Radio detection of air showers with LOPES and LOFAR

Next-Generation Techniques for UHE Astroparticle Physics

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European Research Council

Vrije Universiteit Brussel

KVI university of groningen

KIT Karlsruhe Institute of Technology

Radboud Universiteit Nijmegen

for the LOFAR Cosmic Ray KSP
& LOPES collaboration

A short history

- 1960s: First emission theory charge excess (Askaryan 1962) and geomagnetic radiation (Kahn & Lerche 1967)
- 1970s: Detections by multiple experiments. Efforts are abandoned due to inadequate hardware & theoretical uncertainties.
- 2002: Falcke & Gorham revisit theory (geosynchrotron approach). New interest.
- 2003+: LOPES (LOFAR prototype station) detects air shower in radio, other experiments follow
- Now: detailed understanding of radiation mechanism. Large experiments: LOFAR, AERA (Auger), Tunka-rex

(see review paper: T. Huege, Phys. Reports, arXiv:1601.07426)

LOPES

CODALEMA

LOFAR

AERA (Auger)

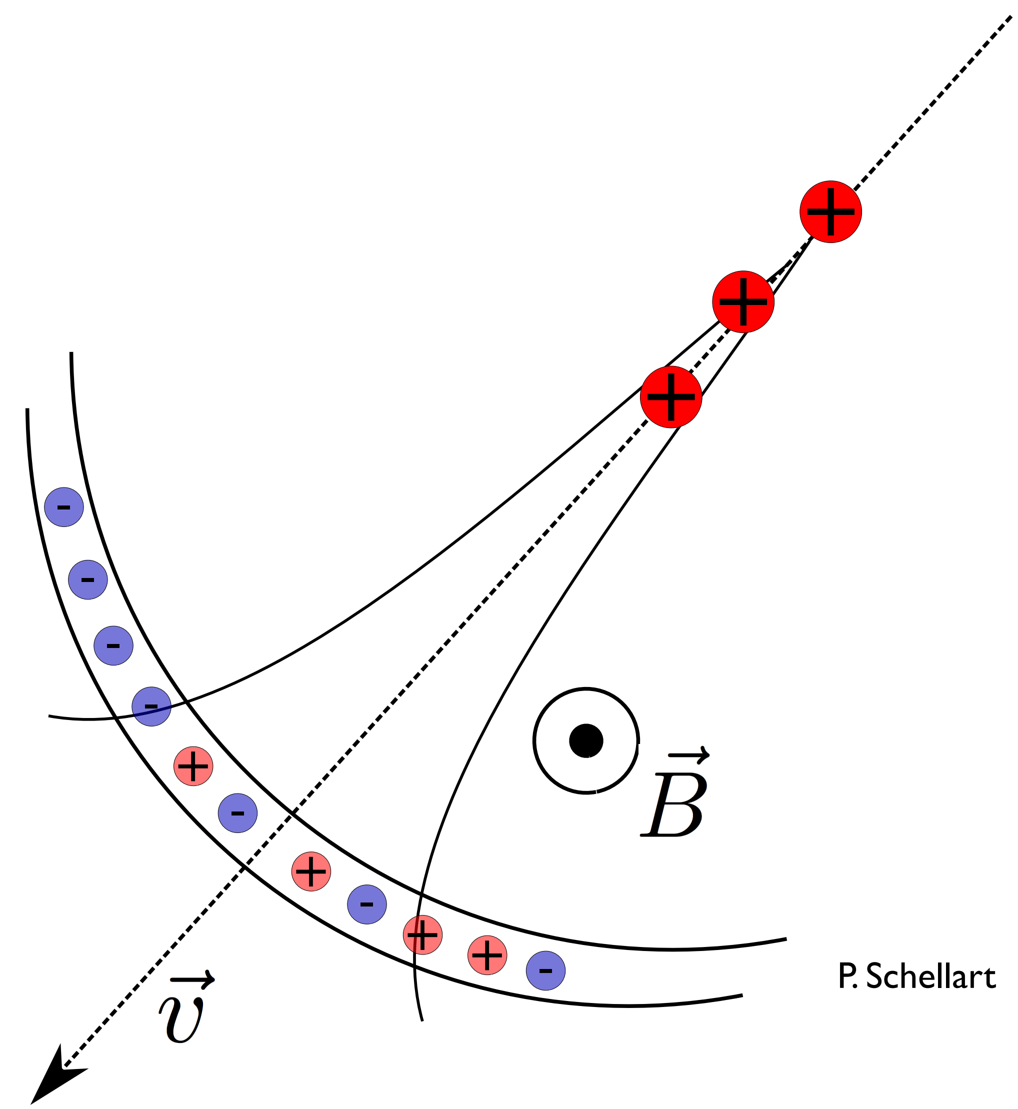
Tunka-REX

What drives the radio emission?

- <u>Earth magnetic field</u>
  electrons/positrons deflected
  $E \sim dn_{ch}/dt$

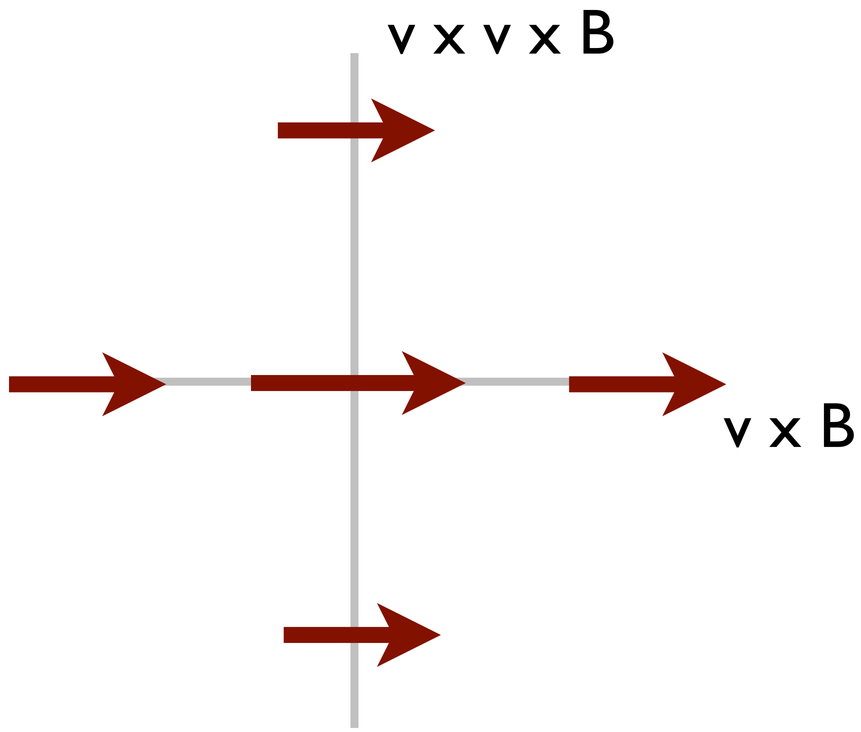
- <u>Charge excess</u>
  negative charge due to electron knockouts
  $E \sim d(n_e - n_p)/dt$

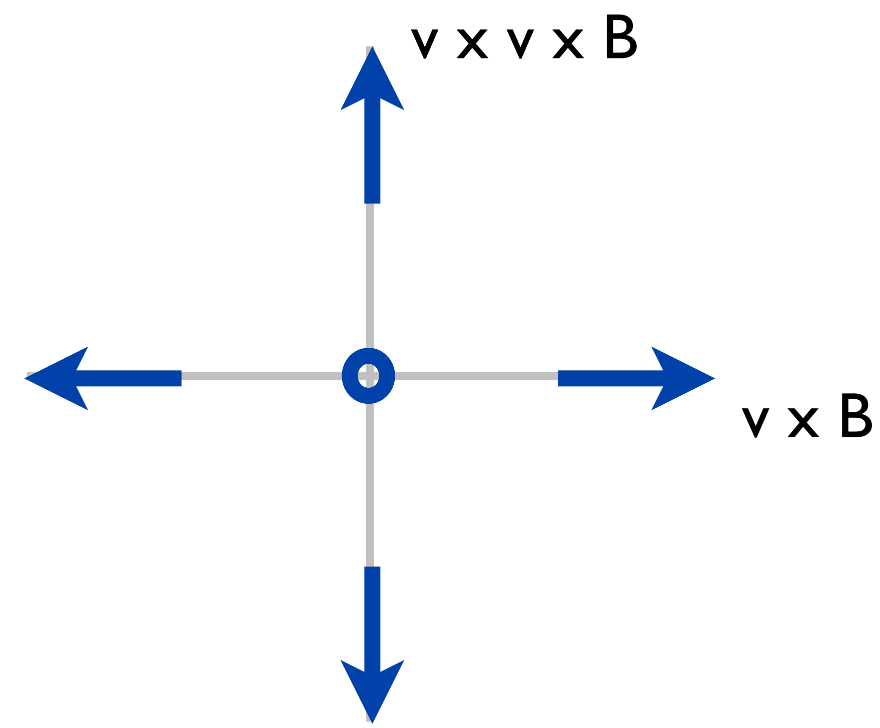
- <u>Non-unity index of refraction</u>
  Cherenkov-like effects
  ring structure possible



Coherent at 100 MHz (higher at Cherenkov angle!)
wavelength > shower front size
$P \sim n^2$

The radio footprint





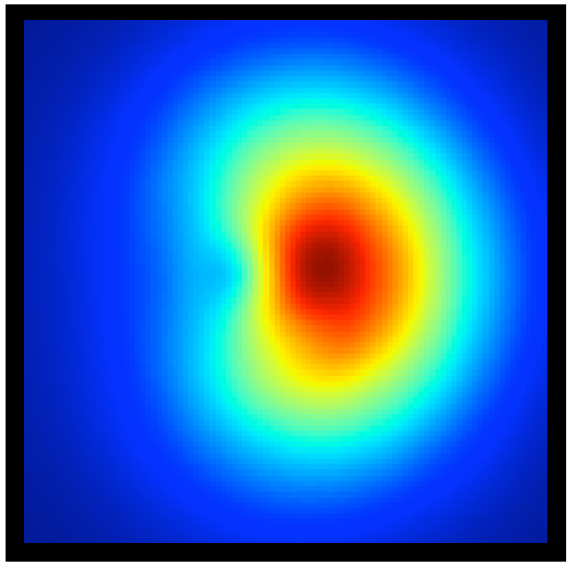
vector sum of geomagnetic and charge excess component

relativistic beaming

Cherenkov-like propagation effects (n≠1)

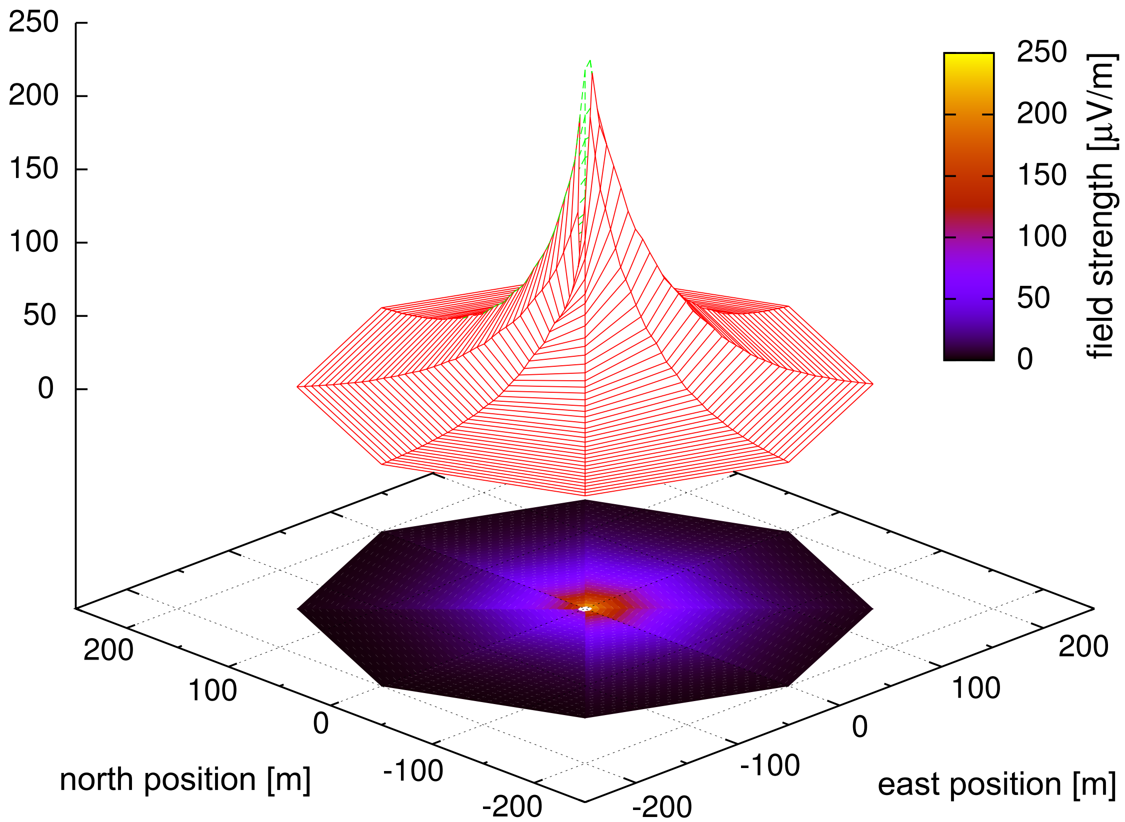
CoREAS: Huege et al. AIP Conf Proc 128-132 (2013)

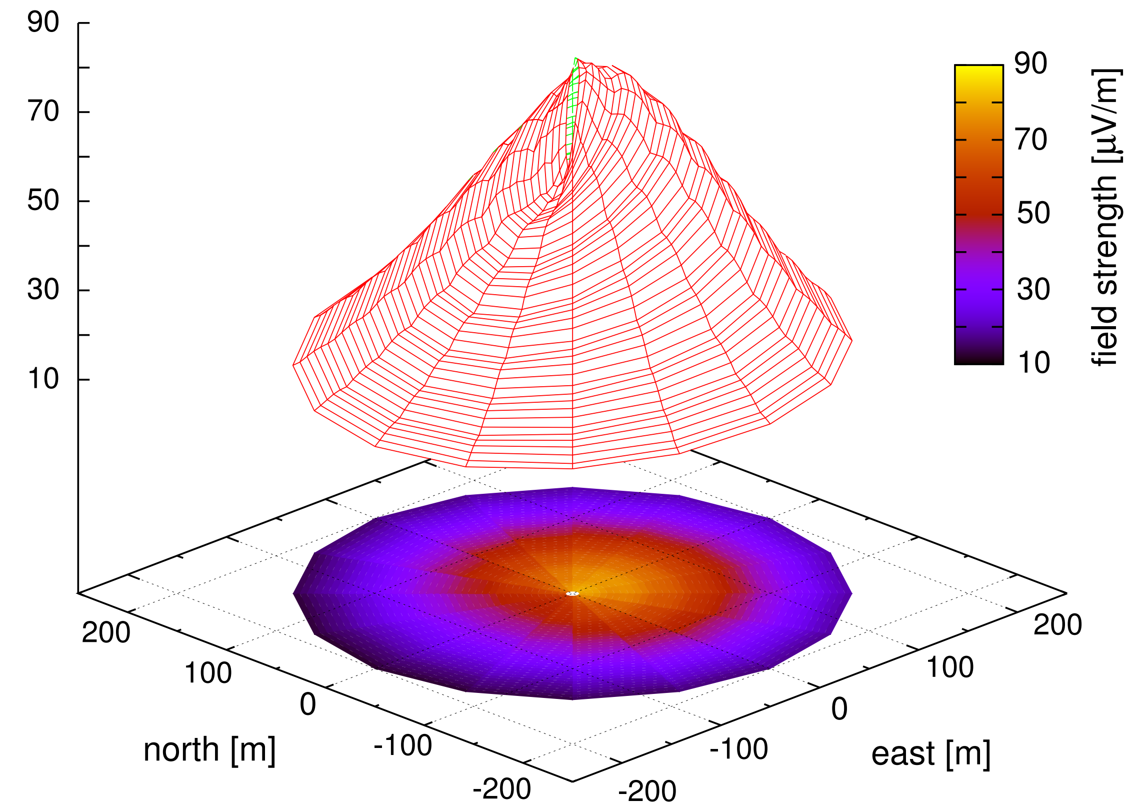
- plugin for CORSIKA
- calculates contribution from each particle
- based on first principles
  (no assumption on emission mechanism)



Measuring Xmax

Xmax = atmopsheric slant depth of shower maximum (g/cm²)





Coreas simulations - Tim Huege

proton primary
high Xmax

iron primary
low Xmax

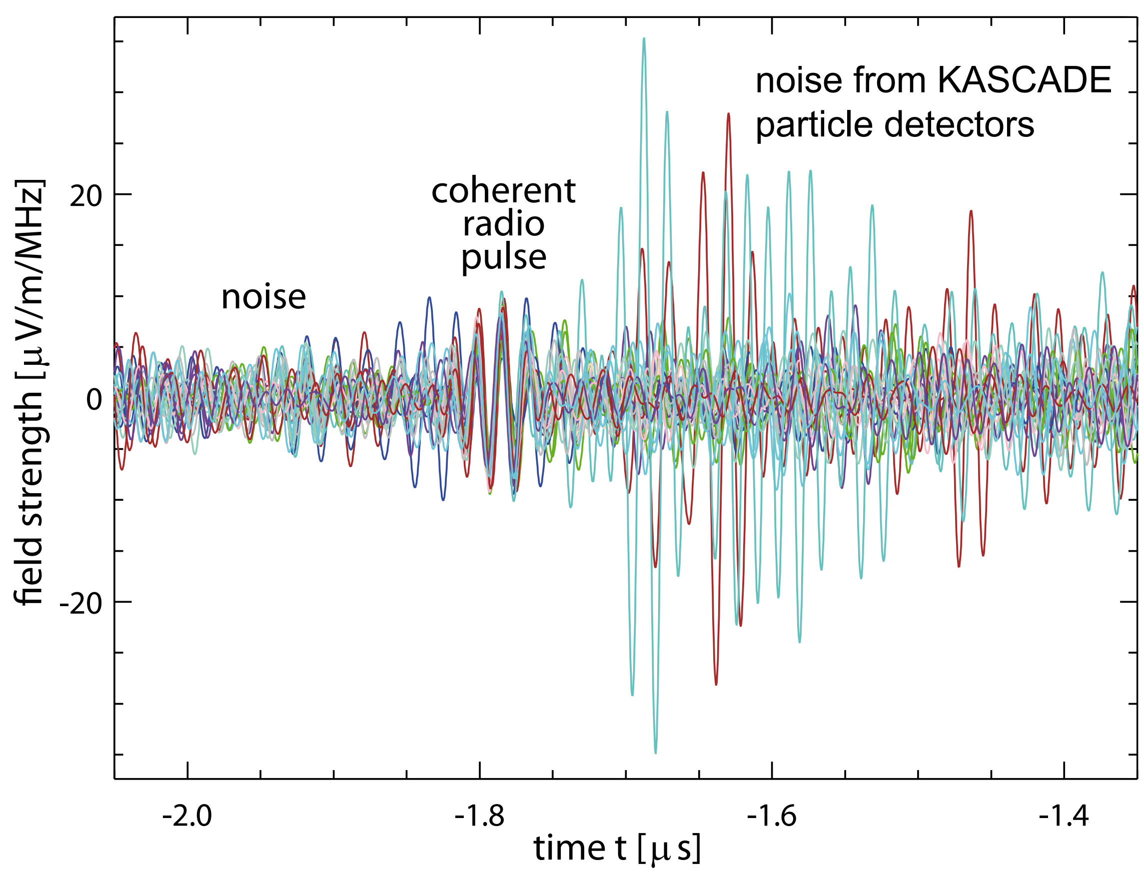
1D approach: measure slope (LOPES)
2D approach: fit complete profile (LOFAR)

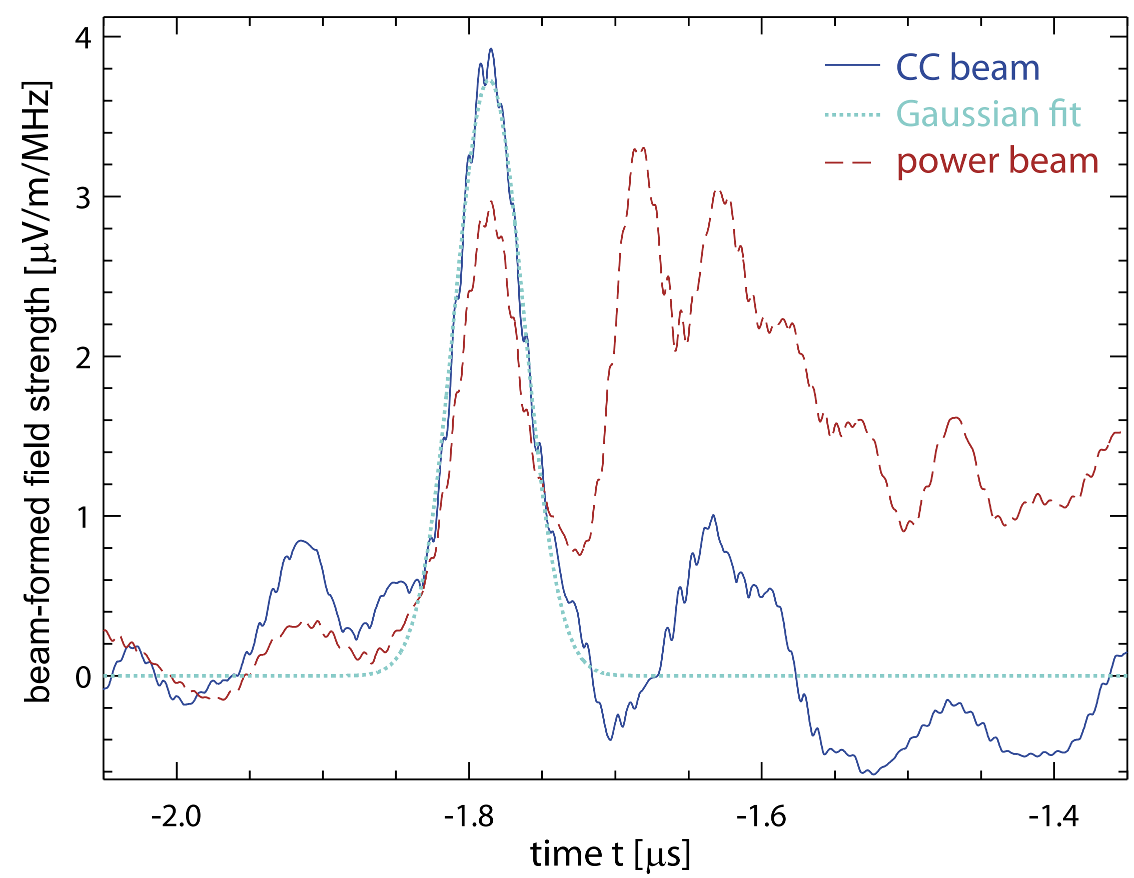
LOPES

co-located with KASCADE

30 prototype LOFAR antennas (40-80 MHz)

direction resolution < 1°





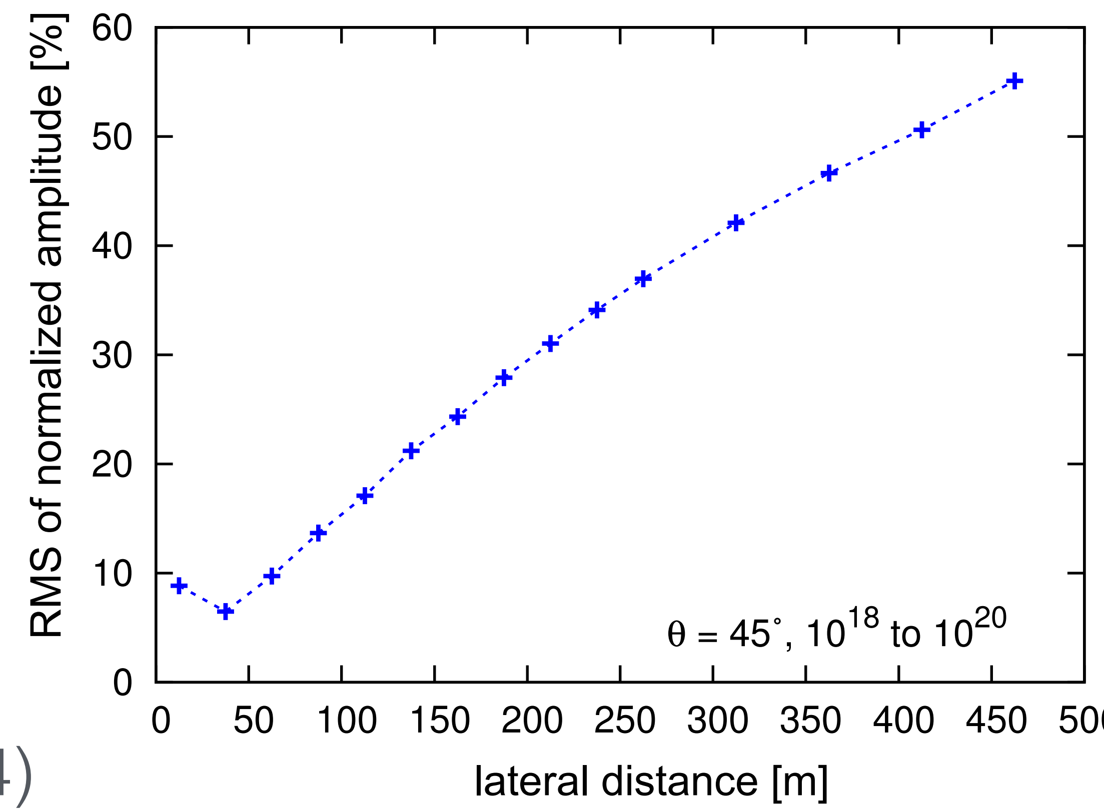
Falcke et al. Nature **435**, 313 (2005)

LOPES - energy

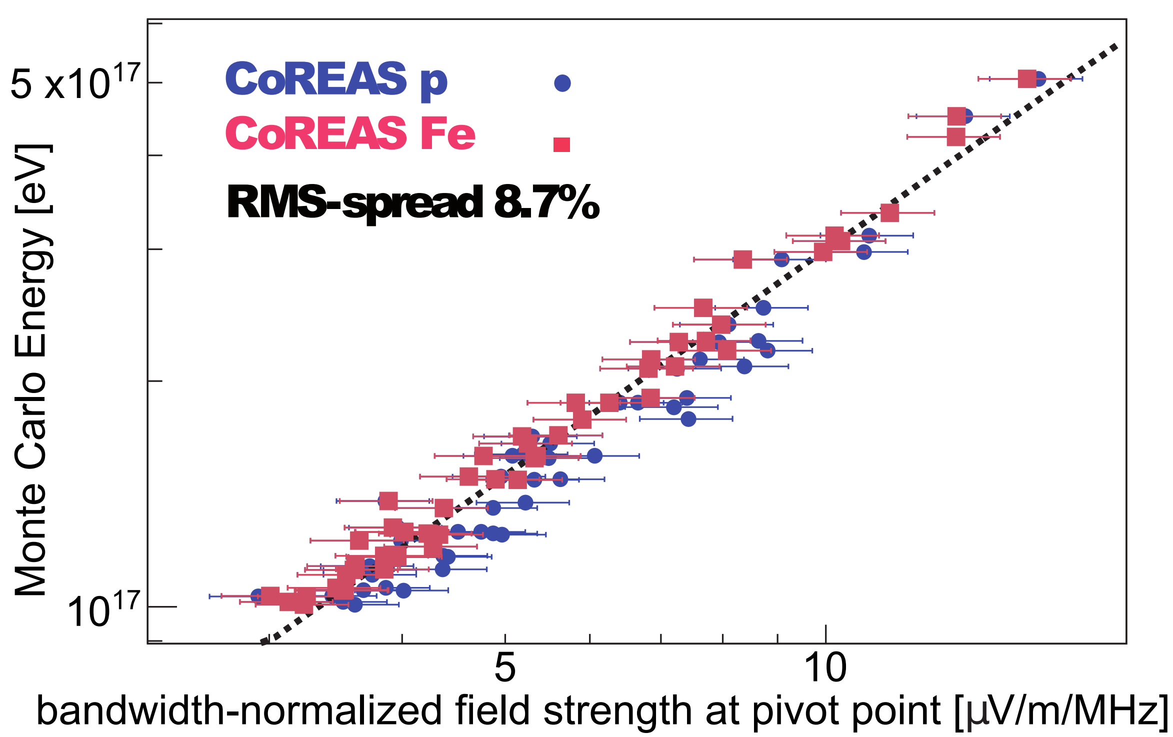
Analysis at “pivot point”

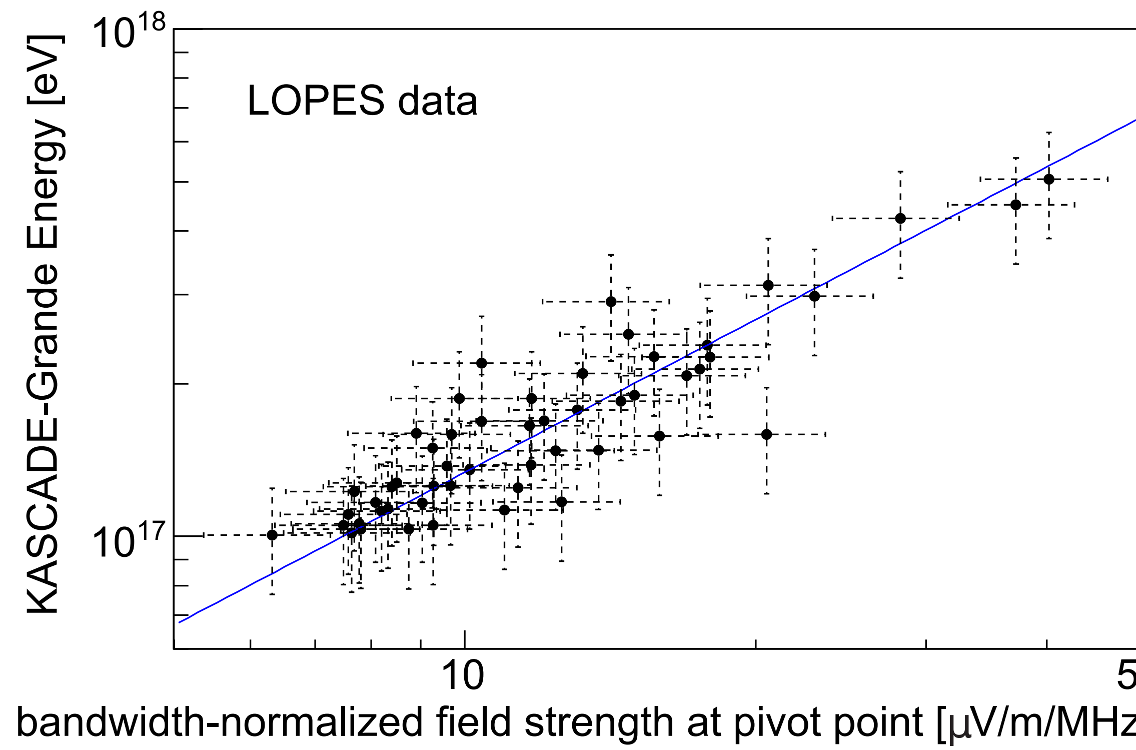
Energy resolution 20-25%
(combined LOPES - KGrande
KGrande alone ~20%)

Very good agreement
to CoREAS (2%)

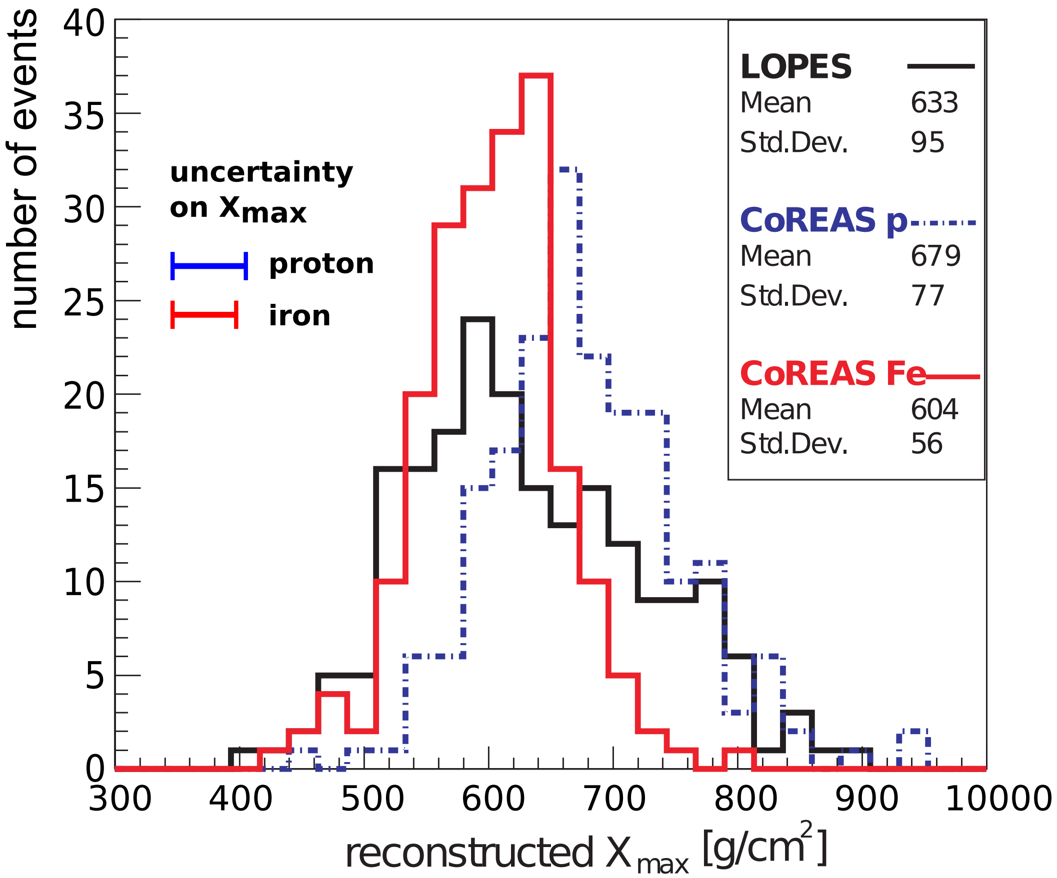


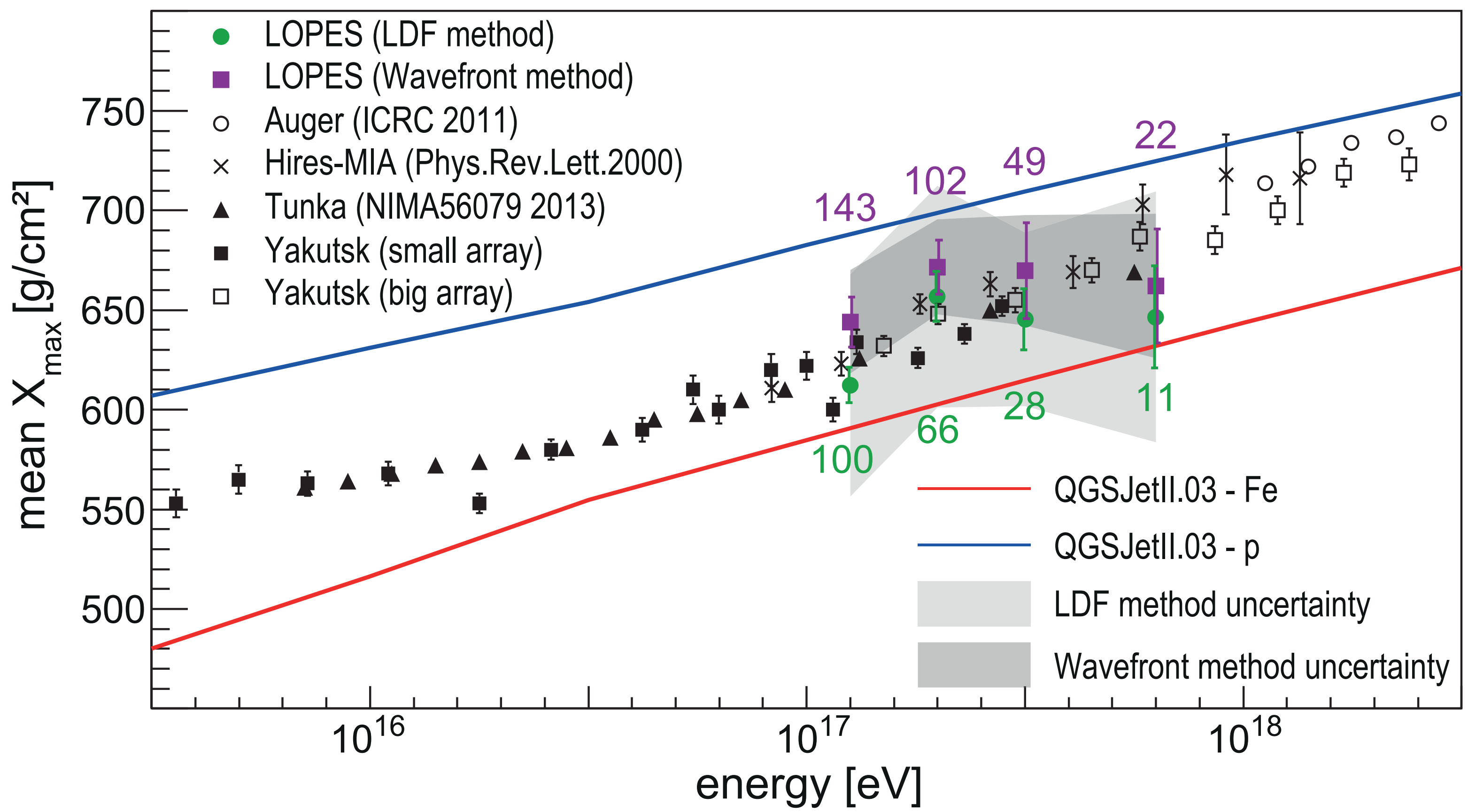
Apel et al. PRD **90**, 062001 (2014)





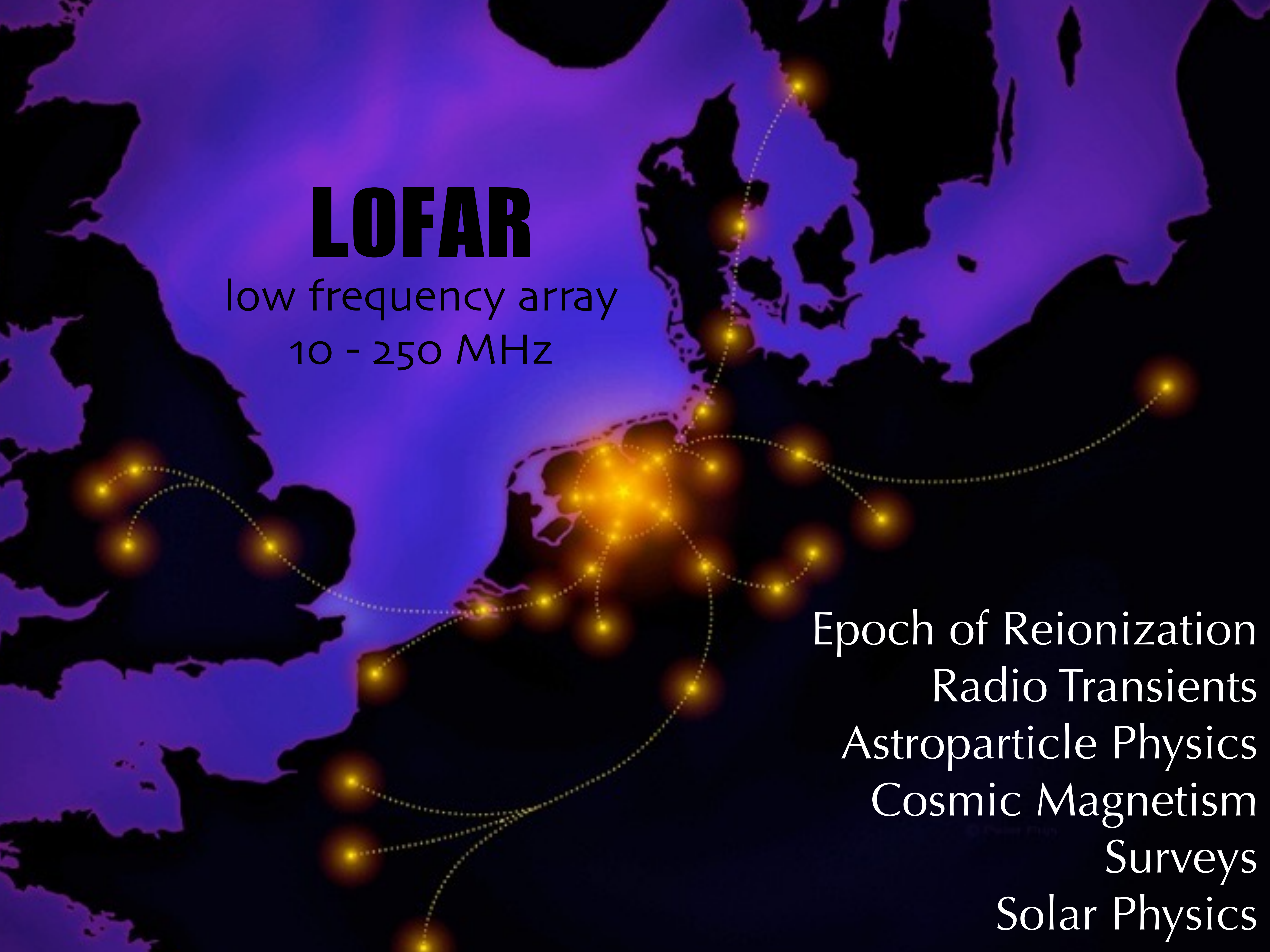
LOPES - Xmax

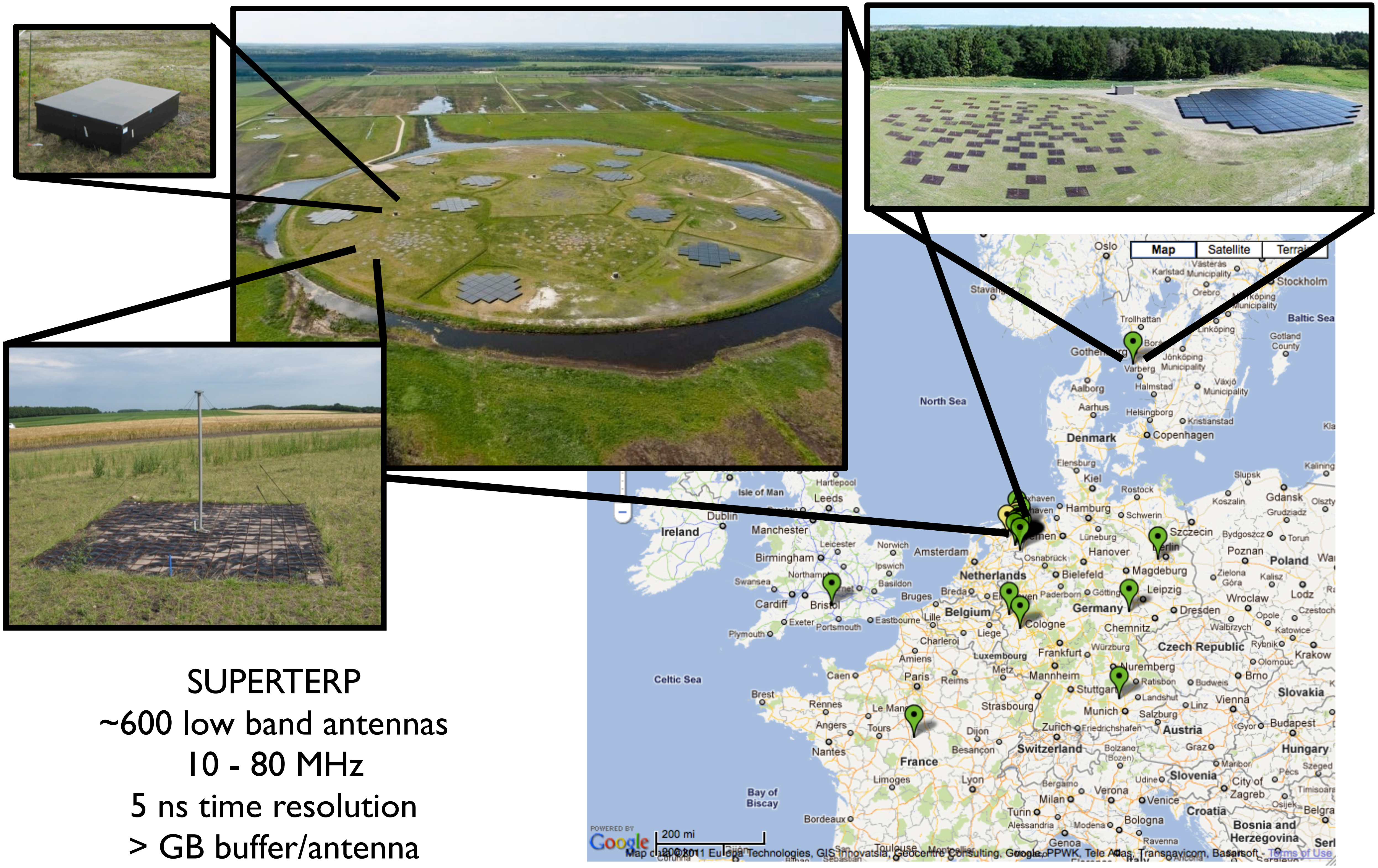




based on 1D slope method
statistical uncertainty ~50 g/cm^2
systematic uncertainty ~90 g/cm^2
proof of concept: first radio composition analysis!

Apel et al. PRD **85**, 071101 (2012)


LOFAR
low frequency array
10 - 250 MHz
Epoch of Reionization
Radio Transients
Astroparticle Physics
Cosmic Magnetism
Surveys
Solar Physics

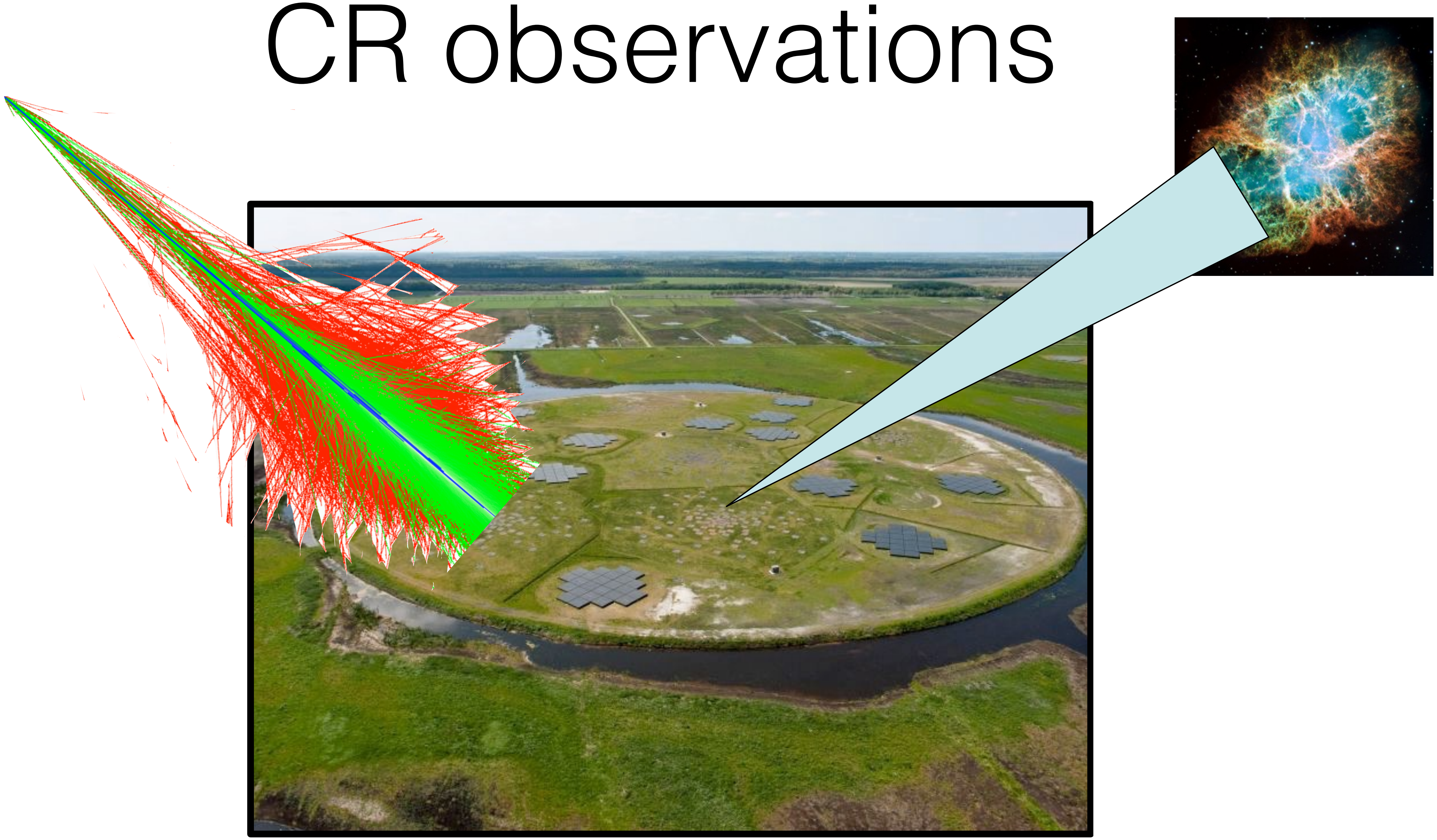


SUPERTERP
~600 low band antennas
10 - 80 MHz
5 ns time resolution
> GB buffer/antenna

+ LORA
LOFAR Radboud air shower array
20 scintillator stations (ex-KASCADE)

24 core stations
9 remote stations
8 international stations

CR observations



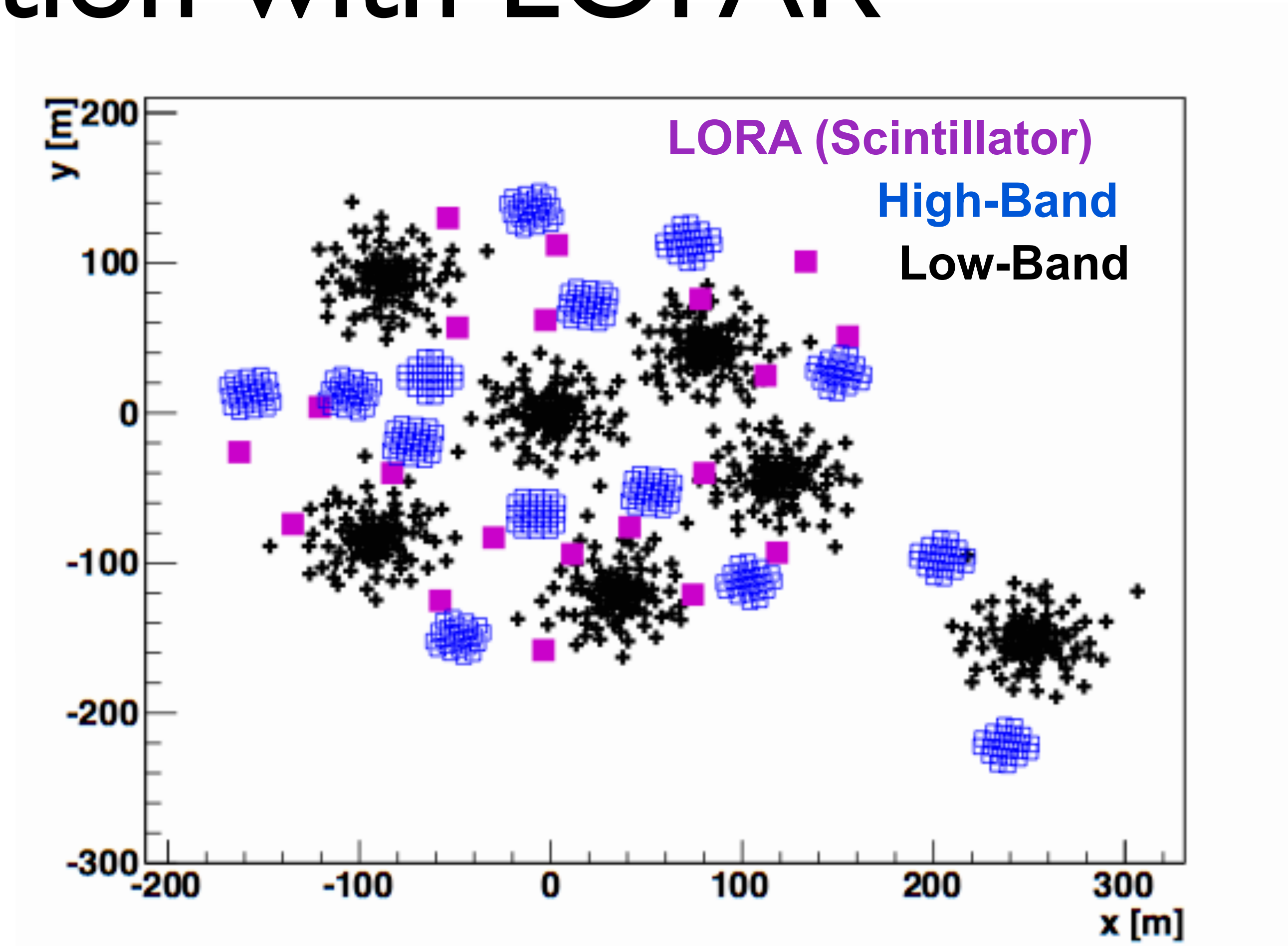
LOFAR is designed to support many different observation strategies

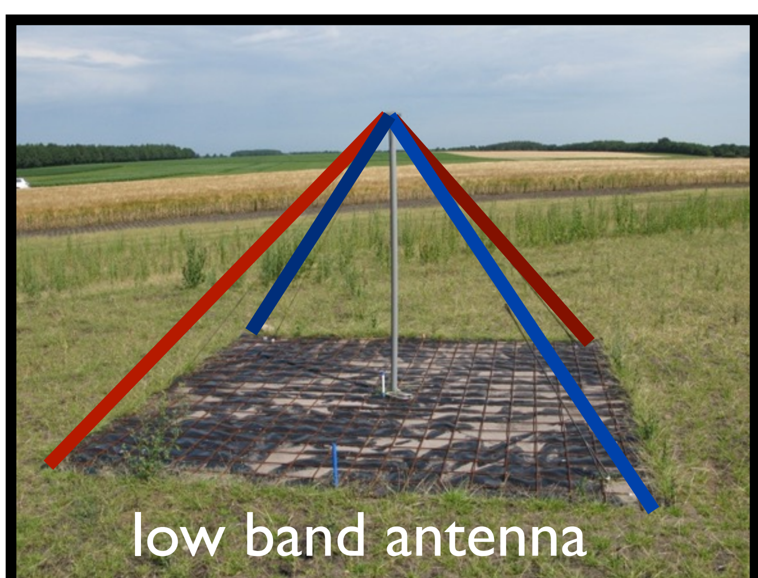
CR detection runs in the background during other observations

Air shower detection with LOFAR

LORA
LOFAR Radboud Array
scintillator detectors

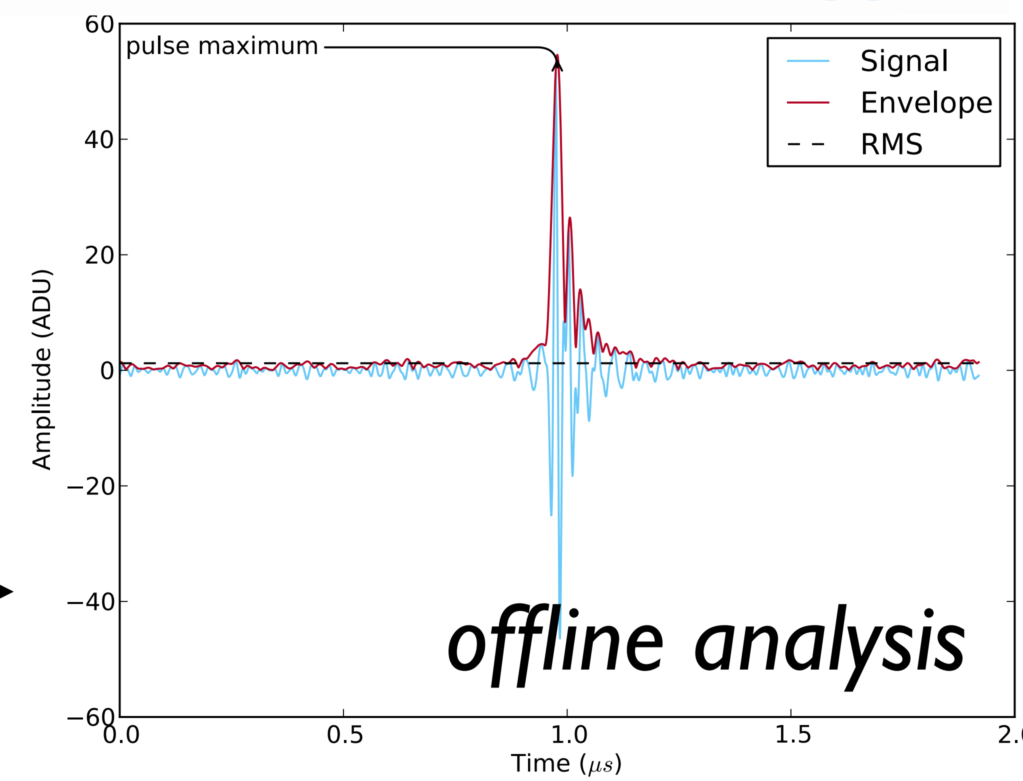
trigger





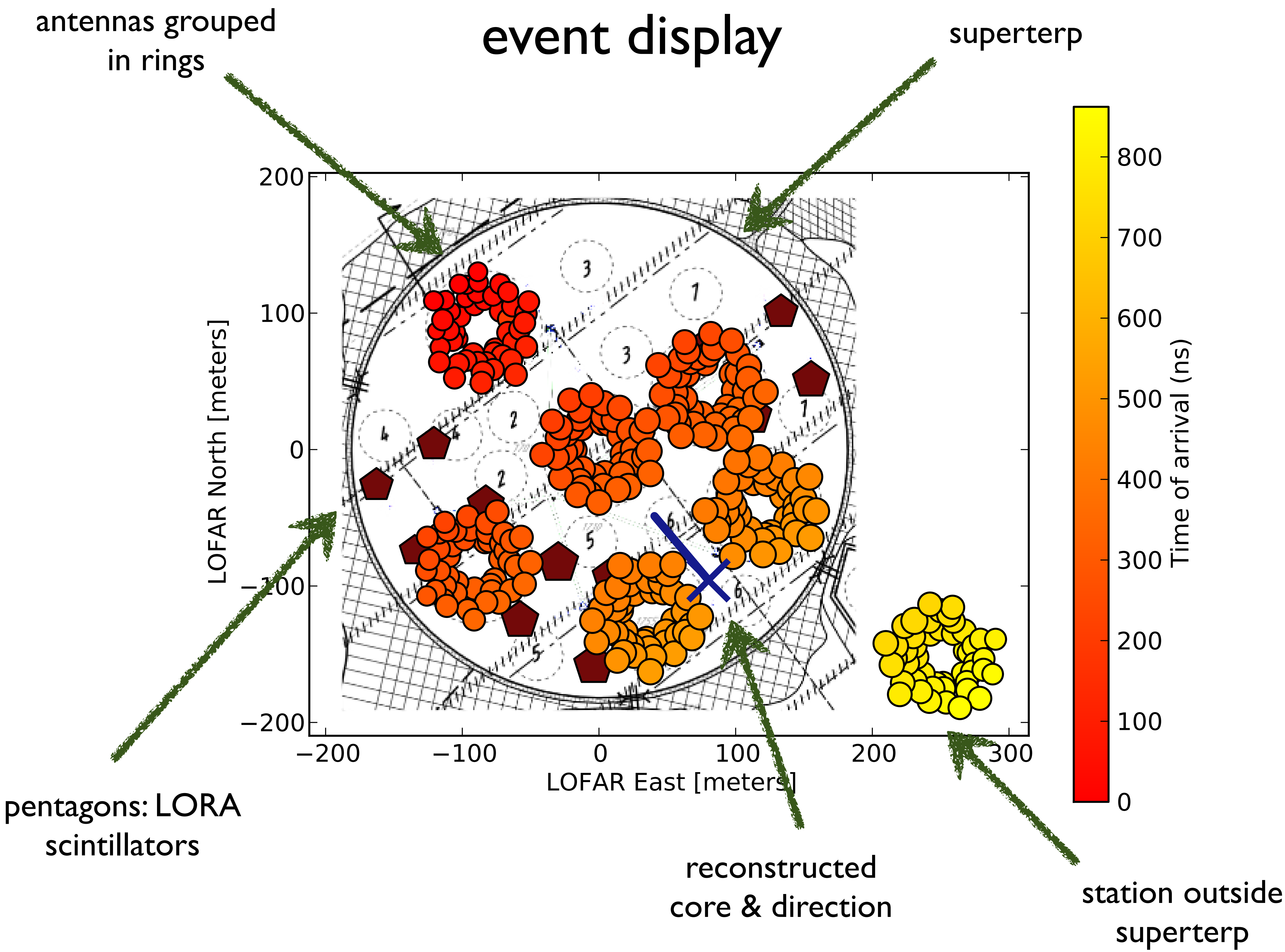
buffer

2 ms read-out

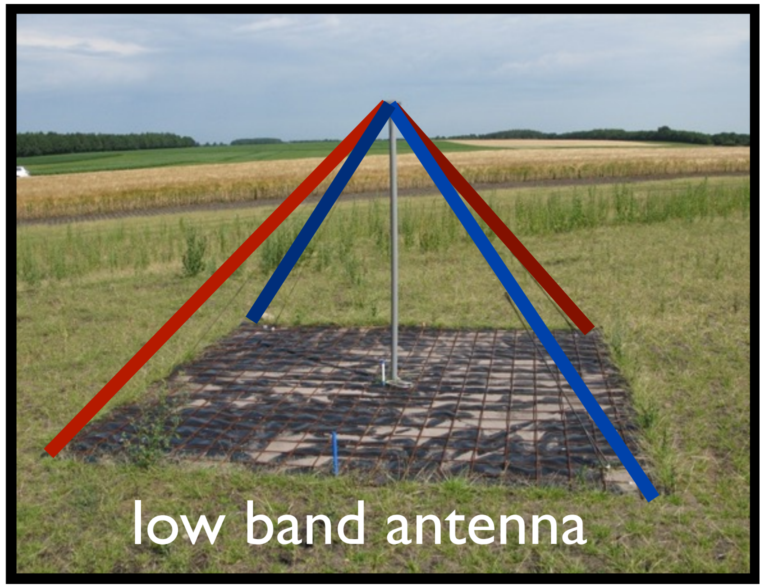


Pim Schellart et al., A&A 560, 98 (2013)

event display



For each LOFAR shower:



- Reconstruct direction from antennas (plane wave) + energy estimate from particle array (LORA)
- Produce 50 p + 25 Fe showers
  CoREAS
  CORSIKA 7.4 (QGSJETII.04, Fluka, thinning 10^{-6})
- Calculate total power in 55 ns around peak emission
- GEANT4 LORA simulation: total deposited energy

Fit for each simulation

Minimize χ^2 of radio and particle data simultaneously

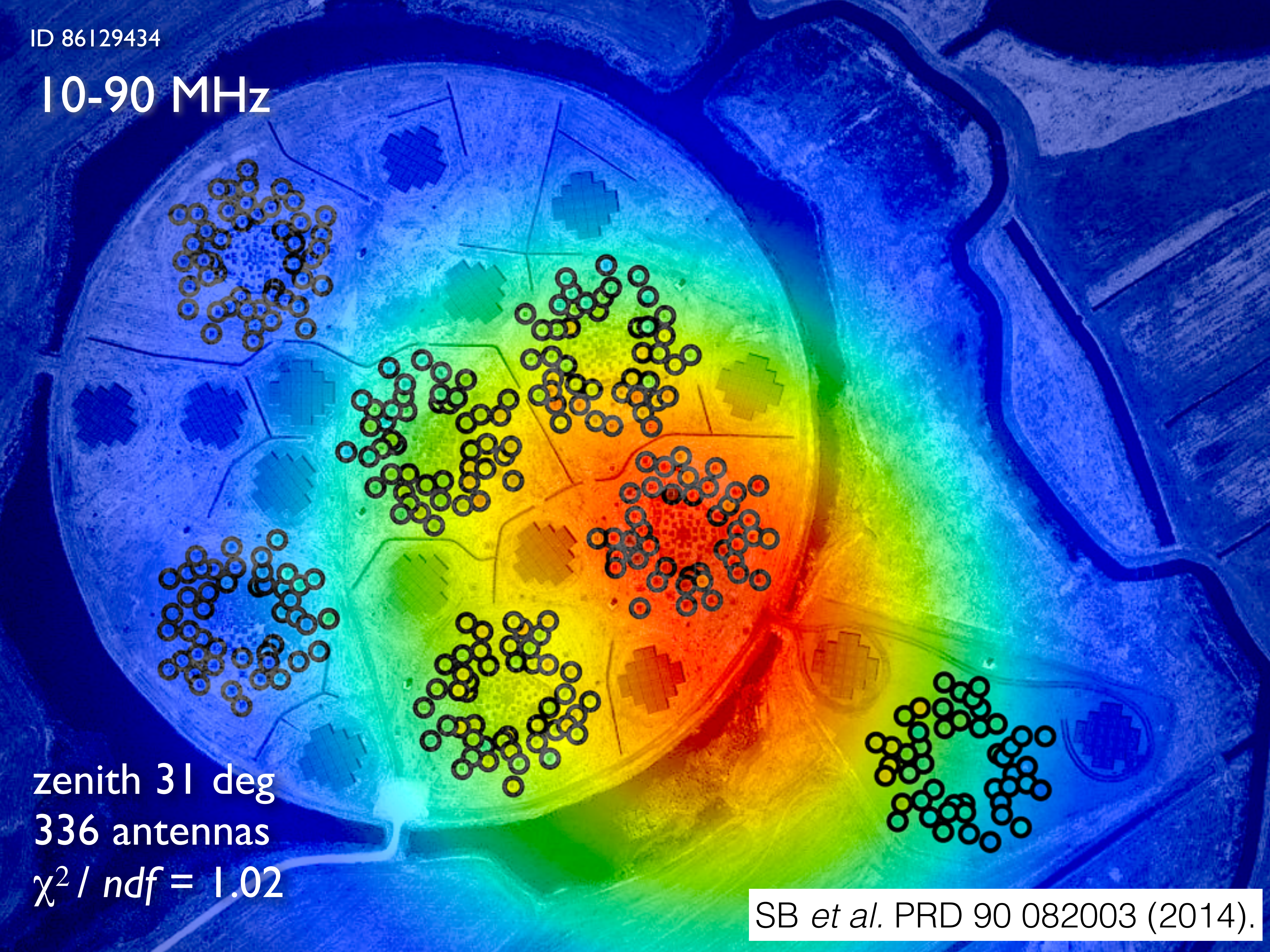
$$\chi^2 = \sum_{antennas} \left(\frac{P_{ant} - \boxed{f_r} P_{sim}(x_{ant} + \boxed{x_{off}}, y_{ant} + \boxed{y_{off}})}{\sigma_{ant}} \right)^2 + \sum_{detectors} \left(\frac{d_{det} - \boxed{f_p} d_{sim}(x_{det} + \boxed{x_{off}}, y_{det} + \boxed{y_{off}})}{\sigma_{det}} \right)^2$$

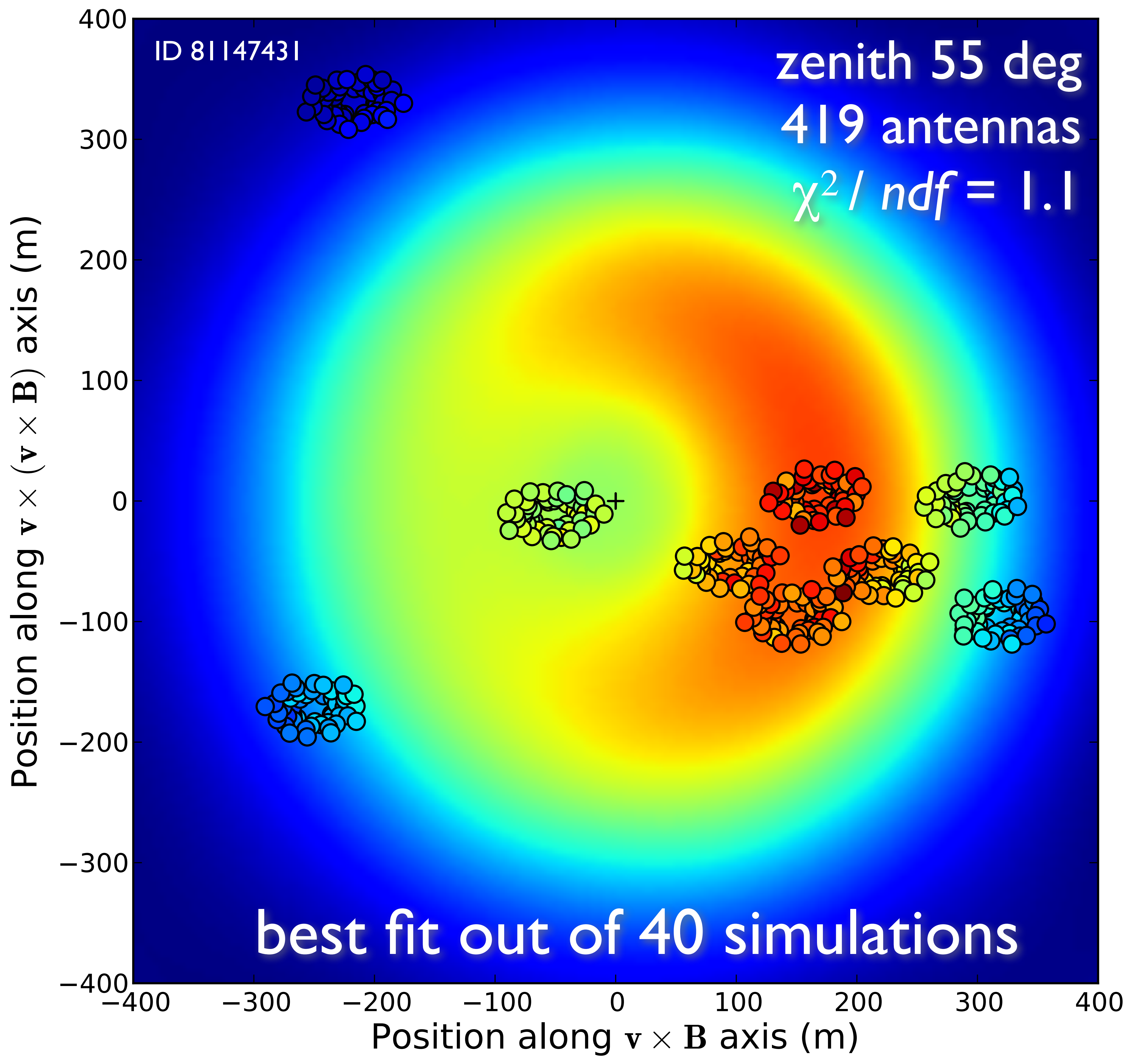
4 fit parameters:

core position

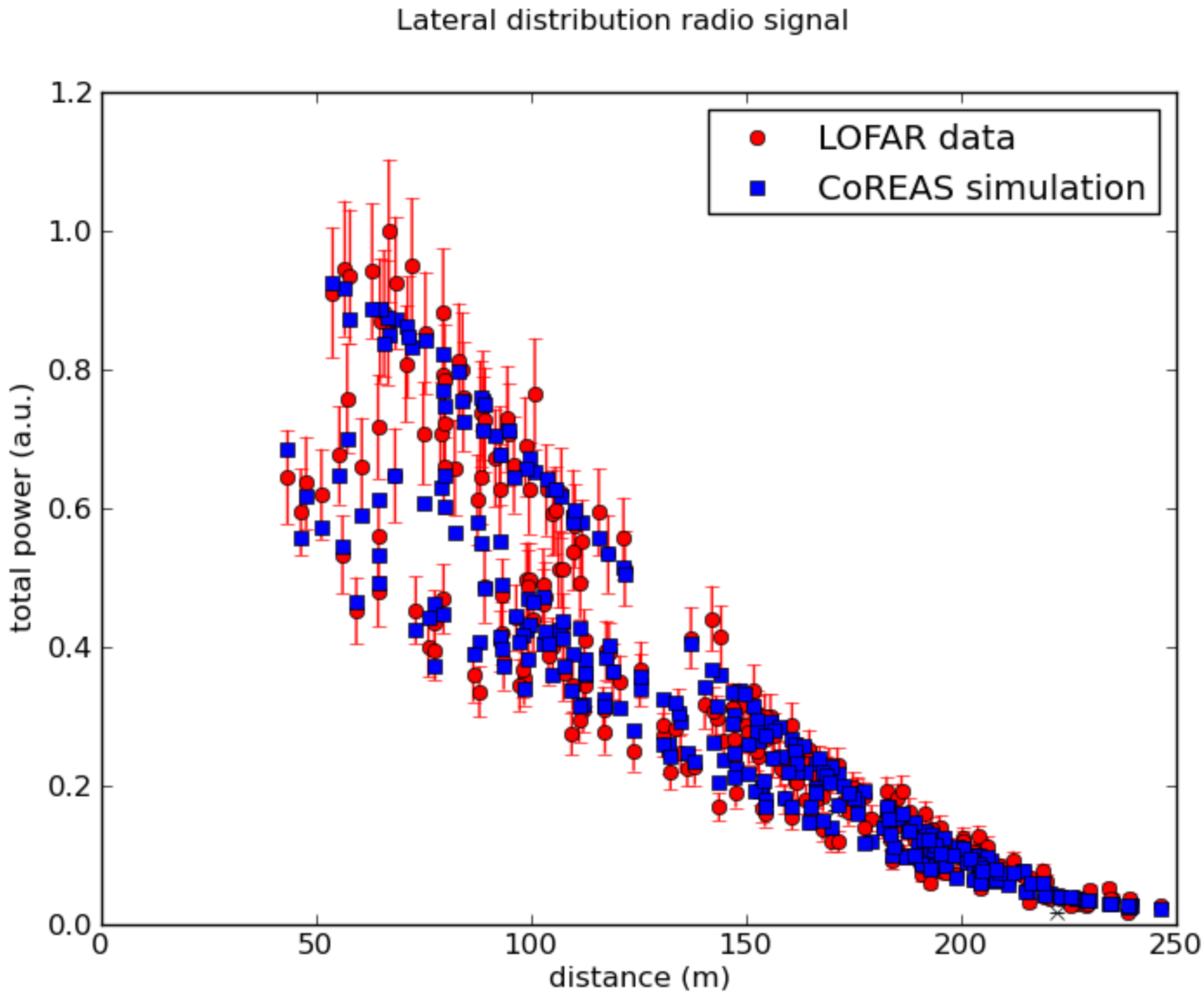
radio power scale factor

particle density scale factor

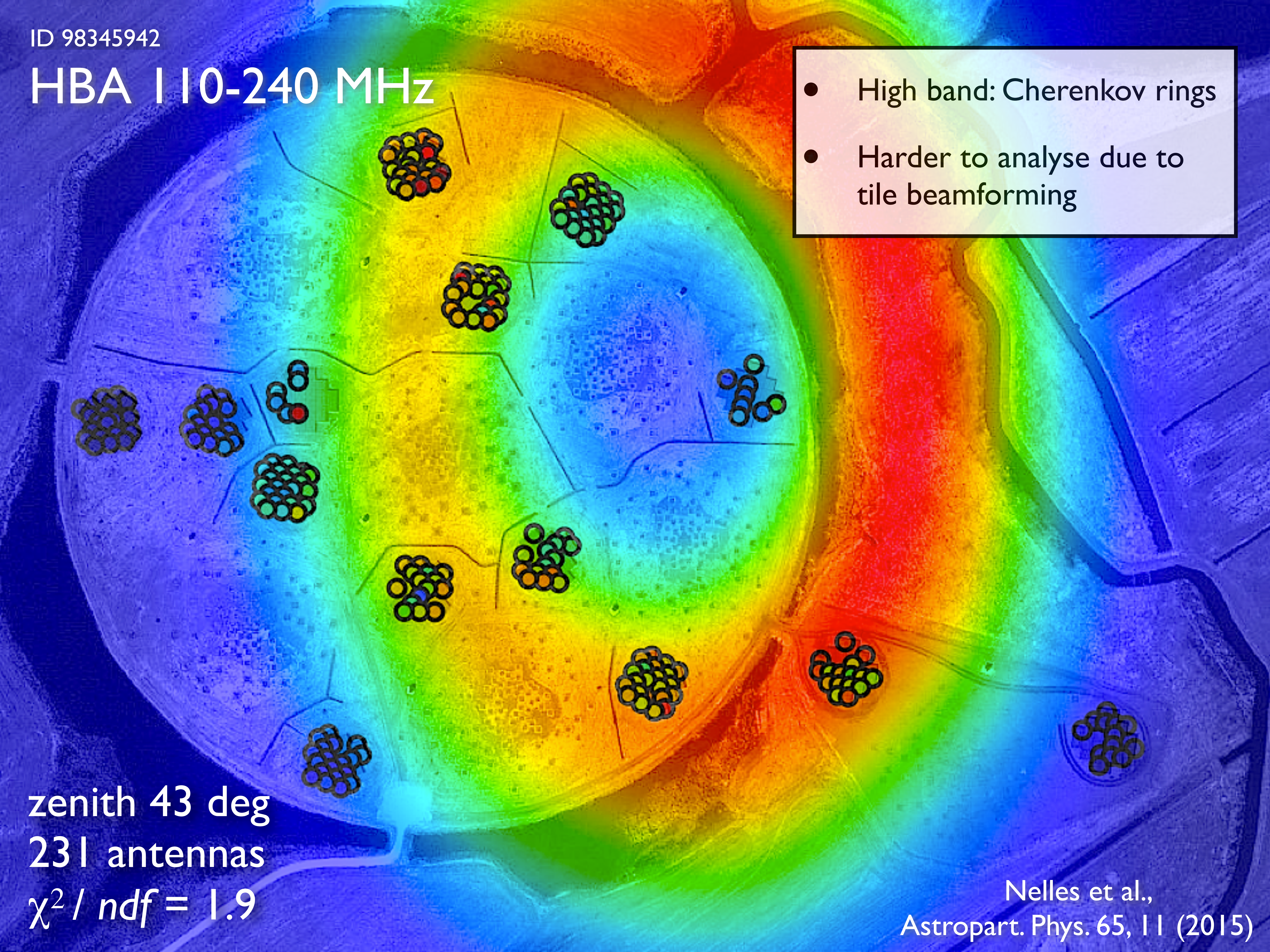

ID 86129434
10-90 MHz
zenith 31 deg
336 antennas
$\chi^2 / ndf = 1.02$
SB *et al.* PRD 90 082003 (2014).

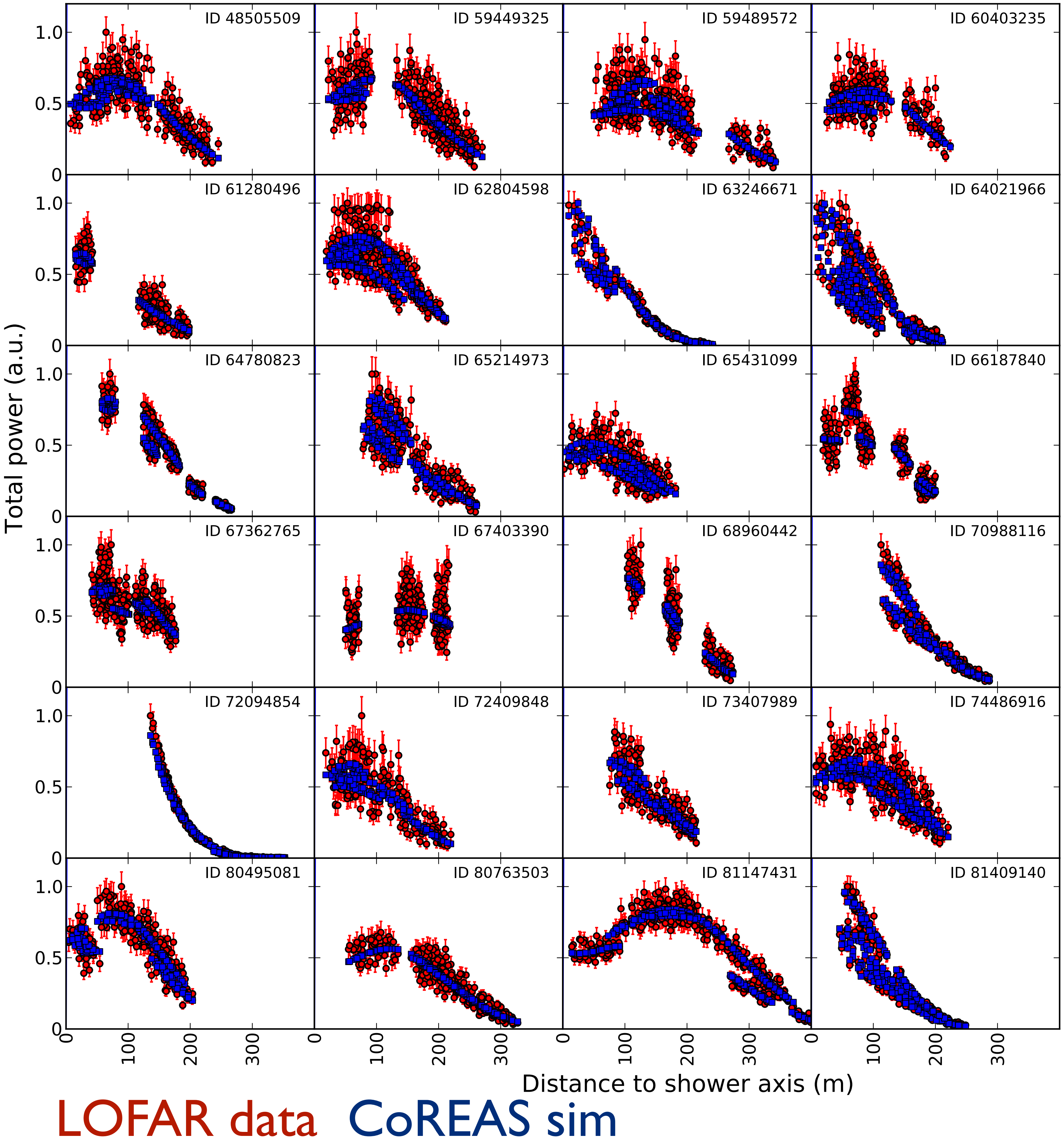


ID 81147431
zenith 55 deg
419 antennas
$\chi^2 / ndf = 1.1$
best fit out of 40 simulations
Position along $\mathbf{v} \times (\mathbf{v} \times \mathbf{B})$ axis (m)
Position along $\mathbf{v} \times \mathbf{B}$ axis (m)
400
300
200
100
0
−100
−200
−300
−400



1D LDFs are multivalued

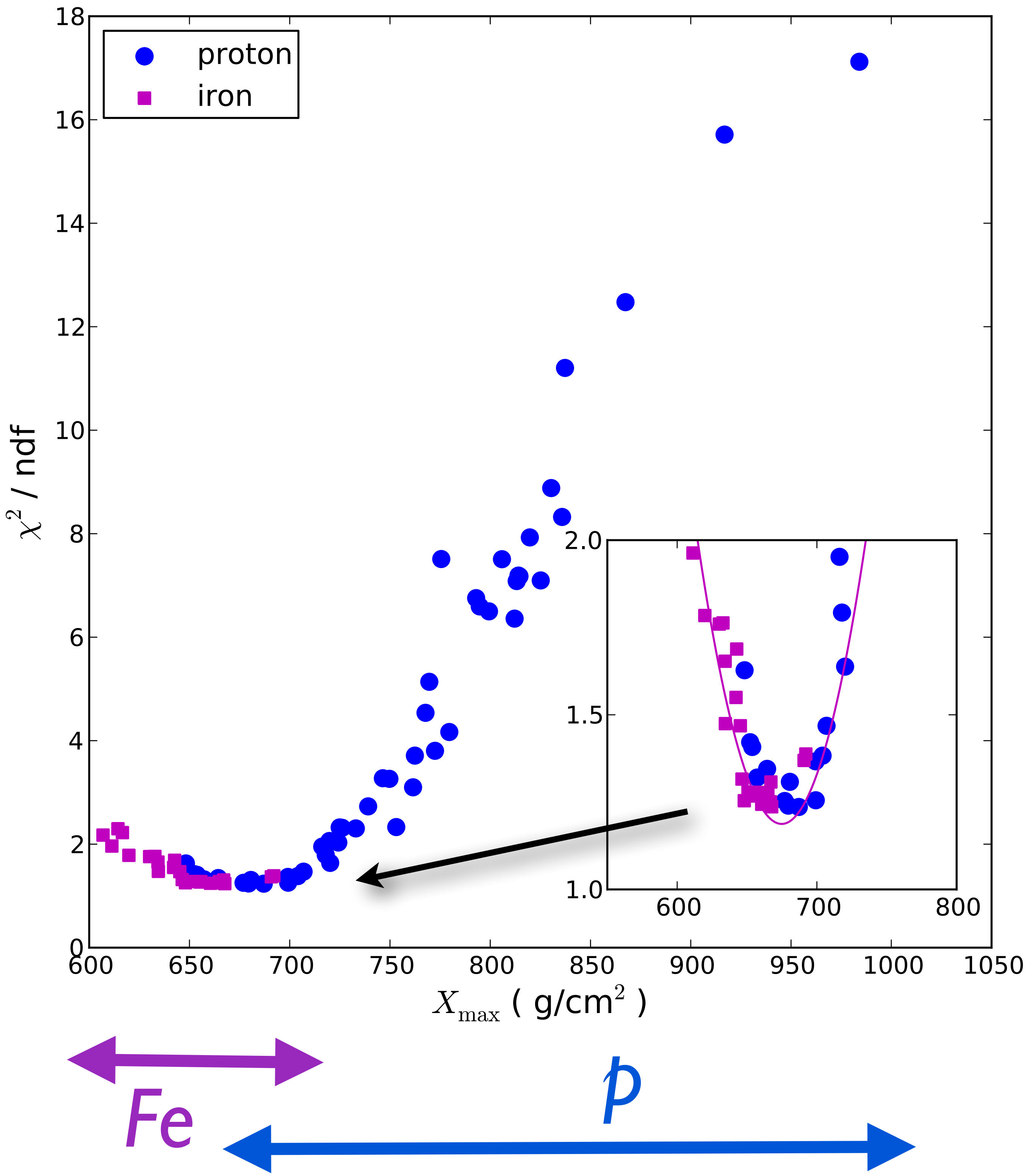

ID 98345942
HBA 110-240 MHz
• High band: Cherenkov rings
• Harder to analyse due to tile beamforming
zenith 43 deg
231 antennas
$\chi^2 / ndf = 1.9$
Nelles et al.,
Astropart. Phys. 65, 11 (2015)



- **First sample: 118 showers**
- 200 - 450 antennas/event
- Fit 0.9 - 2.9
- Radiation mechanism finally completely understood!

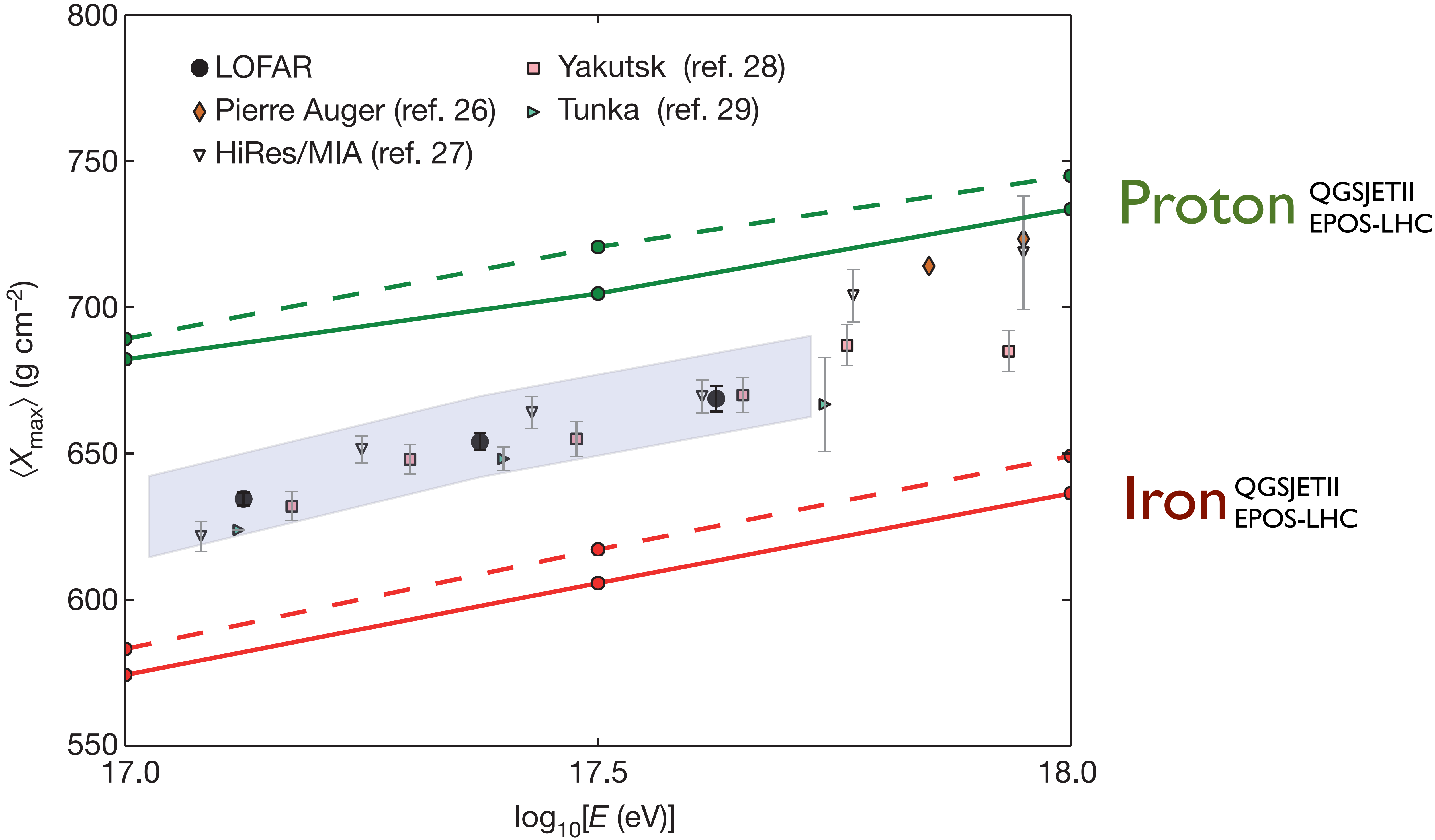
X_{max} reconstruction

protons penetrate deeper than iron nuclei



- Reconstruct depth of shower maximum: Xmax
- Jitter: other variations in shower development
- Correction for atmospheric variations using GDAS
- Resolution < 20 g/cm^2 !!

Mean X_{max} for 118 showers



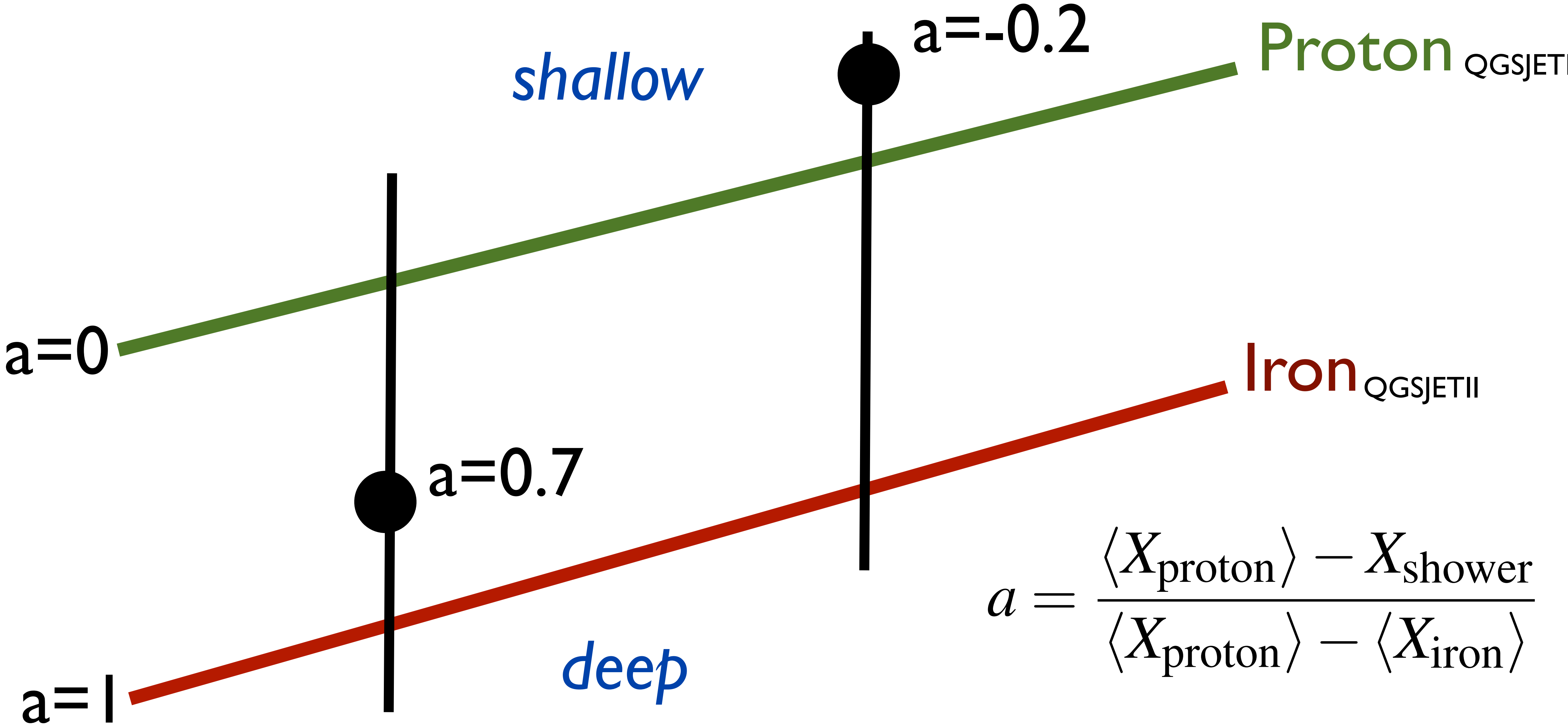
Mean statistical uncertainty per shower ~ 17 g/cm²

Xmax syst. uncertainty +14/-10 g/cm²

energy syst. uncertainty 27% (LORA)

Nature, march 2 2016

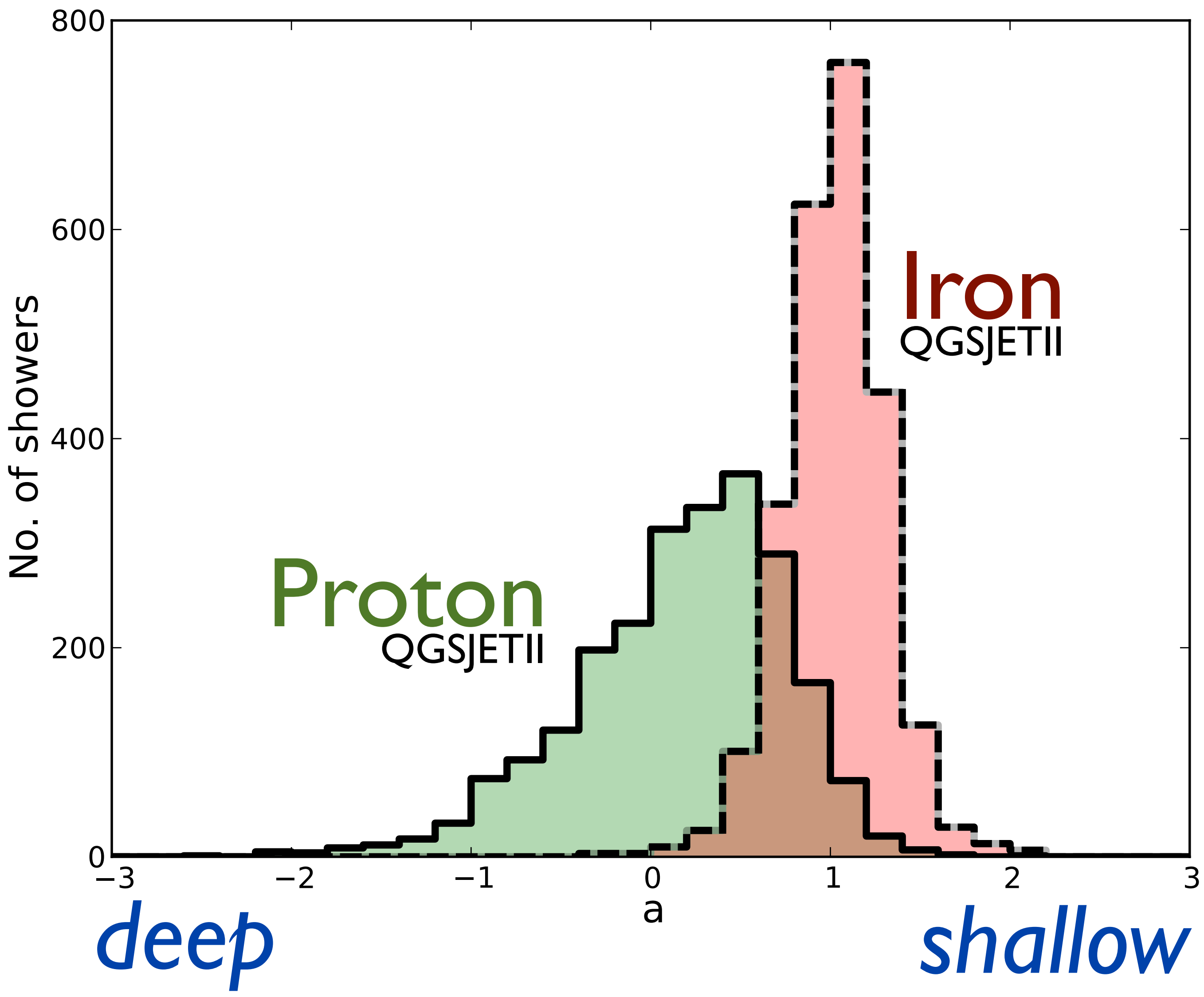
Unbinned analysis



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

Calculate *a* for each individual shower

Composition at 10^{17} -10^{18} eV

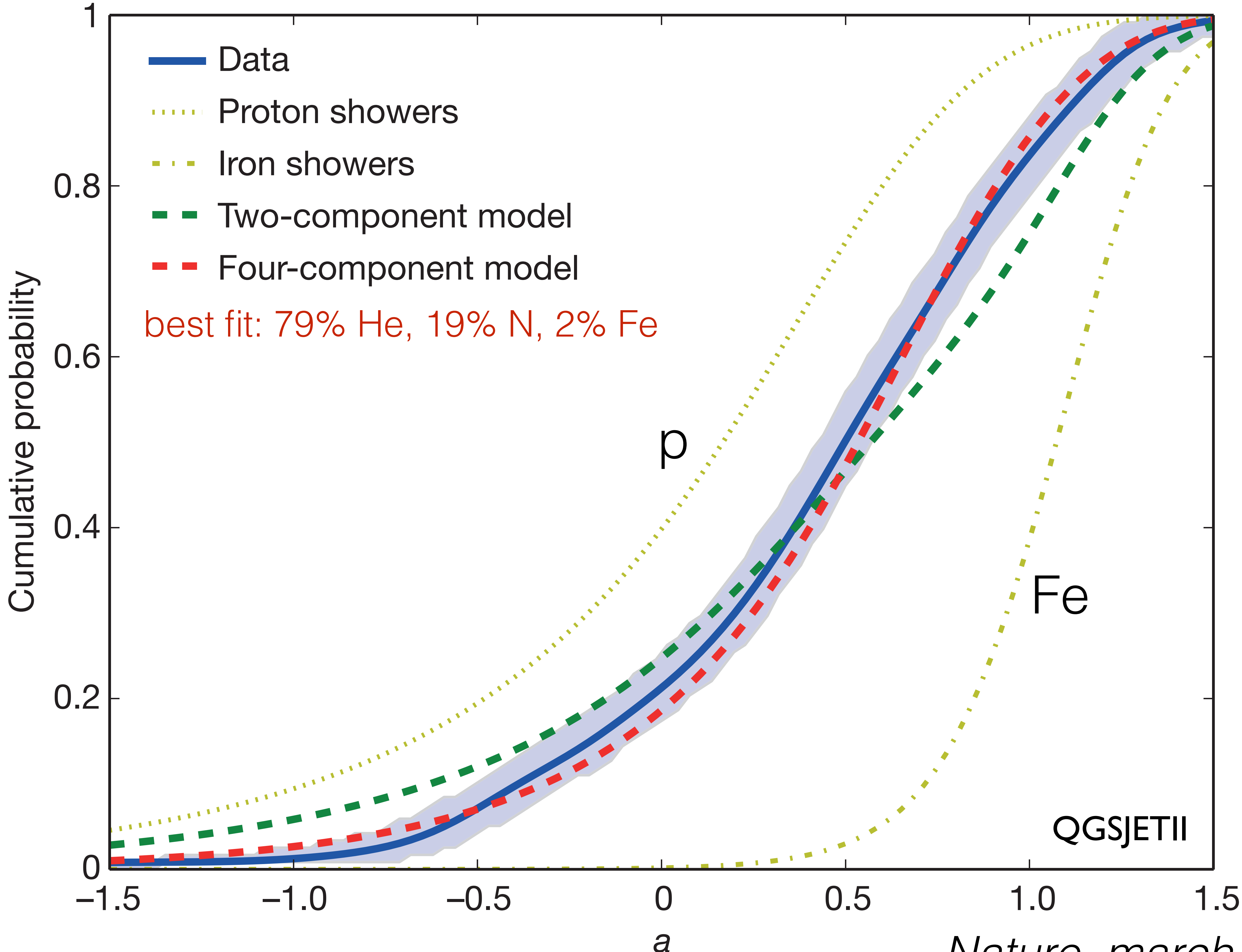


- LOFAR:
  high precision per event!
- Use **full** distribution of Xmax **not** only mean value
- First calculate mass parameter a

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

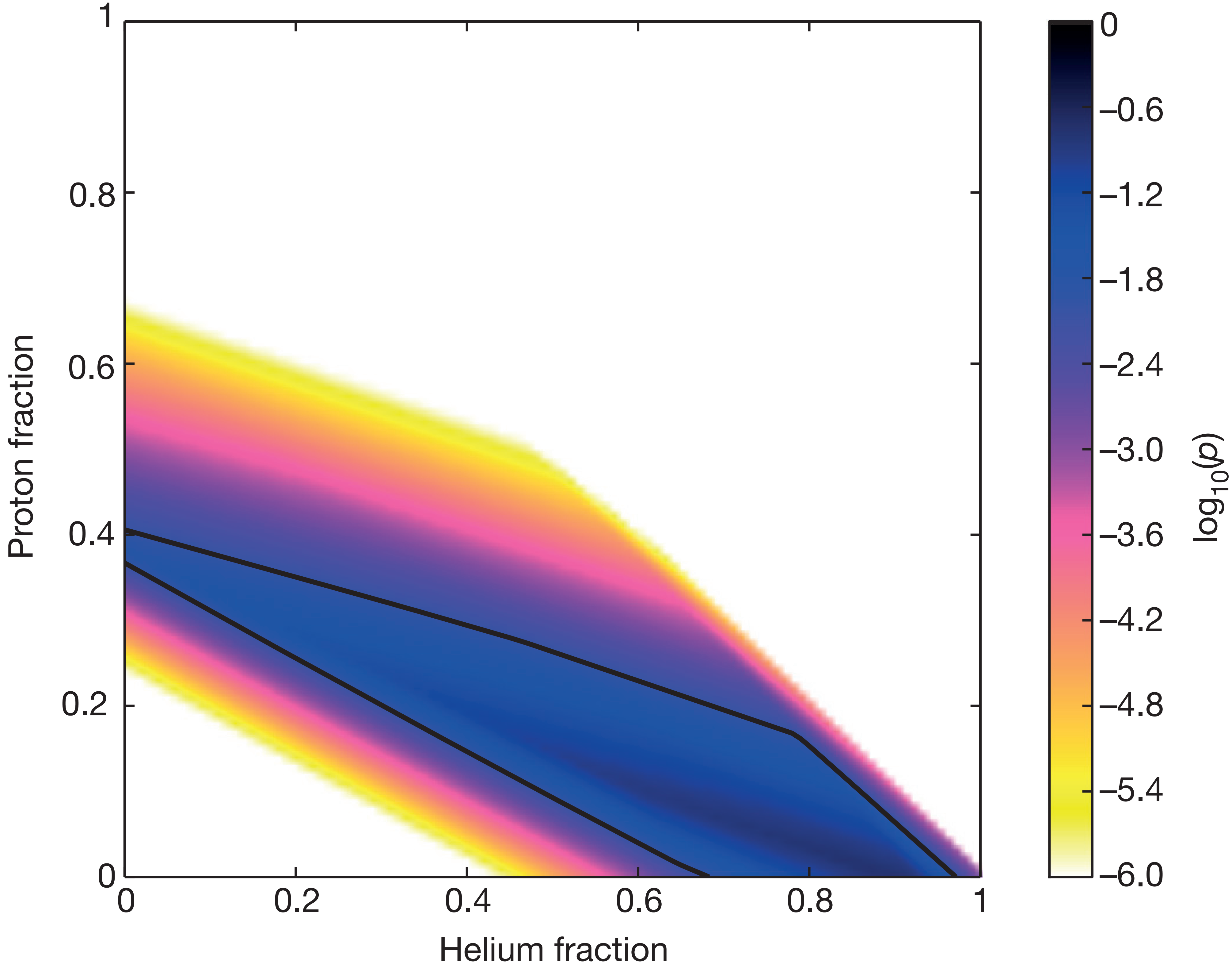
- Fit model distribution to measured distribution

Cumulative distribution: model fits



Nature, march 2 2016

Four component model scan



Total fraction of light elements (p+He) in [0.38,0.98] at 99% C.L.

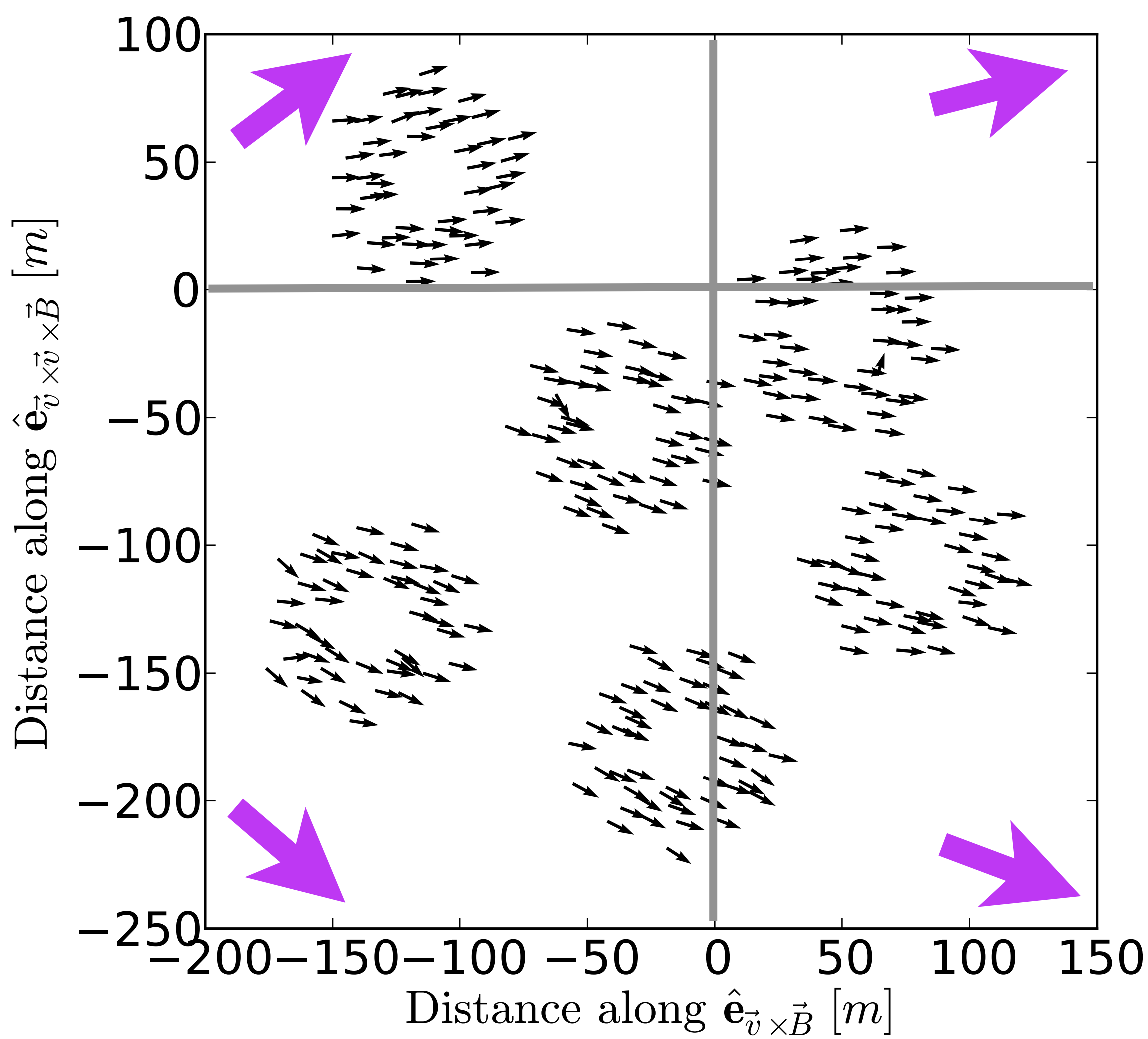
Thunderstorm events

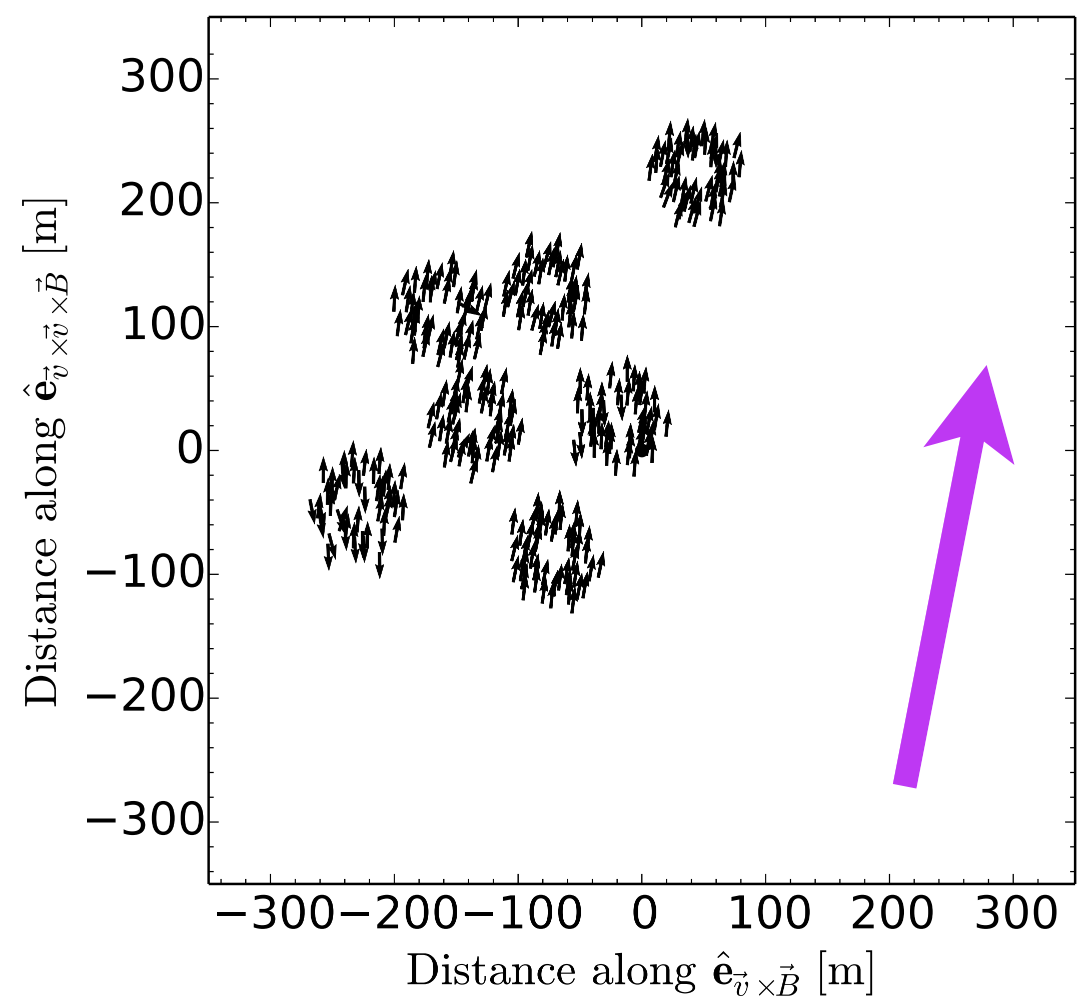
LOPES: Amplification in thunderstorms

Buitink et al. A&A **467**, 385 (2007)

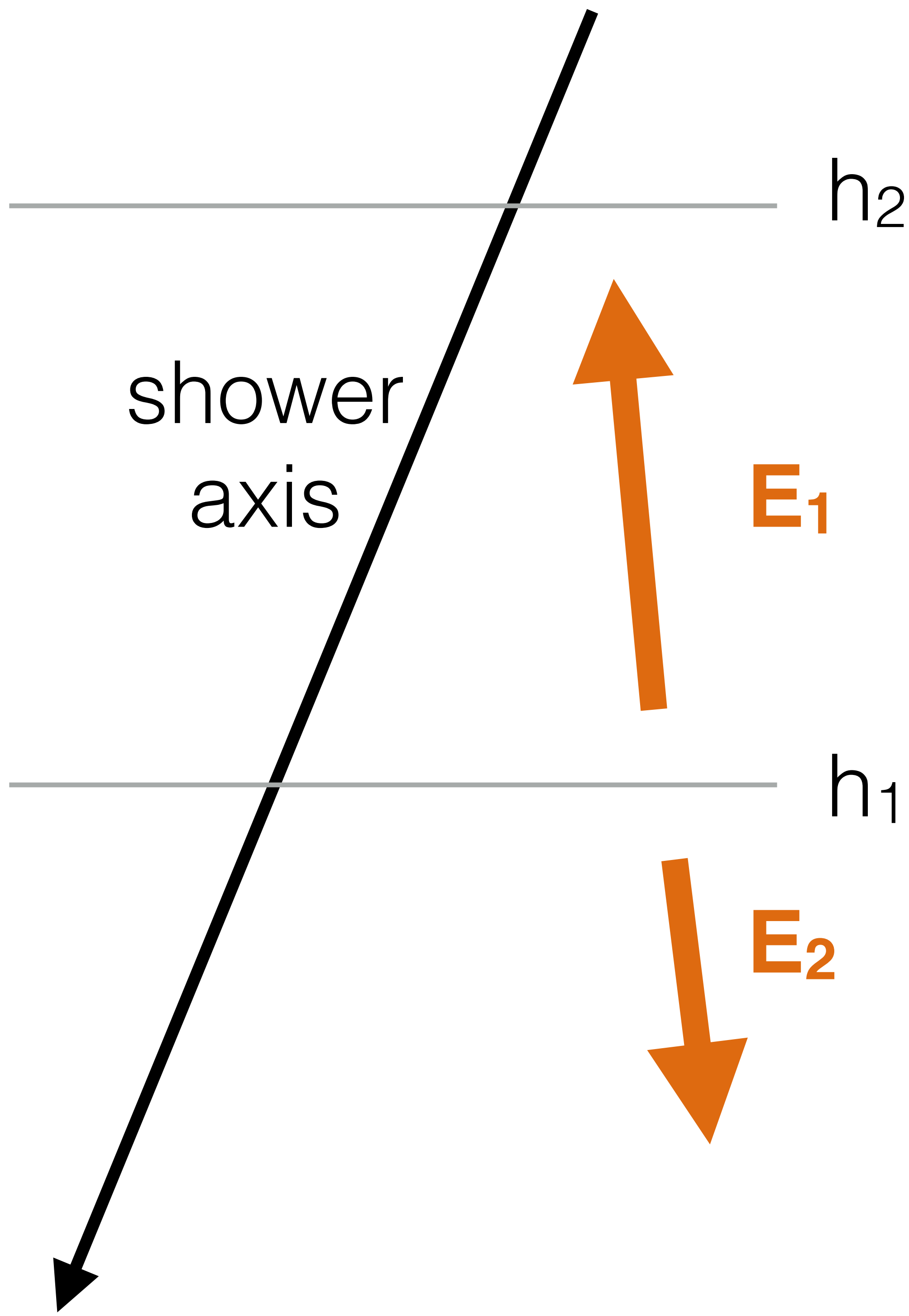
LOFAR: strange polarisation features

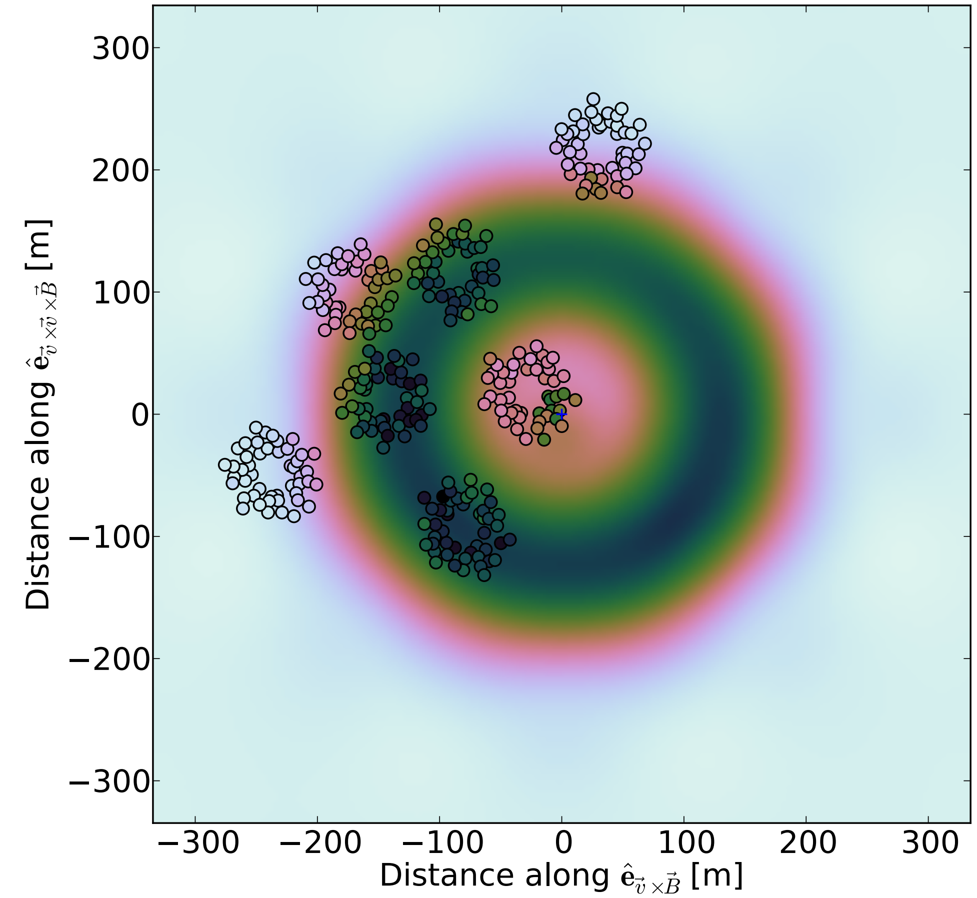
Schellart et al. PRL **114**, 165001 (2015)

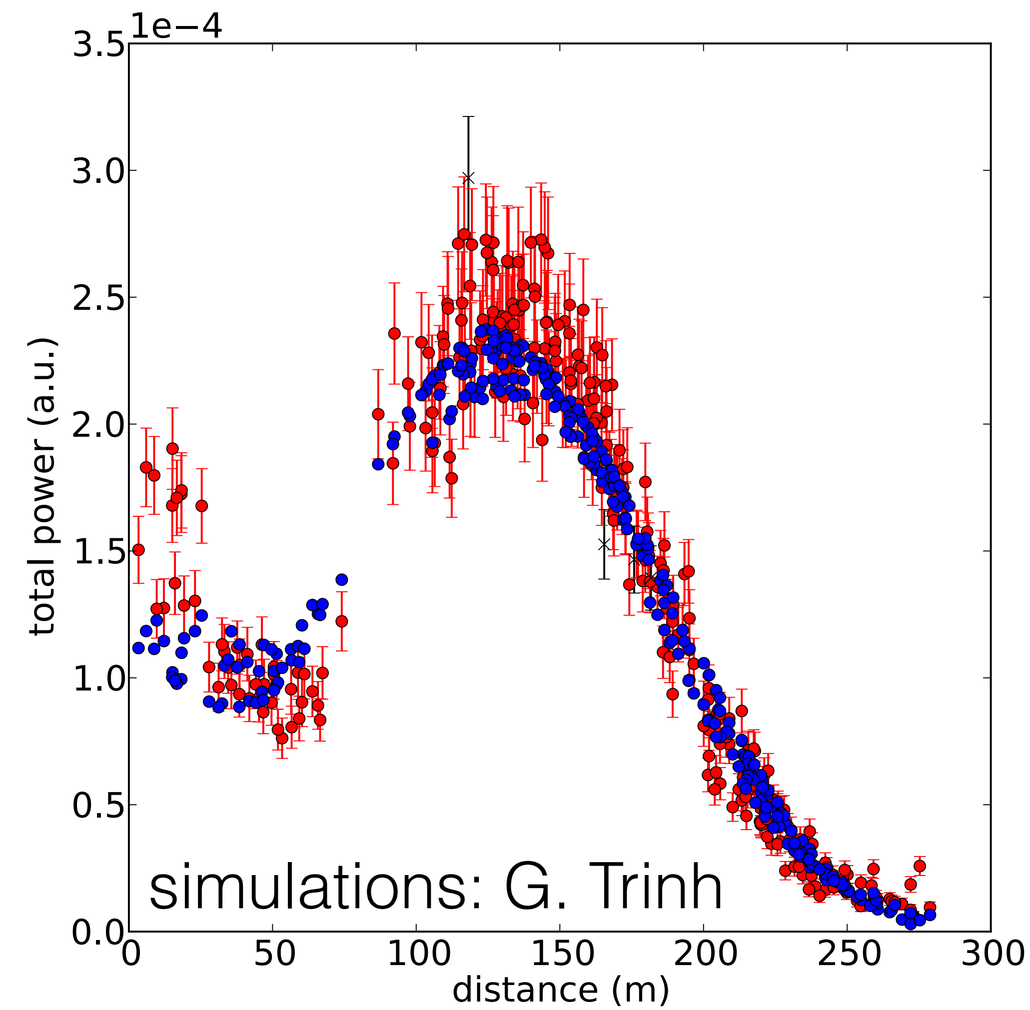




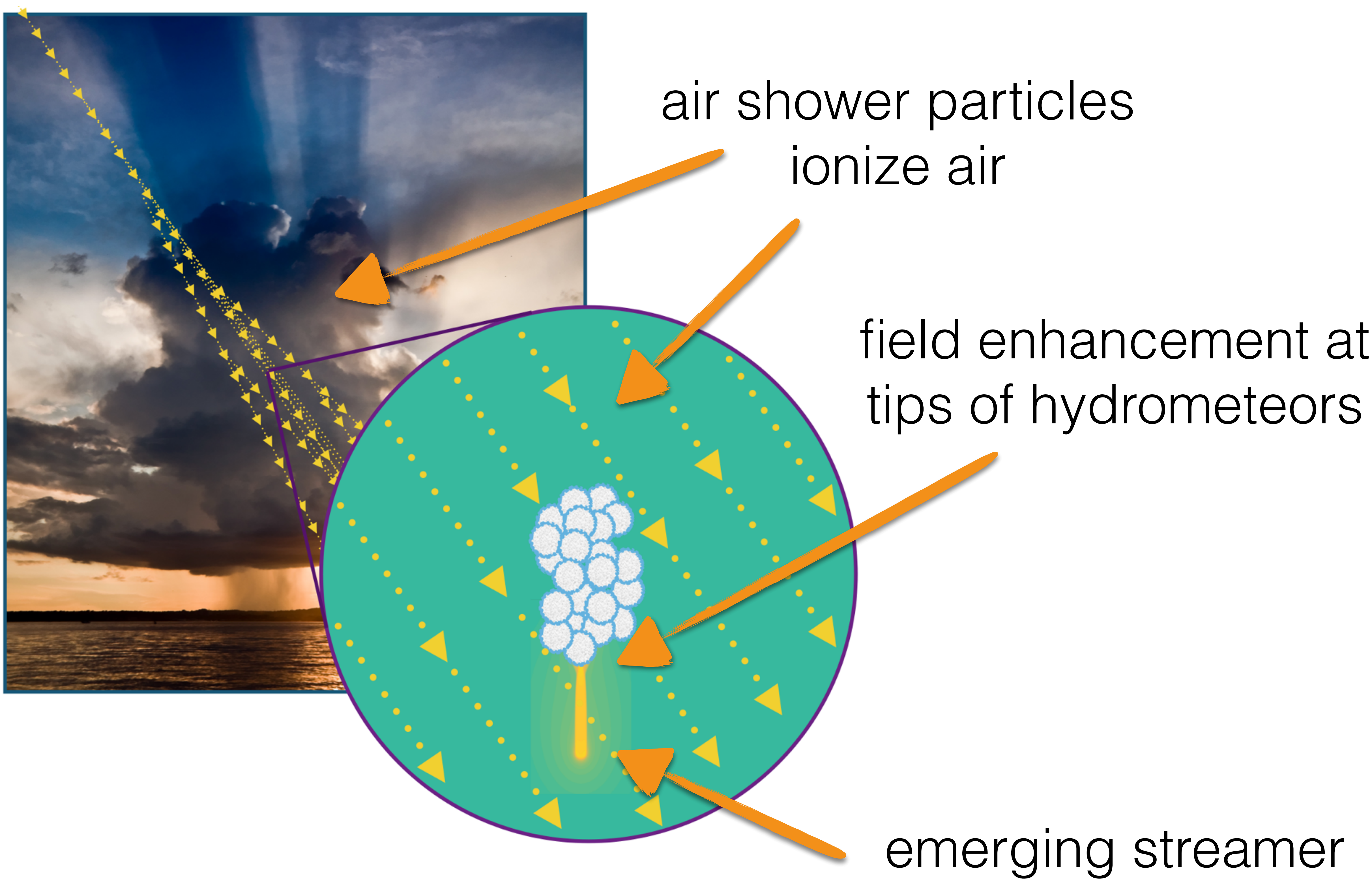
Two layer model



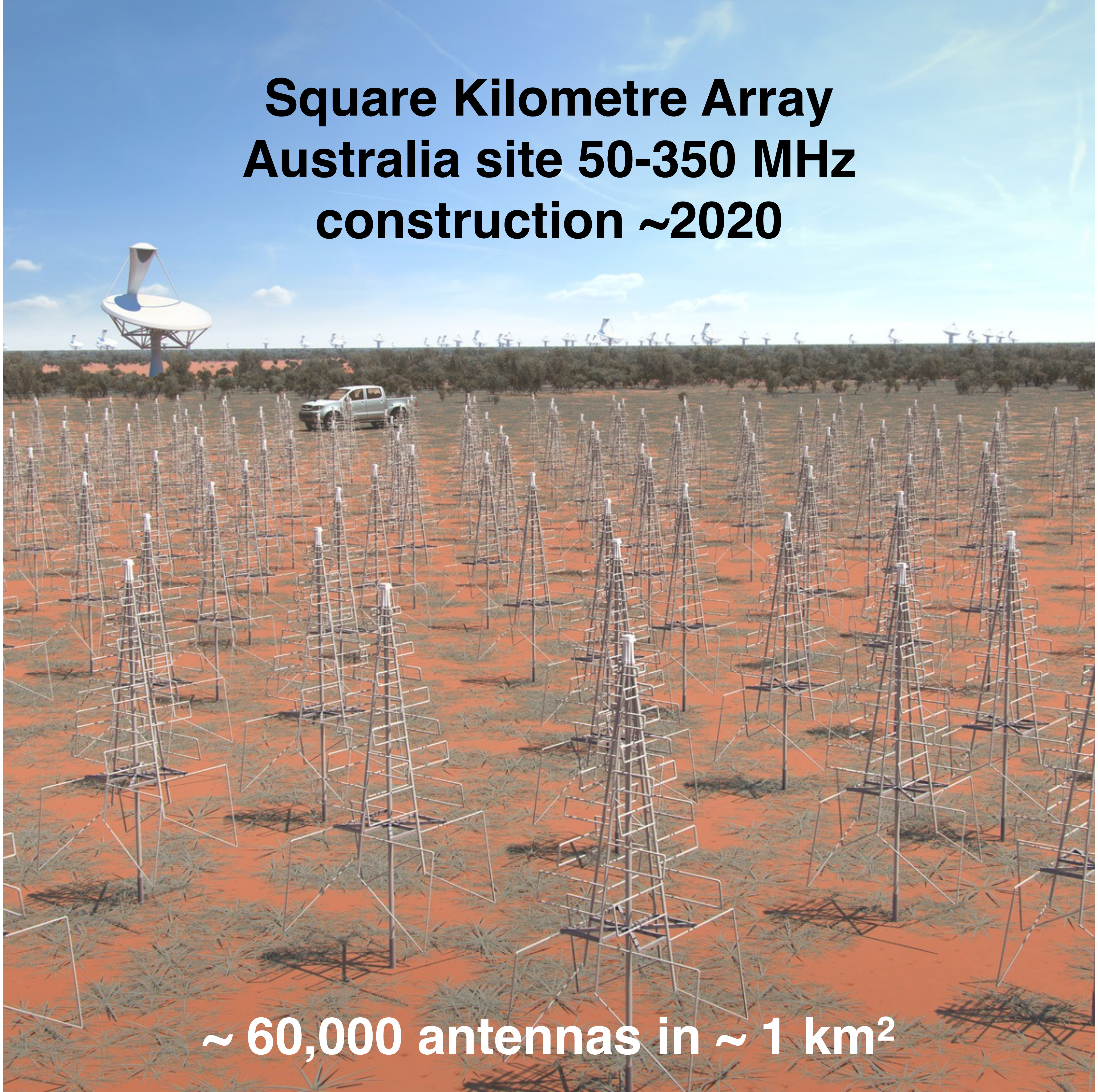




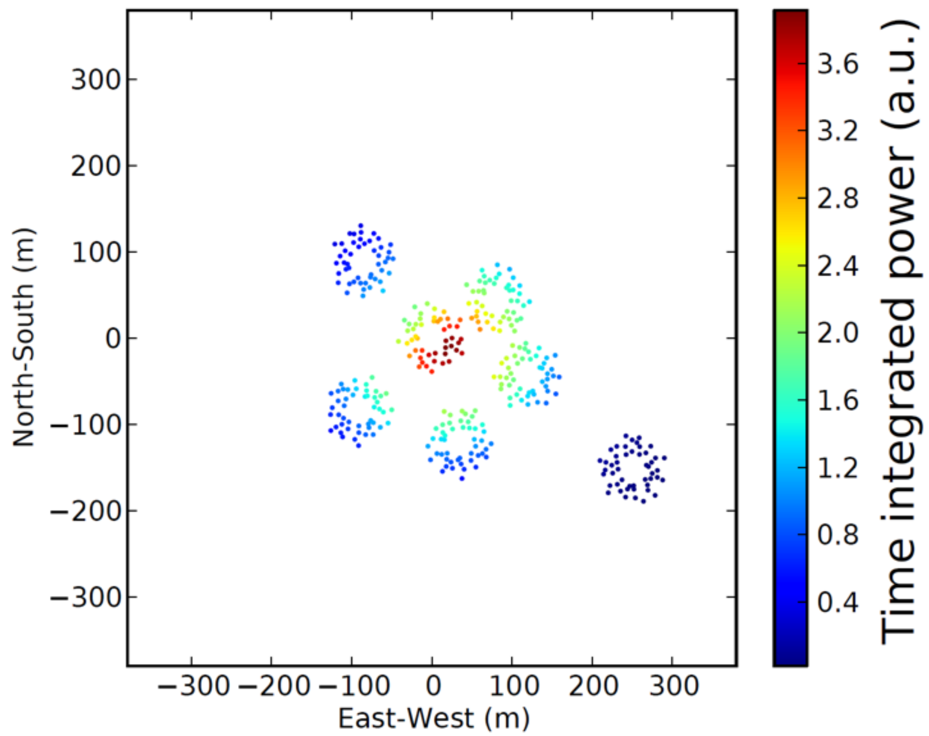
Schellart et al. PRL **114**, 165001 (2015)



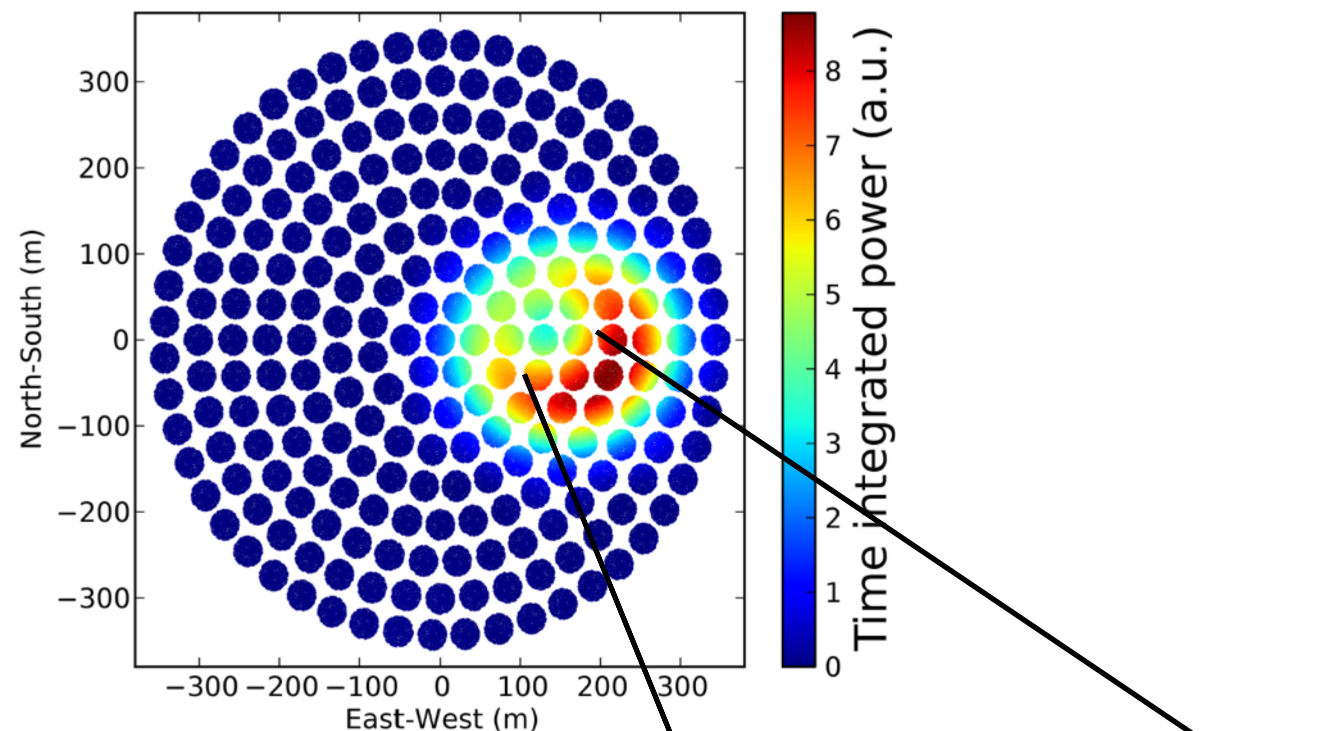
A.Dubinova, C. Rutjes, U. Ebert, S. Buitink, O. Scholten, and G. Trinh, PRL **115**, 015002 (2015)


Square Kilometre Array
Australia site 50-350 MHz
construction ~2020
~ 60,000 antennas in ~ 1 km²

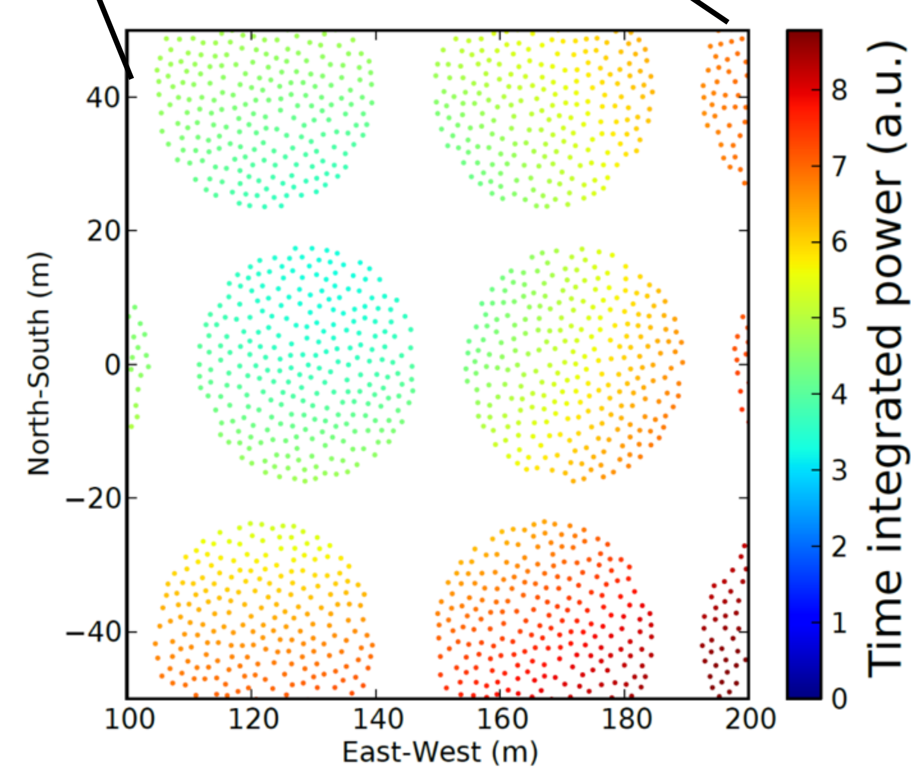
SKA: ultrahigh precision measurements



LOFAR



SKA



<u>Science</u>:

- **origin of CRs**
  mass composition in transition region G/XG
- **hadronic physics at super-LHC energies**
  shower tomography
- **thunderstorm physics**

Huege et al. SKA science 2015 (arXiv:1408.5288)

Conclusions

- Air shower radio emission mechanism finally understood:
  - intensity profiles
  - wavefront shape
  - polarisation
  - Cherenkov rings at high frequency

- Radio method suitable for CR mass composition
  LOPES: proof-of-concept
  LOFAR: X_{max} resolution of < 20 g/cm^2
  similar to fluorescence detection + higher duty cycle

- Composition results based on 100+ high-res reconstructions using full shape of X_{max} distribution
  light mass component at 10^{17} - $10^{17.5}$ eV

- Air showers in thunderstorm:
  remote sensing of electric fields, thunderstorm physics

- Future: ultra-high precision with SKA

Thanks