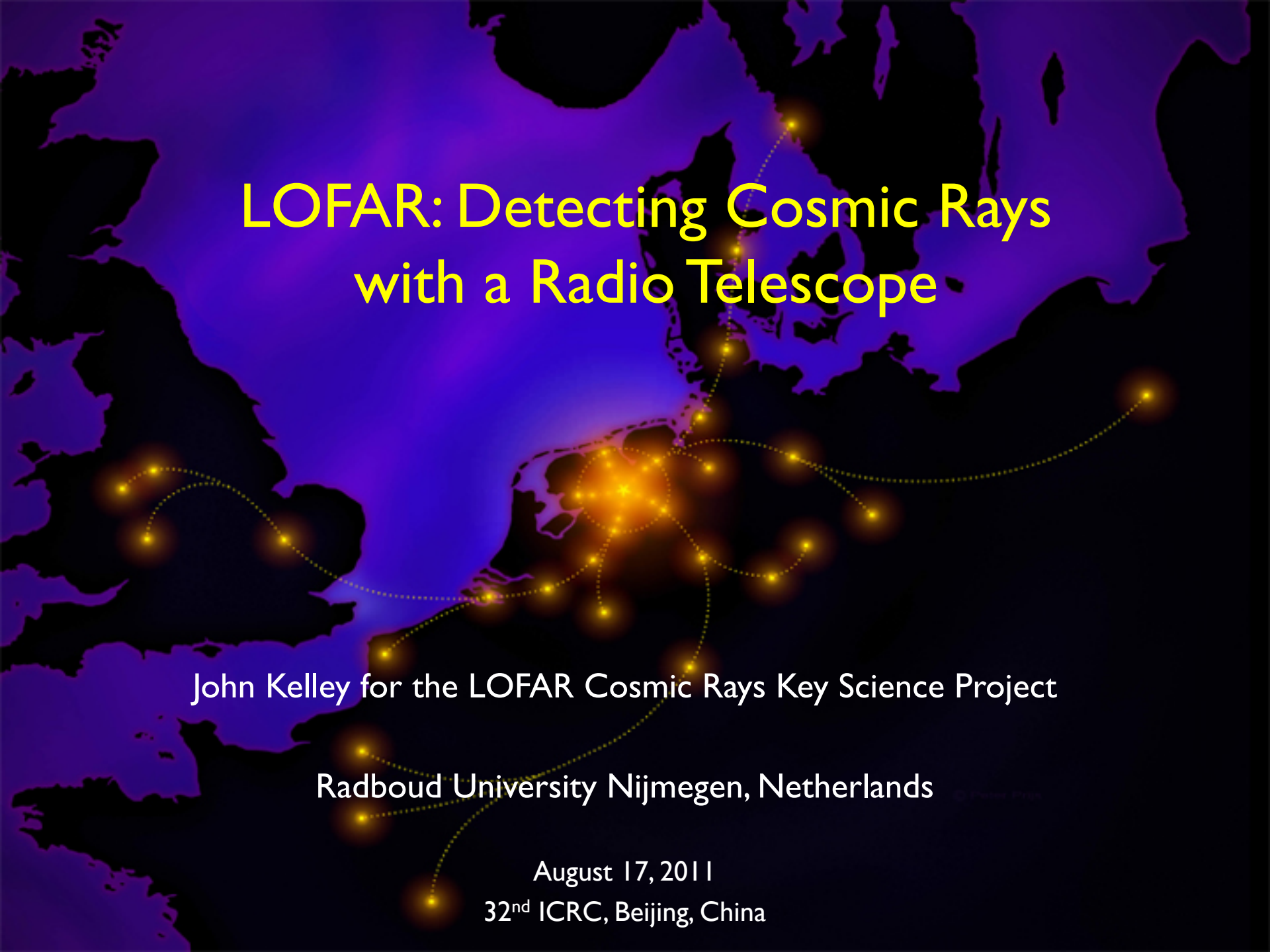


LOFAR: Detecting Cosmic Rays with a Radio Telescope

John Kelley for the LOFAR Cosmic Rays Key Science Project

Radboud University Nijmegen, Netherlands

August 17, 2011

32nd ICRC, Beijing, China

What is LOFAR?

- Low Frequency Array: world's largest radio telescope

- Stations in 5 countries in Europe
  - 24-station core near Exloo, Netherlands

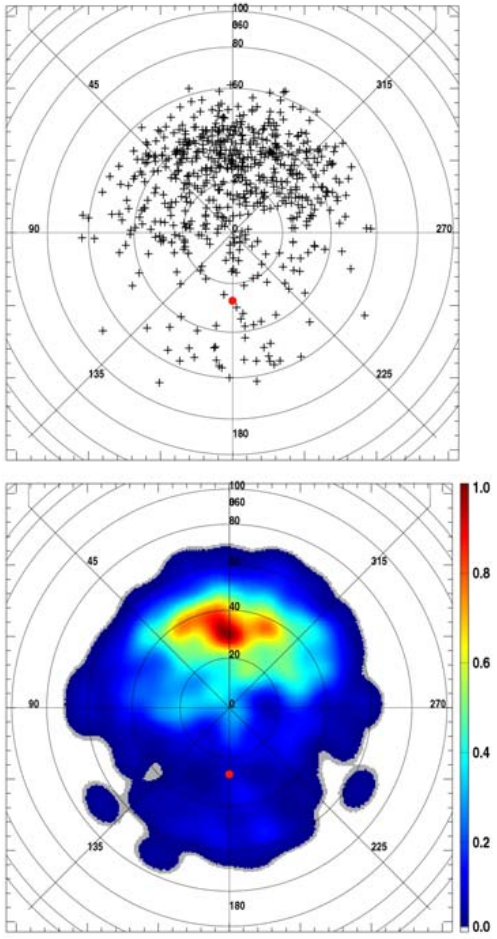
LOFAR Station

Low-band antenna field
- 96 dipoles
- 10-80 MHz

High-band antenna field
- 2 'ears'
- 24 tiles per ear
- 16 antennas per tile
- 110-250 MHz

LOFAR core: the "super-terp"

Radio Emission from Air Showers



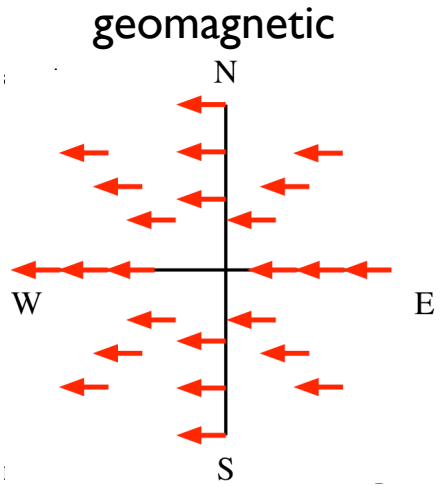
Ardouin *et al.* 2009

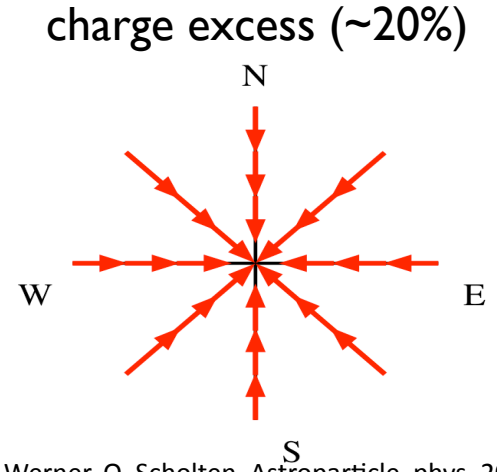
- Coherent pulses of primarily geomagnetic origin
- Simplification:

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

- Asymmetry confirmed with LOPES, CODALEMA experiments
- Full story is actually more complicated...

Multiple Emission Mechanisms





K. Werner, O. Scholten, Astroparticle phys, 2008

- Not simply geomagnetic emission
  - charge excess
  - moving dipole
  - Cherenkov
- How to disentangle sub-dominant emission mechanisms?
  - multiple polarizations
  - dense sampling

LOFAR is ideal!

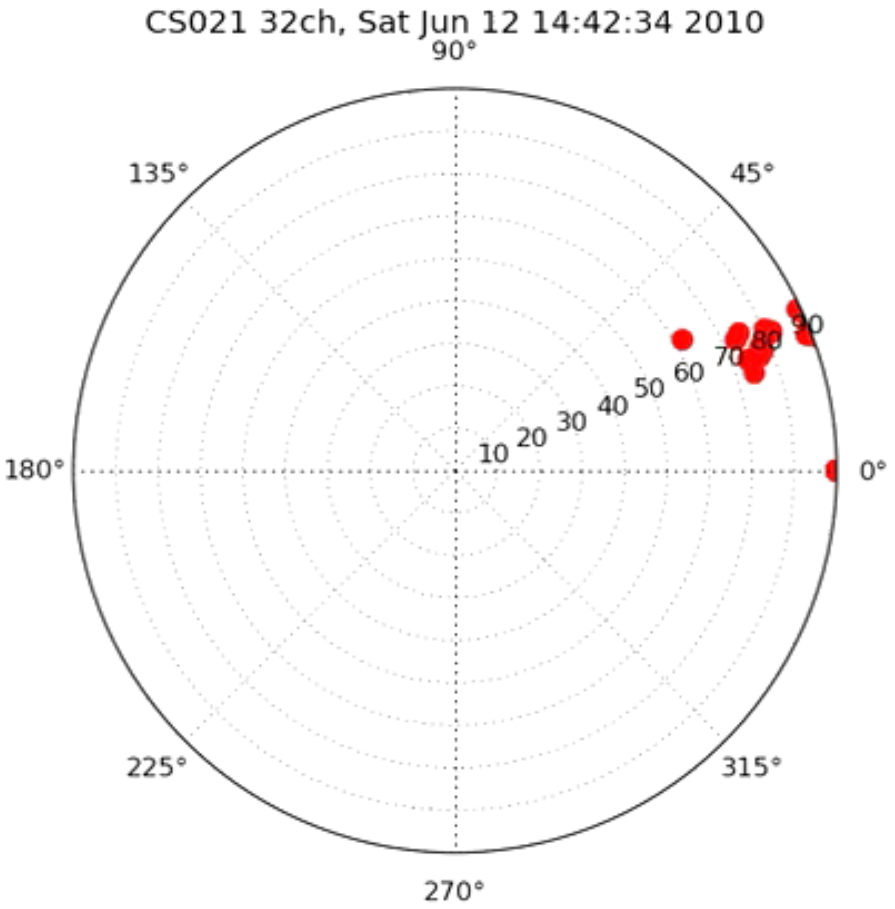
Cosmic Ray Detection with LOFAR

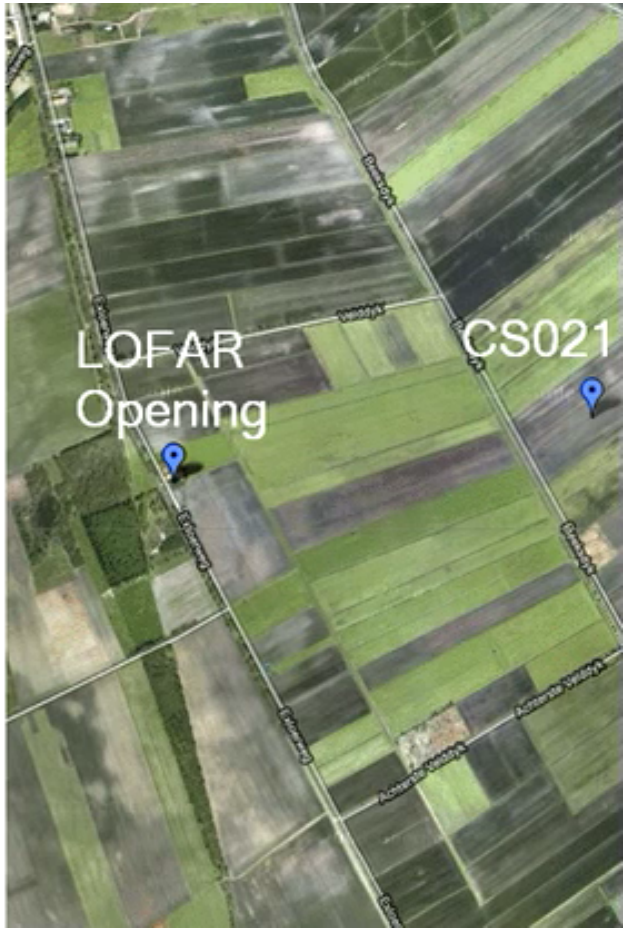
- VHECR mode
  - triggering / readout of individual antennas
  - 200 MHz digitized time-domain signal
  - self-trigger or external trigger

- HECR mode
  - triggering on coherent sum (beam) of antennas
  - trades sky coverage for lower energy threshold
  - still under development

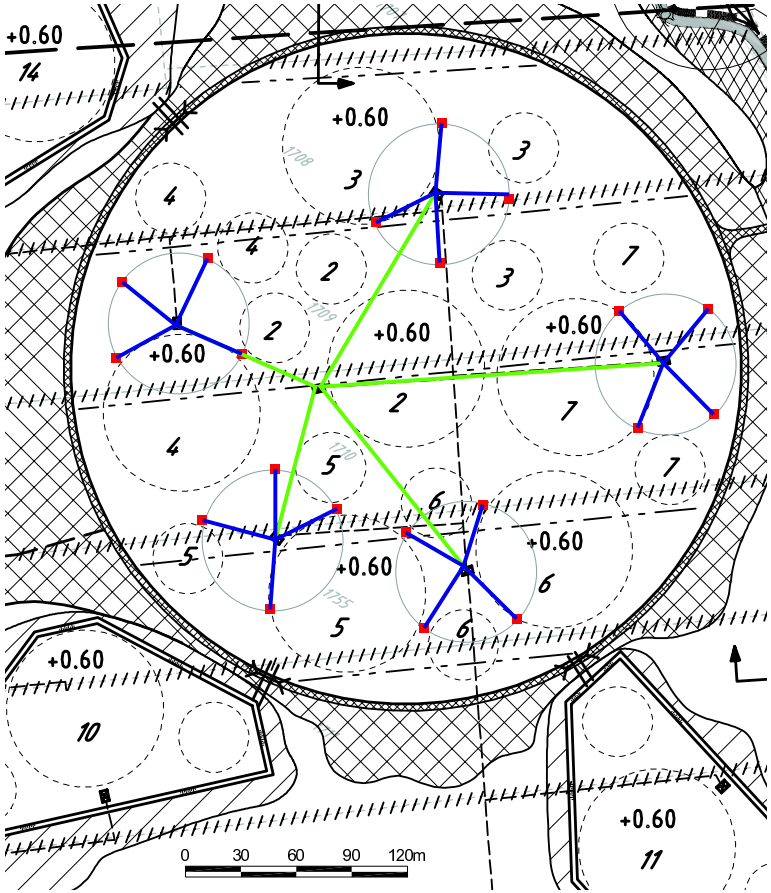
- UHEP mode
  - target Moon to search for CR / neutrino interactions in regolith
  - talks by S. ter Veen and O. Scholten

Self-Trigger: Operational



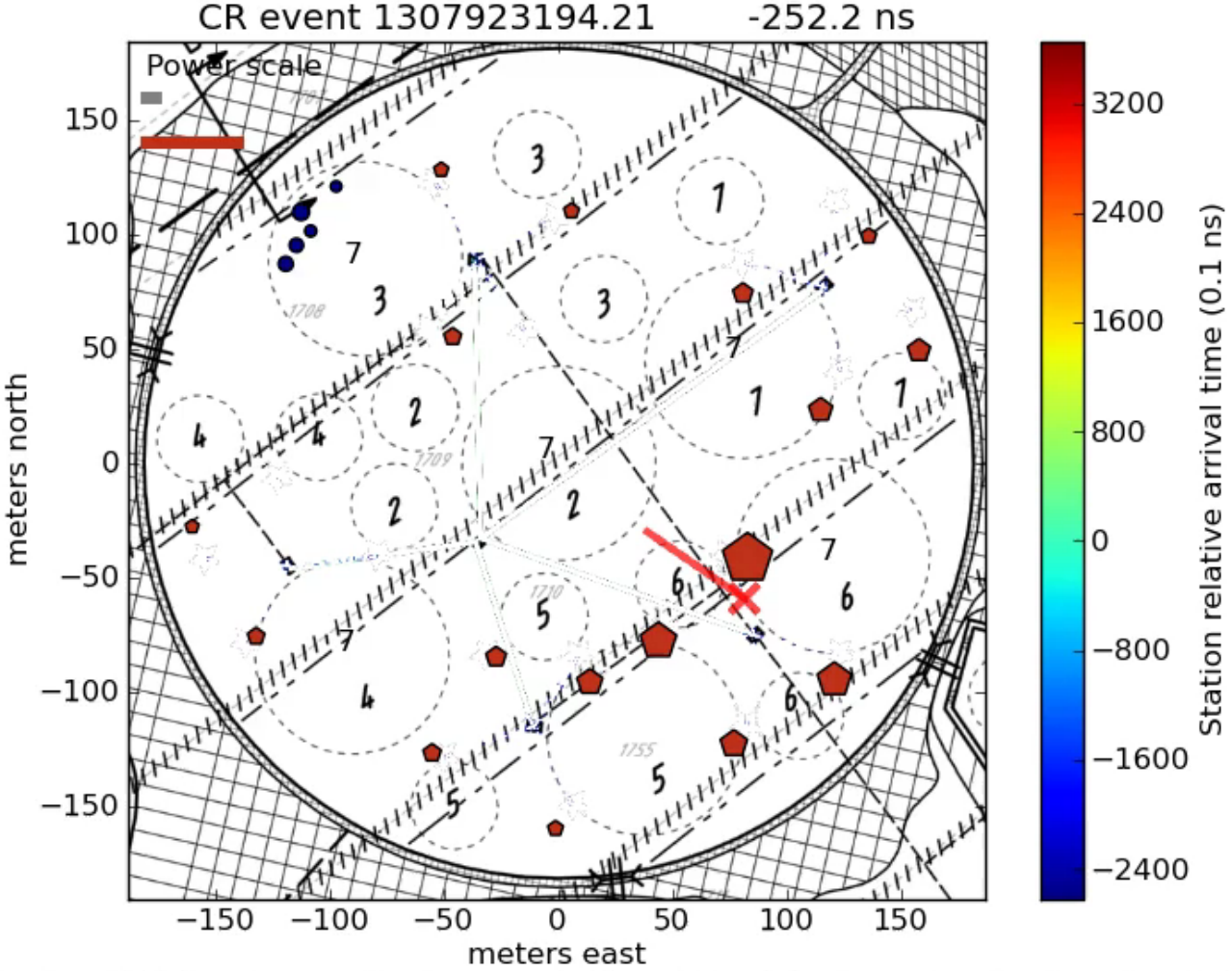


External Trigger



- Trigger LOFAR core with LORA scintillator array
  - essentially background-free
  - contribution by J. Hörandel
- Read out digital buffers of nearby stations
  - use core position and direction from LORA to seed reconstructions

First Cosmic Ray Events (July 2011)

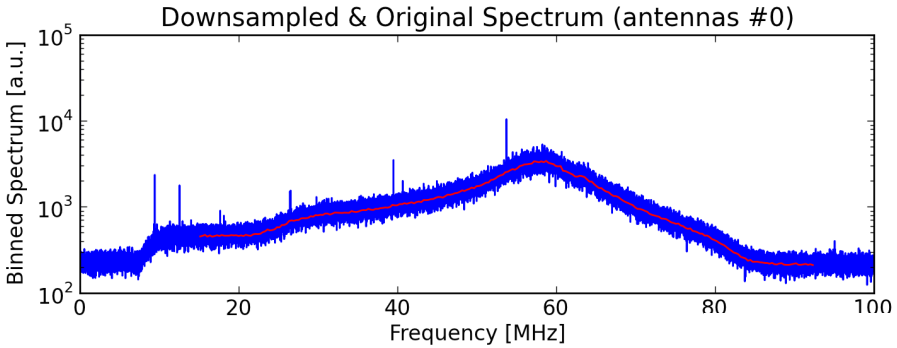


Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

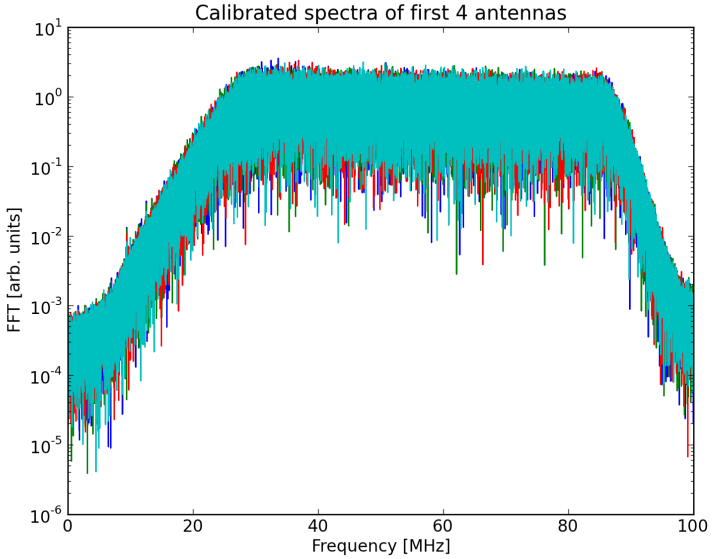
Analysis Pipeline and Data Quality

digitized antenna voltage

raw spectrum

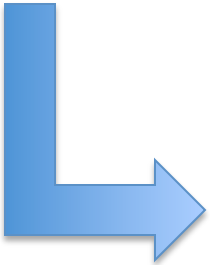


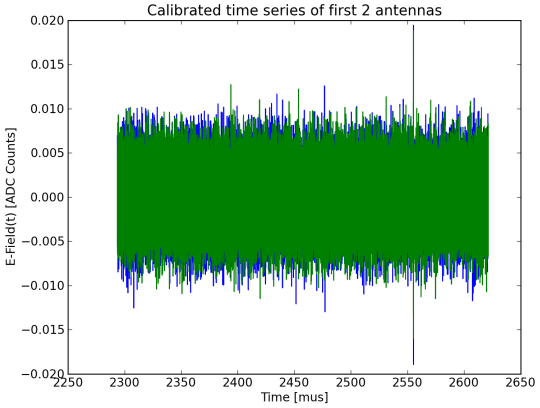
cleaned and normalized spectrum



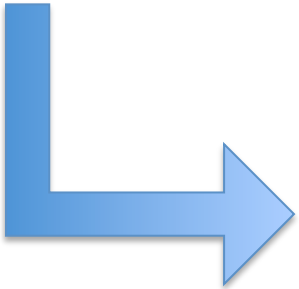
Analysis Pipeline and Data Quality (2)

cleaned spectrum

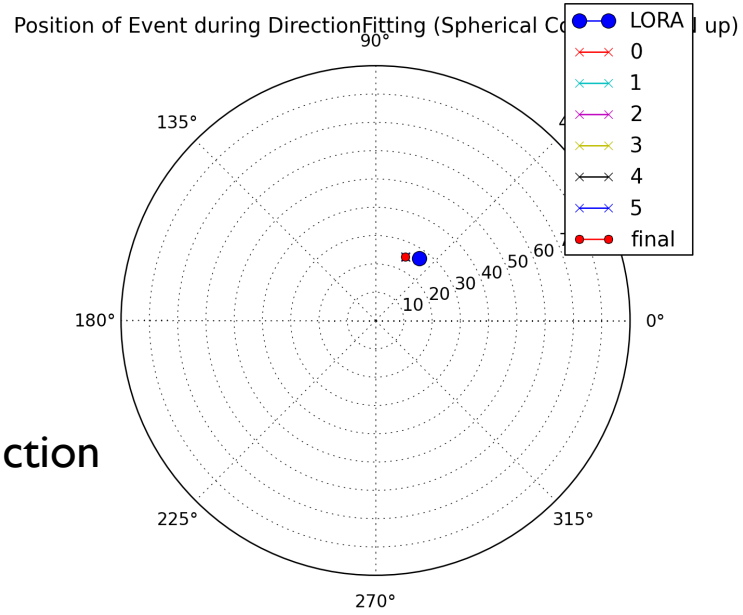




cleaned time series

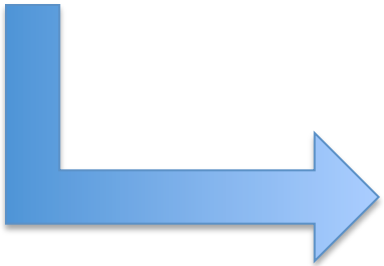


directional reconstruction

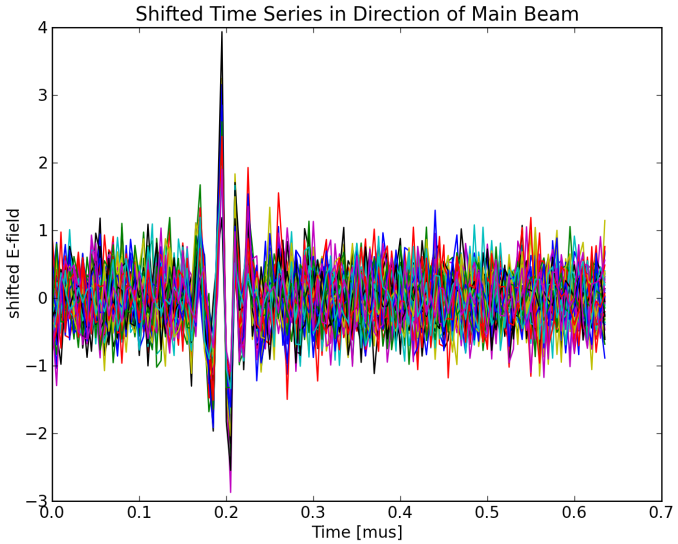


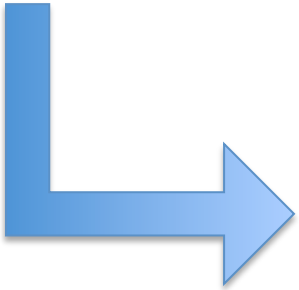
Analysis Pipeline and Data Quality (3)

directional reconstruction

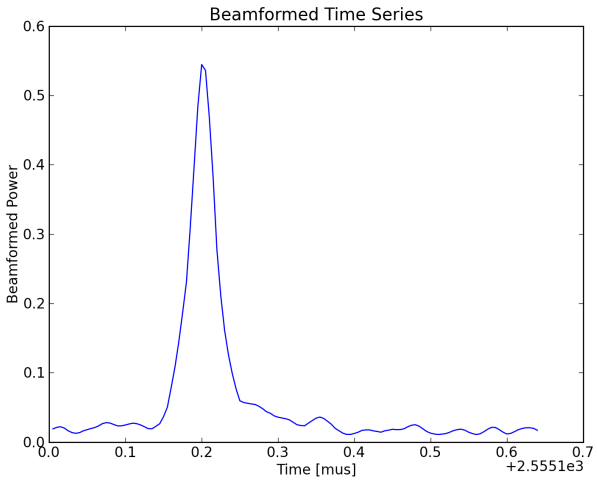


phase-shifted time series

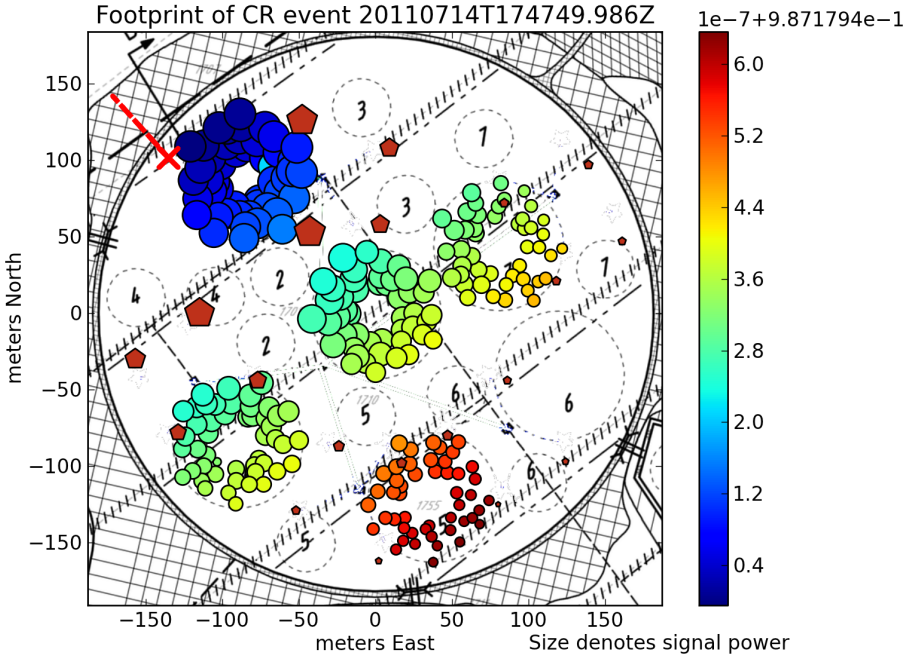


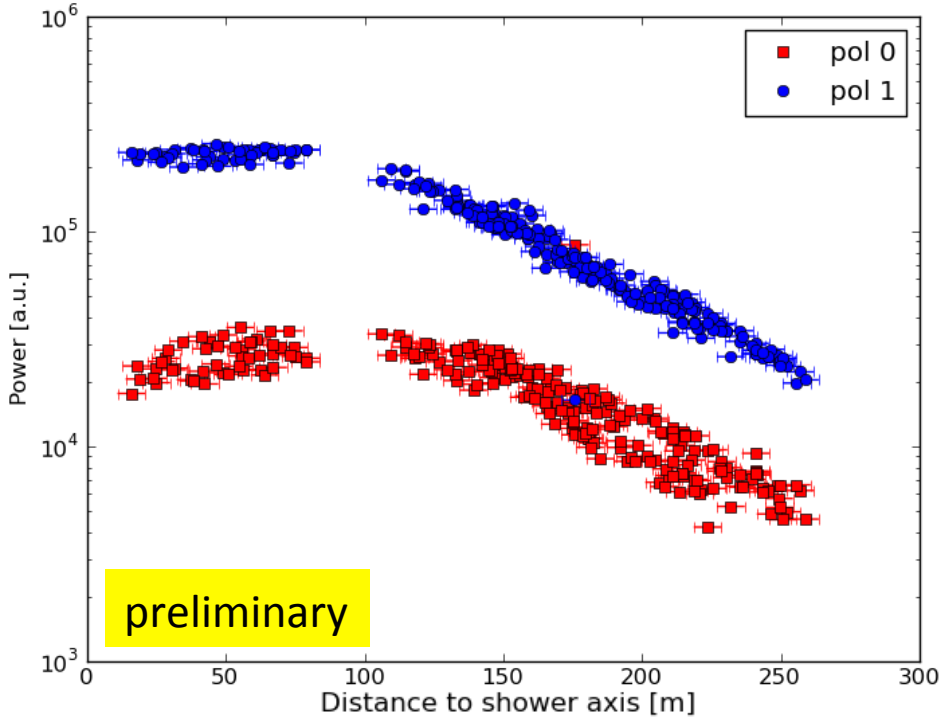


beam-formed radio signal



Footprint and Lateral Distribution





Most densely instrumented measurements of air shower radio emission!

Next Steps

- Self-triggered cosmic ray detection
- Improved calibration
  - time-dependent background modeling
  - antenna coupling effects
  - absolute electric field measurement
- Advanced wavefront reconstruction
  - shower development / composition!
- Multi-dimensional lateral distribution
  - understanding the radio signal in all its glory

Thank you (謝謝)!

LOFAR Cosmic Rays KSP is:

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