

High-energy cosmic rays at LOFAR.

Olaf Scholten



LORA Scintillator



university of
 groningen

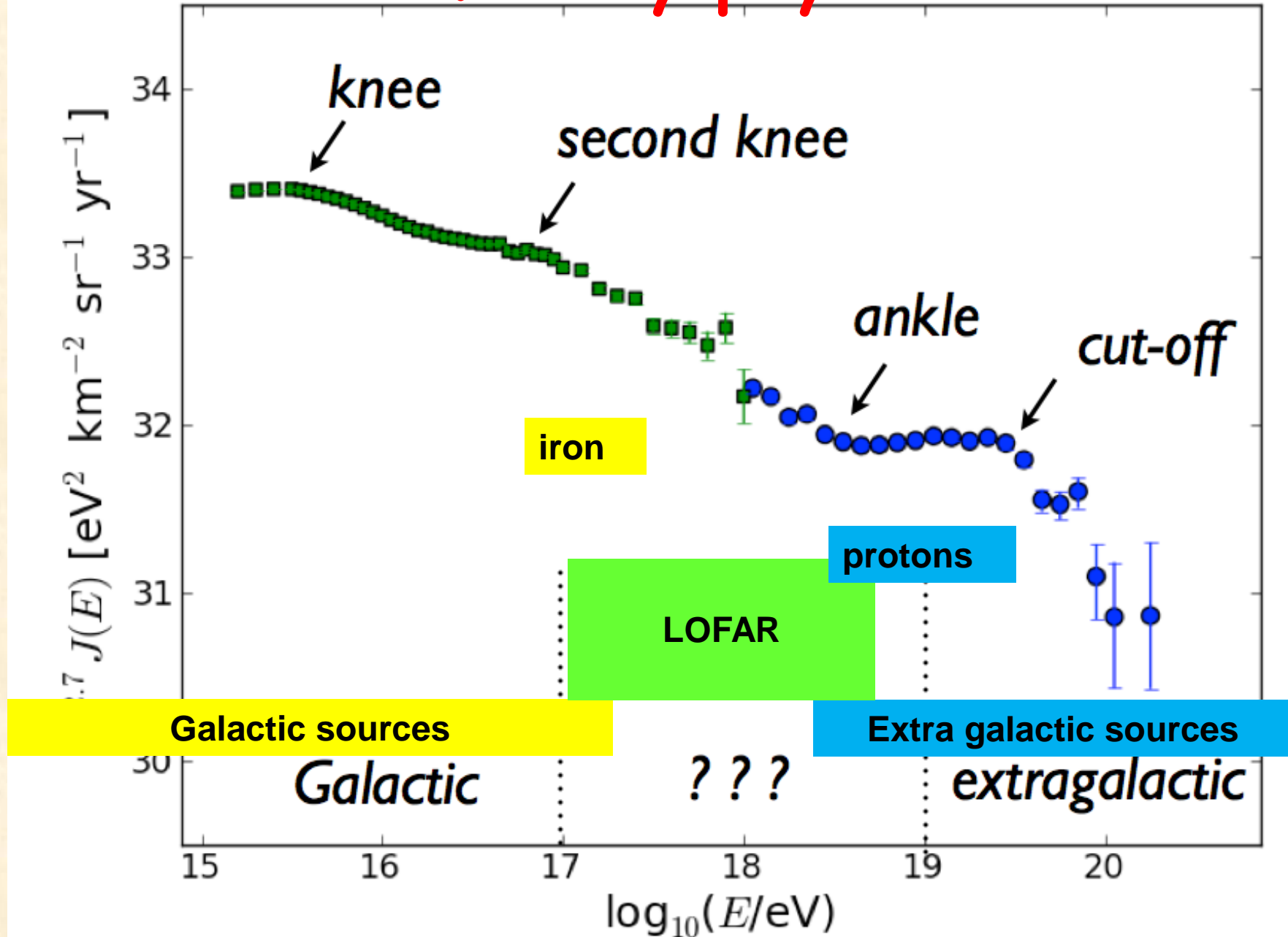
kvi - center for advanced
 radiation technology

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:



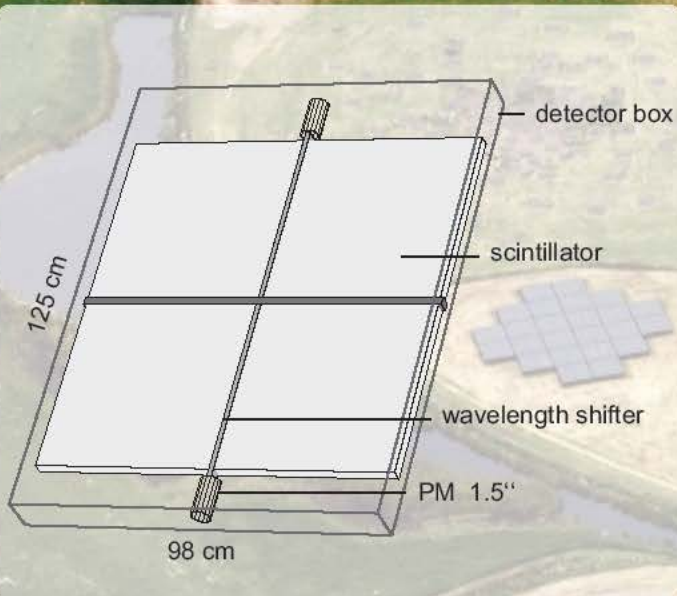
Presentation
by
Stijn Buitink

LOFAR Radboud Air Shower Array - LORA

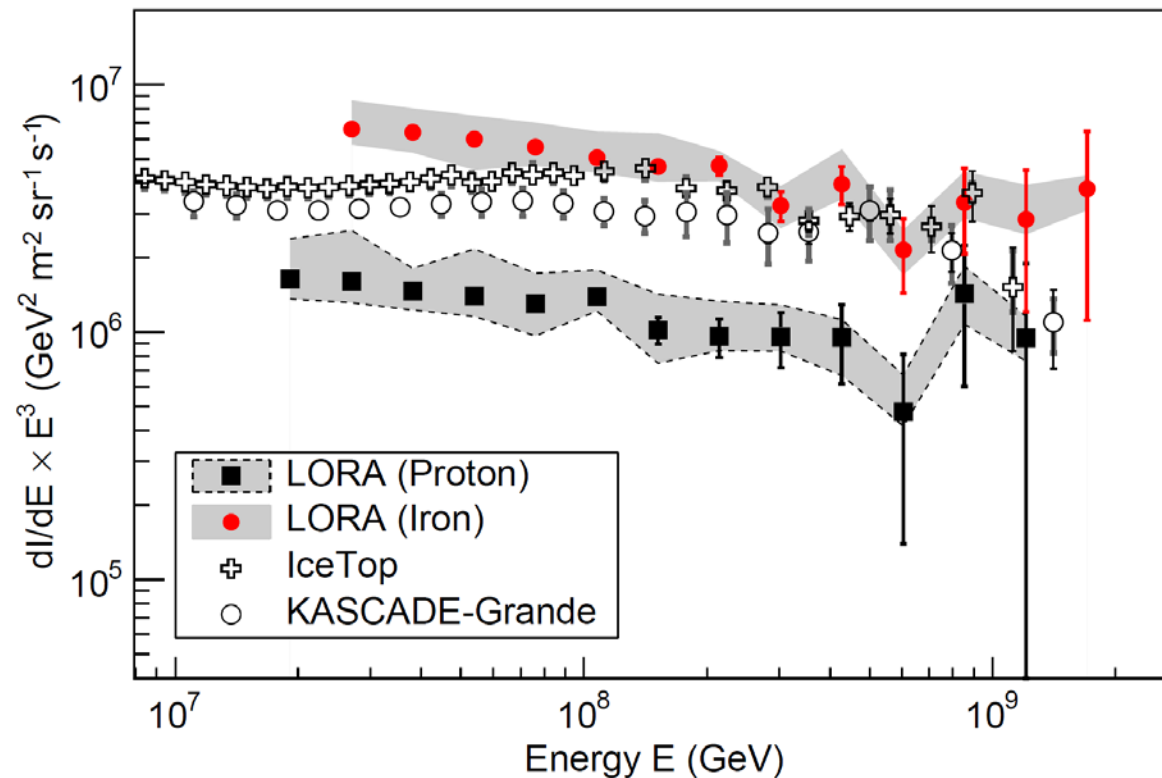
20 scintillator units
($\sim 1 \text{ m}^2$ each)
in LOFAR core

→ provide

- properties of EAS
- and trigger



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

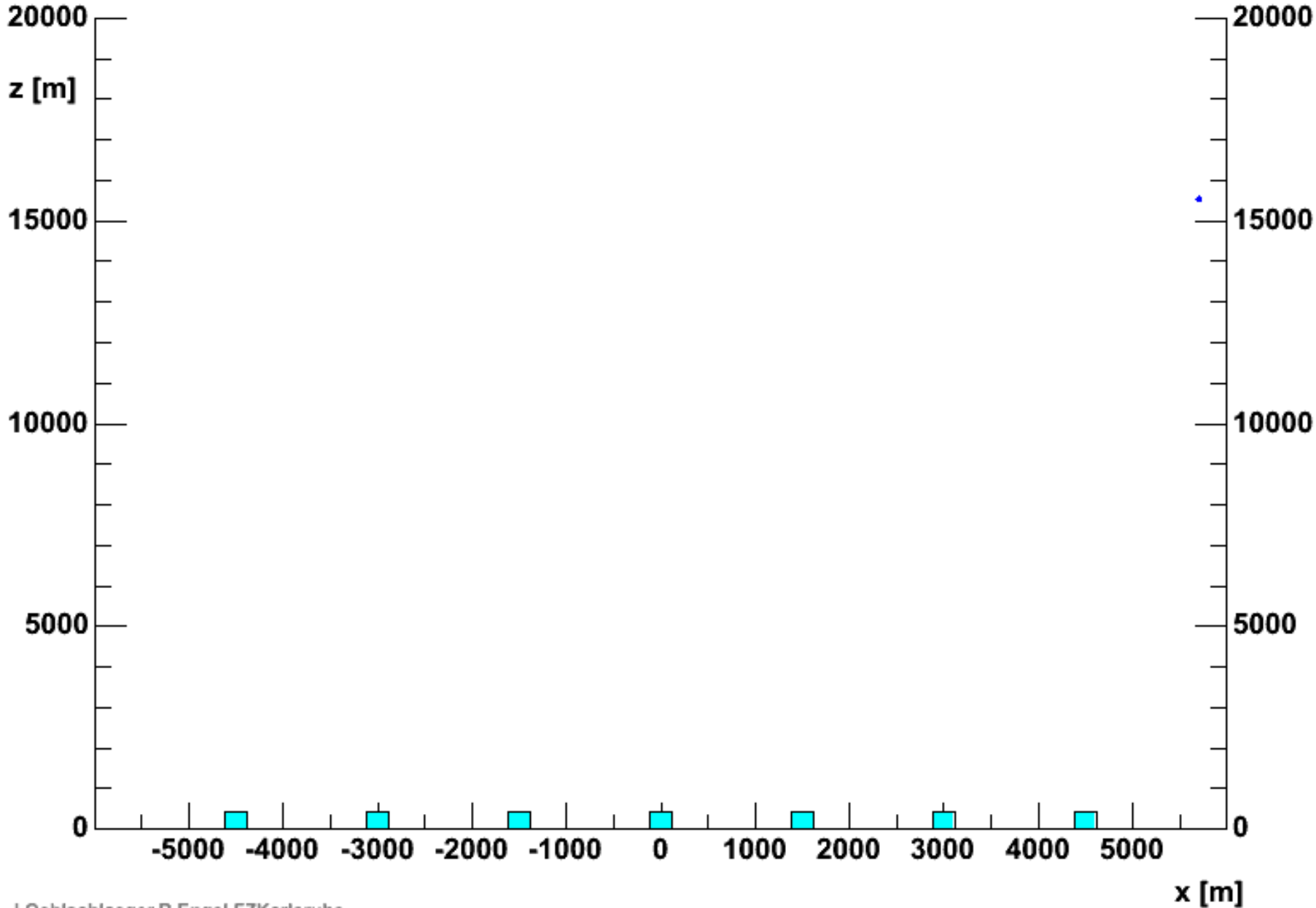


hadrons muons electrs neutrns

Proton 10^{15} eV

15514

Air shower,
side view



Multiple emission mechanisms

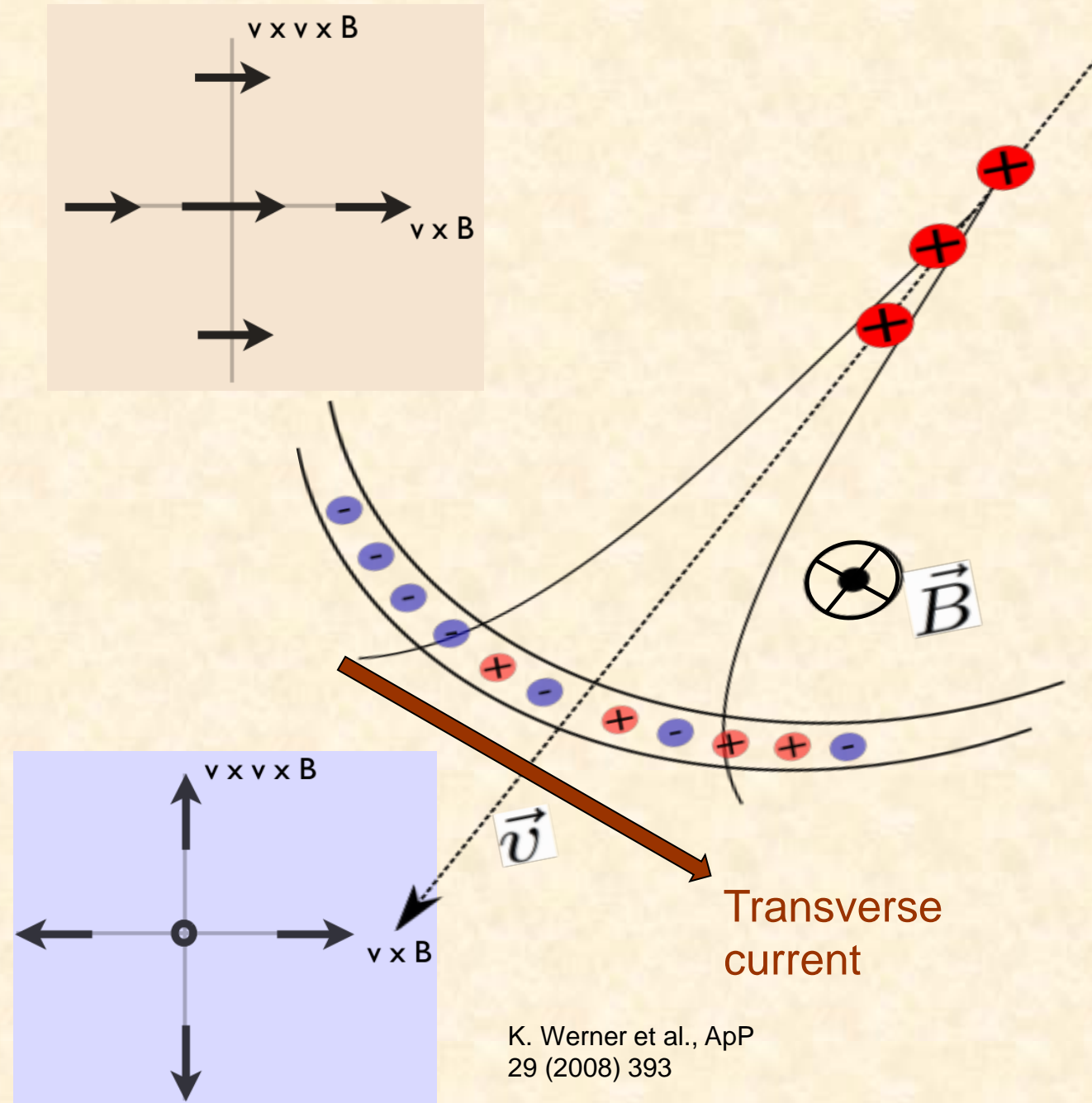
Geomagnetic:

- Electrons & positrons have transverse drift, induced by geomagnetic field.
- Linearly polarized, Unidirectional along $\mathbf{v} \times \mathbf{B}$

Charge excess:

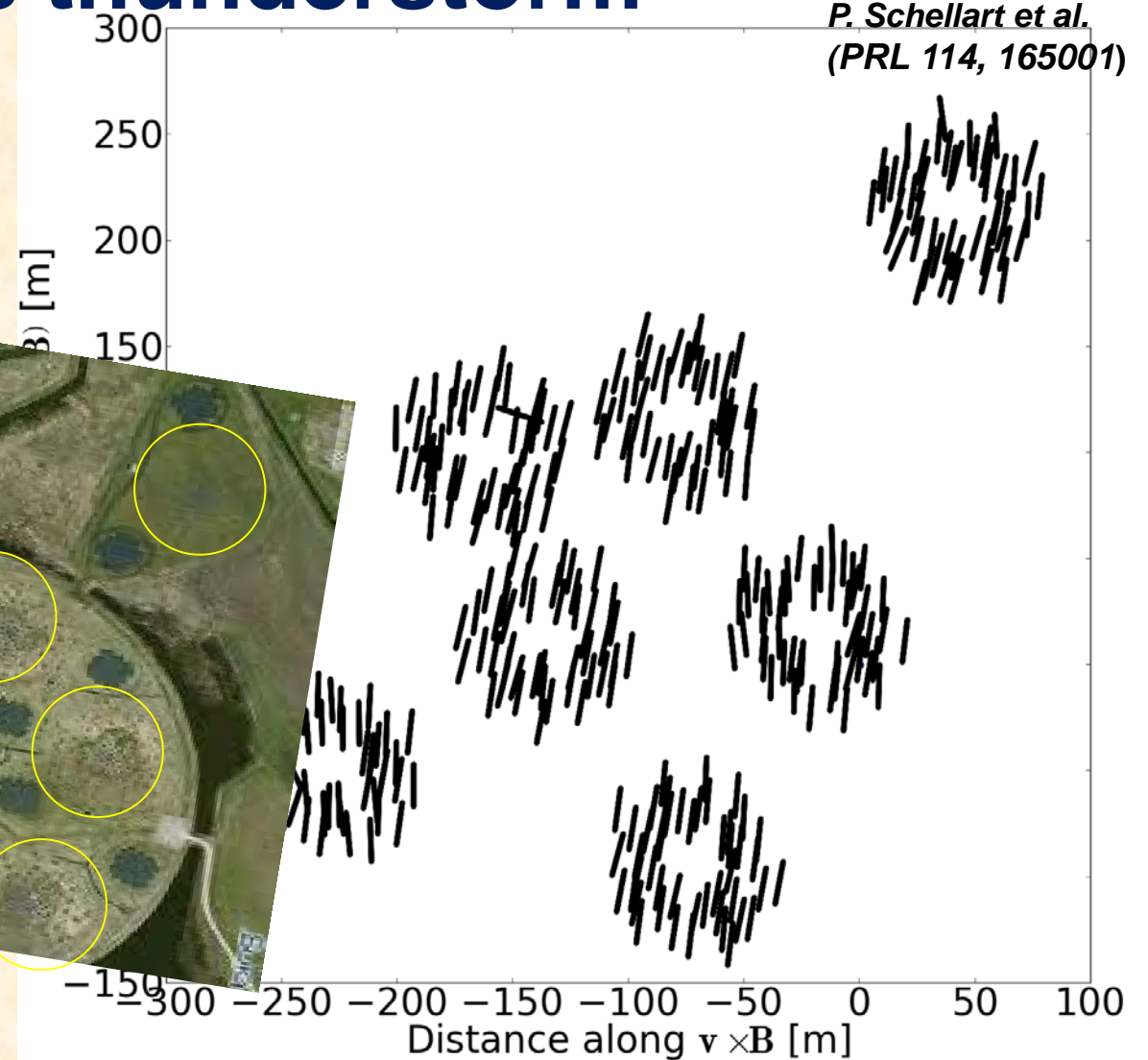
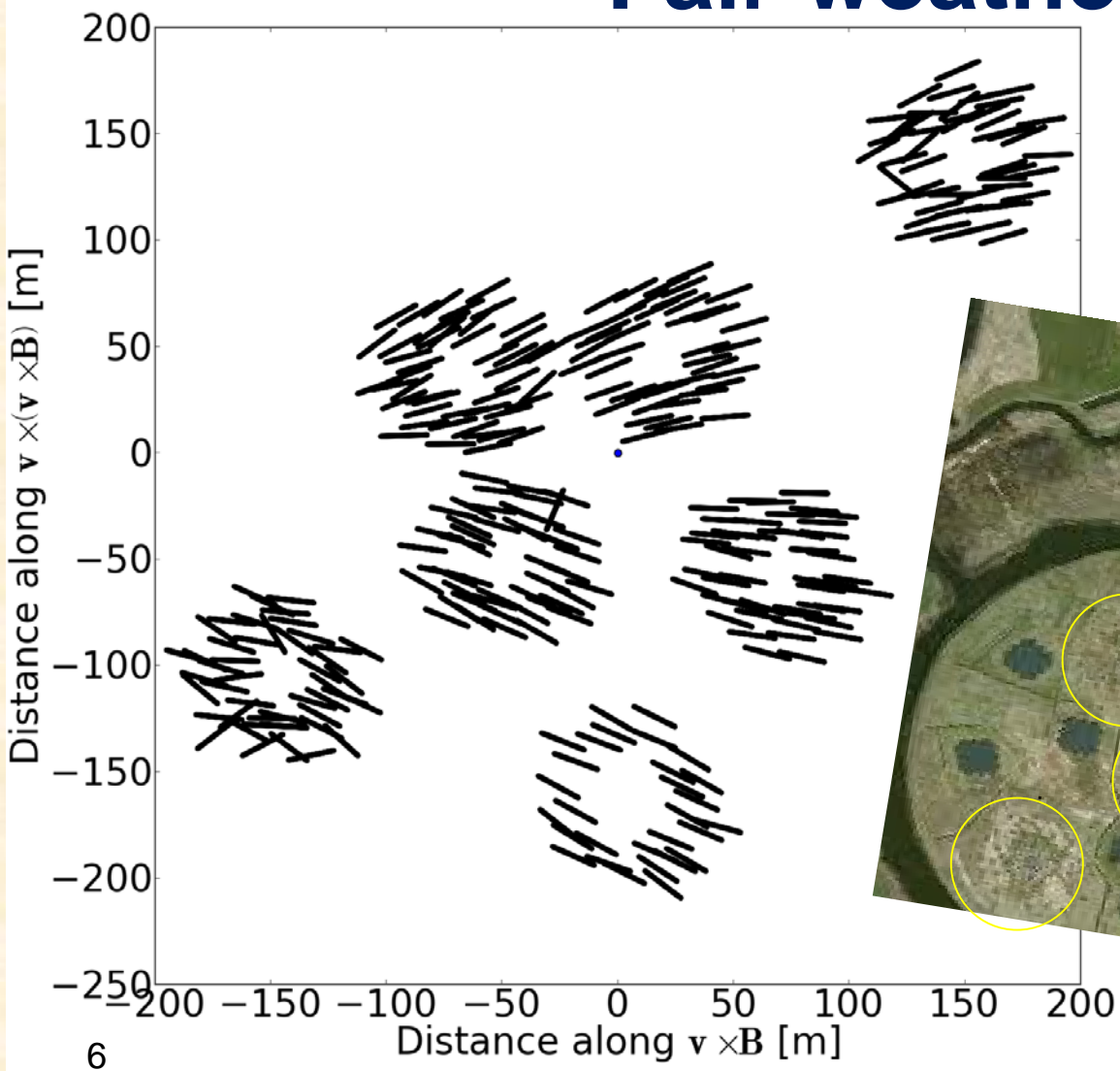
- Negative charge buildup at shower front.
- Linearly polarized, Radially from shower axis

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



Observations: polarization footprint

Fair weather vs thunderstorm

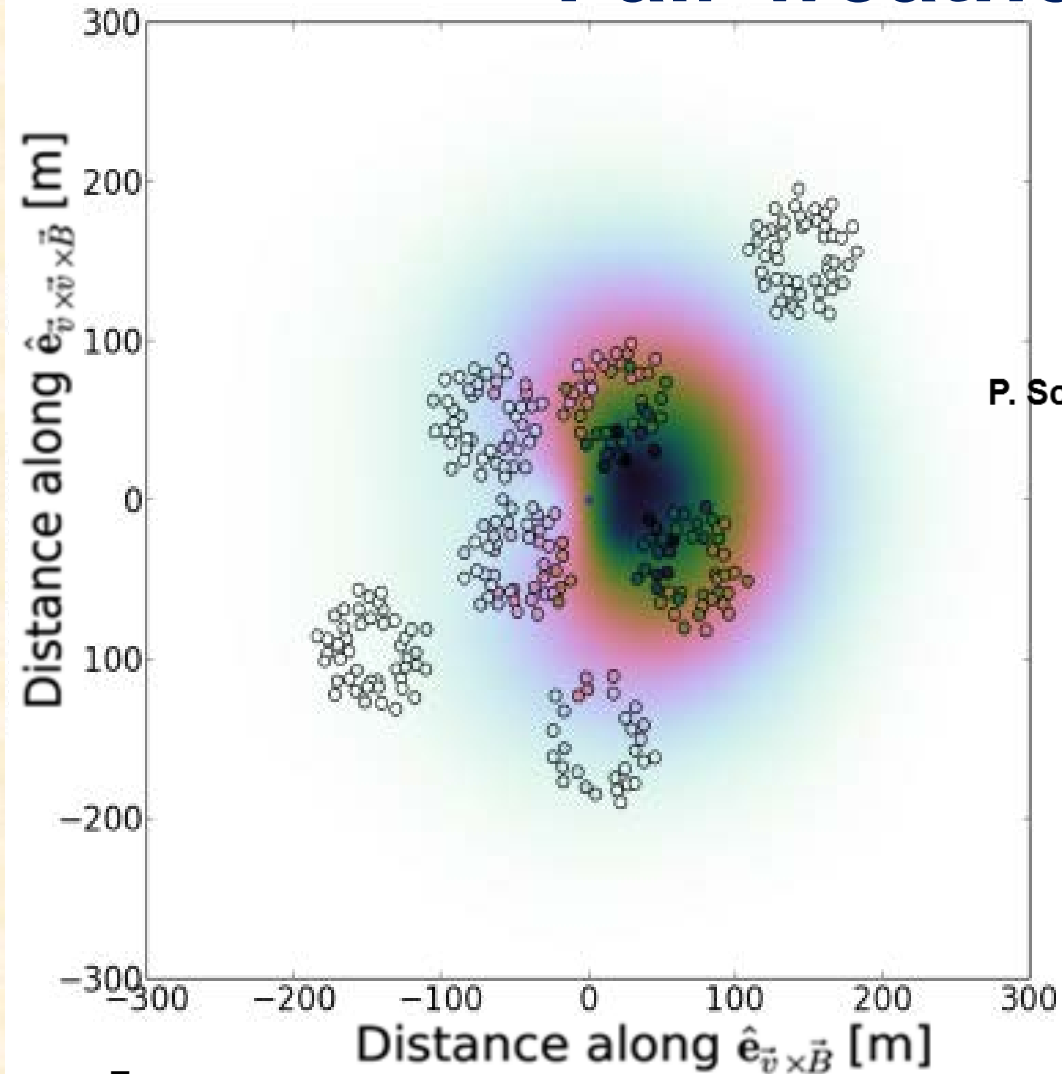


Observations; intensity footprint

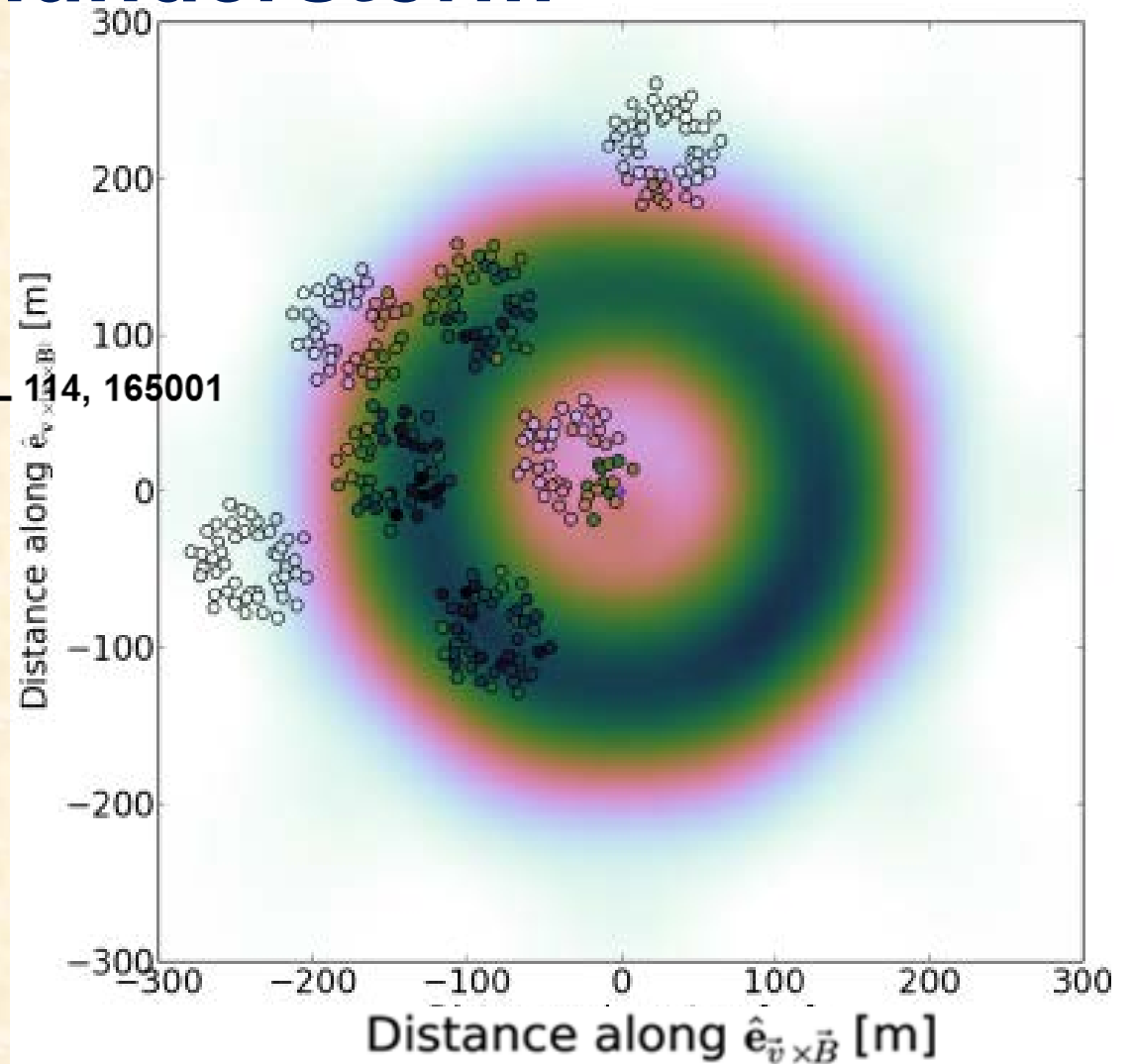
S. Buitink et al.
PRD 90, 082003 (2014)

Fair weather vs thunderstorm

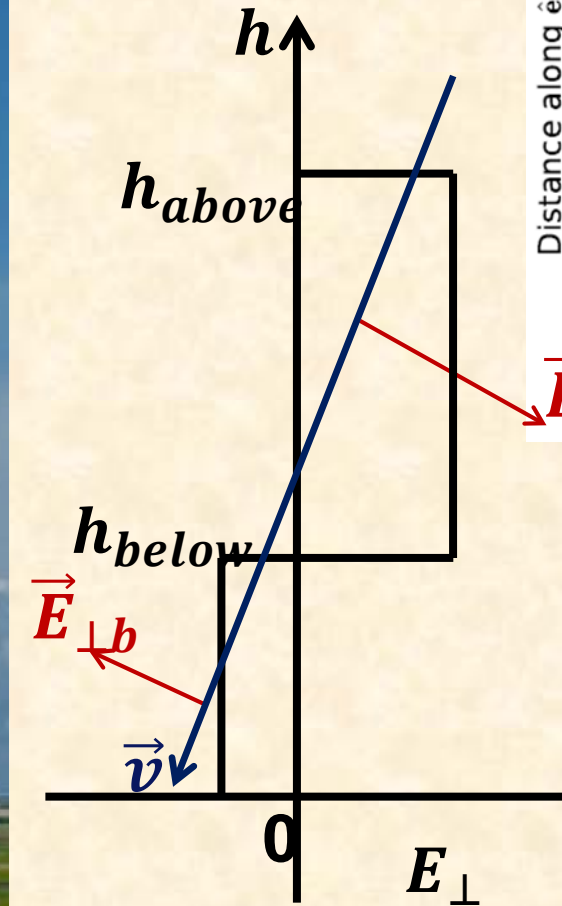
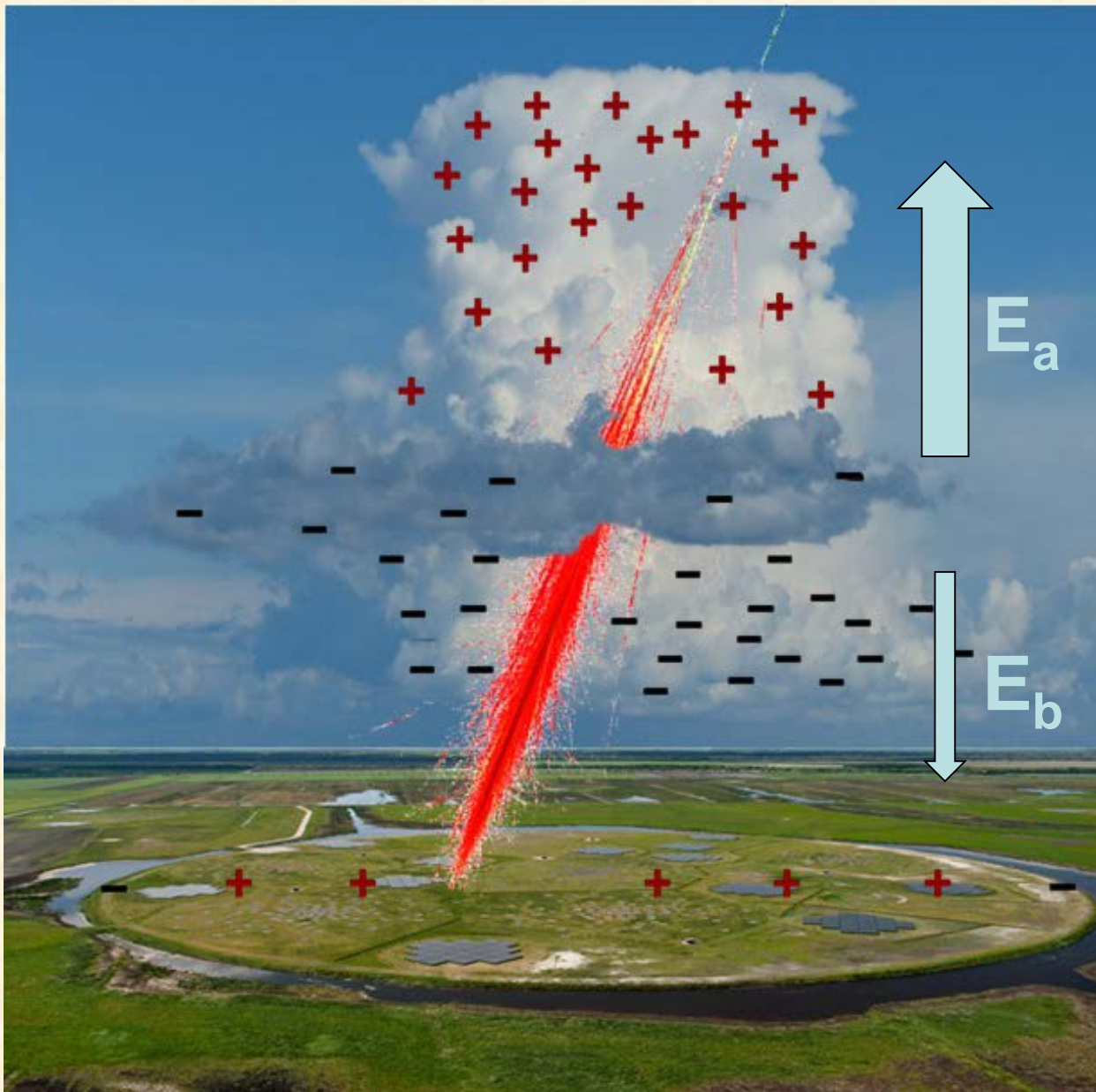
P. Schellart et al.,
PRL 114, 165001 (2015)



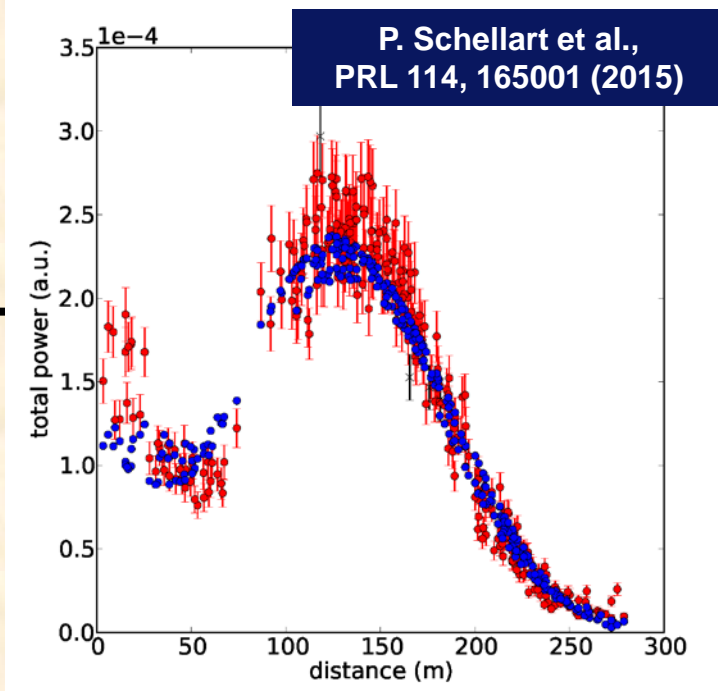
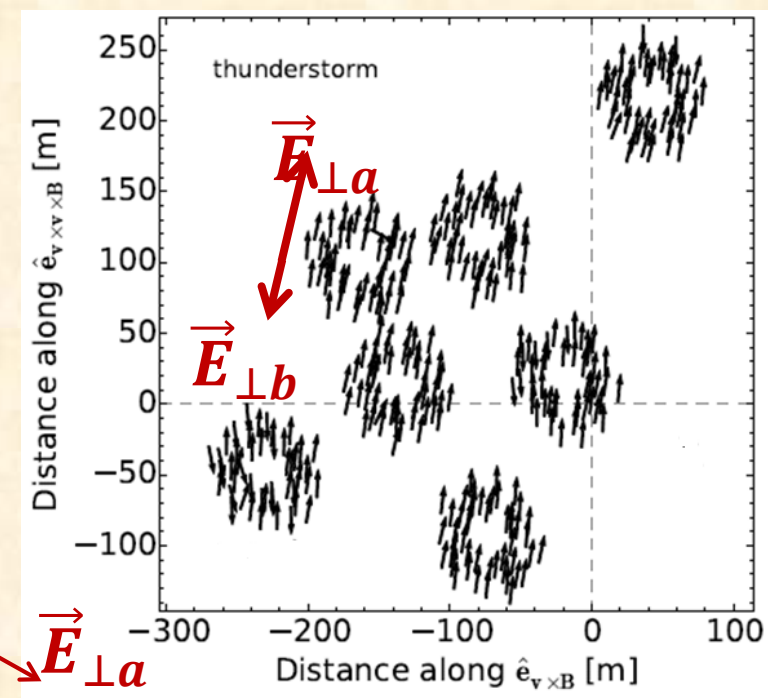
P. Schellart et al., PRL 114, 165001



Structure E-fields



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



Full polarization, Stokes

$$I = \frac{1}{n} \sum_0^{n-1} \left(|\mathcal{E}|_{i, \vec{v} \times \vec{B}}^2 + |\mathcal{E}|_{i, \vec{v} \times \vec{v} \times \vec{B}}^2 \right)$$

$$Q = \frac{1}{n} \sum_0^{n-1} \left(|\mathcal{E}|_{i, \vec{v} \times \vec{B}}^2 - |\mathcal{E}|_{i, \vec{v} \times \vec{v} \times \vec{B}}^2 \right)$$

$$U + iV = \frac{2}{n} \sum_0^{n-1} \left(\mathcal{E}_{i, \vec{v} \times \vec{B}} \mathcal{E}_{i, \vec{v} \times \vec{v} \times \vec{B}}^* \right) .$$

Stokes parameters: I, Q, U, V

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

NEW: Circular polarization = V/I

Interesting results:

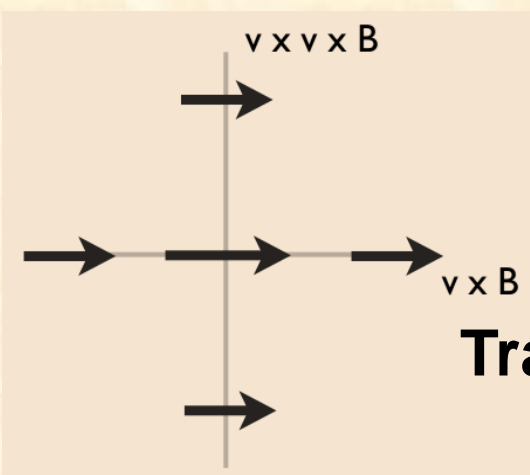
➤ **Fair weather:**

confirmation of emission mechanisms

➤ **Thunderstorm:**

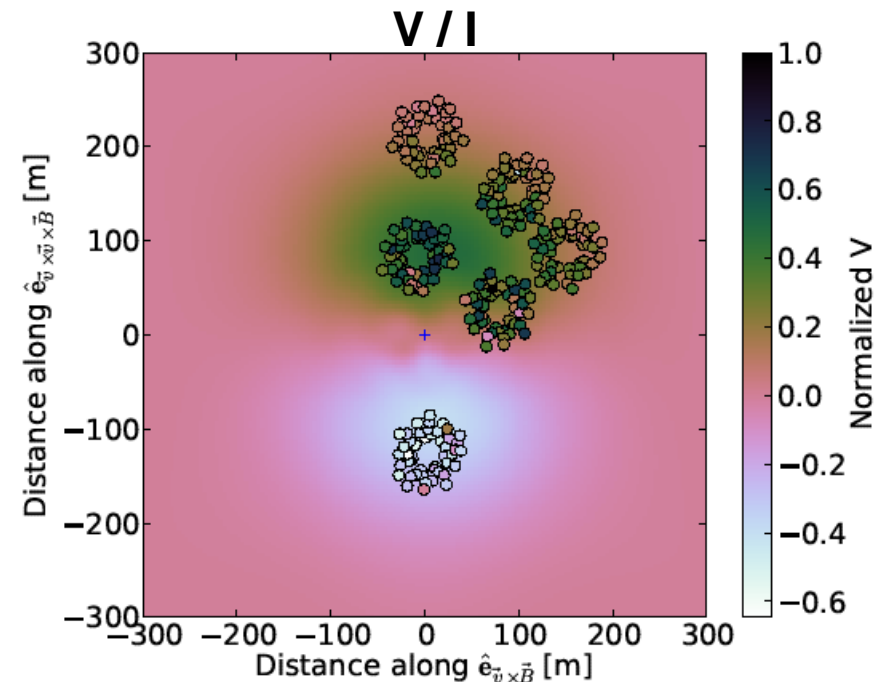
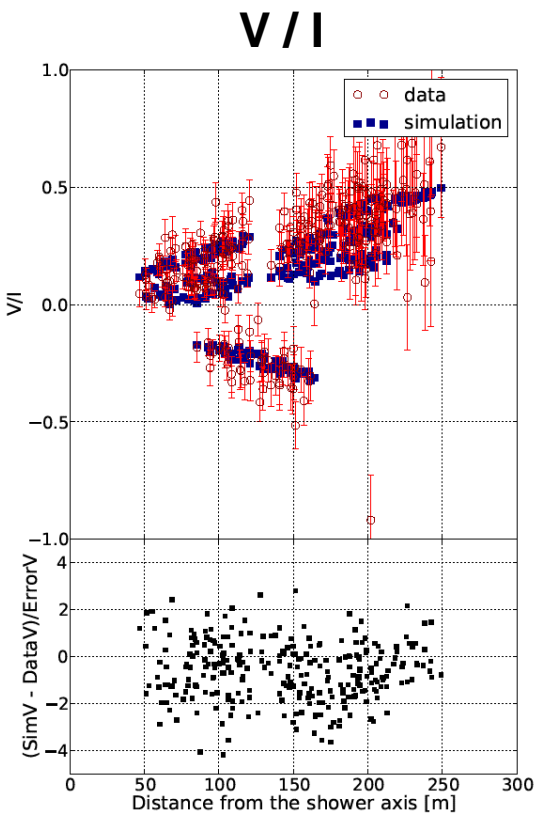
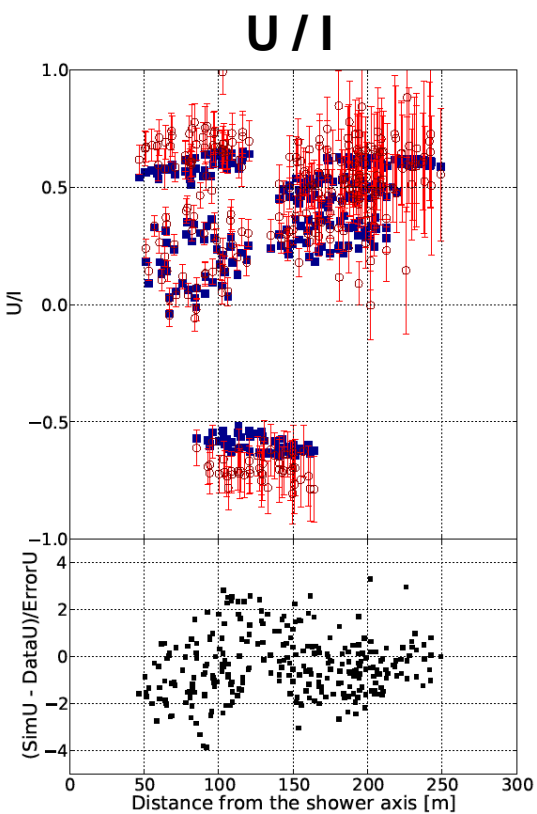
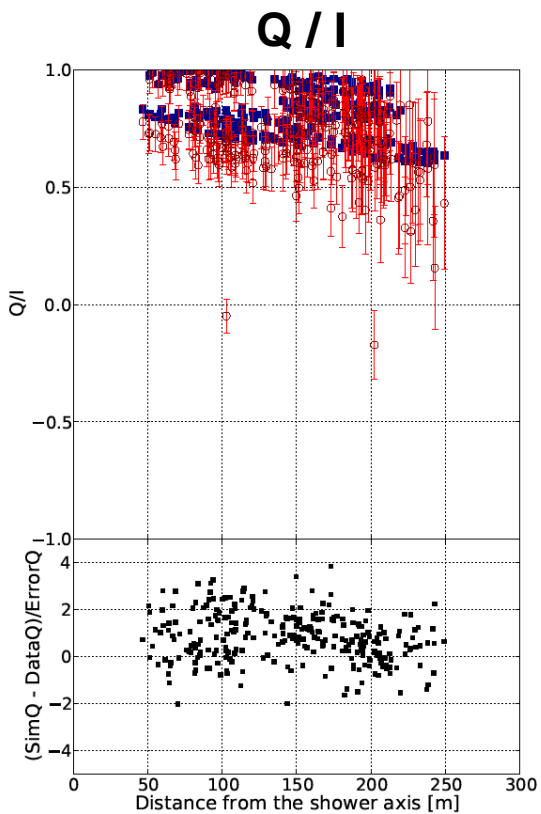
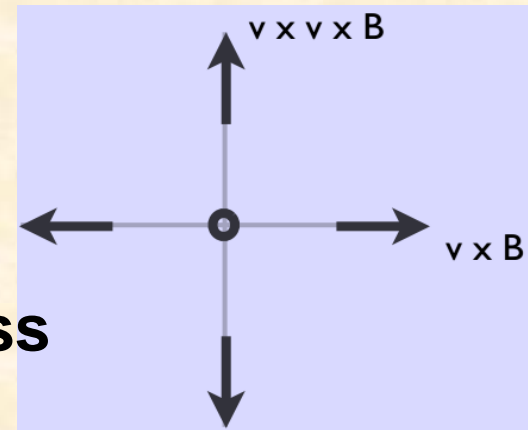
Finite circular pol. near core due to changing atmospheric E-field

Presentation
by
Gia Trinh



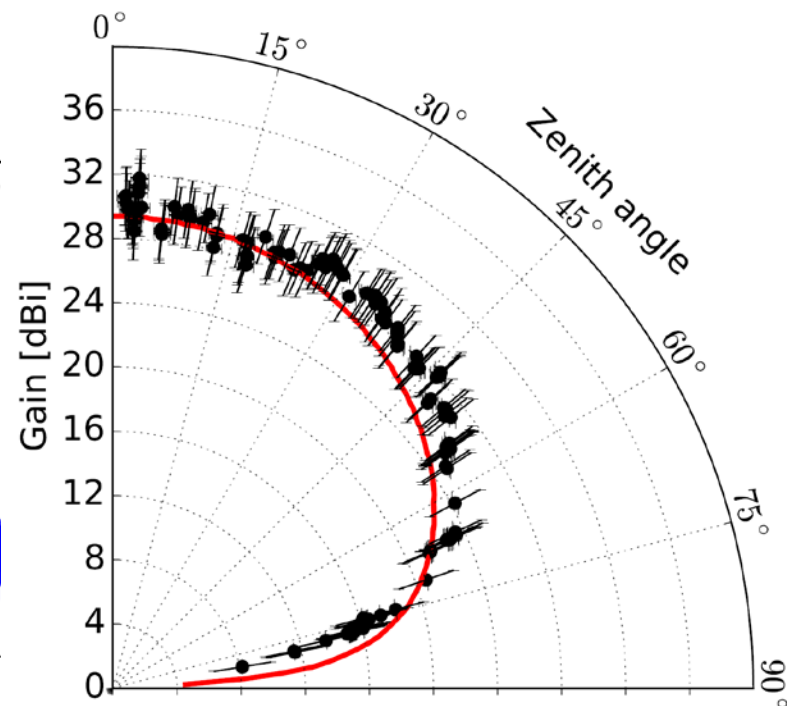
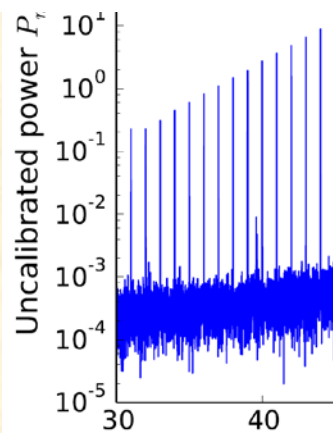
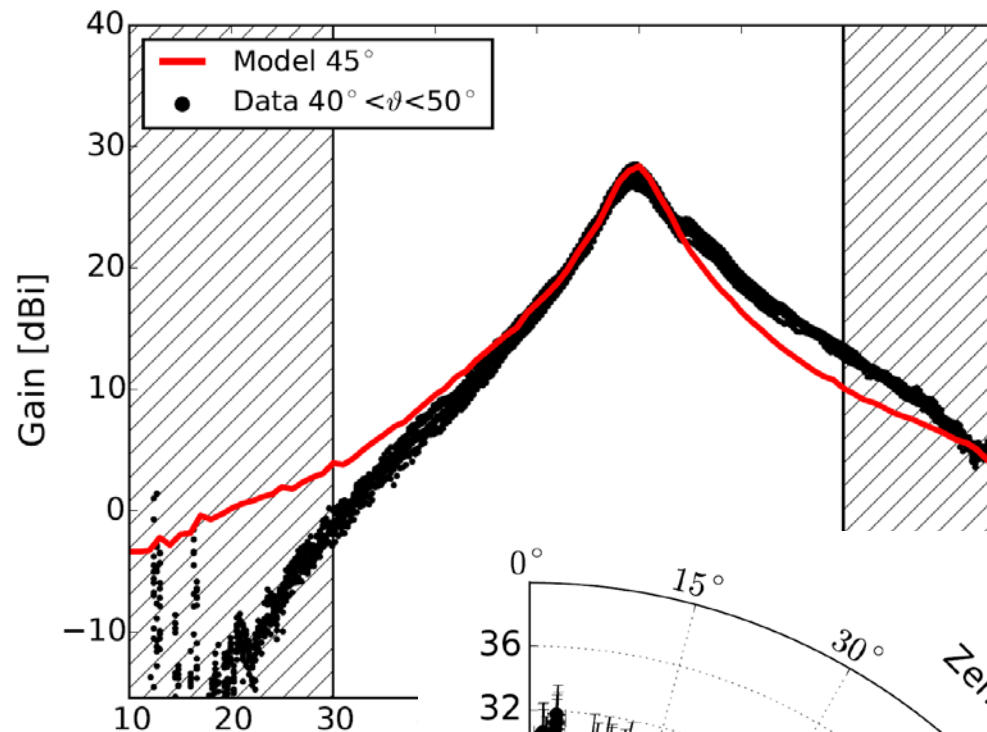
Reason for fair-weather circular polarization:

Transverse current is 1ns ahead of Charge excess pulse



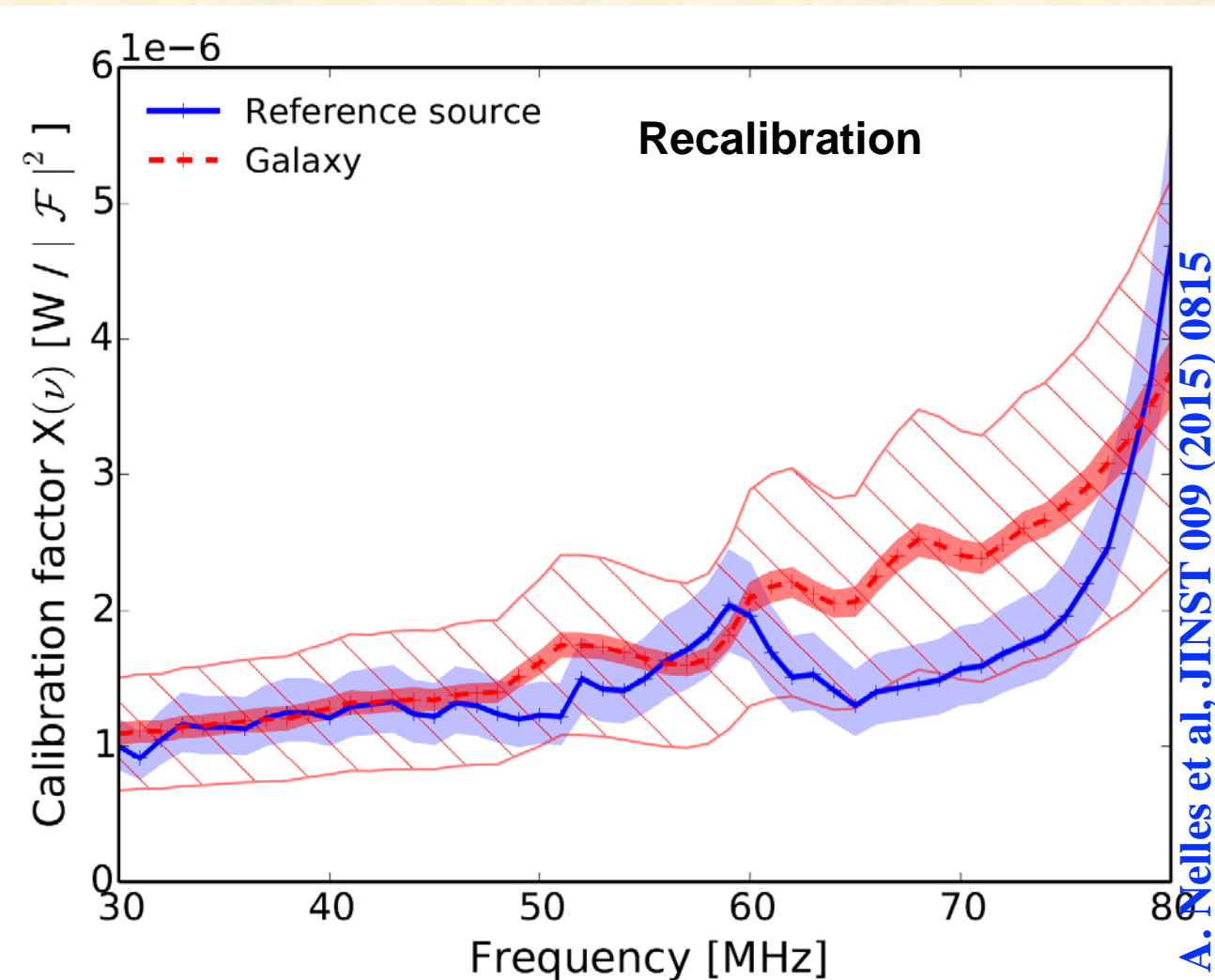
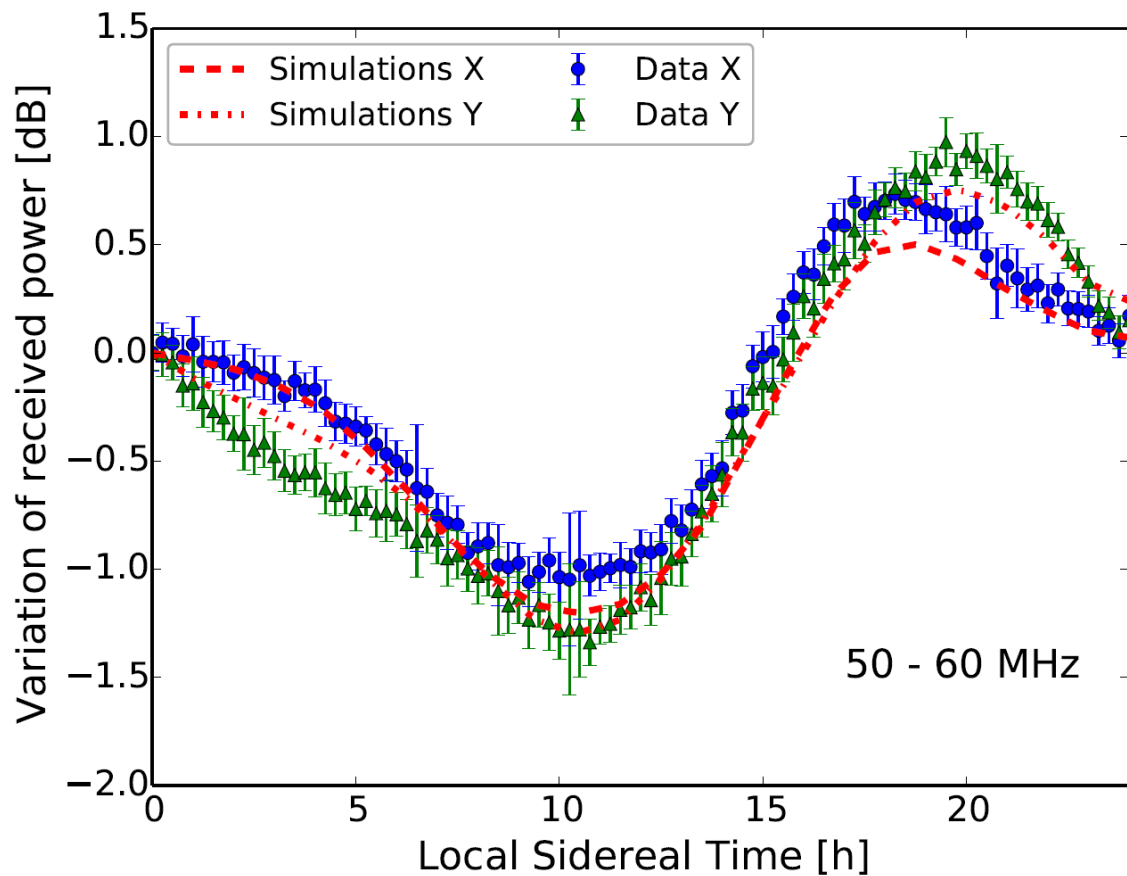
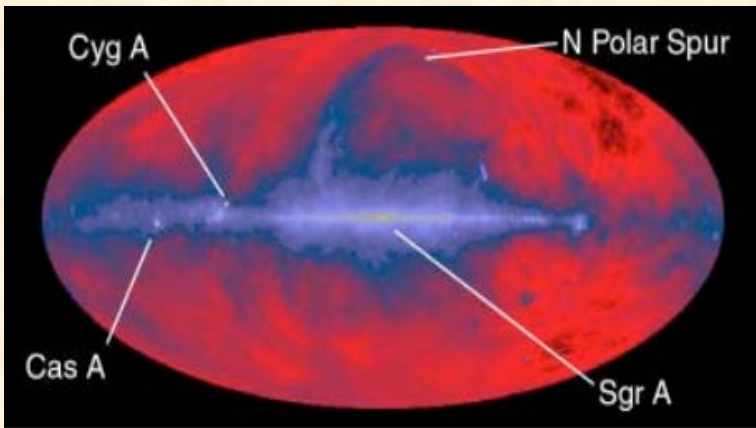


antenna calibration



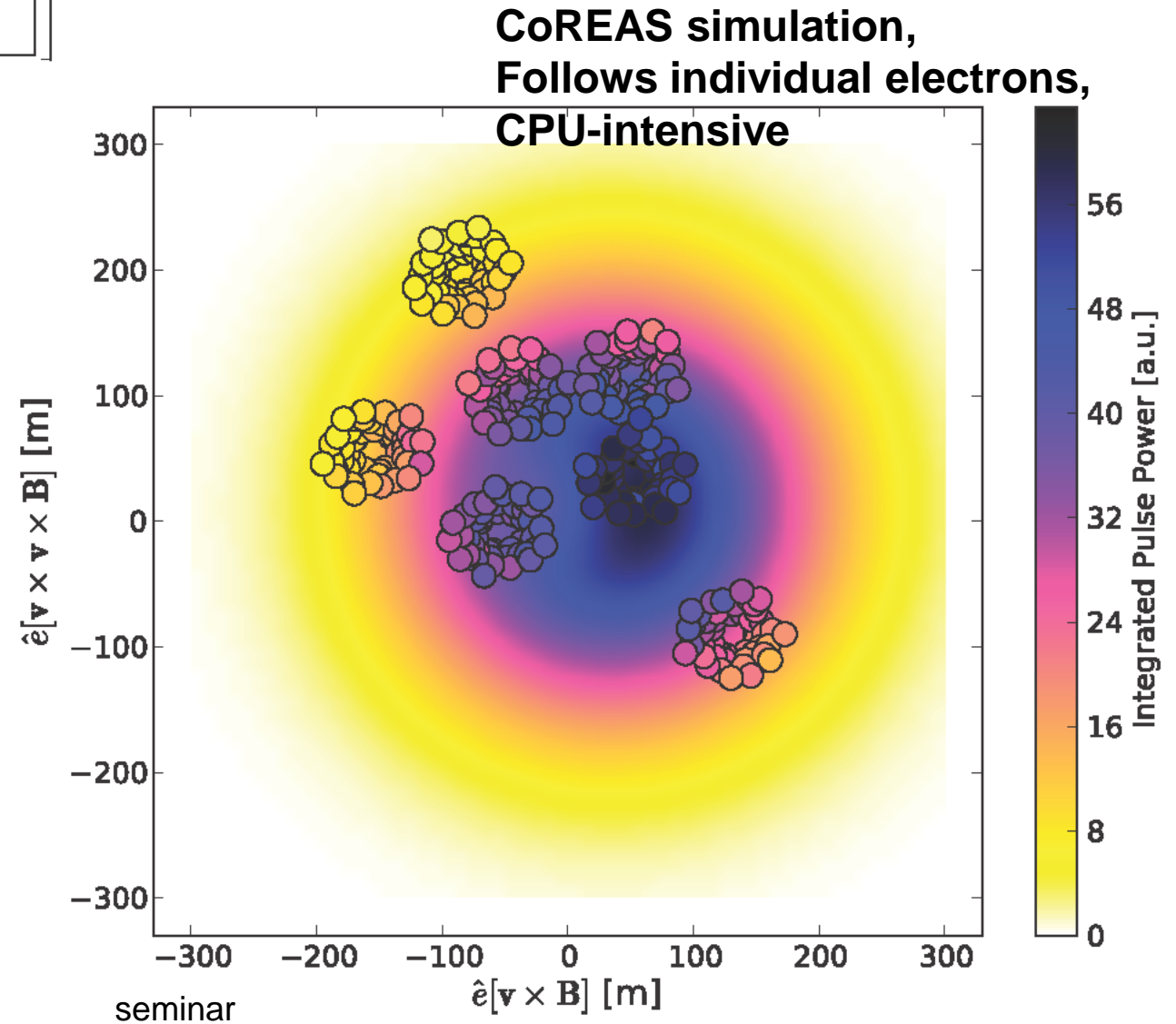
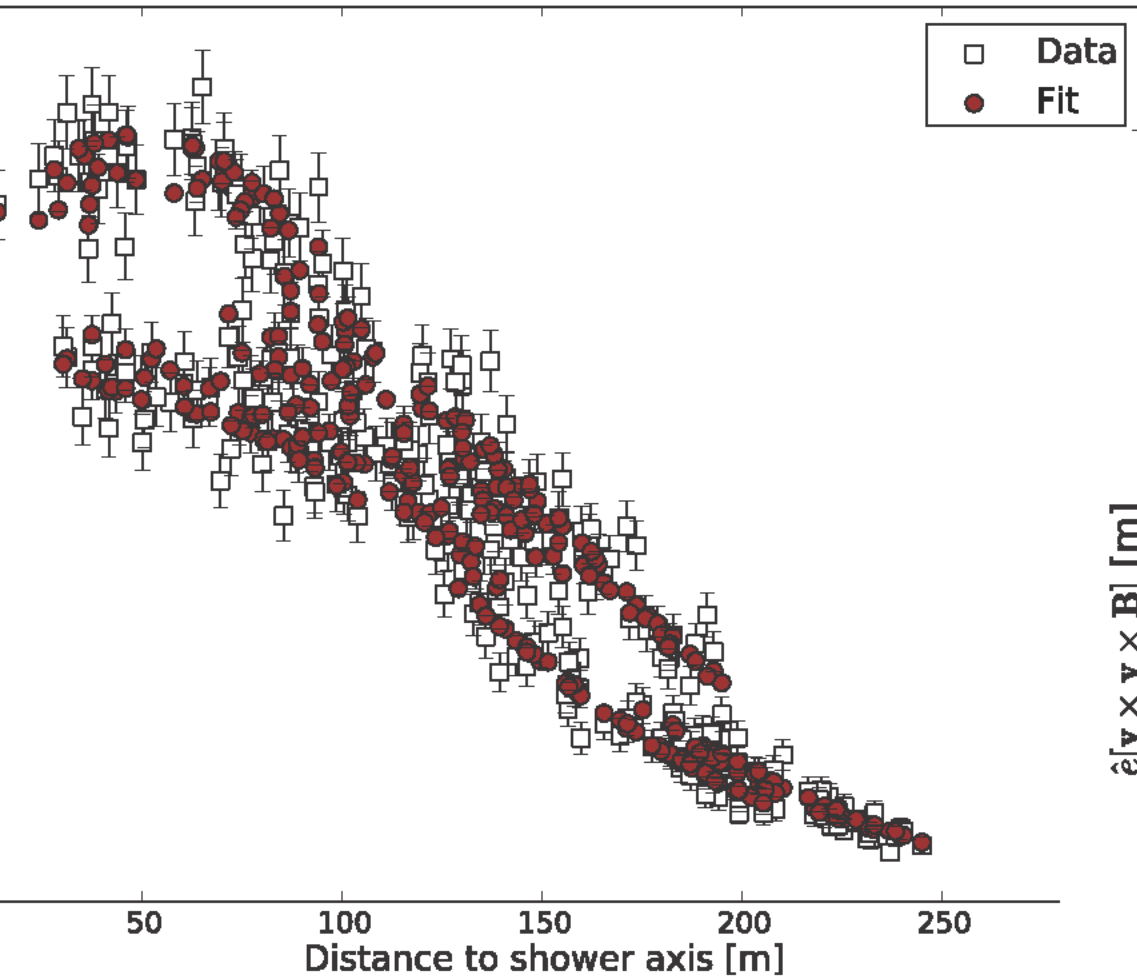
Gain of complete signal chain

Galactic background

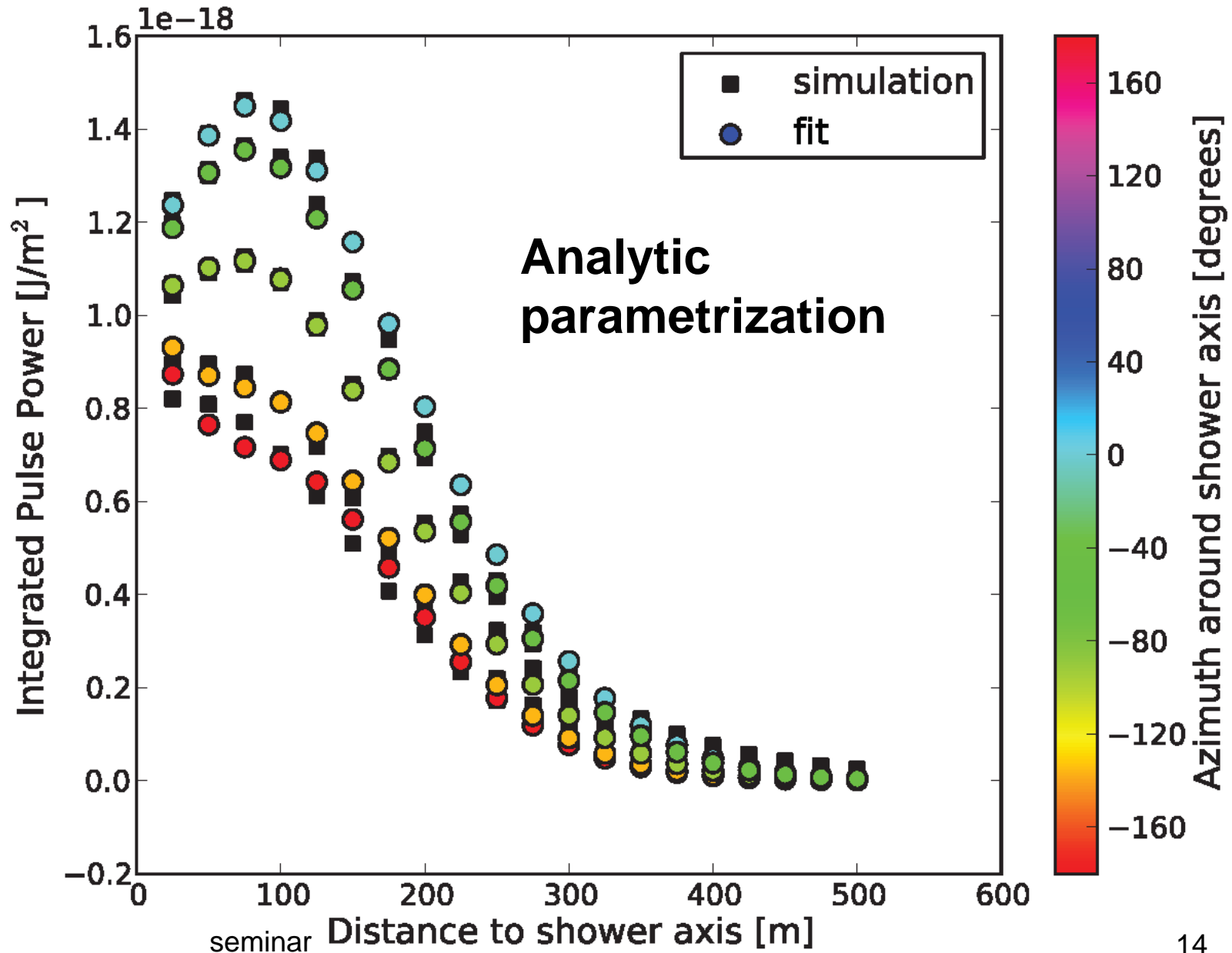
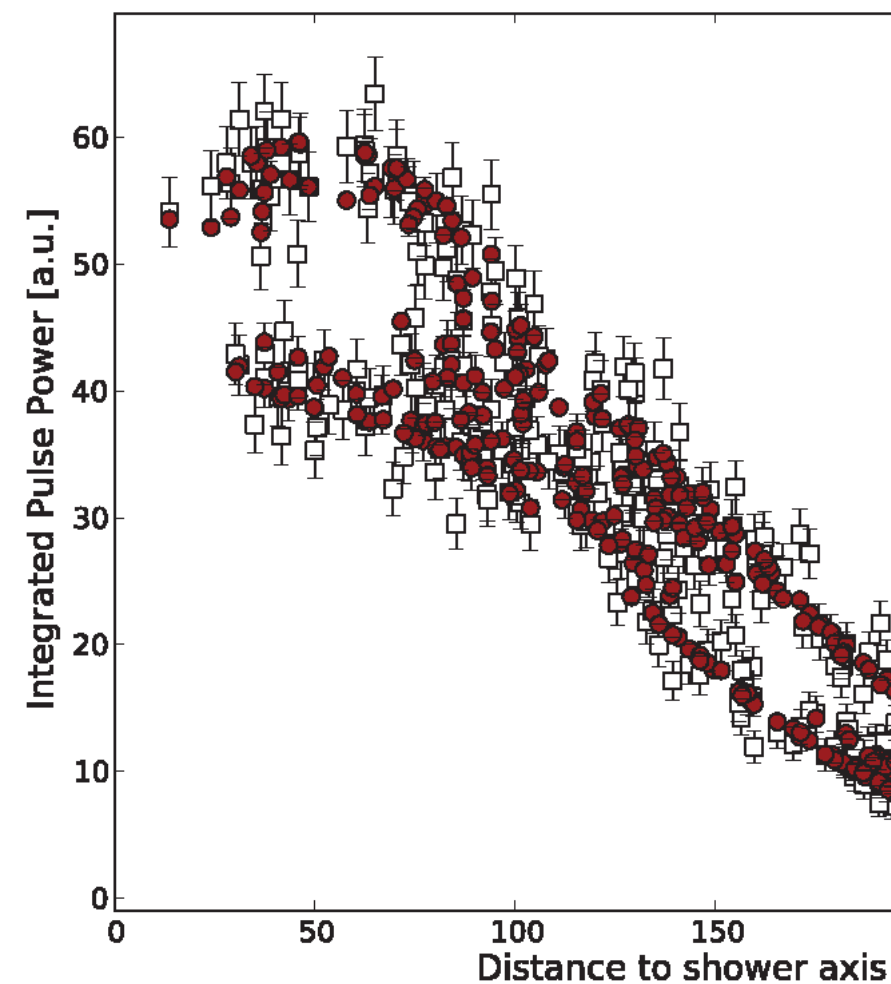


Lateral distribution of radio signals

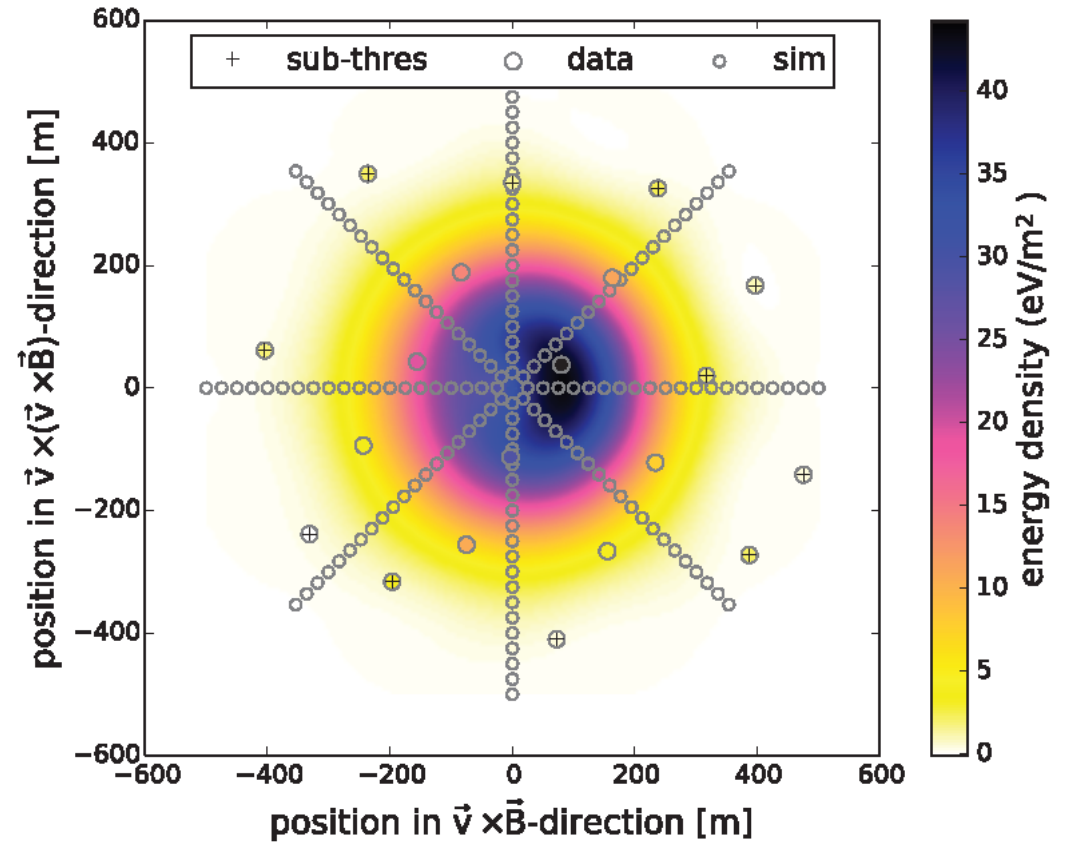
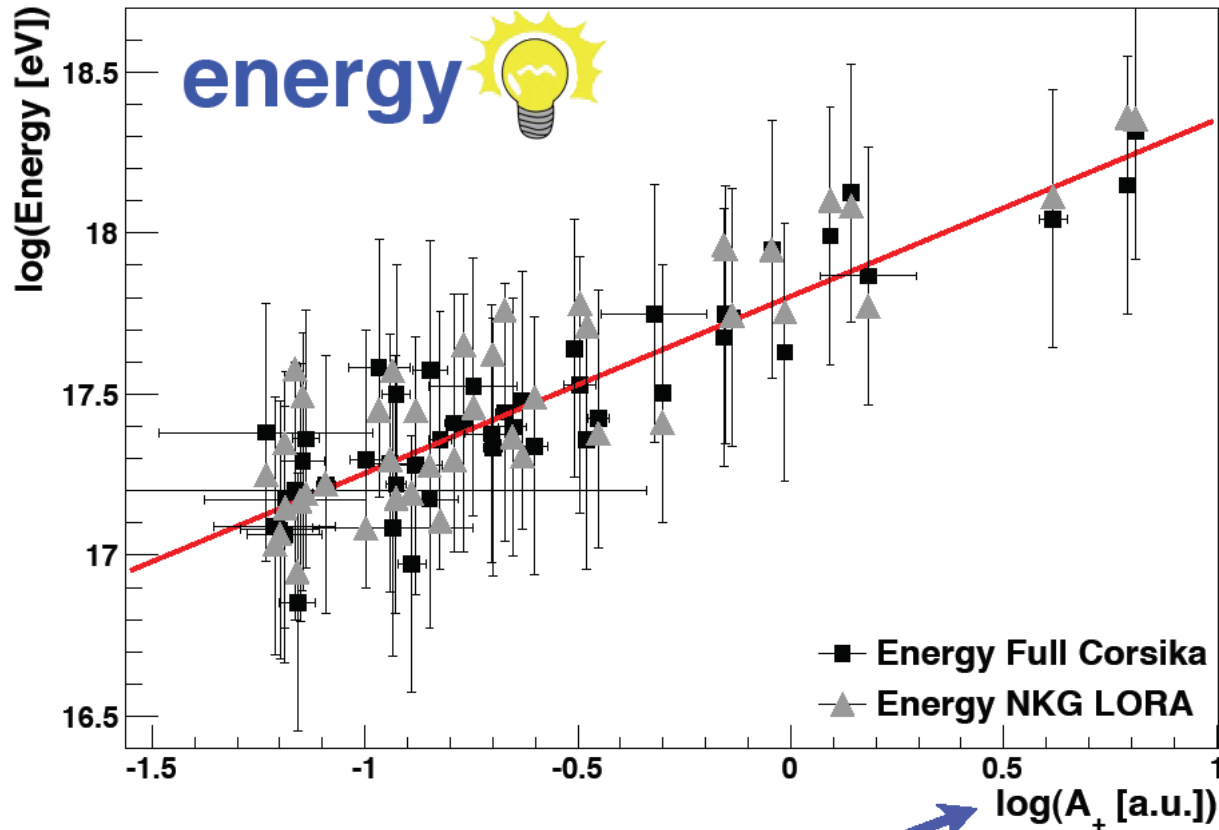
as measured by LOFAR



Lateral distribution of radio signals

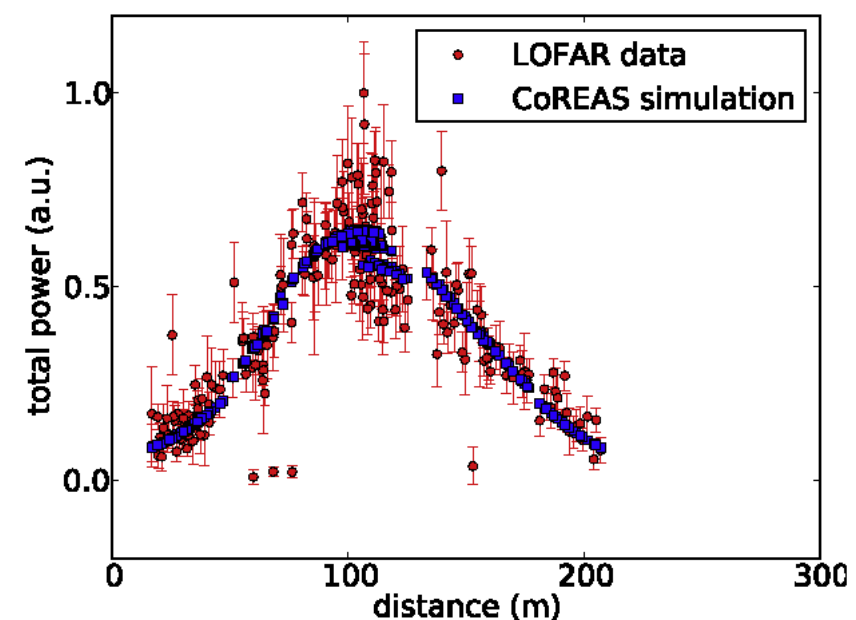
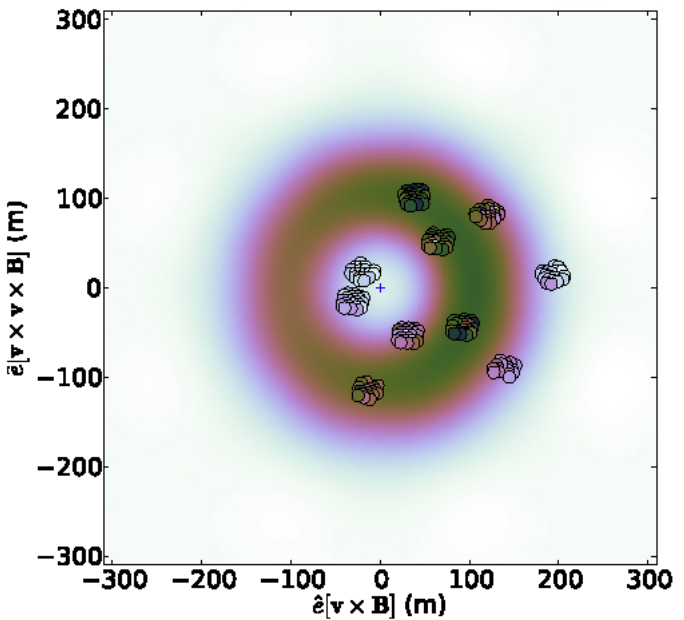
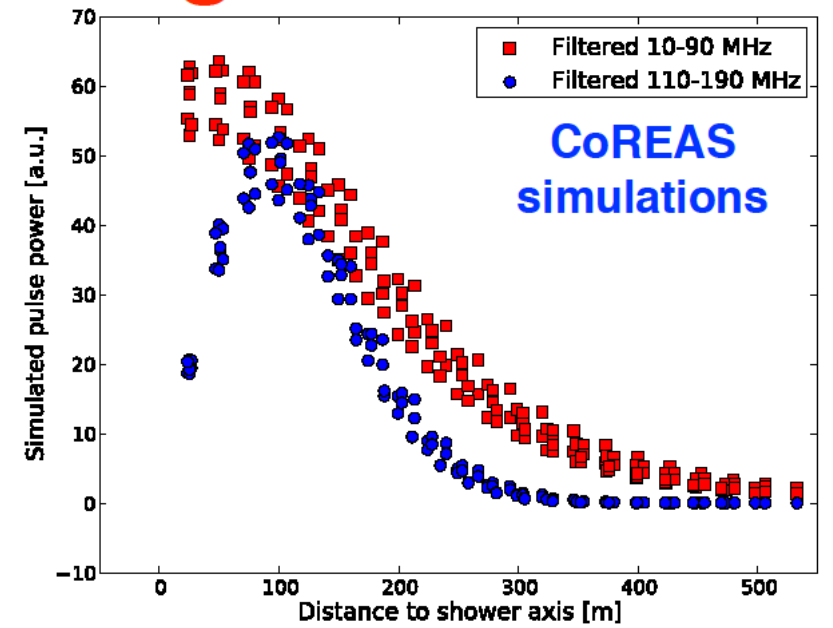
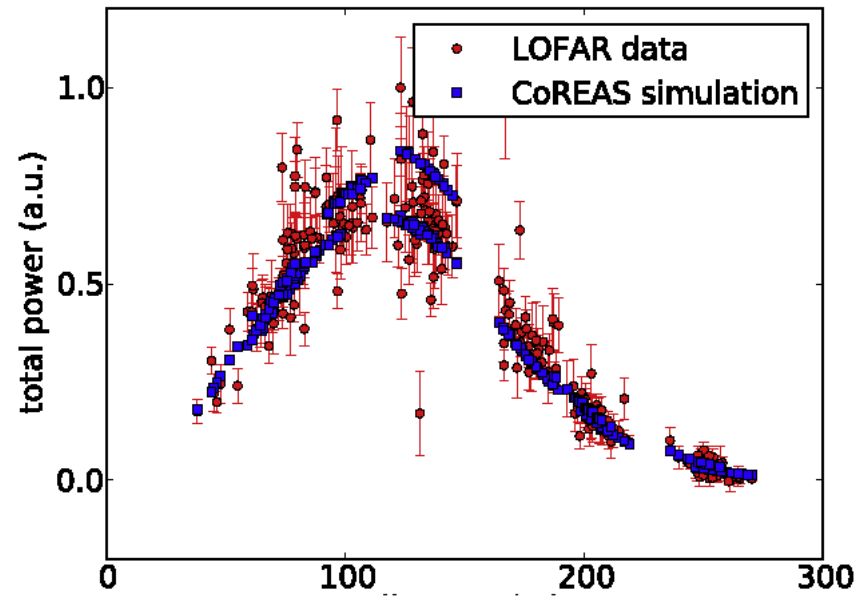
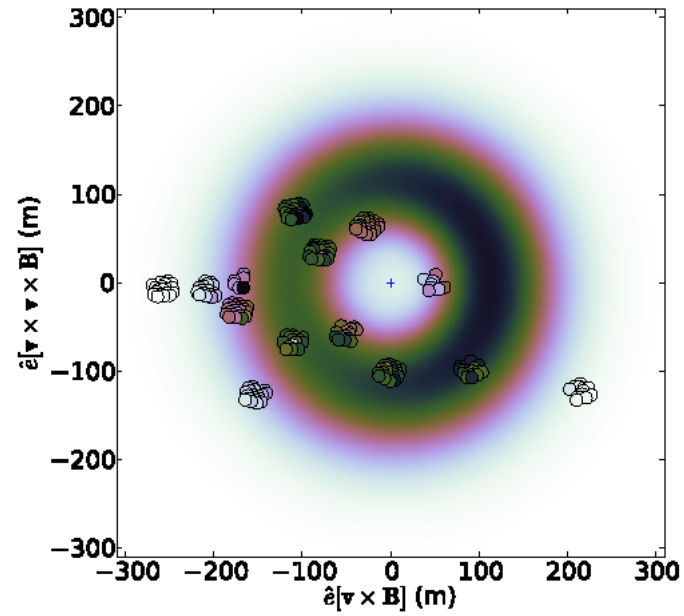


Properties of primary particle

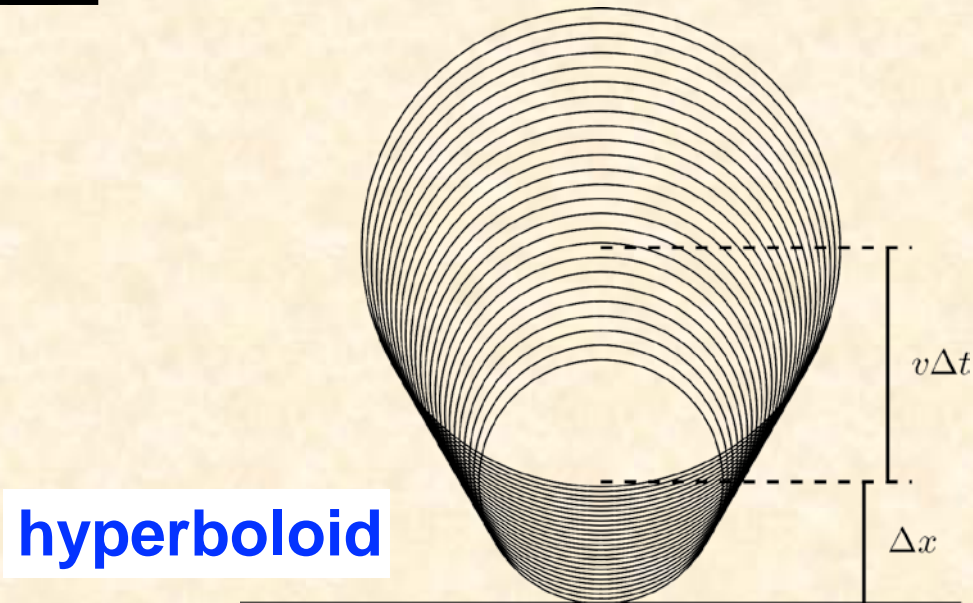
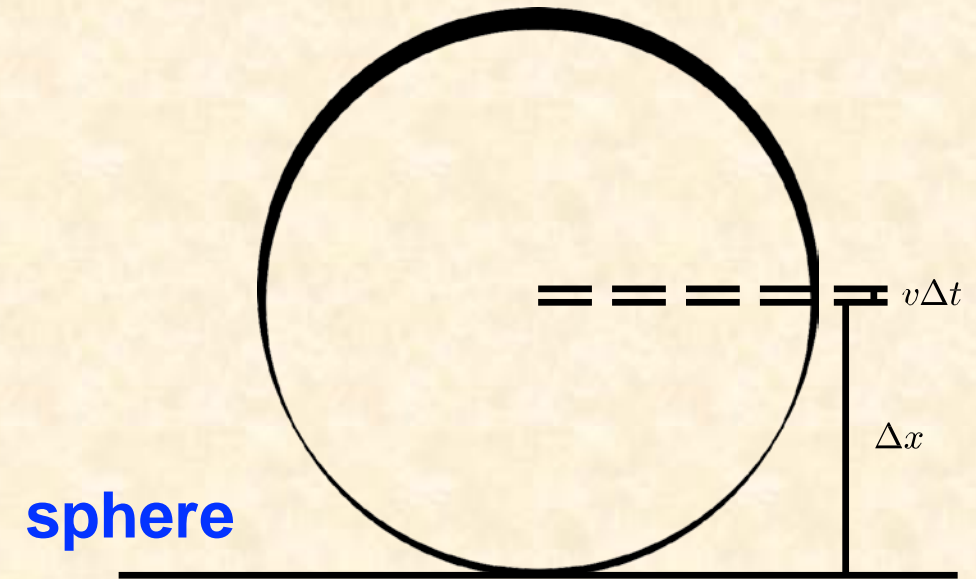
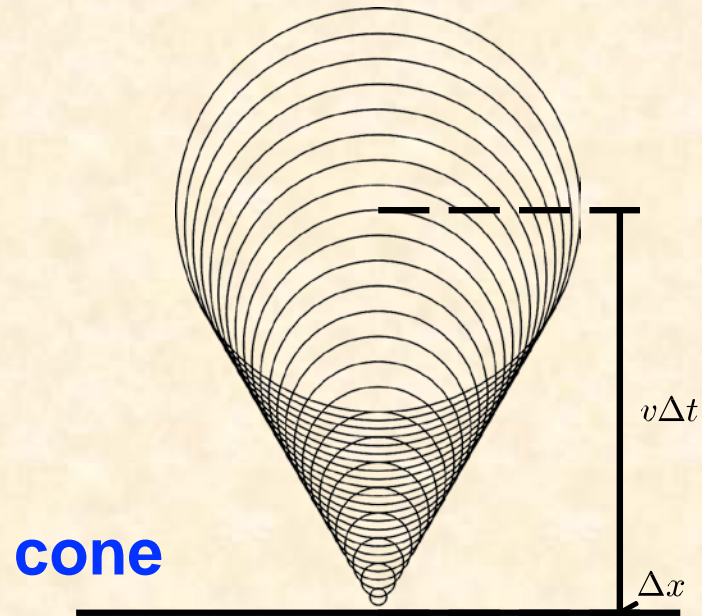


$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_+)^2 + (y' - Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x' - X_-)^2 + (y' - Y_-)^2]}{\sigma_-^2}\right) + O$$

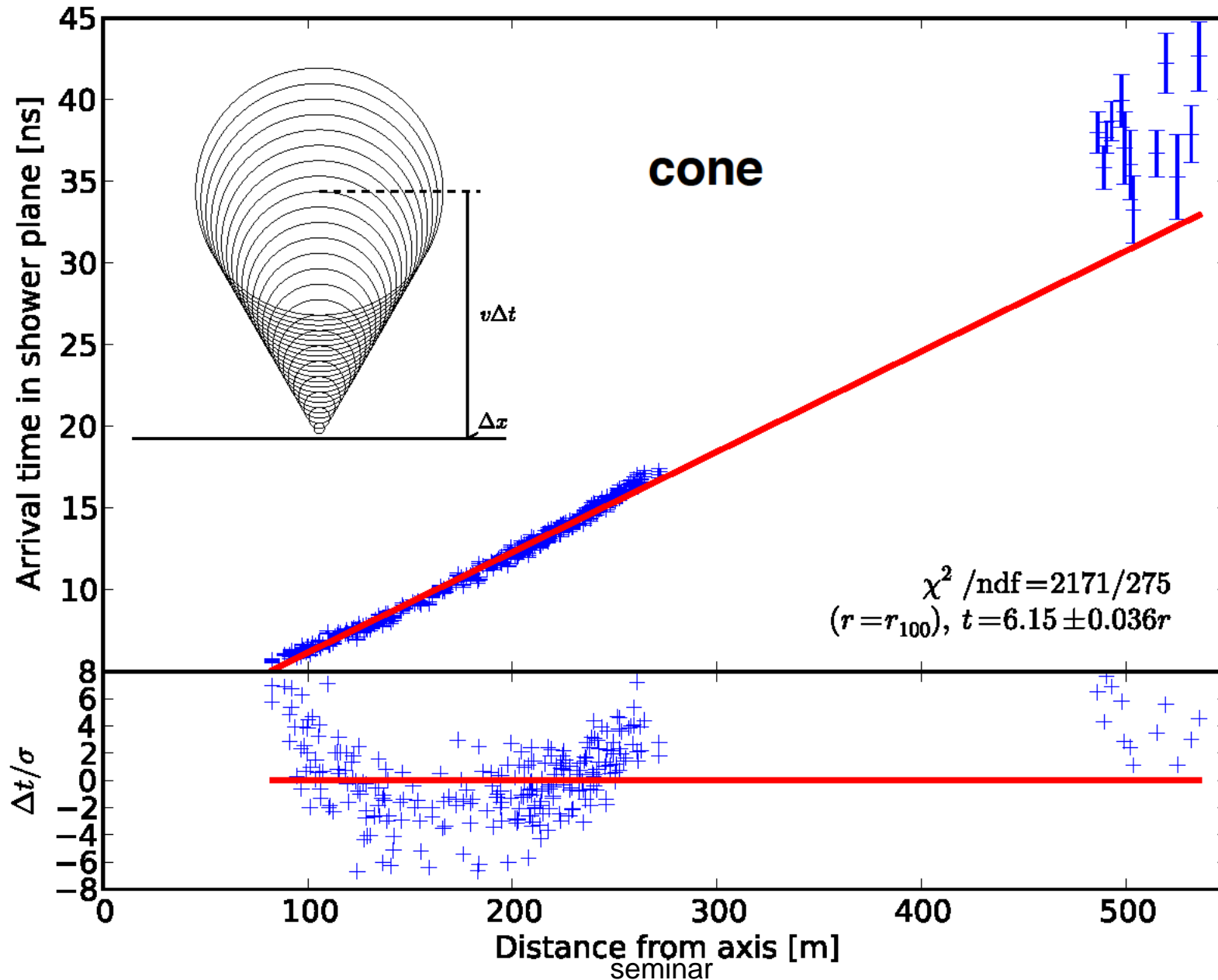
Measuring Cherenkov Rings 110 - 190 MHz



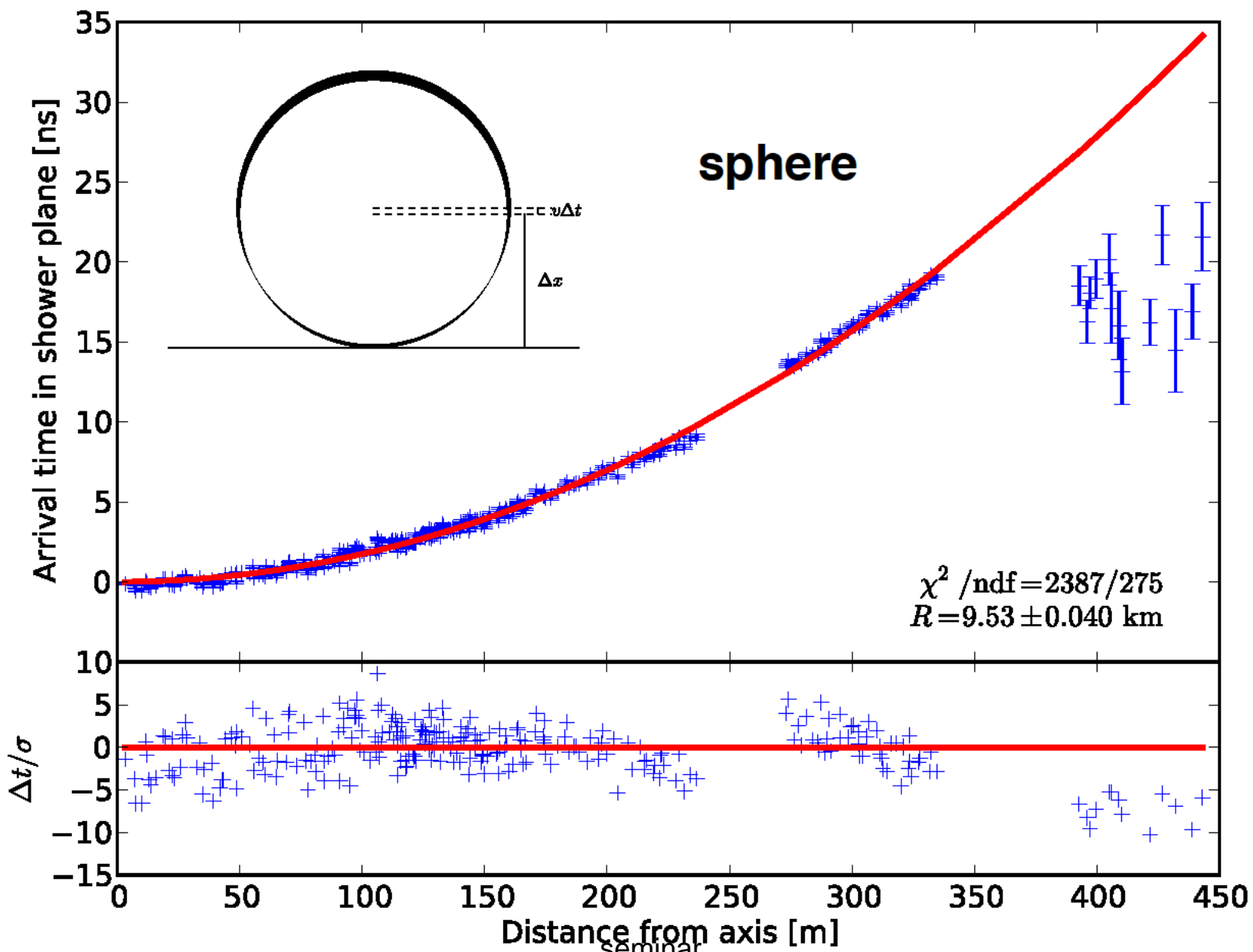
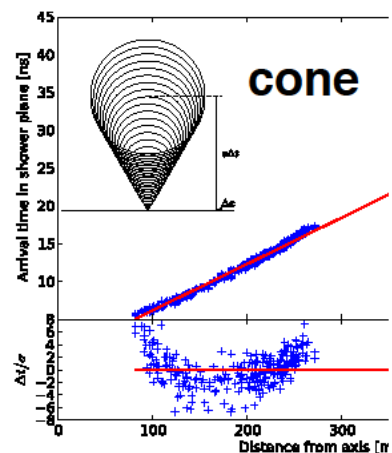
Shape of the Shower Front



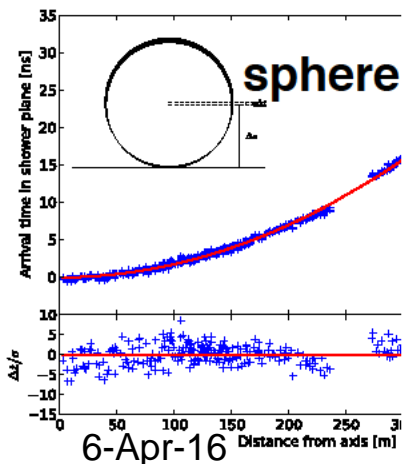
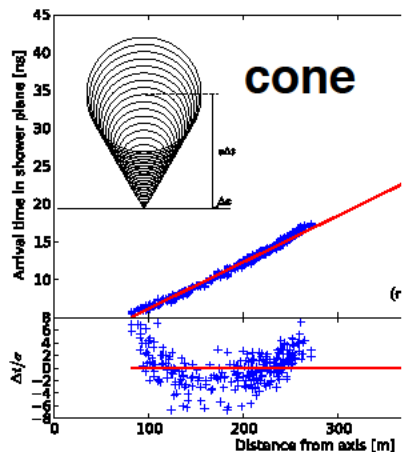
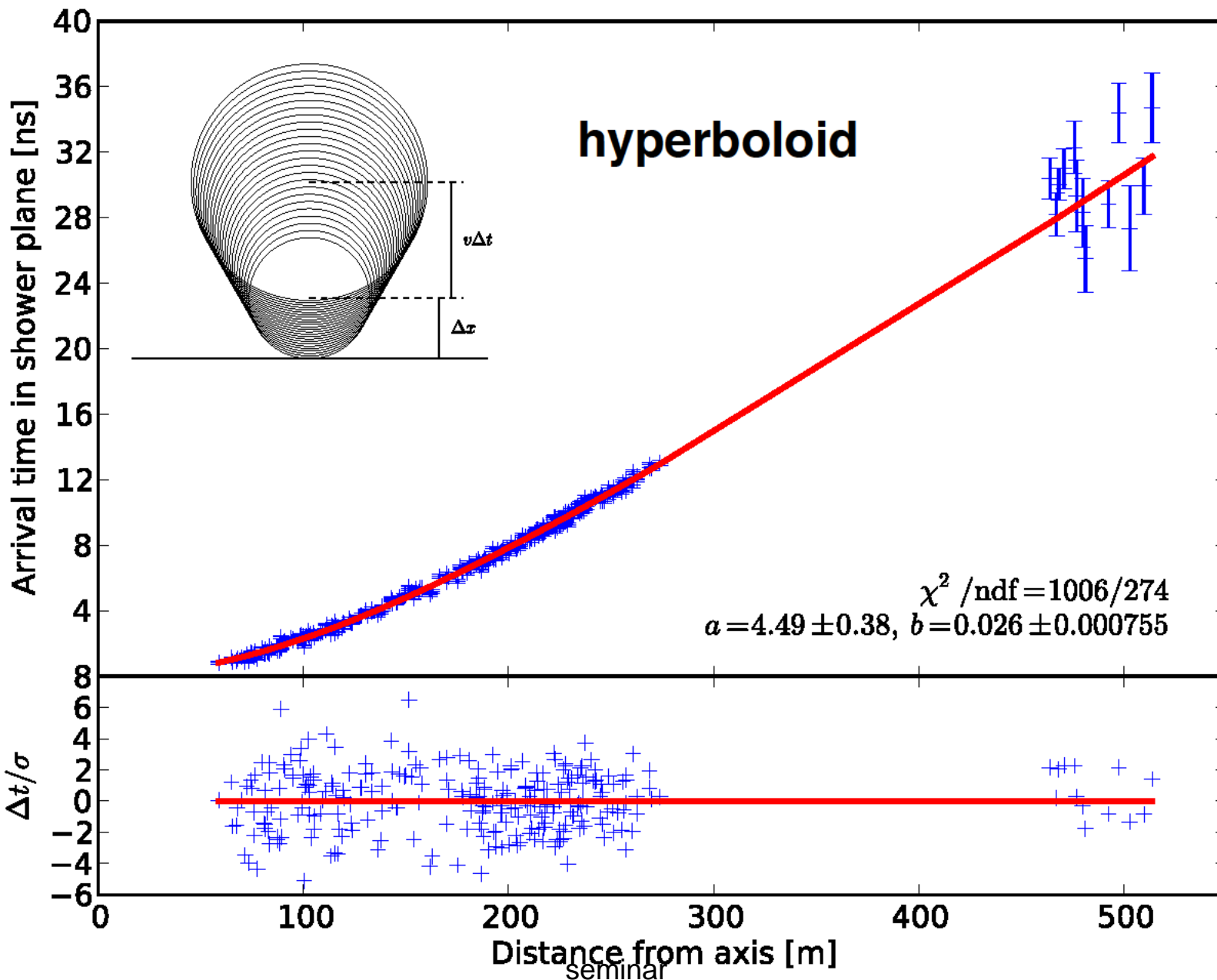
Arrival time of radio signals



Arrival time of radio signals



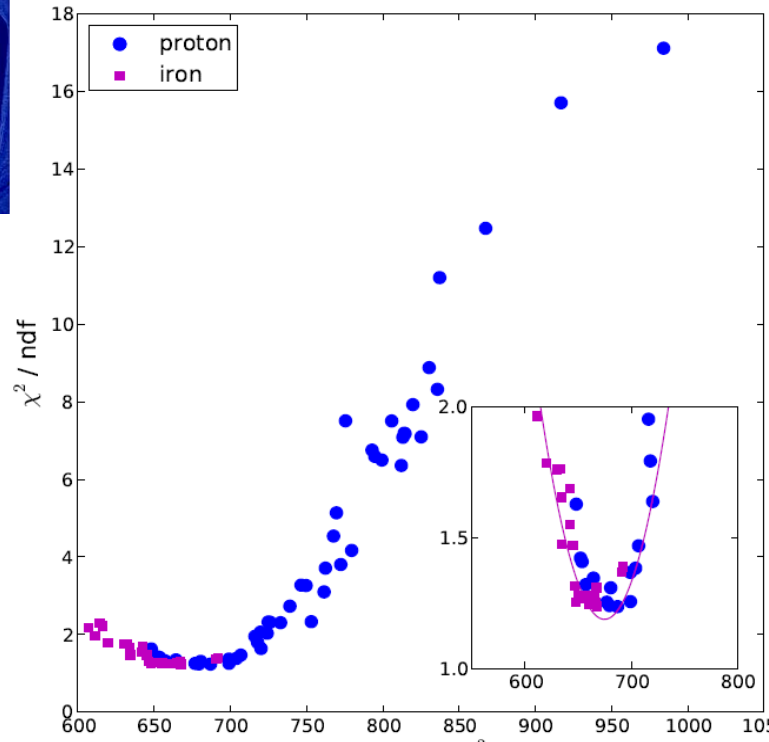
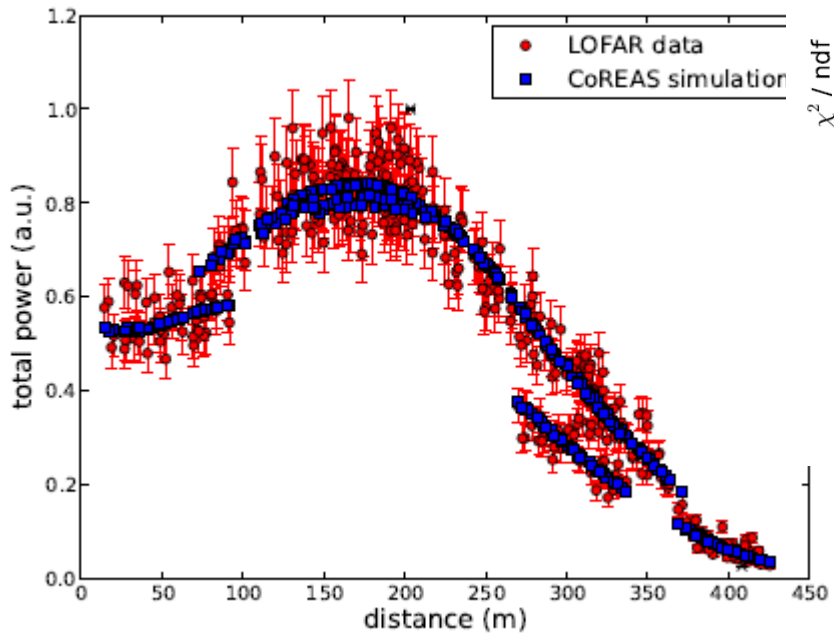
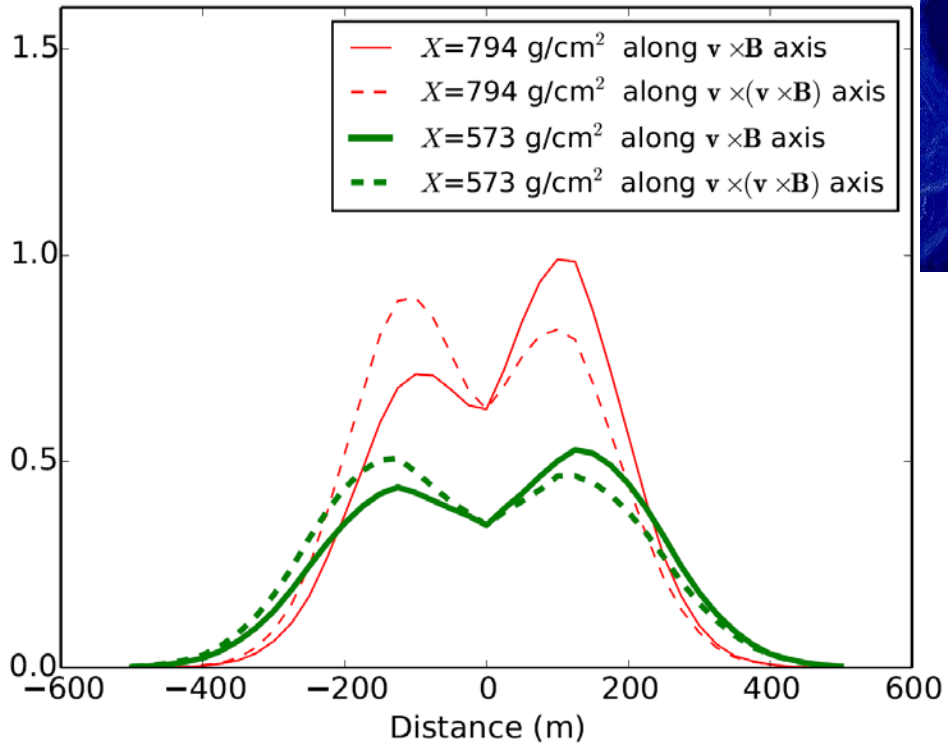
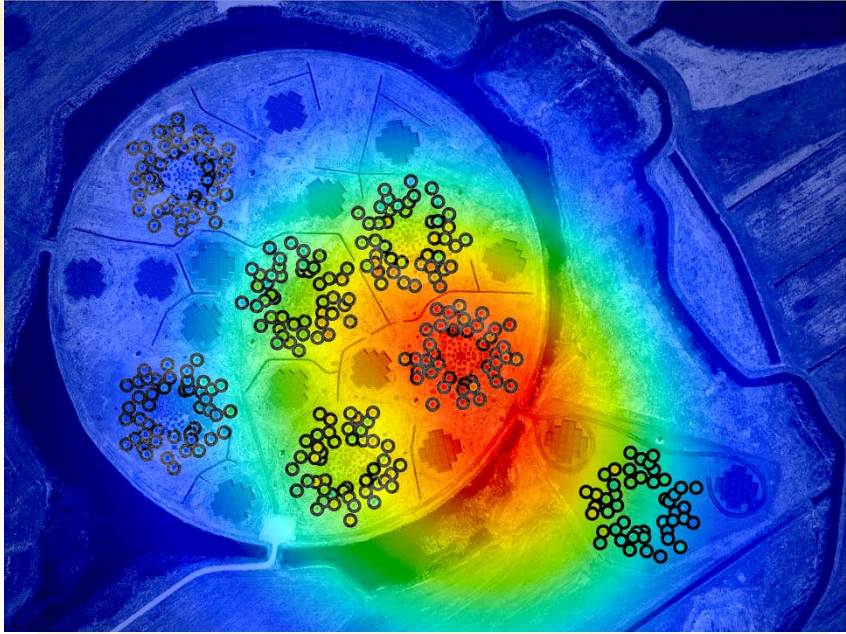
Arrival time of radio signals



LOFAR

CR-radio detection

Presentation Stijn Buitink



X_{max} resolution = 20 g/cm²

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

S. Buitink^{1,2}, A. Corstanje², H. Falcke^{2,3,4,5}, J. R. Hörandel^{2,4}, T. Huege⁶, A. Nelles^{2,7}, J. P. Rachen², L. Rossetto², P. Schellart², O. Scholten^{8,9}, S. ter Veen³, S. Thoudam², T. N. G. Trinh⁸, J. Anderson¹⁰, A. Asgekar^{3,11}, I. M. Avrouk^{12,13}, M. E. Bell¹⁴, M. J. Benton^{3,15}, C. Bernabè^{16,17}, P. Best¹⁸, A. Bonafede¹⁹, F. Breitsing²⁰, J. W. Broderick²¹, W. N. Brown^{3,13}, M. Brüggen¹⁹, H. R. Butcher²², D. Carbone²³, B. Ciardi²⁴, J. E. Conway²⁵, F. de Gasperi²⁶, E. de Geus^{3,26}, A. Deller³, R.-J. Dettmar²⁷, C. van Diepen², S. Duscha³, J. Eisloffel²⁸, D. Engels²⁹, J. E. Enriquez³, R. A. Fallows³⁰, R. Fender³⁰, C. Ferrari³¹, W. Friesswijk³, M. A. Garrett³², J. M. Grieblmeier^{33,34}, A. W. Gunst³, M. P. van Haarlem³, T. E. Hassall², G. Heald³³, J. W. T. Hessels^{3,22}, M. Hoefft³⁵, A. Horneffer³, M. Jacobelli³, H. Intema^{32,35}, E. Juette³⁶, A. Karastergiou³⁰, V. I. Kondratiev^{3,36}, M. Kramer^{3,27}, M. Kuniyoshi³⁷, G. Kuper³, J. van Leeuwen^{22,23}, G. M. Loise³, P. Maat³, G. Mann³⁰, S. Markoff³, R. McPadden³, D. McKay-Bukowicz^{38,40}, J. P. McKean^{3,12}, M. Mevius^{3,12}, D. D. Mulcahy²¹, H. Munk², M. J. Norden³, E. Orrin³, H. Paas⁴⁴, M. Pandey-Pommier⁴², V. N. Pandey³, M. Pietka²⁰, R. Pizzo³, A. G. Polatidis³, W. Reich⁵, H. J. A. Röttgering³², A. M. M. Scaife²¹, D. I. Schwarz⁴³, M. Serylak²⁰, J. Shuman³, O. Smirnov^{37,44}, B. W. Stappers³⁷, M. Steinmetz²⁰, A. Stewart³⁰, J. Swinbank^{23,45}, M. Tagger³³, Y. Tang³, C. Tasse^{44,46}, M. G. Toribio^{3,22}, R. Vermeulen³, C. Vocks²⁰, C. Vogt³, R. I. van Weeren¹⁶, R. A. M. J. Wijers²³, S. I. Wijnholds³, M. W. Wise^{2,22}, O. Wucknitz⁵, S. Yatawatta³, P. Zarka⁴⁷ & J. A. Zensus⁵

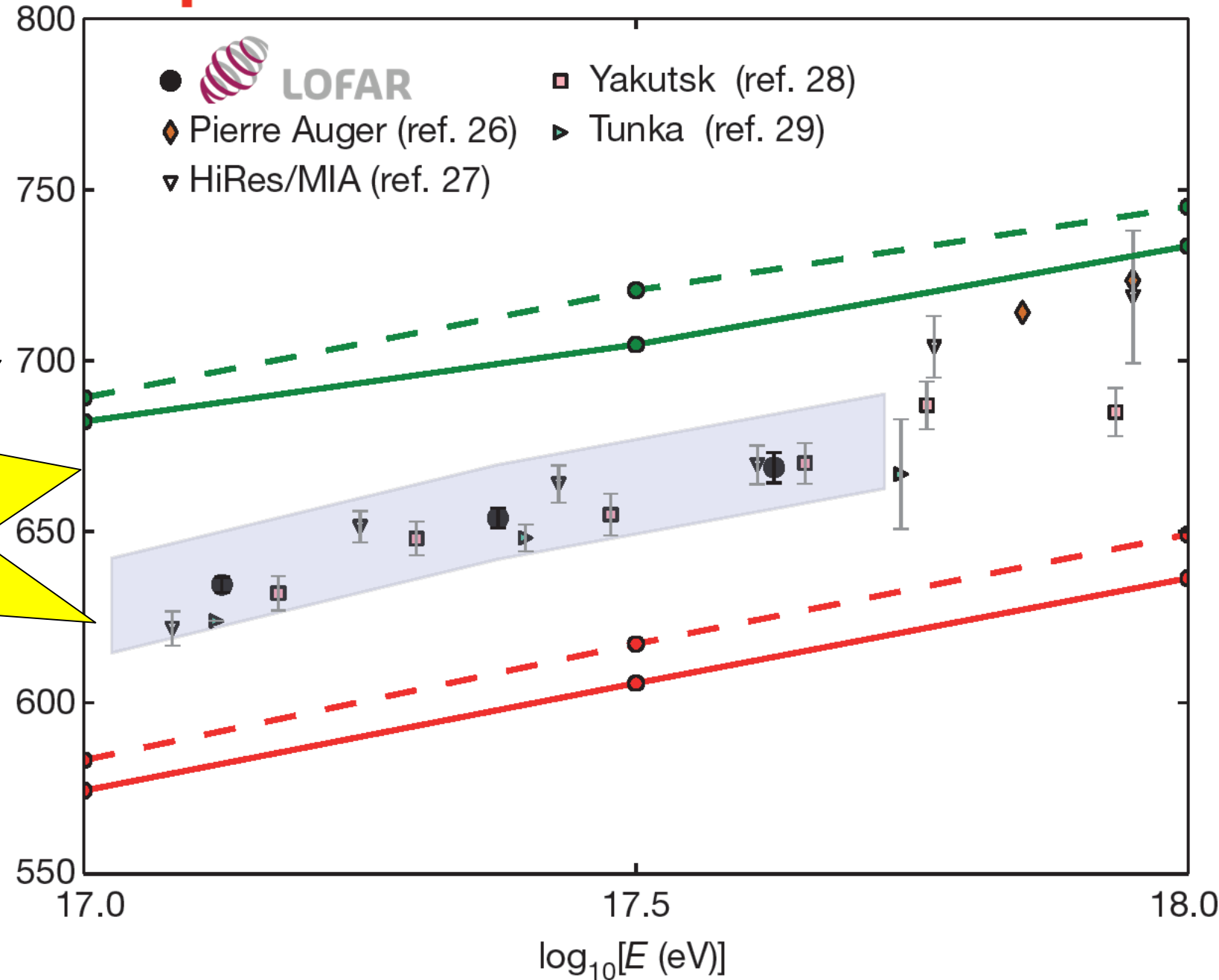
Cosmic rays are the highest-energy particles found in nature. Measurements of the mass composition of cosmic rays with energies of 10^{17} – 10^{18} electronvolts are essential to understanding whether they have galactic or extragalactic sources. It has also been proposed that the astrophysical neutrino signal¹ comes from accelerators capable of producing cosmic rays of these energies². Cosmic rays initiate air showers—cascades of secondary particles in the atmosphere—and their masses can be determined from measurements of the atmospheric depth of the shower maximum, X_{max} : the depth of the air shower when it contains the largest number of particles. The composition of shower particles reaching the ground depends on the mass of the primary particle and the energy of the primary particle. Measurements³ have either high uncertainty or a high energy threshold. Radio detection of air showers is a rapidly developing technique⁴ for determining X_{max} with a duty cycle of, in principle, nearly 100 per cent. It is generated by the separation of relativistic electrons and positrons in the geomagnetic field and a negative charge excess in the shower front^{5,12}. Here we report radio measurements of X_{max} with an uncertainty of 16 grams per square centimetre.

initiated by cosmic rays with energies of 10^{17} – $10^{17.5}$ electronvolts. This high resolution in X_{max} enables us to determine the mass composition of the cosmic rays: we find a mixed composition, with a light-mass fraction (protons and helium nuclei) of about 80 per cent. Unless a significant fraction of the cosmic rays is of extragalactic origin, this light-mass component of cosmic rays contributes substantially to the total flux of cosmic rays below $10^{17.5}$ electronvolts, our measurements confirm the existence of an additional light-mass component. The composition of cosmic rays measured in the 10^{17} – $10^{17.5}$ electronvolt range. Observations with the LOFAR radio telescope, built-in-sky radio telescope, and the LOFAR radio telescope.

Nature

publicly available in nature

Depth of the shower maximum



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 Physics 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
A. Corstanje et al., Astronomy & Astrophysics, accepted, arXiv:1603.08354

A very long title