AMON — Astrophysical Multimessenger Observatory Network

AMON workshop, Cochem, 10 December 2016

Nikhef

How can we contribute with LOFAR and the Pierre Auger Observatory/AERA to AMON multi-messenger observations?

LOFAR

PIERRE AUGER OBSERVATORY

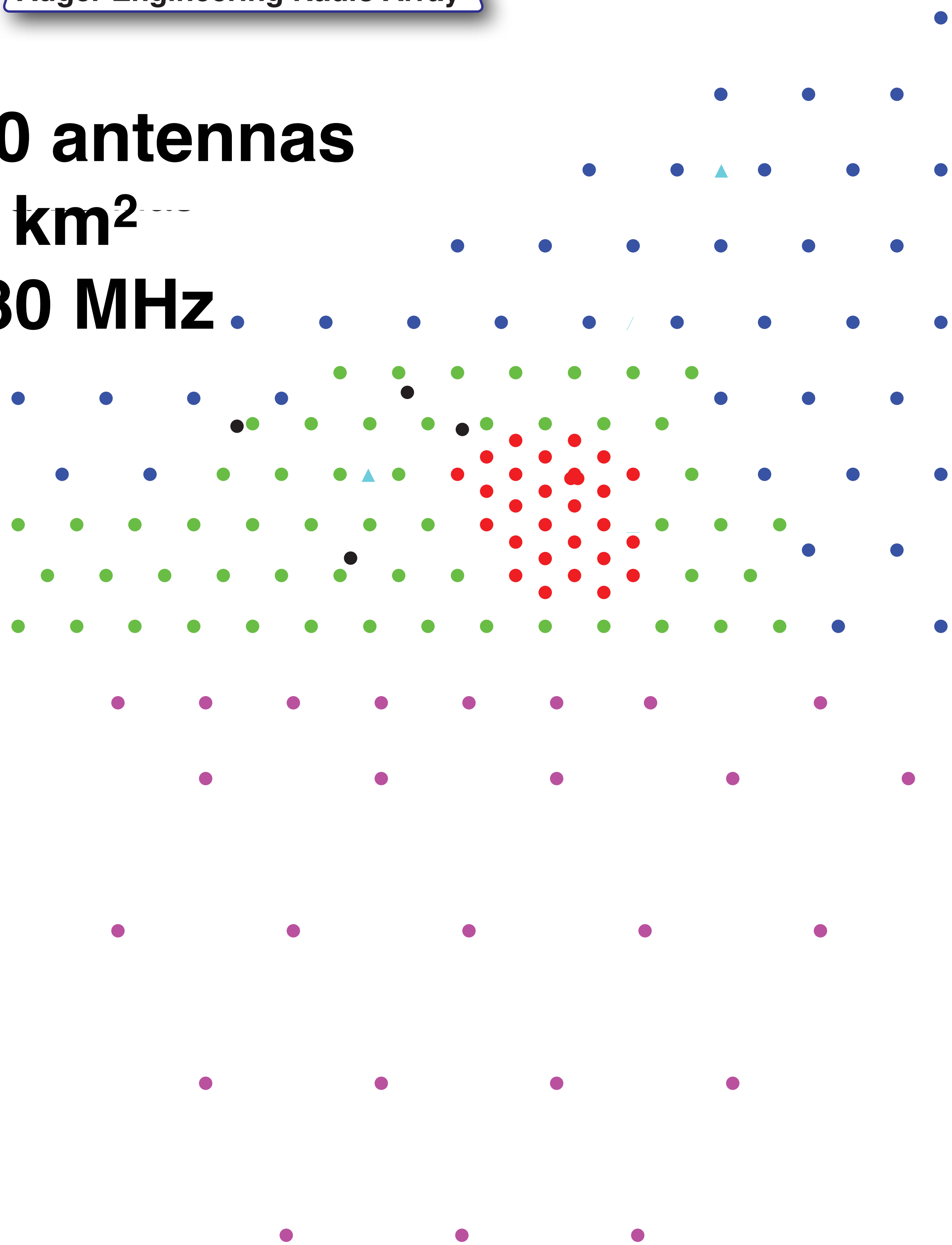
AERA — Auger Engineering Radio Array

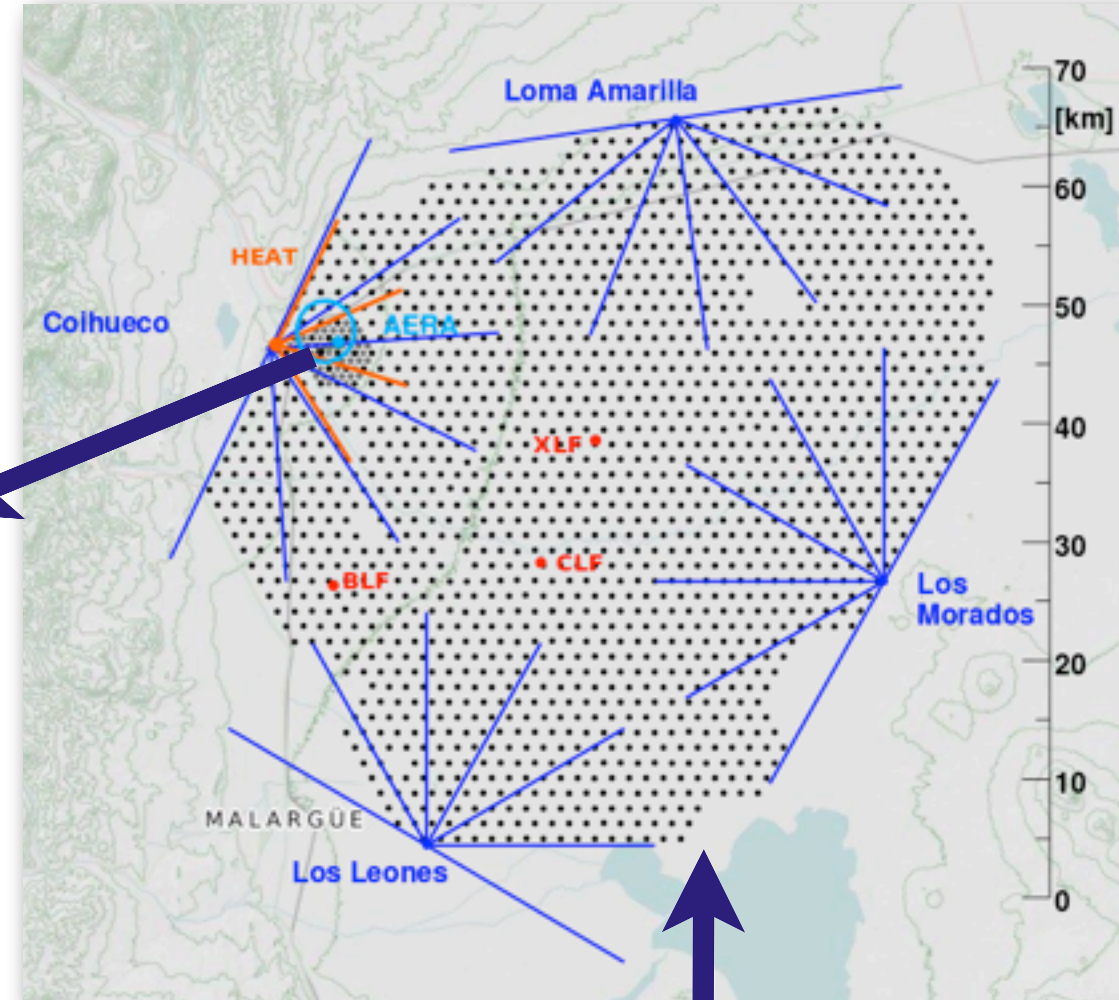
Jörg R. Hörandel   Radboud University Nijmegen/Nikhef   http://particle.astro.ru.nl

PIERRE AUGER OBSERVATORY

AERA
Auger Engineering Radio Array

~150 antennas
~17 km²
30-80 MHz



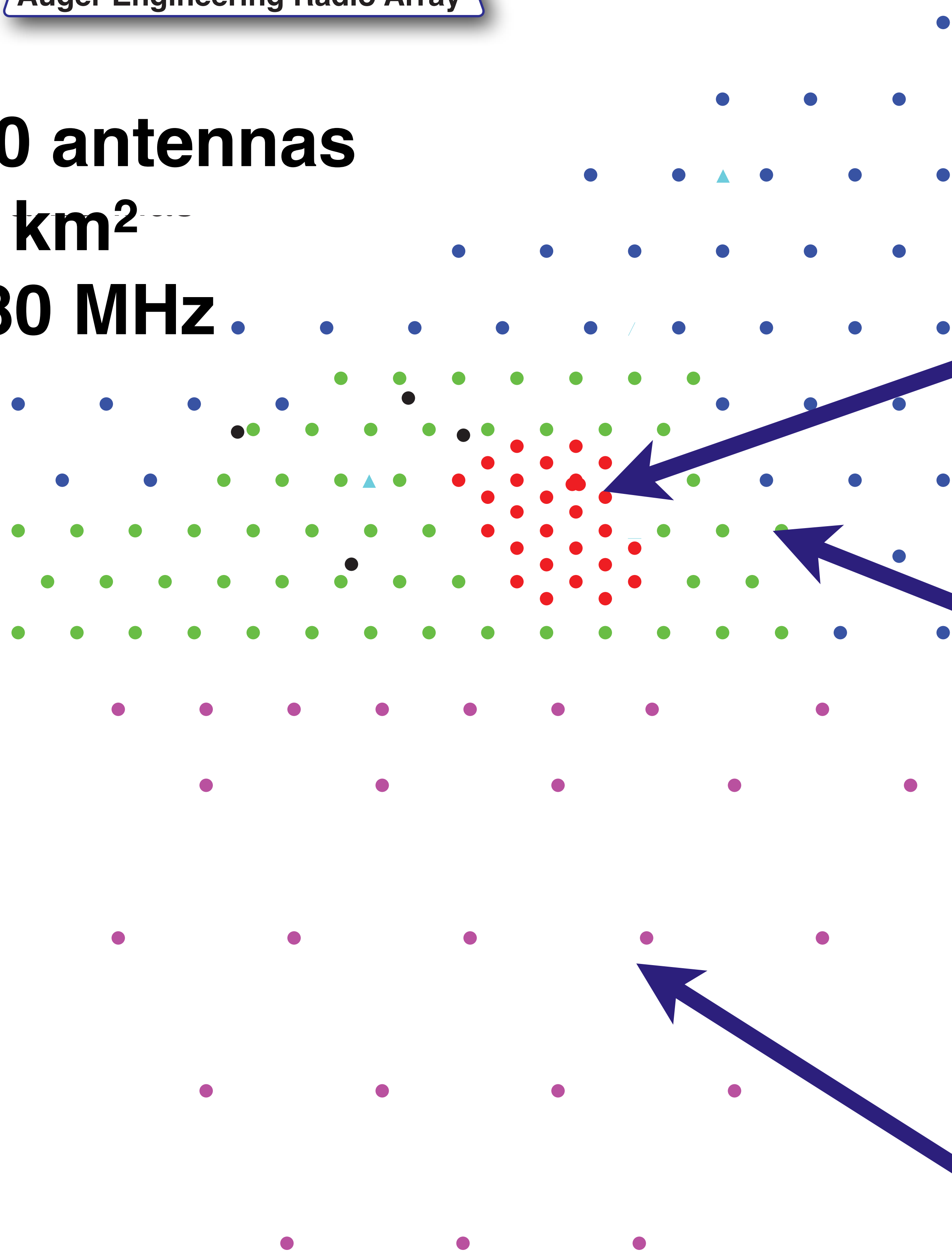


SOUTH AMERICA

PIERRE AUGER OBSERVATORY

AERA
Auger Engineering Radio Array

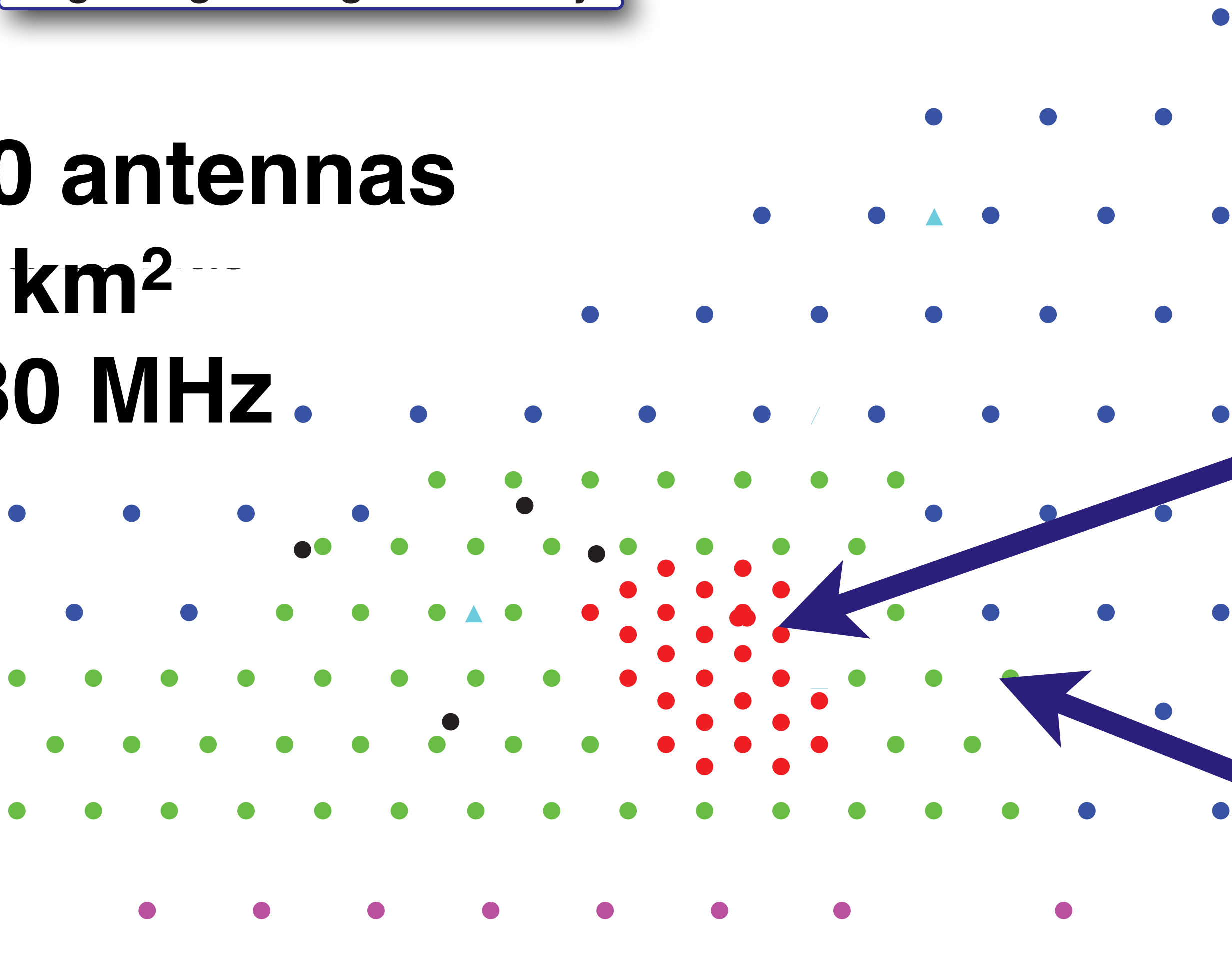
~150 antennas
~17 km²
30-80 MHz

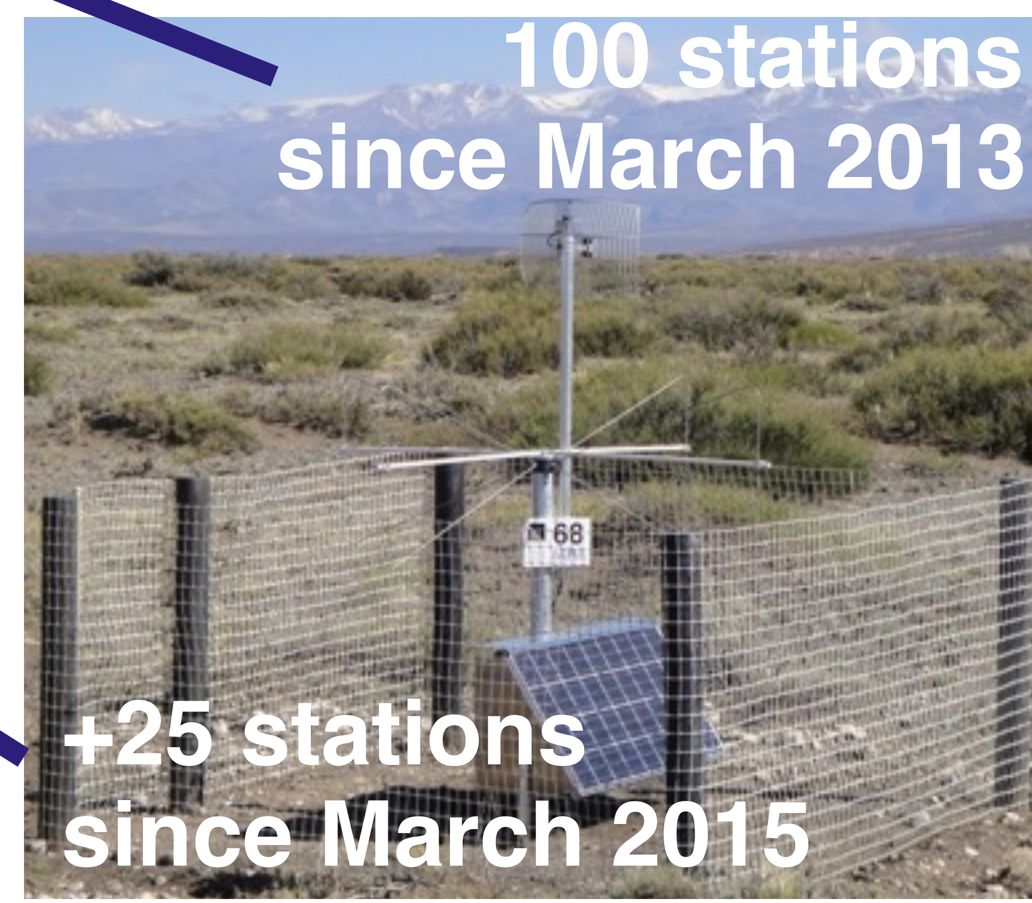


PIERRE AUGER OBSERVATORY

AERA
Auger Engineering Radio Array

~150 antennas
~17 km²
30-80 MHz





trigger through SD
or radio-self trigger

PIERRE AUGER OBSERVATORY

AERA
Auger Engineering Radio Array

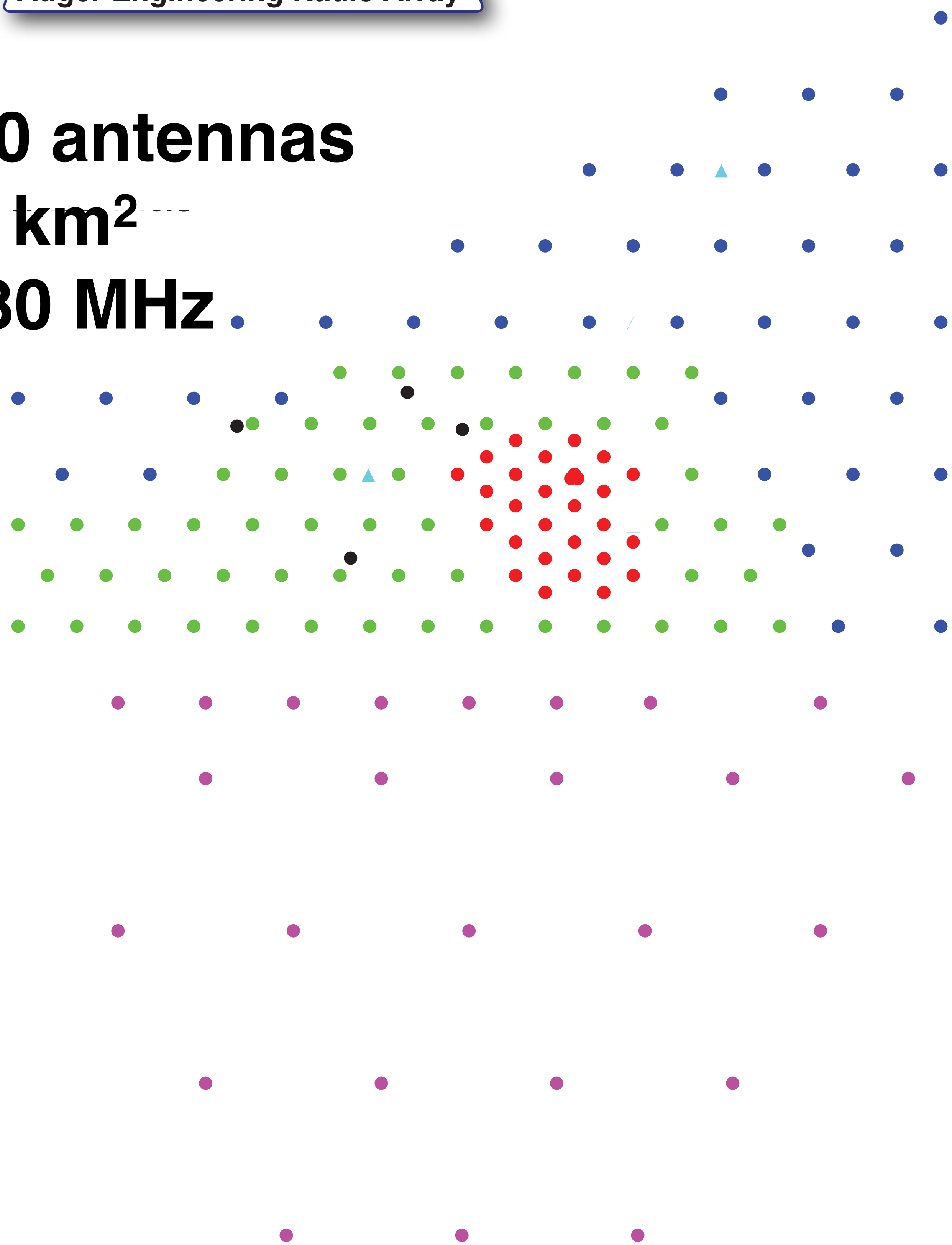
LOFAR core

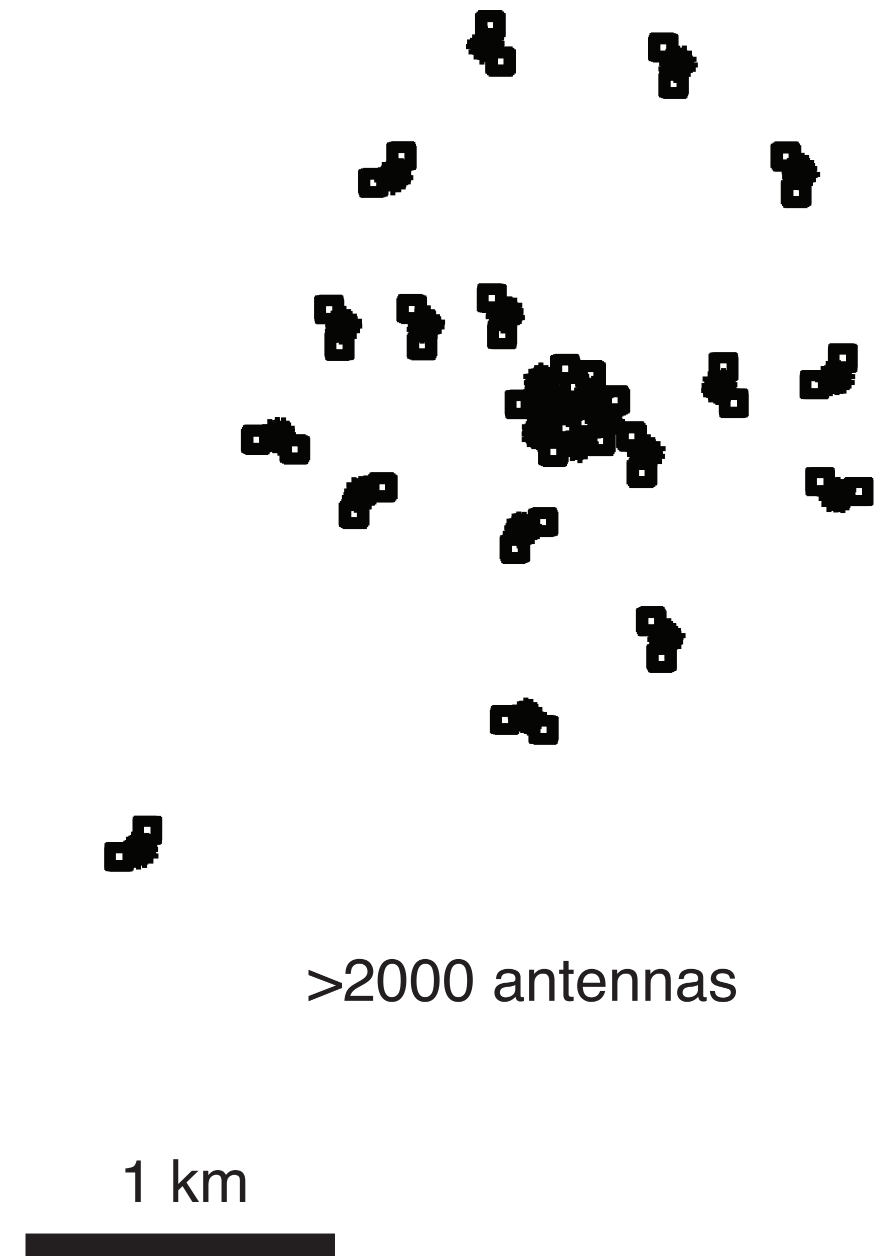
23 stations ~5 km²

~150 antennas

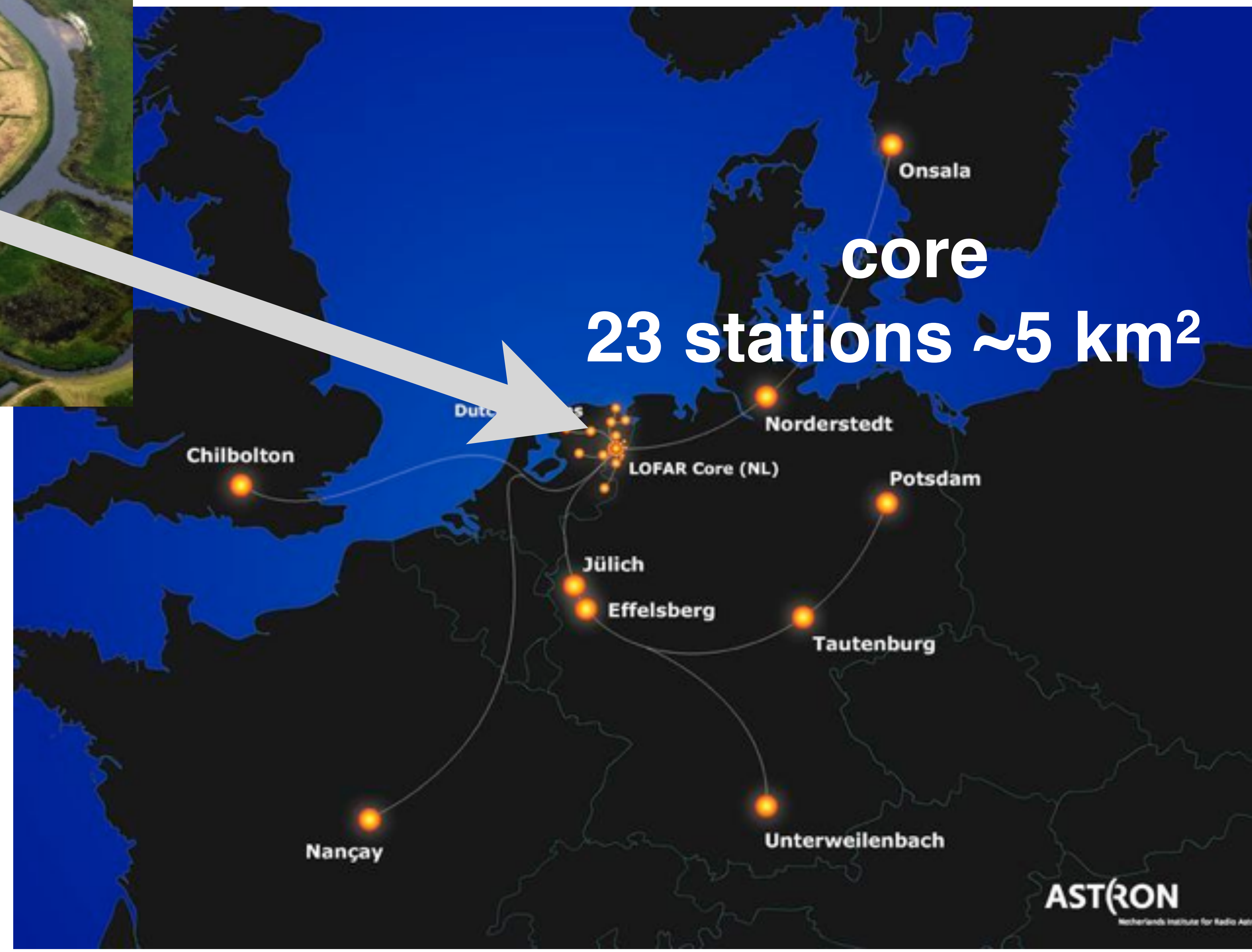
~17 km²

30-80 MHz





LOFAR



each (dutch) station:

96 low-band antennas 30- 80 MHz

high-band antennas (2x24 tiles) 120-240 MHz

M. van Haarlem et al., A&A 556 (2013) A2

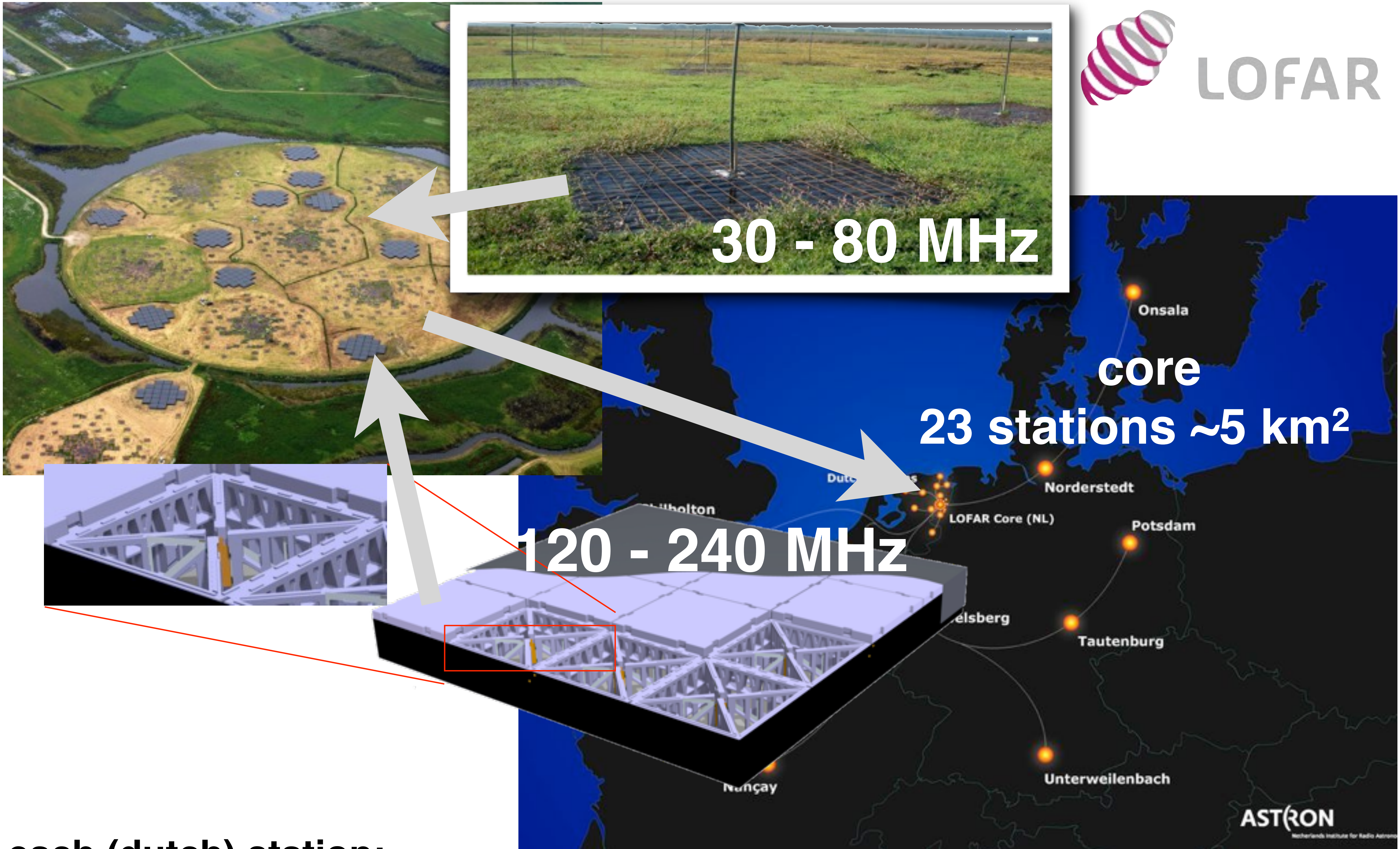
LOFAR

each (dutch) station:

96 low-band antennas 30- 80 MHz

high-band antennas (2x24 tiles) 120-240 MHz

M. van Haarlem et al., A&A 556 (2013) A2



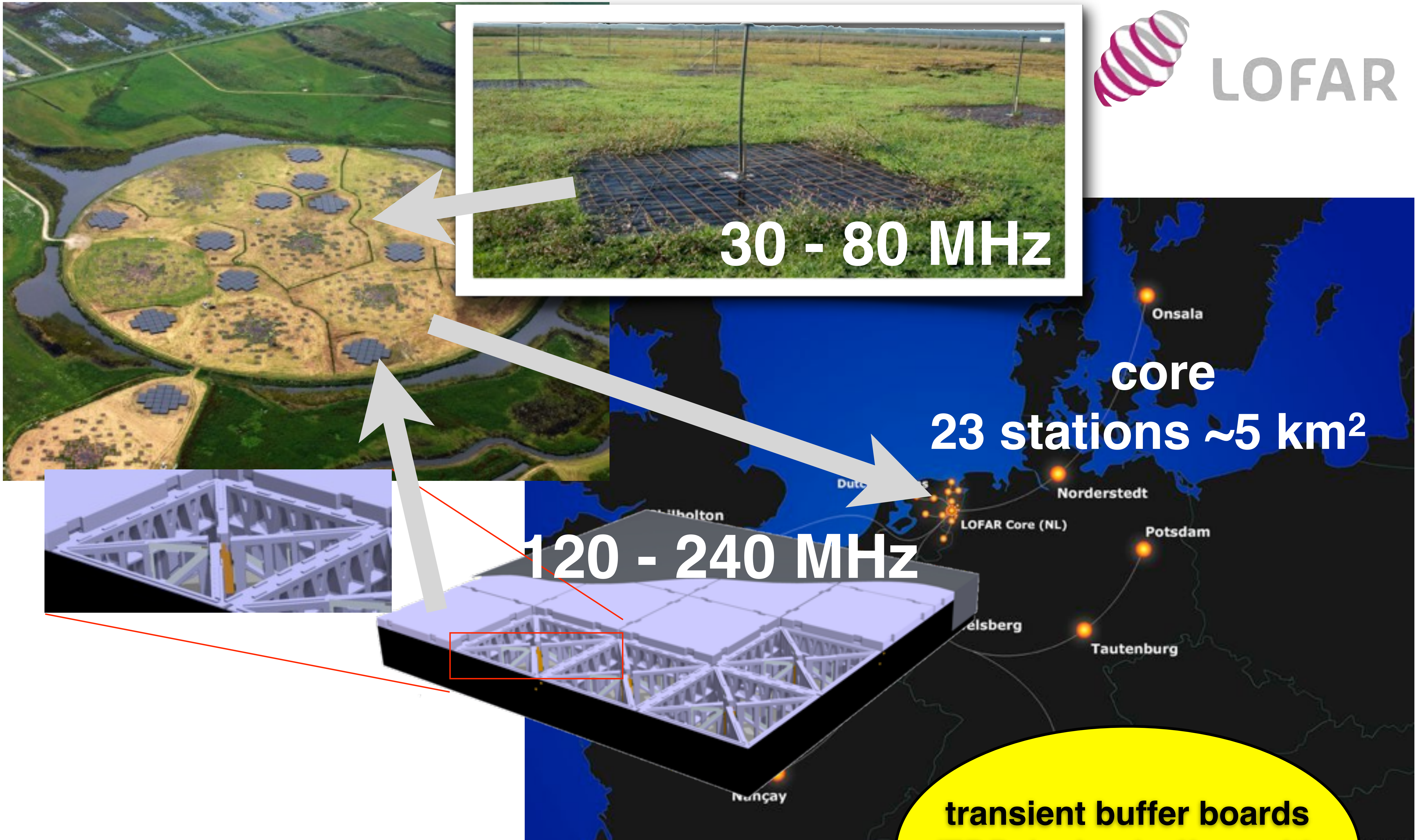
each (dutch) station:

96 low-band antennas 30- 80 MHz

high-band antennas (2x24 tiles) 120-240 MHz

M. van Haarlem et al., A&A 556 (2013) A2

LOFAR



transient buffer boards (TBBs): ring buffers with several secs depth

each (dutch) station:

96 low-band antennas 30- 80 MHz

high-band antennas (2x24 tiles) 120-240 MHz

M. van Haarlem et al., A&A 556 (2013) A2

LOFAR

6 key science projects:

- **Cosmic Rays** - *PI Jörg Hörandel (Nijmegen), co-PI Stijn Buitink (Brussels)*
- **Transients** - *PIs Rob Fender (Oxford), Ben Stappers (Manchester), Ralph Wijers (Amsterdam)*
- **Epoch of reonization**
- **Deep extragalactic surveys**
- **Solar science and space weather**
- **Cosmic magnetism**

LOFAR

6 key science projects:

- **Cosmic Rays** - *PI Jörg Hörandel (Nijmegen), co-PI Stijn Buitink (Brussels)*
- **Transients** - *PIs Rob Fender (Oxford), Ben Stappers (Manchester), Ralph Wijers (Amsterdam)*
- **Epoch of reonization**
- **Deep extragalactic survey**
- **Solar science and space weather**
- **Cosmic magnetism**

radio detection of air showers

radio-astronomical follow-ups

LOFAR Transients Key Project Science Case

Multi-Messenger Follow-Up Working Group

The following facilities are ready to respond to LOFAR transients.

Optical/NIR

- Liverpool Telescope (optical images & spectra)
- William Herschel Telescope (optical/NIR spectra and images
- pt5m (optical images)
- Gran Telescopio CANARIAS (optical spectra)
- PAIRITEL (NIR images)
- PIRATE (Physics Innovations Robotic Astronomical Telescope Explorer)

Gamma Ray

- MAGIC
- HESS
- VERITAS
- Fermi (GBT and LAD)

Radio

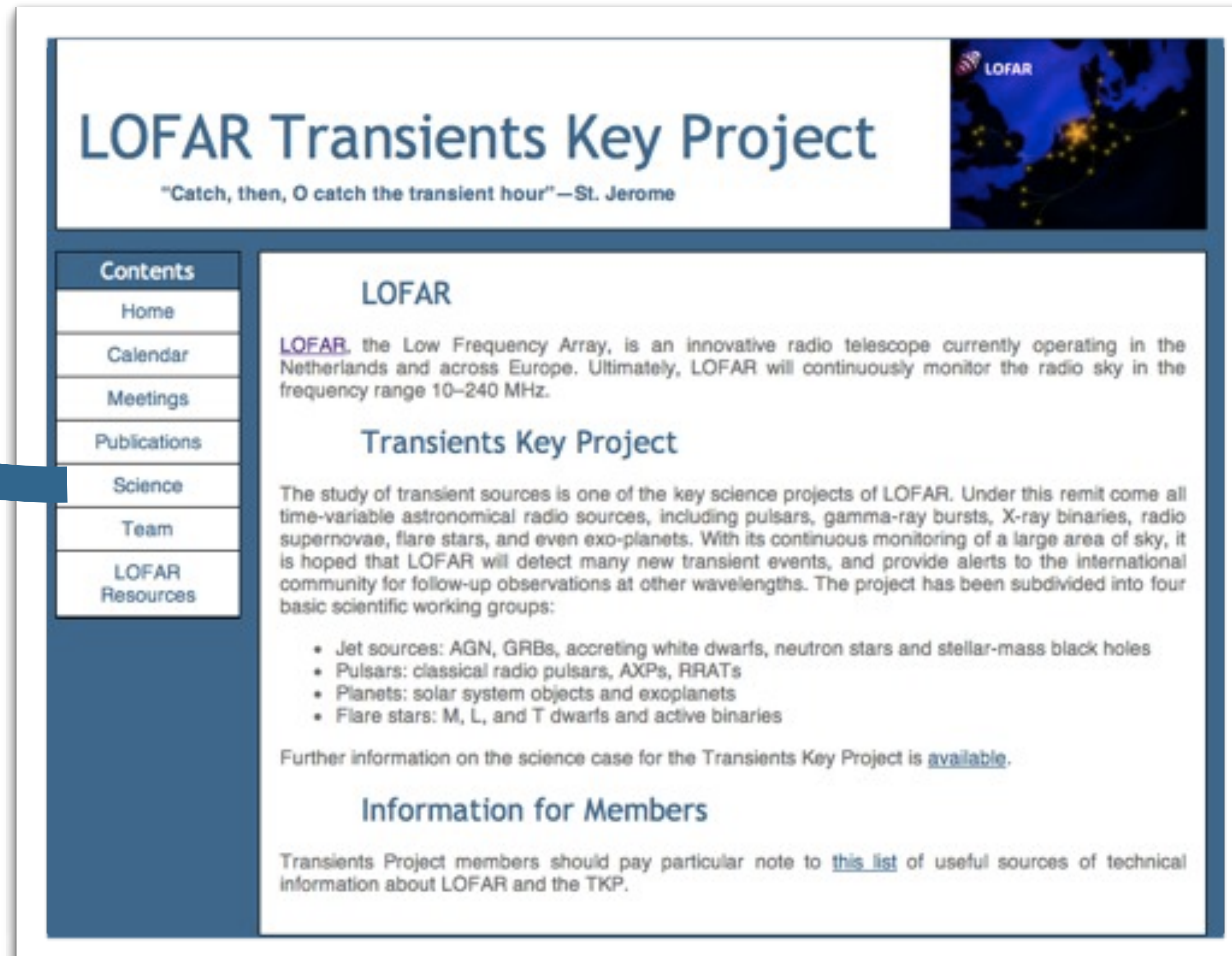
- EVLA
- VLBA
- MeerKAT

X-Ray

- XMM-Newton
- INTEGRAL
- Swift
- MAXI

Gravitational Waves

- LIGO
- VIRGO


LOFAR Transients Key Project

"Catch, then, O catch the transient hour"—St. Jerome

Contents
Home
Calendar
Meetings
Publications
Science
Team
LOFAR Resources

LOFAR

LOFAR, the Low Frequency Array, is an innovative radio telescope currently operating in the Netherlands and across Europe. Ultimately, LOFAR will continuously monitor the radio sky in the frequency range 10–240 MHz.

Transients Key Project

The study of transient sources is one of the key science projects of LOFAR. Under this remit come all time-variable astronomical radio sources, including pulsars, gamma-ray bursts, X-ray binaries, radio supernovae, flare stars, and even exo-planets. With its continuous monitoring of a large area of sky, it is hoped that LOFAR will detect many new transient events, and provide alerts to the international community for follow-up observations at other wavelengths. The project has been subdivided into four basic scientific working groups:

- Jet sources: AGN, GRBs, accreting white dwarfs, neutron stars and stellar-mass black holes
- Pulsars: classical radio pulsars, AXPs, RRATs
- Planets: solar system objects and exoplanets
- Flare stars: M, L, and T dwarfs and active binaries

Further information on the science case for the Transients Key Project is available.

Information for Members

Transients Project members should pay particular note to this list of useful sources of technical information about LOFAR and the TKP.

http://www.transientskp.org

New Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 285, 2011
R.E.M. Griffin, R.J. Hanisch & R. Seaman, eds.

doi:10.1017/S1743921312000130

The Scientific Potential of LOFAR for Time Domain Astronomy

Rob Fender[1], on behalf of the LOFAR Transients Key Science Project

[1]School of Physics & Astronomy, University of Southampton, SO17 1BJ, UK For TKSP member list see: `www.transientskp.org/team.shtml`
email: `r.fender@soton.ac.uk`

Invited Talk

Abstract. LOFAR is a ground-breaking low-frequency radio telescope that is currently nearing completion across northern Europe. As a software telescope with no moving parts, enormous fields of view and multi-beaming, it has fantastic potential for the exploration of the time-variable universe. In this brief paper I outline LOFAR's capabilities, our plans to use it for a range of transient searches, and some crude estimated rates of transient detections.

Keywords. accretion, stars:binaries, stars:pulsars, stars:supernovae:general, ISM: jets and outflows, radio continuum: general

New Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 285, 2011
R.E.M. Griffin, R.J. Hanisch & R. Seaman, eds.

doi:10.1017/S1743921312000130

The Scientific Potential of LOFAR for Time Domain Astronomy

3. Finding Transients with LOFAR

LOFAR can operate in a variety of modes, all of which can be important for the study of transients and variables. Furthermore, all of those modes can be operated at a variety of levels, from a single station to the entire pan-European array.

Interferometric mode. LOFAR is a 'software telescope' which in effect has no moving parts. Pointing of the array and/or individual stations is done by introducing delays appropriate to a certain direction on the sky (phased array). Different frequencies can be therefore set to observe in different directions by introducing different delays. LOFAR can already, as a standard imaging mode, produce 8 beams each of 6 MHz bandwidth. In the low band those beams can be placed anywhere on the sky; in the high band they are limited by the beam of the high-band tiles, an analogue beamformer. That allows for an extraordinary instantaneous field of view: $8 \times 90 = 720$ deg^2 in the low band and $8 \times 25 = 200$ deg^2 in the high band. In other words, the entire northern hemisphere could be mapped in the low band in less than 30 sets of pointings (with sparse tiling). Initial processing of wide-field surveys for transients, including the MSSS (Multifrequency Snapshot Sky Survey) due between late 2011 and early 2012, will only localise sources to a few arcmin, but later and/or responsive observations could localise interesting sources (including transients) to arcsecond precision.

Timing mode. LOFAR also has high-time-resolution ('pulsar') modes, which can achieve 10s of ns time resolution and can map either a full field of view with sensitivity $s \propto N^{-1/2}$ (incoherent sum), or the synthesised beam with sensitivity $s \propto N^{-1}$ (where smaller s is better). Recently it has been possible to record data from over 100 coherent tied-array beams simultaneously and to tile out the entire HBA field. Stappers *et al.* (2011) give more details about searches for fast transients with LOFAR.

Direct storage. The LOFAR Transients Buffer Boards (TBBs) can be used to record up to several seconds of full bandwidth antenna level data (or longer, in a trade-off with bandwidth), *before* the beam-forming stage. That means that beams can be formed retrospectively in a certain direction anywhere in the sky (LBA) or tile beam (HBA) upon receipt of an 'internal' alert (from LOFAR itself) or an 'external' one (e.g. from VOEvent). That mode is currently being developed by the *Cosmic Rays* KSP

Interferometric mode

Timing mode

Direct storage

New Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 285, 2011
R.E.M. Griffin, R.J. Hanisch & R. Seaman, eds.

doi:10.1017/S1743921312000130

The Scientific Potential of LOFAR for Time Domain Astronomy

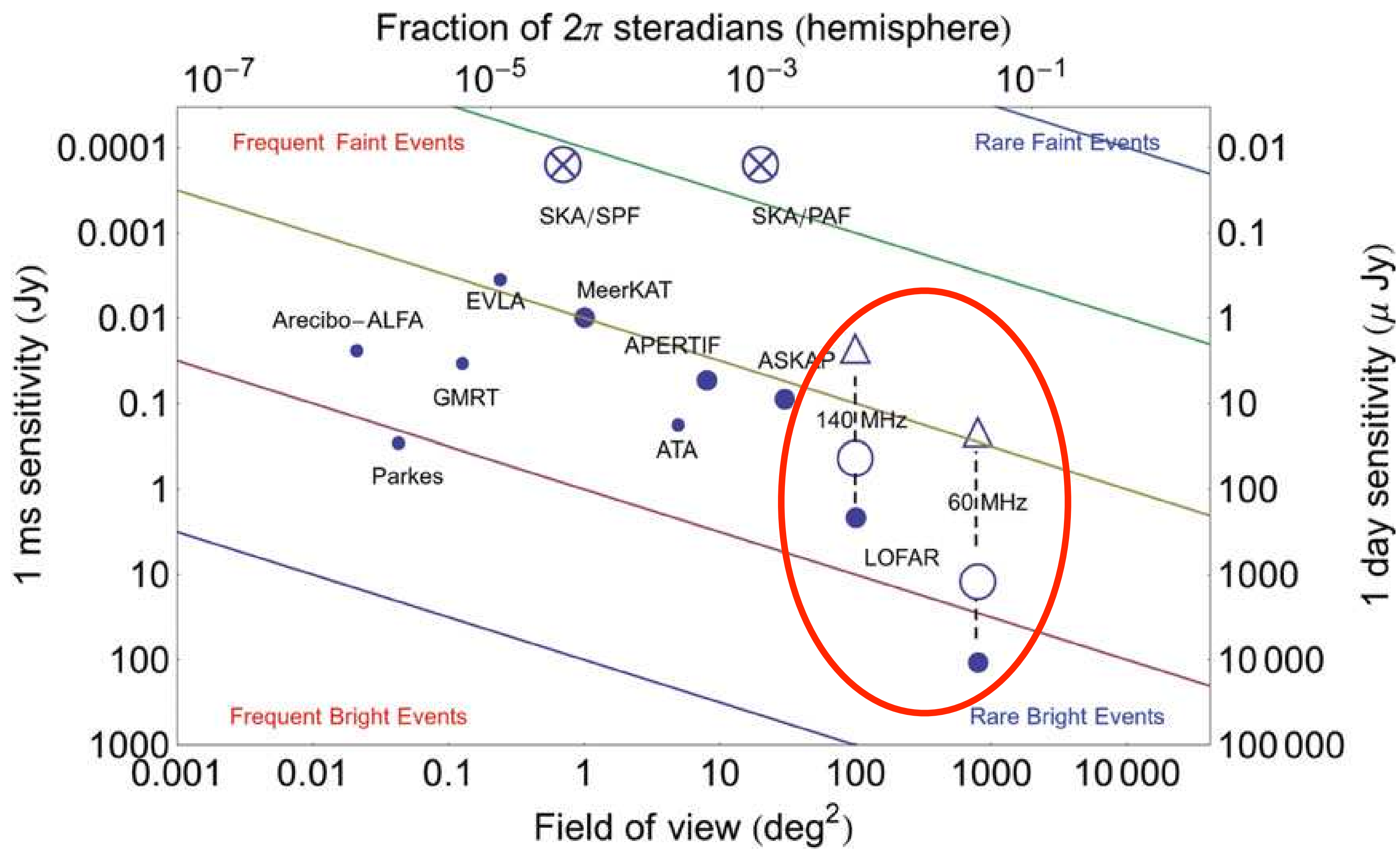


Figure 3. A comparison of sensitivity vs. field of view for a range of existing and planned radio telescopes. The solid lines represent a constant survey figure of merit (FoM, $\propto \Omega s^{-2}$ where Ω is the field of view and s the sensitivity; smaller s implies higher sensitivity). For LOFAR, the dots indicate the raw sensitivities, the open circles represent a spectral correction for a spectral index of –0.7 (where spectral index α is in the sense that $S_\nu \propto \nu^\alpha$), as is appropriate for optically thin synchrotron emission. The open triangles correspond to a correction for a spectral index of −2.0, corresponding to the steepest (most aged) synchrotron sources, as well as some coherent radio sources such as pulsars and other flavours of neutron star.

A&A 530, A80 (2011)
DOI: 10.1051/0004-6361/201116681

Astronomy & Astrophysics

Observing pulsars and fast transients with LOFAR

B. W. Stappers[1], J. W. T. Hessels[2,3], A. Alexov[3], K. Anderson[3], T. Coenen[3], T. Hassall[1], A. Karastergiou[4], V. I. Kondratiev[2], M. Kramer[5,1], J. van Leeuwen[2,3], J. D. Mol[2], A. Noutsos[5], J. W. Romein[2], P. Weltevrede[1], R. Fender[6], R. A. M. J. Wijers[3], L. Bähren[3], M. E. Bell[6], J. Broderick[6], E. J. Daw[8], V. S. Dhillon[8], J. Eislöffel[19], H. Falcke[12,2], J. Griessmeier[2,22], C. Law[24,3], S. Markoff[3], J. C. A. Miller-Jones[13,3], B. Scheers[3], H. Spreeuw[3], J. Swinbank[3], S. ter Veen[12], M. W. Wise[2,3], O. Wucknitz[17], P. Zarka[16], J. Anderson[5], A. Asgekar[2], I. M. Avruch[2,10], R. Beck[5], P. Bennema[2], M. J. Bentum[2], P. Best[15], J. Bregman[2], M. Brentjens[2], R. H. van de Brink[2], P. C. Broekema[2], W. N. Brouw[10], M. Brüggen[21], A. G. de Bruyn[2,10], H. R. Butcher[2,26], B. Ciardi[7], J. Conway[11], R.-J. Dettmar[20], A. van Duin[2], J. van Enst[2], M. Garrett[2,9], M. Gerbers[2], T. Grit[2], A. Gunst[2], M. P. van Haarlem[2], J. P. Hamaker[2], G. Heald[2], M. Hoeft[19], H. Holties[2], A. Horneffer[5,12], L. V. E. Koopmans[10], G. Kuper[2], M. Loose[2], P. Maat[2], D. McKay-Bukowski[14], J. P. McKean[2], G. Miley[9], R. Morganti[2,10], R. Nijboer[2], J. E. Noordam[2], M. Norden[2], H. Olofsson[11], M. Pandey-Pommier[9,25], A. Polatidis[2], W. Reich[5], H. Röttgering[9], A. Schoenmakers[2], J. Sluman[2], O. Smirnov[2], M. Steinmetz[18], C. G. M. Sterks[23], M. Tagger[22], Y. Tang[2], R. Vermeulen[2], N. Vermaas[2], C. Vogt[2], M. de Vos[2], S. J. Wijnholds[2], S. Yatawatta[10], and A. Zensus[5]

(Affiliations can be found after the references)

Received 9 February 2011 / Accepted 22 March 2011

ABSTRACT

Low frequency radio waves, while challenging to observe, are a rich source of information about pulsars. The LOw Frequency ARray (LOFAR) is a new radio interferometer operating in the lowest 4 octaves of the ionospheric "radio window": 10–240 MHz, that will greatly facilitate observing pulsars at low radio frequencies. Through the huge collecting area, long baselines, and flexible digital hardware, it is expected that LOFAR will revolutionize radio astronomy at the lowest frequencies visible from Earth. LOFAR is a next-generation radio telescope and a pathfinder to the Square Kilometre Array (SKA), in that it incorporates advanced multi-beaming techniques between thousands of individual elements. We discuss the motivation for low-frequency pulsar observations in general and the potential of LOFAR in addressing these science goals. We present LOFAR as it is designed to perform high-time-resolution observations of pulsars and other fast transients, and outline the various relevant observing modes and data reduction pipelines that are already or will soon be implemented to facilitate these observations. A number of results obtained from commissioning observations are presented to demonstrate the exciting potential of the telescope. This paper outlines the case for low frequency pulsar observations and is also intended to serve as a reference for upcoming pulsar/fast transient science papers with LOFAR.

Key words. telescopes – pulsars: general – instrumentation: interferometers – methods: observational – stars: neutron – ISM: general

A&A 530, A80 (2011)
DOI: 10.1051/0004-6361/201116681

Astronomy & Astrophysics

Observing pulsars and fast transients with LOFAR

Fig. 1. Three successive zoom-outs showing the stations in the LOFAR core. The different scales of the hierarchically organised HBA elements are highlighted and their respective beam sizes are shown. The large circular area marks the edge of the Superterp, which contains the inner-most 6 stations (i.e. 12 HBA sub-stations: where there are 2 sub-stations, each of 24 tiles, in each HBA core station); other core stations can be seen highlighted beyond the Superterp in the third panel. *Left*: a single HBA tile and associated beam. *Middle*: a single HBA sub-station with three simultaneous station beams. *Right*: the 6 stations of the Superterp plus 3 core stations in the background are highlighted. Four independent beams formed from the coherent combination of all 24 core HBA stations, most of which are outside this photo, are shown. For the LBA stations, a similar scheme applies except that each LBA dipole can effectively see the whole sky. Fields of the relatively sparsely distributed LBA antennas are visible in between the highlighted HBA stations in all three panels.

A&A 530, A80 (2011)
DOI: 10.1051/0004-6361/201116681

Astronomy & Astrophysics

Observing pulsars and fast transients with LOFAR

Table 3. Comparison of the LOFAR beam-forming modes.

Mode	Sensitivity (Norm.)	FoV (sq. deg)	Resolution (deg)	Data rate (TB/h)	FoM (Norm.)
High-Band Antennas (HBAs)					
Single HBA sub-station	1/0.35	18/147	4.8	0.3	1
Single Rem. Station	2/0.7	10/82	3.6	0.3	3
Single Intl. Station	4/1.4	6 /45	2.7	0.3	9
Fly's Eye	1/0.35	1050/8400	4.8	20	56
Dutch Inc. Sum	11/4	10/82	3.6	0.3	77
Intl. Inc. Sum	11/4	6/45	2.7	0.3	73
Coherent Superterp (94 beams)	12/4	18/147	0.5	29	1382
Coherent Sum Core (100 beams)	48/17	0.4/3	0.075	31	3206
Constrained Coherent Core (29 beams)	10/3.5	18/147	0.9	9	512
Low-Band Antennas (LBAs)					
Single Core Station Outer	1/0.35	17/132	4.6	0.3	1
Single Core Station Inner	<1/<0.35	105/840	11.6	0.3	<1
Single Rem. Station	1/0.35	17/132	4.6	0.3	1
Single Intl. Station	2/0.7	26/211	5.8	0.3	5
Fly's Eye	1/0.35	660/5300	4.6	12	40
Dutch Inc. Sum	6/2	17/132	4.6	0.3	40
Intl. Inc. Sum	6/2	26/211	5.8	0.3	44
Coherent Superterp (15 beams)	6/2	17/132	1.2	4.5	138
Coherent Sum Core (100 beams)	24/8.5	3/23	0.19	30	2460

LOFAR

Transients key science project

could be part of AMON

- **issuing triggers to others**
  (low-frequency [30-240 MHz] transient events)

- **receiving external triggers**
  (implemented for ksp CRs to read out radio antennas after particle detector trigger)

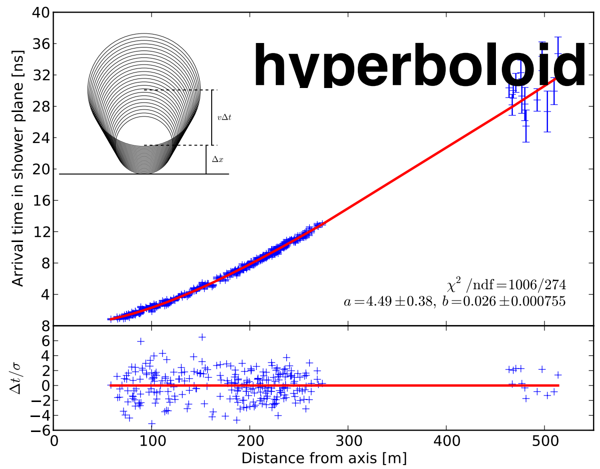
How could we contribute by measuring cosmic rays with LOFAR and AERA?

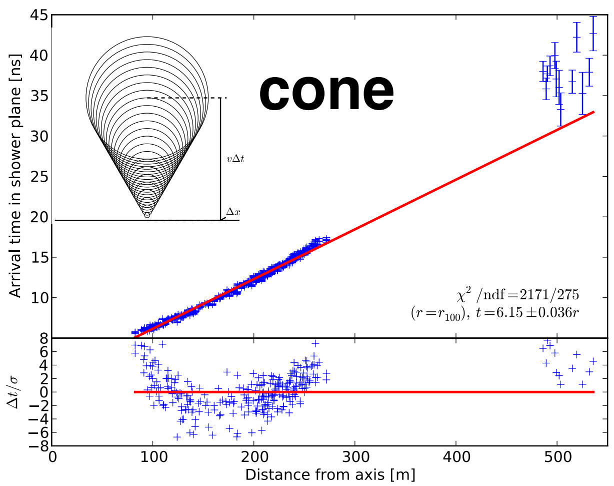
The radio technique is now mature.

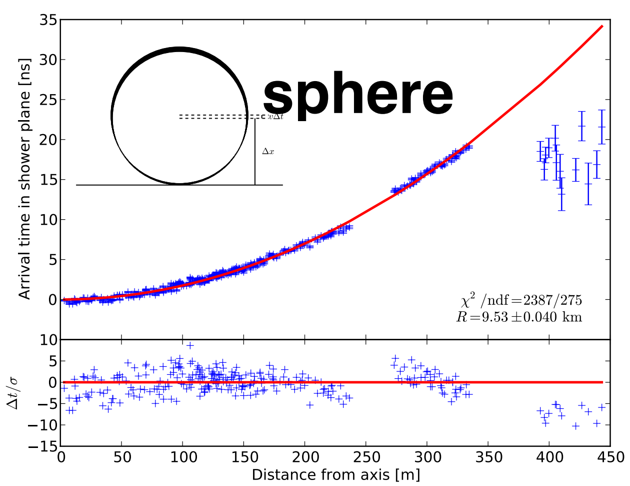
All properties of cosmic rays are being measured:
- direction ~ 0.1° - ~0.5°
- energy ~ 25%
- particle type (mass) X_{max} ~ 20 g/cm^2 ln A ~0.5

--> identify gamma rays & neutrinos

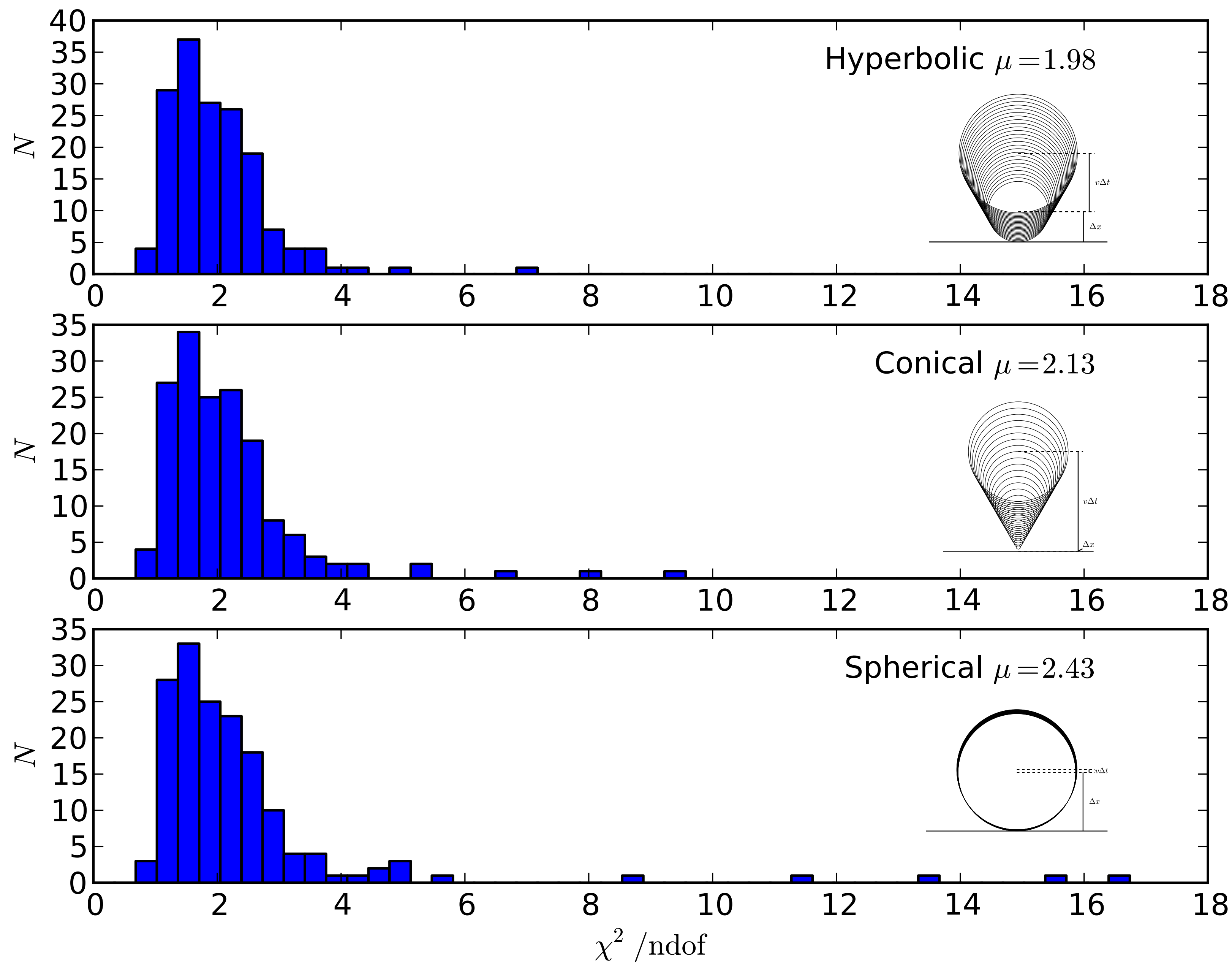
Shape of Shower Front







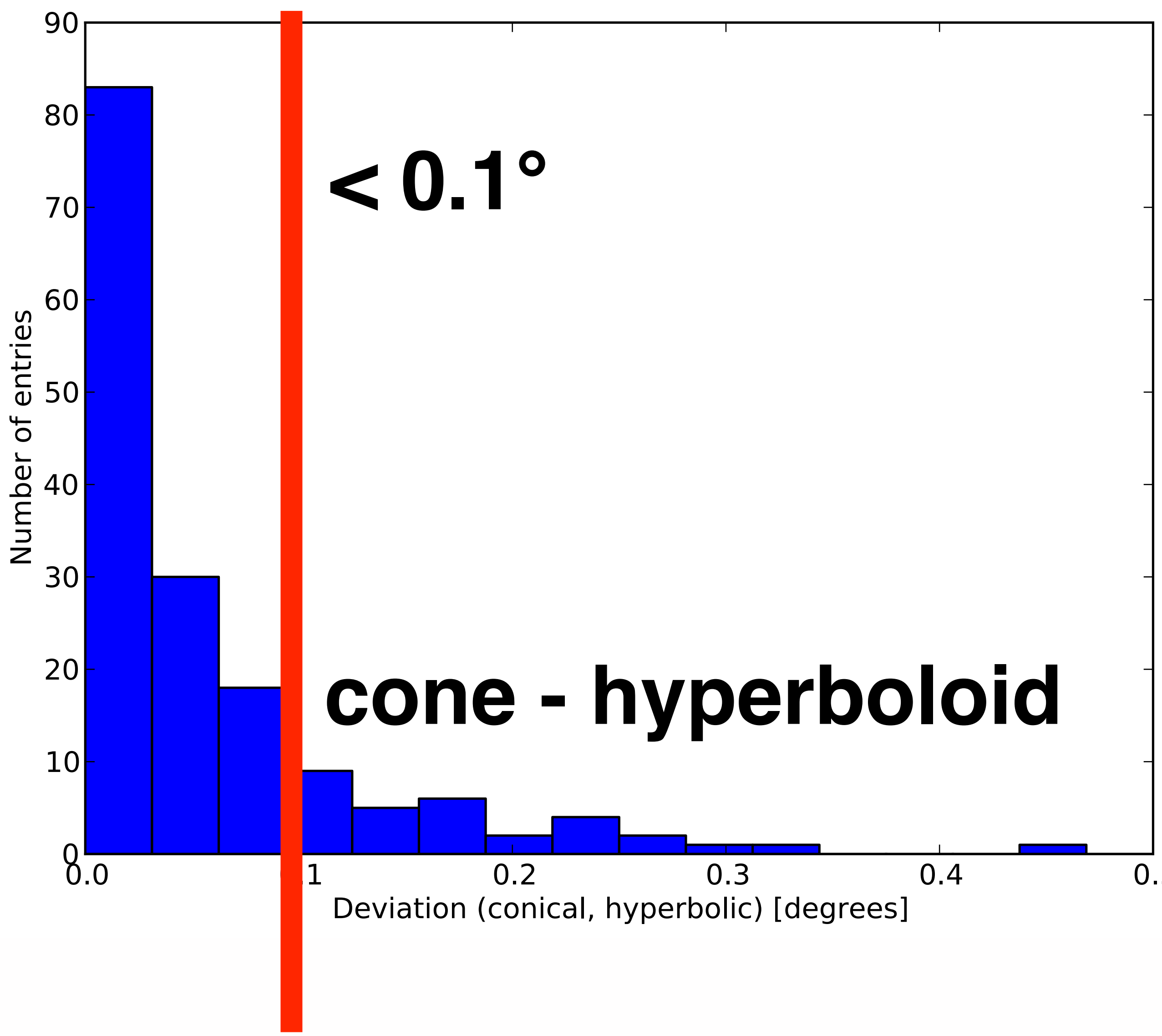
fit quality

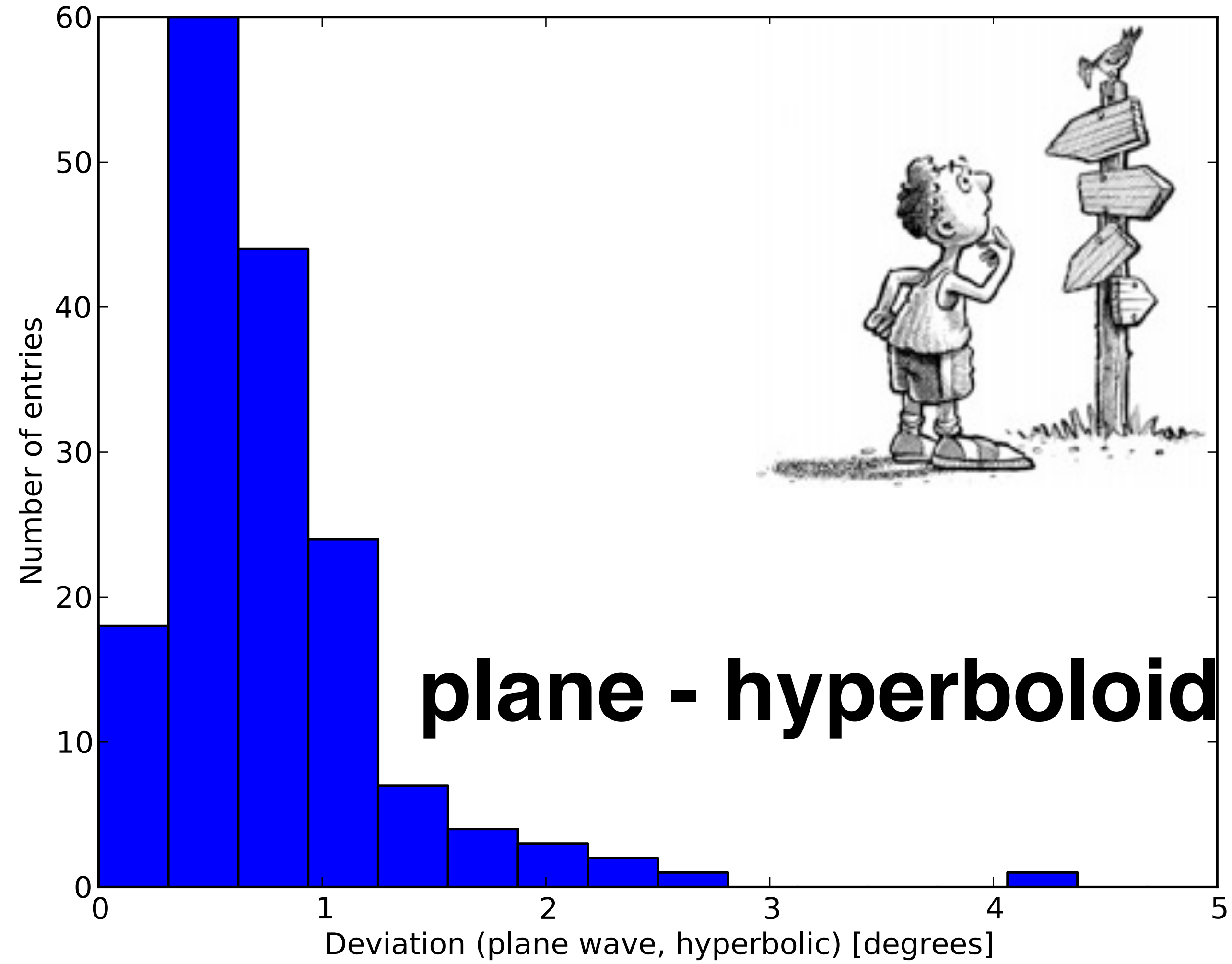


A. Corstanje et al., Astropart. Phys. 61 (2015) 22

Accuracy of Shower Direction

angular difference between..

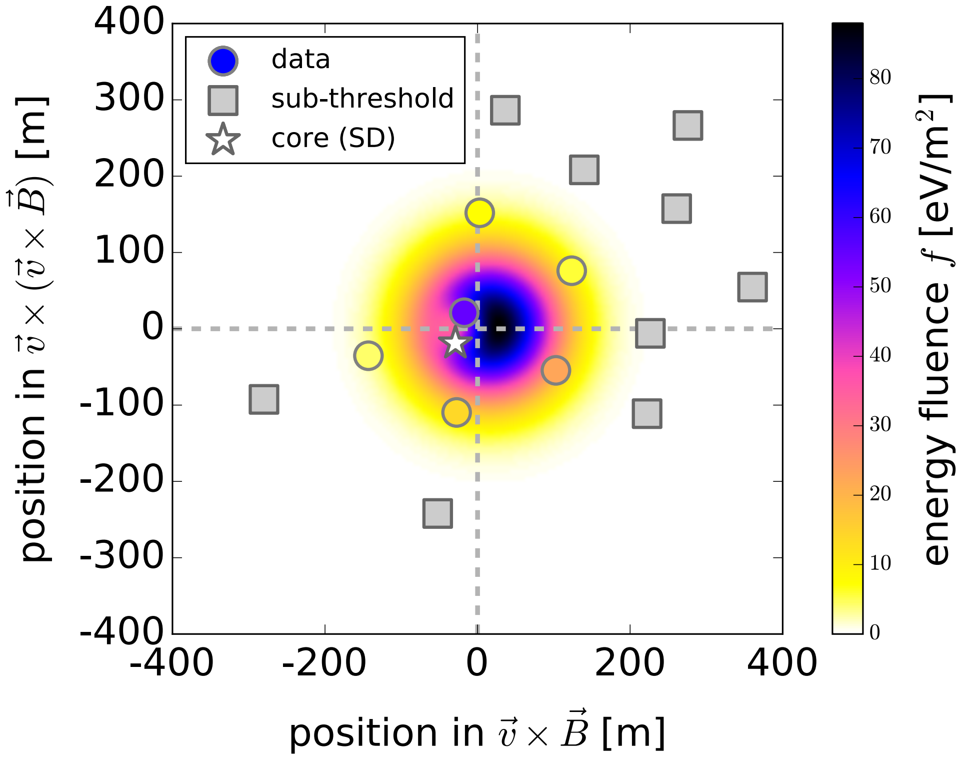




A. Corstanje et al., Astropart. Phys. 61 (2015) 22

LOFAR

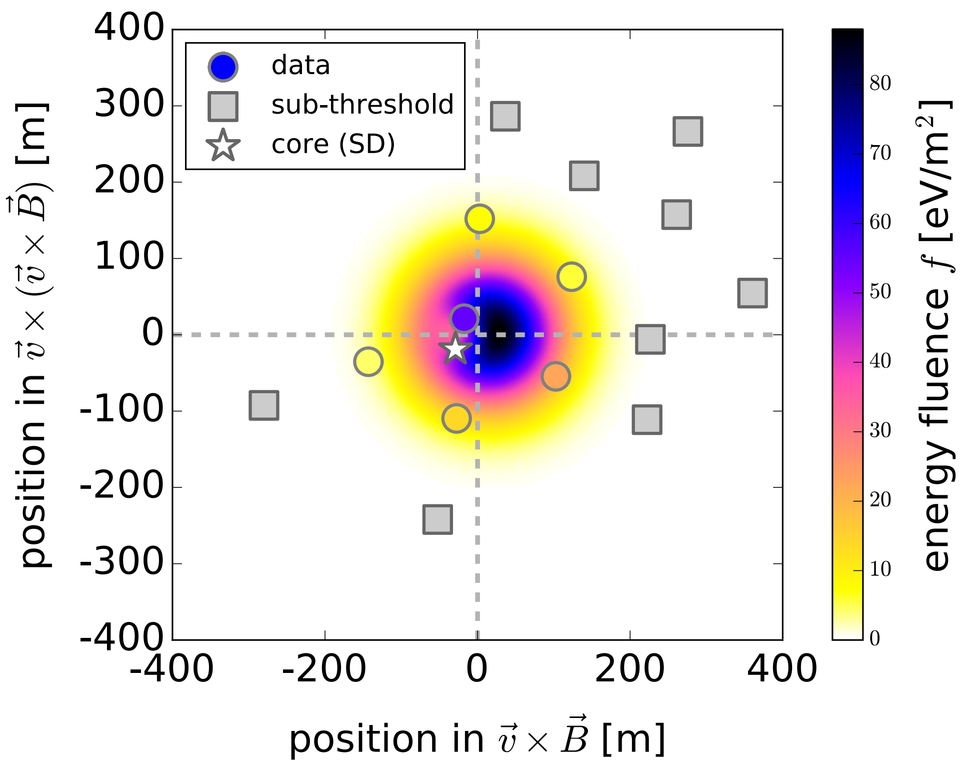
Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy

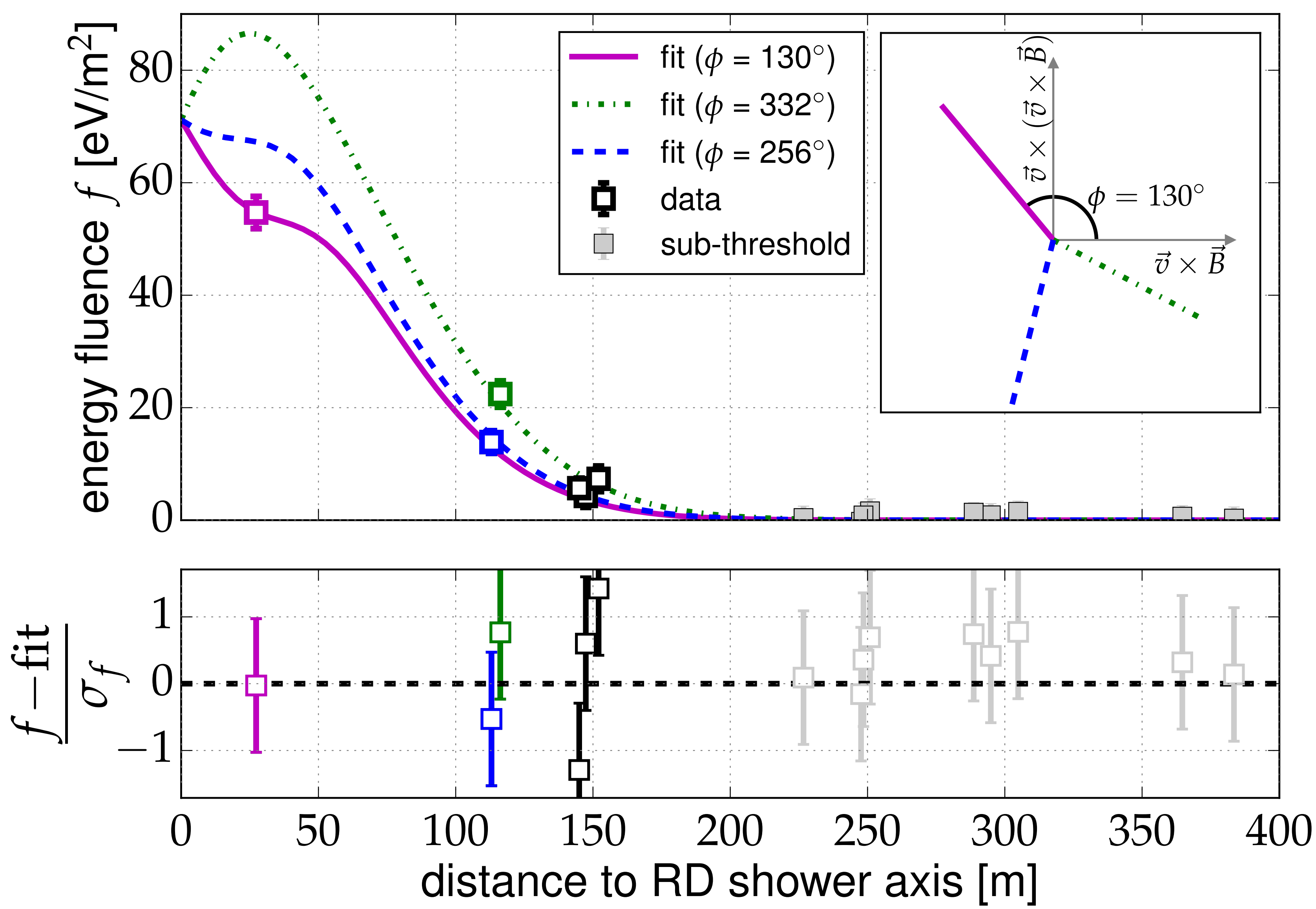


AERA
Auger Engineering Radio Array

A. Aab et al., PRL 116 (2016) no.24, 241101

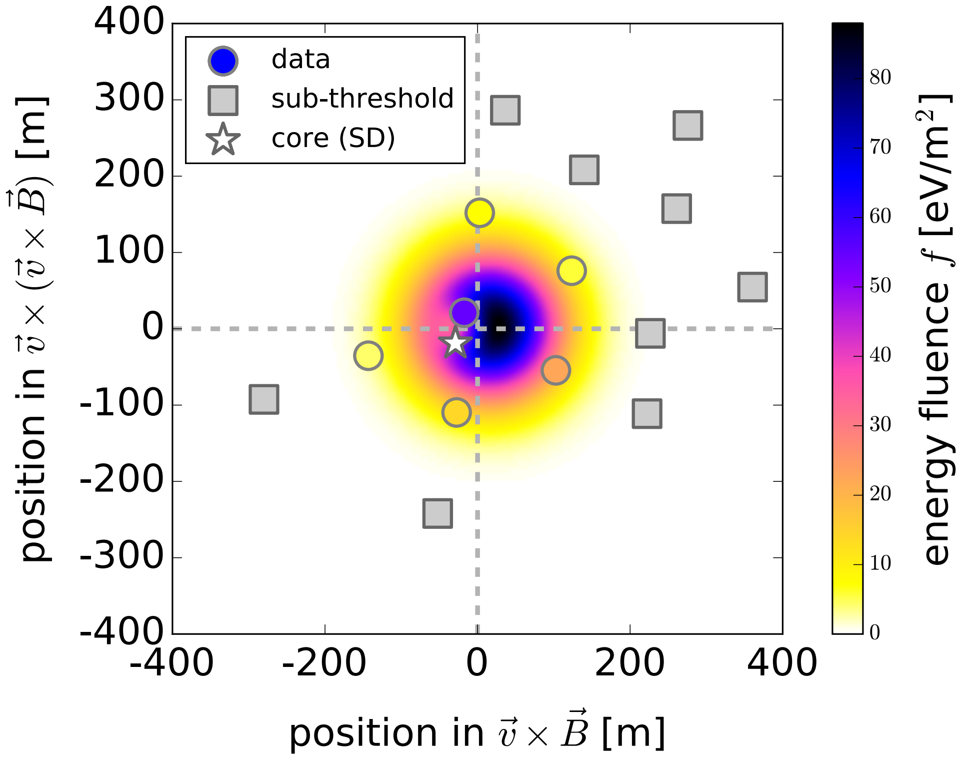
Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy

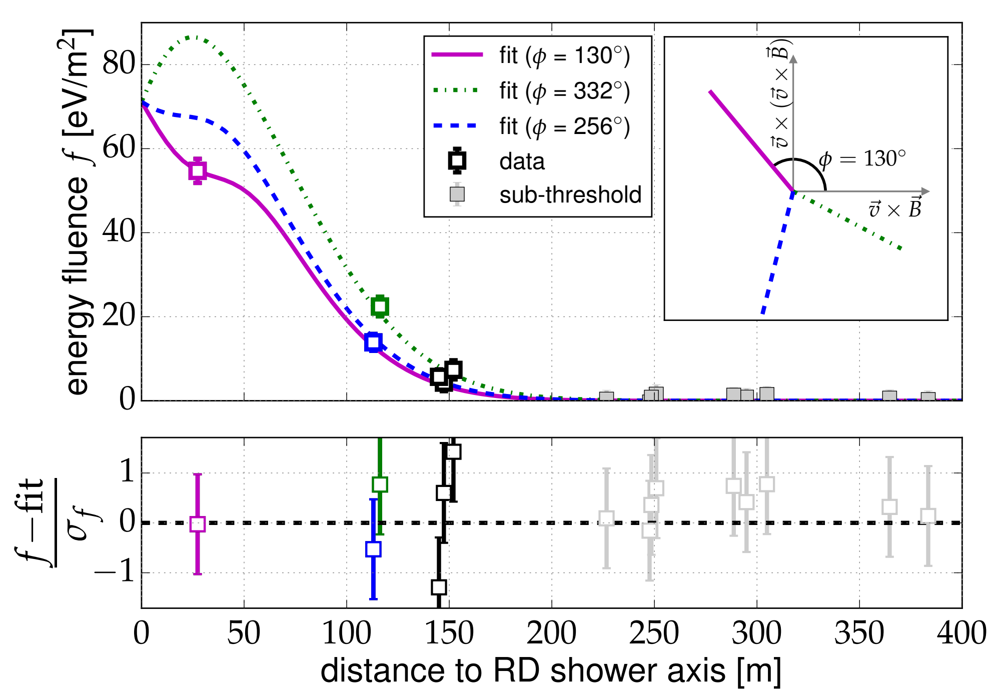




A. Aab et al., PRL 116 (2016) no.24, 241101

Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy

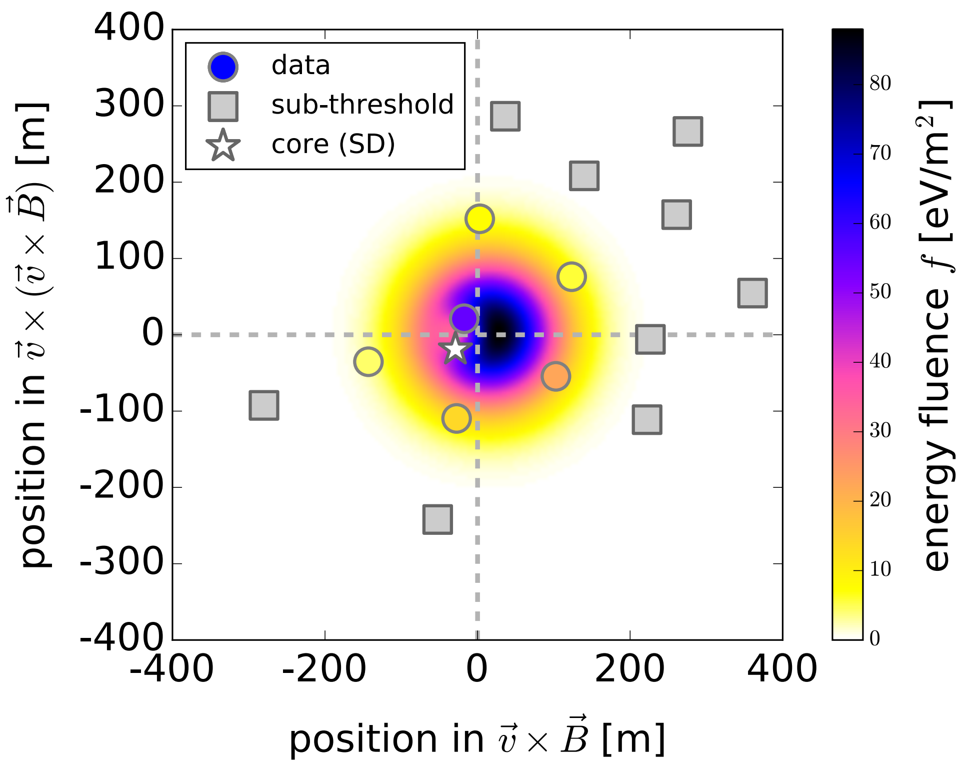


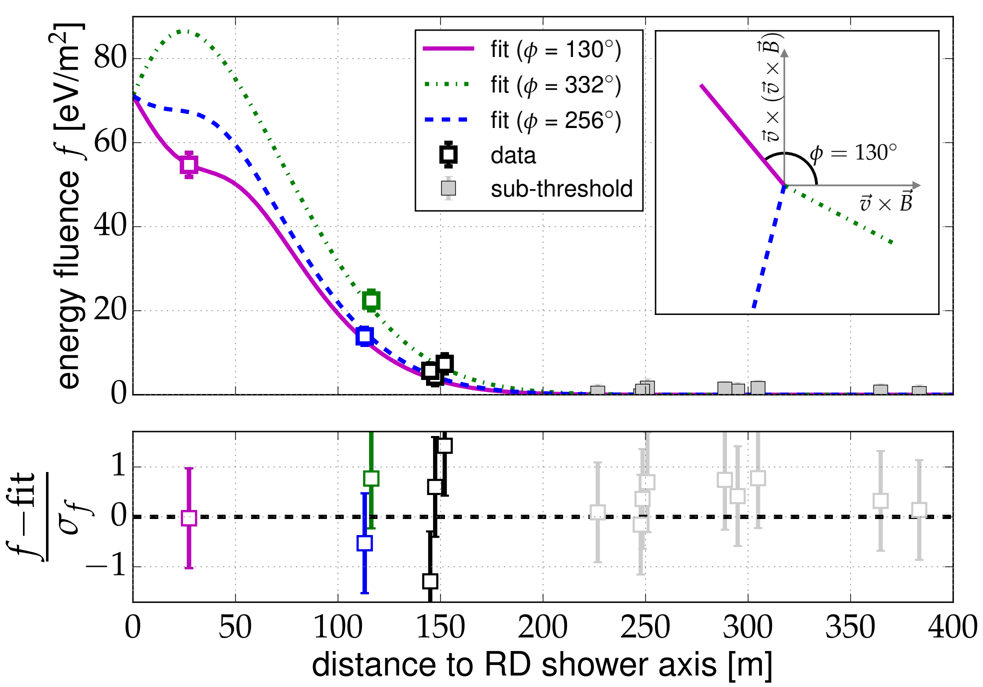


Auger Engineering Radio Array

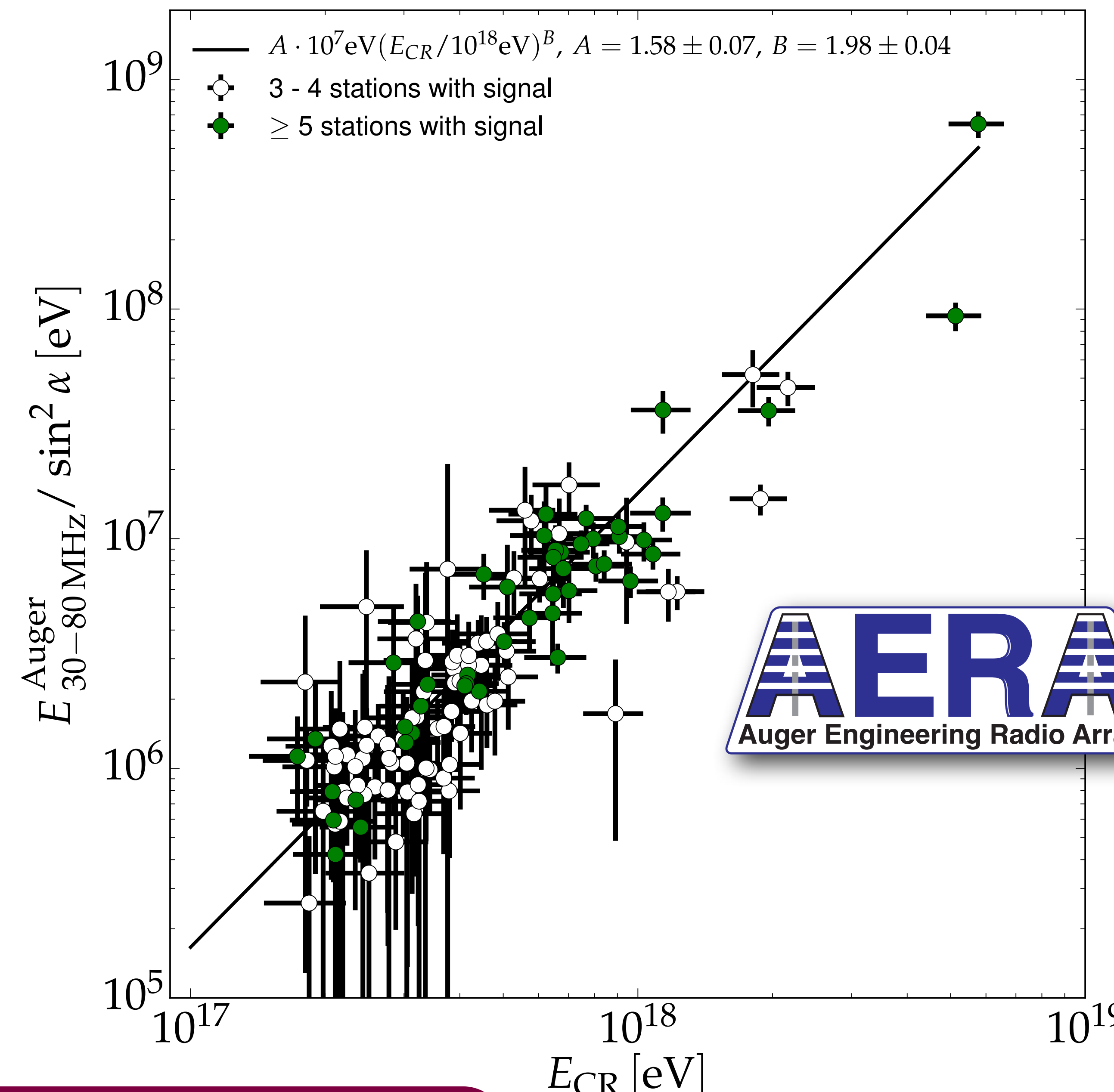
A. Aab et al., PRL 116 (2016) no.24, 241101

Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy





$E_{30\text{-}80}$ MHz = 15.8 MeV @ 10^{18} eV



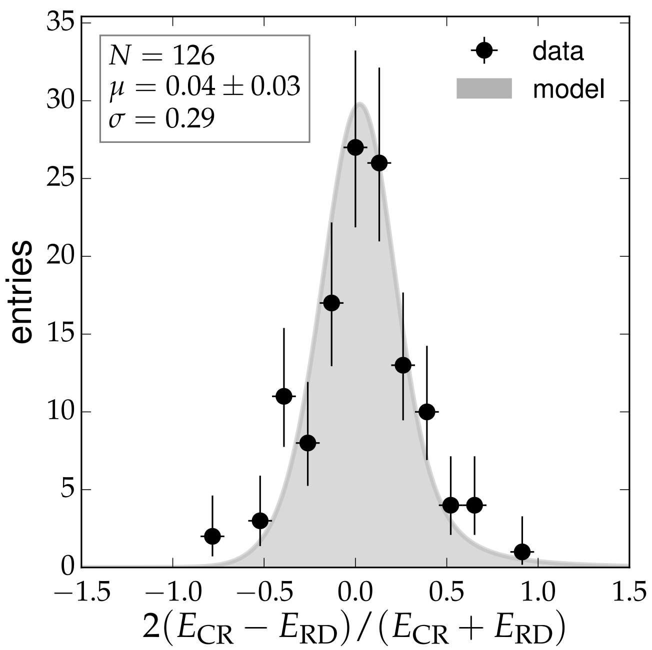
Auger Engineering Radio Array

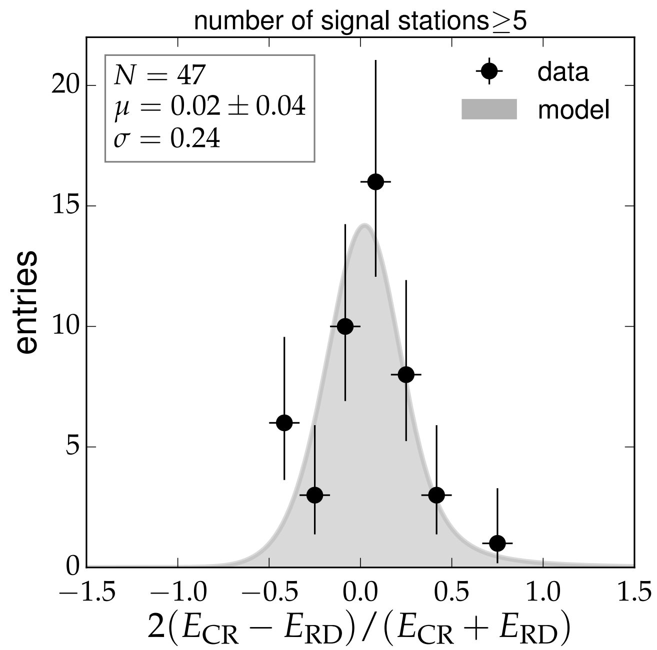
$$E_{30\text{-}80\ \mathrm{MHz}} = (15.8 \pm 0.7(\mathrm{stat}) \pm 6.7(\mathrm{syst})\ \mathrm{MeV}) \times \left(\sin\alpha \frac{E_{CR}}{10^{18}\ \mathrm{eV}} \frac{B_{Earth}}{0.24\ \mathrm{G}}\right)^2$$

A. Aab et al., PRL 116 (2016) no.24, 241101

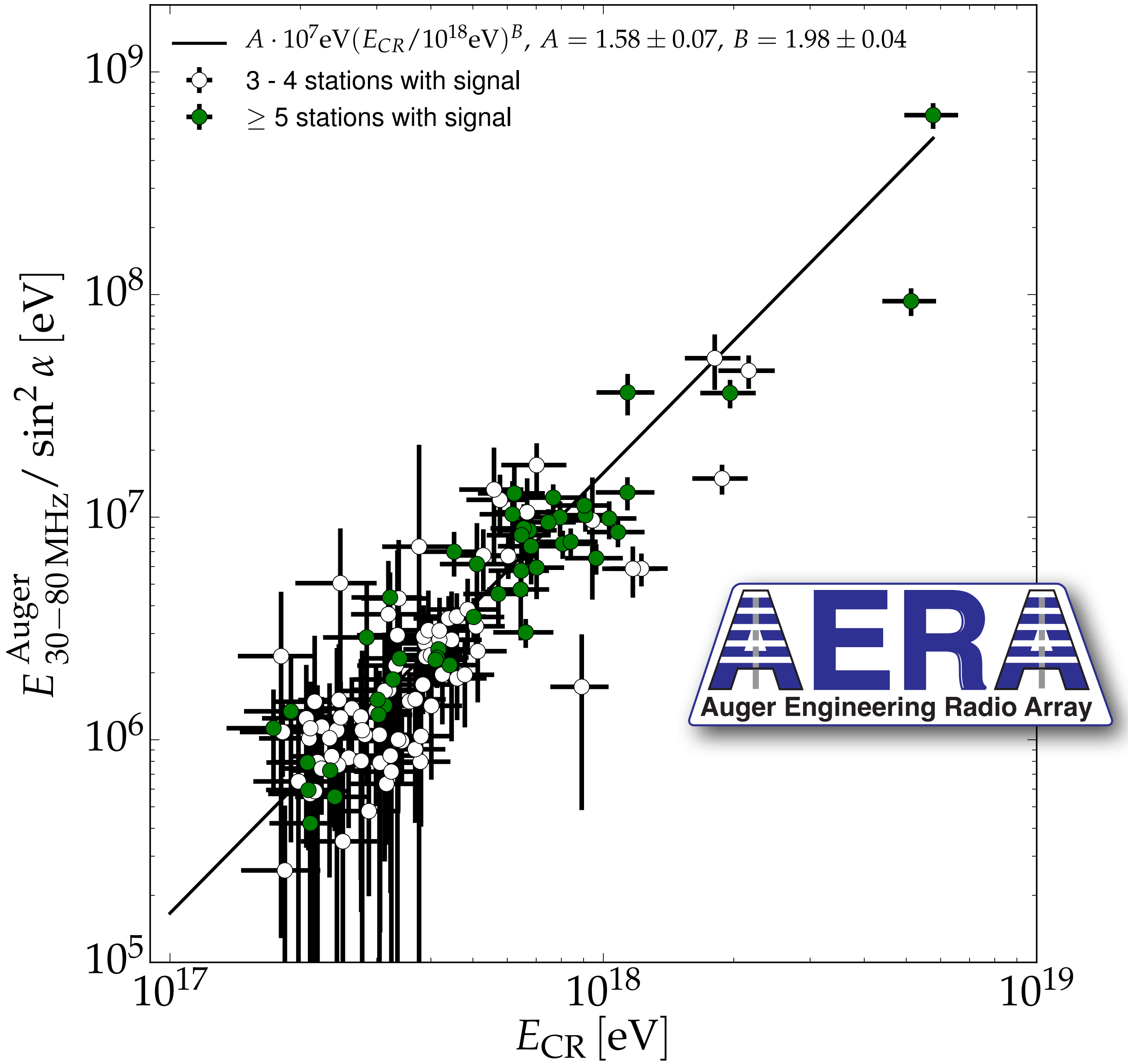
Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory

$E_{30\text{-}80}$ MHz = 15.8 MeV @ 10^{18} eV





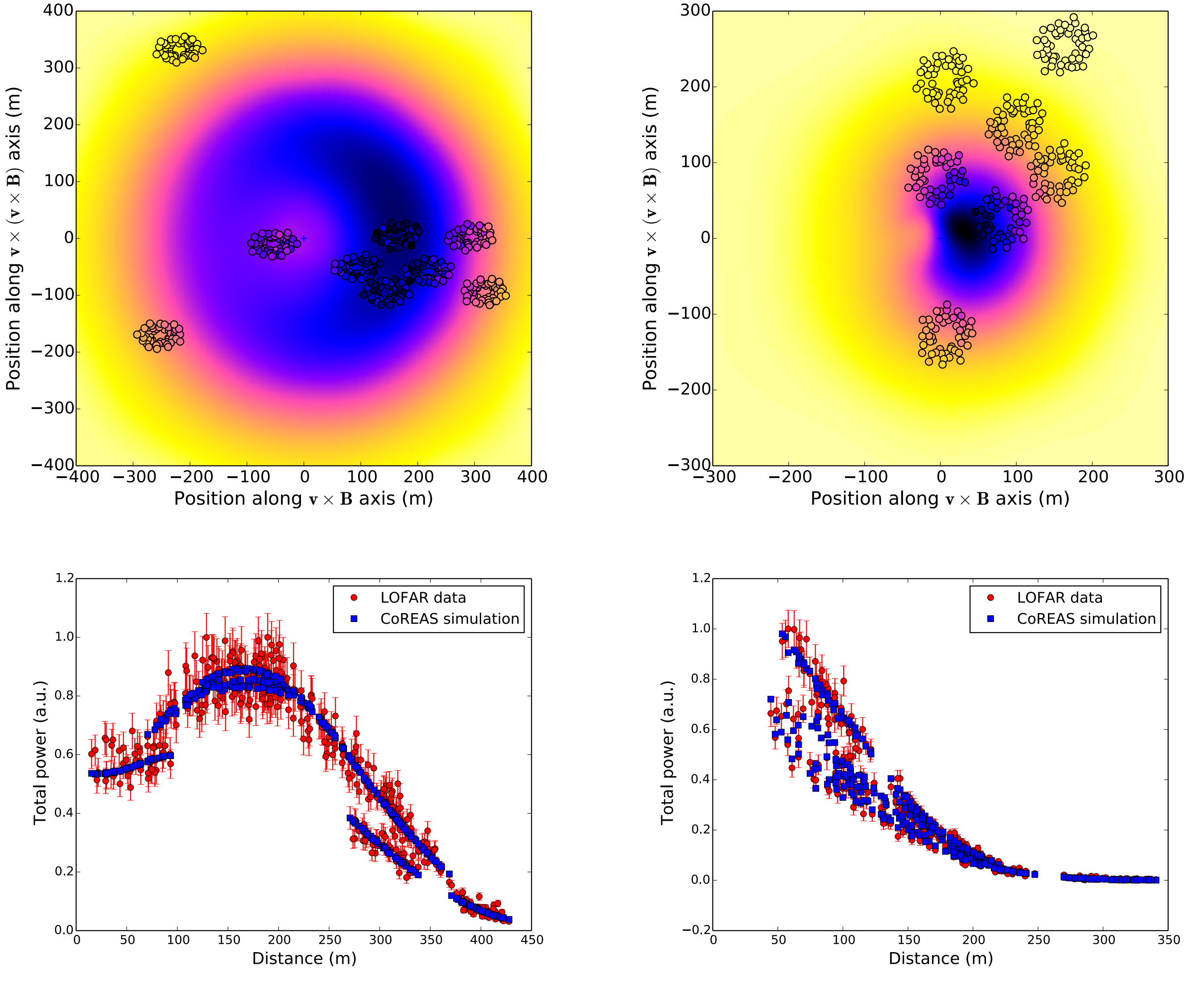
$$\sigma \approx 24\%$$



A. Aab et al., PRD 93 (2016) no.12, 122005

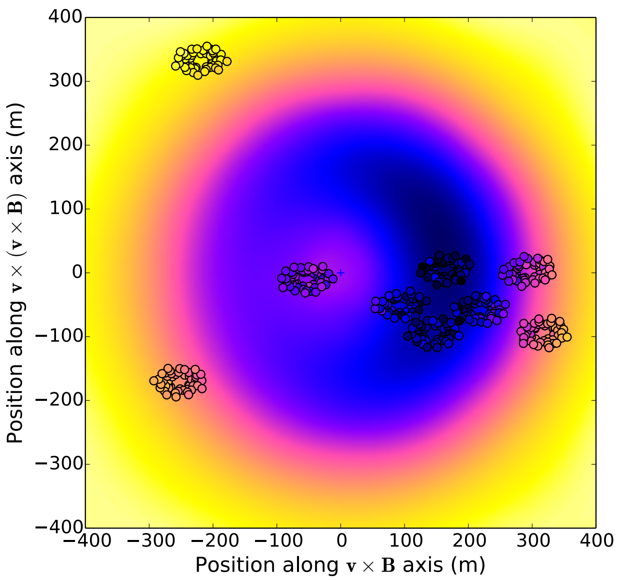
A. Aab et al., PRL 116 (2016) no.24, 241101

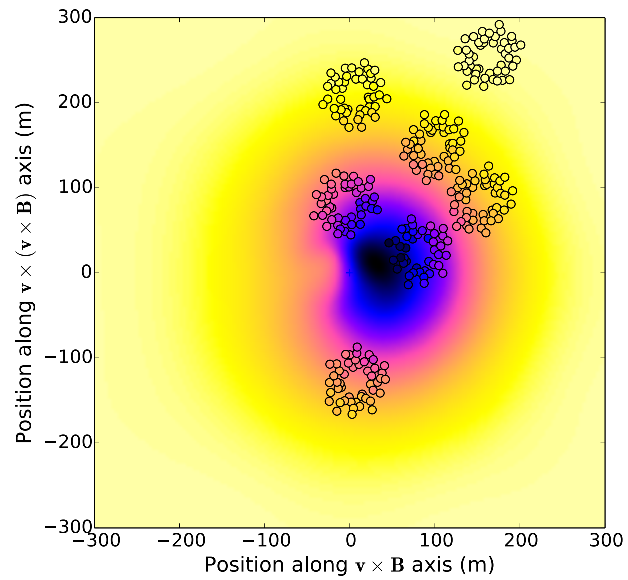
Measurement of particle mass

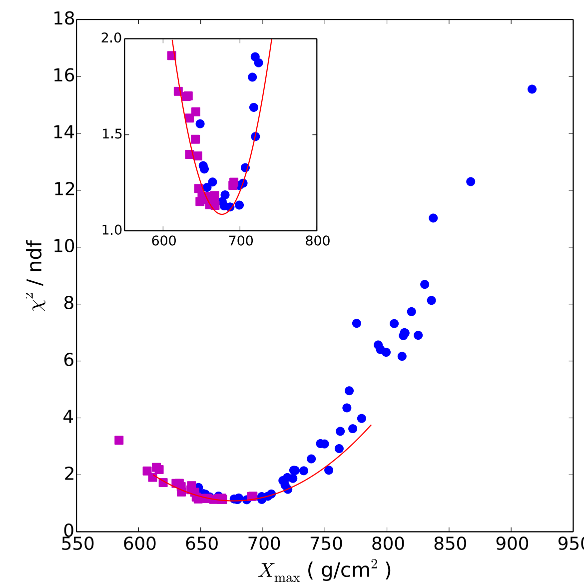


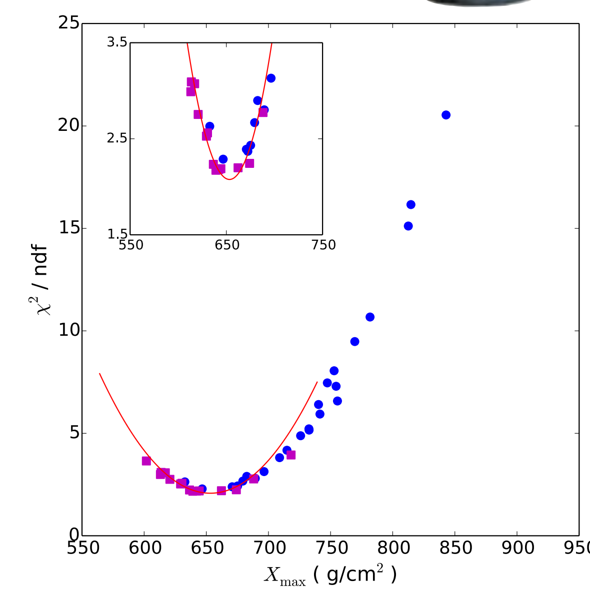
S. Buitink et al., PRD 90 (2014) 082003

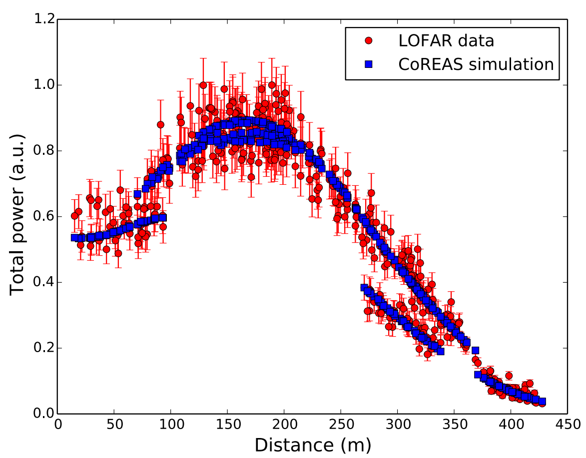
Measurement of particle mass

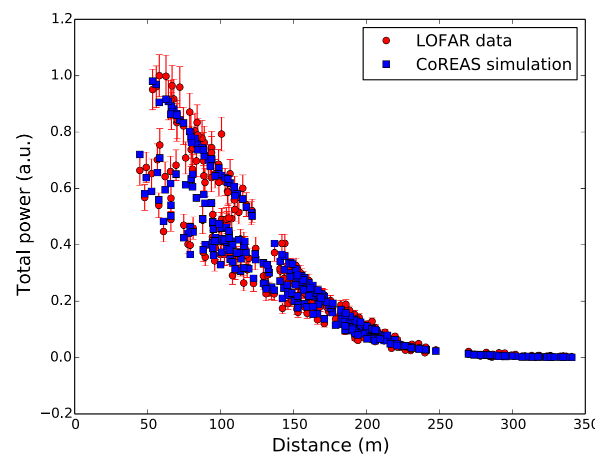






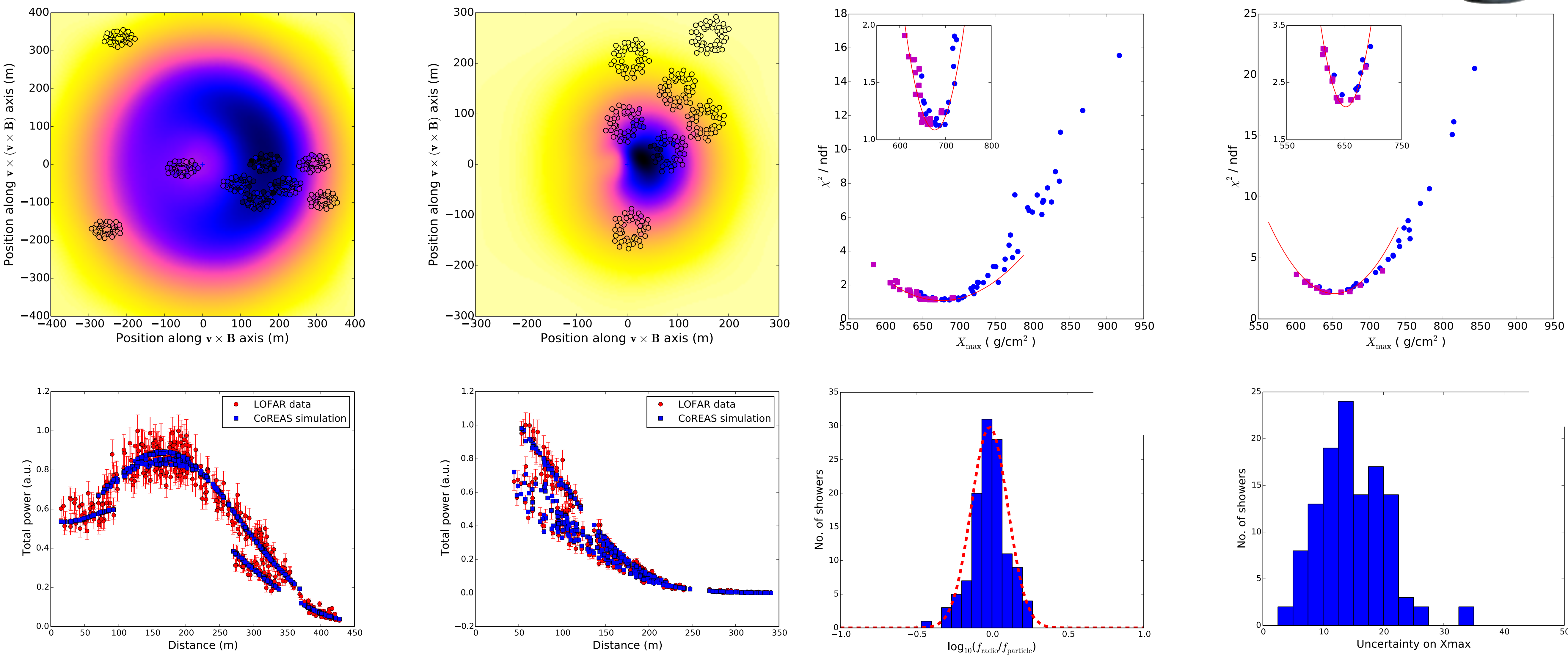






S. Buitink et al., PRD 90 (2014) 082003

Measurement of particle mass



$\sigma_E \approx 32\%$ $\sigma_{X_{max}} \approx 17\ \mathrm{g/cm^2}$

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

Depth of the shower maximum

LETTER nature
doi:10.1038/nature16976

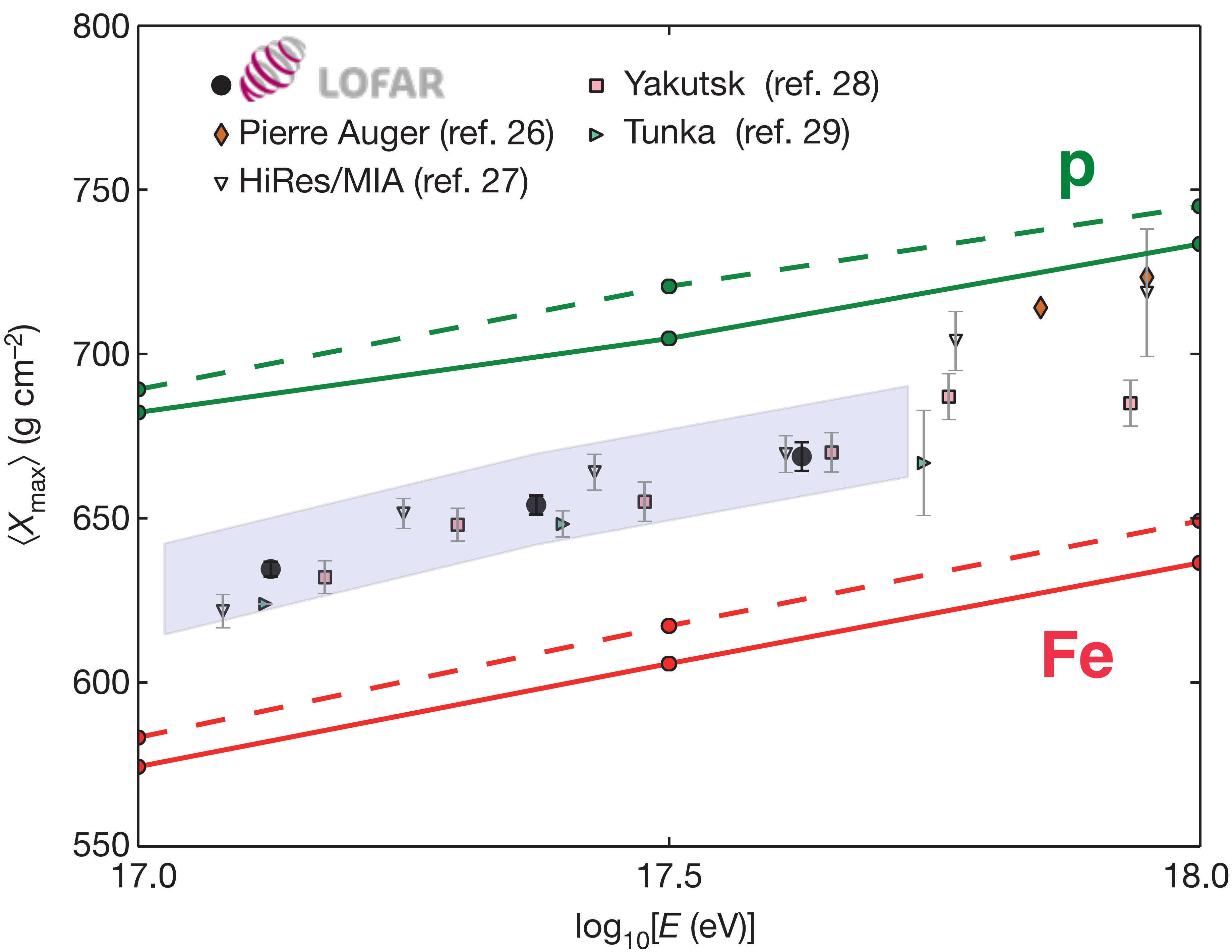
A large light-mass component of cosmic rays at 10^{17}–$10^{17.5}$ electronvolts from radio observations

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]

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 signal[1] comes from accelerators capable of producing cosmic rays of these energies[2]. Cosmic rays initiate air showers—cascades of secondary particles in the atmosphere—and their masses can be inferred from measurements of the atmospheric depth of the shower maximum[3] (X_{max}; the depth of the air shower when it contains the most particles) or of the composition of shower particles reaching the ground[4]. Current measurements[5] have either high uncertainty, or a low duty cycle and a high energy threshold. Radio detection of cosmic rays[6–8] is a rapidly developing technique[9] for determining X_{max} (refs 10, 11) with a duty cycle of, in principle, nearly 100 per cent. The radiation is generated by the separation of relativistic electrons and positrons in the geomagnetic field and a negative charge excess in the shower front[6,12]. Here we report radio measurements of X_{max} with a mean uncertainty of 16 grams per square centimetre for air showers 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 spectrum of the cosmic rays: we find a mixed composition, with a light-mass fraction (protons and helium nuclei) of about 80 per cent. Unless, contrary to current expectations, the extragalactic component of cosmic rays contributes substantially to the total flux below $10^{17.5}$ electronvolts, our measurements indicate the existence of an additional galactic component, to account for the light composition that we measured in the 10^{17}–$10^{17.5}$ electronvolt range.

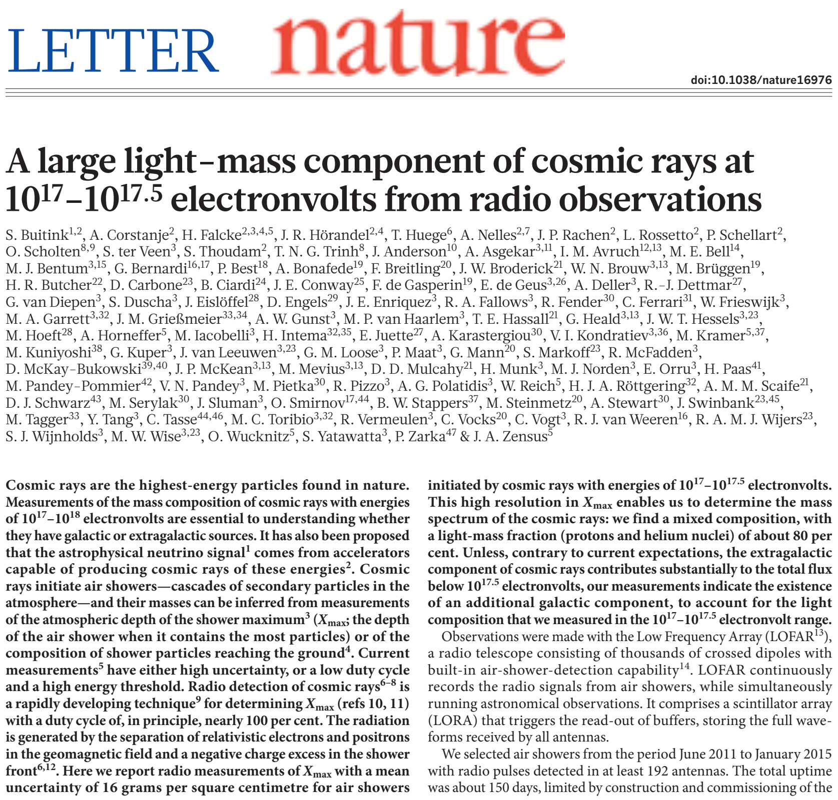
Observations were made with the Low Frequency Array (LOFAR[13]), a radio telescope consisting of thousands of crossed dipoles with built-in air-shower-detection capability[14]. LOFAR continuously records the radio signals from air showers, while simultaneously running astronomical observations. It comprises a scintillator array (LORA) that triggers the read-out of buffers, storing the full wave-forms received by all antennas.

We selected air showers from the period June 2011 to January 2015 with radio pulses detected in at least 192 antennas. The total uptime was about 150 days, limited by construction and commissioning of the



S. Buitink et al., Nature 531 (2016) 70

Depth of the shower maximum



LETTER nature

doi:10.1038/nature16976

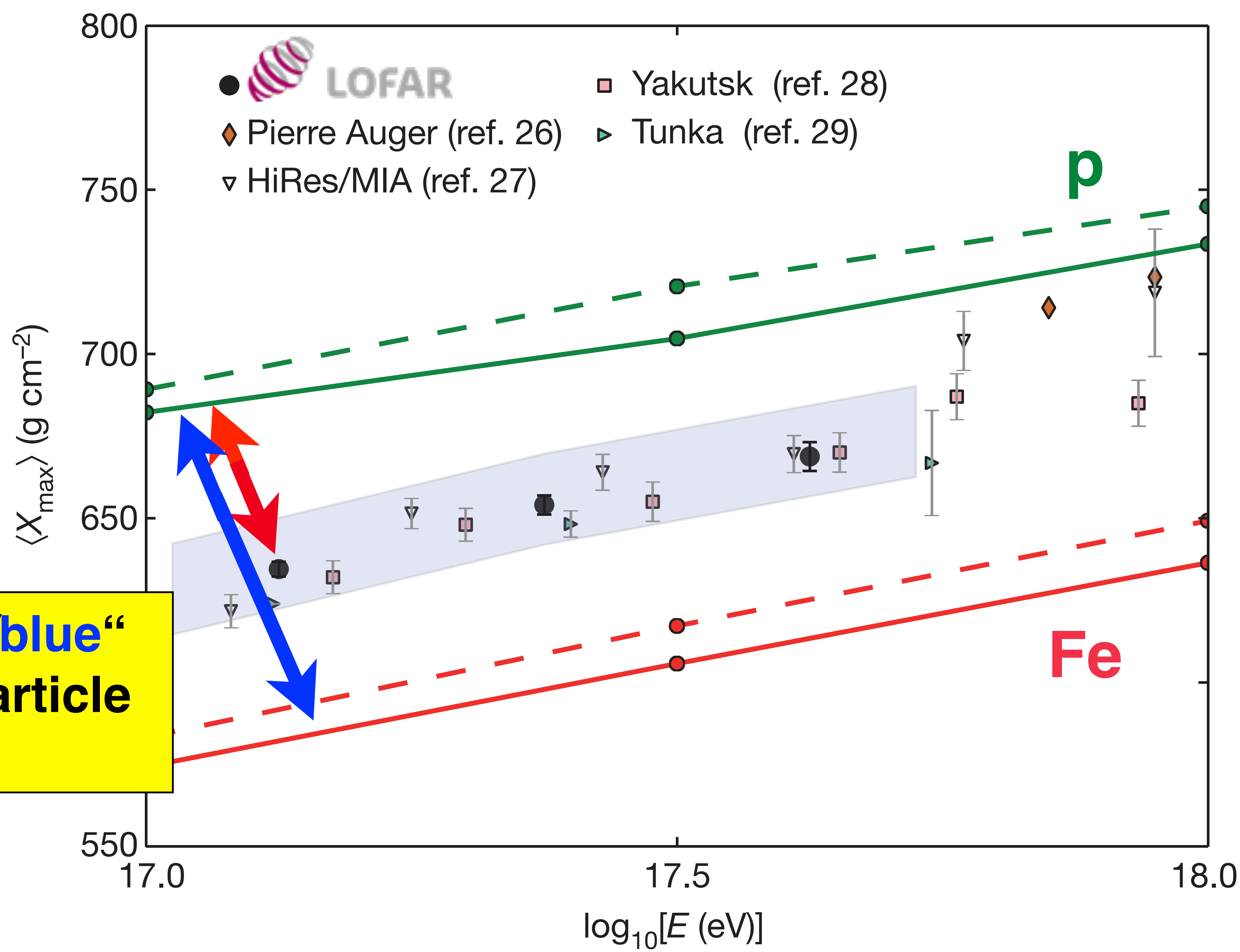
A large light-mass component of cosmic rays at 10^{17}–$10^{17.5}$ electronvolts from radio observations

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]

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 signal[1] comes from accelerators capable of producing cosmic rays of these energies[2]. Cosmic rays initiate air showers—cascades of secondary particles in the atmosphere—and their masses can be inferred from measurements of the atmospheric depth of the shower maximum[3] (X_{max}; the depth of the air shower when it contains the most particles) or of the composition of shower particles reaching the ground[4]. Current measurements[5] have either high uncertainty, or a low duty cycle and a high energy threshold. Radio detection of cosmic rays[6–8] is a rapidly developing technique[9] for determining X_{max} (refs 10, 11) with a duty cycle of, in principle, nearly 100 per cent. The radiation is generated by the separation of relativistic electrons and positrons in the geomagnetic field and a negative charge excess in the shower front[6,12]. Here we report radio measurements of X_{max} with a mean uncertainty of 16 grams per square centimetre for air showers 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 spectrum of the cosmic rays: we find a mixed composition, with a light-mass fraction (protons and helium nuclei) of about 80 per cent. Unless, contrary to current expectations, the extragalactic component of cosmic rays contributes substantially to the total flux below $10^{17.5}$ electronvolts, our measurements indicate the existence of an additional galactic component, to account for the light composition that we measured in the 10^{17}–$10^{17.5}$ electronvolt range.

Observations were made with the Low Frequency Array (LOFAR[13]), a radio telescope consisting of thousands of crossed dipoles with built-in air-shower-detection capability[14]. LOFAR continuously records the radio signals from air showers, while simultaneously running astronomical observations. It comprises a scintillator array (LORA) that triggers the read-out of buffers, storing the full wave-forms received by all antennas.

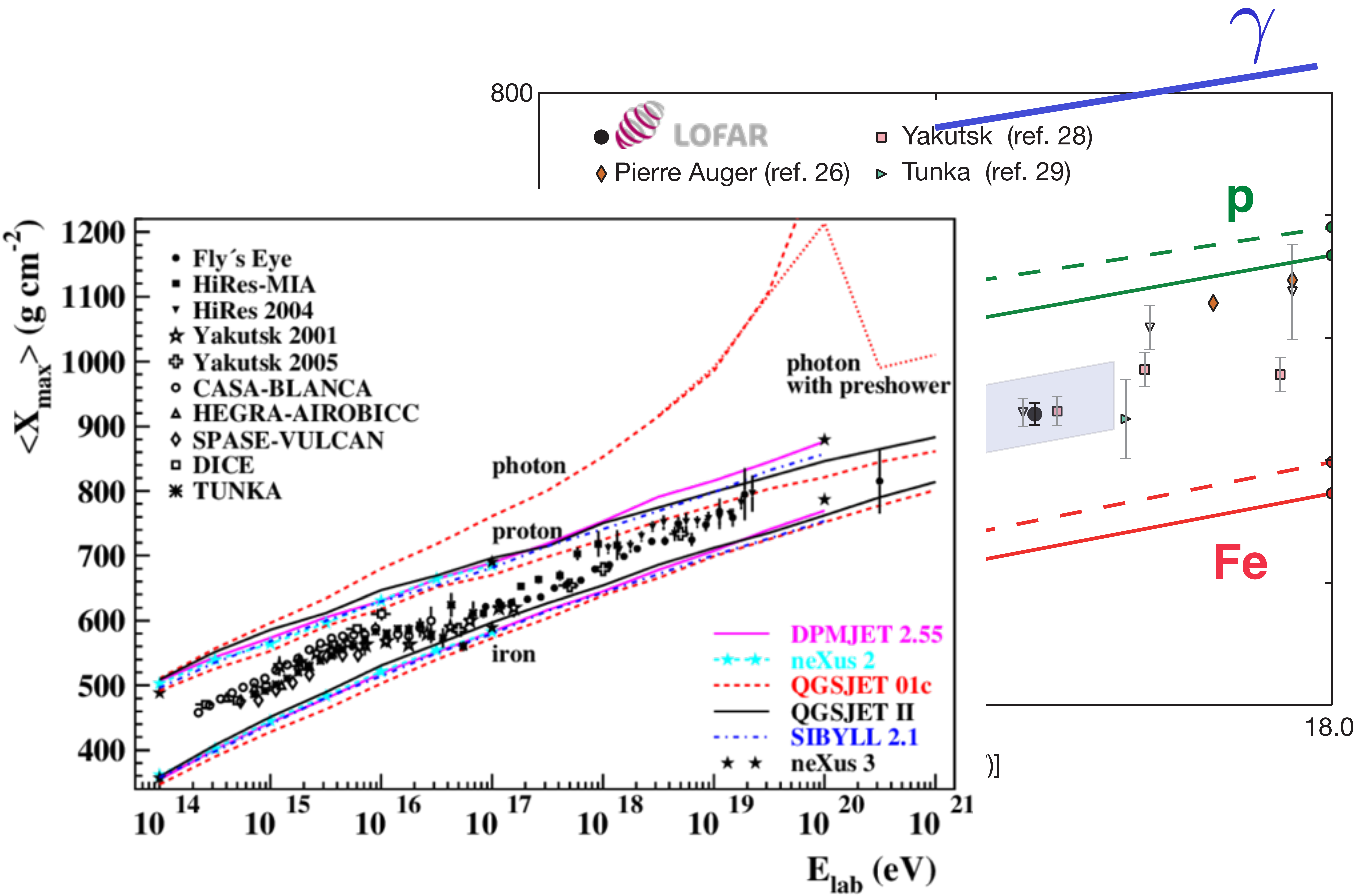
We selected air showers from the period June 2011 to January 2015 with radio pulses detected in at least 192 antennas. The total uptime was about 150 days, limited by construction and commissioning of the



relative distance "red/blue" is measure for ln A (particle type)

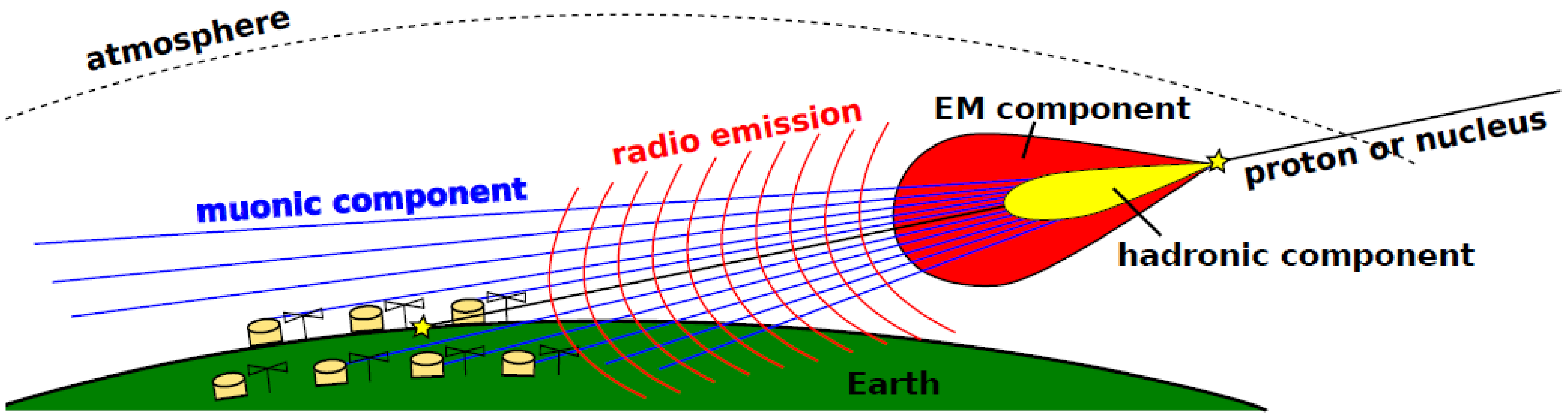
S. Buitink et al., Nature 531 (2016) 70

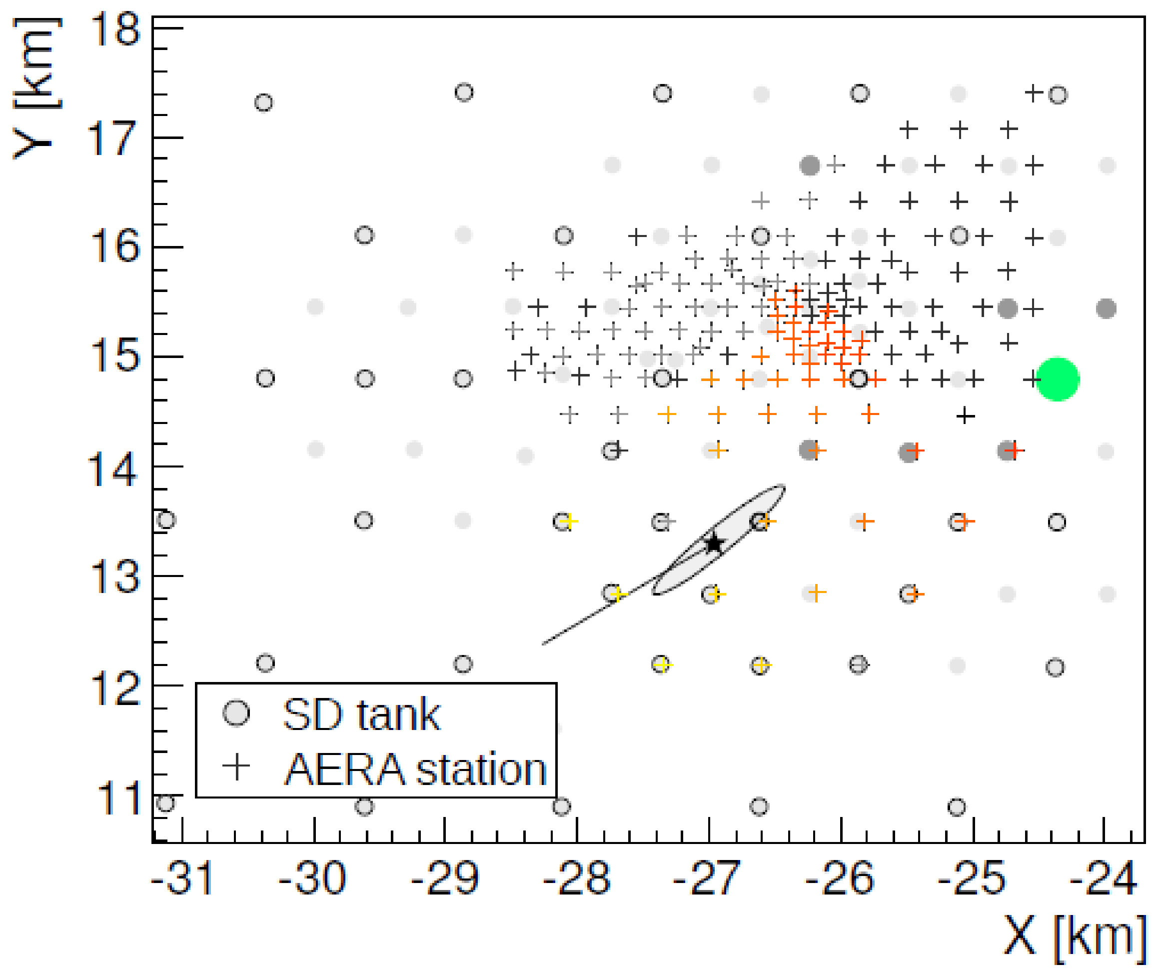
Depth of the shower maximum

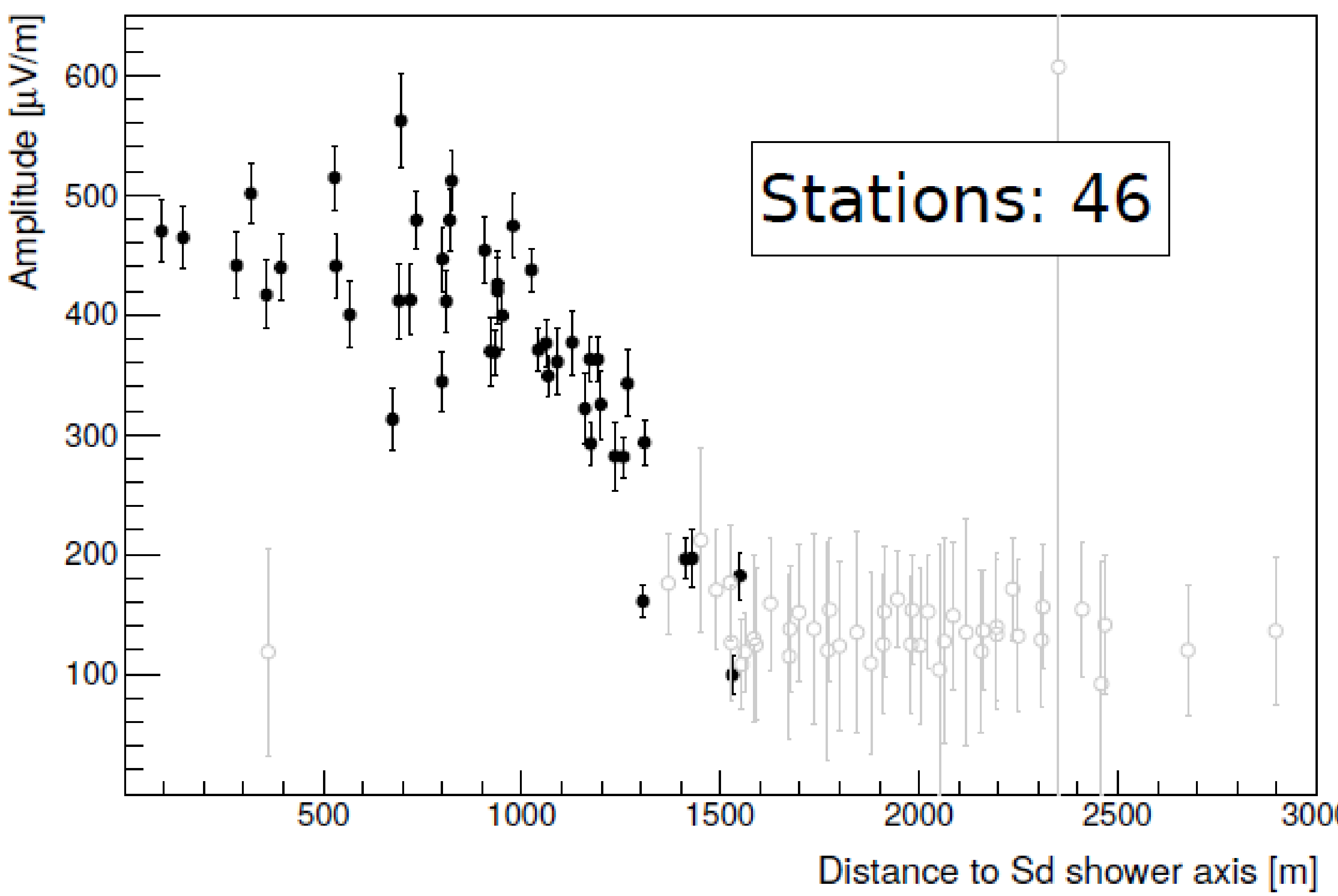


Horizontal Air Showers

large footprint
several km²







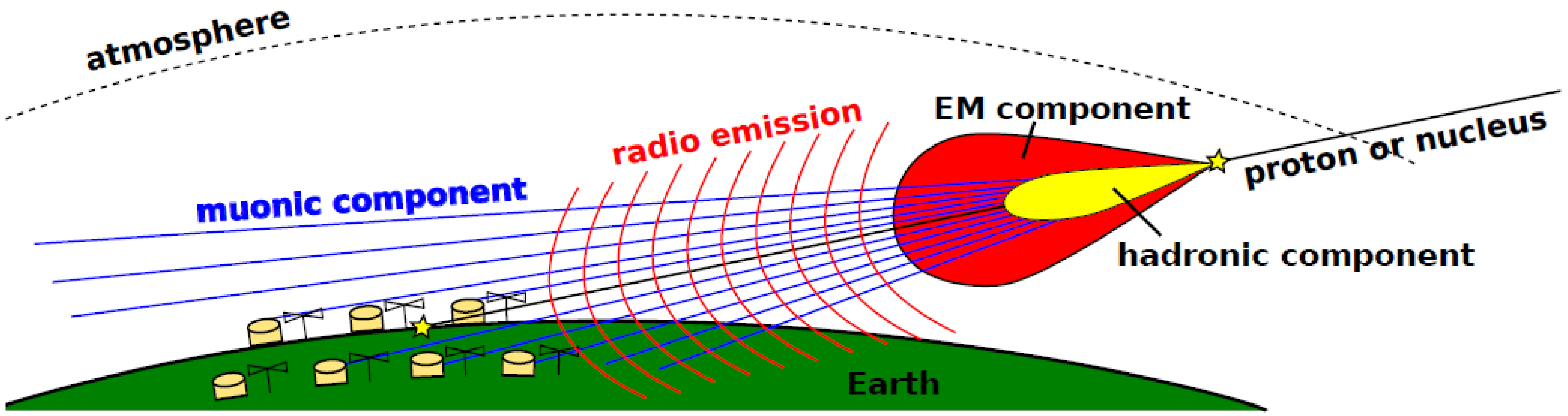
in shower plane

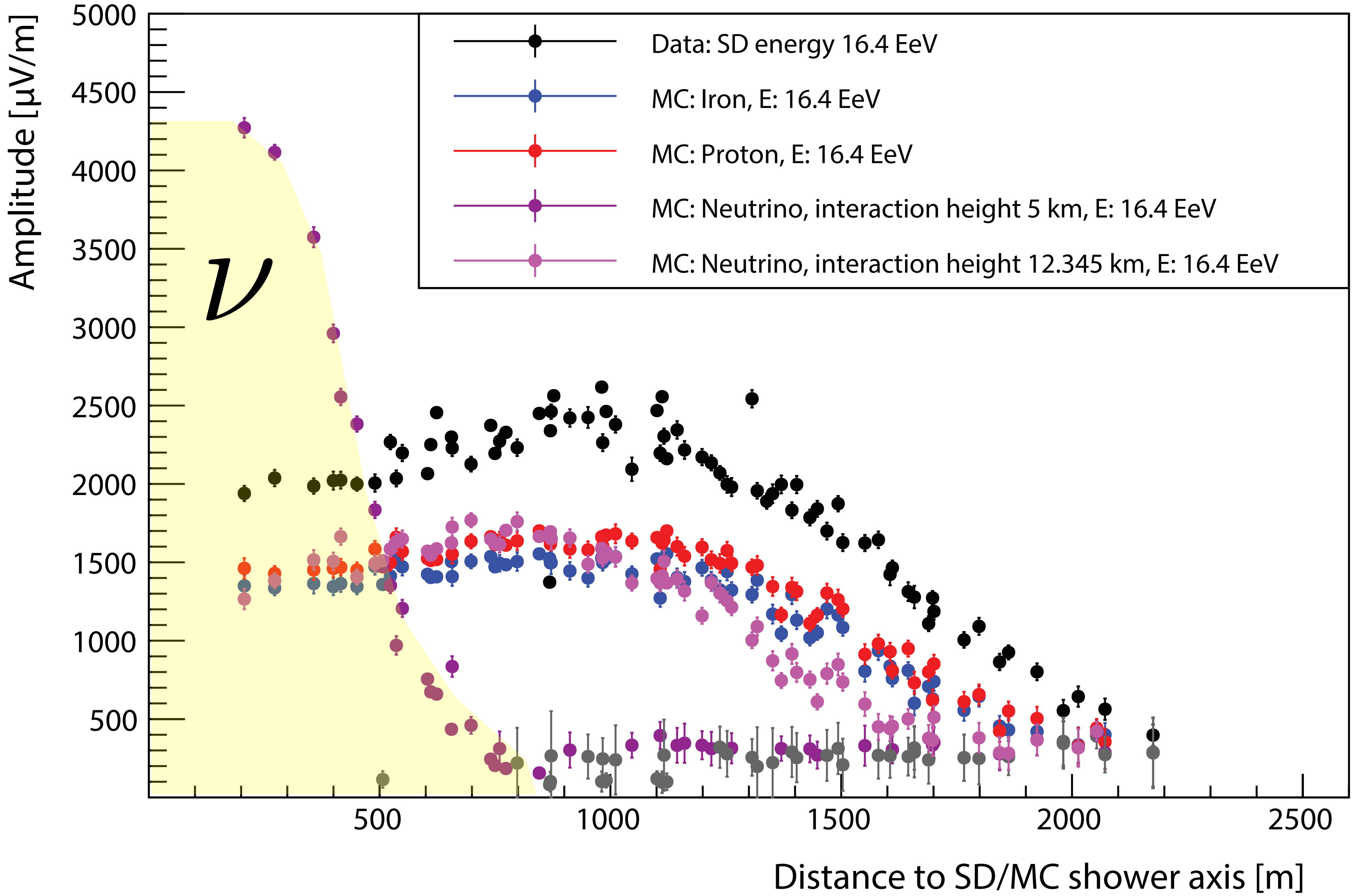
O. Kambeitz, ARENA (2016)

Horizontal Air Showers

AERA
Auger Engineering Radio Array

large footprint several km²





can be used to identify neutrinos

O. Kambeitz, ARENA (2016)

LOFAR
Cosmic Rays & PIERRE AUGER OBSERVATORY AERA Auger Engineering Radio Array

could contribute to AMON by

- **detecting air showers in time and/or spatial coincidence with external signal (offline correlation or realtime trigger)**

- **provide particle type (isolate gamma rays and/or neutrinos)**

How can we contribute with LOFAR and the Pierre Auger Observatory/AERA to AMON multi-messenger observations?

LOFAR Transients

- **issuing triggers to others (low-frequency [30-240 MHz] transient events)**
- **receiving external triggers (implemented for ksp CRs to read out radio antennas after particle detector trigger)**

LOFAR Cosmic Rays

AERA – Auger Engineering Radio Array

- **detecting air showers in time and/or spatial coincidence with external signal (offline correlation or realtime trigger)**
- **provide particle type (isolate gamma rays and/or neutrinos)**