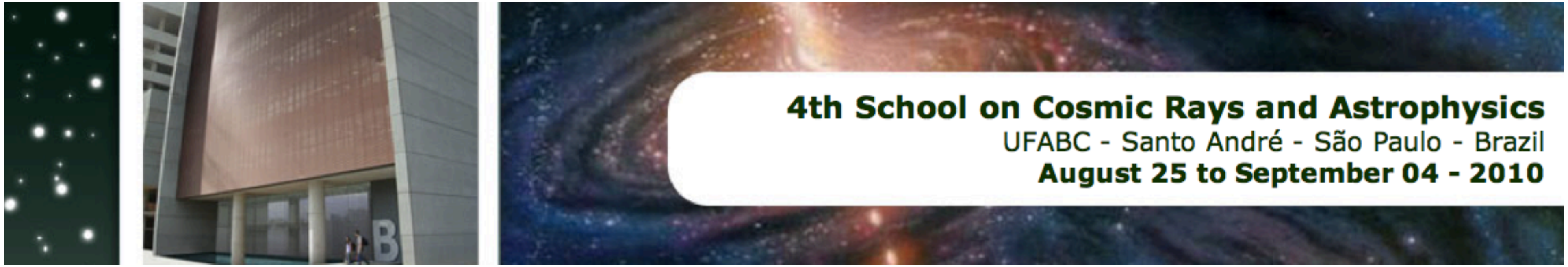
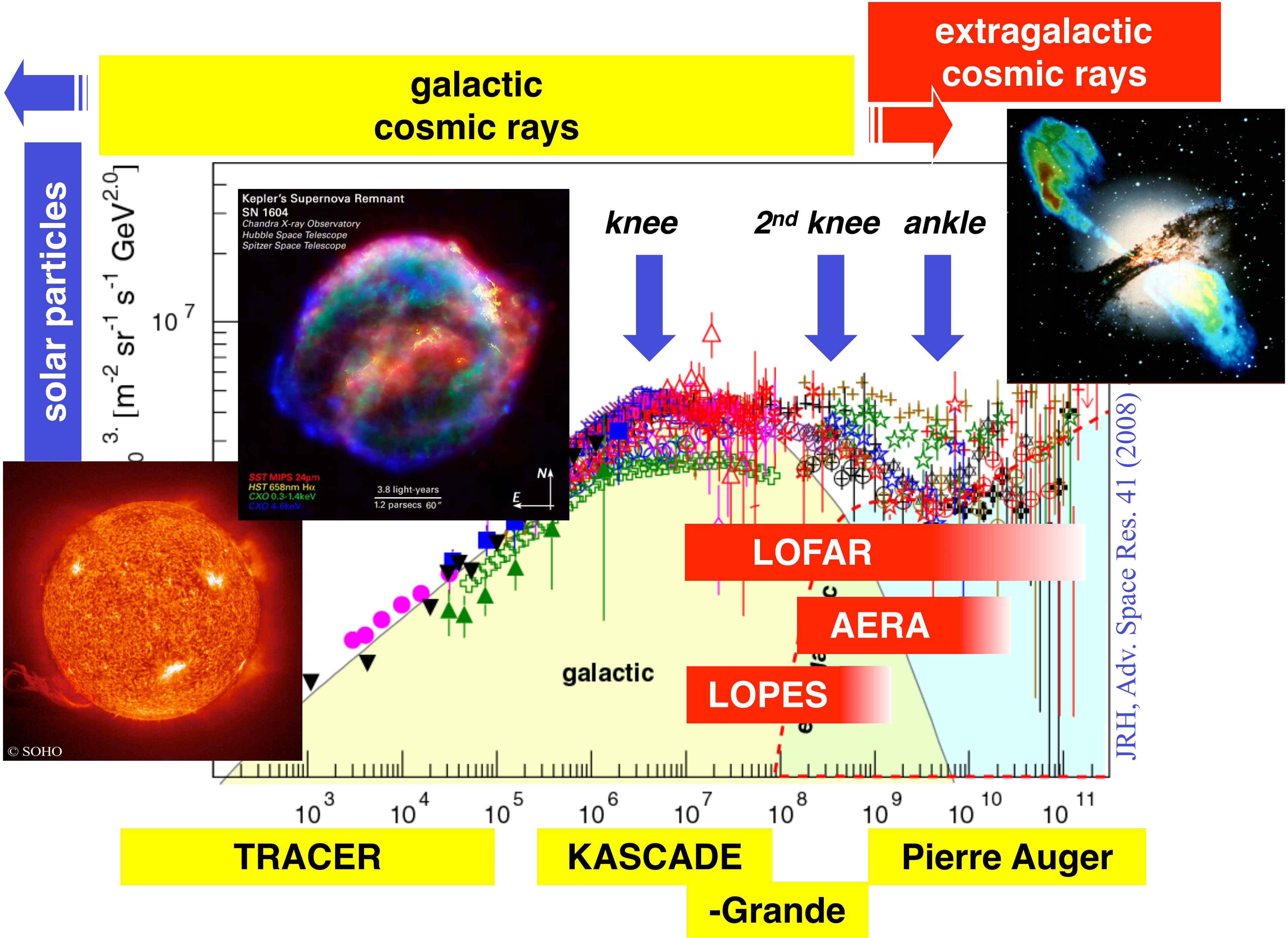


Radio Detection of Extensive Air Showers

Jörg R. Hörandel
Radboud University Nijmegen

http://particle.astro.kun.nl



galactic
cosmic rays
extragalactic
cosmic rays
solar particles
Kepler's Supernova Remnant
SN 1604
Chandra X-ray Observatory
Hubble Space Telescope
Spitzer Space Telescope
knee
2nd knee
ankle
LOFAR
AERA
LOPES
galactic
© SOHO
JRH, Adv. Space Res. 41 (2008)
TRACER
KASCADE
-Grande
Pierre Auger

Present Detection Methods

The Pierre Auger Observatory

Hybrid detection of extensive air showers

Water Cherenkov detectors

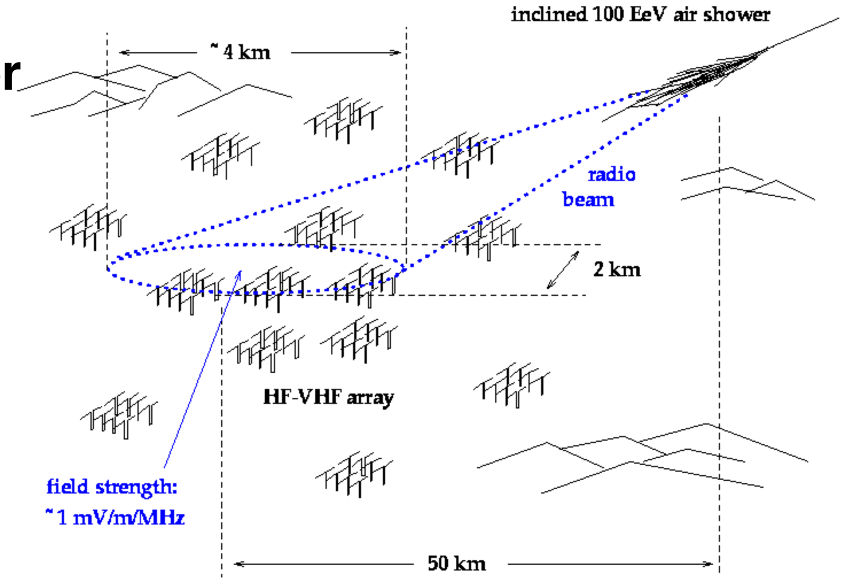
- **lateral distributions on ground level**
- **~100% duty cycle**

Fluorescence telescopes

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

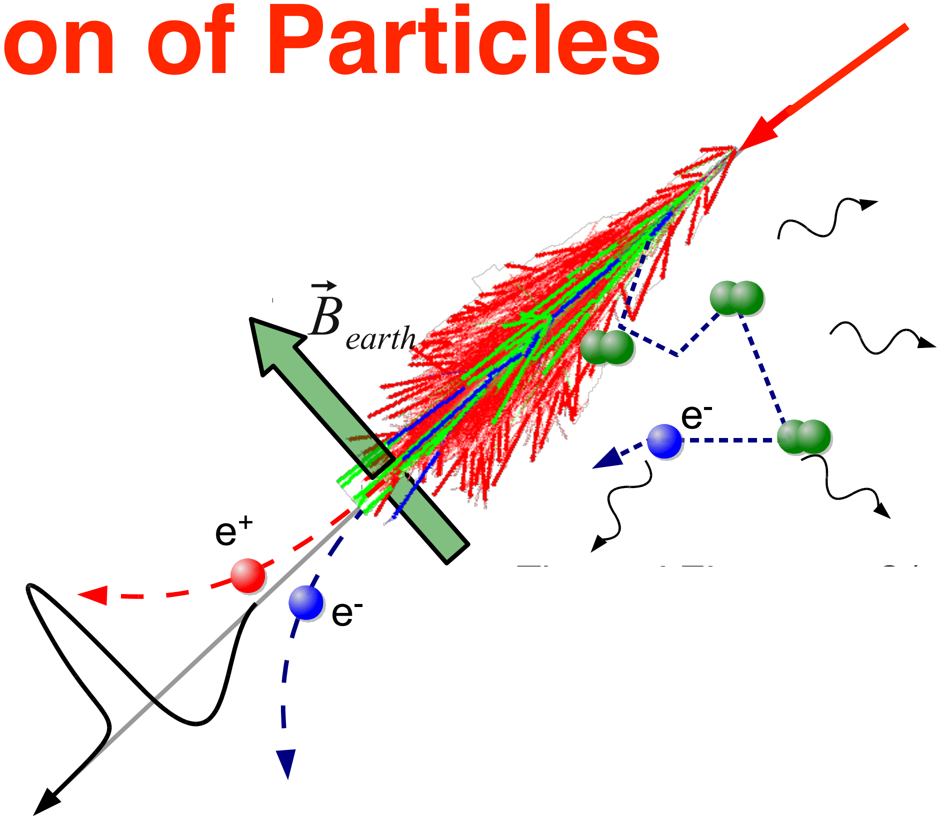
Advantages of radio detection

- Cheap detectors (expensive electronics)
- High duty cycle (24 hours/day)
- Low attenuation, good calibratability (also distant and inclined showers)
- Calorimetric, i.e. good energy measurement (integral over shower evolution)
- Interferometry gives precise directions
- Complementarity with SD gives composition
- But, does it work?
- Problems before 2001:
  - No theoretical understanding
  - No experimental work since 1974



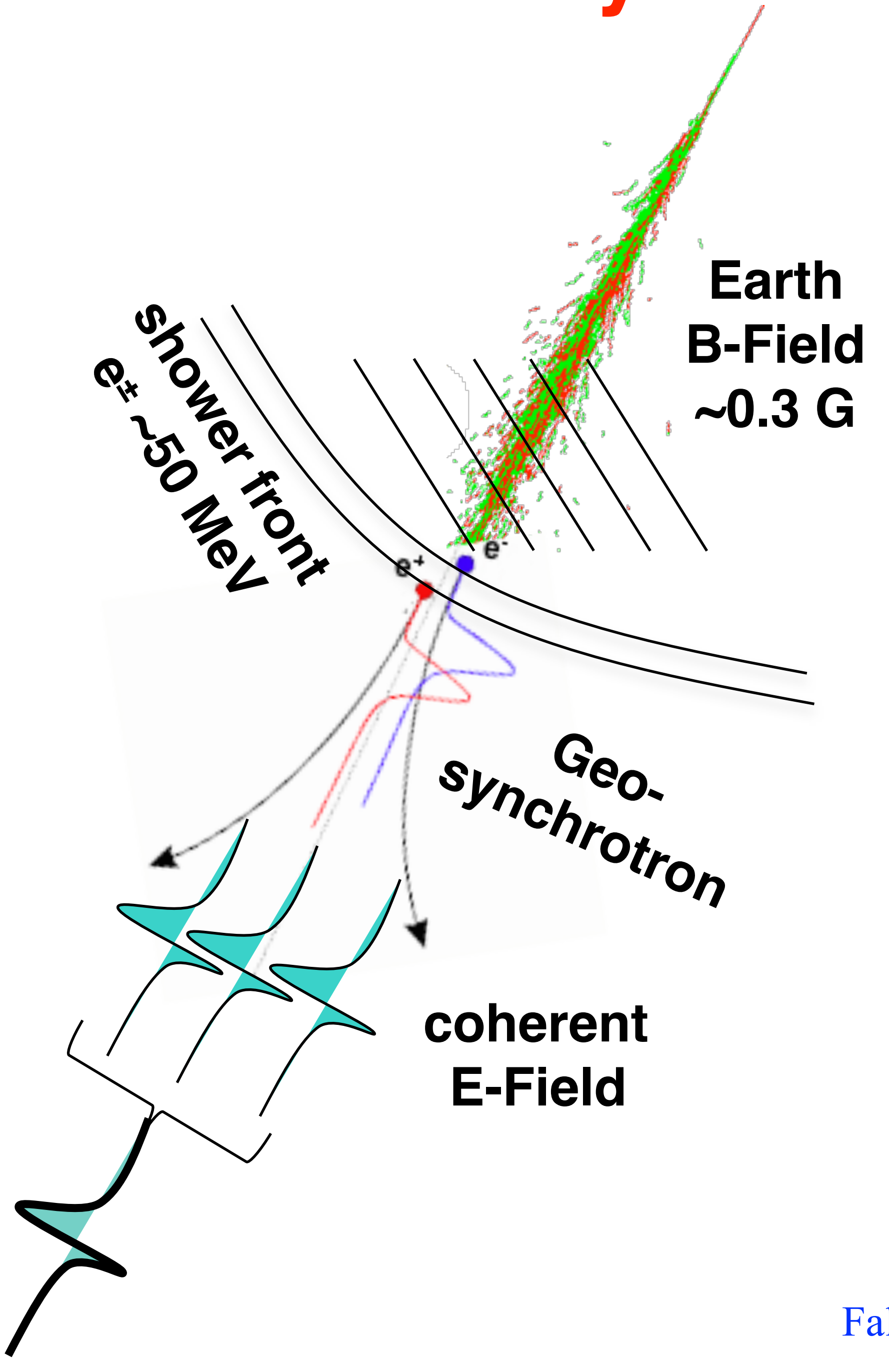
Radio Detection of Particles

- **Cosmic Rays in atmosphere:**
  - **Geosynchrotron emission (10-100 MHz)**
  - **Radio fluorescence and Bremsstrahlung (~GHz)**
  - **Radar reflection signals (any?)**
  - **VLF emission, process unclear (<1 MHz)**
- **Neutrinos and cosmic rays in solids: Cherenkov emission (100 MHz - 2 GHz)**
  - **polar ice cap (balloon or in-ice)**
  - **inclined neutrinos through earth crust (radio array)**
  - **CRs and Neutrinos hitting the moon (telescope)**



Askaryan effect

Coherent Geosynchrotron Radio Emission



- **UHECRs produce particle showers in atmosphere**
- **Shower front is ~2-3 m thick ~ wavelength at 100 MHz**
- **e± emit synchrotron rad. in geomagnetic field**
- **Emission from all e± (N_e) add up coherently**
- **Radio power grows quadratically with N_e**

⇒ **total Energy** $E_0 = N_e \cdot E_e$

⇒ **Power** $\propto E_e^2 \propto N_e^2$

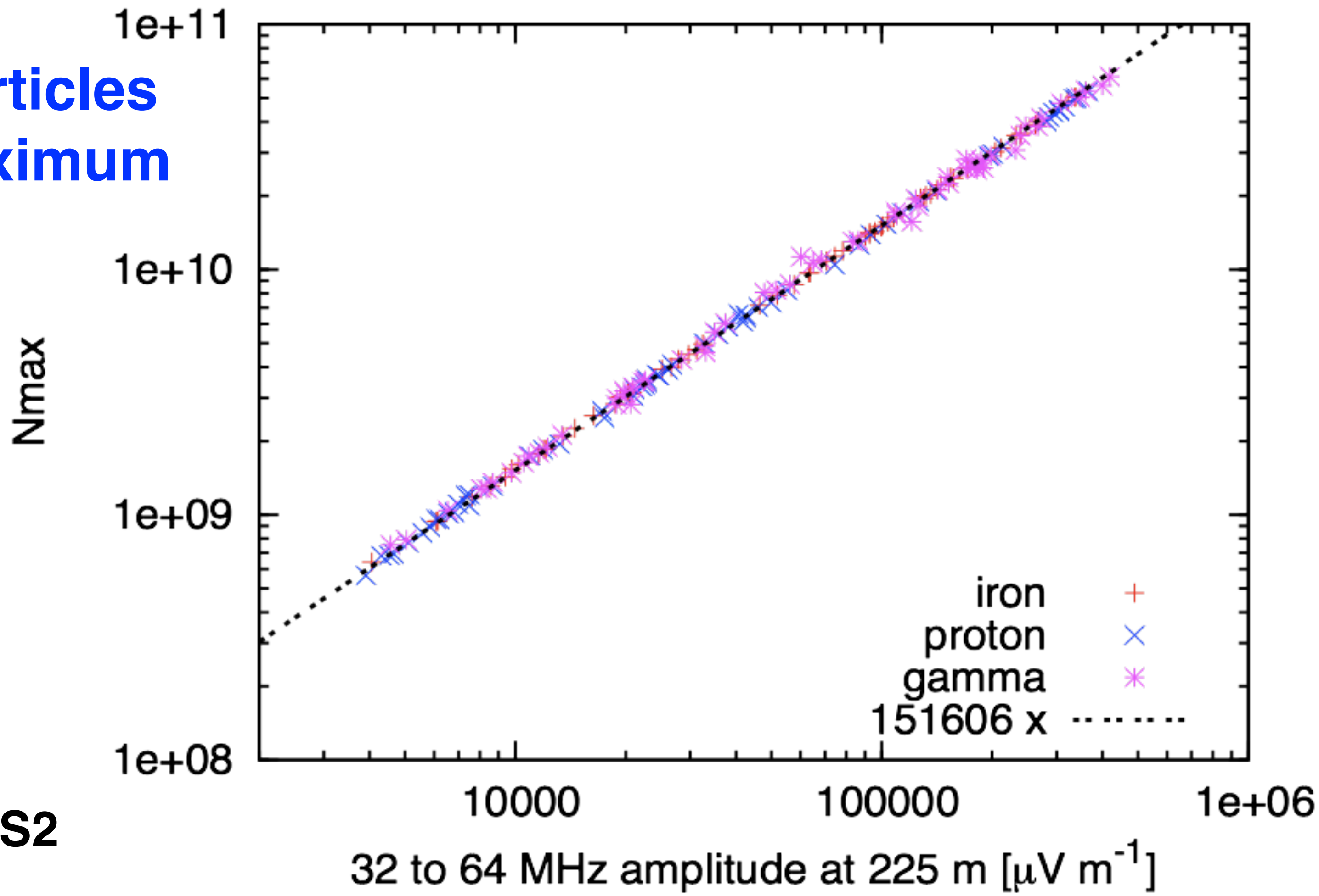
⇒ **GJy flares on 20 ns scales**

Falcke & Gorham (2003), Huege & Falcke (2004,2005)

Reconstruction of Shower Parameters with Radio Measurements

Energy

Number of particles at shower maximum N_{max}



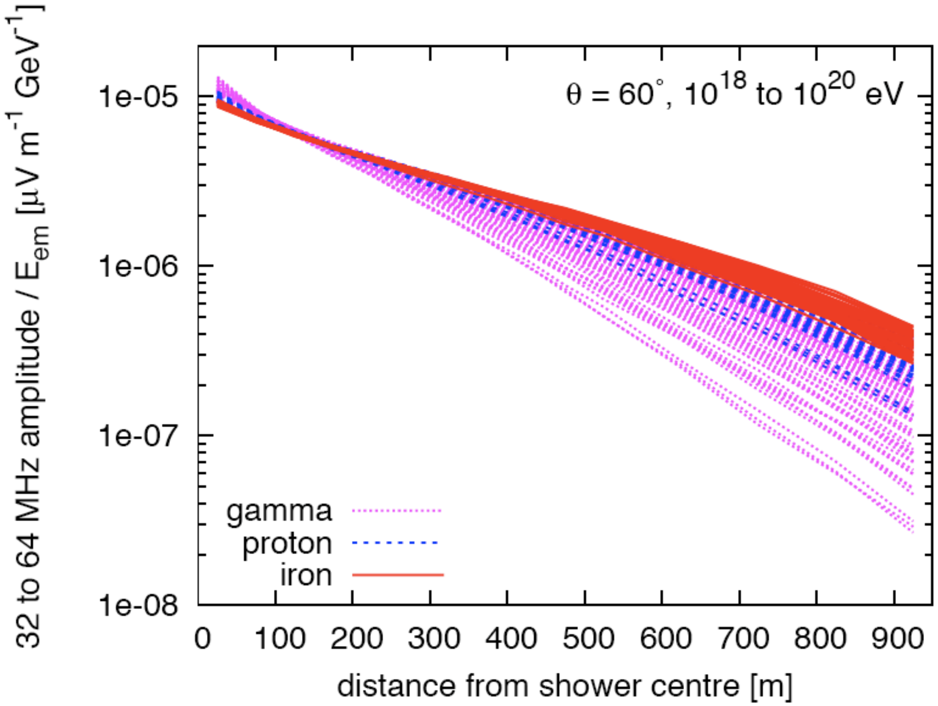
Huege et al. (2008)

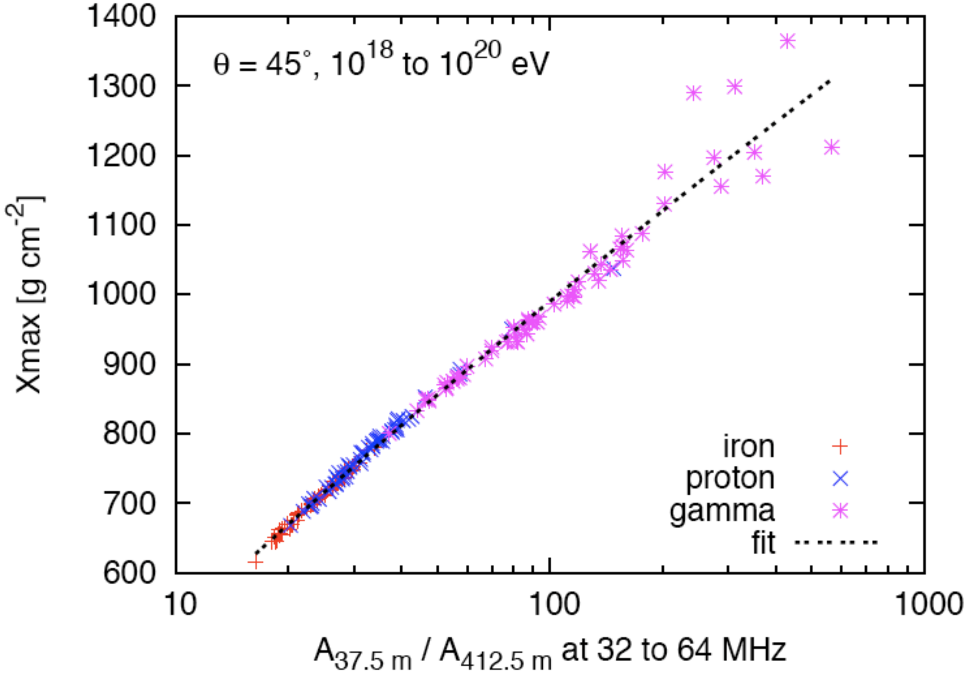
CORSIKA & REAS2 simulations

Reconstruction of Shower Parameters with Radio Measurements

Mass -X_{max} **- Lateral distribution**

ratio of amplitudes



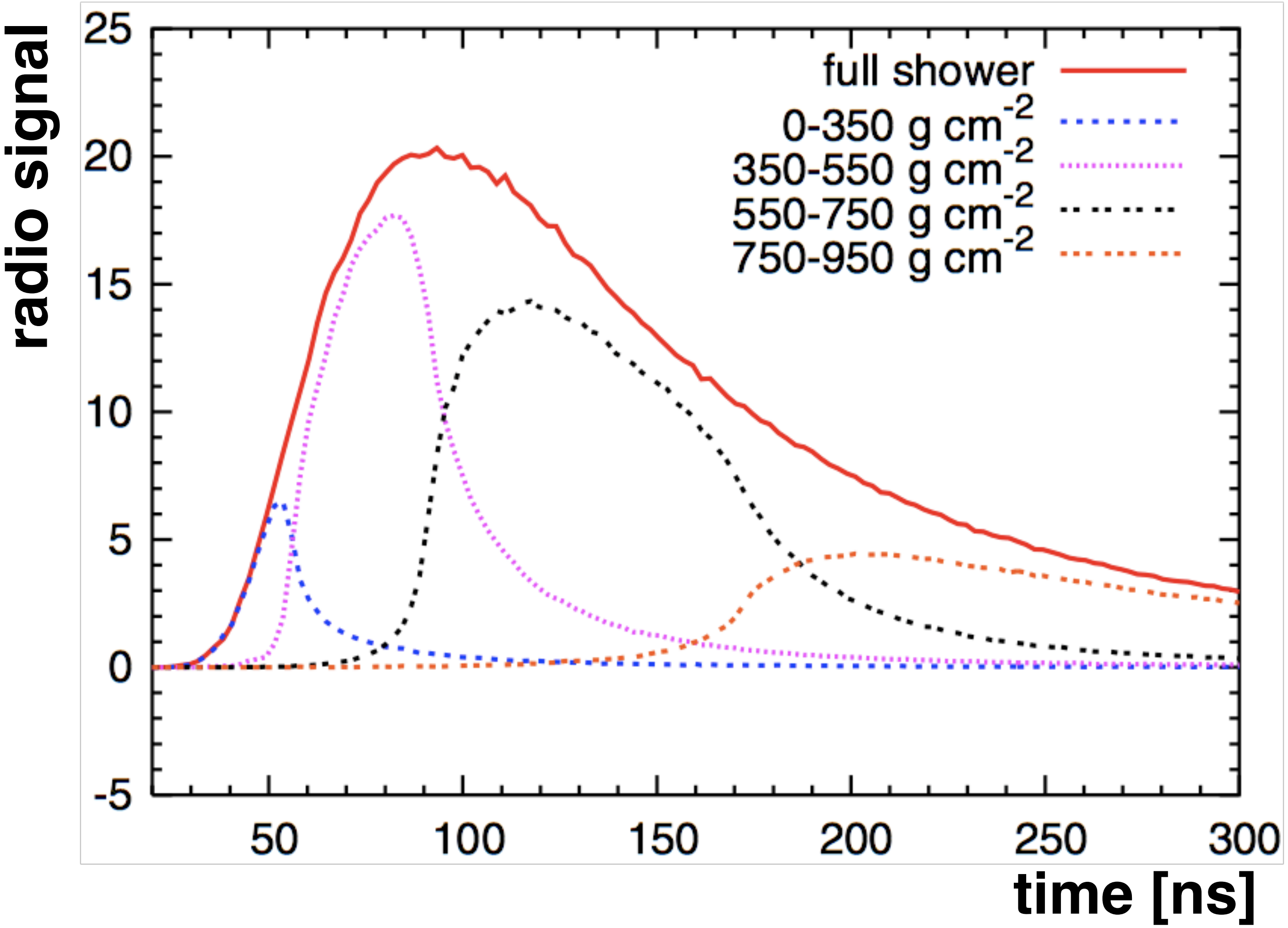


CORSIKA & REAS2 simulations

Huege et al. (2008)

Reconstruction of Shower Parameters with Radio Measurements

Mass -X_{max} **- Pulse shape**



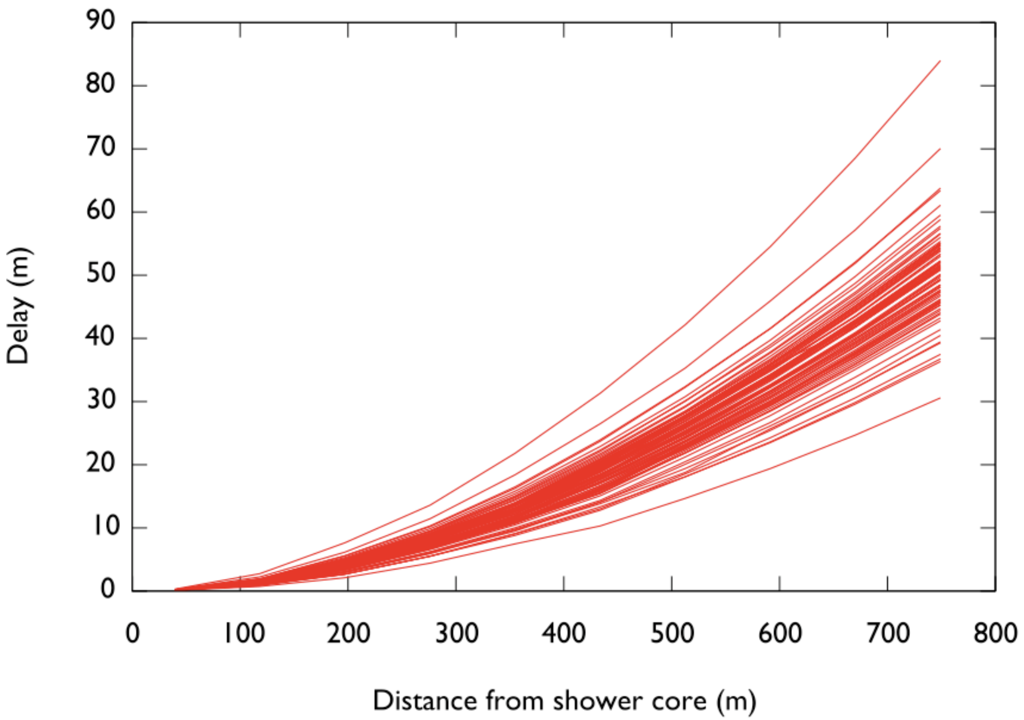
CORSIKA & REAS2 simulations

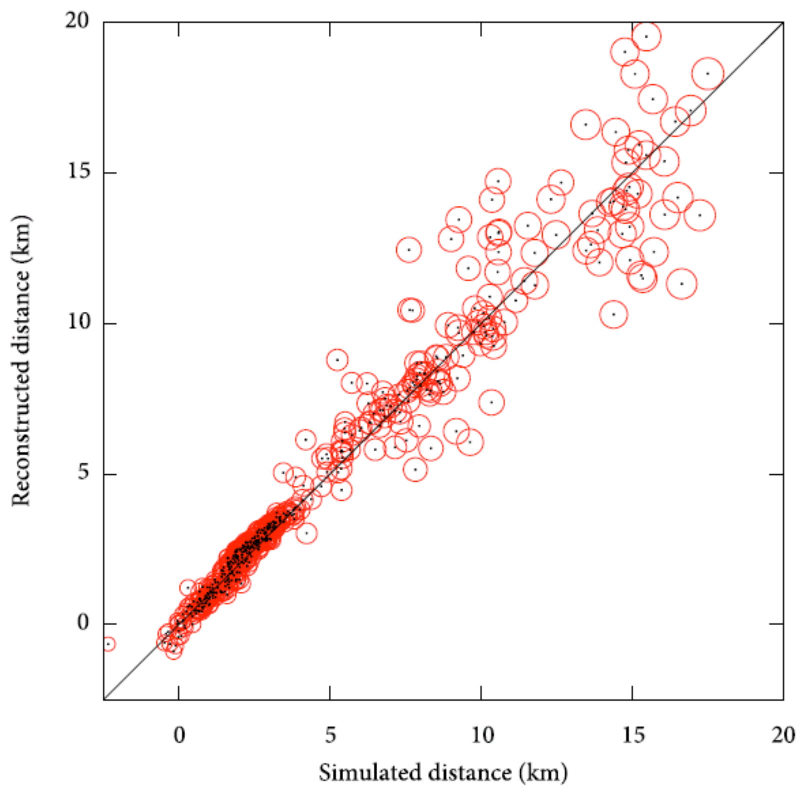
Huege et al. (2008)

Reconstruction of Shower Parameters with Radio Measurements

***Mass -X_{max}* - Curvature**

distance to shower core





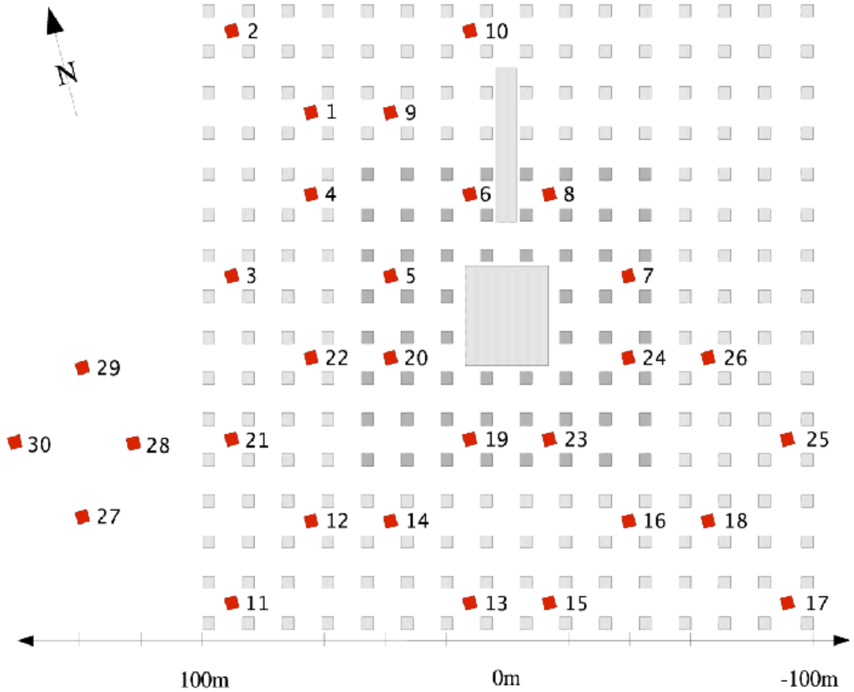
CORSIKA & REAS2 simulations

Lafèbre (2008)

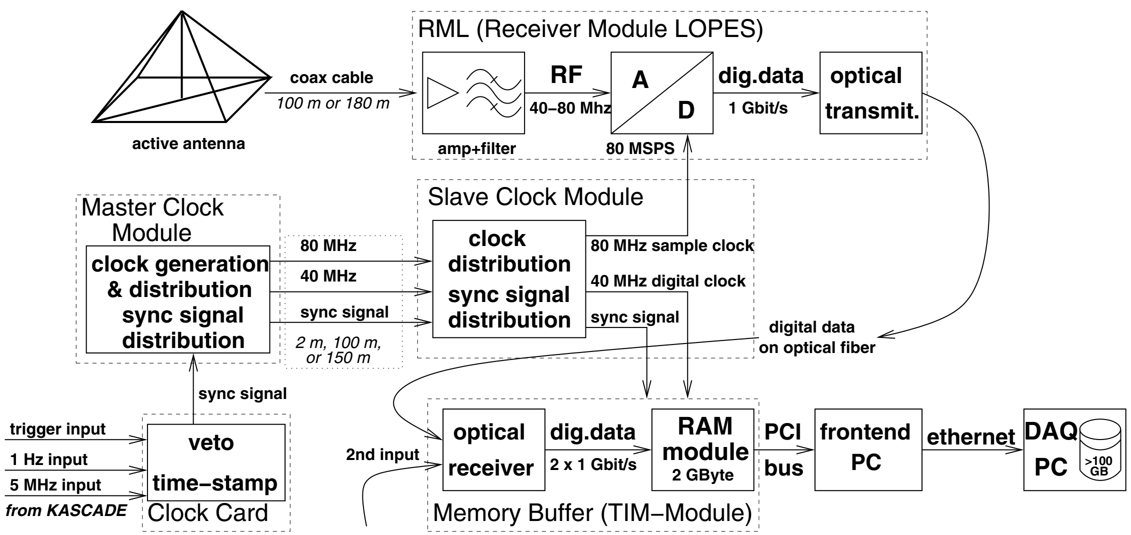
LOPES

Lofar Prototype Station

30 antennas operating at KASCADE-Grande



digital radio interferometer

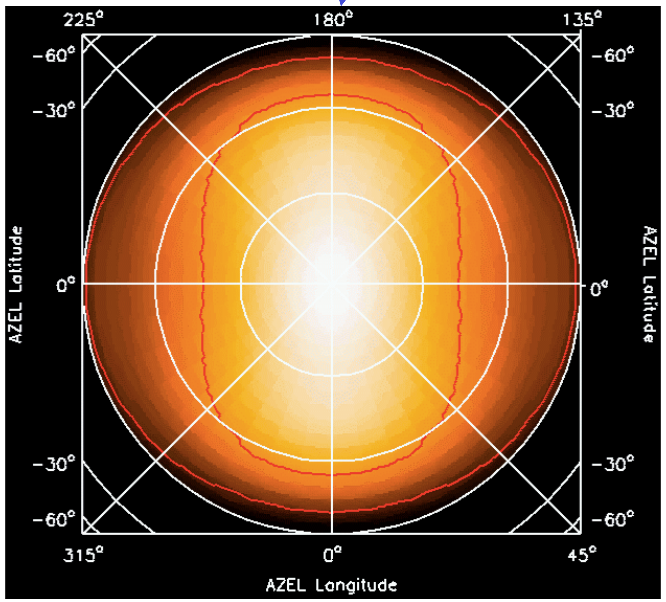


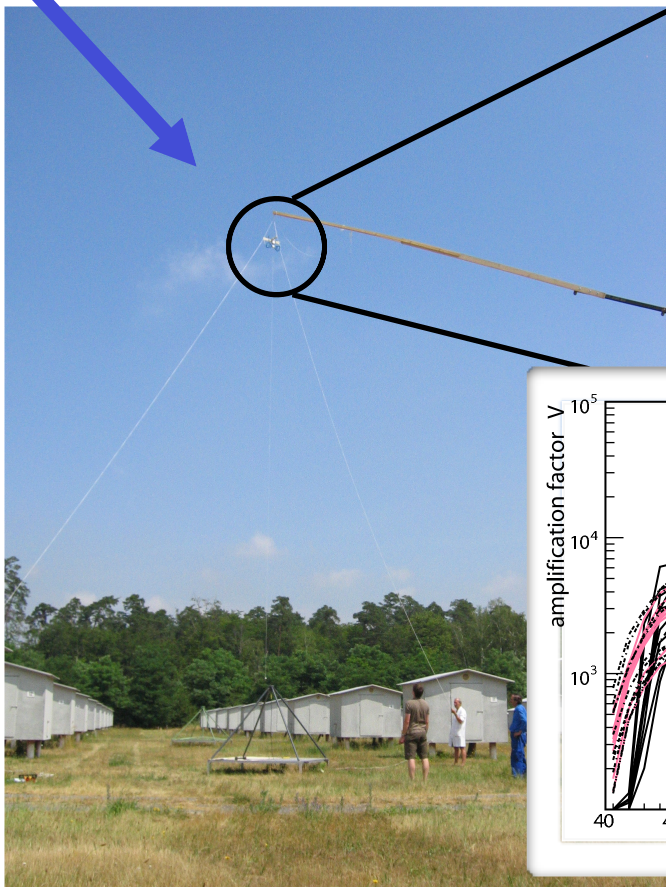
Antenna Calibration

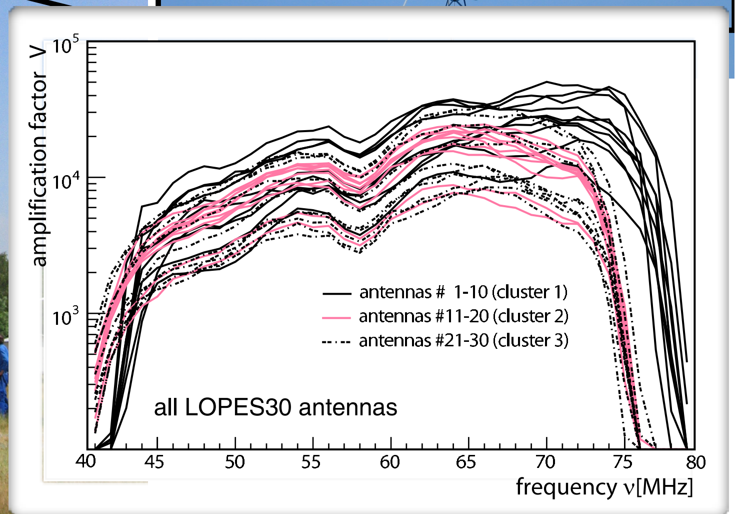
electric field strength:

$$\varepsilon = \sqrt{\frac{4\pi\mu_0\nu}{\boxed{G(\theta,\phi,\nu)}\,c\,\boxed{A_{ele}(\nu)}\,R_{ADC}}}\,V_{ADC}$$

- ν **observation frequency**
- V_{ADC} **measured voltage**
- G **antenna pattern**
- A_{ele} **amplification (gain)**
- R_{ADC} **impedance**

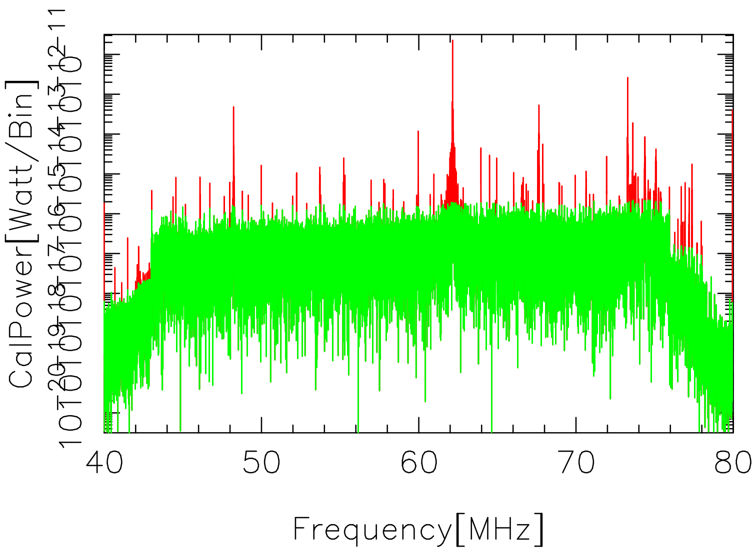




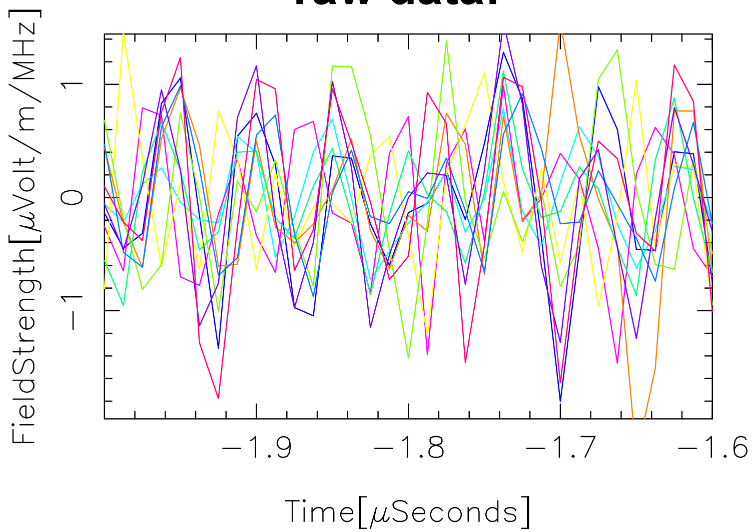


LOPES Data Processing

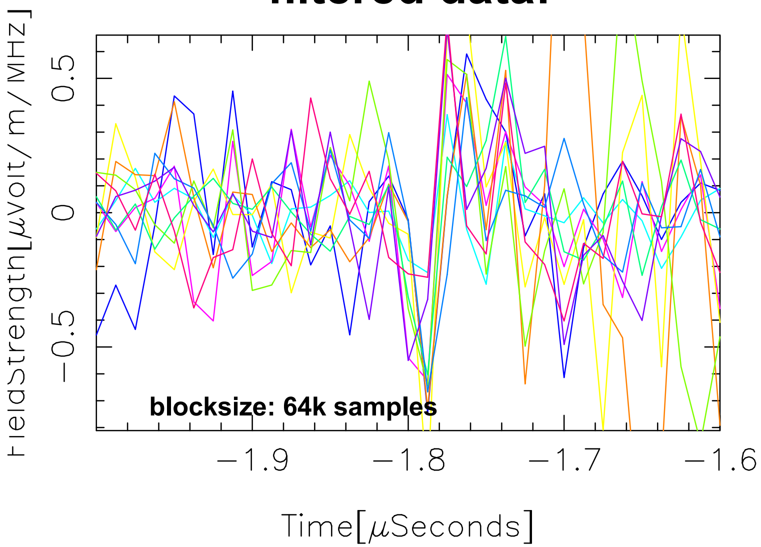
1. Instrumental delay correction (TV transmitter or beacon)
2. Frequency dependent gain correction
3. Filtering of narrow band interference
4. Flagging of bad antennas



raw data:



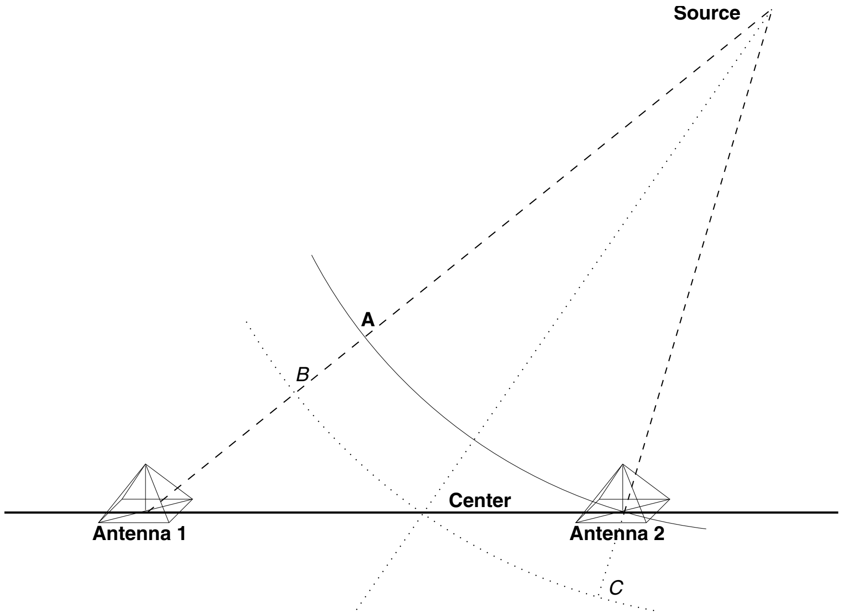
filtered data:

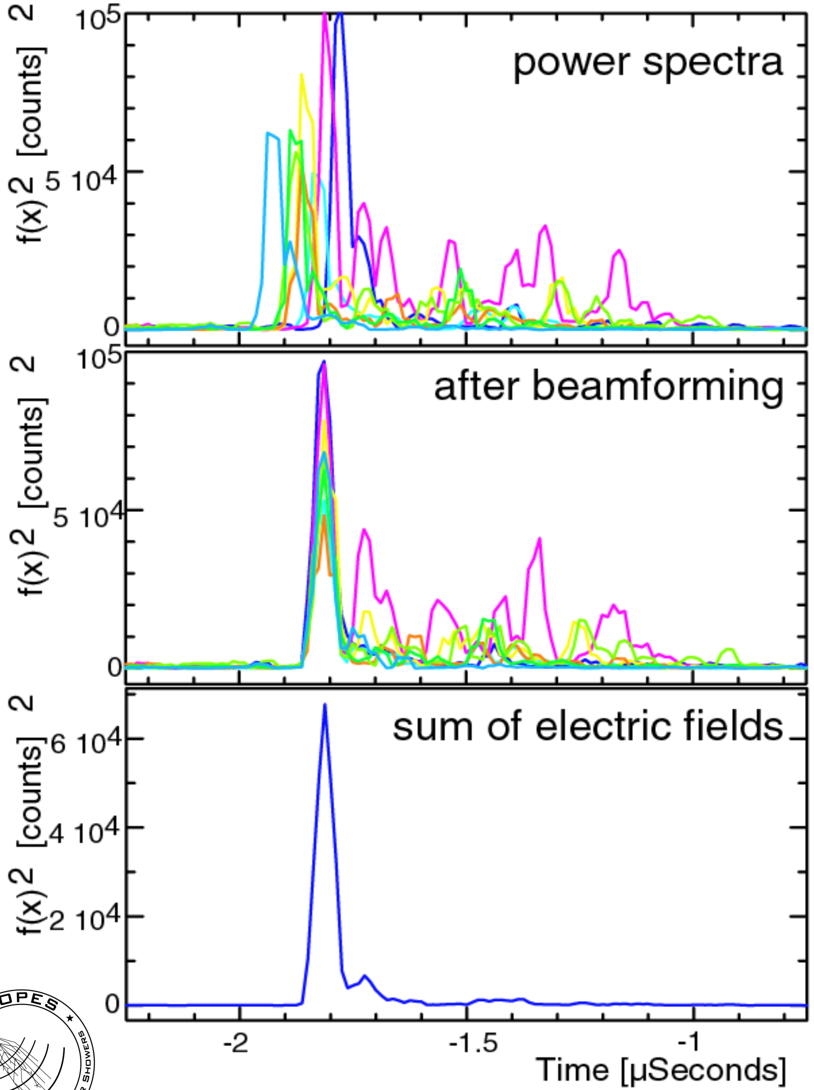


LOPES Data Processing

5. Beam forming in direction of air shower

$$cc[t] = \pm\sqrt{\left|\frac{1}{N_{Pairs}}\sum_{i=1}^{N-1}\sum_{j>i}^{N} s_i[t]s_j[t]\right|}$$



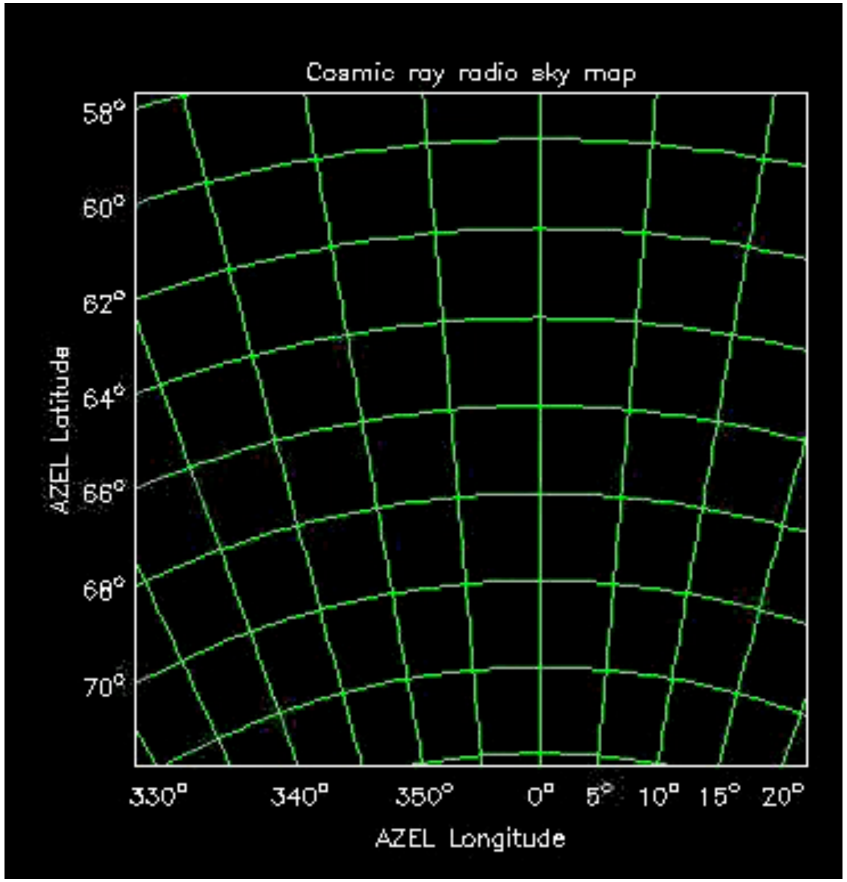


Proof of principle

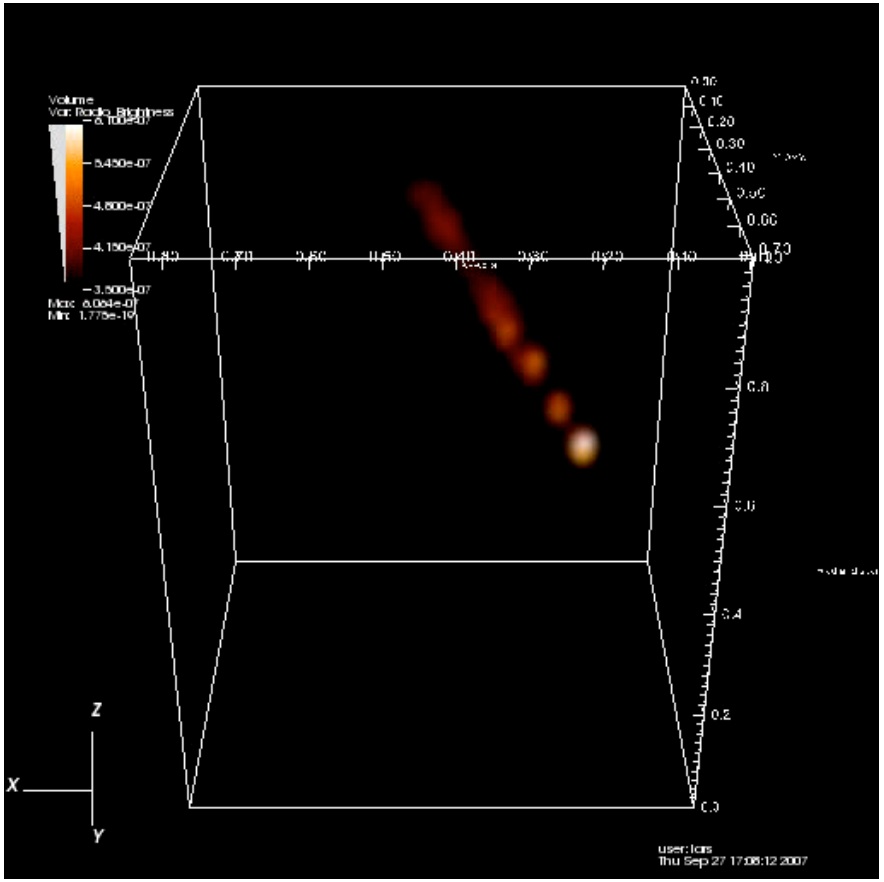
LOPES-10

1. EAS properties (KASCADE)
2. radio signal analysis (cc beam)
3. sky map

Position of shower in sky



Nanosecond radio imaging in 3D



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

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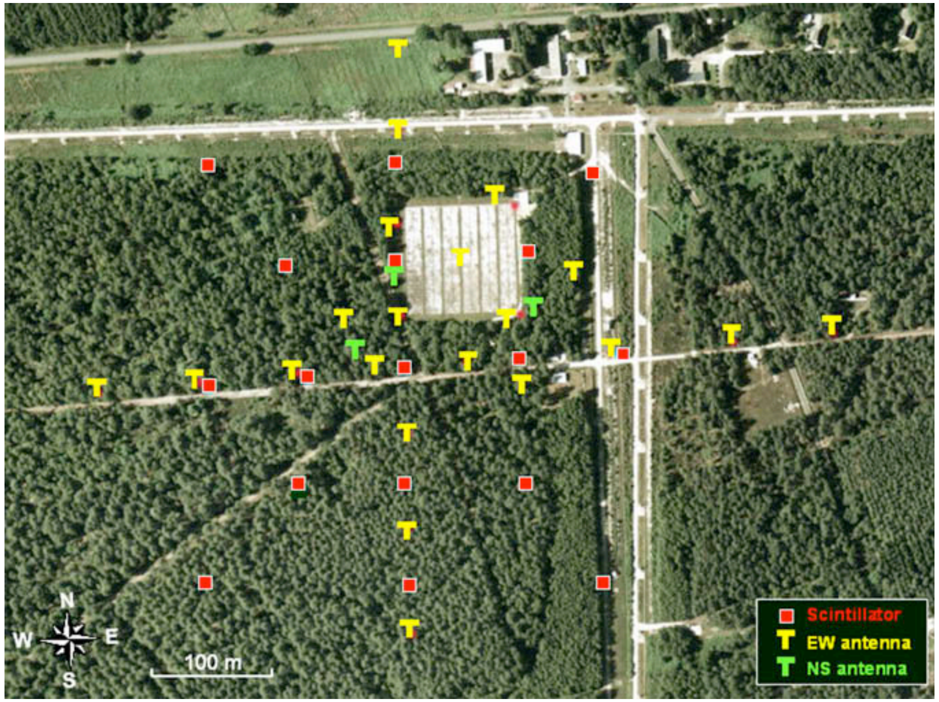
CODALEMA

1st stage: decametric array, Nancay

COsmic ray
Detection
Array with
Logarithmic
Electro
Magnetic
Antennas



now: low noise, active dipole antenna,
21 dipoles EW pol., 3 dipoles NS pol.
1-220 MHz
17 scintillators for EAS identification

D. Arduin et al., Astropart. Phys. 31 (2009) 192
Nucl. Instr. & Meth. A 572 (2007) 481

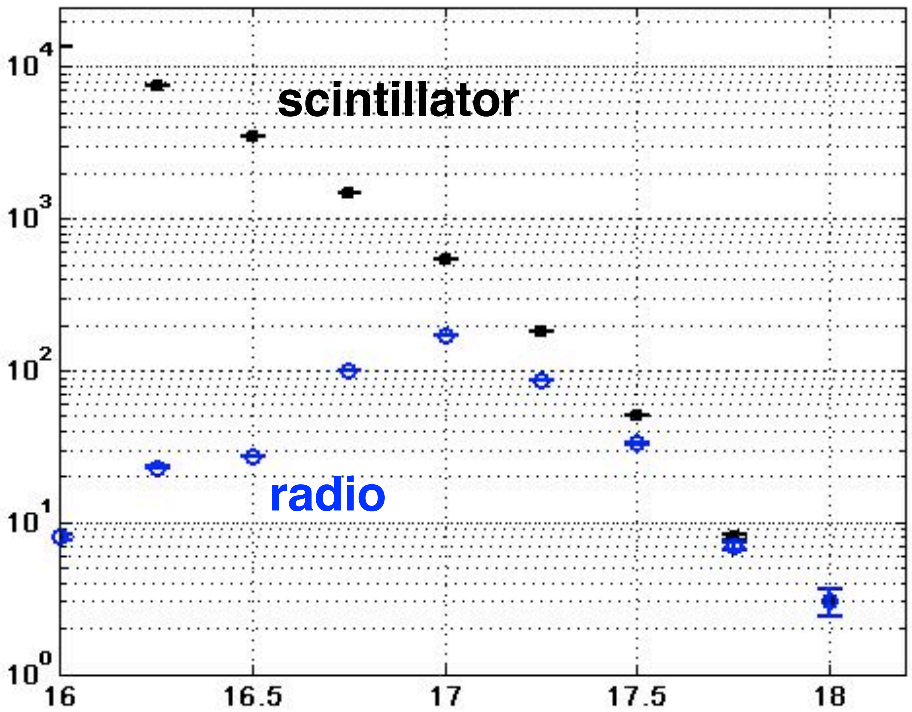
CODALEMA detection efficiency

Radio detection threshold
~5.10^{16} eV

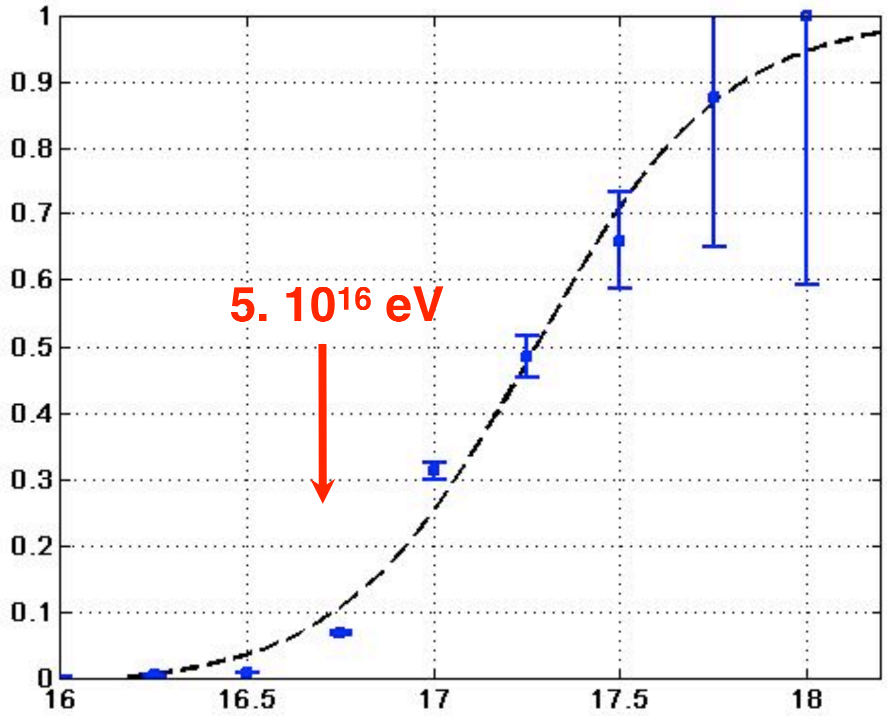
Particle detection threshold
10^{15} eV

Effective data taking time	659 days
Trigger (SD events)	143795
Coincidences (SD and antennas)	1553
Coincidences (Internal)	450

Energy distribution



Efficiency

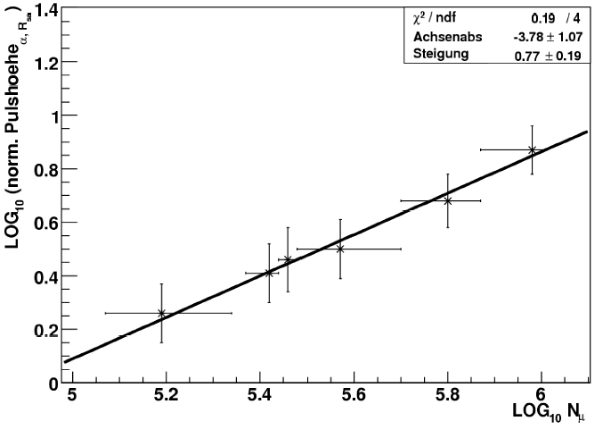


Full efficiency reached above 10^{18} eV

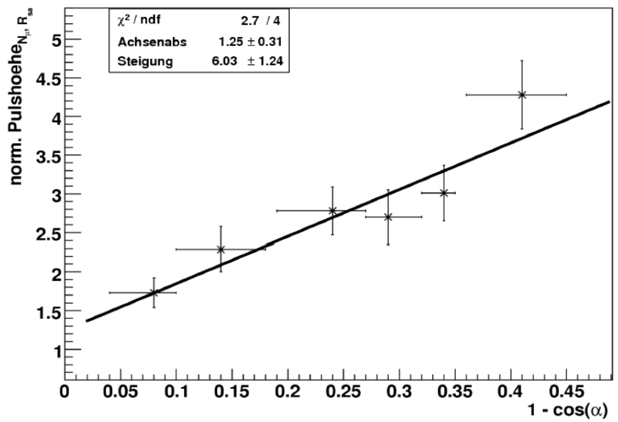
Correlation between radio signal and

air shower parameters

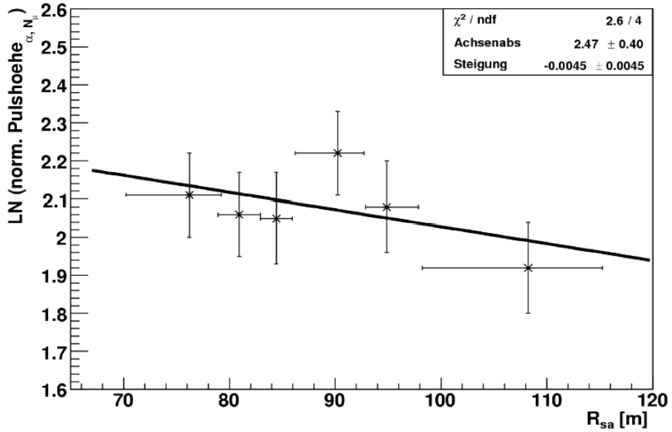
.. number of muons, i.e. primary energy



.. angle with respect to geomagnetic field



.. distance to shower axis



E. Bettini, diploma thesis, U Karlsruhe, 2006

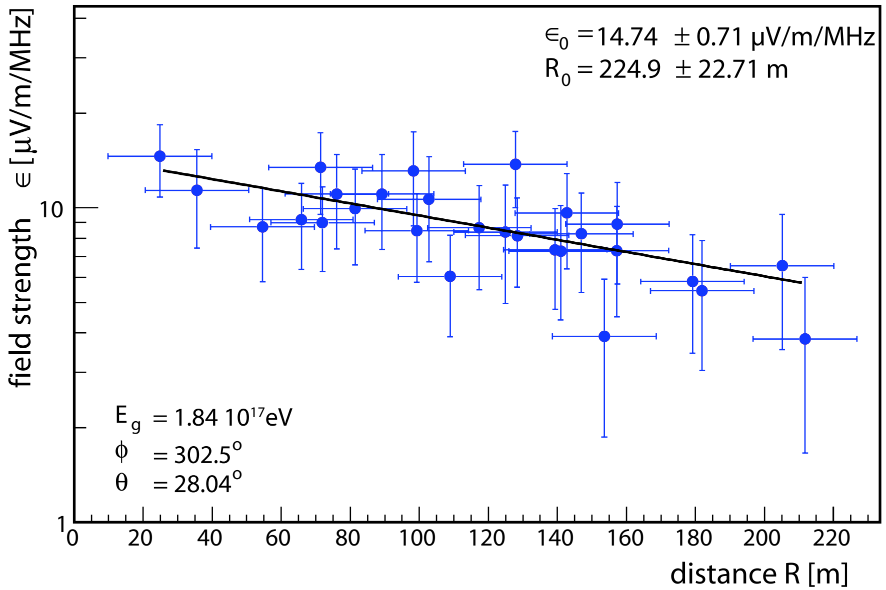
$$\varepsilon_{est} = (11 \pm 1)((1.16 \pm 0.025) - \cos\alpha)\cos\theta \exp\left(\frac{-R}{236 \pm 81\ \mathrm{m}}\right)\left(\frac{E_p}{10^{17}\ \mathrm{eV}}\right)^{0.95 \pm 0.04}\left[\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\right]$$

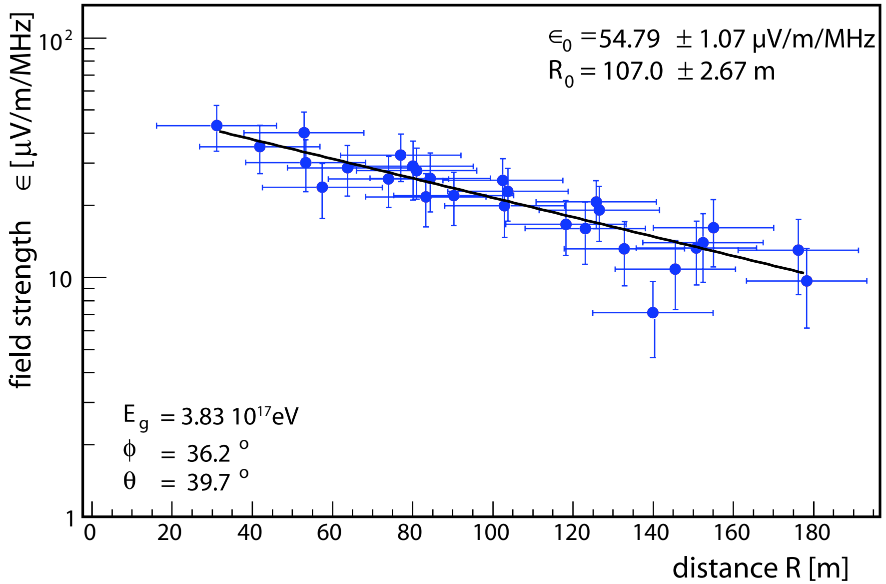
- **α geomagnetic angle**
- **θ zenith angle**
- **r distance to shower axis**
- **E_0 energy of primary particle**

A. Horneffer et al., 30th ICRC 4 (2008) 83

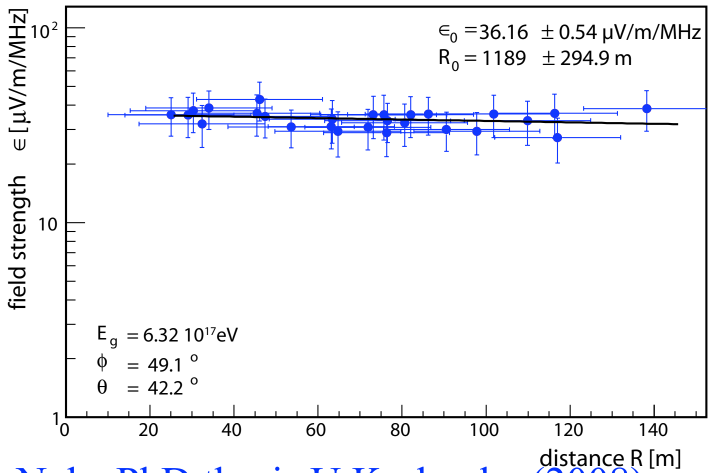
LOPES-30: Lateral Distribution Revisited

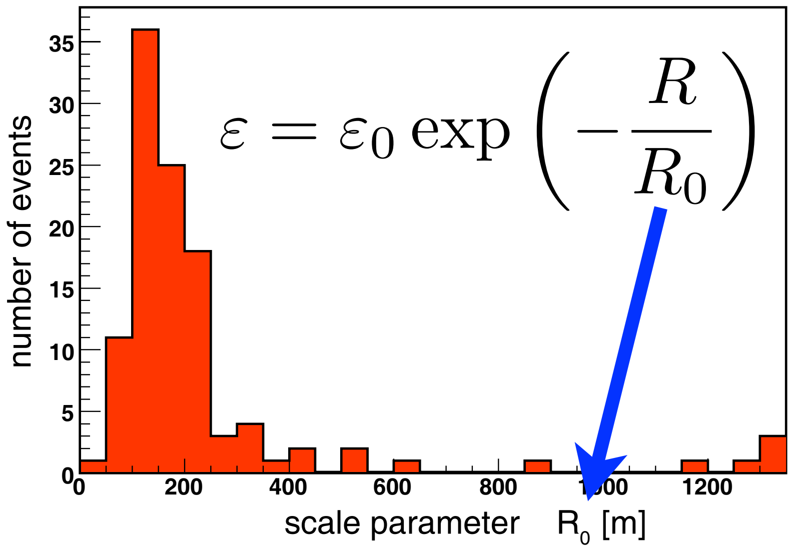
typical events





but also „interesting“ events



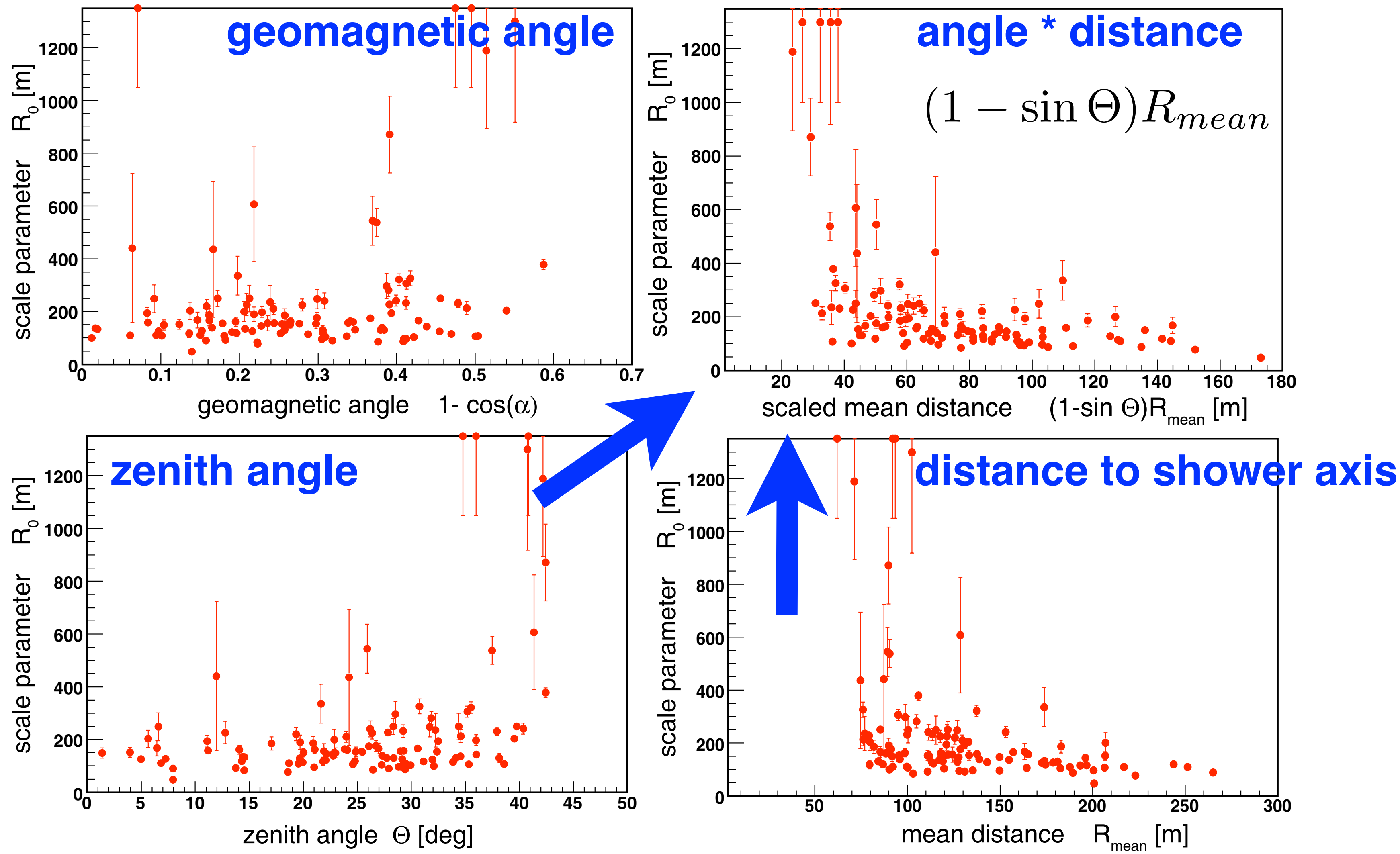


S. Nels, PhD thesis U Karlsruhe (2008)

LOPES-30: Lateral Distribution Revisited

correlation of scale parameter R_0 with ...

$$\varepsilon = \varepsilon_0 \exp\left(-\frac{R}{R_0}\right)$$

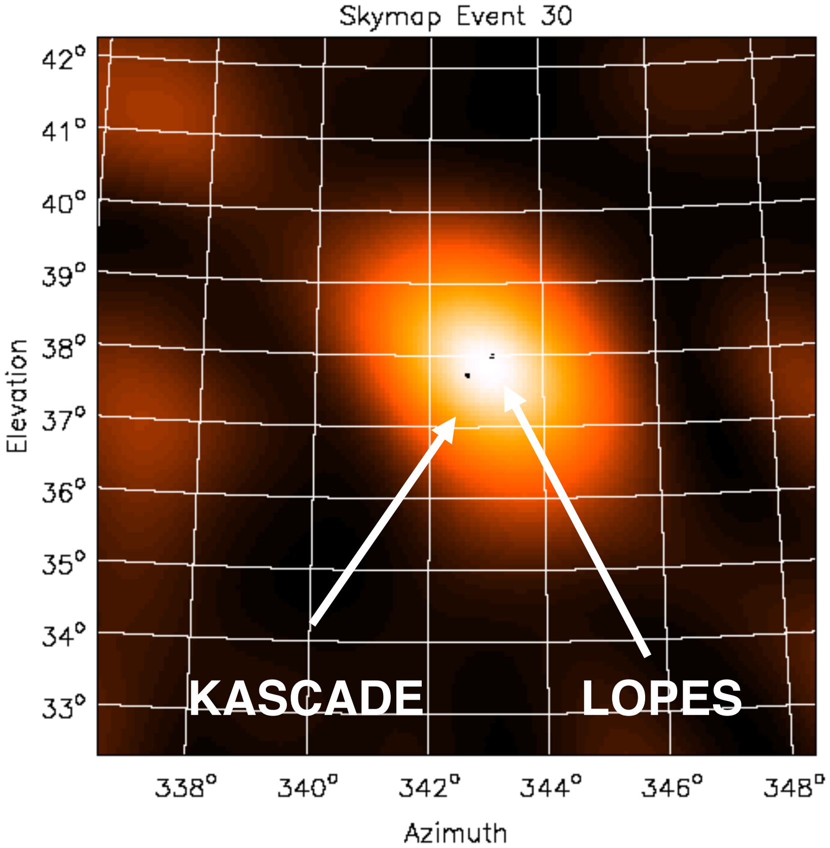


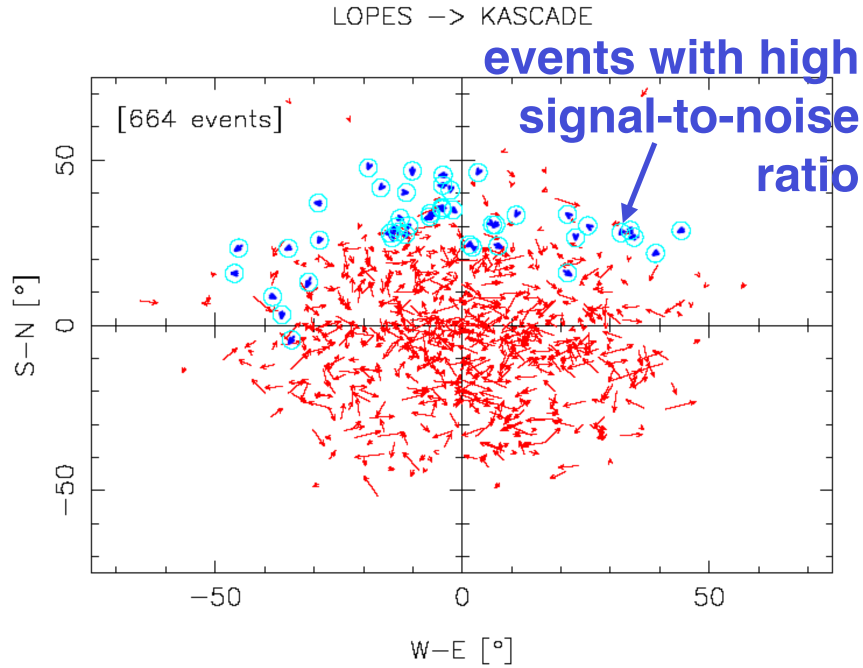
S. Nehls, PhD thesis U Karlsruhe (2008)

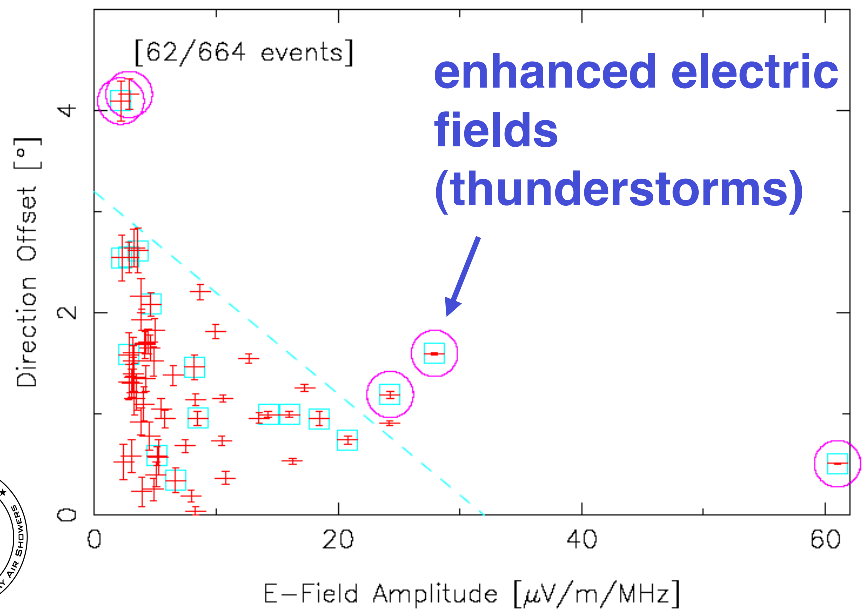
W.D. Apel et al., subm. to Astropart. Phys.

Shower reconstruction with radio data

Reconstructed direction on sky







direction offset σ = 1.3°+/-0.8°

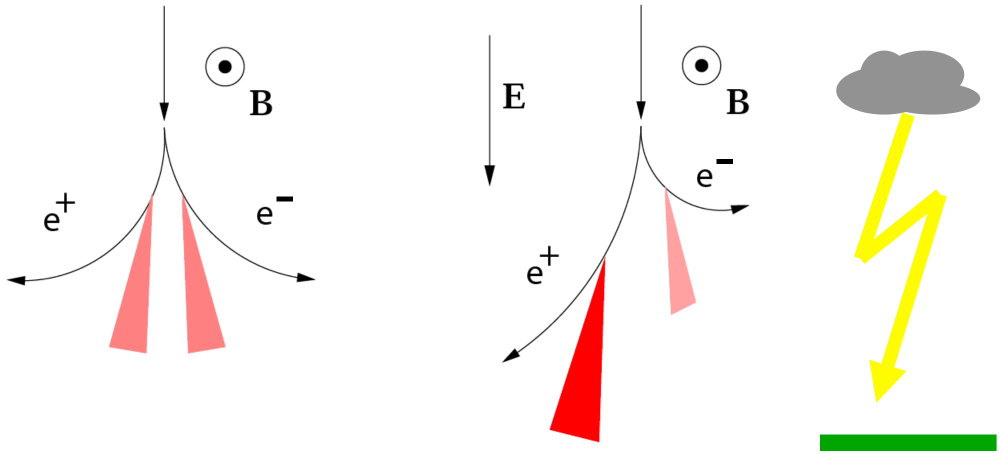
KASCADE $\sigma_\Theta < 0.2°$

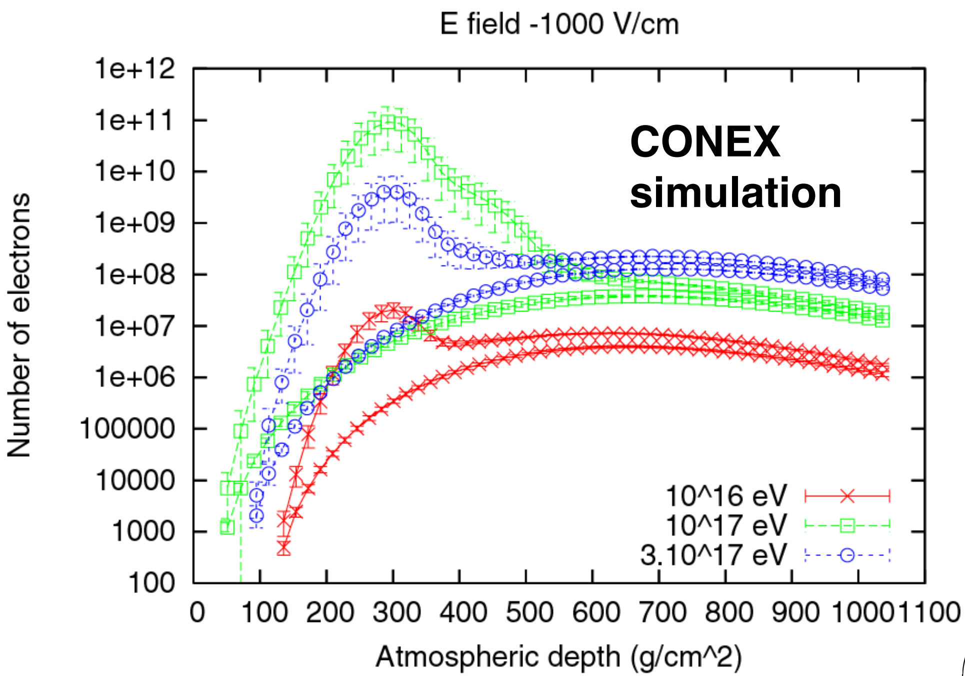
LOPES $\sigma_\Theta \sim 1.2°$

A. Nigl et al., A&A 487 (2008) 781

Air shower detection during thunderstorms

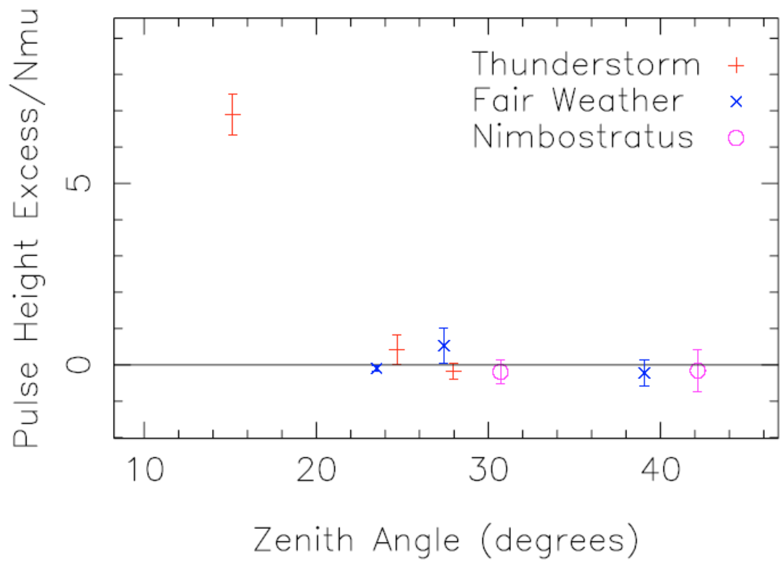
high electric fields

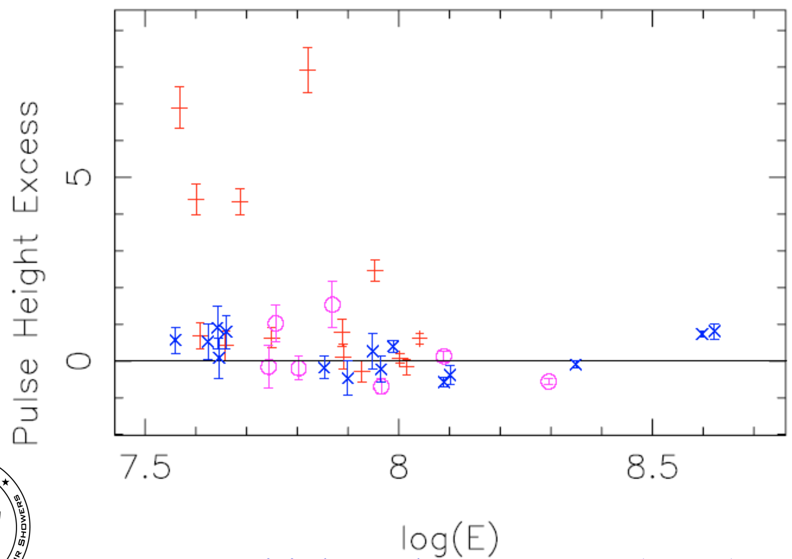




S. Buitink et al., 30th ICRC 4 (2008) 161

LOPES measured

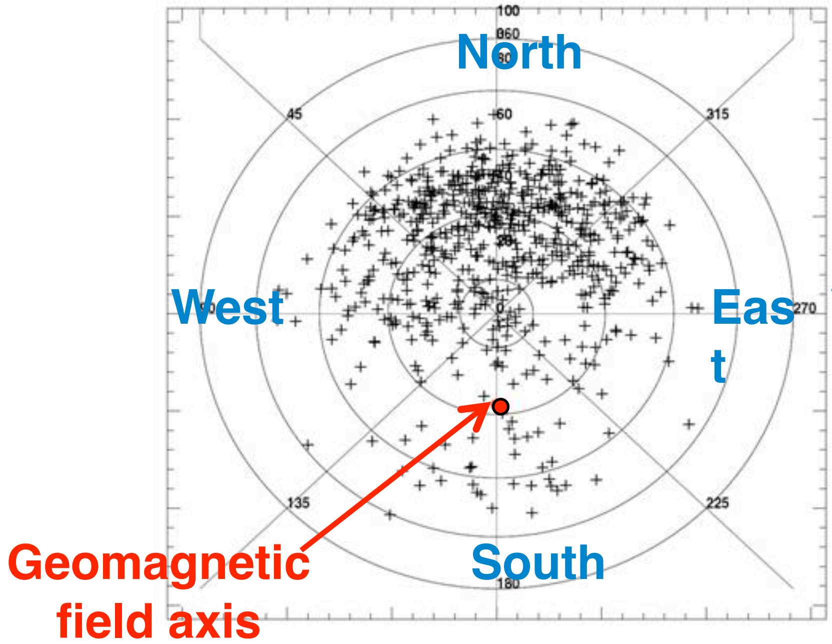




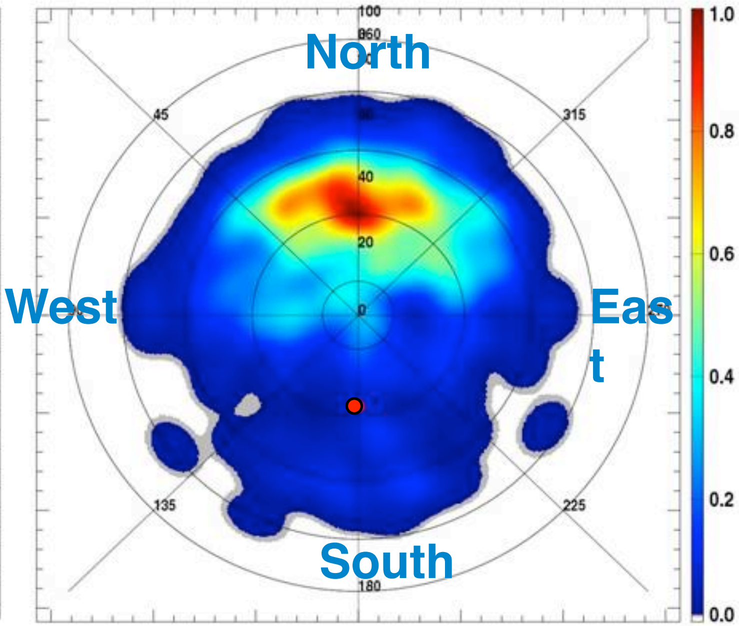
S. Buitink et al., A&A 467 (2007) 385

CODALEMA: shower arrival direction

Sky map



Density map



- **Large north/south asymmetry, relative deficit of events in the geomagnetic field axis area**

- **For the scintillators, the azimutal acceptance is uniform**

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

Synchrotron radiation of electrons (and positrons) in magnetic field of Earth

geosynchrotron radiation

general formula *(e.g. Jackson)* **for accelerated relativistic particle:**

$$E = \frac{e}{4\pi\epsilon_0}\left[\frac{n-v}{\gamma^2(1-v\cdot n)^3 R^2}\right]_{ret} + \frac{e}{4\pi\epsilon_0 c}\left[\frac{n\times\{(n-v)\times\dot{v}\}}{(1-v\cdot n)^3 R}\right]_{ret}$$

v **velocity of particle**

n **direction of observer**

second term represents synchrotron emission when

$$\dot{v} = \frac{e}{\gamma m} v \times B$$ **Lorentz acceleration in magnetic field**

geosynchrotron radiation

$$E = \frac{e}{4\pi\epsilon_0}\left[\frac{n-v}{\gamma^2(1-v\cdot n)^3R^2}\right]_{ret} + \frac{e}{4\pi\epsilon_0 c}\left[\frac{n\times\{(n-v)\times\dot{v}\}}{(1-v\cdot n)^3 R}\right]_{ret}$$

assume: observation point on shower axis $v \mid\mid n$

$$\Rightarrow E_2 \propto n \times \{(n-v)\times(v\times B)\}$$

$$\propto \underbrace{\{n(v\times B)\}}_{=0 \text{ on axis}}(n-v) - \{n(n-v)\}\,(v\times B)$$

$$\propto -(1-v)(v\times B)$$

$$\propto -(v\times B)$$

geosynchrotron radiation

field strength of observed radiation is expected as

$$E \propto -(v \times B)$$

total field amplitude

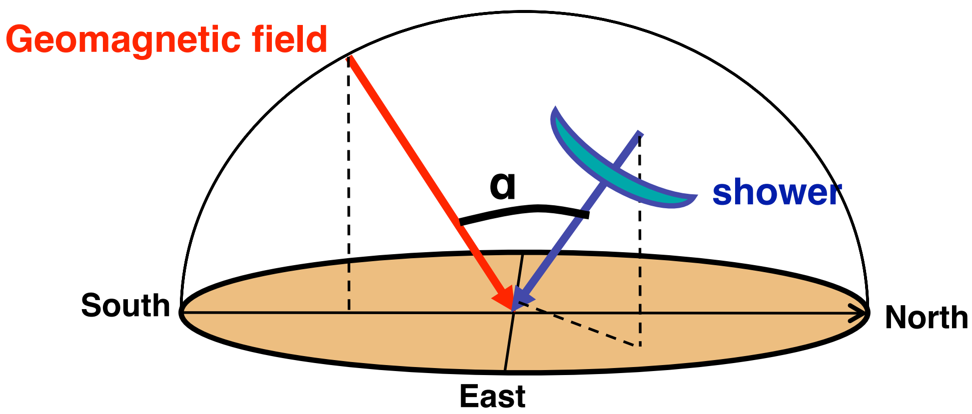
in experiments, projection on E-W or N-S direction is measured

CODALEMA: Geomagnetic Origin v x B

A model to understand the asymmetry

Hypothesis:

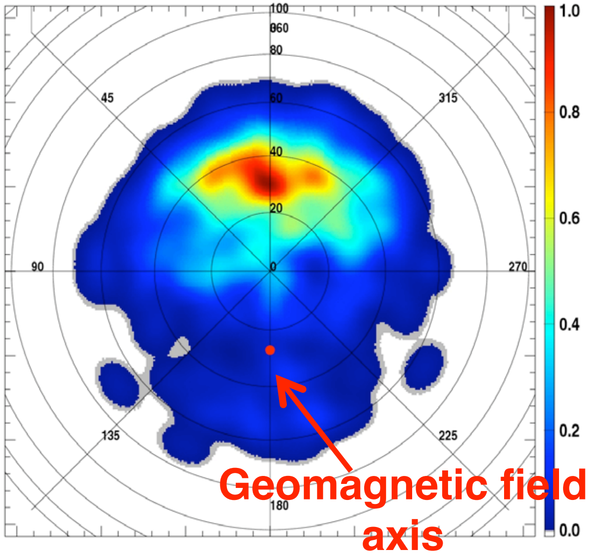
- The electric field is proportional to the Lorentz force $E \sim |v \times B|$
    - Charged particles in the shower are deflected by the geomagnetic field
    - Electric field polarization in the direction of the Lorentz force :
      a linear polarization is assumed E // to v x B
- The number of count (i.e. the efficiency) depends on the electric field magnitude:
  a simple linear dependence is assumed

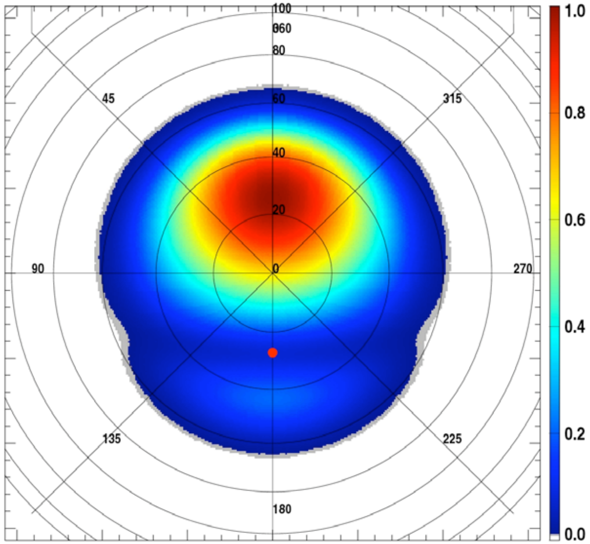


D. Arduin et al., Astropart. Phys. 31 (2009) 192

CODALEMA: Geomagnetic Origin v x B

sky map of radio events (E-W component)



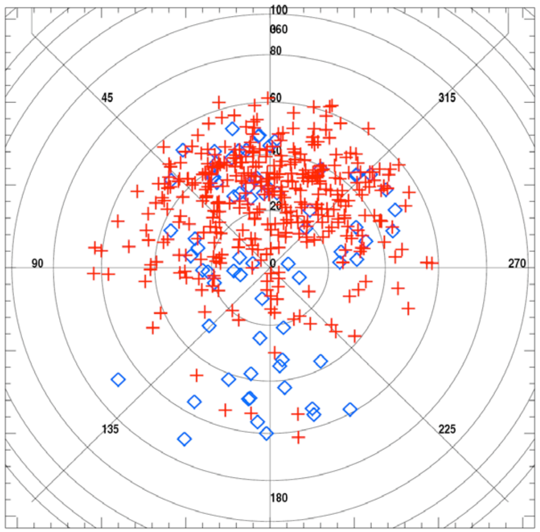


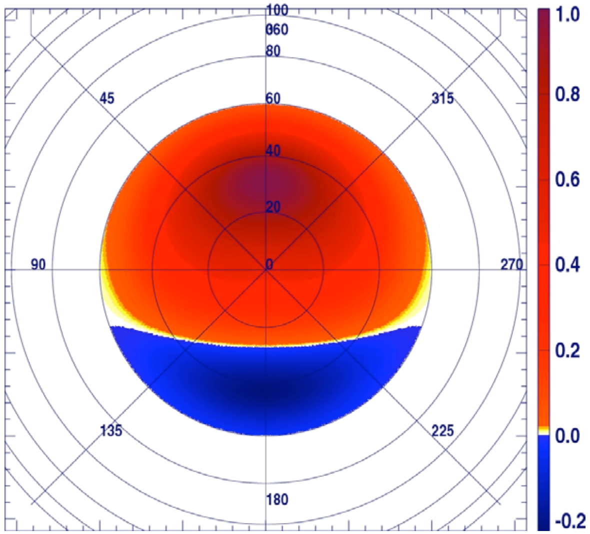
measured **simulated**

asymmetry of observed events

Lorentz force $\vec{v} \times \vec{B}$

v direction of shower axis
B direction of Earth magnetic field



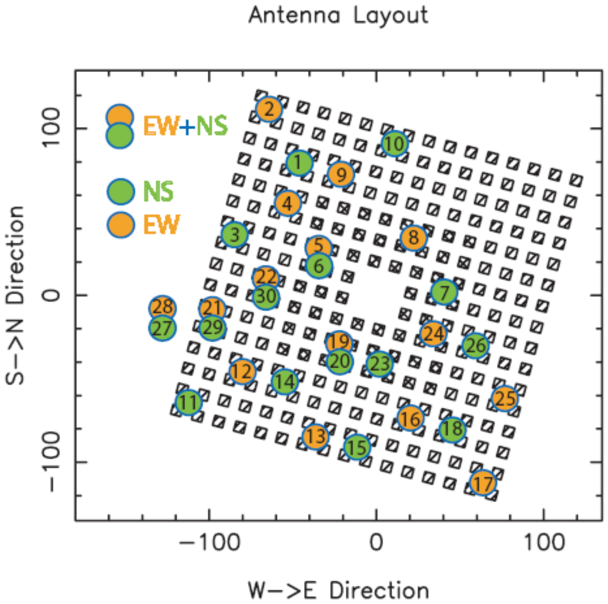


polarity of electric field

geomagnetic origin

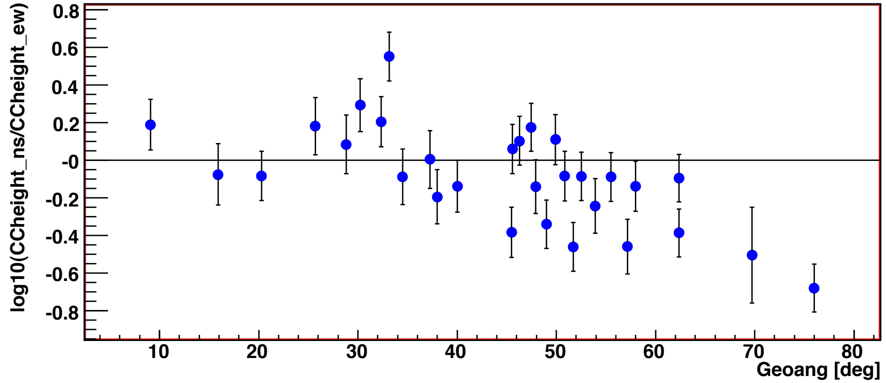
D. Arduin et al., Astropart. Phys. 31 (2009) 192

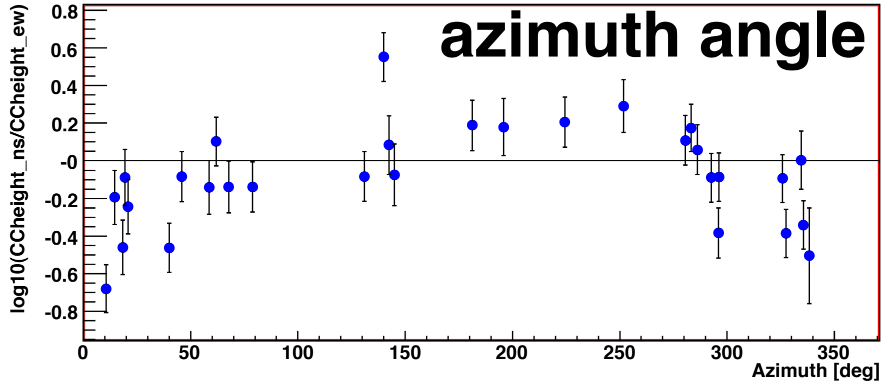
LOPES: Polarization Measurements

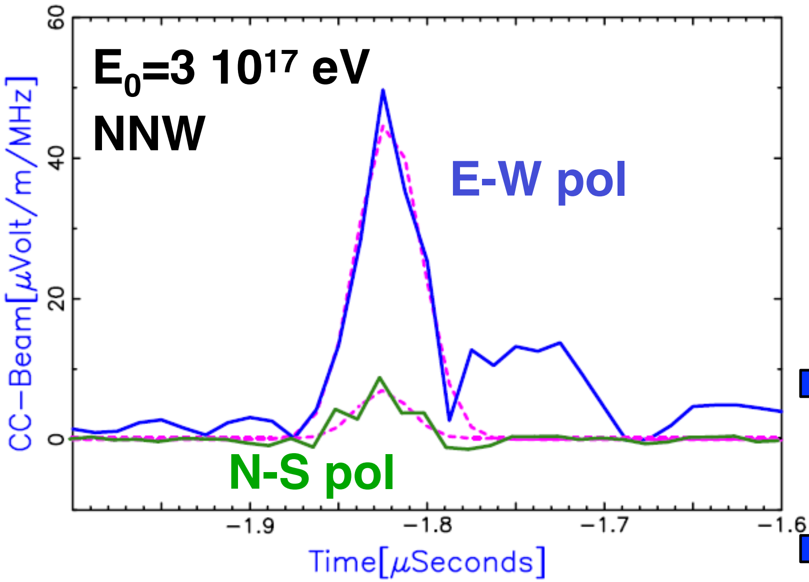


N-S / E-W

geomagnetic angle







emission mechanism related to Earth's magnetic field

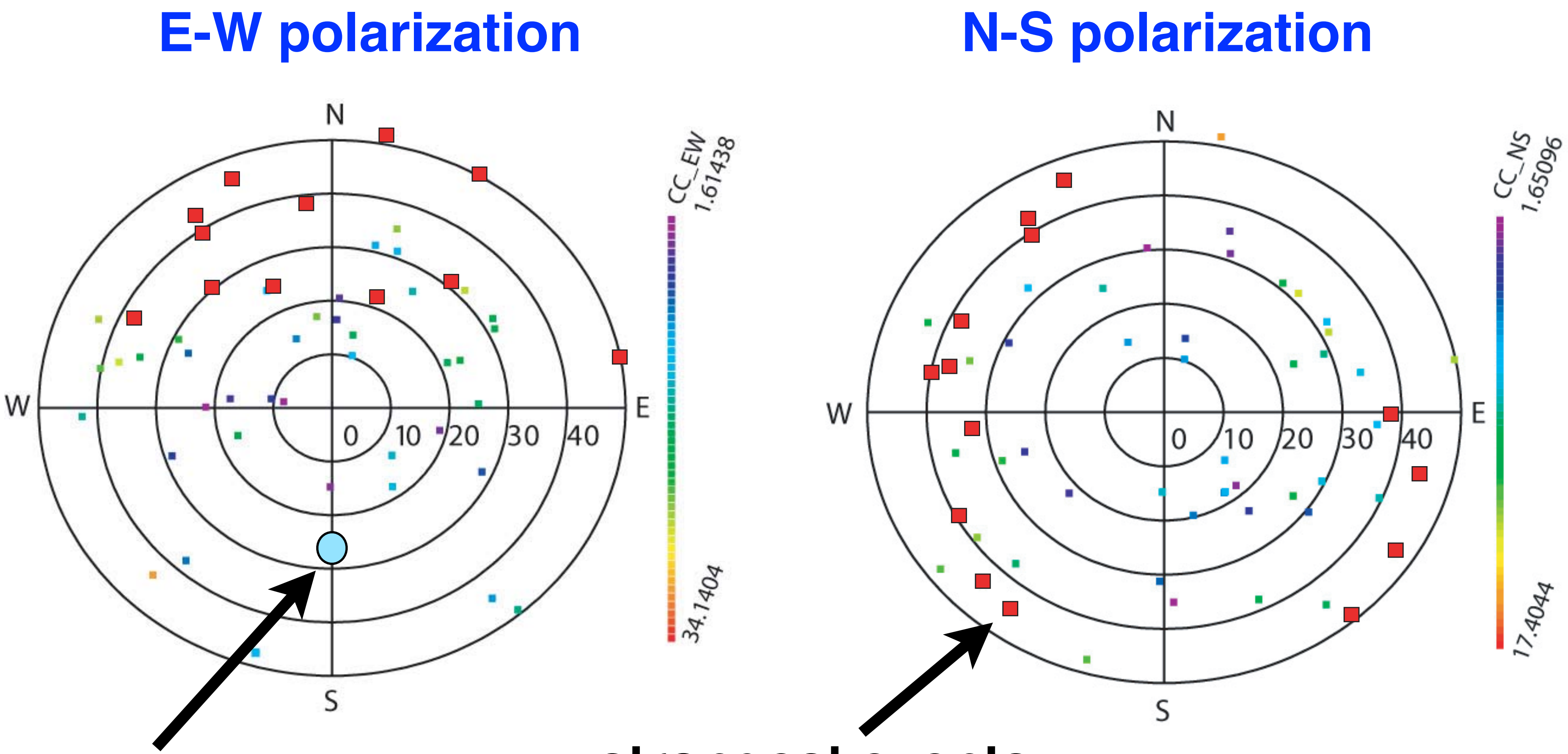
geo-synchrotron radiation

G. Isar et al., 30th ICRC 5 (2008) 1093

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

LOPES: Polarization Measurements

arrival direction of cosmic rays (sky map)

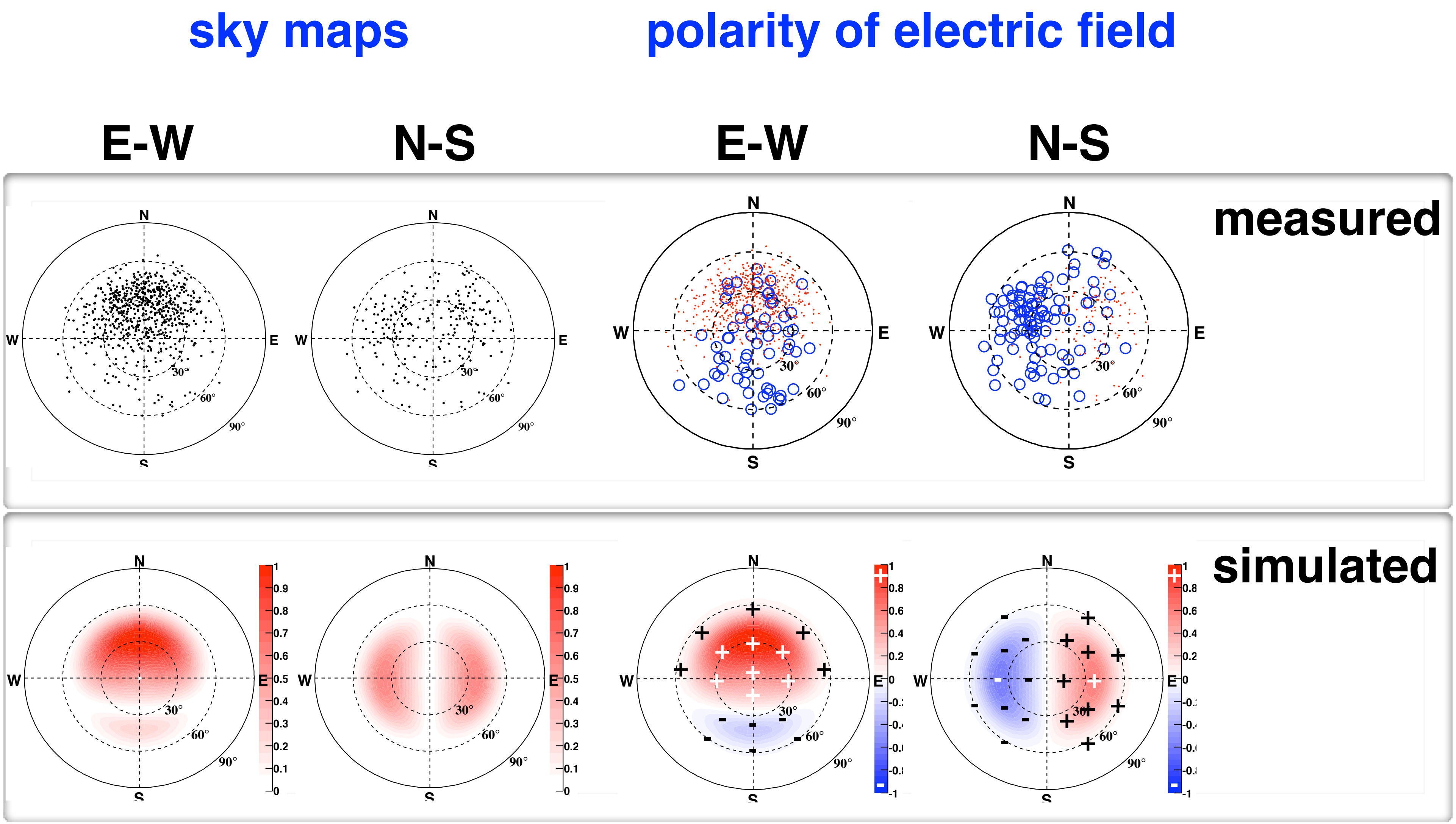


magnetic field
inclination: 64° 36'
declination: 1° 22'

strongest events

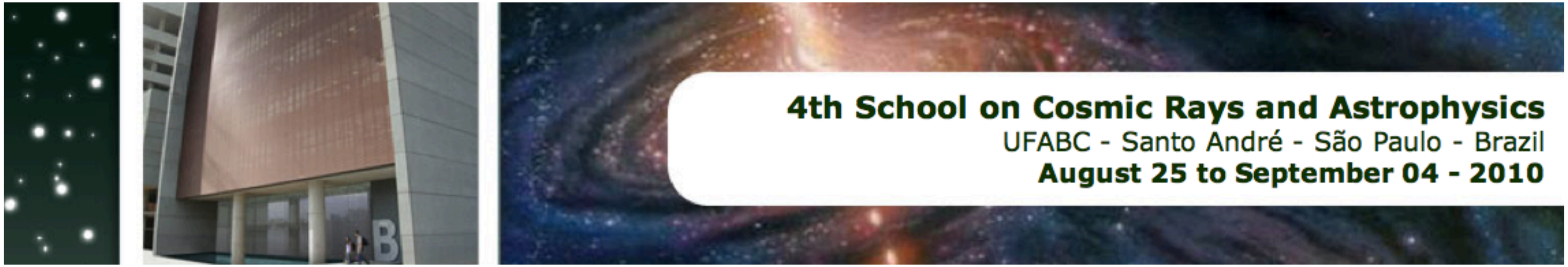
P.G. Isar et al., Nucl. Instr. & Meth. A 604(2009) S81

CODALEMA: Polarization of radio signal



polarization proportional to $E \propto \vec{v} \times \vec{B}$

C. Rivière et al., ICRC 2009



Radio Detection of Extensive Air Showers

Jörg R. Hörandel
Radboud University Nijmegen

IN·DEI·NOMINE·FELICITER

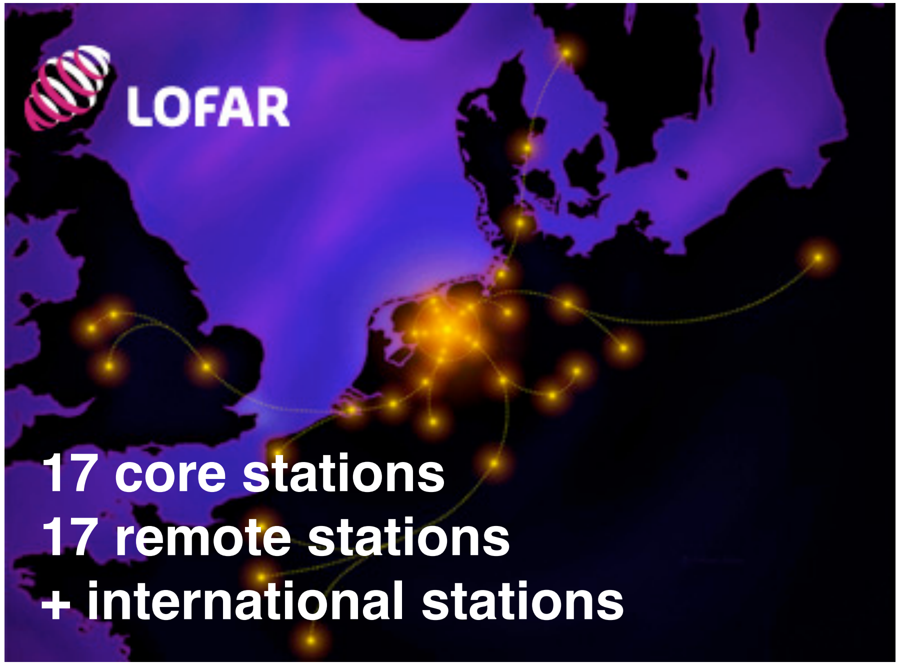
http://particle.astro.kun.nl

the next steps ...

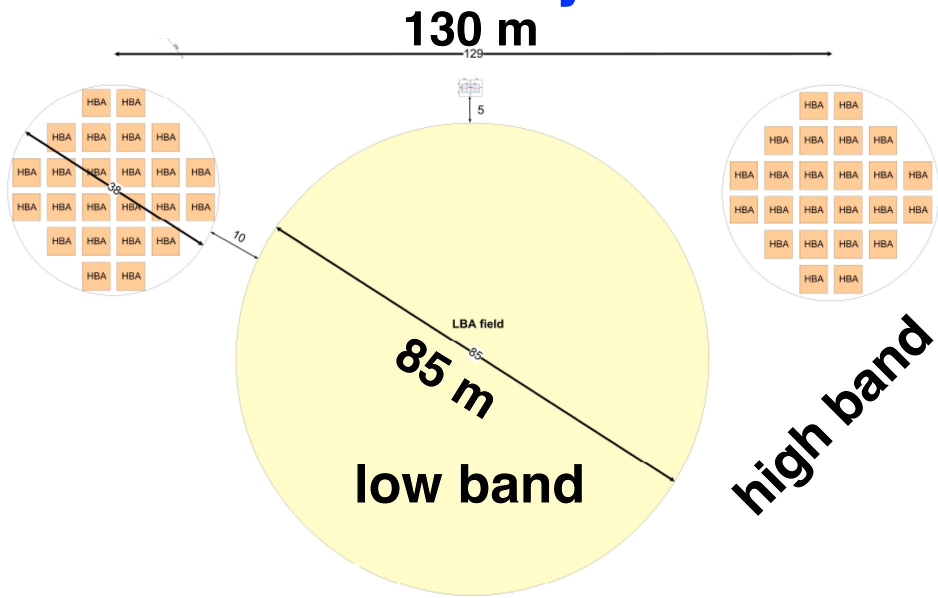
Radio Detection of Air Showers with LOFAR

LOFAR key science projects

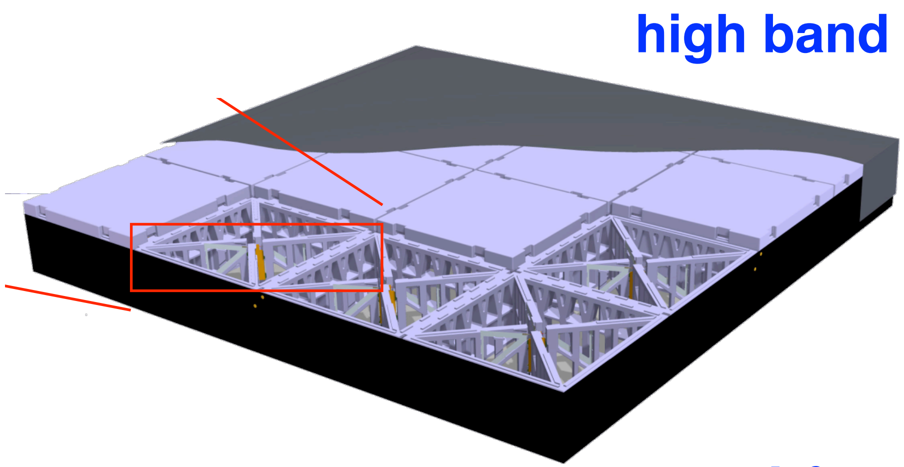
- Cosmology (Groningen)
  - Epoch of Reionization
- All-Sky Surveys (Leiden)
  - Star forming galaxies, AGN, Clusters, etc.
- Transient detection (Amsterdam)
  - Everything that bursts and varies
- Cosmic Rays (Nijmegen)
  - Measurement of extensive air showers
  - Cosmic rays & neutrinos impacting the moon
- Cosmic Magnetism (Bonn)
  - Strength and distribution of weak intergalactic magnetic fields.
- The Sun (Potsdam)



Station Layout



each (dutch) station:
96 low-band antennae 30- 80 MHz
high-band antennae (2x24 tiles) 120-240 MHz

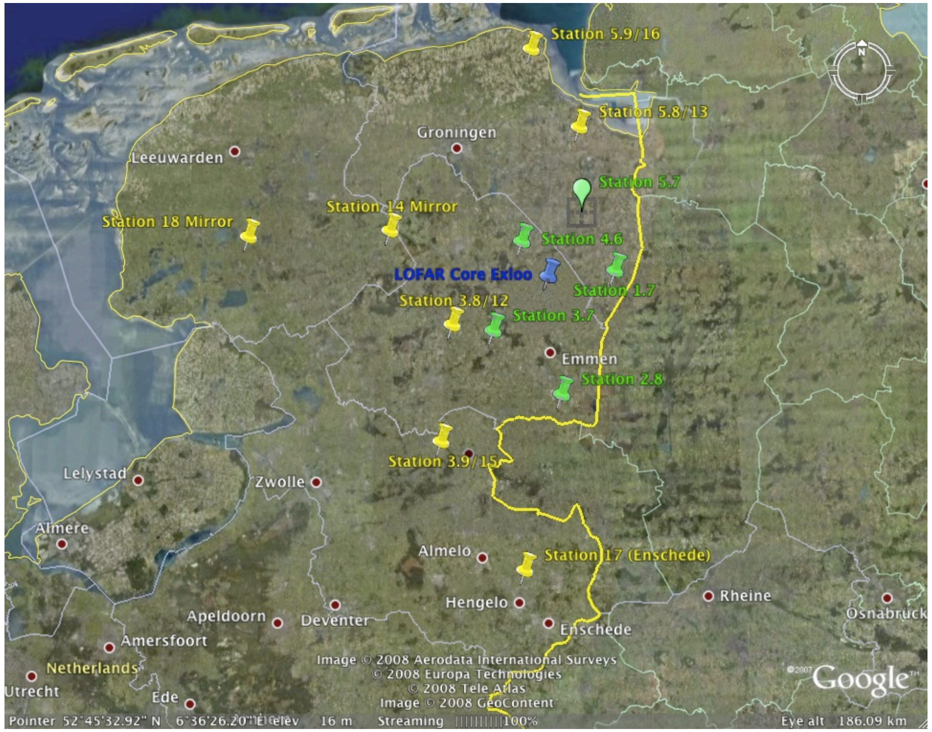


www.lofar.org

LOFAR Station Layout

Remote NL stations

(12 + 6 stations)



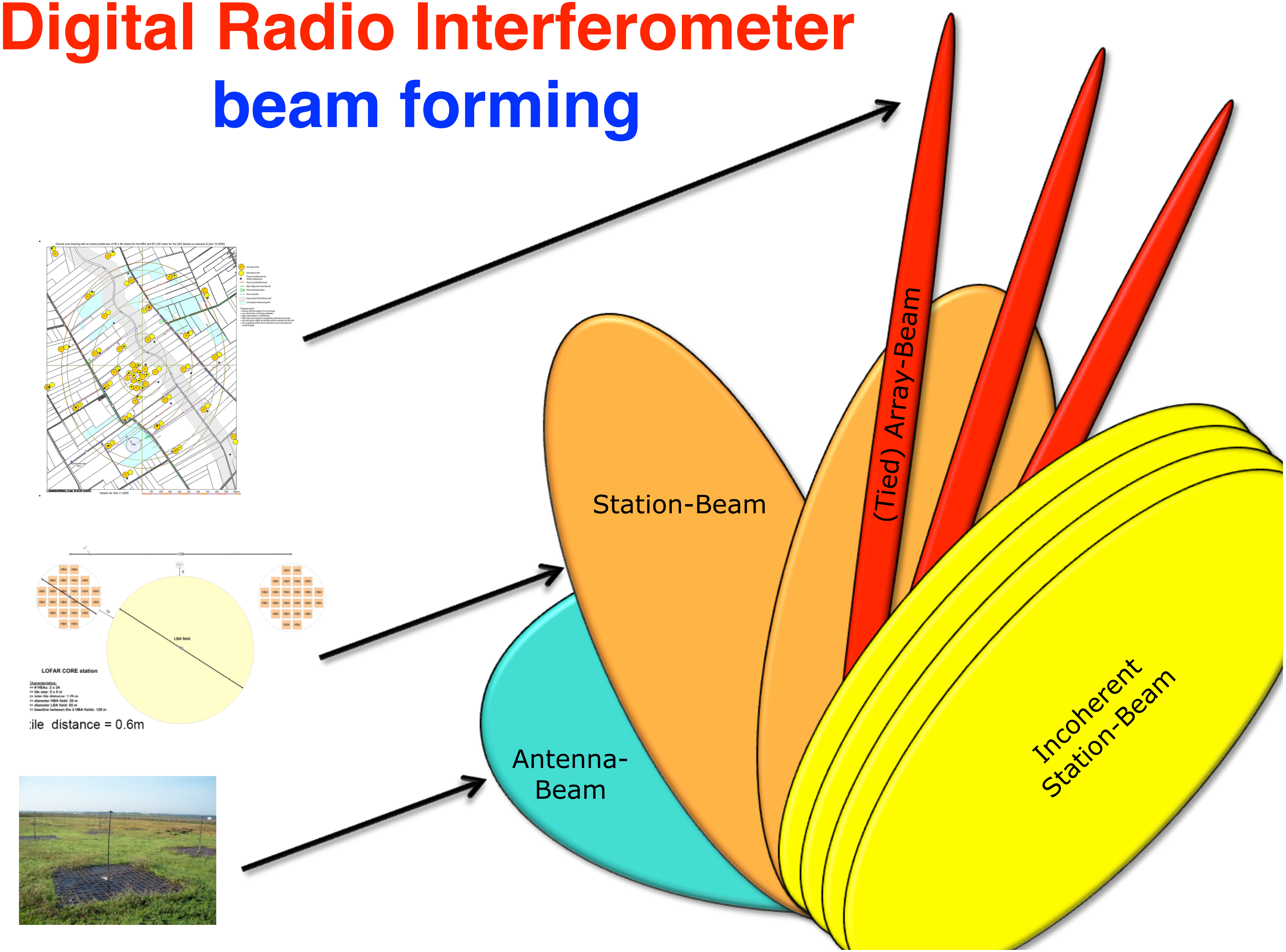
Core: 2 km

18 stations

First stations in the field

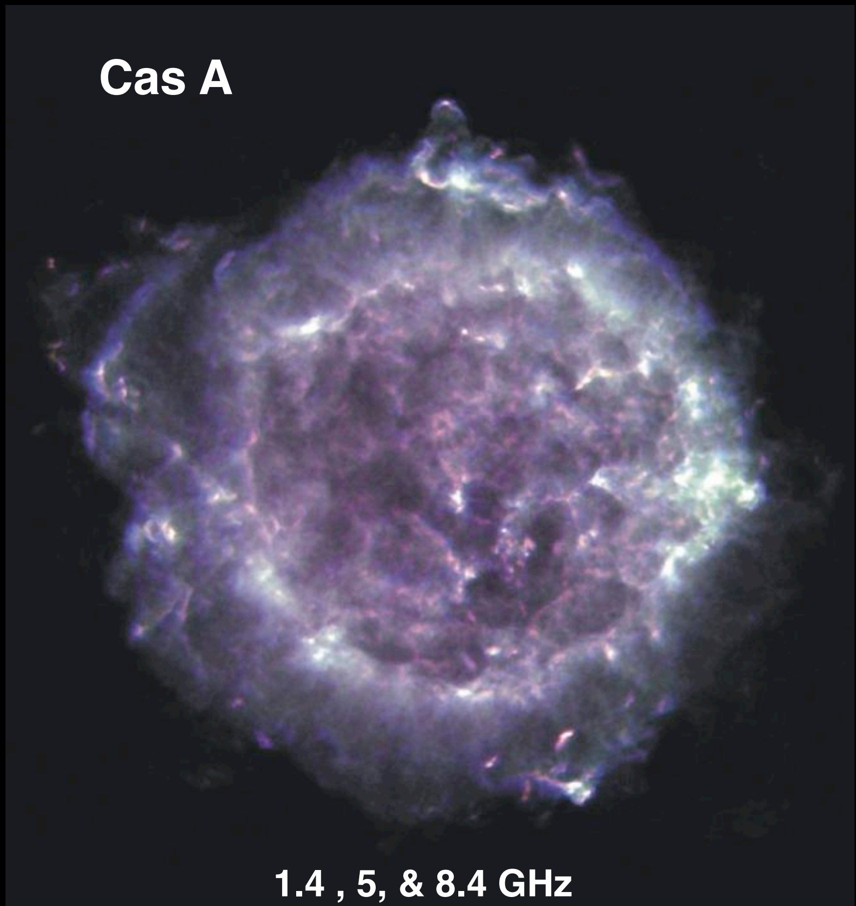
LOFAR Opening 12th June 2010

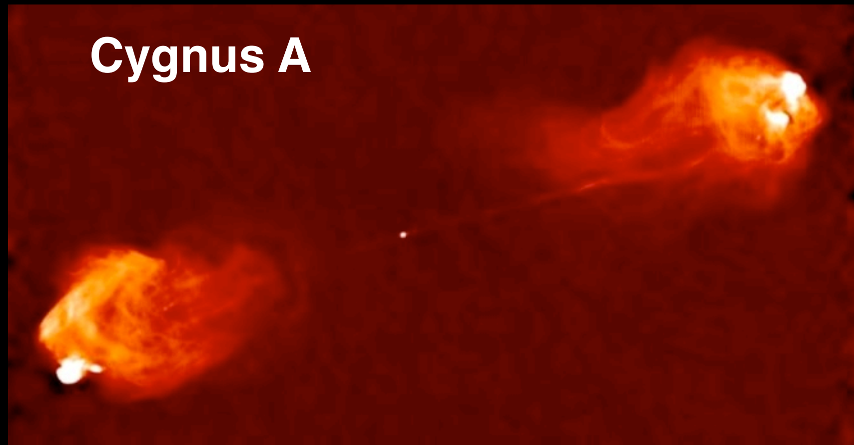
Digital Radio Interferometer
beam forming



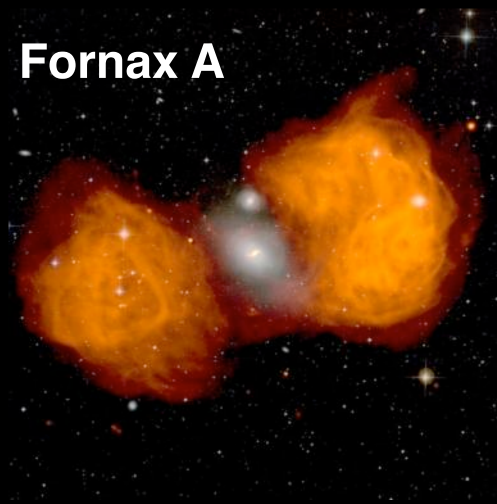
Main goal of LOFAR is imaging

Radio images of cosmic accelerators …





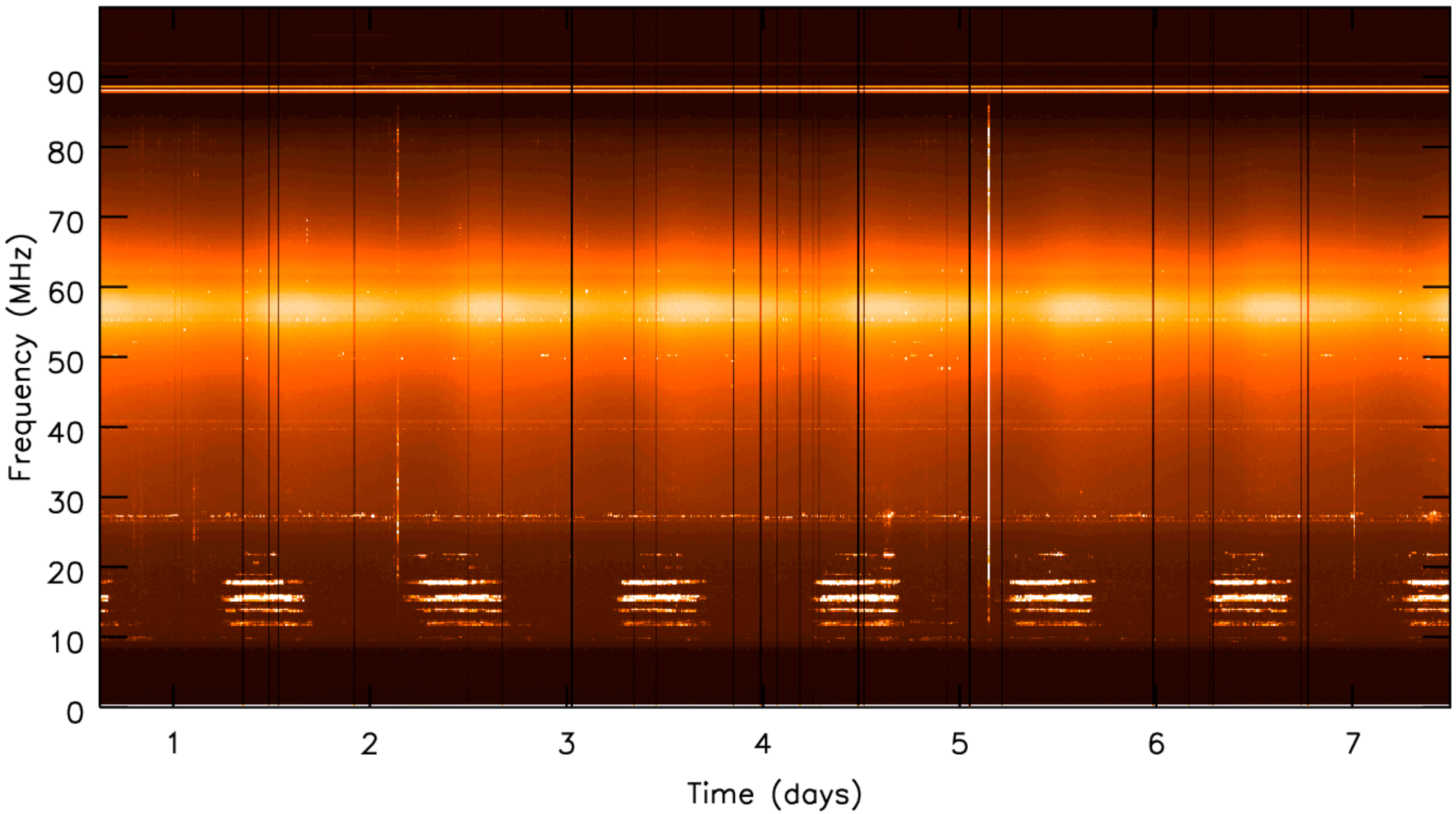
NRAO/AUI



Transient Buffer Board

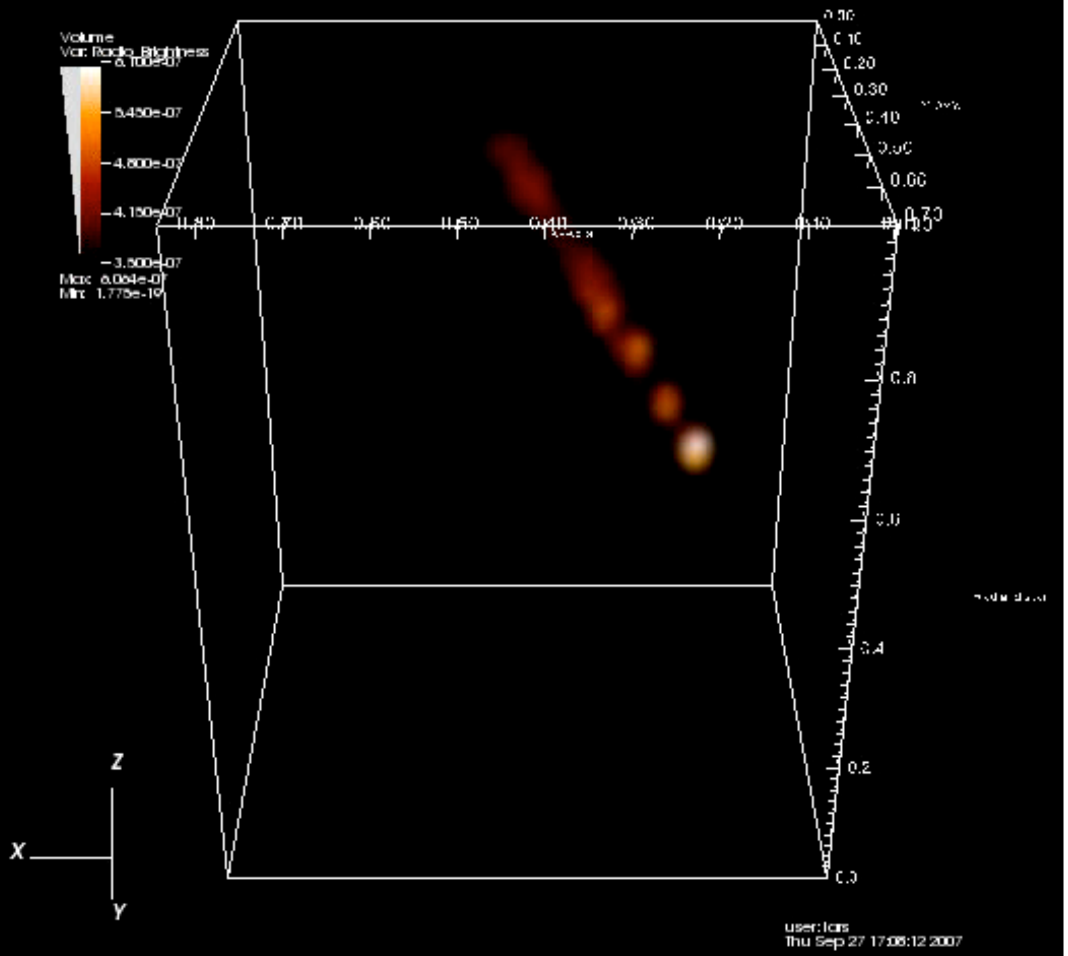
(0.5 GB Ram + FPGA)

first background data (Feb 2008)



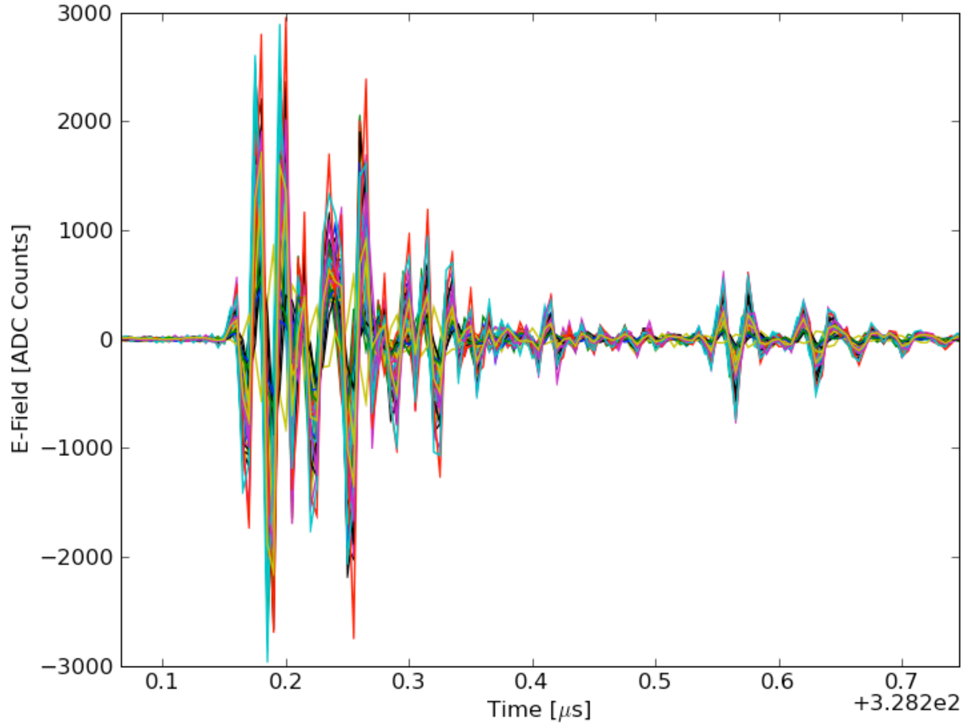
Nanosecond Radio Imaging in 3D

- Off-line correlation of radio waves captured in buffer memory
- We can map out a 5D image cube:
  - 3D: space
  - 2D: frequency & time
- Image shows brightest part of a radio air shower in a 3D volume at $t=t_{max}$ and all frequencies



Actual 3D radio mapping of a CR burst

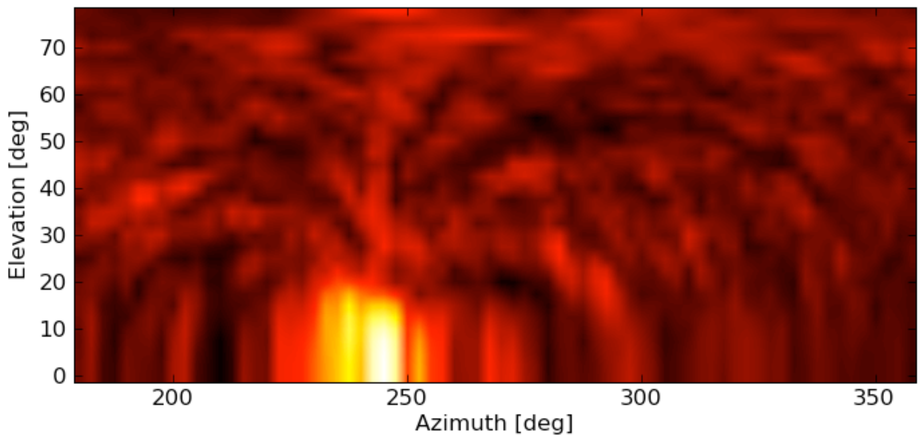
No simulation!



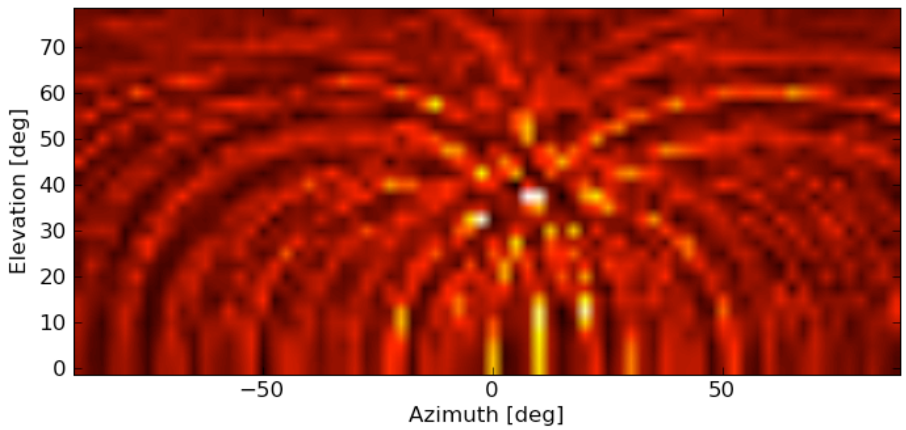
Radio Triggered Event

Skymap of Triggered Event

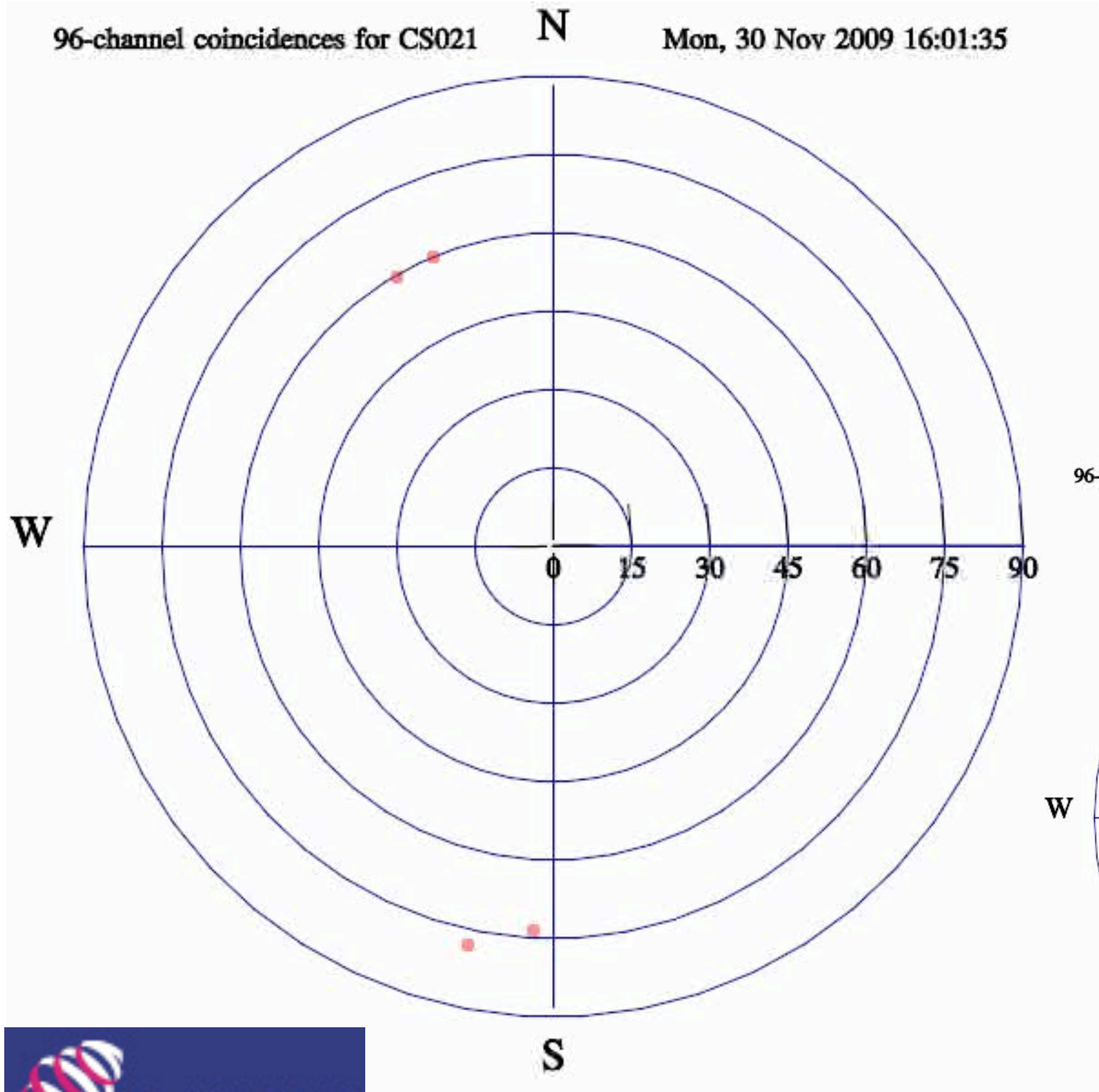
LOFAR



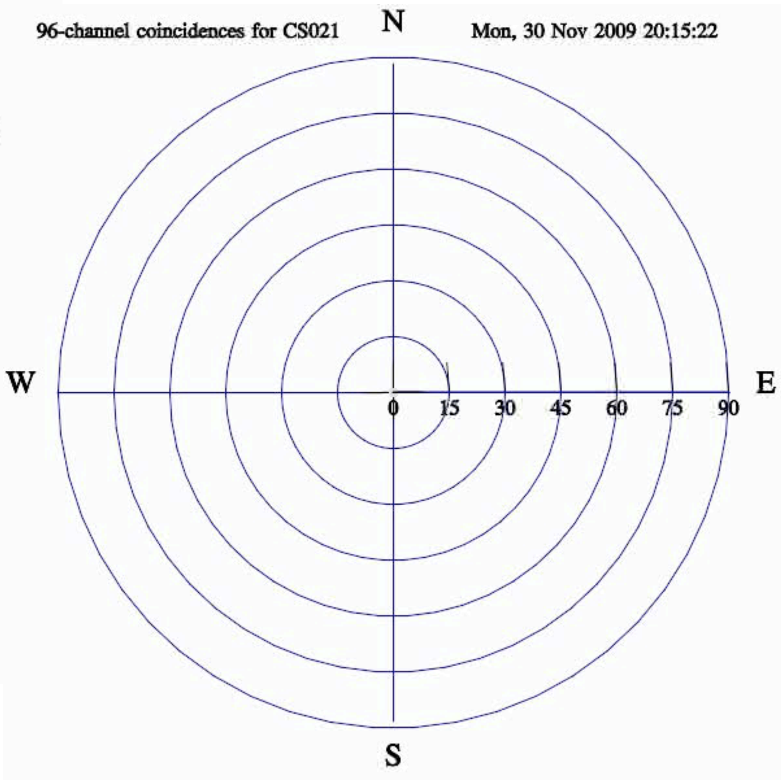
LOPES



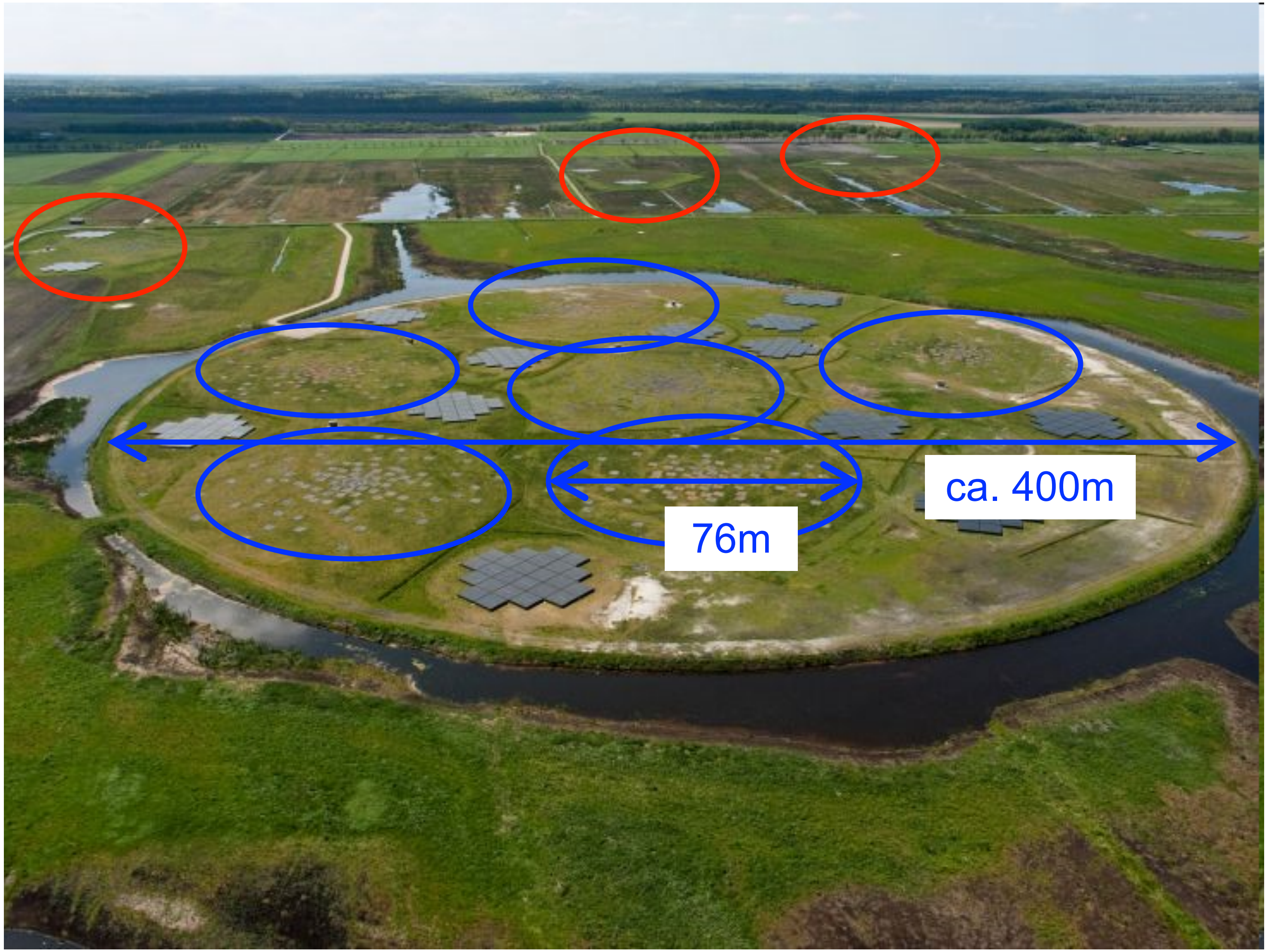
Sky map of TBB triggers



airplane



LOFAR core

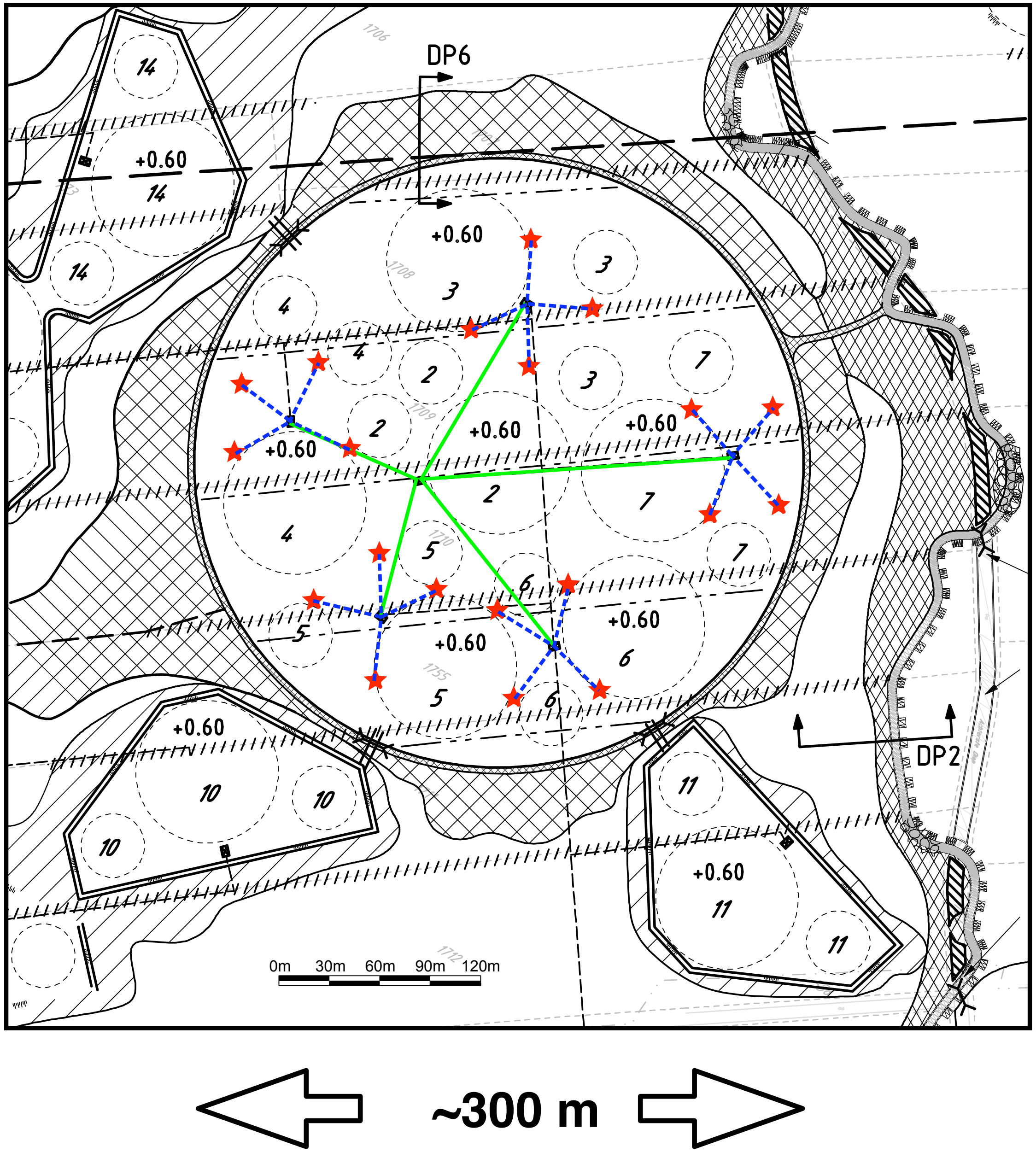


LOFAR

LOFAR Radboud Air Shower Array - LORA

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

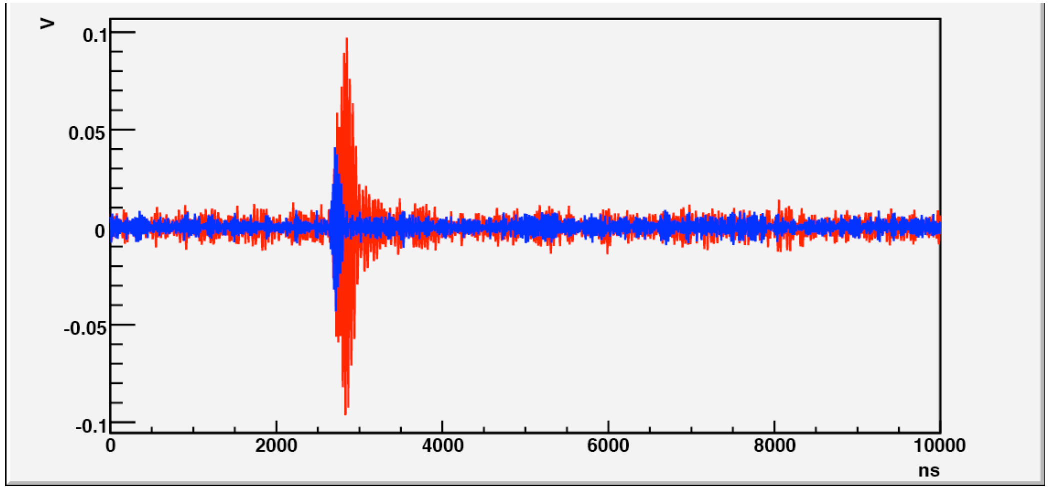
➡ provide basic information on EAS and trigger



the next steps ...

Radio Detection at the Pierre Auger Observatory

Cosmic-Ray Event measured at Auger site



Antennas installed at Auger site in Malargue

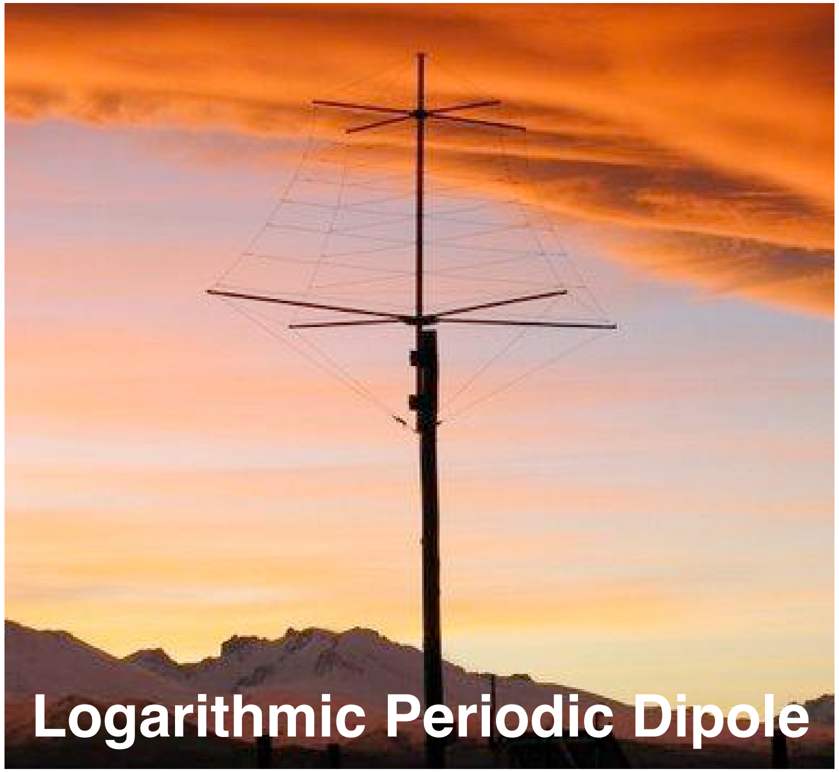
first signals detected

Explore possibility to instrument large area

AERA
Auger Engineering Radio Array

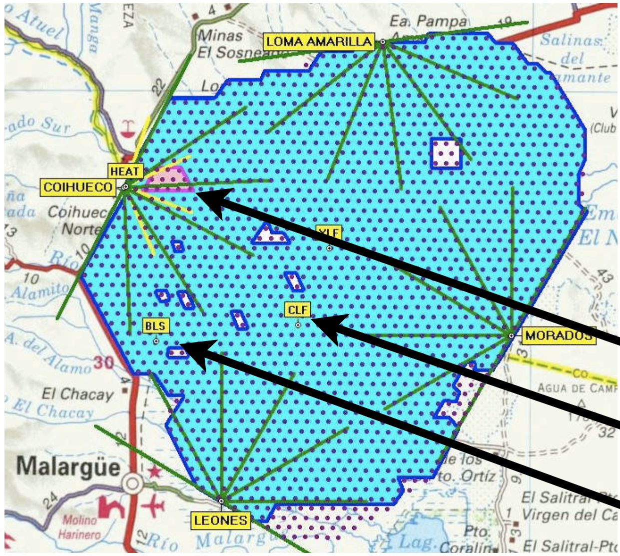
PIERRE AUGER OBSERVATORY

Test measurements at Pierre Auger Observatory



AERA Auger Engineering Radio Array

PIERRE AUGER OBSERVATORY



presently 3 radio test sites:

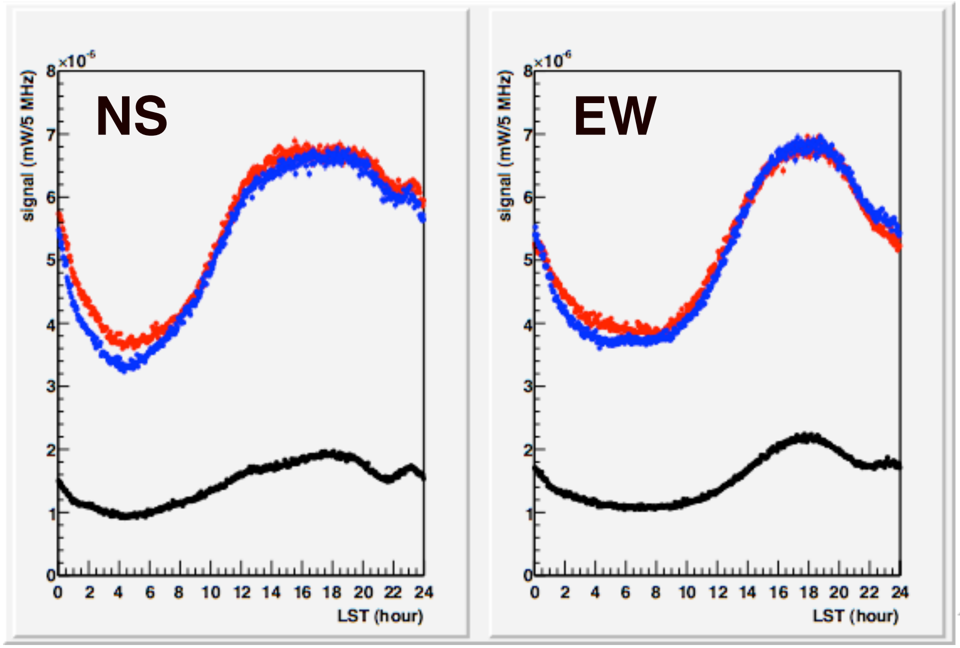
- AERA Auger Engineering Radio Array
- CLF
- BLS

Test of different antenna designs

Galactic background measured with LPDA

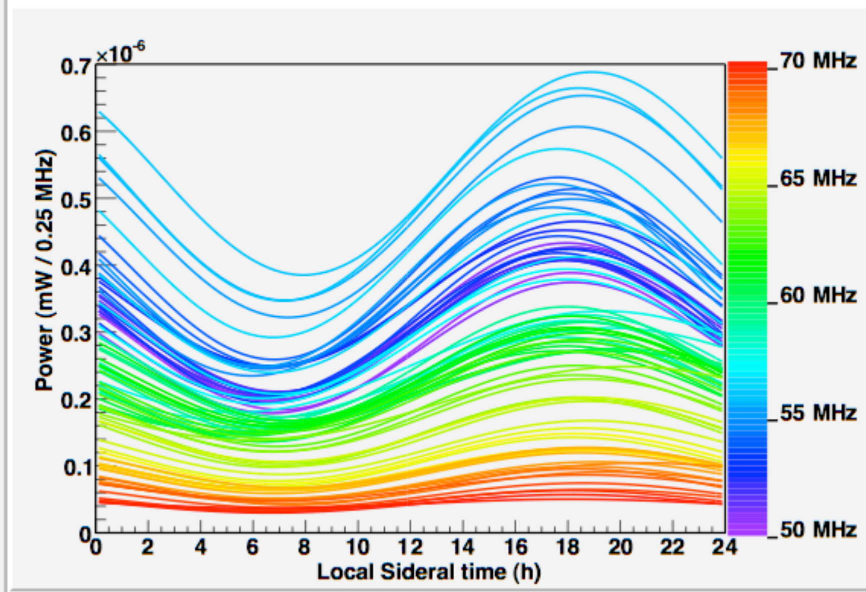
measured

signal (mW/5MHz)



LST (hour)

expected



Use galactic background to calibrate individual antennas in-situ

Power as function of time for every 0.25 MHz between 50 and 70 MHz

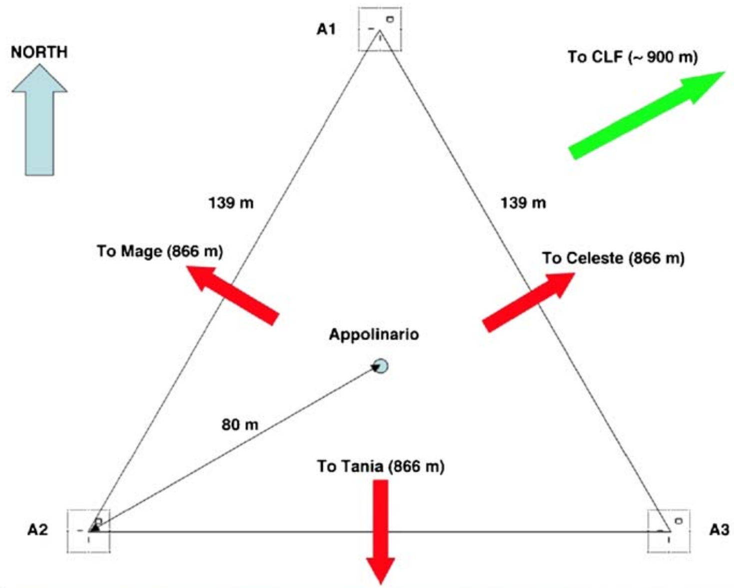
PIERRE AUGER OBSERVATORY

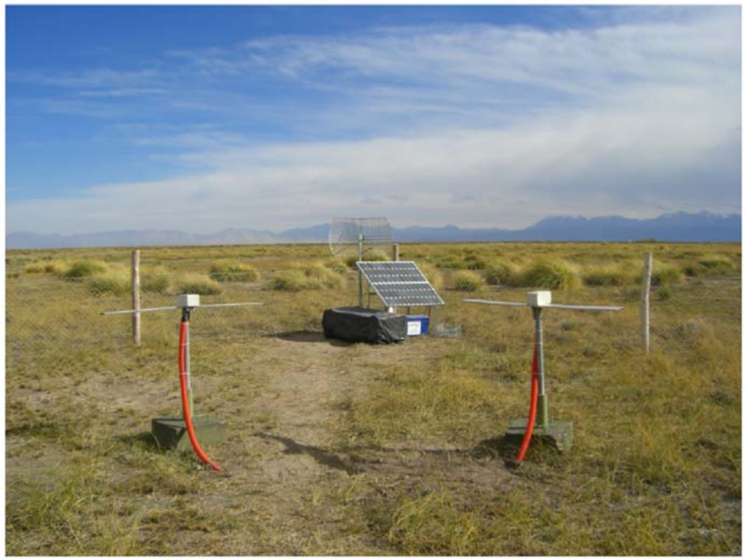
AERA Auger Engineering Radio Array

J. Coppens et al., Nucl. Instr. & Meth. A 604 (2009) S41

Test measurements at Auger: short dipoles

set-up





sky map - thunderstorm

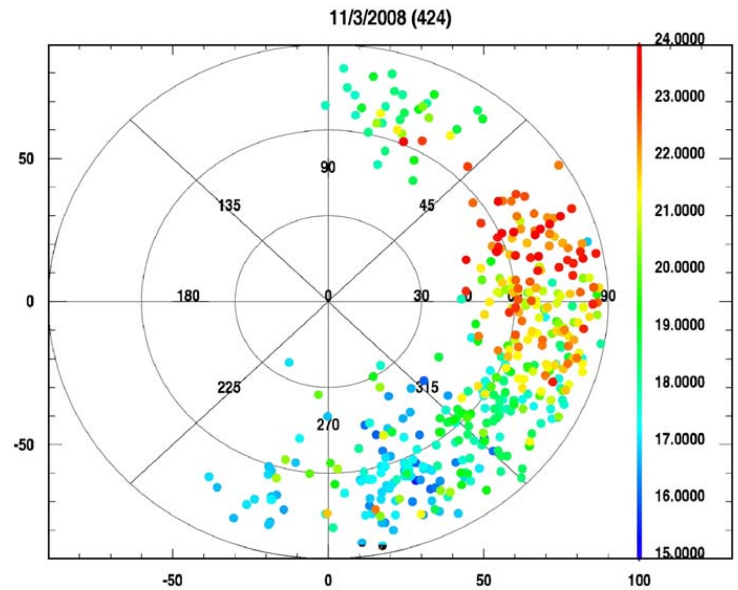


Fig. 6. Sky map in local coordinates of the 424 three-fold radio events detected on March 11, 2008. The color scale corresponds to the UTC time of each event. The "source" (thunderstorm) is moving from South to East between 17 h UTC and 24 h UTC at zenith between 55° and 70°.

B. Revenu, Nucl. Instr. & Meth. A 604 (2009) S37

Test measurements at Auger: short dipoles

event density on ground

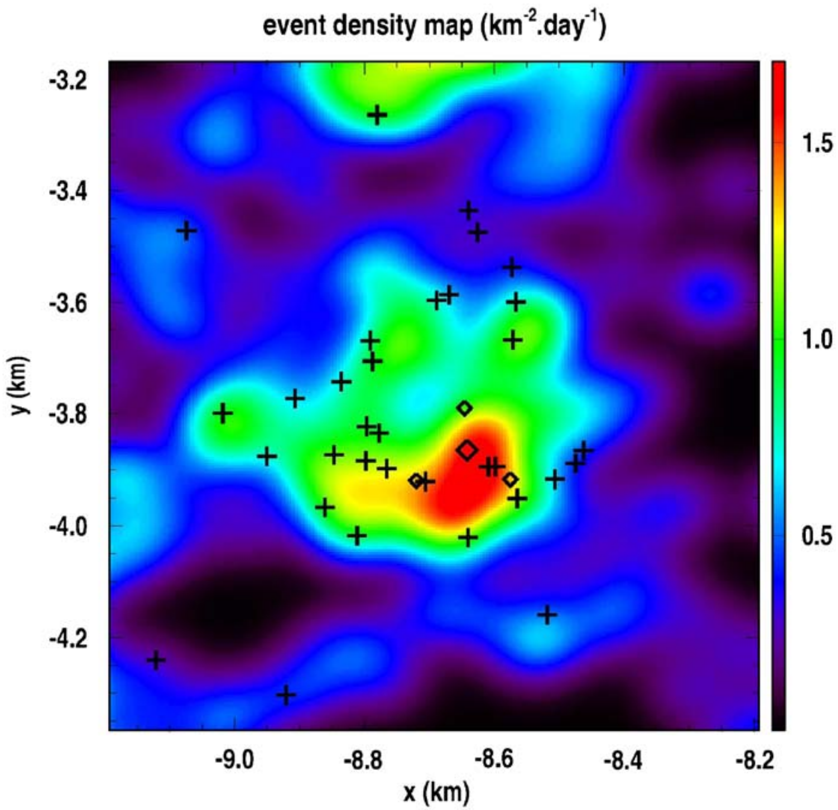


Fig. 4. Event ground density map around Apolinario, computed from the official Auger event list and smoothed by a 50 m width Gaussian. The color scale is in number of events m^{-2} day^{-1}. The Auger events with a radio counterpart are indicated by the black crosses. Apolinario is the largest diamond at the center and the three radio stations are the smallest diamonds around.

sky map

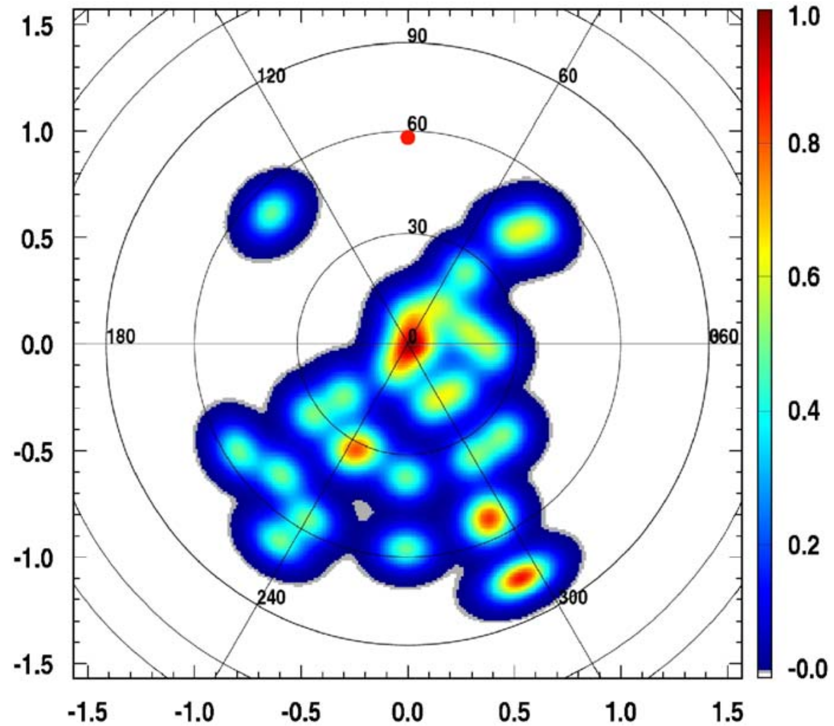


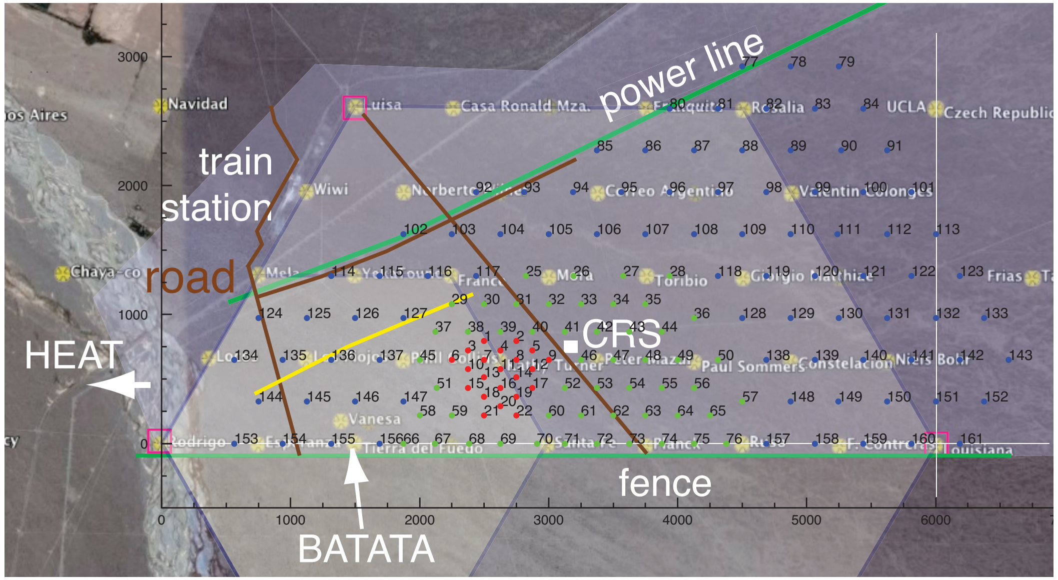
Fig. 5. Sky map in local coordinates of the radio events seen in coincidence with Auger SD and smoothed by a 10° Gaussian beam. The zenith is at the center, North at the top, East on the right. The 75.8% of the events are coming from the South while the Auger SD events sky map is uniform in azimuth. The red dot towards the north at $\theta \sim 58^\circ$ is the location of the geomagnetic field in Malargüe. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

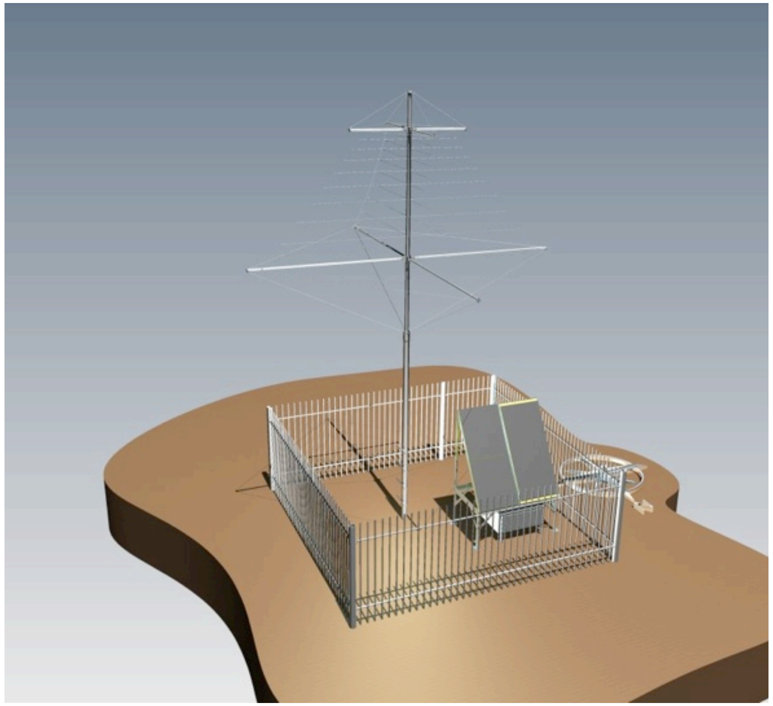
PIERRE AUGER OBSERVATORY

AERA Auger Engineering Radio Array

B. Revenu, Nucl. Instr. & Meth. A 604 (2009) S37

Auger Engineering Radio Array

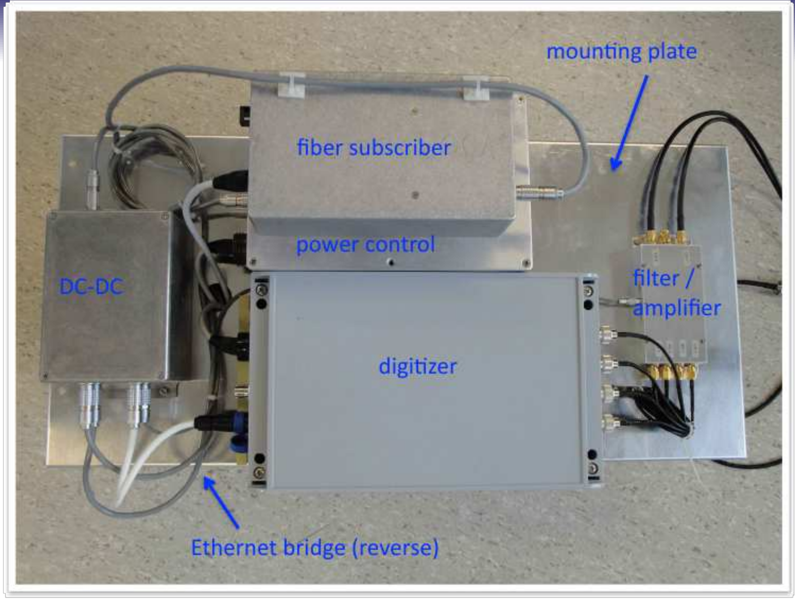


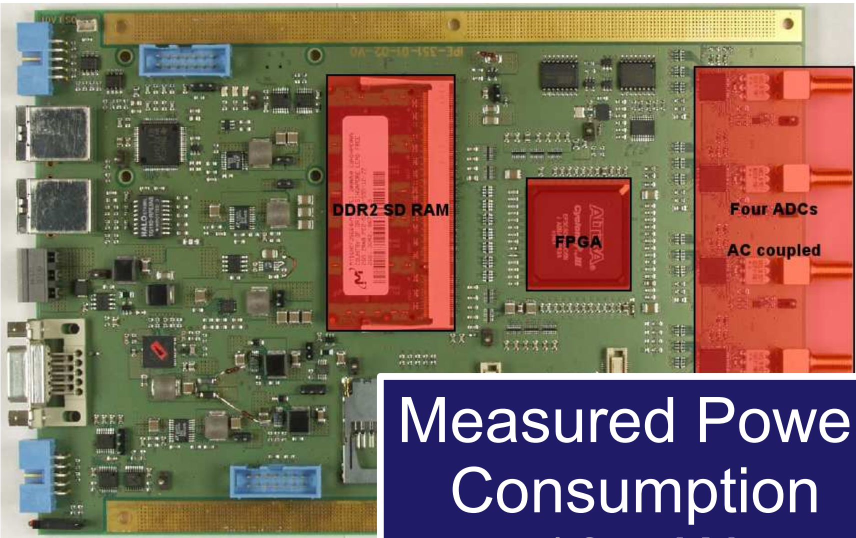


- ~20 km²
- ~150 antennas
- operation together with infill/HEAT/AMIGA
- three antenna spacings to cover efficiently 17.2 < lg E < 19.0
- measure composition of cosmic rays in energy region of transition from galactic to extragalactic cosmic rays

Radio Detector Station Electronics

- Filter / Amplifier
- ADCs
- Comms
- Monitoring
- Power control
- 3 Seconds Ring Buffer





Measured Power Consumption 16.5 W

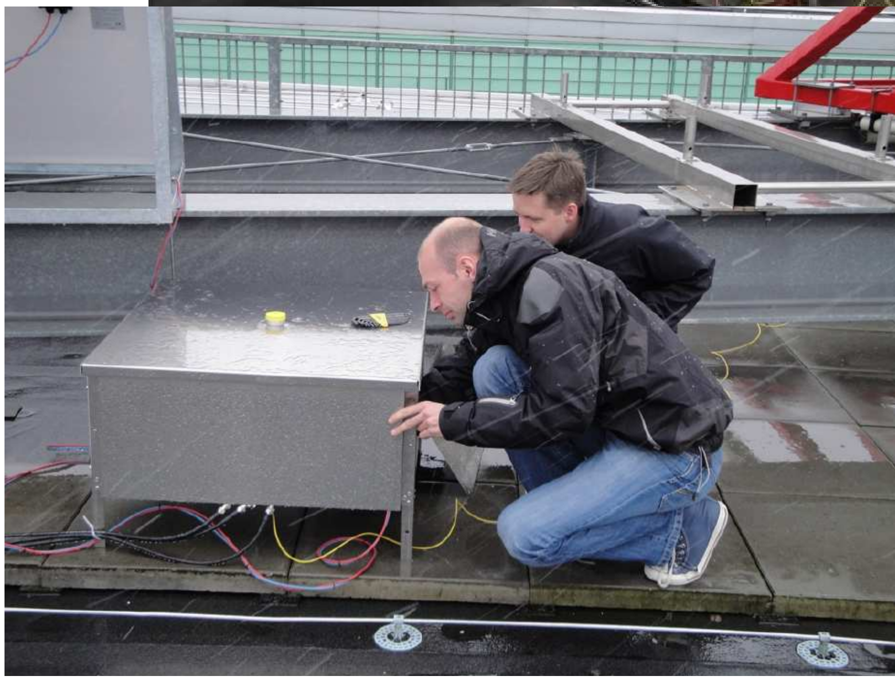
FPGA - on the fly:

- FFT
  - Noise Reduction
  - Dispersion Correction
- FFT $^{-1}$
- Trace Envelope
- Signal Analysis

} Trigger Decision

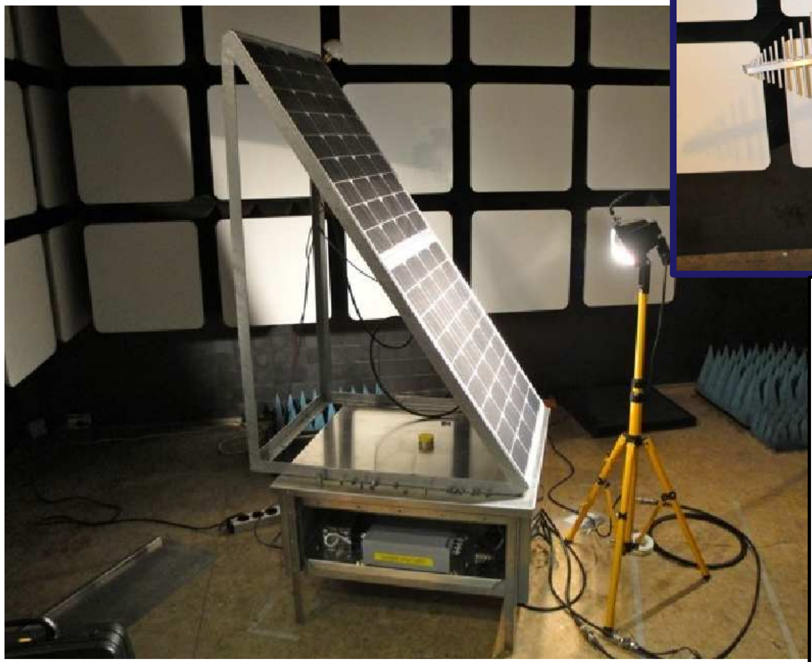
AERA
Auger Engineering Radio Array

AERA system integration at Radboud University Nijmegen



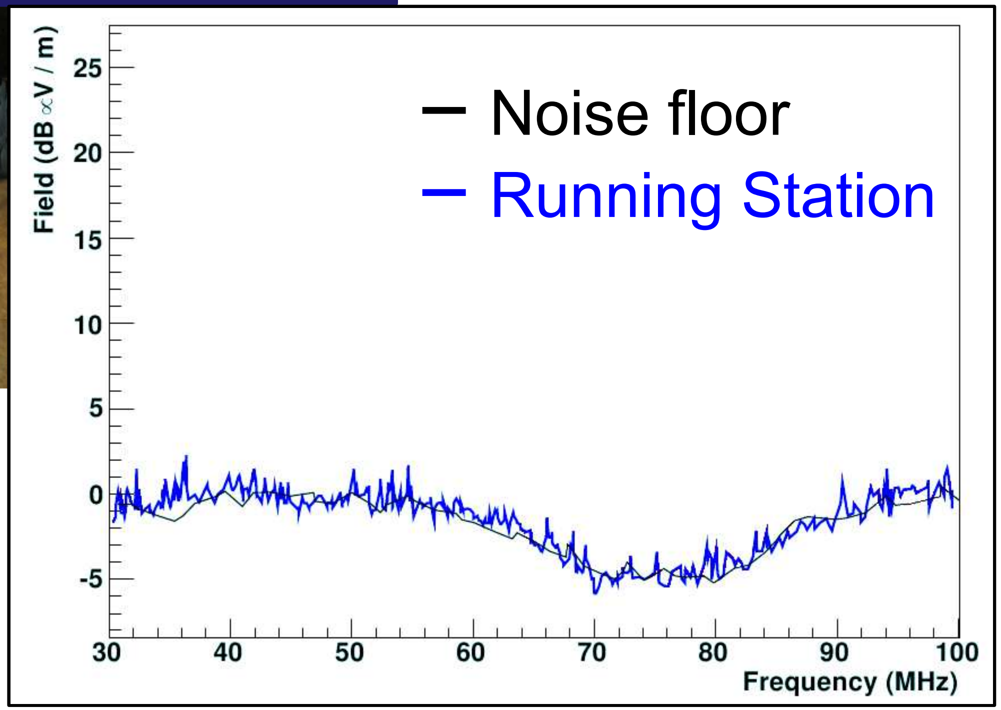
Test of Assembled Hardware Components

EMC Testing Chamber



'Radio Quietness' of the hardware:

- Shielded box
- Carefully selected items

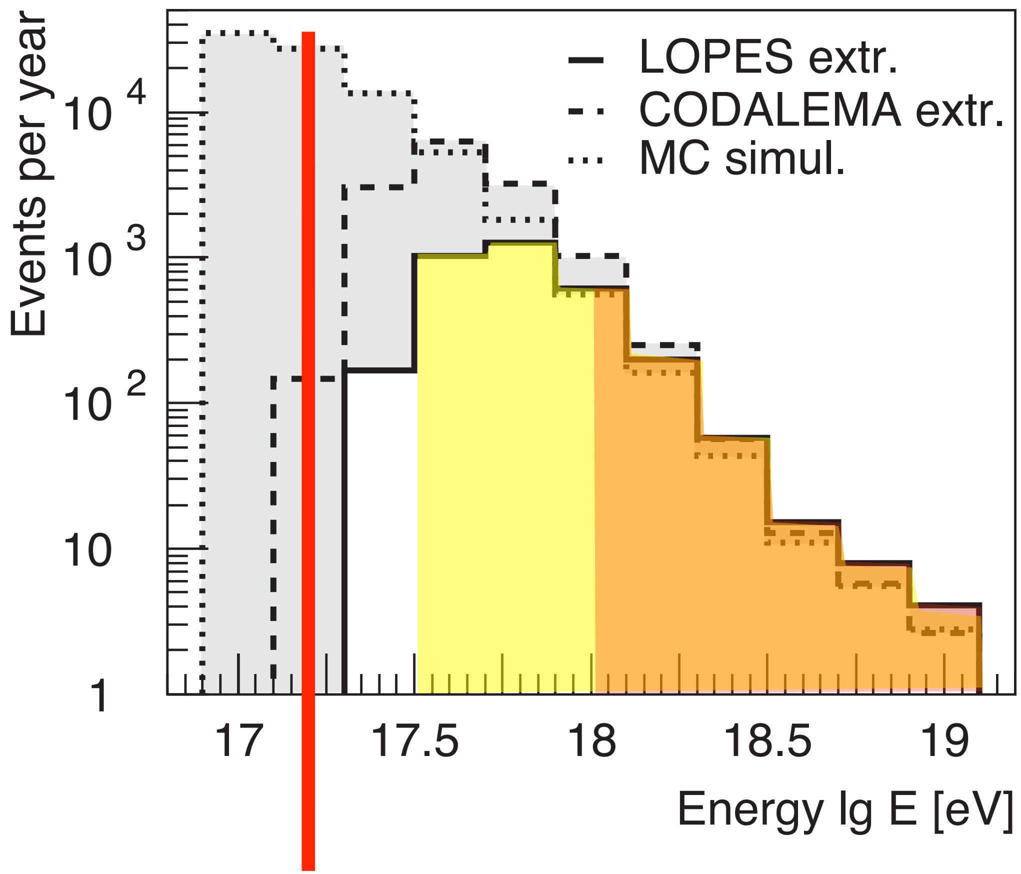


Auger Engineering Radio Array

First AERA hardware installed at the Pierre Auger Observatory

Expected event rates

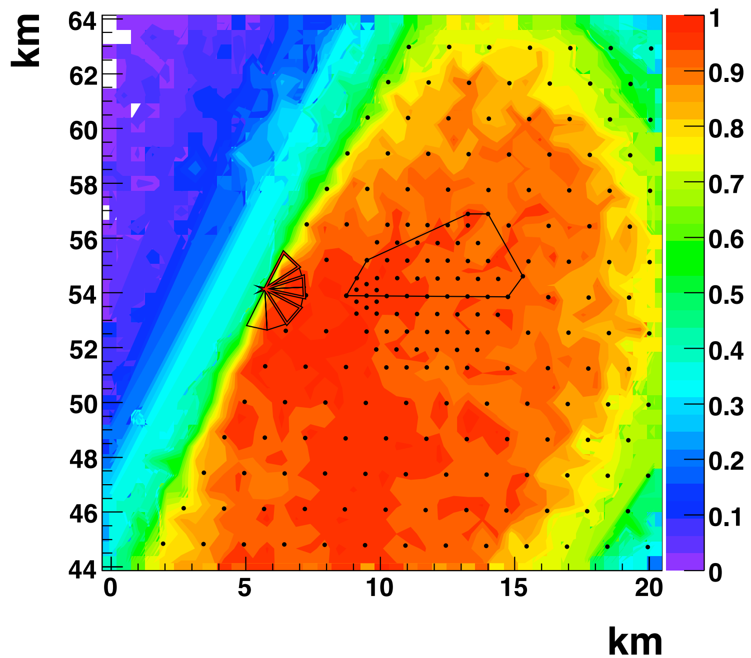
effective area + Auger energy spectrum (PRL)



$$\lg E_{thr}/\mathrm{eV} \approx 17.2$$

conservative estimate:
> 3 10^{17} eV: >5000 ev/yr
> 10^{18} eV: > 800 ev/yr

FD (HEAT & Coihueco)
trigger efficiency, E=10^{18} eV

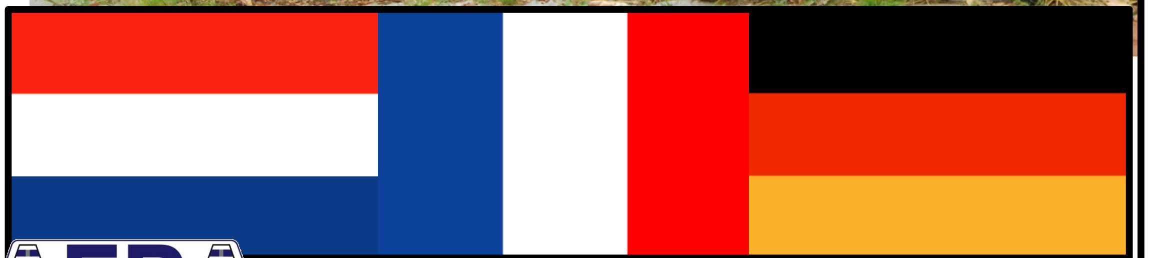


(Steffen Müller, Karlsruhe)

AERA
Auger Engineering Radio Array

PIERRE AUGER OBSERVATORY

The AERA Group



Bergische Universität, Wuppertal
KIT, Campus North, IK, Karlsruhe
IMAPP, Radboud University, Nijmegen
KIT, Campus North, IPE, Karlsruhe
KVI, University of Groningen, Groningen
LPSC, Grenoble
Nikhef, Amsterdam & Nijmegen
RWTH Aachen University, Aachen
SUBATECH, Nantes
KIT, Campus South, EKP, Karlsruhe

LOFAR & AERA are complementary

- ~900 dual-polarized dipoles within 2x2 km
- ~900 dual-polarized dipoles out to 50 km
- high antenna density

⇒ Precise shower front (curvature) and hence accurate composition & direction

- 20 km^2 dual polarized test array (~150 antennas)
- Gives high duty cycle for hybrid events (+SD)
- Combination with surface detectors and fluorescence telescopes will allow triple coincidences ("tri"-brid events)

⇒ Cross-calibration between methods

⇒ Accurate determination of all UHECR parameters

LOFAR

AERA
Auger Engineering Radio Array

Radio Emmission Processes

Geo-Magnetic-Radiation Model

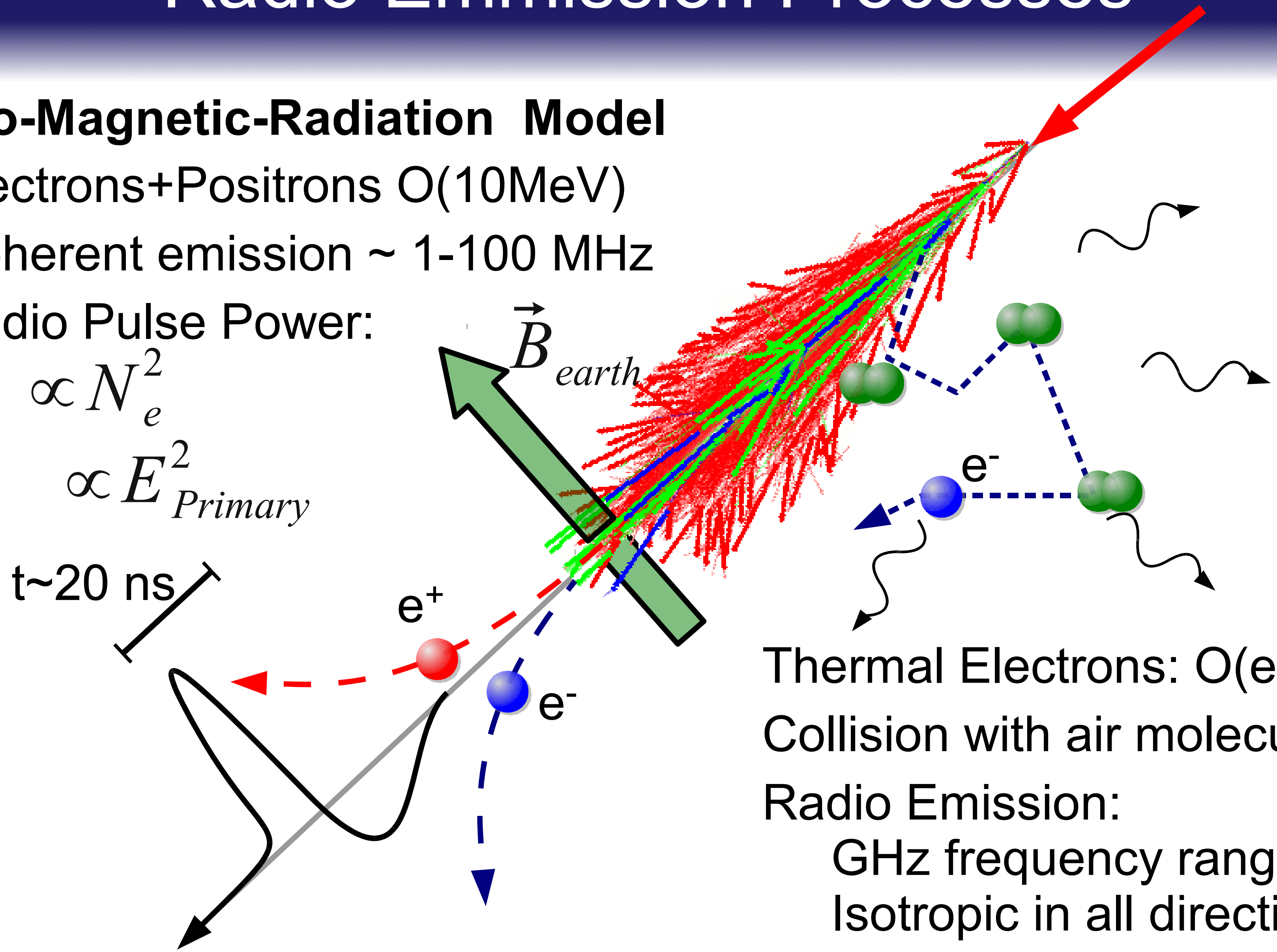
Electrons+Positrons O(10MeV)

Coherent emission ~ 1-100 MHz

Radio Pulse Power:

$$\propto N_e^2$$

$$\propto E_{Primary}^2$$



Thermal Electrons: O(eV)

Collision with air molecules

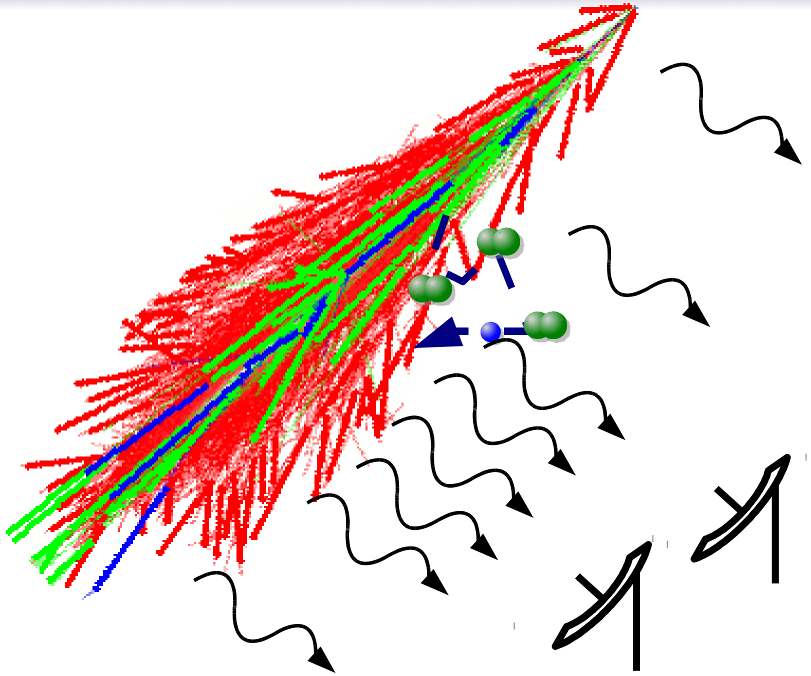
Radio Emission:

GHz frequency range

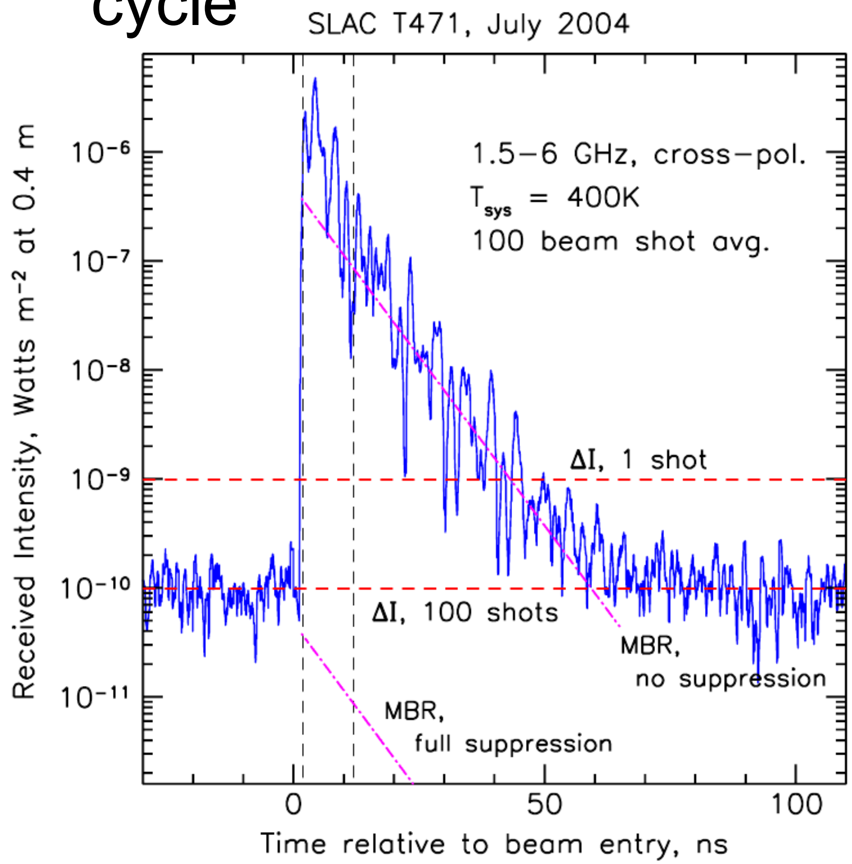
Isotropic in all directions

Molecular Bremsstrahlung

Molecular Bremstrahlung for Air Shower Detection



Watching shower evolution
→ Fluorescence Detector like measurement at 100% duty cycle



Molecular Bremsstrahlung observed at accelerator setup:
- Beam on fixed target mimics airshower

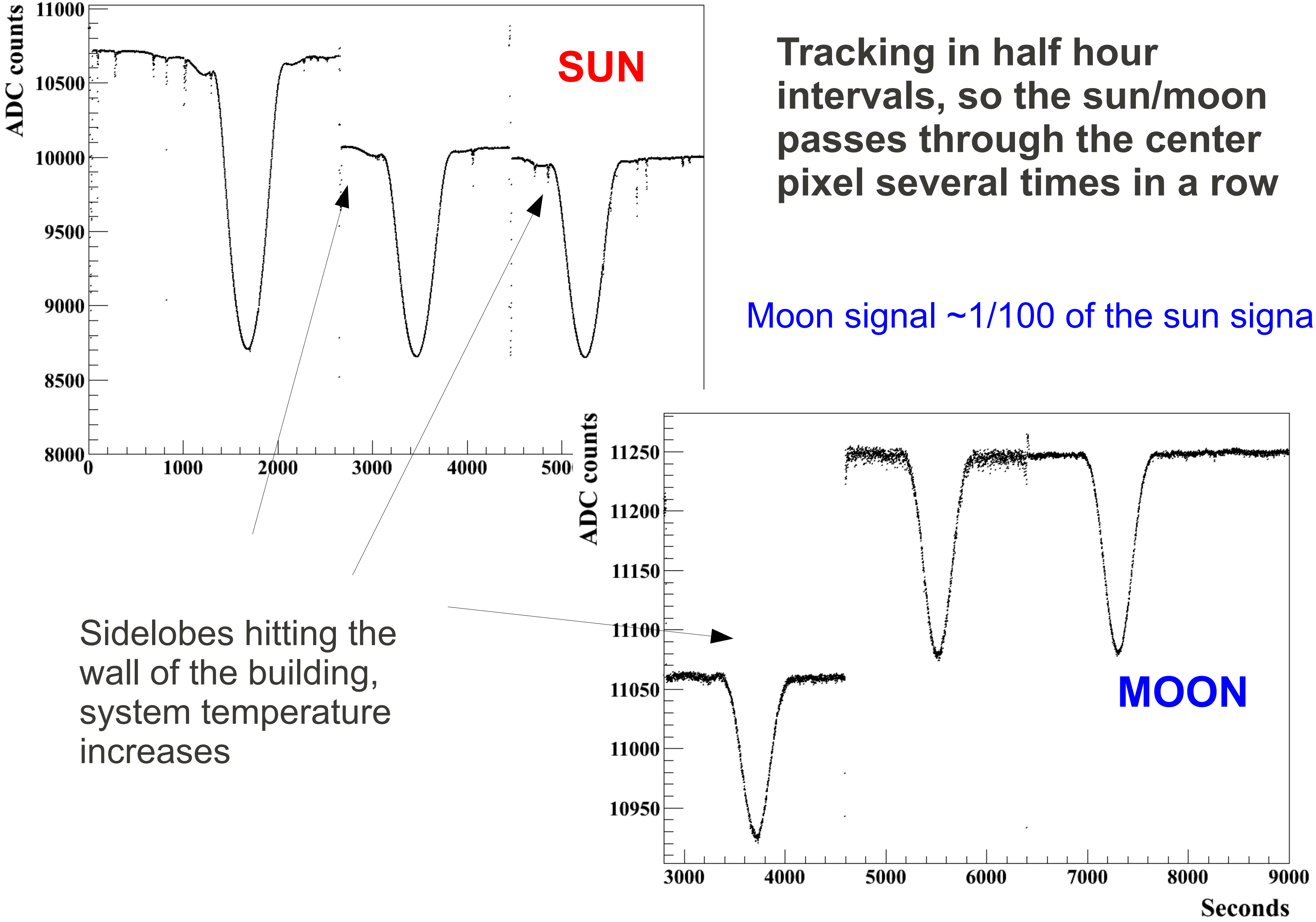
(SLAC & Argonne Wakefield)

→ Phys. Rev. D 78, 032007

MIDAS prototype installed on top of UChicago Physics.
Installation completed March 10

4.5 m, prime focus dish [100° az, 90° ze] mount

Tracking different sources



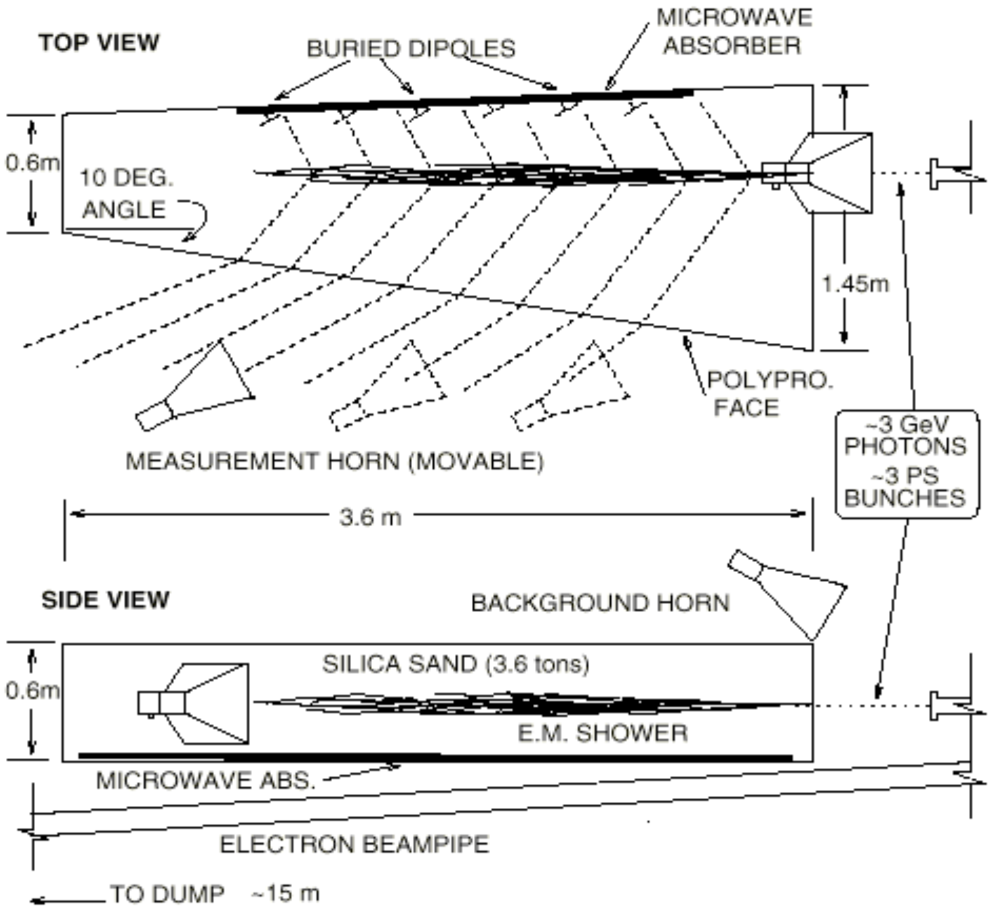
Tracking in half hour intervals, so the sun/moon passes through the center pixel several times in a row

Moon signal ~1/100 of the sun signal

Sidelobes hitting the wall of the building, system temperature increases

Radio Emission from Showers in Dense Media

Radio Cherenkov has been observed!



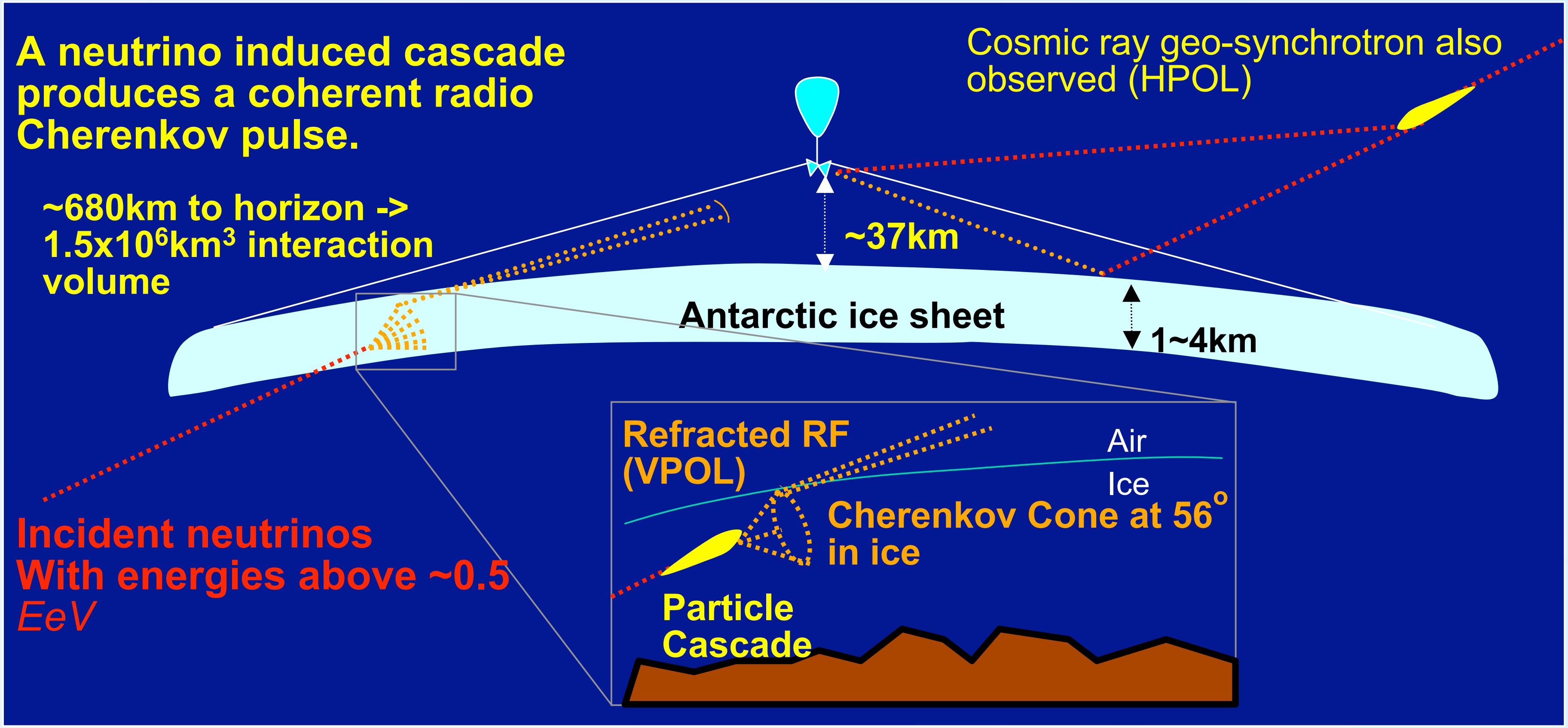
From Saltzberg, Gorham, Walz et al PRL 2001

- Use 3.6 tons of sand
- Repeated with ice for ANITA experiment

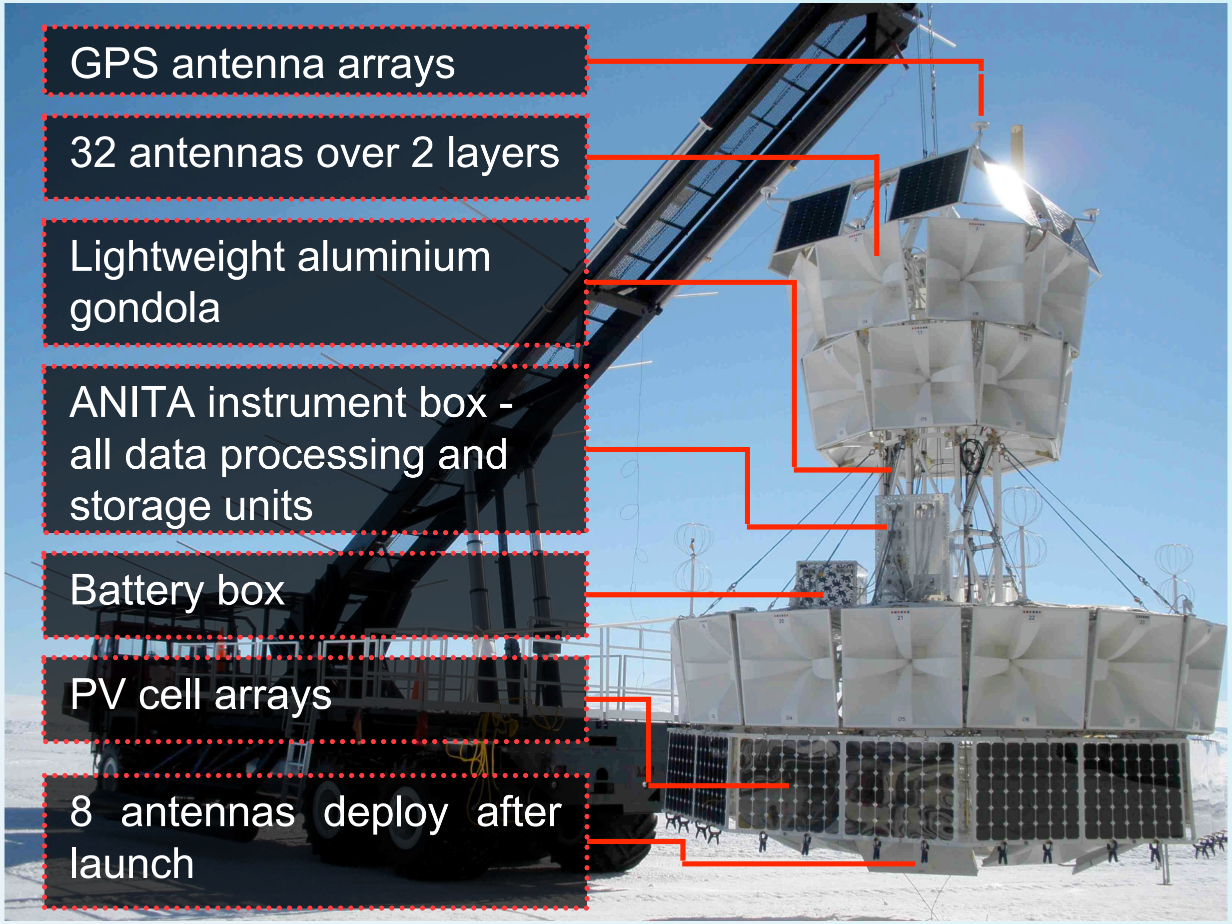
ANITA concept

ν interaction causes EM shower, develops charge imbalance

At GHz and lower frequencies Cherenkov radiation is coherent - strong radio pulse



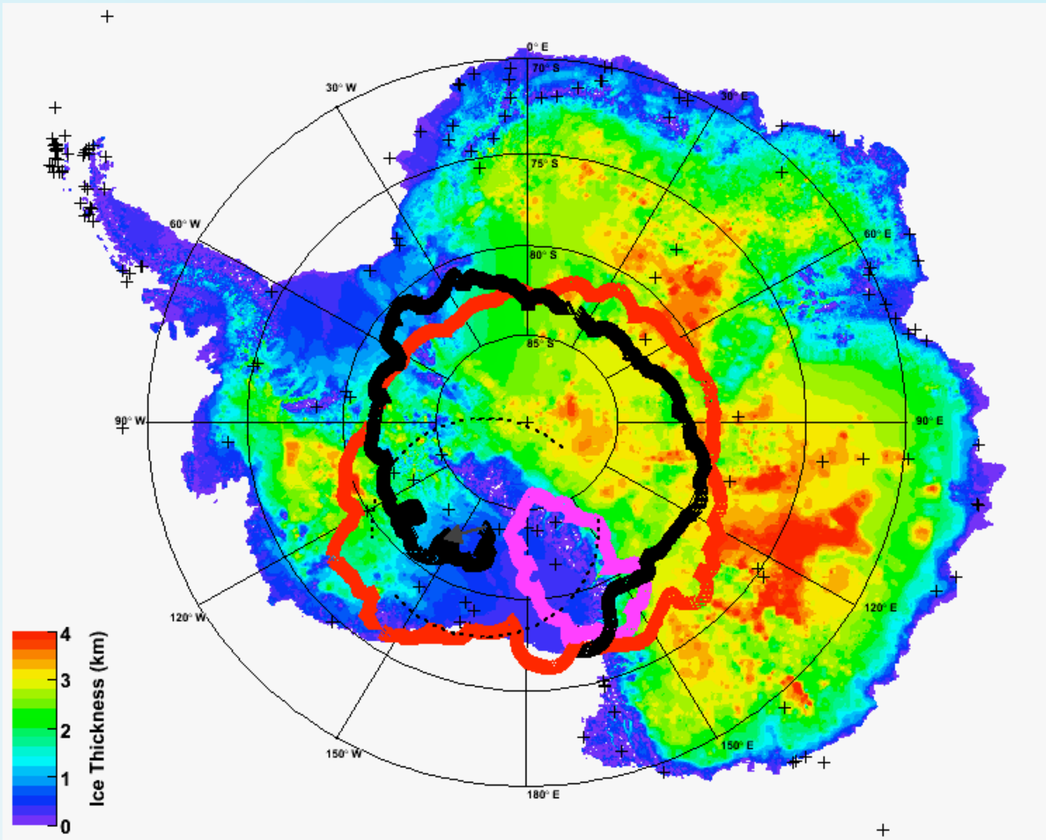
ANITA-2 design



- Antennas 3dB point at 30º - full 360º coverage
- RF recorded in both VPOL and HPOL
- Telemetry (line of sight & satellite linkups) provide data relay and ability to send commands

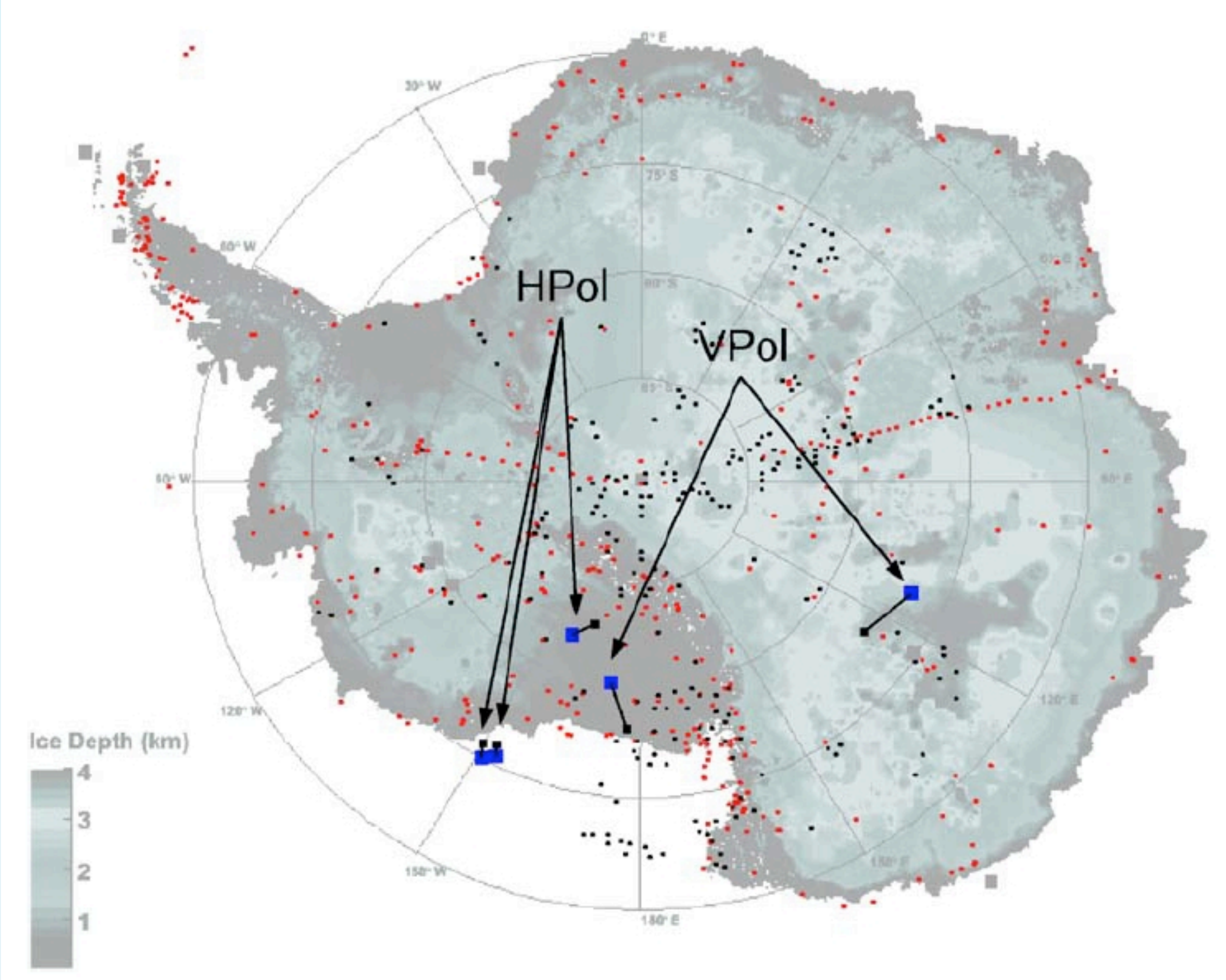
ANITA-2 flight

- Launched 21/12/08
- Aloft for 31 days
- Took ~27M events (~21M RF triggers, ~6M cal pulses etc)
- Landed 22/01/09 with full recovery of instrument and data

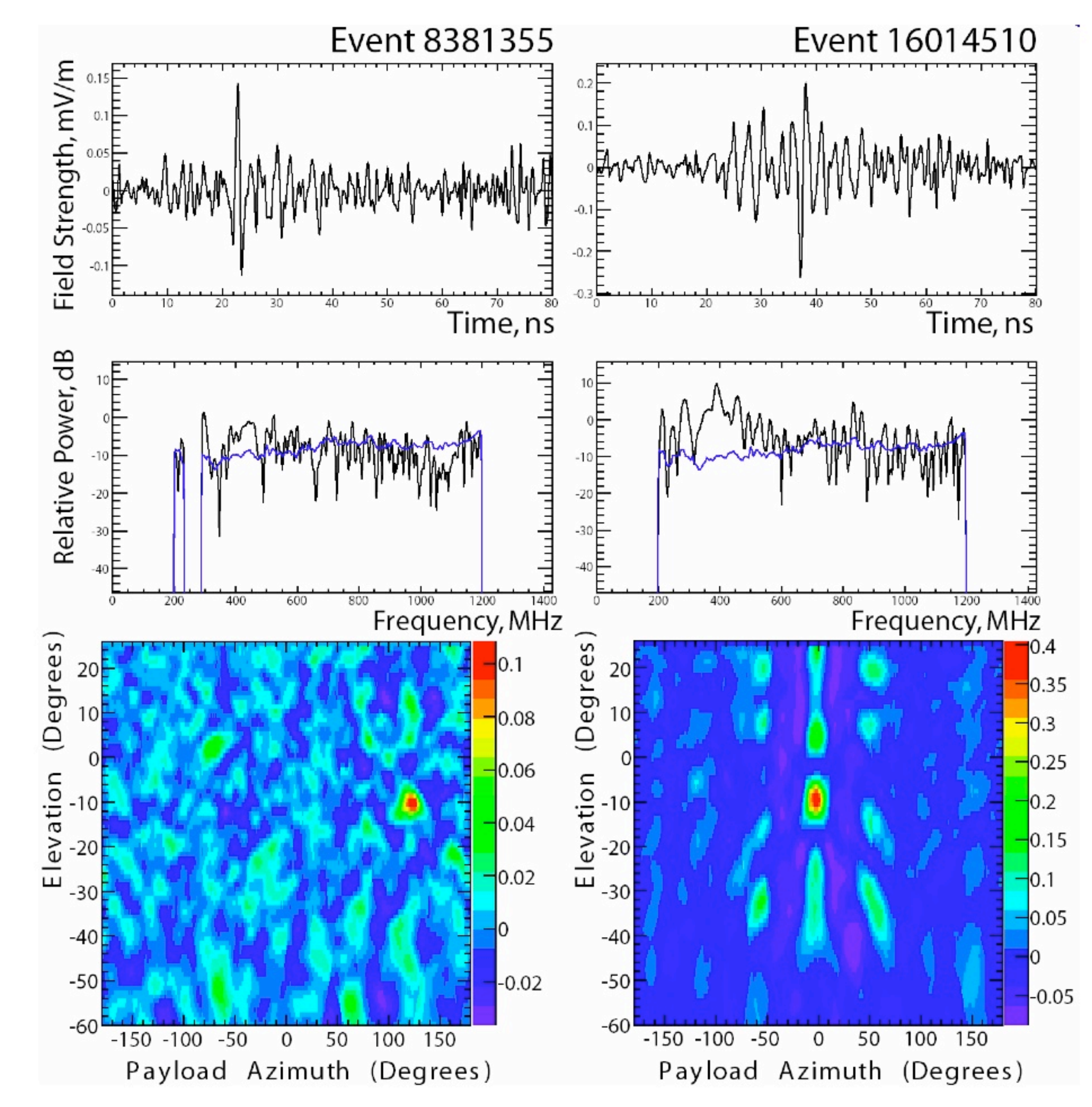


Analysis results

- Remaining events in the signal box:
  - 2 VPOL events
  - 3 HPOL events (see talk by A. Romero-Wolf)



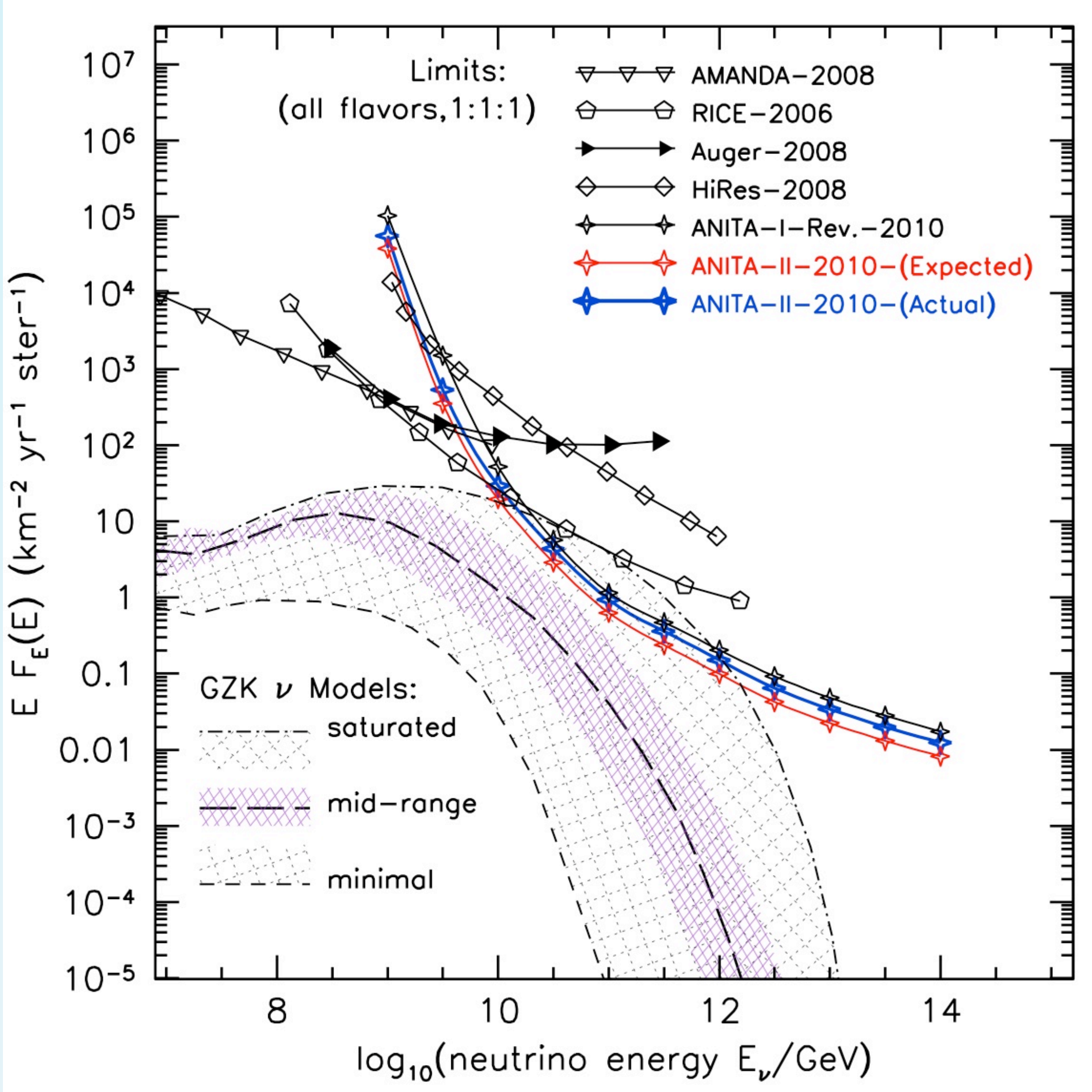
Candidate events - VPOL



- 2 candidate VPOL events:
  - Top: deconvolved coherently summed waveform
  - Middle: power spectrum
  - Bottom: cross correlation image

ANITA 2 results

- V-POL candidates are not sufficient for claim of detection
- ANITA-2 can set a new limit on the UHE cosmic neutrino flux
- ArXiv 1003.2961

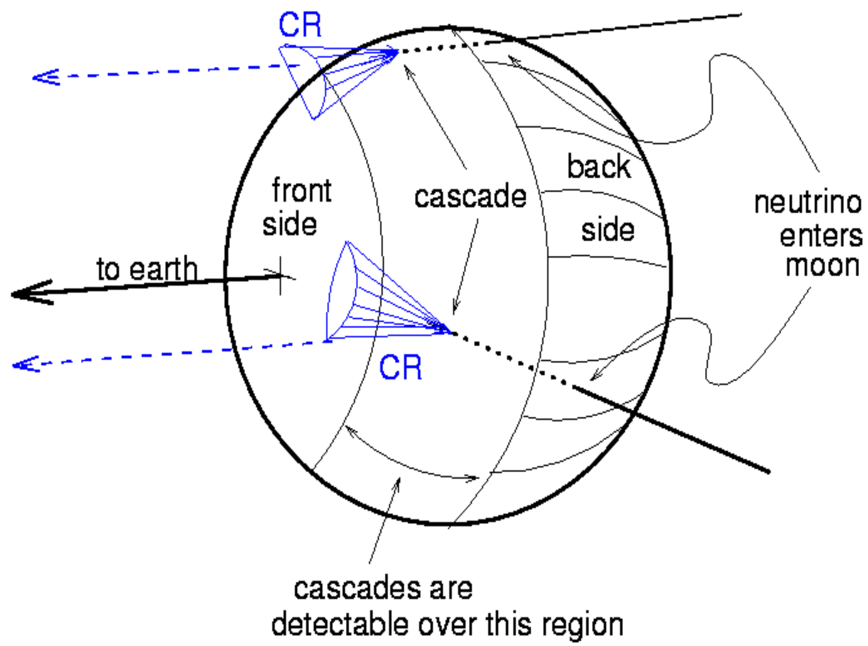


10^{17} 10^{19} 10^{21} eV

Ultra-High Energy (Super-GZK) Neutrino Detections

- Ultra-high energy particle showers hitting the moon produce radio Cherenkov emission in the regolith.
- The moon provides the largest and cleanest detector volume – needed at ultra-high energies.
- 2 GHz: strong but beamed emission
- 100 MHz: lower but isotropic emission

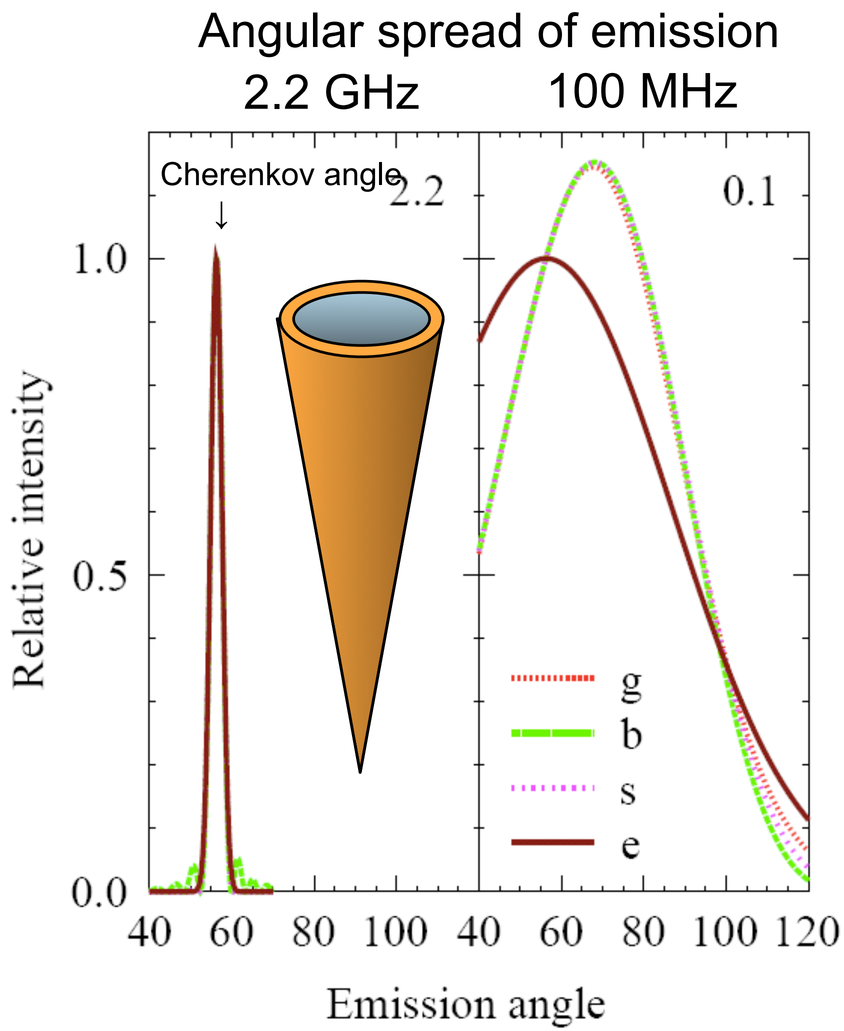
radio from neutrinos hitting the moon



from Gorham et al. (2000)

Radio Observations of the Moon: Different Frequencies

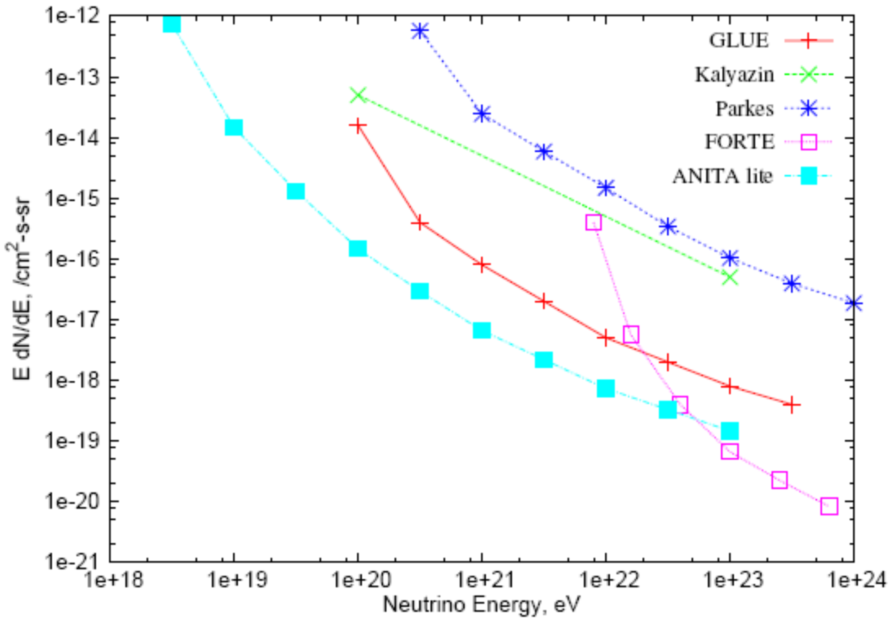
- The shower is ~10 cm wide but 2 m long!
- Cherenkov emission is anisotropic:
  - maximum emission in narrow forward ring at GHz frequencies
  - Lower emission but almost isotropic at lower frequencies
- Low Frequencies have longer attenuation lengths and sample larger volume.



Scholten, et al. (2006)

Radio Moon Experiments

James et al. (2007)

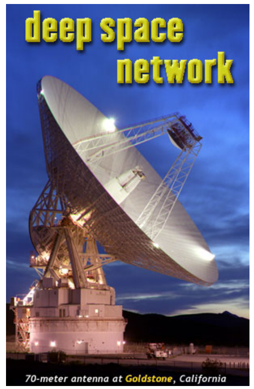


Hankins, Ekers, O'Sullivan (1996)

Scholten et al. (2007, ICRC)

Beresnyak A. R. et al. (2005)

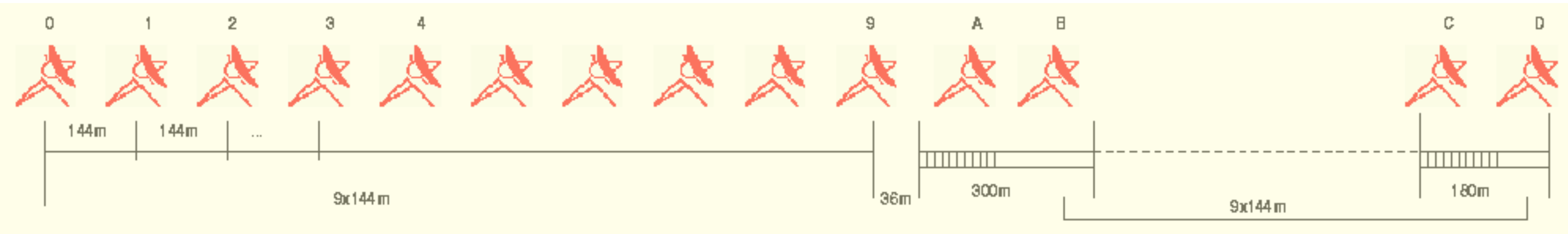
Gorham et al. (2004)



Westerbork (WSRT) Experiment

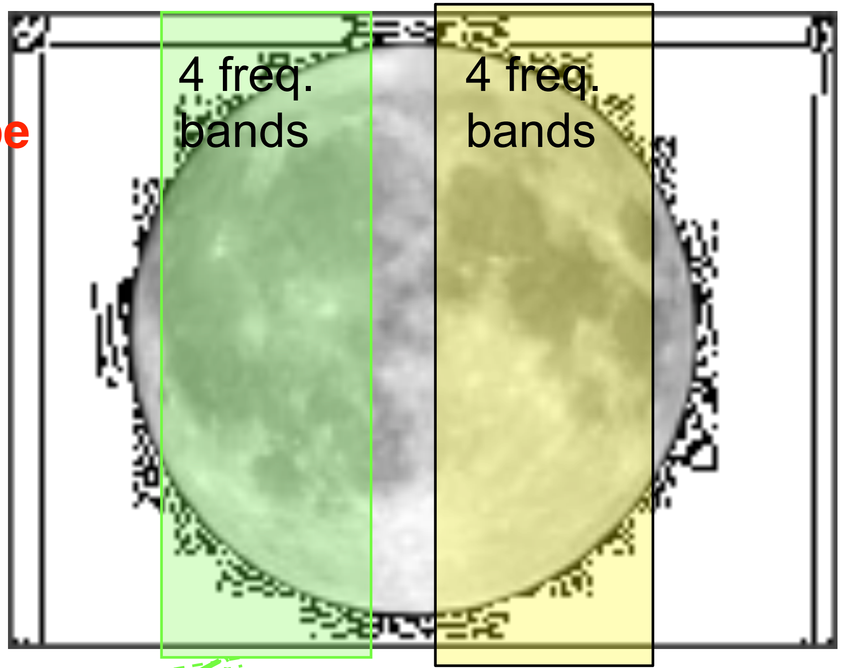
Westerbork Synthesis Radio Telescope

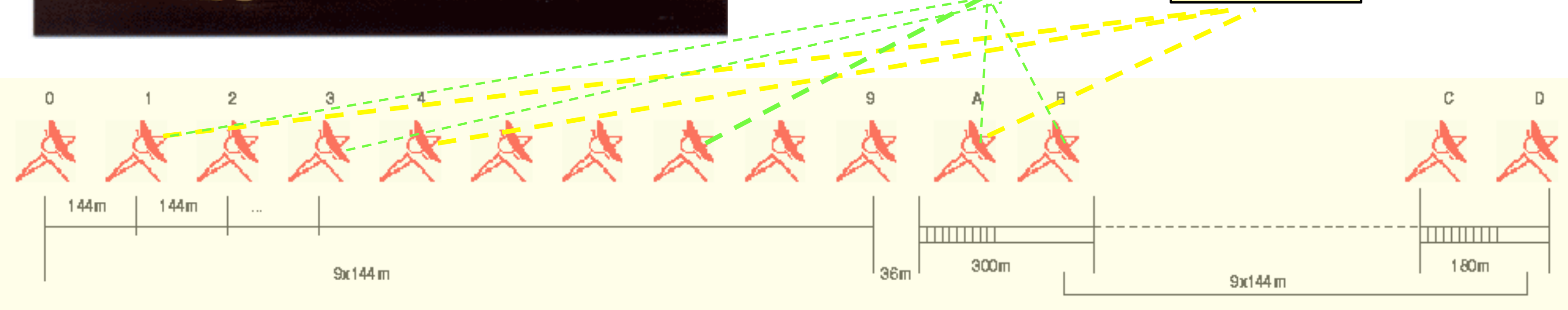
Basic Properties:
- 14 x 25 m diameter dishes
- 12 dishes phased-up
- 110 hour observation time
- 40 M samples/sec (PuMa II)
- Full Polarization information
- 117-175 MHz band
- 8 dual-pol bands of 20 MHz
- 3×10^{20} eV would give 15 σ peak (req.)
- 2 separate 4' × 6° pencil beams
- covering 50% of moon



Westerbork (WSRT) Experiment

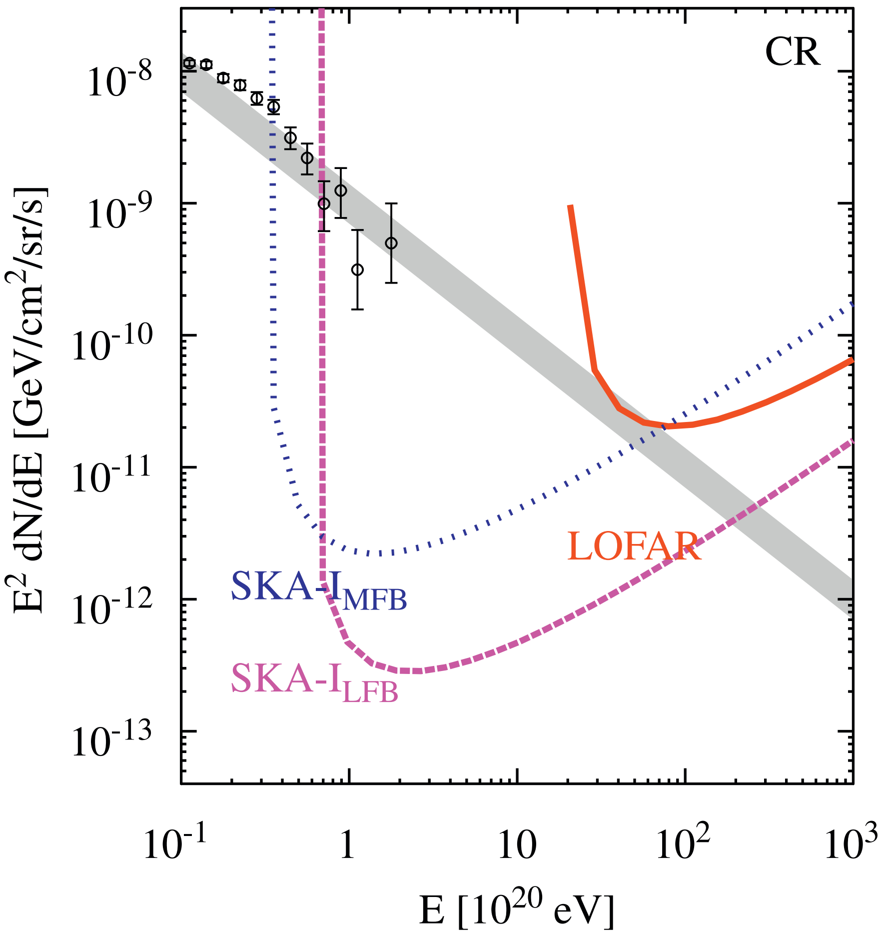
Westerbork Synthesis Radio Telescope



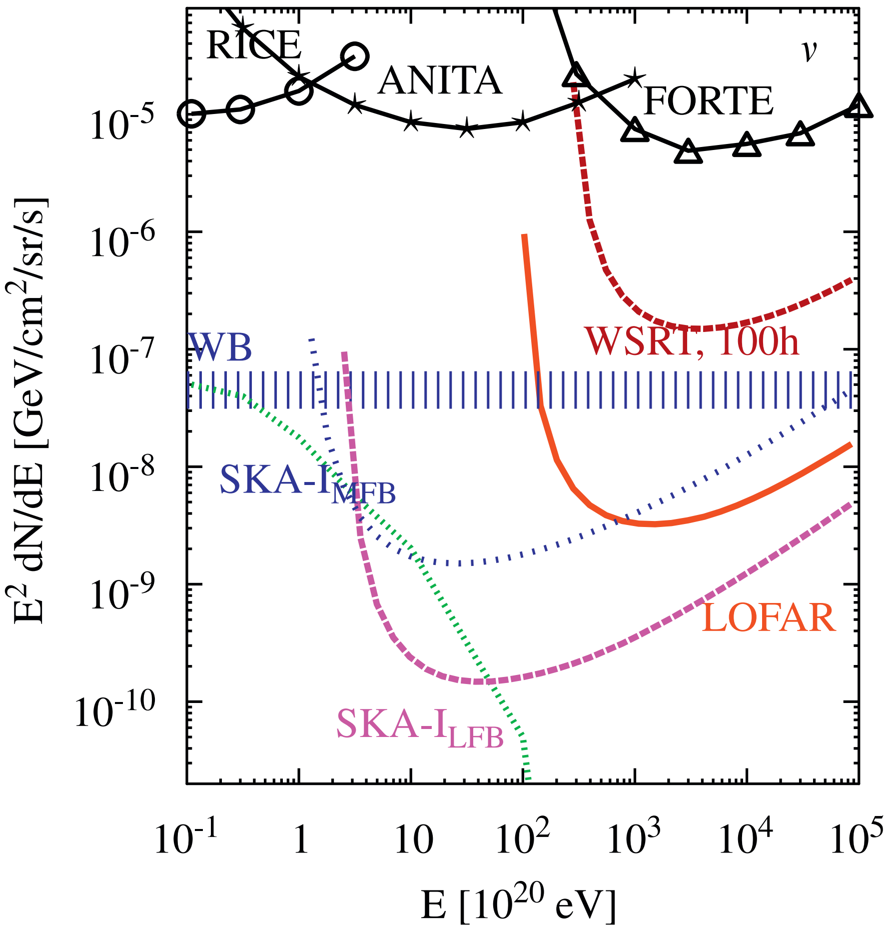


νMoon Results

Cosmic Rays



Neutrinos



O. Scholten et al., Nucl. Instr. & Meth. A 604 (2009) S102

Radio detection activities at South Pole

South Pole Under Ice RF instrumentation:

- **RICE**

Part of IceCube DAQ:

- **"AURA" sub-working group (Full WF digitization)**
  Askaryan Underice Radio Array

- **"SATRA" sub-working group (Transient detection)**
  Sensor Array for Transient Radio Astrophysics

2008 **"NARC"**
Neutrino Array
Radio Calibration

Future independent collaboration:

- **ARA – Askaryan Radio Array**

South Pole Surface RF Instrumentation:

- **Surface radio - RASTA – Radio Air Shower Transient Array**

Radio Detection of Extensive Air Showers

Thanks to all my colleagues from LOPES, LOFAR, and the Pierre Auger Observatory

pioneer experiments
LOPES & CODALEMA
paved the way to large-scale a

- **LOFAR**
- **Pierre Auger Observatory - AERA**
- **Ice Cube extensions (South Pole)**

➡ **objective:** **independent air shower measurements with radio detection**

➡ **astrophysics** **in transition region (galactic/extragalctic cosmic rays)**

physics of radio emission:
geosynchrotron radiation is dominant in atmosphere

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