Radio Detection of Cosmic Rays with LOFAR

Heino Falcke

Radboud University Nijmegen

ASTRON, Dwingeloo

& NIKHEF

&

LOFAR Cosmic Ray KSP

S. Buitkink, A. Corstanje, J.R. Hörandel, A.Nelles, L. Rossetto, S. Thoudam, J.P. Rachen, O.Scholten (RUG), S. ter Veen, T. Huege (KIT)

European Research Council
Executive Agency
Advanced Grant
erc

LOFAR Memo

Radboud University Nijmegen

Detecting Radio Emission from Cosmic Ray Air Showers and Neutrinos with a Software Radio Telescope

Heino Falcke[1] and Peter Gorham[2]

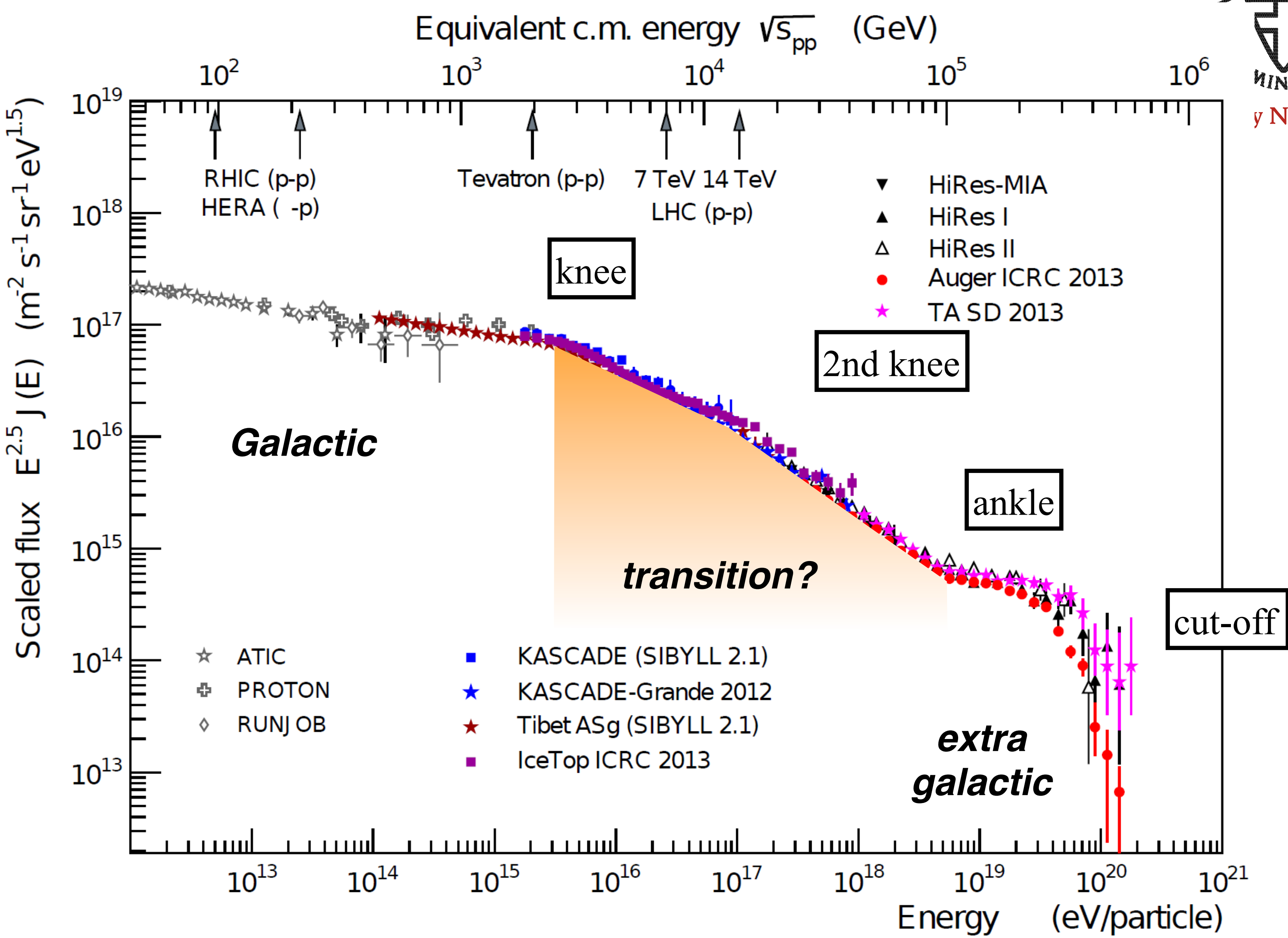
[1]Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany (hfalcke@mpifr-bonn.mpg.de)
[2]Dept. of Physics & Astronomy, Univ. of Hawaii at Manoa, 2505 Correa Rd., Honolulu, HI, 96822 USA (gorham@phys.hawaii.edu)

Abstract

In this paper we discuss the possibilities to measure ultra-high energy cosmic rays and neutrinos with radio techniques. We review a few of the properties of radio emission from cosmic ray air showers that have been found in the past. We show how these properties can be qualitatively explained through coherent synchrotron emission from electron-positron pairs in the shower as they move through the earth's magnetic field. A new generation of software telescopes makes it now possible to study this radio emission in greater detail. For example, the planned the Low-Frequency Array LOFAR, operating at 10-200 MHz, will be a uniquely suited instrument to study extensive air showers and even detect neutrino-induced showers on the moon. We discuss sensitivities, count rates and possible detection algorithms for LOFAR which should also be applicable to other software radio telescopes such as the Square-Kilometer-Array (SKA). We find that LOFAR is capable of detecting air-shower radio emission from $> 2 \cdot 10^{14}$ eV to $\sim 10^{20}$ eV. The technique could be easily extended to include air shower arrays consisting of particle detectors, thus providing crucial additional information for obtaining energy and chemical composition of cosmic rays and to extend the cosmic ray search well beyond an energy of 10^{21} eV. Other issues that LOFAR can address are to determine

1970ies → P.L. Biermann → Falcke & Gorham (2001, memo) → F&G (2003, Astropart. Phys.)

Cosmic ray all-particle spectrum



y Nijmegen

Cosmic Ray Spectrum (×E^3)

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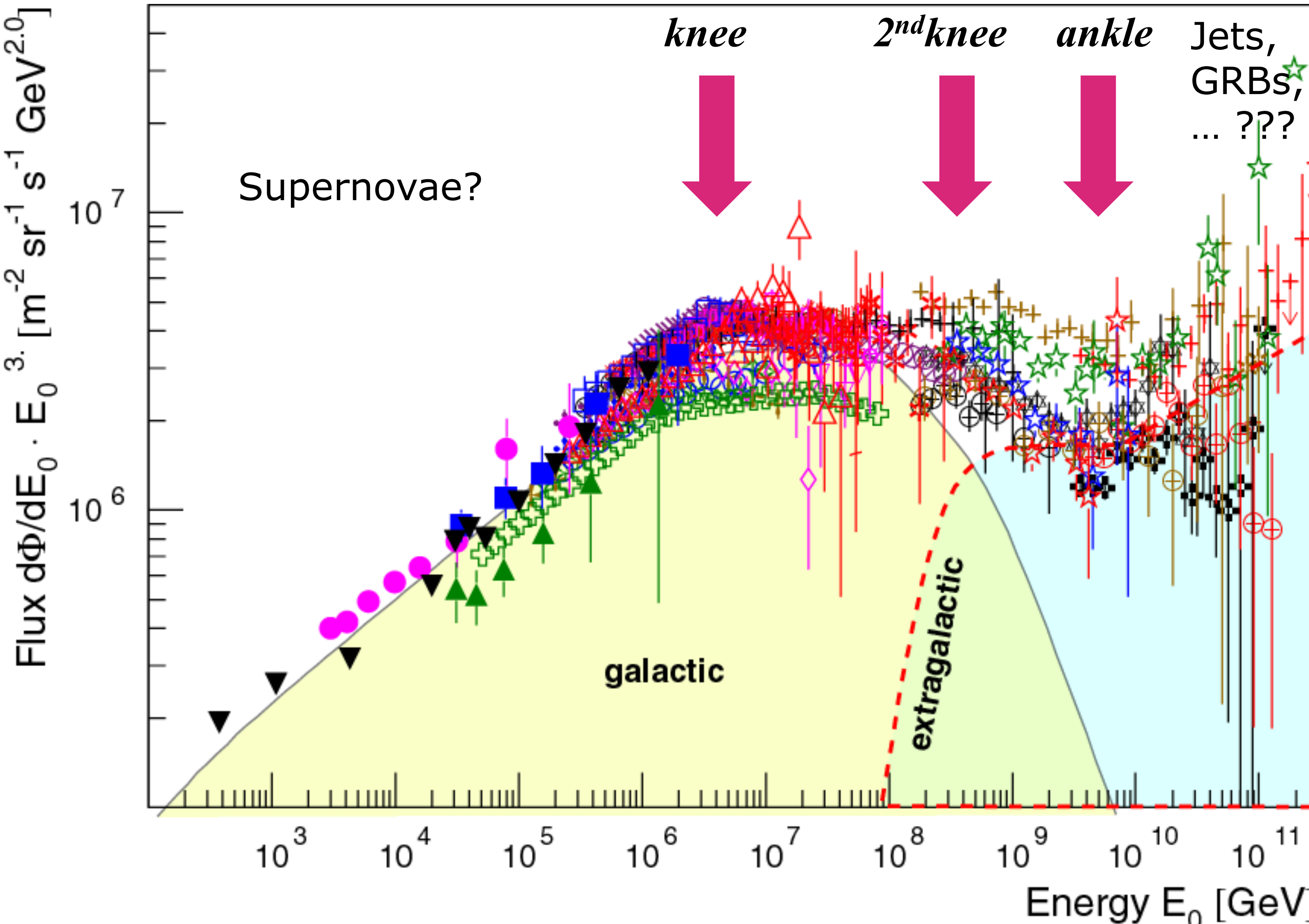

Hörandel (2008)

Air showers: simulations

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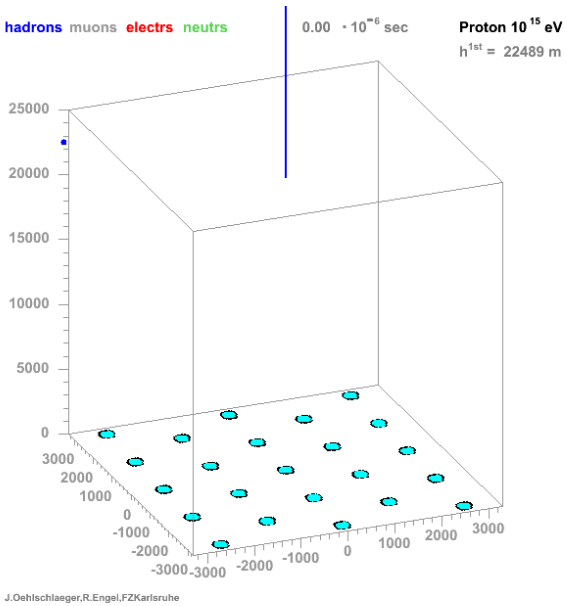
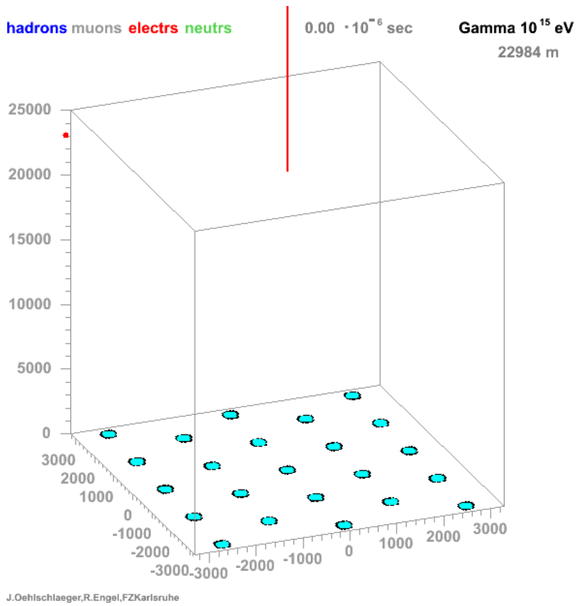
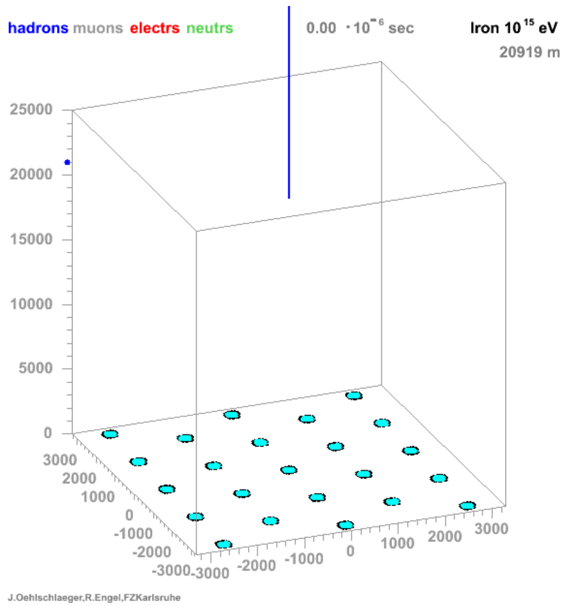


proton



photon



iron nucleus

Extensive Air Shower

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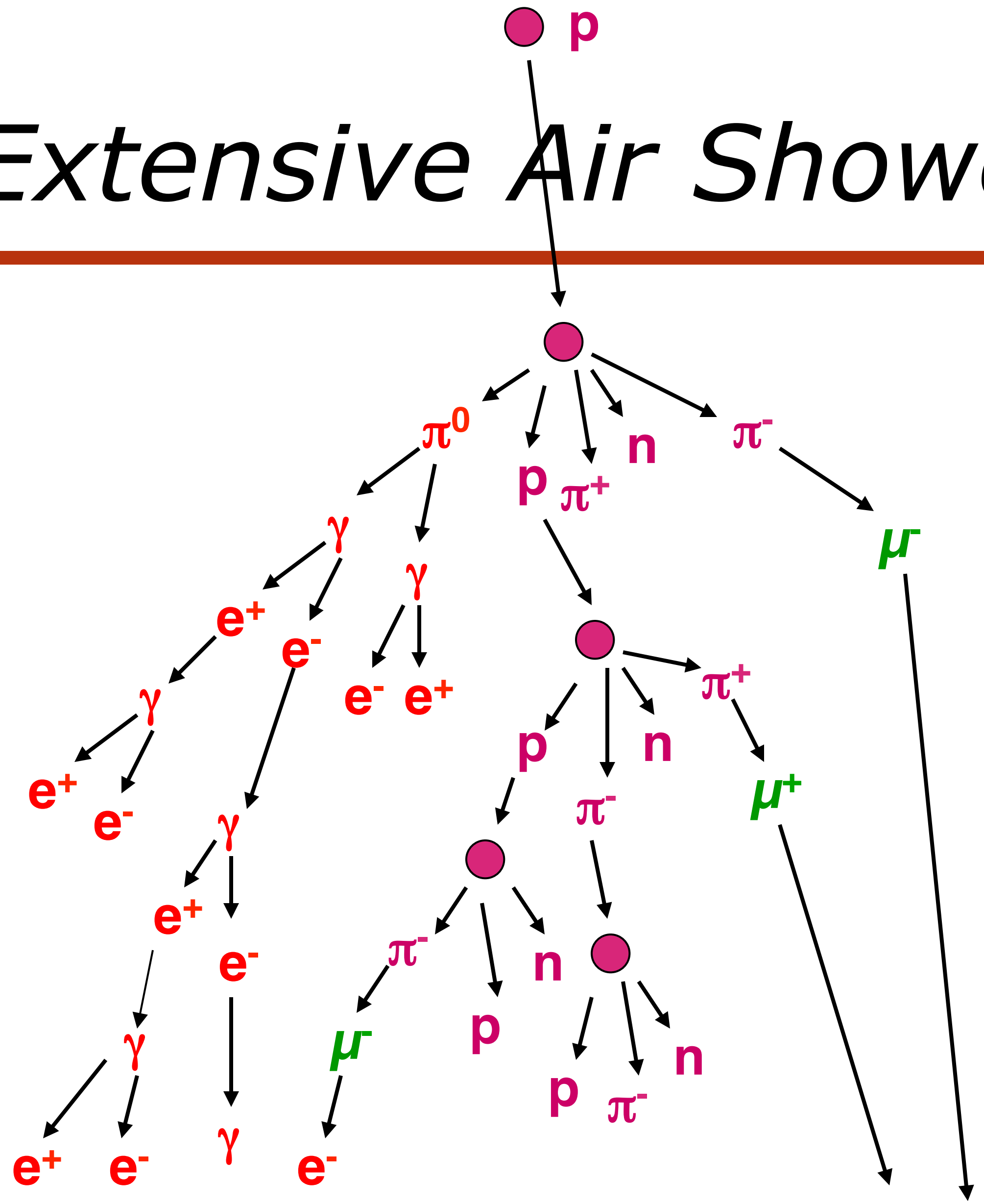


electromagnetic hadronic muonic

shower components

Proton 10^{15} eV:

On ground:

10^6 particles

80% photons

18% el./positron

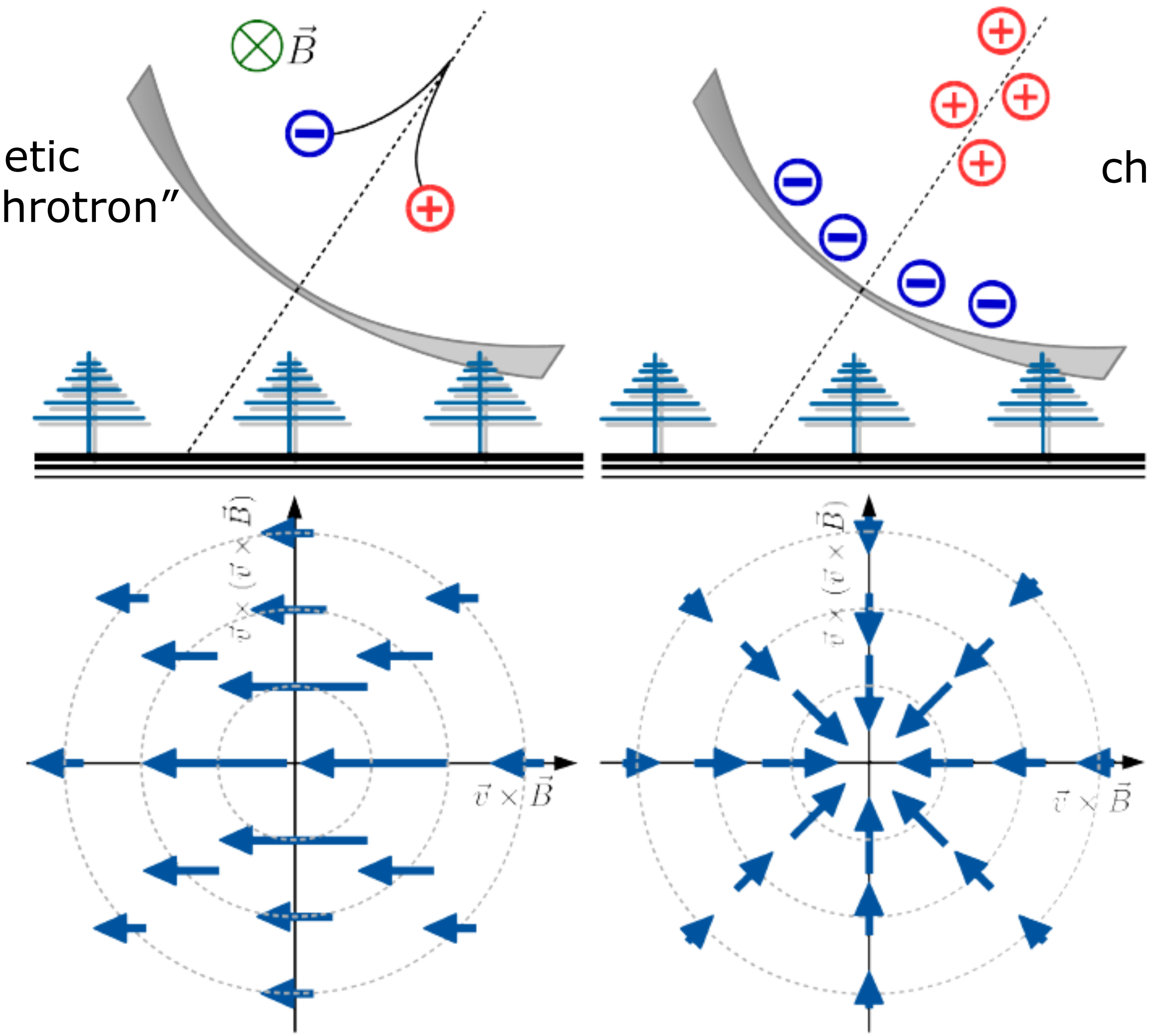
1.7% Muons

0.3% Hadrons

J. Hörandel

Radio Radiation

Geomagnetic
aka. "geosynchrotron"



charge excess &
separation

From Glaser et al. (2017)

Monte Carlo Simulation of Radiation Processes: The Endpoint Formalism

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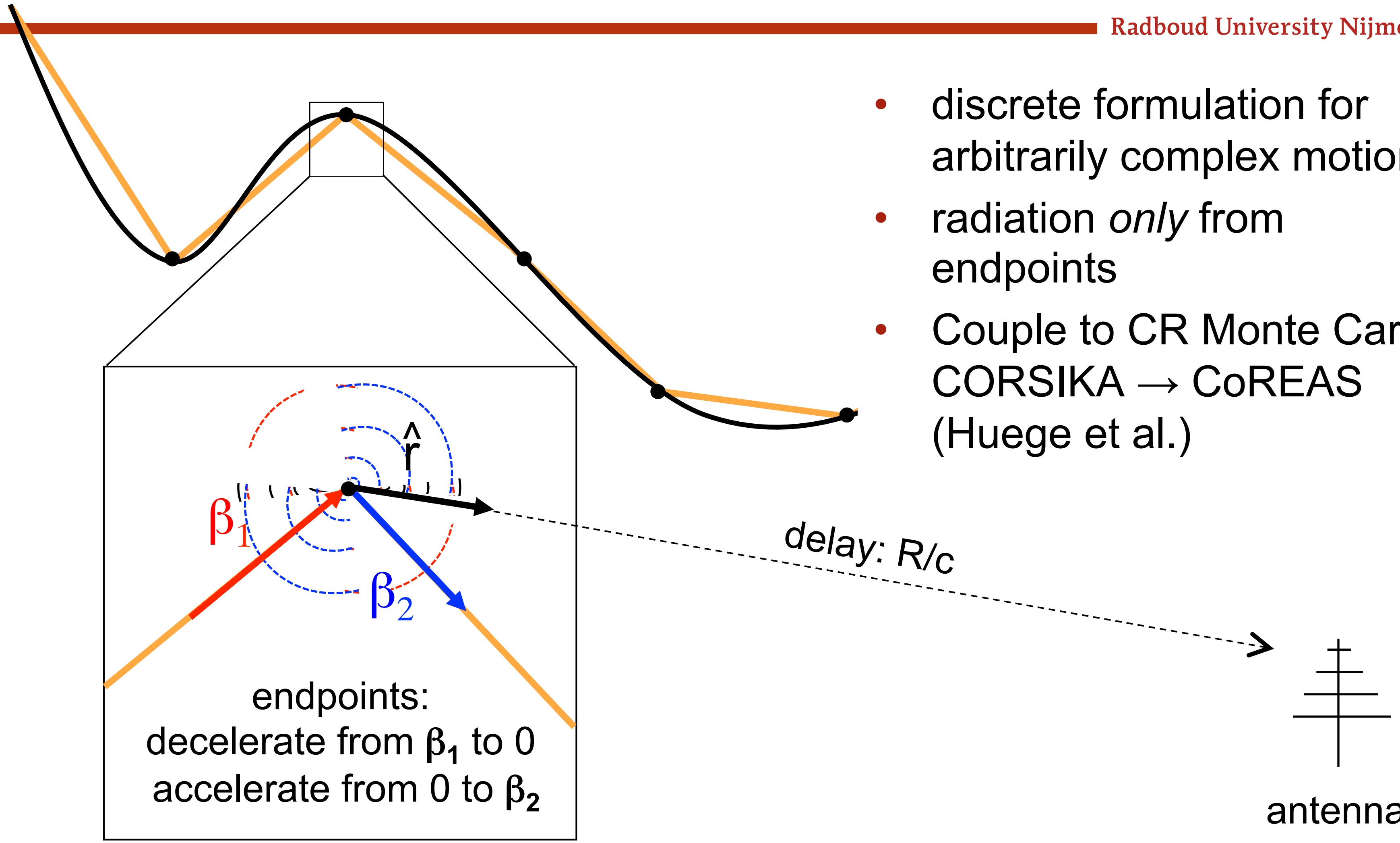

- discrete formulation for arbitrarily complex motion
- radiation *only* from endpoints
- Couple to CR Monte Carlo: CORSIKA → CoREAS (Huege et al.)

James, Falcke, Huege, Ludwig (2011), Phys. Rev. E
see also Alvarez-Muniz, Vàsquez, Zas 2000, Phys. Rev. D.

Coherent Geosynchrotron Radio Pulses in Earth Atmosphere

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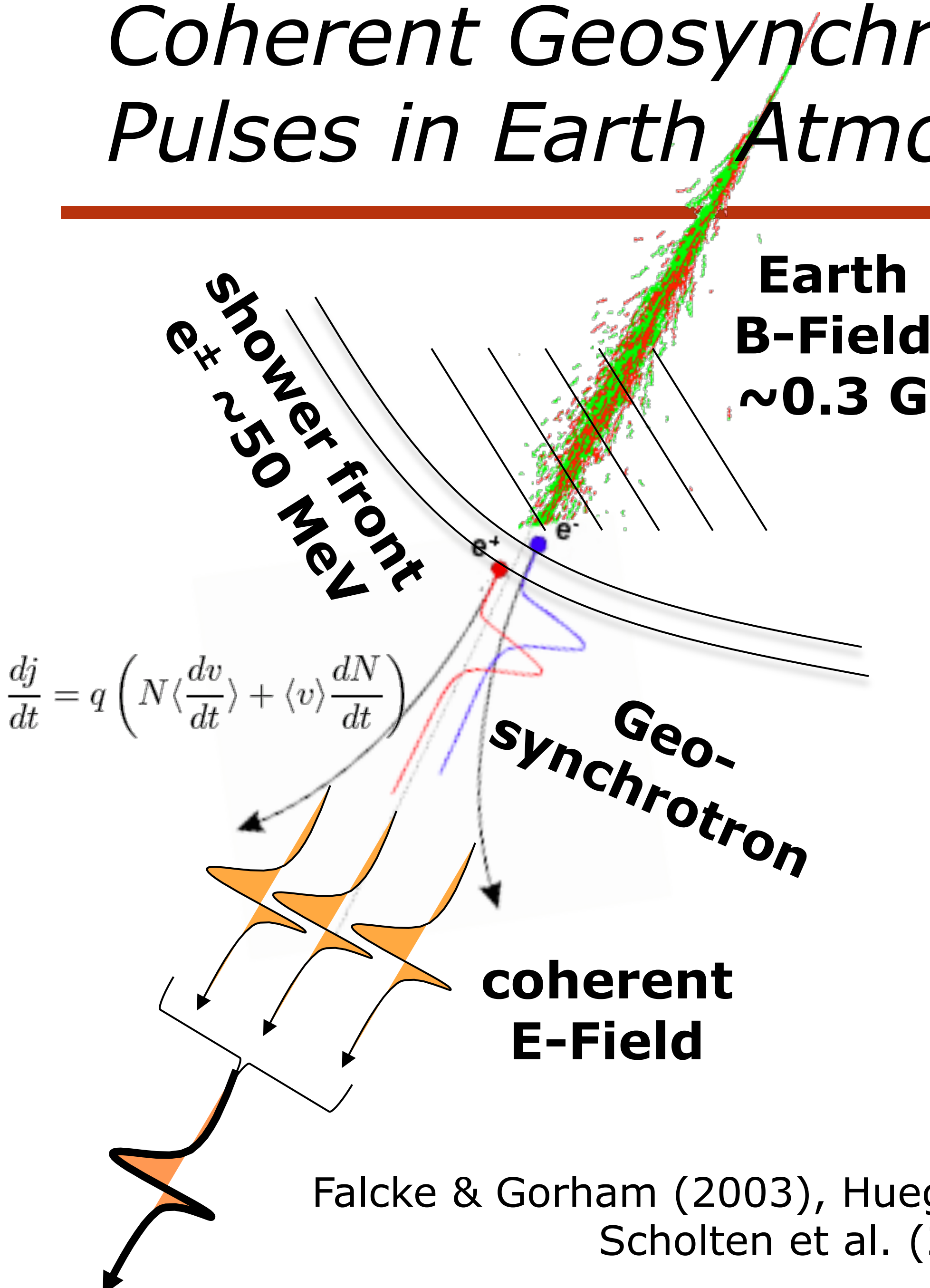

- UHECRs produce particle showers in atmosphere
- Shower front is ~2-3 m thick ~ wavelength at 100 MHz
- $e^{\pm}$ emit synchrotron in geomagnetic field
- Emission from all $e^{\pm}$ (N_e) add up coherently
- Radio power grows quadratically with N_e

⇒ $E_{total}=N_e*E_e$
⇒ Power $\propto E_e^2 \propto N_e^2$
⇒ GJy flares on 20 ns scales

Falcke & Gorham (2003), Huege & Falcke (2004,2005), Scholten et al. (2007-2011)

LOPES-4 @ Effelsberg: First Tests

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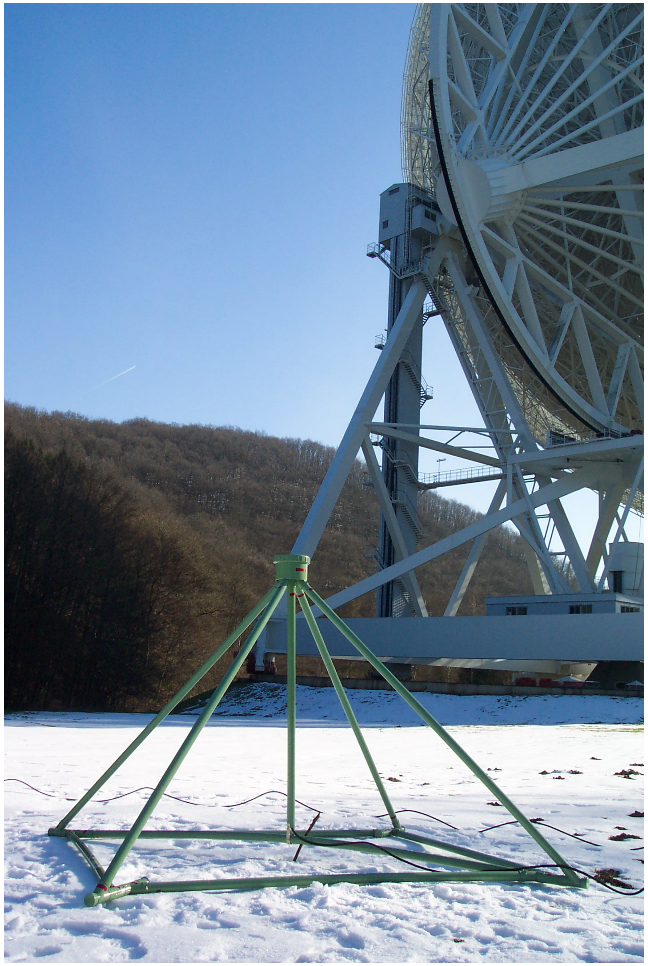
Slide from (2003)



LOPES @ Dwingeloo: Test-Setup

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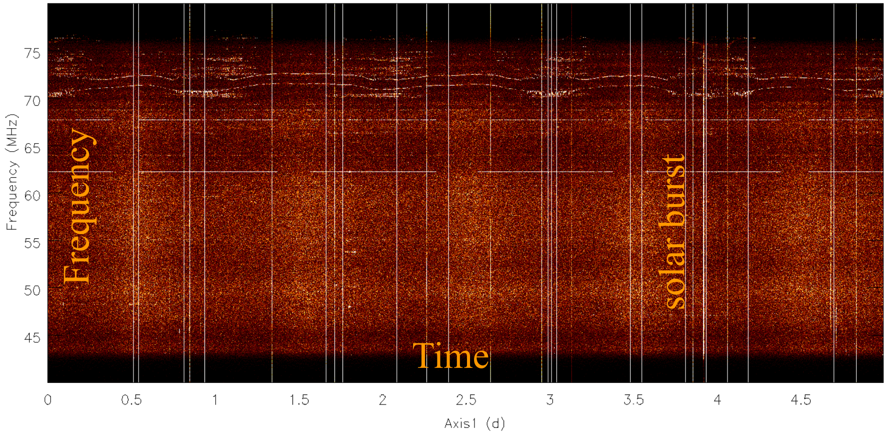
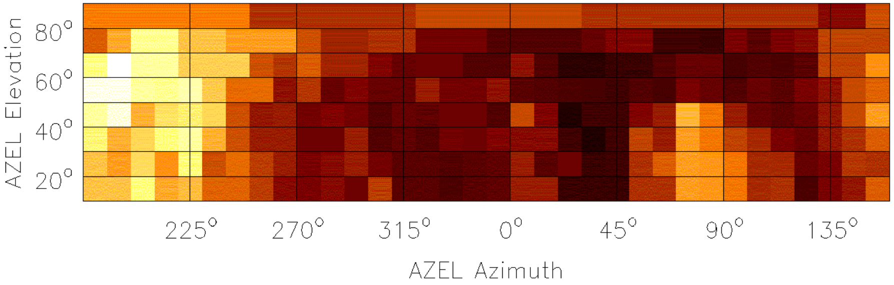
Detection of the sun in „cosmic ray mode"

Series of „artificially" triggered data sets





all-sky map (16 events of 1ms each)

Building LOPES

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Radio detection of CRs: Complementarity approach

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modern
pioneering
experiments

Simulations
(CoREAS, ZHAires,
EVA, Selfas)

Complementarity

Radio-add ons

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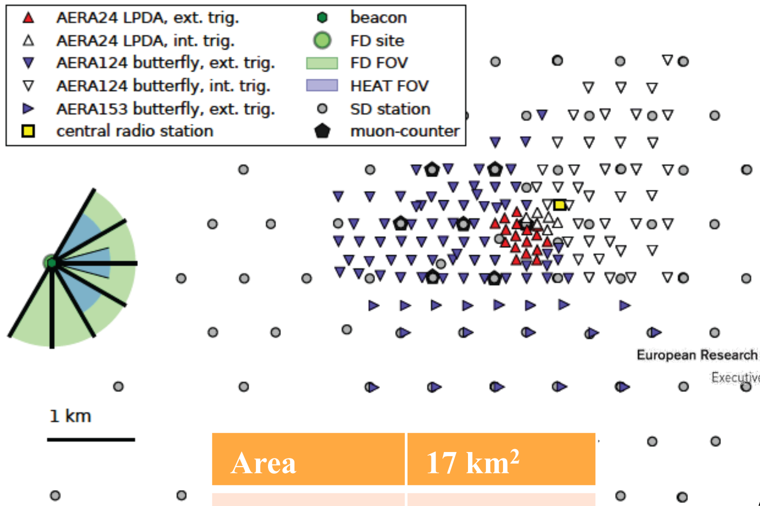

Area	17 km^2
Antennas	150
Type	LPDA/ Butterfly

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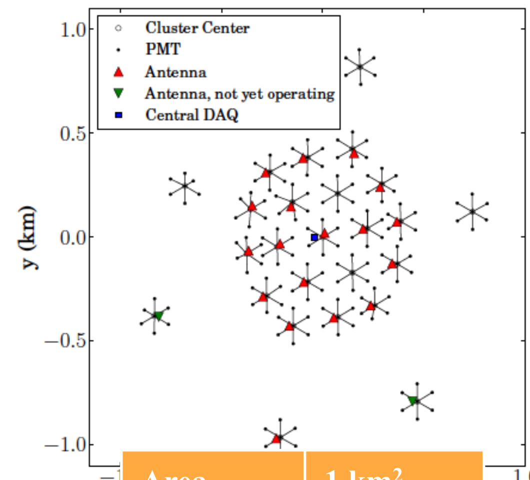
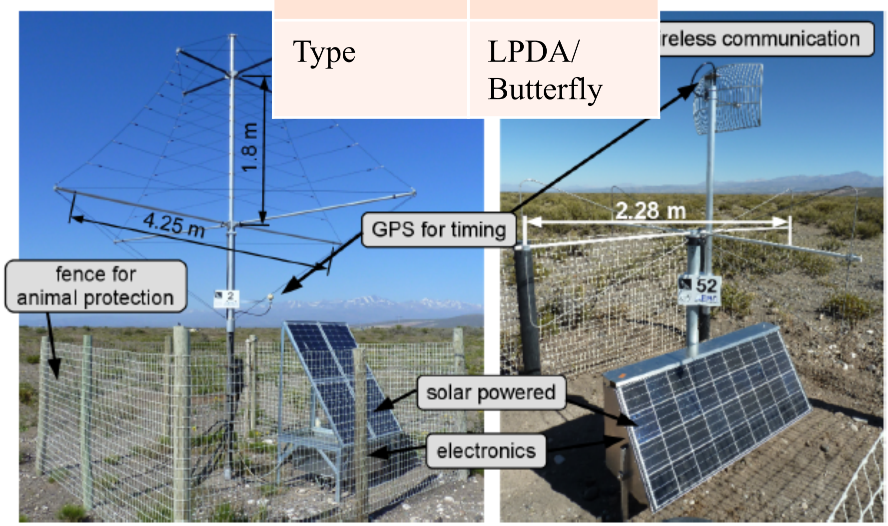
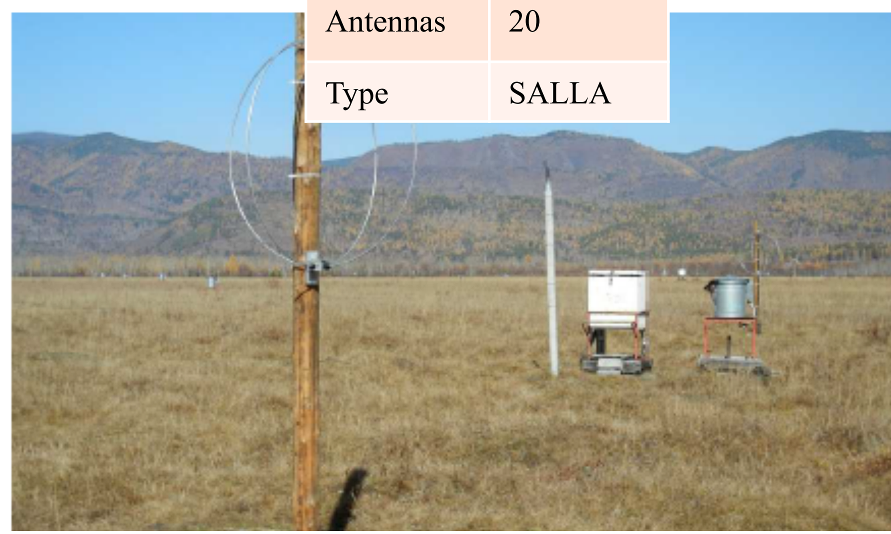


Area	1 km^2
Antennas	20
Type	SALLA



AERA @ AUGER



TUNKA-REX

The LOFAR “Superterp”

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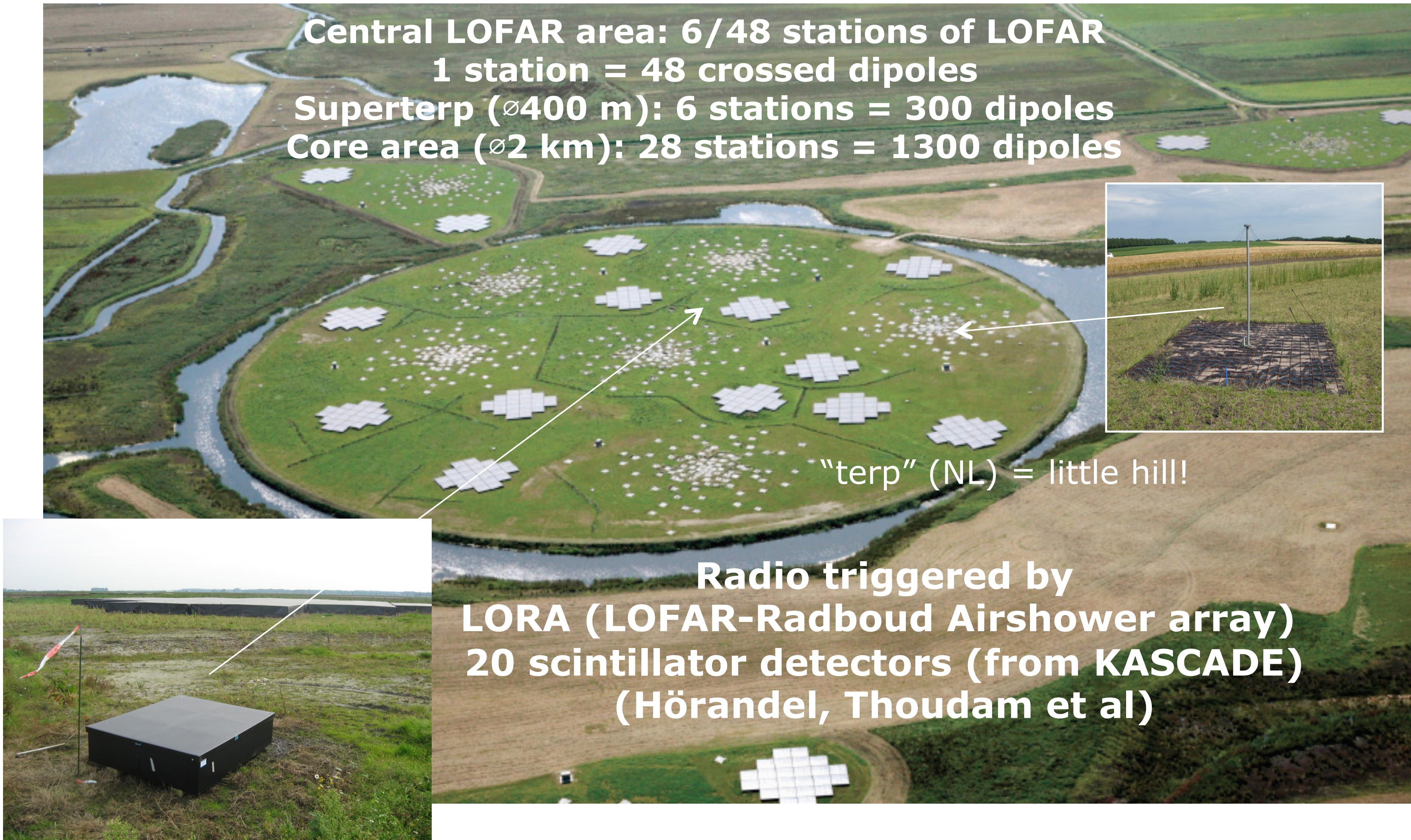

Footprint of an Air Shower

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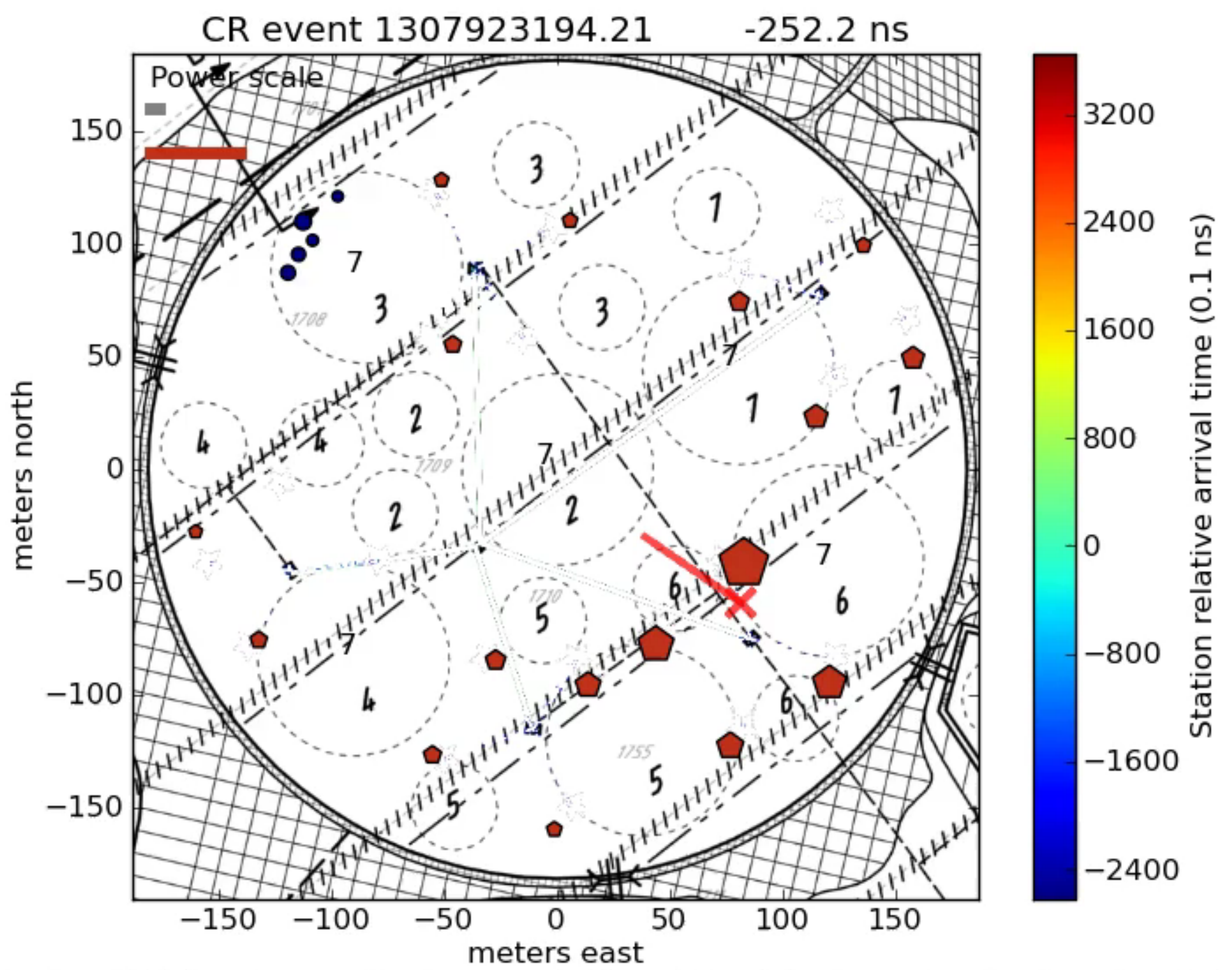

Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

S. ter Veen

Imaging through direct beamforming

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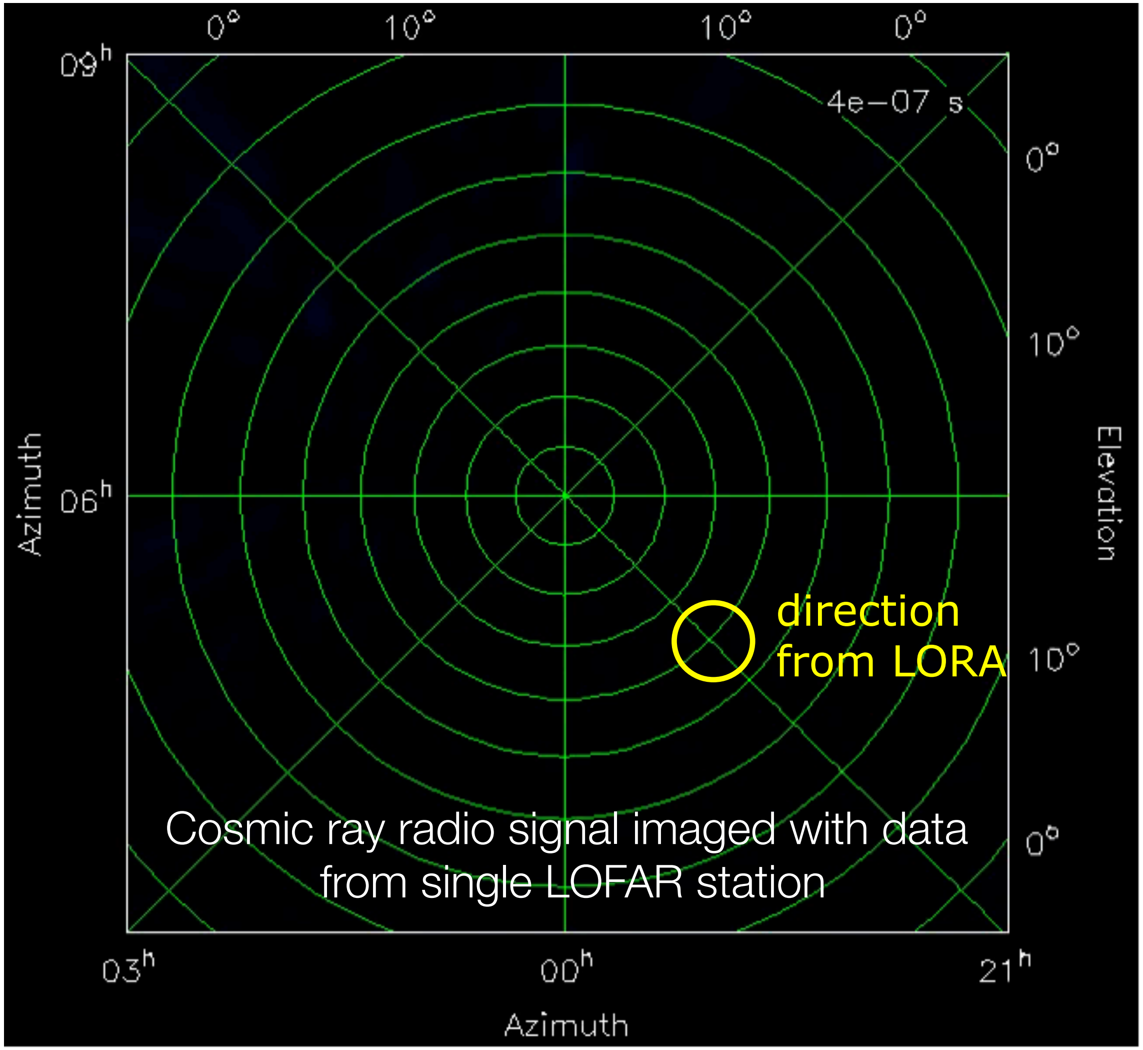

Wavefront – Radio Shower Shape

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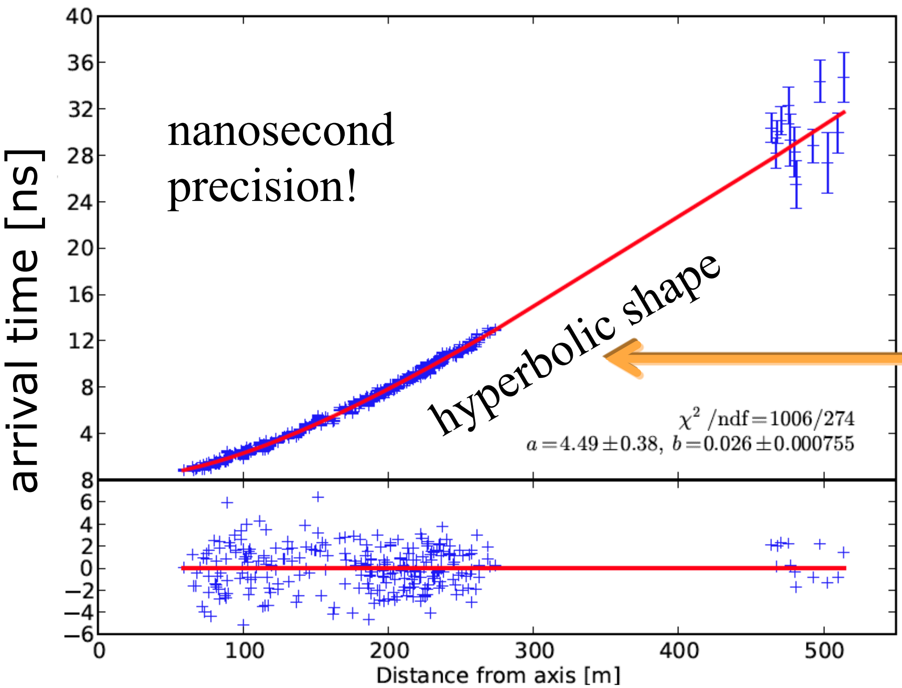
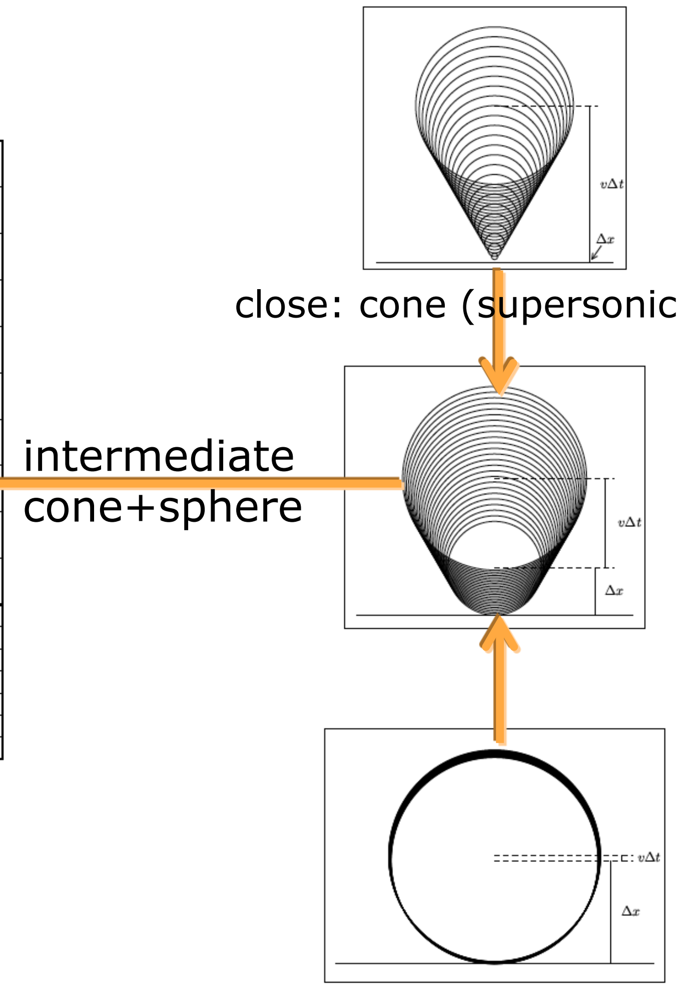
Precise shower front allows directional accuracy of 0.1°



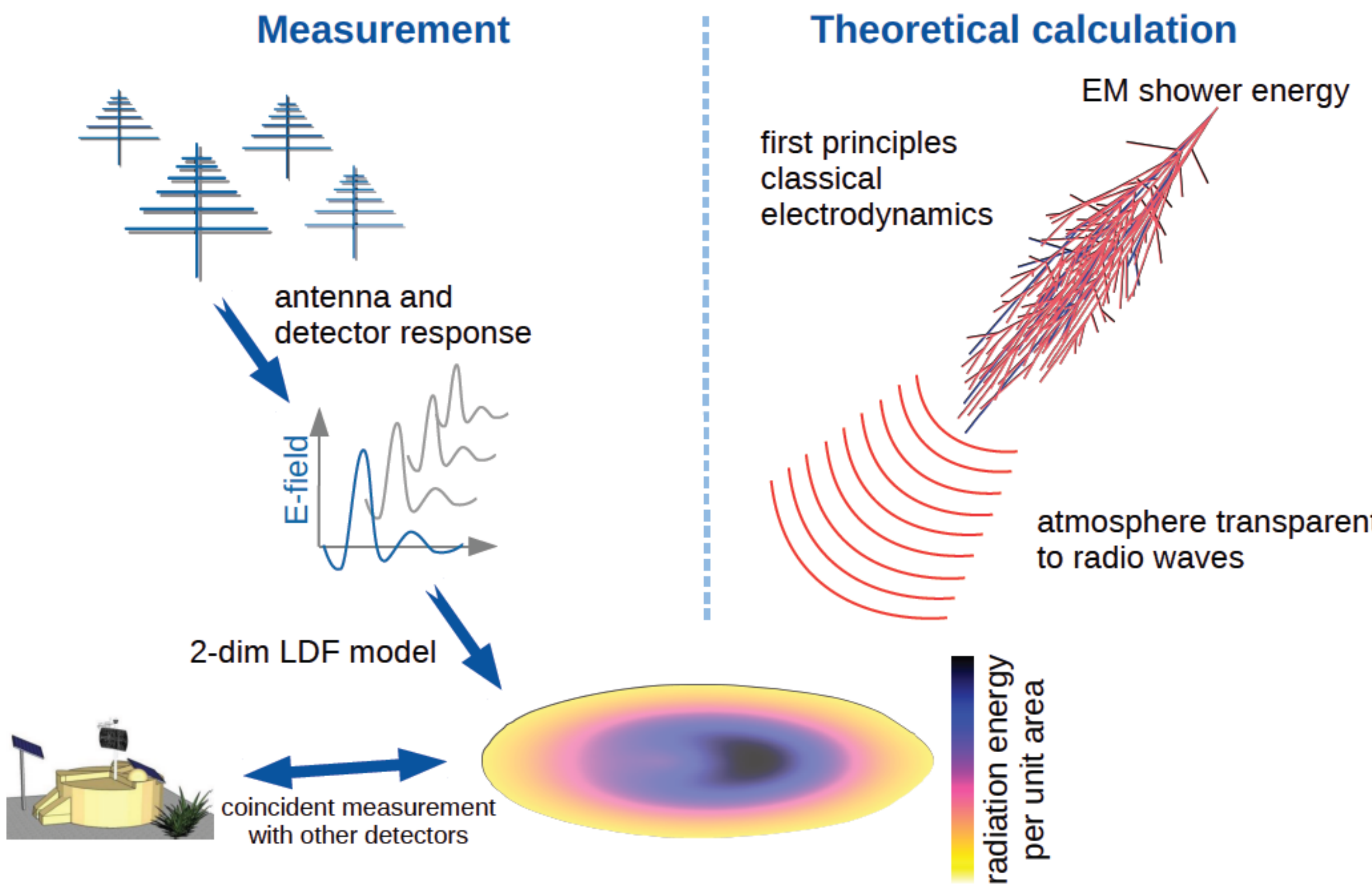
radial distance to core [m]

Corstanje et al. (2014, *Astropart. Phys.*)

Emission for finite relativistic track:



Absolute Calibration



Auger collaboration (Aab et al. 2016, Glaser et al. 2017)

Absolute Calibration

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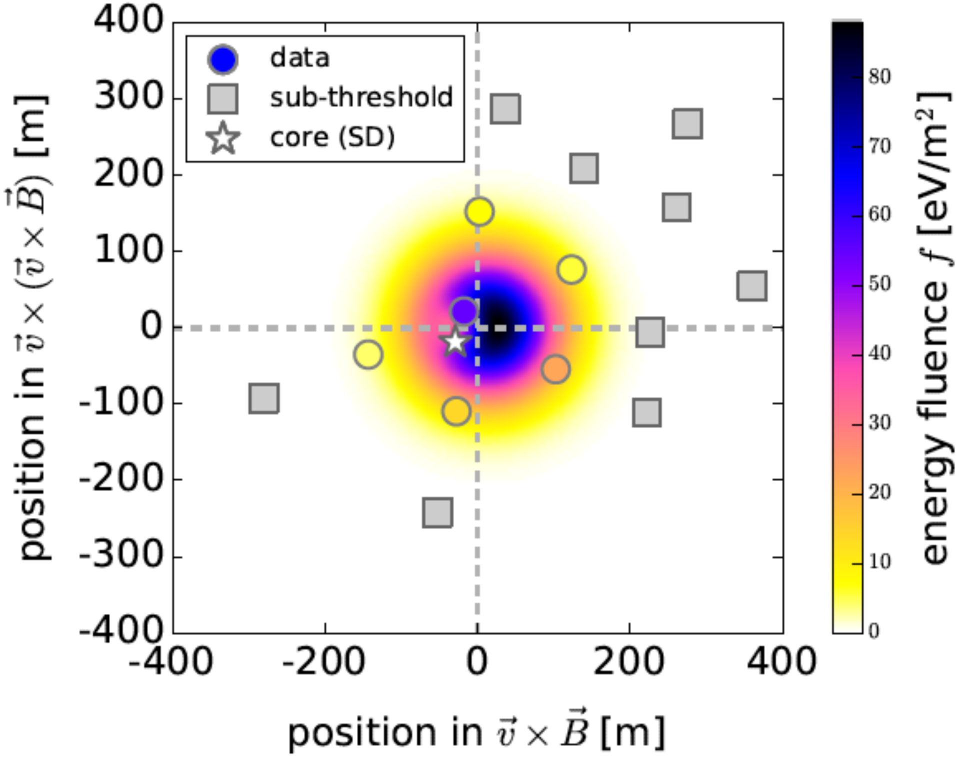

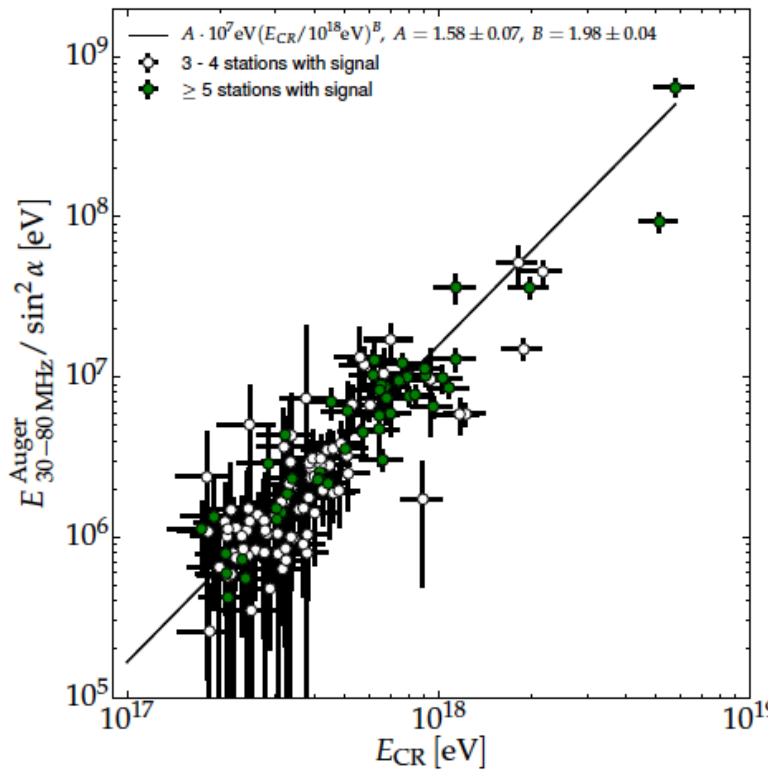

Auger collaboration (Aab et al. 2016)

Using LOFAR parameterization from Nelles et al.

Absolute Calibration

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$$E_{30-80\,\mathrm{MHz}} = (15.8 \pm 0.7(\mathrm{stat}) \pm 6.7(\mathrm{sys}))\,\mathrm{MeV} \times \left(\sin\alpha\,\frac{E_{\mathrm{CR}}}{10^{18}\,\mathrm{eV}}\,\frac{B_{\mathrm{Earth}}}{0.24\,\mathrm{G}}\right)^2$$

source of uncertainty	
experimental uncertainties	**9.4%**
antenna response pattern [25]	9%
analog signal chain	<1%
LDF model	<2.5%
theoretical uncertainties	**2%**
environmental uncertainties	**1.6%**
atmosphere	1.25%
ground conditions [25]	1%
invisible energy correction [19]	**3.0%**
total absolute scale uncertainty	**10.2%**

Glaser et al. (2017)

Radio Emission Pattern inherently 2D

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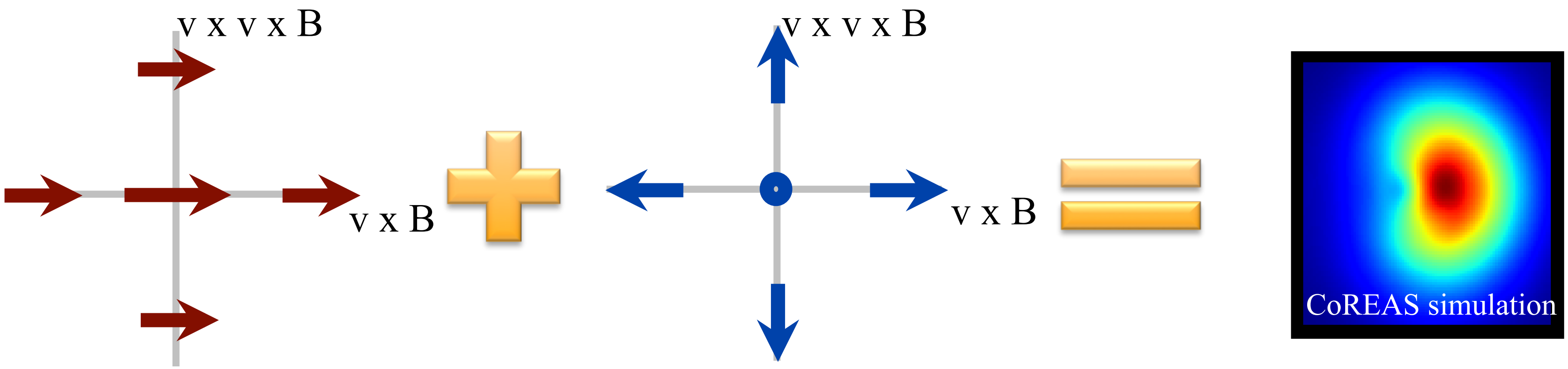

E-field vectors geomagnetic

E-field vectors charge excess

- vector sum of geomagnetic and charge excess component
- relativistic beaming
- Cherenkov-like propagation effects ($n \neq 1$)

All radiation effects covered in simulations automatically by endpoint-method!

Emission Pattern at Low Frequencies: Theory & Observation

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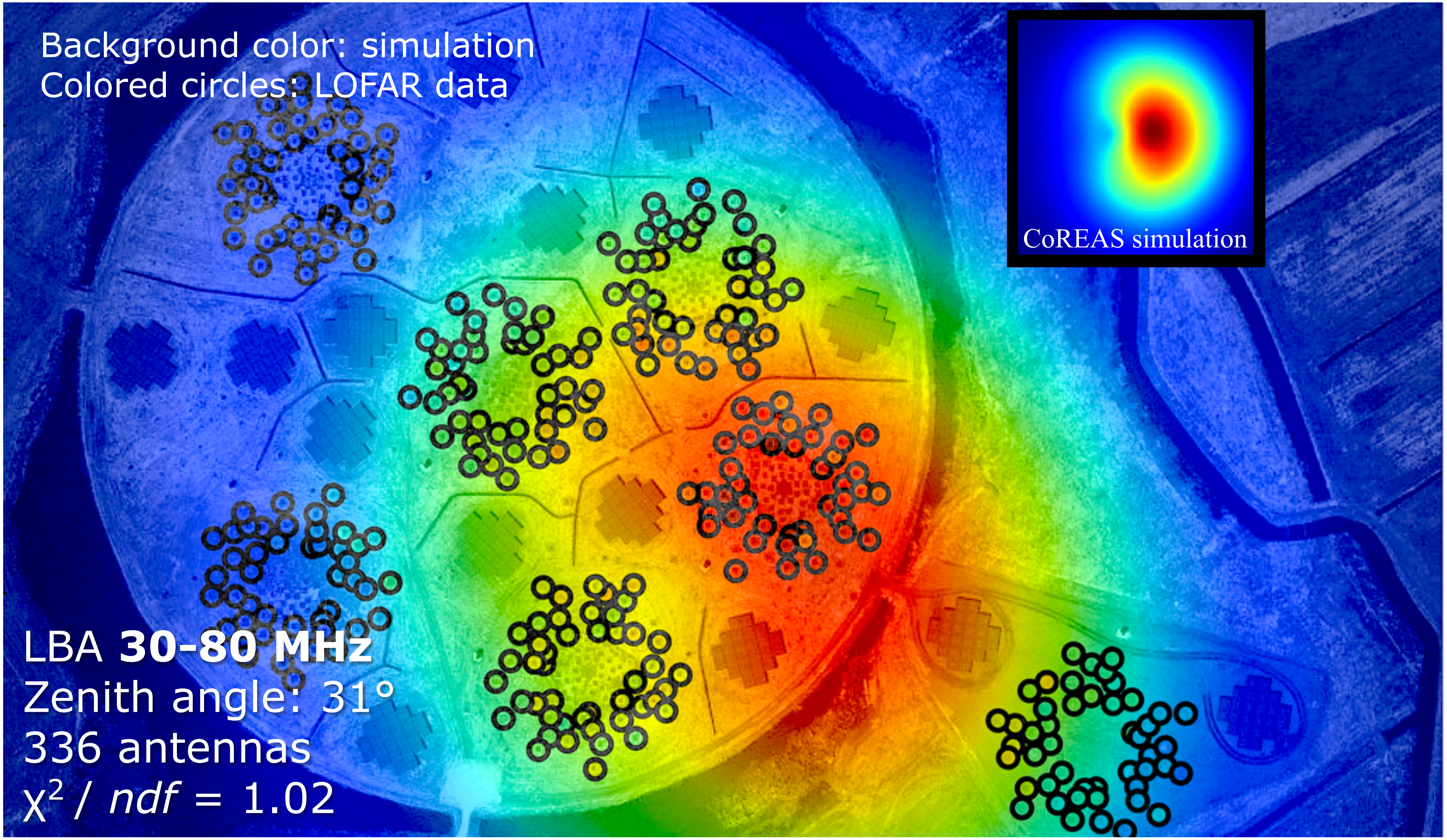

Polarization – Charge Excess Radiation

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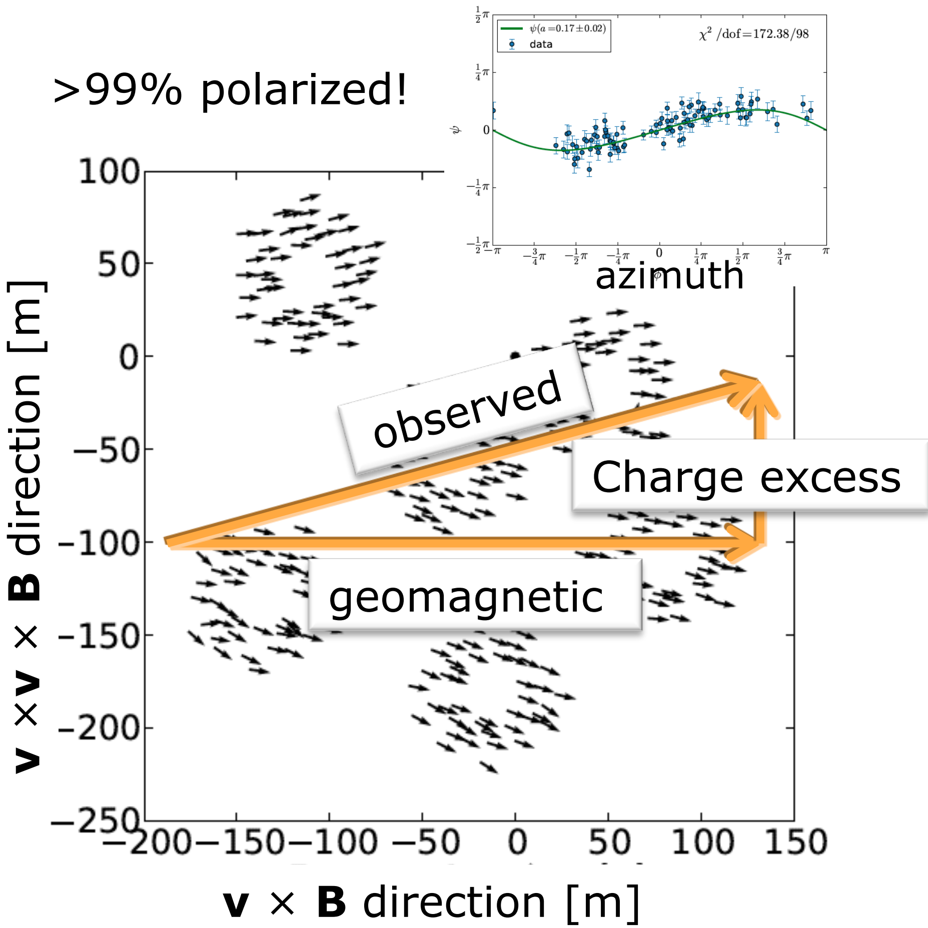
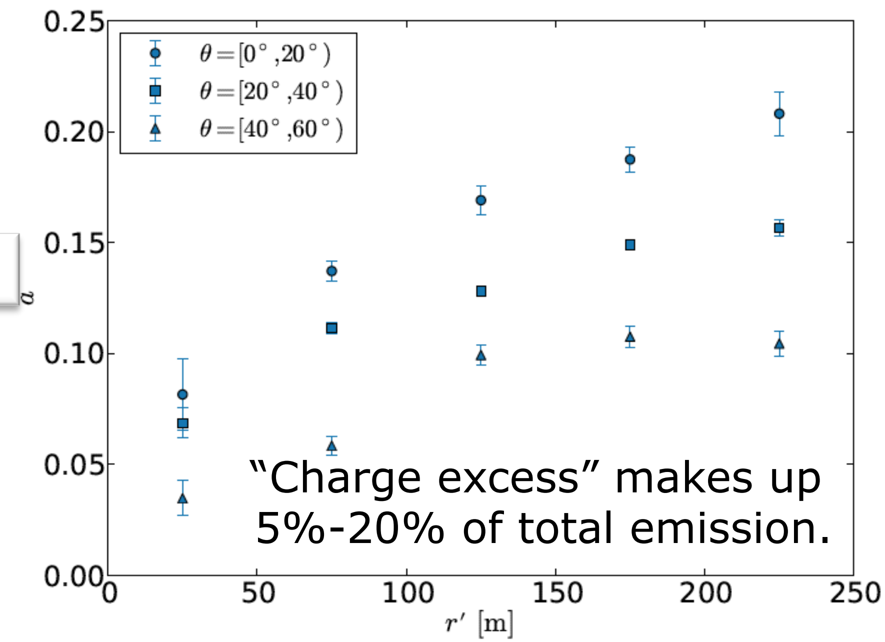


Fractional contribution of charge excess radiation as function of distance



LOFAR: ~ 3% - 20%

pioneered at AERA (Auger): ~ 14%

Schellart et al. (2014, JCAP)

Polarization – Thunderstorms and Geoelectric Fields

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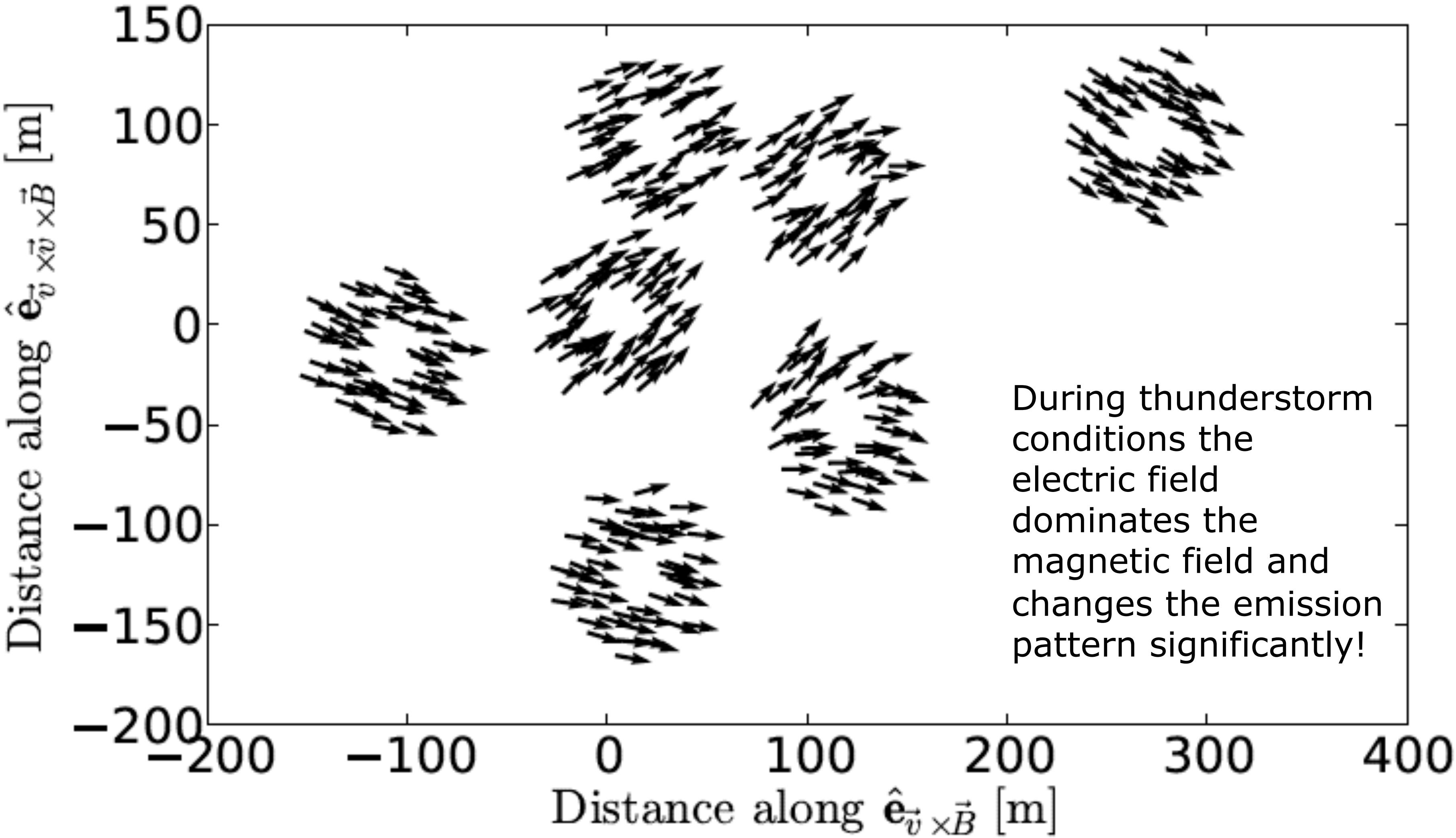

During thunderstorm conditions the electric field dominates the magnetic field and changes the emission pattern significantly!

Schellart et al., in prep.

Radio Lateral Distribution Function (LDF)

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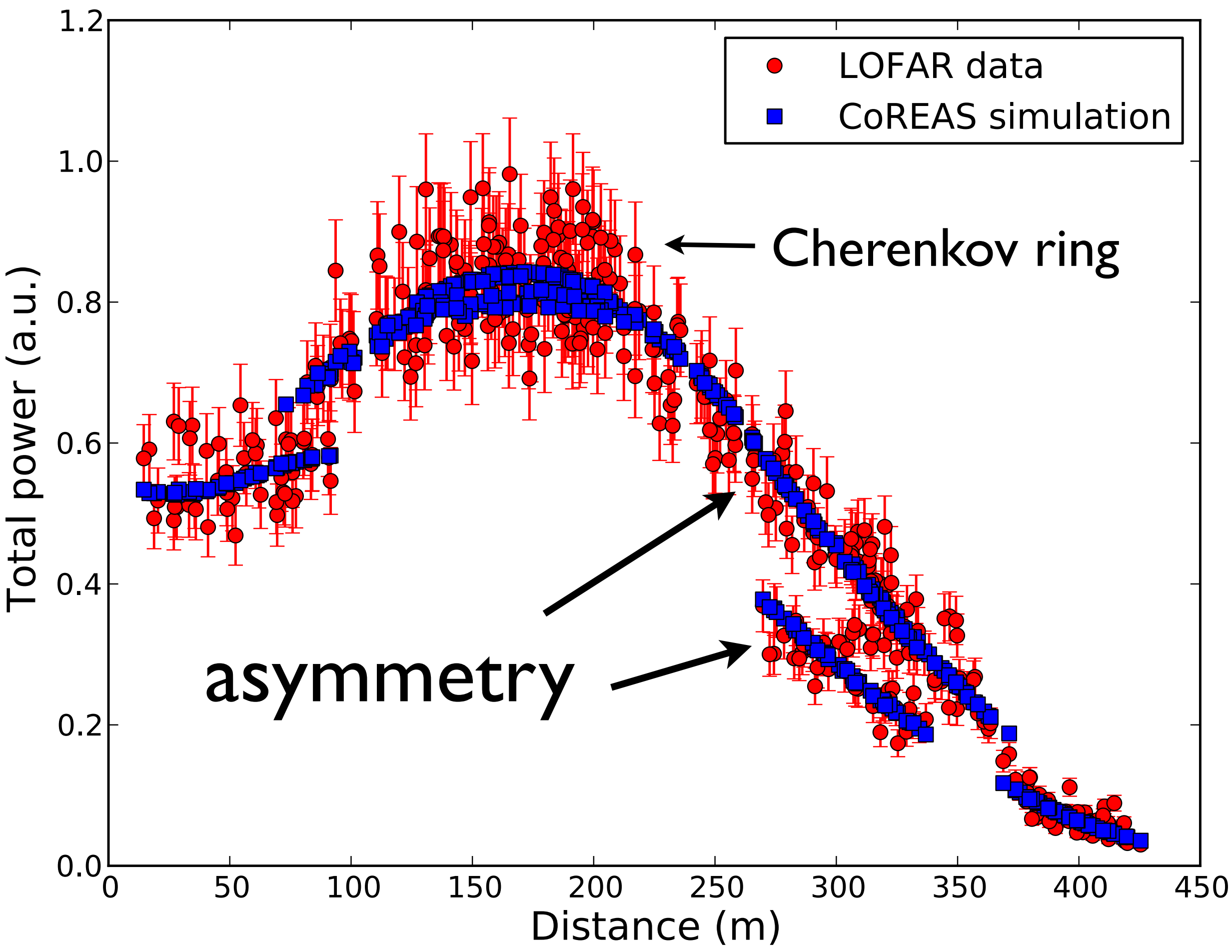

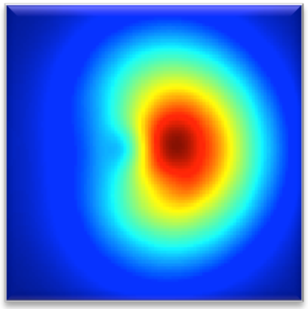

Analyzing the first LOFAR Events

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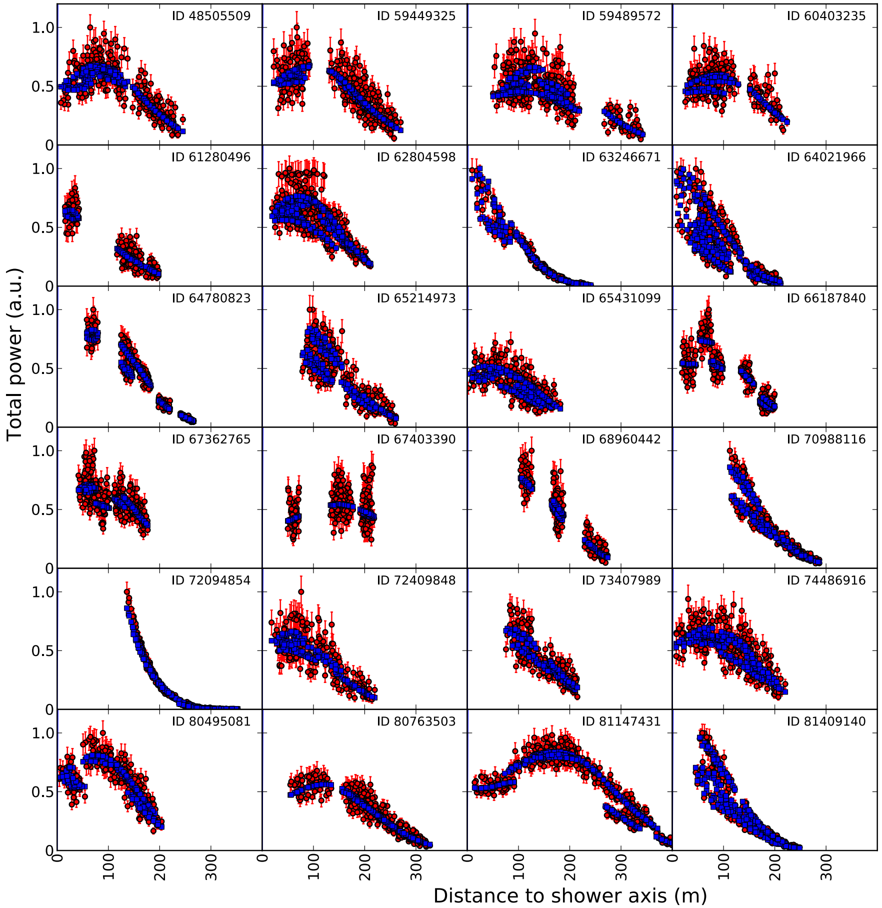
LOFAR data vs. CoREAS sim.



Buitink et al. (2014, in prep.)

- **First sample**: ~100 brightest events, no thunderstorms.
- 200-450 antennas per event.
- All events reproduced with reduced χ^2 from 0.9 - 2.6!
- Radiation mechanism finally completely understood!

Linear & Circular Polarization

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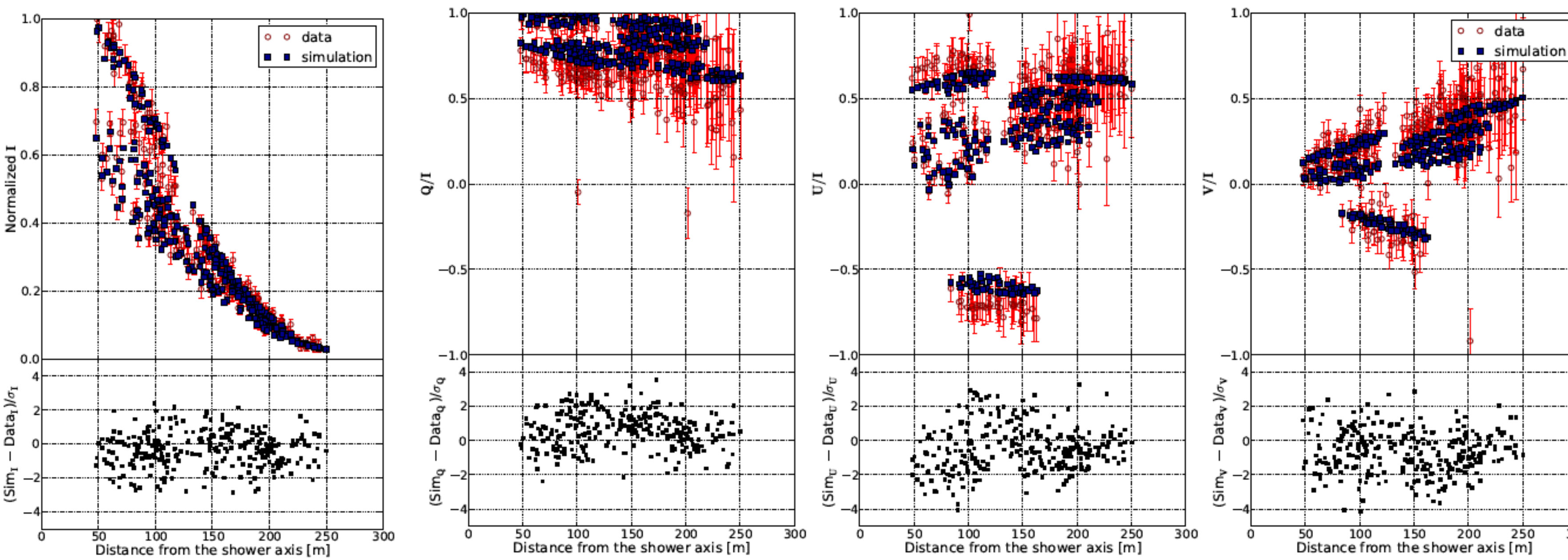

Scholten et al. (2017)

Emission Pattern at High Frequencies: Cherenkov-Like Ring

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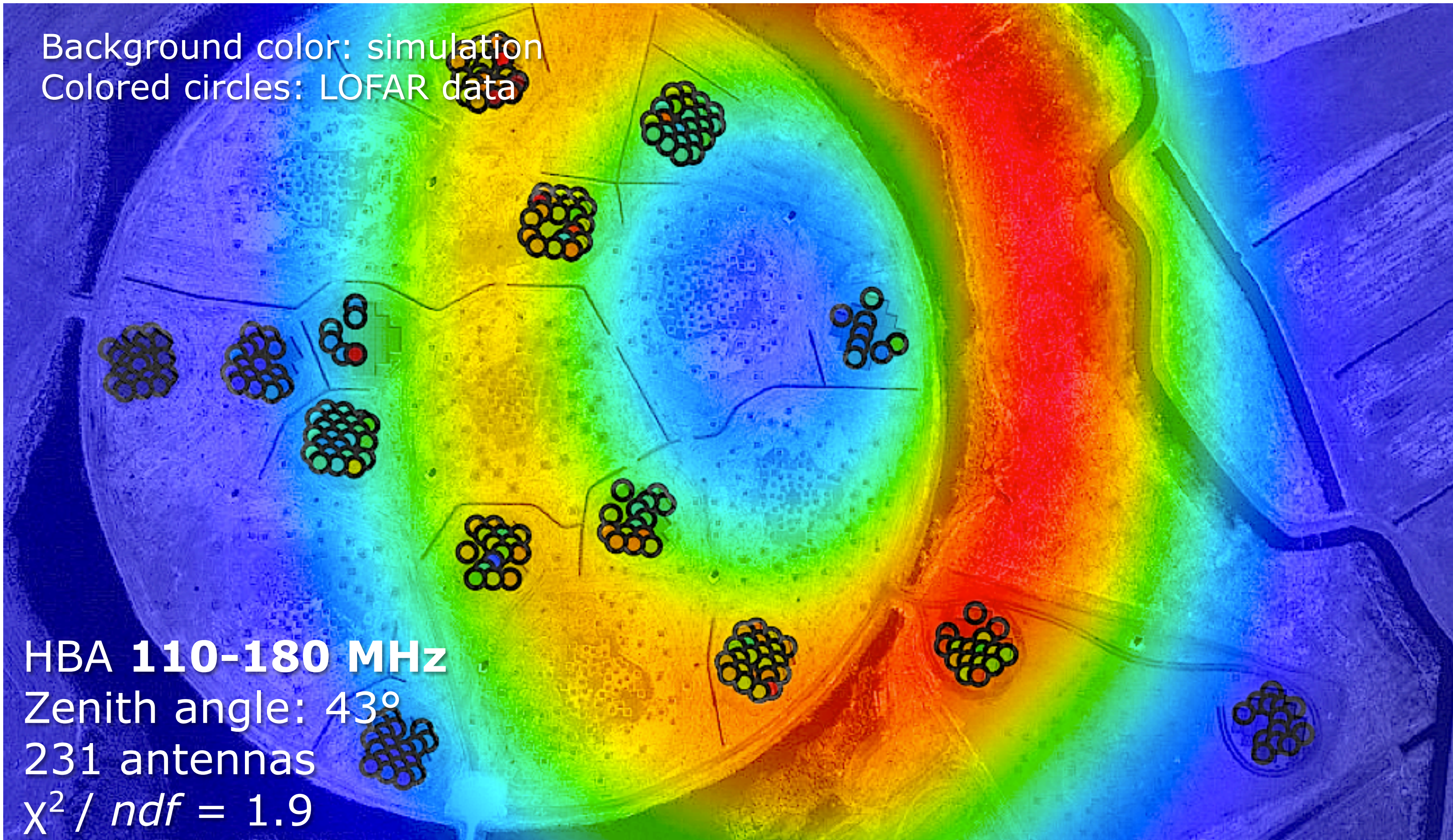

Nelles et al. (2014), Astropart. Phys., subm.

Reconstructing X_{max} for each shower:

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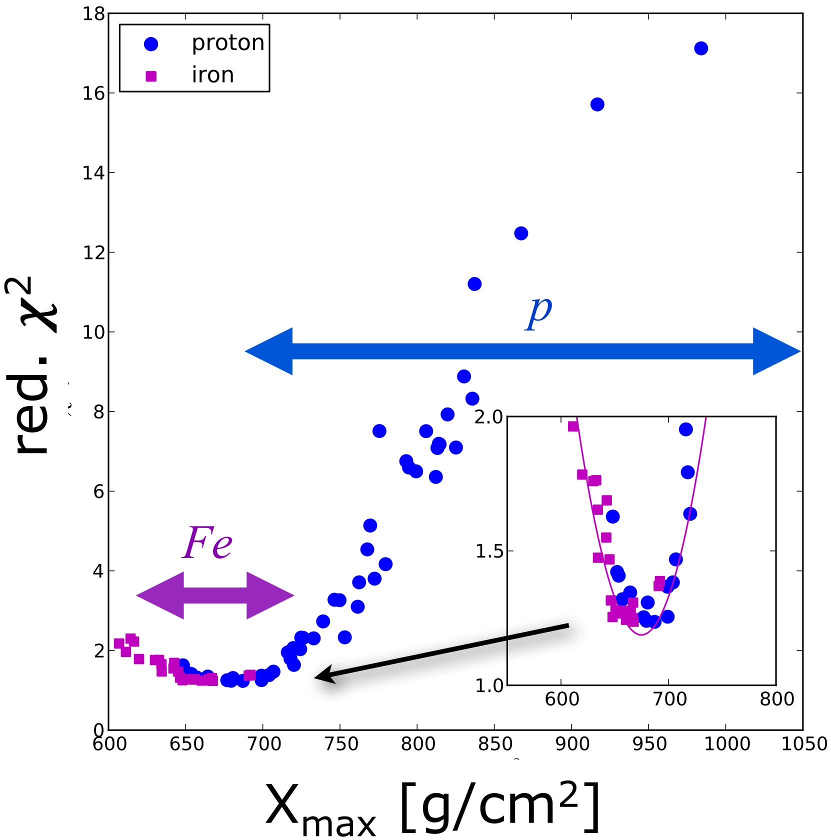


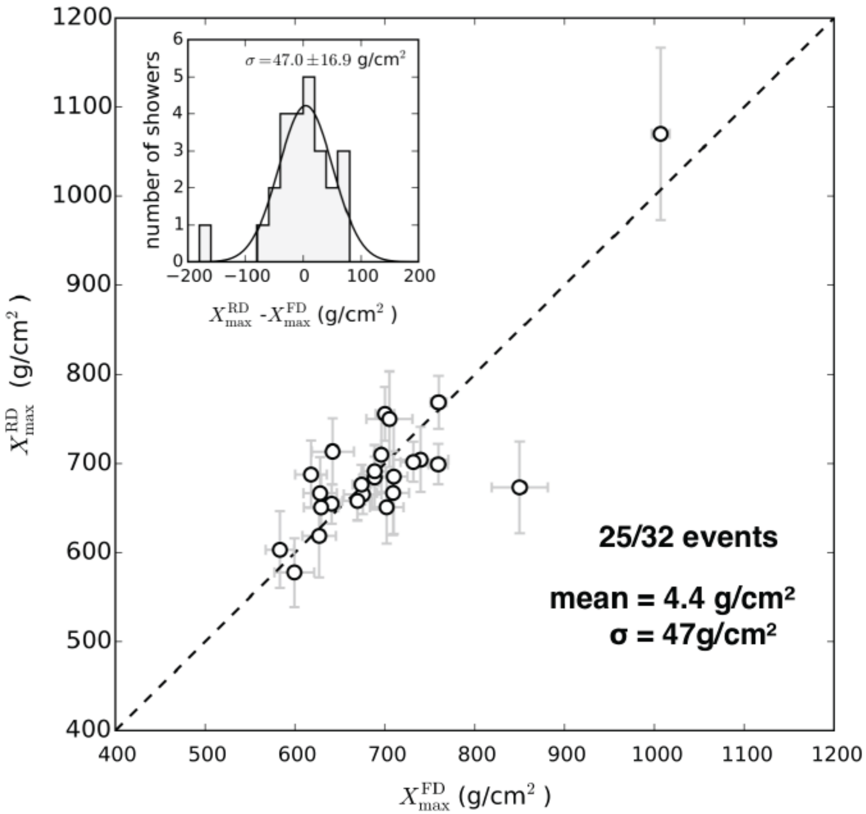
- Simulate **25 proton and 15 iron** showers for same energy and direction
- Find best-fitting simulation for radio & particle detectors
- **Iterate core & energy**
- Atmospheric variations
- sim-vs-best-fit sim for error
- Check for systematics:
  - different hadronic models (QGSJETII, EPOS, SIBYLL)
  - Different radio codes (CoREAS, ZHAireS, EVA, Selfas)

⇒ **Resolution < 20 g/cm²!**

Buitink et al. (2014, PRD)

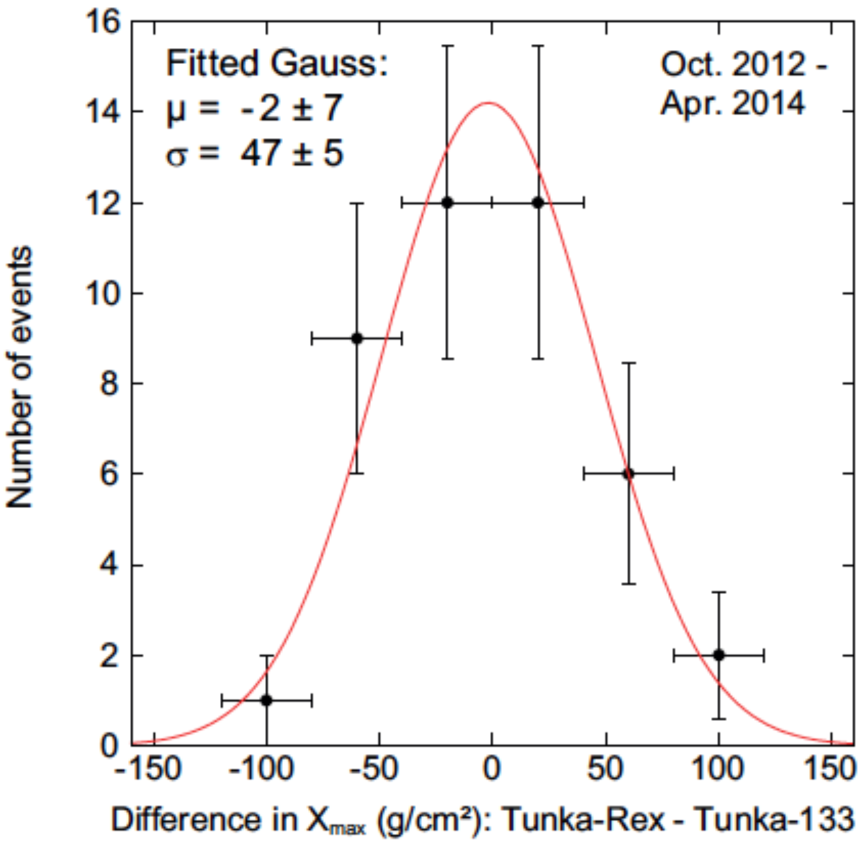
Radio comparison with other methods

Auger – optical fluorescence

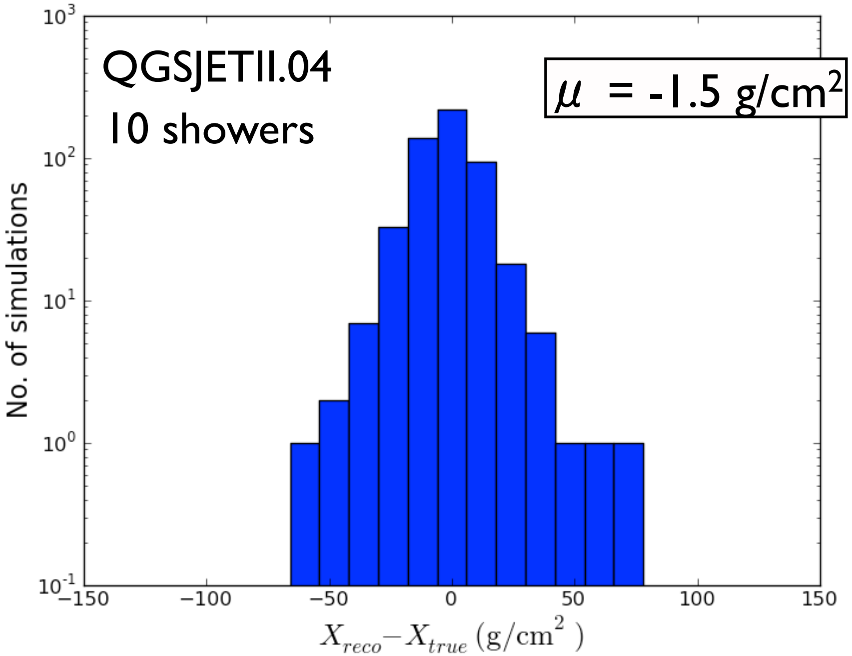


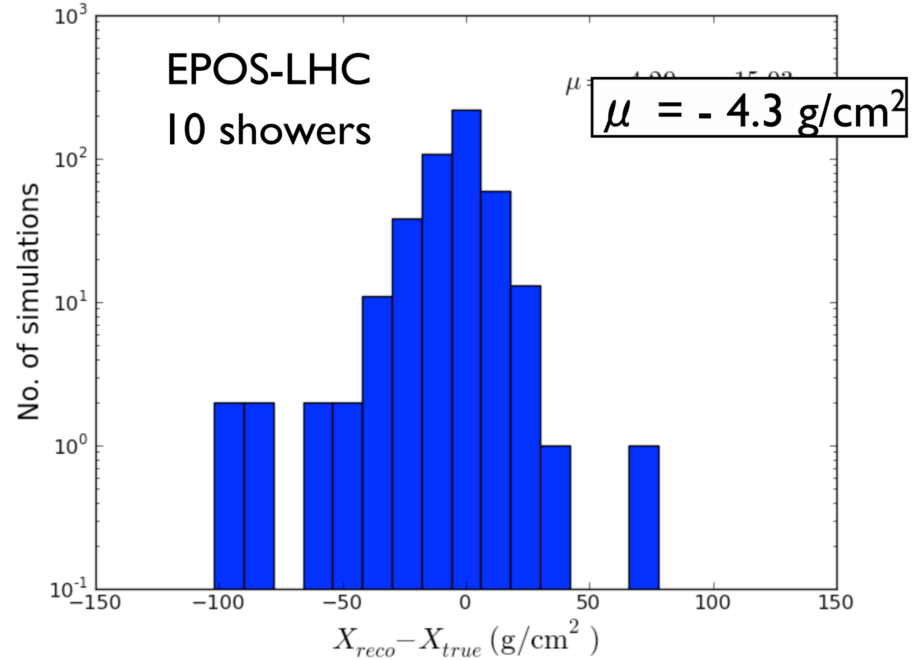
Gaté et al. (2016)

Tunka-Rex – optical Cherenkov

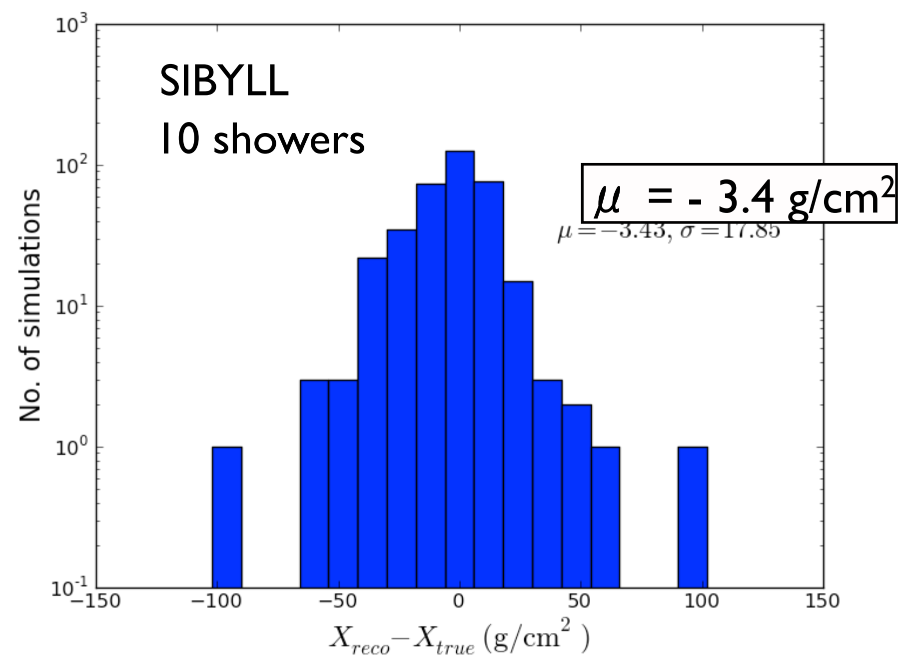


Bezyazeekov et al. (2017)





- **Shower simulated with QGSJETII EPOS & SIBYLL**
- Reconstructed using QGSJETII
- 10 showers; 25 p + 15 Fe each
- Systematic effect on Xmax reconstruction is small *geometrical measurements*



Unbinned Composition Analysis

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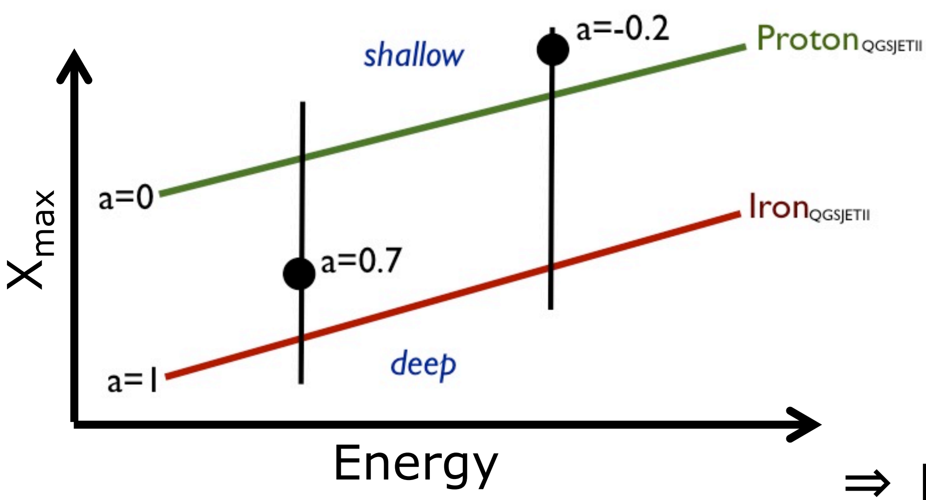
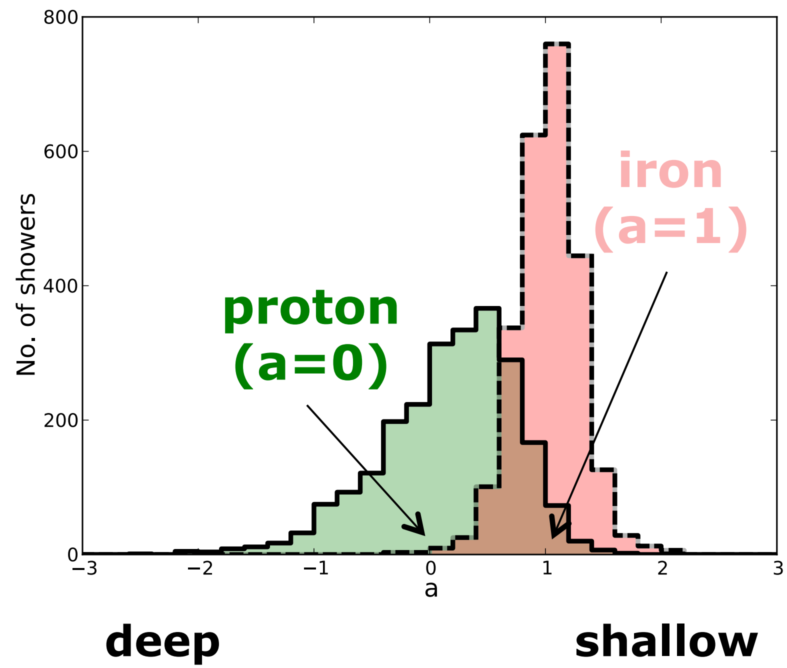
Calculate energy-independent mass parameter *a* for each event.

$$a = \frac{\langle X_{\mathrm{proton}} \rangle - X_{\mathrm{shower}}}{\langle X_{\mathrm{proton}} \rangle - \langle X_{\mathrm{iron}} \rangle}$$



Buitink et al. (2014, PRD)

Simulated distribution of iron and proton showers for LOFAR resolution



⇒ High X_{max} resolution allows distinction between pure iron, pure proton, or mixed composition!

LOFAR Xmax

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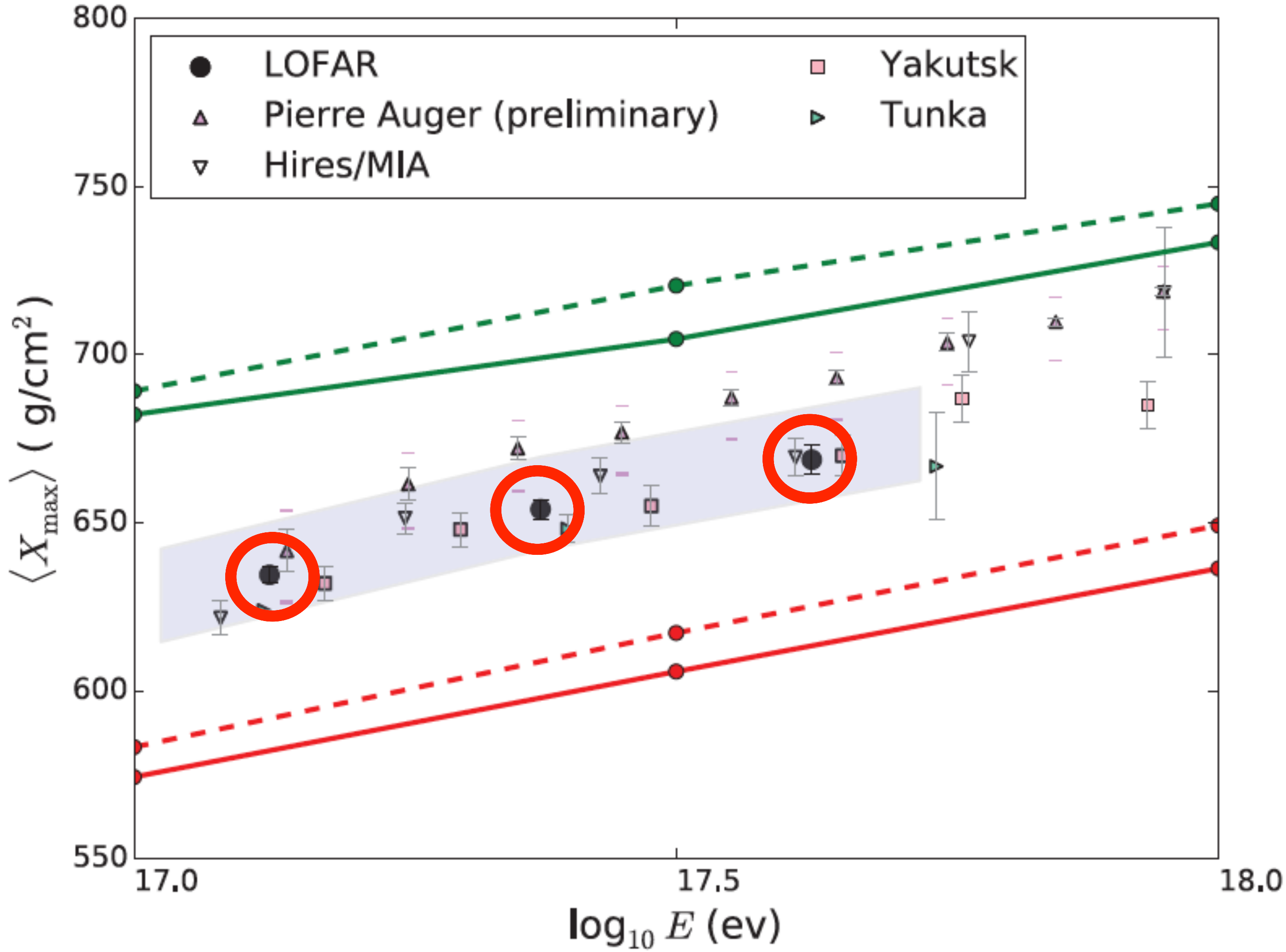

Cumulative distribution function for 50 events

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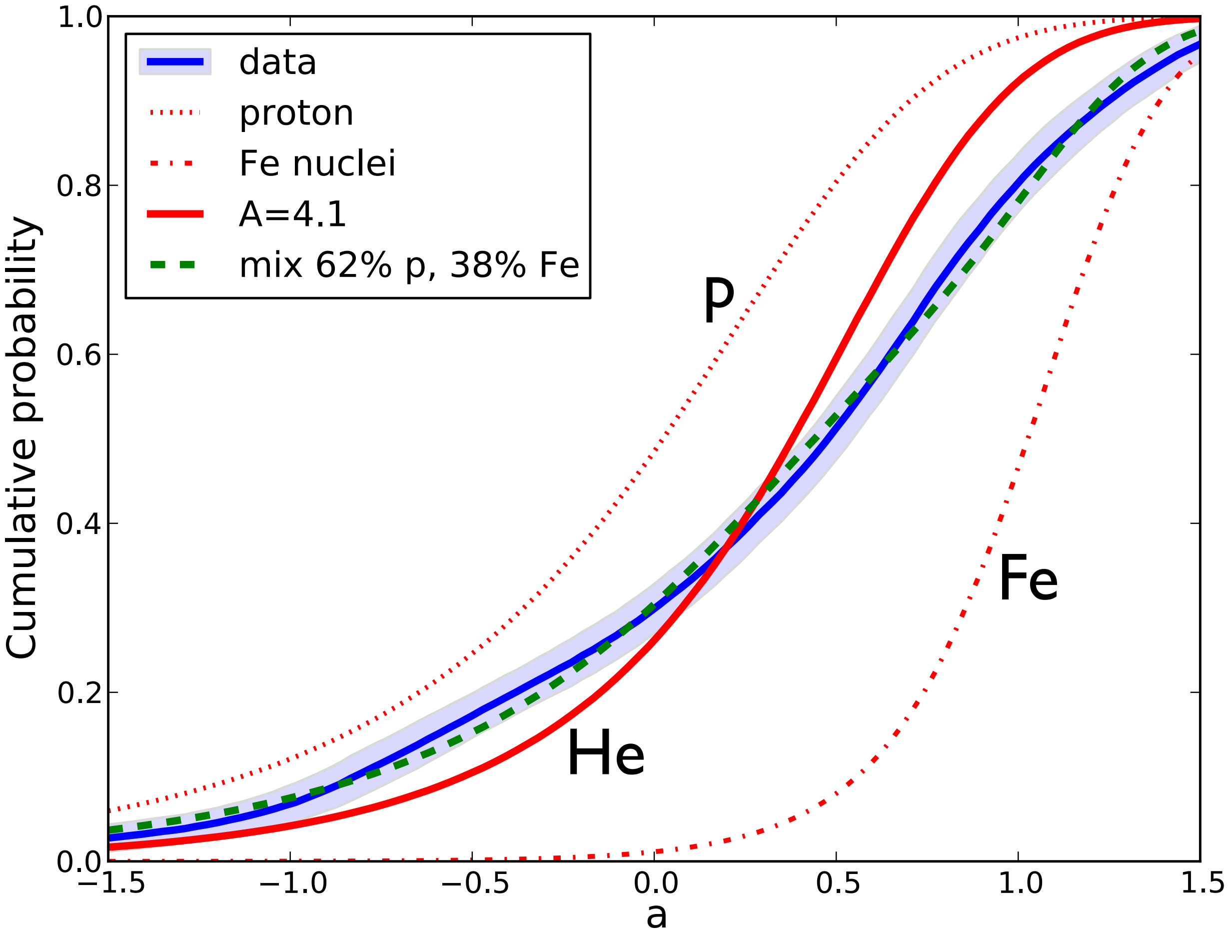
We can already separate 2 mass components with only 50 showers!



Energy $\sim 10^{17.6}$ eV

Buitink et al. (2014, in prep.)

Cumulative mass distribution

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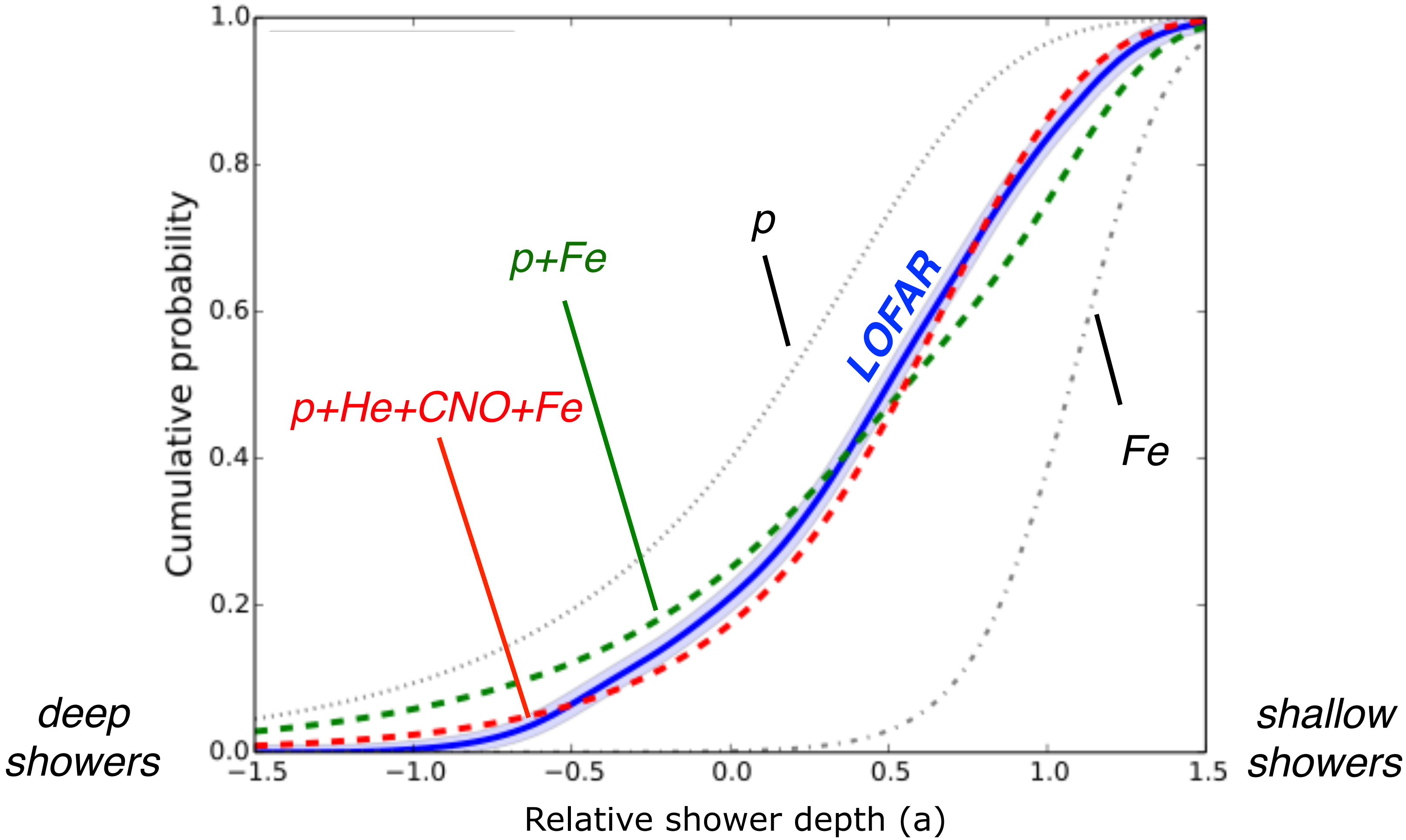
Best fit: 80% light particles (p+He) at 10^{17} -$10^{17.5}$ eV [within 38% - 98% at 99% C.L.]



Buitink et al. (2016, Nature)

Energy Spectrum

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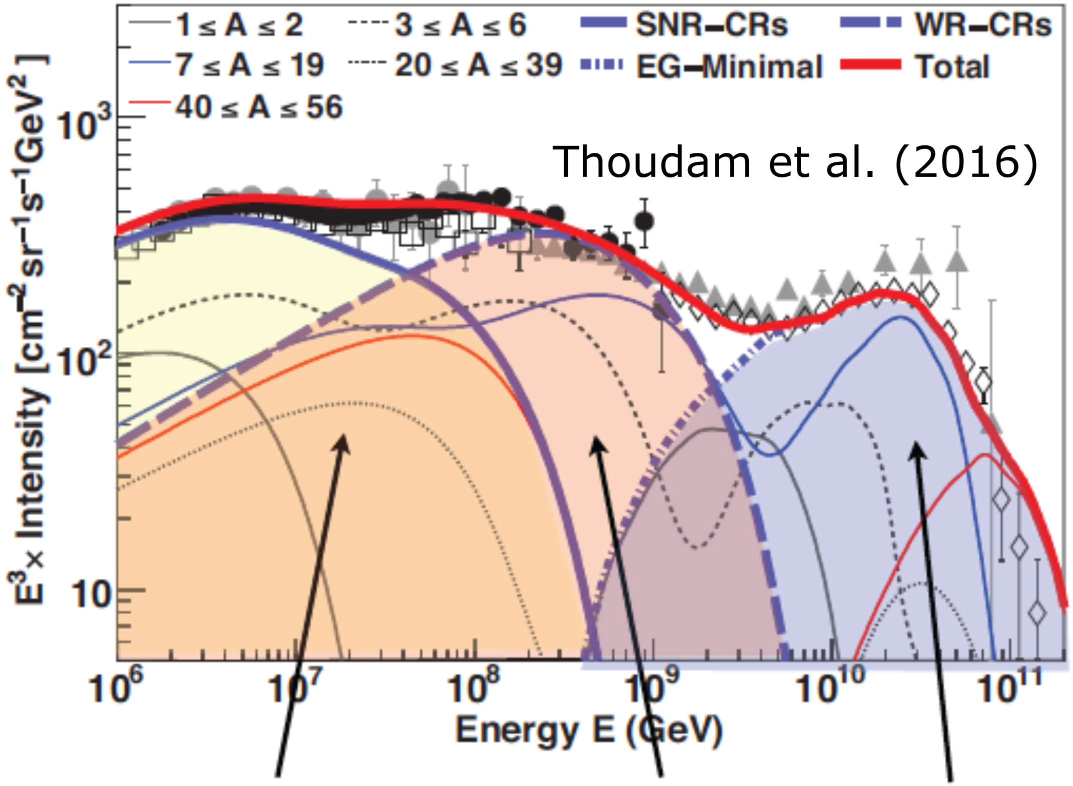

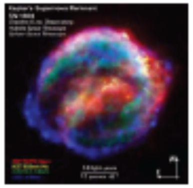

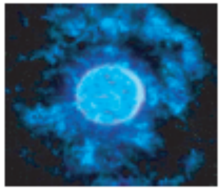

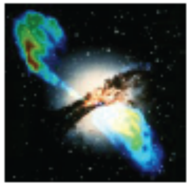

Supernovae

Galactic Pevatron
e.g., SNe in WR-stars

Extragalactic
e.g. AGN

Mean atomic mass

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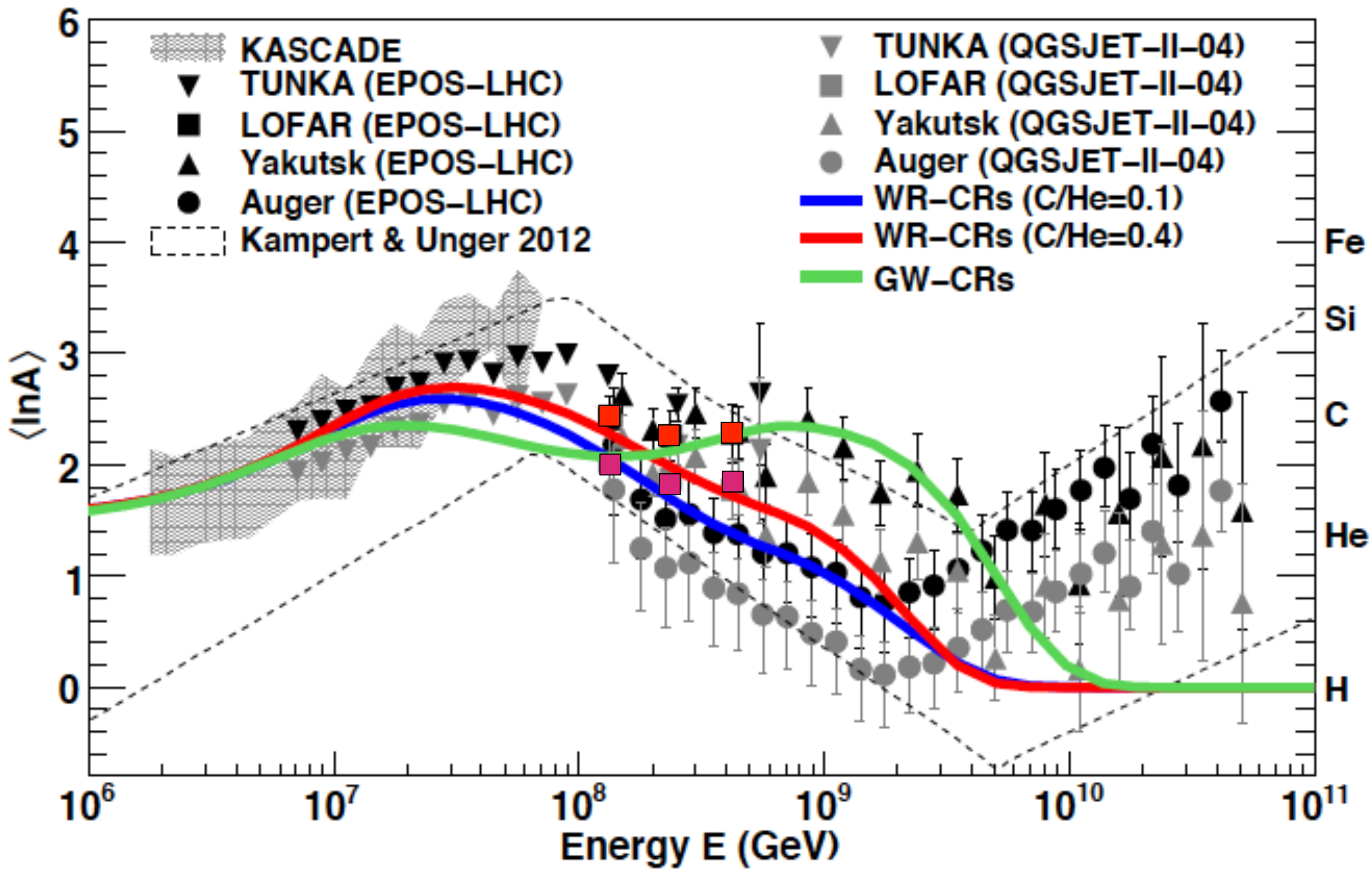

Thoudam et al. (2016)

All Particle Cosmic Ray Spectrum

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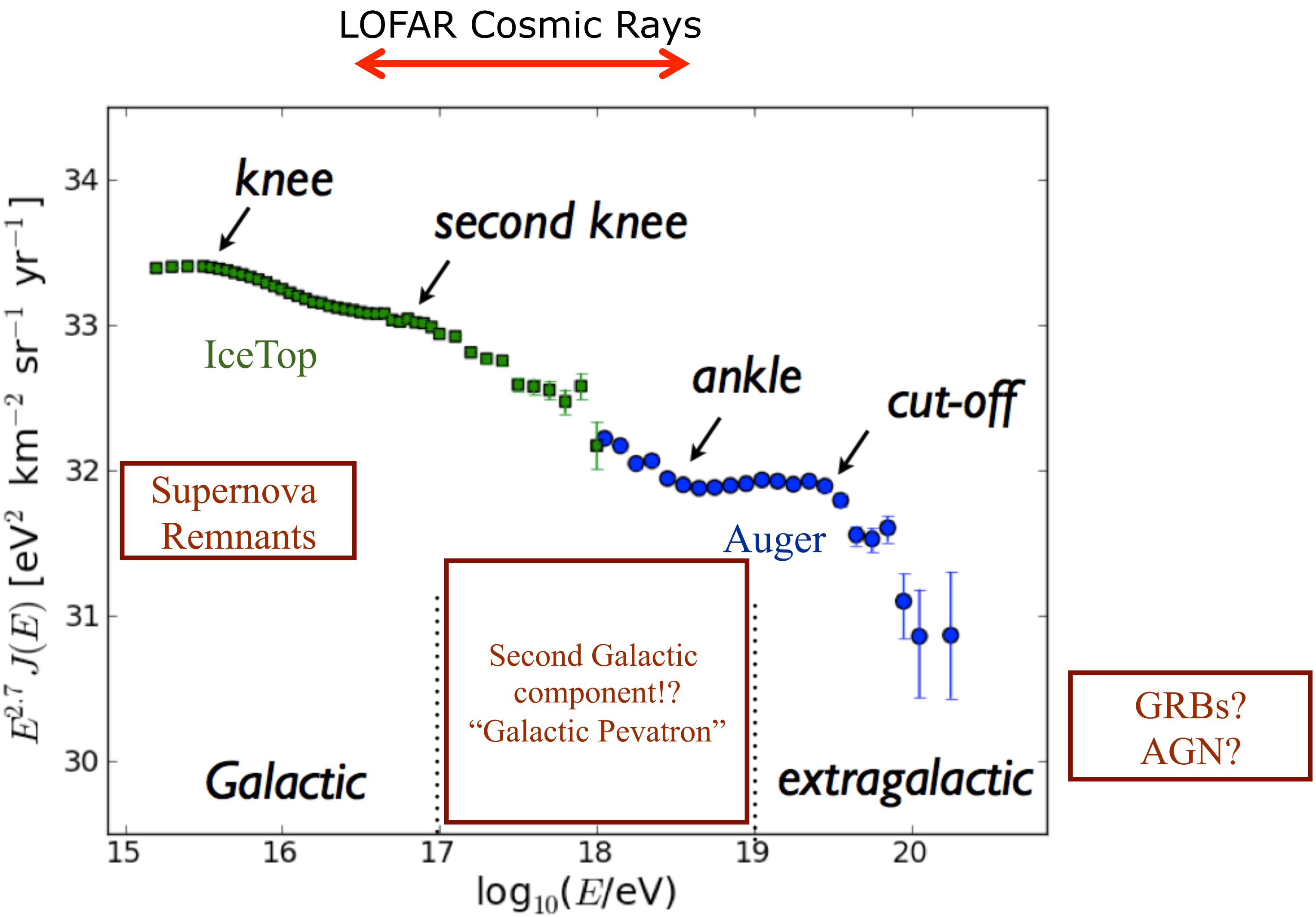

Conclusions

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- LOFAR data & COREAS simulations agree in great detail: intensity profile, polarisation (full Stokes), spectrum
- Auger, Tunka: Absolute energy calibration of CRs with radio, confirmation of Xmax measurement
- LOFAR can measure cosmic ray mass composition X_{max} resolution of < 20 g/cm^2 at least *similar to fluorescence detection + higher duty cycle*
- LOFAR composition results based on 100+ events: light mass component at 10^{17} - $10^{17.5}$ eV (2nd knee)
- Consistent with 2nd Galactic component (Wolf-Rayet SN?)
- Factor 3 more data to be analyzed by end of this year.
- Hoping for SKA CR capability in the future!

Mean Xmax for 50 showers

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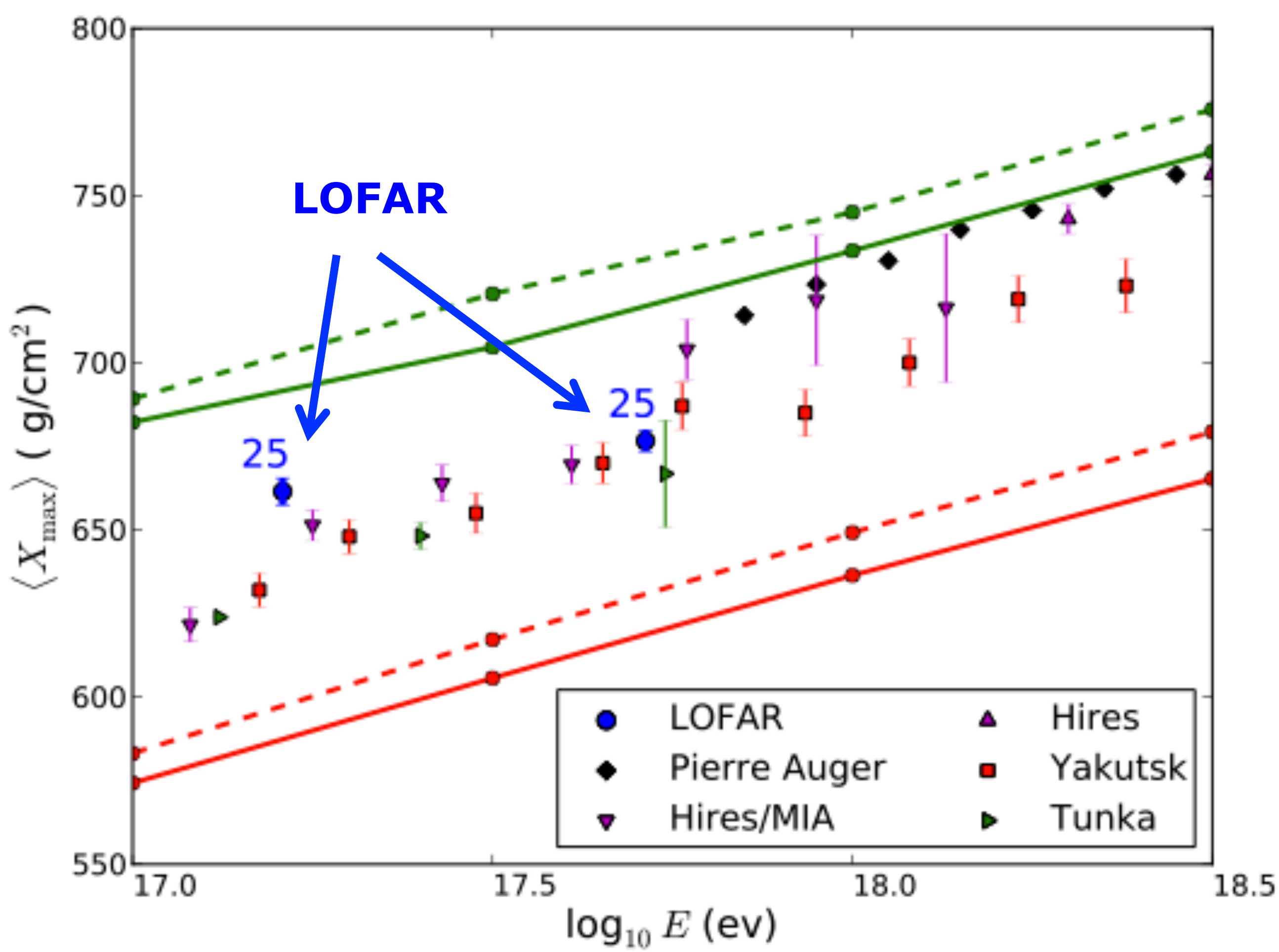

Fit for each simulation

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Minimize χ^2 of radio and particle data simultaneously

$$\chi^2 = \sum_{antennas} \left(\frac{P_{ant} - f_r P_{sim}(x_{ant} + x_{off}, y_{ant} + y_{off})}{\sigma_{ant}} \right)^2 + \sum_{detectors} \left(\frac{d_{det} - f_p d_{sim}(x_{det} + x_{off}, y_{det} + y_{off})}{\sigma_{det}} \right)^2$$

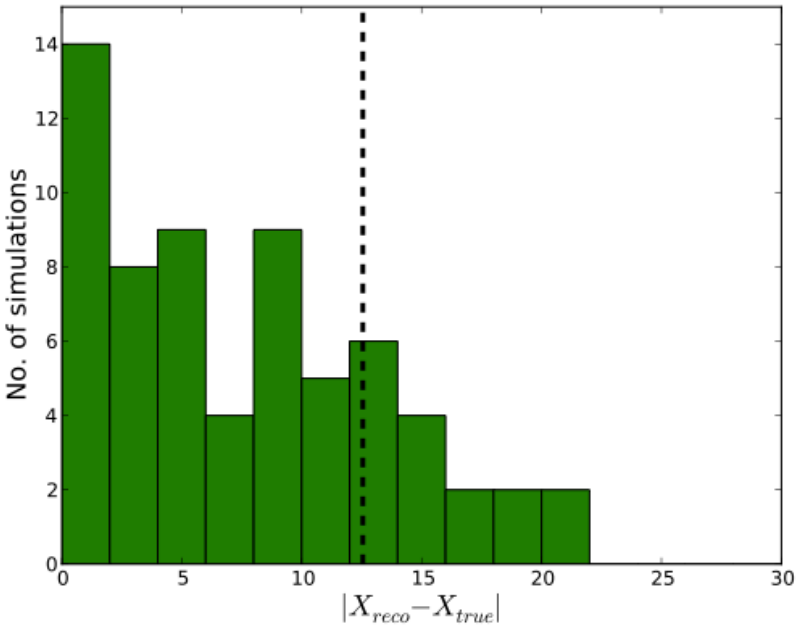
4 fit parameters:

core position

radio power scale factor

particle density scale factor

Uncertainty on Xmax



Monte Carlo vs Monte Carlo method

reconstruct Xmax for many simulations of the same event

construct region that contains 68% of $| X_{reco} - X_{true} |$

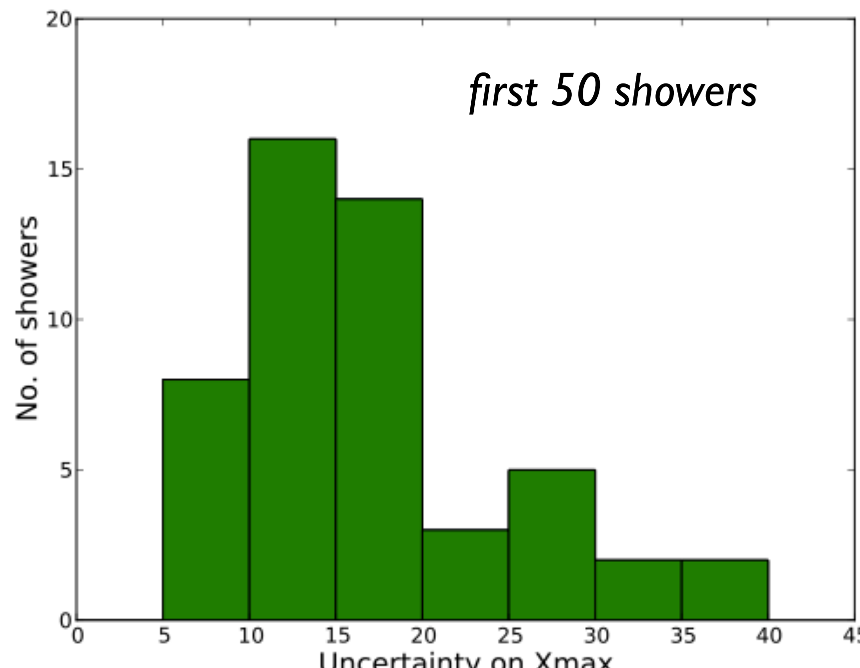
σ_{meth} = 12.7 g/cm^2
σ_{atm} = 1 g/cm^2 (after correction)
σ = 13 g/cm^2

first event sample:

σ ranges from 7.5 to 37 g/cm^2

mean value 17 g/cm^2

SB *et al.* PRD 90 082003 (2014).



Energy resolution

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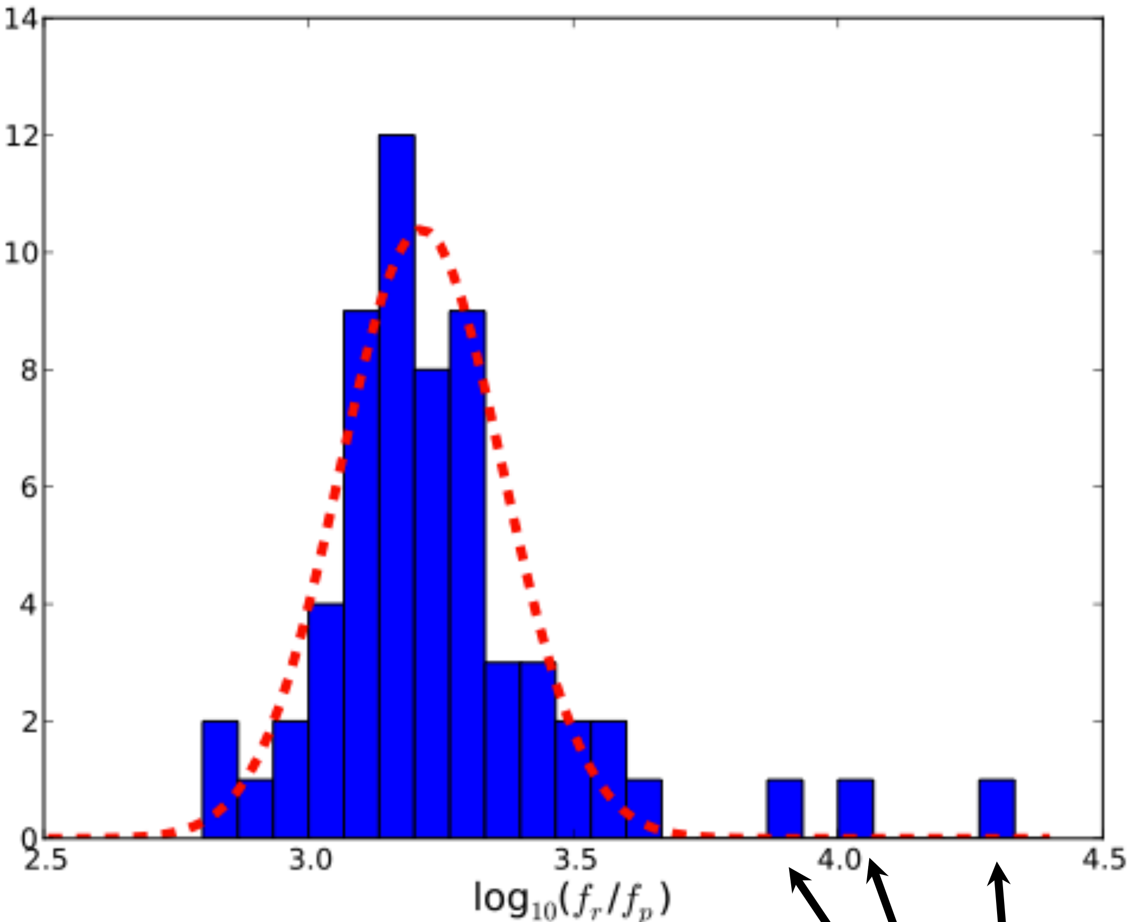
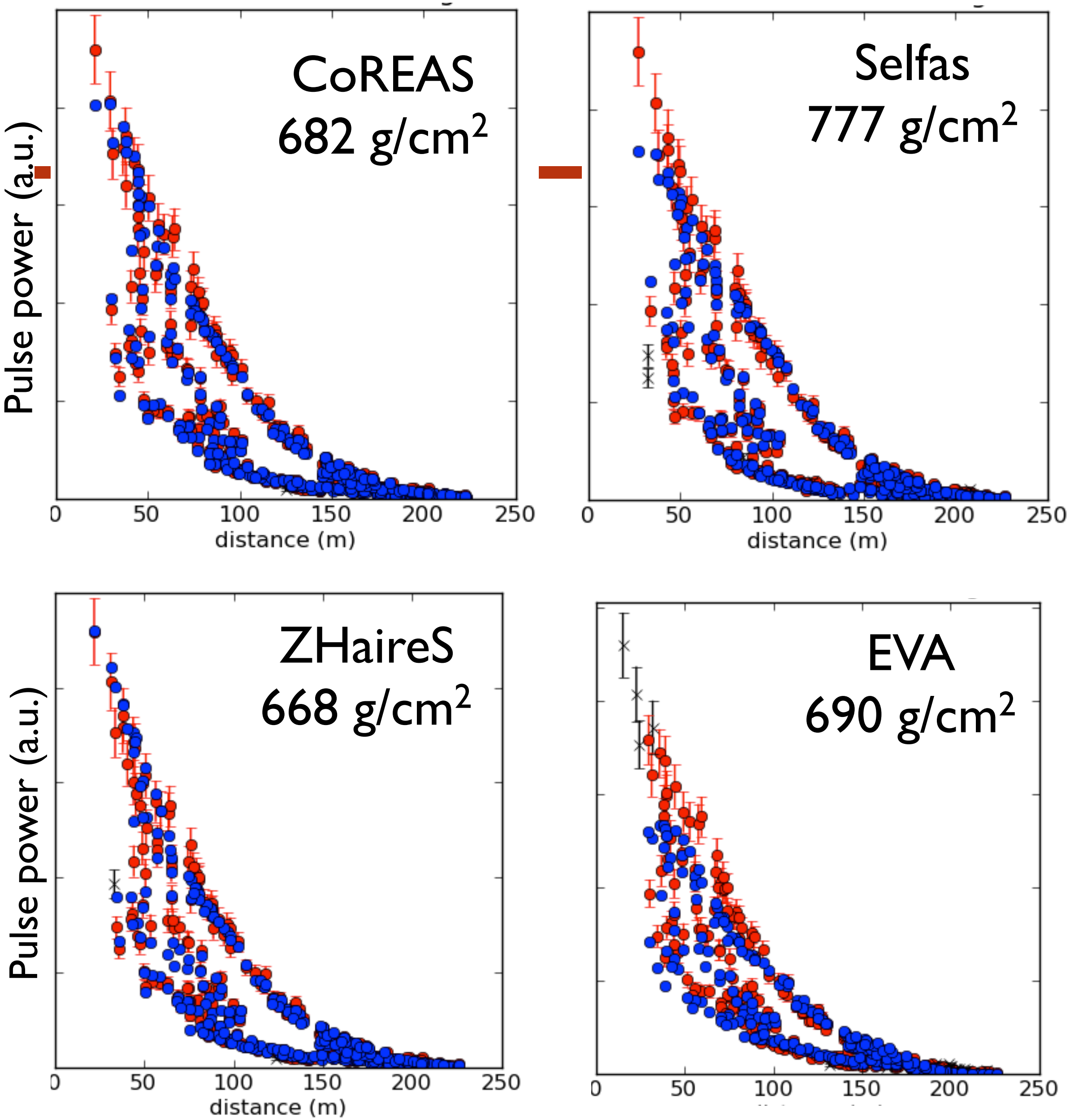


misreconstructed core position

- $E_{reco} = f_p * E_{sim}$
  if f_p is large: run new simulation at E_{reco} until convergence
- consistency:
  f_r/f_p should be constant!
- energy resolution: 40%



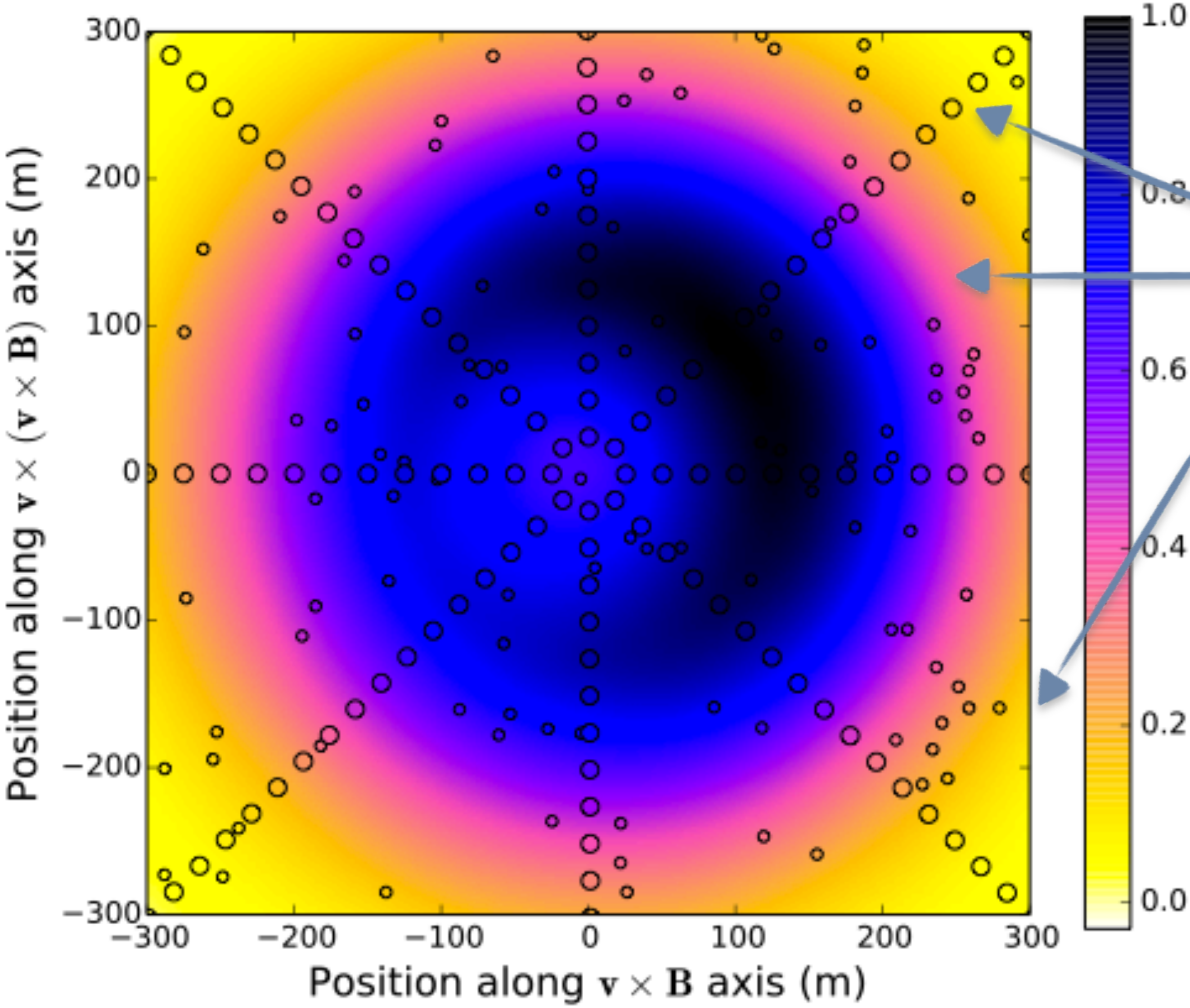
- Simulation workshop Nijmegen (february 2014)

  simulation by all 4 codes for 10 LOFAR events

- Preliminary results:

  Microscopic models (CoREAS & ZHaireS) very similar

  Macroscopic models are close; parametrizations break down near shower axis?



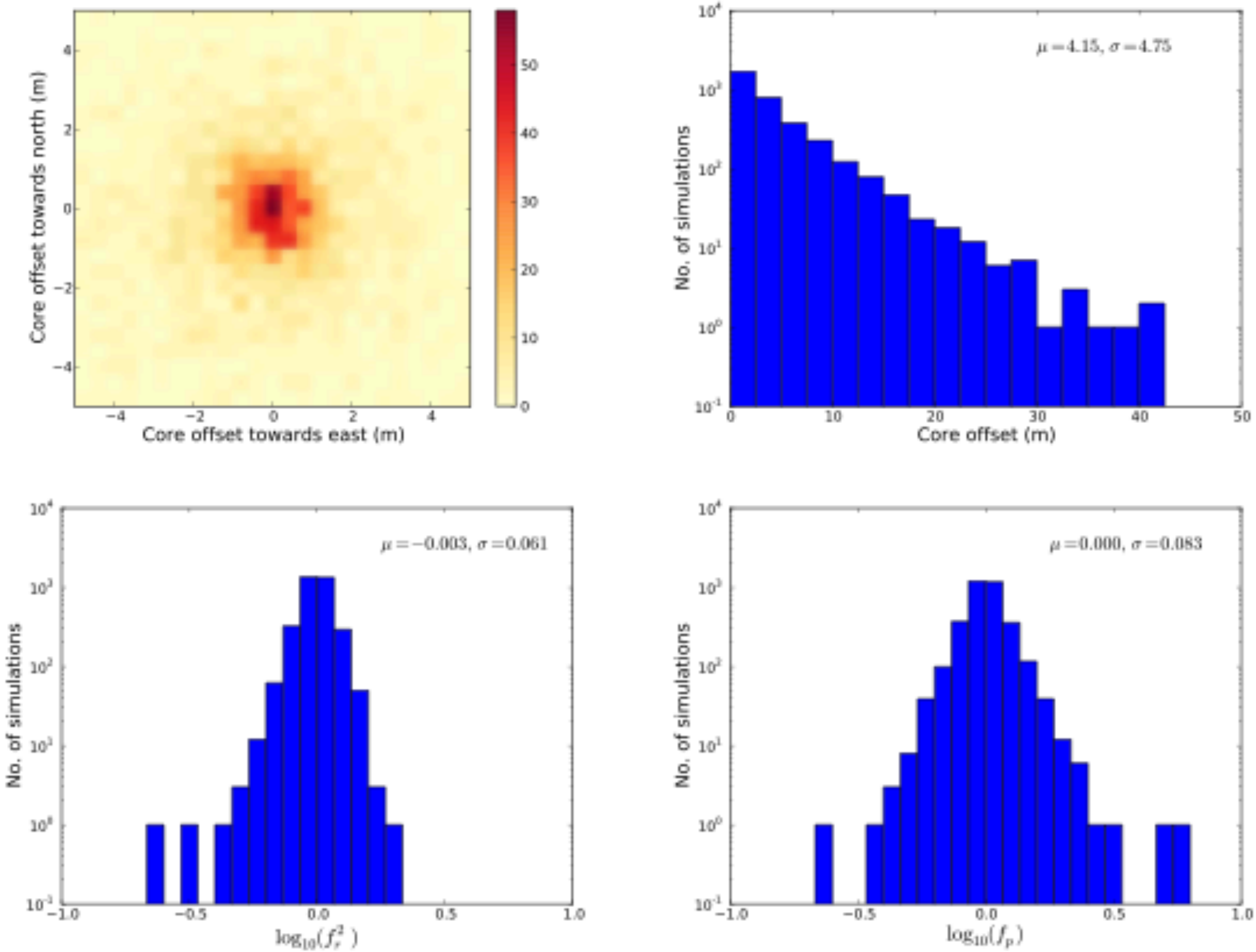
large circles: simulation

background color: interpolation

small circles: verification

error < 2.5% of P_{max}

no bias due to multivariate fit



Emission Pattern at High Frequencies: Cherenkov-Like Ring

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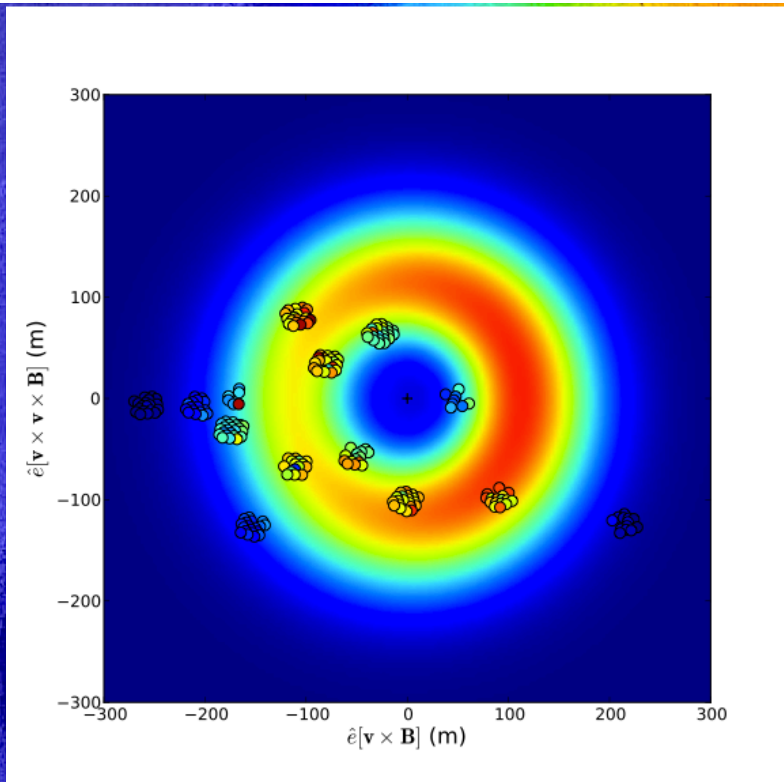
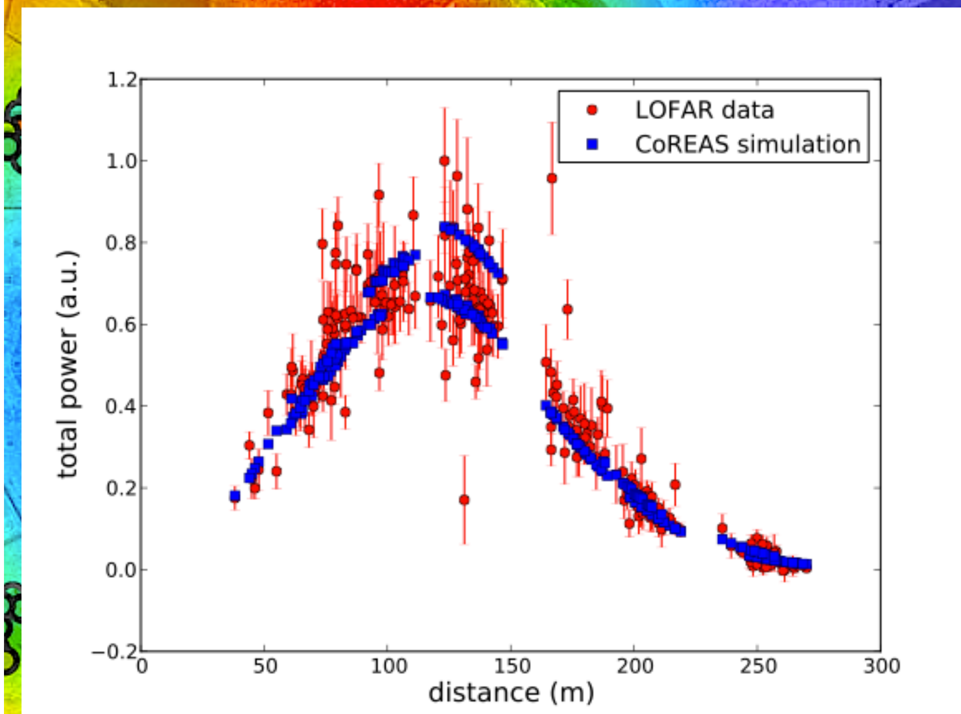
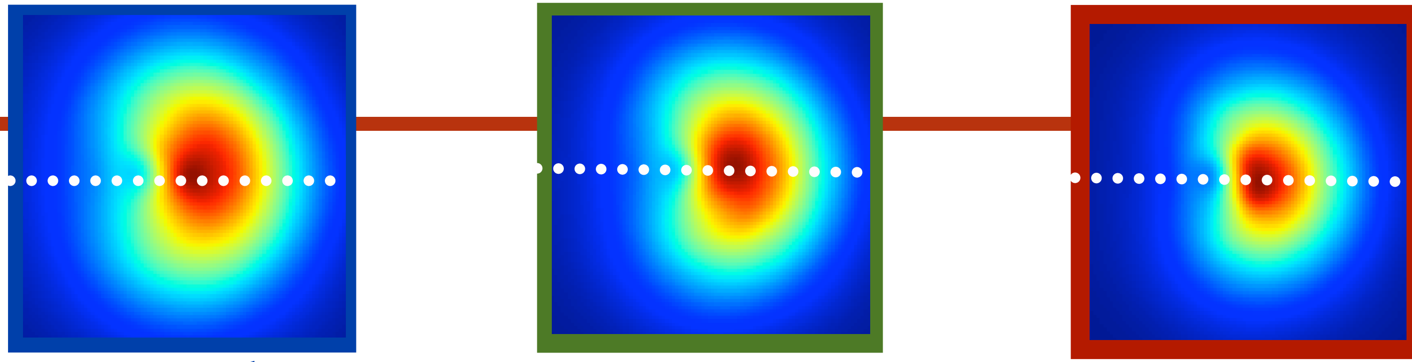


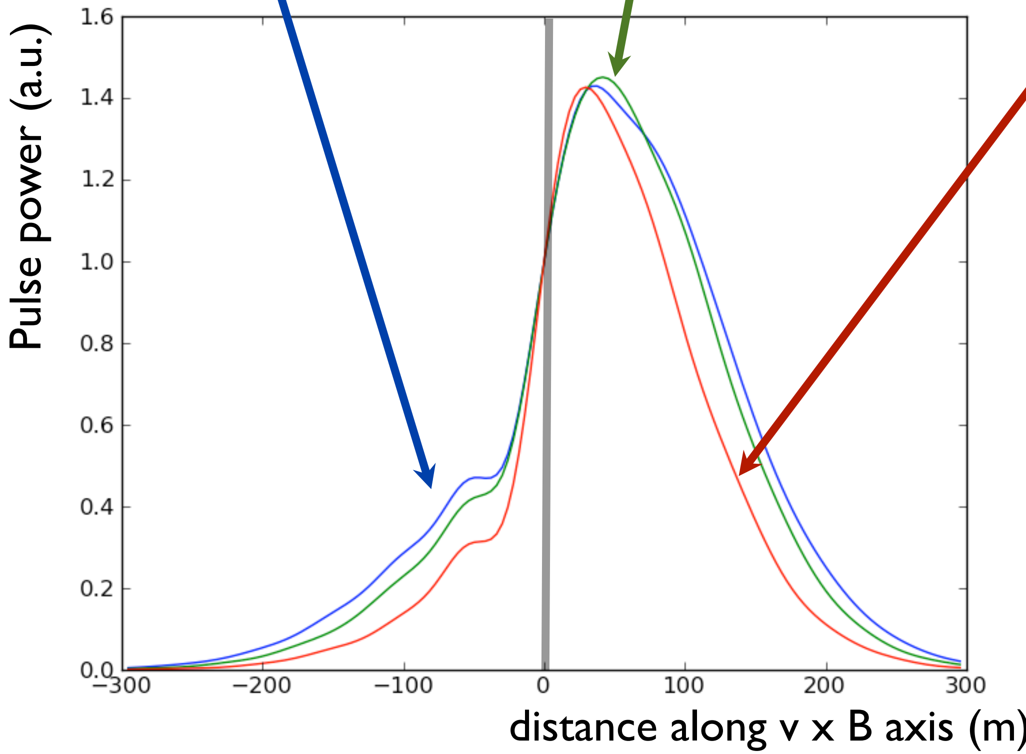


HBA **110-180 MHz**
Zenith angle: 43°
231 antennas
χ^2 / *ndf* = 1.9

Nelles et al. (2014), Astropart. Phys., subm.

X_{max} ~ 600 g/cm^2 X_{max} ~ 650 g/cm^2 X_{max} ~ 700 g/cm^2





shape depends on X_{max}

LOFAR:
200 - 400 antennas/event

→ *fit full 2D pattern !*

Radio Emission from Air Showers in Geomagnetic Field

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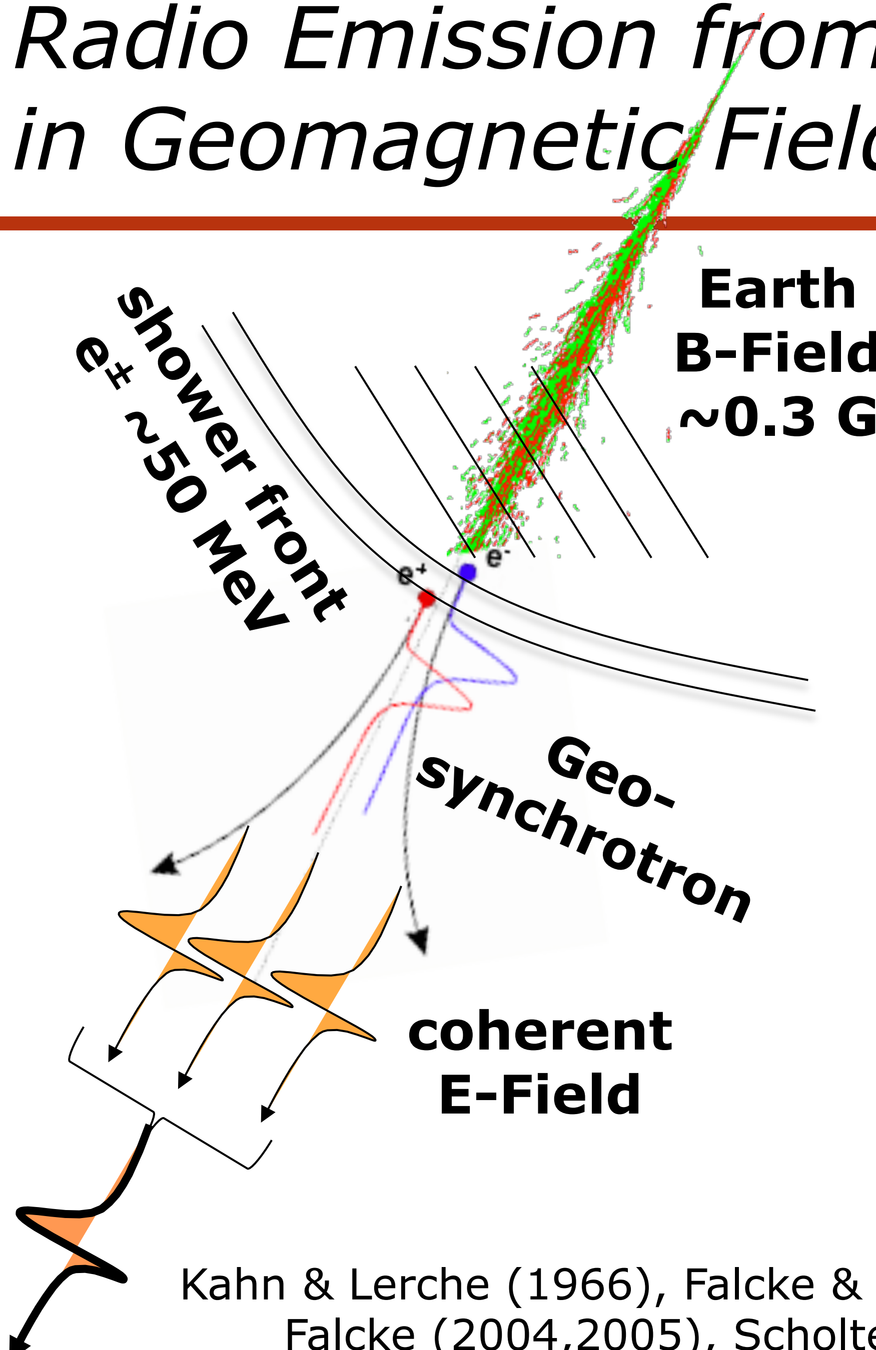

- UHECR initiates air shower
- Shower thickness: ~2-3 m ~ wavelength at 100 MHz
- $e^{\pm}$ bent by magnetic field
- Waves add up coherently
- Radio power grows quadratically with N_e

⇒ $E_{total}=N_e*E_e$

⇒ Power $\propto E_e^2 \propto N_e^2$

⇒ GJy flares on 20 ns scales

⇒ Experimental verification: LOPES, Codalema, Auger, TunkaRex, LOFAR ...

Kahn & Lerche (1966), Falcke & Gorham (2003), Huege & Falcke (2004,2005), Scholten et al. (2007-2011)

Galactic - Extragalactic Transition

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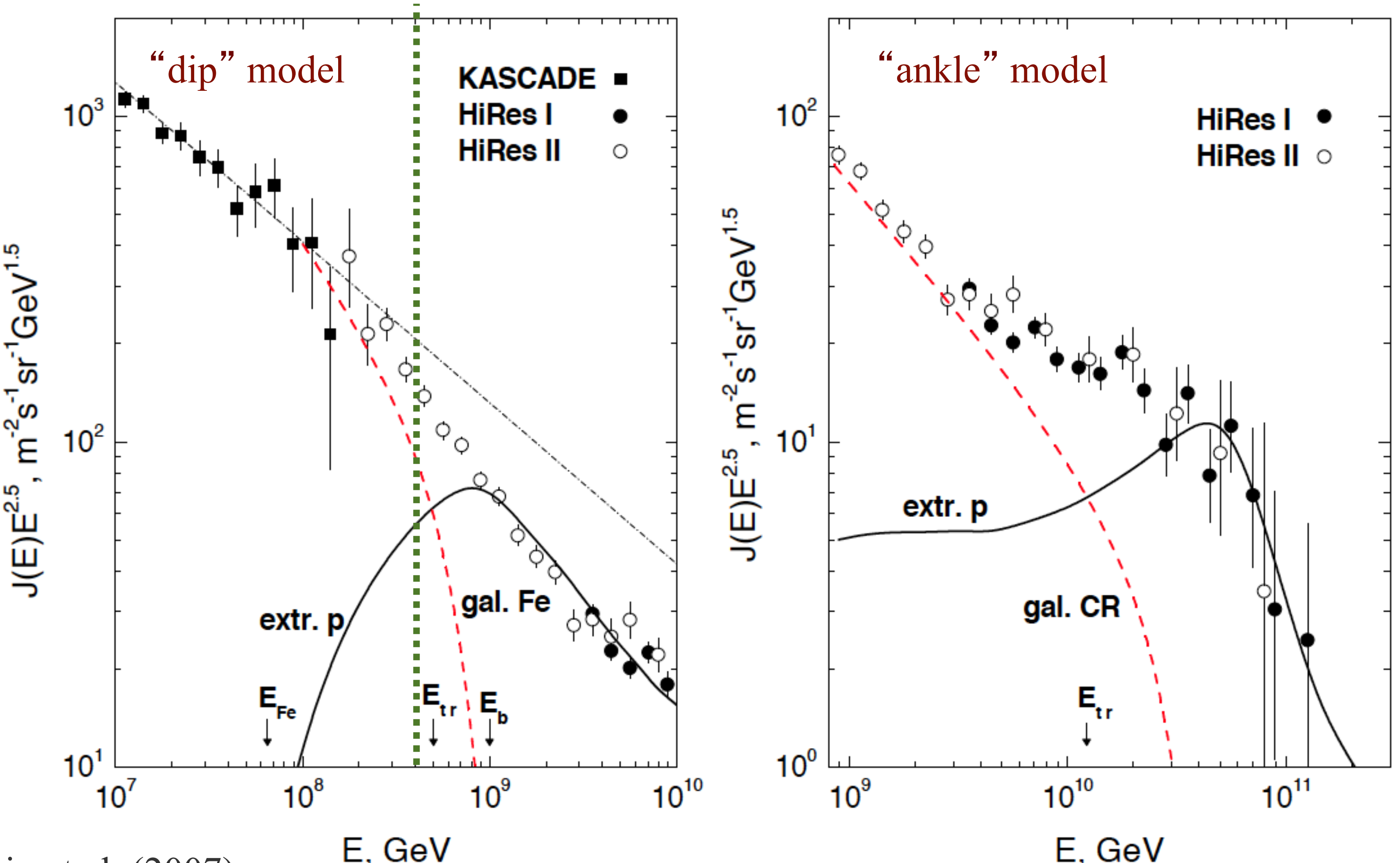

Aloisio et al. (2007)

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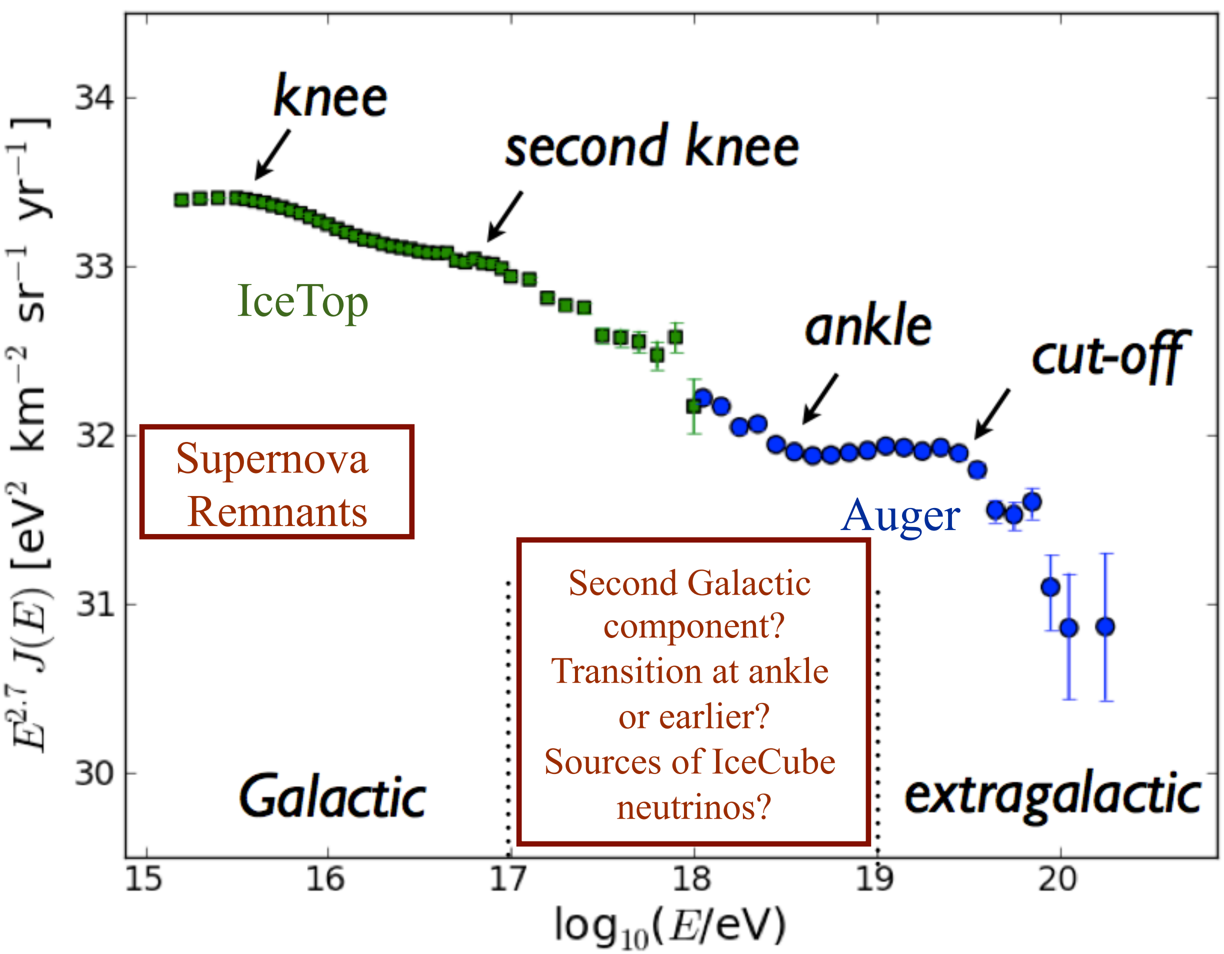
LOFAR Cosmic Rays

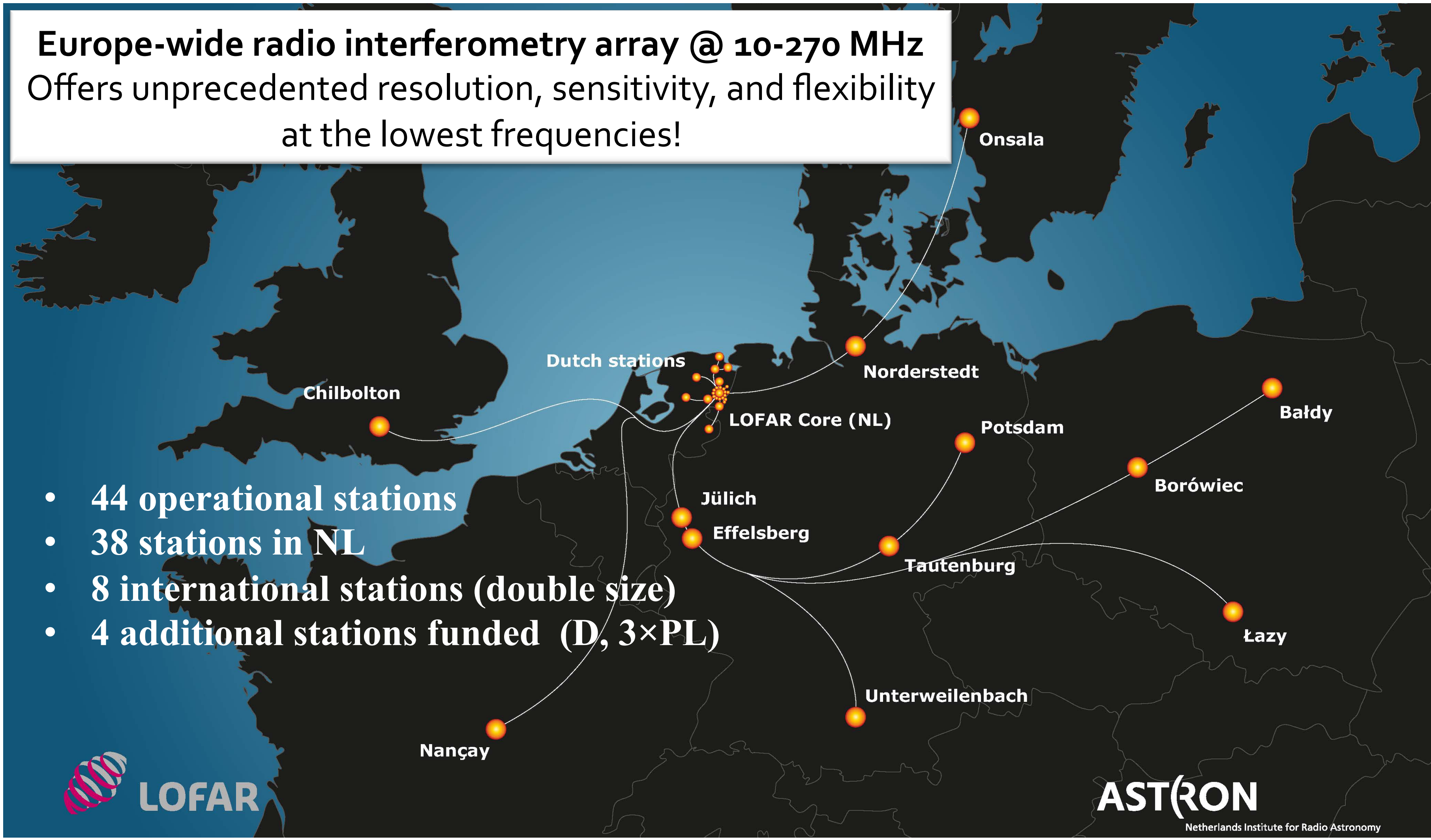


GRBs?
AGN?

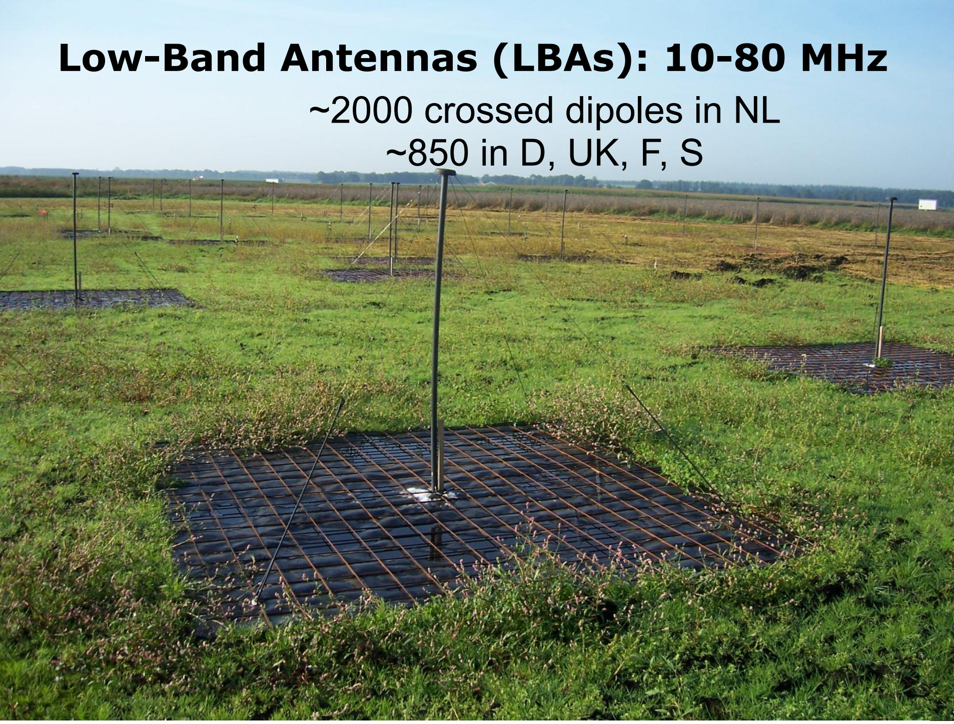
The International LOFAR Telescope (ILT)

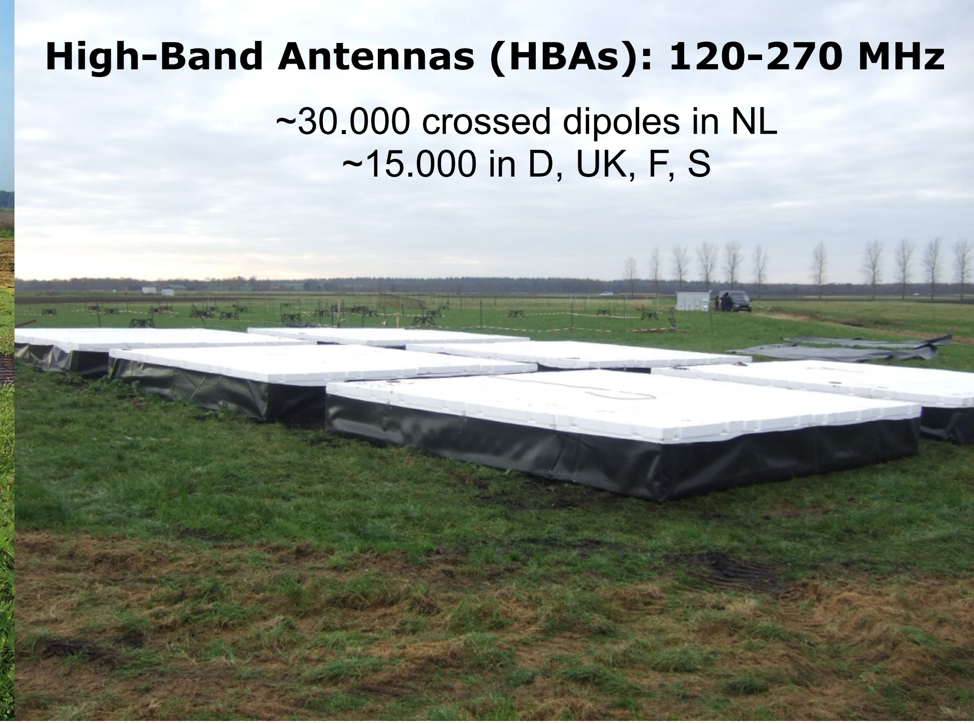
Radboud University Nijmegen

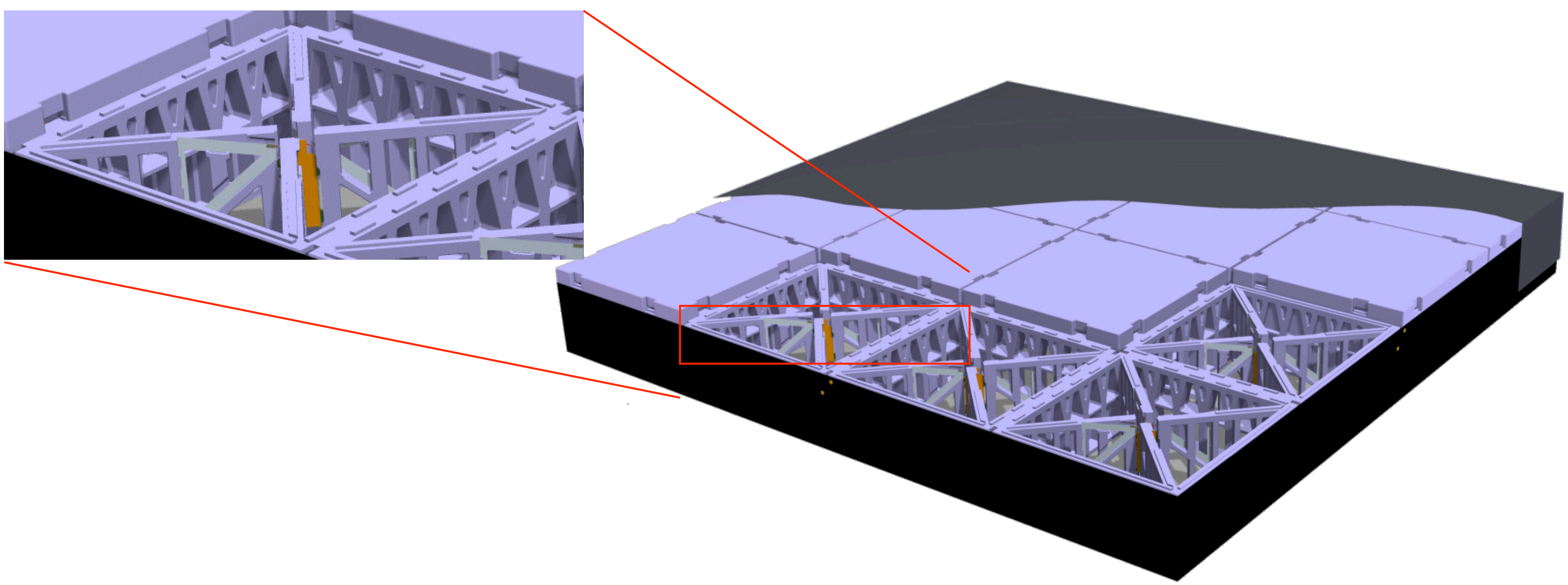
Europe-wide radio interferometry array @ 10-270 MHz
Offers unprecedented resolution, sensitivity, and flexibility at the lowest frequencies!



- 44 operational stations
- 38 stations in NL
- 8 international stations (double size)
- 4 additional stations funded (D, 3×PL)


Low-Band Antennas (LBAs): 10-80 MHz
~2000 crossed dipoles in NL
~850 in D, UK, F, S

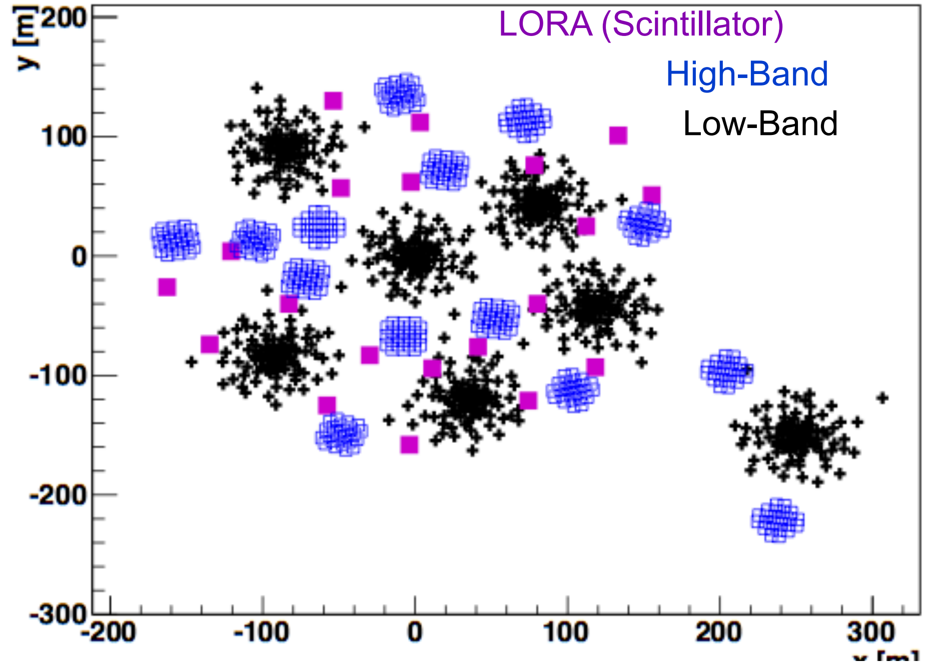

High-Band Antennas (HBAs): 120-270 MHz
~30.000 crossed dipoles in NL
~15.000 in D, UK, F, S

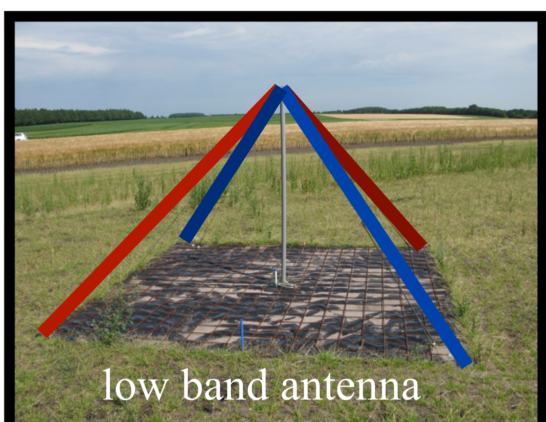


LOFAR Analysis

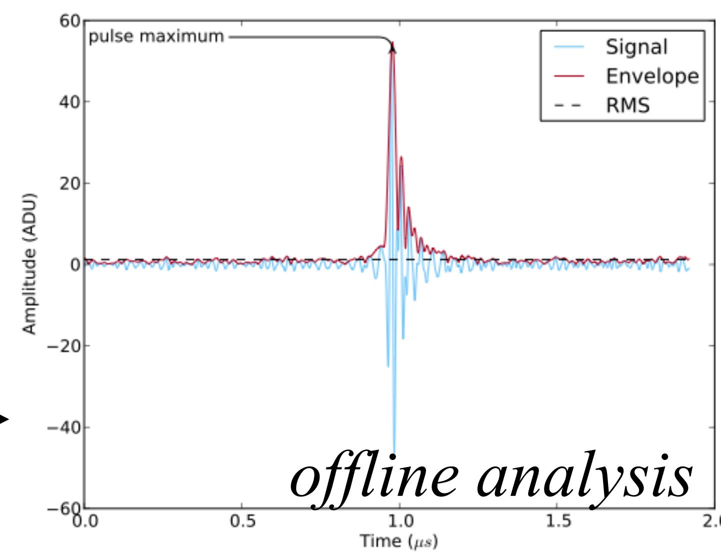
LORA
LOFAR Radboud Array
scintillator detectors

trigger





buffer



offline analysis

Pim Schellart et al., A&A 560, 98 (2013)