High-energy cosmic rays at LOFAR.

Olaf Scholten

LORA Scintillator

university of groningen

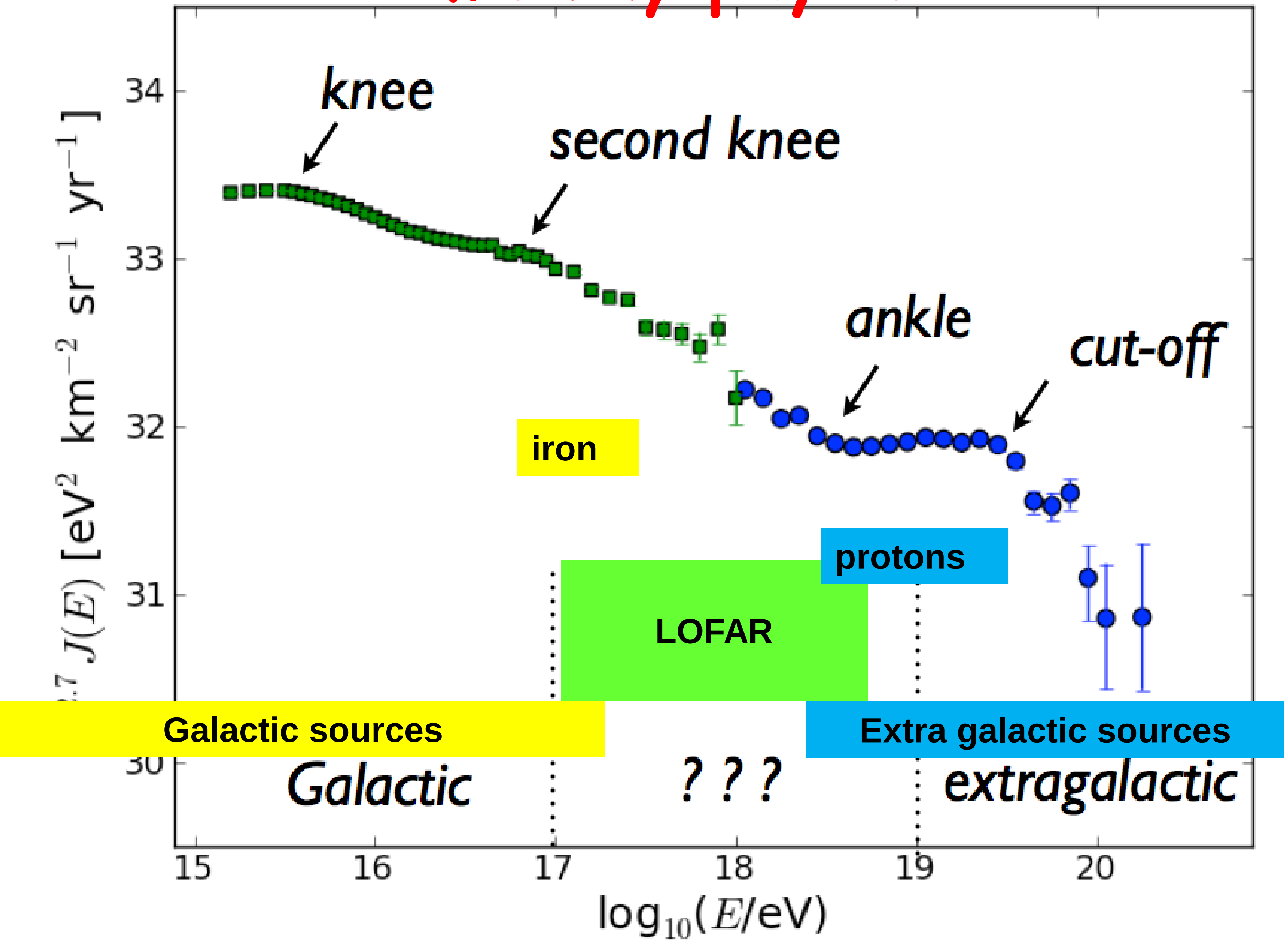
kvi - center for advanced radiation technology

TBB

LOFAR Cosmic Ray KSP & Cosmic Lightning Project

A. Bonardi, S. Buitink, A. Corstanje, J.E. Enriquez, H. Falcke, J.R. Hörandel, T. Karskens, M. Krause, P. Mitra, K. Mulrey, B. A. Nelles, J.P. Rachen, L. Rossetto, P. Schellart, O. Scholten, S. Thoudam, T.N.G. Trinh , S. ter Veen, T. Winchen

Cosmic ray physics:



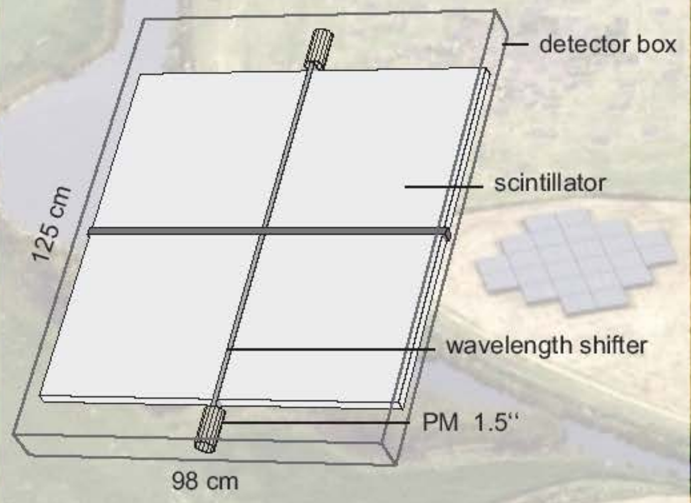
Presentation
by
Stijn Buitink

LOFAR Radboud Air Shower Array - LORA

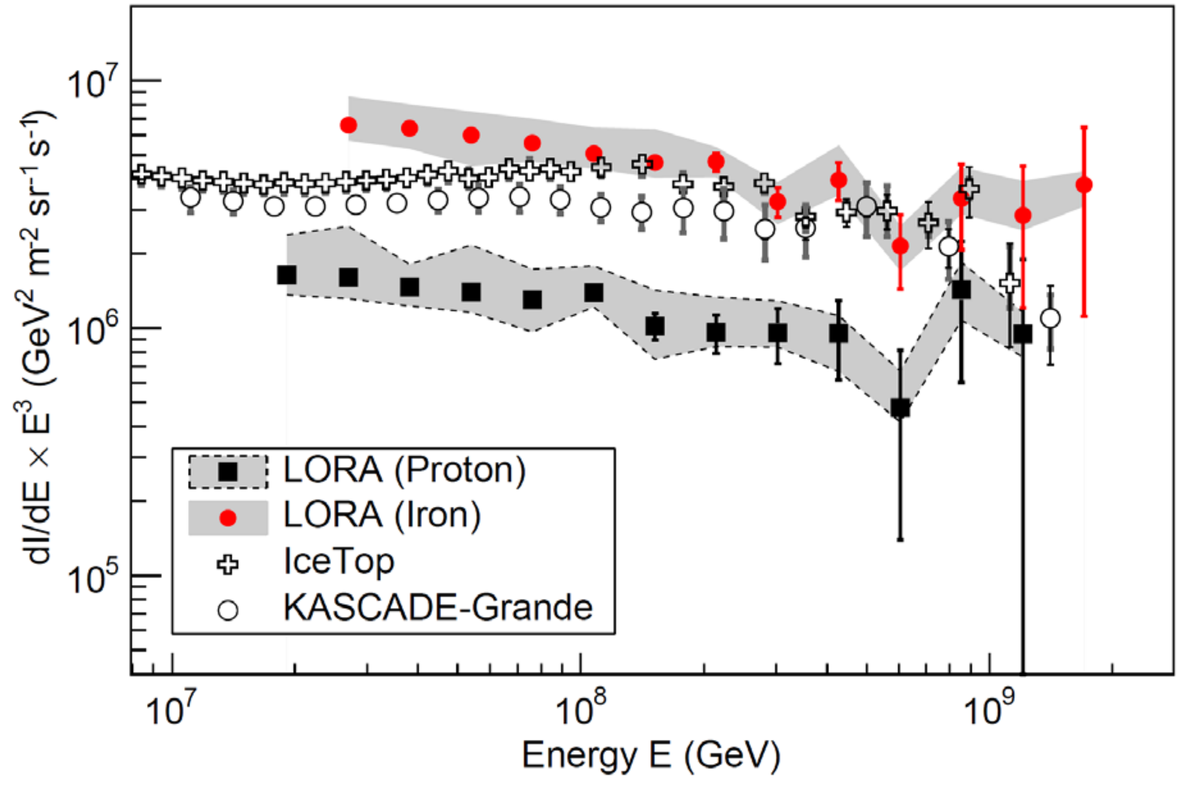
20 scintillator units (~1 m² each) in LOFAR core

→ provide

- properties of EAS
- and trigger

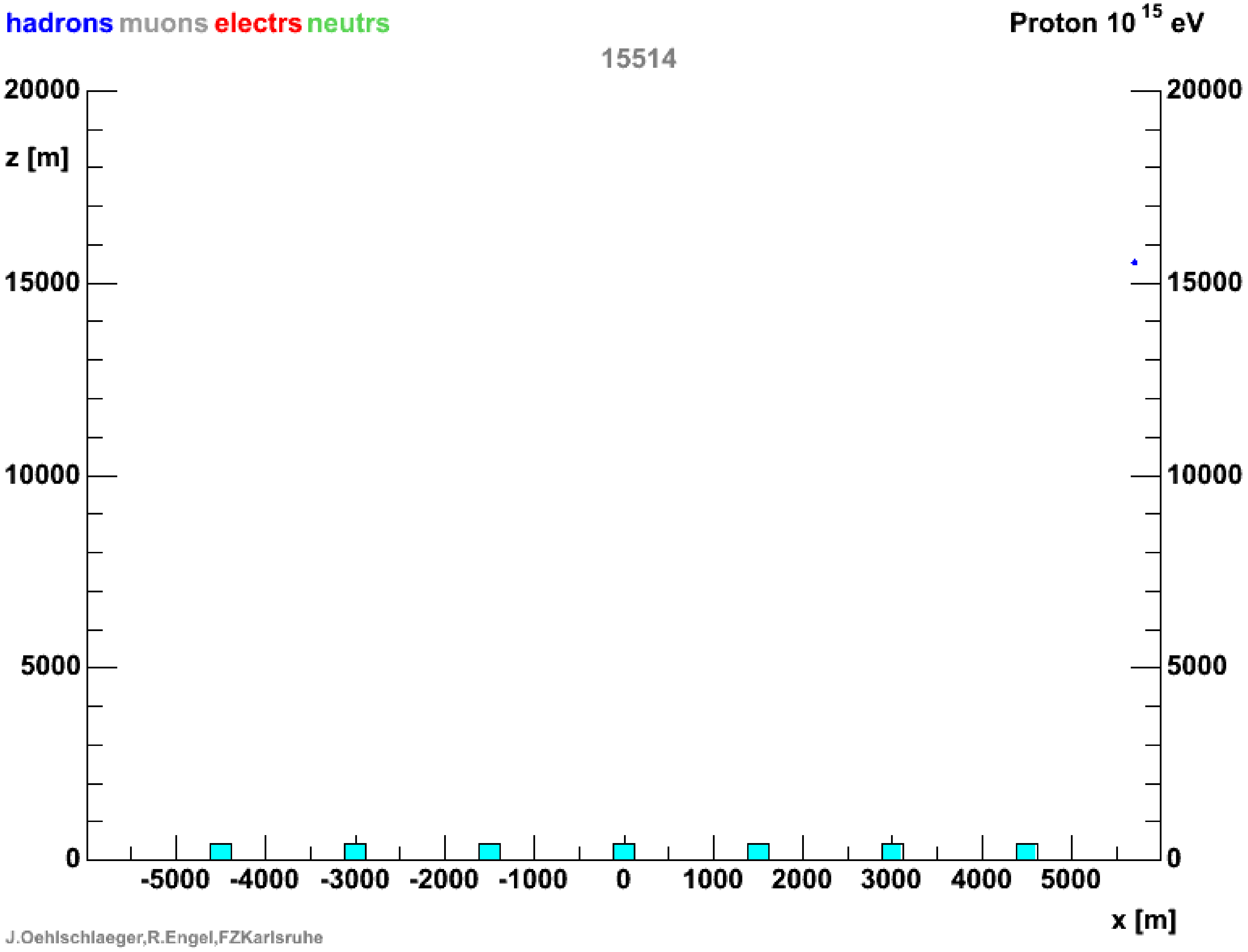


S. Thoudam et al, Astroparticle Physics 73 (2016) 34



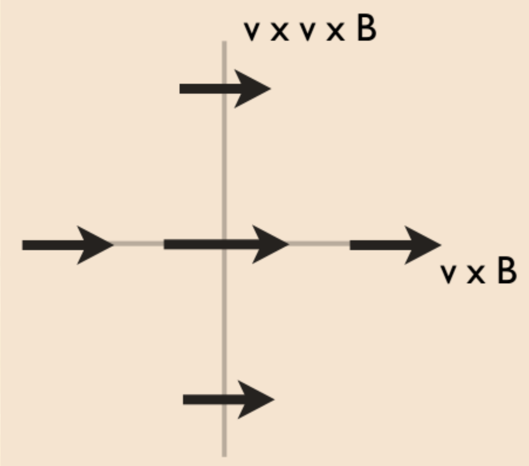
S. Thoudam et al, Nucl. Instr. Meth. A 767 (2014) 339

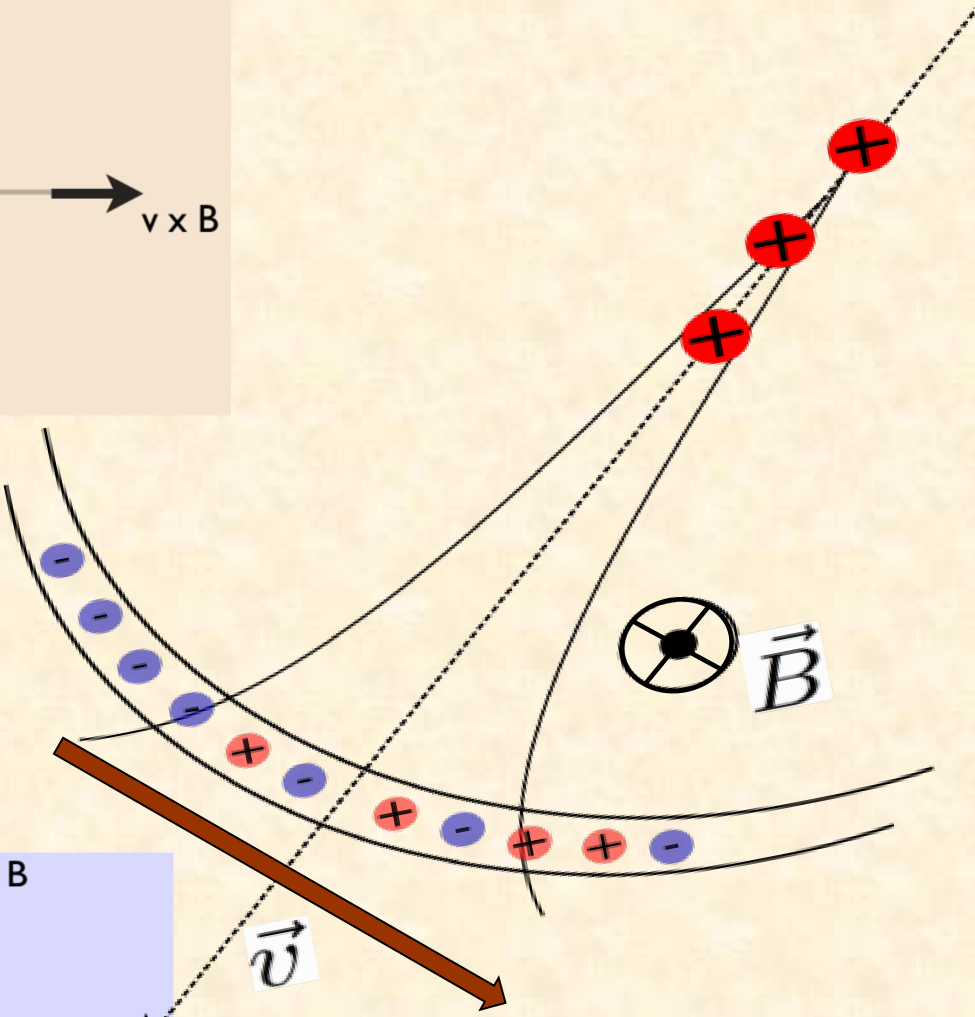
Air shower, side view



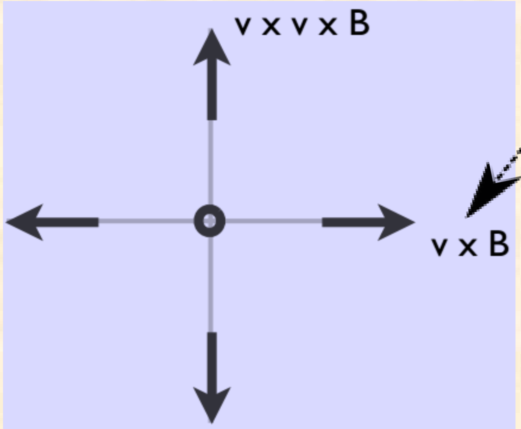
Multiple emission mechanisms

 # Geomagnetic:
- Electrons & positrons have transverse drift, induced by geomagnetic field.
- Linearly polarized, Unidirectional along v x B





 # Charge excess:
- Negative charge buildup at shower front.
- Linearly polarized, Radially from shower axis



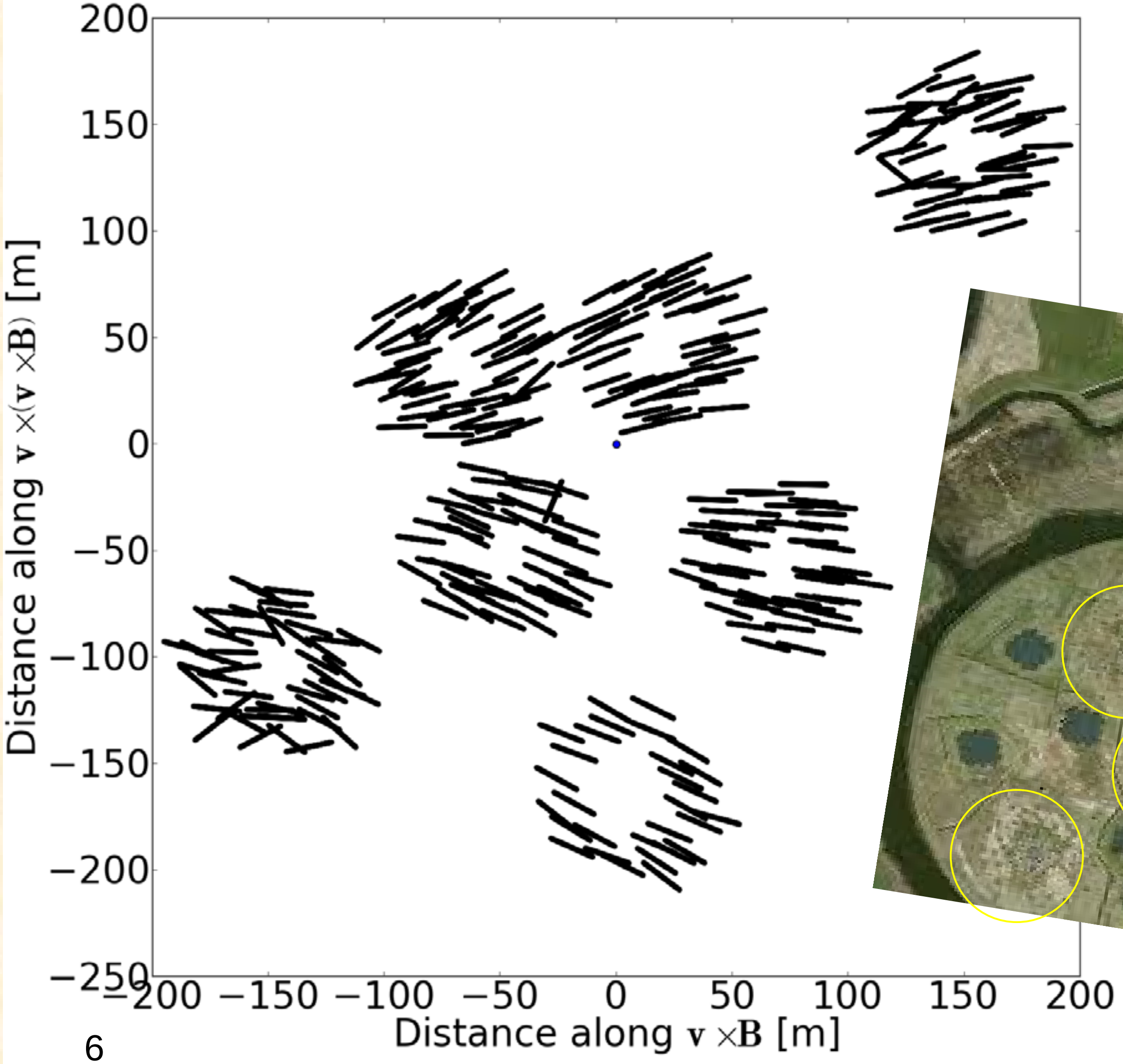
K. Werner et al., ApP 29 (2008) 393

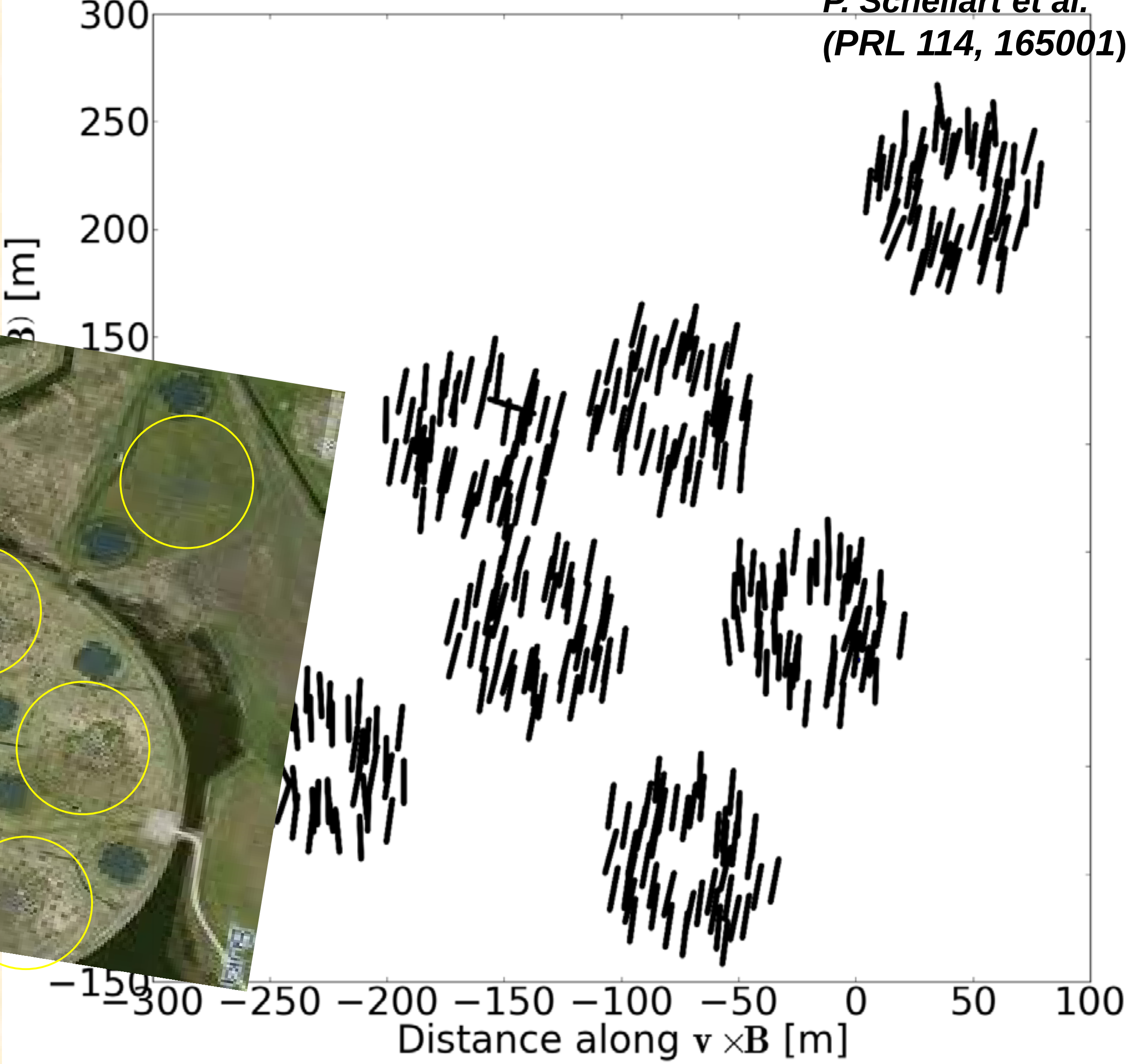
The full signal: $\vec{E} = \vec{E}_G + \vec{E}_C$ modified by Time-compression effects.

Observations; polarization footprint

Fair weather vs thunderstorm

P. Schellart et al. (PRL 114, 165001)



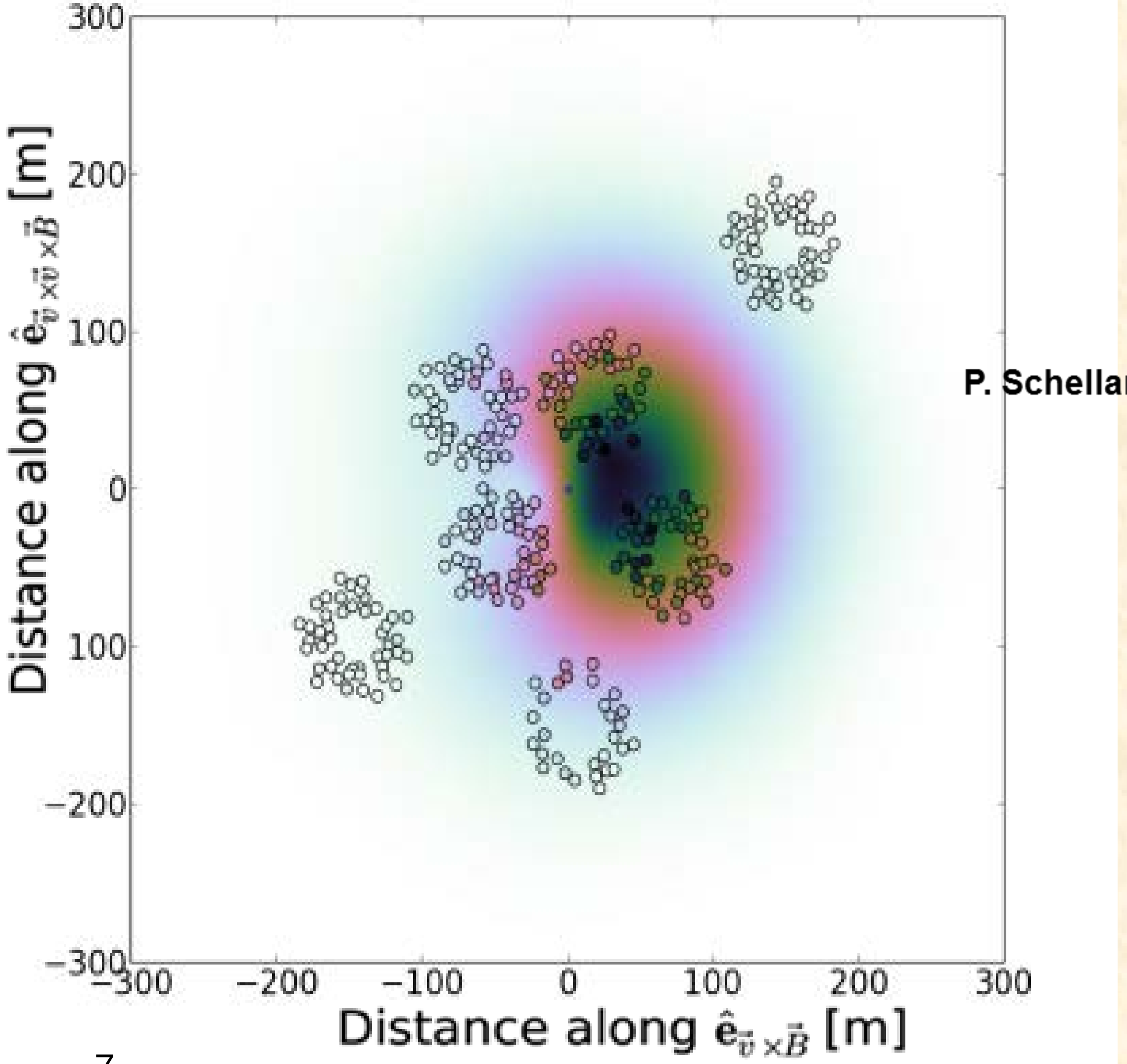


Observations; intensity footprint

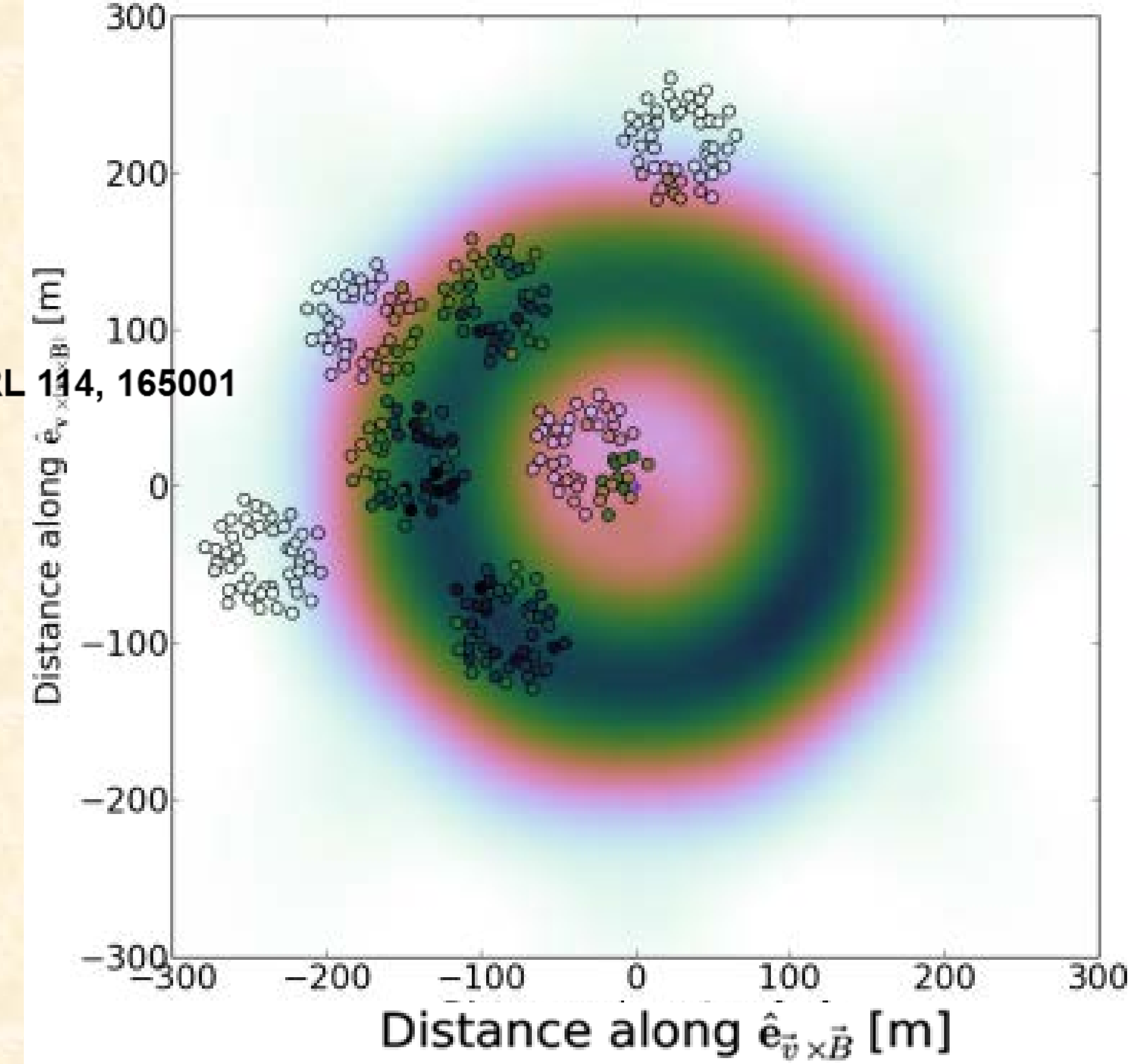
S. Buitink et al.
PRD 90, 082003 (2014)

Fair weather vs thunderstorm

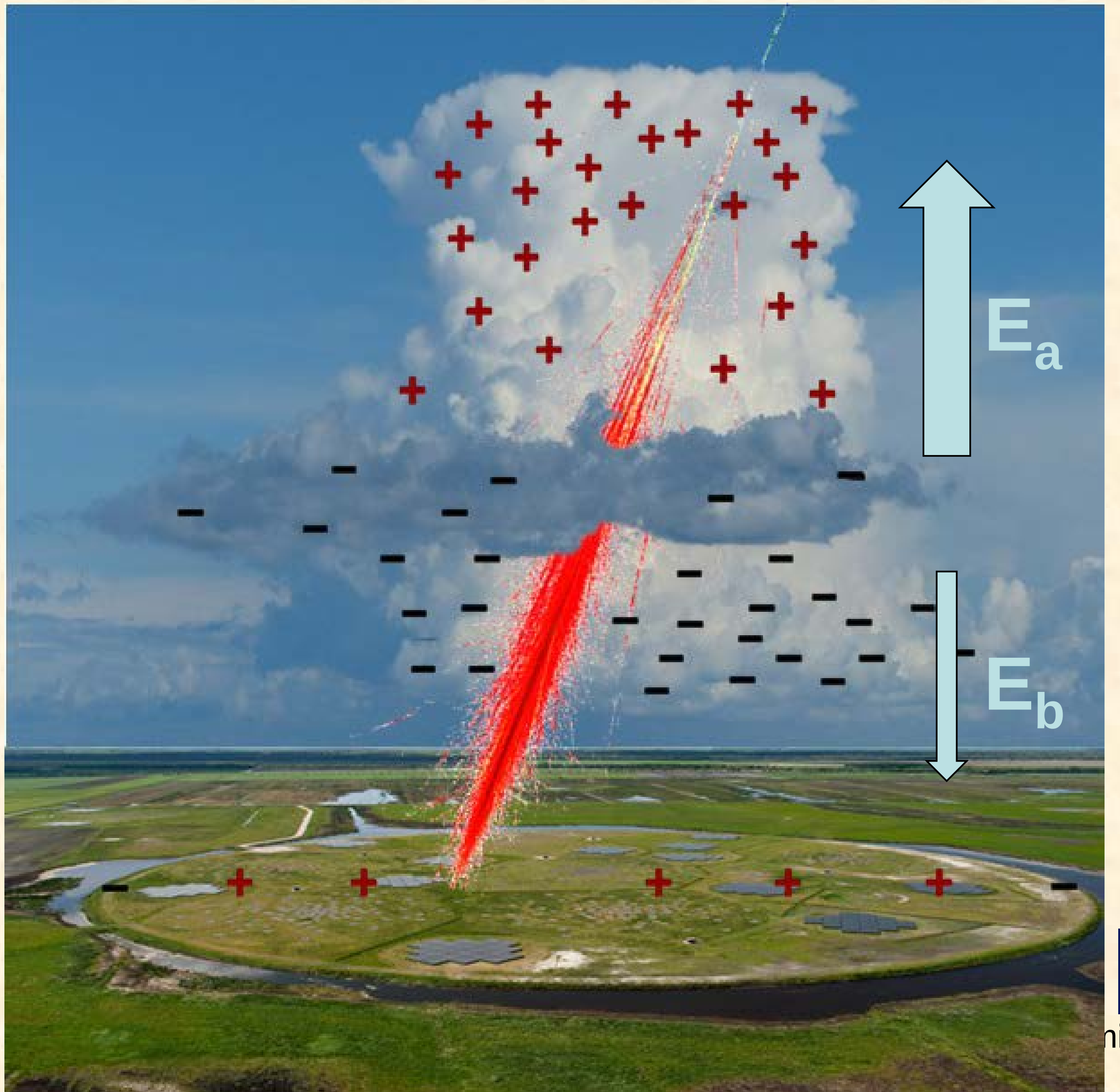
P. Schellart et al.,
PRL 114, 165001 (2015)

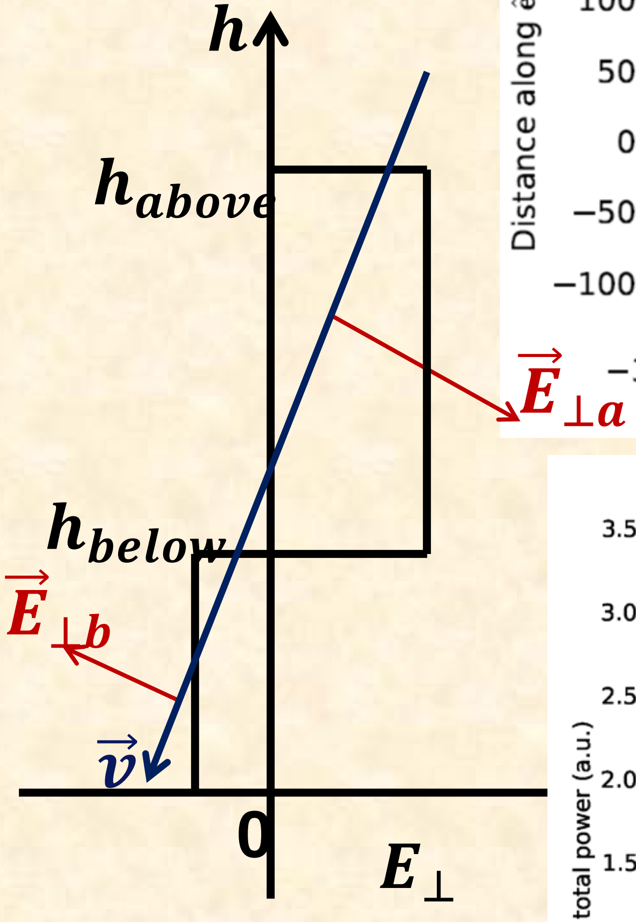


P. Schellart et al., PRL 114, 165001

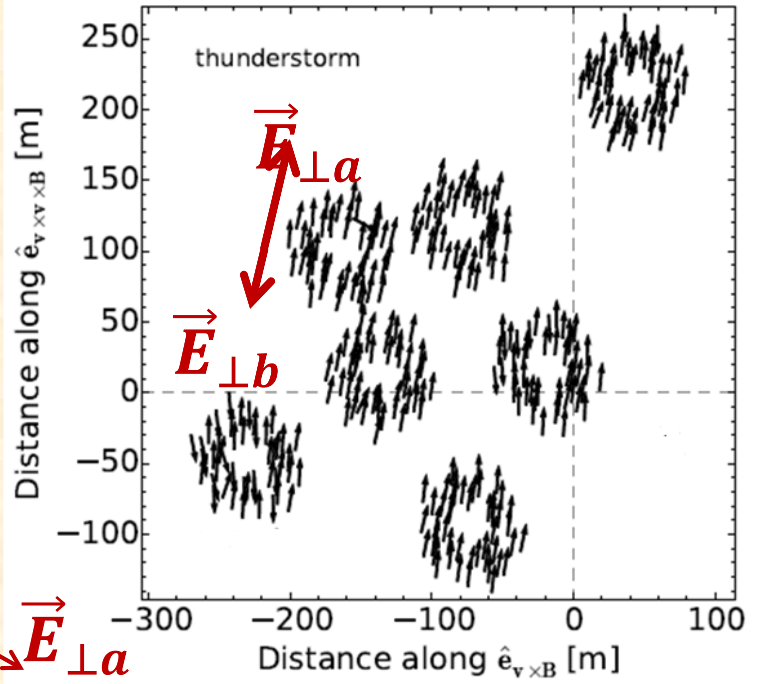


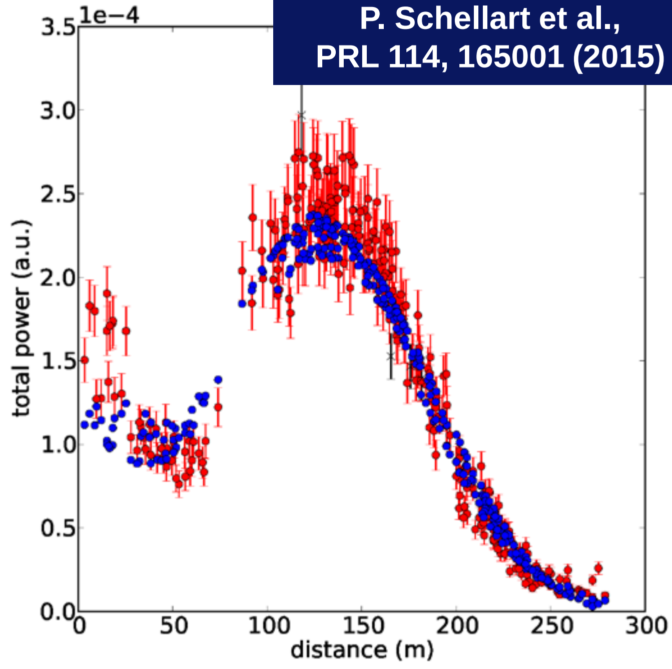
Structure E-fields





T.N.G. Trinh et al.,
Phys Rev D 93 (2016) 023003





P. Schellart et al.,
PRL 114, 165001 (2015)

ninar

Full polarization, Stokes

$$I = \frac{1}{n}\sum_{0}^{n-1}\left(|\mathcal{E}|^2_{i,\vec{v}\times\vec{B}} + |\mathcal{E}|^2_{i,\vec{v}\times\vec{v}\times\vec{B}}\right)$$

$$Q = \frac{1}{n}\sum_{0}^{n-1}\left(|\mathcal{E}|^2_{i,\vec{v}\times\vec{B}} - |\mathcal{E}|^2_{i,\vec{v}\times\vec{v}\times\vec{B}}\right)$$

$$U + iV = \frac{2}{n}\sum_{0}^{n-1}\left(\mathcal{E}_{i,\vec{v}\times\vec{B}}\mathcal{E}^{*}_{i,\vec{v}\times\vec{v}\times\vec{B}}\right) .$$

Interesting results:

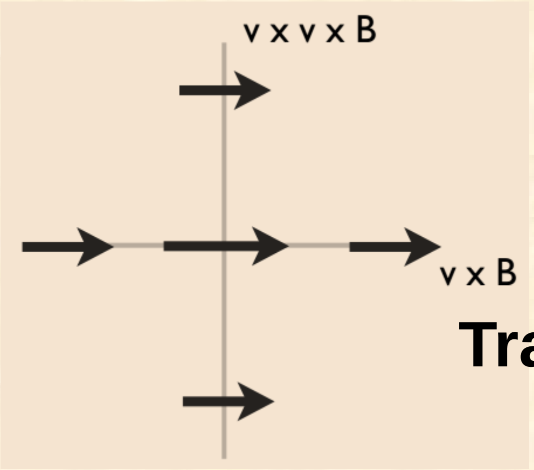
- **Fair weather:**
  - **confirmation of emission mechanisms**
- **Thunderstorm:**
  - **Finite circular pol. near core due to changing atmospheric E-field**

Stokes parameters: I, Q, U, V

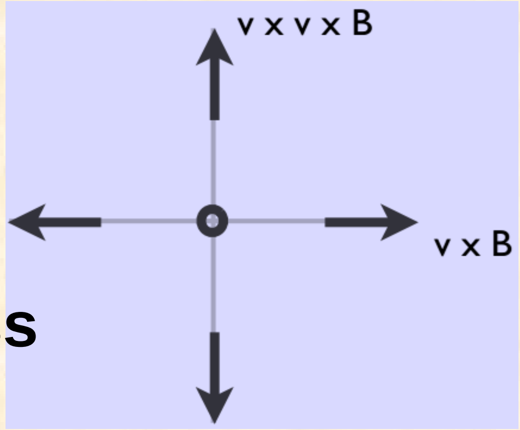
Linear polarization angle: $2\varphi = \mathrm{atan}(U/Q)$

NEW: Circular polarization = V/I

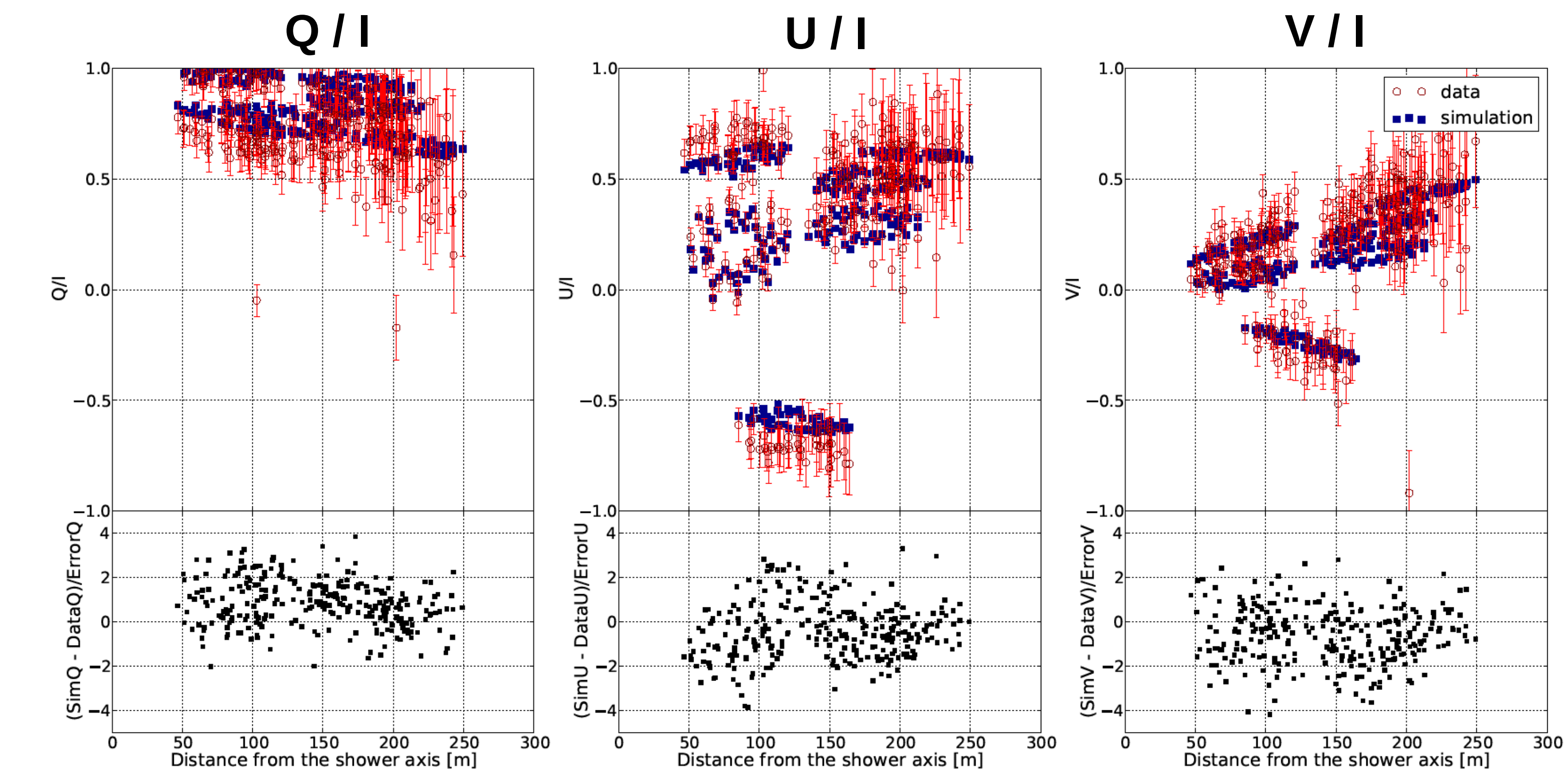
Presentation by Gia Trinh

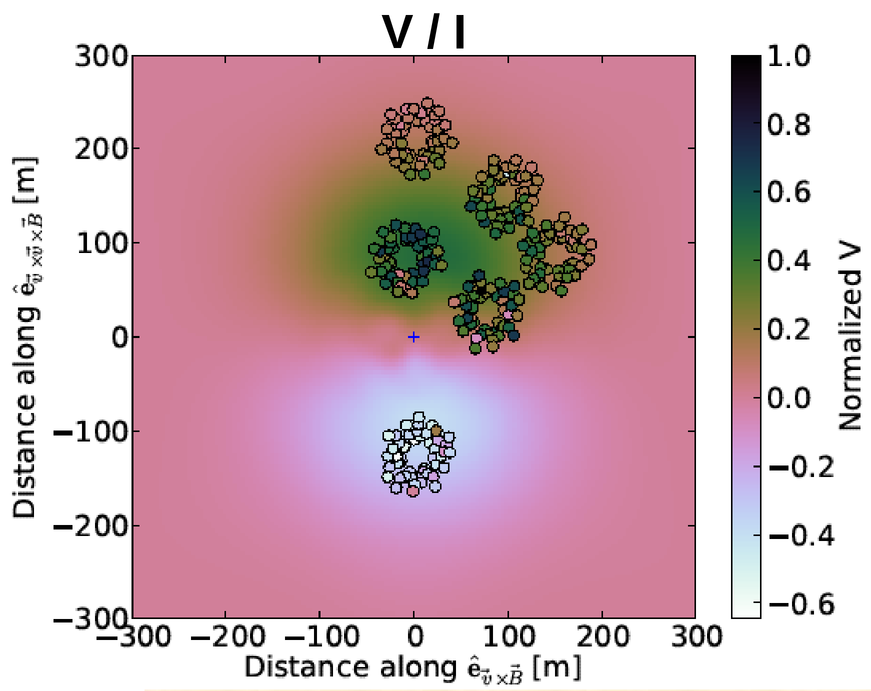


Reason for fair-weather circular polarization:

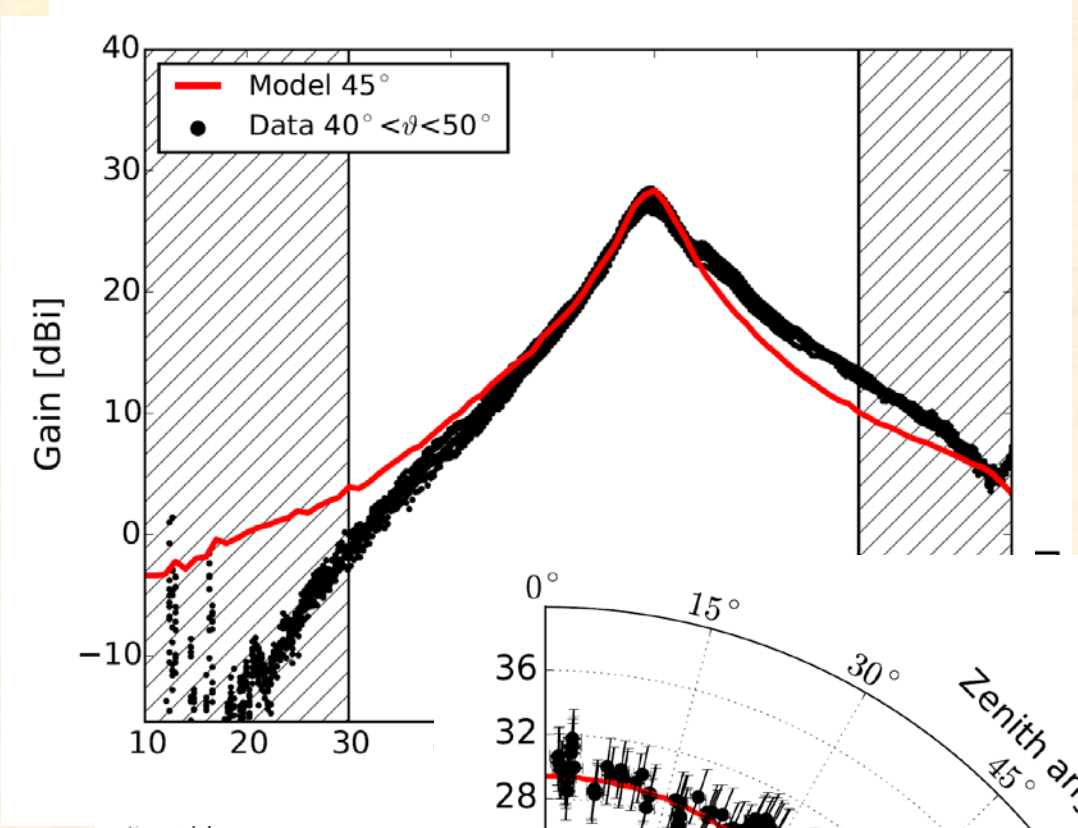


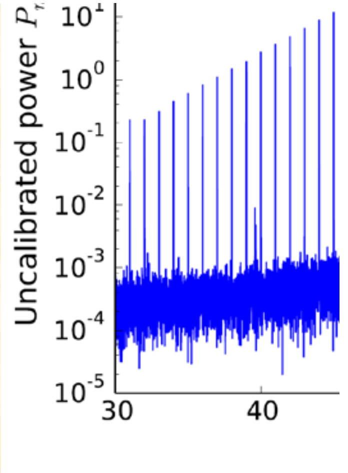
Transverse current is 1ns ahead of Charge excess pulse

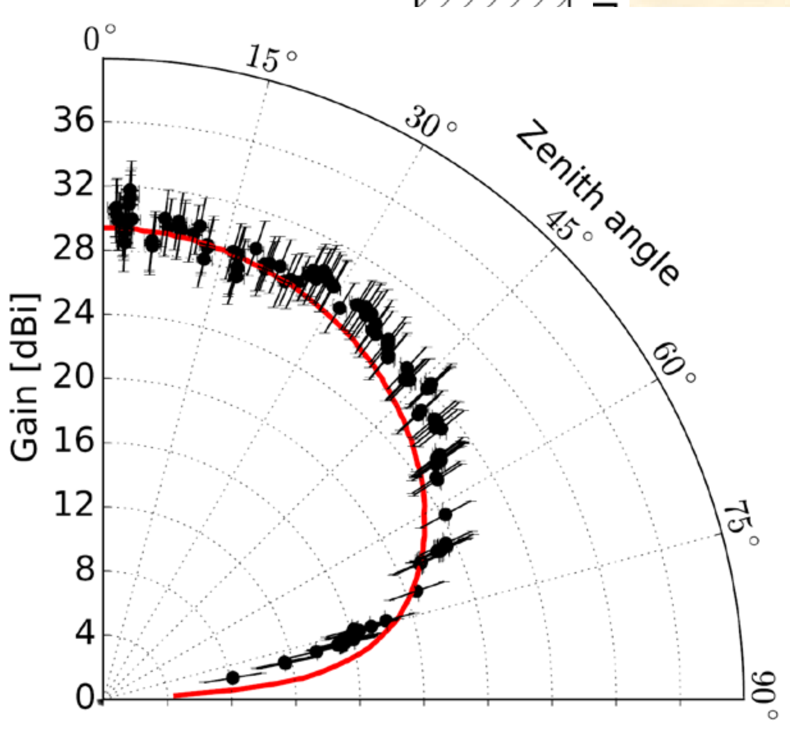




antenna calibration



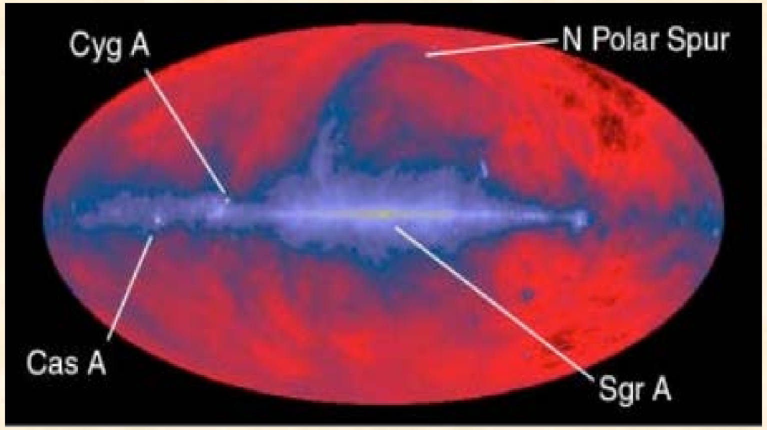


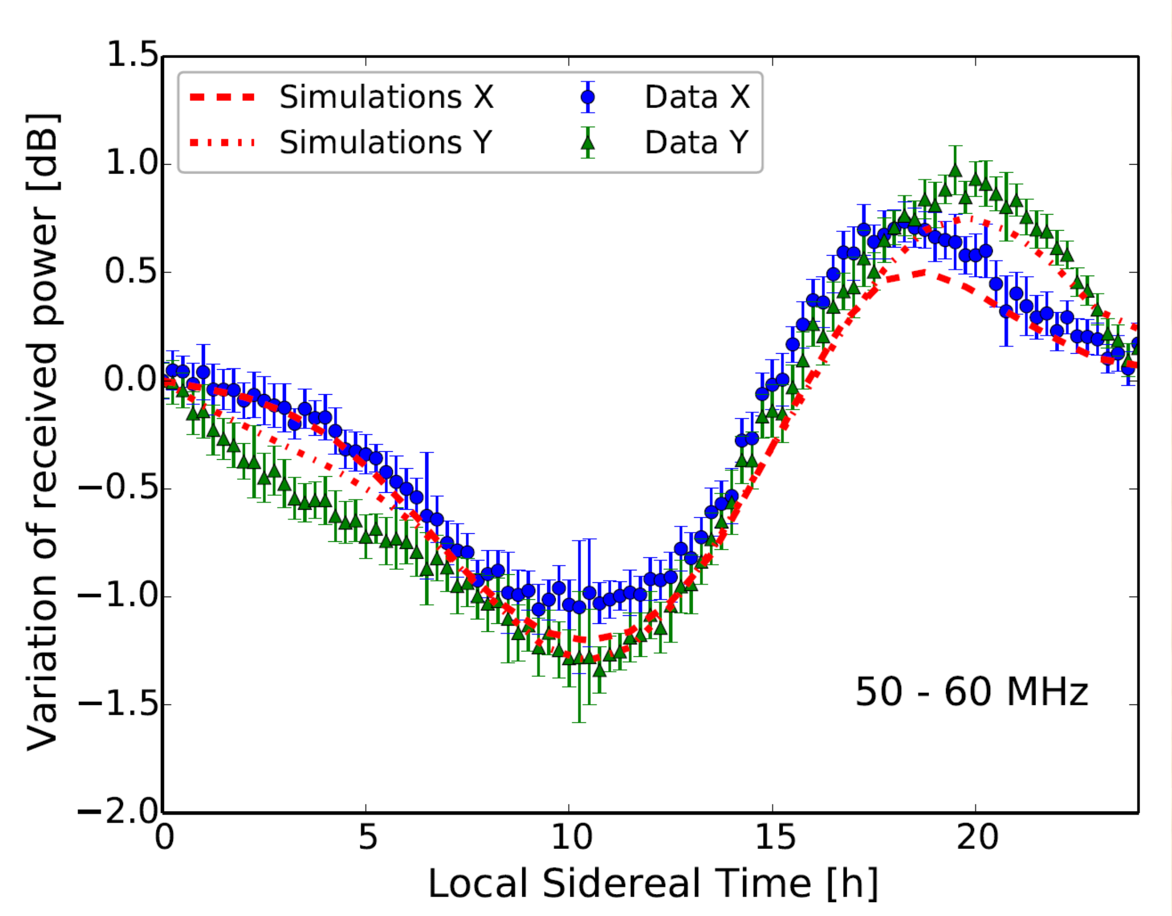


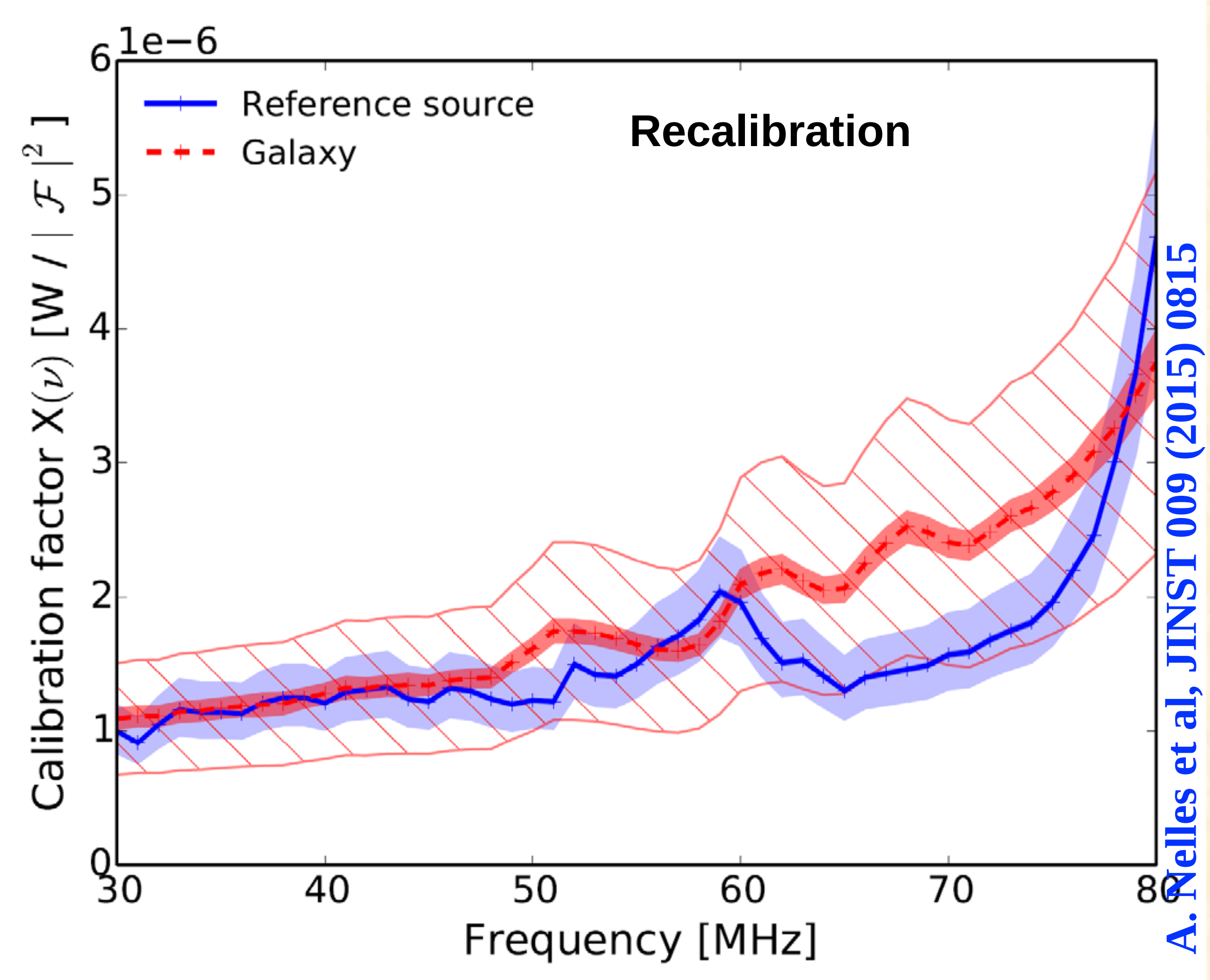
A. Nelles et al, JINST 009 (2015) 0815

Gain of complete signal chain

Galactic background



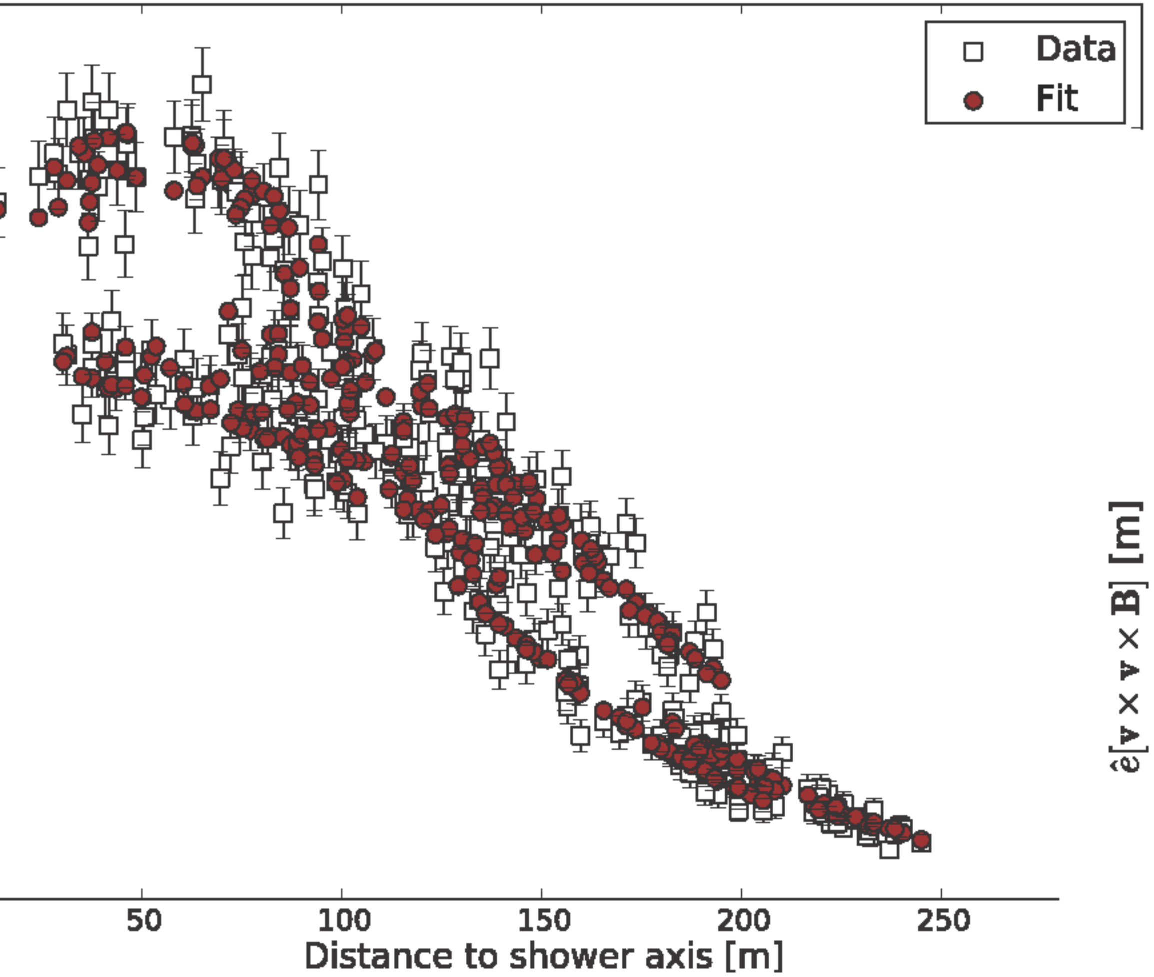




A. Nelles et al, JINST 009 (2015) 0815

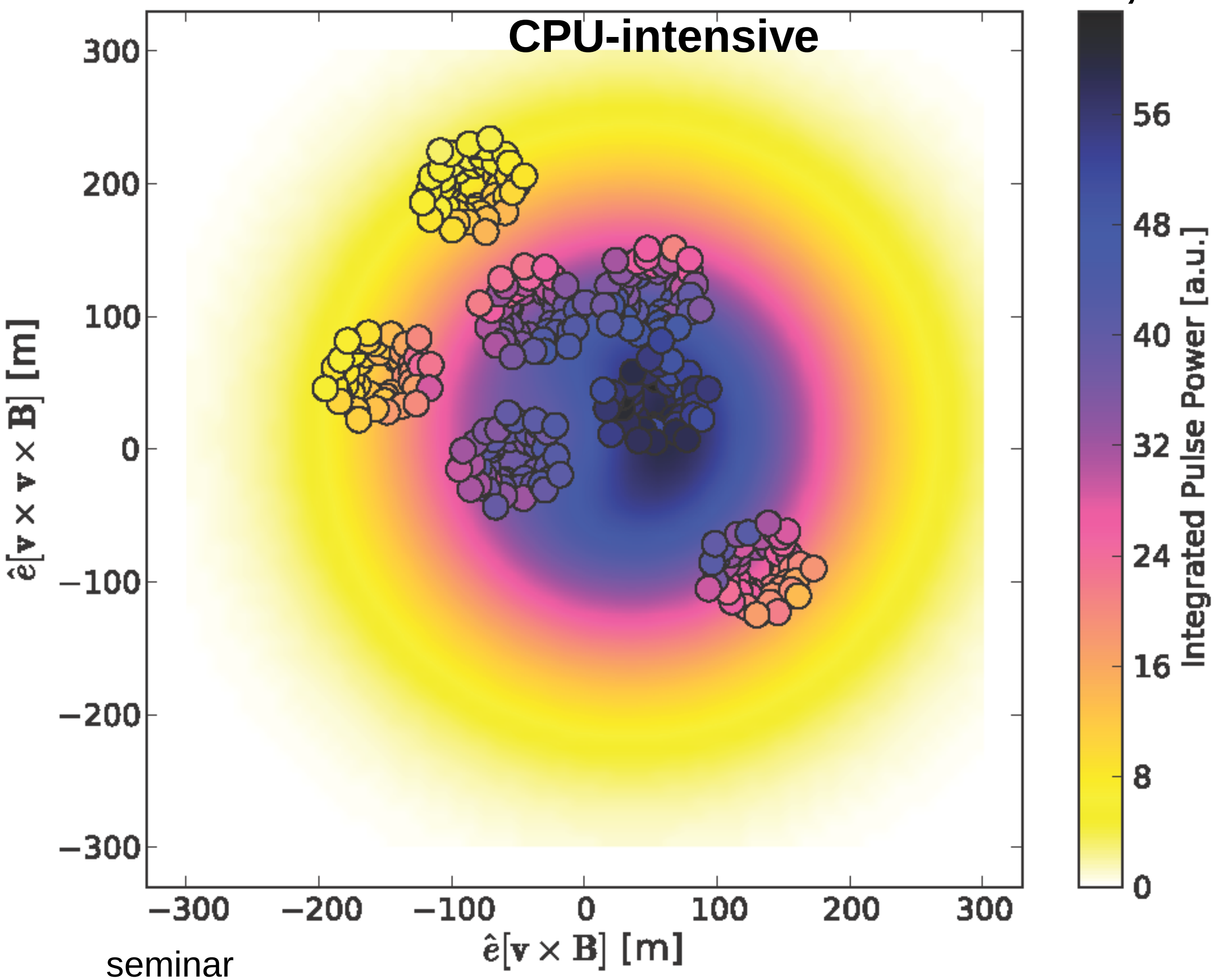
Lateral distribution of radio signals

as measured by LOFAR

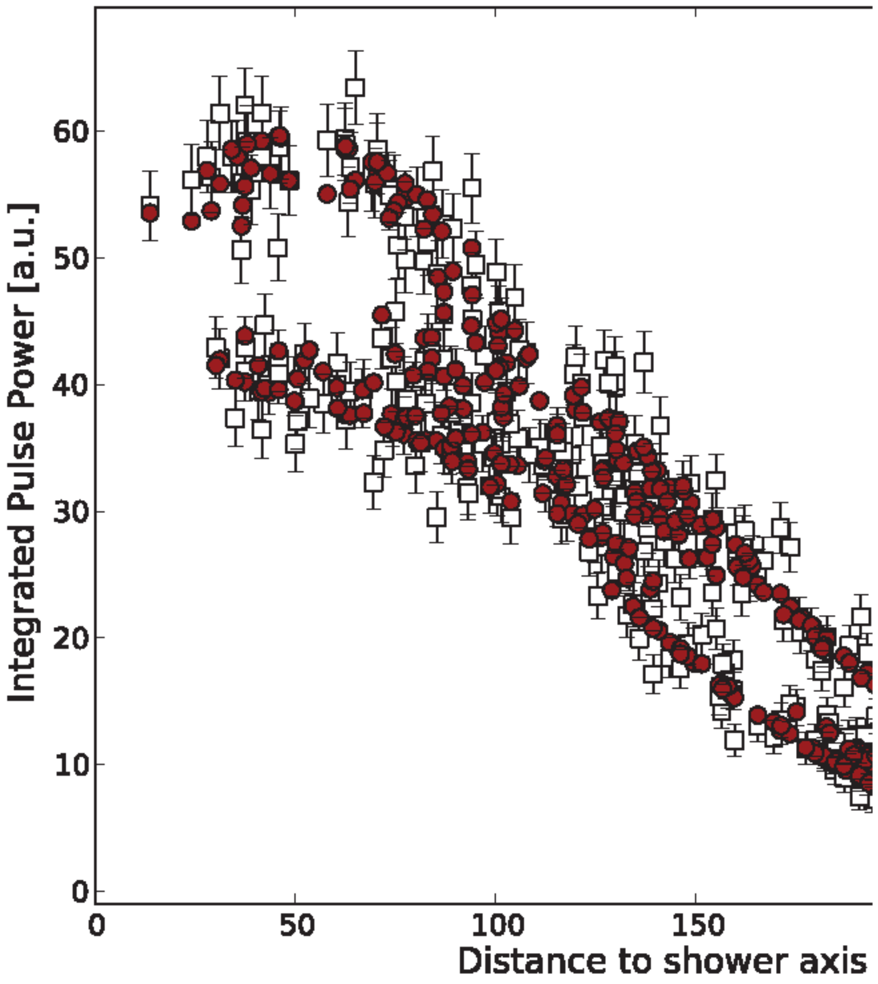


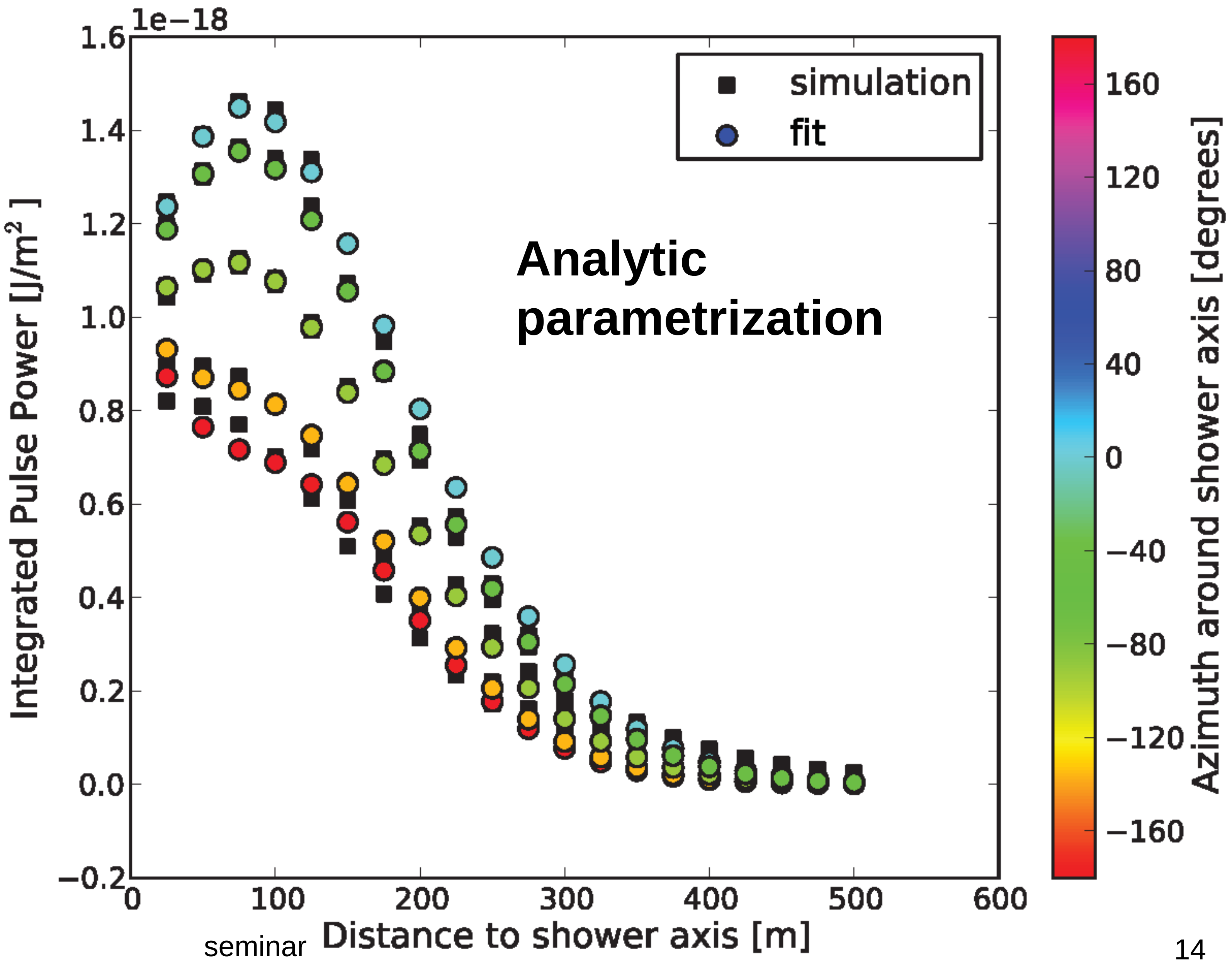
les et al., Astropart. Phys. 60 (2015) 13

CoREAS simulation,
Follows individual electrons,
CPU-intensive

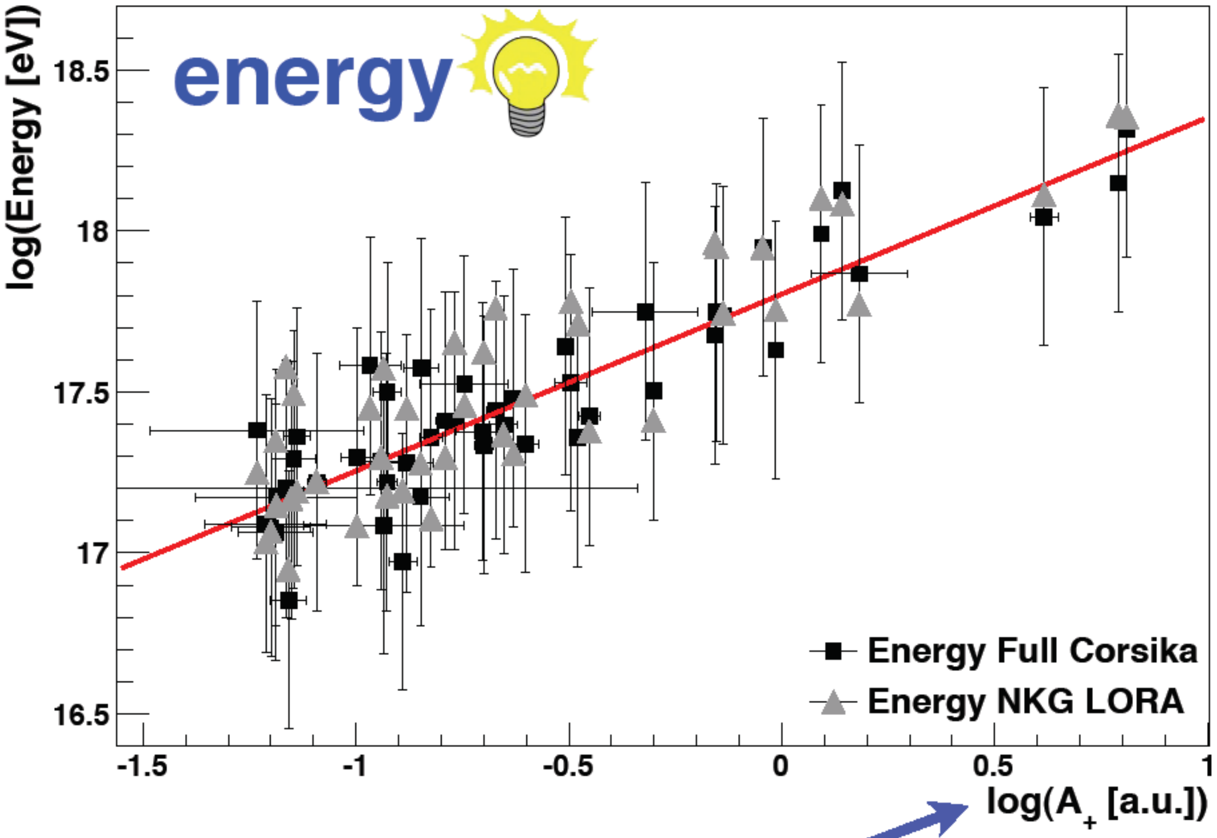


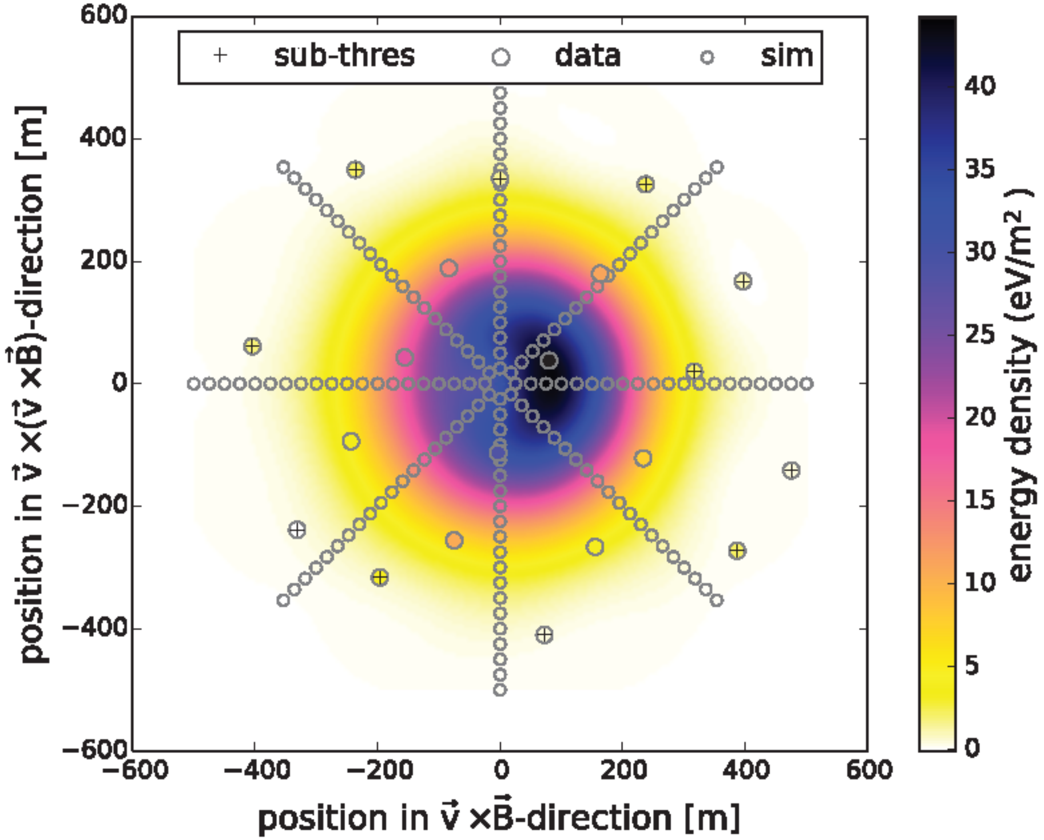
Lateral distribution of radio signals





Properties of primary particle

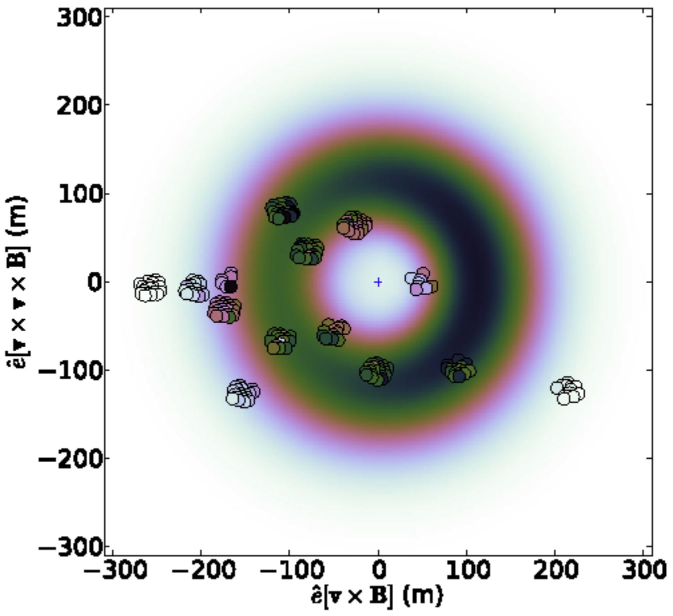


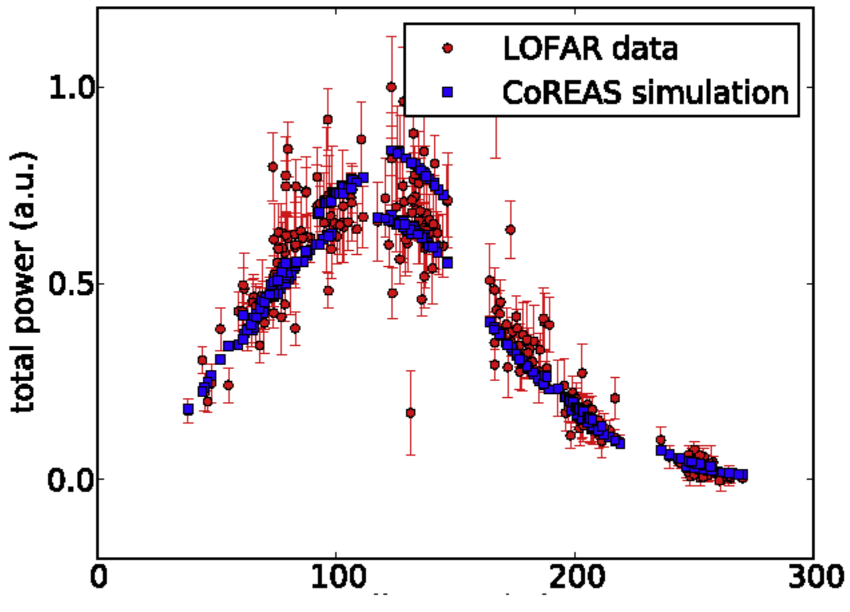


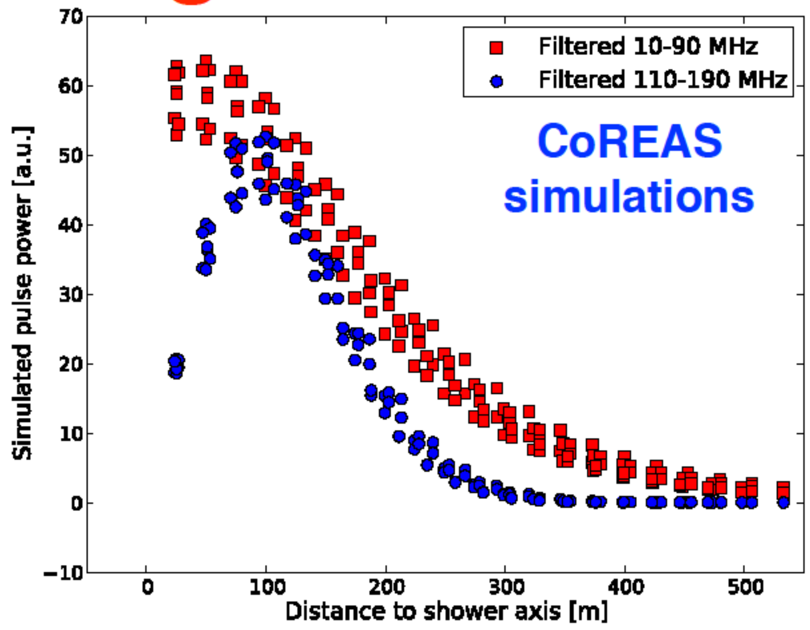
$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right) + O$$

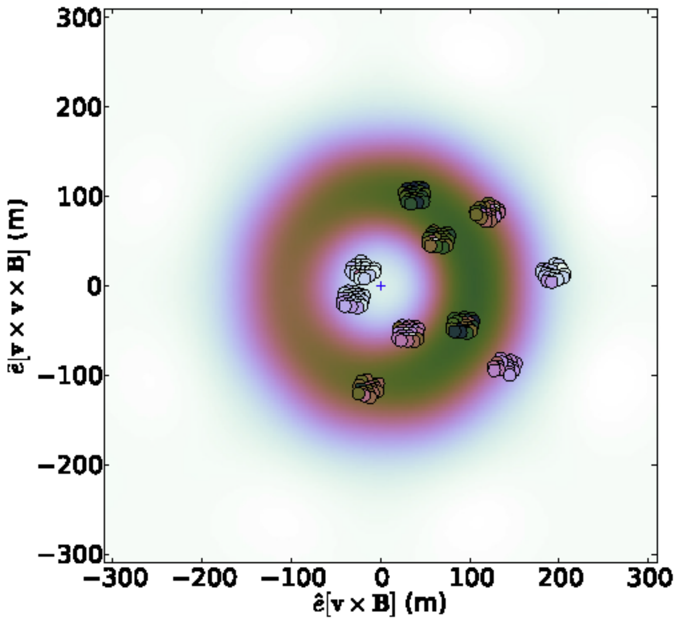
A. Nelles et al., JCAP 05 (2015) 018

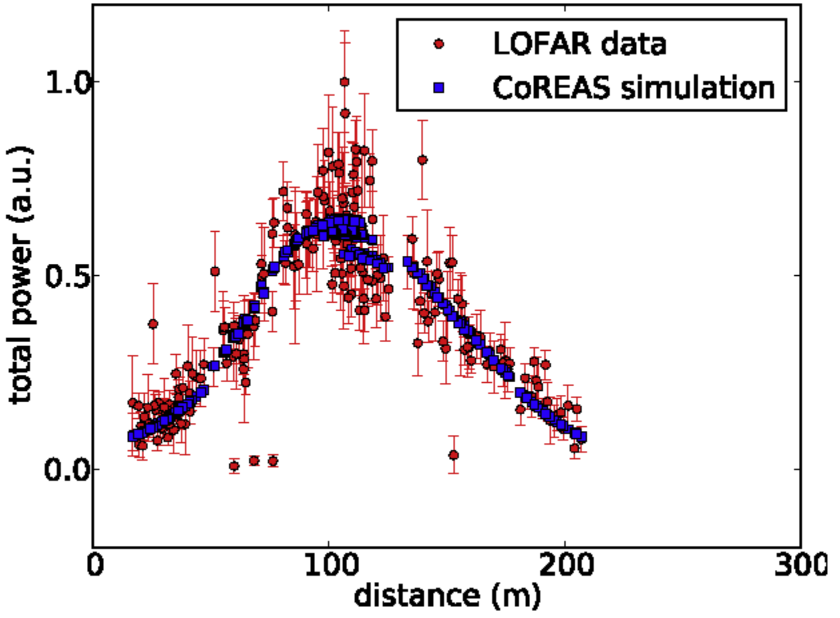
Measuring Cherenkov Rings 110 - 190 MHz





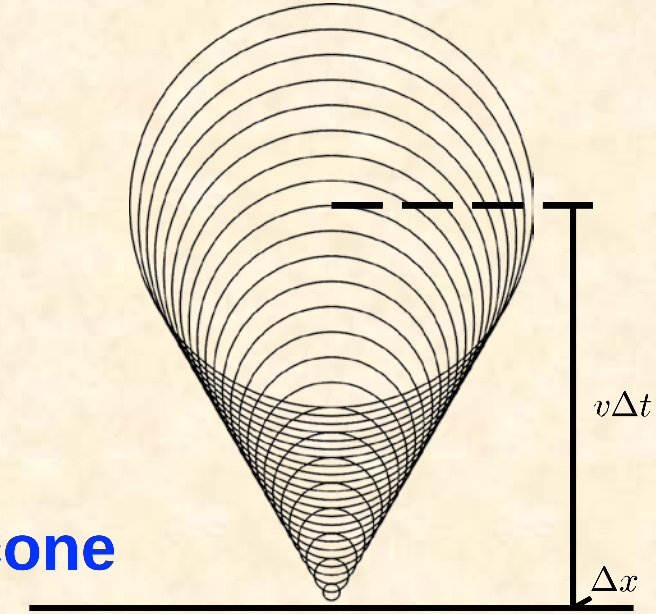




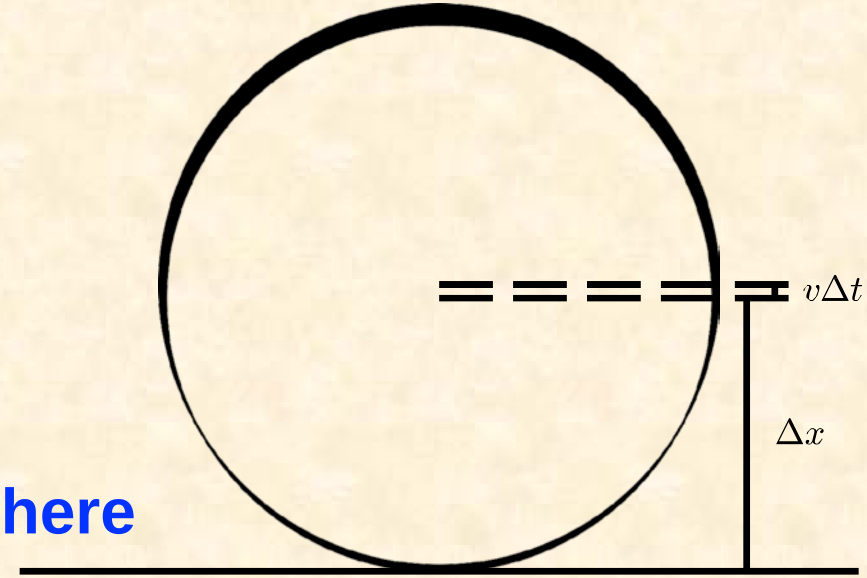


A. Nelles et al., Astroparticle Physics 65 (2015) 11

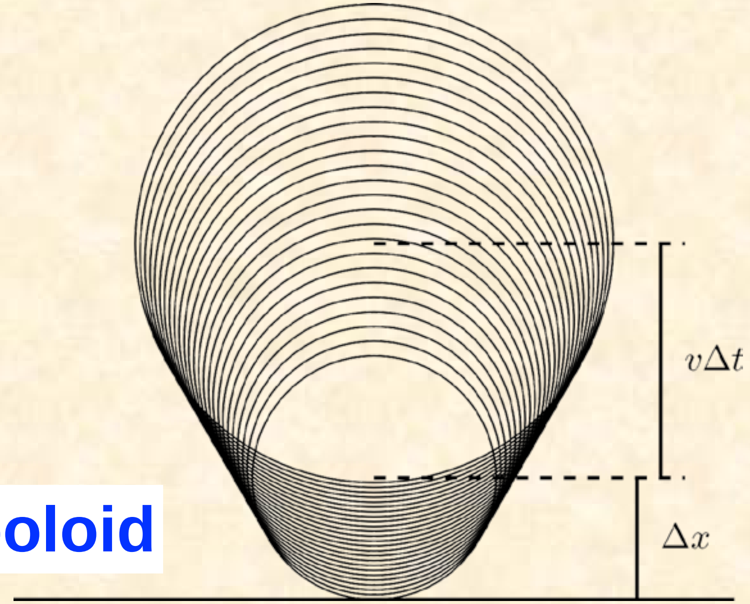
Shape of the Shower Front



cone

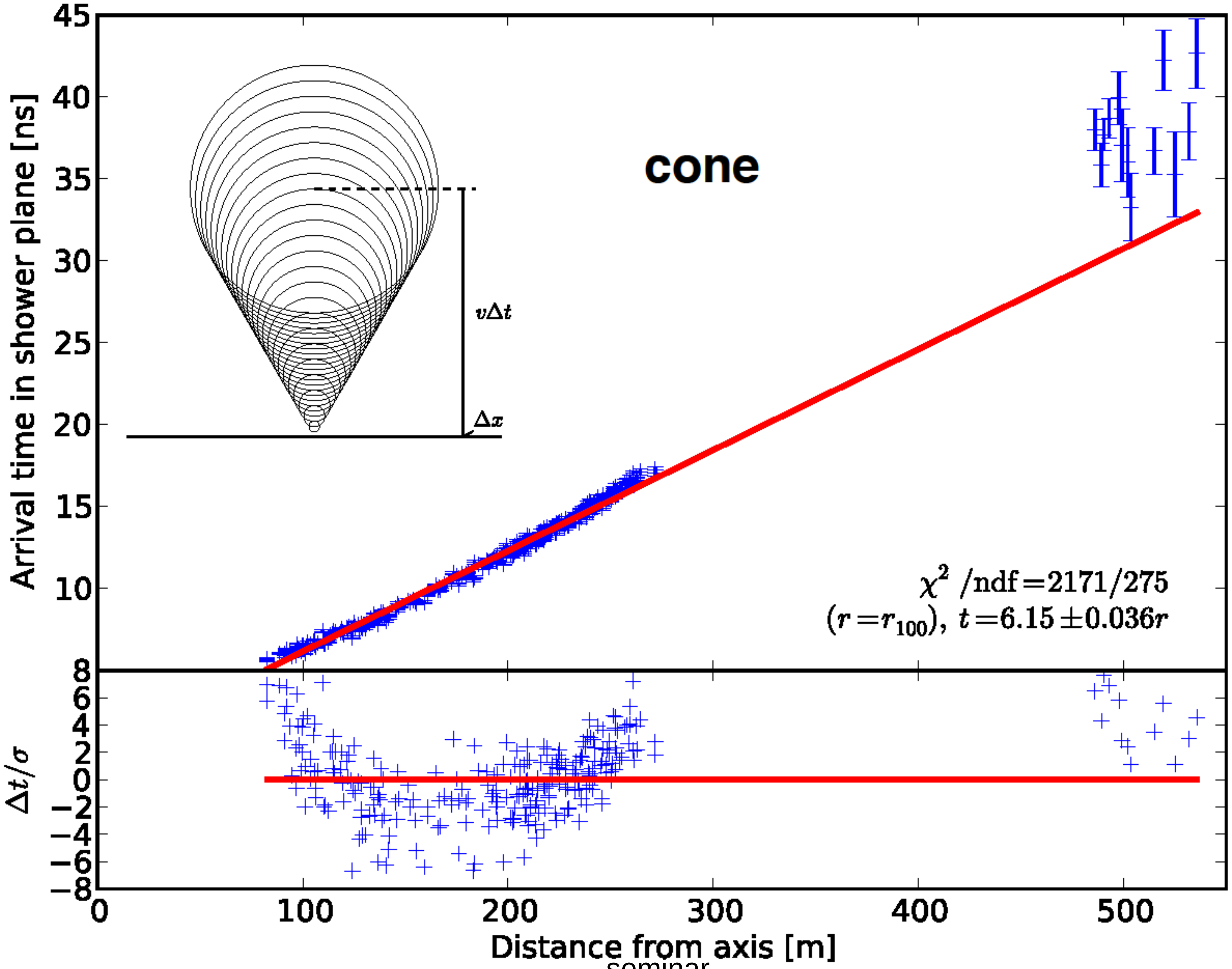


sphere



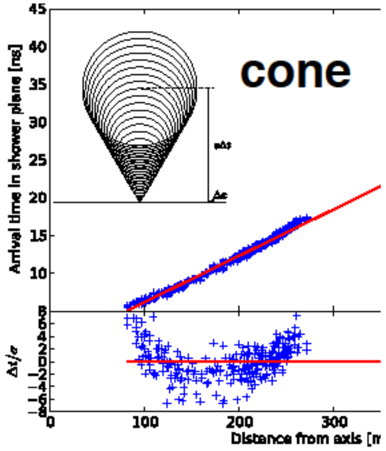
hyperboloid

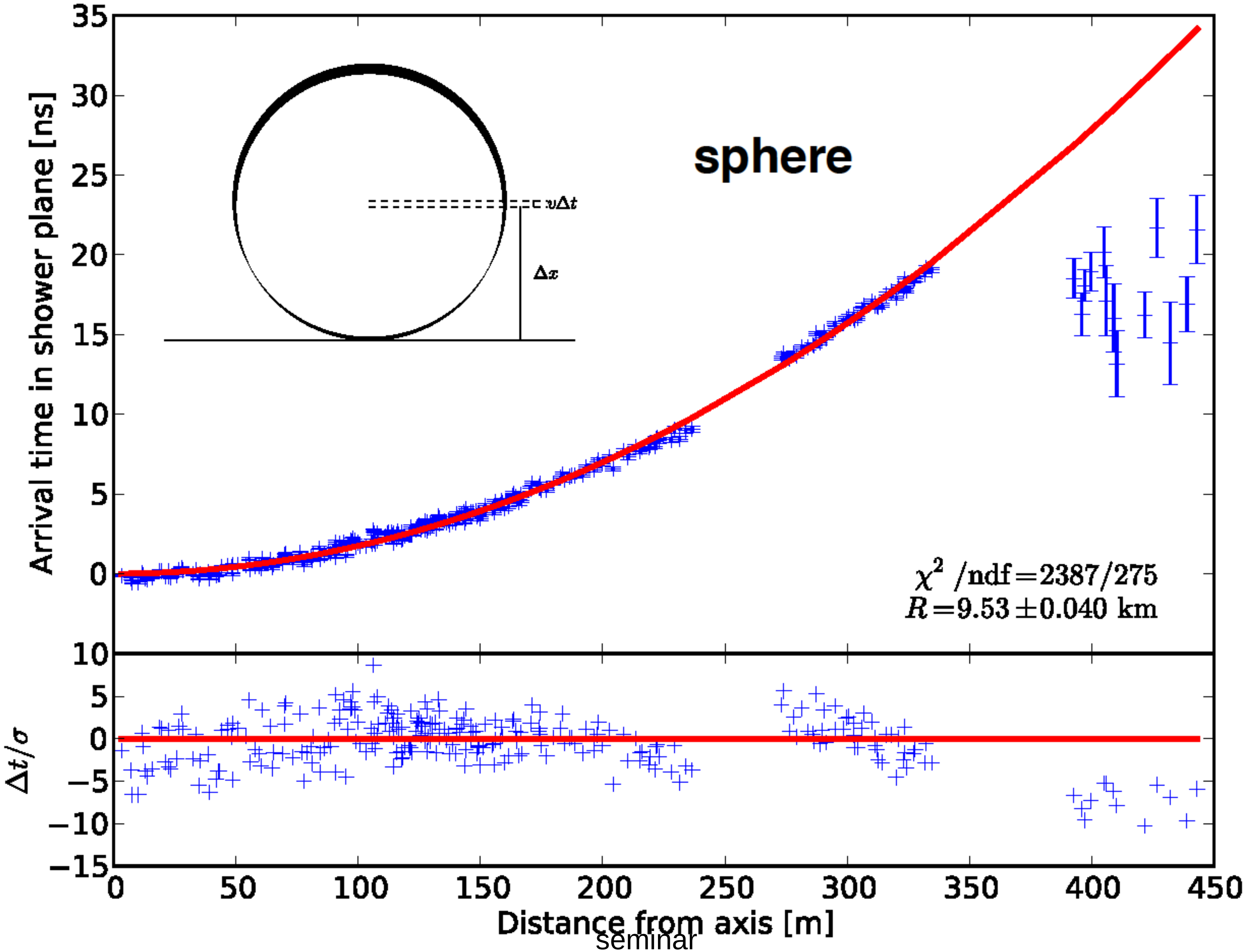
Arrival time of radio signals



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

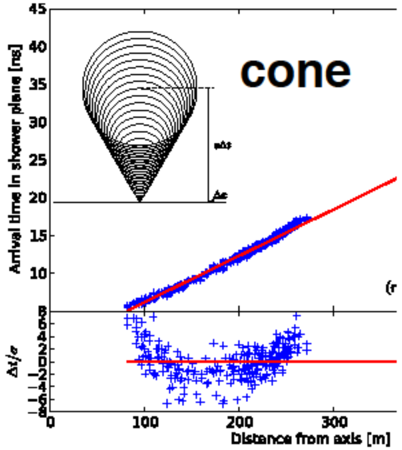
Arrival time of radio signals

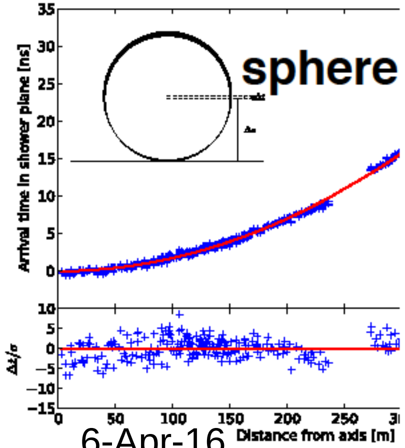


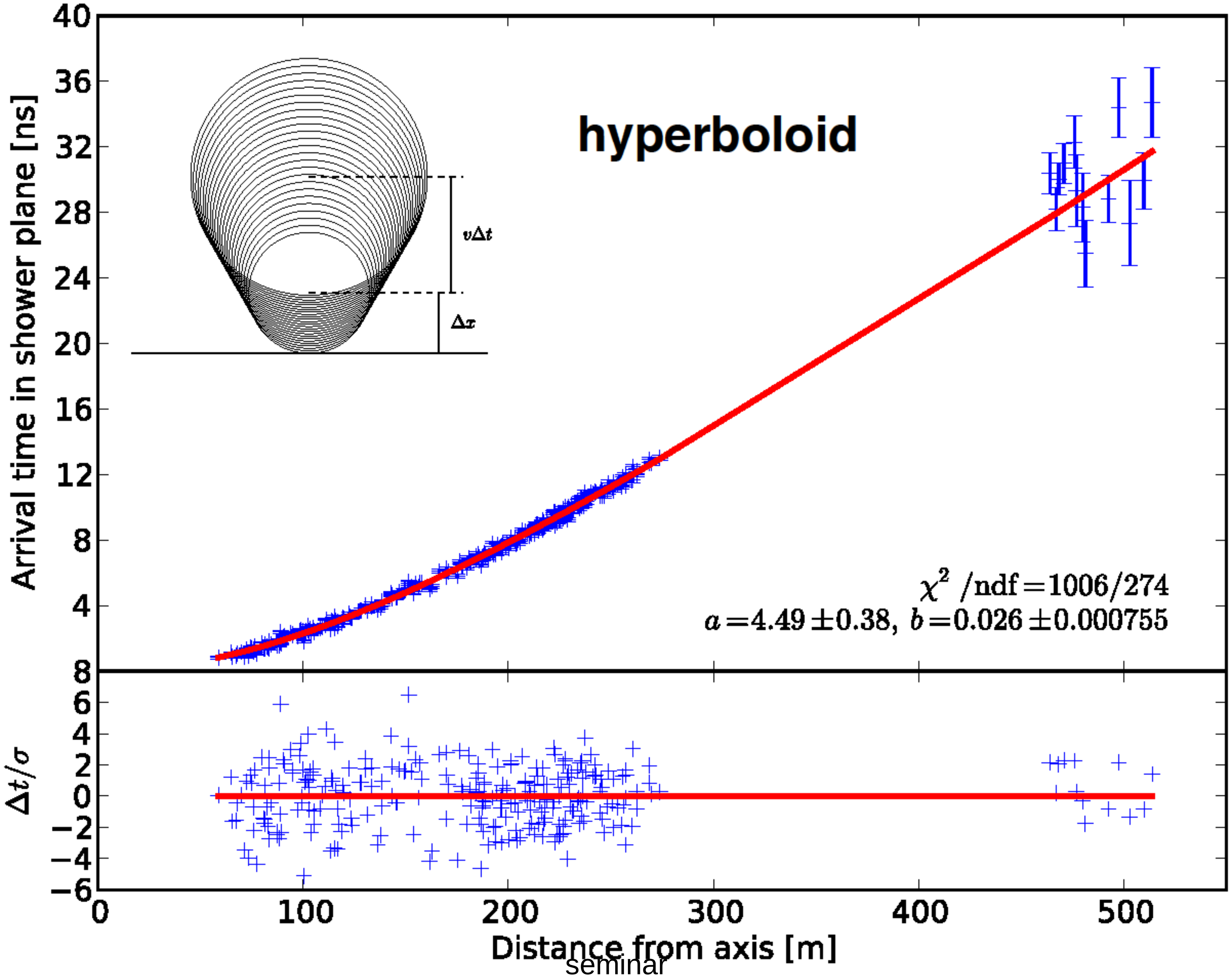


A. Corstanje et al., Astropart. Phys. 61 (2015) 22

Arrival time of radio signals

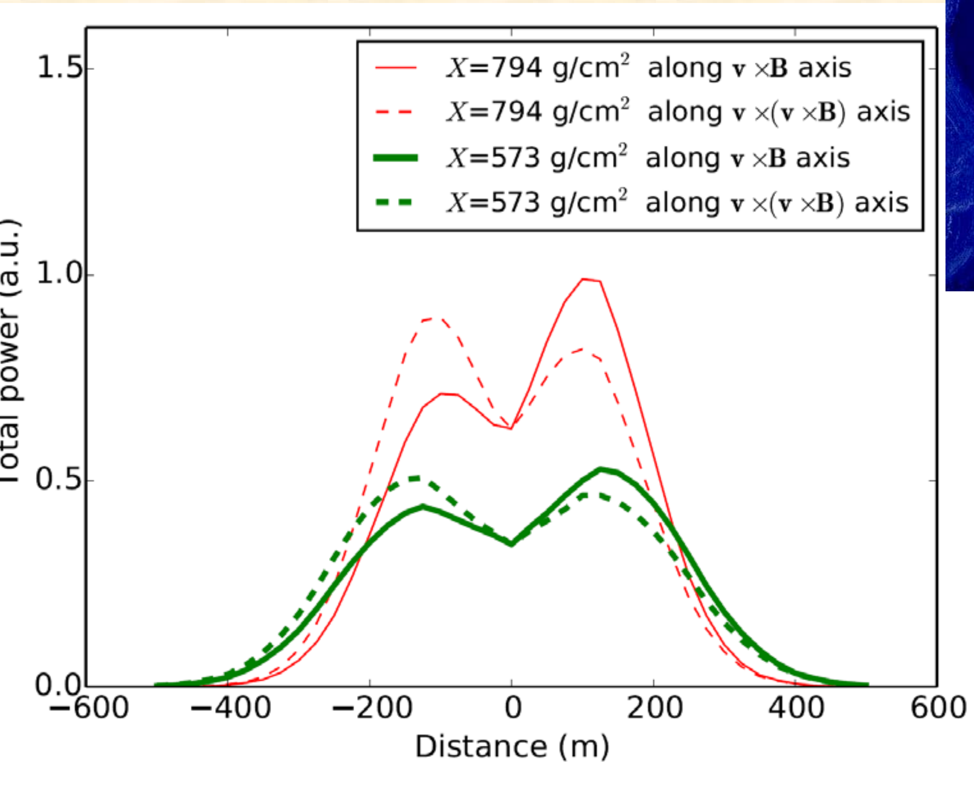


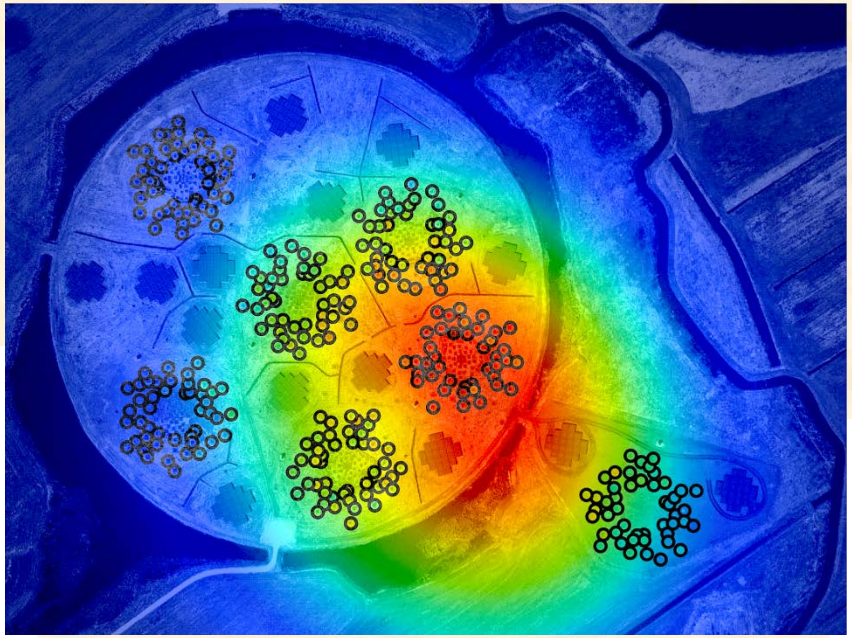


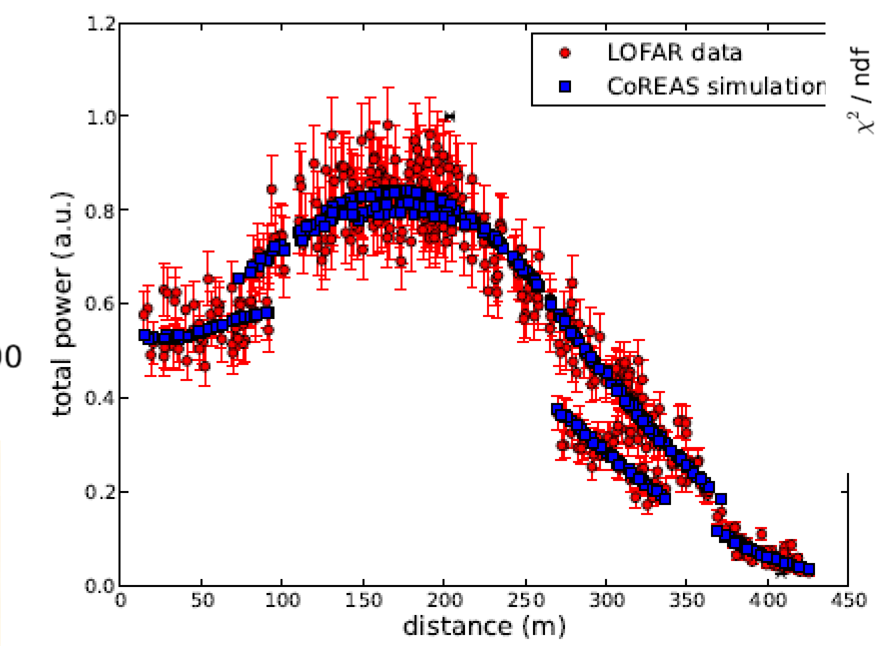


A. Corstanje et al., Astropart. Phys. 61 (2015) 22

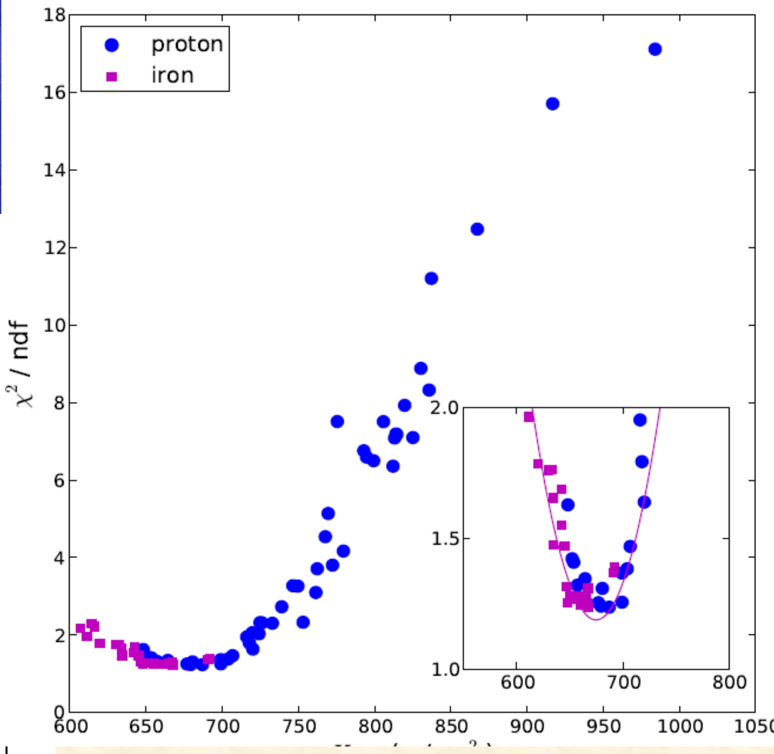
LOFAR
CR-radio detection







Presentation Stijn Buitink



X_{max} resolution = 20 g/cm^2

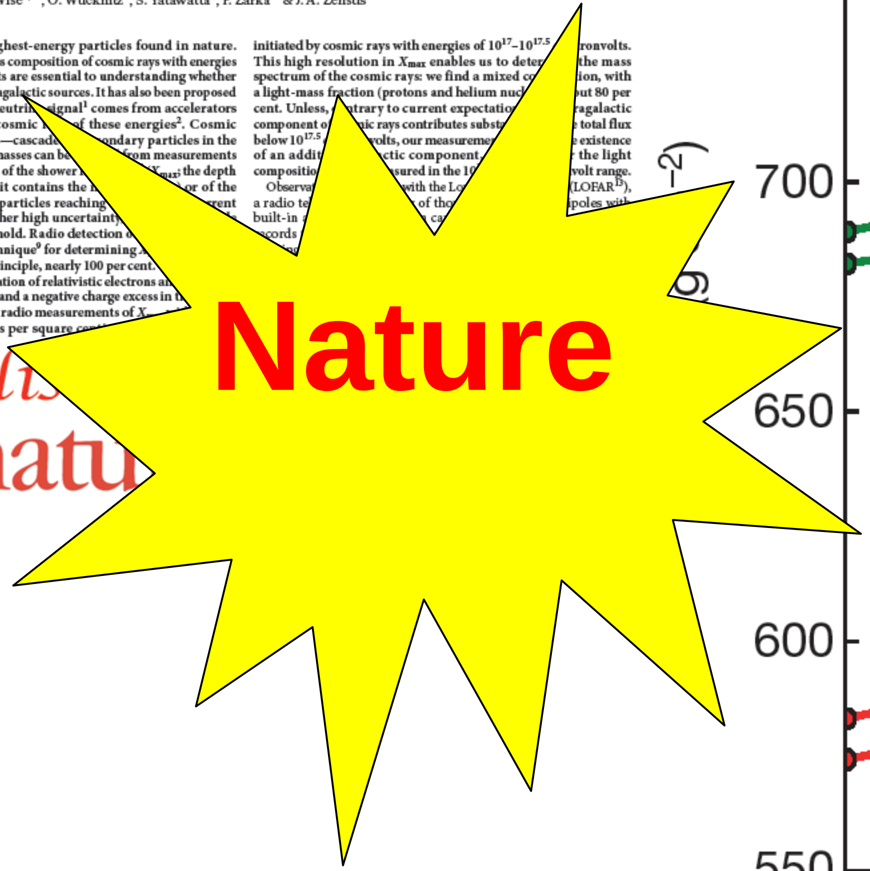
Depth of the shower maximum

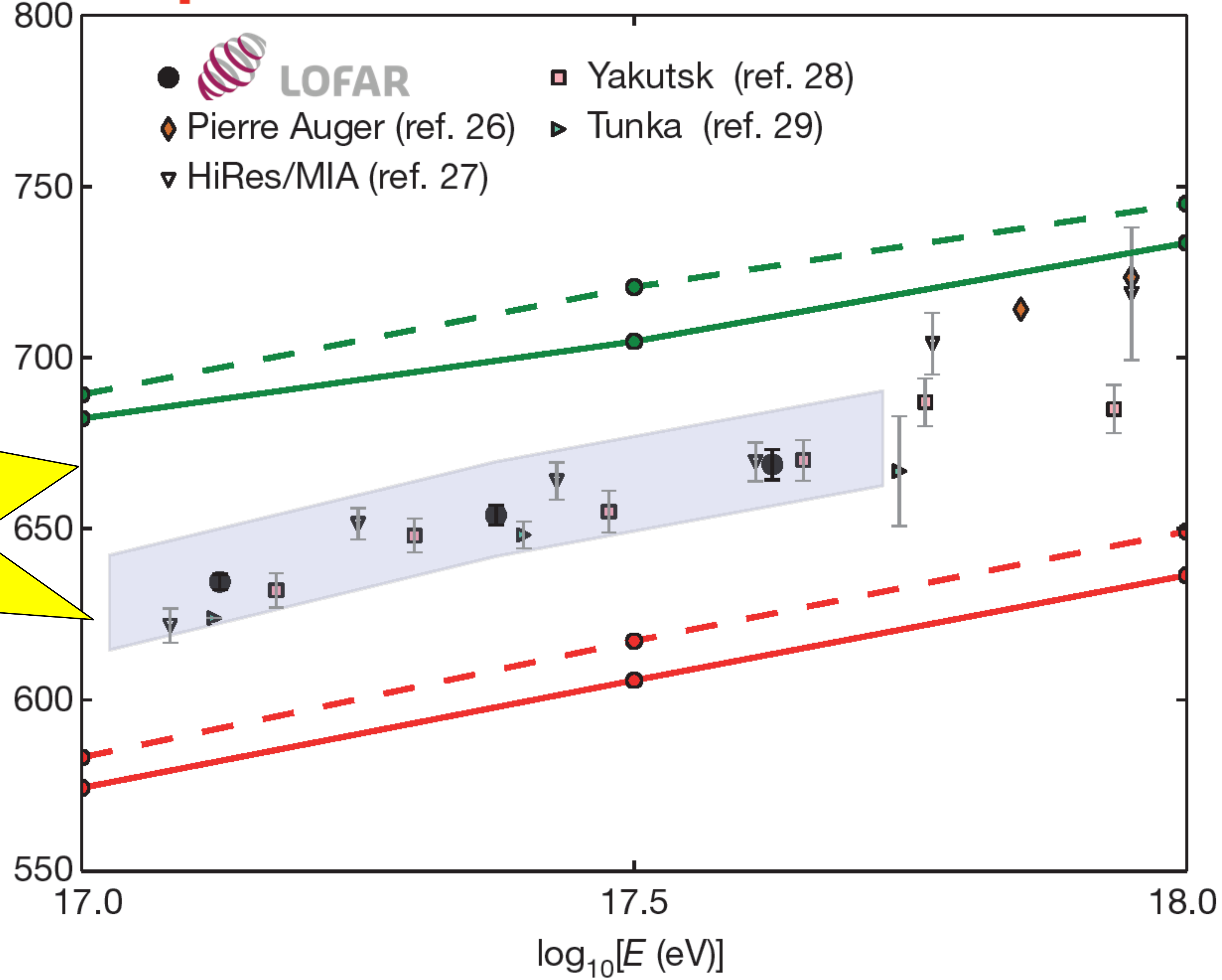
LETTER

doi:10.1038/nature16976

A large light-mass component of cosmic rays at 10^{17}–$10^{17.5}$ electronvolts from radio observations

S. Buitink[1,2], A. Corstanje[2], H. Falcke[2,3,4,5], J. R. Hörandel[2,4], T. Huege[6], A. Nelles[2,7], J. P. Rachen[2], L. Rossetto[2], P. Schellart[2], O. Scholten[8,9], S. ter Veen[3], S. Thoudam[2], T. N. G. Trinh[8], J. Anderson[10], A. Asgekar[3,11], I. M. Avruch[12,13], M. E. Bell[14], M. J. Bentum[3,15], G. Bernardi[16,17], P. Best[18], A. Bonafede[19], F. Breitling[20], J. W. Broderick[21], W. N. Brouw[3,13], M. Brüggen[19], H. R. Butcher[22], D. Carbone[23], B. Ciardi[24], J. E. Conway[25], F. de Gasperin[19], E. de Geus[3,26], A. Deller[3], R.-J. Dettmar[27], G. van Diepen[3], S. Duscha[3], J. Eislöffel[28], D. Engels[29], J. E. Enriquez[3], R. A. Fallows[3], R. Fender[30], C. Ferrari[31], W. Frieswijk[3], M. A. Garrett[3,32], J. M. Grießmeier[33,34], A. W. Gunst[3], M. P. van Haarlem[3], T. E. Hassall[21], G. Heald[3,13], J. W. T. Hessels[3,23], M. Hoeft[28], A. Horneffer[5], M. Iacobelli[3], H. Intema[32,35], E. Juette[27], A. Karastergiou[30], V. I. Kondratiev[3,36], M. Kramer[5,37], M. Kuniyoshi[38], G. Kuper[3], J. van Leeuwen[3,23], G. M. Loose[3], P. Maat[3], G. Mann[20], S. Markoff[23], R. McFadden[3], D. McKay-Bukowski[39,40], J. P. McKean[3,13], M. Mevius[3,13], D. D. Mulcahy[21], H. Munk[3], M. J. Norden[3], E. Orru[3], H. Paas[41], M. Pandey-Pommier[42], V. N. Pandey[3], M. Pietka[30], R. Pizzo[3], A. G. Polatidis[3], W. Reich[5], H. J. A. Röttgering[32], A. M. M. Scaife[21], D. J. Schwarz[43], M. Serylak[30], J. Sluman[3], O. Smirnov[17,44], B. W. Stappers[37], M. Steinmetz[20], A. Stewart[30], J. Swinbank[23,45], M. Tagger[33], Y. Tang[3], C. Tasse[44,46], M. C. Toribio[3,32], R. Vermeulen[3], C. Vocks[20], C. Vogt[3], R. J. van Weeren[16], R. A. M. J. Wijers[23], S. J. Wijnholds[3], M. W. Wise[3,23], O. Wucknitz[5], S. Yatawatta[3], P. Zarka[47] & J. A. Zensus[5]





S. Buitink et al., Nature (2016)

LOFAR key science project Cosmic Rays:

Papers 2015 & 16

A. Bonardi, S. Buitink, A. Corstanje, J.E. Enriquez, H. Falcke,
J.R. Hörandel, T. Karskens, M. Krause, P. Mitra, K. Mulrey, A. Nelles,
J.P. Rachen, L. Rossetto, P. Schellart, O. Scholten, S. Thoudam, T.N.G. Trinh , S. ter Veen, T. Winchen

1 - Calibrating the absolute amplitude scale for air showers measured at LOFAR,
A. Nelles et al., JINST 009 (2015) 0815

2 - 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

3 - 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

4 - The shape of the radio wavefront of extensive air showers as measured with LOFAR
A. Corstanje et al., Astroparticle Physics 61 (2015) 22

5 - A parameterization for the radio emission of air showers as predicted by CoREAS simulations and applied to LOFAR measurements
A. Nelles et al., Astroparticle Physics 60 (2015) 13

6 - 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

7 - Influence of atmospheric electric fields on the radio emission from extensive air showers
T.N.G. Trinh et al., Physical Review D 93 (2016) 023003

8 - Measurement of the cosmic-ray energy spectrum above 1016 eV with the LOFAR Radboud Air Shower Array,
S. Thoudam et al., Astroparticle Physics 73 (2016) 34

9 - Radio detections of cosmic rays reveal a strong light mass component at 10^{17} - $10^{17.5}$ eV
S. Buitink et al., Nature 531 (2016), 70-73

10 - Timing calibration and spectral cleaning of LOFAR time series data
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A very long title