# Present Detection Methods


**The Pierre Auger Observatory**

**Hybrid detection of extensive air showers**

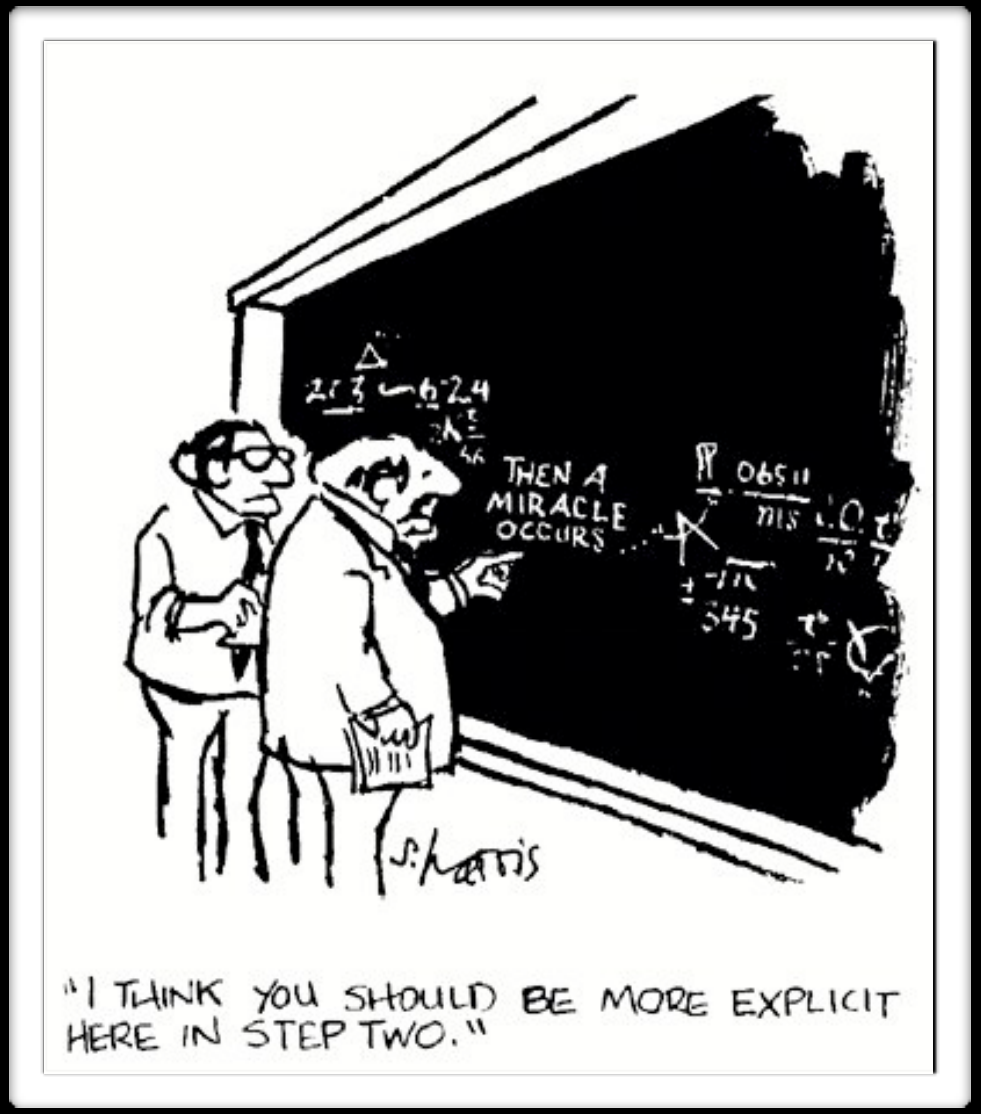
**Water Cherenkov detectors**

- **lateral distributions on ground level**
- **~100% duty cycle**

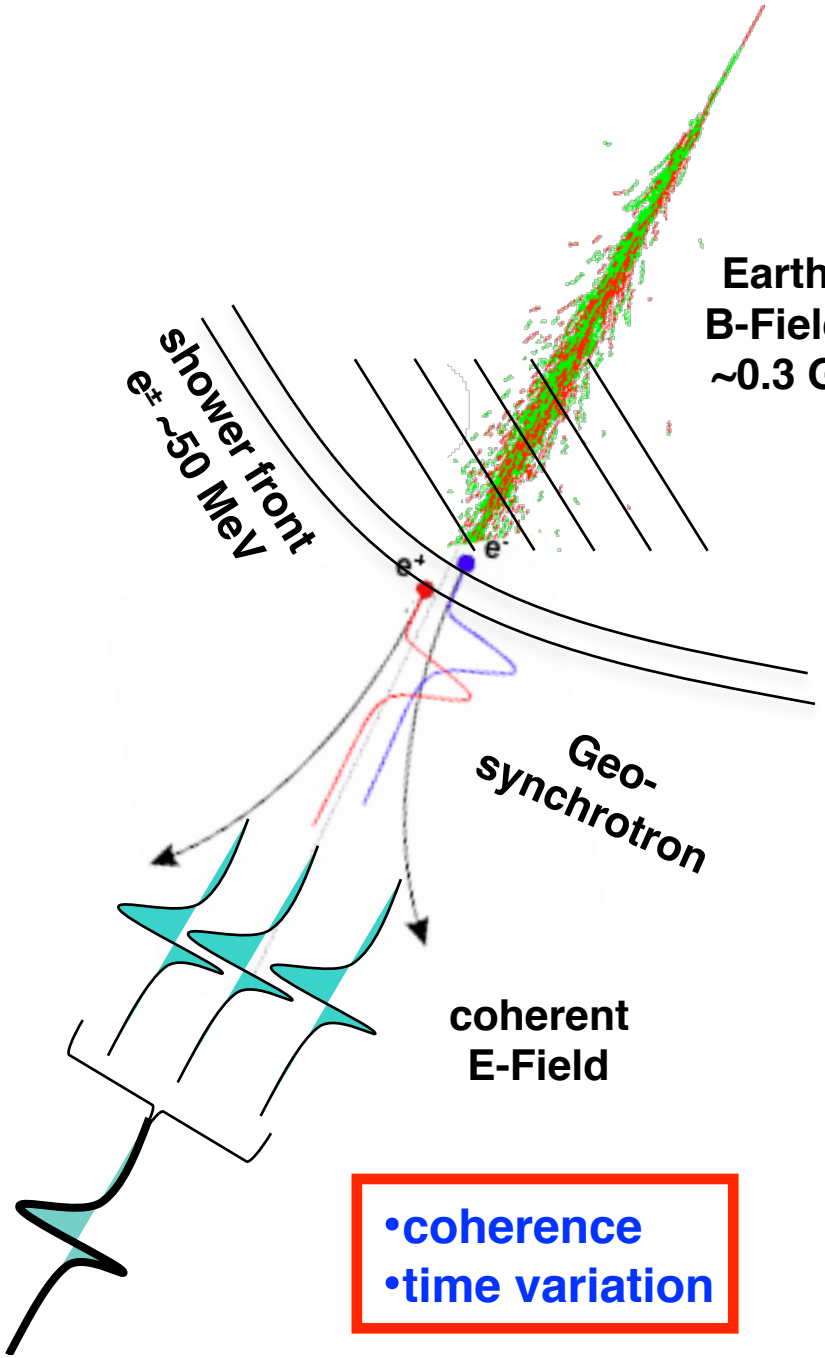
**Fluorescence telescopes**

- **longitudinal shower development**
- **~15 % duty cycle (moonless nights)**
- **light absorption by aerosols**

# Radio Emission



# Radio Emission in Air Showers




- UHECRs produce particle showers in atmosphere
- Shower front is ~2-3 m thick ~ wavelength at 100 MHz
- $e^{\pm}$ emit (mostly) synchrotron rad. in geomagnetic field
- Emissions from all $e^{\pm}$ ($N_e$) add up coherently
- Radio power grows quadratically with $N_e$
- Mainly: Charge separation in geomagnetic field

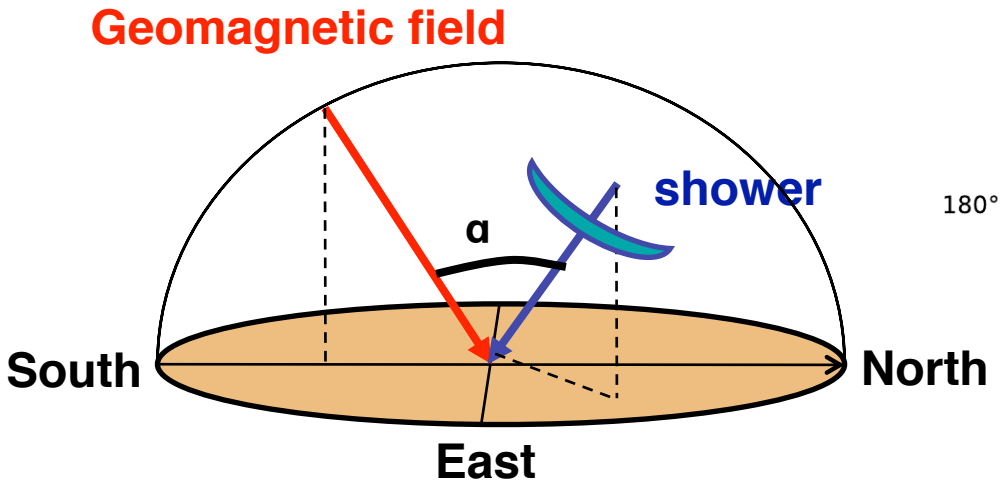
$$\vec{E} \propto \vec{v} \times \vec{B}$$

Theory predicts additional mechanisms:

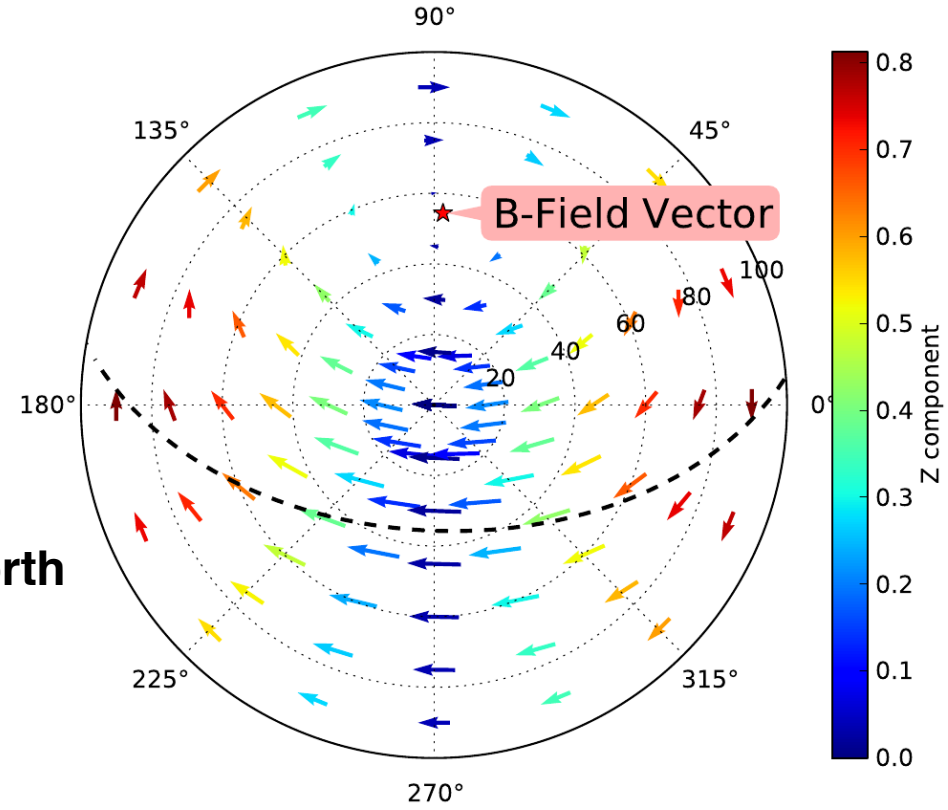
- excess of electrons in shower: charge excess
- superposition of emission due to Cherenkov effect in atmosphere

# Synchrotron radiation in Geomagnetic Field

- radio emission dominated by geosynchrotron emission
- emission strength depends on angle to Earth's B field




$$\vec{\epsilon} \propto \vec{v} \times \vec{B}$$




expected polarisation
here simply **v** x **B**

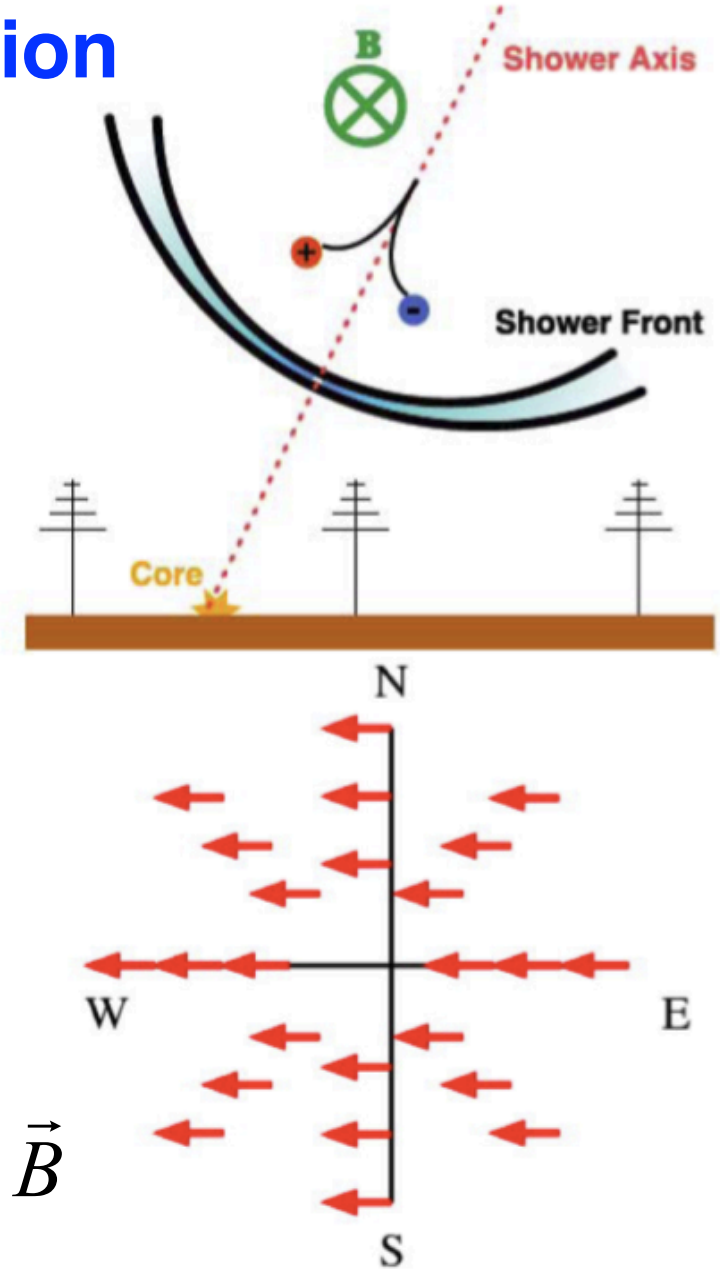
D. Arduin et al., Astropart. Phys. 31 (2009) 192

C. Glaser, ARENA (2012)

# Radio Emission in Air Showers

## 1st order: geomagnetic emission

- *time-varying* transverse currents
- signal strength
  ~ *v* x *B* = v B sin(α)
- purely linear polarisation
  - E-field vector aligned with *v* x *B for all oberver locations*
- emission can be „compressed“ by Cherenkov effects



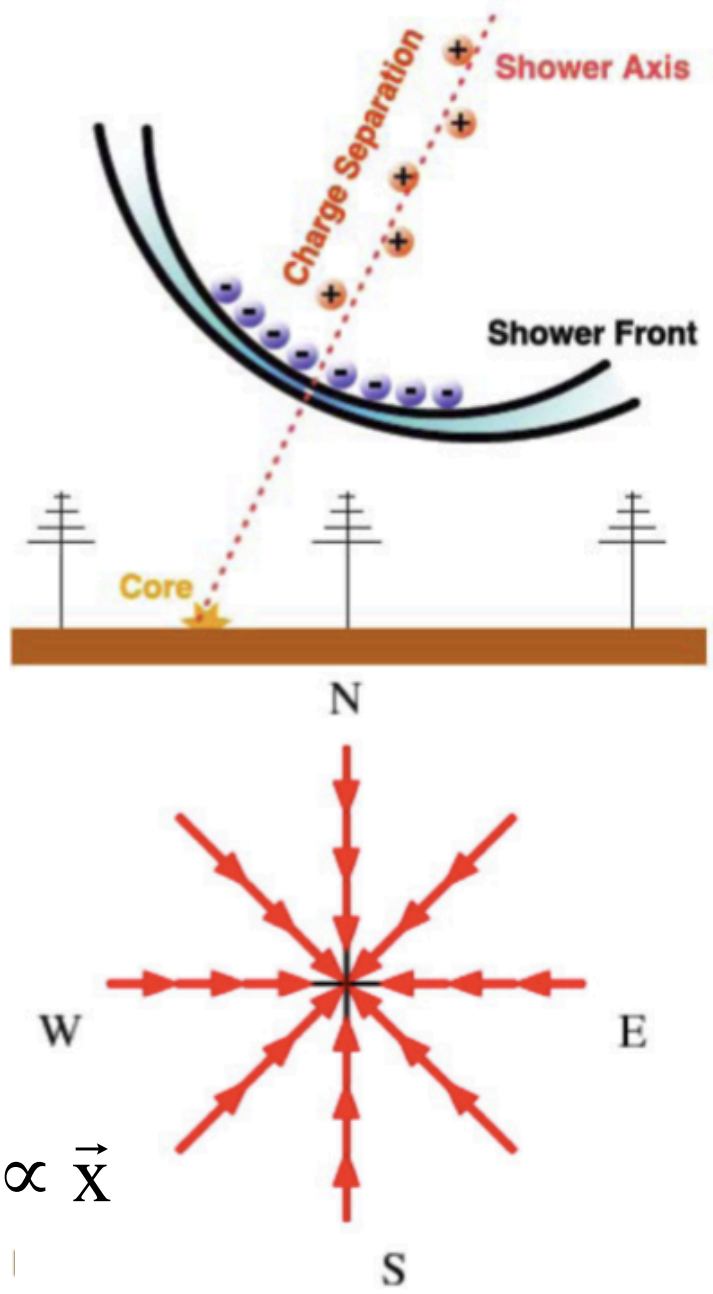

$$\vec{A} \propto \vec{J}_{Lorentz} \qquad \vec{E} = \frac{d\vec{A}}{dt} \propto \vec{v} \times \vec{B}$$

T. Huege, K. de Vries

# Radio Emission in Air Showers

## 2nd order: Askaryan emission

- **Askaryan: *time-varying* charge-excess**
- **also occurs for n=1!**
- **Cherenkov effects „compress“ the emission**
- **not „classical“ Cherenkov emission of a non-varying net charge**
- **linearly polarized**
- **E-field vector radially oriented, varies with observer location relative to core**

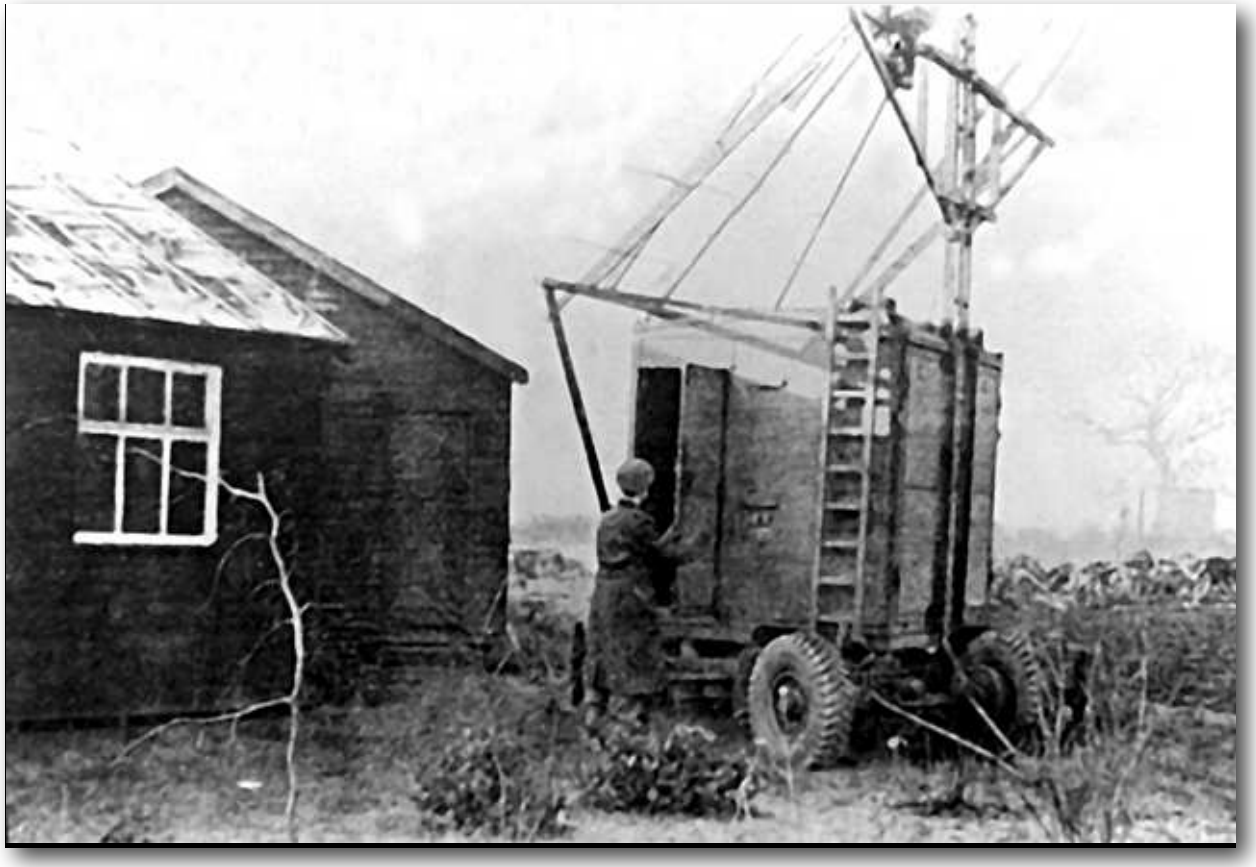



$$A \propto J^0 \qquad \vec{E} = \frac{d\vec{A}^0}{d\vec{x}} \propto \vec{x}$$

T. Huege, K. de Vries

# History

# Jodrell Bank 1946



**No air showers detected**

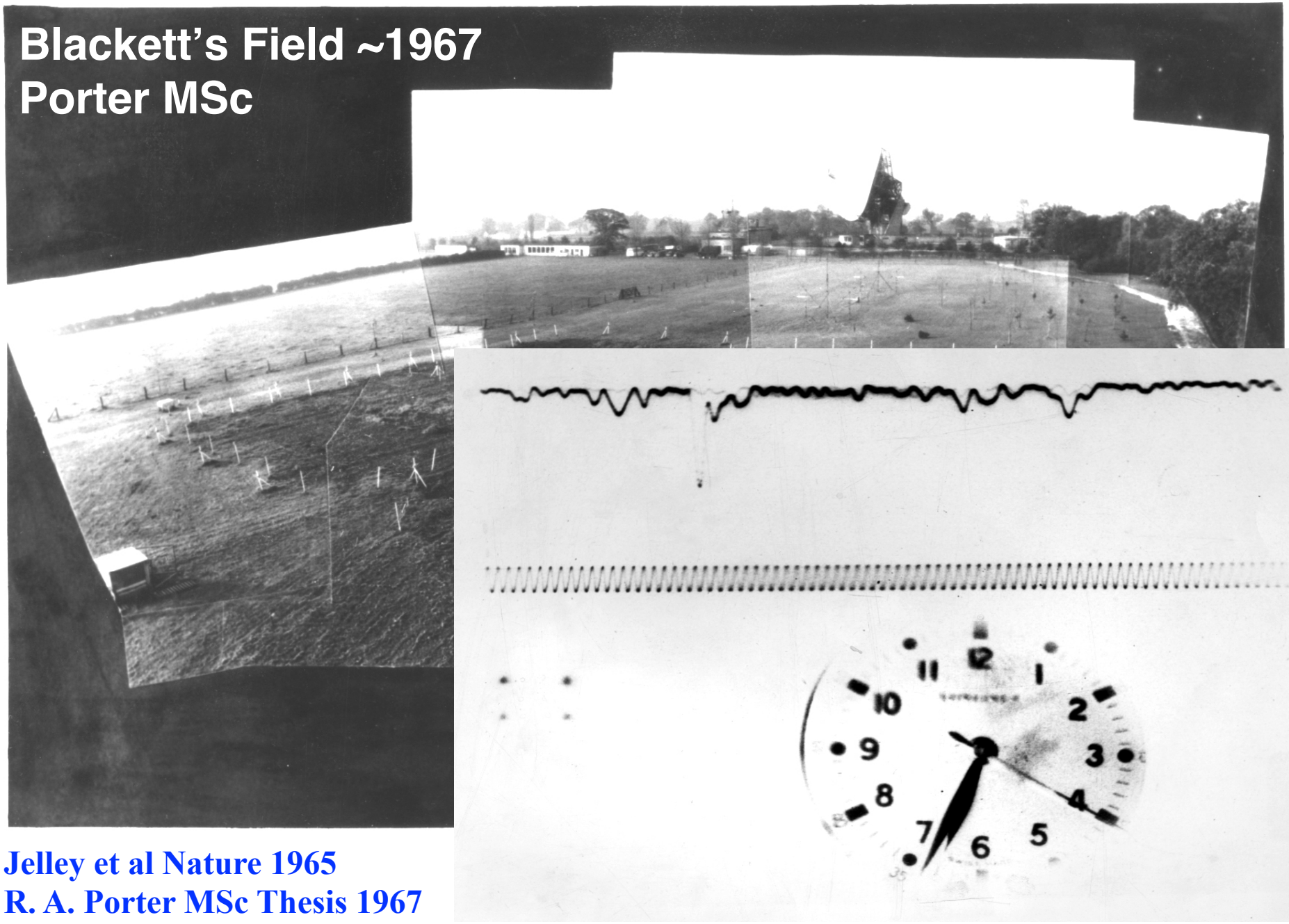
$$O_2 + e \rightarrow O_2^-$$

**No luck due to rapid attachment time (ns) of free electrons in the lower atmosphere (damping factor)**

**Echos from meteor trails**
**Radio emission from M31**

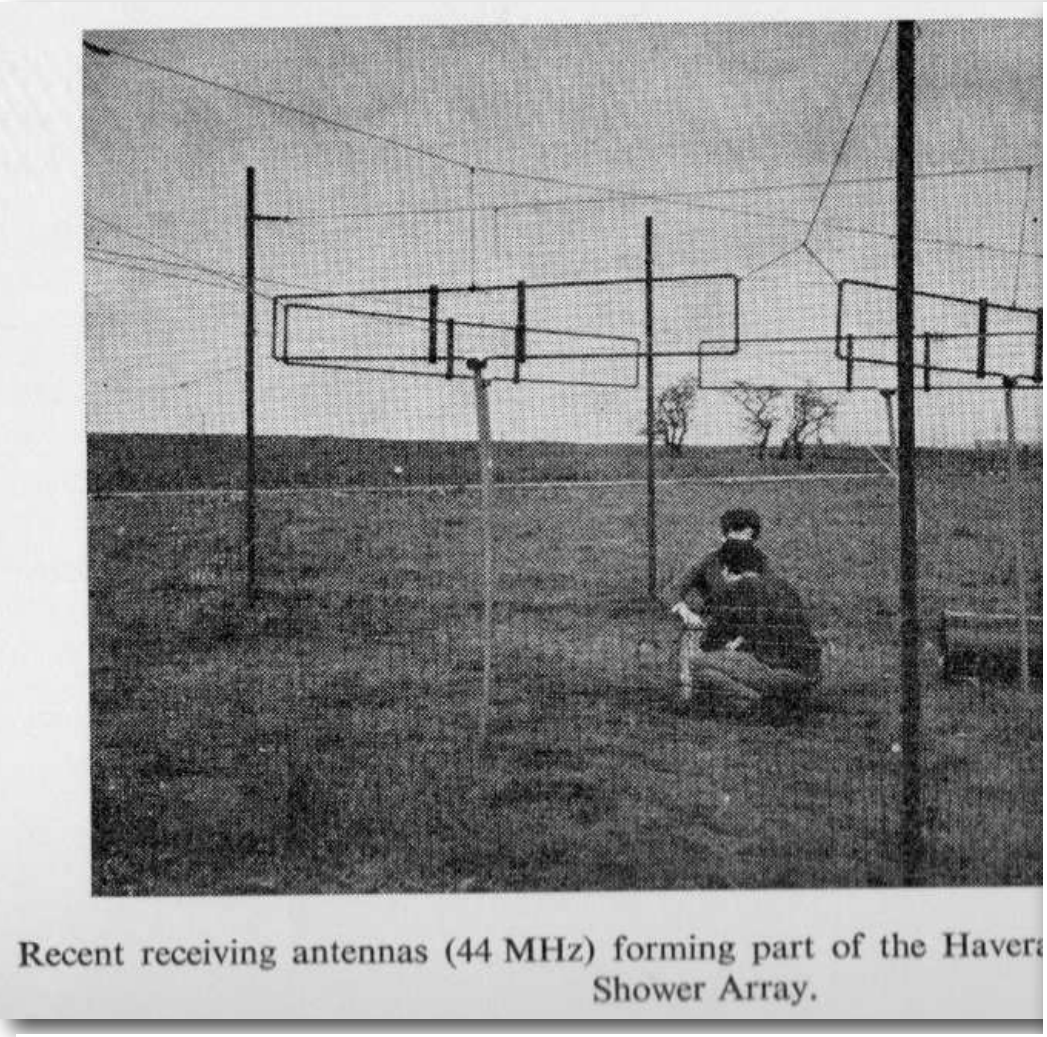
→ **radio astronomy**

# First radio detection of air showers 1965

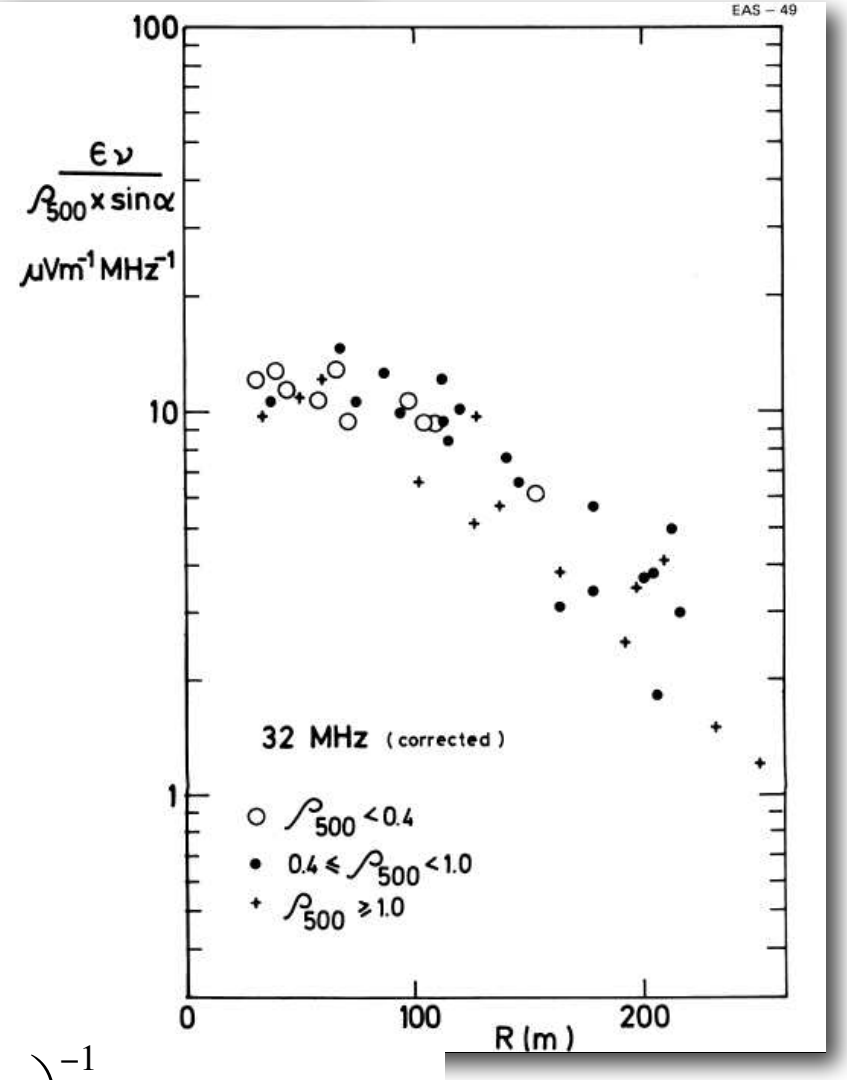



Jelley et al Nature 1965
R. A. Porter MSc Thesis 1967

# Haverah Park (Leeds)  Allan 1971



Recent receiving antennas (44 MHz) forming part of the Haver
Shower Array.




$$\varepsilon_\nu = 2\left(\frac{E_p}{10^{17}}\right)\left(\frac{\sin\alpha\cos\theta}{\sin 45\cos 30}\right)\exp\left(\frac{-r}{r_0}\right)\left(\frac{\nu}{50}\right)^{-1} \quad \mu\text{V/m/MHz}$$

$r_0 = 110$ m at $\nu$=55 MHz. $\alpha$=angle to B, $\theta$=Zenith angle

# Radio Detectors

# Large-scale radio detectors to measure extensive air showers

LOPES
RADIO EMISSION FROM COSMIC RAY AIR SHOWERS

0.5 km²

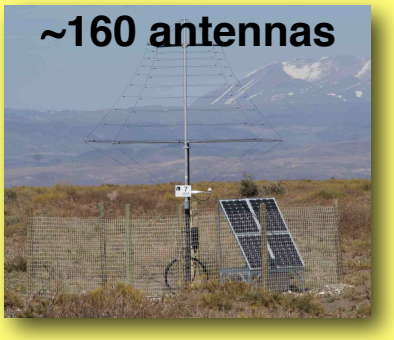
CODALEMA 0.5 km²

LOFAR

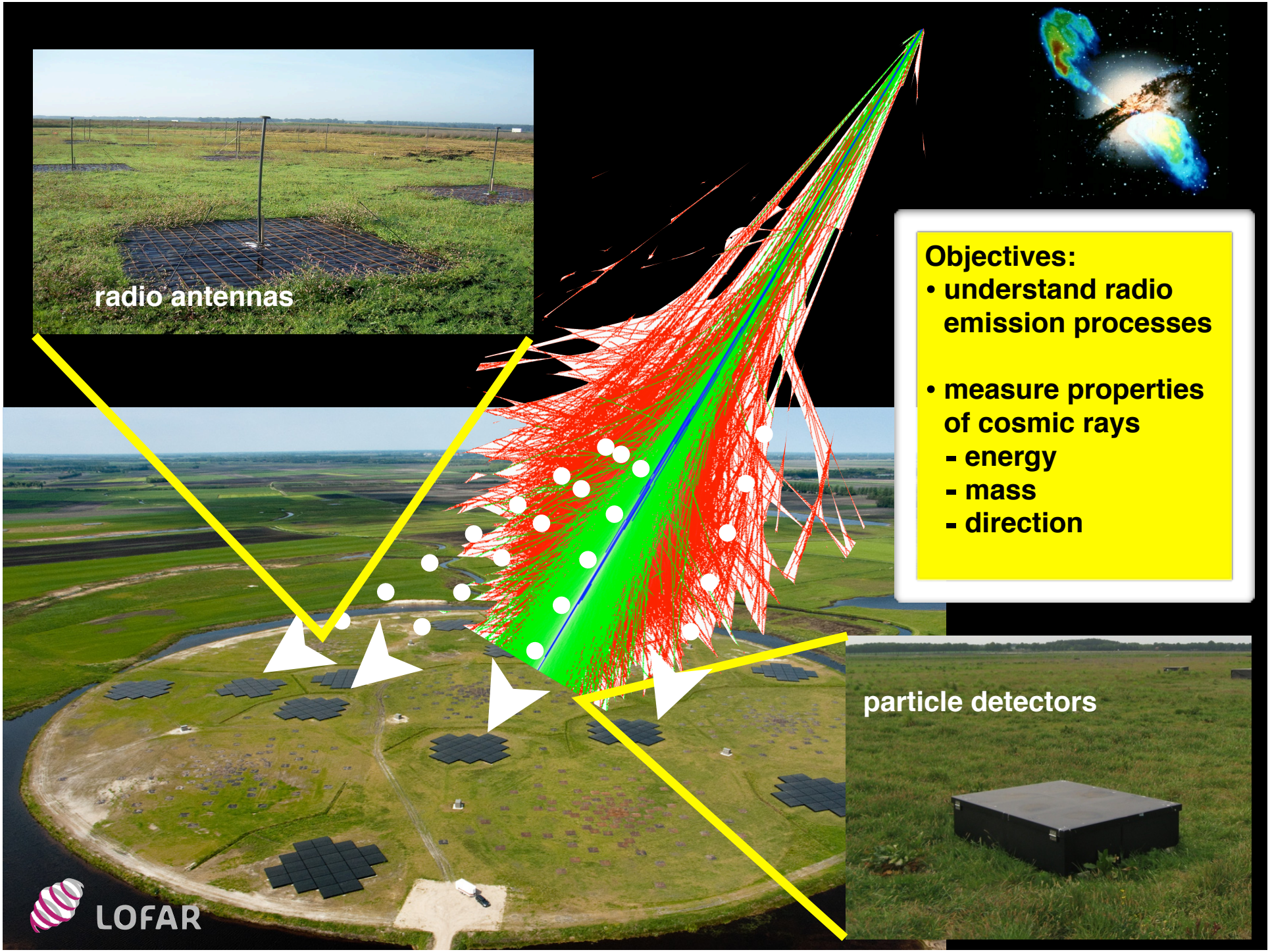
5 km² (core)
~1800 antennas

AERA
Auger Engineering Radio Array

20 km²
~160 antennas



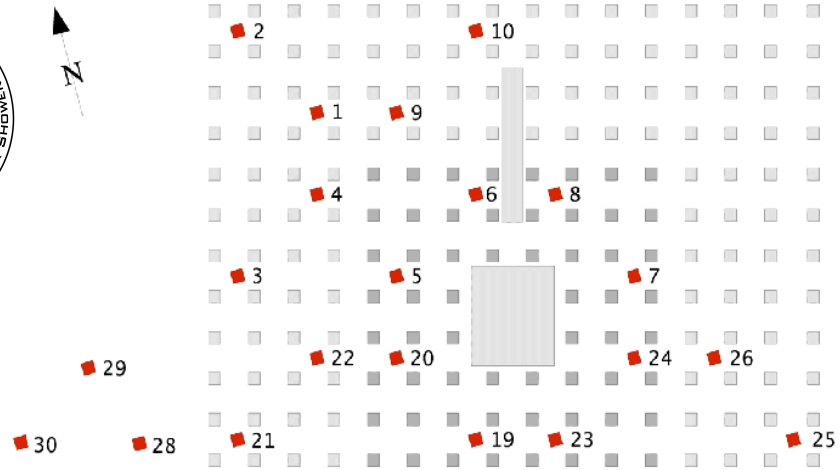
**next-generation cosmic-ray detector**
20 000 km²

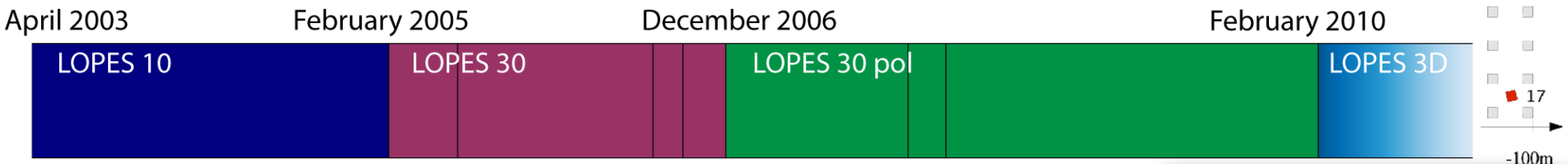

radio antennas
Objectives:
• understand radio emission processes
• measure properties of cosmic rays
- energy
- mass
- direction
particle detectors
LOFAR

# LOPES

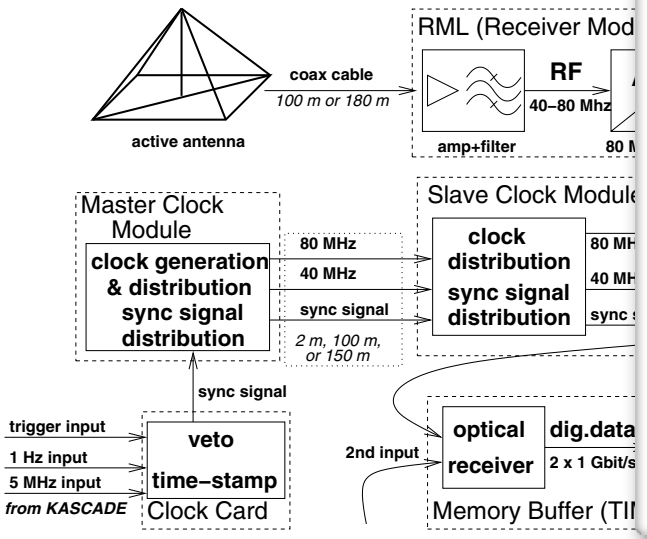
## Lofar Prototype Station

**30 antennas operating at KASCADE-Grande**



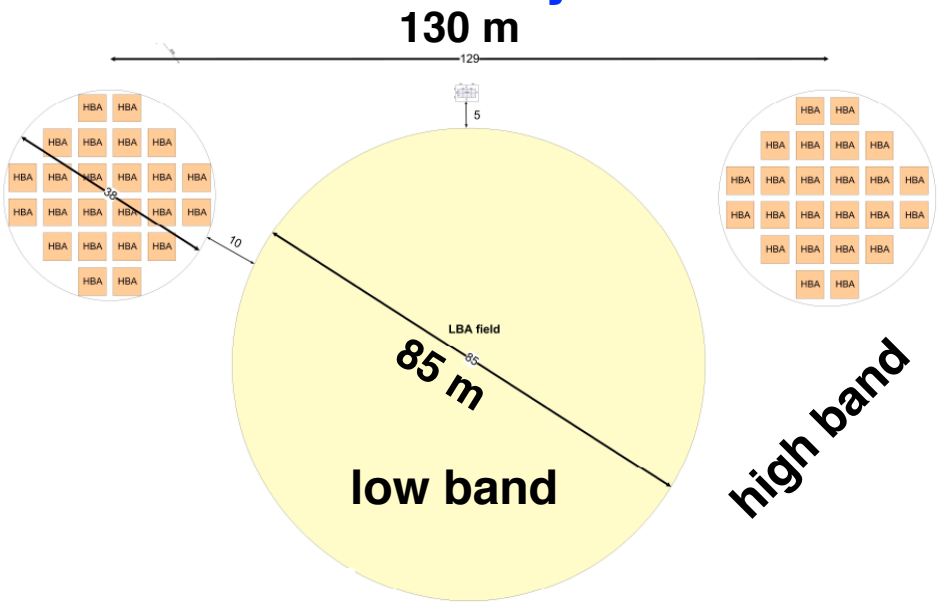




## digital radio interferom





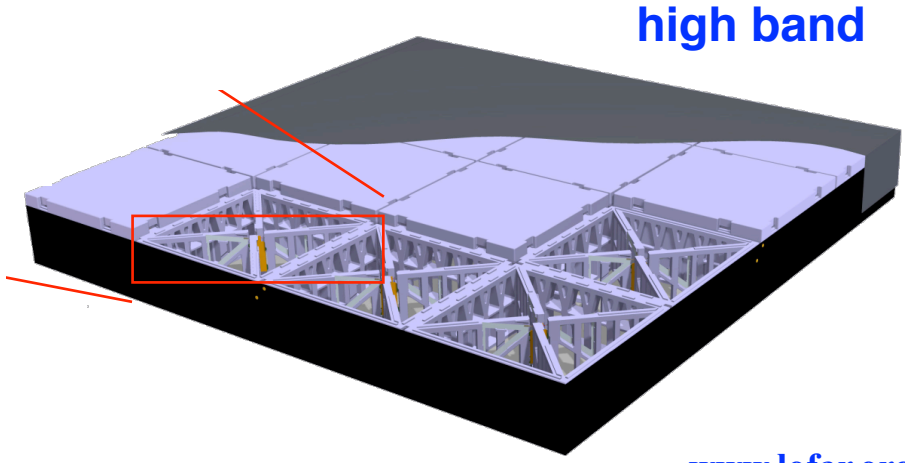
## Station Layout




**each (dutch) station:**

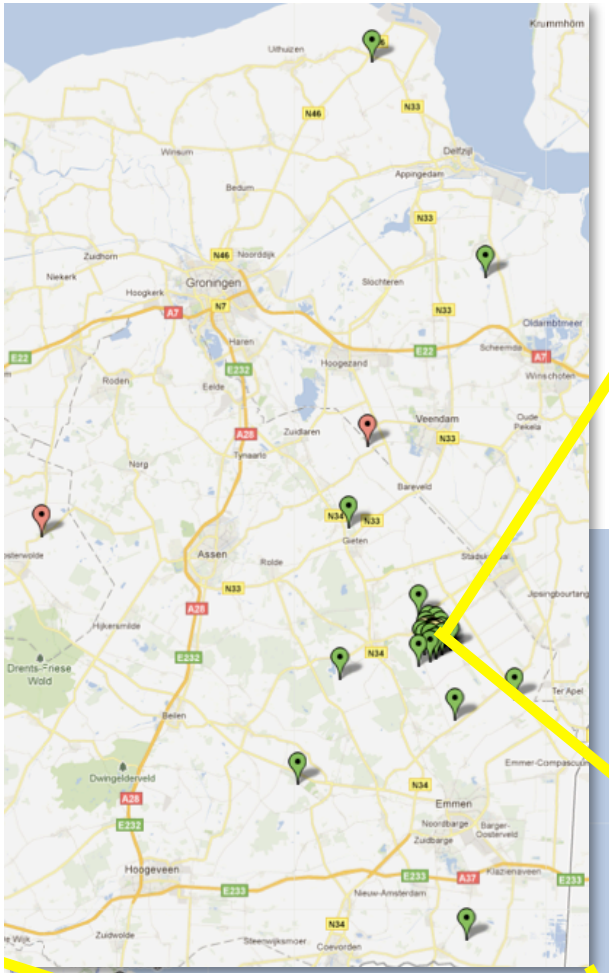
**96 low-band antennas 30- 80 MHz**

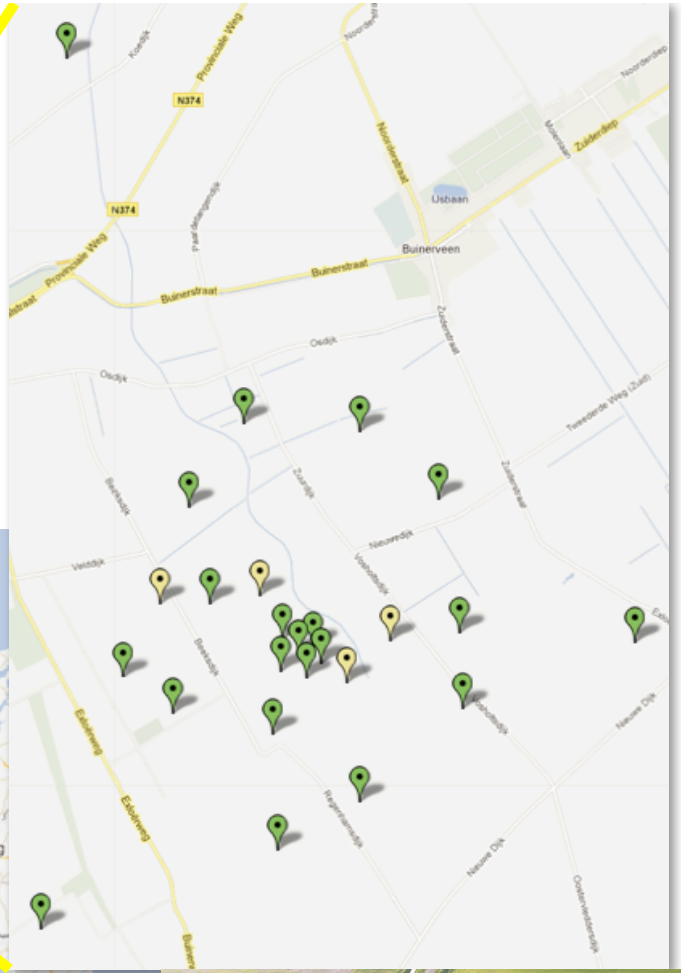
**high-band antennas (2x24 tiles) 120-240 MHz**


www.lofar.org

# LOFAR stations across Europe

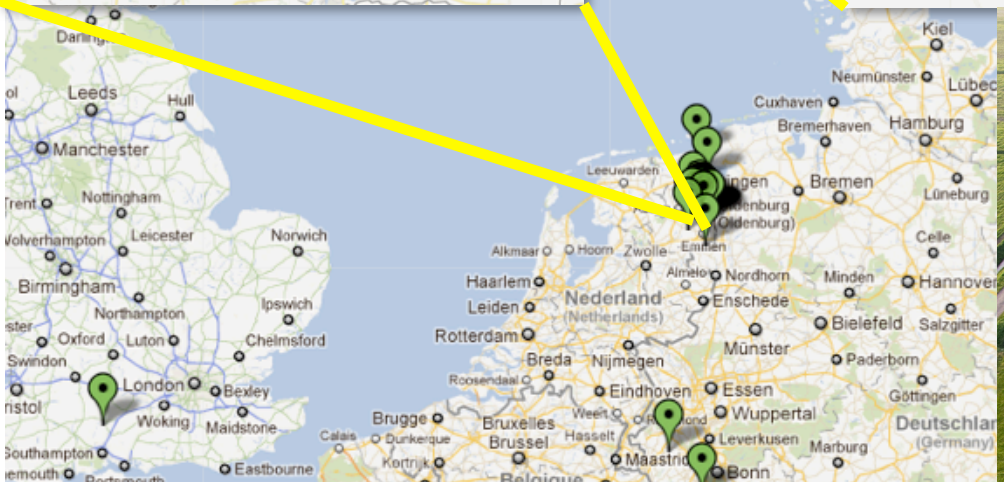



# Dense core in NL

## 18 stations
## ~ 5 km²

LOFAR

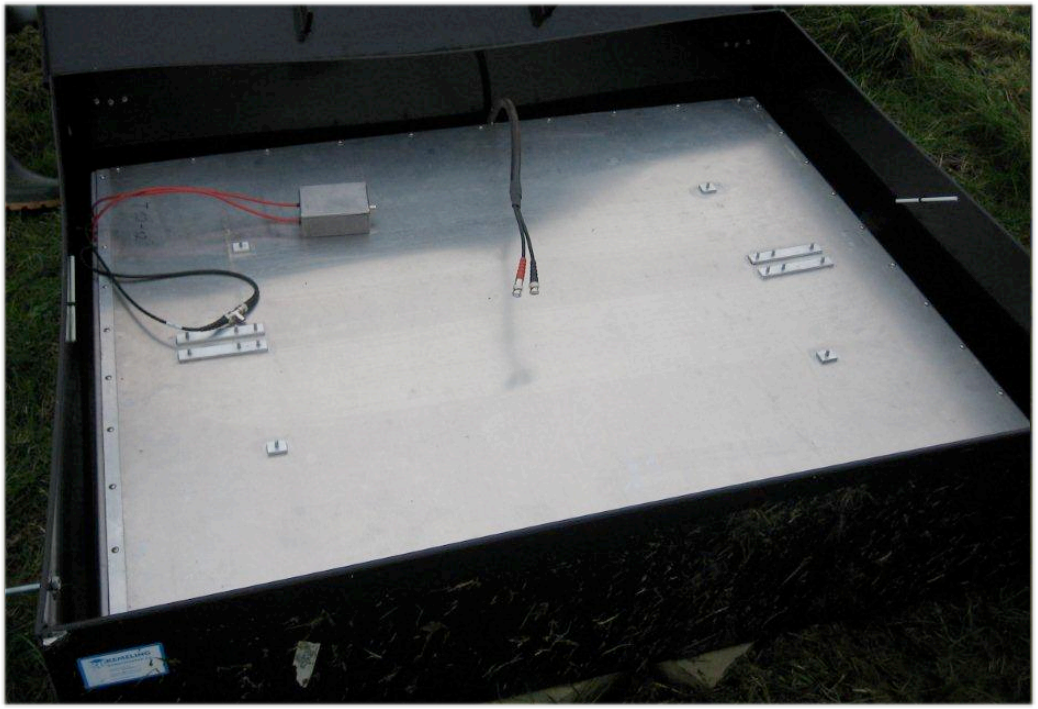



# LOFAR Radboud Air Shower Array - LORA

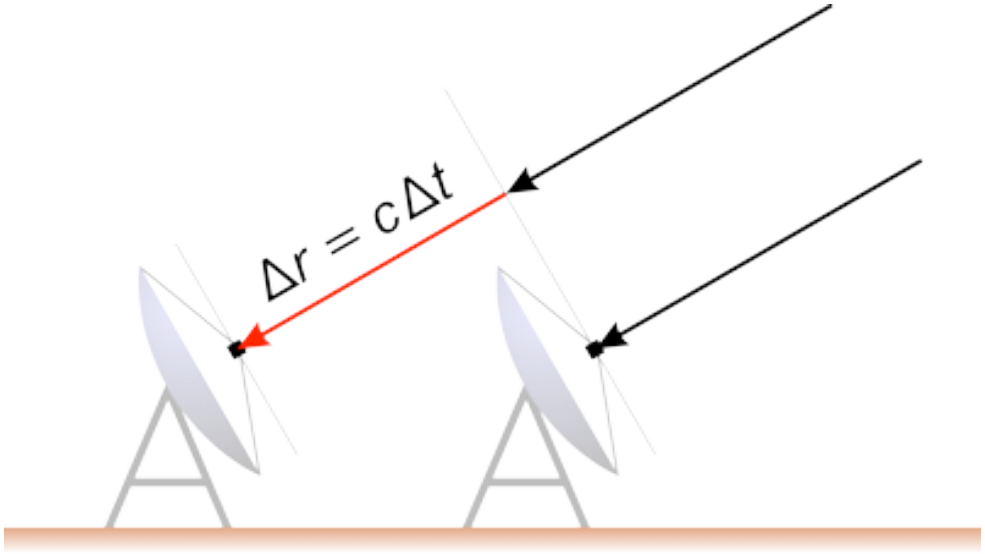
20 scintillator units
(~1 $m^2$ each)
read out by
wavelength shifter
bar and PMT
in LOFAR core

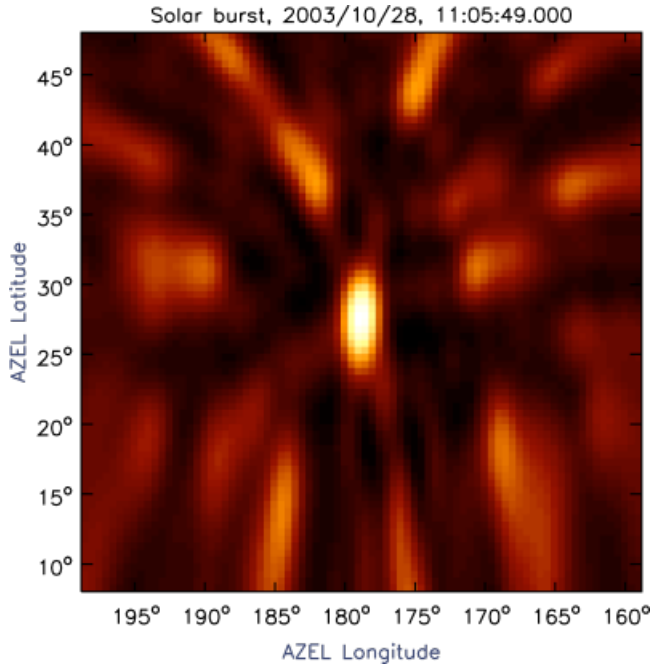
→ provide

- properties of EAS
- and trigger

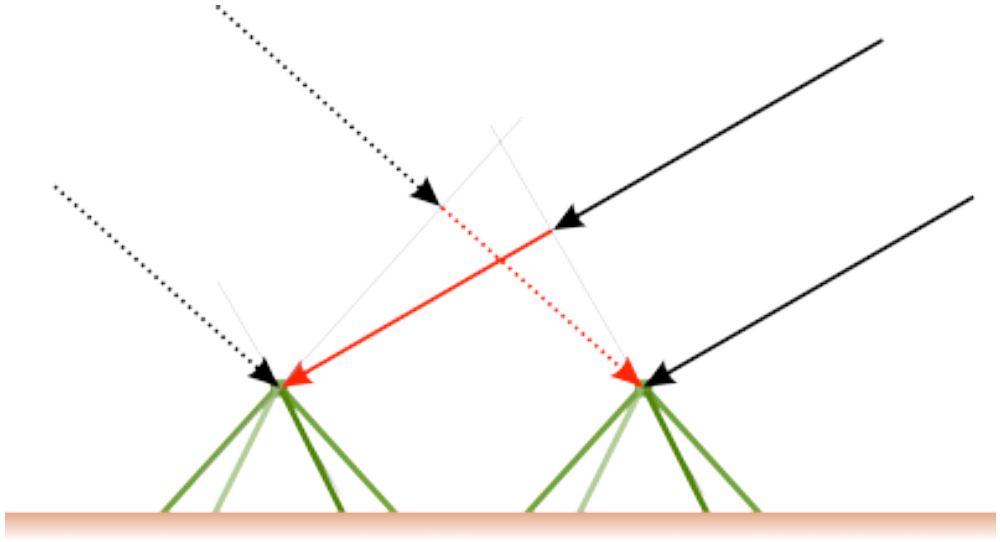


# Digital beam forming

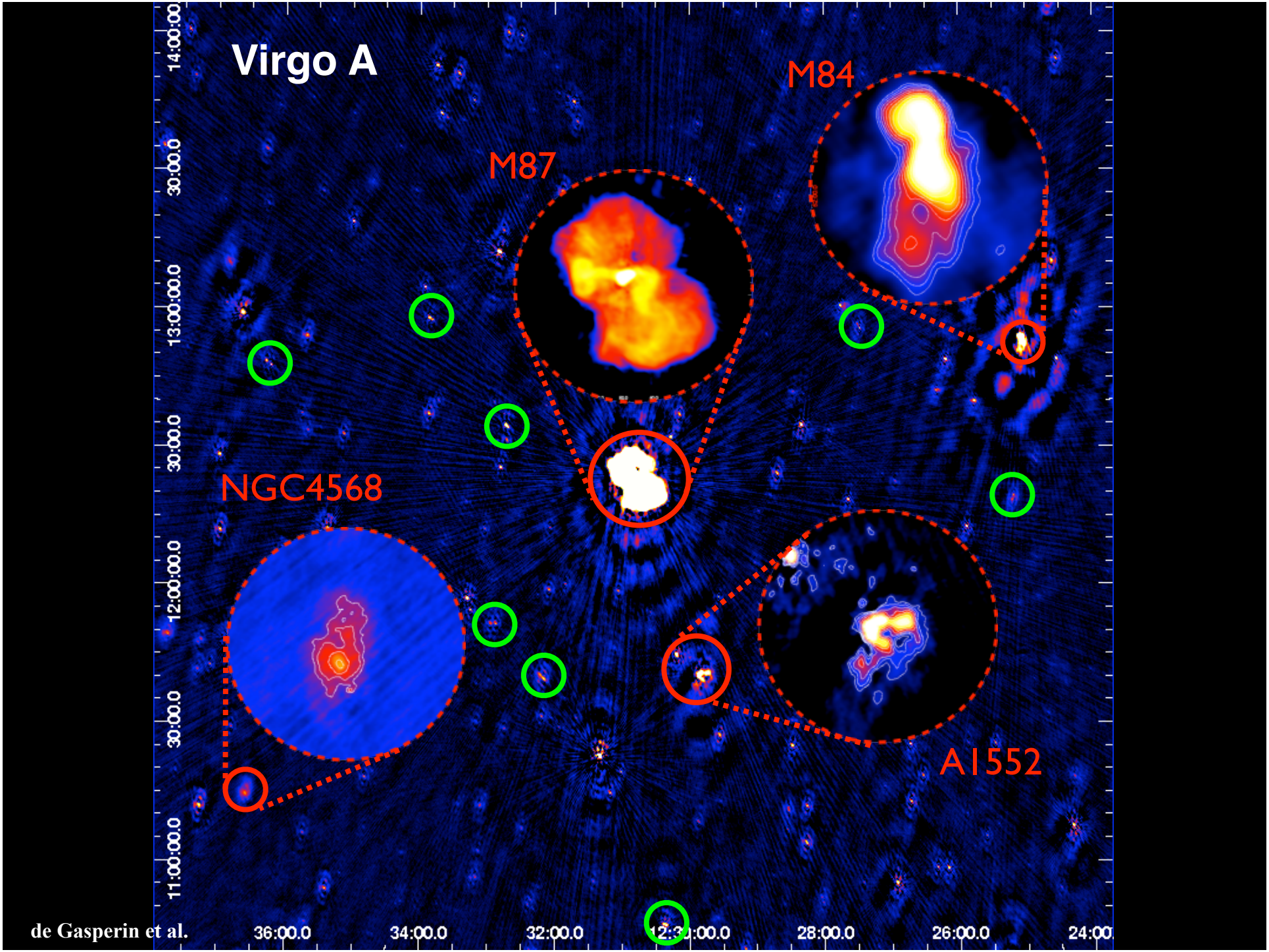



Solar burst observed with LOPES



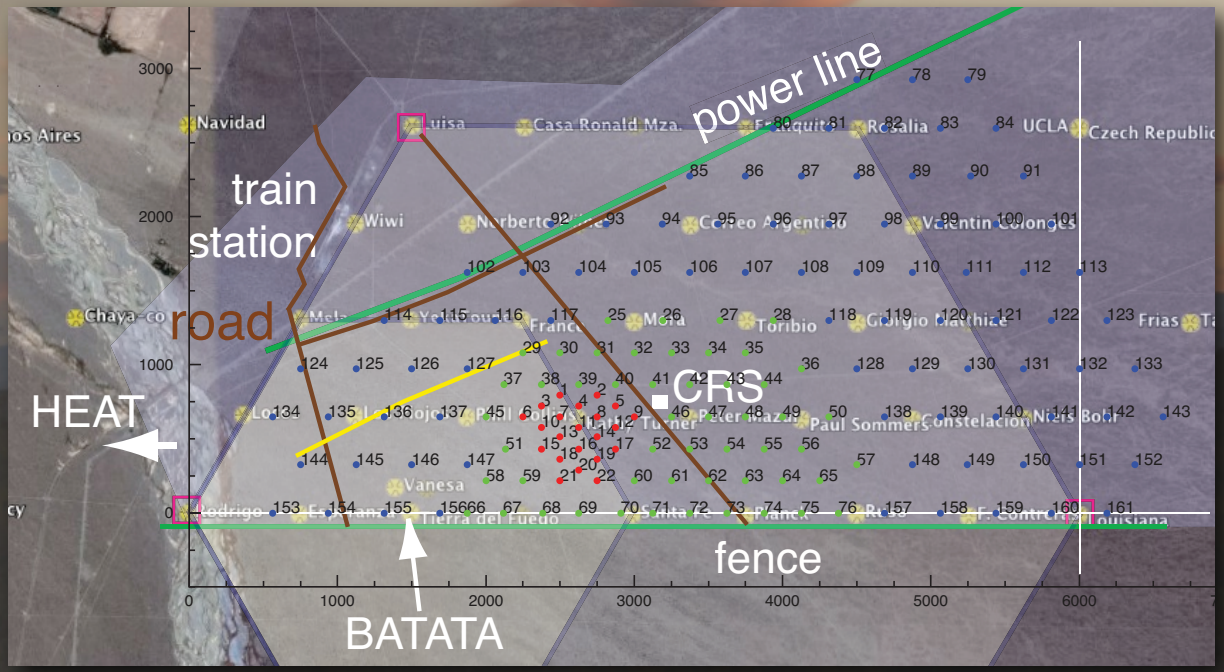

IBM Blue Gene Supercomputer

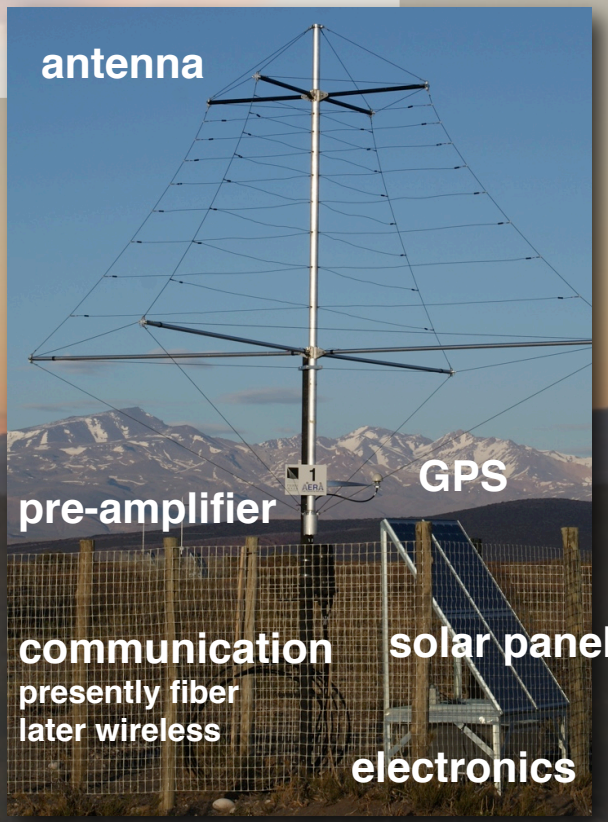

Virgo A
M84
M87
NGC4568
A1552
14:00:00
30:00.0
13:00:00.0
30:00.0
12:00:00.0
30:00.0
11:00:00.0
36:00.0
34:00.0
32:00.0
28:00.0
26:00.0
24:00
de Gasperin et al.

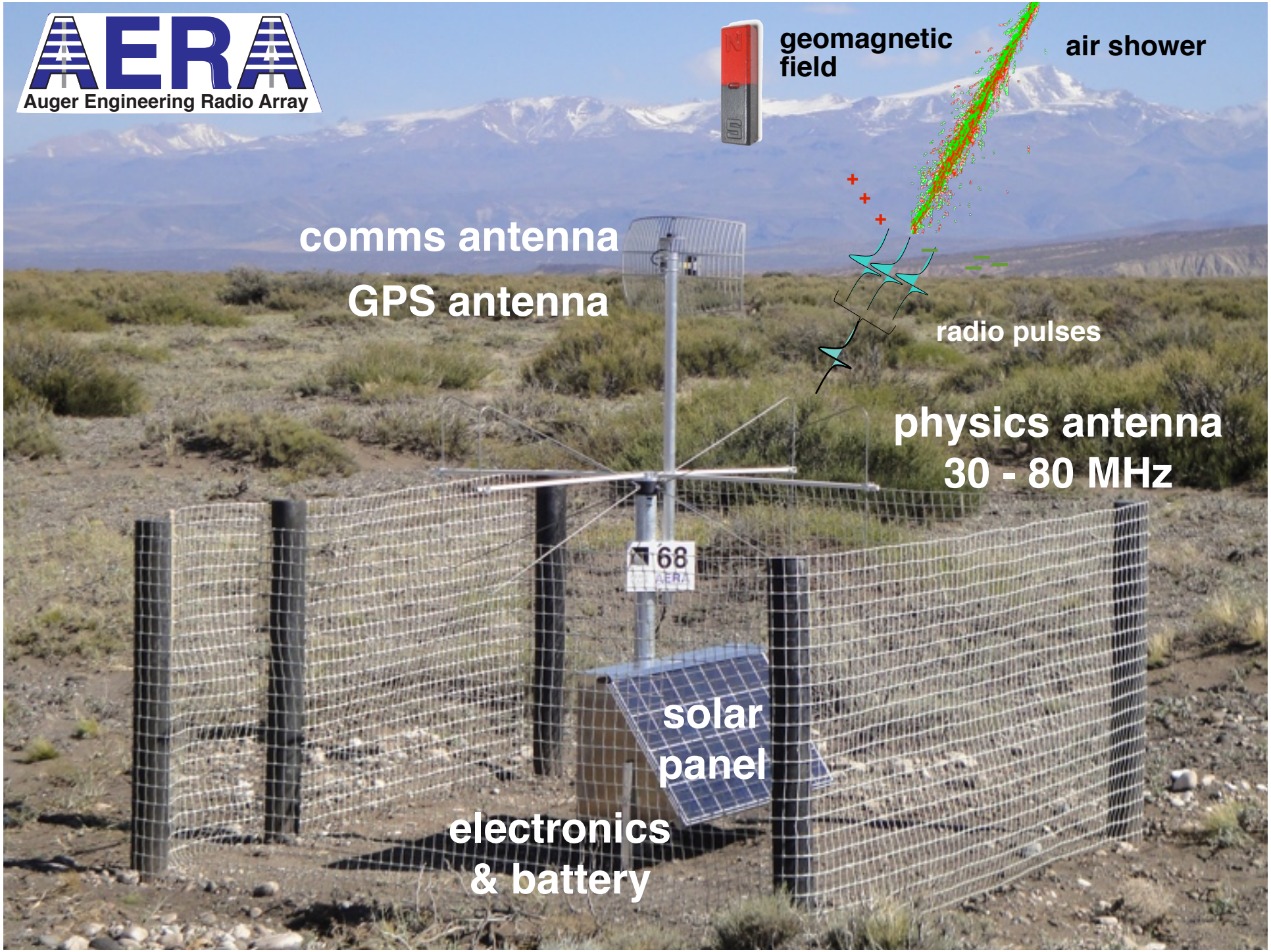
AERA
Auger Engineering Radio Array

**Objective:**

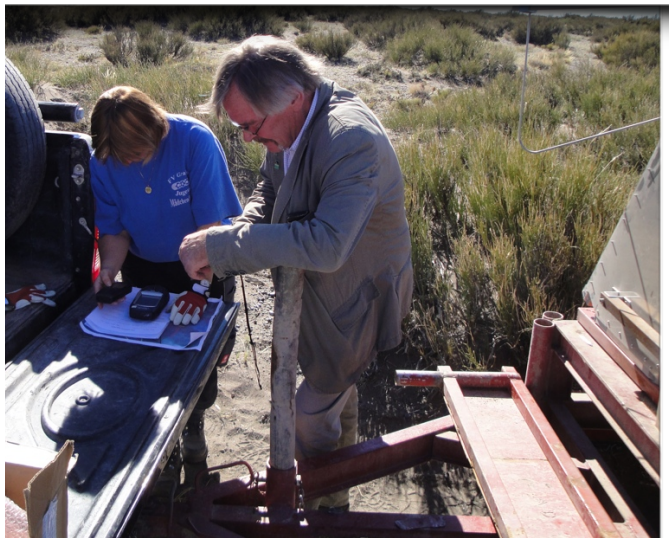
- measure radio emission from EAS in frequency range 30 MHz - 80 MHz
- ~20 km$^2$ array with ~160 antennas
- operation together with infill/HEAT/AMIGA
- three antenna spacings to cover efficiently 17.2 < lg E/eV < 19.0
- measure composition of cosmic rays in energy region of transition from galactic to extragalactic cosmic rays

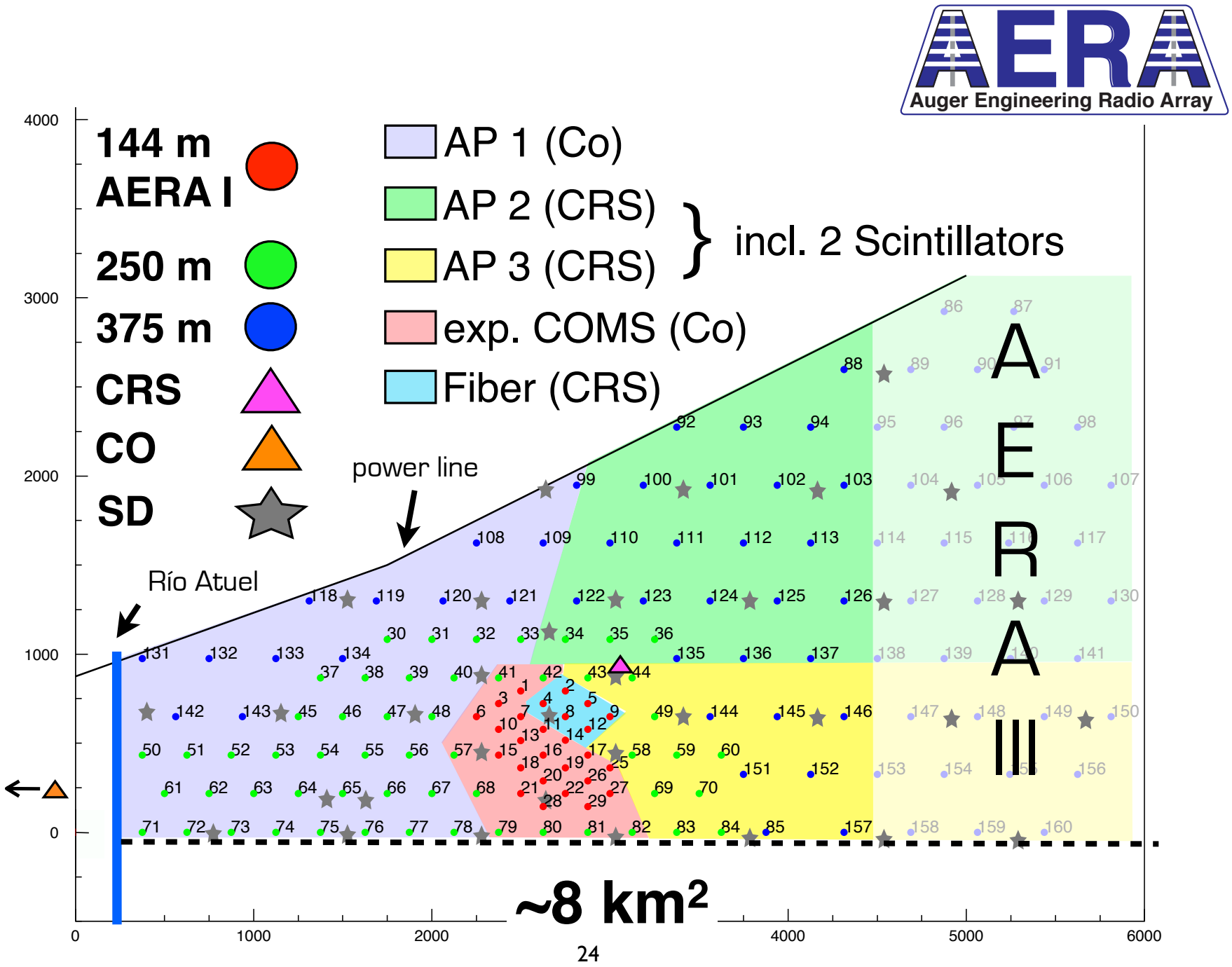



AERA
Auger Engineering Radio Array
geomagnetic field
air shower
comms antenna
GPS antenna
radio pulses
physics antenna
30 - 80 MHz
68
solar panel
electronics & battery

# installation




AERA
Auger Engineering Radio Array
144 m
AERA I
250 m
375 m
CRS
CO
SD
AP 1 (Co)
AP 2 (CRS)
AP 3 (CRS)
} incl. 2 Scintillators
exp. COMS (Co)
Fiber (CRS)
power line
Río Atuel
AERA III
~8 km²
24
0
1000
2000
3000
4000
5000
6000

LOFAR

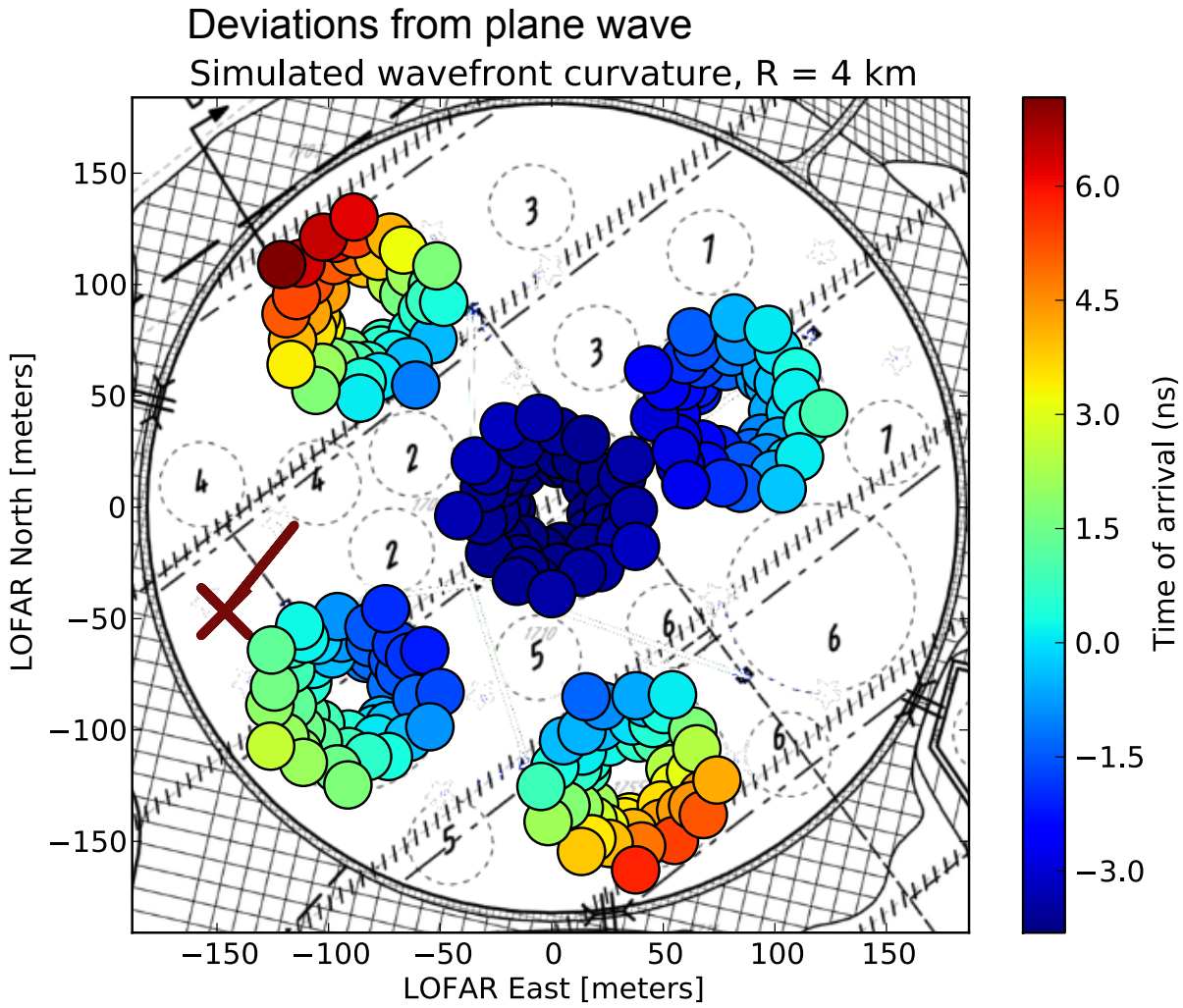
# high antenna density: precission measurements of radio emission

**Ability of LOFAR to measure shape of shower front**

LOFAR can resolve 2 ns (no additional phase calibration)

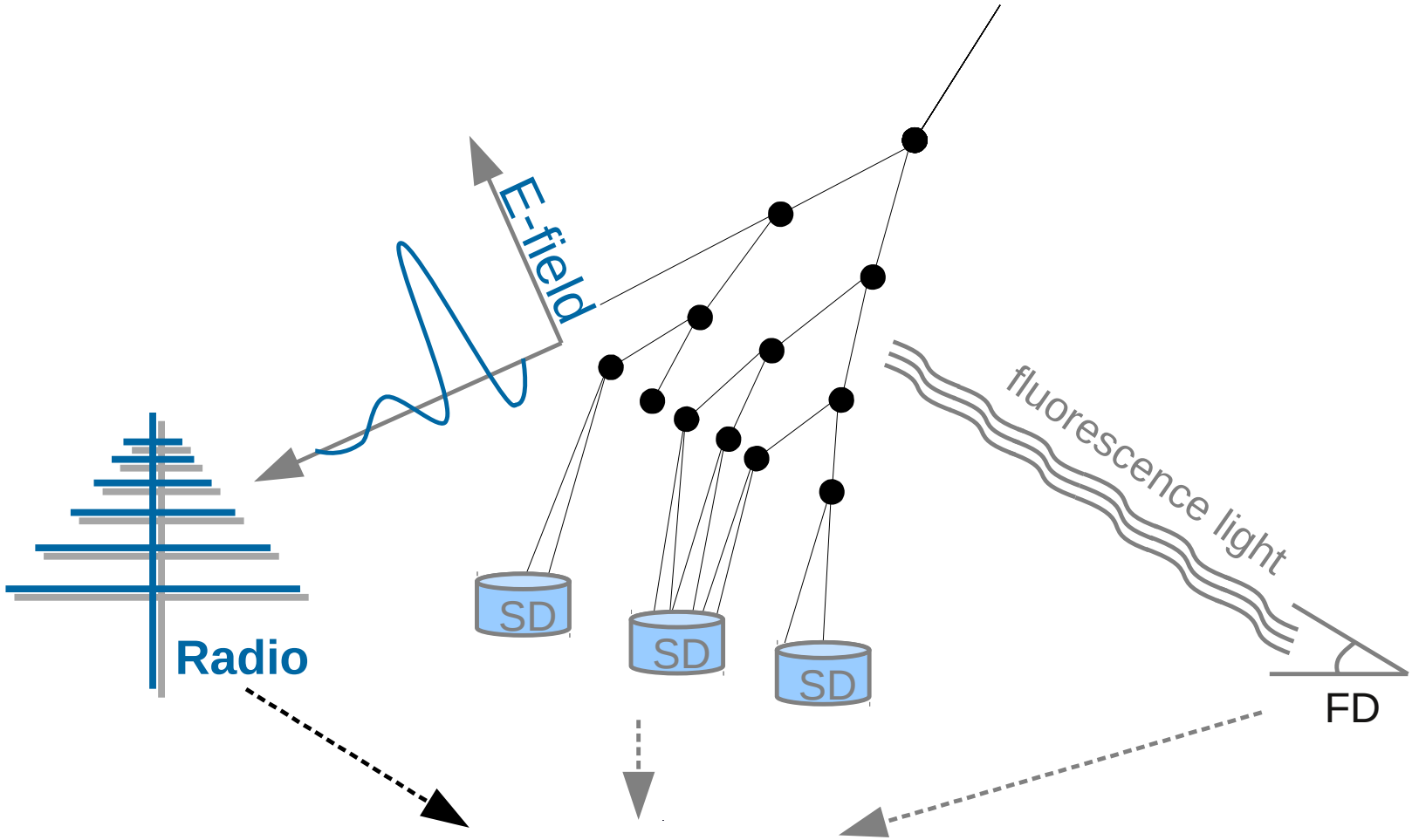
Simulated spherical shower front for measured air shower signals

**Differences in time with respect to plane wave are resolvable**



Auger Engineering Radio Array

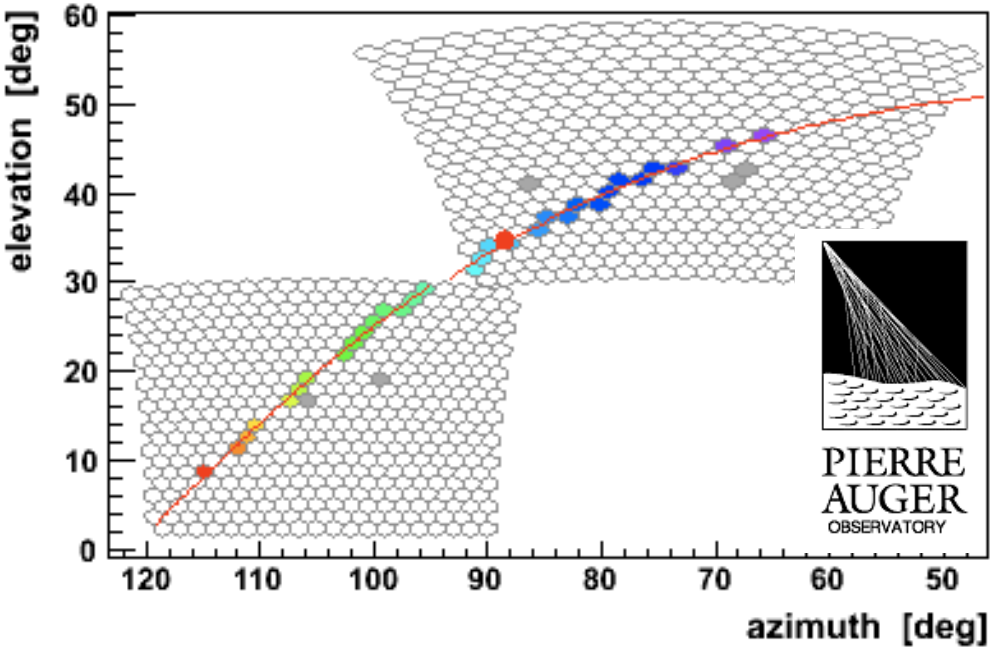
## complementary techniques to observe air showers:
## cross calibration between techniques

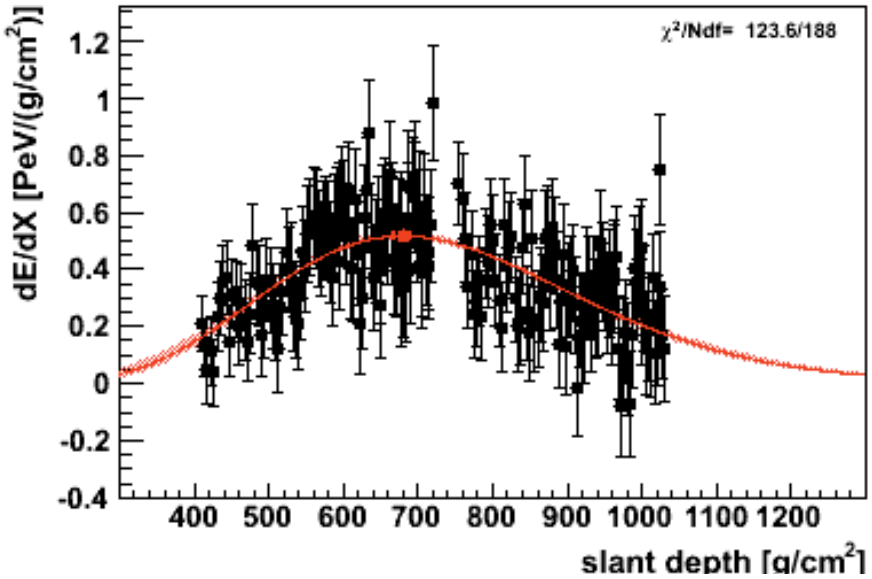



**shower properties:** energy, mass, direction

# Air shower measured in

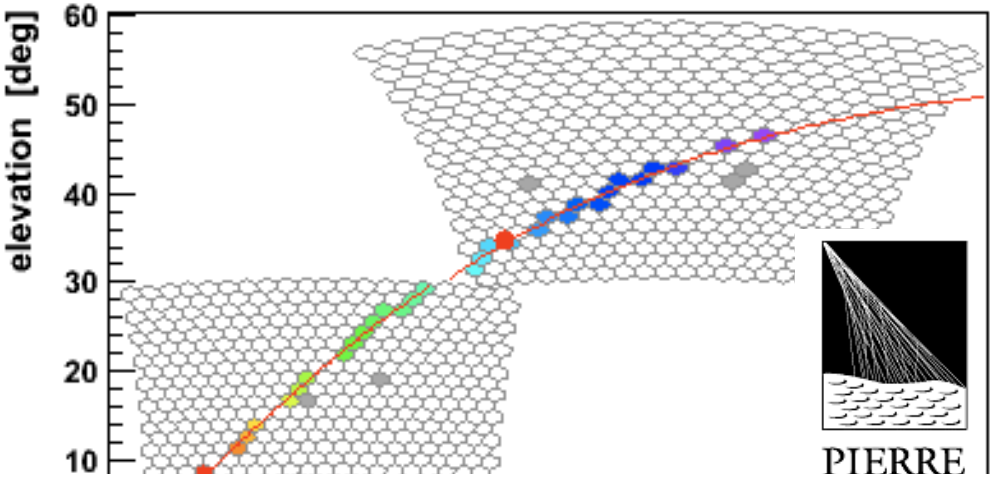
## fluorescence light

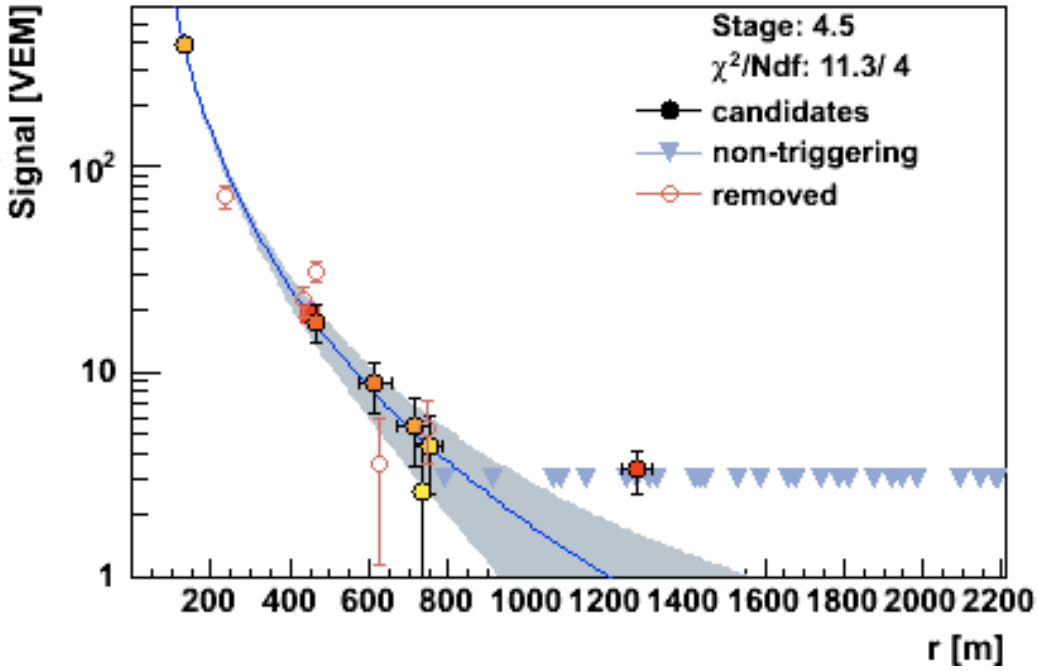


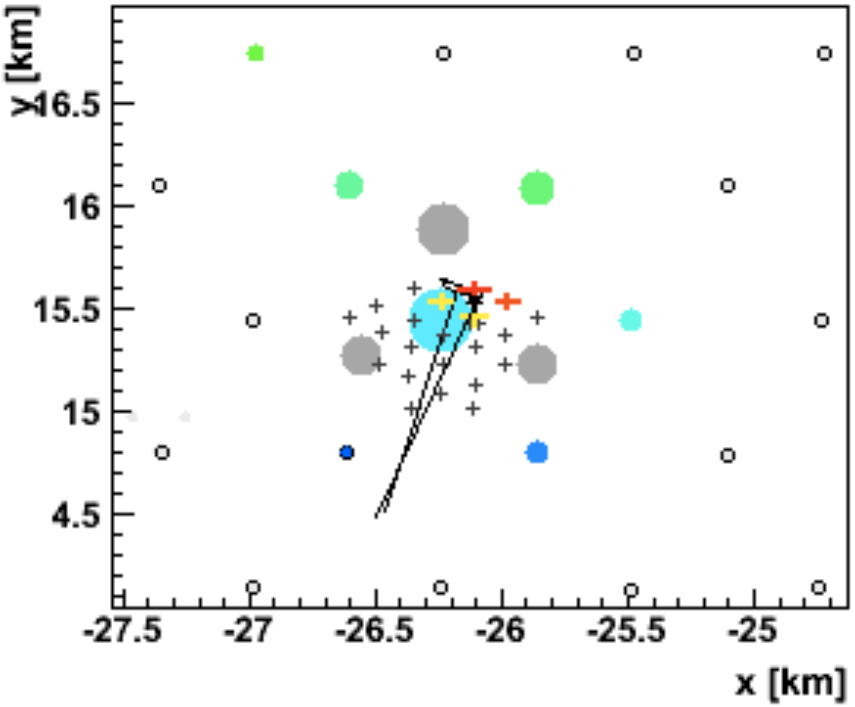
# Air shower measured in

## fluorescence light



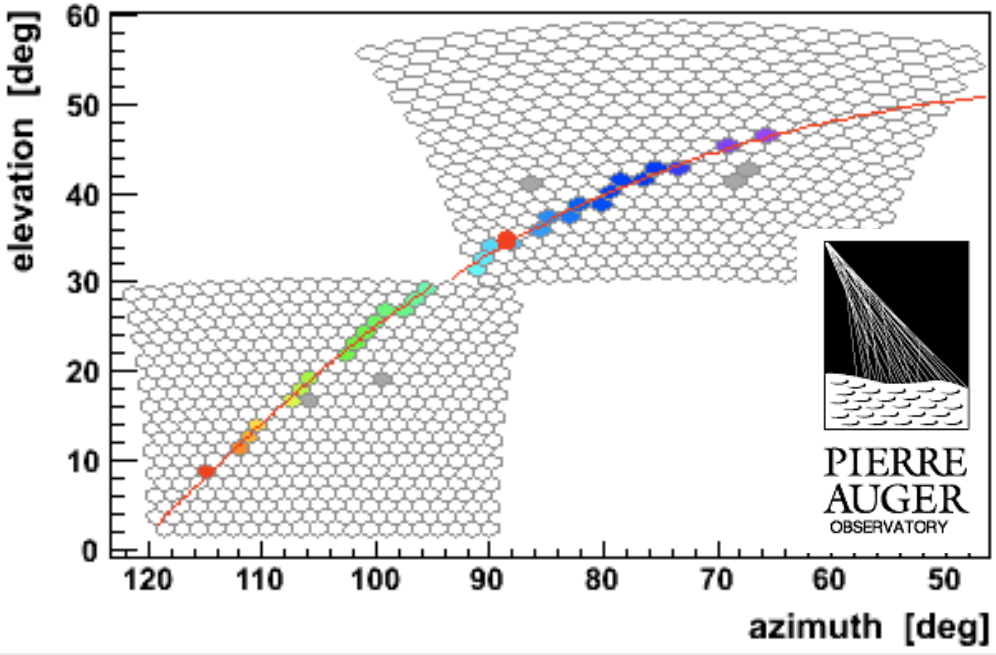




## water Cherenkov detectors

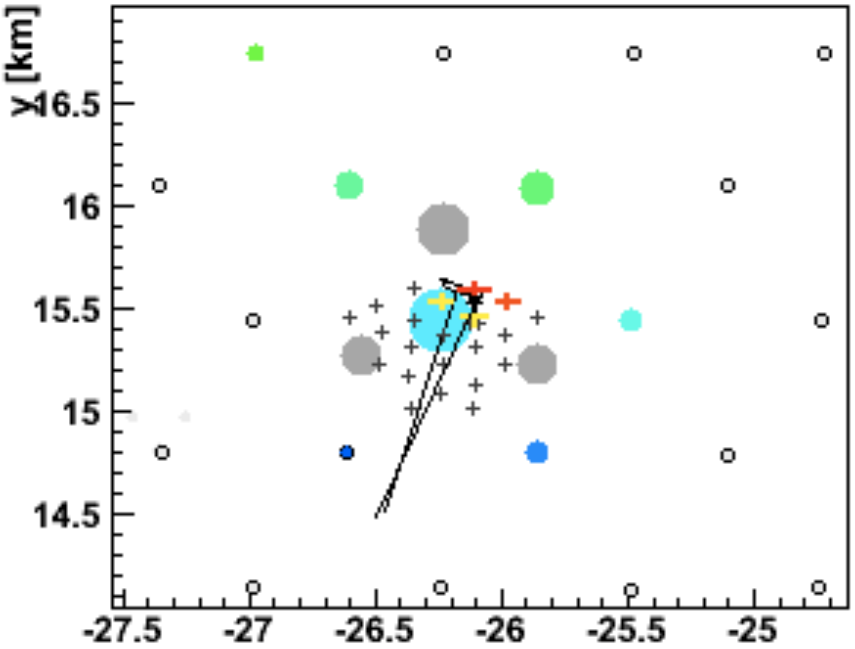


# Air shower measured in

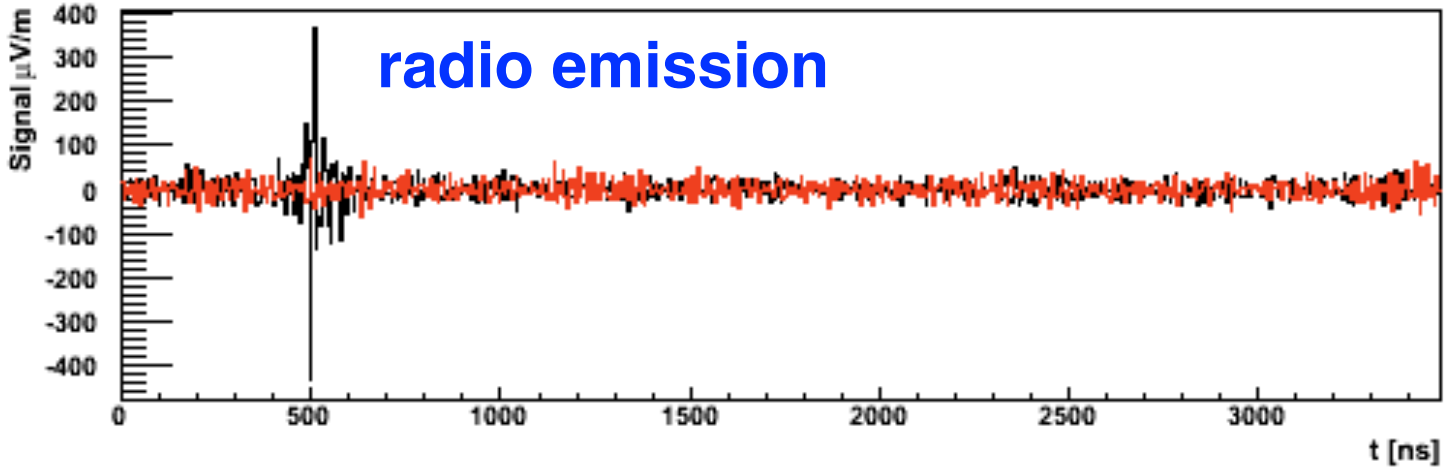
## fluorescence light



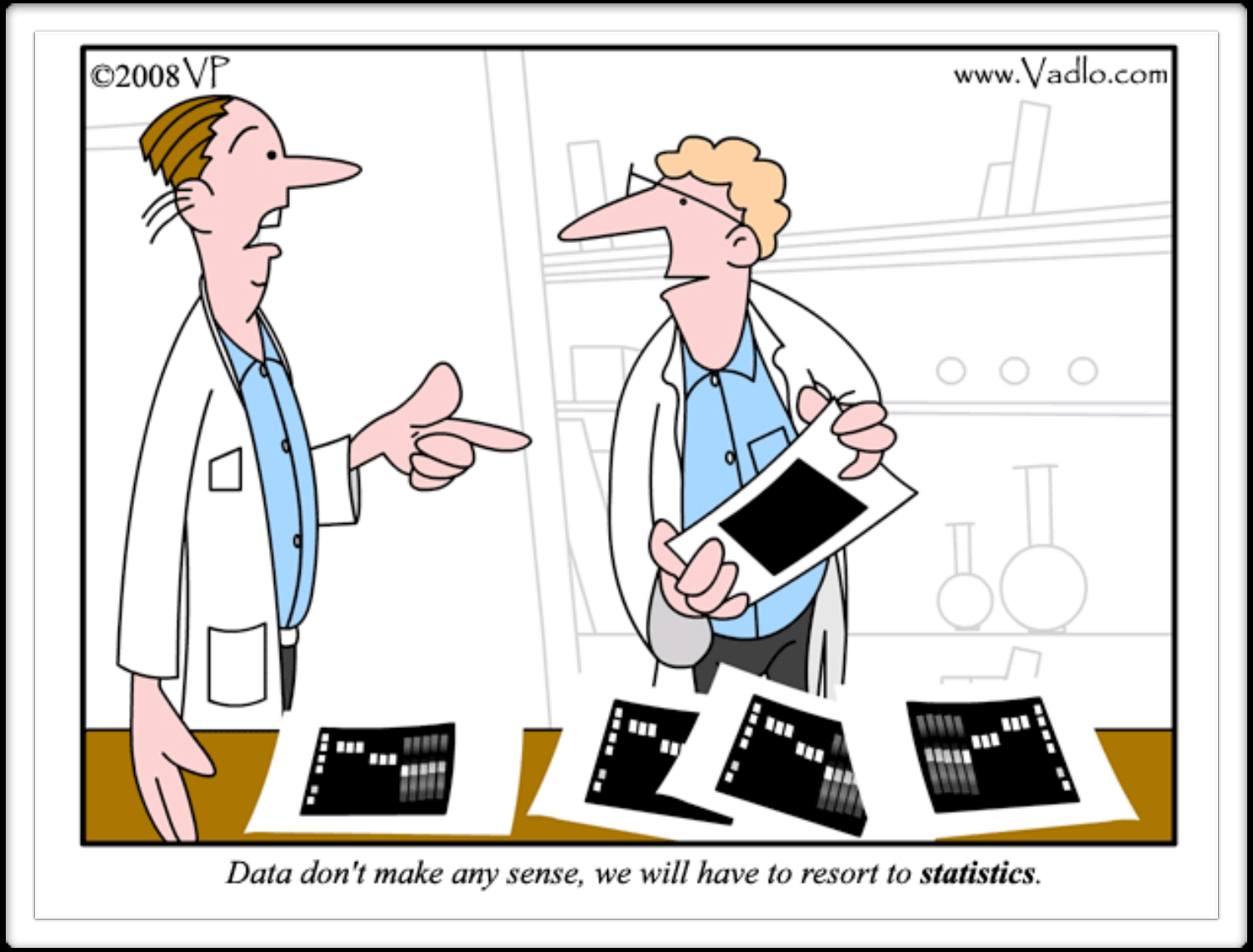

## water Cherenkov detectors



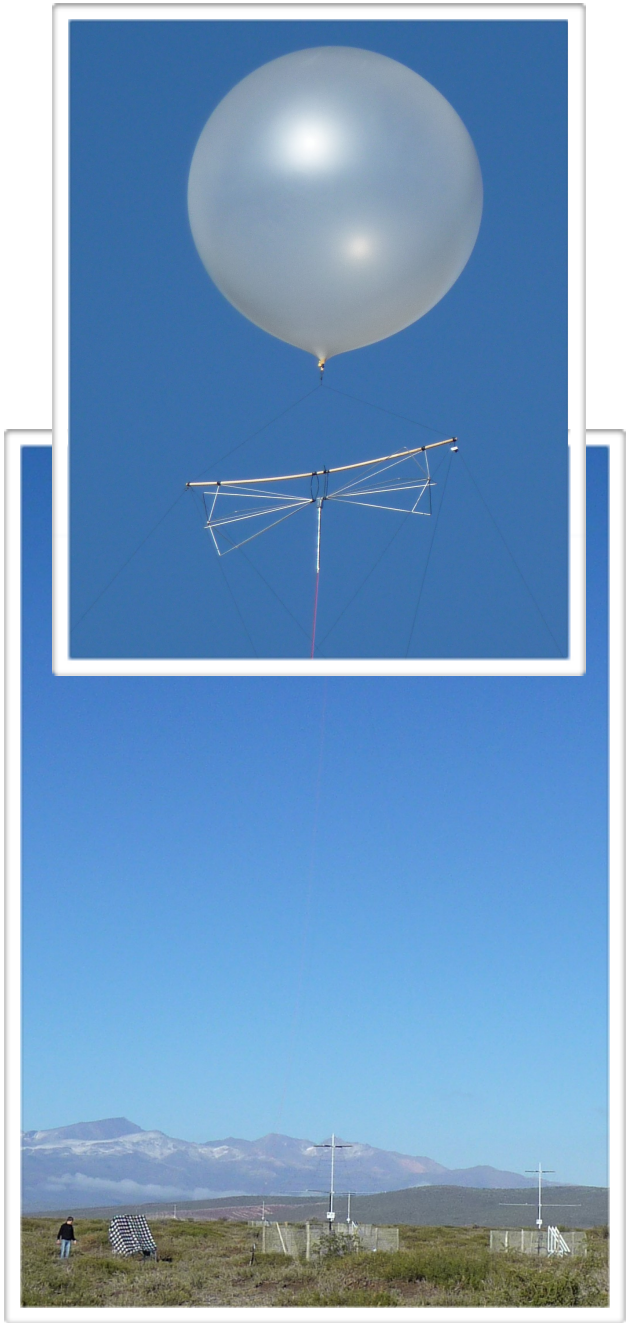

## radio emission



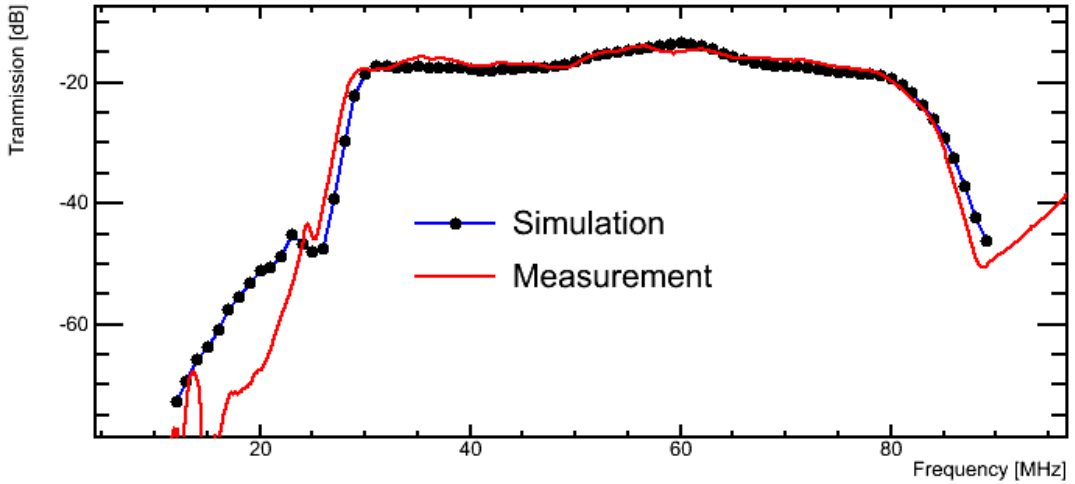
# Calibration & Data Analysis

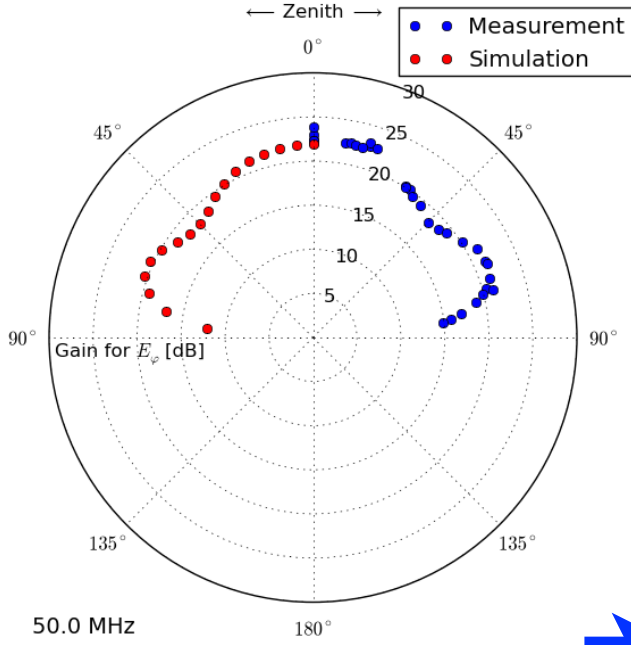


# In-situ calibration



## frequency dependent antenna gain




## horizontal gain

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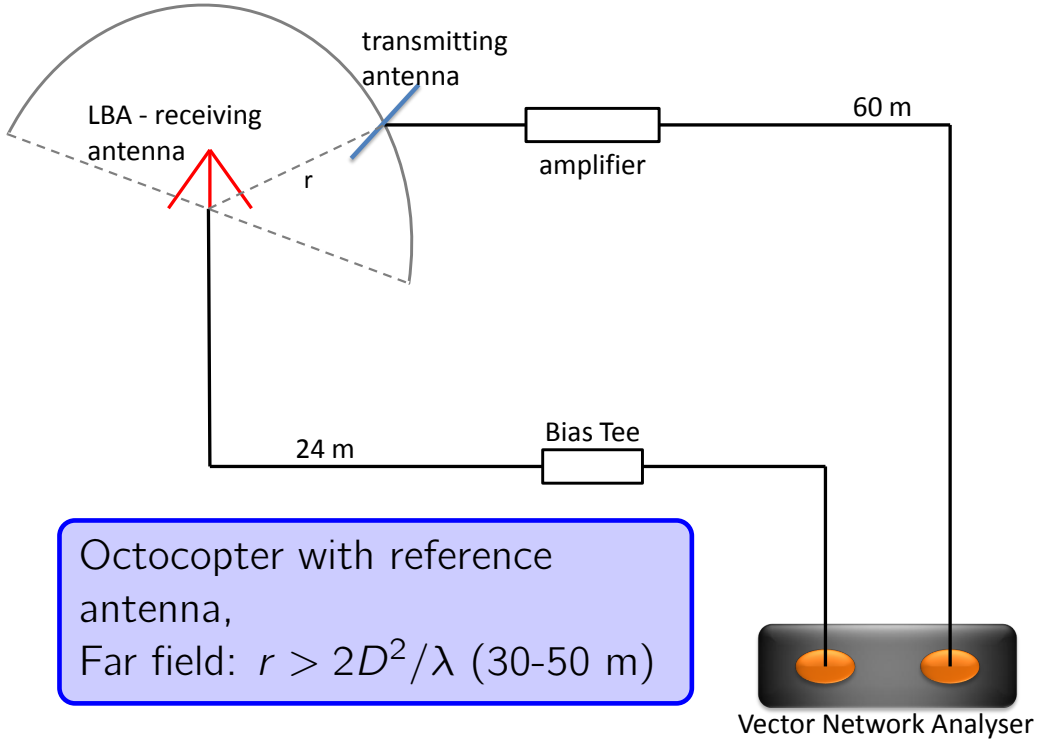
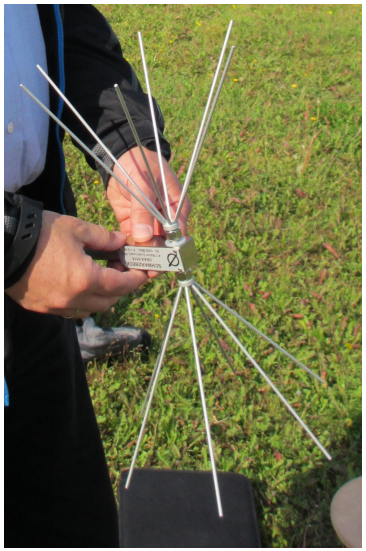
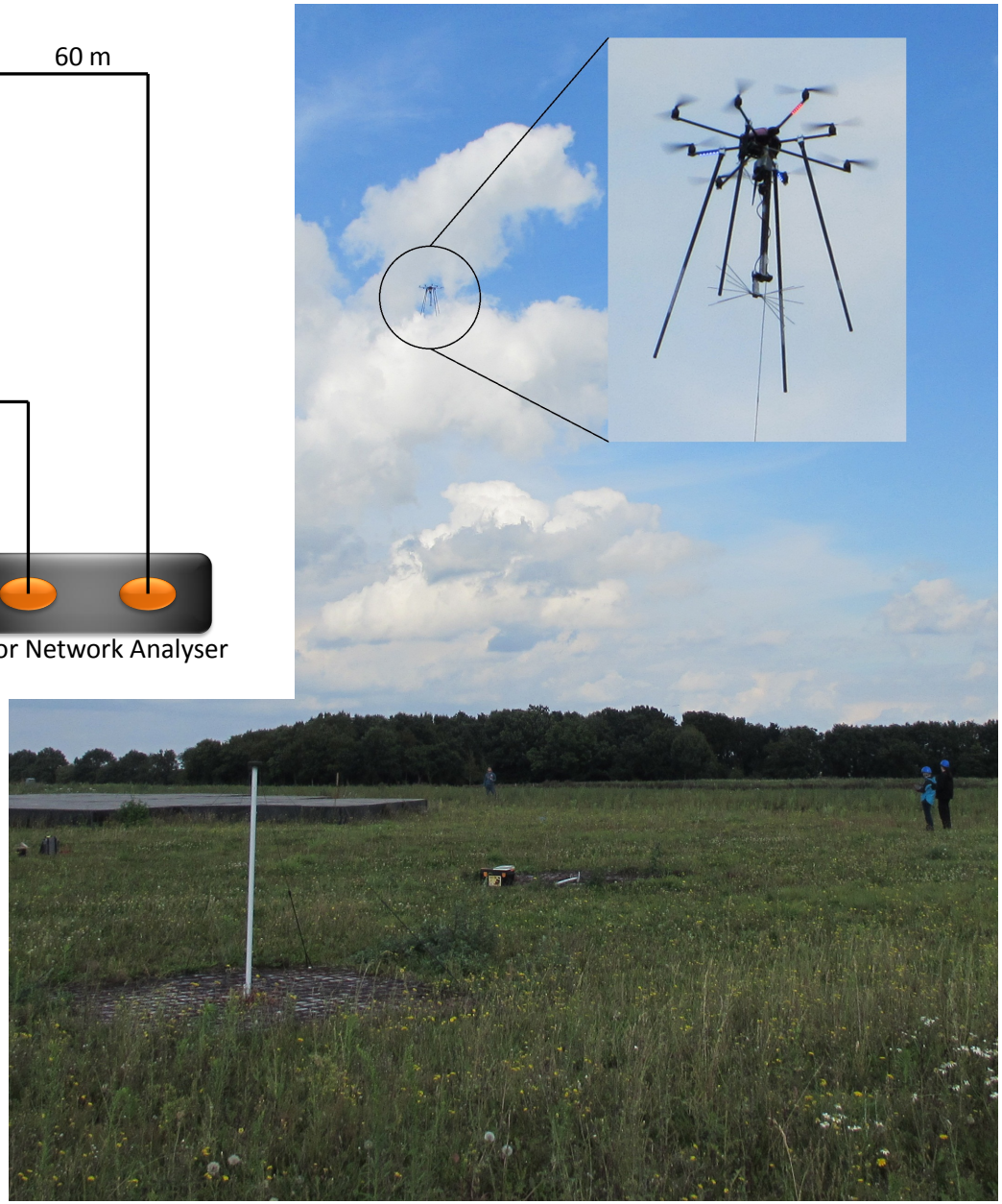
# In-situ calibration of the antennas




Octocopter with reference antenna,
Far field: $r > 2D^2/\lambda$ (30-50 m)







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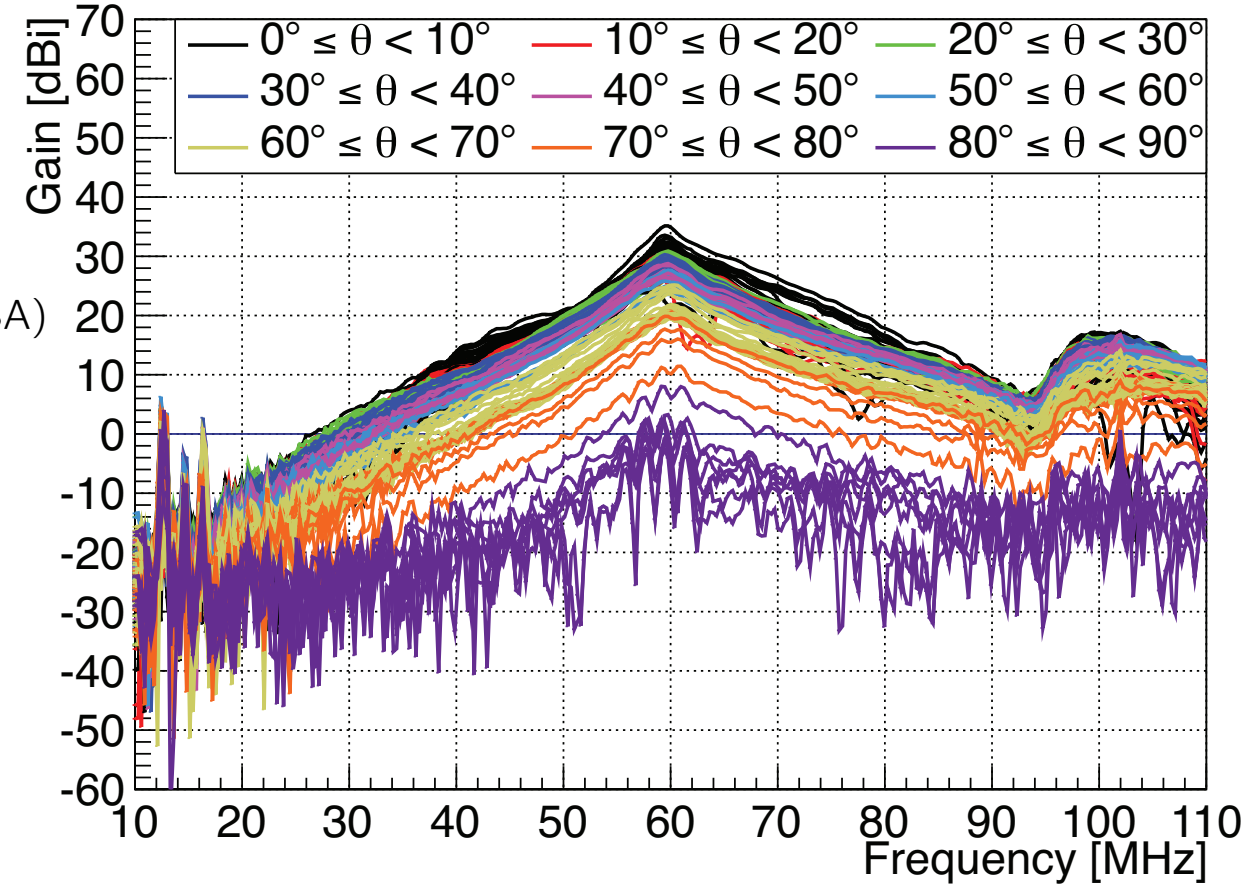
# In-situ calibration of the antennas

**Friis transmission equation**

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 G_r G_t$$

$P_r$ - Power of receiver
$P_t$ - Power of transmitter
$\lambda$ - Wavelength
$G_t$ - Gain of transmitting antenna
$R$ - Distance between antennas
$G_r$ - Gain of receiving antenna (LBA)



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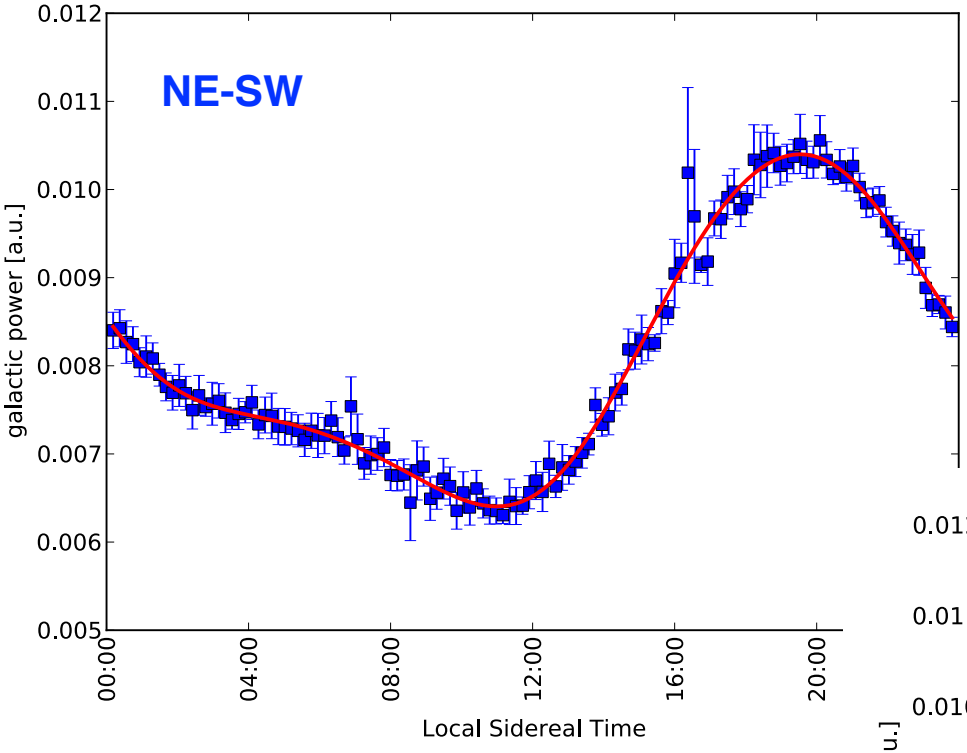
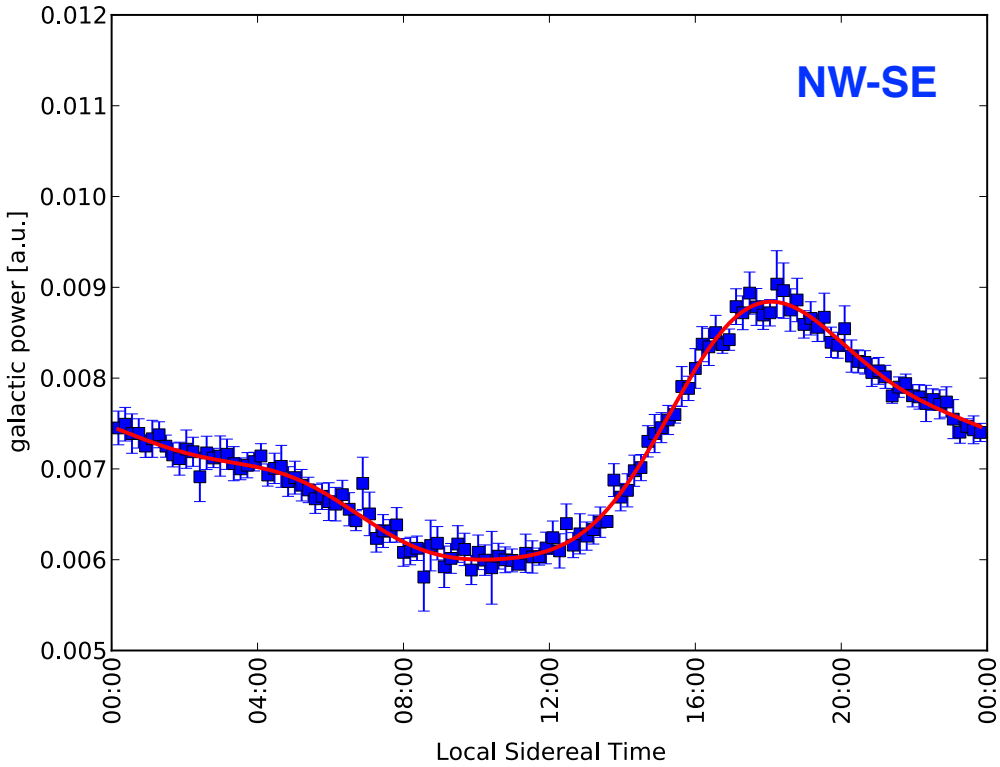
# Integrated spectral power vs. local siderial time

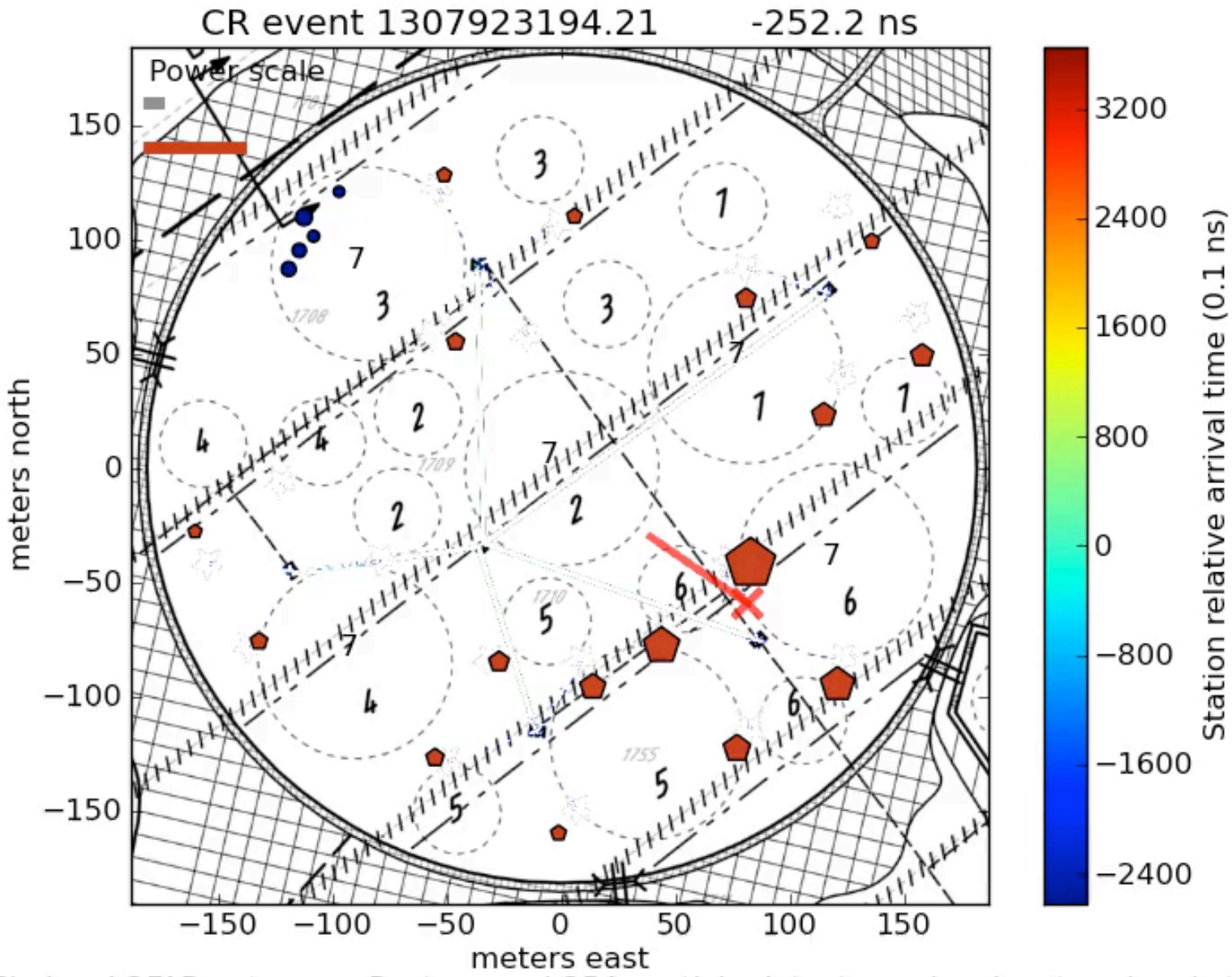



**background dominated by Galactic emission**

# Lateral Distribution

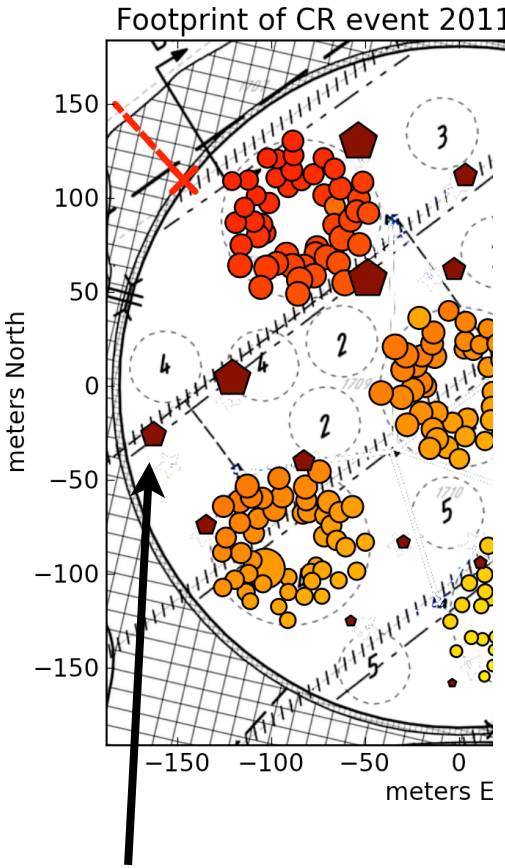
# A measured air shower



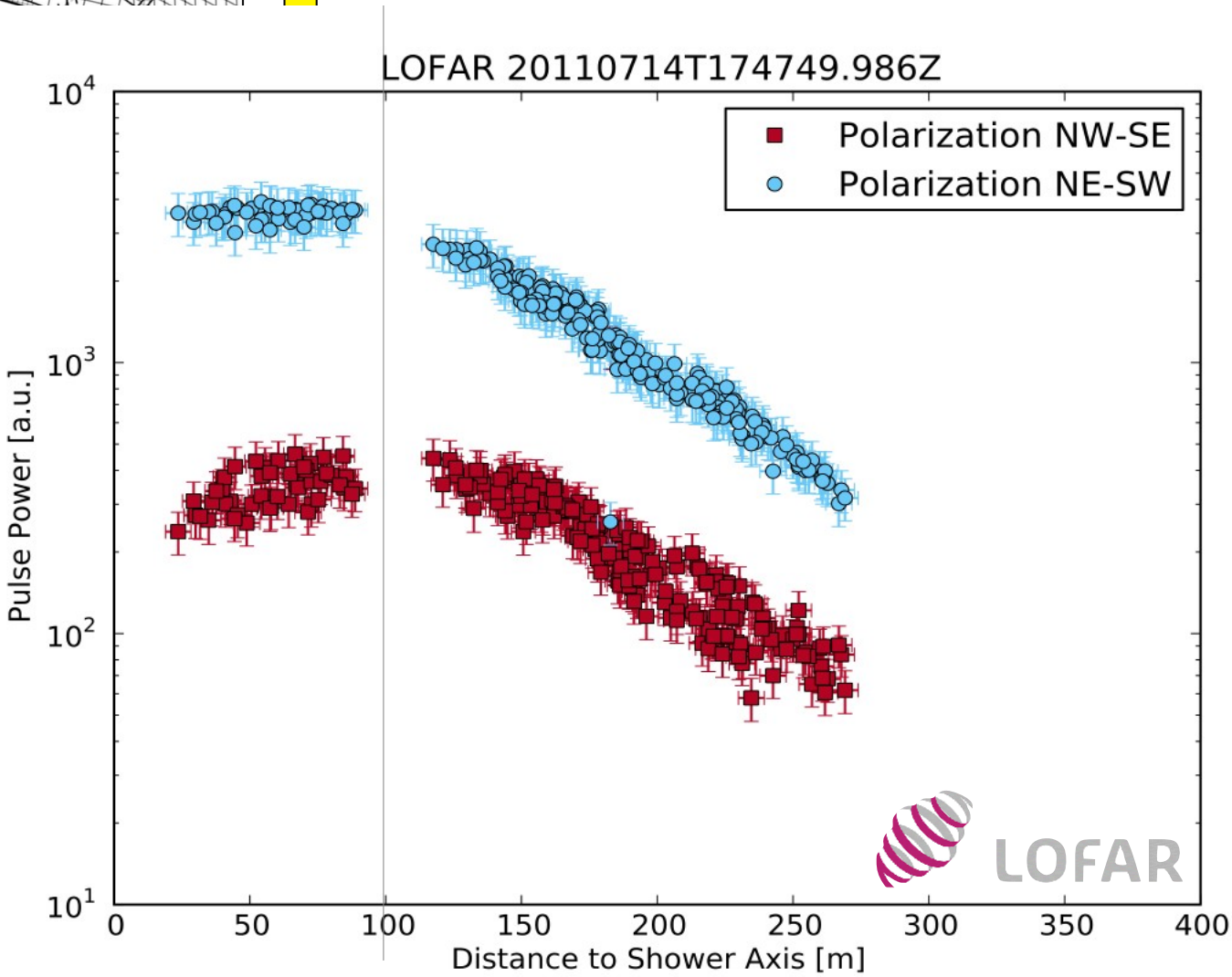

Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

# A measured air shower

## lateral distribution

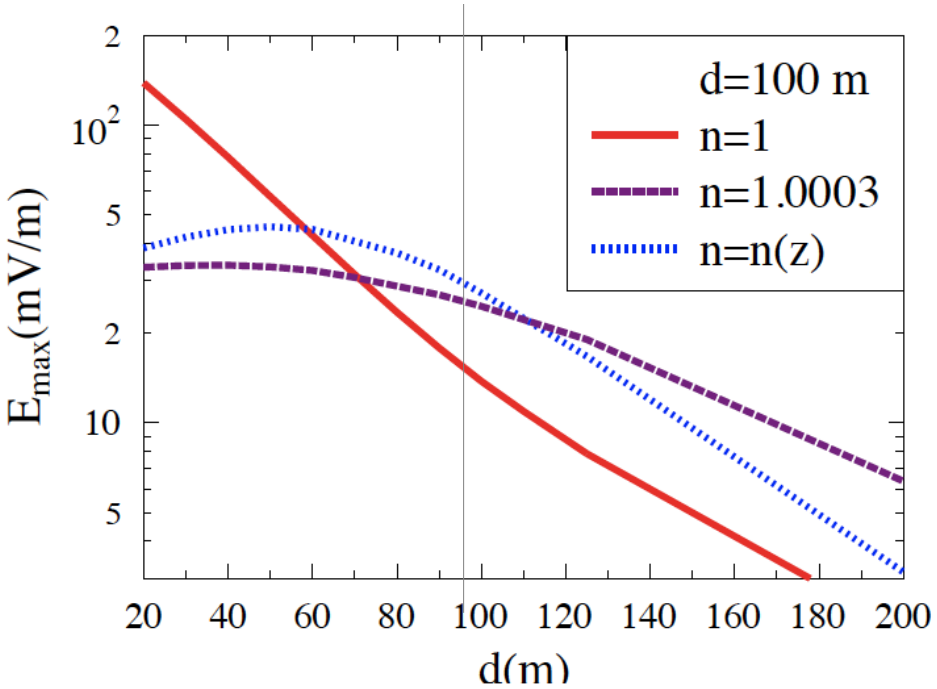



scintillation detector



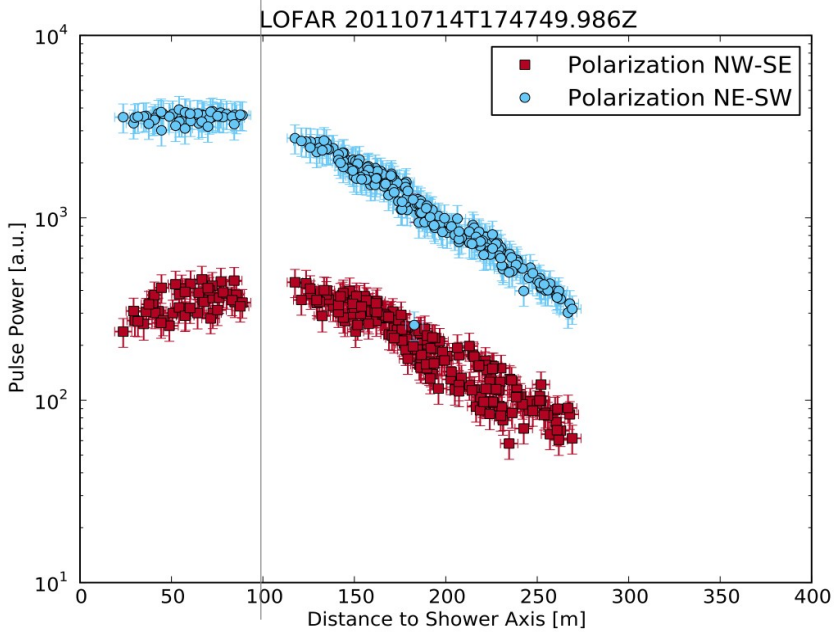
# Measured lateral distribution of radio signal

100 m




prediction (Scholten et al.)

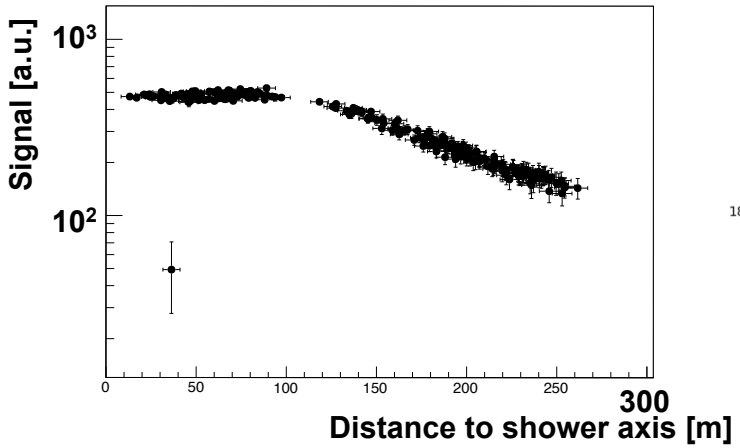
100 m

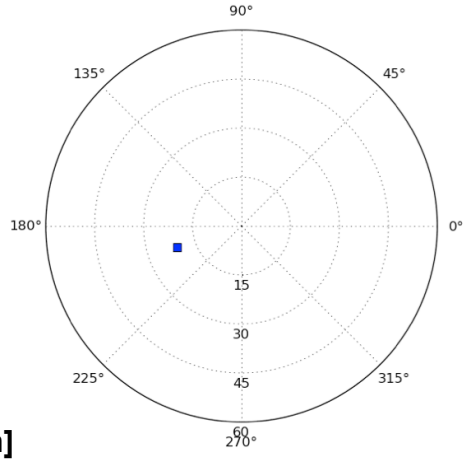


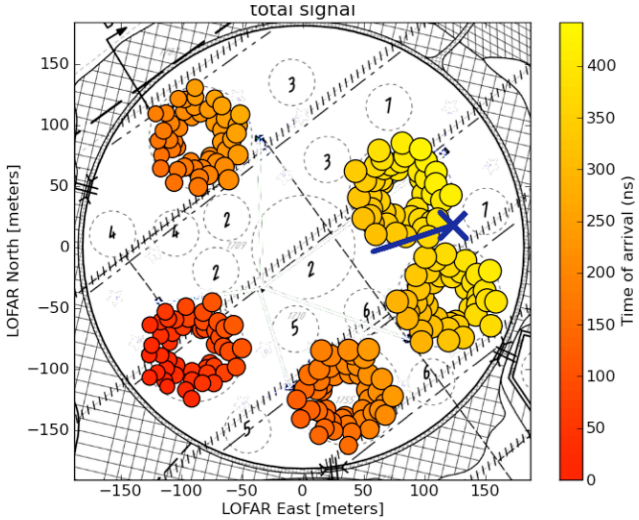

K. de Vries et al., PRL 107 (2011) 061101

LOFAR

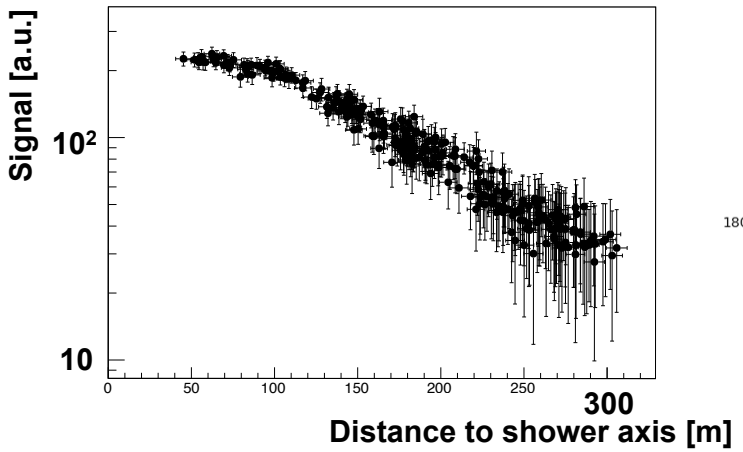
# Measured air showers

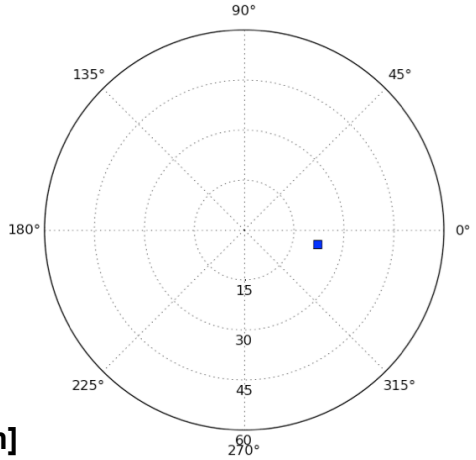


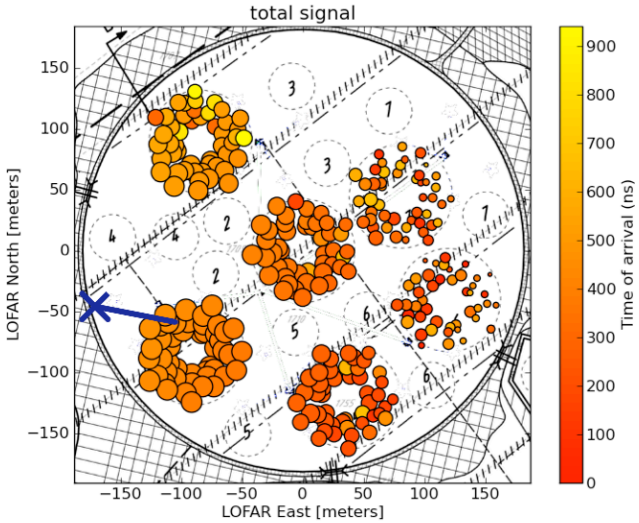




Energy: 1.2 x $10^{17}$ eV




Energy: 3.5 x $10^{16}$ eV

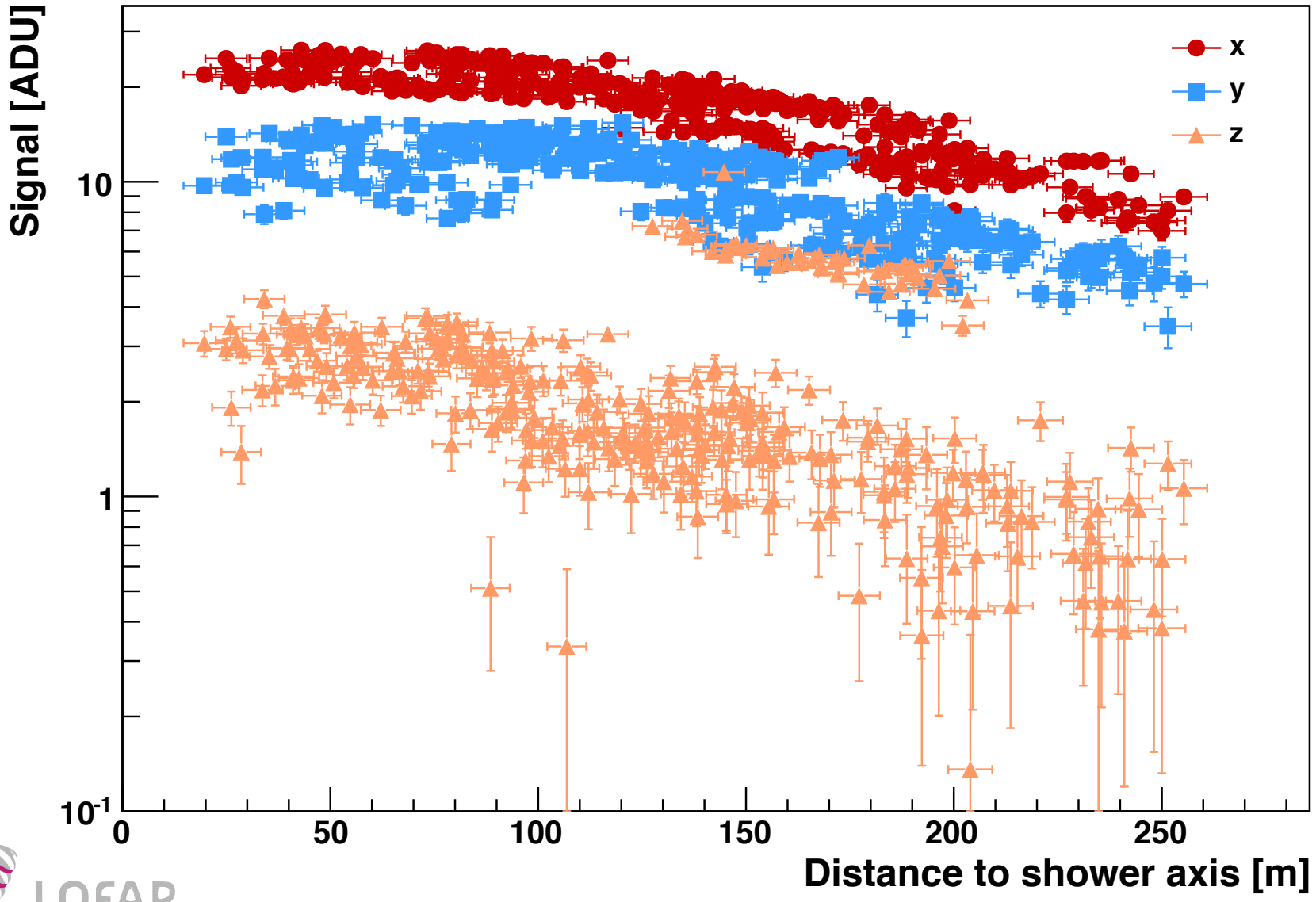
LOFAR

Energy uncertainty from LORA: ~ 30% per event

A. Nelles

# Lateral distribution in 3 polarization components

## A measured air shower




LOFAR



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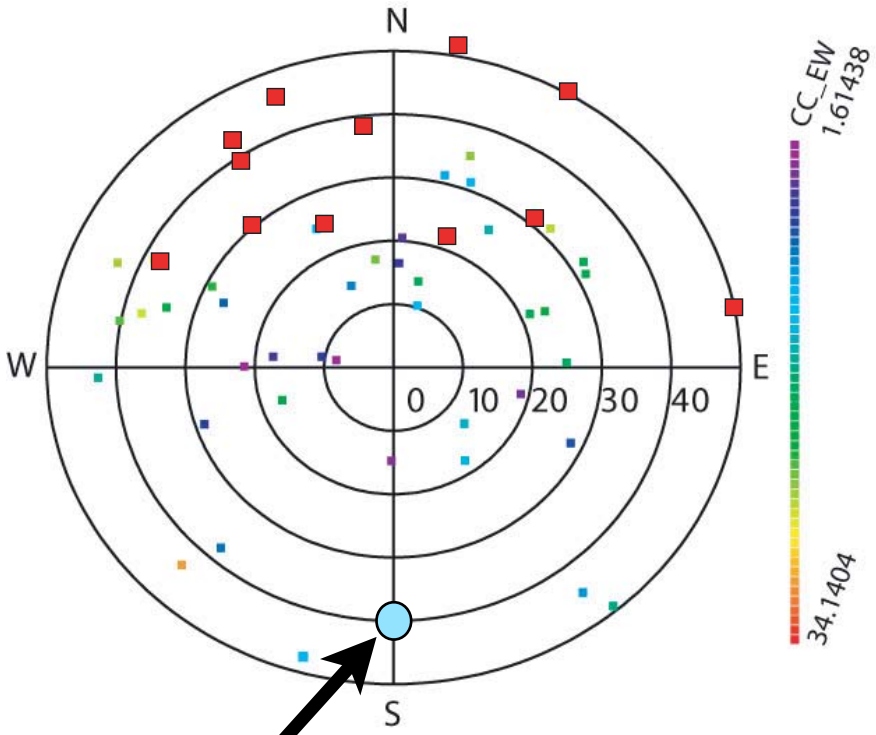
# Polarization

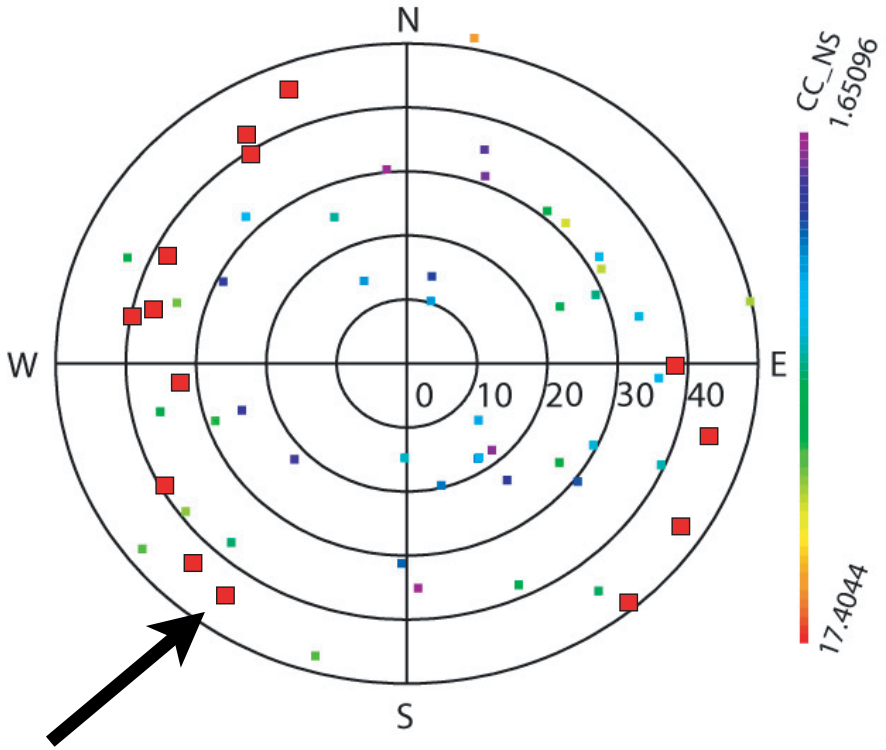
# Geosynchrotron component

**arrival direction of cosmic rays (sky map)**

## E-W polarization




## N-S polarization



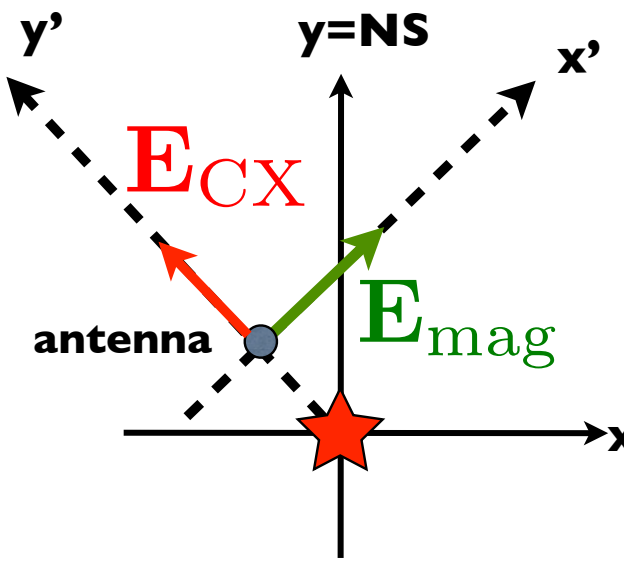

**strongest events**

**magnetic field**
**inclination: 64° 36‘**
**declination: 1° 22‘**

**v x B effect**
**synchrotron radiation dominates signal**

P.G. Isar et al., Nucl. Instr. & Meth. A 604(2009) S81

# Charge excess component

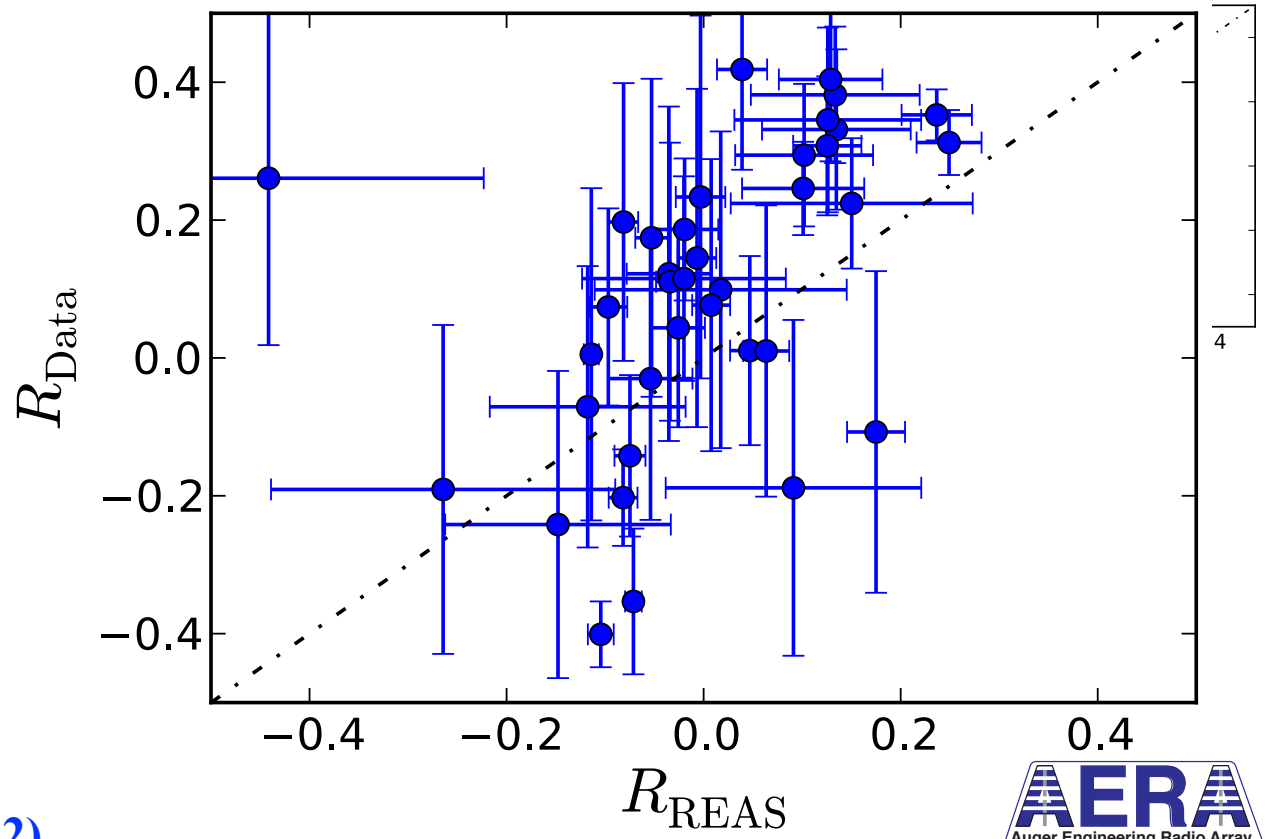



in (x',y'), define:

$$R = \frac{\sum_{i=1}^{N} E_{x'}(t_i)\, E_{y'}(t_i)}{\sum_{i=1}^{N} E_{x'}^2(t_i) + E_{y'}^2(t_i)}$$

if no charge excess: R=0 compare $R_{data}$ and $R_{sim}$

| $\chi^2$/dof values |
|---|
| MGRM |
| REAS |




A. van den Berg, UHCRE (2012)

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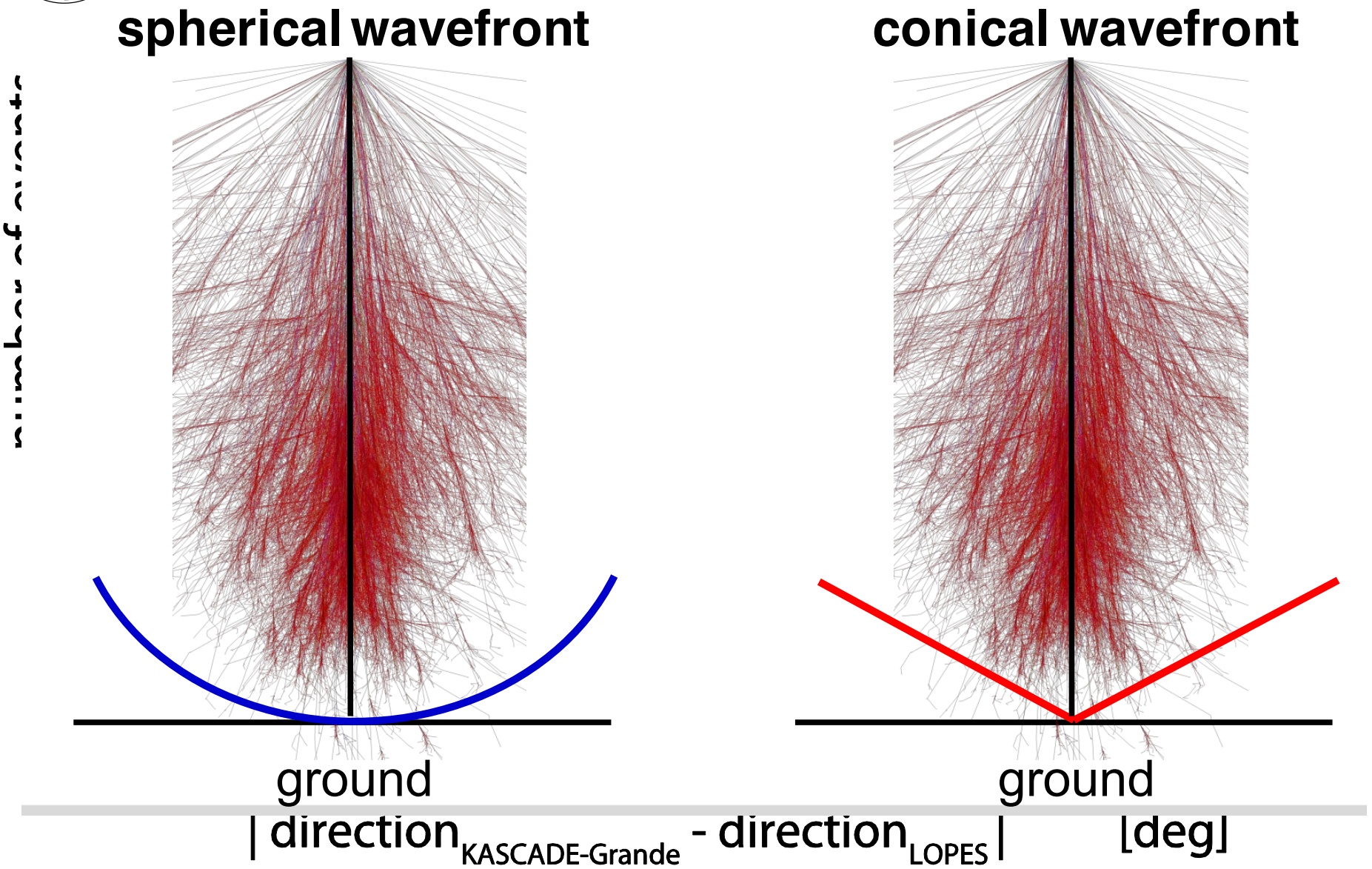
# Direction

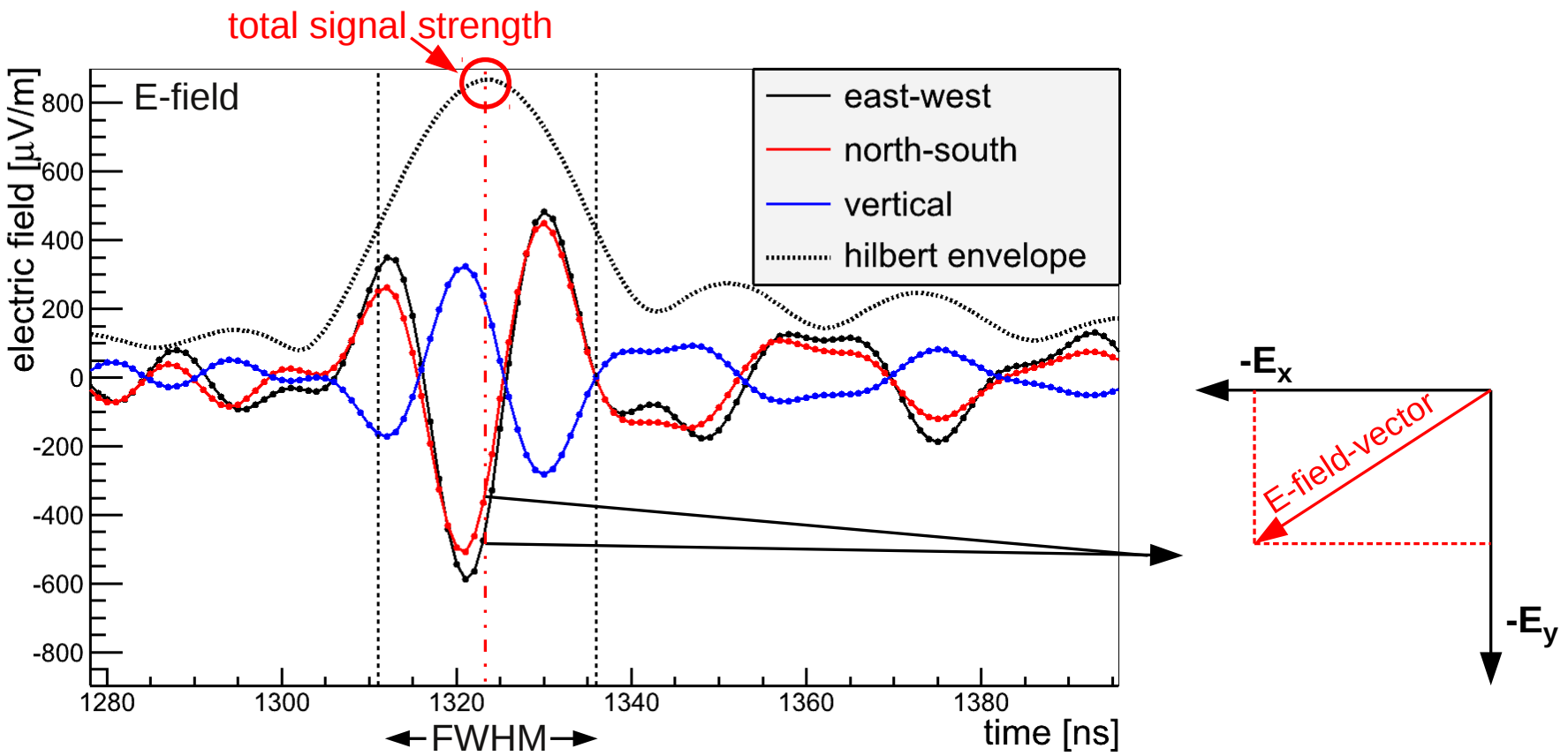
# LOPES: direction of shower




F. Schröder, ARENA (2012)

# Energy

# AERA: direction of E field vector




C. Glaser, ARENA (2012)

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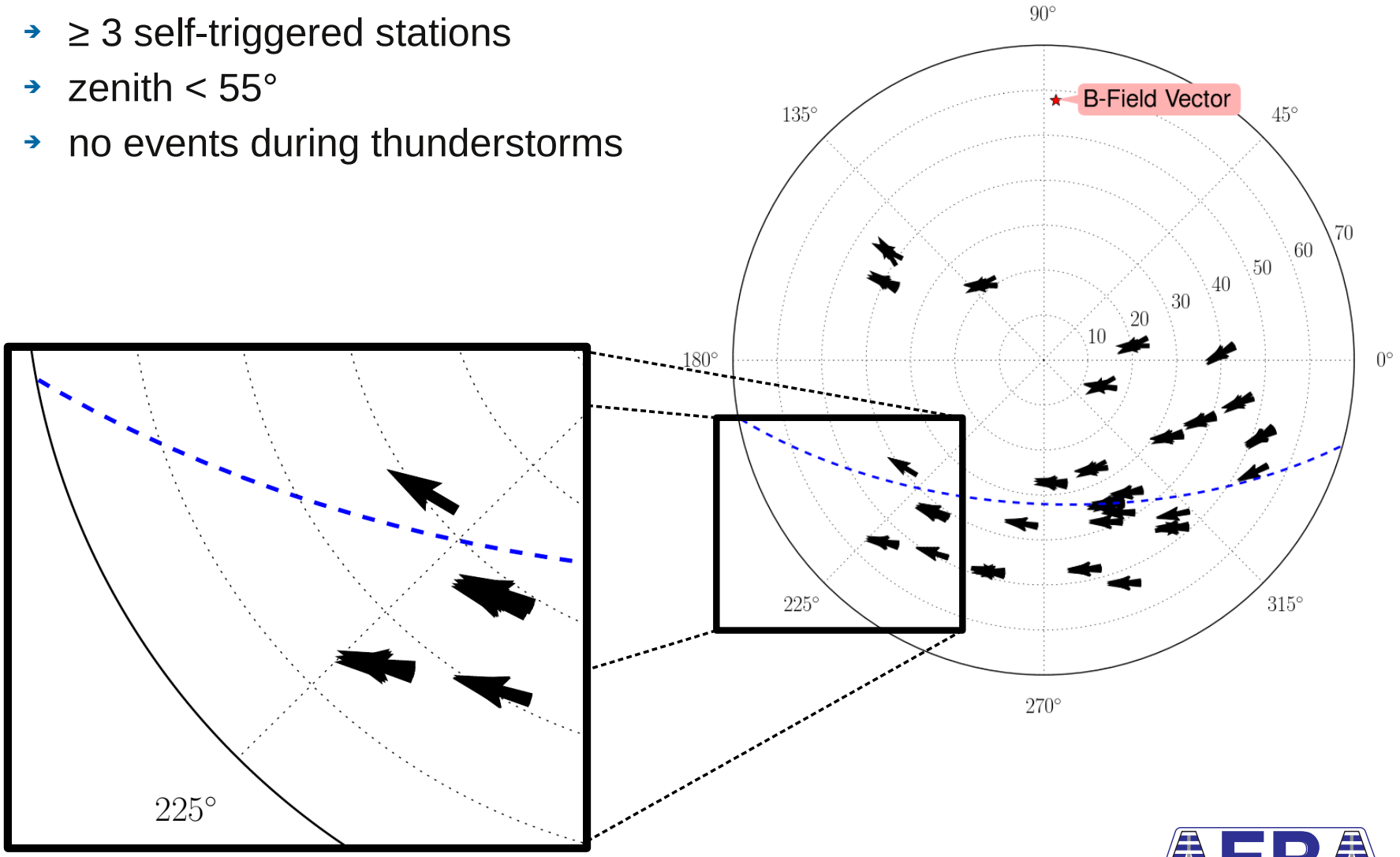
# AERA: direction of E field vector

- event selection:
  - ≥ 3 self-triggered stations
  - zenith < 55°
  - no events during thunderstorms




C. Glaser, ARENA (2012)

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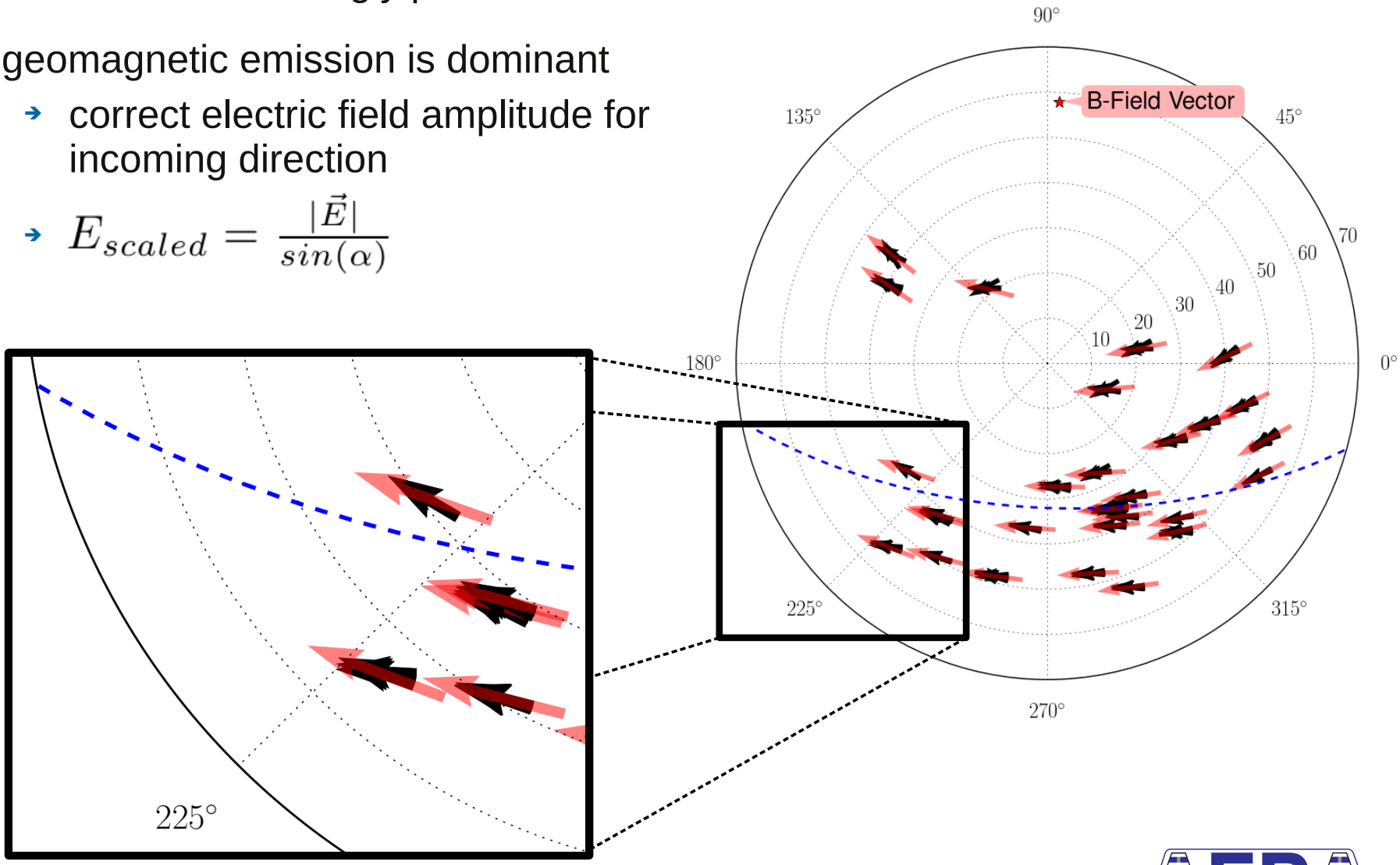
# AERA: measured vs. expected values

- electric field is strongly polarised
- geomagnetic emission is dominant
  - correct electric field amplitude for incoming direction
  - $E_{scaled} = \frac{|\vec{E}|}{sin(\alpha)}$




C. Glaser, ARENA (2012)

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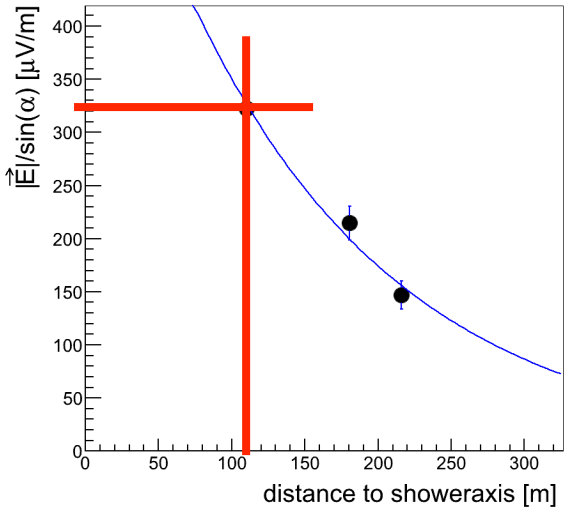
# AERA: energy correlation




$$E_{scaled} = \frac{|\vec{E}|}{sin(\alpha)}$$

$$E_{scaled} = A \cdot exp(D/R_0)$$

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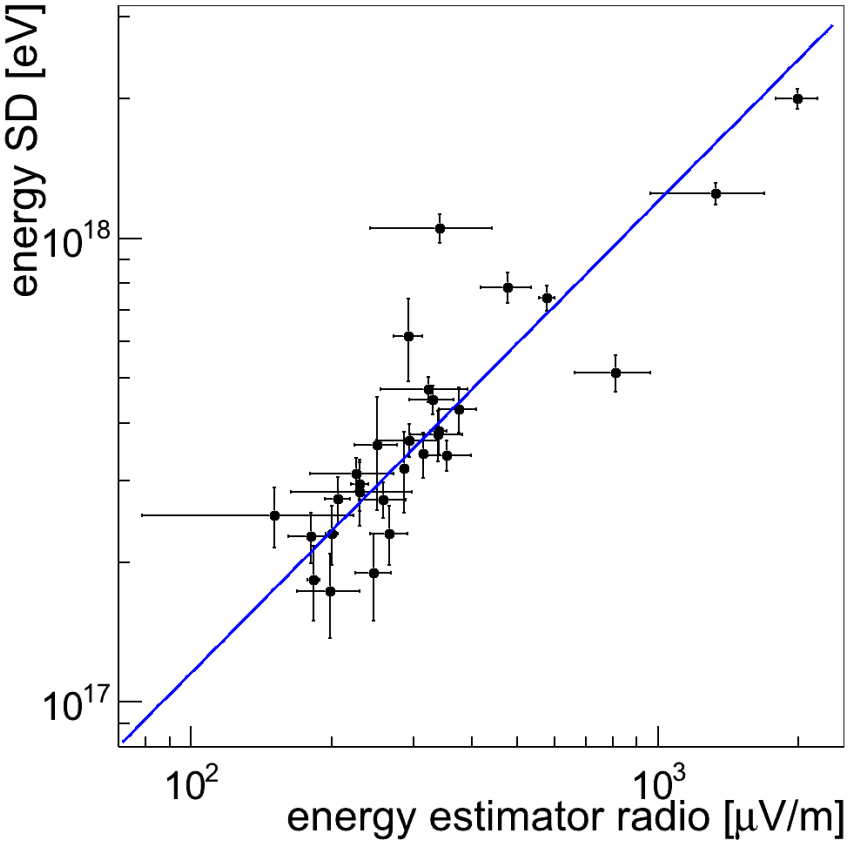
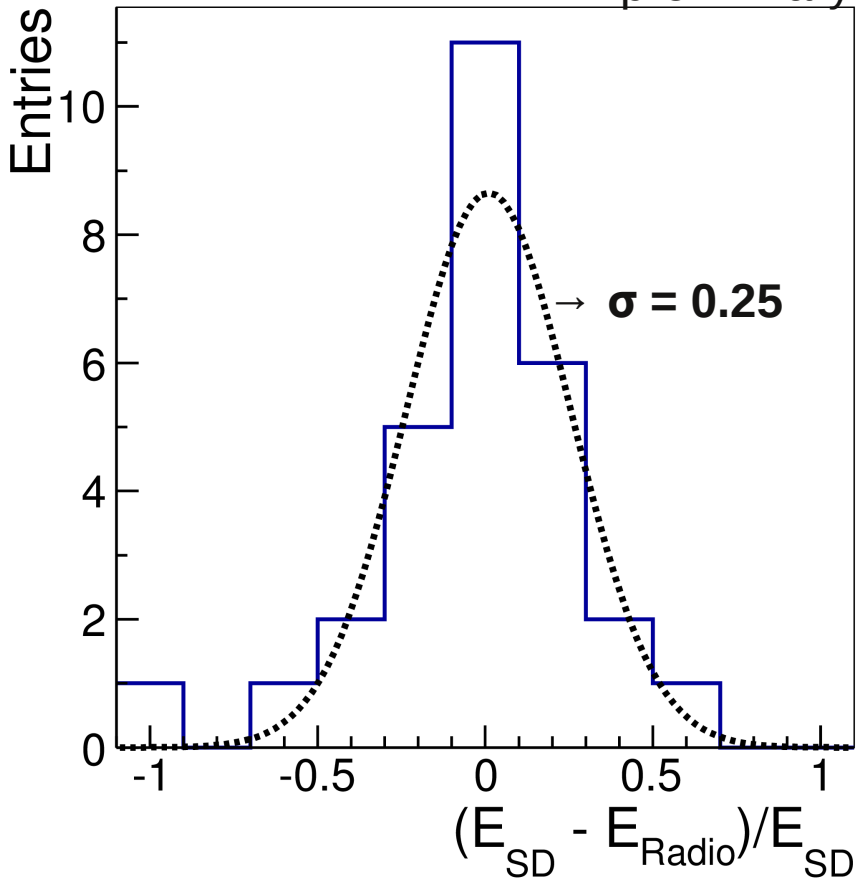
**energy resolution 25%**
**(incl. surface detector resolution)**

preliminary

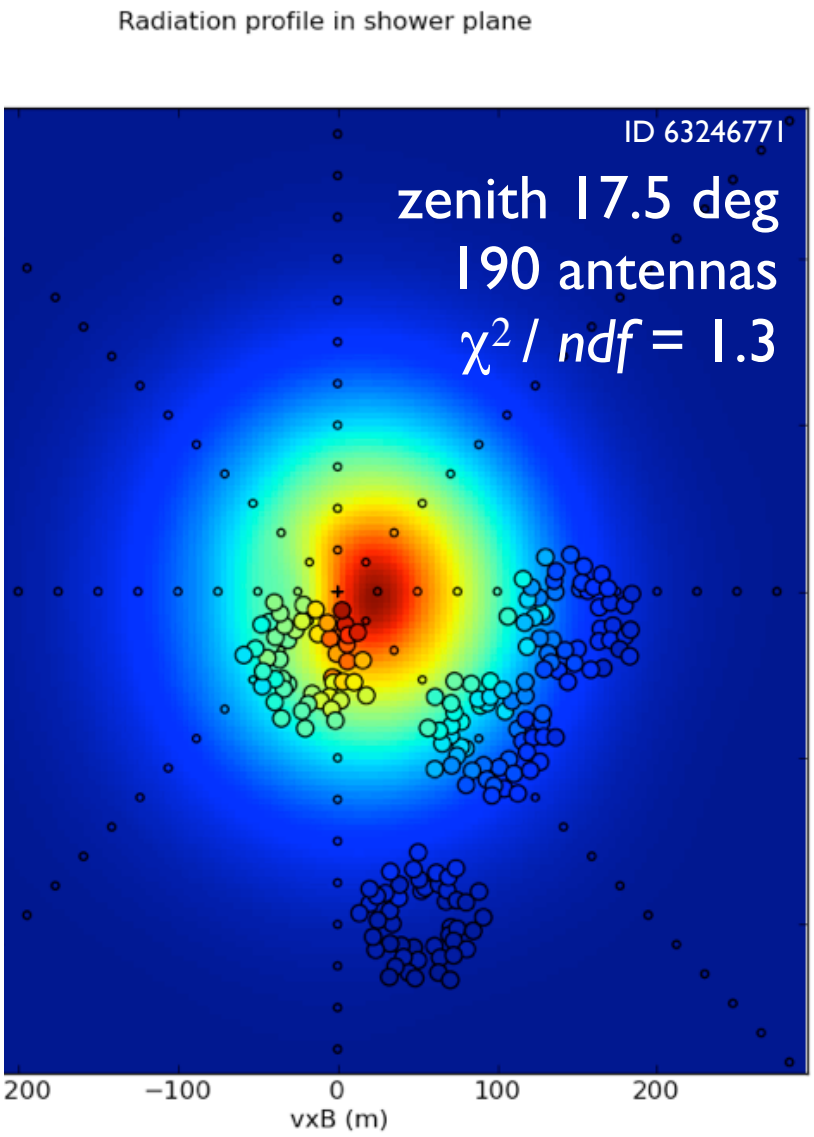


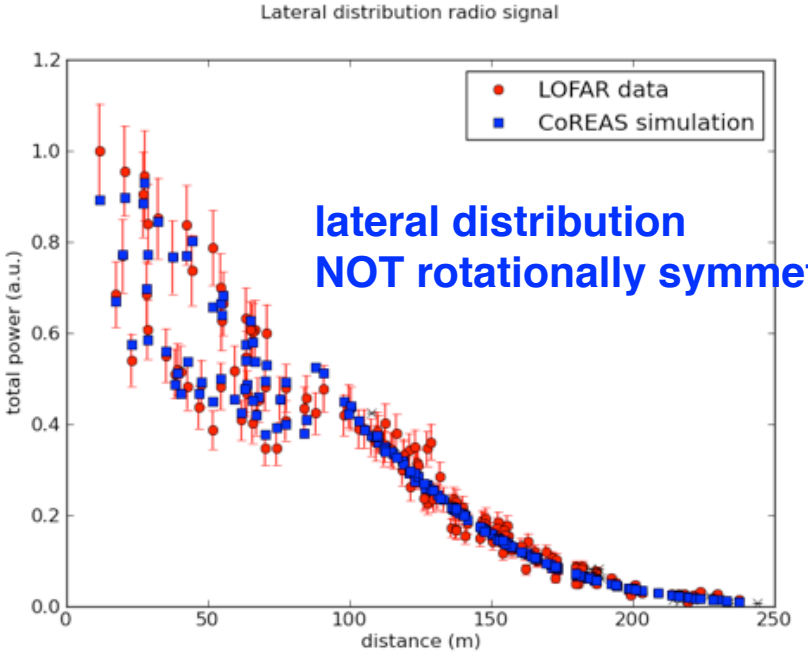



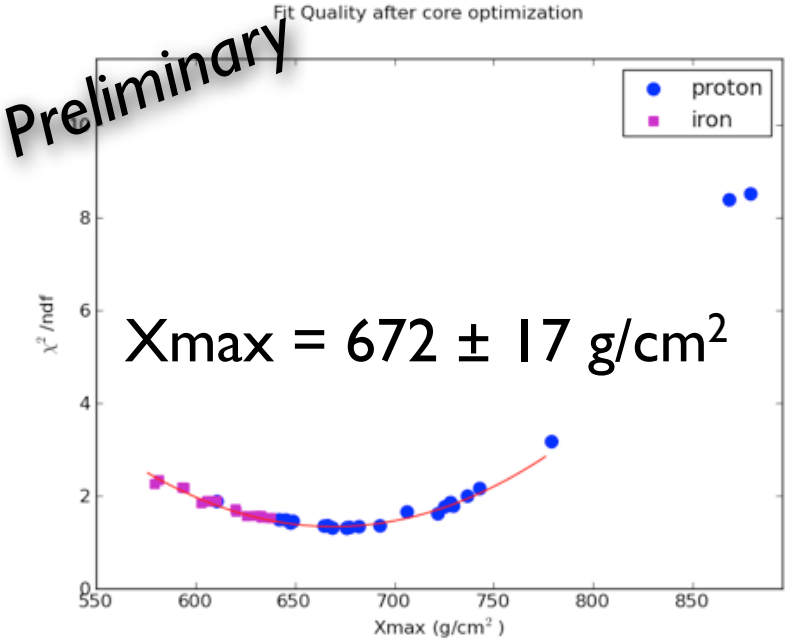

C. Glaser, ARENA (2012)

# Mass

# First measurement of Xmax with the radio technique




Stijn Buitink - ICRC 2013

## High energy γ rays

In addition to charged particles we obtain information on the high-energy Universe from γ-rays

$E \sim 100\,\mathrm{MeV} \longrightarrow 50\,\mathrm{TeV}$

## Production & interactions

1) synchrotron radiation of electrons in B fields


depending on the energy of electrons and strength of B field, the energy of photons ranges from radio (neV) to ~10 MeV

$E_\gamma \propto B^2 \cdot \gamma_e^2$ radiation is polarized



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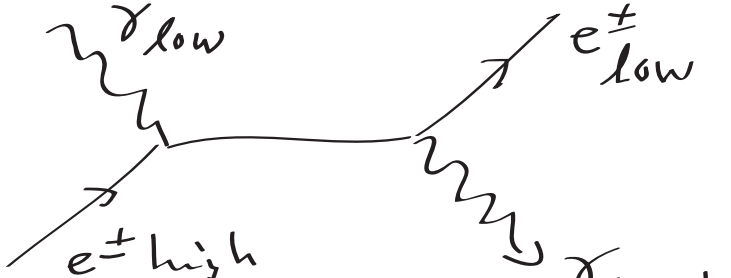
2) Inverse Compton Scattering




energy of electrons is transferred to photons

"heating of photons through electrons"

$E_\gamma \propto U_{rad} \cdot \gamma_e^2$

↑ temperature (kinetic energy) of photons

3) Hadronic interactions

$p + ISM \rightarrow \pi^0 + X$

$\hookrightarrow \gamma + \gamma$

requires presence of hadronic particles



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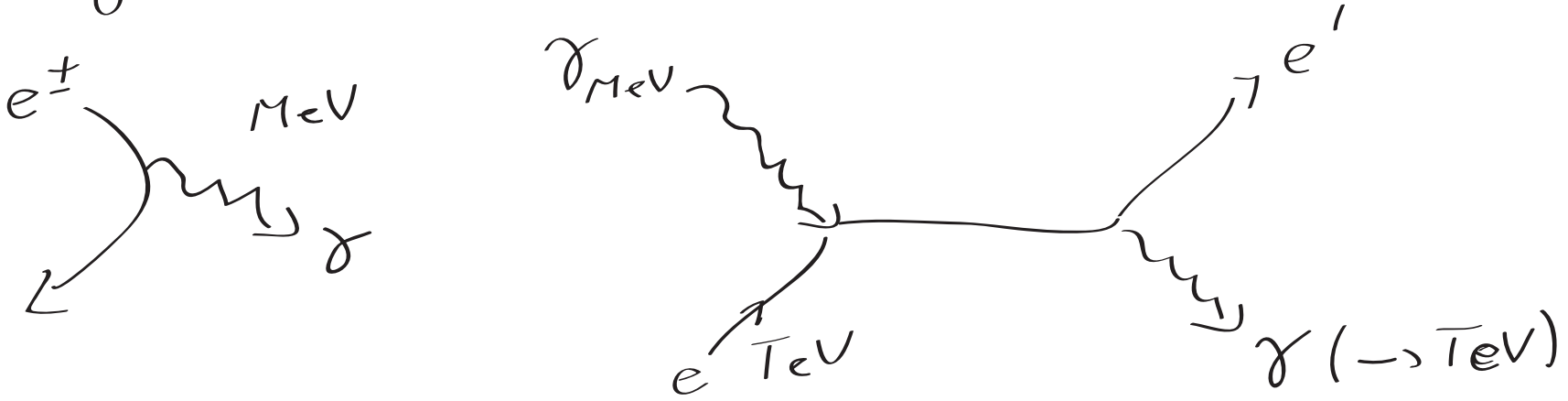
4) Bremsstrahlung

e + target → Bremsstrahlung

$E_\gamma \sim \frac{E_e}{2}$ (power law)

important combination of 1 & 2

synchrotron self Compton (SSC)




the photons for inverse Compton scattering are produced in situ



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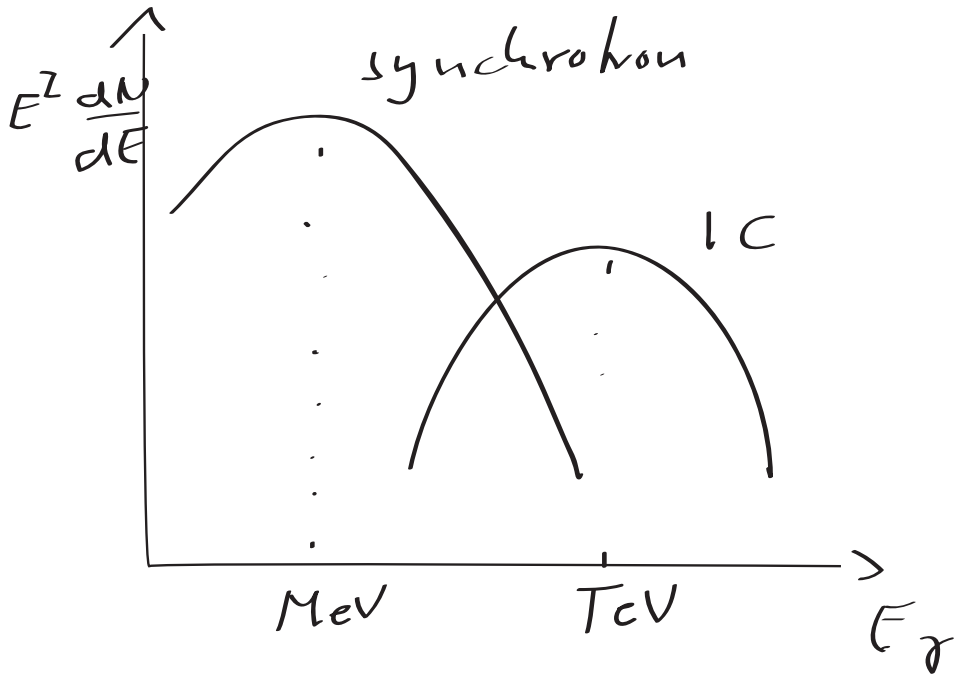
typical form of spectrum



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