Radboud University
Nijmegen

Recent results from cosmic-ray measurements with LOFAR

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The Netherlands
(For the LOFAR Cosmic-ray Key-science project)

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Roma, Italy

The LOFAR cosmic-ray group:

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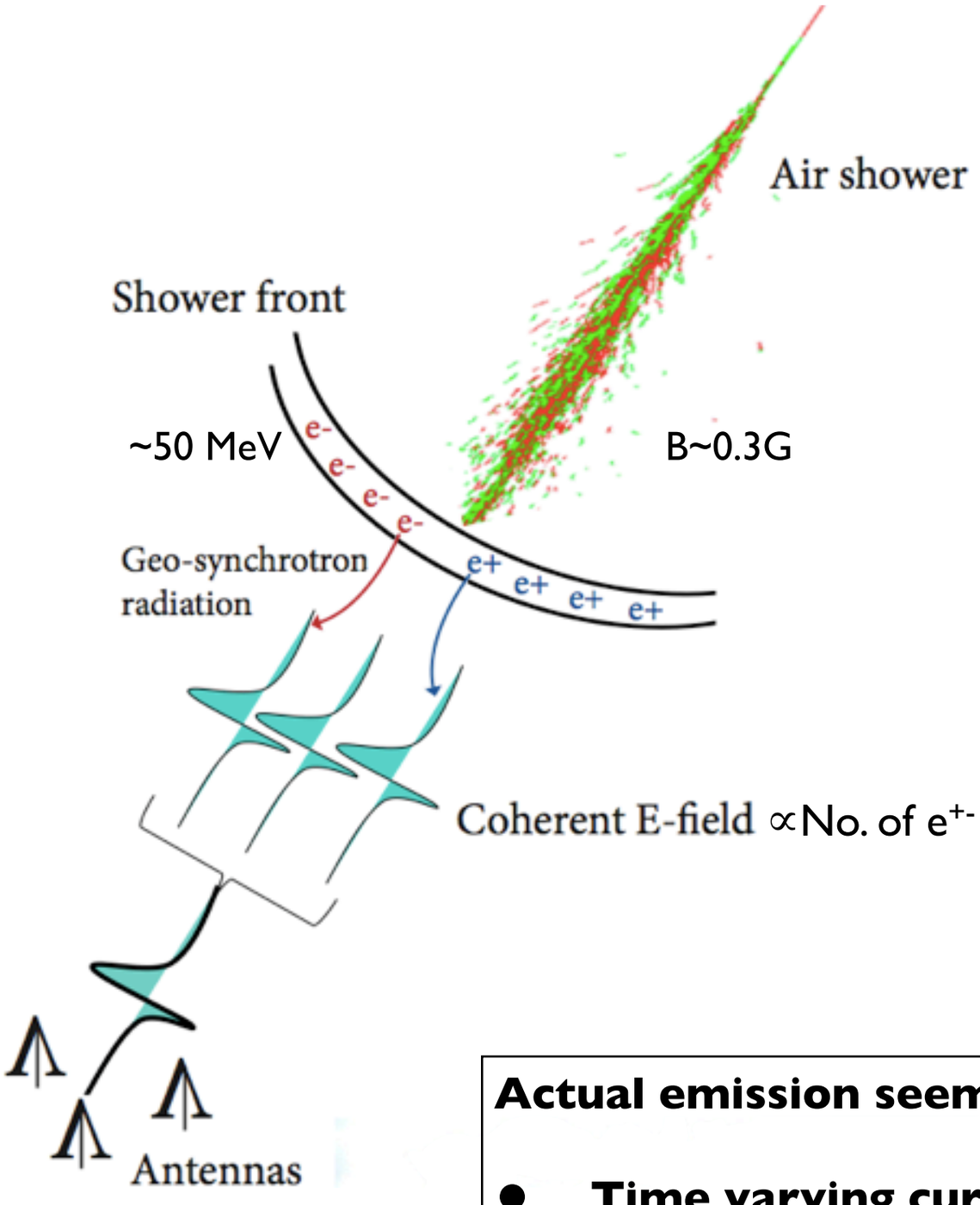
Radio emission from air showers



- **Shower disc is ~ (2-3)m thick**
- **e- & e+ produce (mostly) synchrotron radiation in geo-magnetic field**
- **This corresponds to a wavelength of ~ 100 MHz radiation**
- **Coherence effect expected at frequencies below ~100 MHz**

- **Two main contributions to signal:**

$$j' = (Q \cdot v)' = Q' \cdot v + Q \cdot v'$$

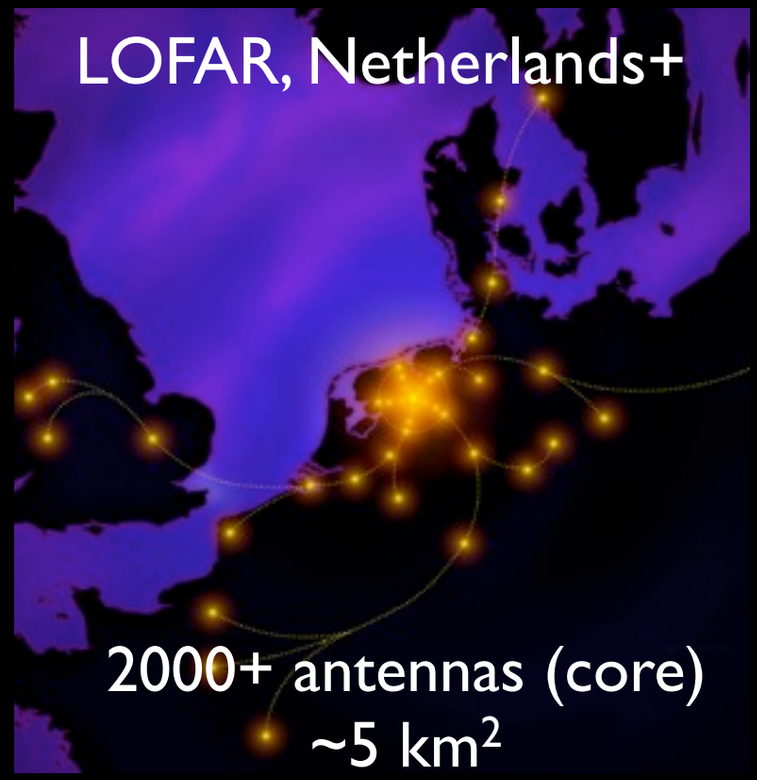
Total charge variation (~20%)

Synchrotron radiation (~80%)

Actual emission seems far more complicated:

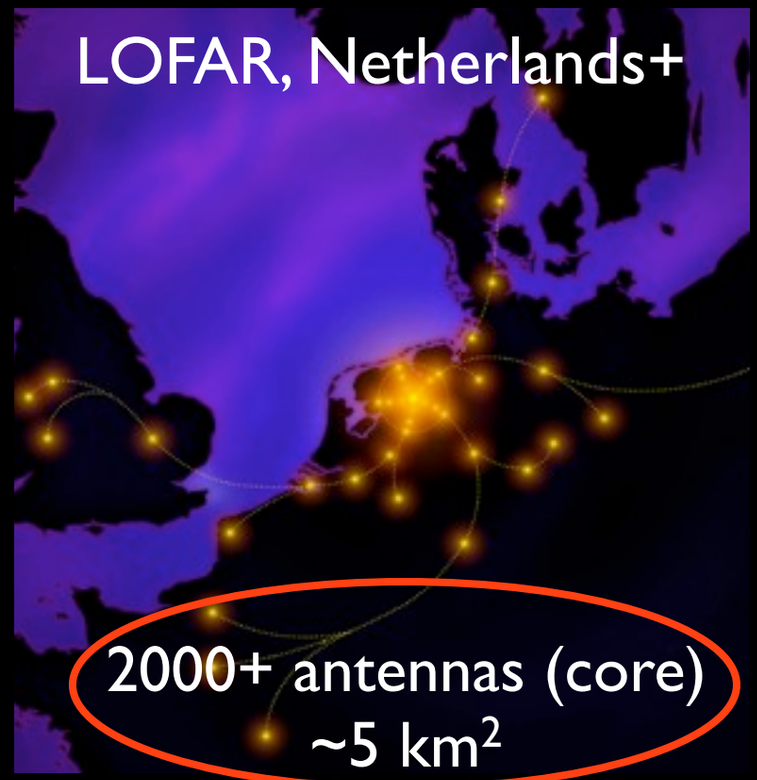
- **Time varying currents**
- **Cherenkov effects**
- **Transition radiation, ...**

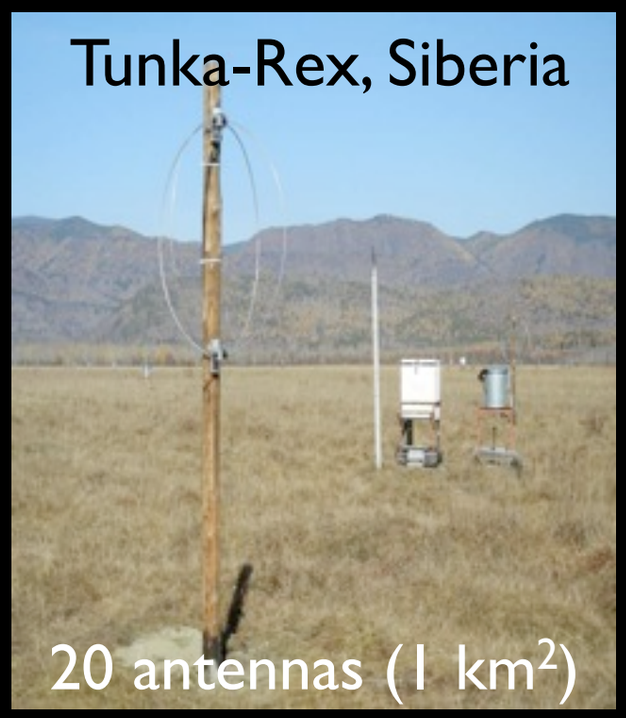
Air shower radio measurements:
Recent experiments



Air shower radio measurements:

Recent experiments





An ideal instrument to probe complex radio properties of air showers

LOFAR: The LOw Frequency ARray

(2013, A&A accepted, arXiv: 1305.3550)

- **An astronomical radio telescope in the Netherlands and its neighboring countries**

- **33 Dutch + 8 International stations**

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- **Replaced big dishes by many cheap dipole antennas**

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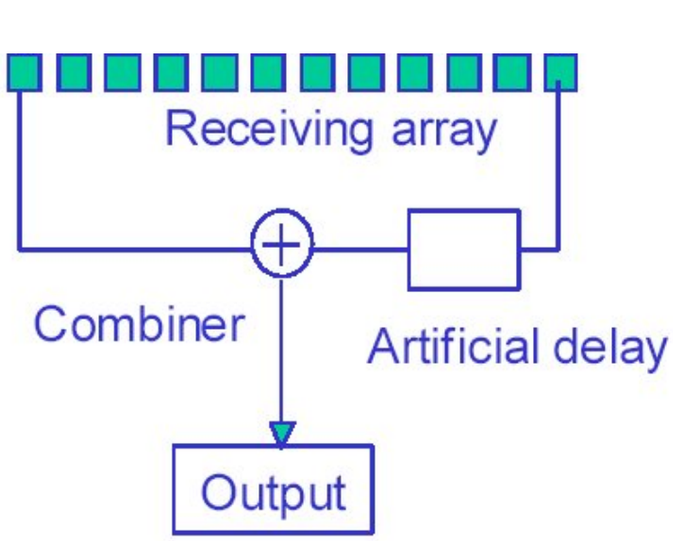
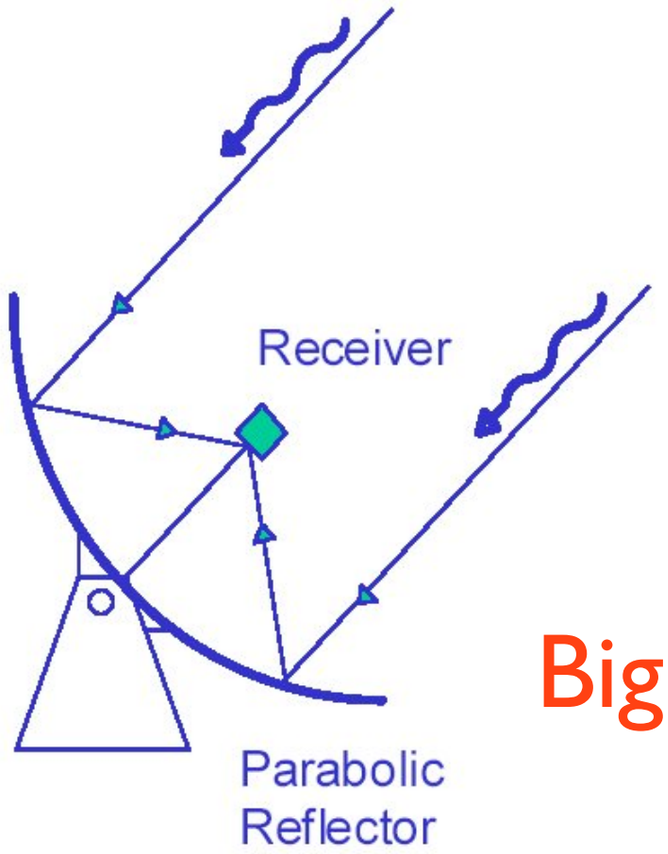
- **An astronomical radio telescope in the Netherlands and its neighboring countries**
- **33 Dutch + 8 International stations**
- **Replaced big dishes by many cheap dipole antennas**
- **24 stations in a dense core of ~5 km² in the Netherlands**
- **Each station consists of 96 low band + 48 high band antennas**
- **Low band: (10-80) MHz and High band: (100-240) MHz**
- **For air shower measurements: Only core stations ~ 2000+ low band antennas**

LOFAR: Phased Array Detectors

- **It can point to different directions in the sky at one time**
- **Also, useful for cosmic-ray measurements**

LOFAR





Big dishes

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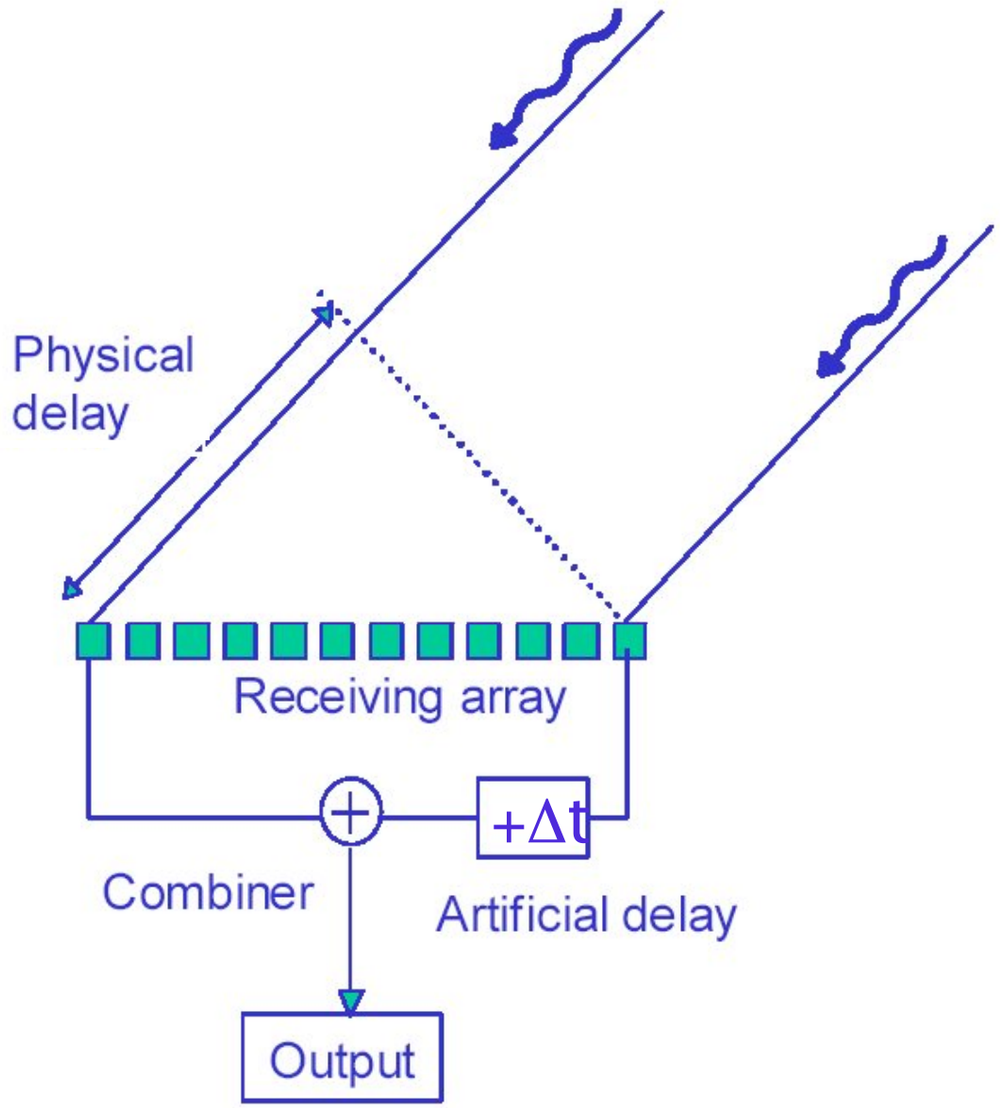

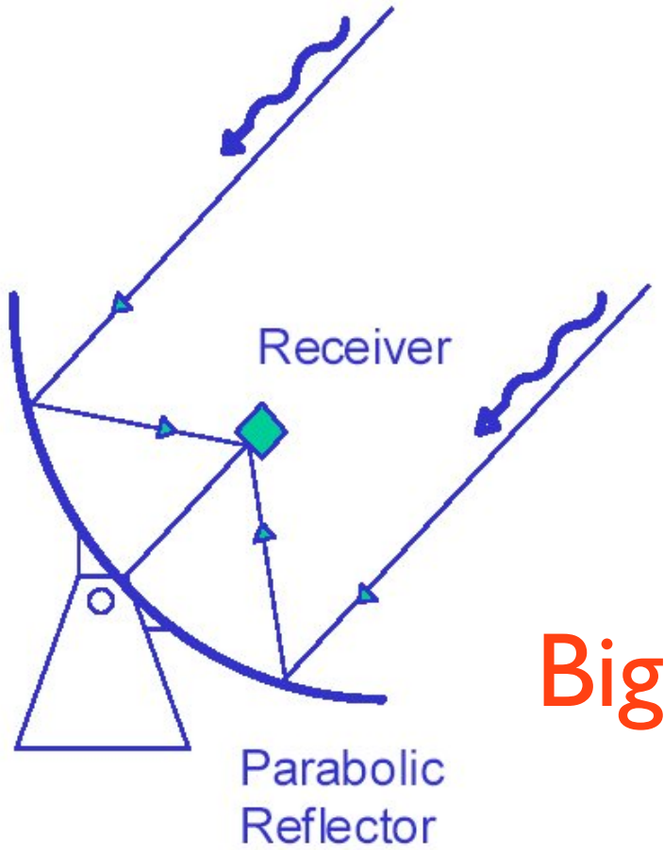

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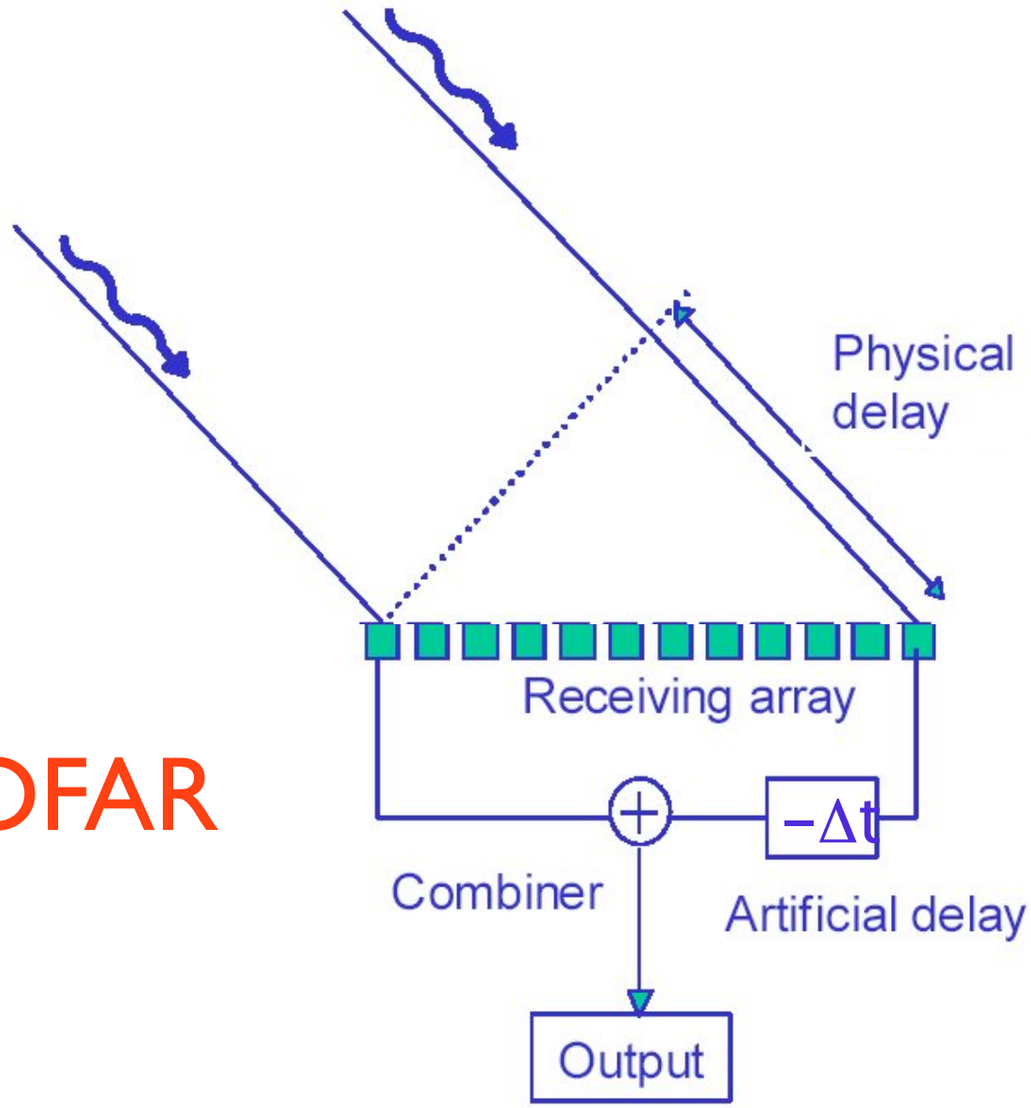

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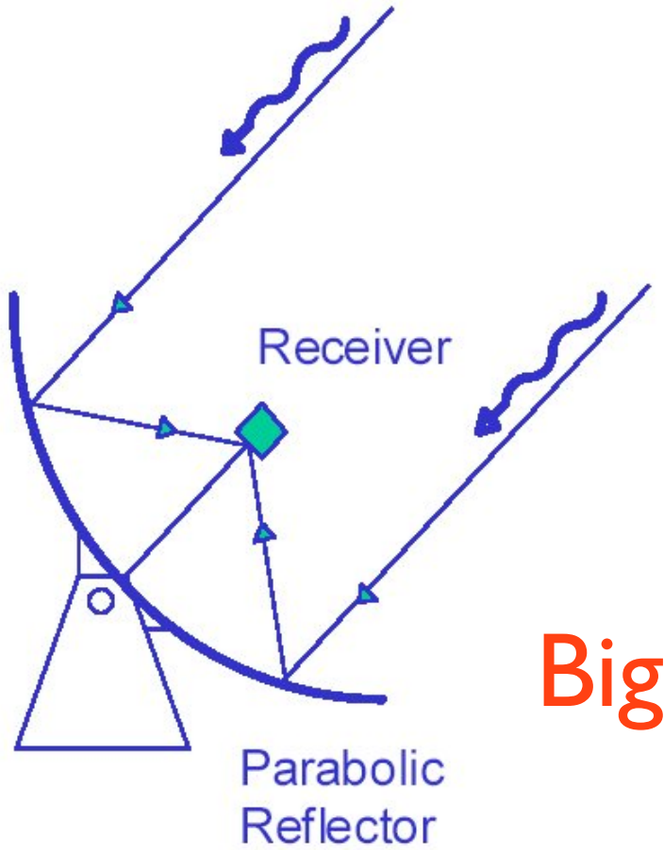

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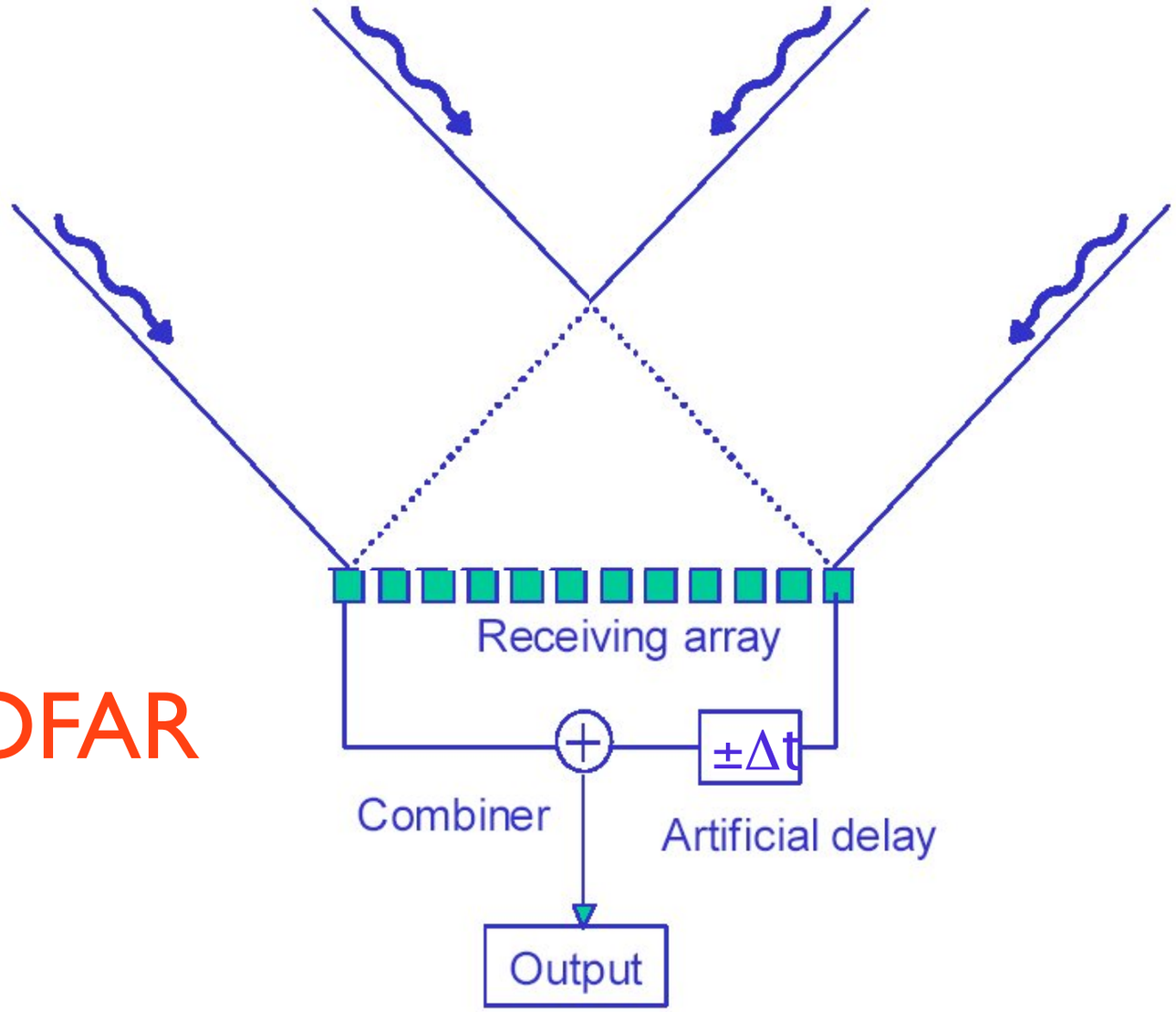
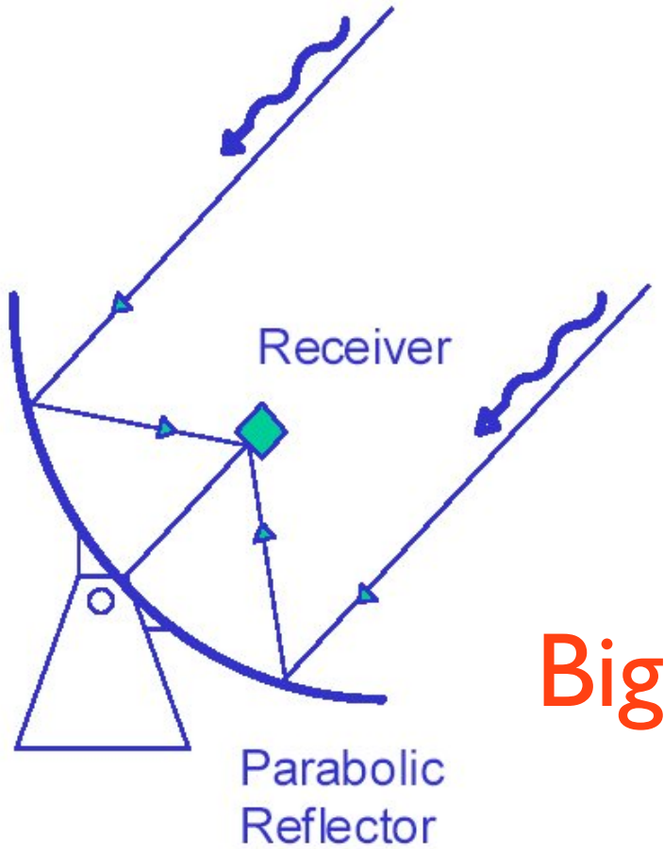
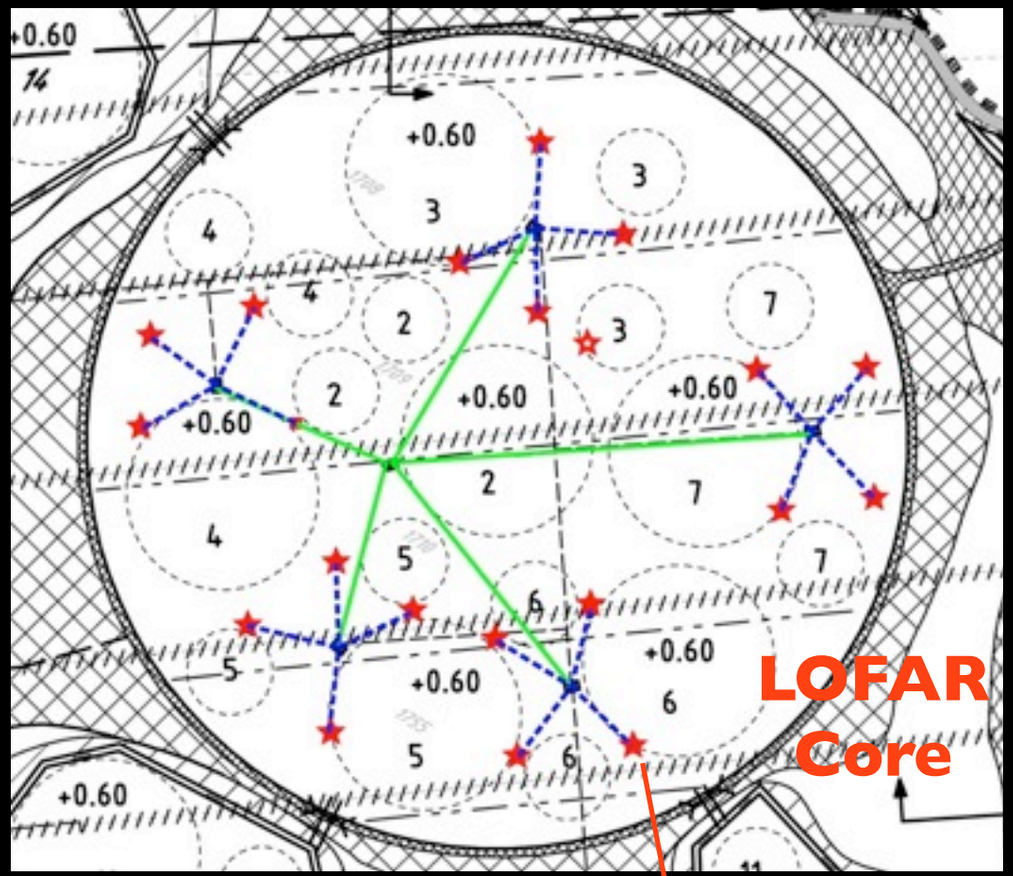


LOFAR

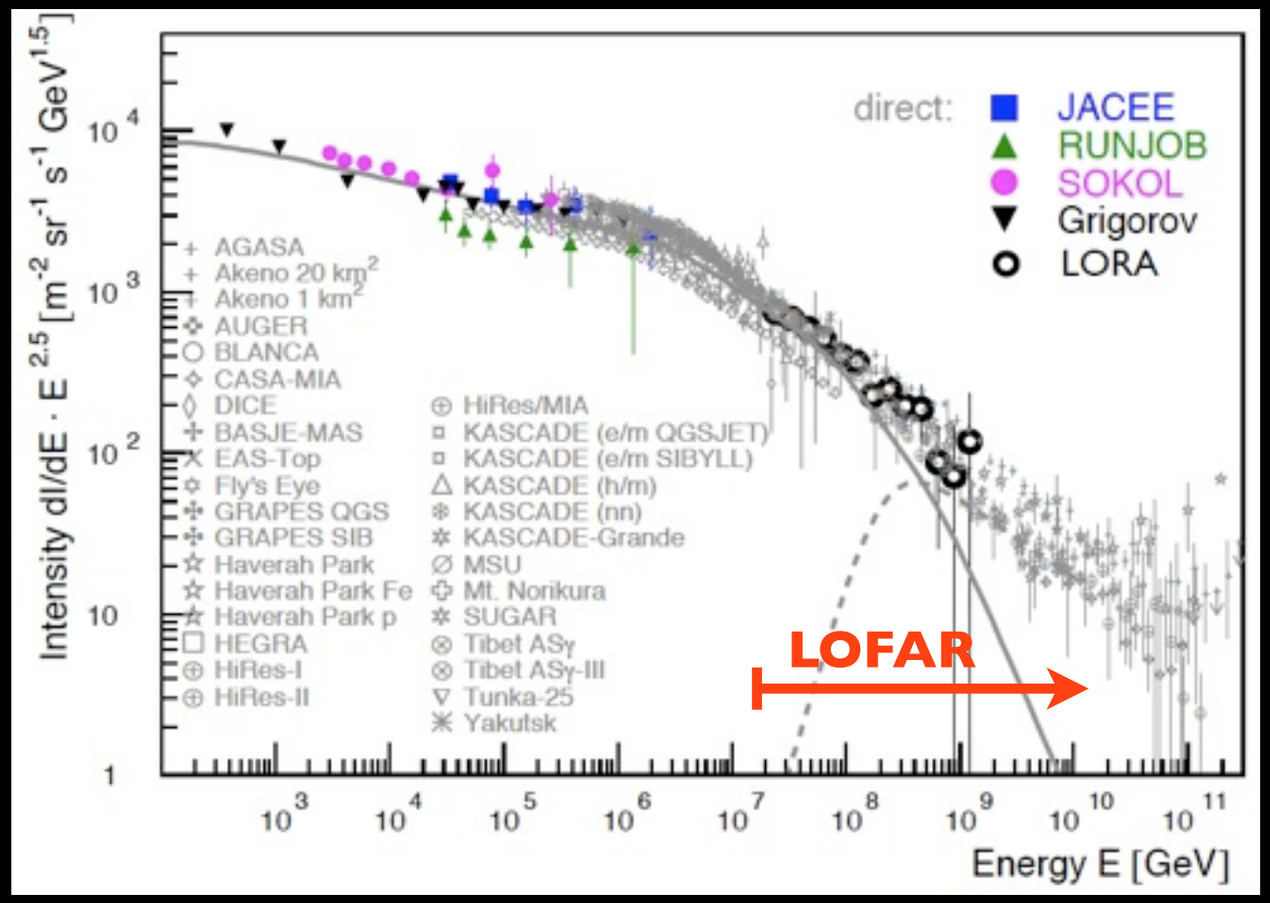


Big dishes

LORA: LOFAR Radboud air shower Array



- Purpose is to provide:
  - CR trigger to LOFAR
  - Air shower parameters
- 20 scintillation detectors
- Detector spacings ~ 50-100 m
- Energy range > 10^{16} eV
- Energy resolution ~30%
- Core position accuracy <5m
- Arrival direction accuracy <1°



Cosmic-ray observation

CR event

LORA

*Online processing

*Determine shower parameters

*Overall processing time ~ (100+30) ms

*For bright events (>10^{16} eV):
Send trigger to LOFAR

* Trigger rate ~ 1/hr

LOFAR

(Data stored in a memory ring buffer for 1.3 s)

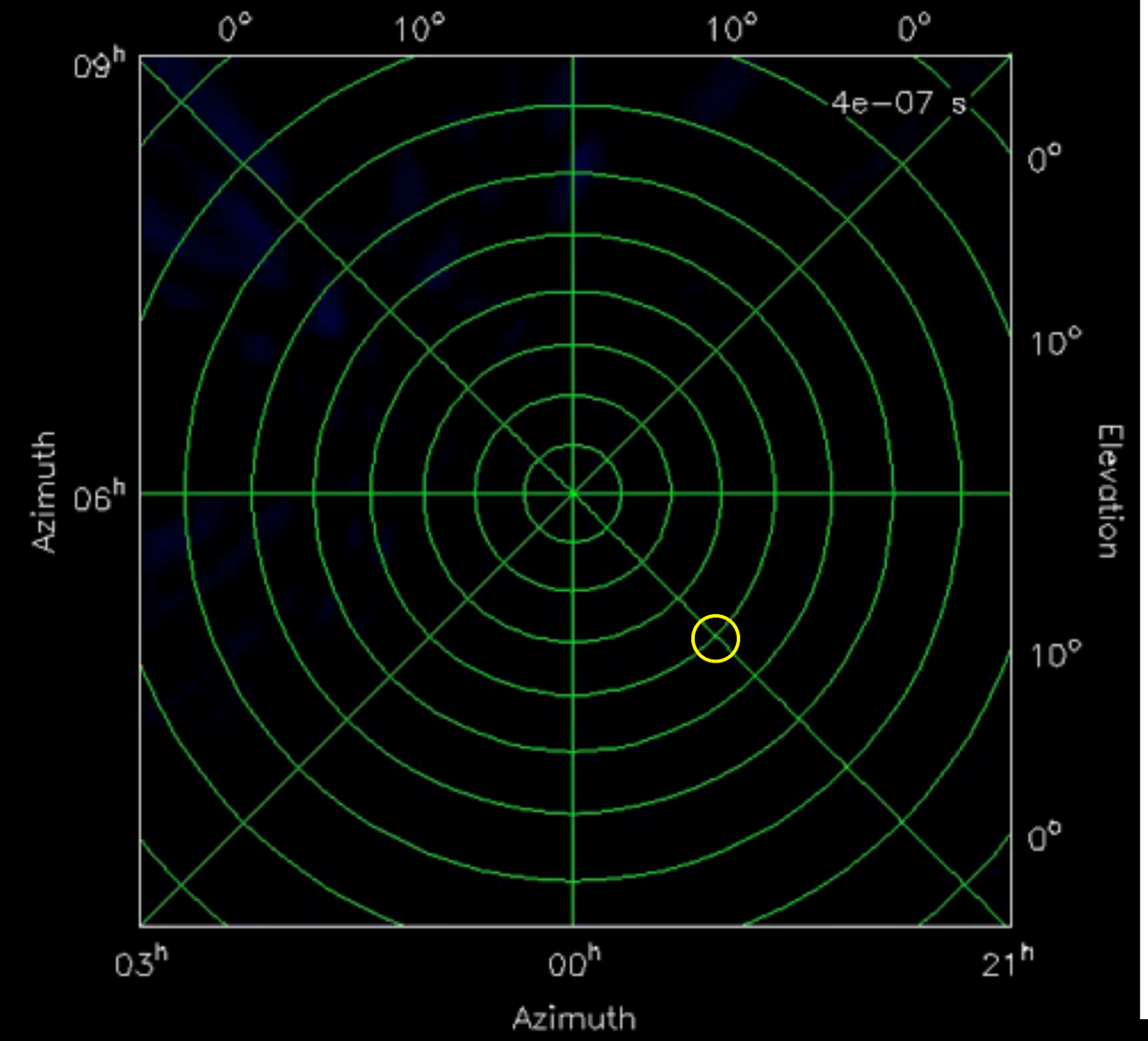
*Dump radio data

***LOFAR started taking data in June 2011**

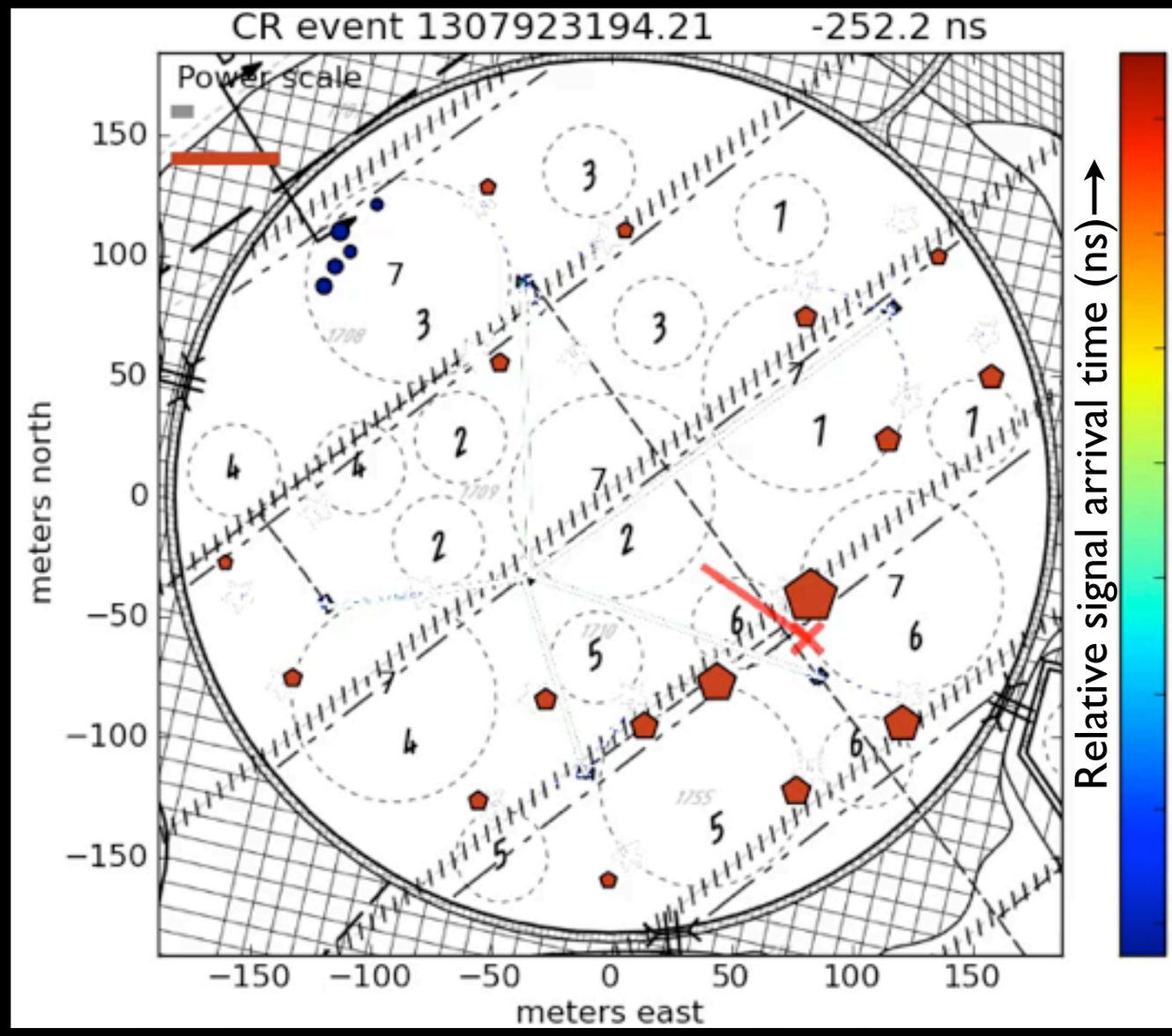
***Regular observation started early 2012**

***Collected ~400 good quality events**

A measured cosmic-ray event



○ LORA directional estimate



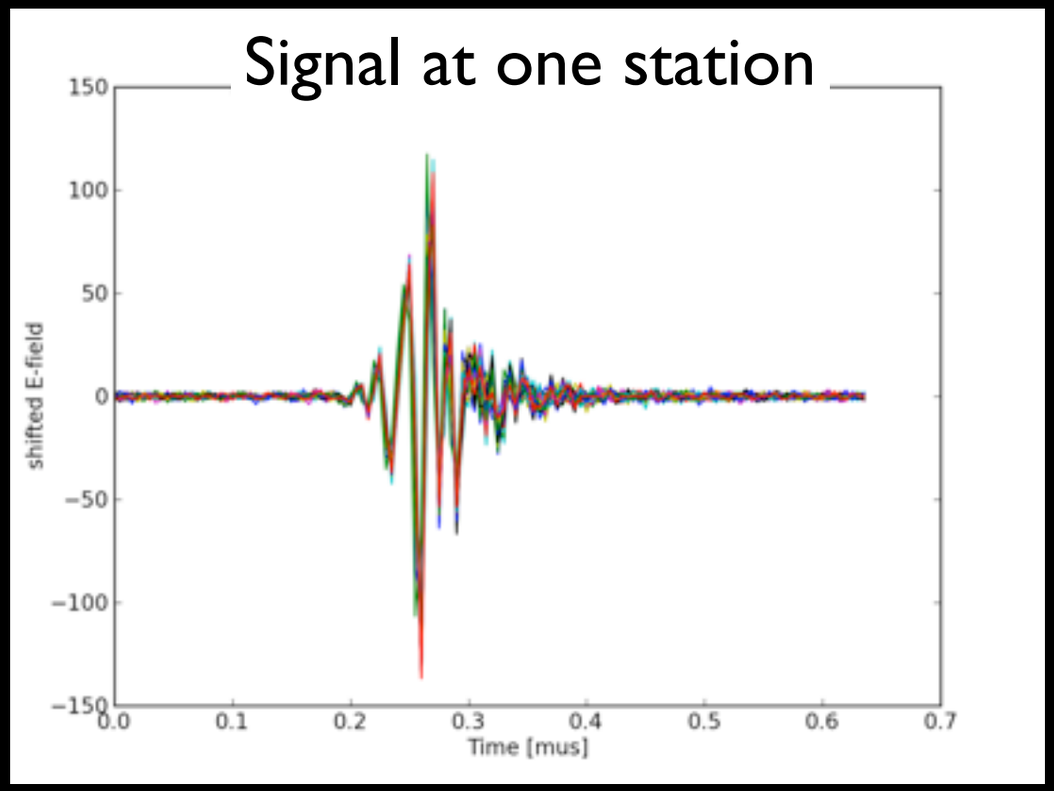
○ LOFAR antennas

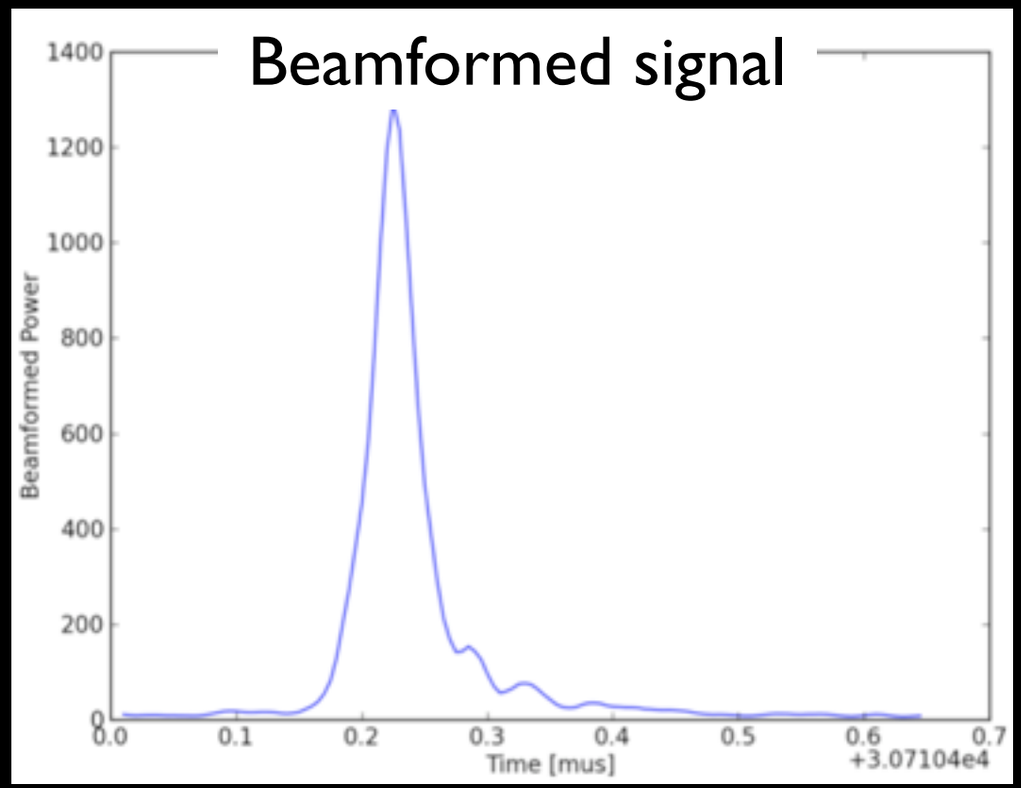
⬟ LORA detectors

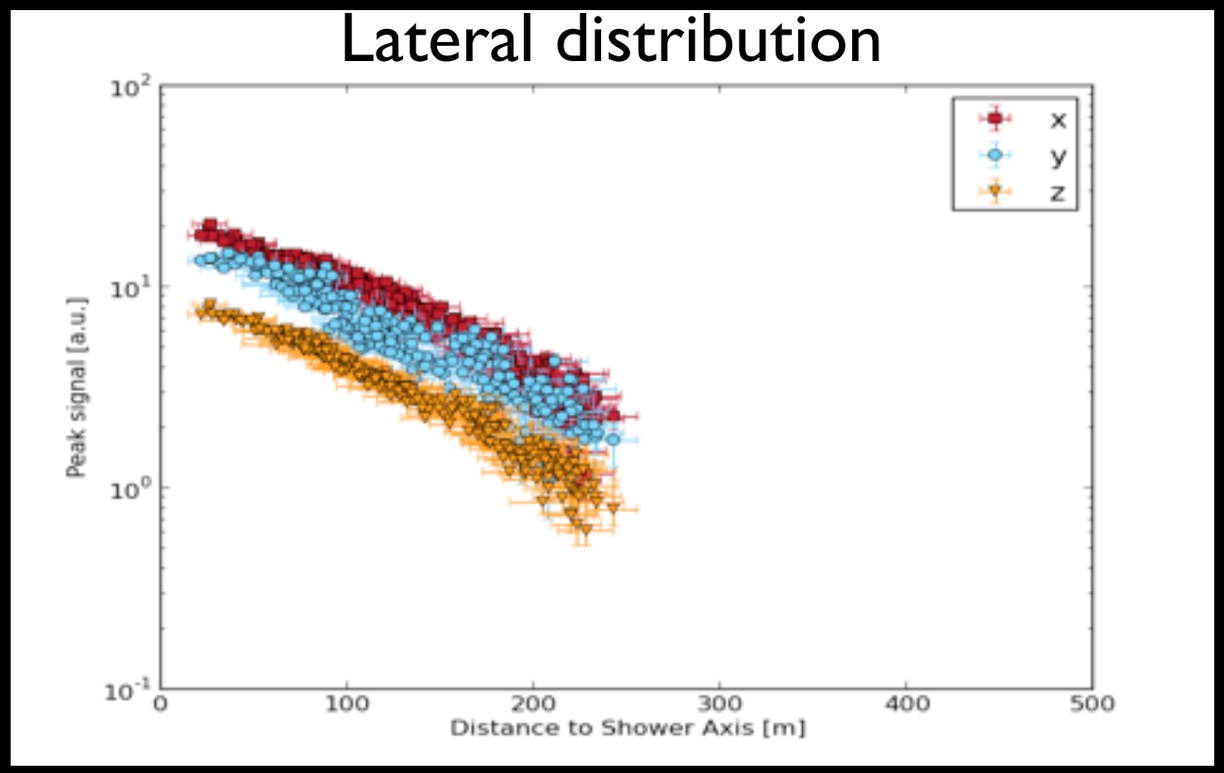
Size denotes signal strength

P. Schellart

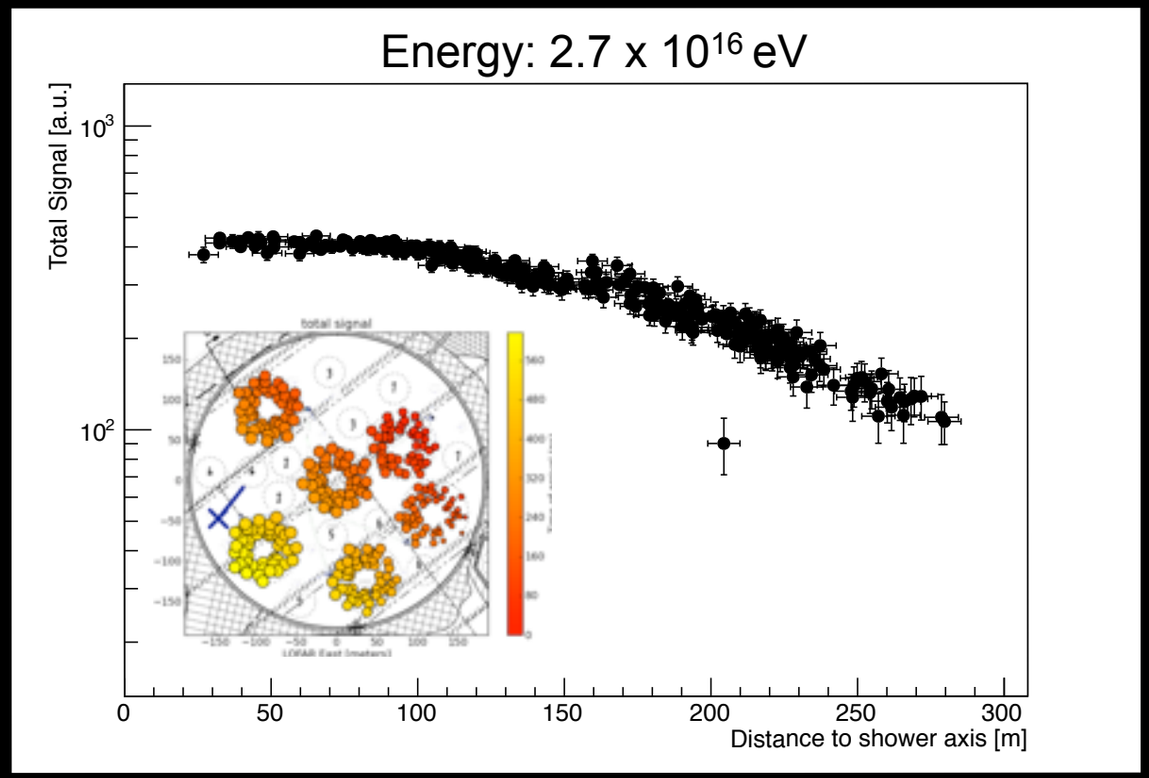
A measured cosmic-ray event

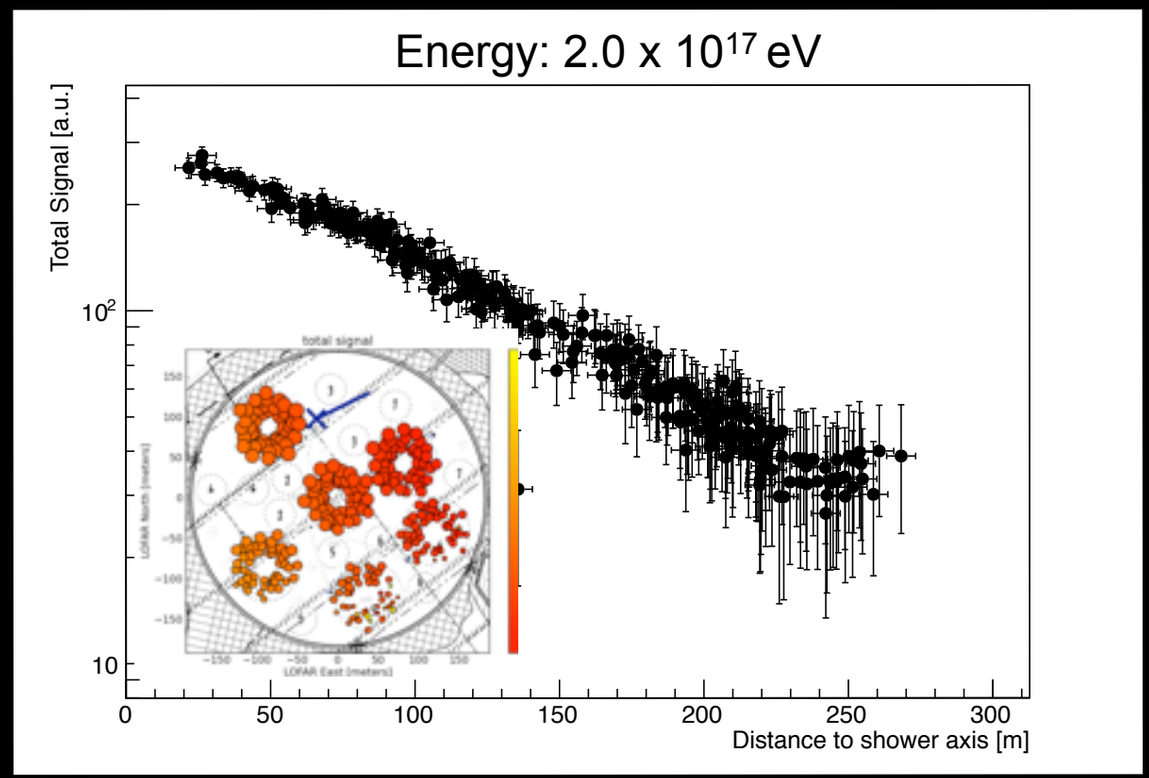


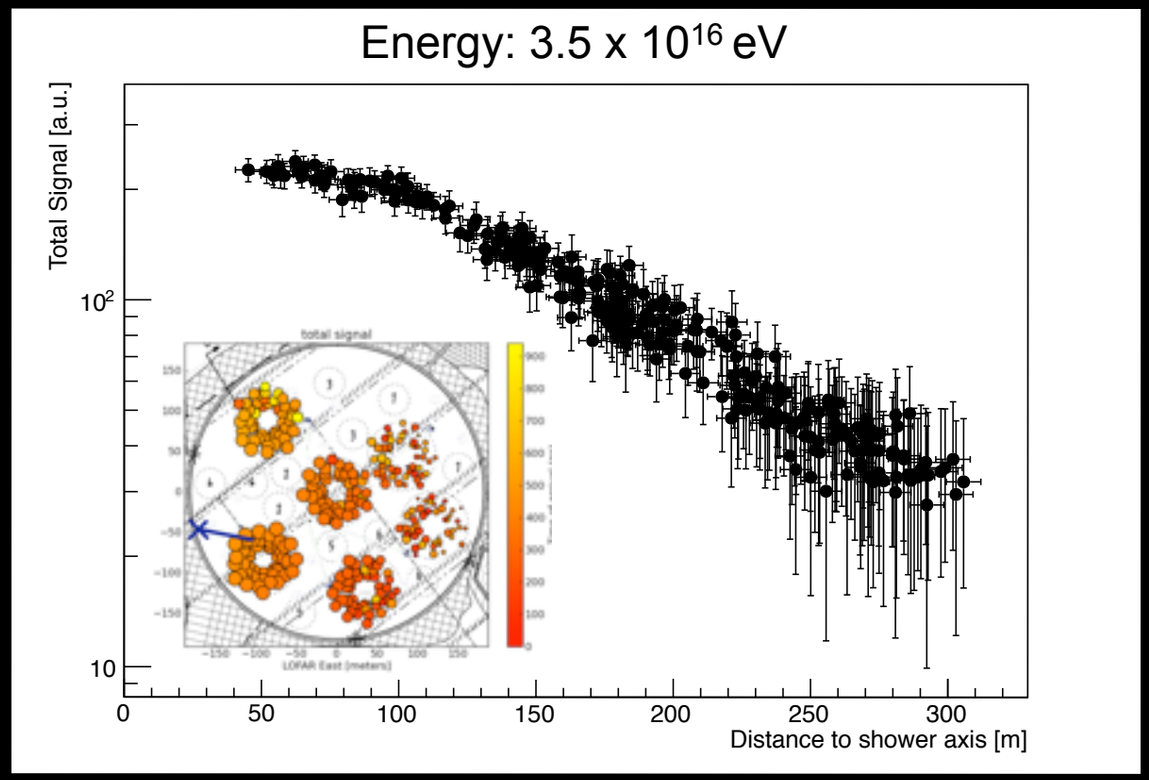


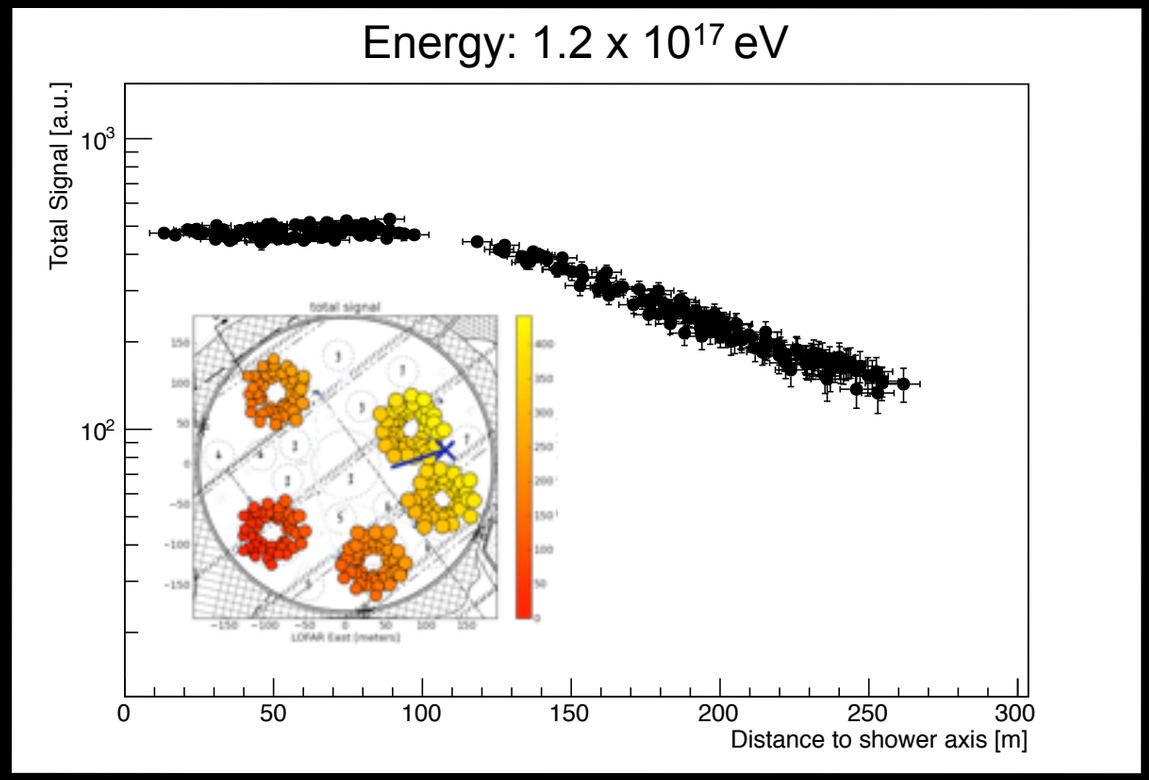


More events





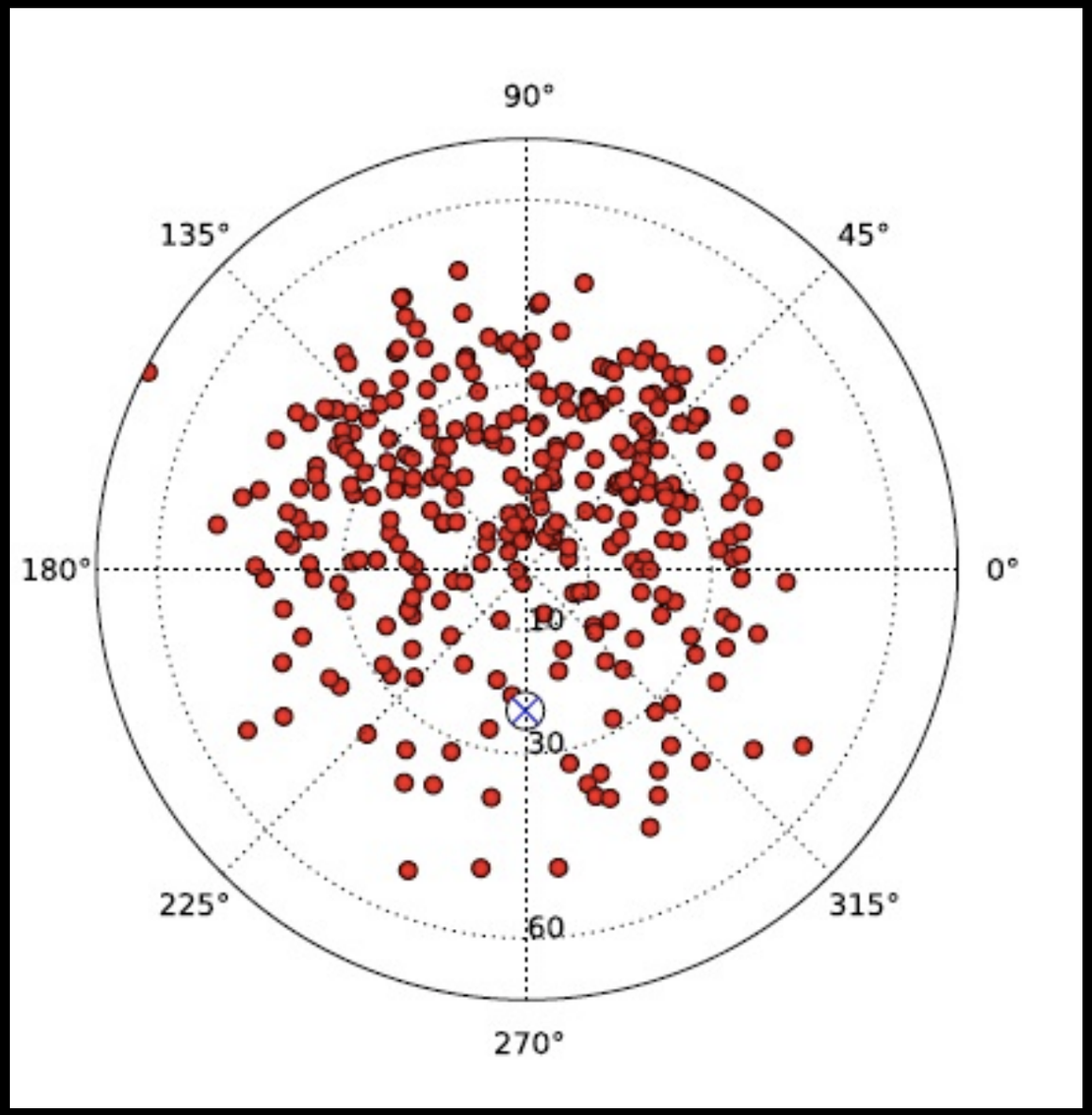




P. Schellart, A. Nelles

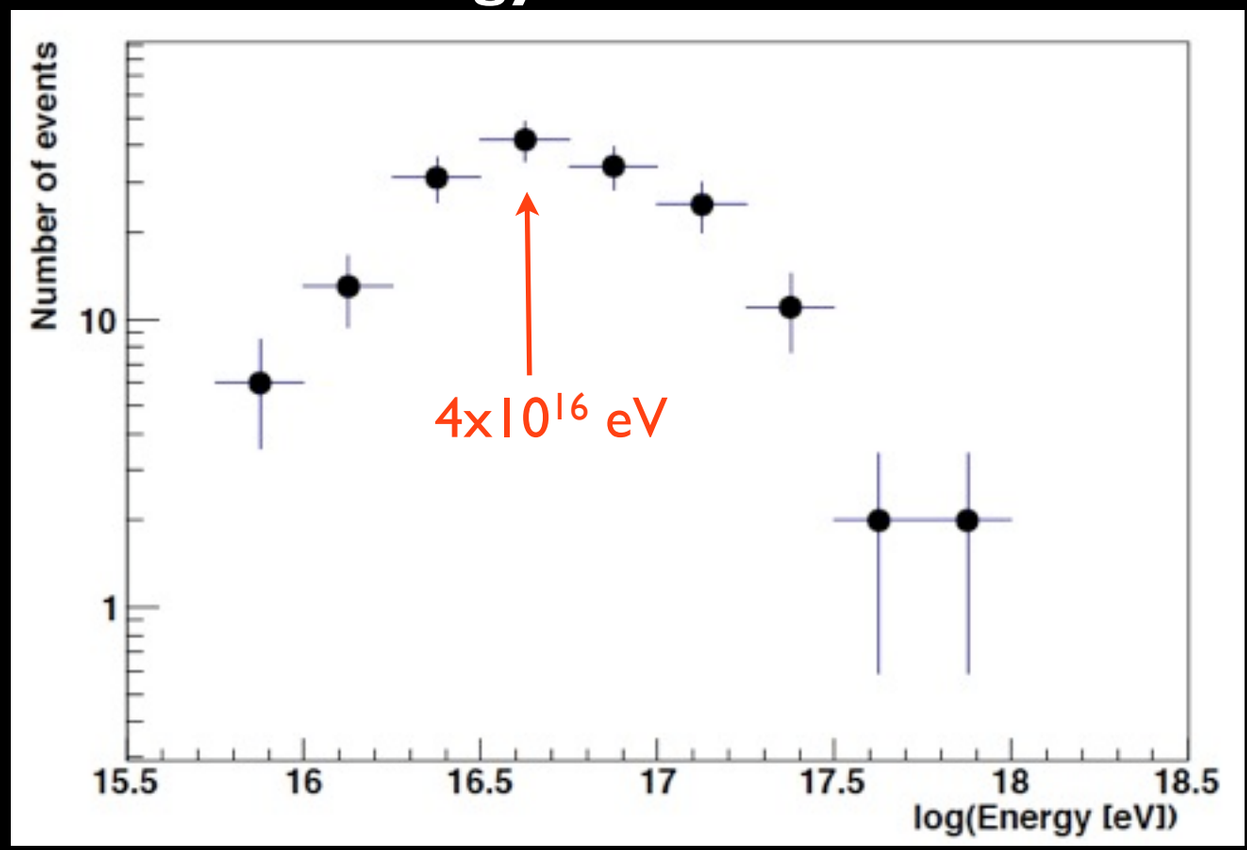
Measured distribution of events

Arrival direction distribution



- **All events triggered by LORA**
- **367 events fully reconstructed**
- **North-South asymmetry: (vxB) effect**

Energy distribution



P. Schellart, A. Nelles

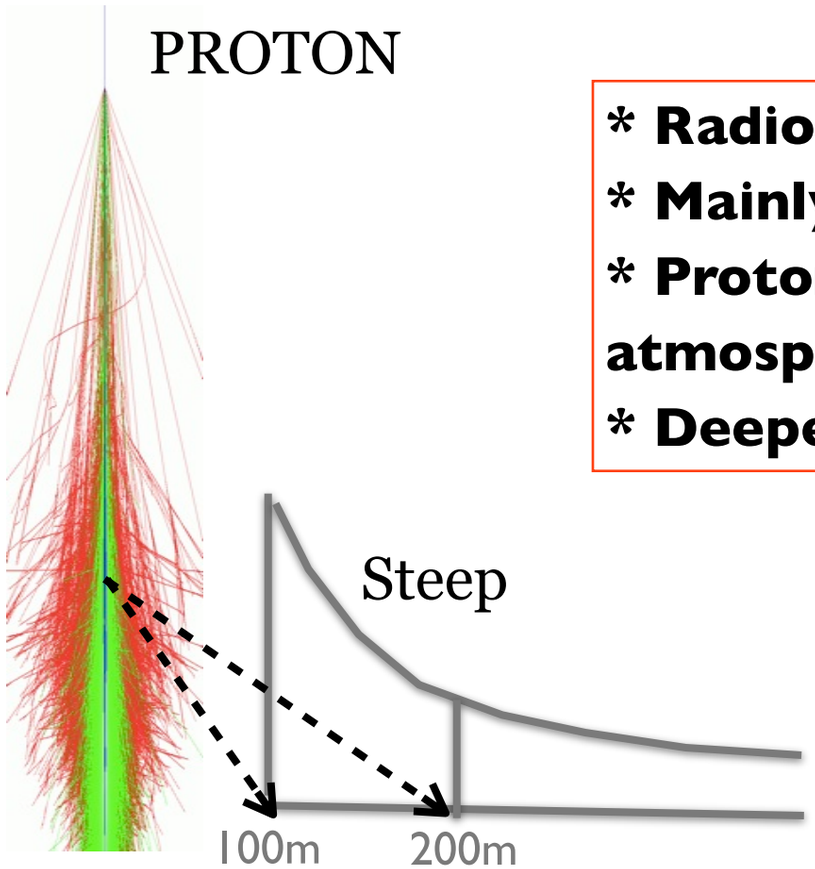
On-going works

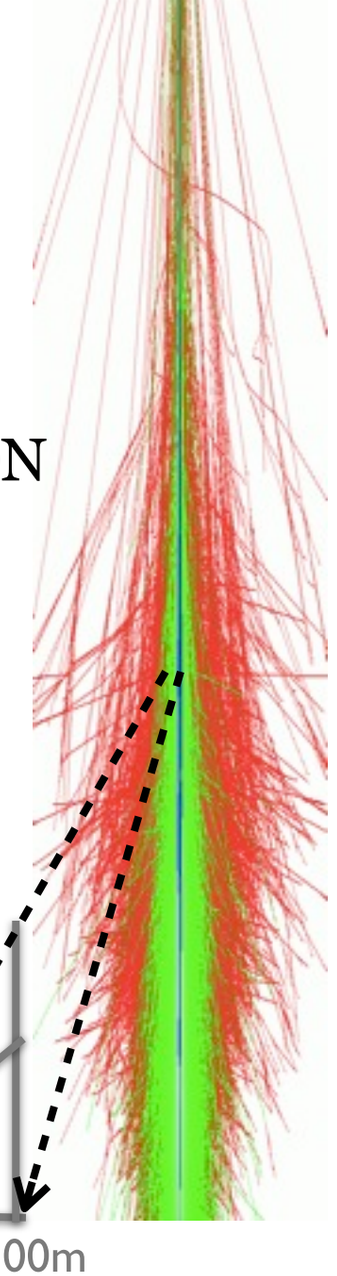
X_{max} measurements

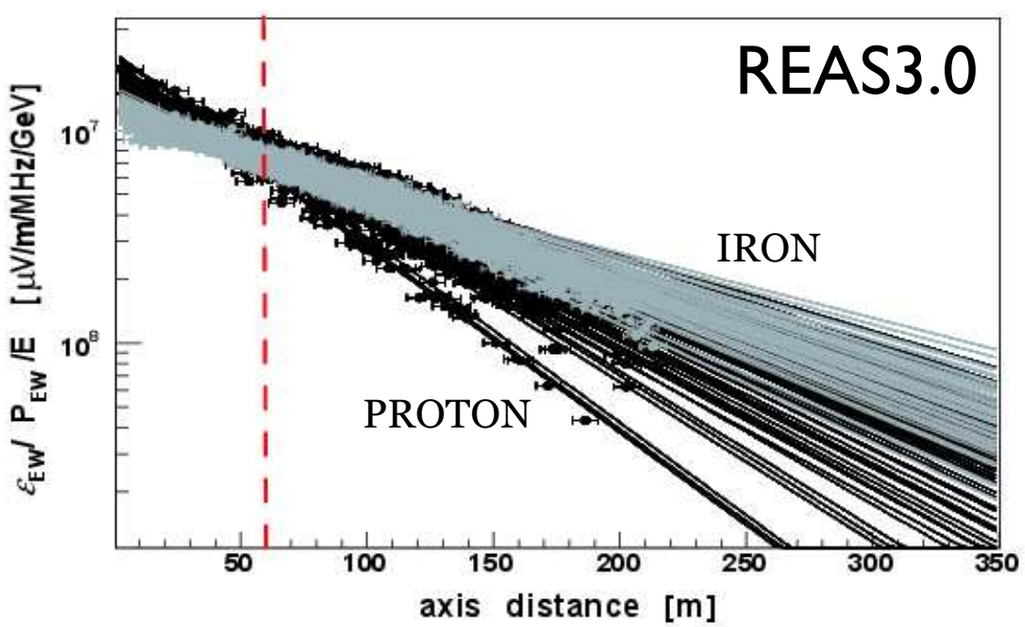
PROTON

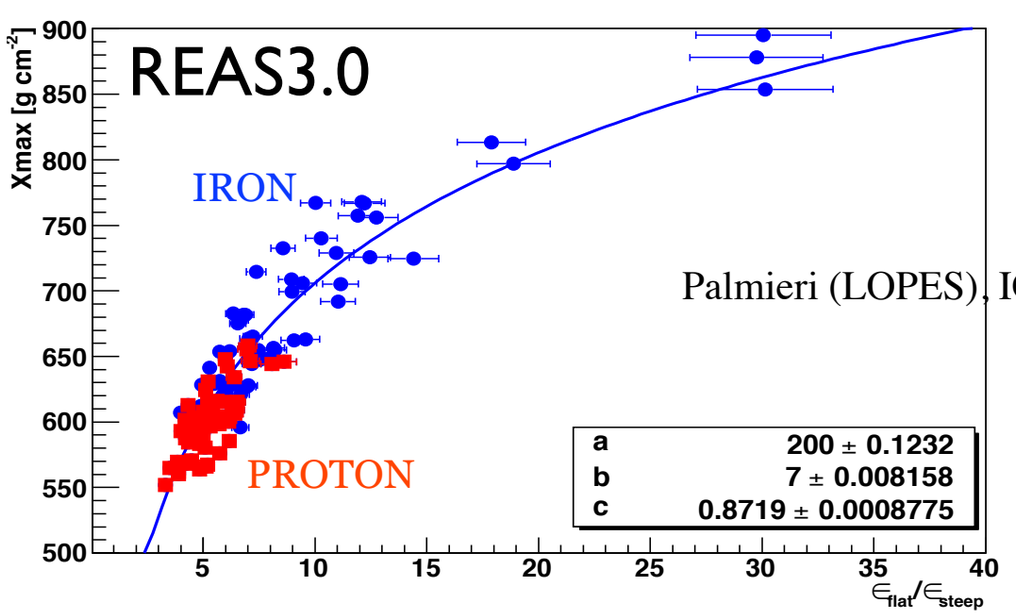
IRON

* Radio lateral distribution is sensitive to X_{max}
* Mainly due to geometrical effect
* Protons penetrate deeper into the atmosphere
* Deeper Xmax=> Steeper distribution



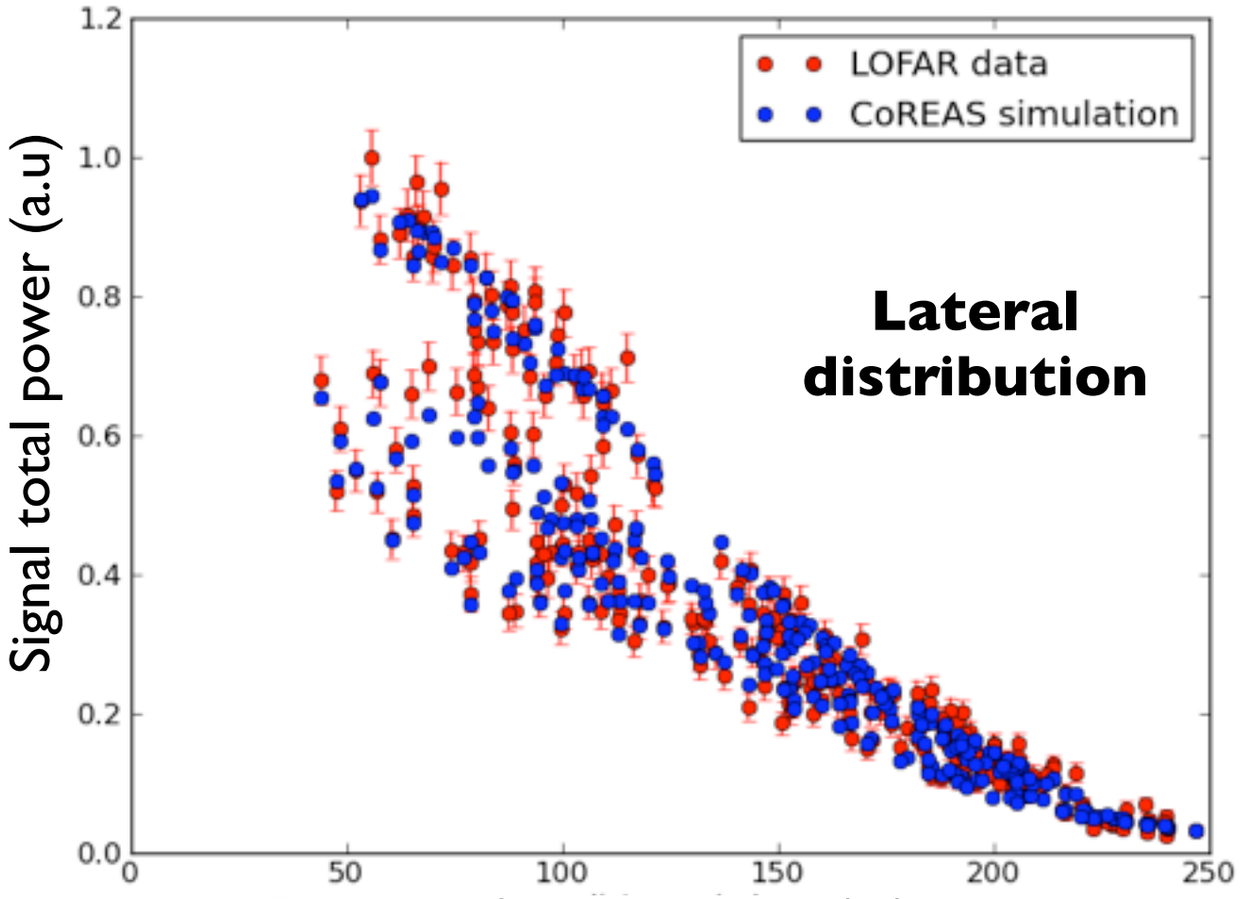


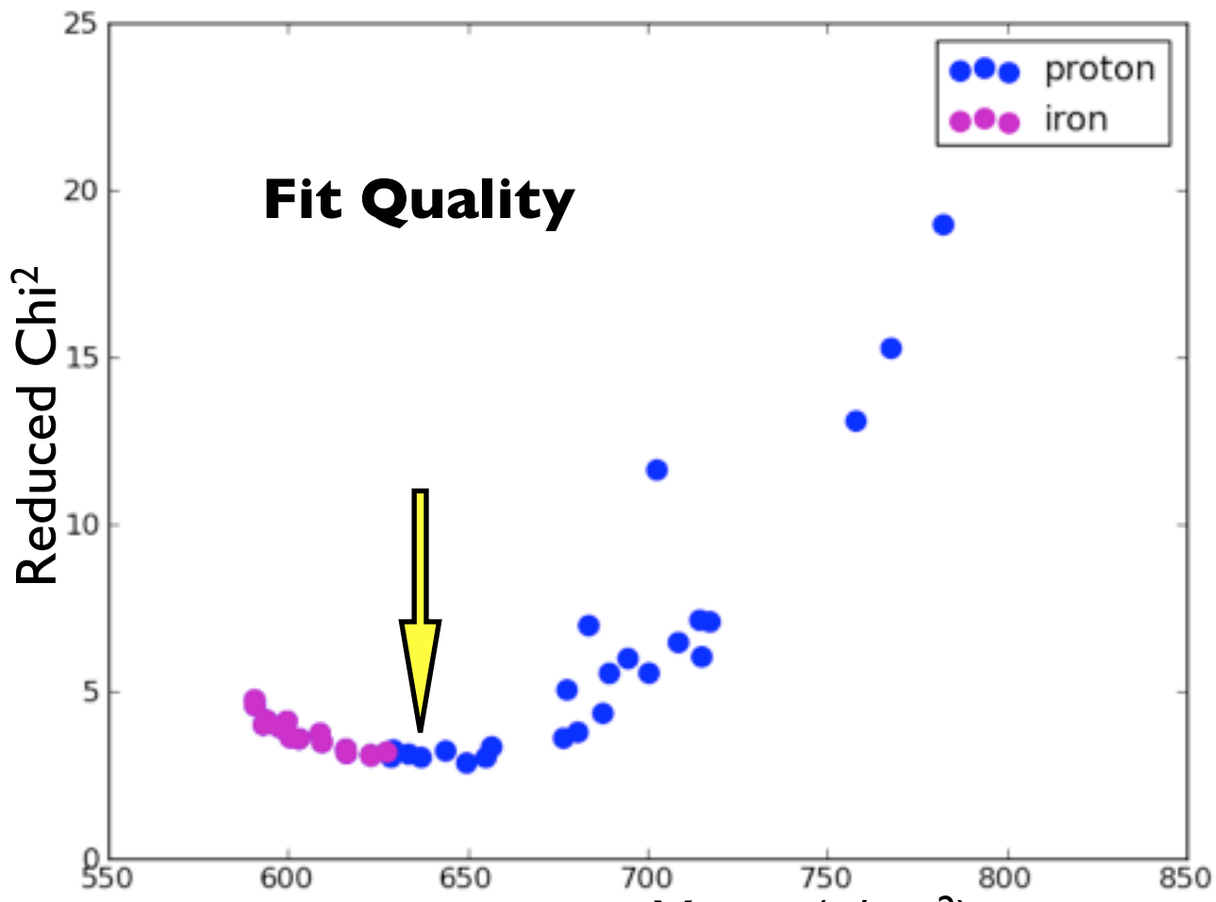




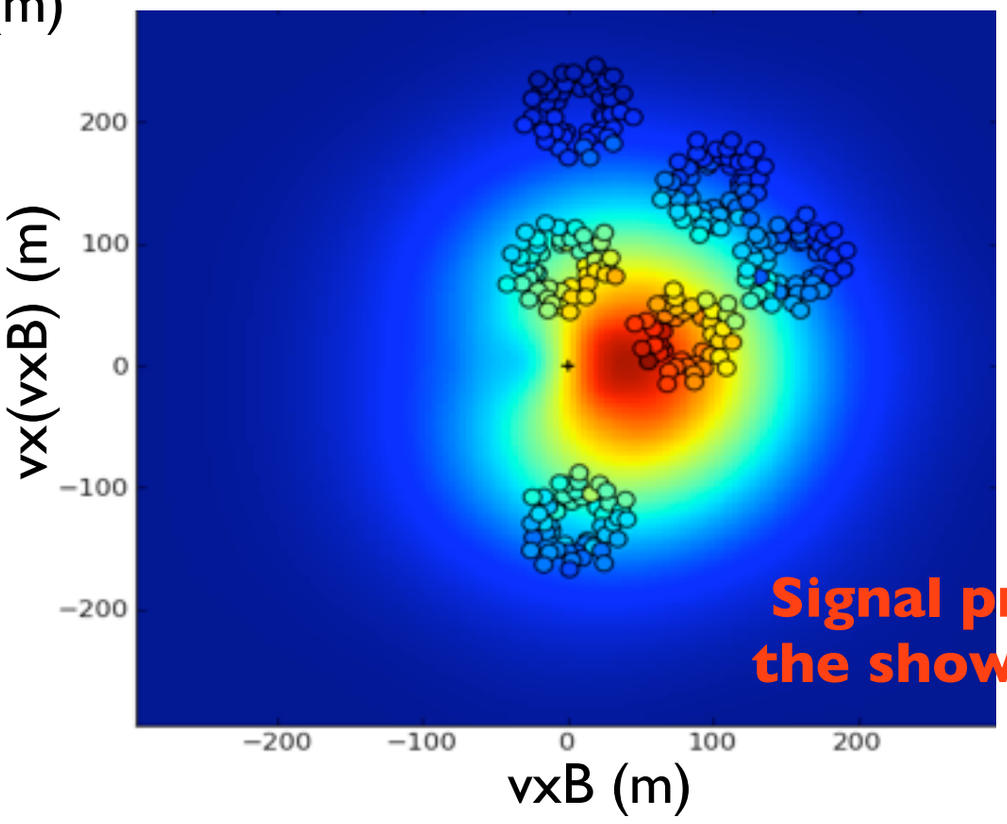
Palmieri (LOPES), ICRC 2011

X_{max} measurements





Preliminary



Signal profile in the shower plane

S.Buitink, in preparation

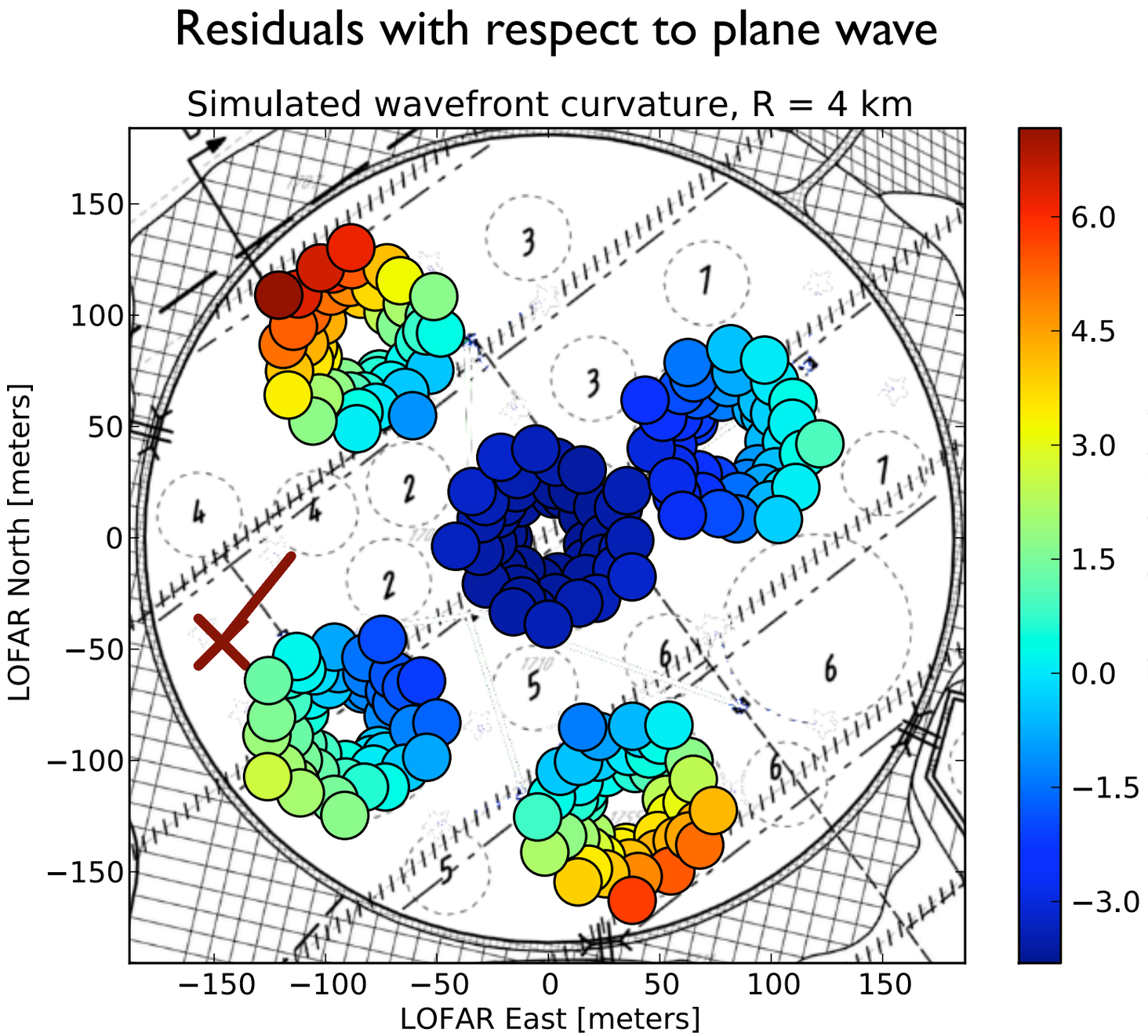
Shower front studies

Ability of LOFAR to measure shape of shower front

LOFAR can resolve 2 ns (no additional phase calibration)

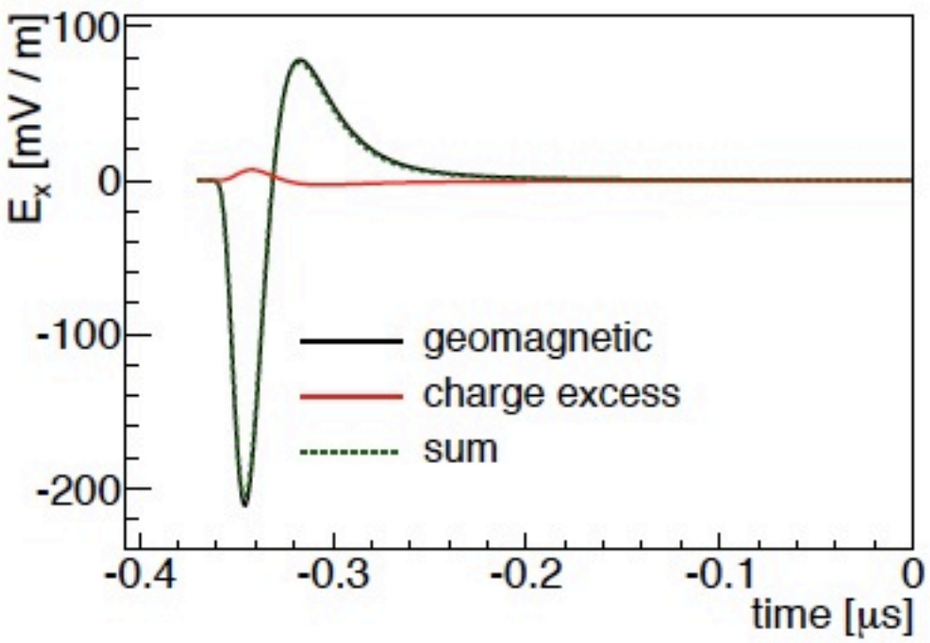
Simulated spherical shower front for measured air shower signals

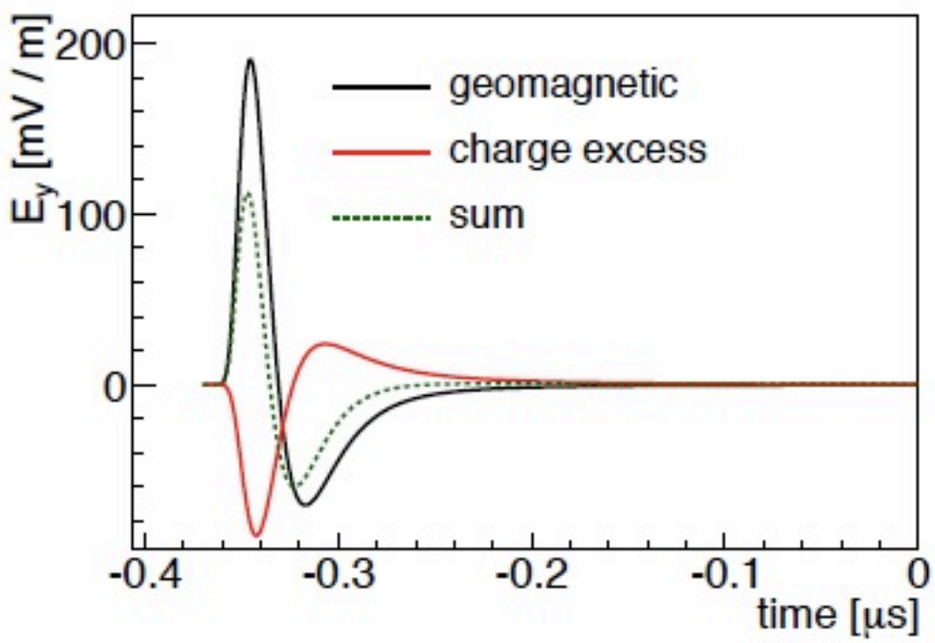
Differences in time with respect to plane wave are resolvable

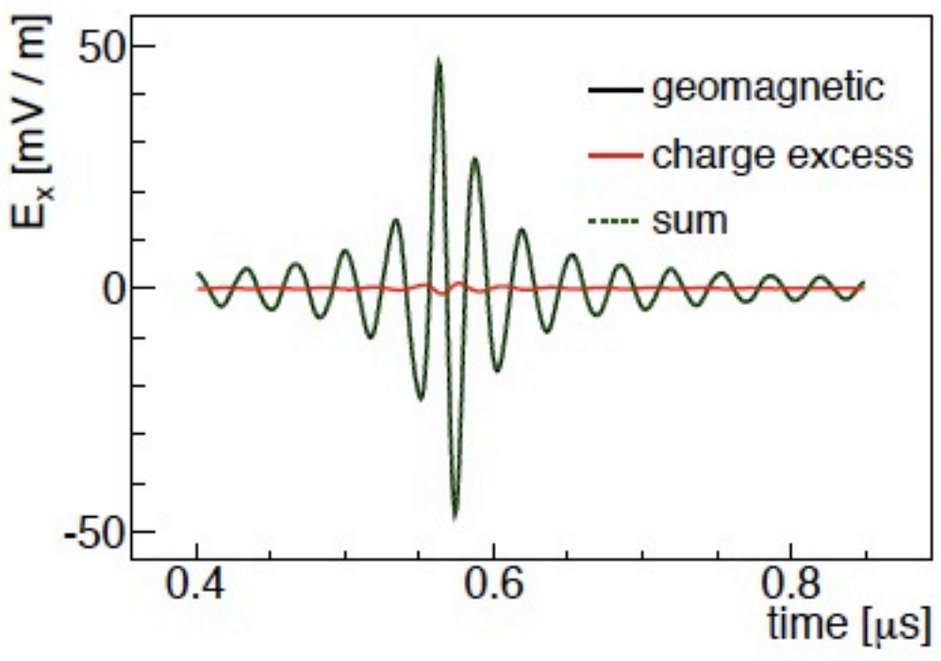


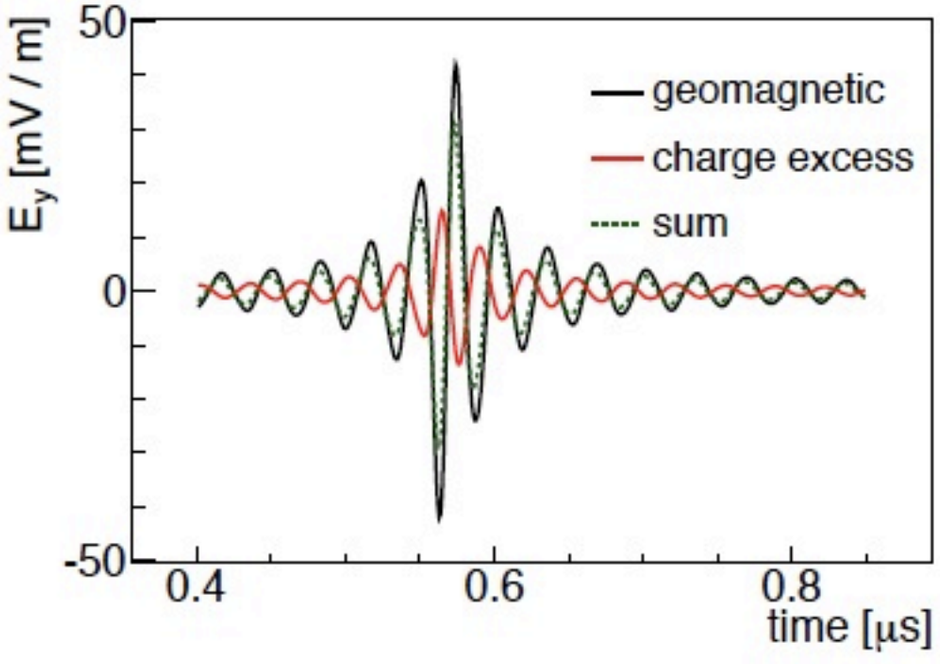
A.Corstanje

Understanding the emission components









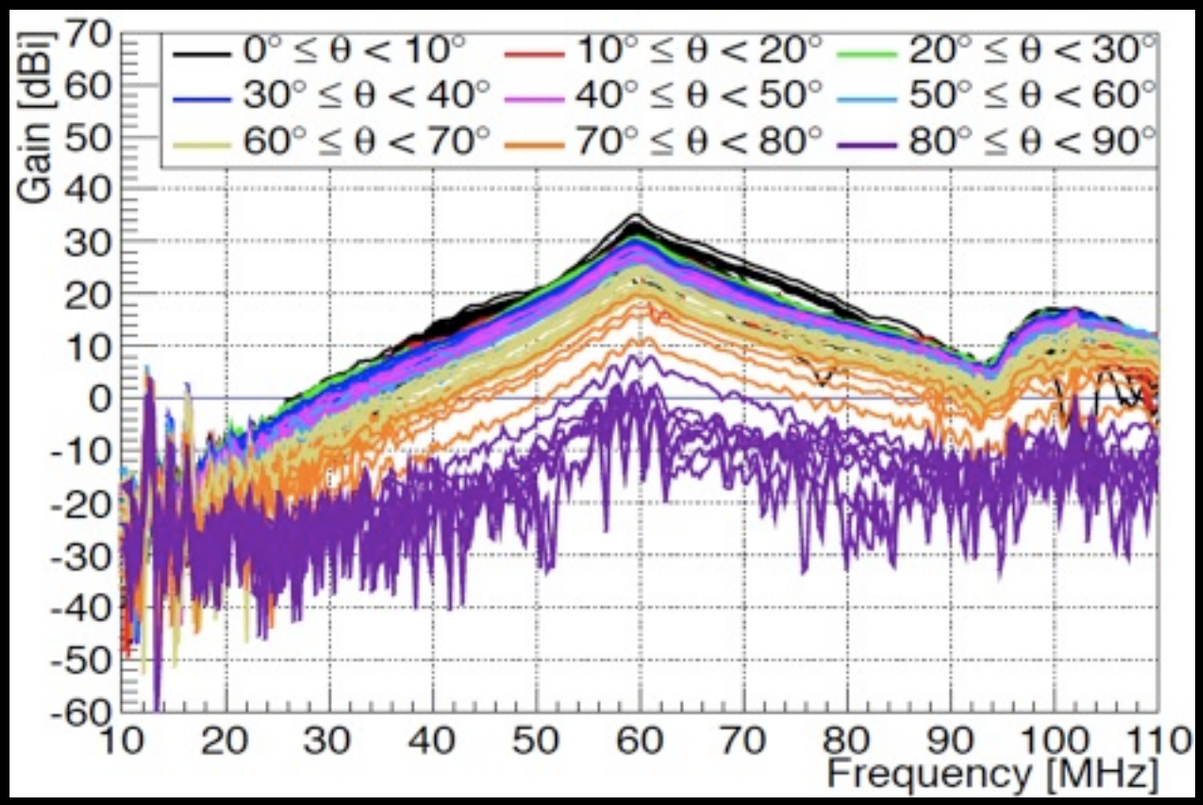
***Unfolding the antenna pattern to get xyz polarization of the signal**

Image credit Harm Schoorlemmer

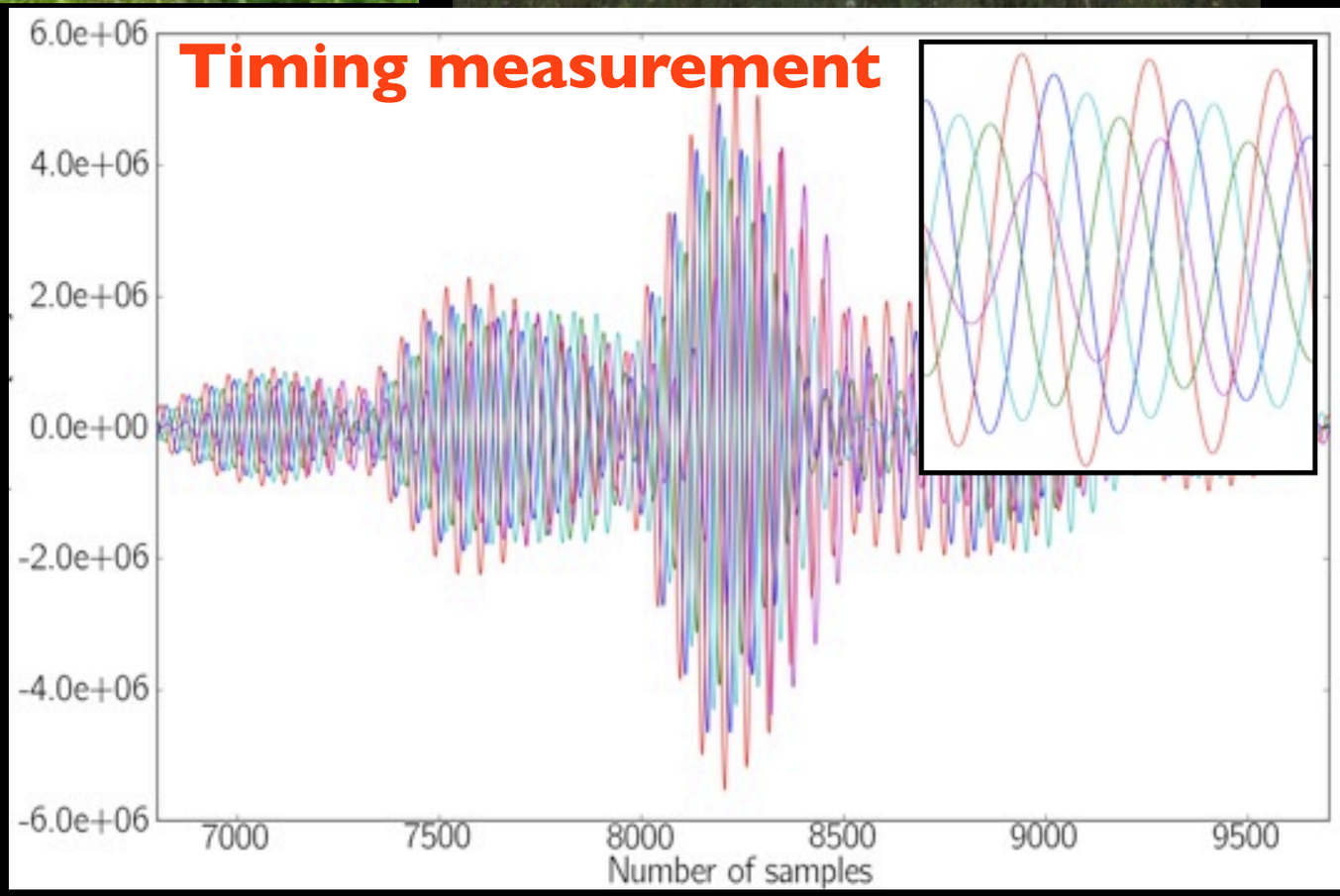
P. Schellart

In-situ gain & timing measurements

Gain measurements



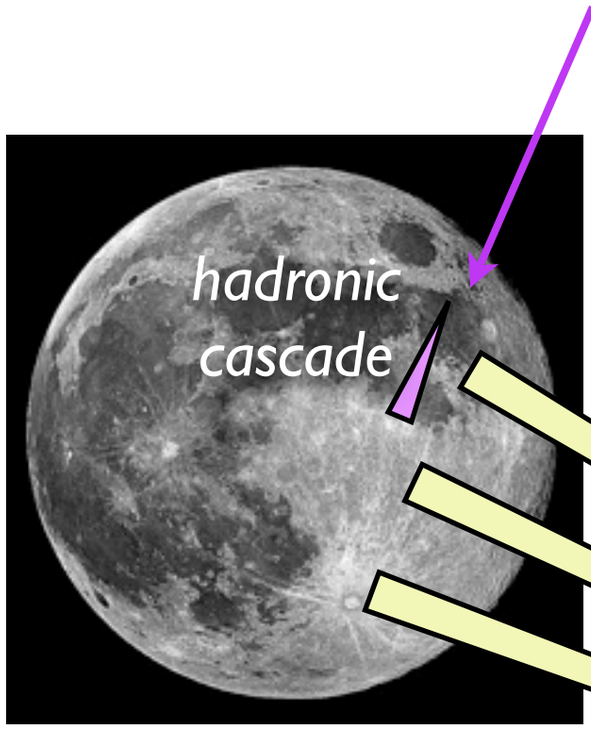
Timing measurement



M. Krause, A.Corstanje

NuMoon: Measurement of the highest energy neutrinos & CRs

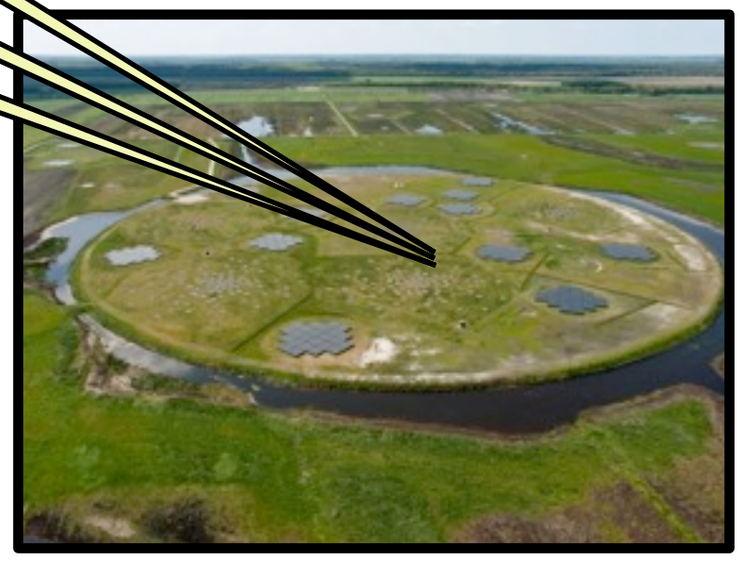
Lunar surface:
10^7 km^2

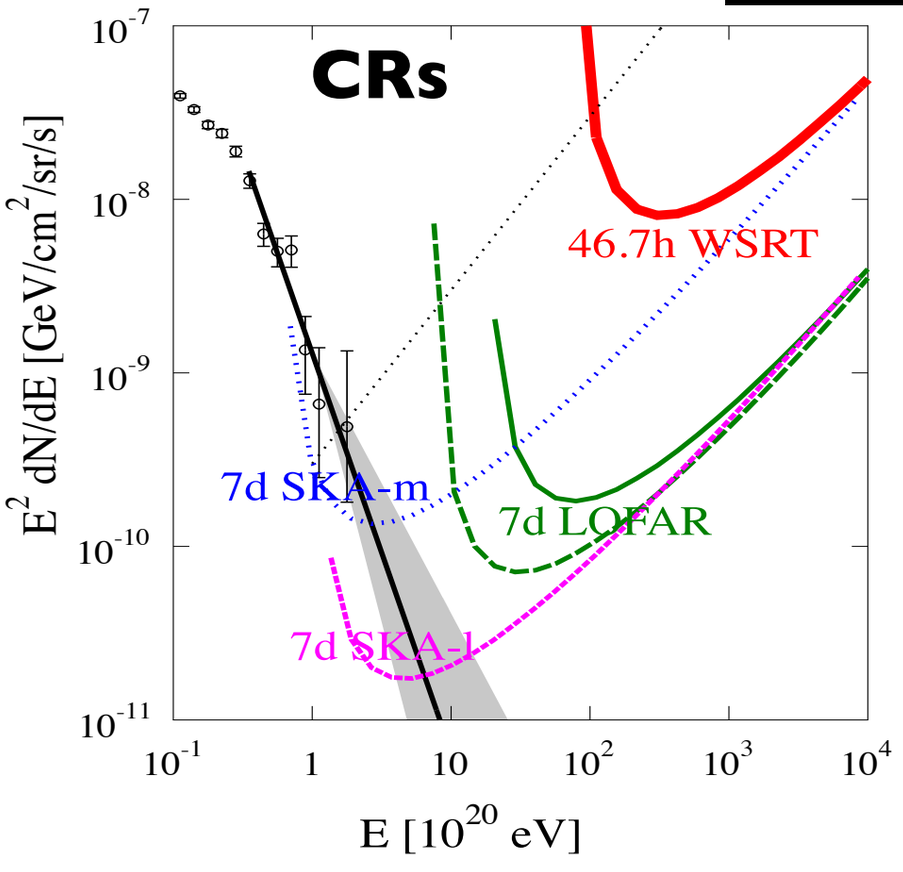


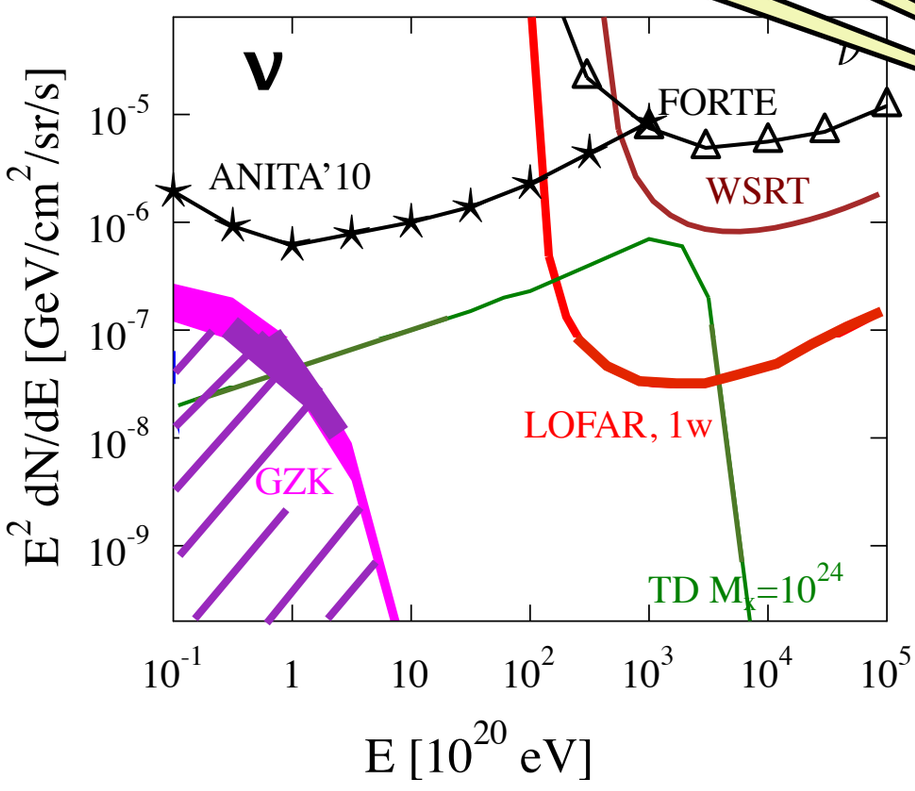
coherent radio emission (Askaryan effect)

This will be performed using the high band antennas (100-240 MHz)

50 LOFAR beams at Moon







S.Buitink

Summary

- **LOFAR, with its high density antennas, is an ideal instrument to measure complex radio properties of air showers**
- **Since June 2011, LOFAR has measured ~370 good quality cosmic-ray events**
- **Current studies mainly focus on:**
  - **Detailed comparison with simulations**
  - **Xmax estimation**
  - **Understanding emission mechanisms**
  - **Shape of the shower front**
- **In near future, LOFAR will give us a detailed understanding of radio emission from air showers**

Thank you for your attention