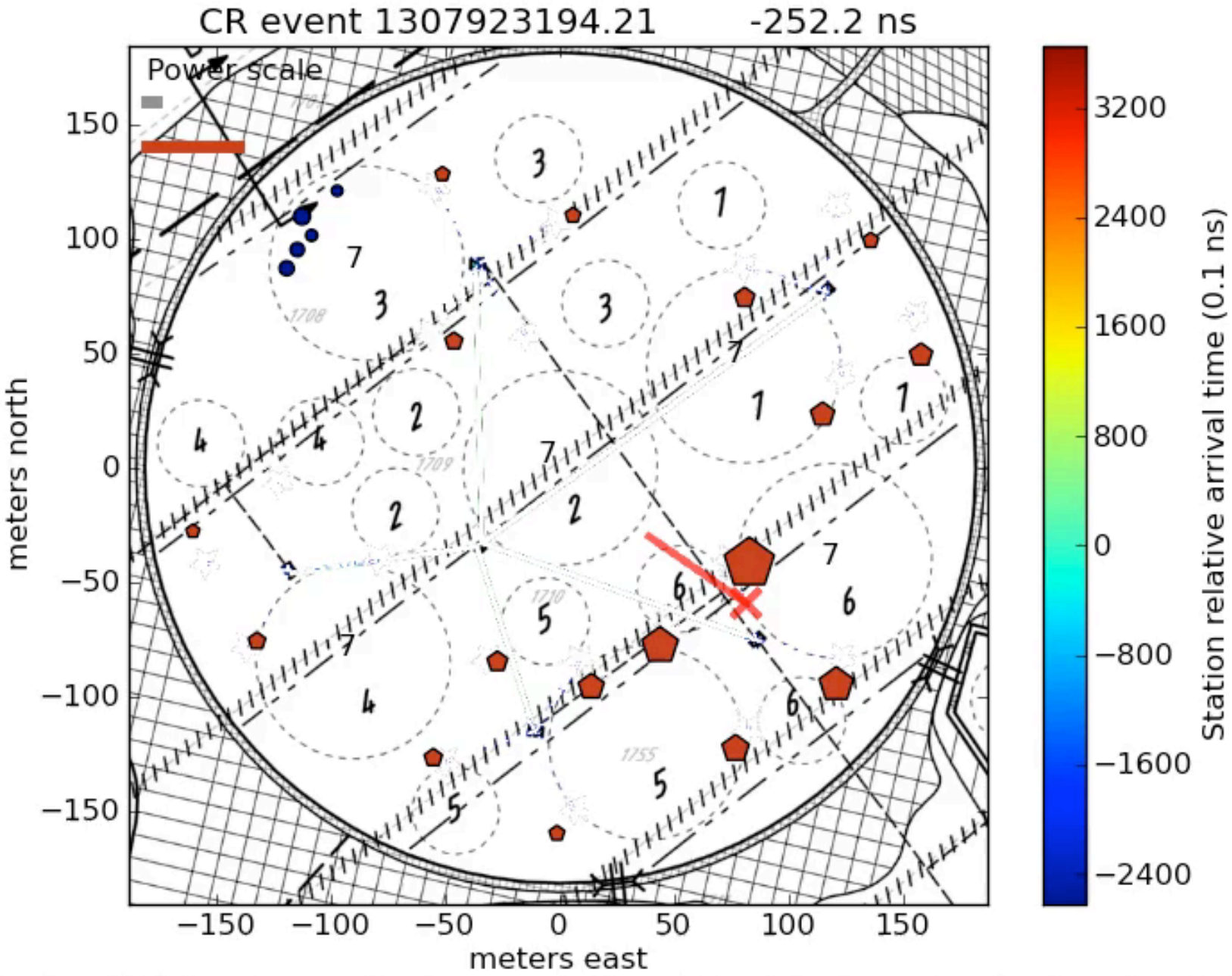
- properties of EAS
- and trigger



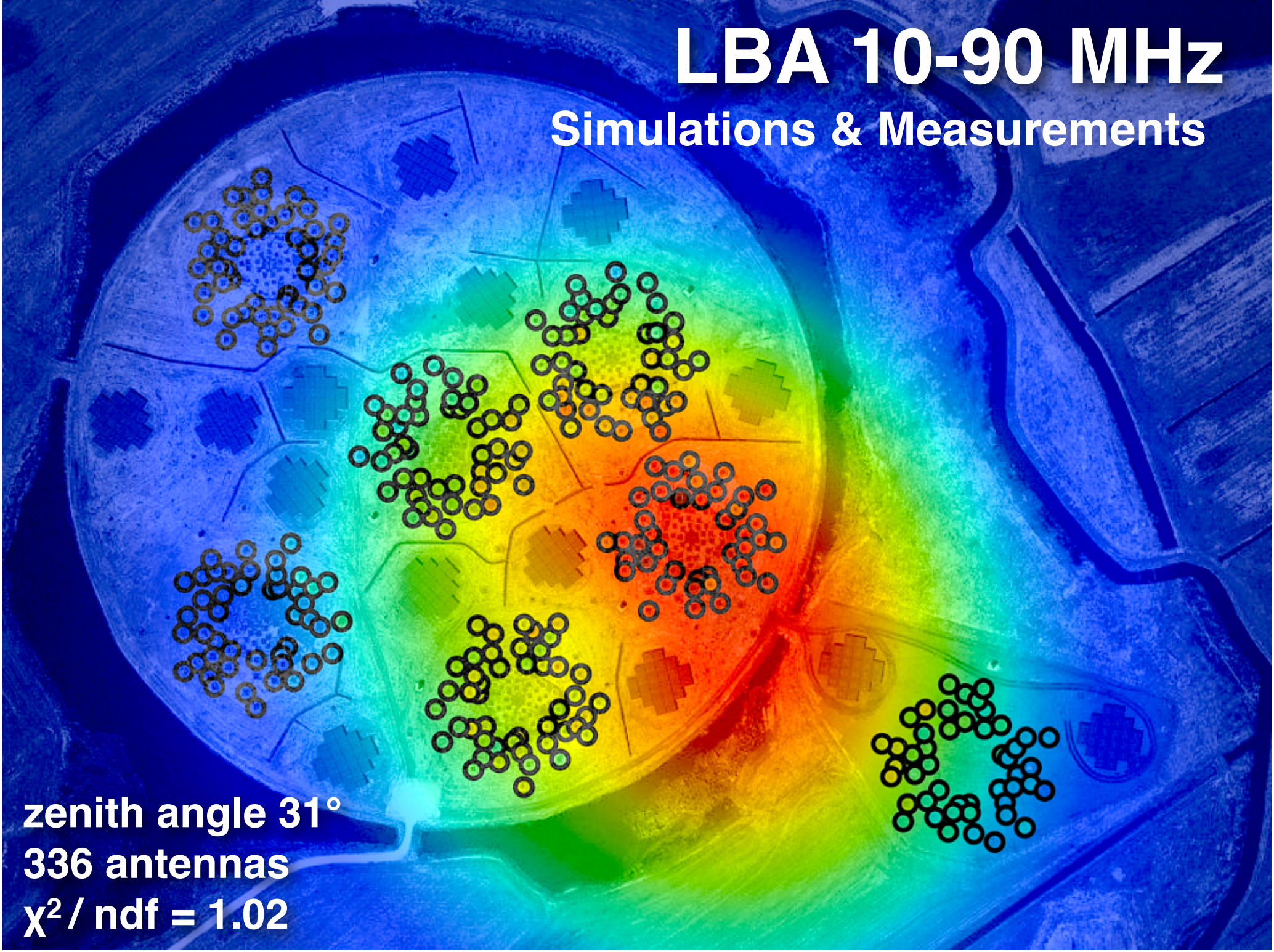
LOFAR

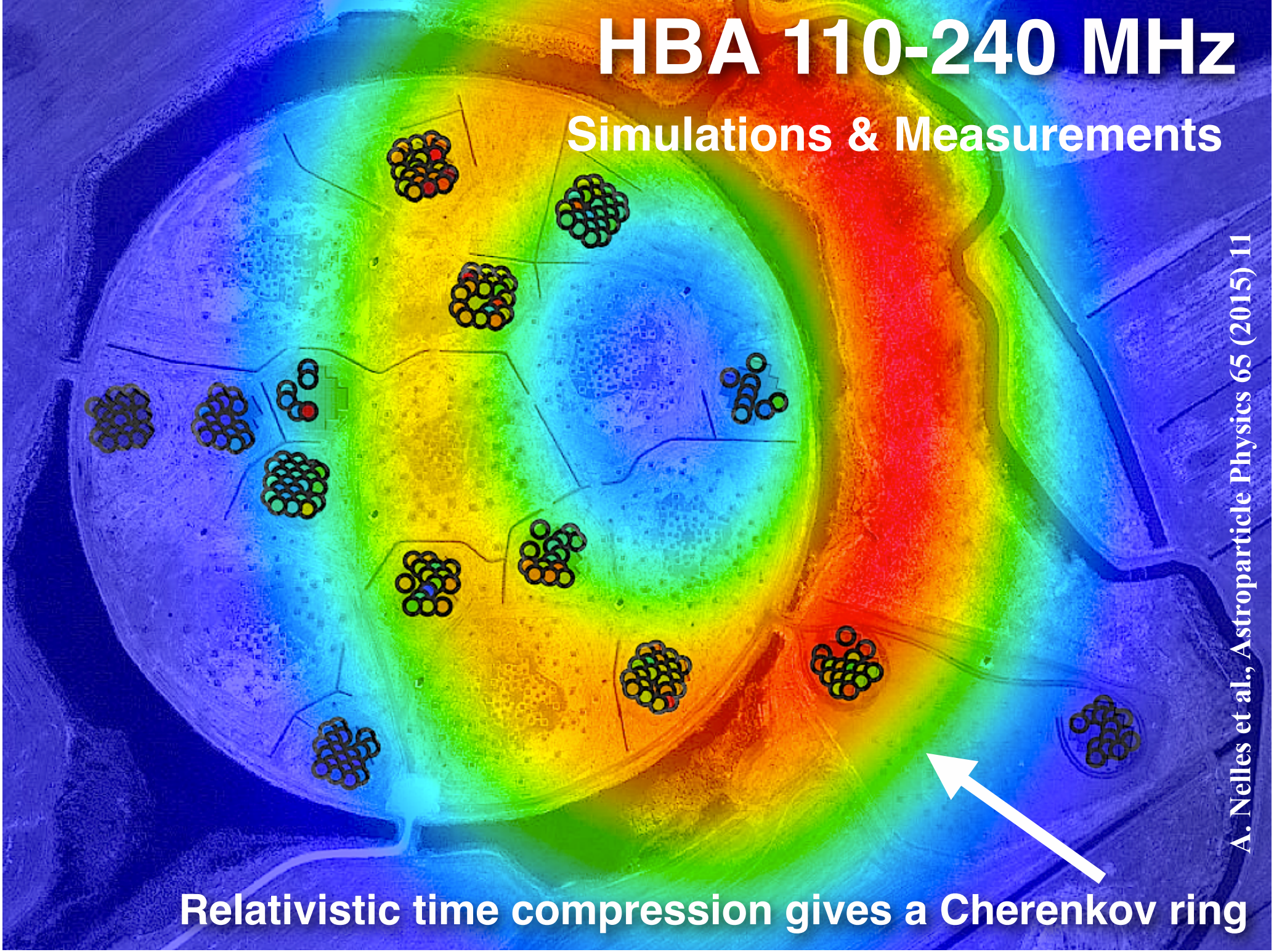
S. Thoudam et al., Nuclear Instruments and Methods A 767 (2014) 329

A measured air shower

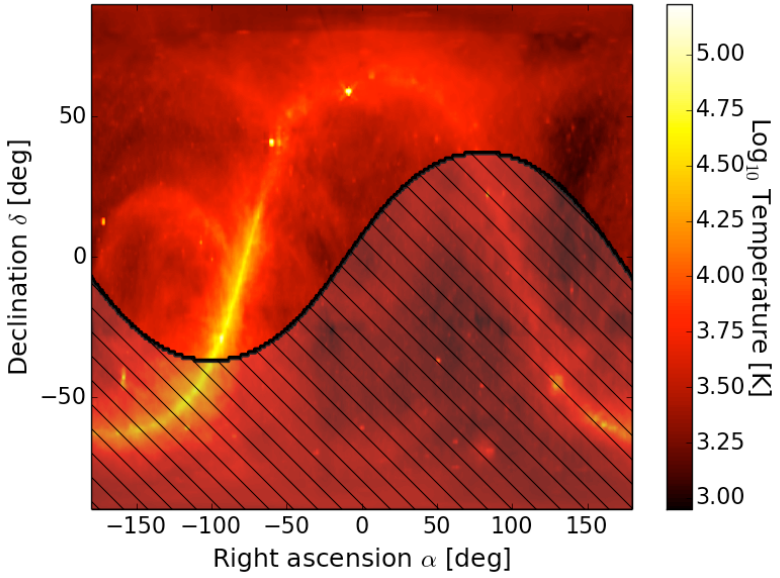


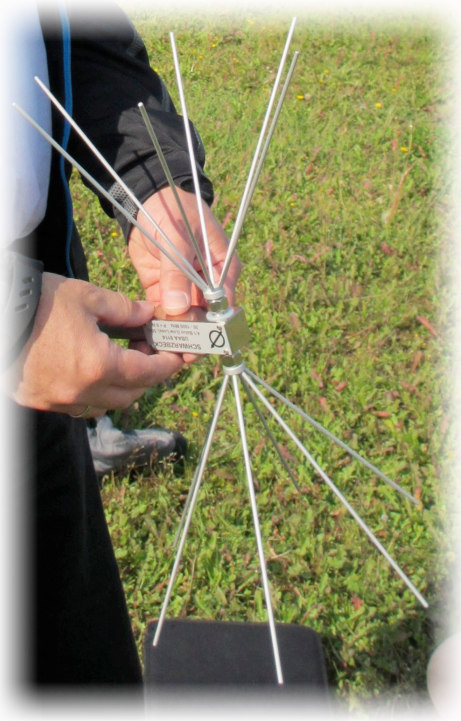
Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength


LBA 10-90 MHz
Simulations & Measurements
zenith angle 31°
336 antennas
χ² / ndf = 1.02

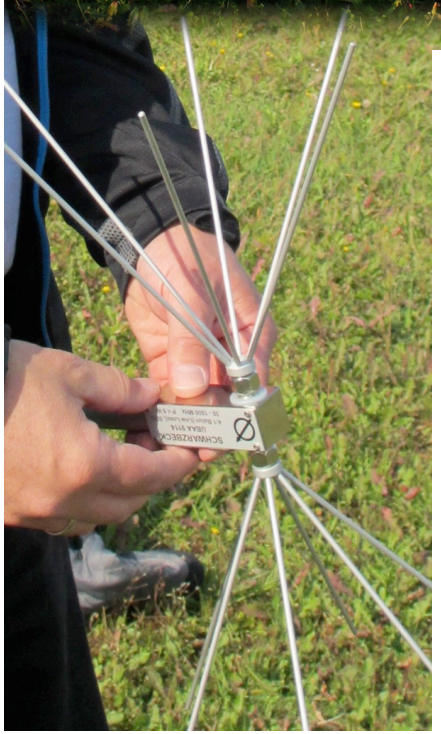

HBA 110-240 MHz
Simulations & Measurements
A. Nelles et al., Astroparticle Physics 65 (2015) 11
Relativistic time compression gives a Cherenkov ring

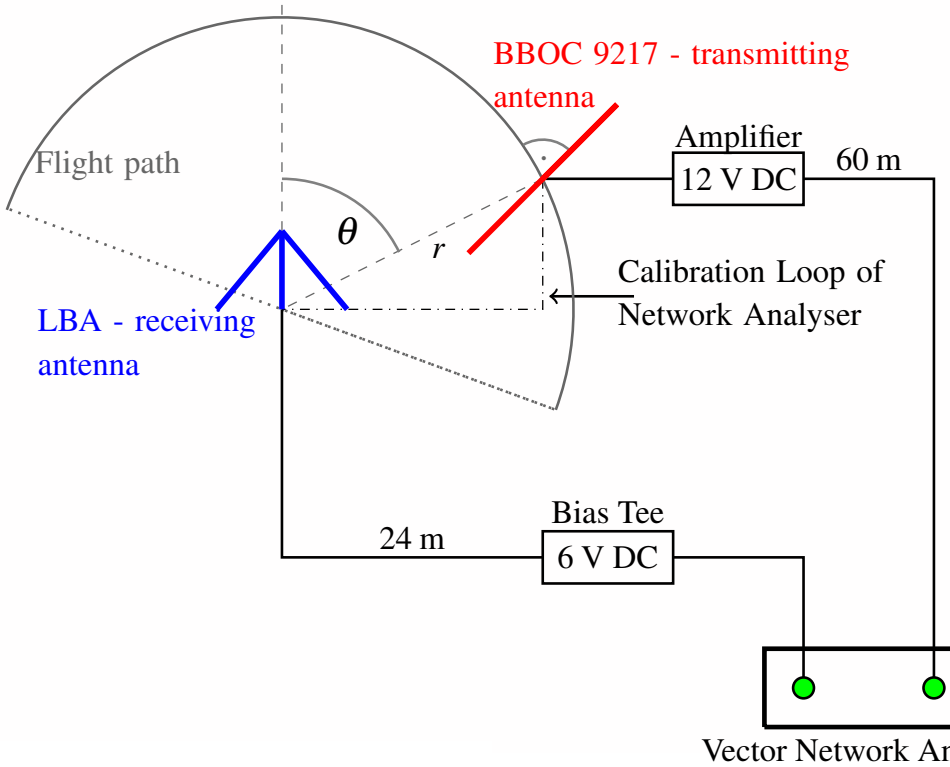
Three sources - one goal: calibration of LOFAR

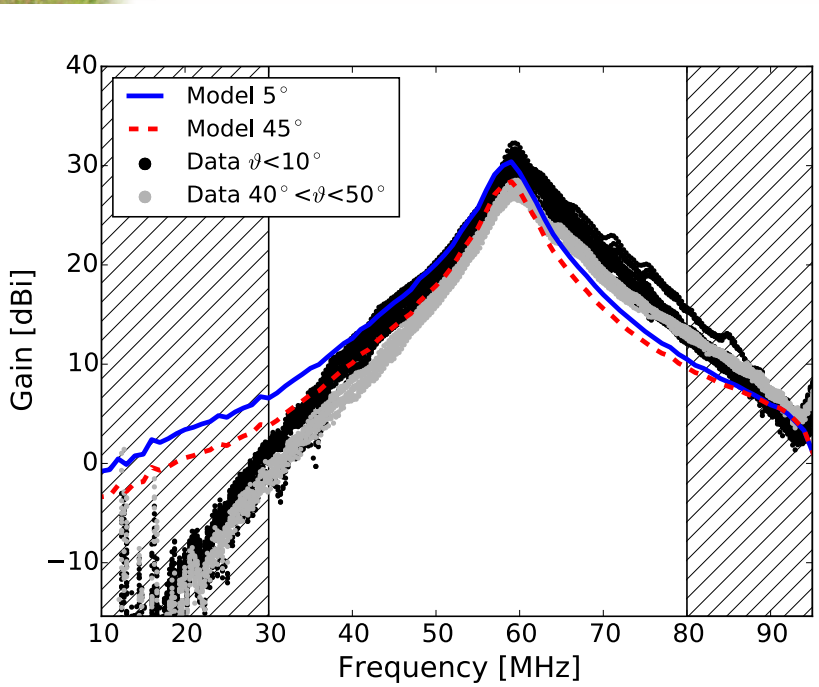


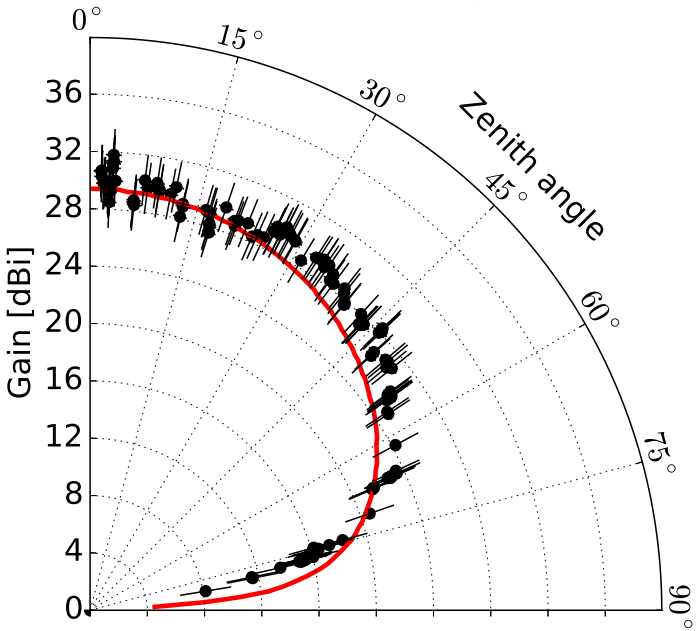


Shape of antenna pattern



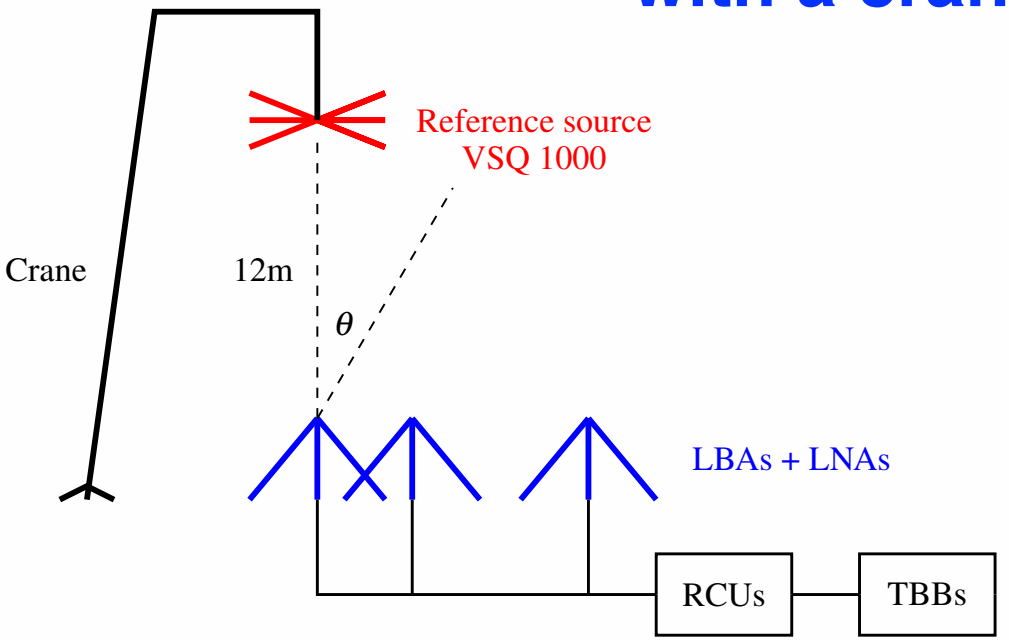


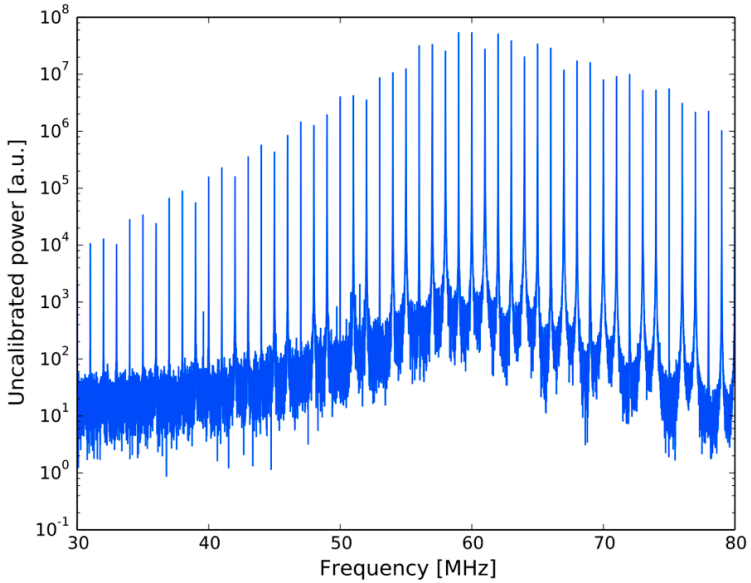


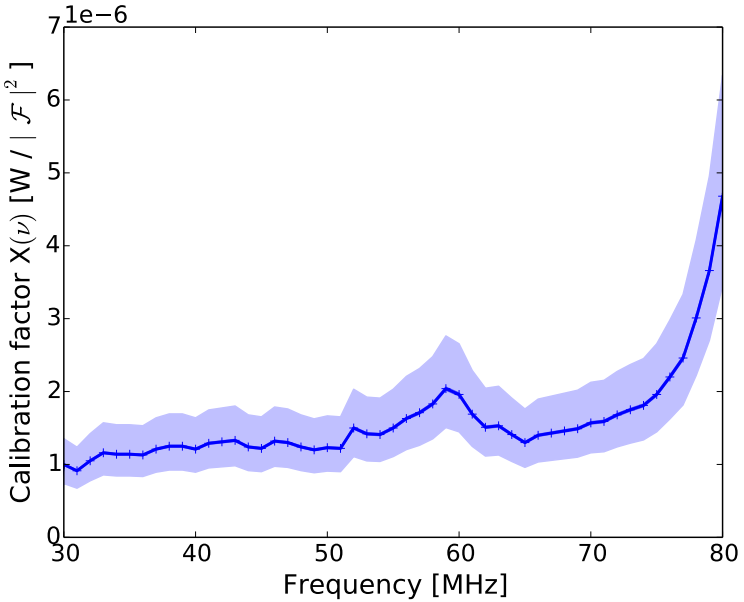


Gain of complete chain

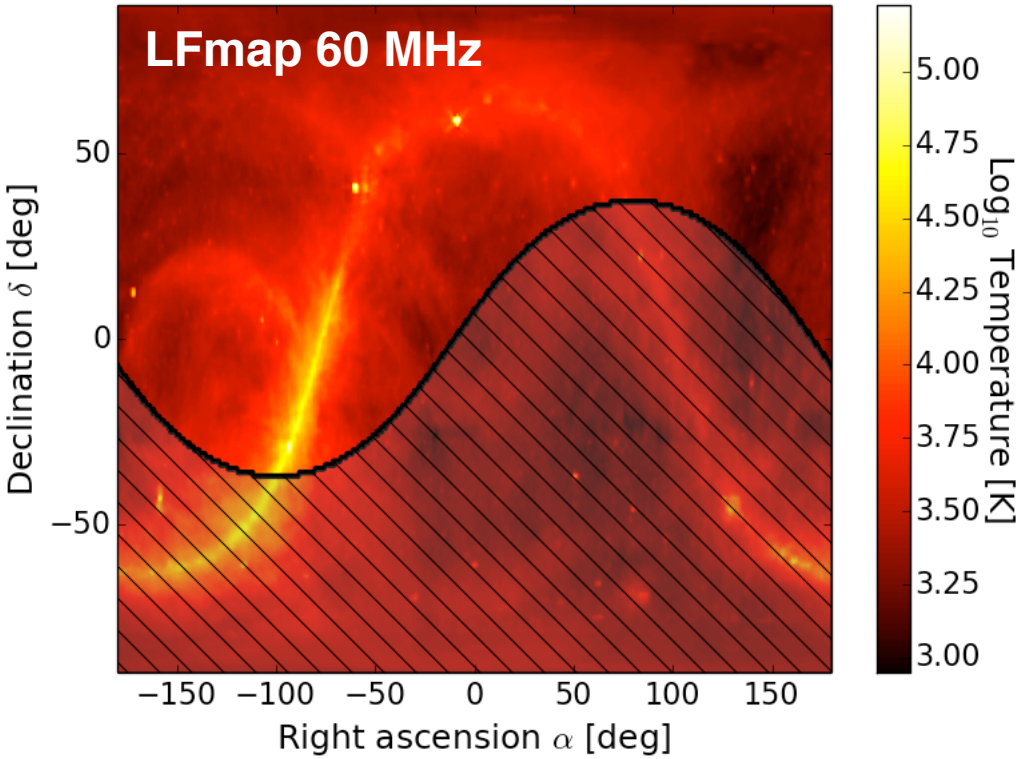
with a crane

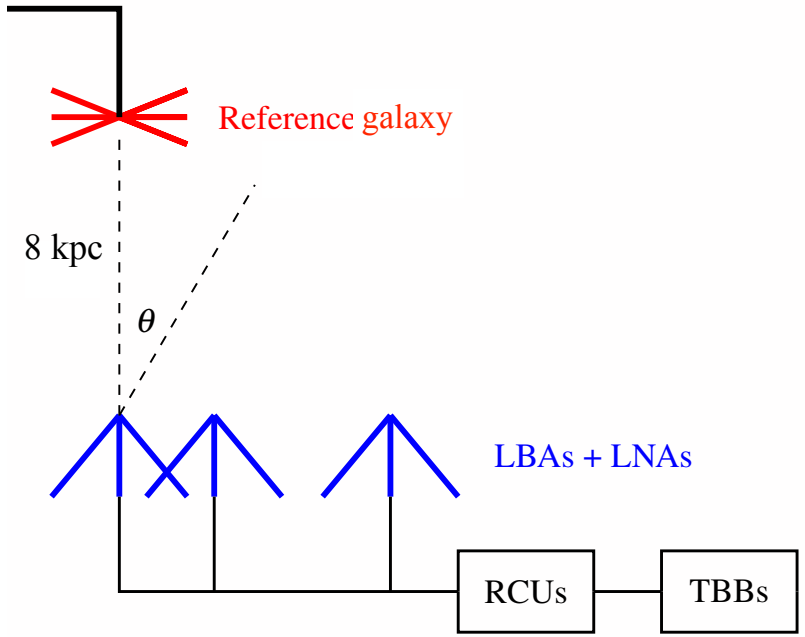


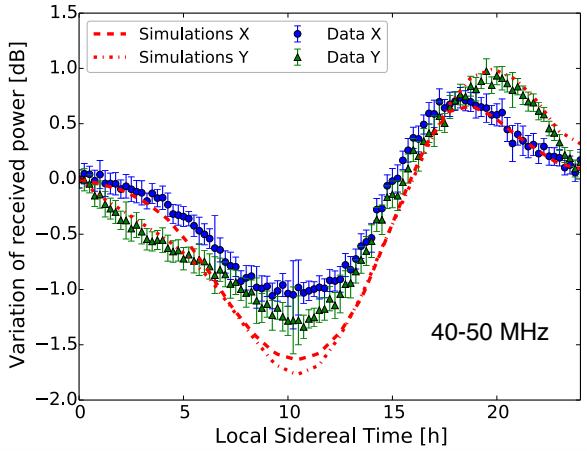


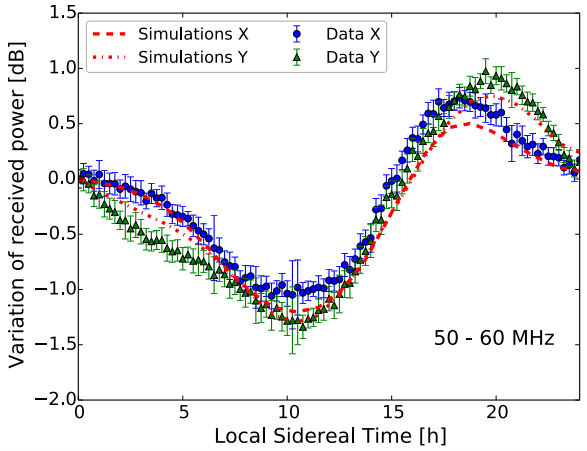


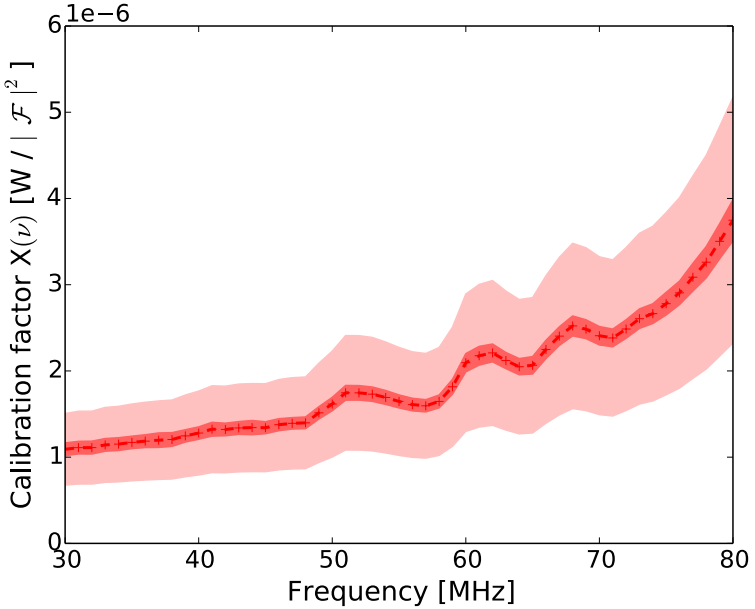
Gain of complete chain



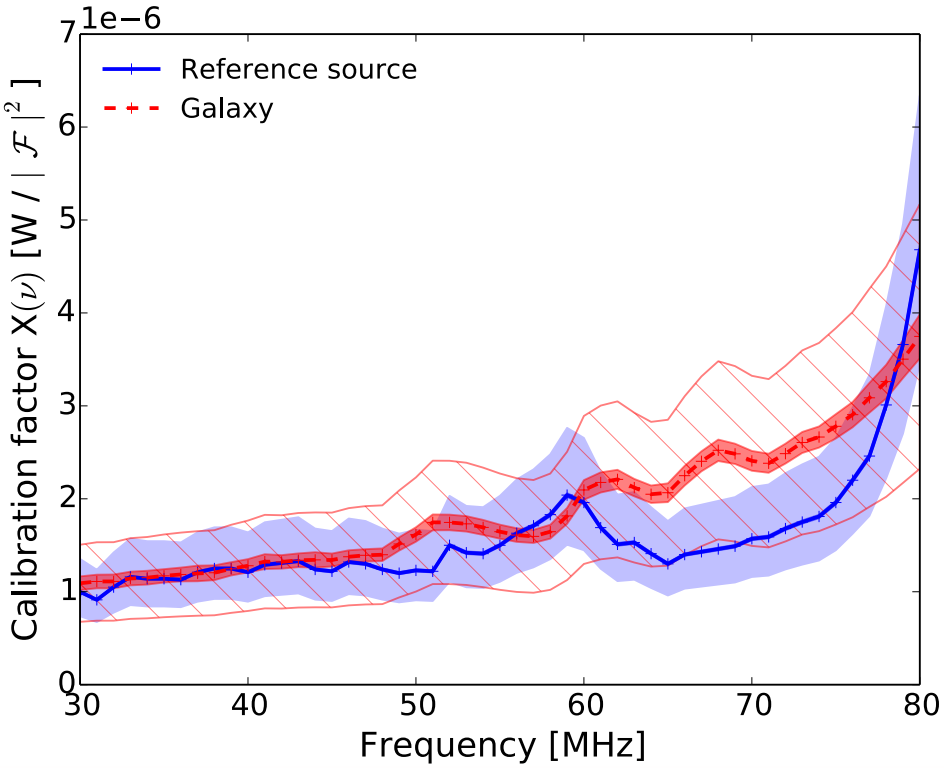


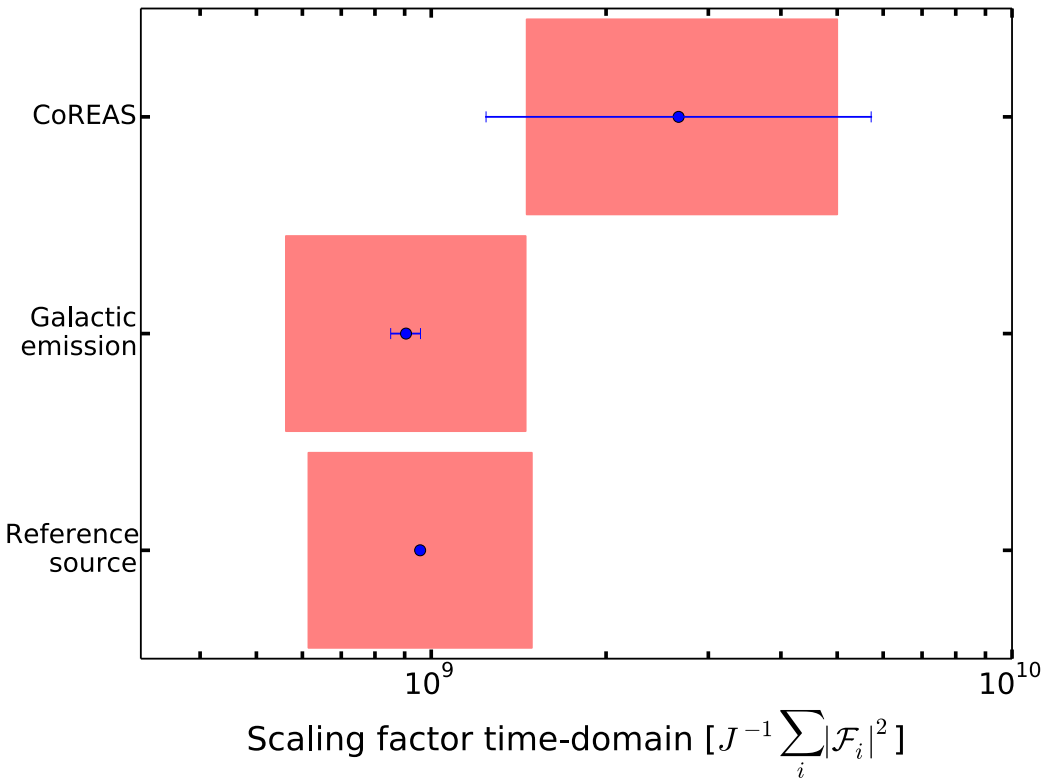




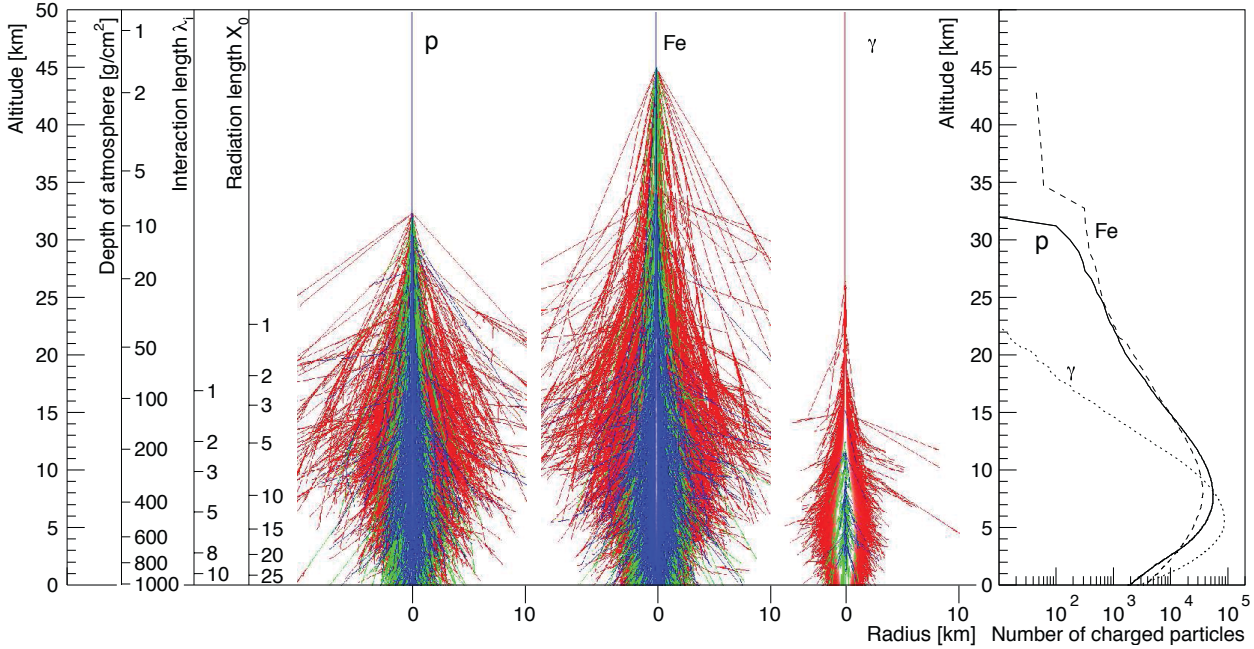


Three methods - one goal: calibration of LOFAR

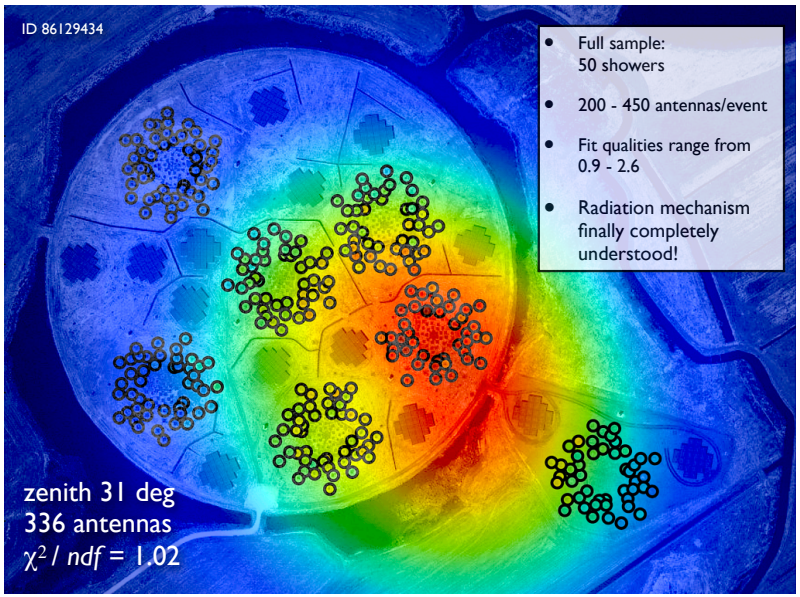


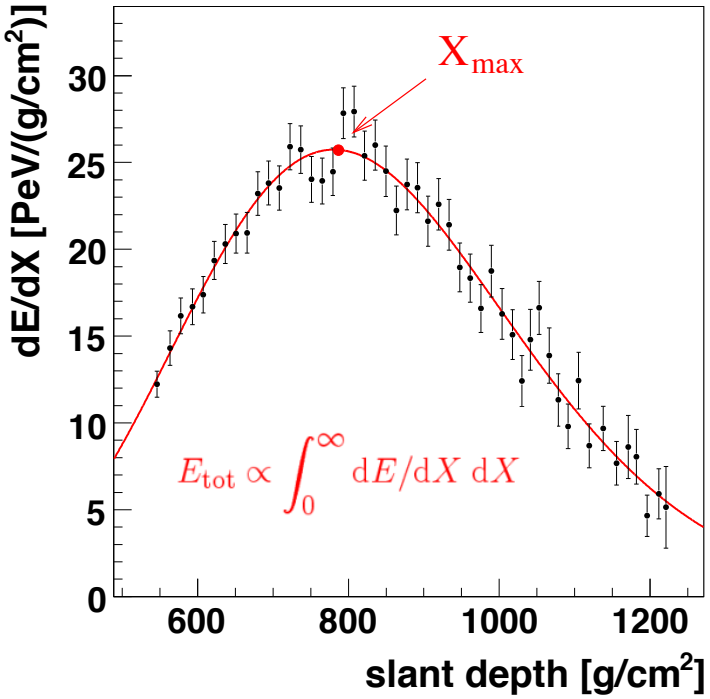


Reconstruction of the depth of the shower maximum (X_{max})

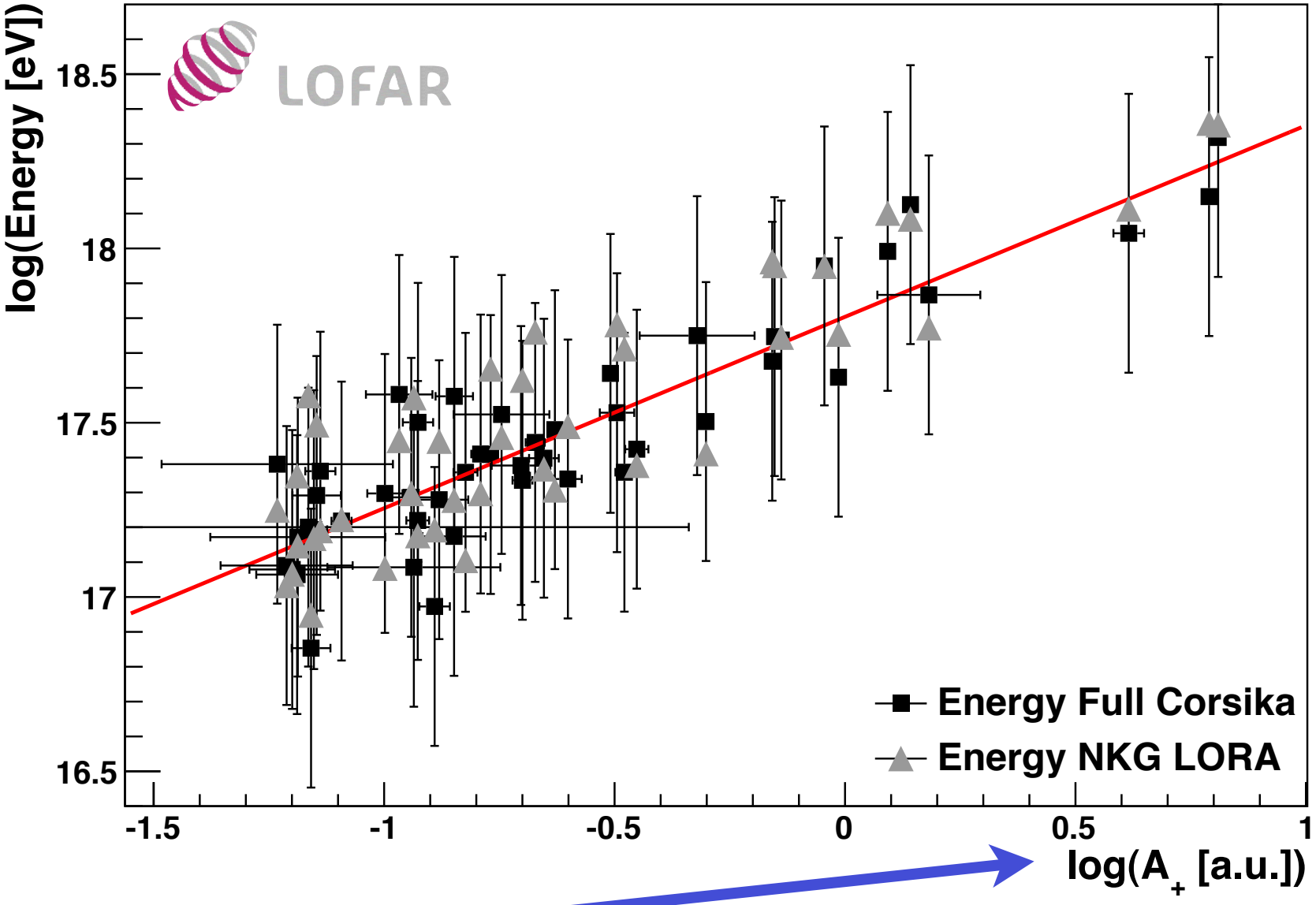


properties of incoming cosmic ray:
- direction
- energy
- particle type





Energy of air shower

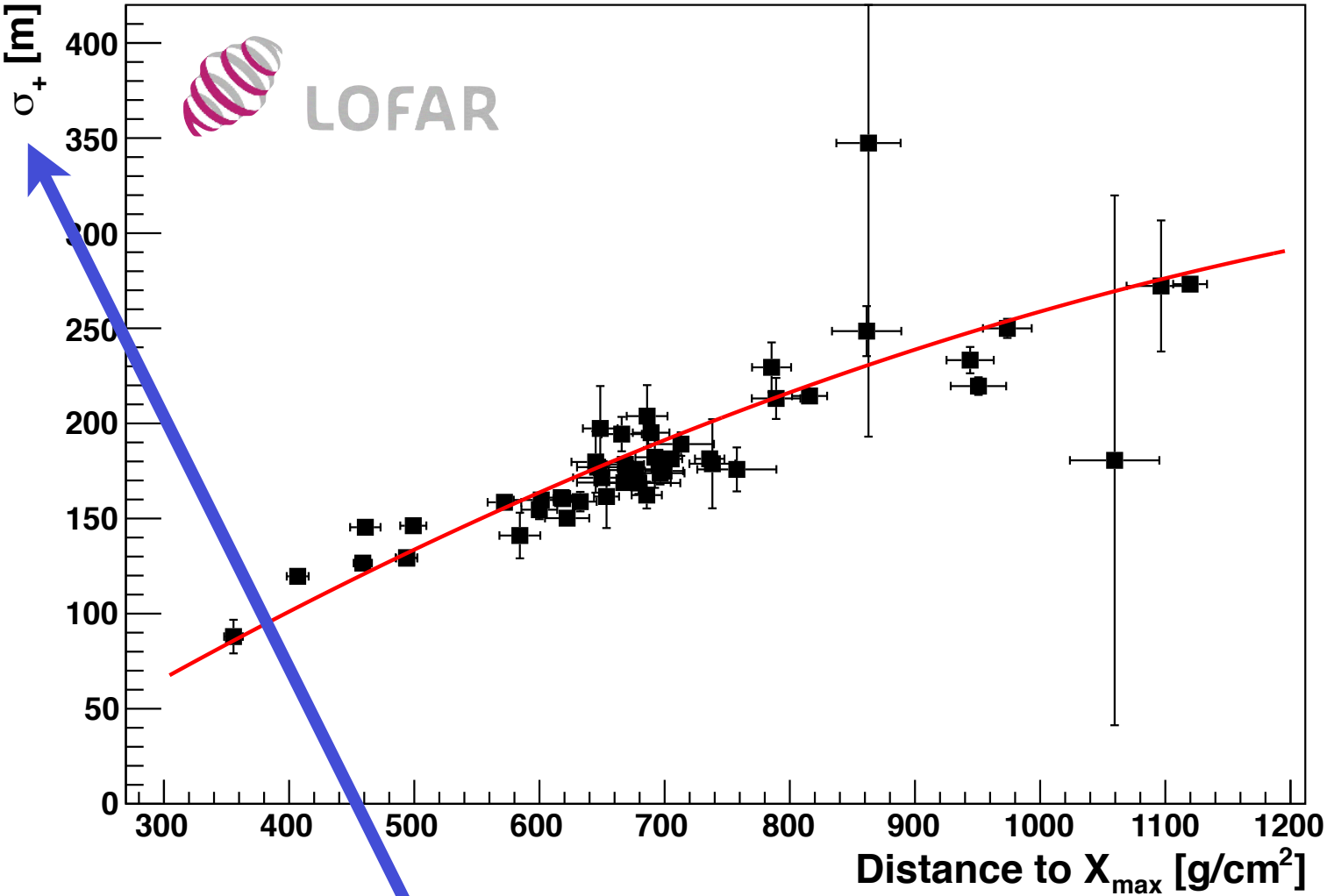


A. Nelles et al., JCAP 05 (2015) 018

$$P(x',y') = A_+ \cdot \exp\left(\frac{[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right) + O$$

Particle type/mass

distance to Xmax



A. Nelles et al., JCAP 05 (2015) 018

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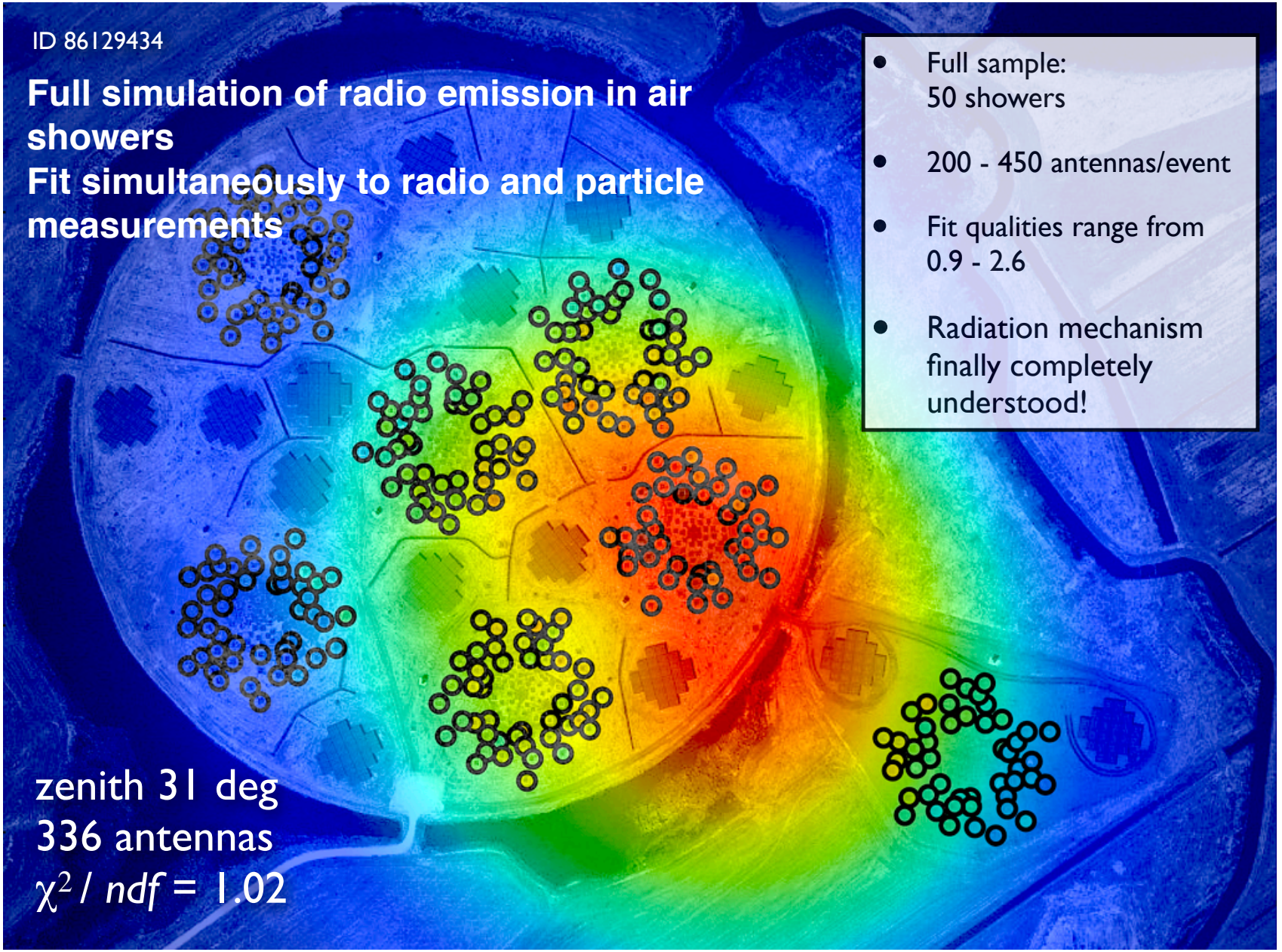
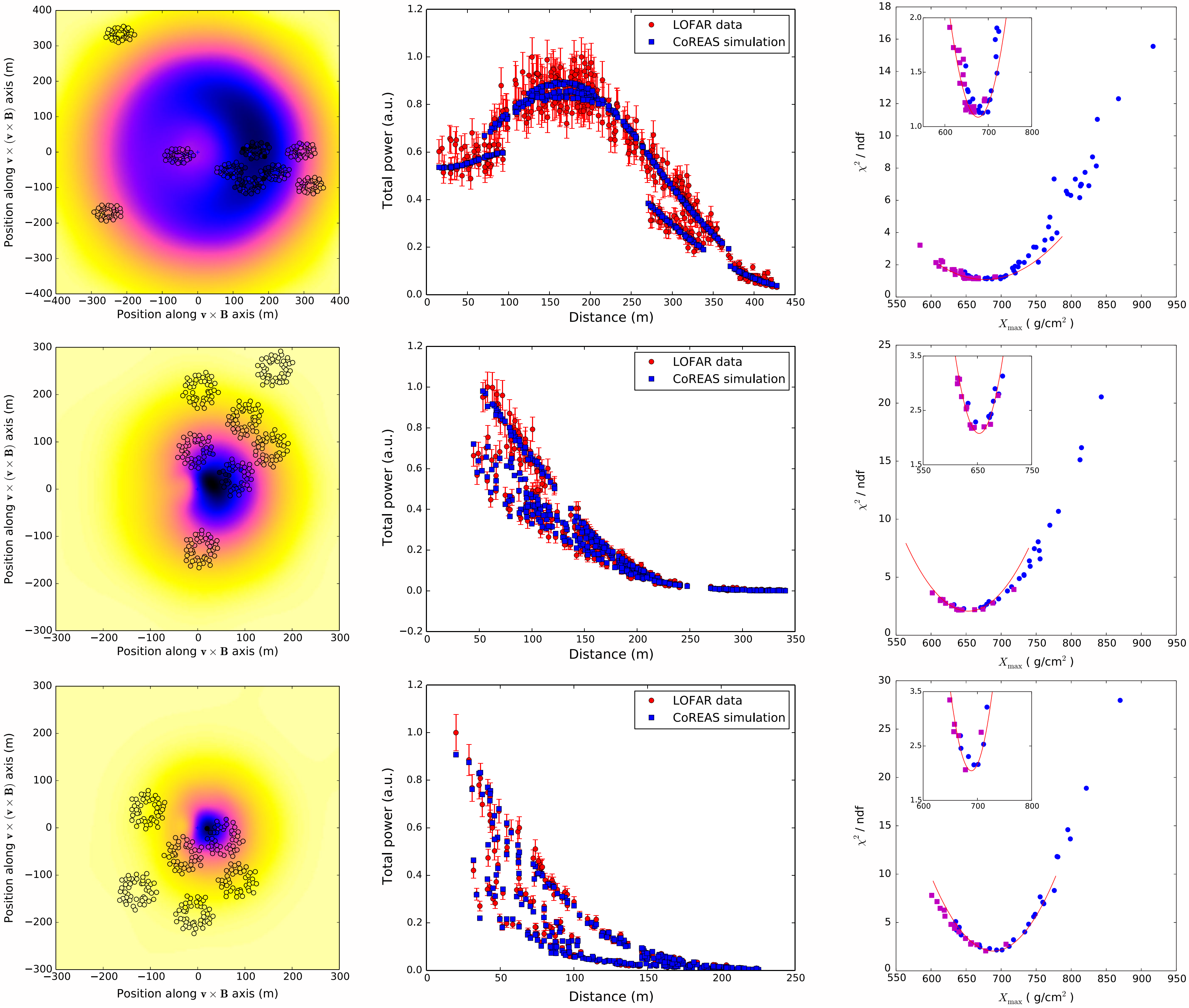
Reconstruction of the depth of the shower maximum (X_{max})



S. Buitink et al, Phys. Rev. D 90 (2014) 082003

Reconstruction of the depth of the shower maximum (X_{max})



S. Buitink et al, Phys. Rev. D 90 (2014) 082003

LOFAR key science project Cosmic Rays

Precission measurements of the radio emission from extensive air showers

- Detecting cosmic rays with the LOFAR radio telescope
  Astronomy & Astrophysics 560 (2013) A98
- Calibrating the absolute amplitude scale for air showers measured at LOFAR
  in preparation
- Polarized radio emission from extensive air showers measured with LOFAR
  Journal for Cosmology and Astroparticle Physics 10 (2014) 014
- Method for high precision reconstruction of air shower Xmax using two-dimensional radio intensity profiles
  Physical Review D 90 (2014) 082003

} JRH

- Radio detections of cosmic rays reveal a strong light mass component at 10^{17} - $10^{17.5}$ eV
  in preparation for Nature
- LORA - A scintillator array for LOFAR
  Nuclear Instruments and Methods A 767 (2014) 329
- Measurement of the cosmic-ray energy spectrum above 10^{16} eV with the LOFAR Radboud Air Shower Array
  submitted to Astroparticle Physics

} S. Thoudam

- A parameterization for the radio emission of air showers as predicted by CoREAS sumulations and applied to LOFAR measurements
  Astroparticle Physics 60 (2015) 13
- The radio emission pattern of air showers as measured with LOFAR - a tool for the reconstruction of the energy and the shower maximum
  Journal of Cosmology and Astroparticle Physcis 05 (2015) 018

} L. Rossetto

- Measuring a Cherenkov ring in the radio emission from air showers at 110 - 190 MHz with LOFAR
  Astroparticle Physics 65 (2015) 11
- The shape of the radio wavefront of extensive air showers as measured with LOFAR
  Astroparticle Physics 61 (2015) 22

} A. Corstanje

- Probing atmospheric electric fields in thunderstorms through radio emission from cosmic-ray induced air showers
  Physical Review Letters 114 (2015) 165001

} G. Trinh