

Cosmic-ray measurements with LOFAR

Science at Low Frequencies II
3 December 2015 - Albuquerque NM

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European Research Council



Vrije Universiteit Brussel



university of
 groningen

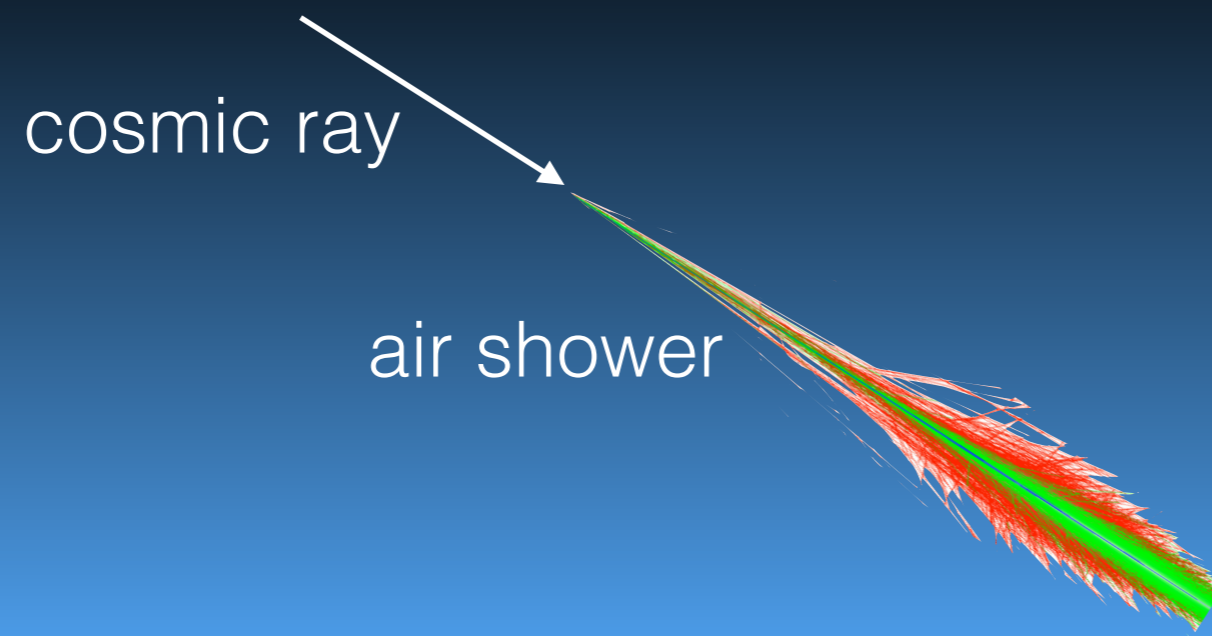
KVI

Radboud Universiteit Nijmegen



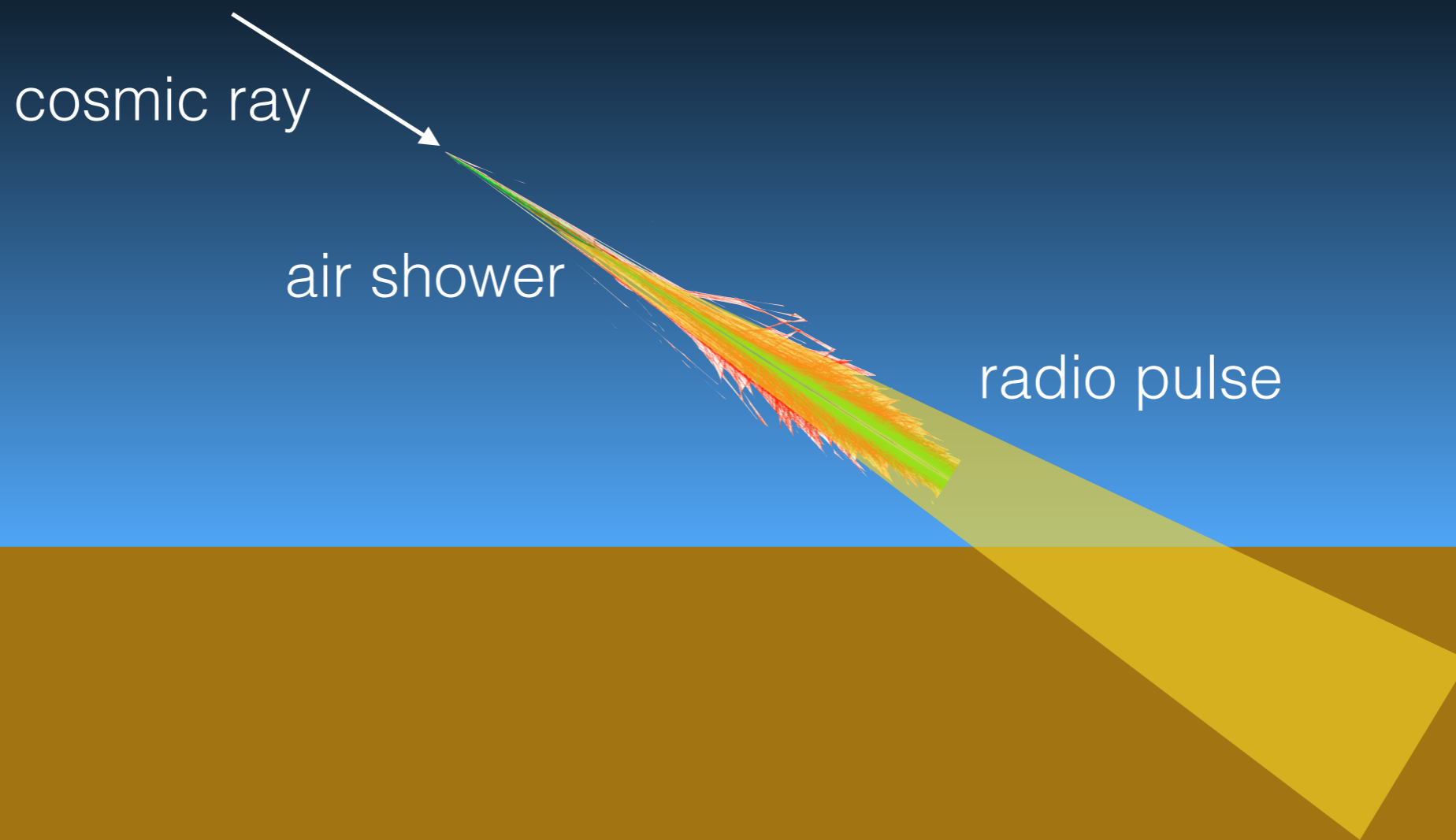
for the LOFAR Cosmic Ray KSP

A. Corstanje, J.E. Enriquez, H. Falcke, J.R. Hörandel, M. Krause, A. Nelles,
S. Thoudam, J.P. Rachen, L. Rossetto, P. Schellart, O. Scholten, G. Trinh, S. ter Veen.



cosmic ray

air shower



cosmic ray

air shower

radio pulse

cosmic ray



air shower

radio pulse

LOFAR superterp



source?

cosmic ray

air shower

radio pulse

LOFAR superterp



source?

source!



cosmic ray

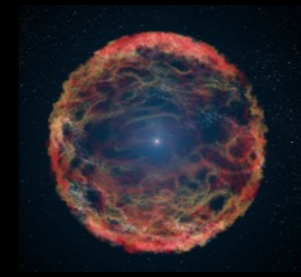
air shower

radio pulse

LOFAR superterp



source?



source!

cosmic ray

air shower

radio pulse

LOFAR superterp

to identify sources: measure CR mass!

**lighter nuclei penetrate
deeper in atmosphere**



How to measure the mass?

Atmospheric depth of shower maximum X_{\max}

fluorescence light

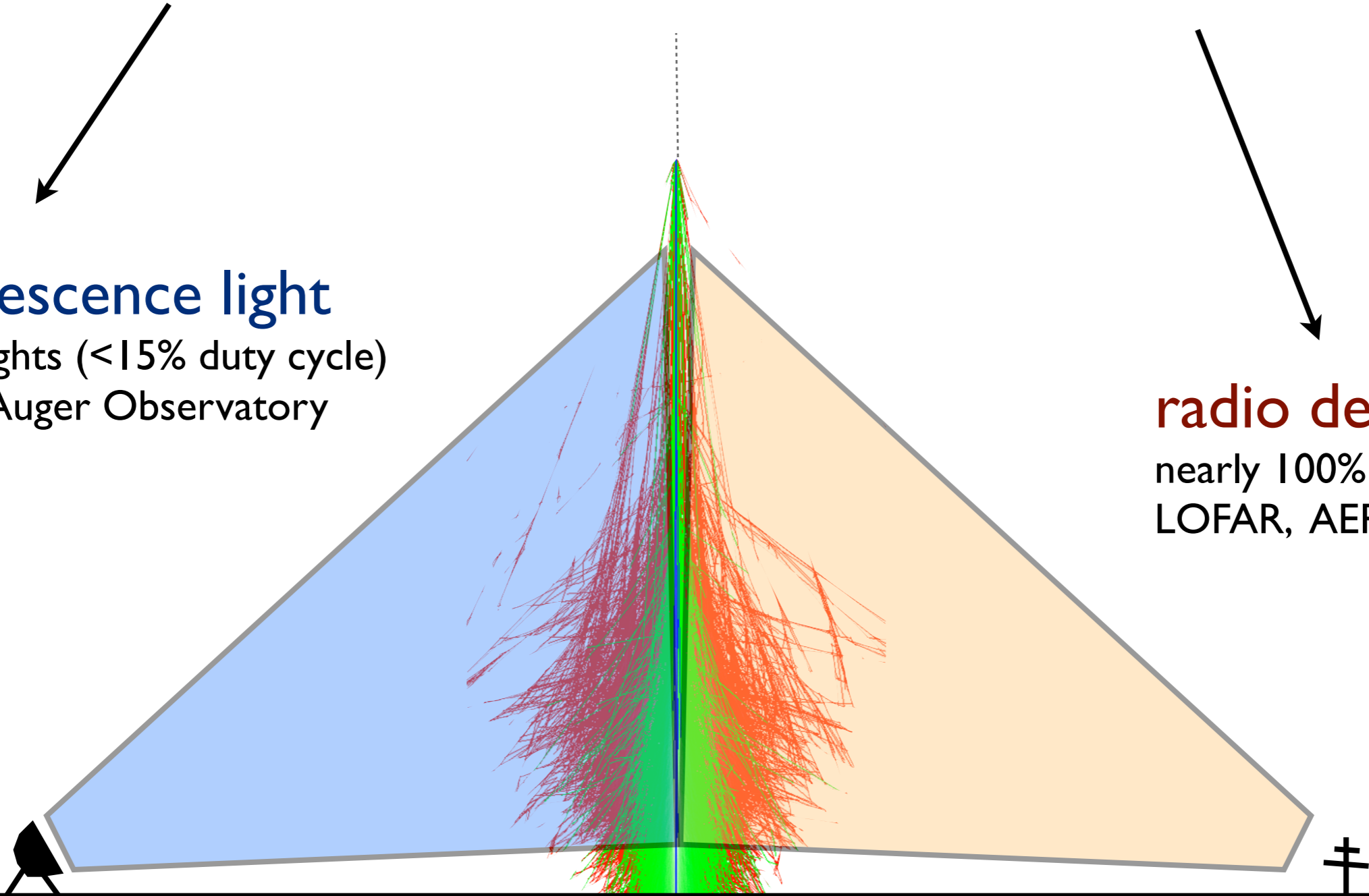
dark nights (<15% duty cycle)
Pierre Auger Observatory

radio detection

nearly 100% duty cycle
LOFAR, AERA, Tunka

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



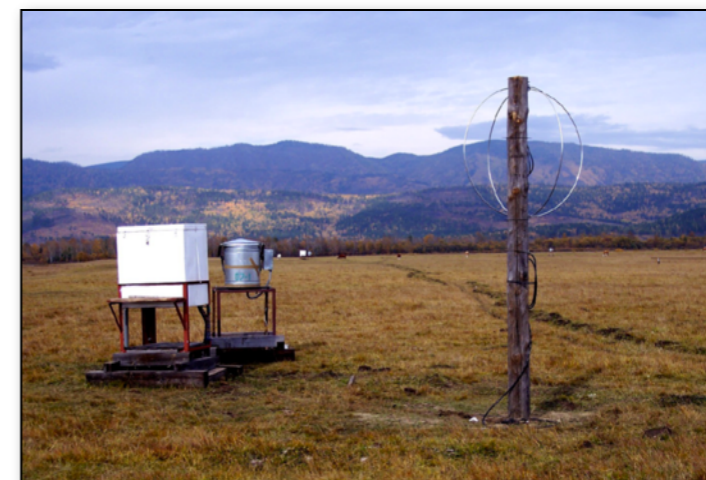
CODALEMA



LOFAR



AERA (Auger)



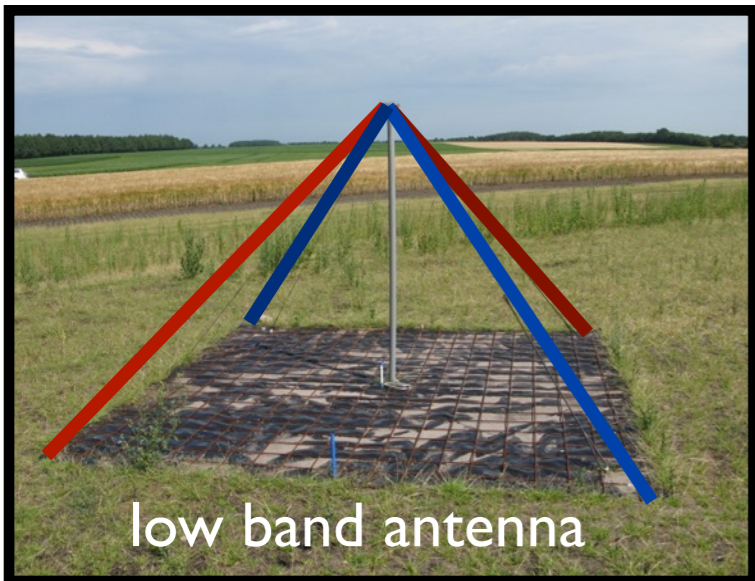
Tunka-REX

Air shower detection with LOFAR



LORA
LOFAR Radboud Array
scintillator detectors

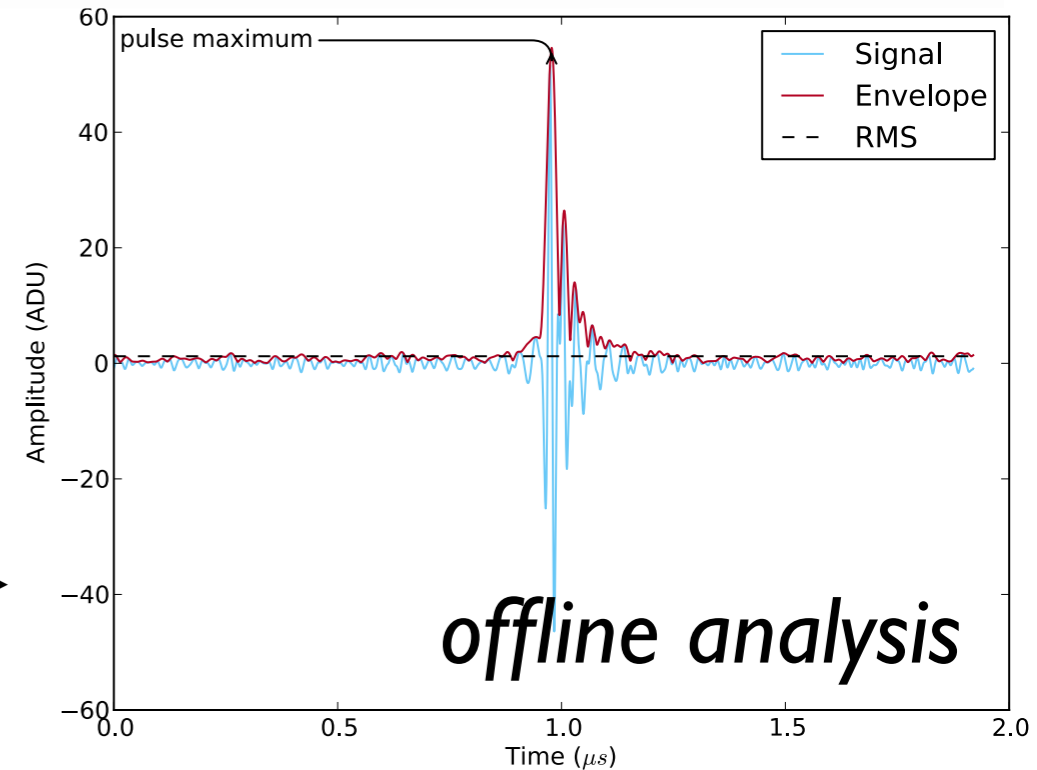
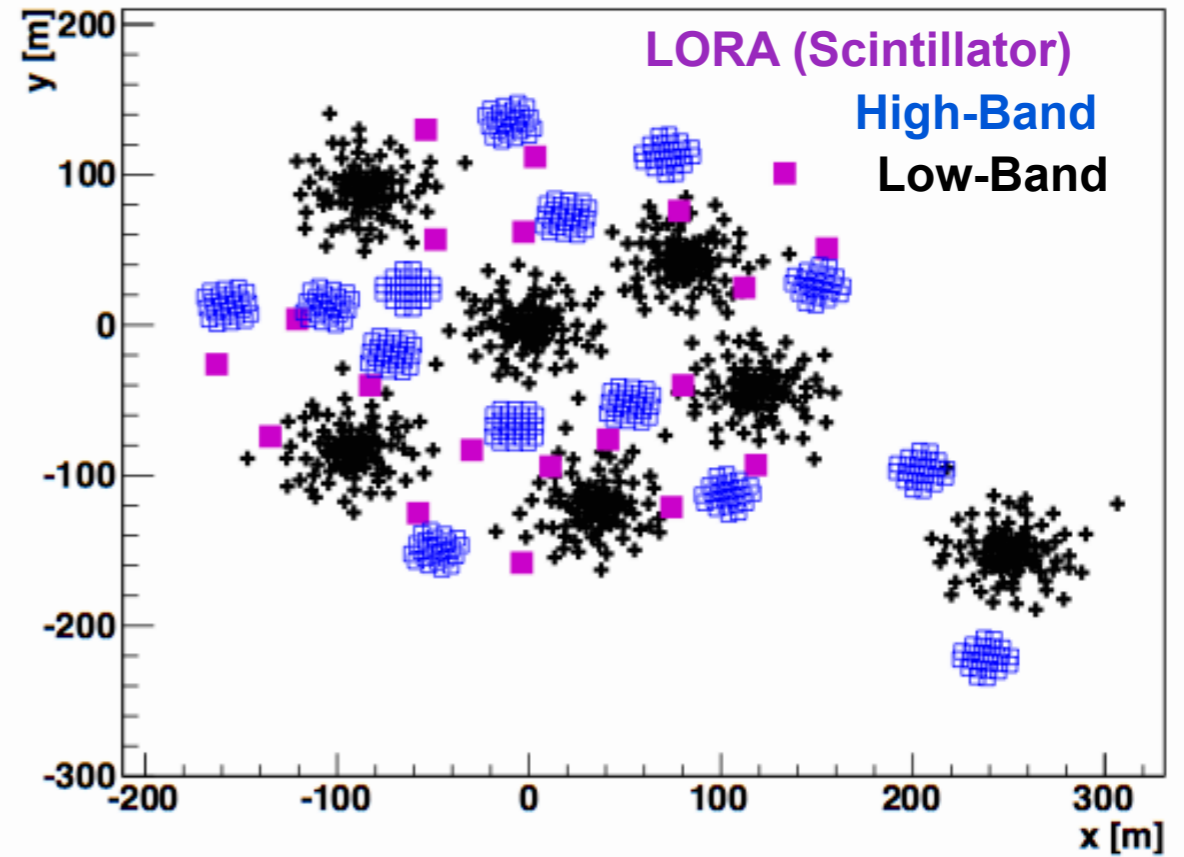
trigger



low band antenna

buffer

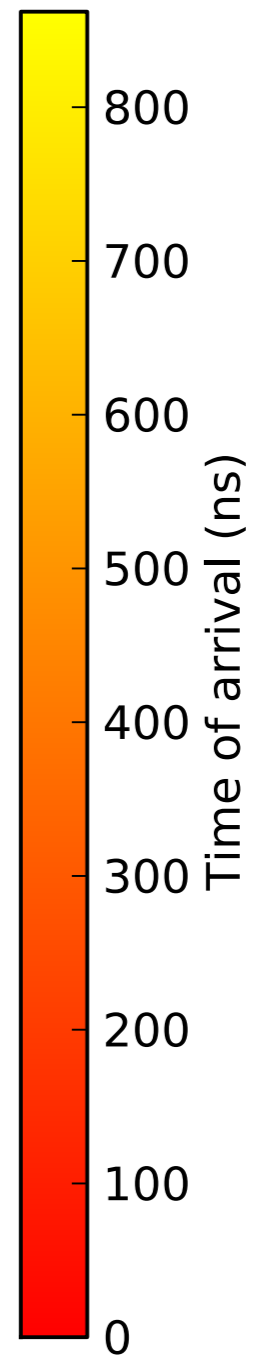
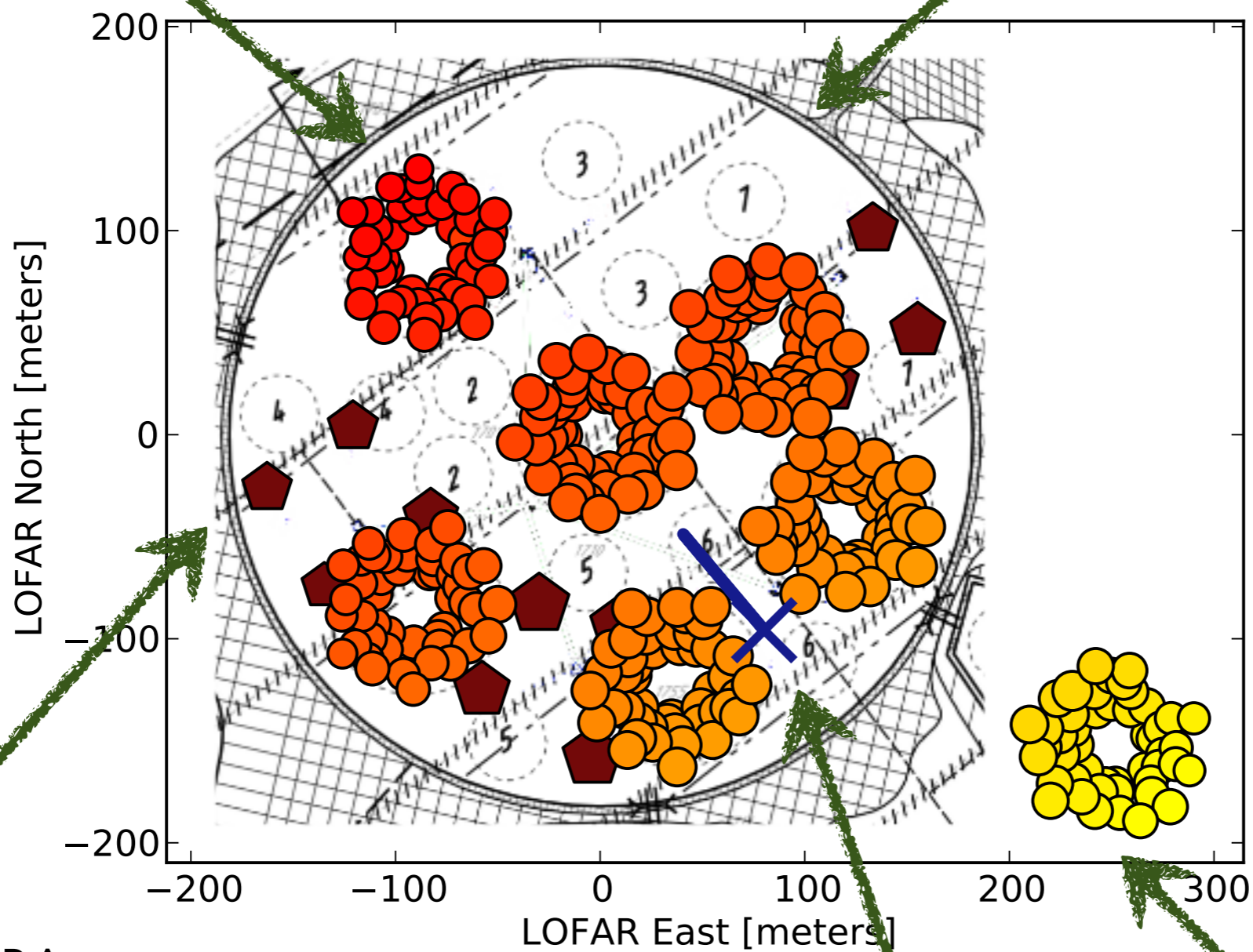
2 ms read-out



antennas grouped
in rings

event display

superterp



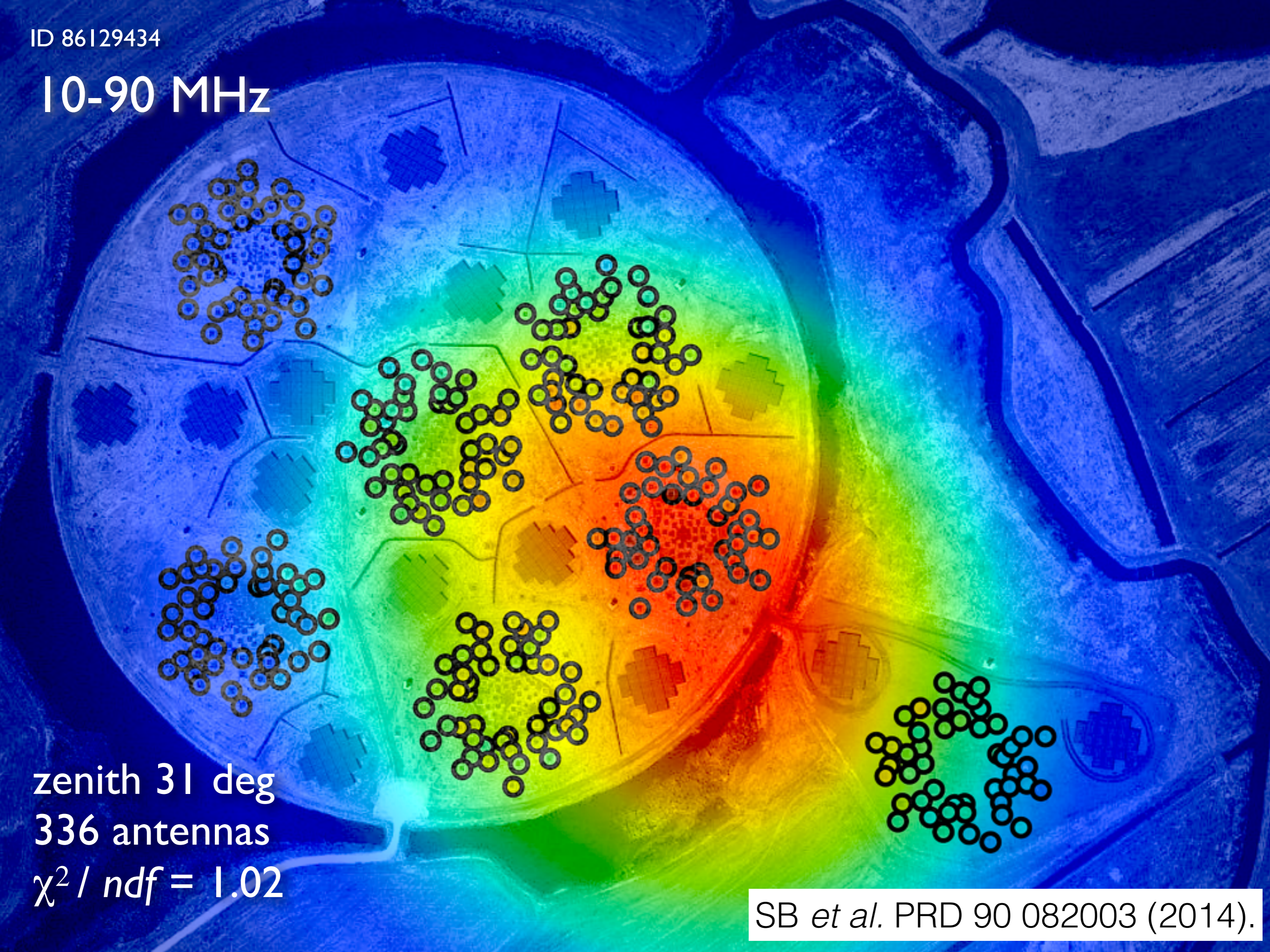
pentagons: LORA
scintillators

reconstructed
core & direction

station outside
superterp

ID 86129434

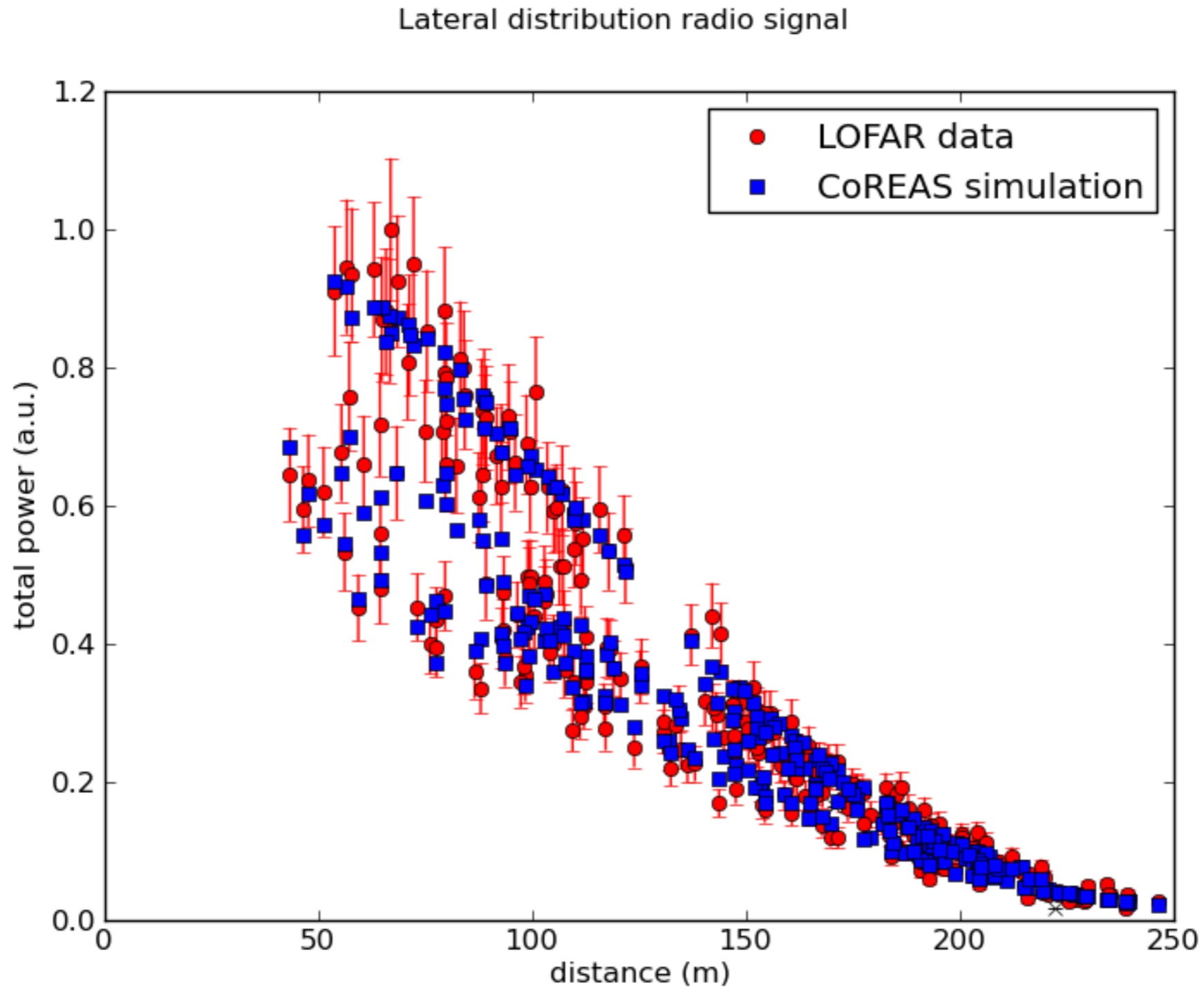
10-90 MHz



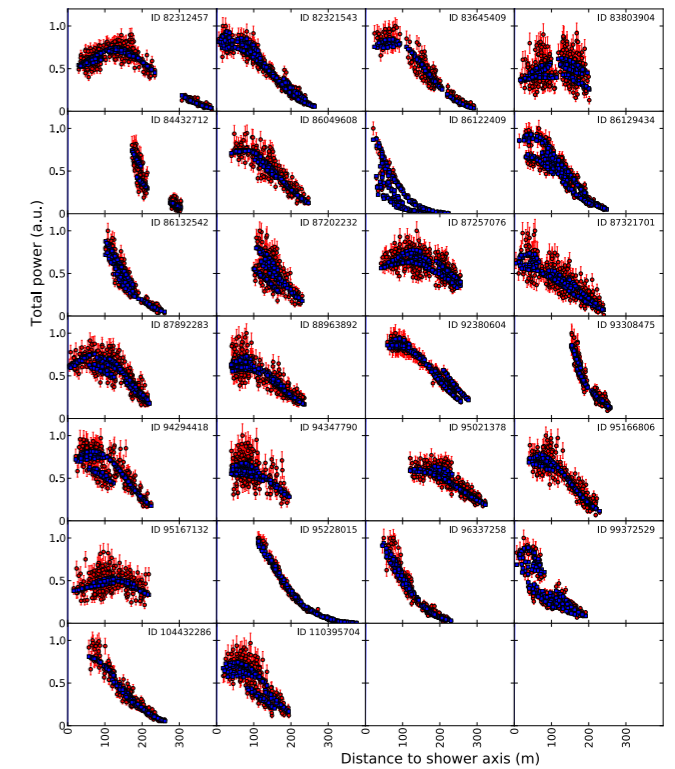
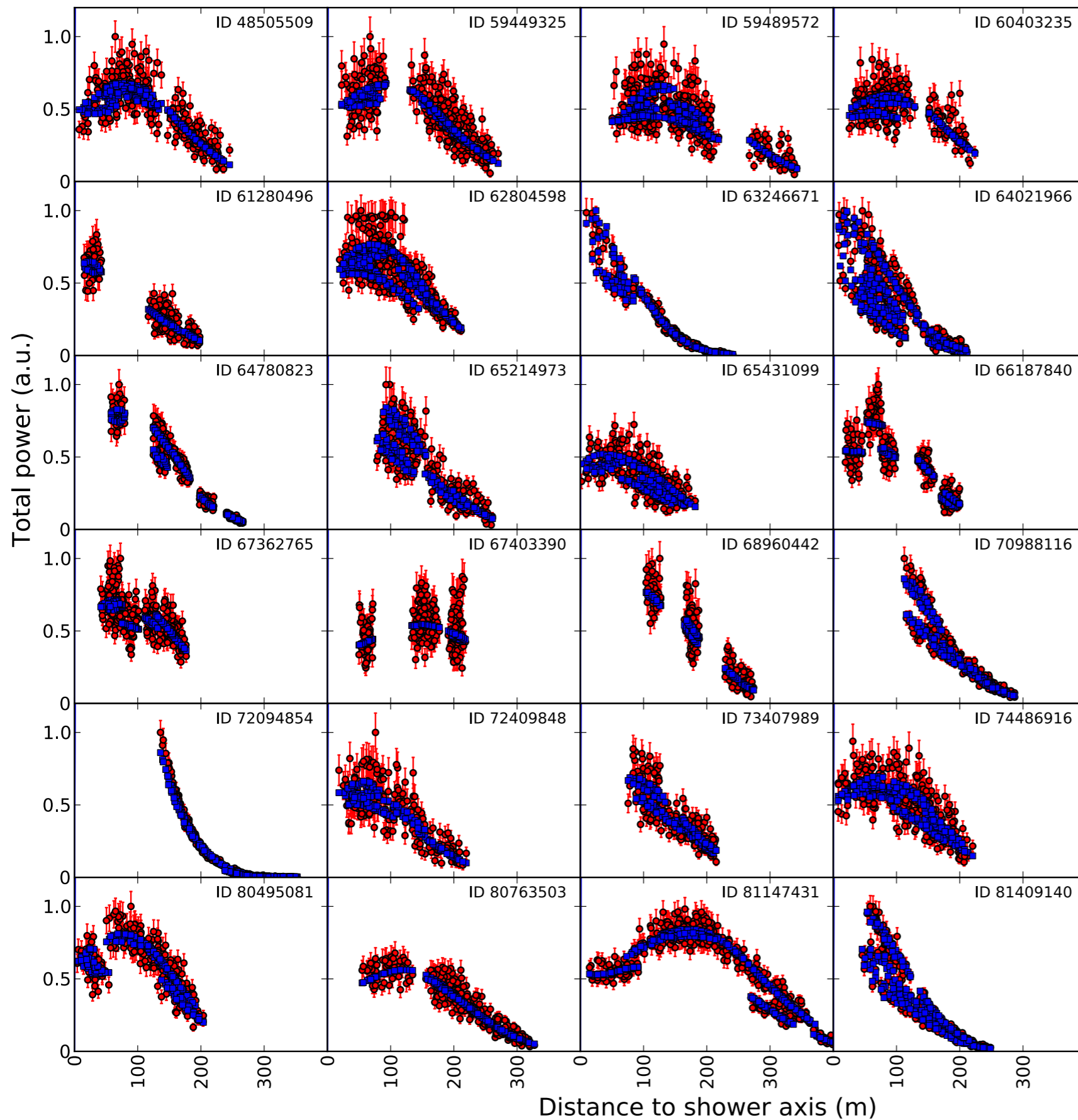
zenith 31 deg
336 antennas
 $\chi^2 / \text{ndf} = 1.02$

SB *et al.* PRD 90 082003 (2014).

best fit out of 40 simulations



1D LDFs don't fit !

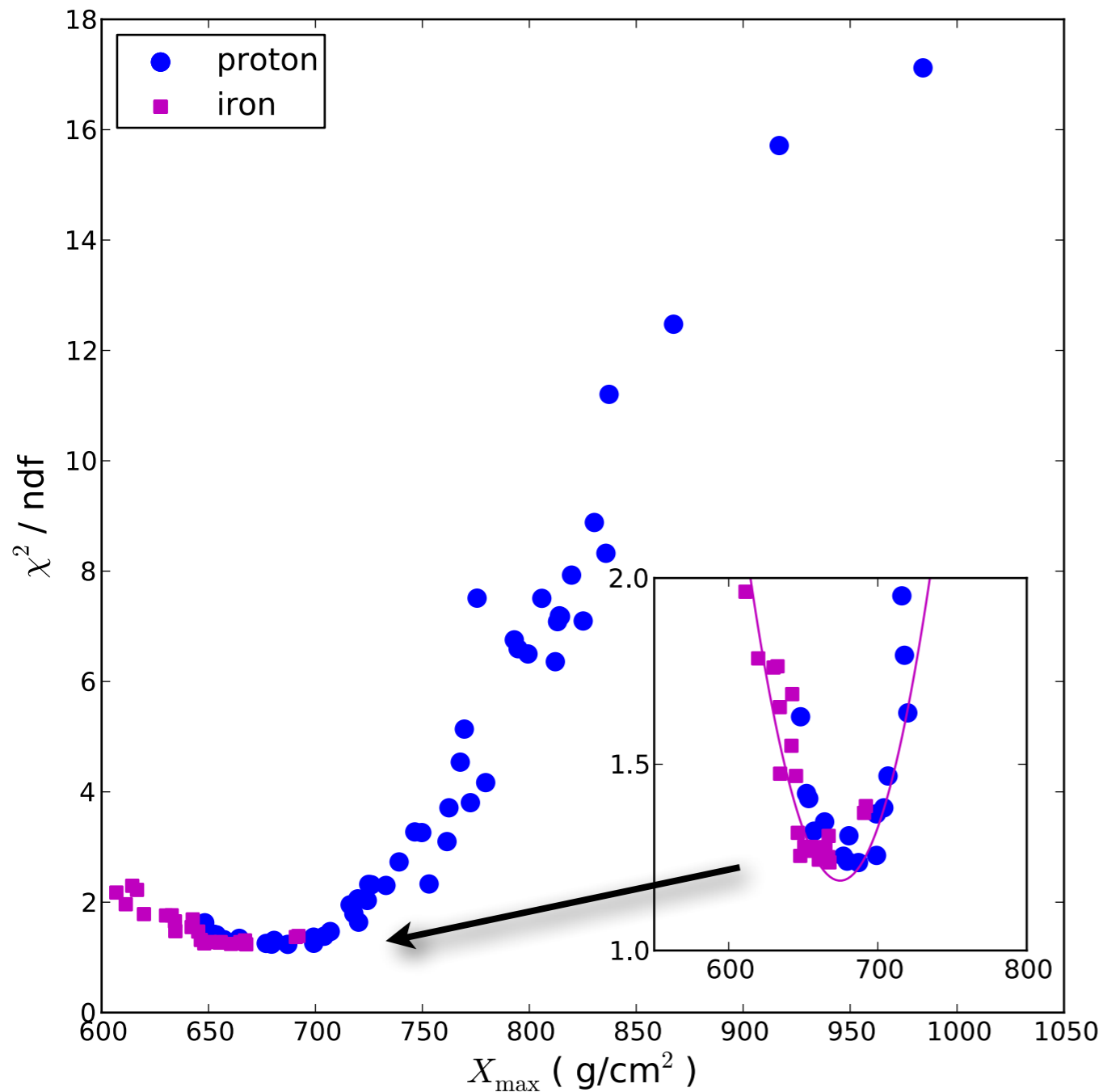


- First sample: >100 showers
- 200 - 450 antennas/event
- Fit 0.9 - 2.6
- Radiation mechanism finally completely understood!

LOFAR data CoREAS sim

X_{\max} reconstruction

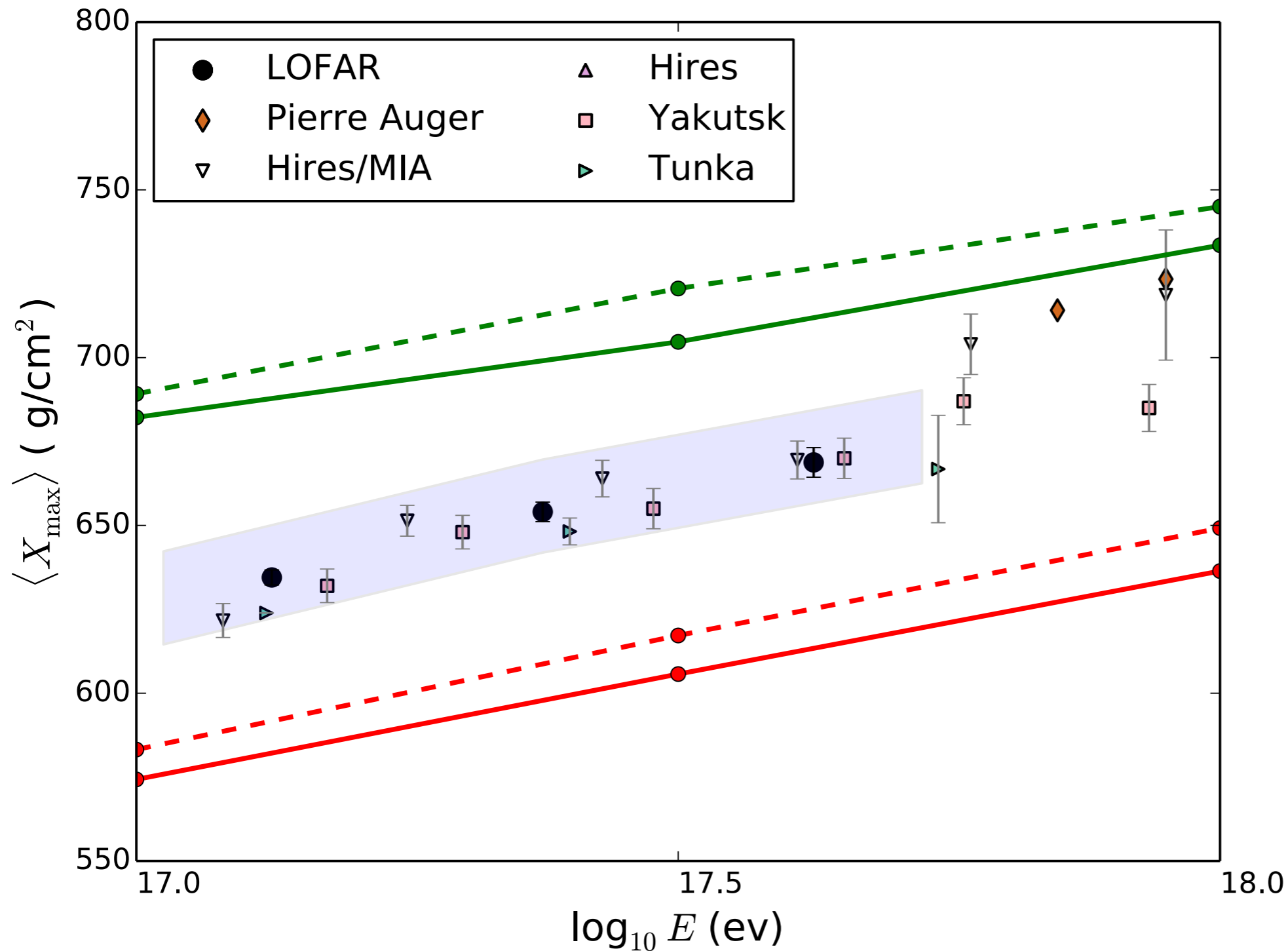
protons penetrate deeper than iron nuclei



- Reconstruct depth of shower maximum: X_{\max}
- Jitter: other variations in shower development
- Correction for atmospheric variations using GDAS
- Resolution $< 20 \text{ g/cm}^2$!!



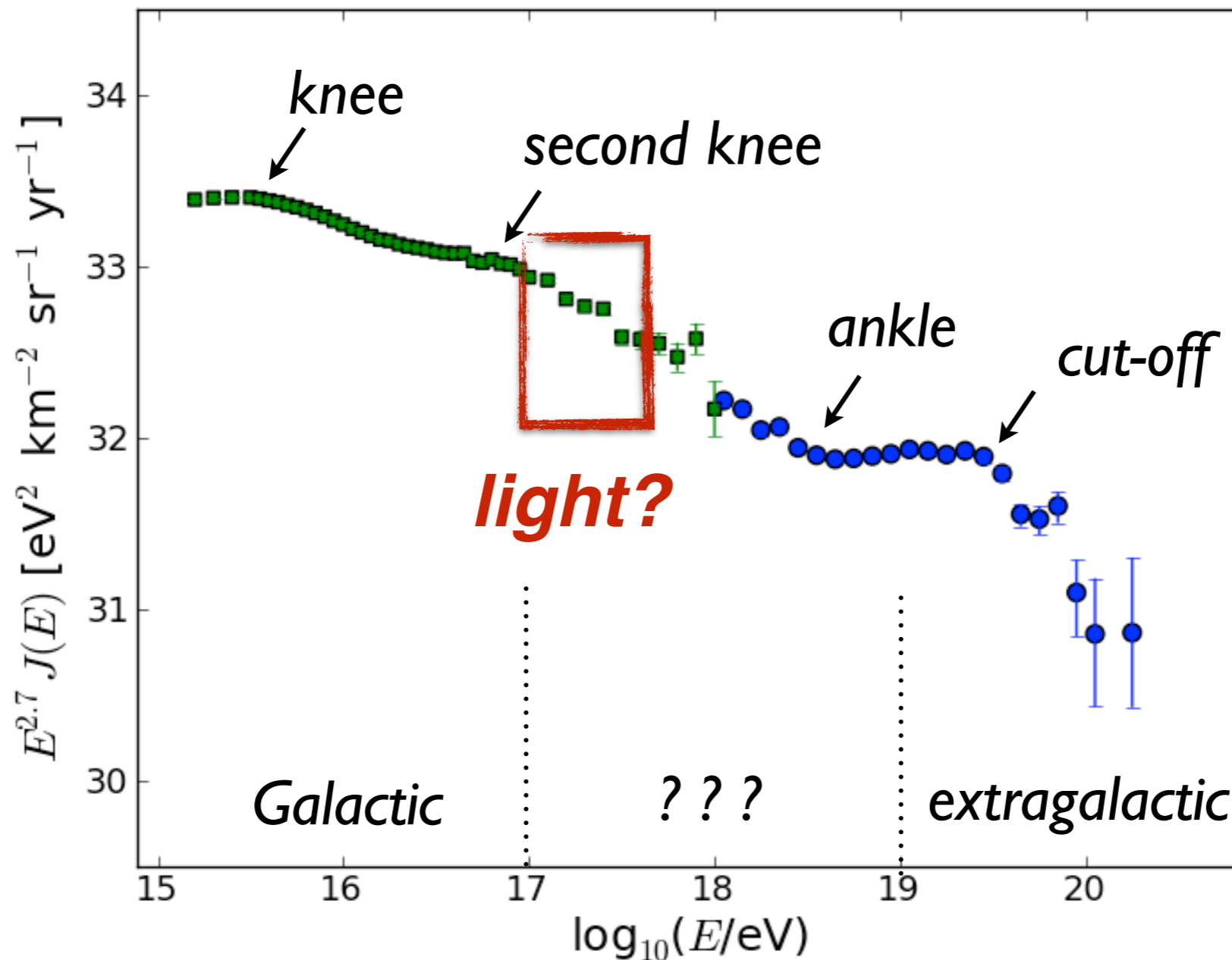
Mean X_{\max} for 114 showers



Proton QGSJETII
EPOS-LHC

Iron QGSJETII
EPOS-LHC

What does it mean?



Already **extragalactic** component?

Secondary Galactic population?

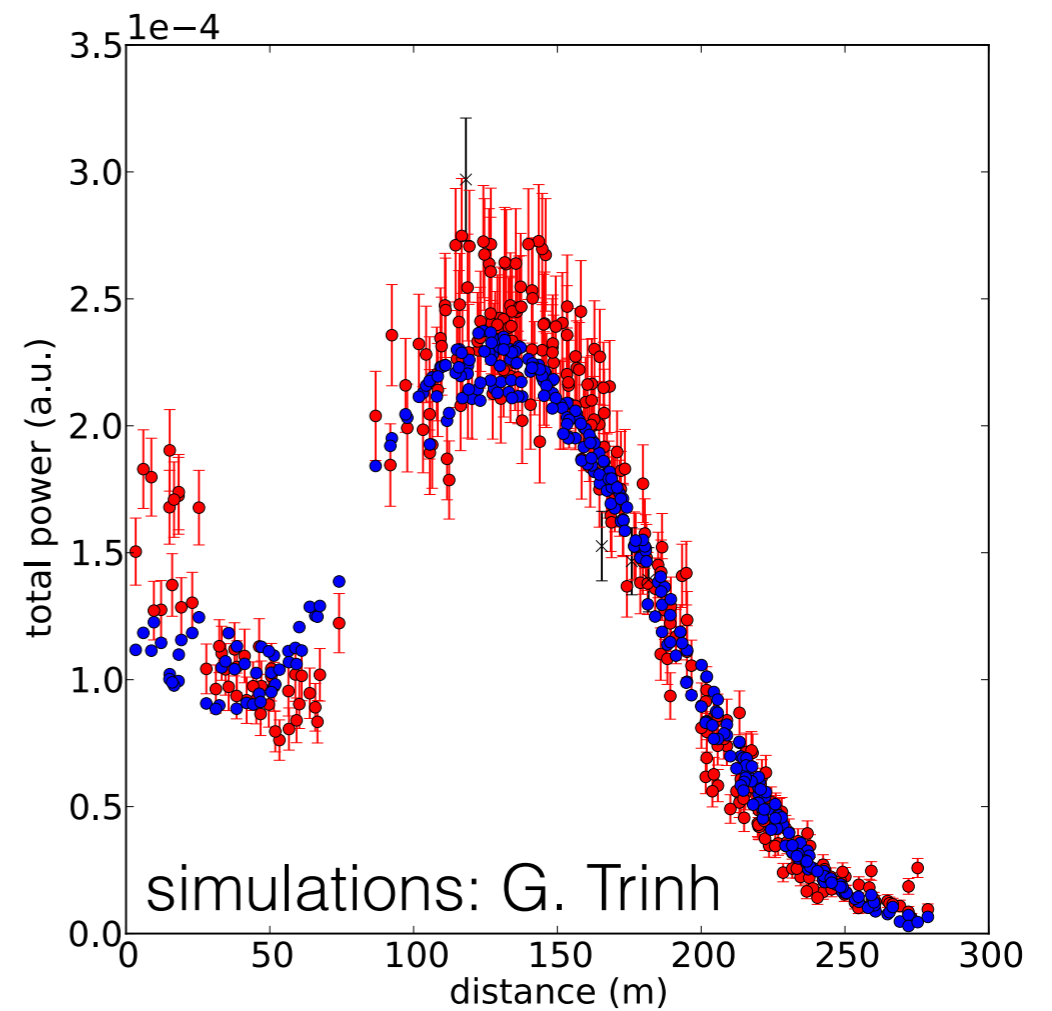
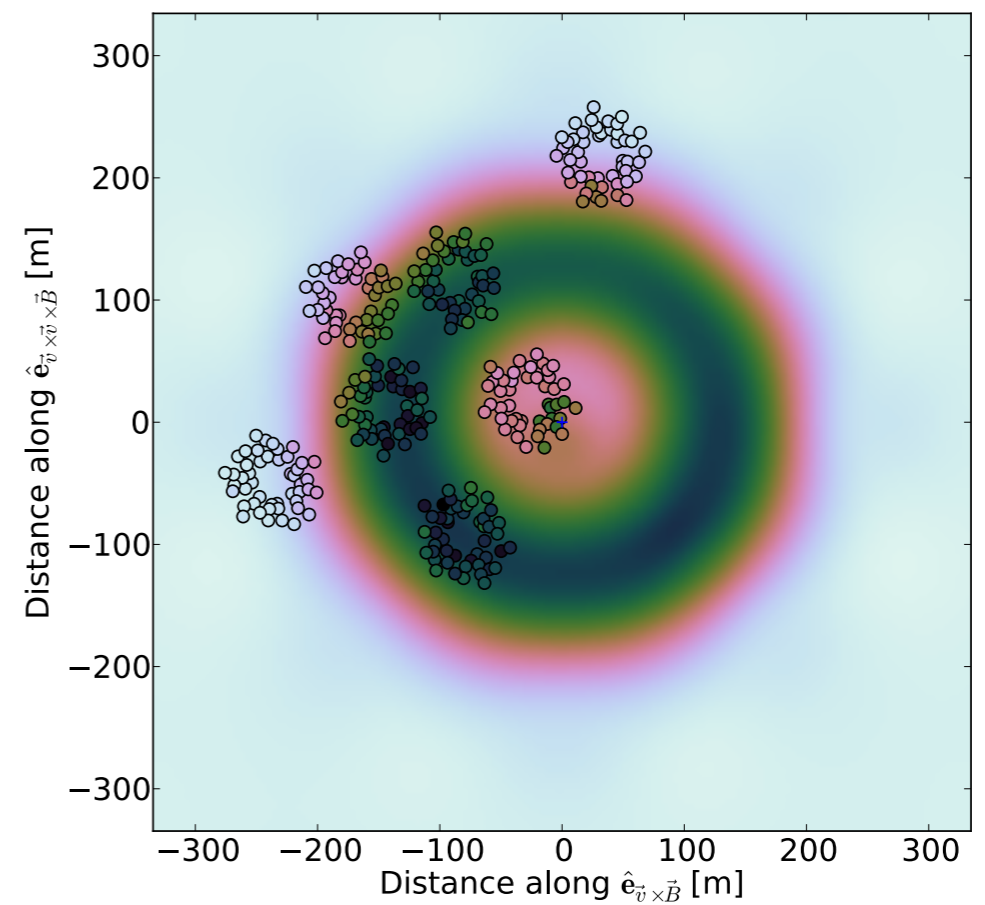
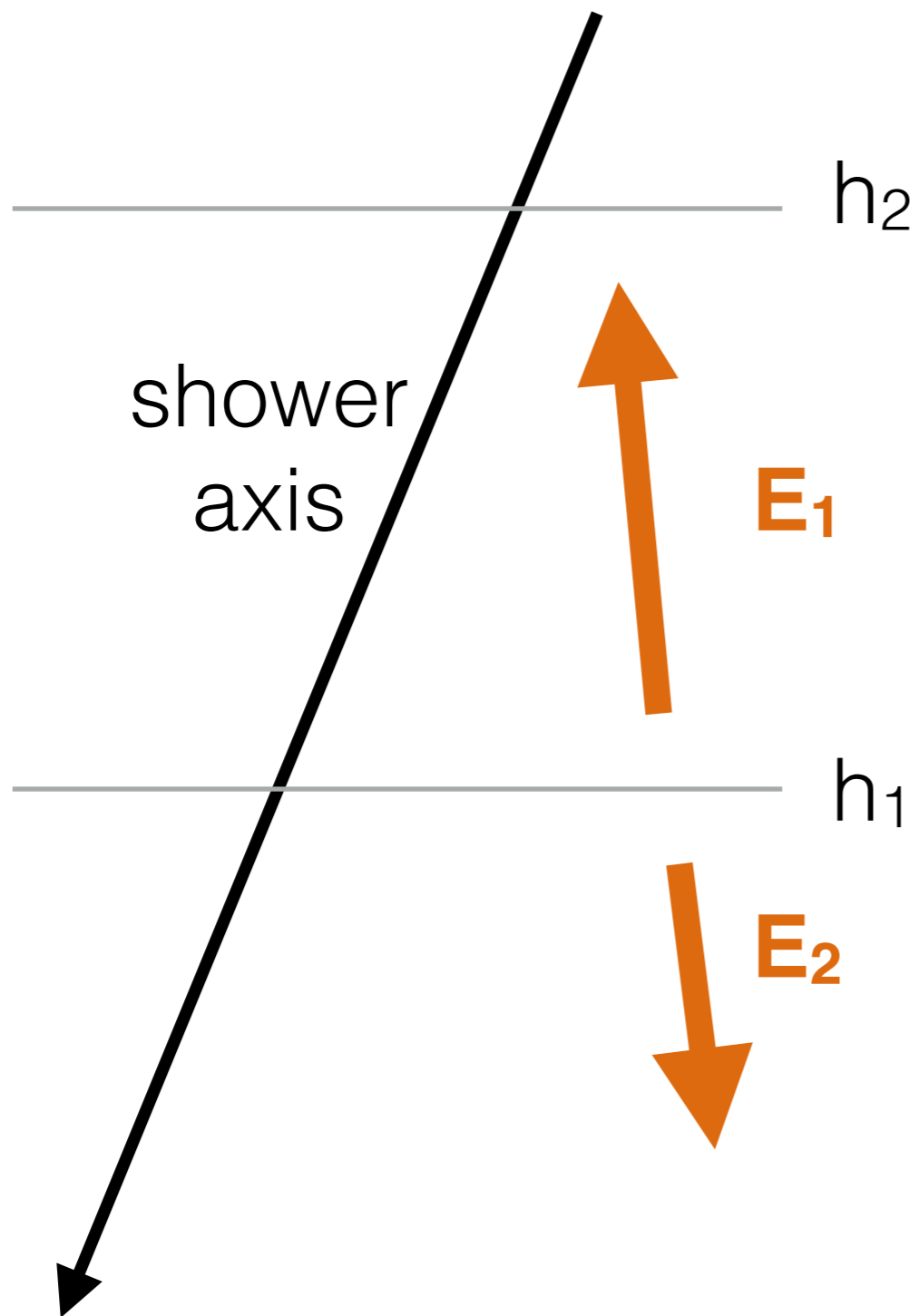
Galactic evatron sources? Reacceleration in **halo**?

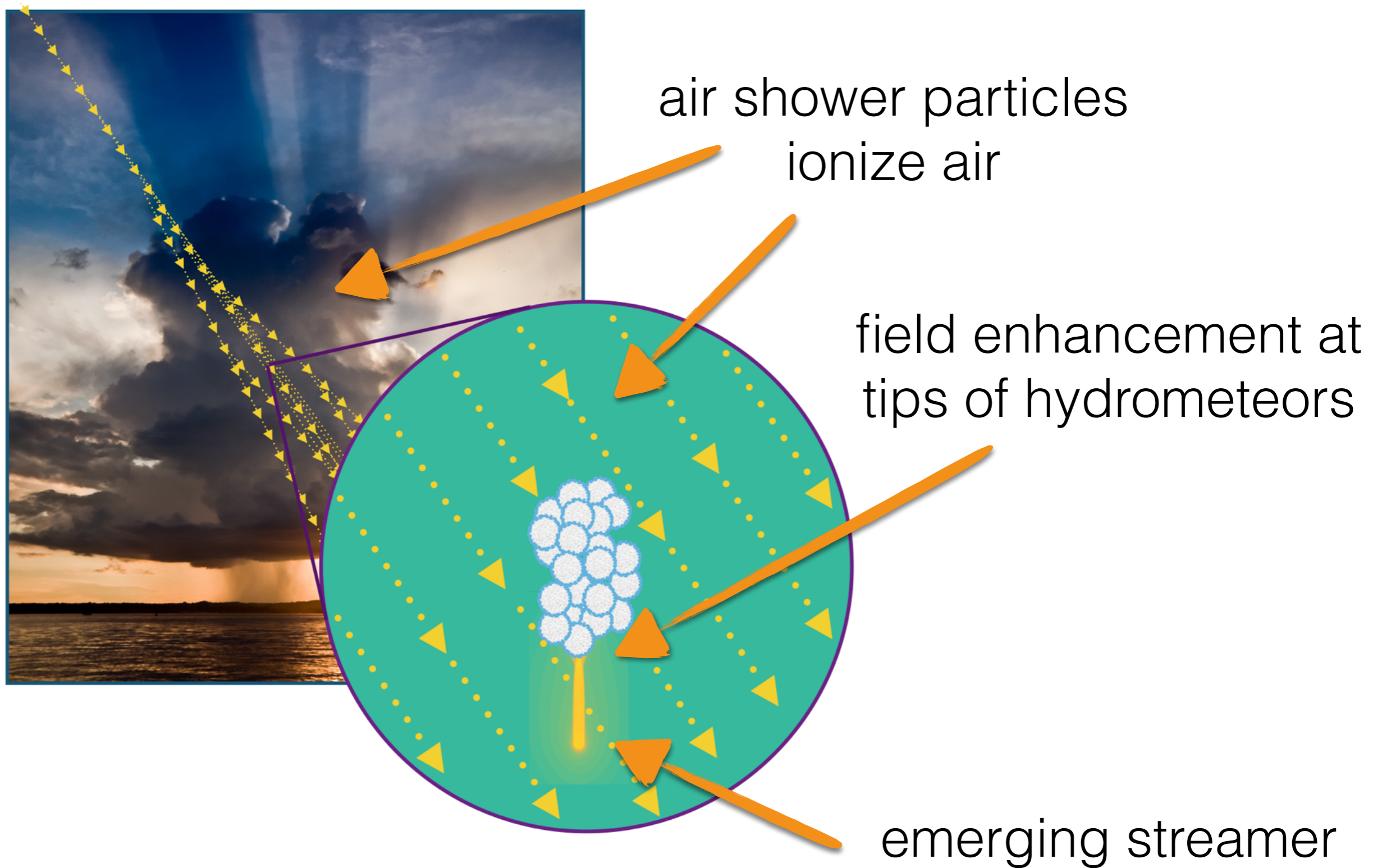
Same sources as **IceCube neutrinos**?

An aerial photograph of a solar farm in a rural landscape. The solar panels are arranged in several clusters on a green field. A large, bright purple and white lightning bolt strikes the ground near the solar panels, extending upwards into a dark, stormy sky. Other white lightning bolts are visible in the background. The scene is surrounded by green fields and a winding river.

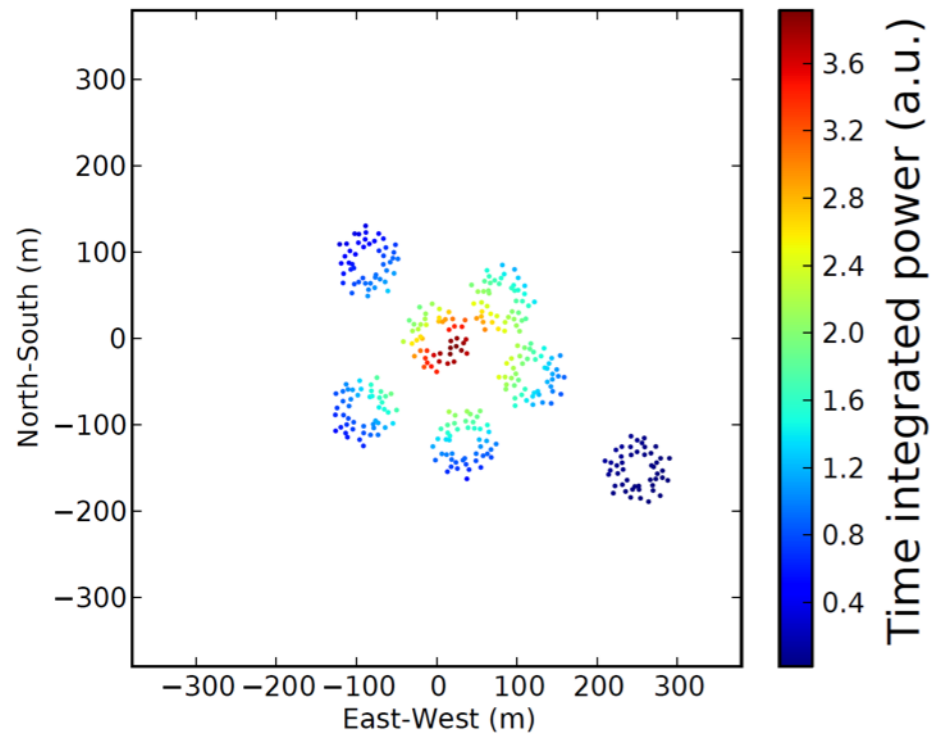
Cosmic lightning
FOM project
KVI, CWI, VUB

Two layer model





SKA: ultrahigh precision measurements

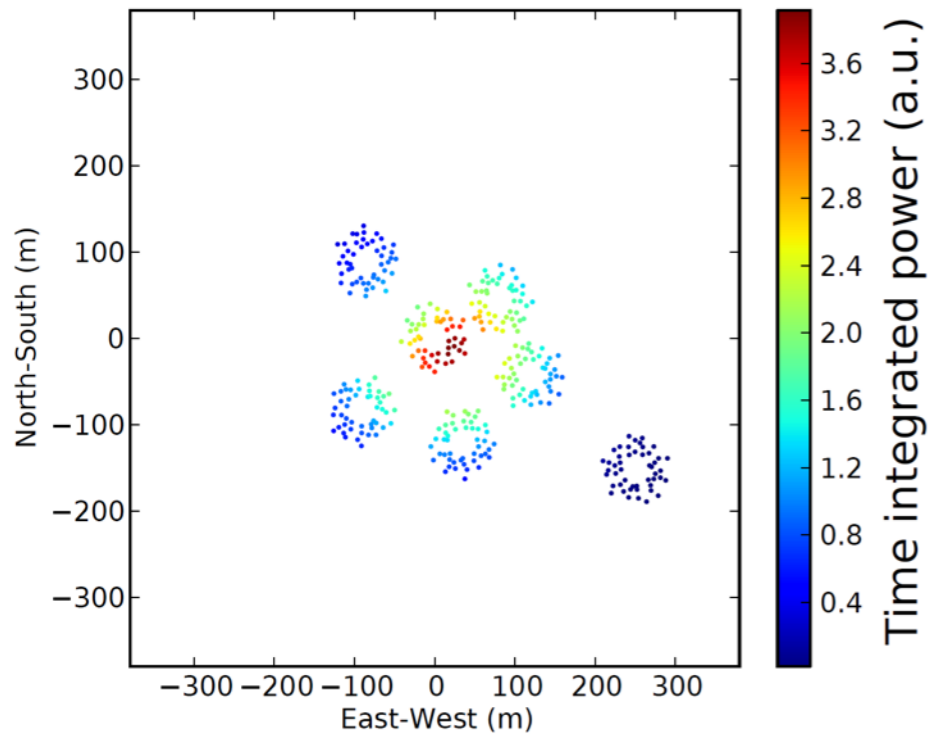


LOFAR

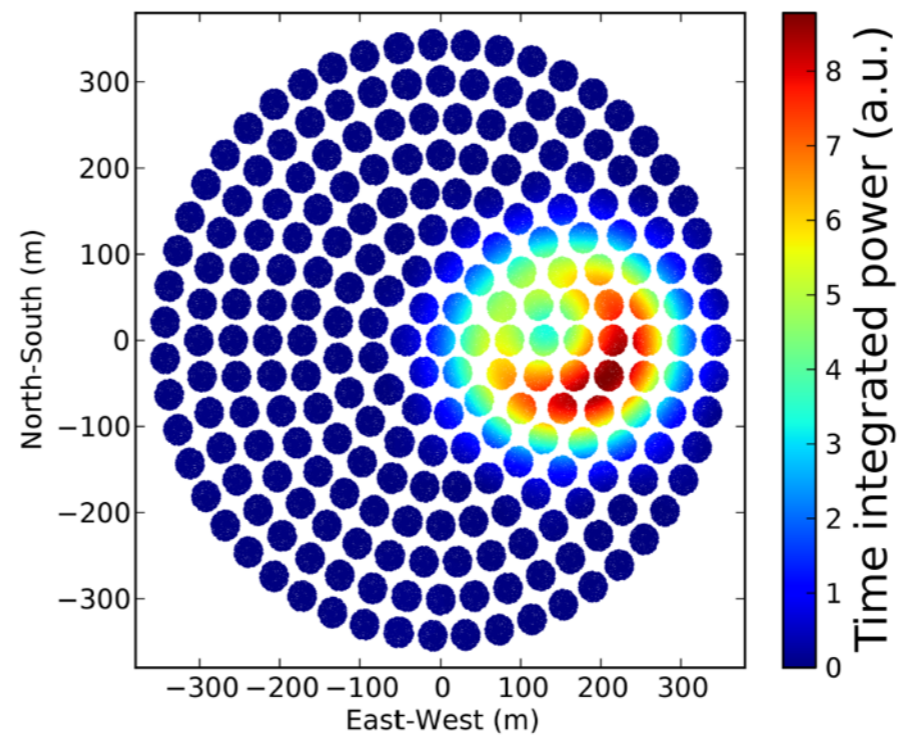
Science:

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

SKA: ultrahigh precision measurements



LOFAR

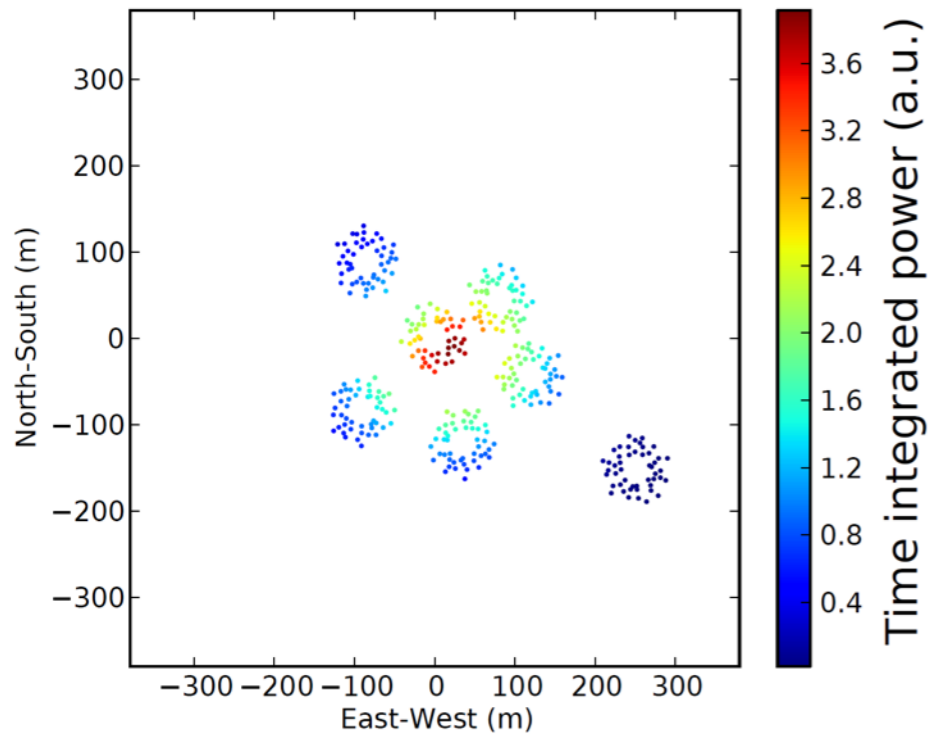


SKA

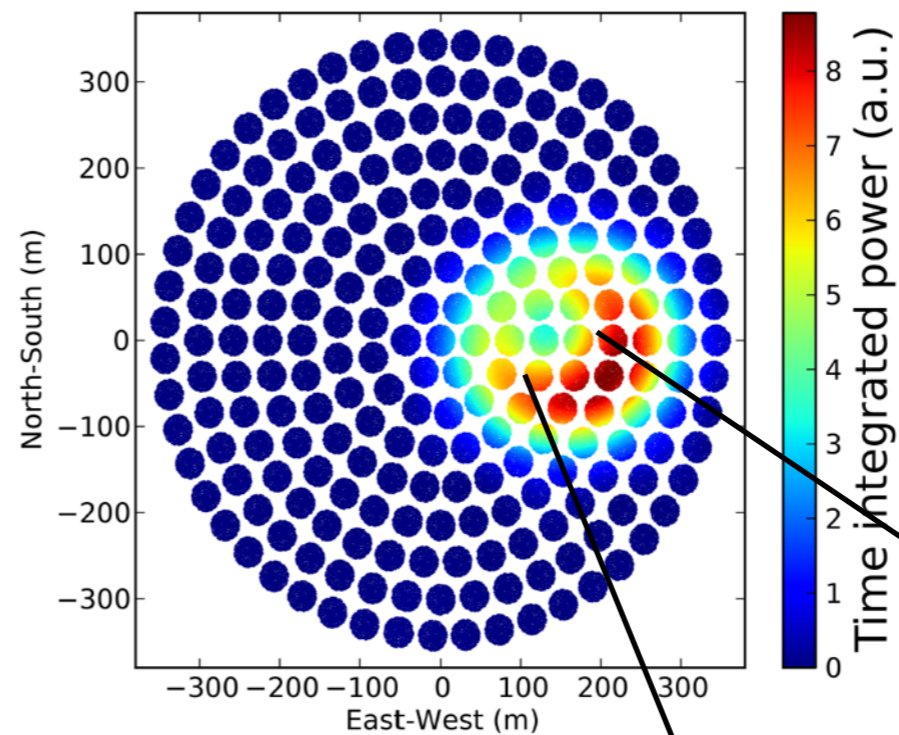
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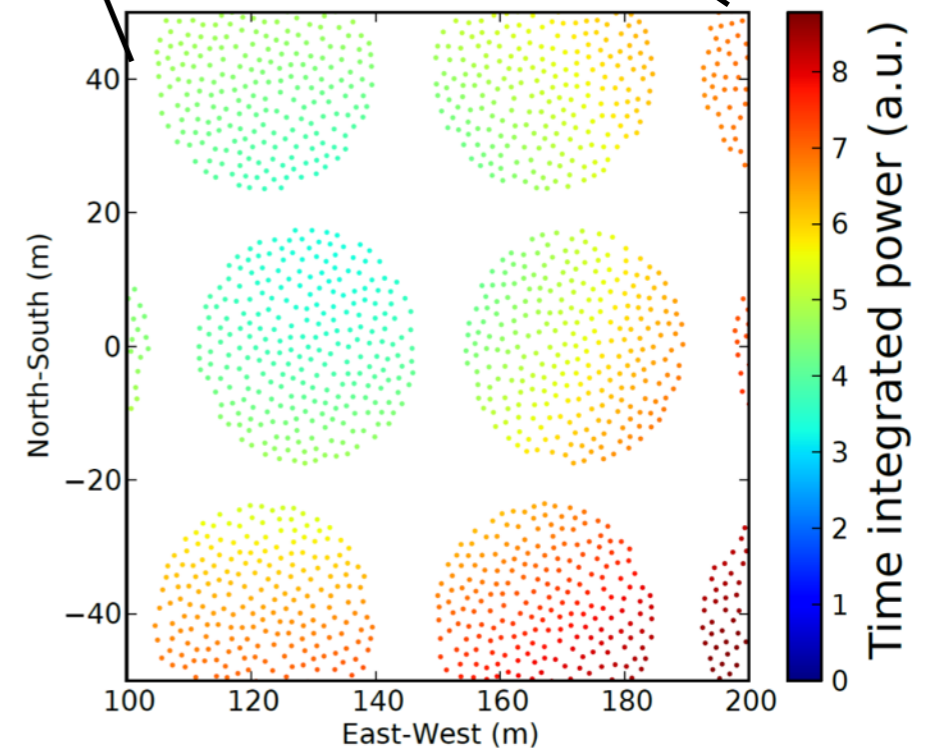
LOFAR



SKA

Science:

- **origin of CRs**
mass composition in transition region G/XG
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shower tomography
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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 **$< 20 \text{ g/cm}^2$**
similar to fluorescence detection + higher duty cycle
- First composition results based on 100+ high-res reconstructions using **full shape of X_{\max} distribution**
light mass component at $10^{17} - 10^{17.5} \text{ eV}$
- Air showers in thunderstorm:
remote sensing of electric fields, thunderstorm physics
- Future: ultra-high precision with **SKA**

Thanks

$10^{20} - 10^{??}$ eV: Moon = 10^7 km² detector area



WSRT



LOFAR

best sensitivity now:
Buitink et al. A&A 521, 47(2010)

radio flash
ns scale!

CR/neutrino

