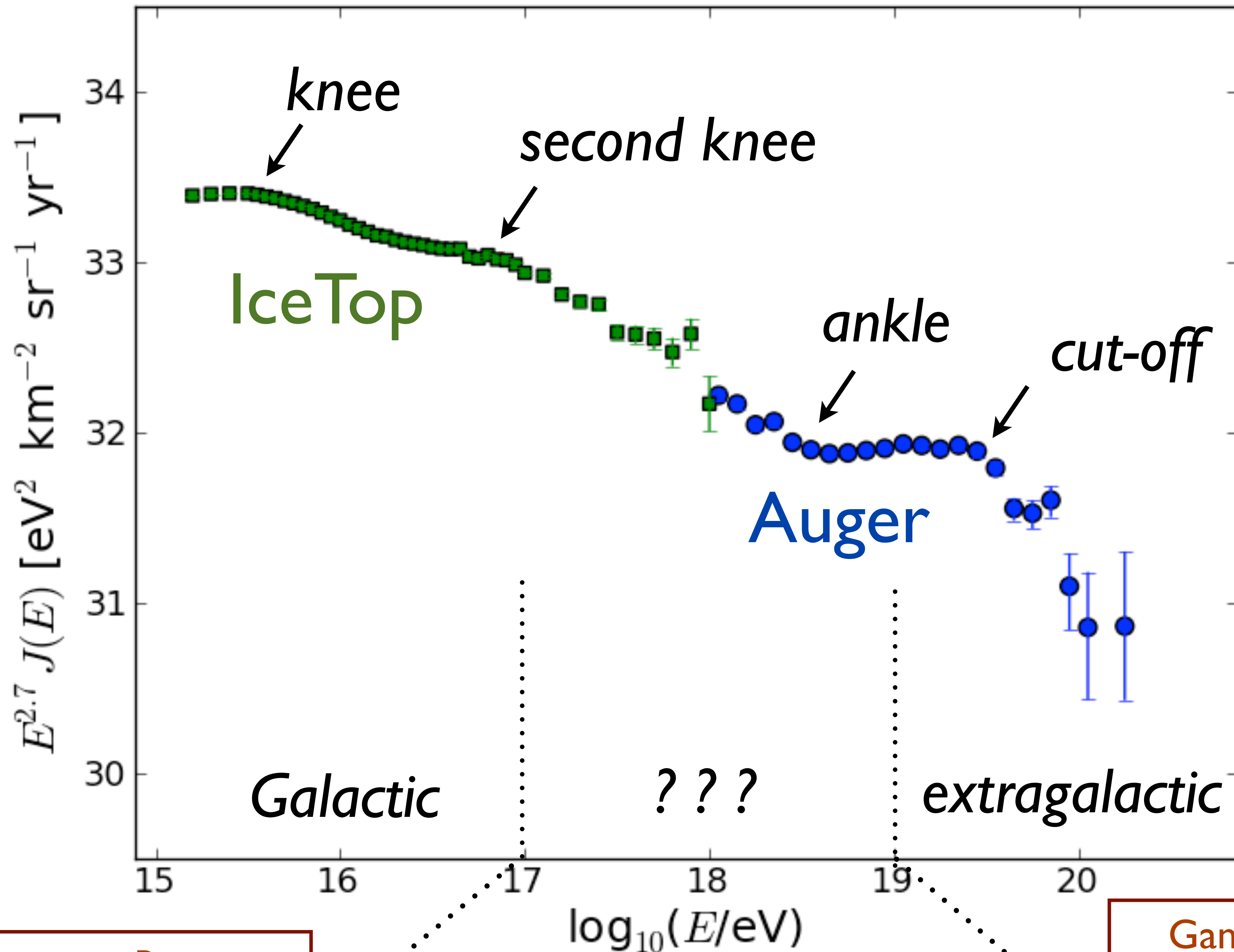
Cosmic-ray mass composition with LOFAR

Fundamental interactions and IAP meeting
June 19 2015 - ULB Brussels

Stijn Buitink for the LOFAR Cosmic Ray KSP

A. Corstanje, J.E. Enriquez, H. Falcke, W. Frieswijk, J.R. Hörandel, M. Krause, A.Nelles, S. Thoudam, J.P. Rachen, P.Schellart, O.Scholten, S. ter Veen.

The all-particle cosmic ray spectrum

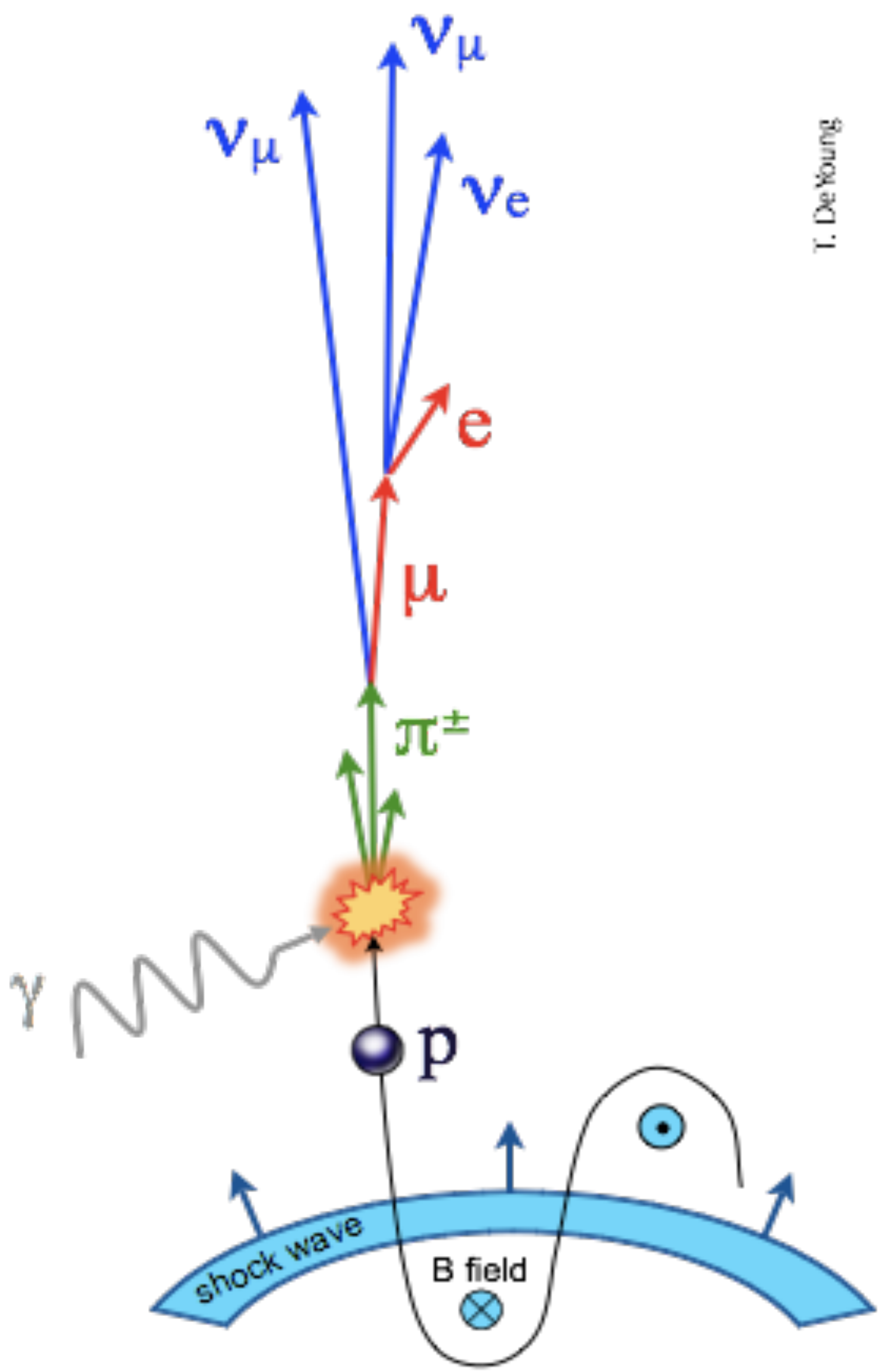


Supernova Remnants

Second Galactic component?
Transition at ankle or earlier?
Sources of IceCube neutrinos?

Gamma Ray Bursts ?
Active Galactic Nuclei ?

Particle acceleration in shock waves

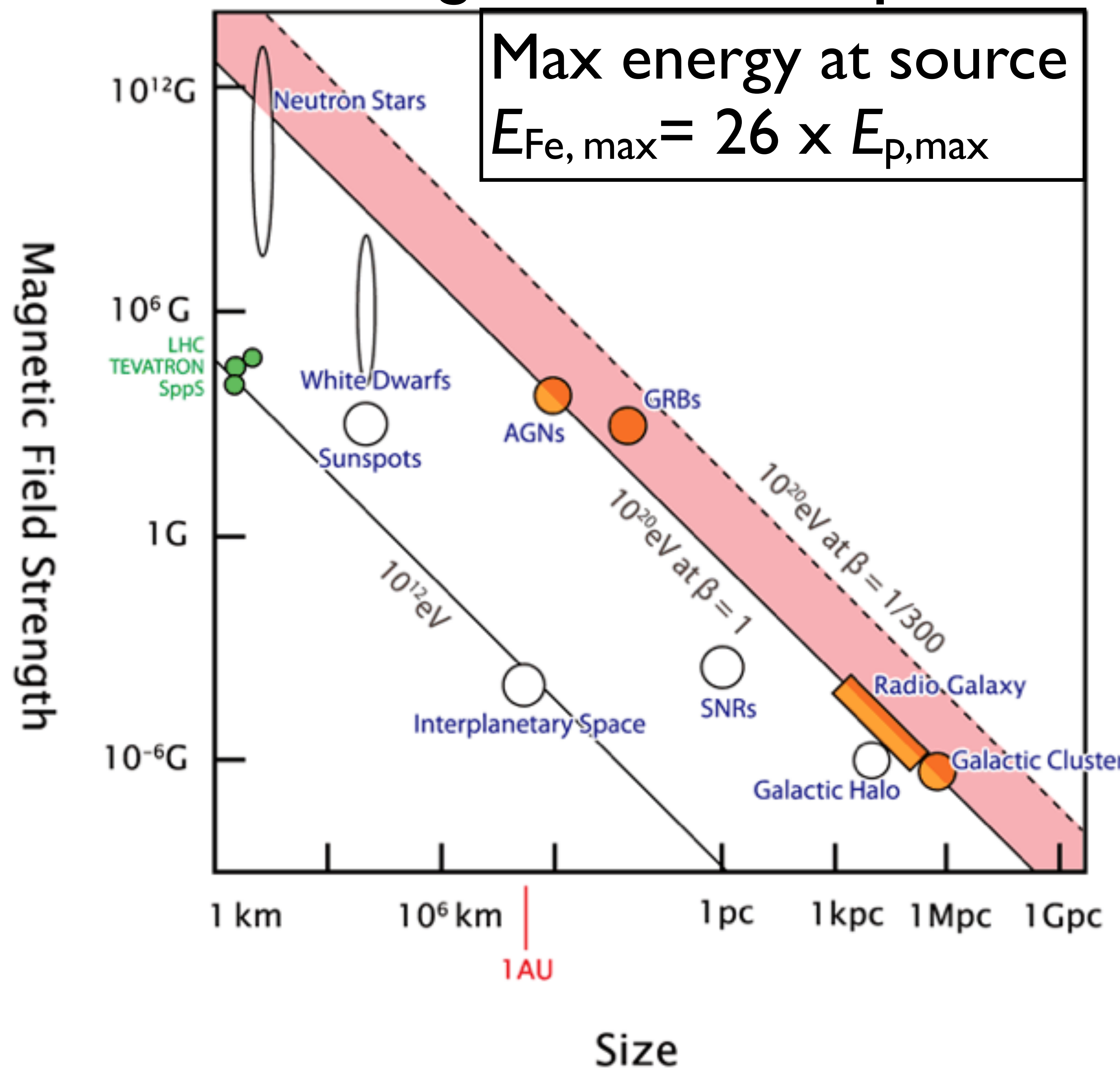


supernovae, AGNs, GRBs, ...

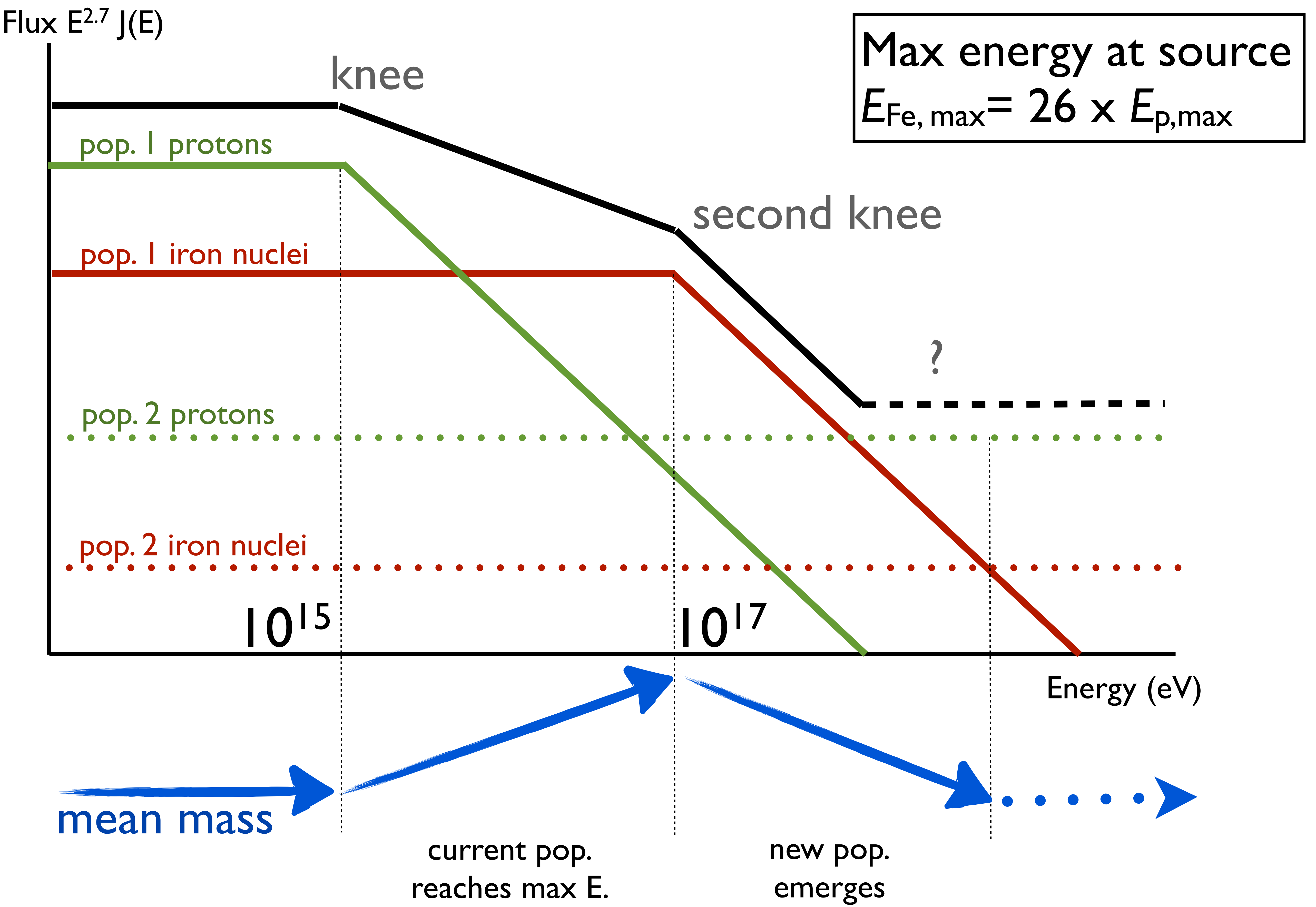
Hillas diagram $E_{max} \sim \beta ZeBR/\Gamma$

Max energy at source

$E_{Fe,\,max} = 26 \times E_{p,max}$

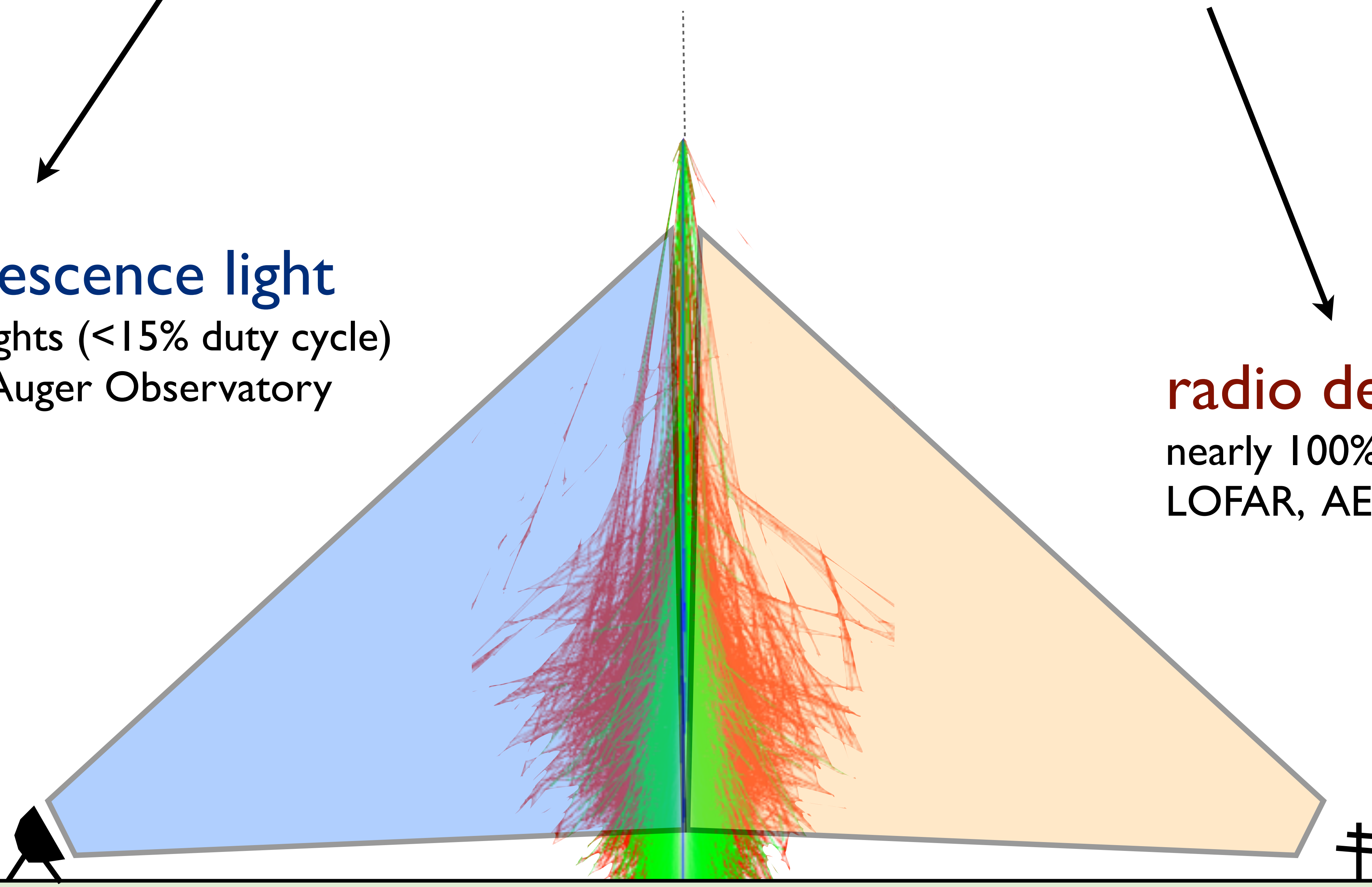


What Cosmic-Ray Masses tell us...



How to measure the mass?

Atmospheric depth of shower maximum Xmax



fluorescence light

dark nights (<15% duty cycle)
Pierre Auger Observatory

radio detection

nearly 100% duty cycle
LOFAR, AERA

Electron/Muon ratio

particles on ground,
sensitive to shower-to-shower fluctuations
Kascade Grande, IceTop

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

LOPES

CODALEMA

LOFAR

AERA (Auger)

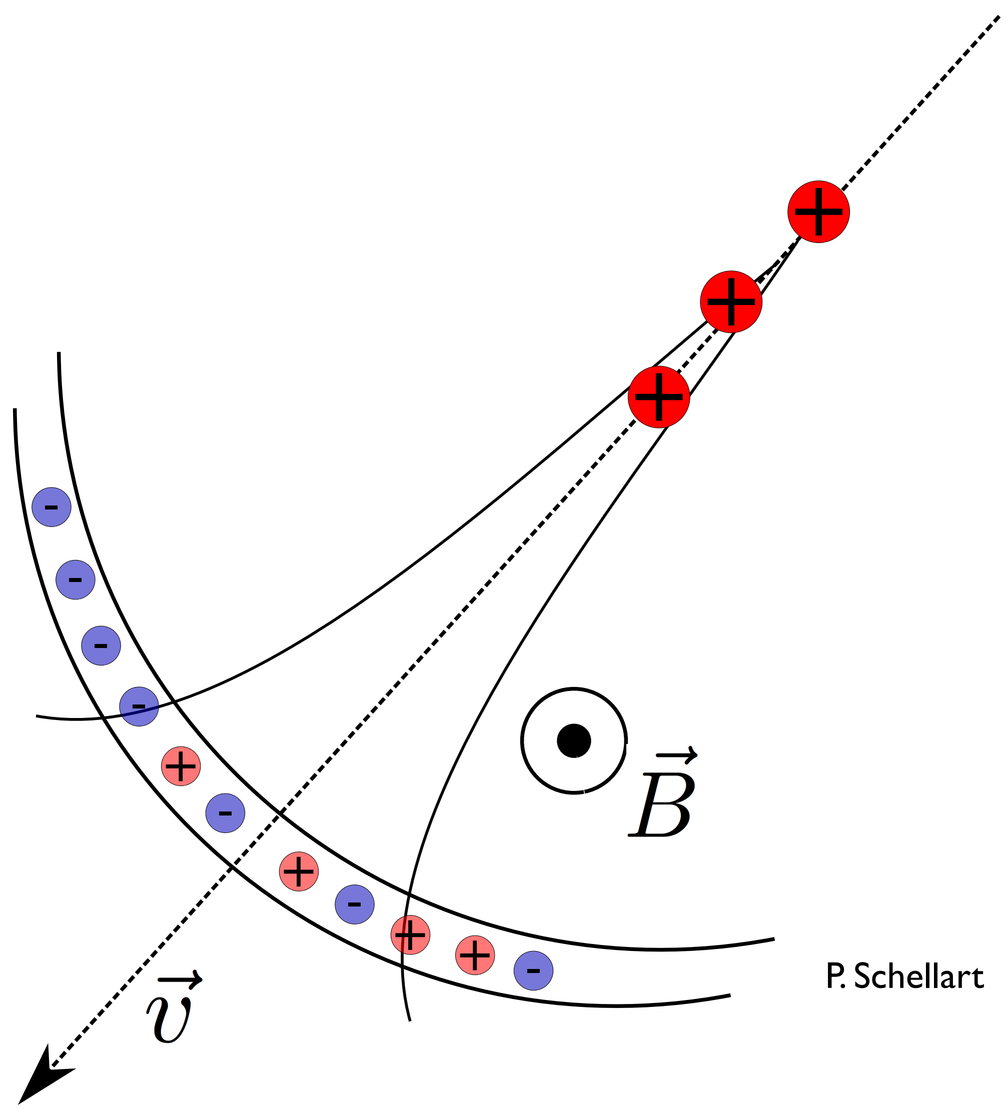
Tunka-REX

What drives the radio emission?

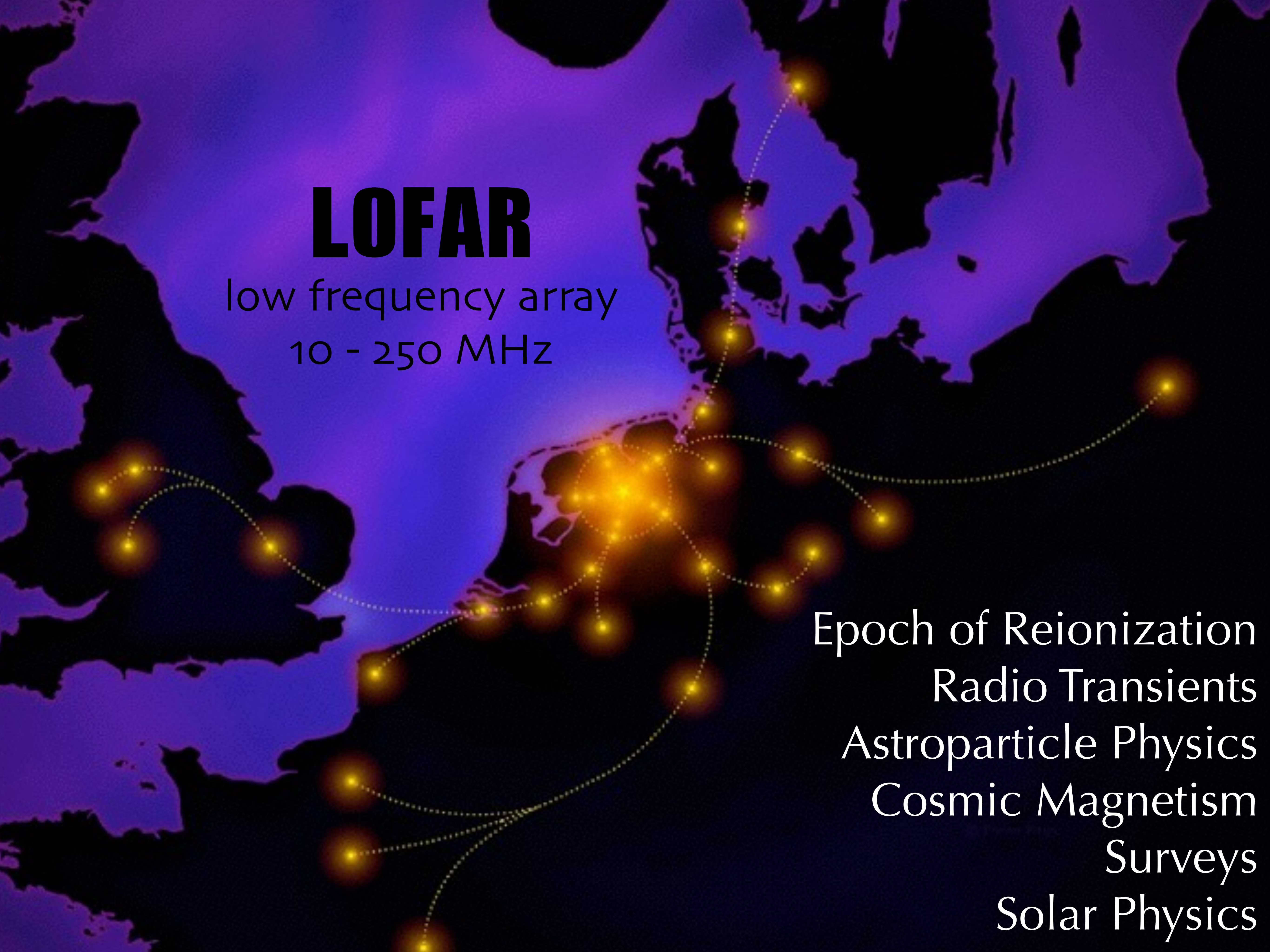
- <u>Earth magnetic field</u>
  electrons/positrons deflected
  $E \sim dn_{ch}/dt$

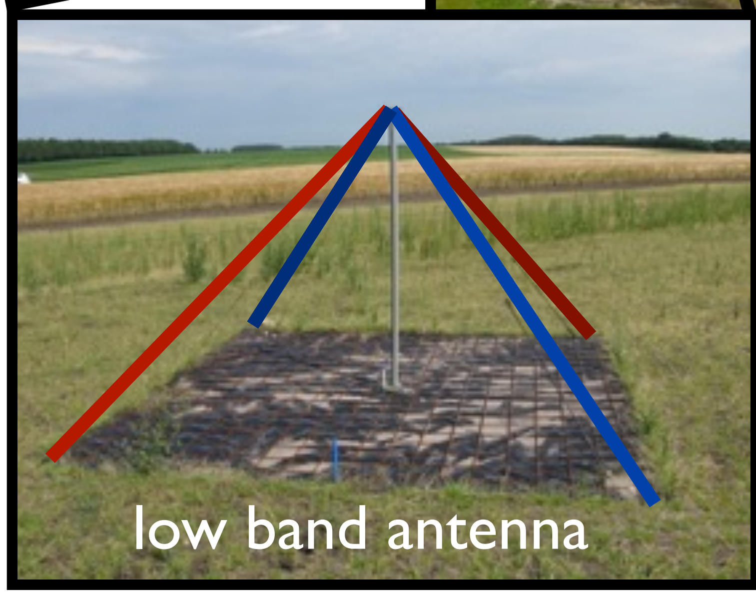
- <u>Charge excess</u>
  negative charge due to electron knockouts
  $E \sim d(n_e - n_p)/dt$

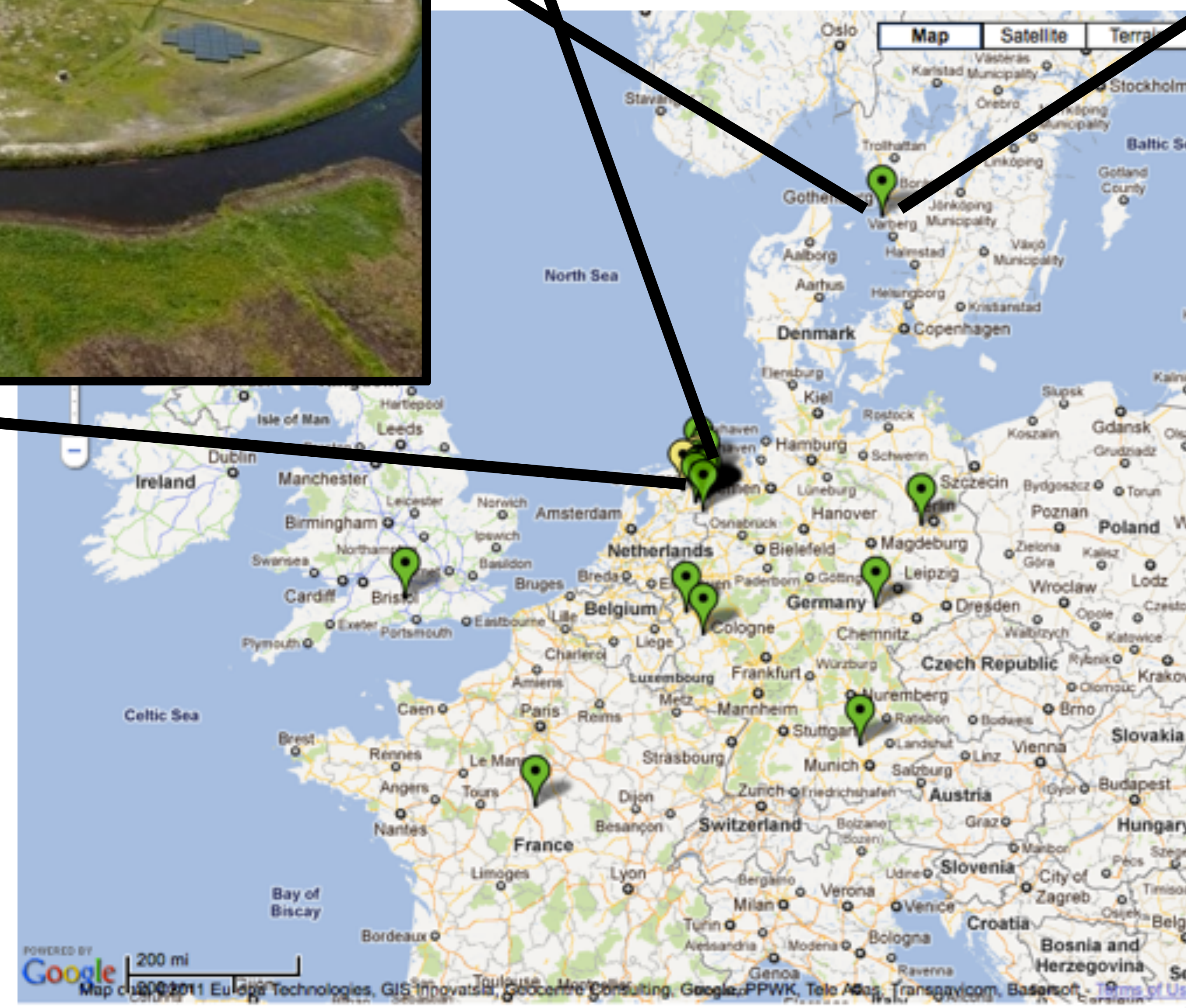
- <u>Non-unity index of refraction</u>
  Cherenkov-like effects
  ring structure possible



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


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



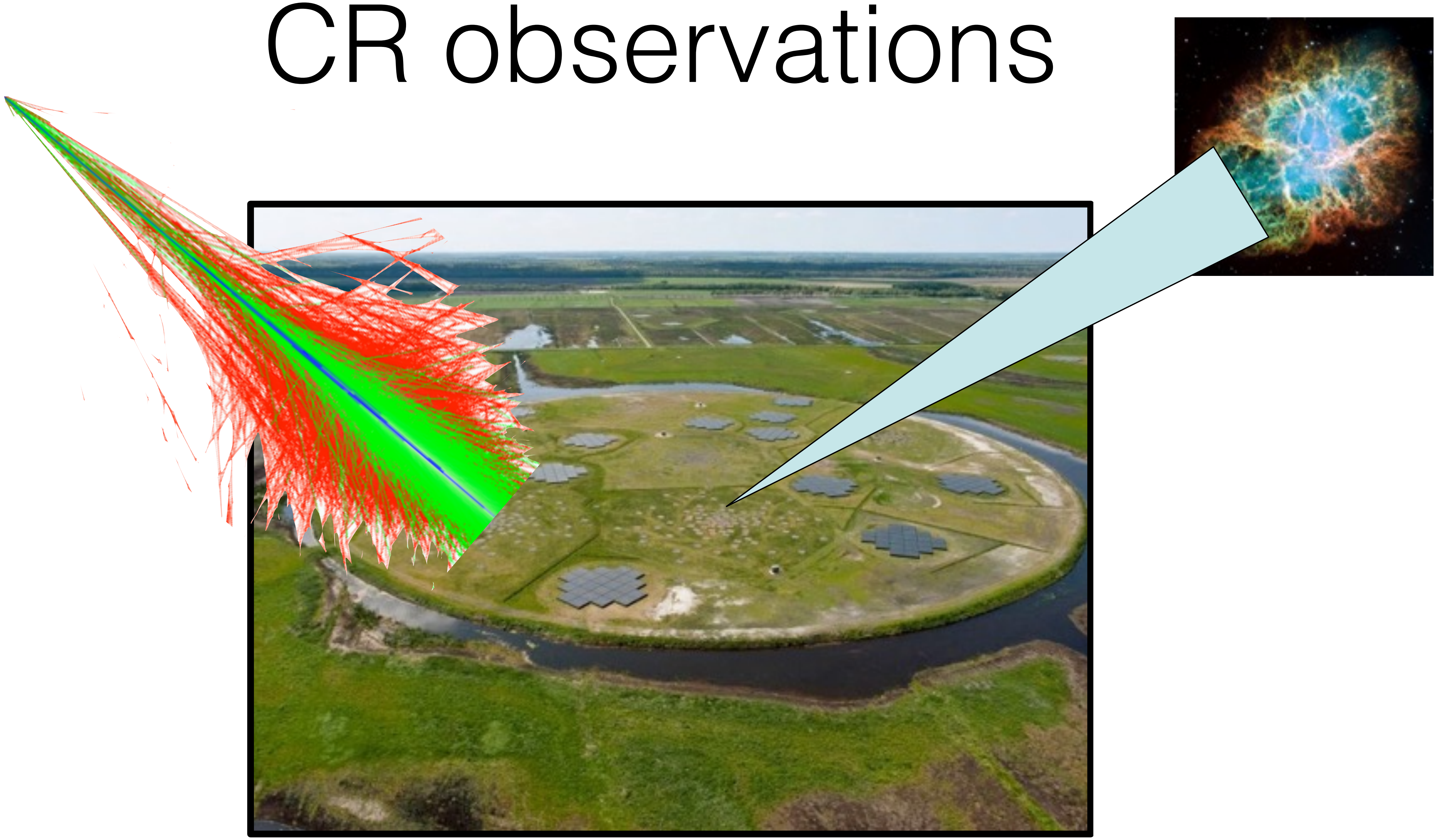


SUPERTERP
~600 low band antennas
30 - 80 MHz
5 ns time resolution
> GB buffer/antenna

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

24 core stations
9 remote stations
8 international stations

CR observations

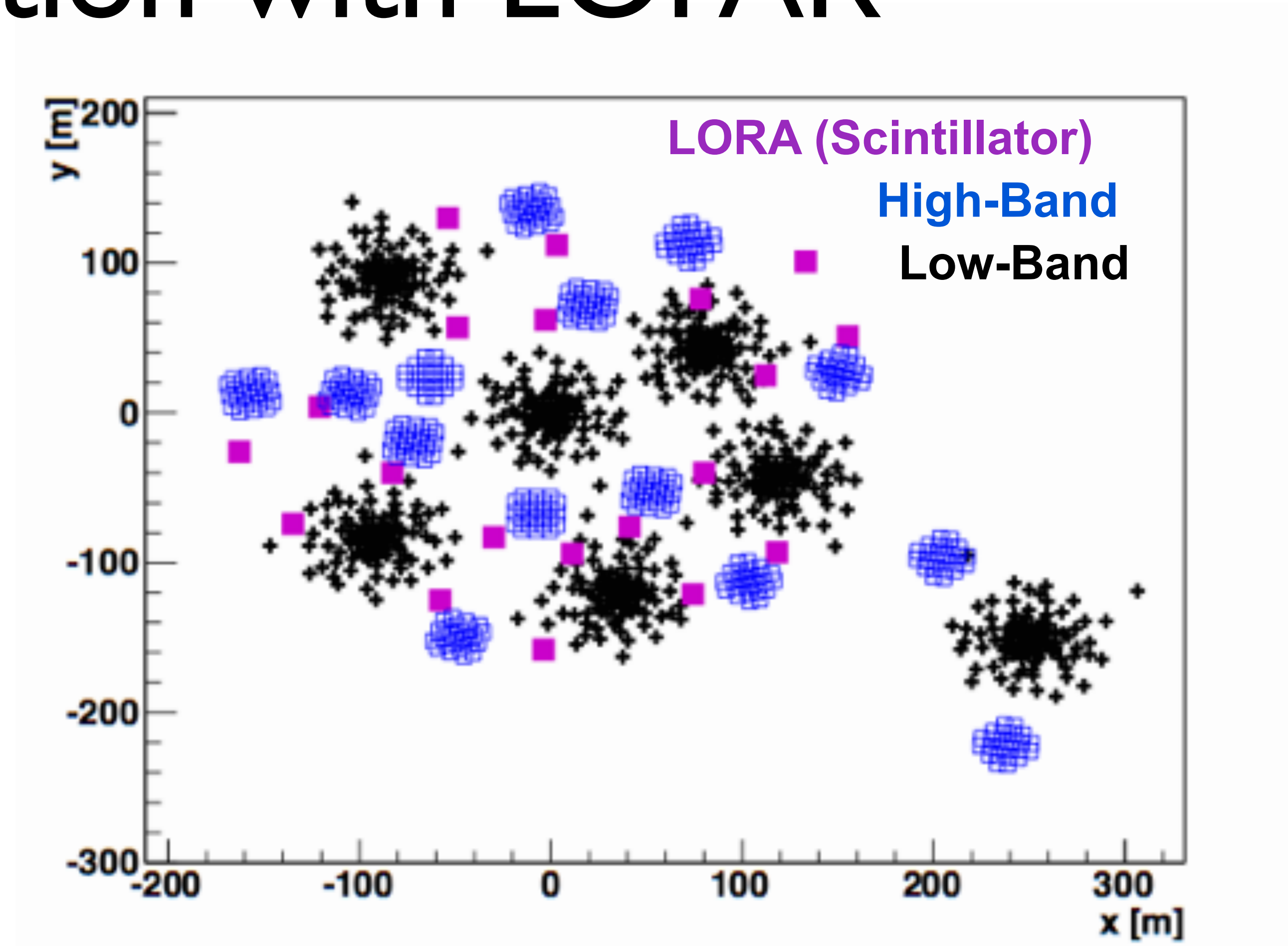


LOFAR is designed to support many different observation strategies

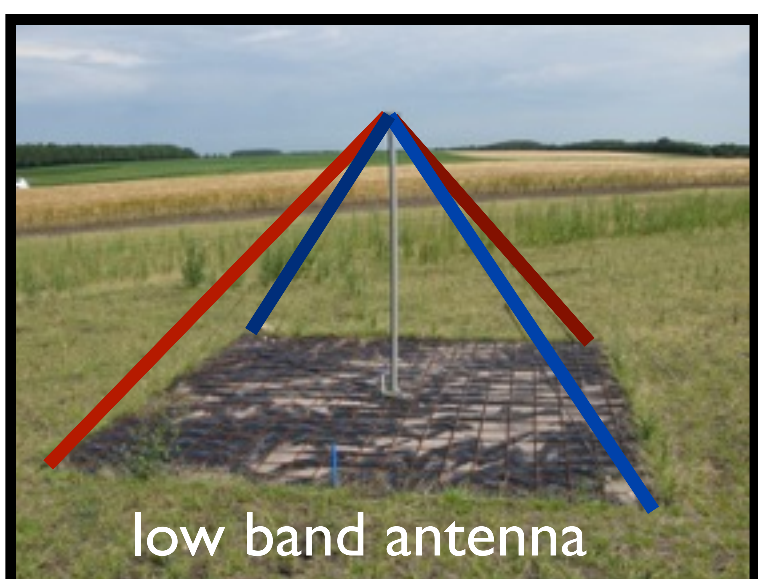
CR detection runs in the background during other observations

Air shower detection with LOFAR

LORA
LOFAR Radboud Array
scintillator detectors

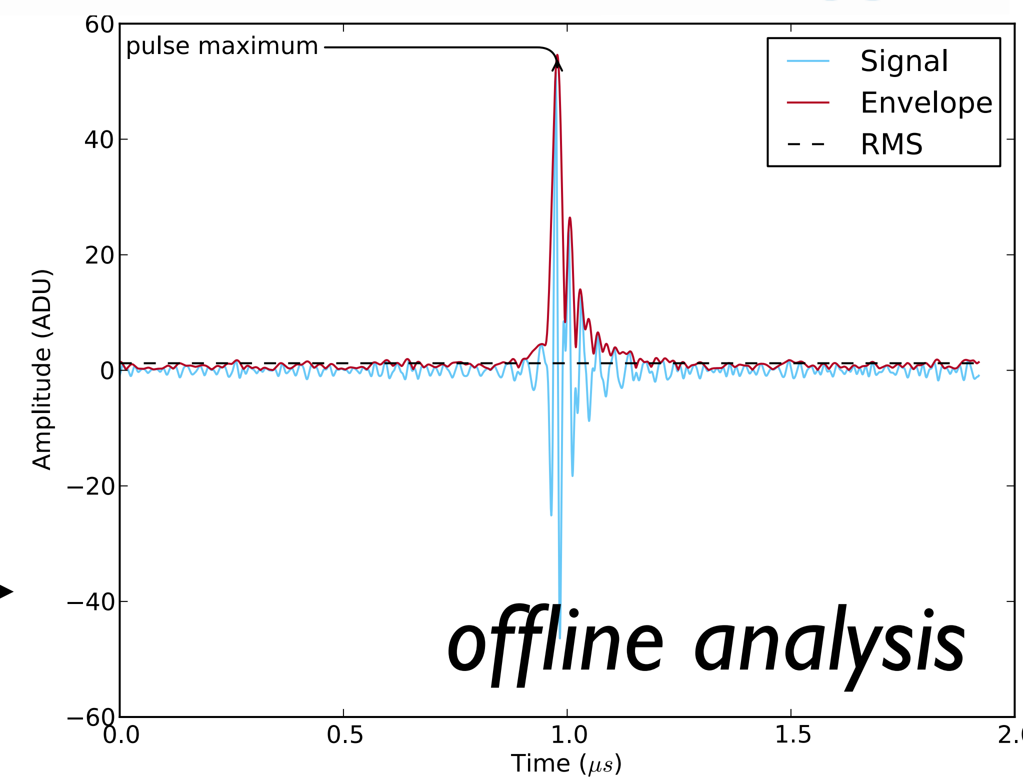


trigger



buffer

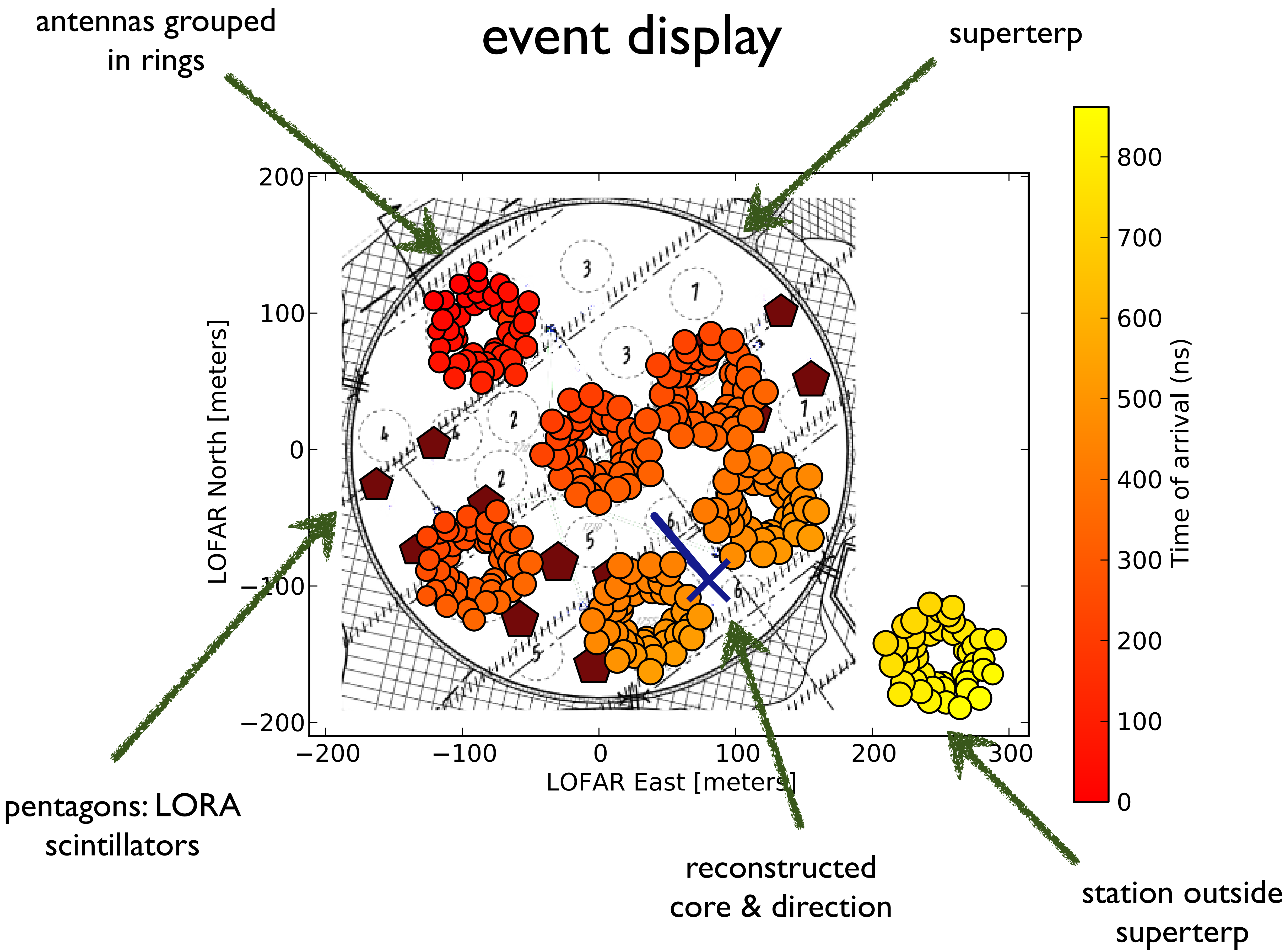
2 ms read-out



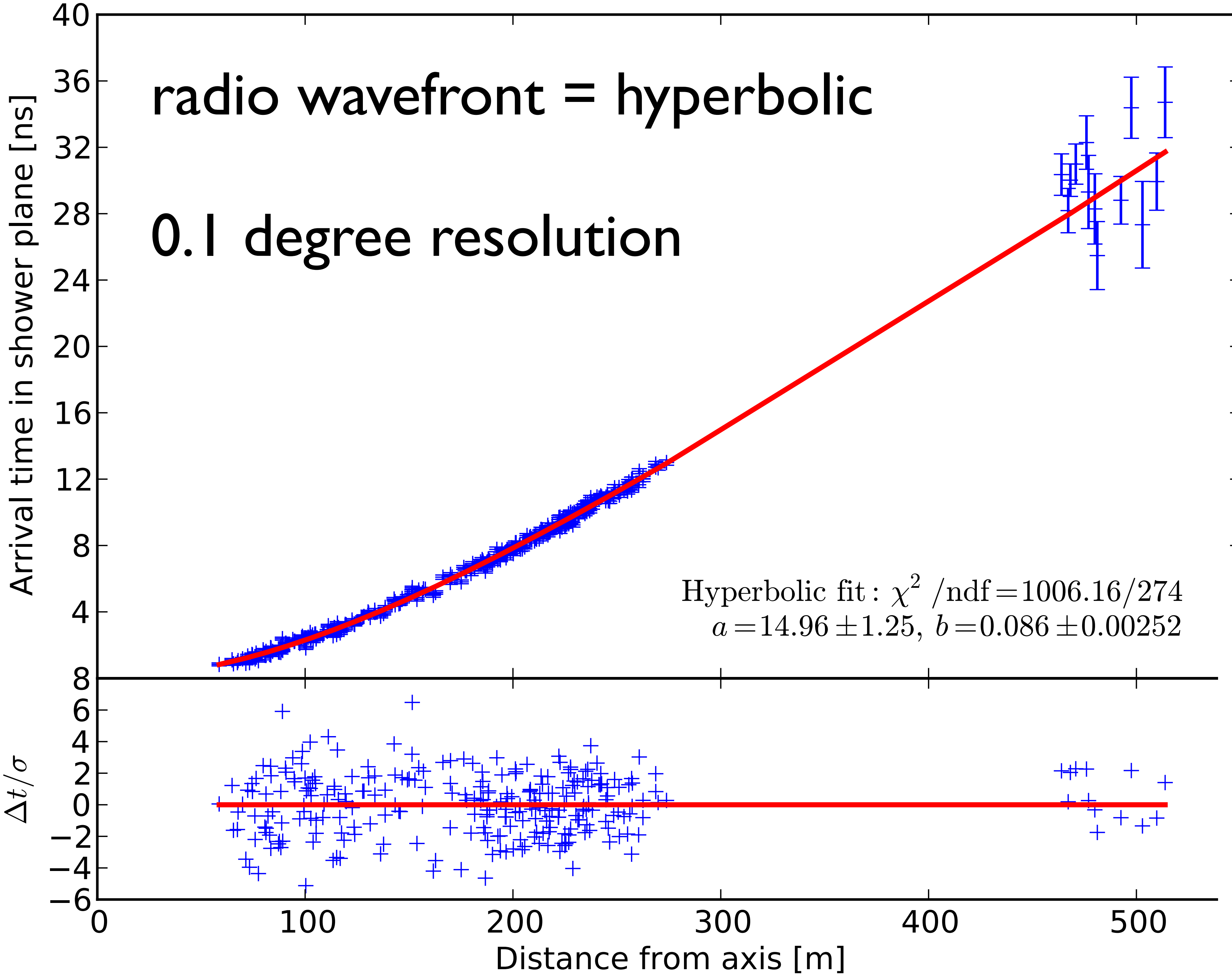
offline analysis

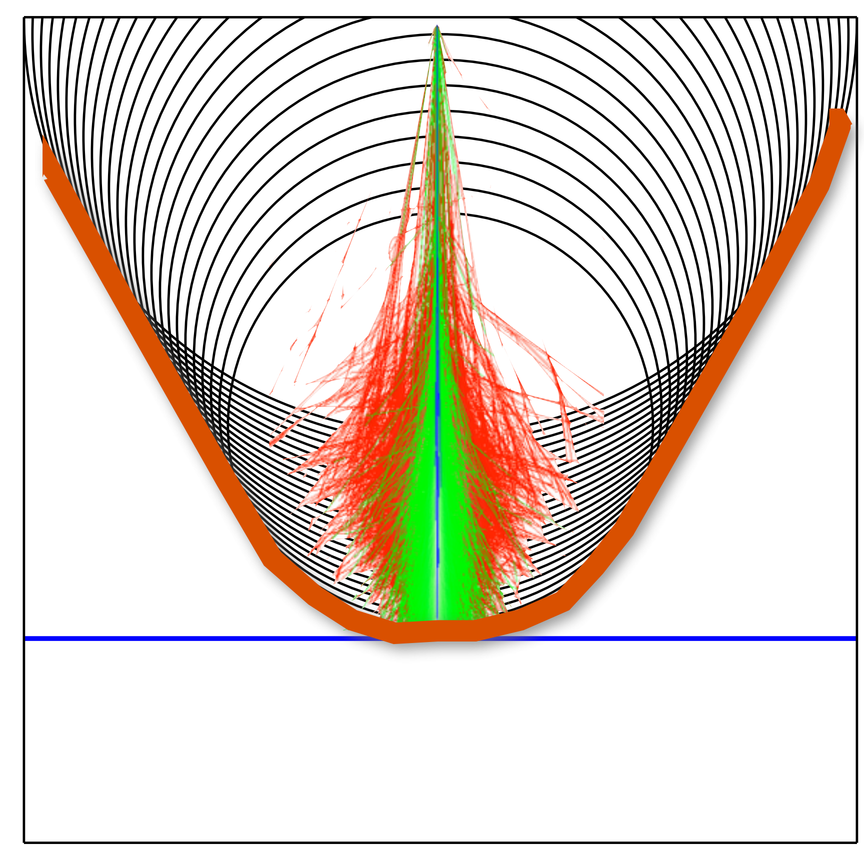
Pim Schellart et al., A&A 560, 98 (2013)

event display



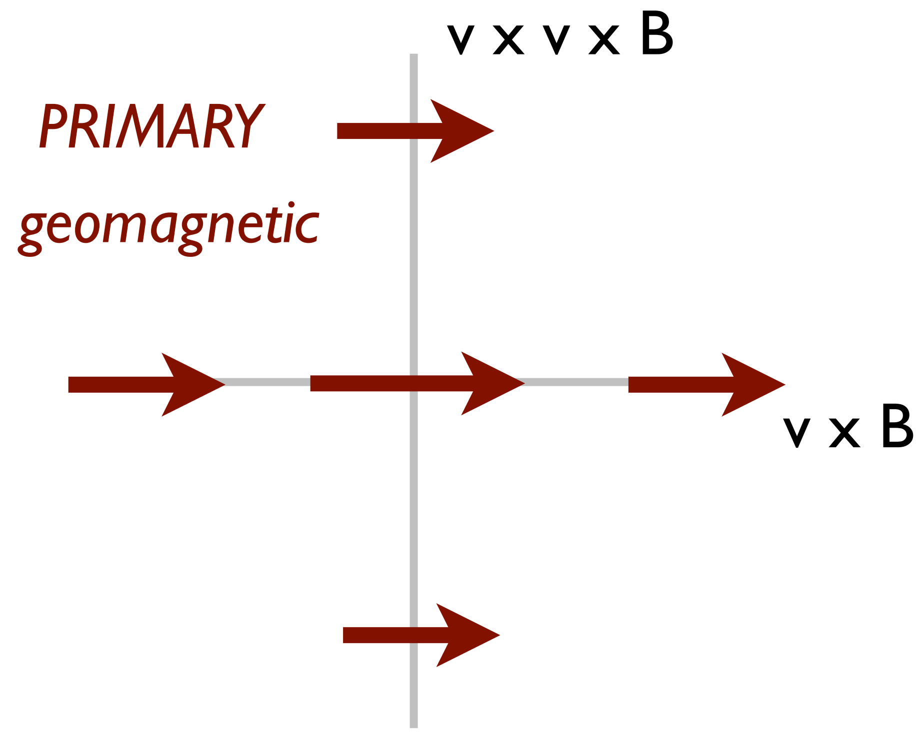
Nanosecond timing precision

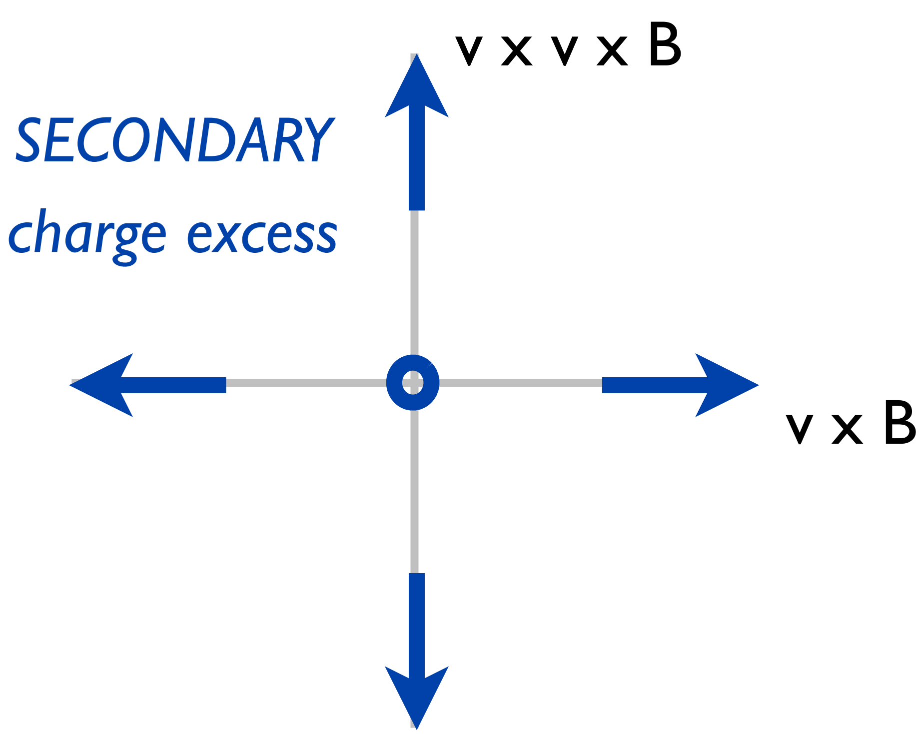


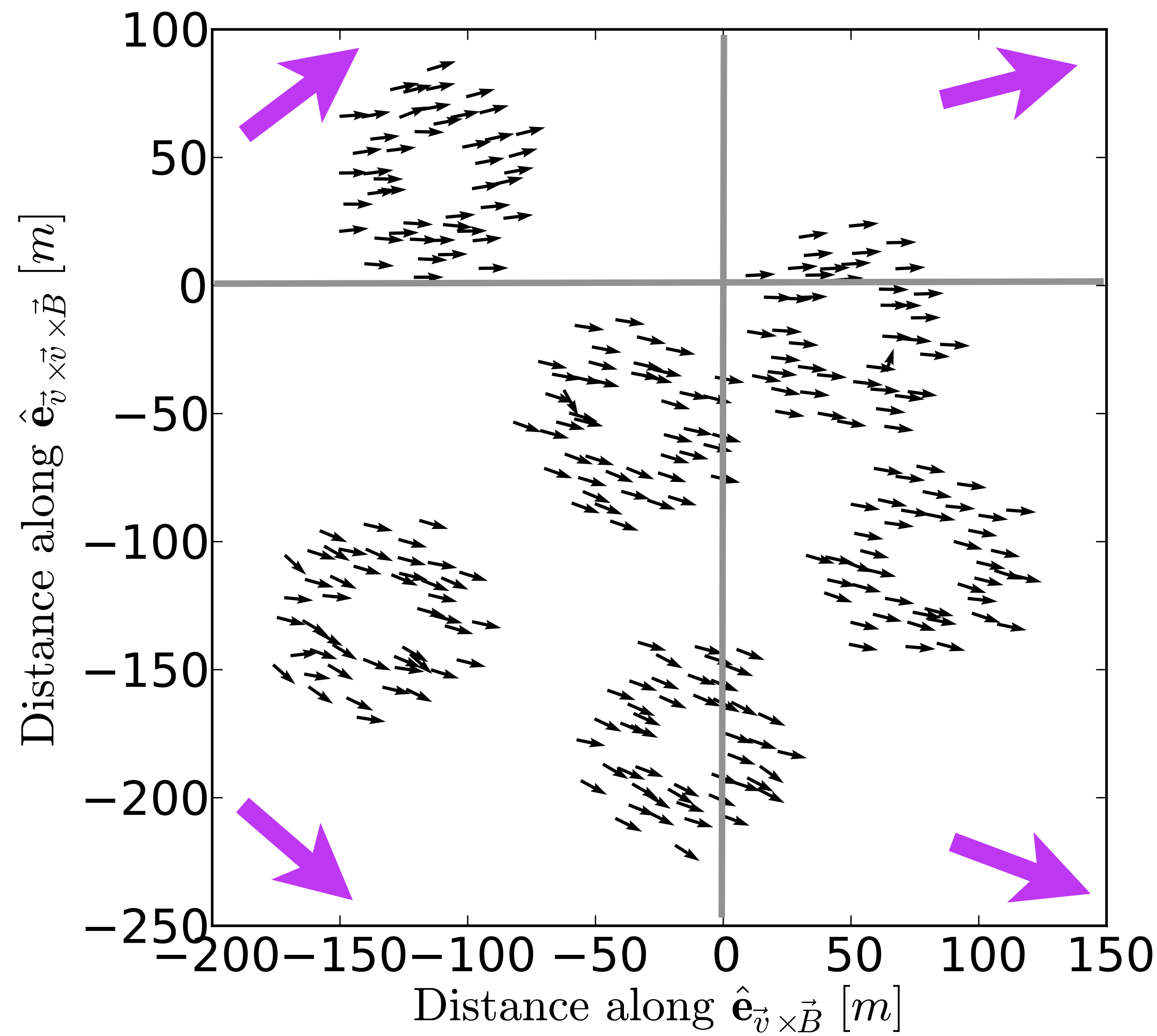


Arthur Corstanje et al., *Astropart. Phys.* **61** 22 (2015)

Understanding the polarization





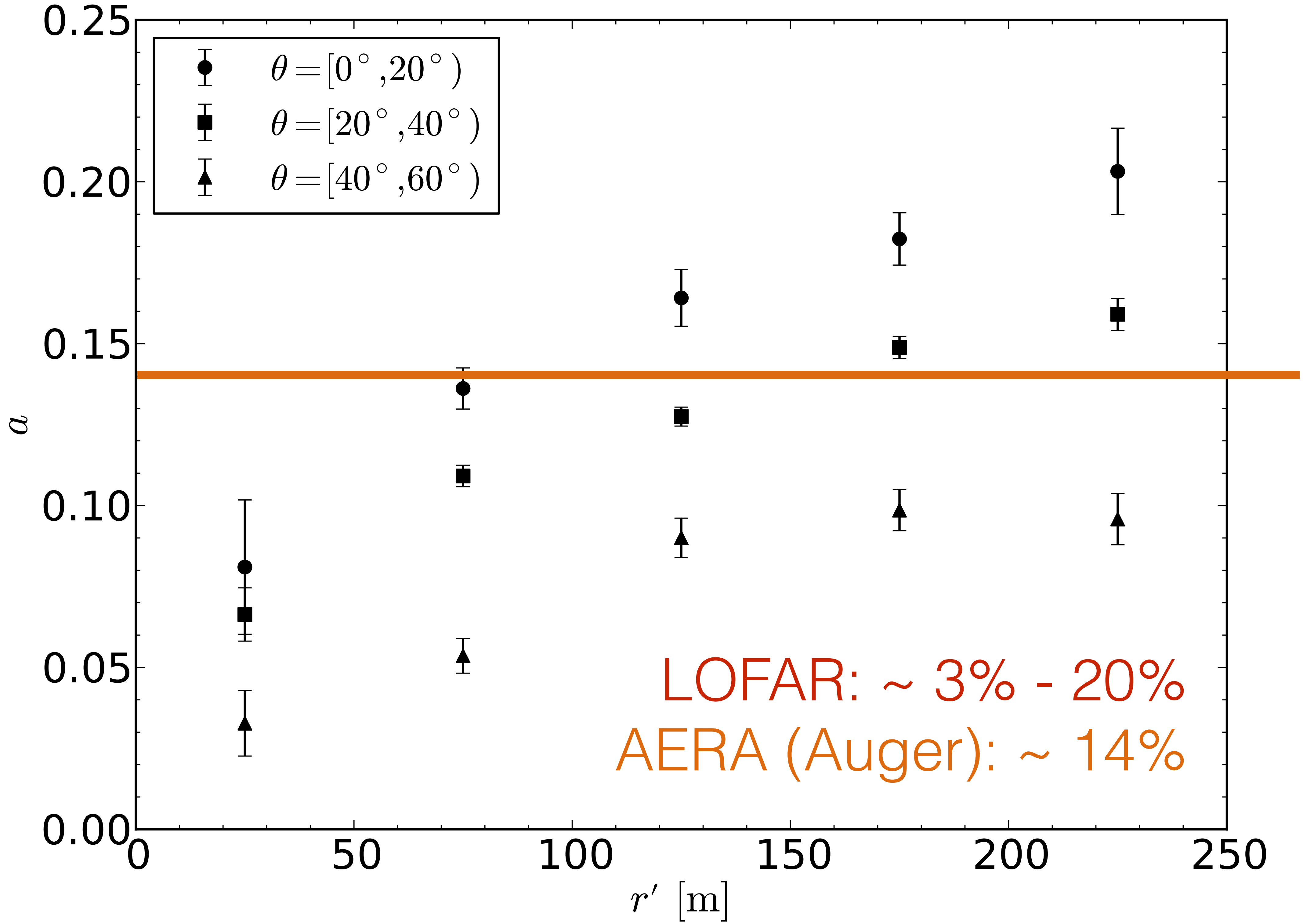


Interference: emission pattern = asymmetric

Pim Schellart et al., *JCAP* **10** 14 (2014)

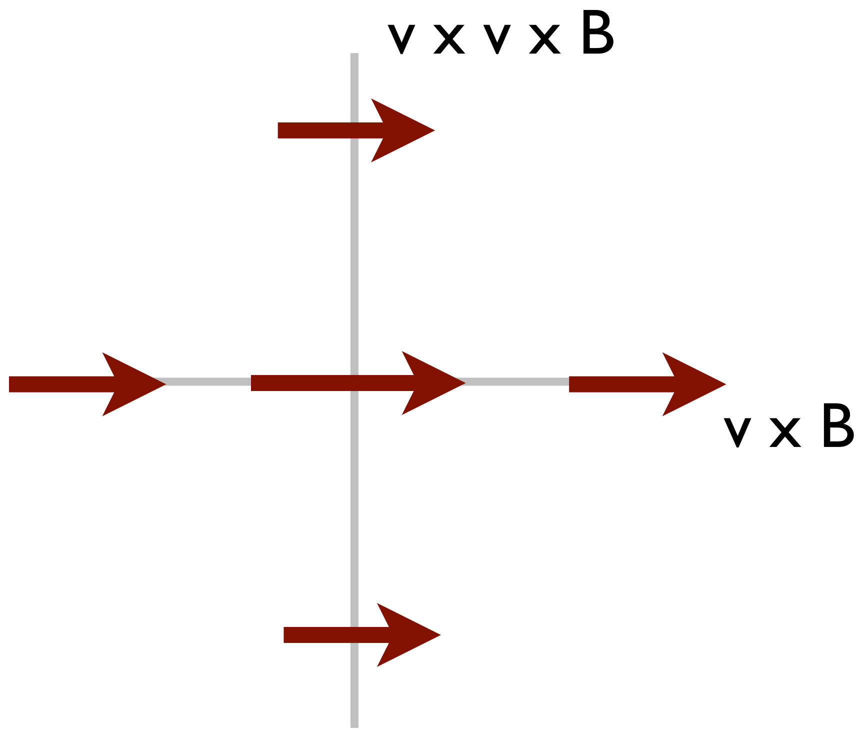
Charge excess fraction *a*

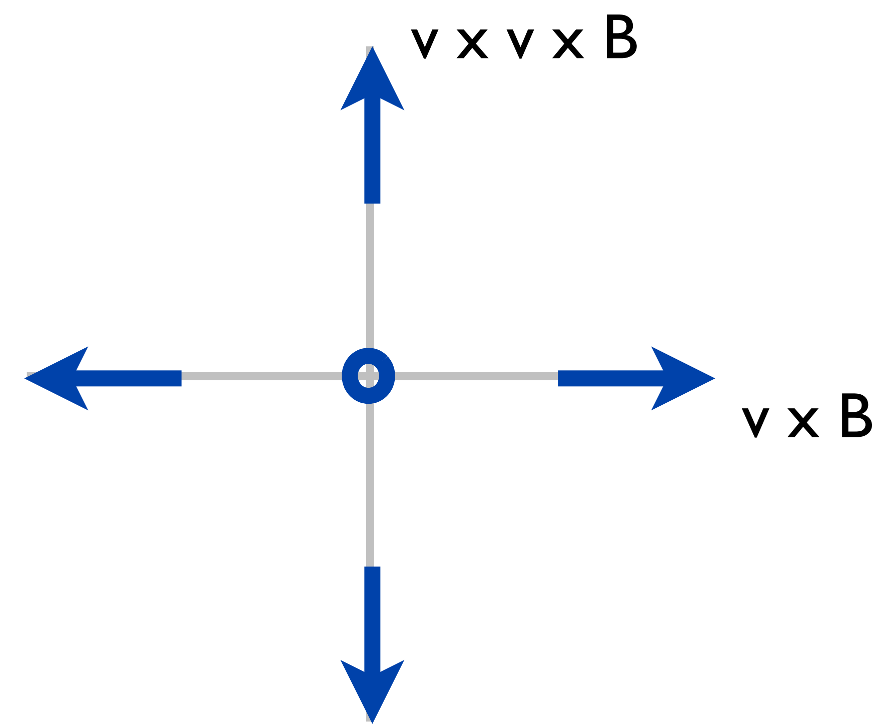
based on polarization measurements



Pim Schellart et al. [LOFAR], *JCAP* **10** 14 (2014)
Aab et al. [Auger] *PRD* **89** 052002 (2014)

CoREAS simulations





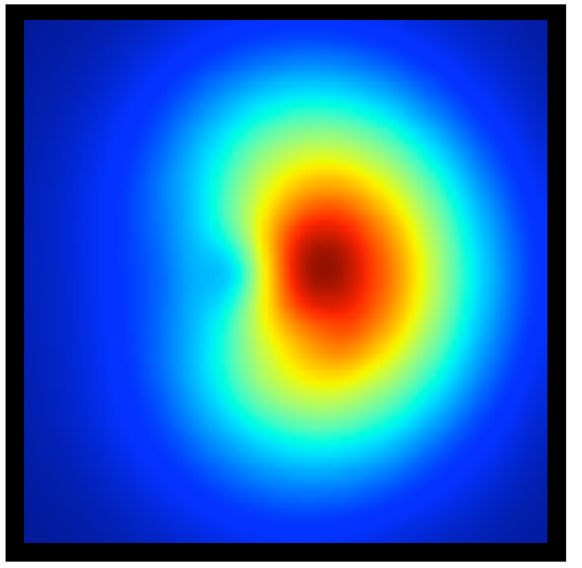
vector sum of geomagnetic and charge excess component

relativistic beaming

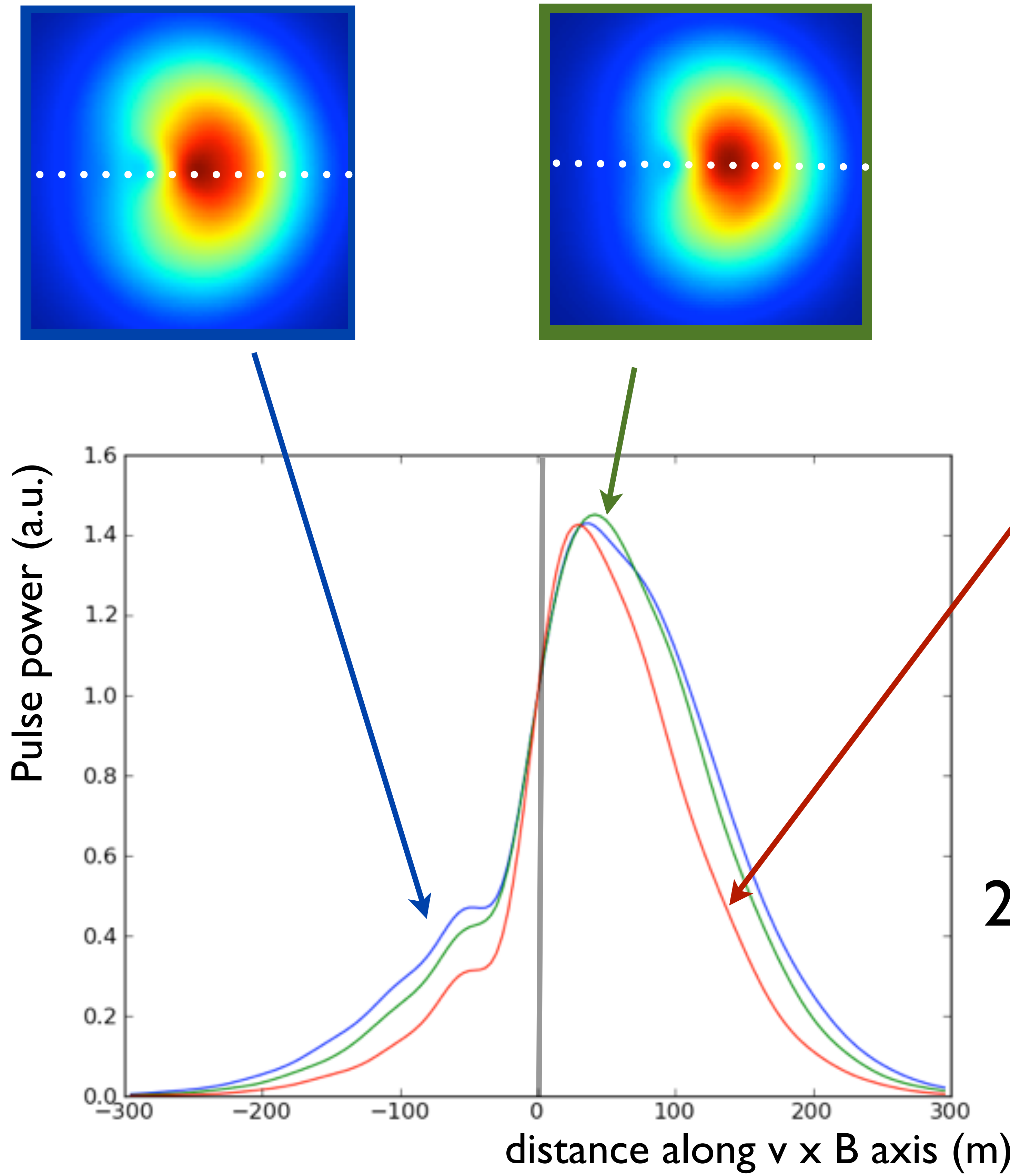
Cherenkov-like propagation effects (n≠1)

CoREAS:

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



X_{max} ~ 600 g/cm^2 X_{max} ~ 650 g/cm^2 X_{max} ~ 700 g/cm^2

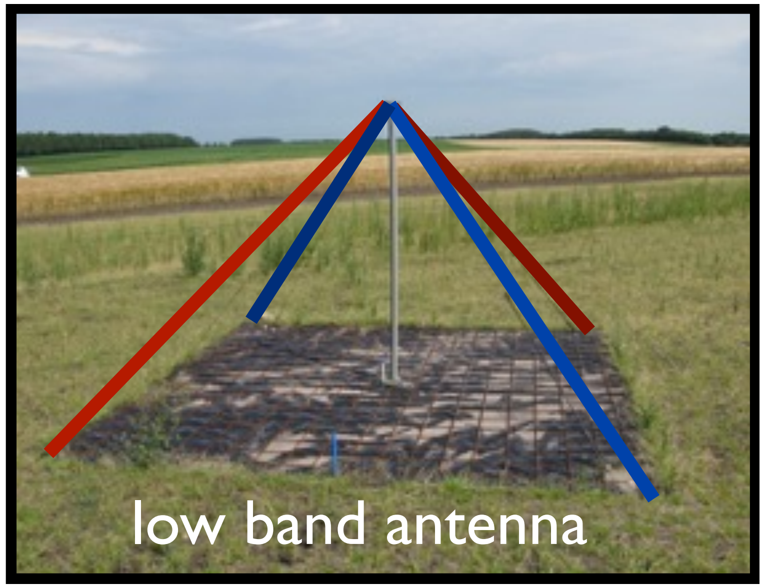


shape depends on X_{max}

LOFAR:
200 - 400 antennas/event

→ *fit full 2D pattern !*

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

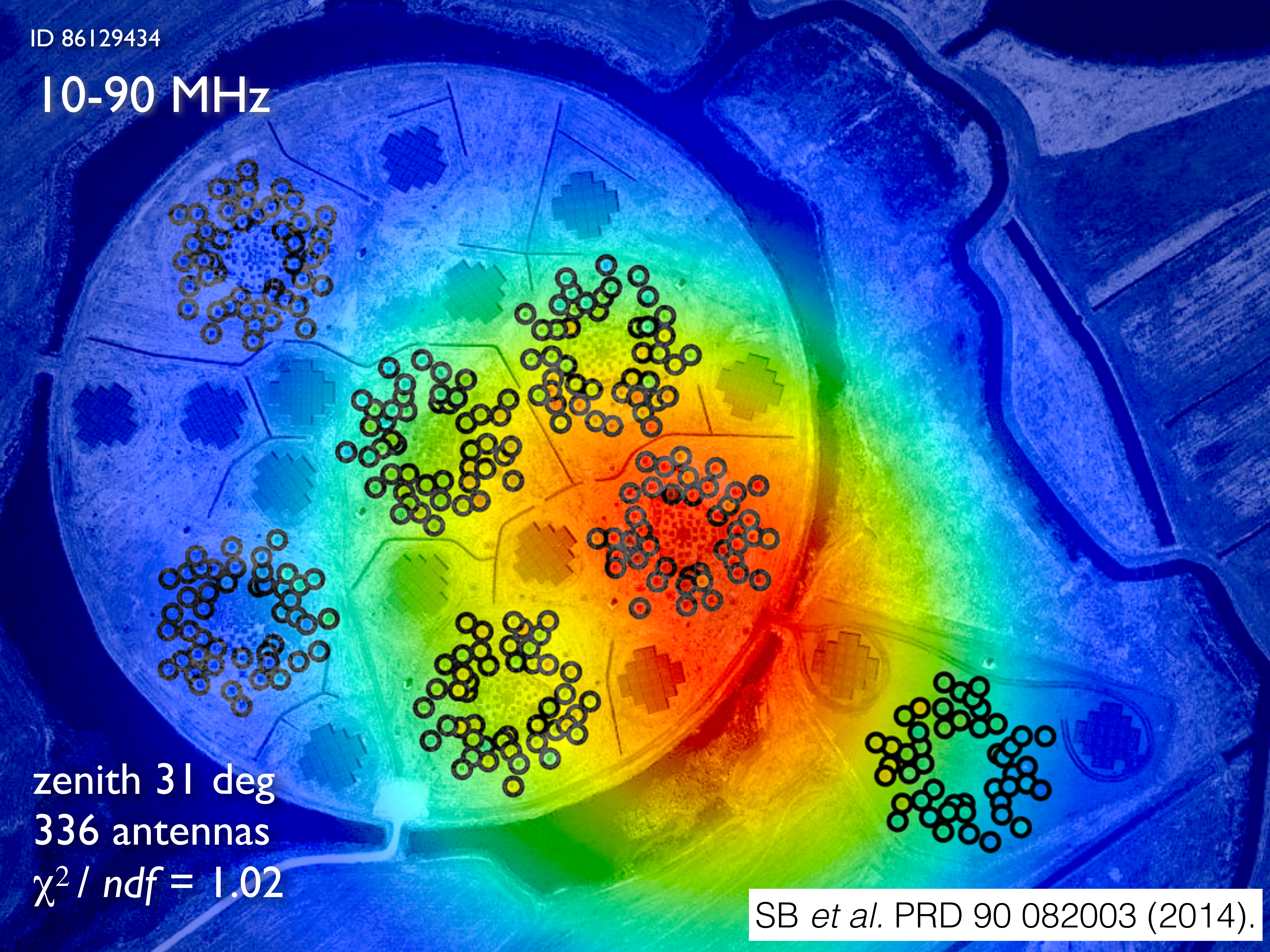
$$\chi^2 = \sum_{antennas} \left(\frac{P_{ant} - f_r P_{sim}(x_{ant} + x_{off}, y_{ant} + y_{off})}{\sigma_{ant}} \right)^2 + \sum_{detectors} \left(\frac{d_{det} - f_p d_{sim}(x_{det} + x_{off}, y_{det} + y_{off})}{\sigma_{det}} \right)^2$$

4 fit parameters:

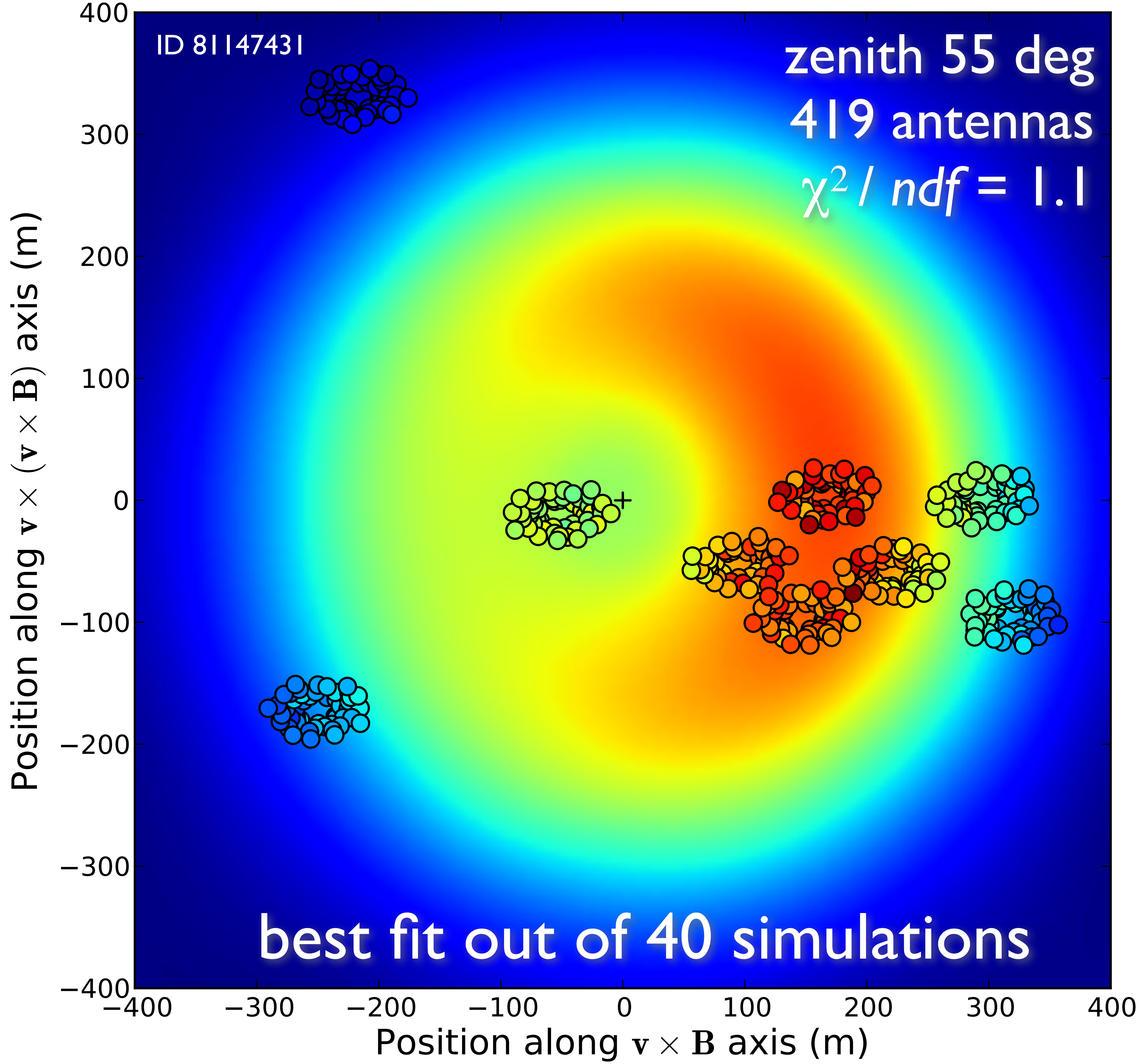
core position

radio power scale factor

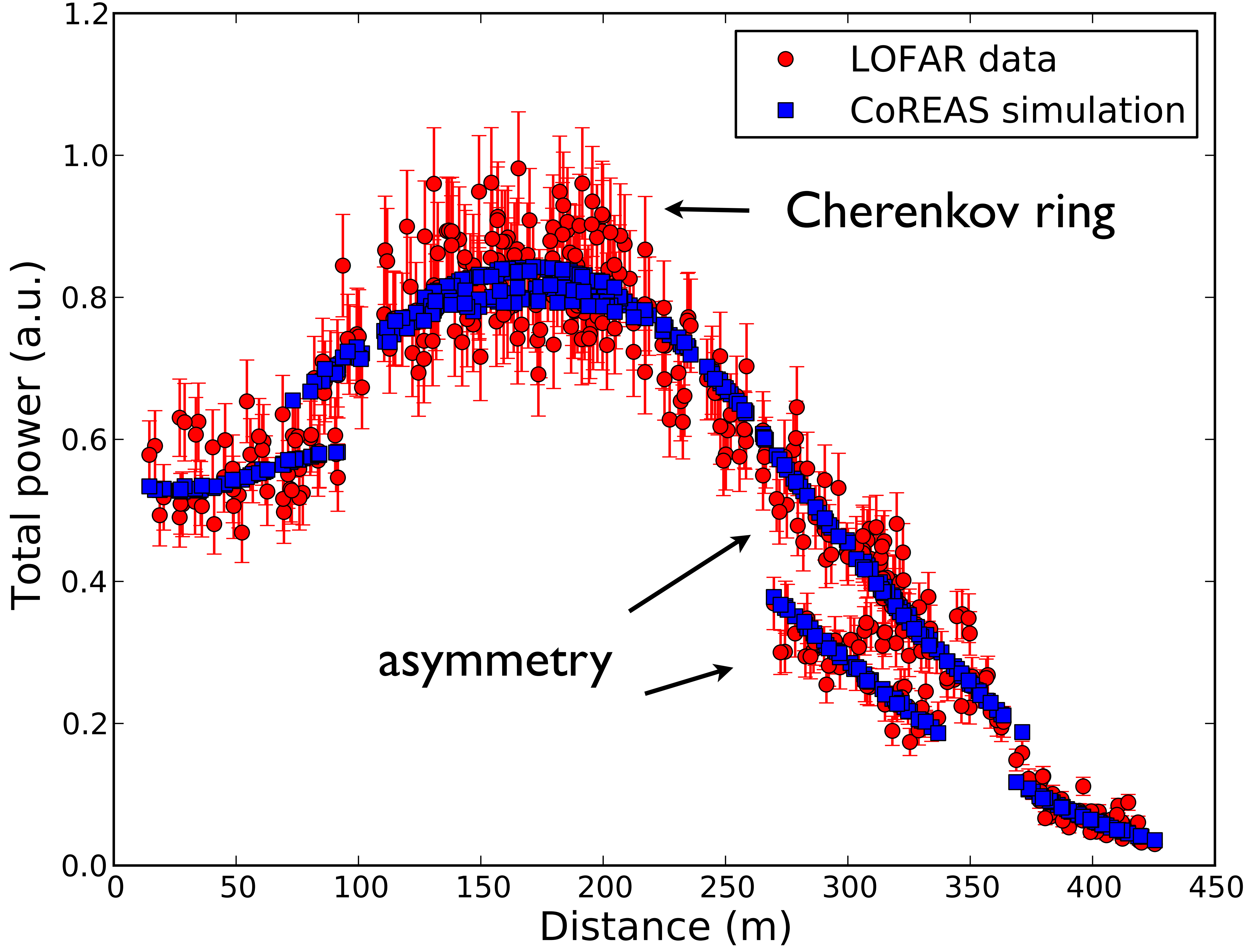
particle density scale factor



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

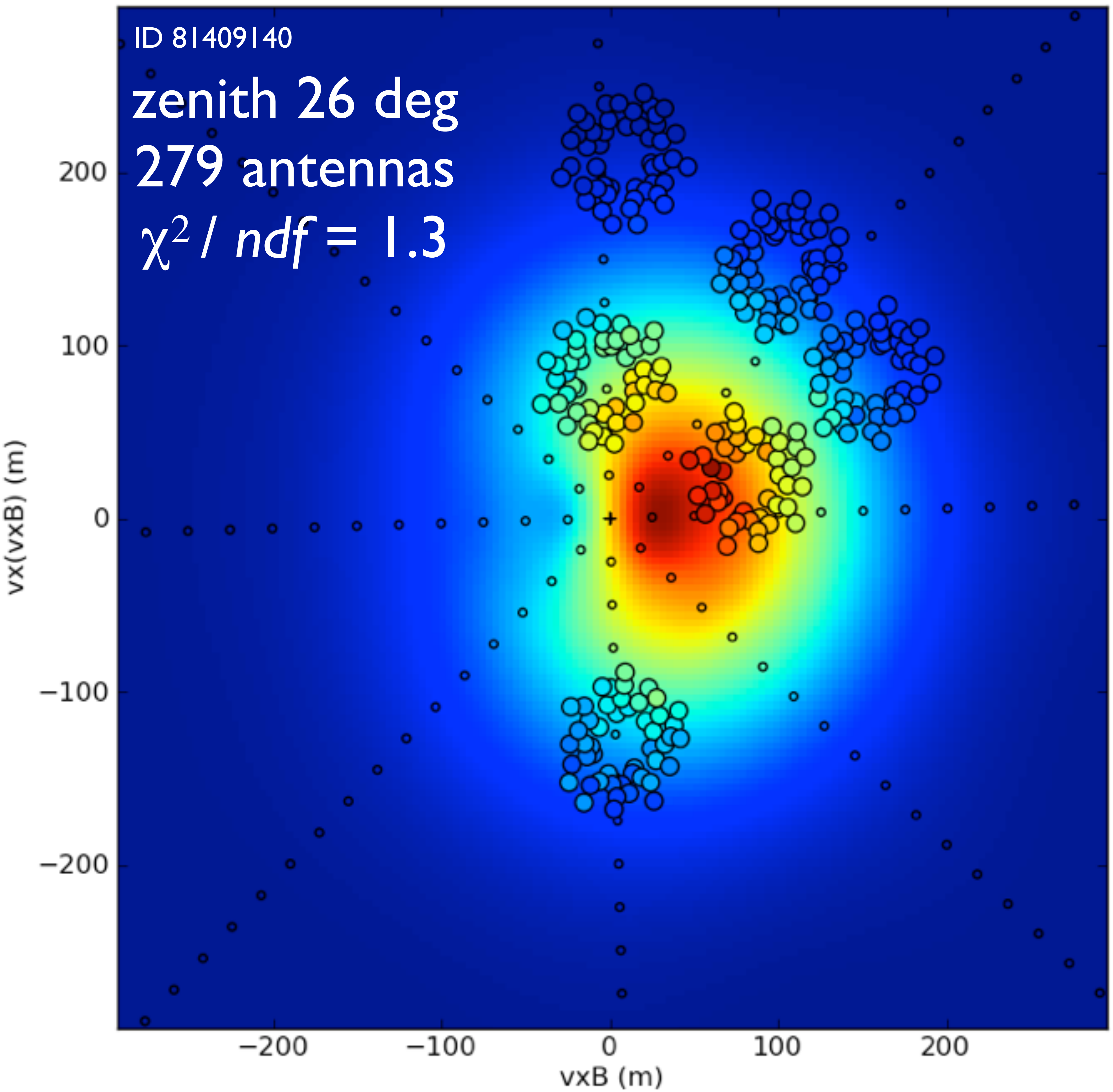


ID 81147431
zenith 55 deg
419 antennas
$\chi^2 / ndf = 1.1$
best fit out of 40 simulations
Position along $\mathbf{v} \times (\mathbf{v} \times \mathbf{B})$ axis (m)
Position along $\mathbf{v} \times \mathbf{B}$ axis (m)
400
300
200
100
0
−100
−200
−300
−400
−400
−300
−200
−100
0
100
200
300
400

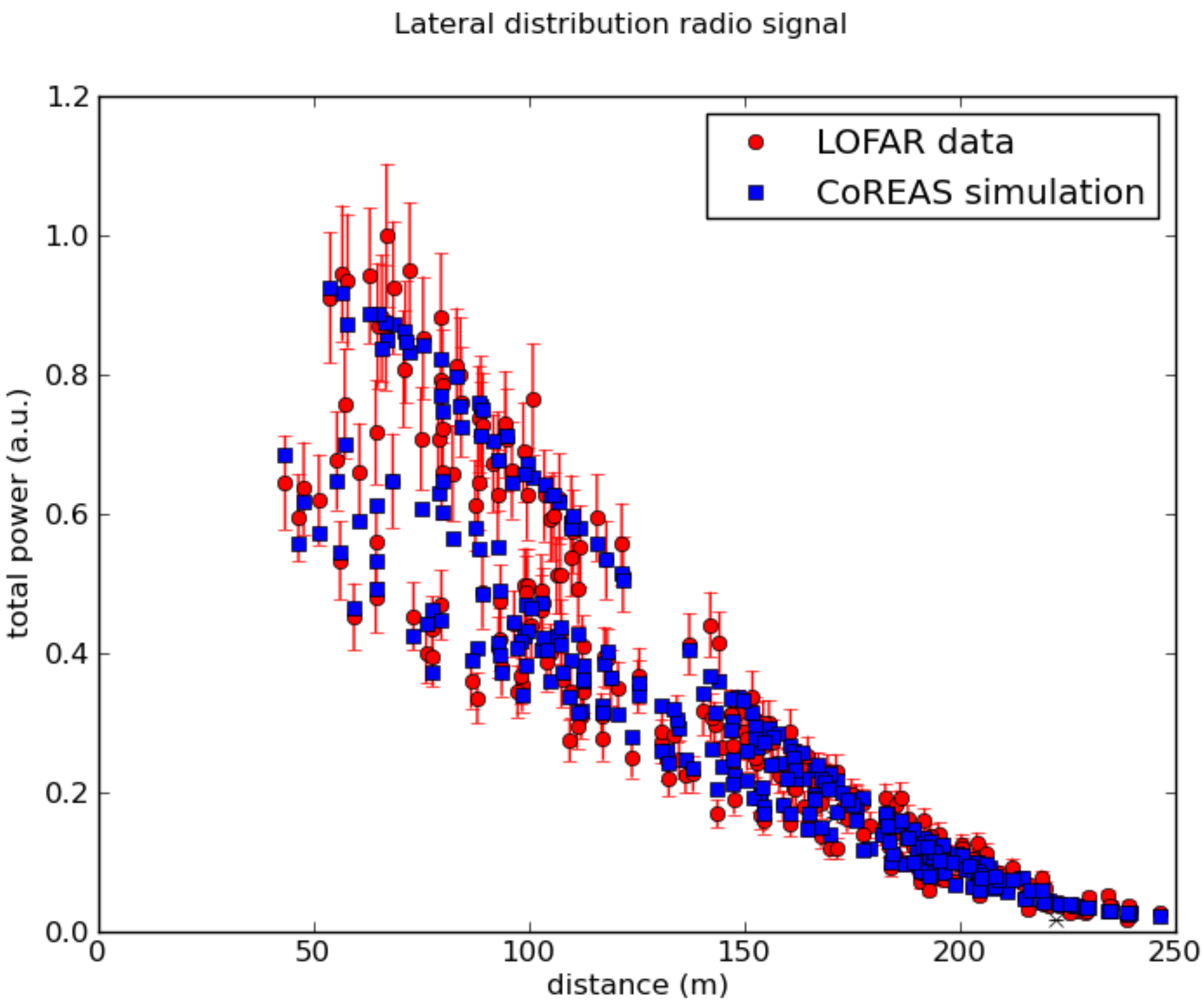


LOFAR data
CoREAS simulation
Cherenkov ring
asymmetry
Total power (a.u.)
Distance (m)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
50
100
150
200
250
300
350
400
450

best fit out of 40 simulations



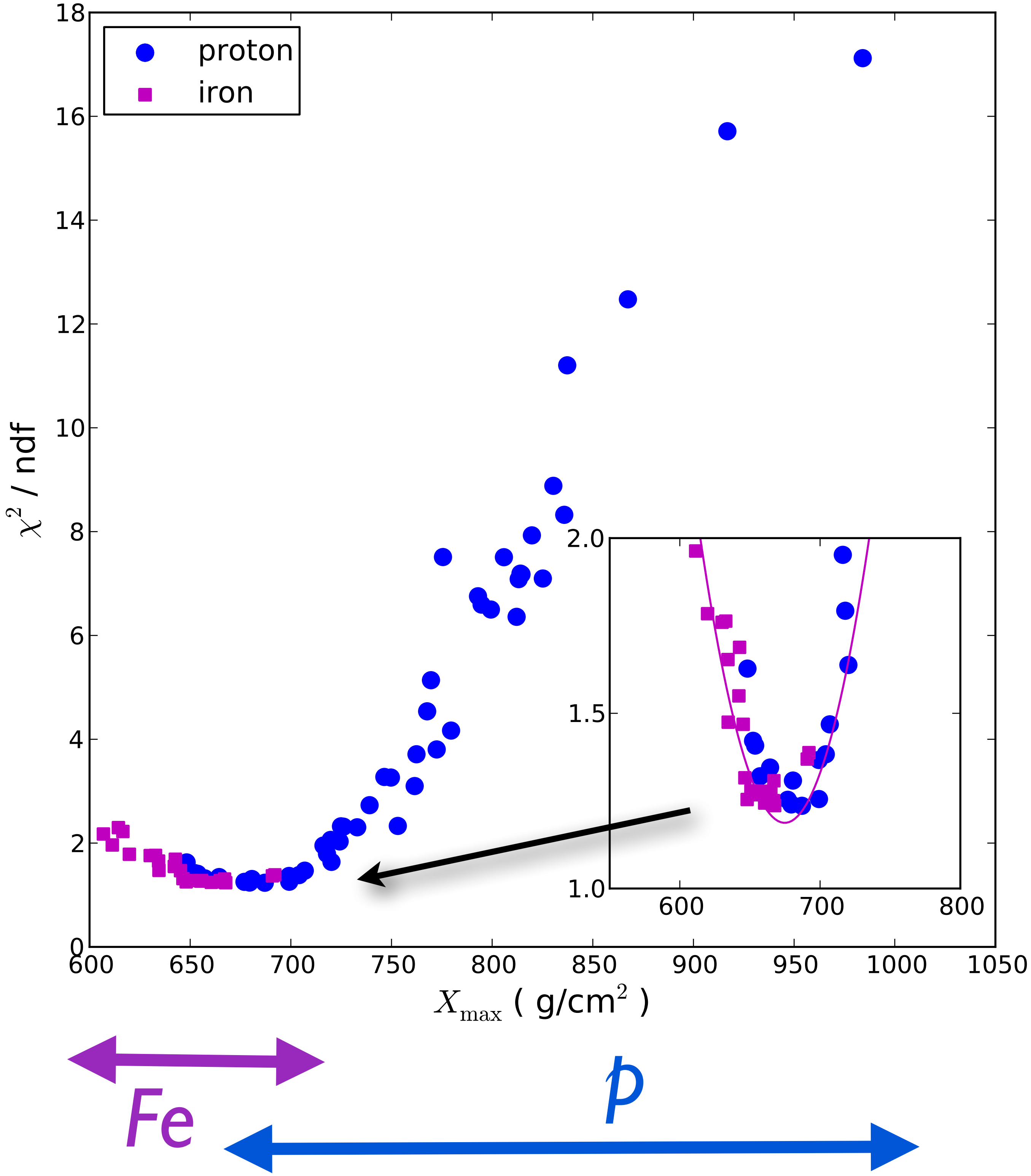
best fit out of 40 simulations



1D LDFs don't fit !

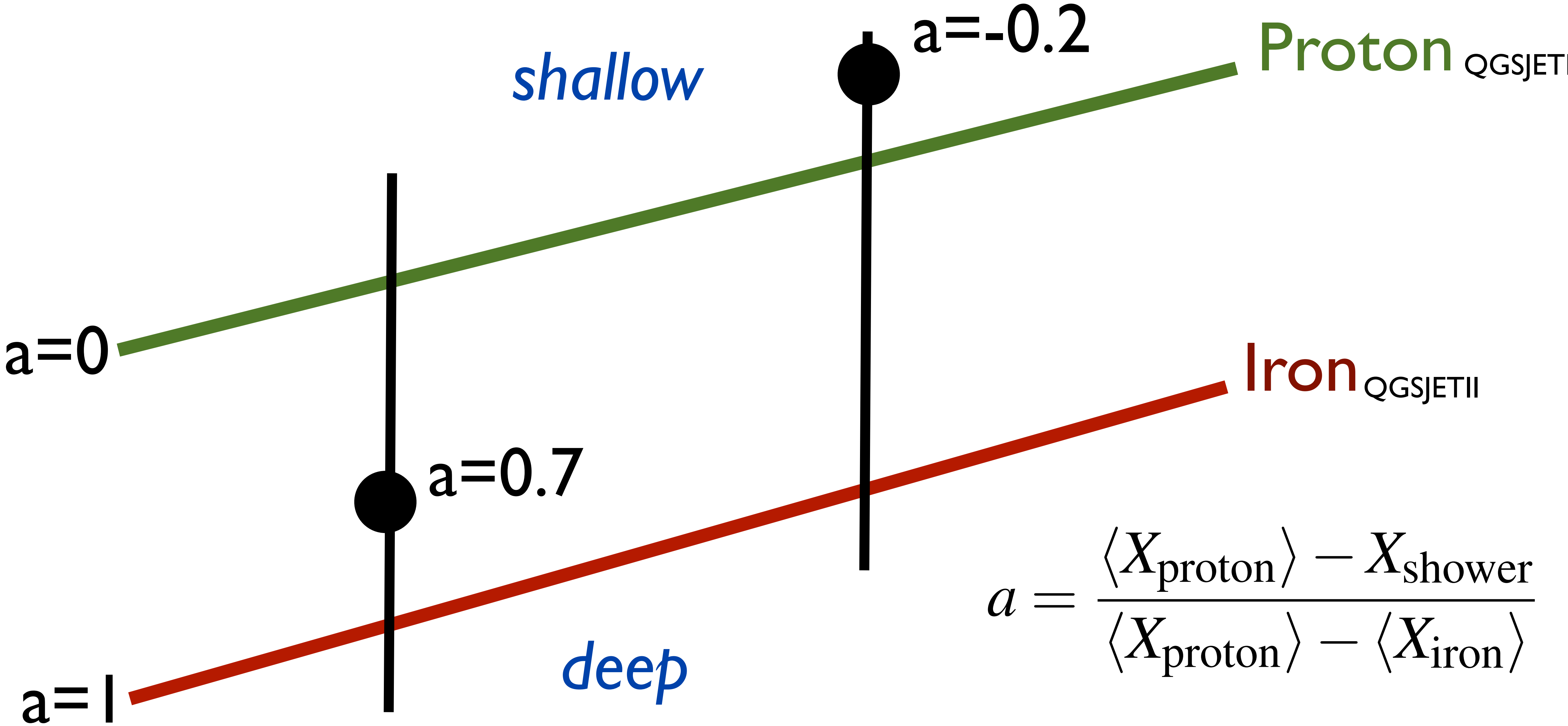
X_{max} reconstruction

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 !!

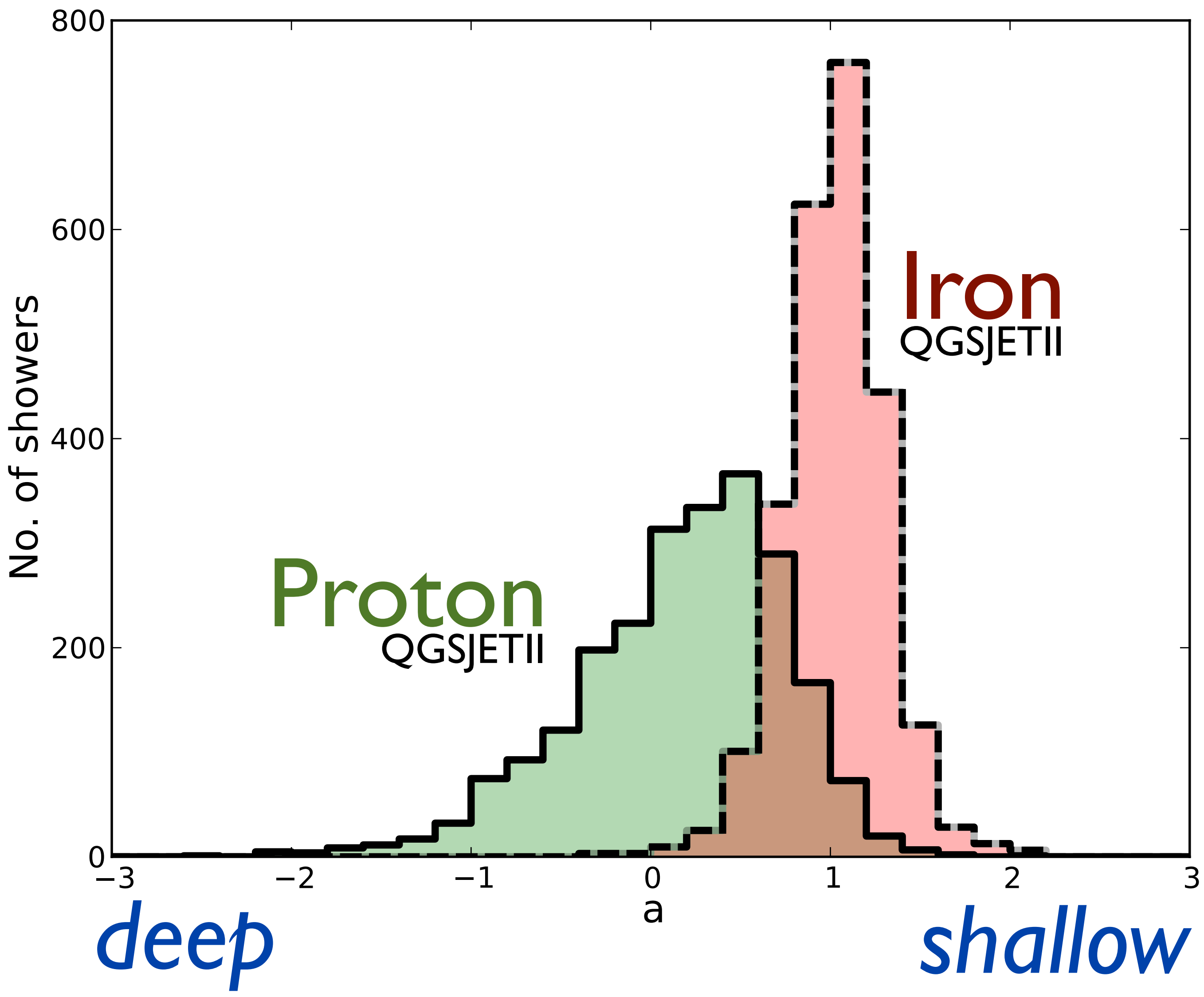
Unbinned analysis



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

Calculate *a* for each individual shower

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

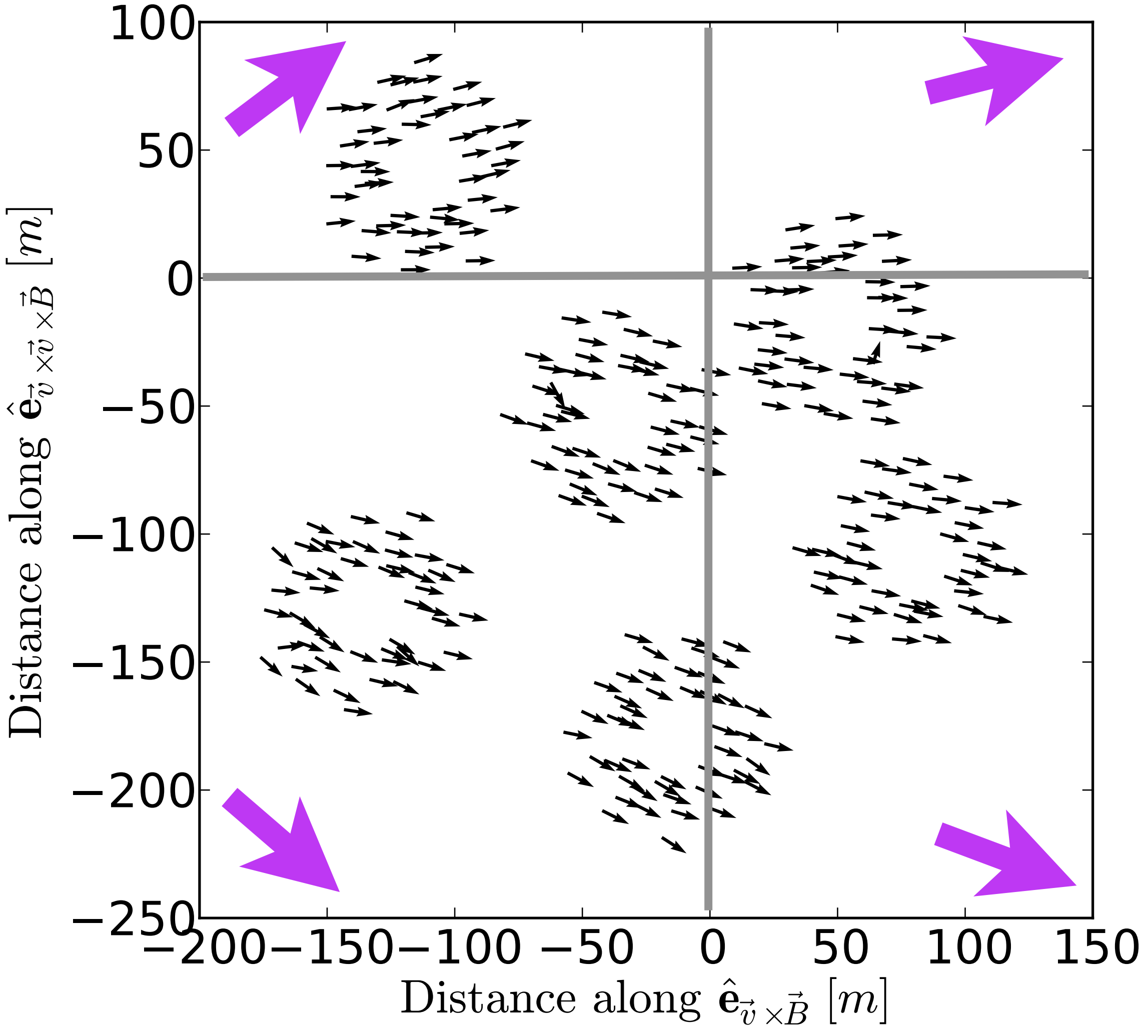


- LOFAR:
  high precision per event!
- Use **full** distribution of Xmax
  not only mean value
- First calculate mass parameter a

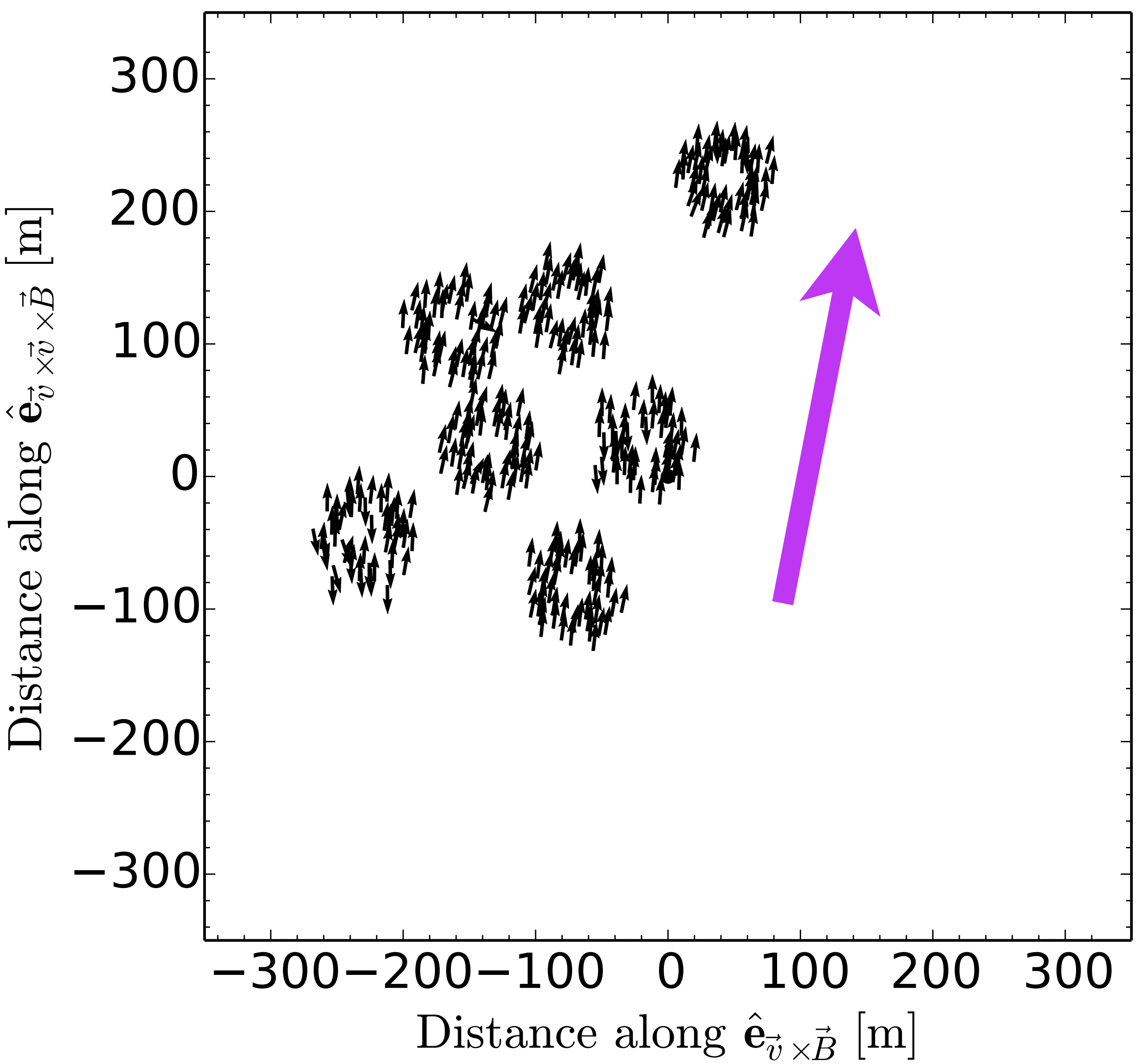
$$a = \frac{\langle X_{\text{proton}} \rangle - X_{\text{shower}}}{\langle X_{\text{proton}} \rangle - \langle X_{\text{iron}} \rangle}$$

- Fit model distribution to measured distribution

Strange polarization patterns



regular polarisation

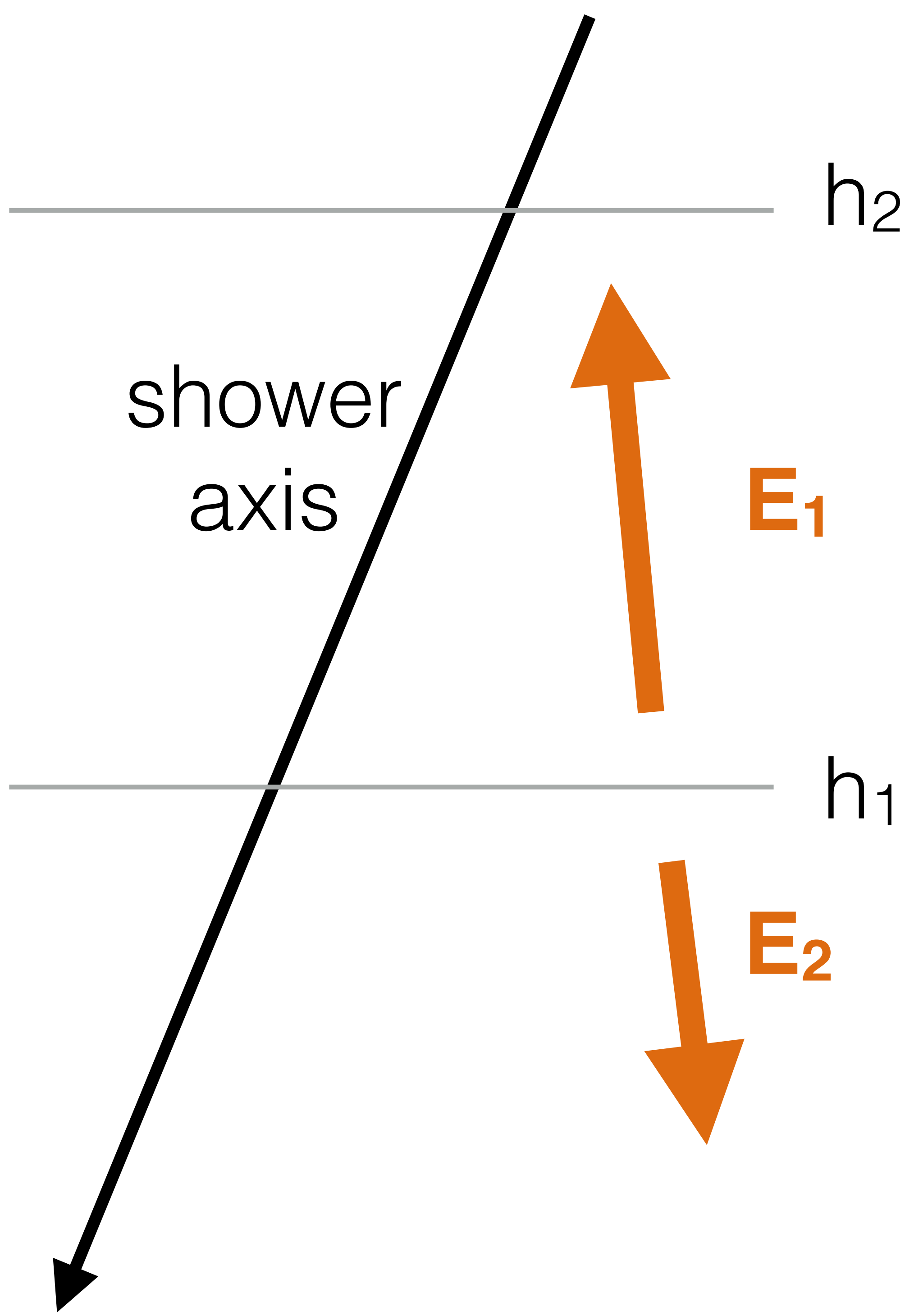


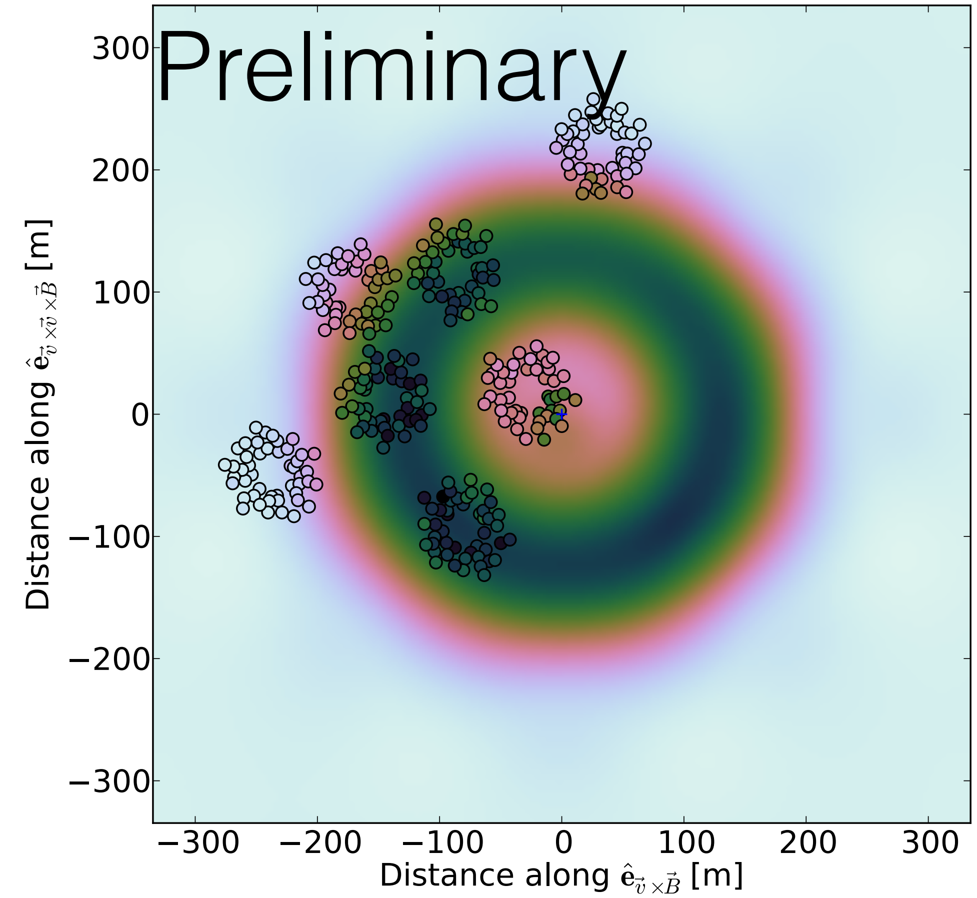
what is going on??

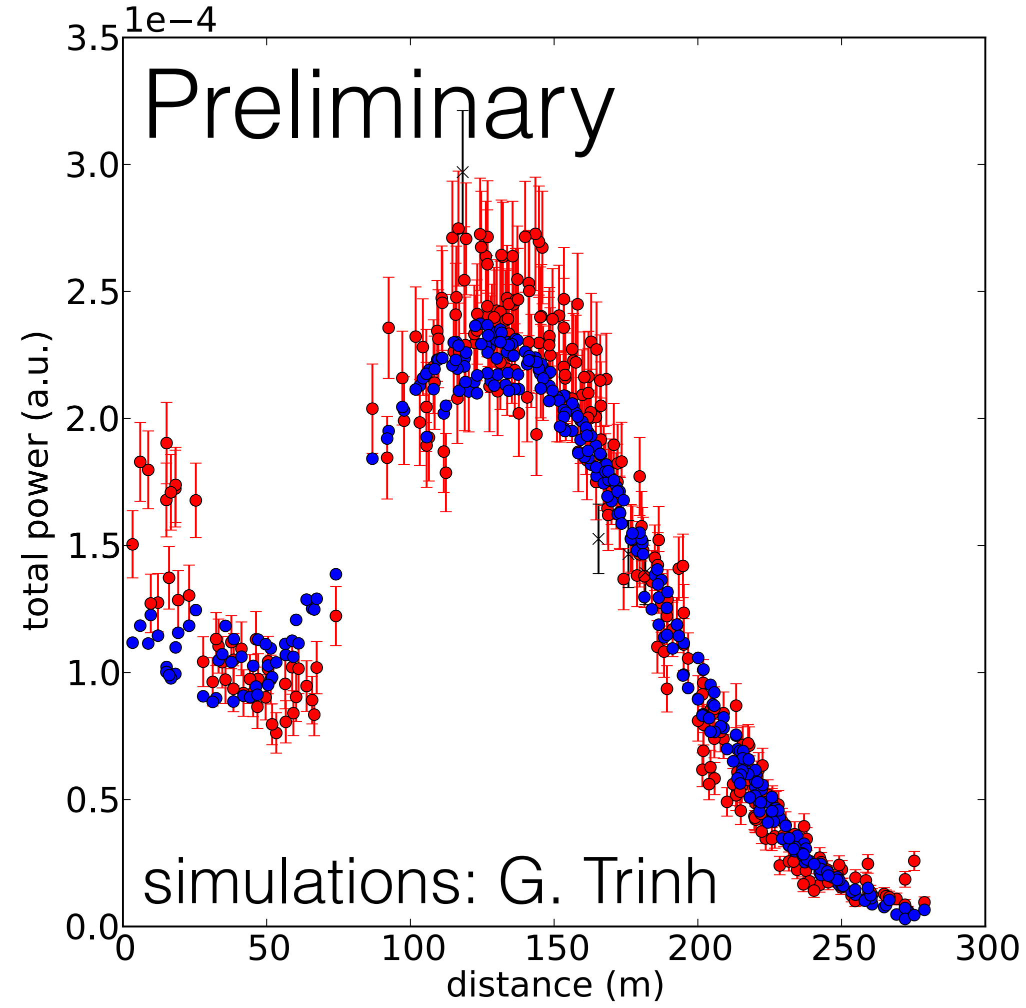
Air showers in thunderstorms

- Regular: geomagnetic field induces traverse current (vxB direction)
- Strong E-field (E ~ cB): current direction changes
- Air showers in thunderstorms: different polarisation & different intensity pattern
- Allows remote sensing of thunderstorm fields!

Two layer model







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

Thunderstorm events

- What can we infer from two-layer model fits?
  Field direction, strength, altitudes?

- Do air showers influence the thunderstorm?
  deposit of large amounts of free electrons
  formation of streamers…. lightning initiation?

- LOFAR can image electrical processes in the thunderstorm with nanosecond precision!

Future of CR radio detection

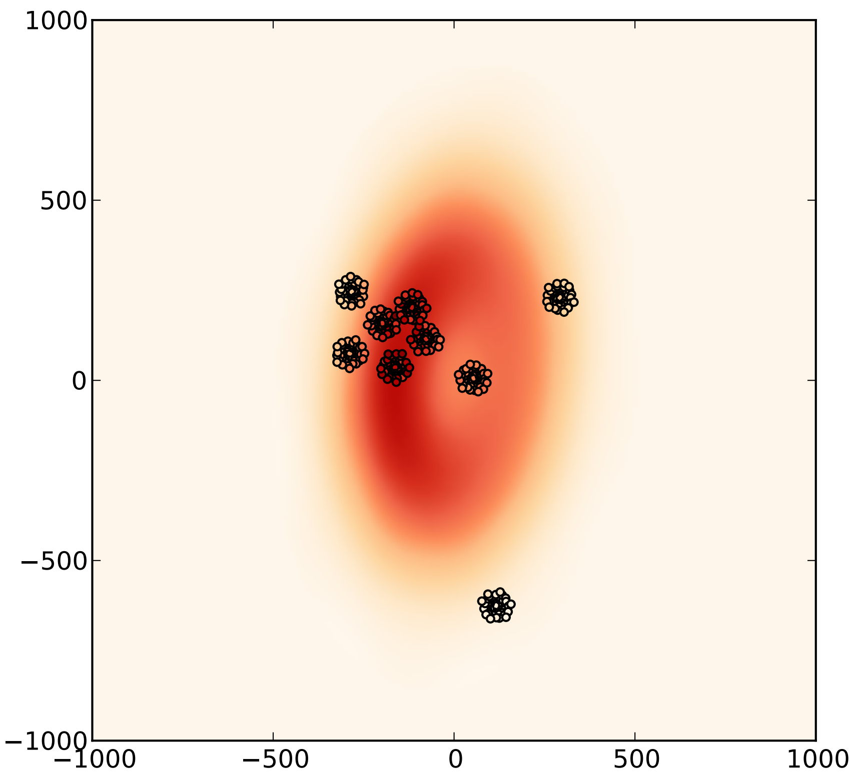
LOFAR

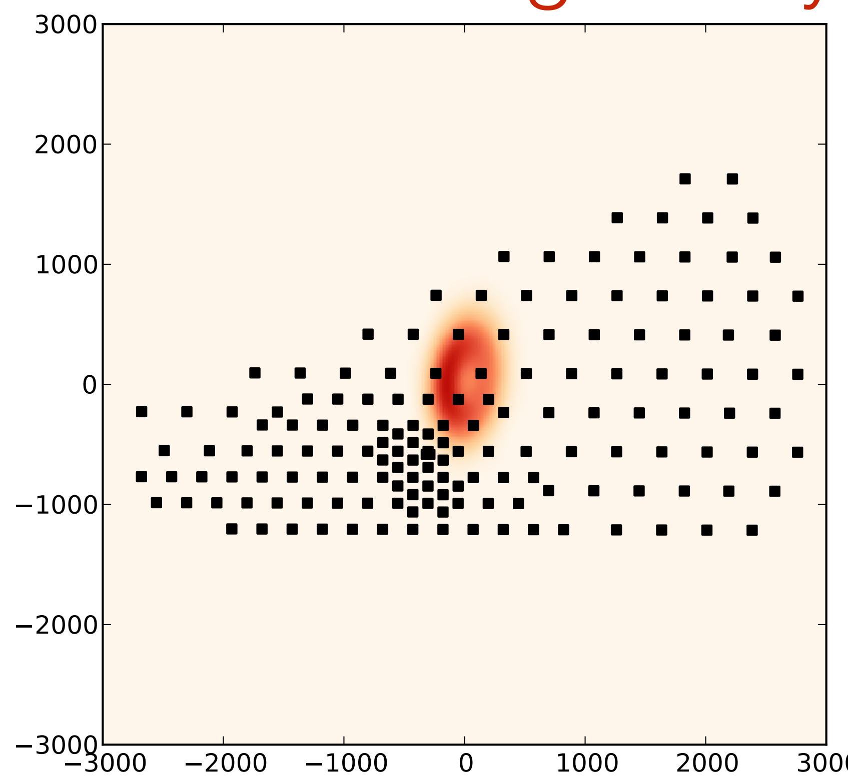
AERA (Auger)

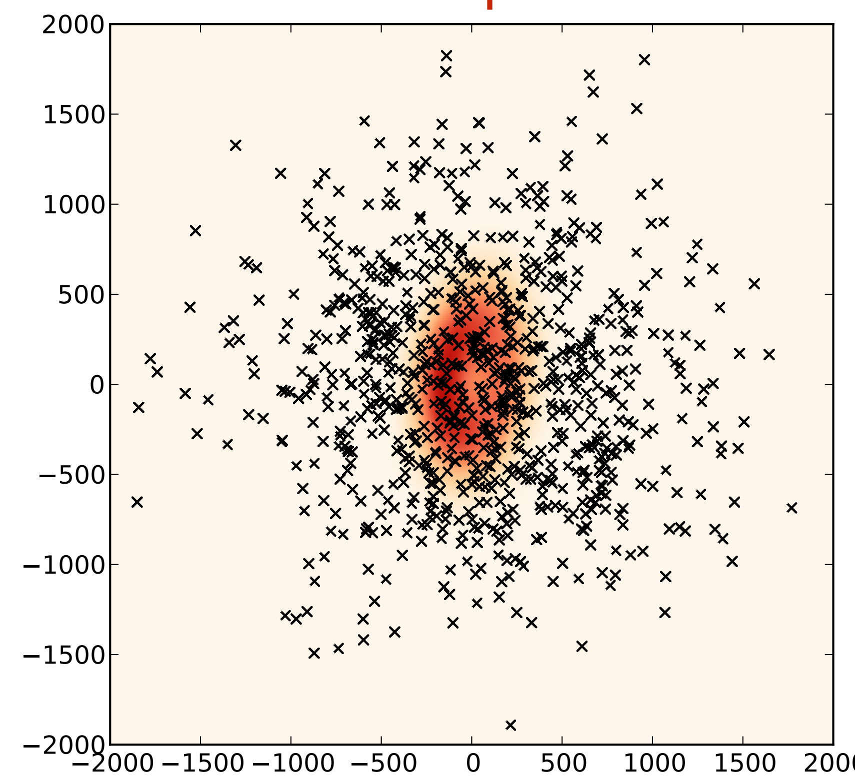
towards large array

SKA

extreme precision







2 km

6 km

4 km

Conclusions

- Air shower radio emission mechanism finally understood:
  - intensity profiles
  - wavefront shape
  - polarisation
  - Cherenkov rings at high frequency
- LOFAR can measure CR mass composition
  X_{max} resolution of < 20 g/cm^2
  similar to fluorescence detection + *higher duty cycle*
- First composition results based on 100+ high-res reconstructions using full shape of X_{max} distribution
- Air showers in thunderstorm:
  remote sensing of electric fields, thunderstorm physics
- Future:
  CR-radio with Auger, SKA, …
  lunar technique with LOFAR & SKA

Thanks