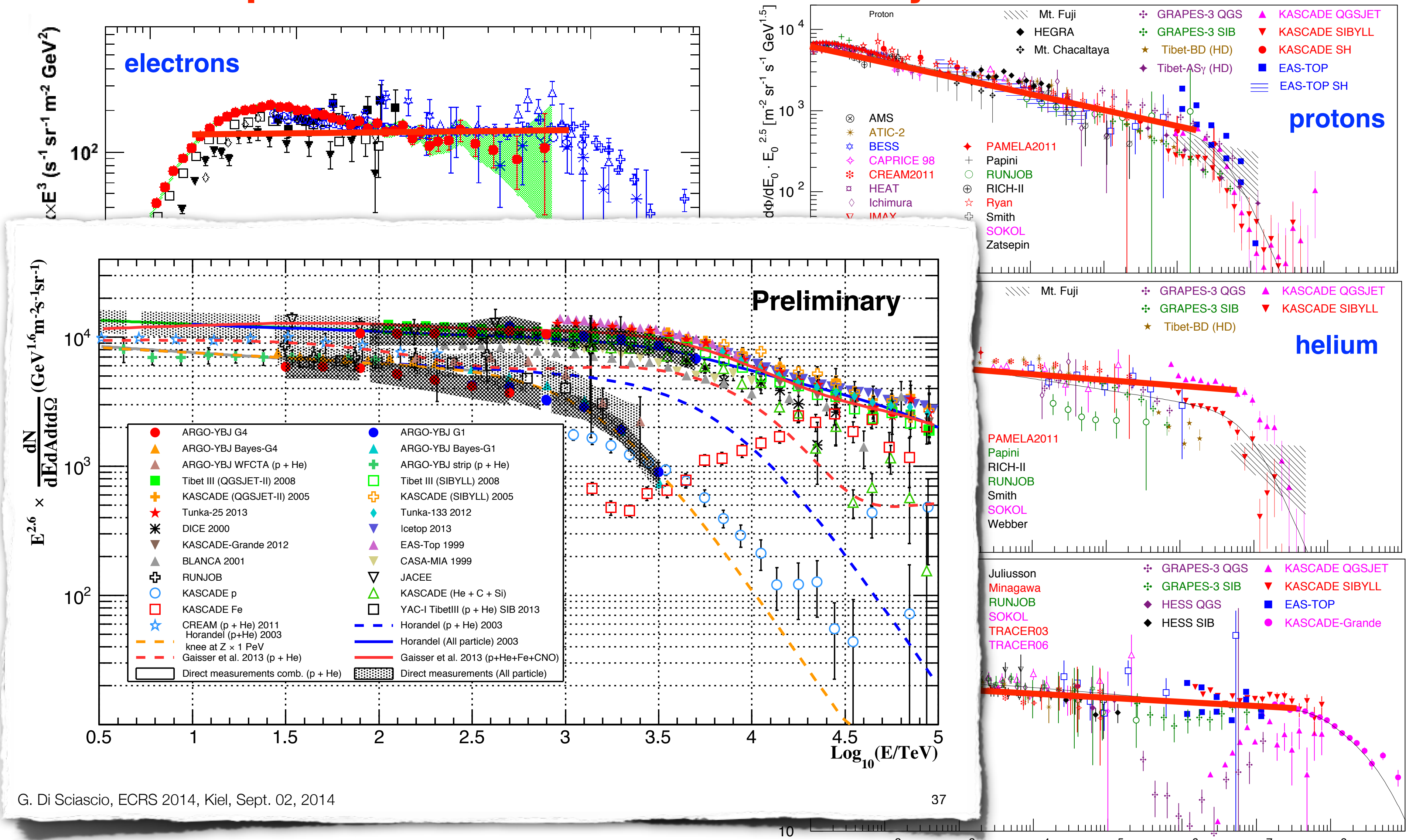
# The Elemental Composition of Galactic Cosmic Rays

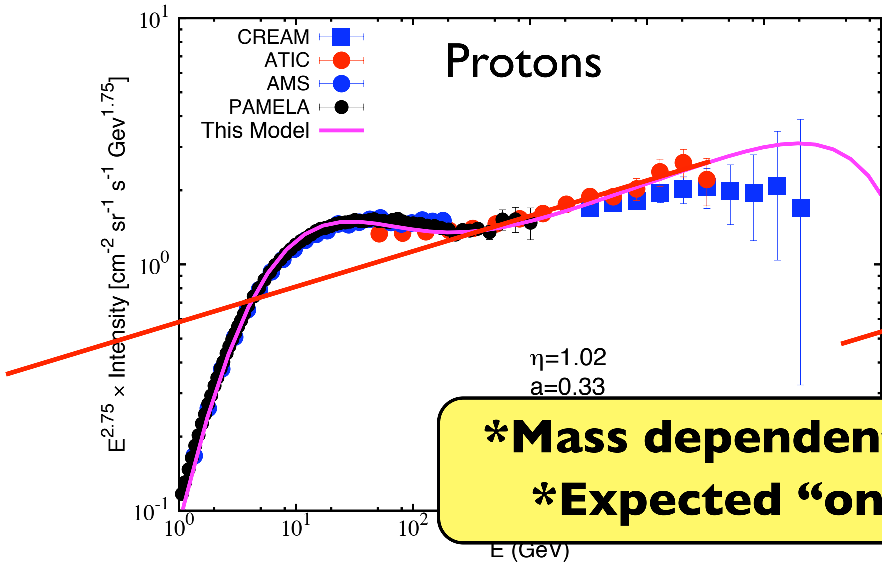
***ECRS Kiel 2014***

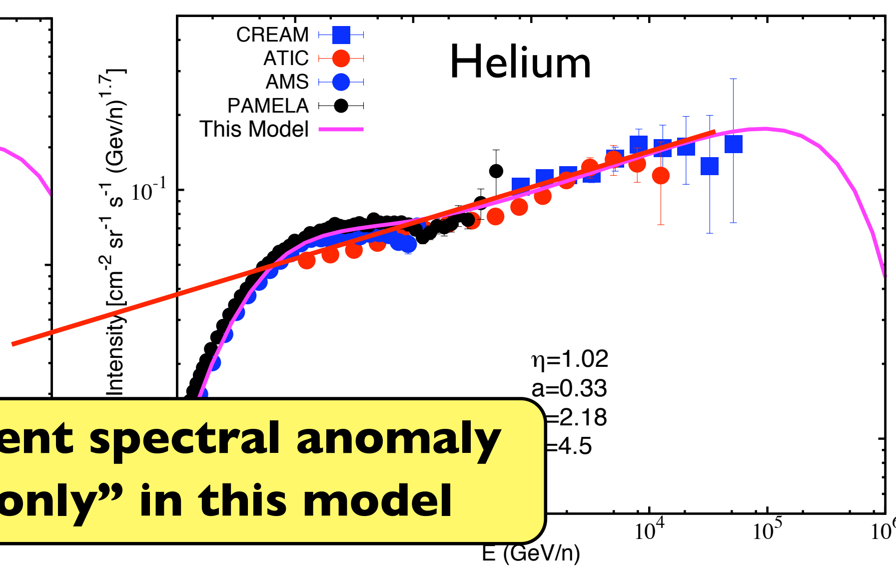



**Jörg R. Hörandel** **Radboud University Nijmegen** **http://particle.astro.ru.nl**

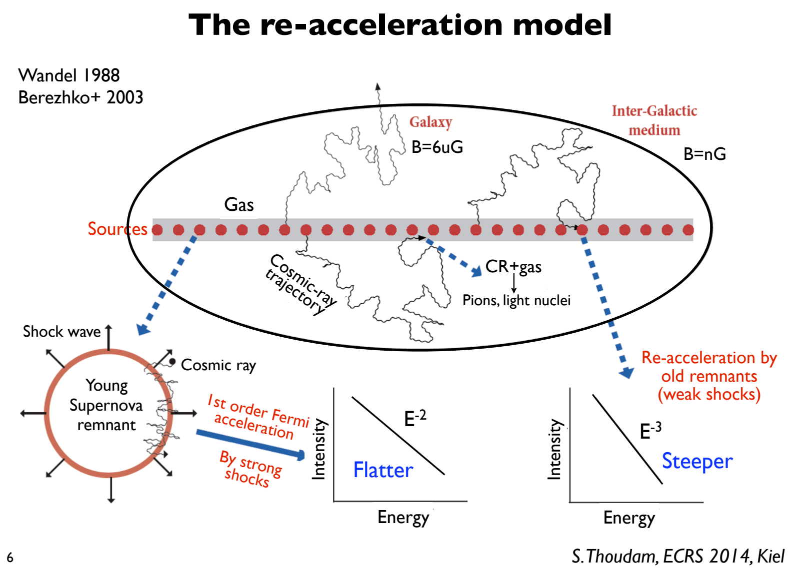
**JRH arXiv: 1212.0739**

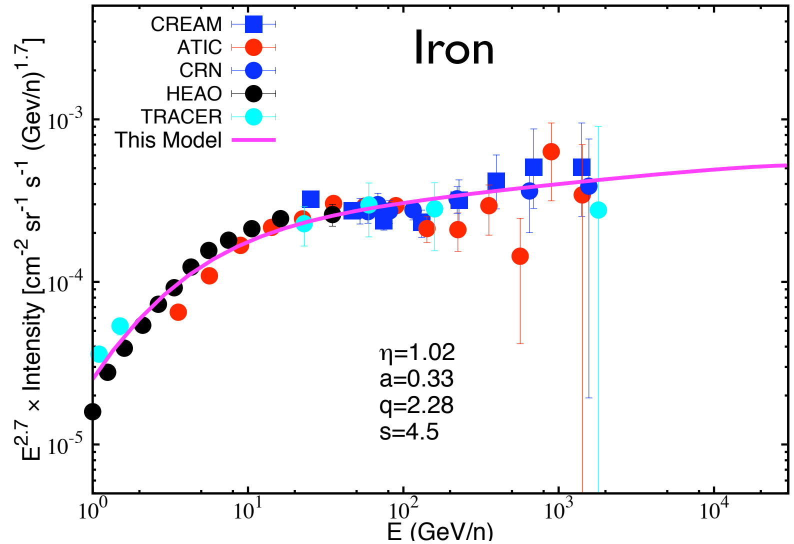
# Results: Protons, Helium & Iron spectra



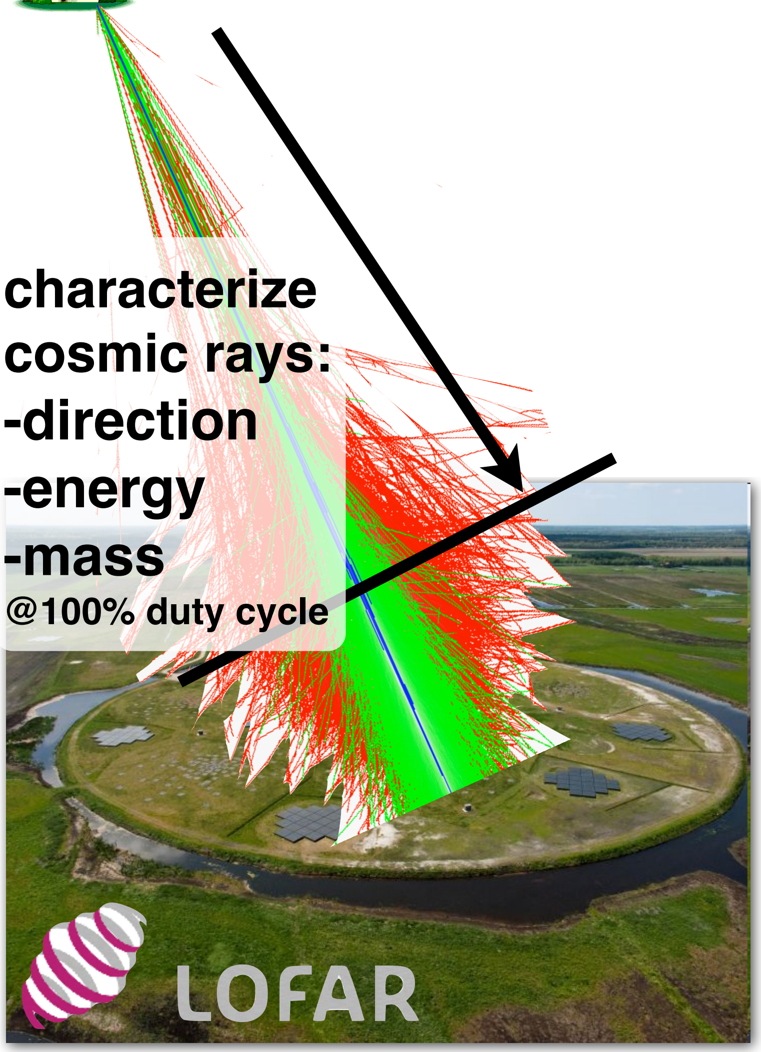

***Mass dependent spectral anomaly**
***Expected "only" in this model**

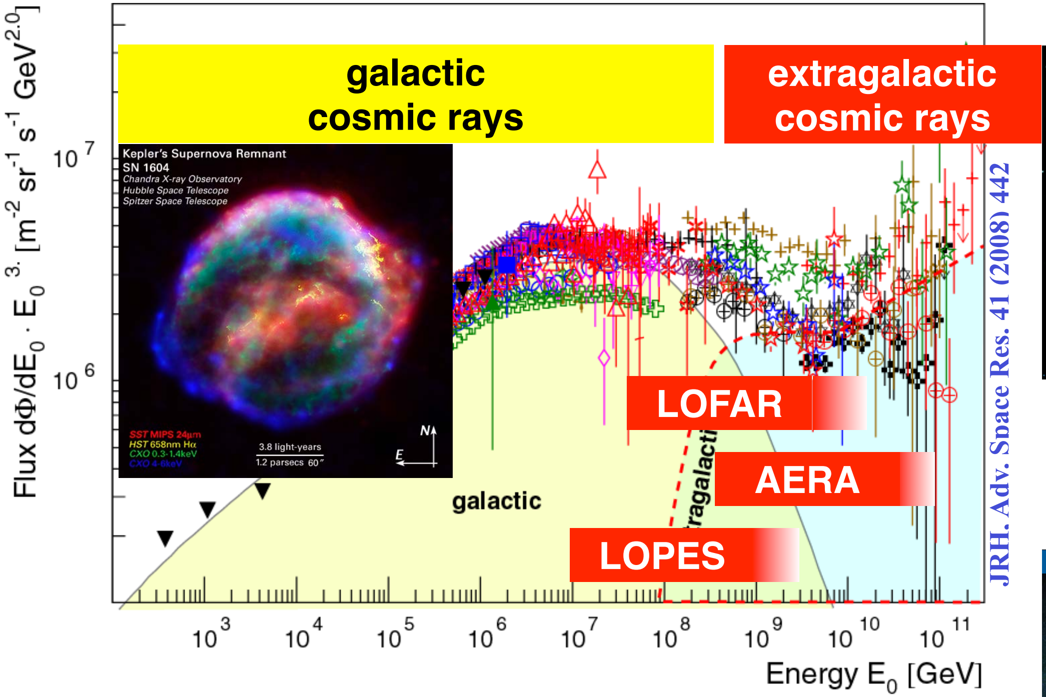



S. Thoudam, J.R. Hörandel, A&A 567 (2014) A33

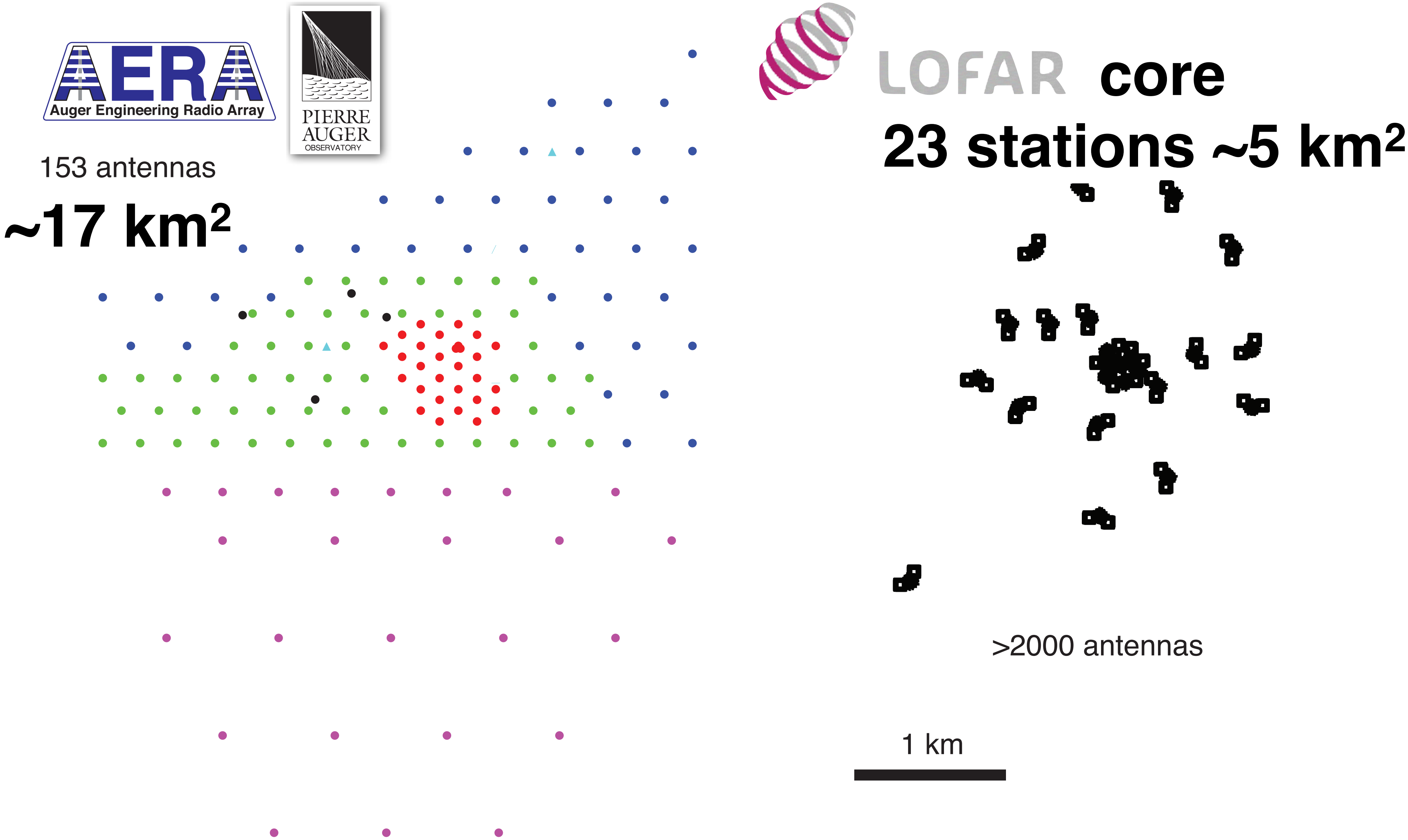
# Radio Xmax detection with LOFAR and AERA






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


AERA
Auger Engineering Radio Array
PIERRE AUGER
OBSERVATORY
153 antennas
~17 km²
LOFAR core
23 stations ~5 km²
>2000 antennas
1 km

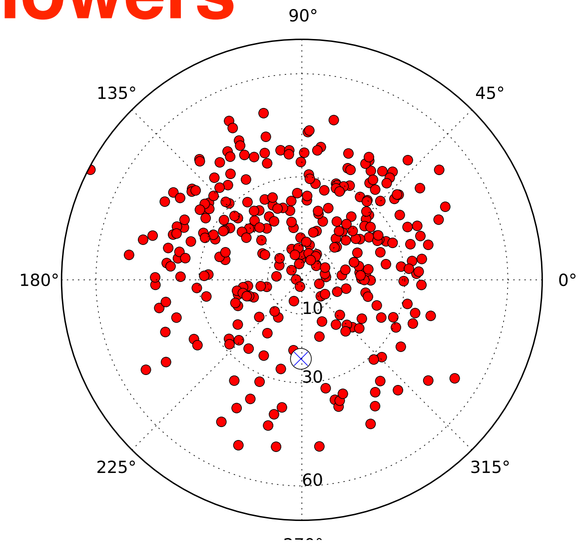
# Radio Emission in Air Showers

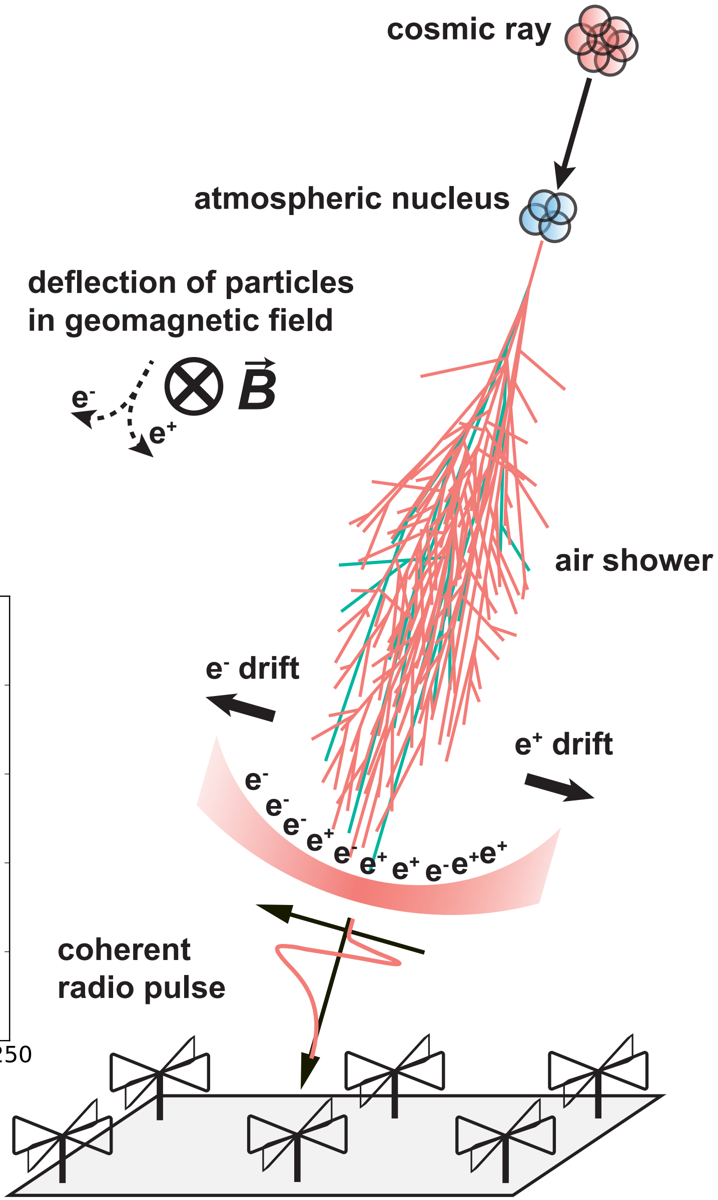
- Mainly: Charge separation in geomagnetic field

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

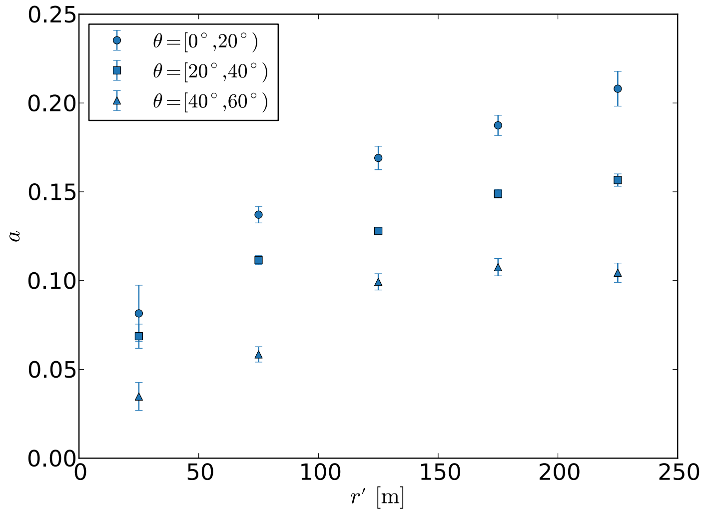
Theory predicts additional mechanisms:

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

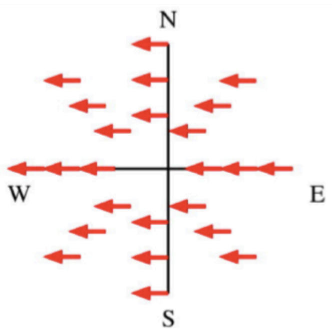


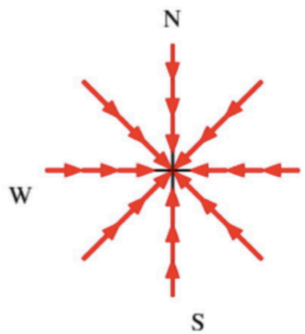

## polarization of radio signal



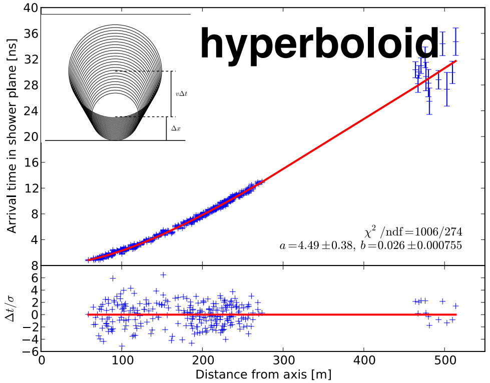

geomagnetic

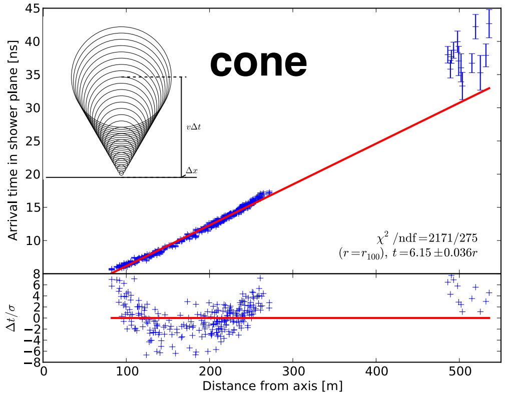


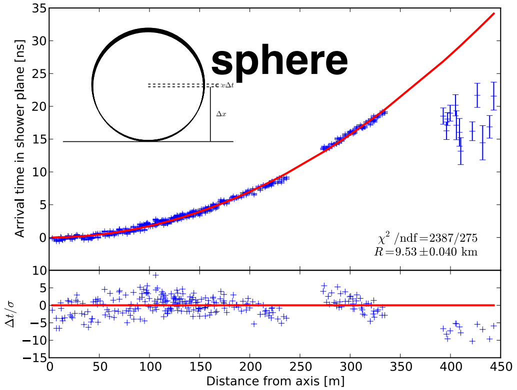

Askaryan

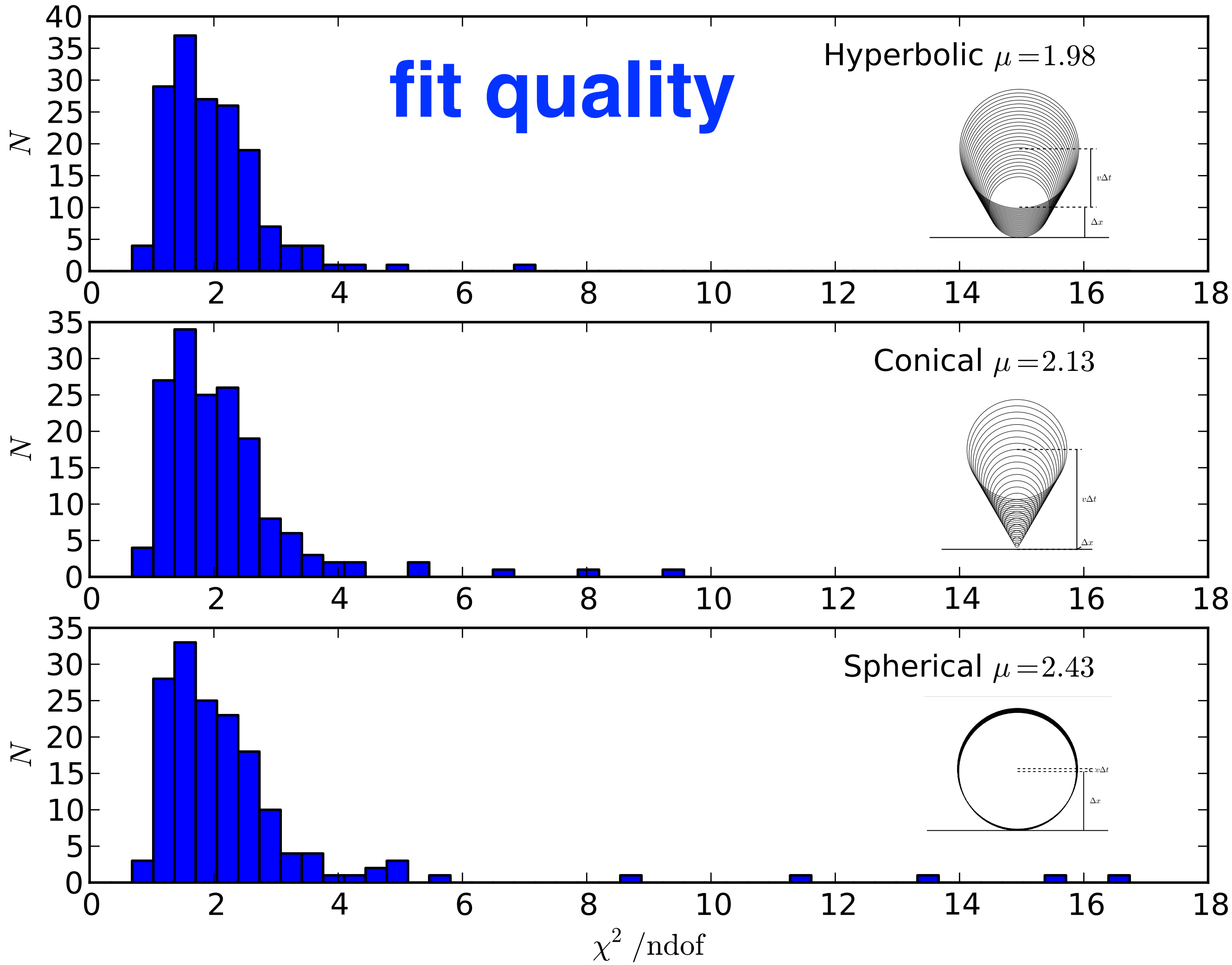


# Shape of Shower Front



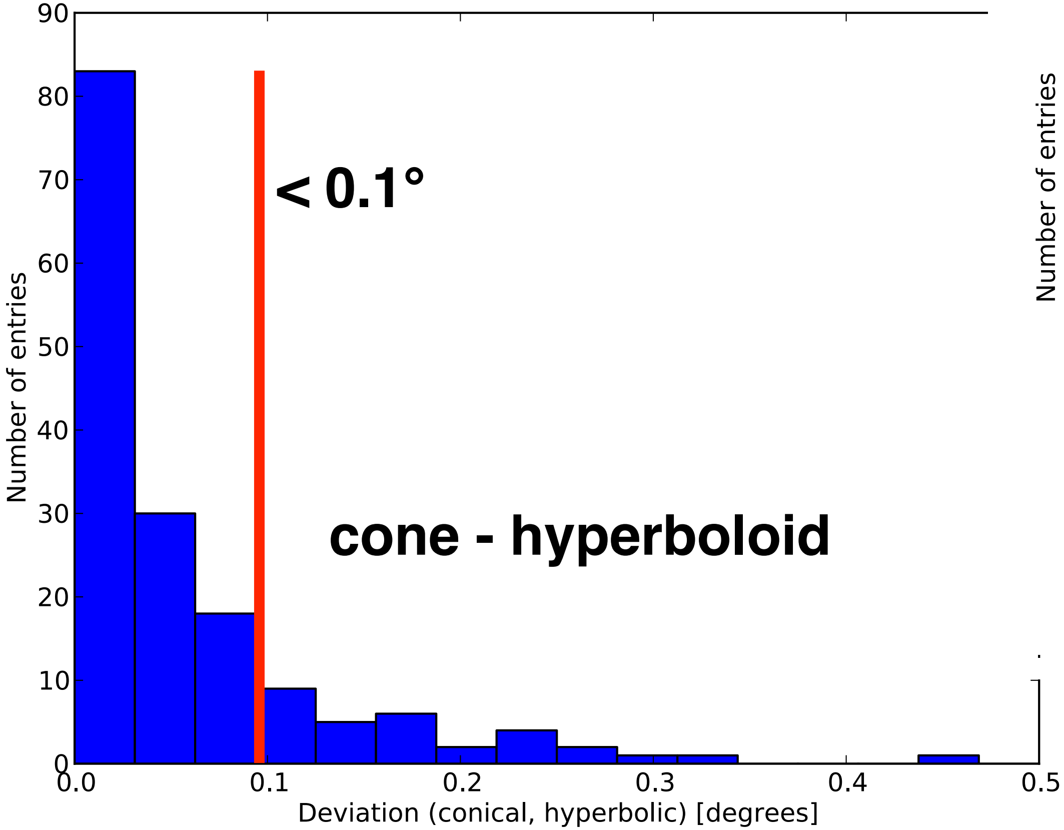



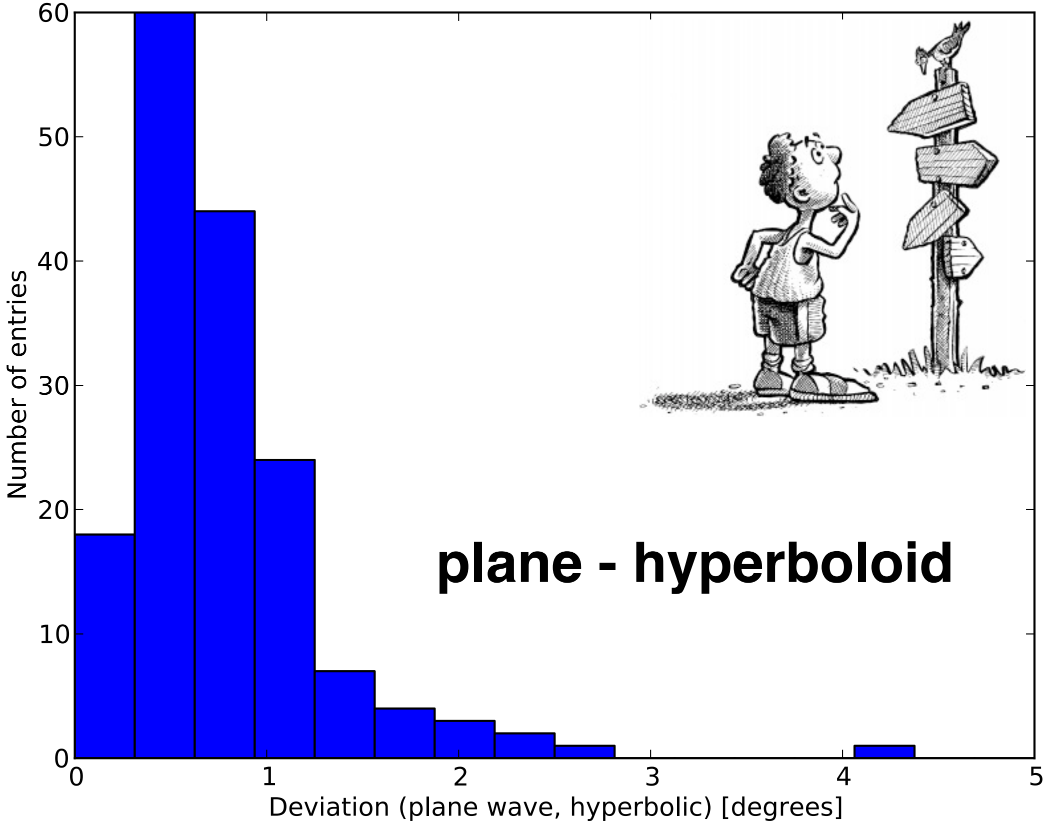




A. Corstanje et al., Astropart. Phys. 61 (2015) 22

# Accuracy of Shower Direction

**angular difference between..**




A. Corstanje et al., Astropart. Phys. 61 (2015) 22

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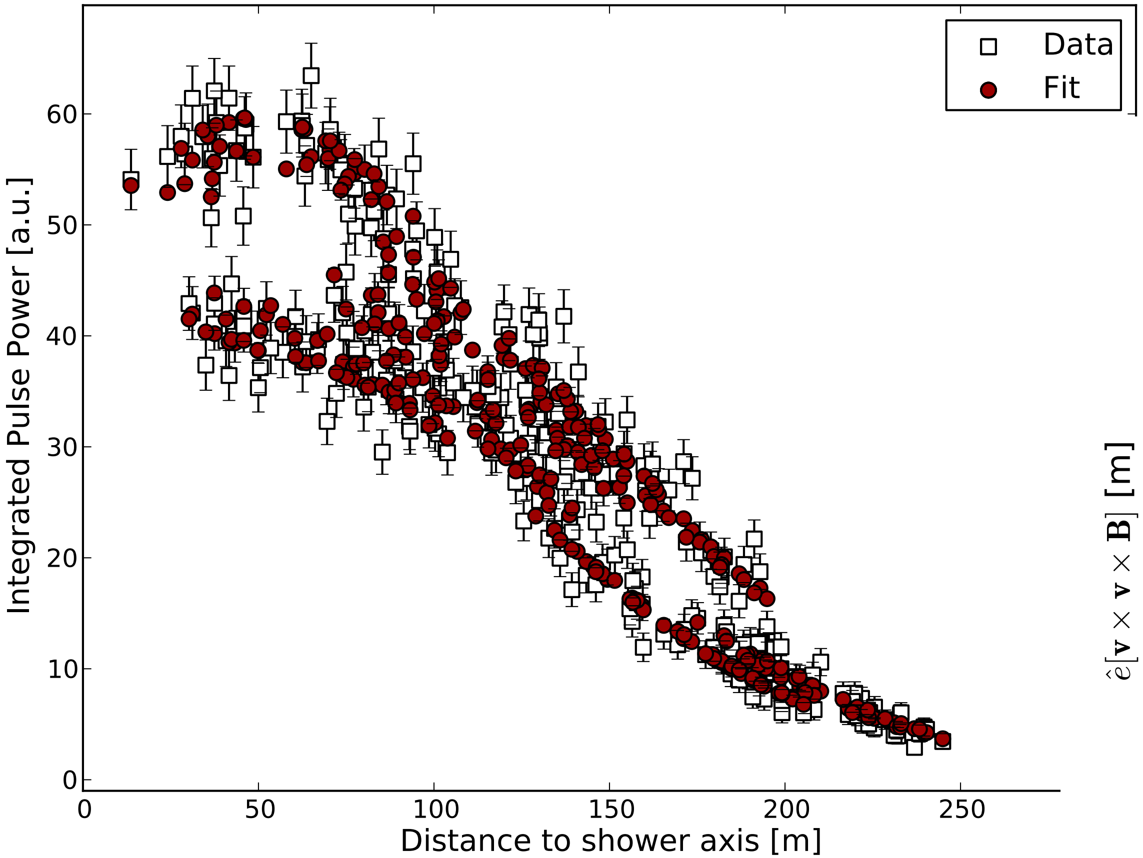
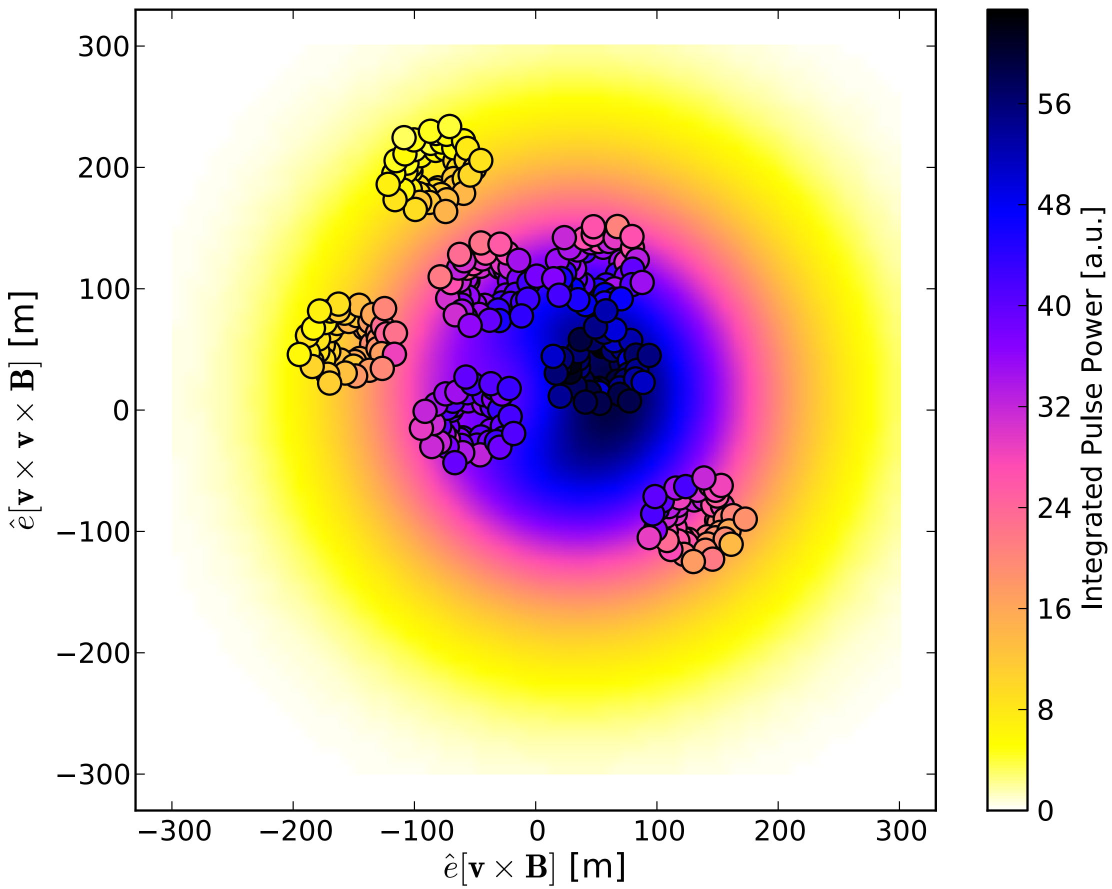
# Lateral distribution of radio signals

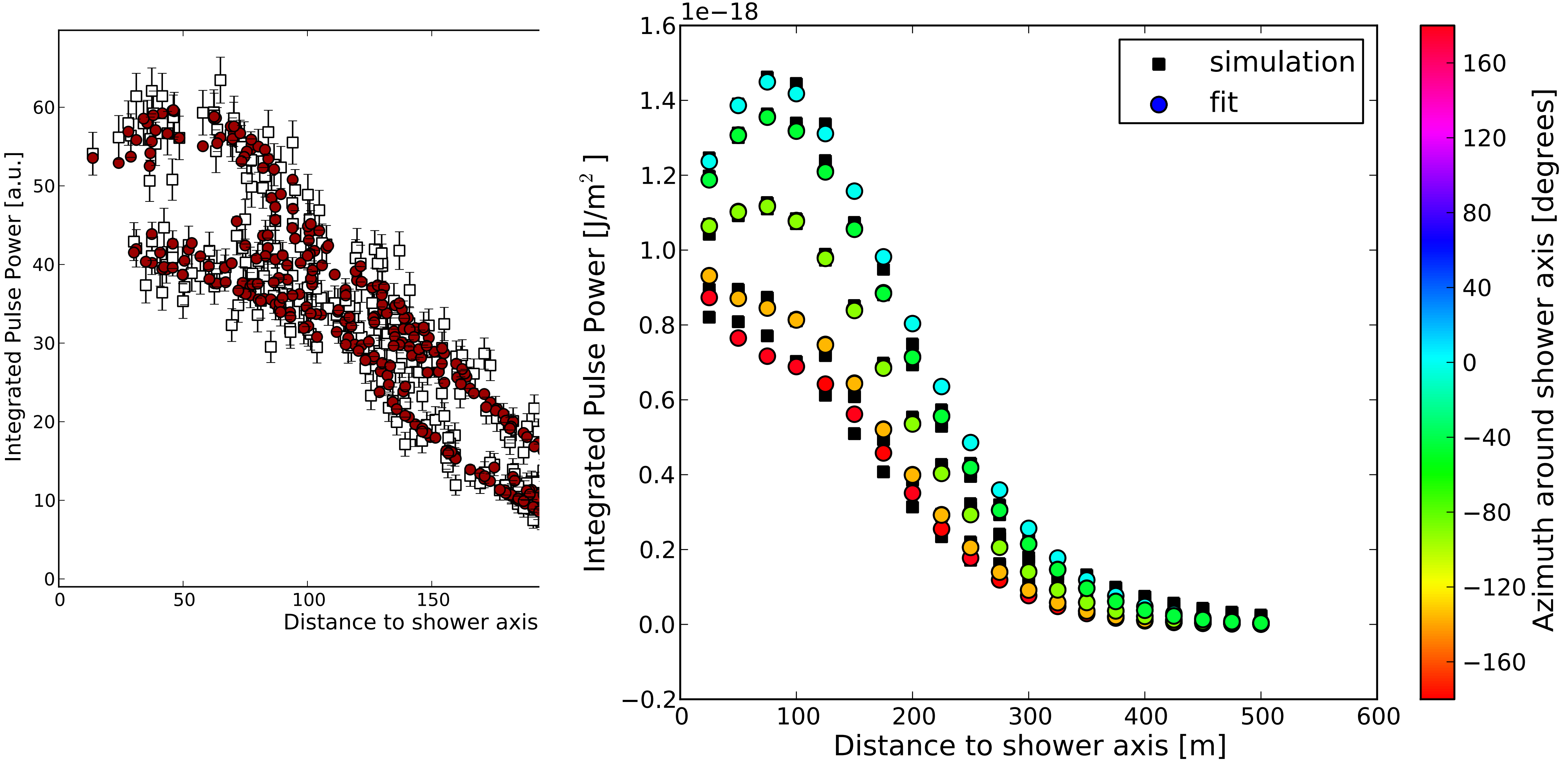
## as measured by LOFAR




A. Nelles et al., Astropart. Phys. 60 (2015) 13

# Lateral distribution of radio signals

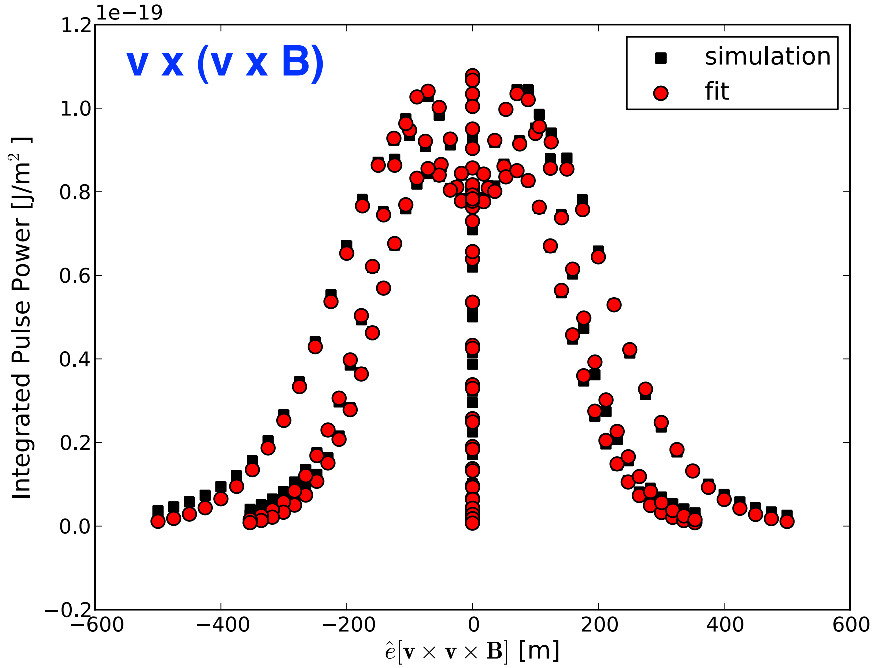


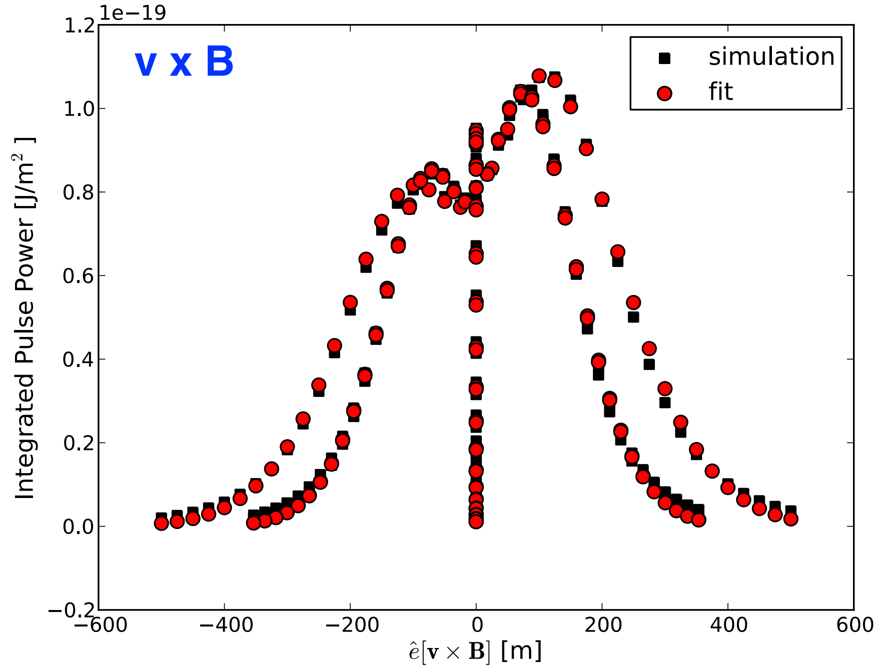
# Lateral distribution of radio signals

**not rotationally symmetric**

➡ **fit two Gaussian functions**

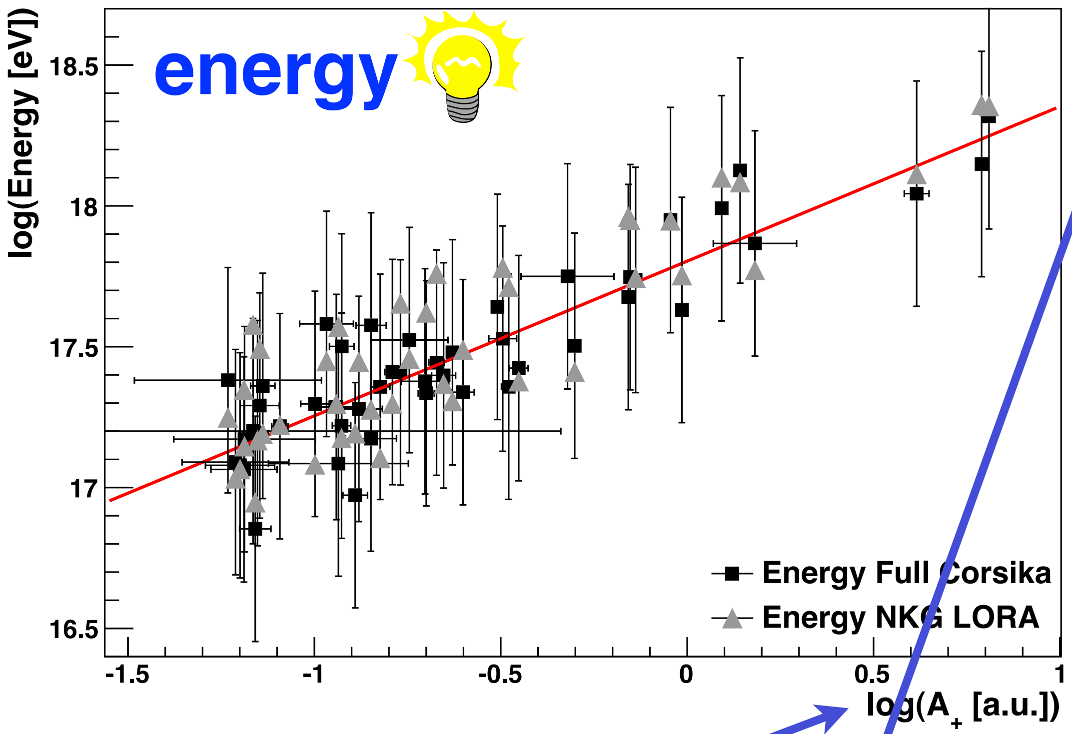
$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_+)^2 + (y' - Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x' - X_-)^2 + (y' - Y_-)^2]}{\sigma_-^2}\right) + O$$

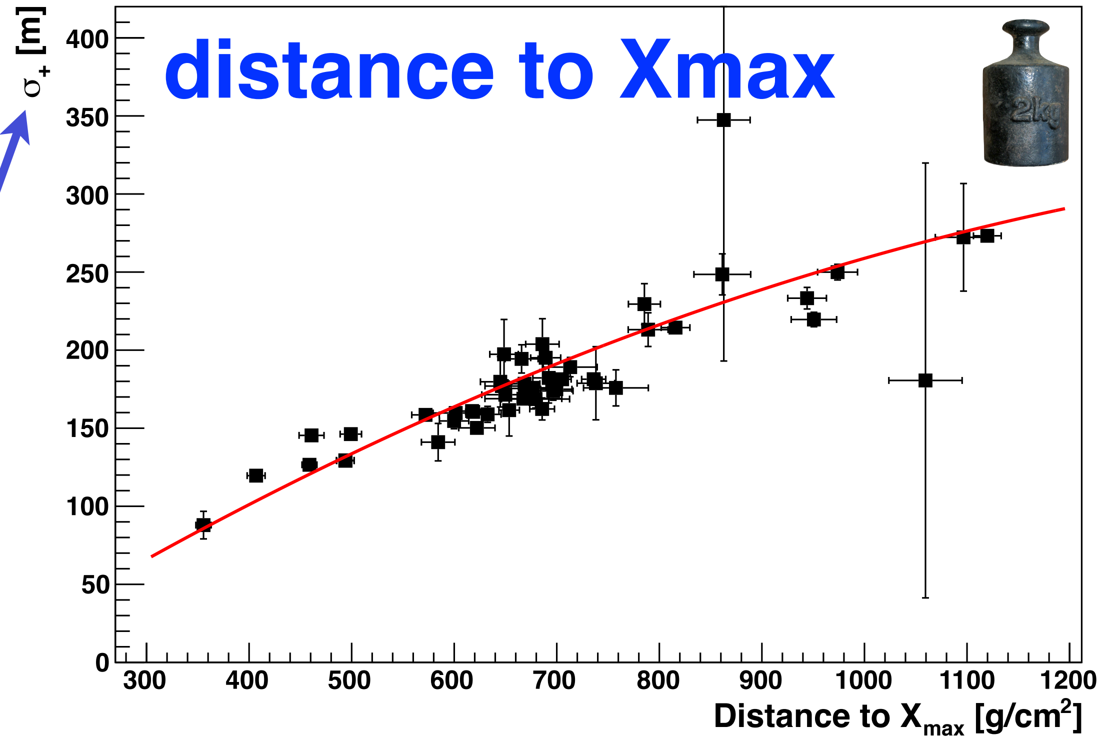



A. Nelles et al., Astropart. Phys. 60 (2015) 13

# Properties of primary particle




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

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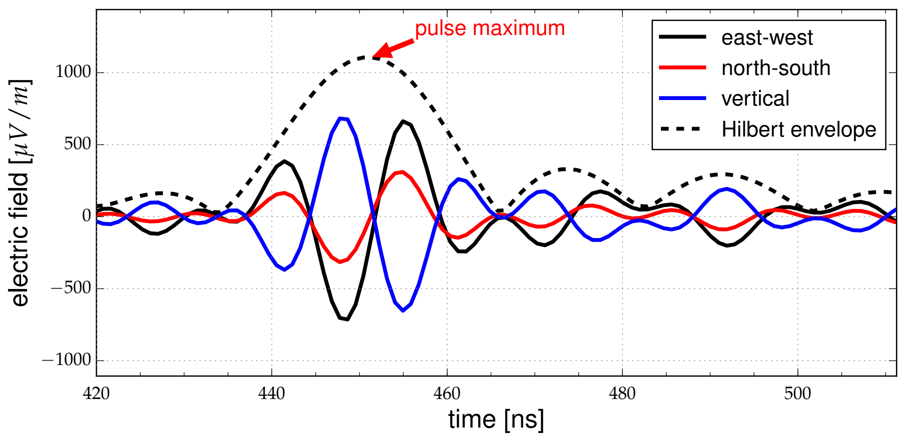
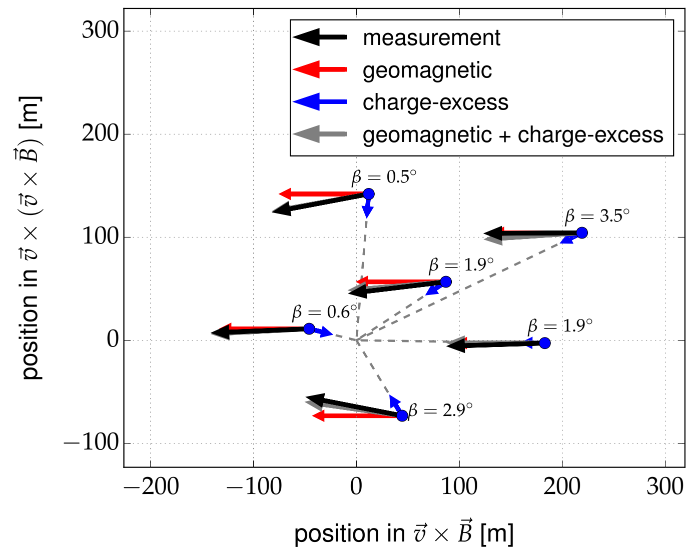
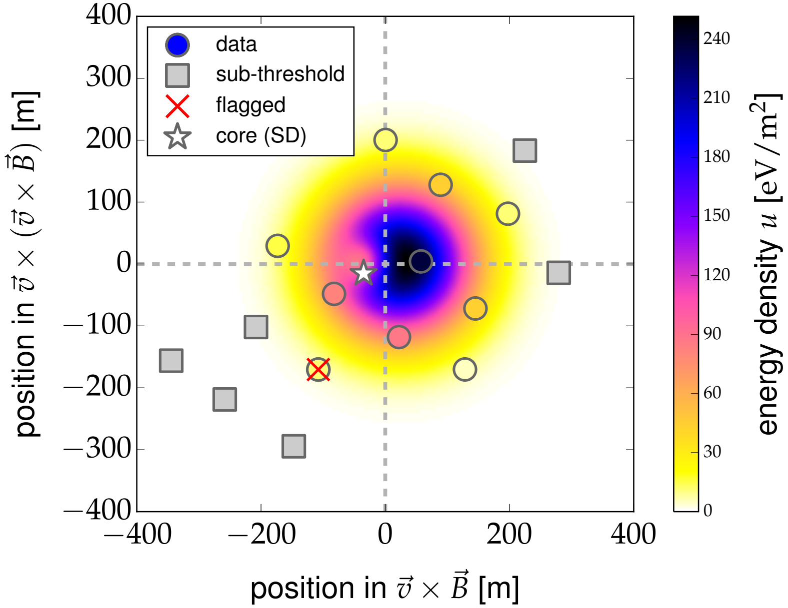
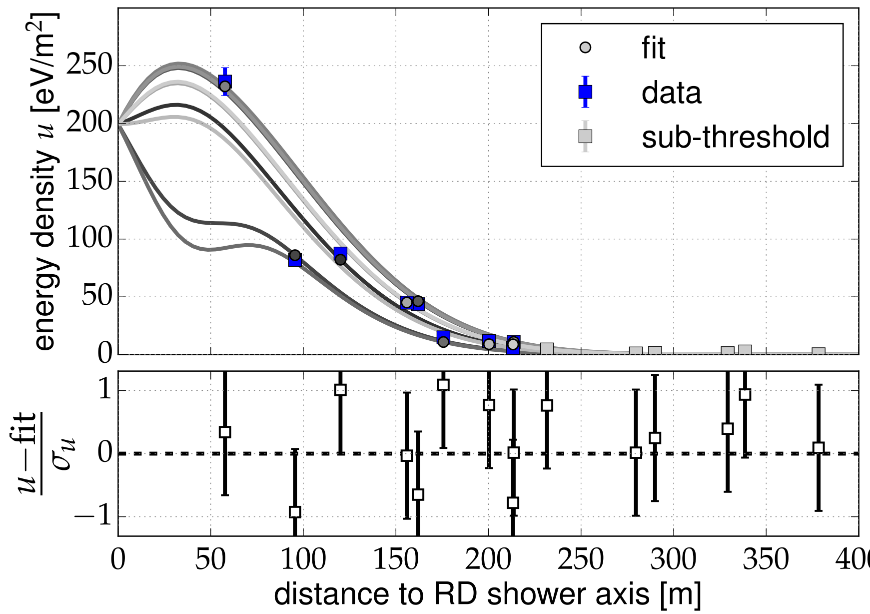
A. Nelles et al., JCAP 05 (2015) 018

# Measurement of shower energy



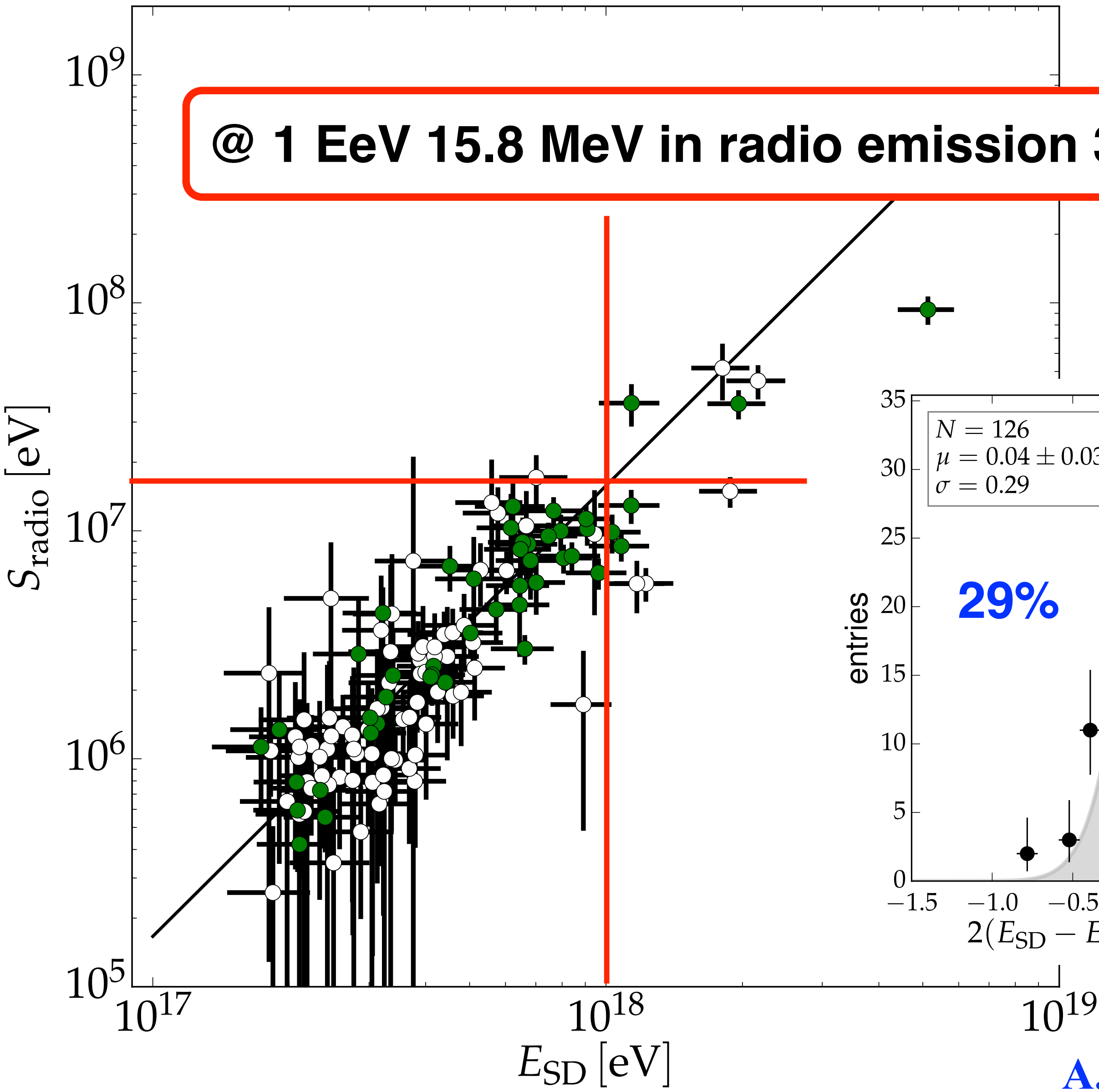



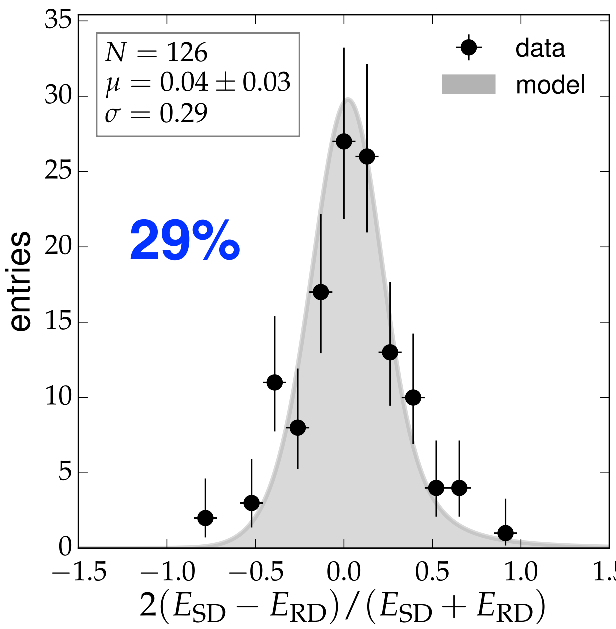


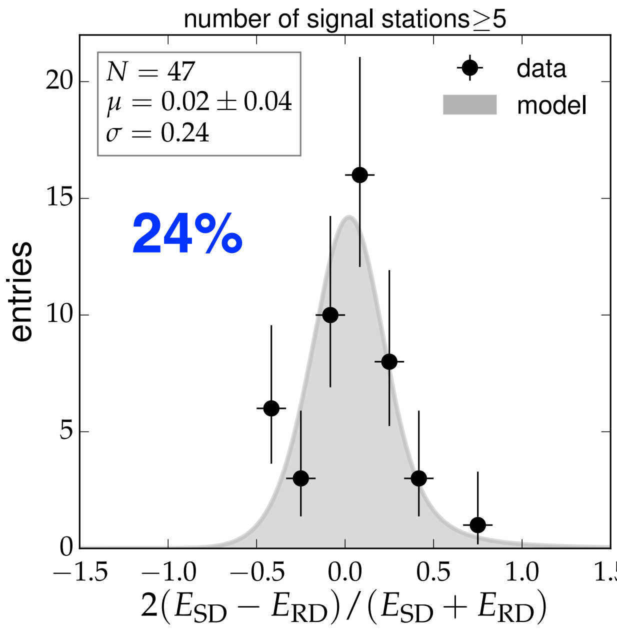

Auger Engineering Radio Array

A. Aab et al, submitted to PRD, arXiv 1508.04267

# Measurement of shower energy



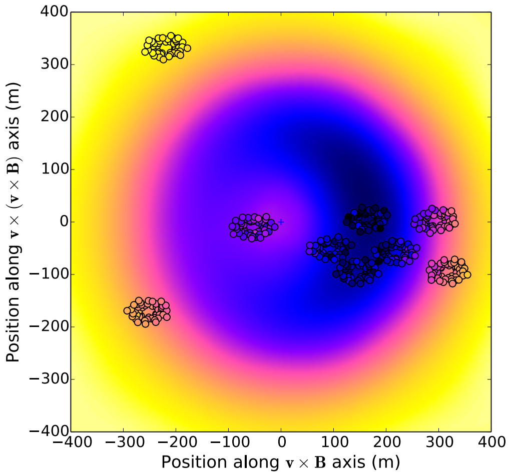



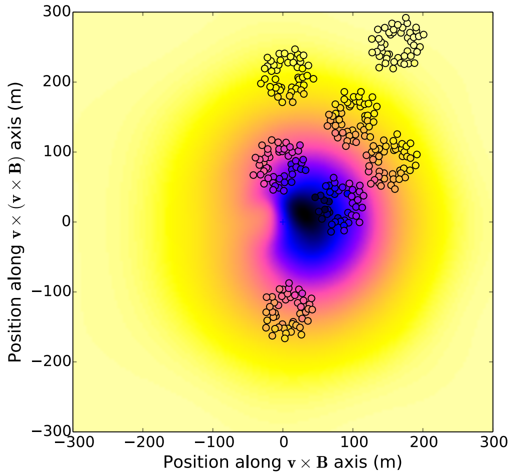



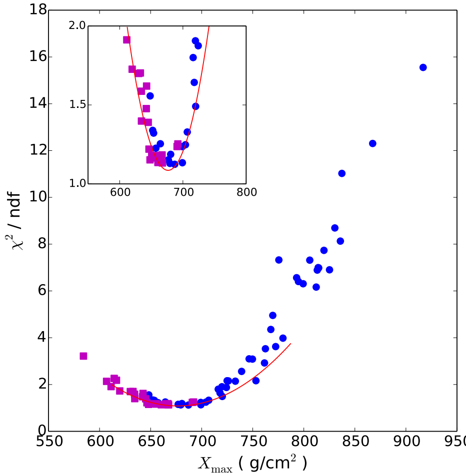


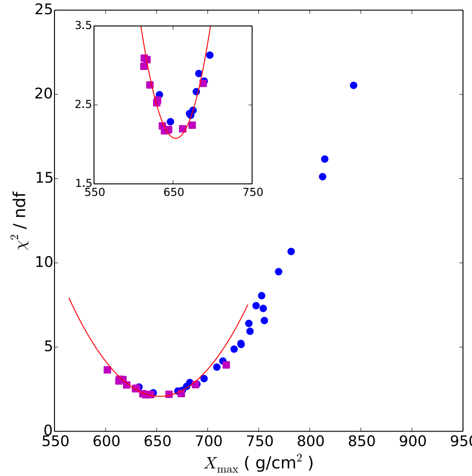

A. Aab et al, submitted to PRD, arXiv 1508.04267

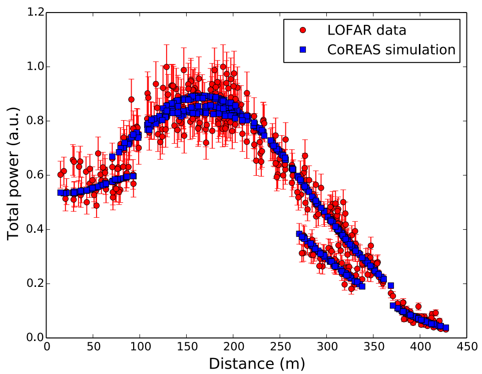
# Measurement of particle mass

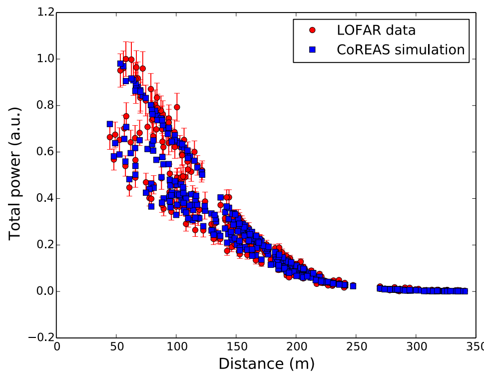


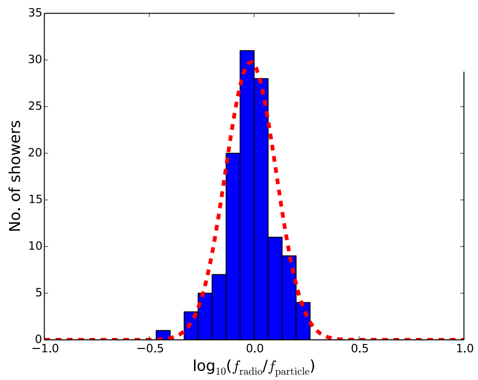



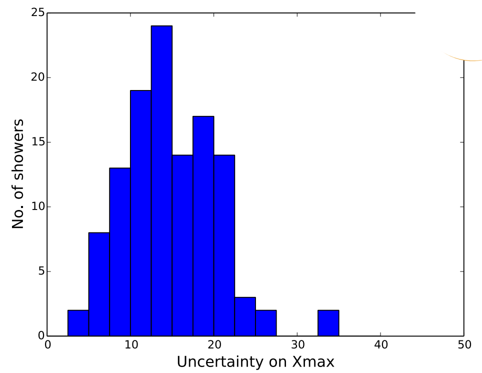




$\sigma_E \approx 32\%$

$\sigma_{X_{max}} \approx 17\ \mathrm{g/cm^2}$

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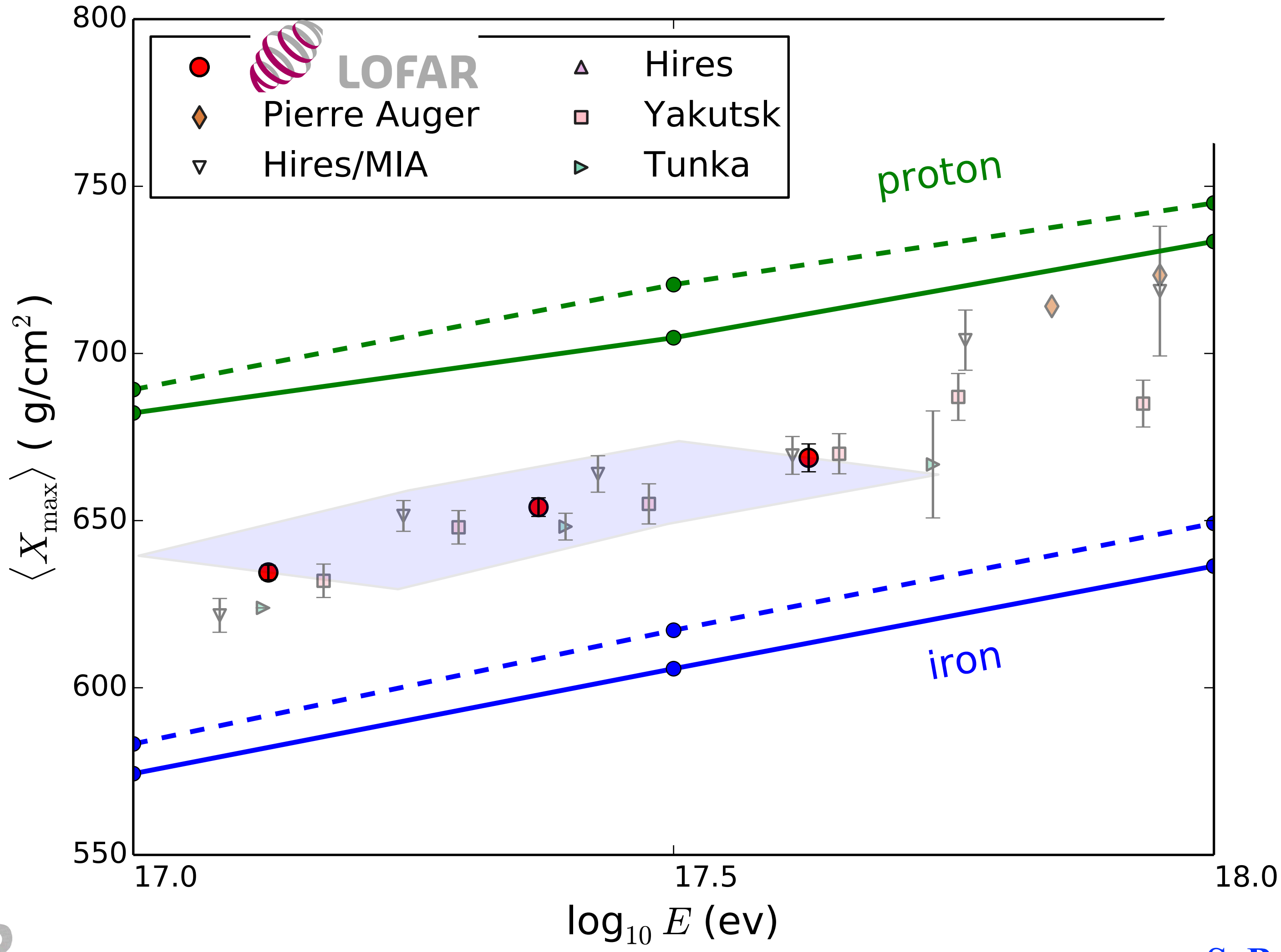
S. Buitink et al., PRD 90 (2014) 082003

# Depth of the shower maximum

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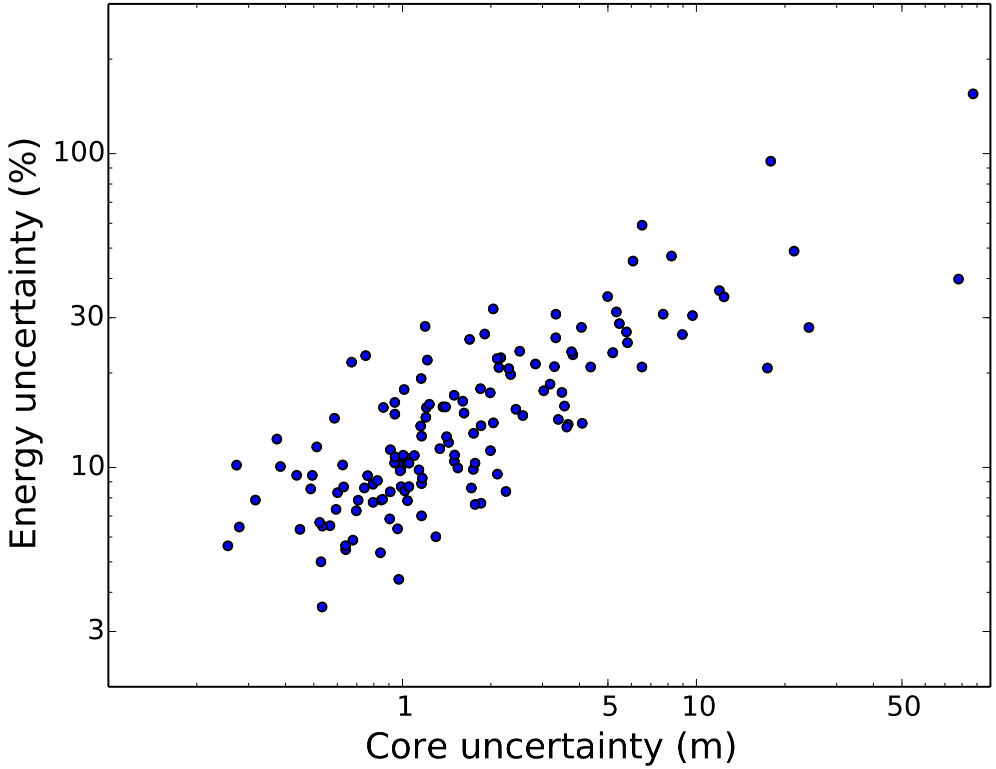
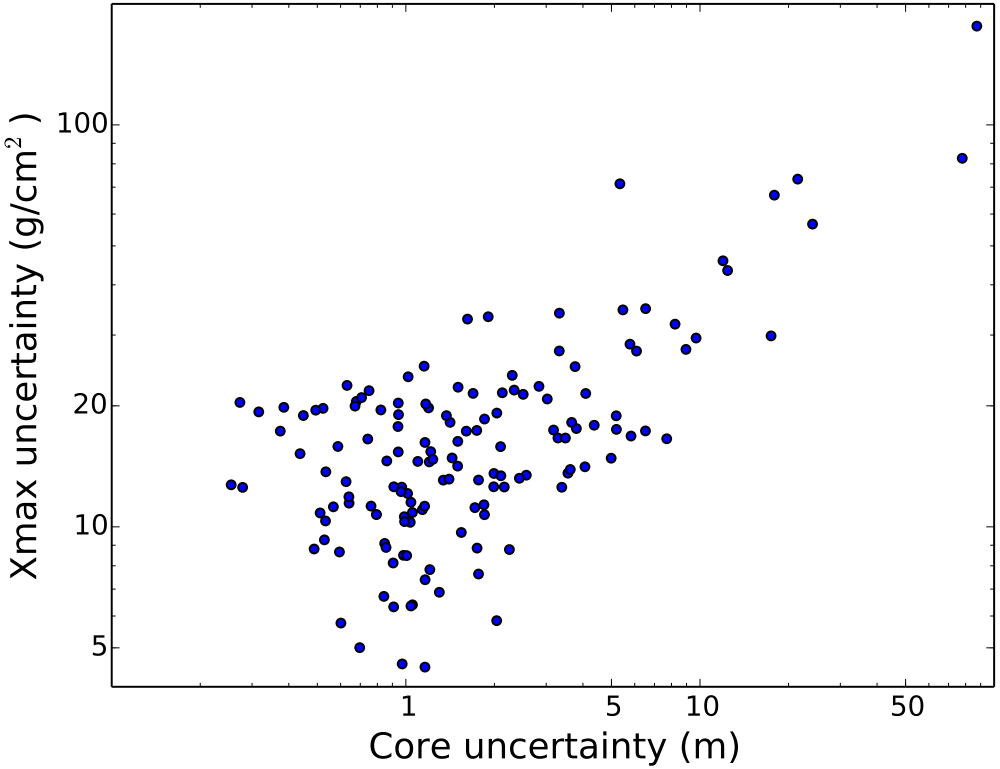
S. Buitink et al., ICRC 2015

# uncertainties




S. Buitink et al., ICRC 2015

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## further reading:


1. LOFAR; The LOw-Frequency ARay,
   M. van Haarlem et al., Astronomy & Astrophysics 556 (2013) A2
2. Detecting cosmic rays with the LOFAR radio telescope,
   P. Schellart et al., Astronomy & Astrophysics 560 (2013) A98
3. Calibrating the absolute amplitude scale for air showers measured at LOFAR,
   A. Nelles et al., submitted to JINST
4. LORA - A scintillator array for LOFAR,
   S. Thoudam et al., Nuclear Instruments and Methods A 767 (2014) 329
5. Measurement of the cosmic-ray energy spectrum above $10^{16}$ eV with the LOFAR Radboud Air Shower Array,
   S. Thoudam et al., Astroparticle Physics in press (arXiv: 1506.09134)
6. Probing atmospheric electric fields in thunderstorms through radio emission from cosmic-ray induced air showers
   P. Schellart et al., Physical Review Letters 114 (2015) 165001
7. Polarized radio emission from extensive air showers measured with LOFAR,
   P. Schellart et al., Journal for Cosmology and Astroparticle Physics 10 (2014) 014
8. Measuring a Cherenkov ring in the radio emission from air showers at 110 - 190 MHz with LOFAR
   A. Nelles et al., Astroparticle Physics 65 (2015) 11
9. The shape of the radio wavefront of extensive air showers as measured with LOFAR
   A. Corstanje et al., Astroparticle Physics 61 (2015) 22
10. A parameterization for the radio emission of air showers as predicted by CoREAS sumulations and applied to LOFAR measurements
    A. Nelles et al., Astroparticle Physics 60 (2015) 13
11. The radio emission pattern of air showers as measured with LOFAR - a tool for the reconstruction of the energy and the shower maximum
    A. Nelles et al., Journal of Cosmology and Astroparticle Physcis 05 (2015) 018
12. Method for high precision reconstruction of air shower Xmax using two-dimensional radio intensity profiles,
    S. Buitink et al., Physical Review D 90 (2014) 082003

Radio detection of air showers with LOFAR and AERA, Proc. UHECR2014, Springdale
J.R. Hörandel, arXiv:1509.04960

1. Antennas for the detection of radio emission pulses from cosmic-ray induced air showers at the Pierre Auger Observatory,
   P. Abreu et al., JINST 7 (2012) P10011

2. Advanced functionality for radio analysis in the Offline software framework of the Pierre Auger Observatory,
   P. Abreu et al., Nucl. Instr. & Meth. A 635 (2011) 92

3. Probing the radio emission from air showers with polarization measurements,
   A. Aab et al., PRD 89 (2014) 052002

4. Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory
   A. Aab et al., arXiv 1508.04267