Radio Detection of Extensive Air Showers

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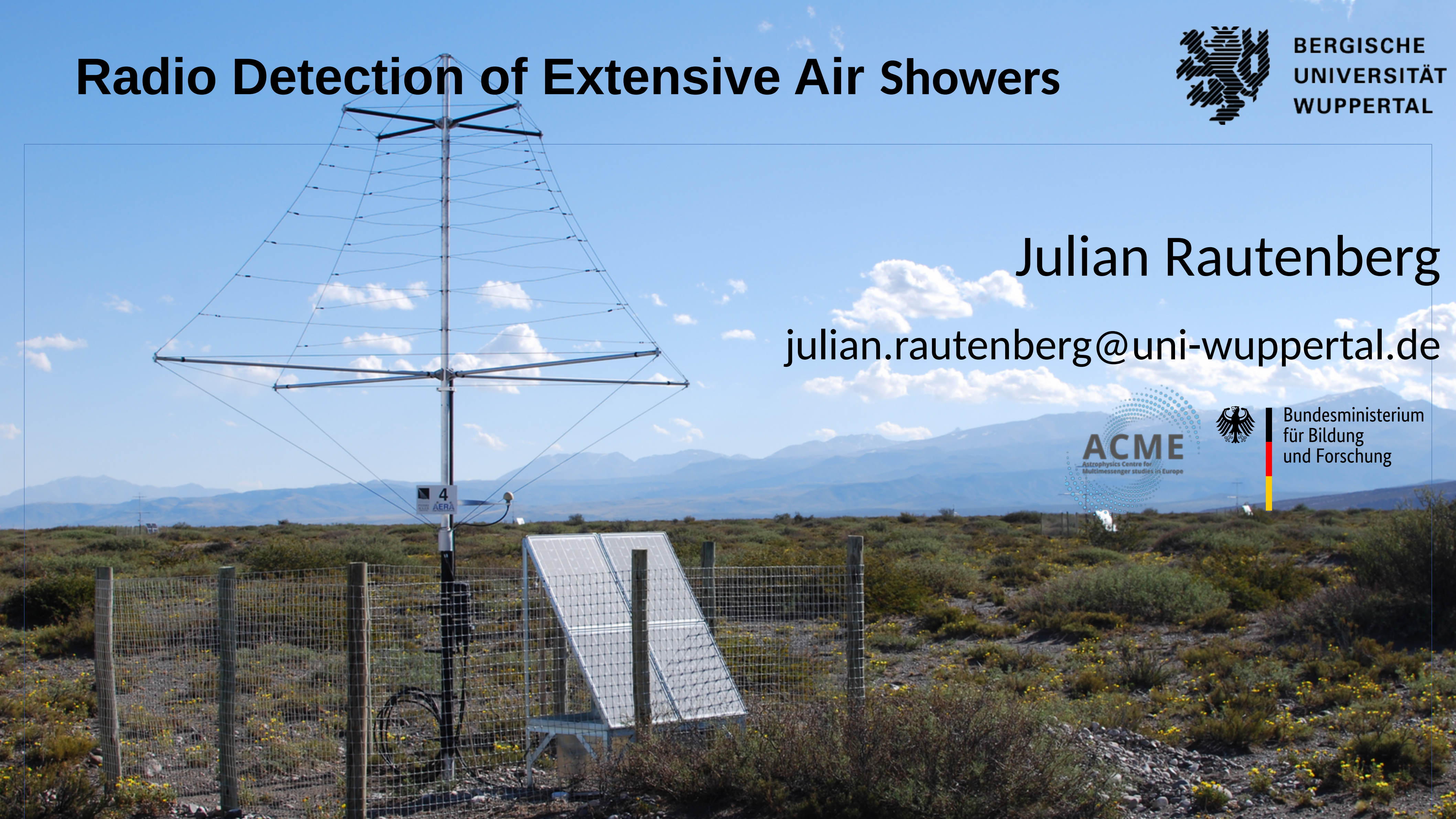
Bundesministerium für Bildung und Forschung



Renaissance of Radio Detection: Theory

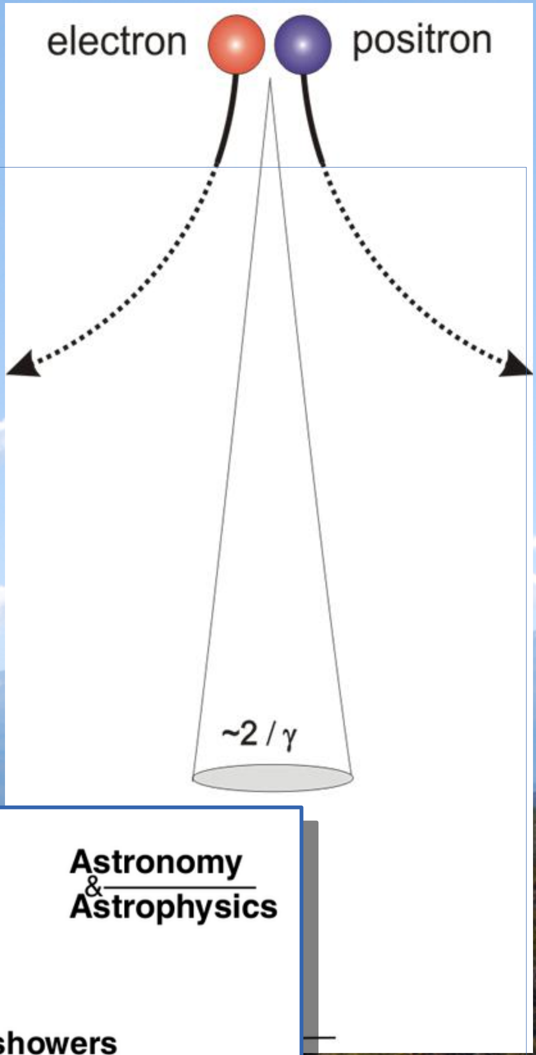
Early measurements in the 70ties

Renaissance: **Falcke & Gorham A.Ph. (2003)**
Huege & Falke, A&A (2003)

Geomagnetic effect: v x B

Coherent emissions from billions of Elektrons

Emission is focused in beam direction



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Astroparticle Physics
Astroparticle Physics 19 (2003) 477–494
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Detecting radio emission from cosmic ray air showe
and neutrinos with a digital radio telescope

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Astronomy & Astrophysics

Radio emission from cosmic ray air showers

Coherent geosynchrotron radiation

Renaissance of Radio Detection: Theory

Early measurements in the 70ties

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Huege & Falke, A&A (2003)

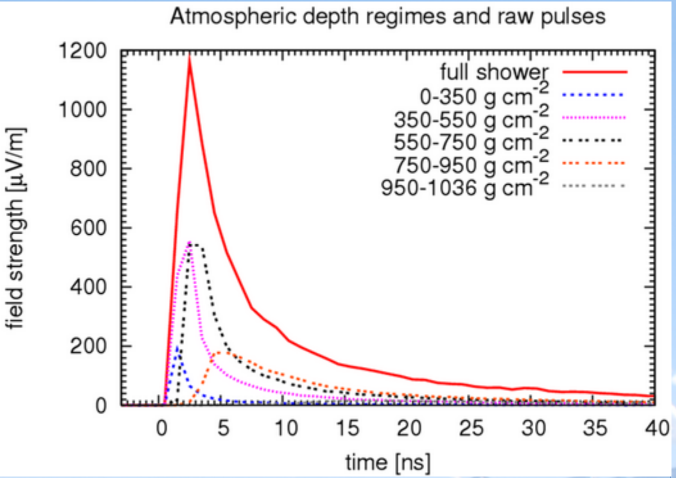
Geomagnetic effect: v x B

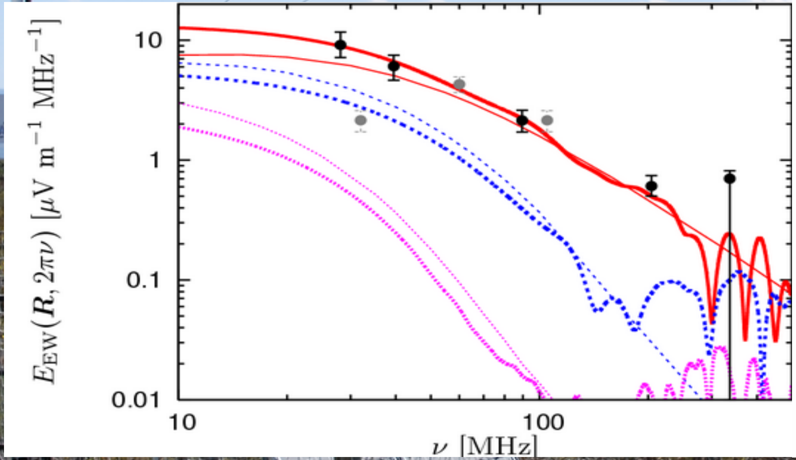
Coherent emissions from billions of Elektrons

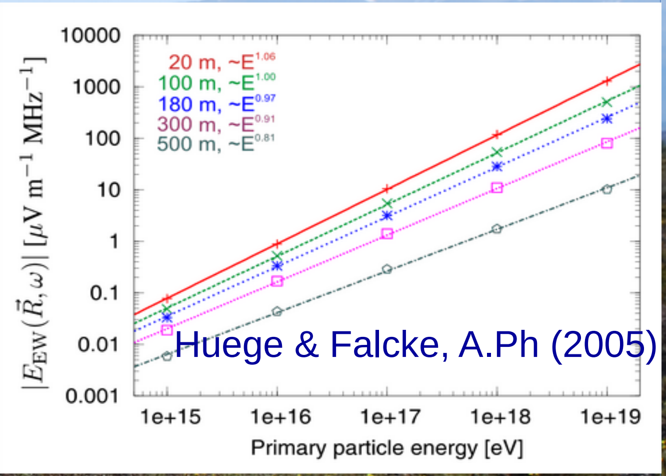
Emission is focused in beam direction

Full MC predicting:

- few-ns pulses
- smoothly falling frequency
- scaling energy







Huege & Falcke, A.Ph (2005)

Renaissance of Radio Detection: Experiment

For R&D ideal environment:

- **take a running experiment (KASCADE-Grande)**
- **add new hardware (from new experiment, LOFAR)**
- **have a look, how EAS look like (Nature 435, 2005)**

externally triggered
understand radio-emission
of extended air shower

Publisher: NPG; Journal: Nature:Nature; Article Type: Physics letter
DOI: 10.1038/nature03614
to appear in Nature, May 19, 2005 issue

Detection and imaging of atmospheric radio flashes from cosmic ray air showers

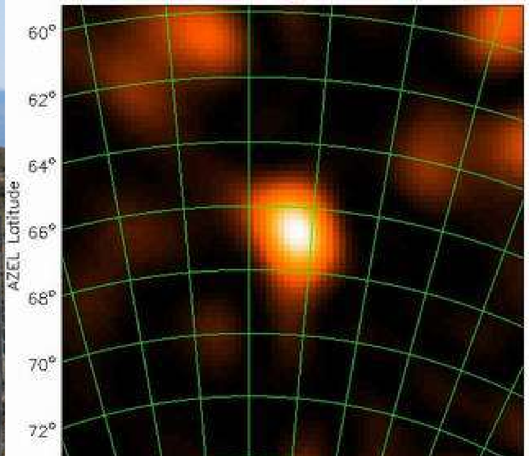
Renaissance of Radio Detection: Experiment

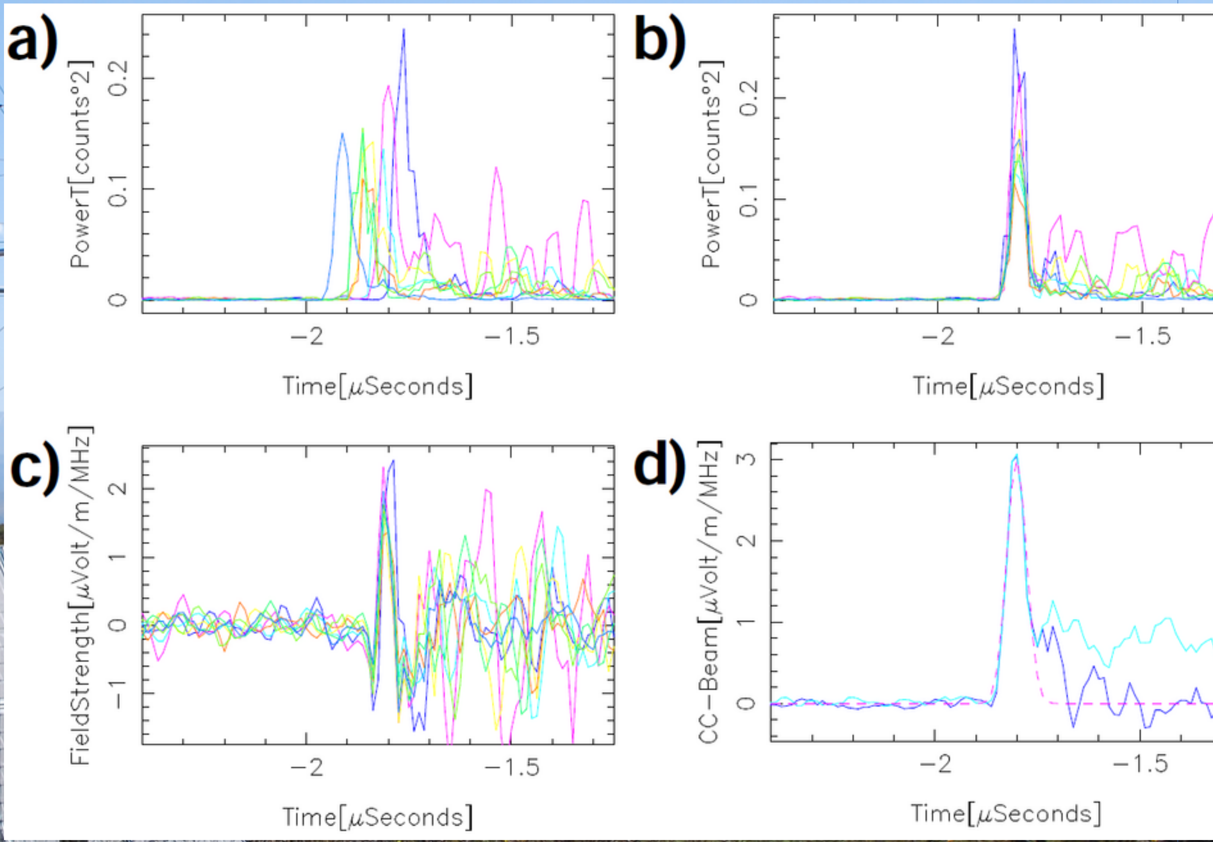
Interferometric reconstruction:

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

$s_i[t]$: signal of station i at time t

Signal to noise scales with #antenna





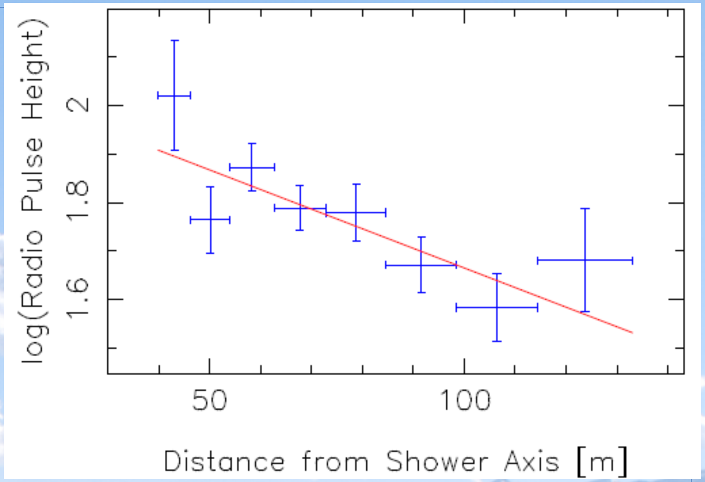
Renaissance of Radio Detection: Experiment

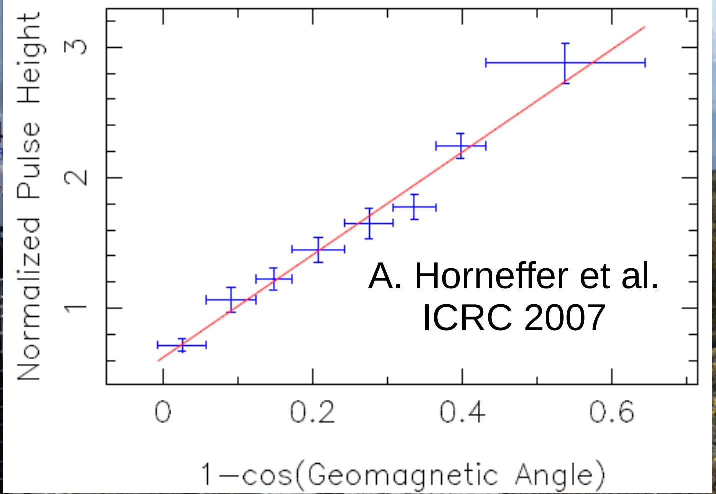
Correlation of radio pulse-height with shower-variables (KASCADE-Grande reconstruction)

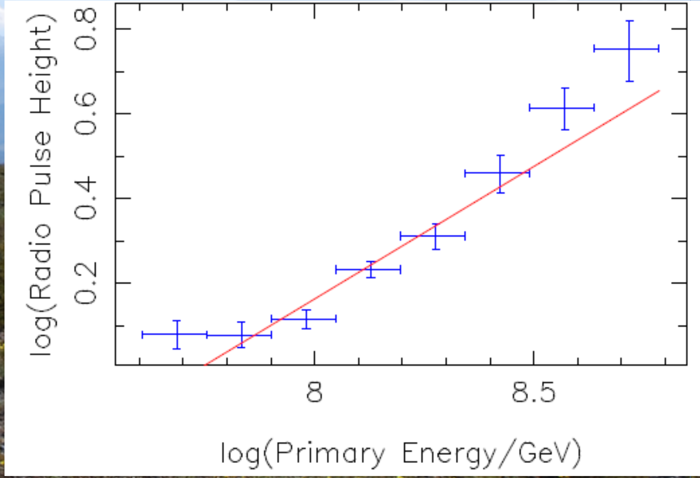
$$\varepsilon_{est\text{-}EW} = A(B - \cos\alpha)\cos\theta\,\exp(-R/R_0)(E/10^{17}\,\mathrm{eV})^{\gamma}$$

$A = 11. \pm 1.$ $B = 1.16 \pm 0.03$

$R_0 = 236 \pm 81$ m $\gamma = 0.95 \pm 0.04$







Towards a Radio-Detector for high energies $E>10^{18}$ eV:

Self-triggering!

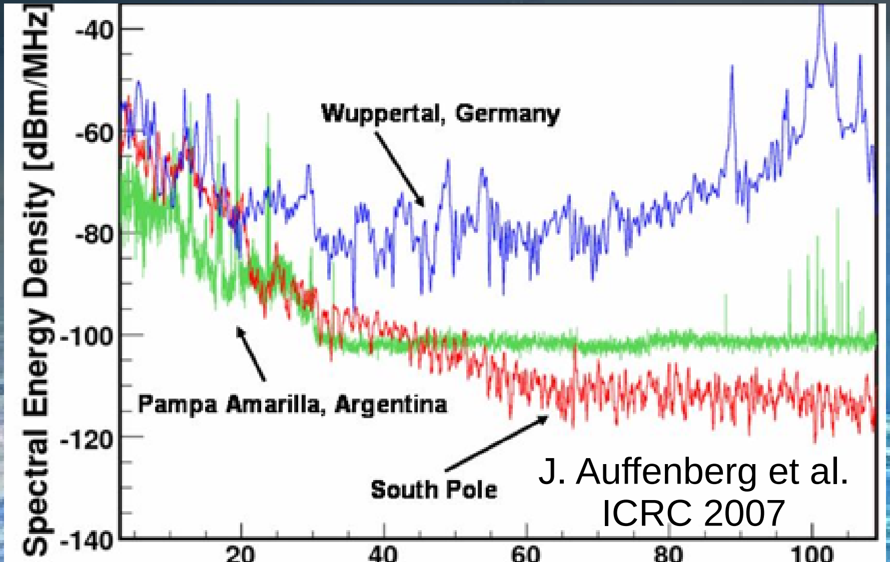
EAS radio-detection at the Pierre Auger Observatory

Start of radio-detection on-site investigtions fall 2006

Mono-frequent background

Quiet in 30-80 MHz down to galactic noise level

But for a threshold-trigger need to look at the time-domain

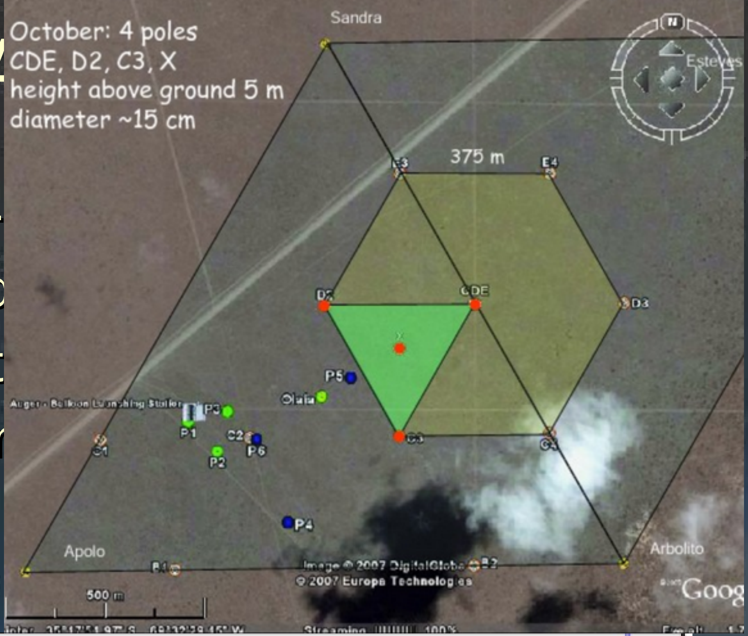


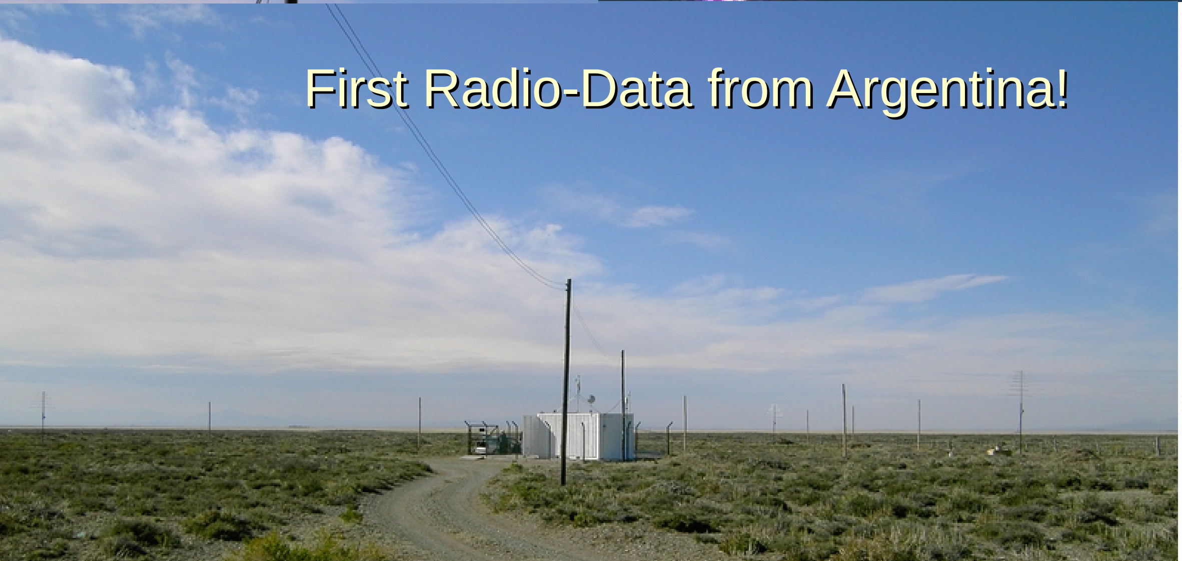
J. Auffenberg et al.
ICRC 2007

ection at the Pierre A

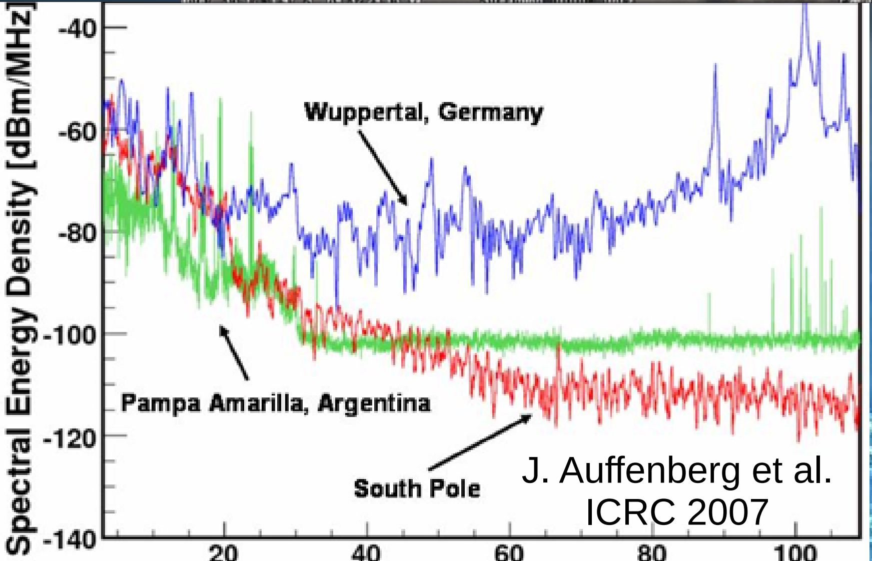
X-mas tree in the pampa

- Start of radio-detection on-
- Mono-frequent backgroun
- Quiet in 30-80 MHz down t
- But for a threshold-trigger r





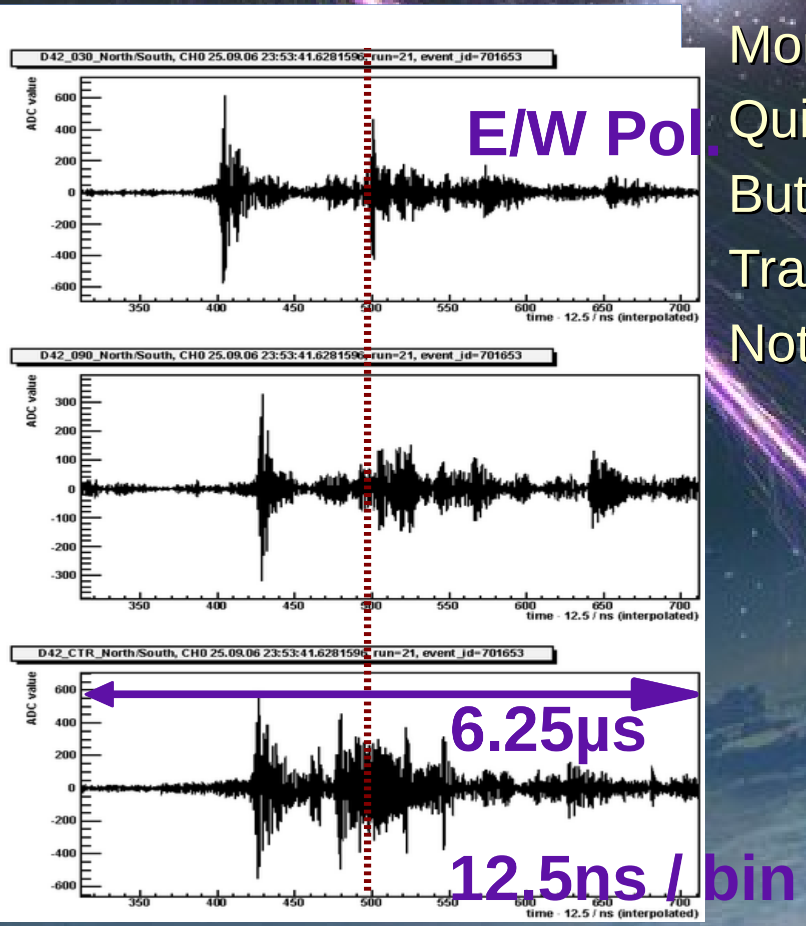
First Radio-Data from Argentina!

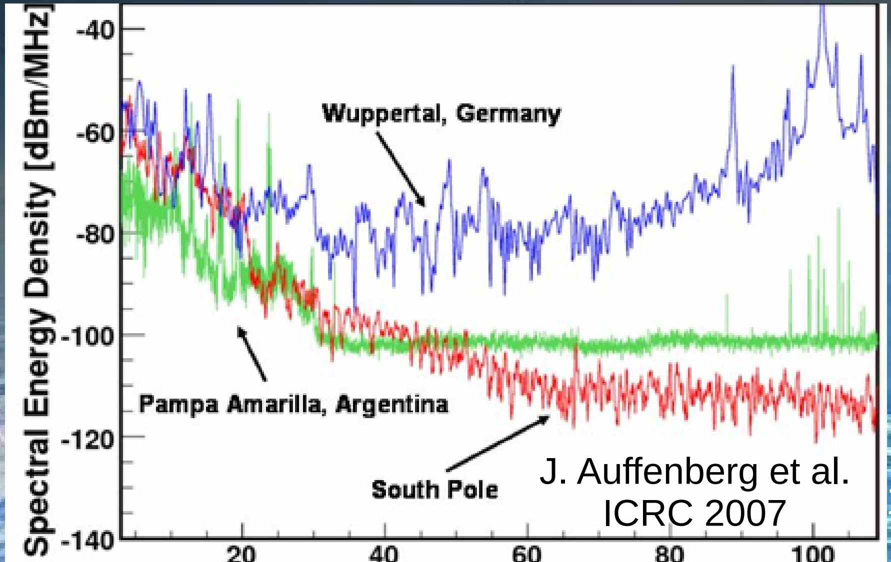


J. Auffenberg et al.
ICRC 2007

EAS radio-detection at the Pierre Auger Observatory

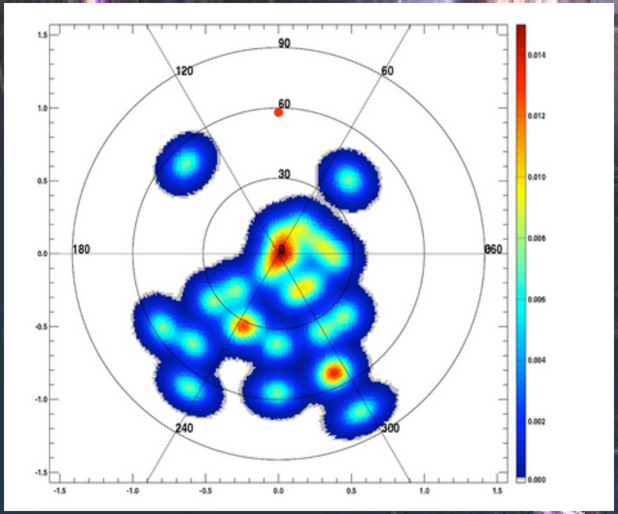
- Start of radio-detection on-site investigtions fall 2006
- Mono-frequent background
- Quiet in 30-80 MHz down to galactic noise level
- But for a threshold-trigger need to look at the time-domain
- Transient noise! --- not visible in dynamic spectra
- Not suppressible by up-ward coincidence window



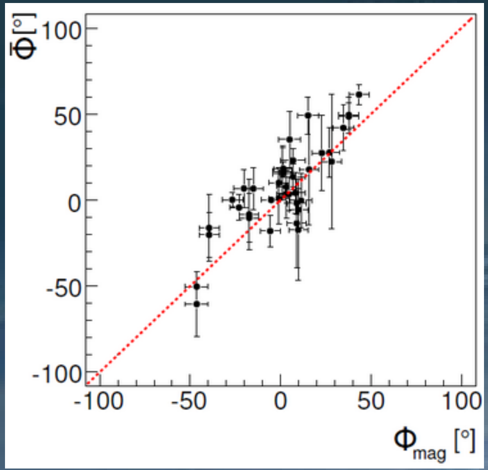


J. Auffenberg et al.
ICRC 2007

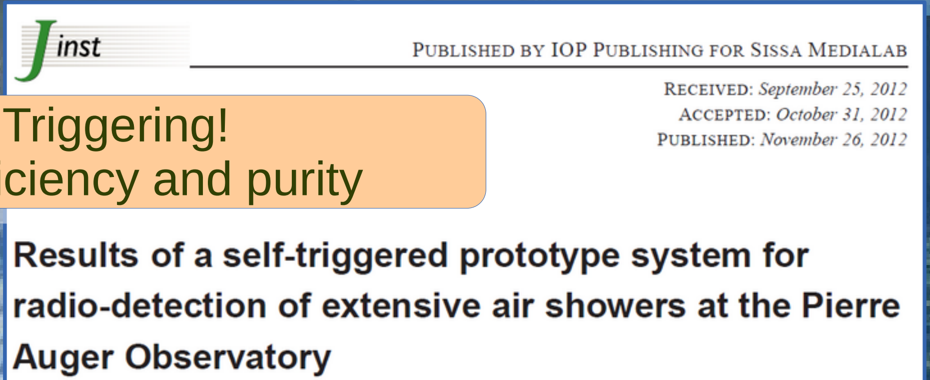
Radio at Pierre Auger Observatory: Prototype Phase



- Sky-plot of arrival direction of **self-triggered** events in coincidence with Auger surface detector
- Typical v x B distribution
- Core position around test set-up of 496 coincident events triggered by attached scintillators
- Up to 1.5 km with E-threshold of 0.4 EeV
- Polarisation in agreement with v x B



Self-Triggering!
But low efficiency and purity



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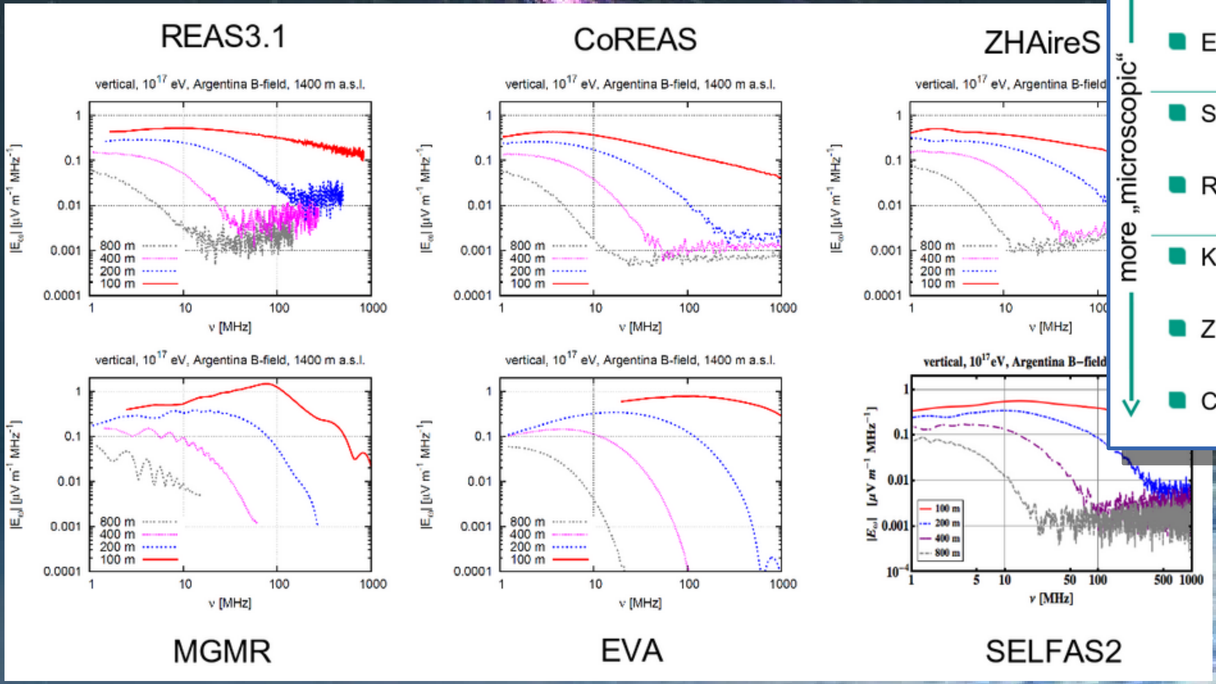
ACCEPTED: October 31, 2012
PUBLISHED: November 26, 2012

Results of a self-triggered prototype system for radio-detection of extensive air showers at the Pierre Auger Observatory

Radio at Pierre Auger Observatory: Simulations

Developper of Simulation code member of Pierre Auger Collaboration
Increasing consolidation of results by detailed comparison
T. Huege (Helmholtz-Group)



more „microscopic"

MGMR	time-domain, analytic, parametrized shower, fast, free parameters, summing up „mechanisms"
Dave's model	frequency-domain, analytic, parametrized shower, fast, free parameters, summing up „mechanisms"
EVA	frequency-domain, analytic, fitted CONEX shower,summing up „mechanisms"
SELFAS2	time-domain, shower from universality, summing up vector potentials for tracks
REAS3.1	time-domain, histogrammed CORSIKA showers, endpoint formalism, open source
Kalmykov et al.	frequency-domain, CORSIKA showers, ZHS-like formalism
ZHAireS	time- and frequency-domain, Aires showers, ZHS formalism
CoREAS	time- (later frequency-) domain, CORSIKA showers, endpoint formalism

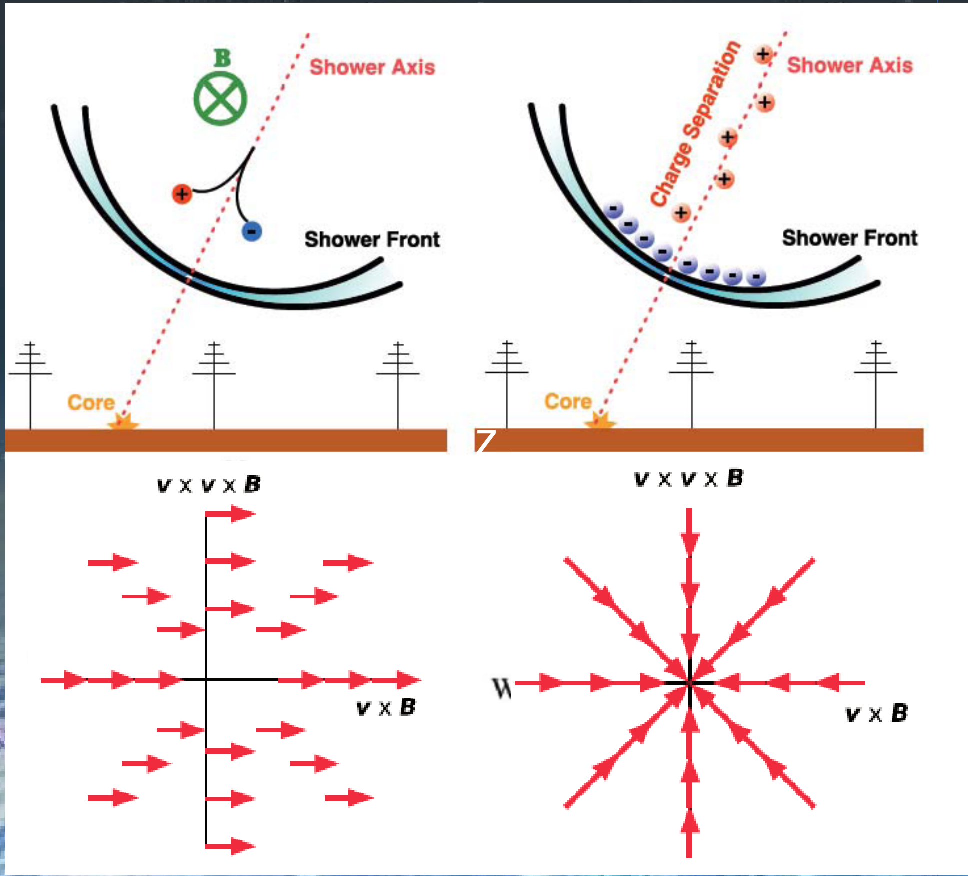
T. Huege, ARENA 2012

Radio at Pierre Auger Observatory: Simulations

- Macroscopic model:
  - Time variation of transverse current
  - Time variation of charge access
- Compatible with microscopic model:
  - end-point formalism

James et al. Phys.Rev.E (2011)

- Separable with Polarisation!
- Depending on antenna-position w.r.t. shower core constructive or destructive interference



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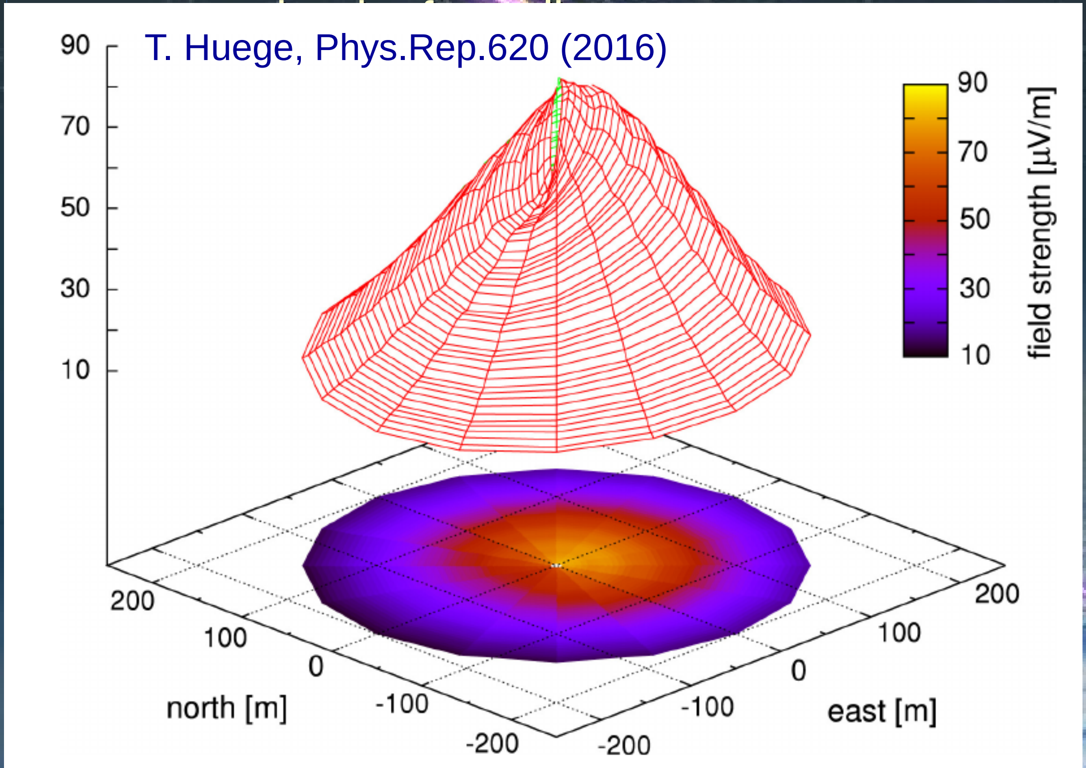

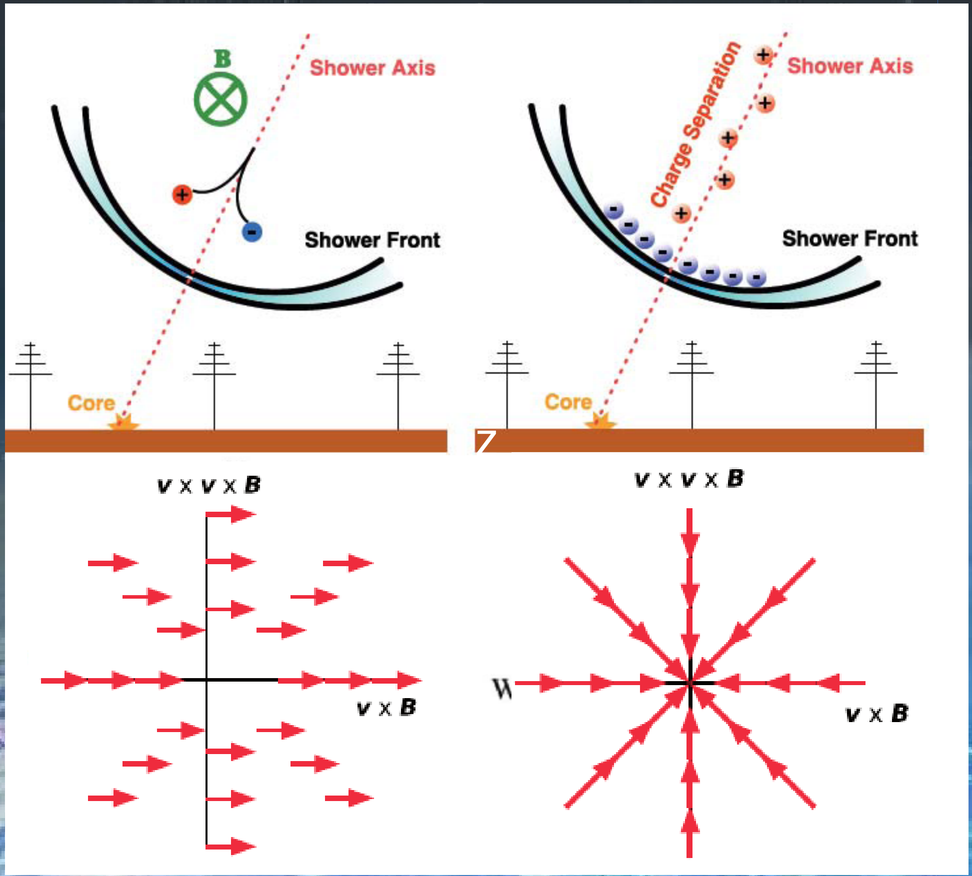

Radio at Pierre Auger Observatory: Simulations

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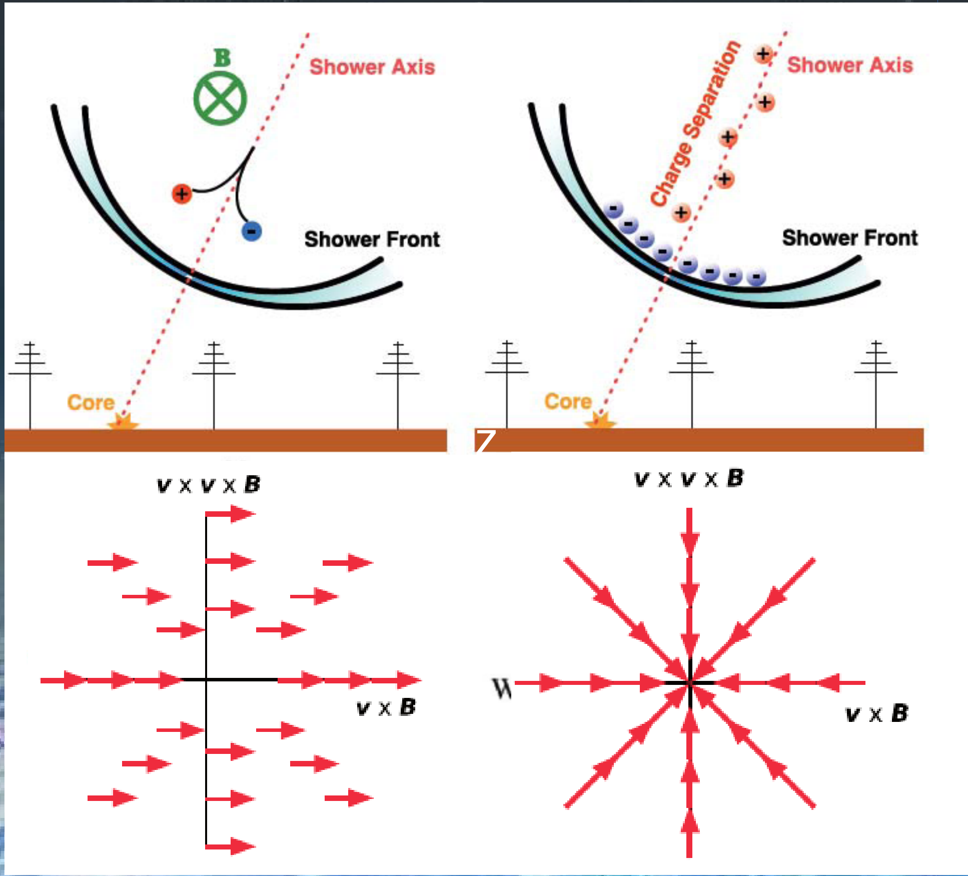


Time Compression:
- On Cherenkov angle emission of moving source arrives at same time

In dense media:
- no geomagnetic, but Askaryan dominating
- Smaller scale of shower → higher frequencies

Radio at Pierre Auger Observatory: AERA

Deployed in three phases:
Phase I: 24 RDS in 09/2010
Phase II: +100 RDS in 05/2013
Phase III: +25 RDS in 02/2015

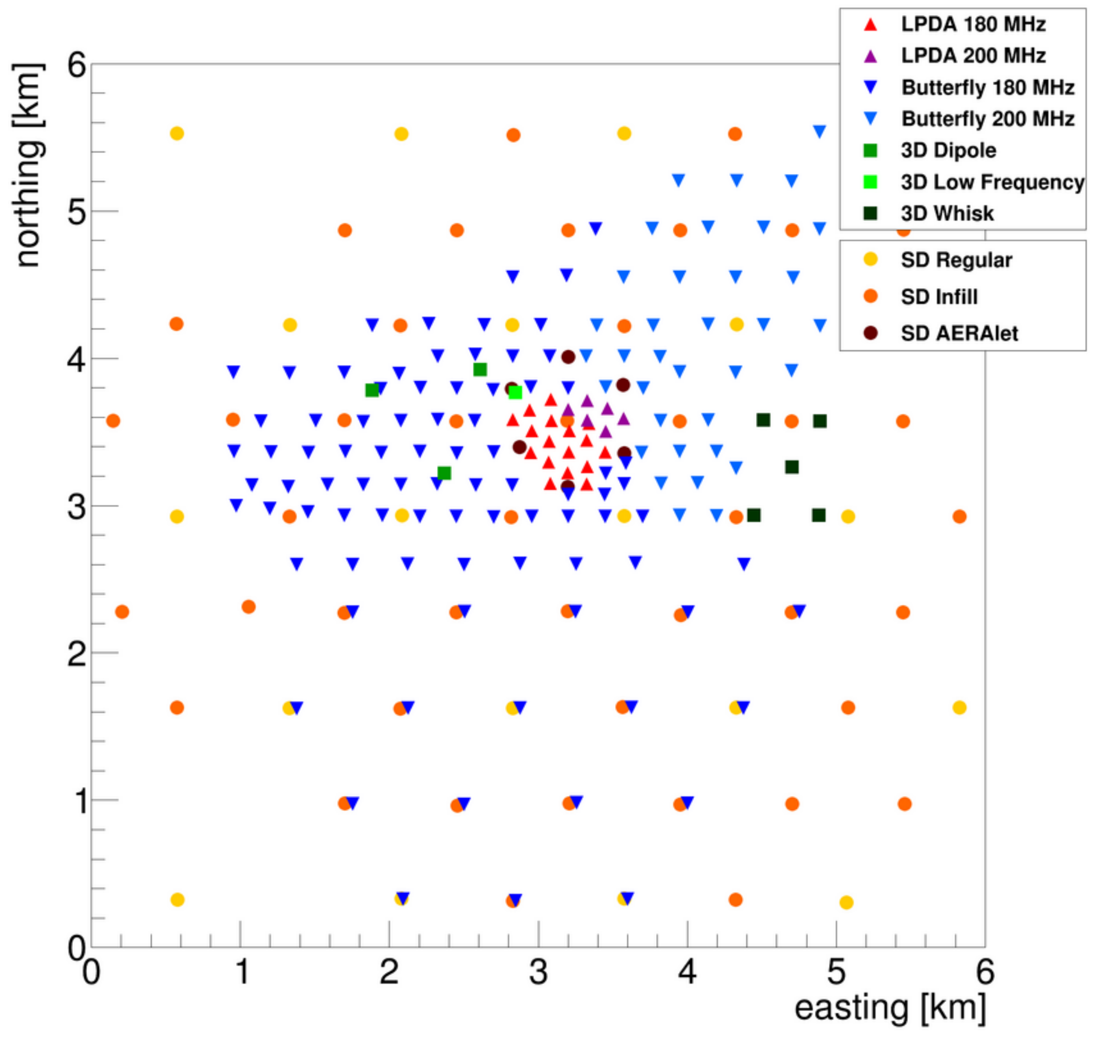
Four grid spacings:
150, 250, 375 / 750 m

Two antenna types
LPDA / Butterfly

Two main trigger schemes
External / scintillator

Prototype RDS (3D, lowFreq)

AERAlet (SDS on 433 m grid)



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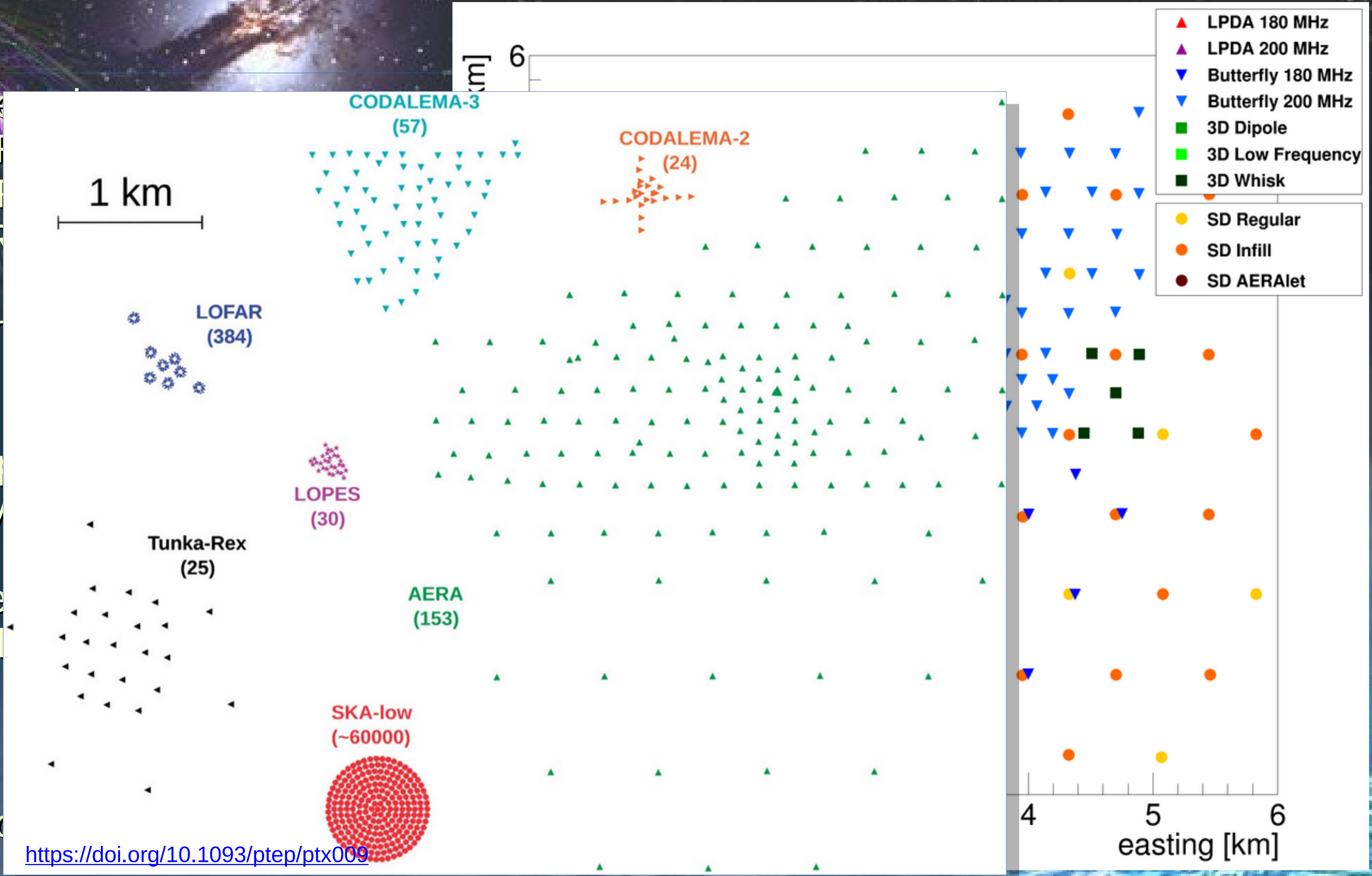
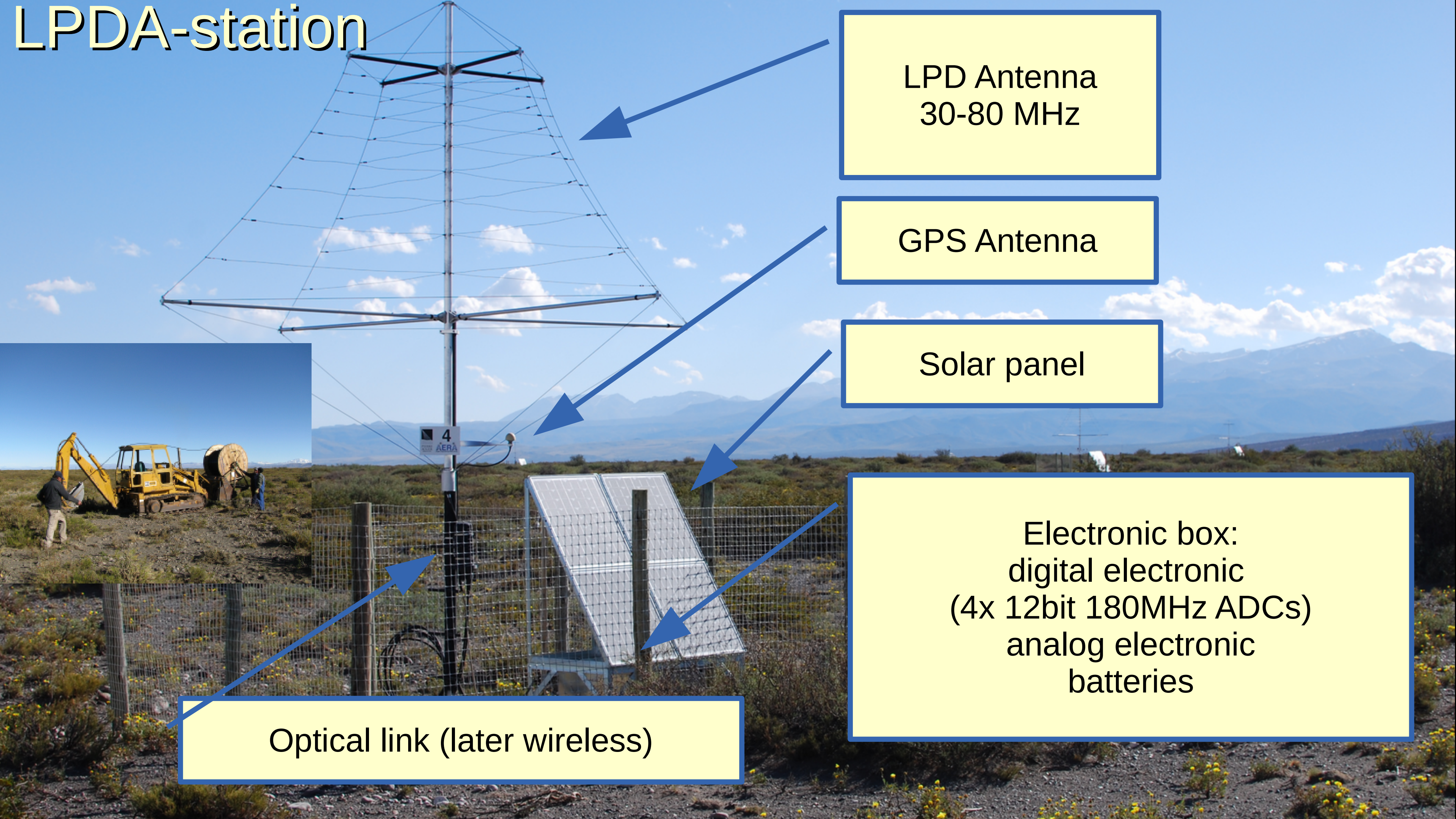
AERAlet (SDS c

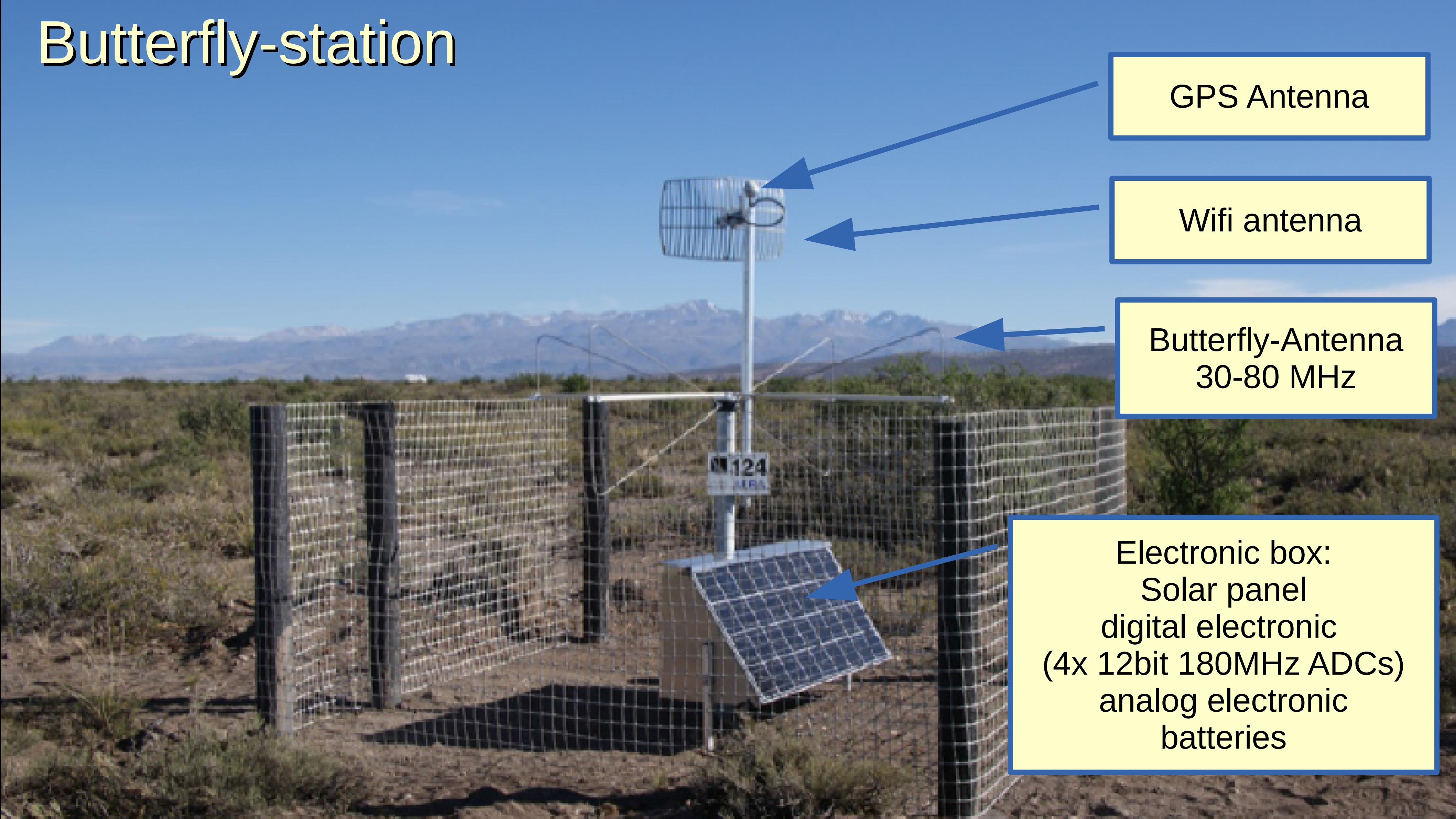


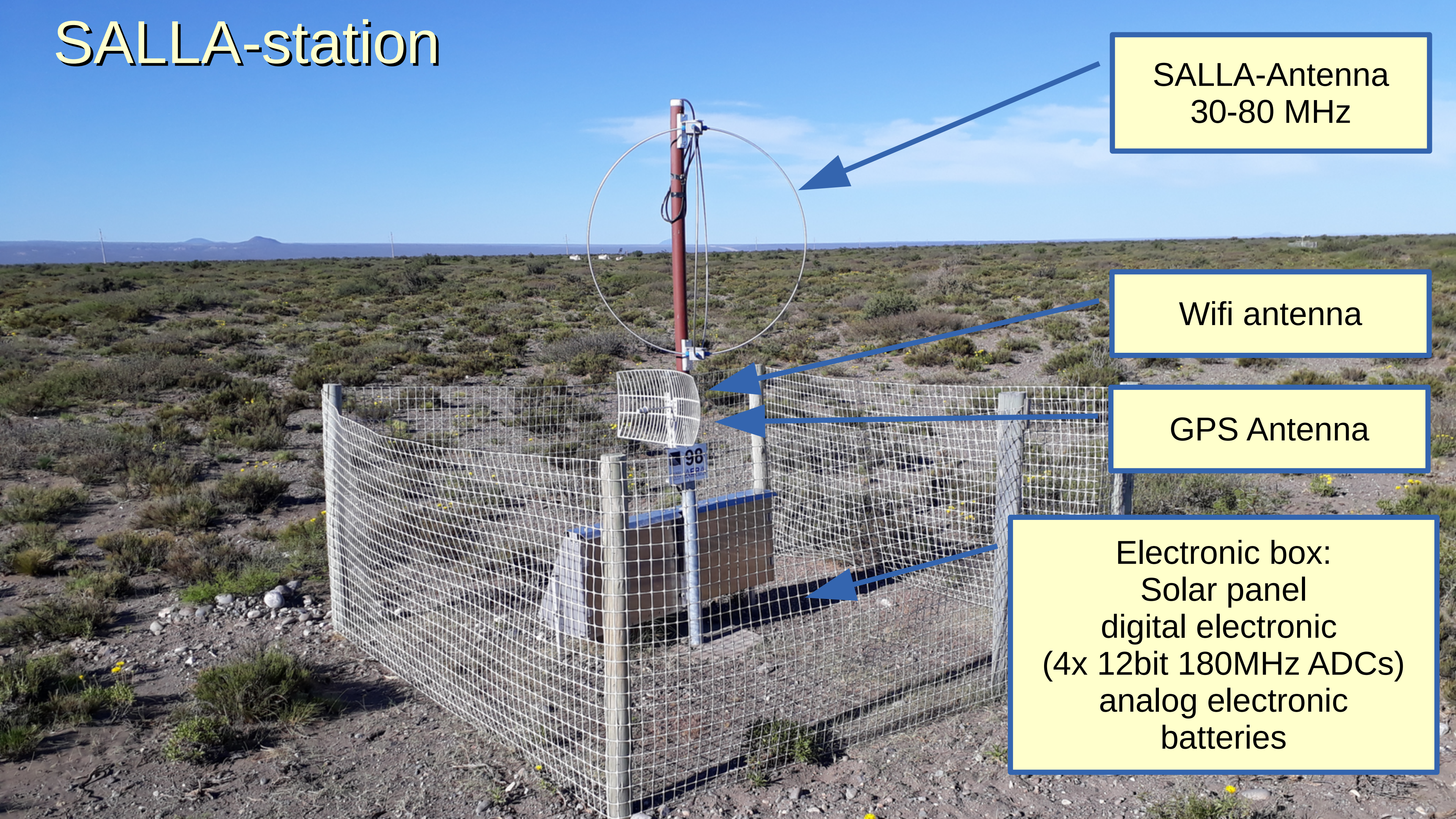
https://doi.org/10.1093/ptep/ptx009

LPDA-station



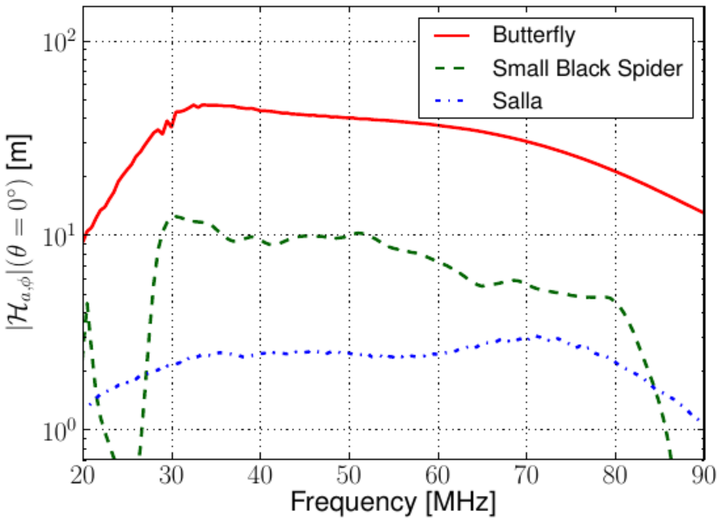
Butterfly-station

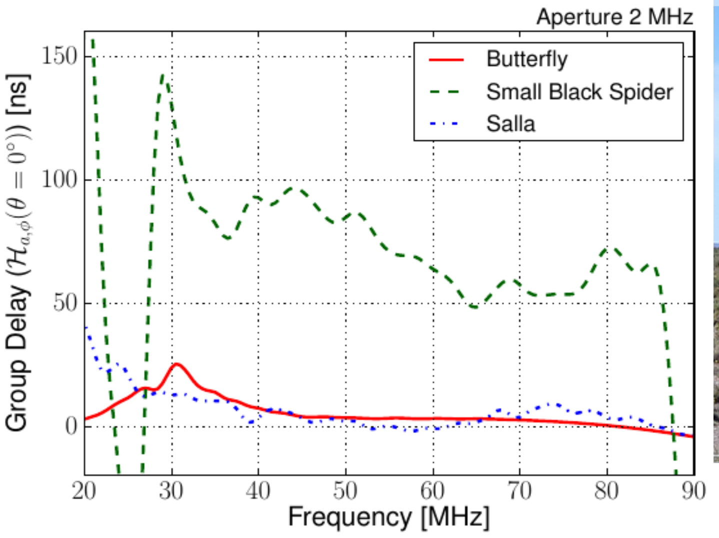



SALLA-station
SALLA-Antenna
30-80 MHz
Wifi antenna
GPS Antenna
98
Electronic box:
Solar panel
digital electronic
(4x 12bit 180MHz ADCs)
analog electronic
batteries

Comparison of Antennas

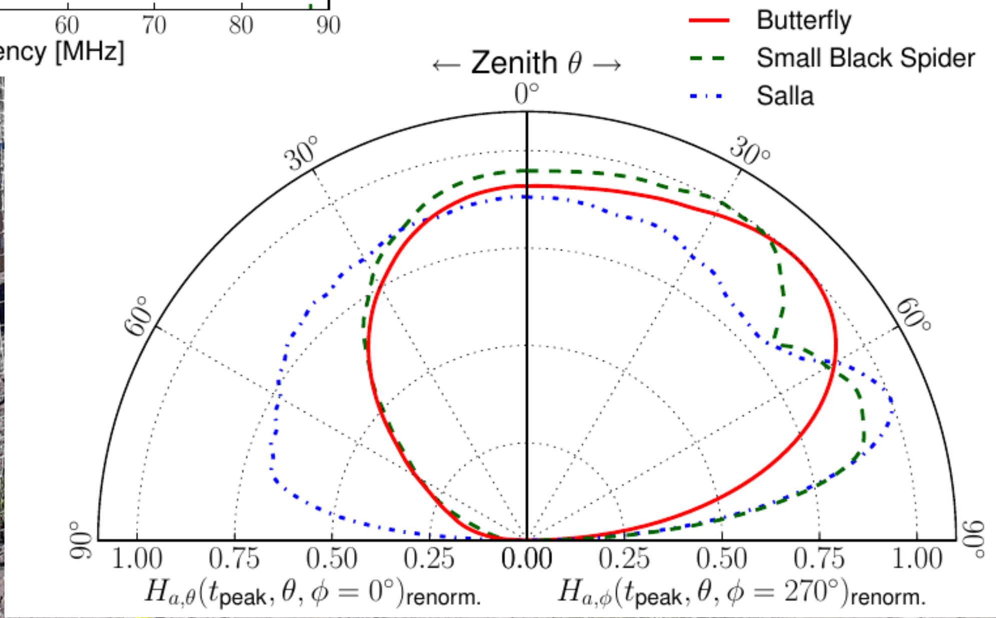
P. Abreu et al 2012 JINST 7 P10011





Phase I: better understood LPDA (prototypes)
Phase II: better sensitivity and group delay

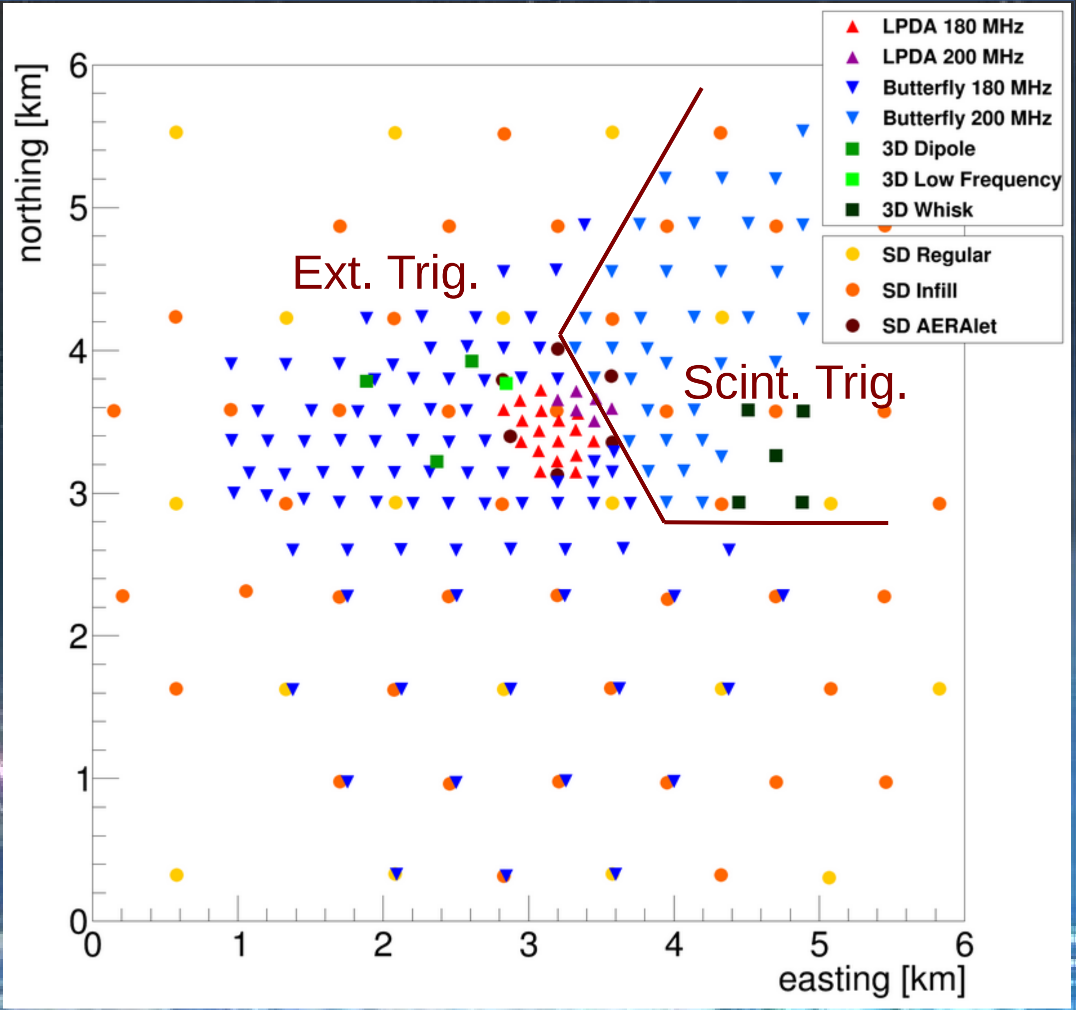
RD-Extension: simplest design



Radio at Pierre Auger Observatory: AERA

Deployed in three phases:

Phase I:	24 RDS in 09/2010 150 m spacing LPDA Fibre comm
Phase II:	100 RDS in 05/2013 Butterfly 250/375 m spacing Wifi comm
Phase III:	25 RDS in 02/2015 Butterfly 750 m spacing Wifi comm (RD-Extension)



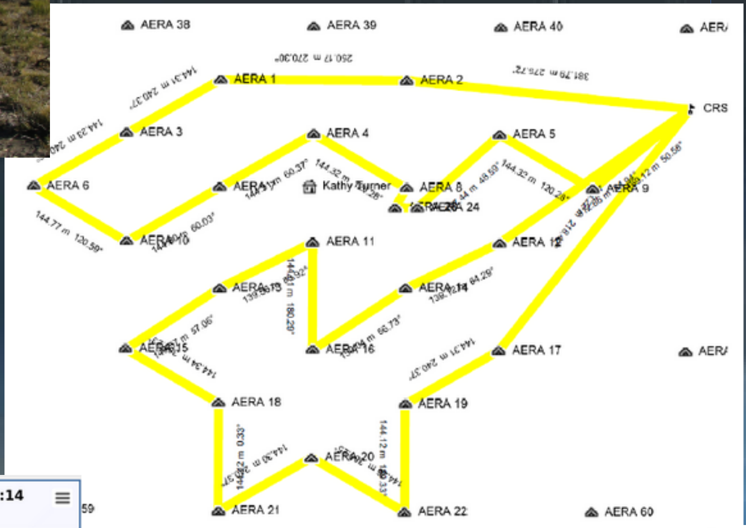
External trig.:	7 sec of buffer (power) → interference analysis
Scintillator trig.:	Autonomous, inefficient for inclined

Radio at Pierre Auger Observatory: AERA

Power: ~ 13 W

Communication:

- optical fibre in Phase I
- Ubiquiti buttel/rocket wifi with concentrater in the field (CRS) and at FD-building (Coihueco)



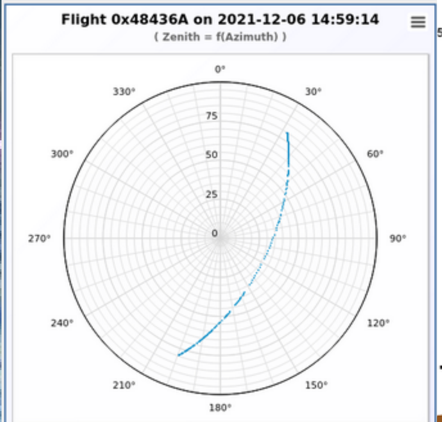
Continuous data taking, ~20GB day:

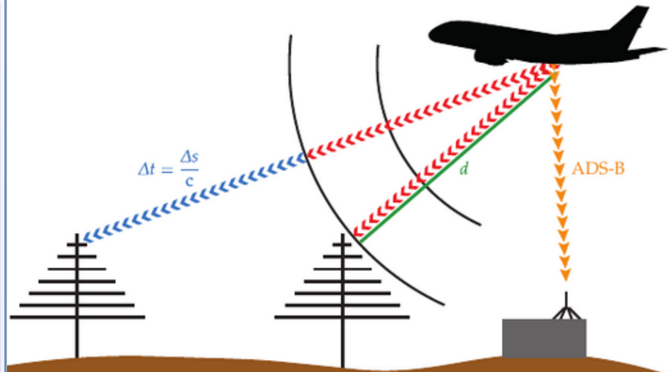
JINST 11 (2016) P01018 11

- External triggered
- Self triggered
- Periodic 100sec (e.g. for realistic noise)
- Airplane trigger

Time synchronization:

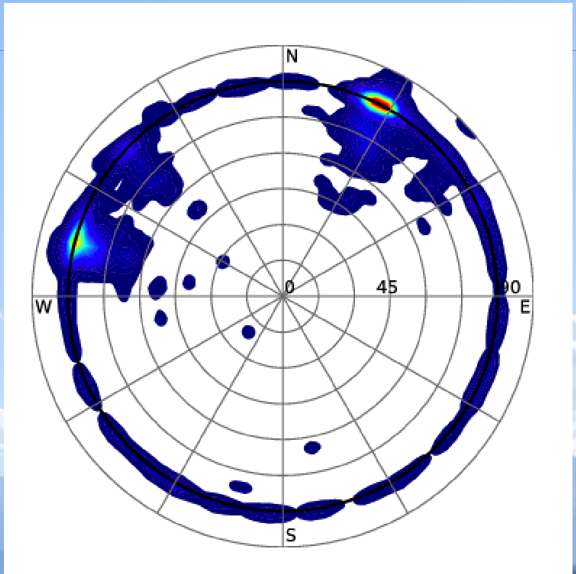
- Beacon with 4 frequences at Coihueco
- Calibration using airplanes

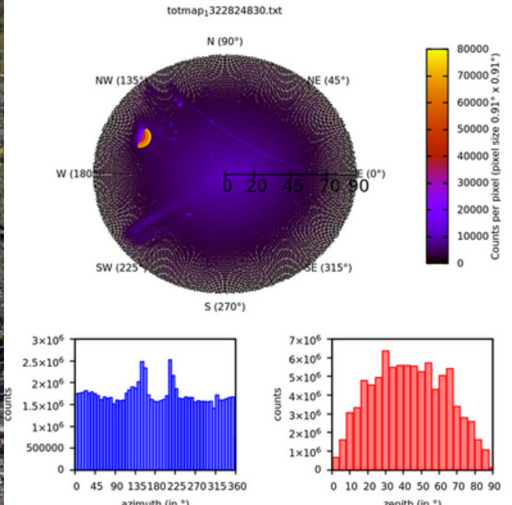




AERA: Self-Trigger?

- Direction reconstruction of self-triggered events point to horizontal hot-spots
- Spikes are very similar to EAS
- High trigger-rate and very low purity
  Need external trigger to understand signal/BG discrimination
- Two different Ansatz:
  - Buffer Signal long enough to use trigger from Auger (up to 7 sec, power-conssuming)
  - Use additional Szintillator as local coincidence trigger (inefficient, i.e. towards horizont)





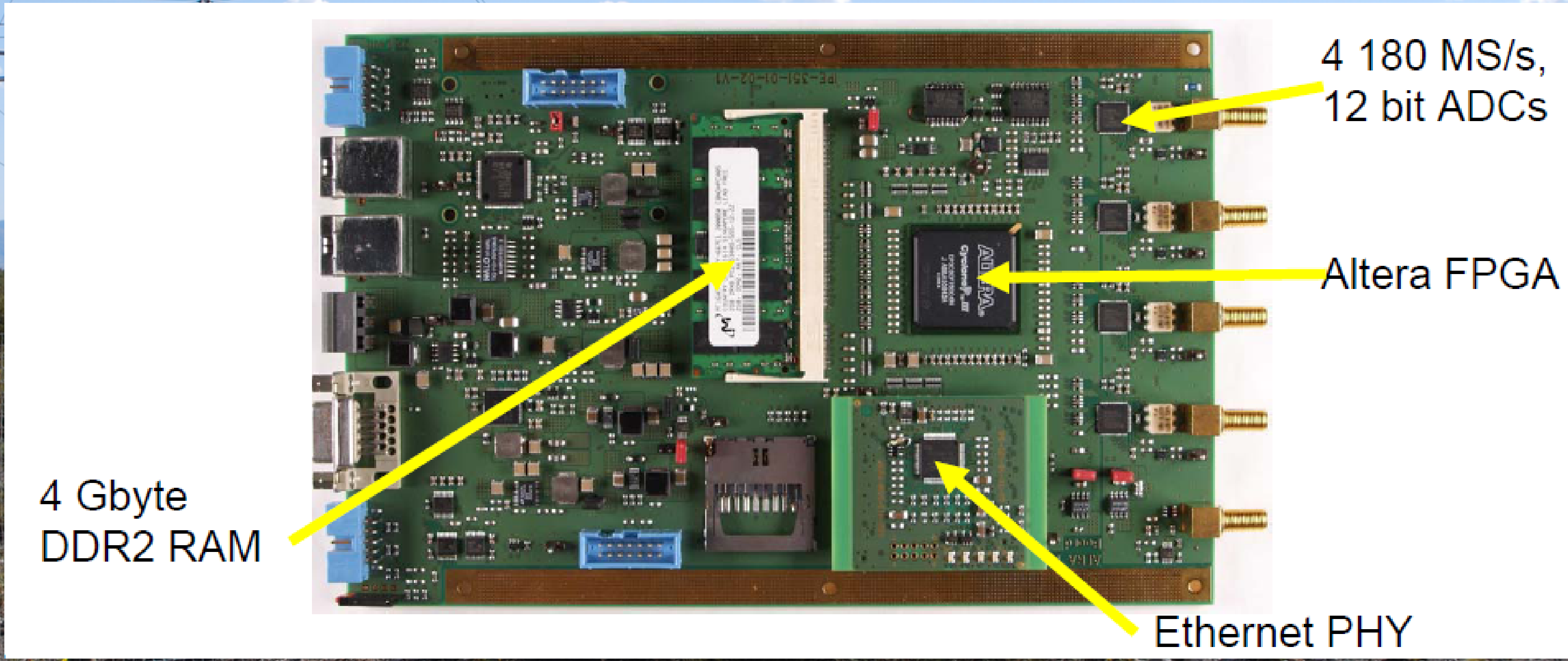
AERA: External-Trigger

KIT/BUW developed digitizer cards in the field since March 2012

Full buffering of 7 sec (4GB SODIMM, 3W)

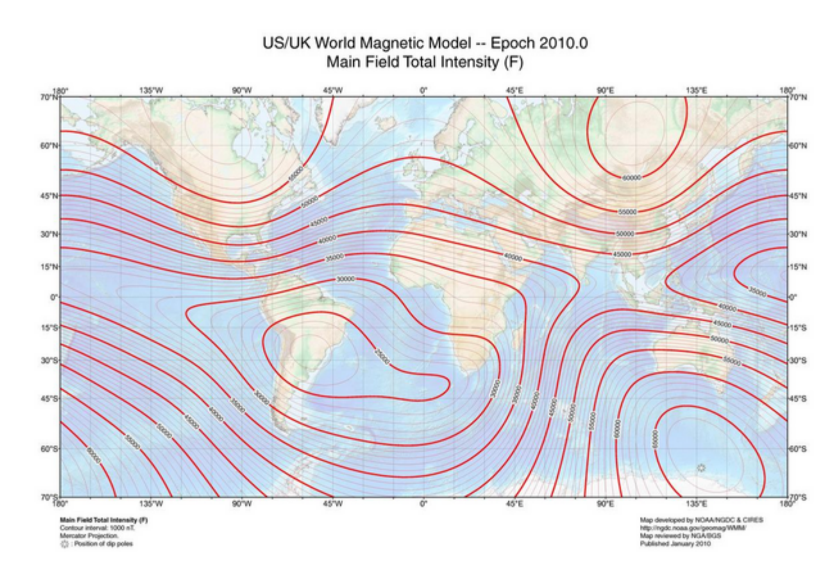
Externally triggered by SD & untriggered read-out of stations

ALTERA Cyclone III for intelligent trigger algorithm (FFT-filter-iFFT)

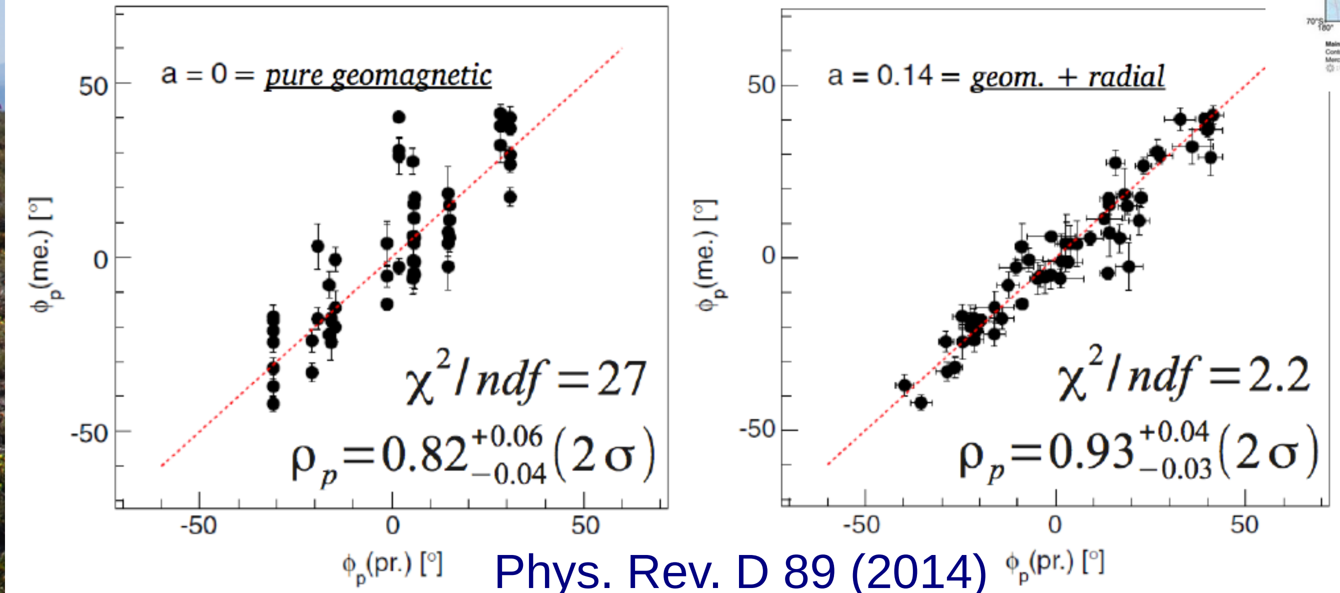


AERA: Charge Excess

- Polarization clear signature for emission mechanism
- Fit of charge-excess fraction to polarisation data
- Significant increase in correlation of expected to measured polarisation with on average 14% charge excess contribution



- Earth magnetic field at the Pierre Auger Observatory ½ of that in Europe



Phys. Rev. D 89 (2014)

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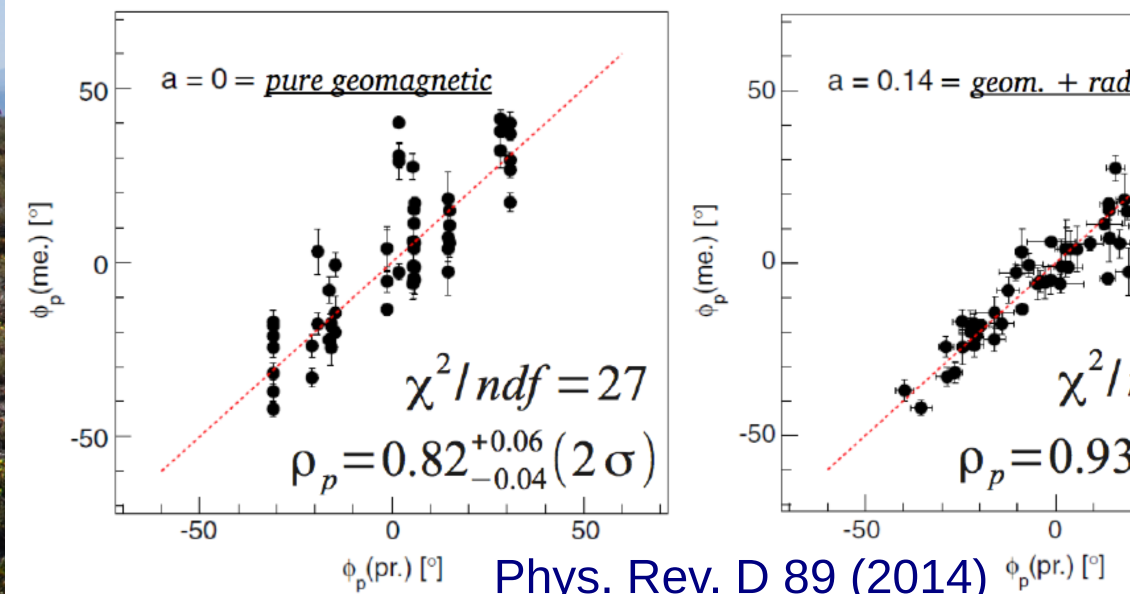


Phys. Rev. D 89 (2014)

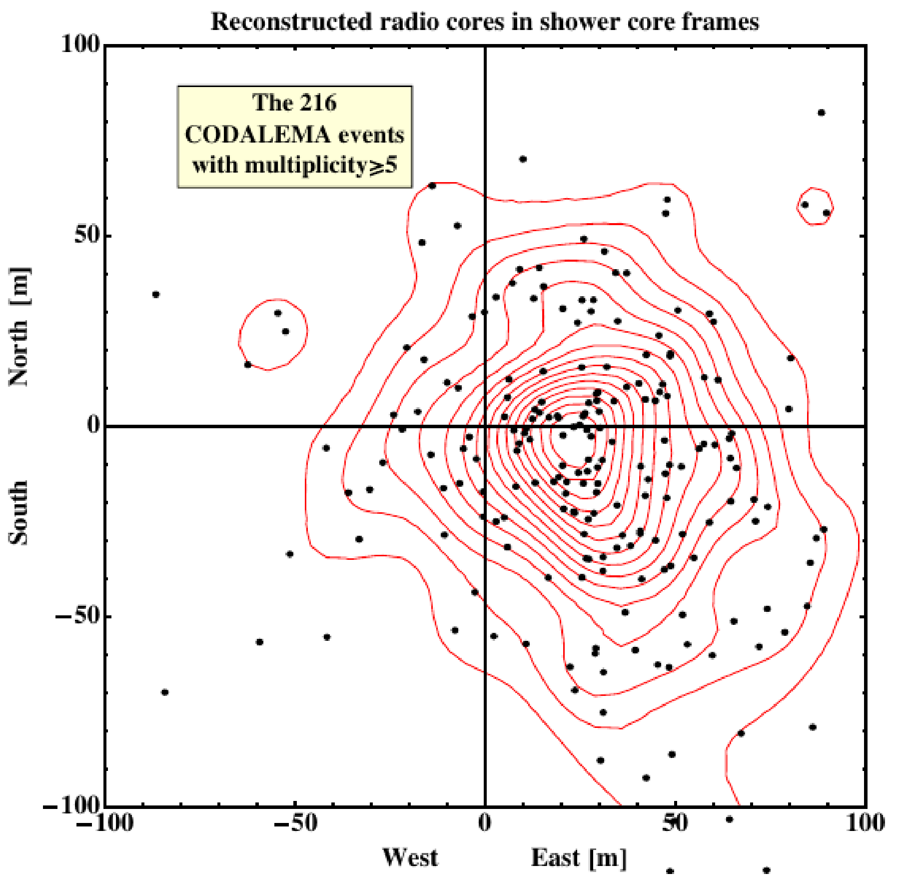
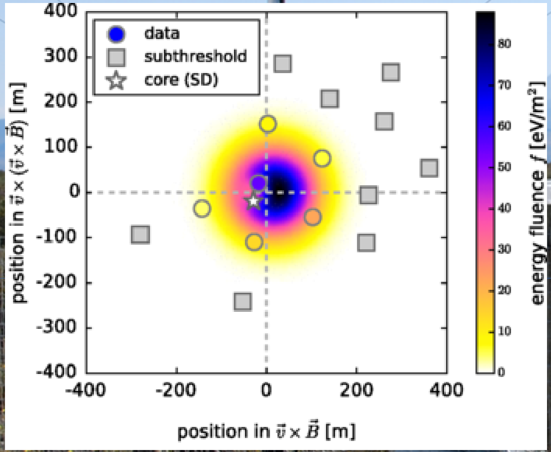


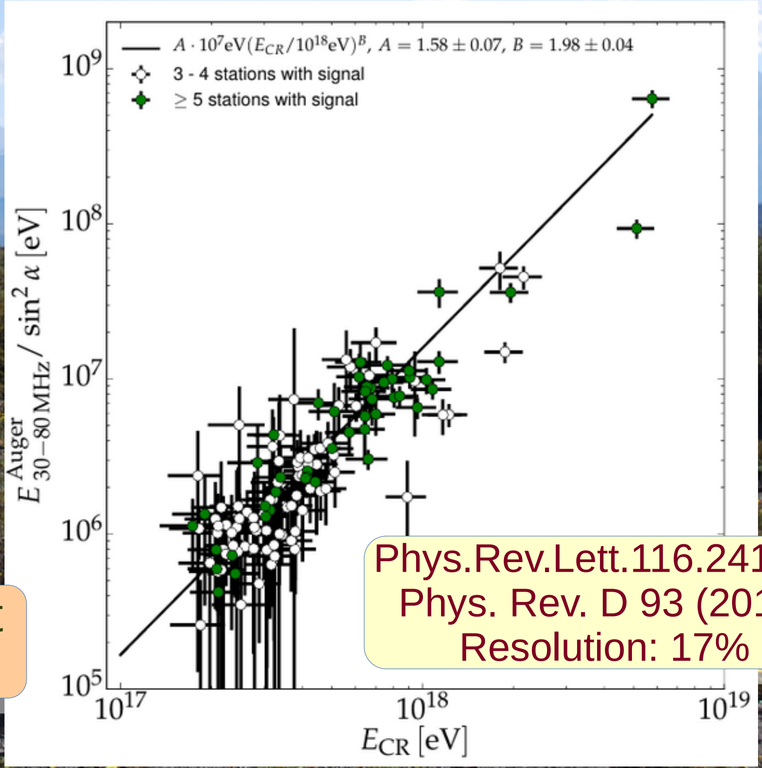
Fig. 3. The experimentally observed core shift. The black dots represent the radio core positions relatively to the particle core positions of the 216 selected events detected by CODALEMA. The red lines are the contour levels of a 10 m Gaussian smoothed map. The average radio core position is shifted toward the east by ∼30 m.

AERA: Energy

- Emission well understood
- Optimal EM detector for inclined shower
- No attenuation in atmosphere
- Composition sensitivity promissing
- High potential for absolute e-scale

Radiation energy in 30-80 MHz for 1 EeV CR perpendicular to B-field: 15.8 ± 0.7 (stat) ± 6.7 (sys) MeV
Direct access to calorimetric energy in the electromagnetic cascade of EAS.



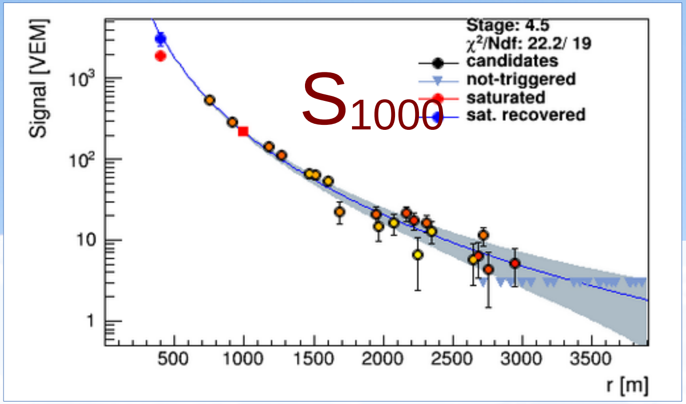


Phys.Rev.Lett.116.241101
Phys. Rev. D 93 (2016)
Resolution: 17%

Correlation with well calibrated Energy measurment of the Pierre Auger Obsevatory

AERA: Energy

Paradigm change:
From: Sym. LDF characterized at optimal point (S1000)
To: Integral of signal like calorimetric measurement



Radiation Energy

$E_{30-80\,\mathrm{MHz}}$

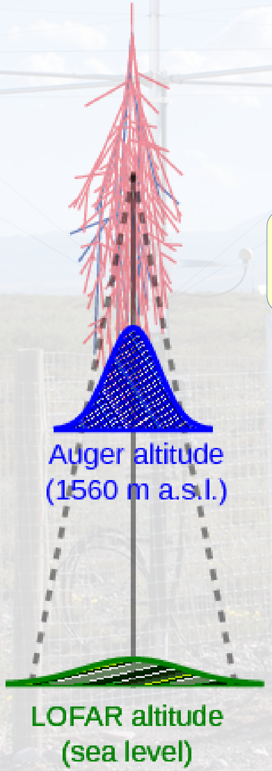
$\propto \int A^2 \mathrm{d}^2 r$

Amplitude at optimal lateral distance

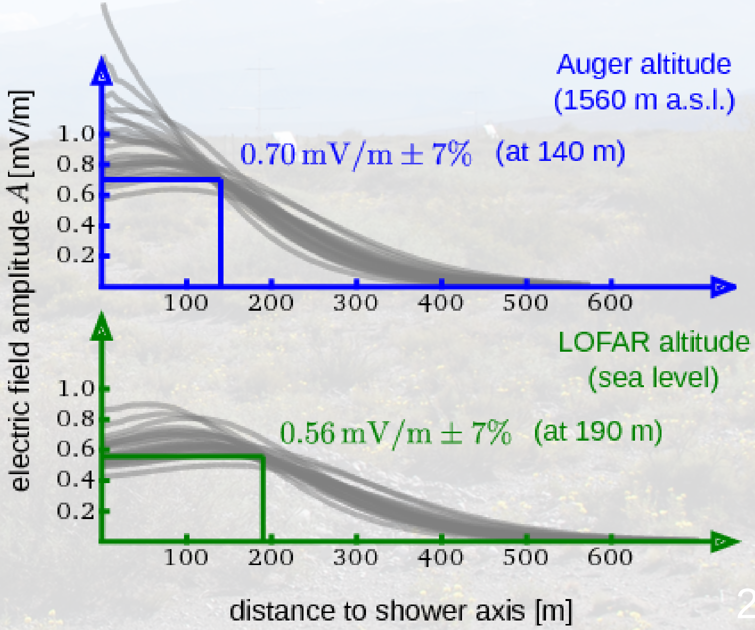
A

Supplement to
Phys.Rev.Lett.116.241101

The Radiation Energy reflects the calorimetric energy of the air shower. It is independent of observation altitude.



The optimal lateral distance and the amplitude measured there vary with observation altitude (even after charge-excess and zenith-angle correction).



AERA: Energy

Better undestanding of emission:

Ch. Glaser et al JCAP09(2016)024

M. Gottowik et al.,
Astropart. Phys. 103 (2018) 87

E_{emag}: 3 % stat, 2 % sys.

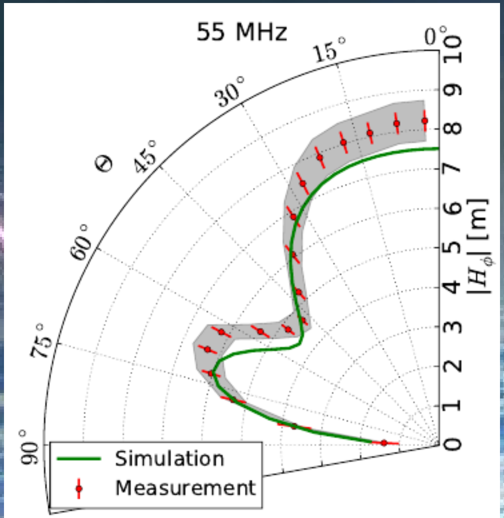
Better understanding of detector:

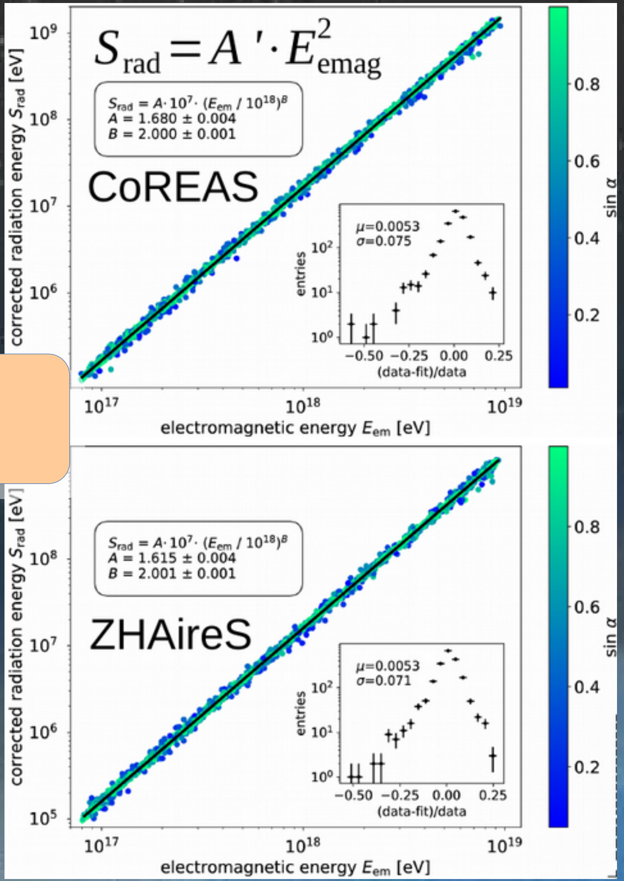
Calibration of LPDA

A. Aab et al 2017 JINST 12 T10005

Paper to be pubished soon

Source of uncertainty / %	Systematic	Statistical
flight dependent uncertainties	**6.9**	**2.7**
transmitting antenna XY-position	1.5	1.0
transmitting antenna height	0.1	0.6
transmitting antenna tilt	< 0.1	< 0.1
size of antenna under test	1.4	–
uniformity of ground	< 0.1	–
RSG1000 output power	2.9	2.3
influence of octocopter	< 0.1	–
electric-field twist	0.4	0.2
LNA temperature drift	1.0	0.6
receiving power	5.8	–
background	0.4	–
global uncertainties	**6.3**	**< 0.1**
injected power	2.5	< 0.1
transmitting antenna gain	5.8	–
cable attenuation	0.5	< 0.1
all / %	**9.3**	**4.7**





AERA: Composition

General strategies:

1) Use simulation to fit the measured amplitudes
   S. Buitink, Phys. Rev. D 90, 082003

2) Direct sensitivity from radio

   2.a) LDF

   2.b) Frequency

   2.c) Wavefront

3) Combined sensitivity

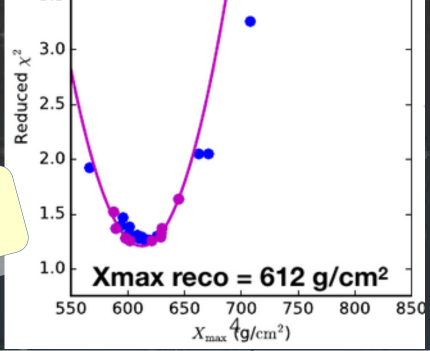
   3.a) radio+WCD

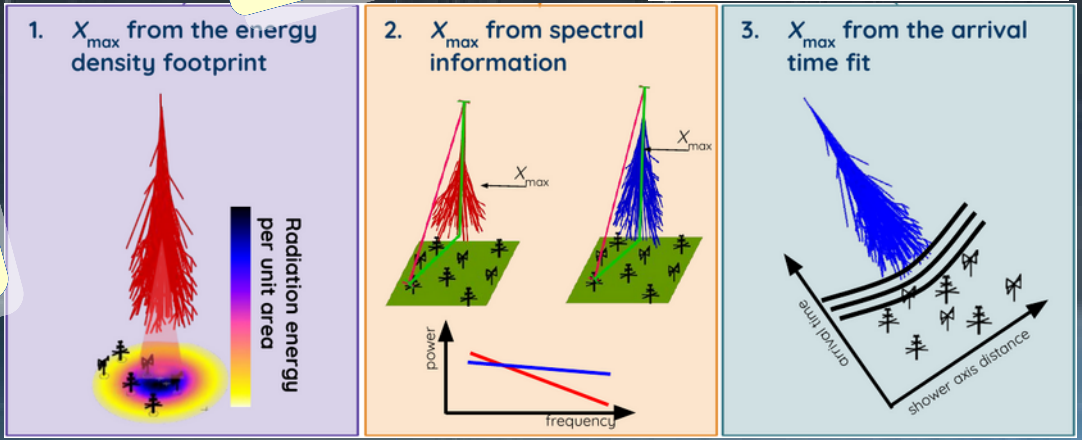
   3.b) radio+muon

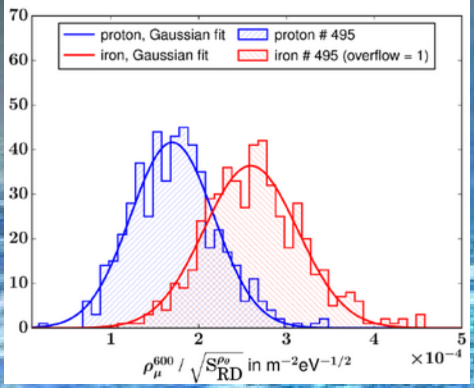
CPU-intensive!

Sensitivity decreases with distance to X_{max}

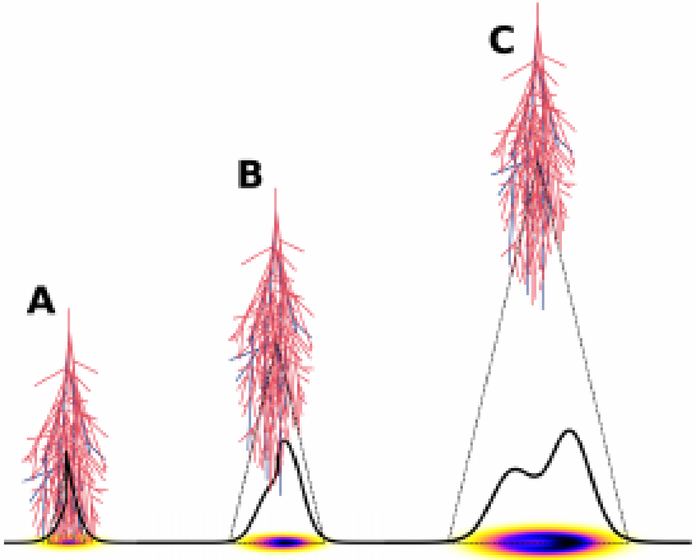
Low data statistics

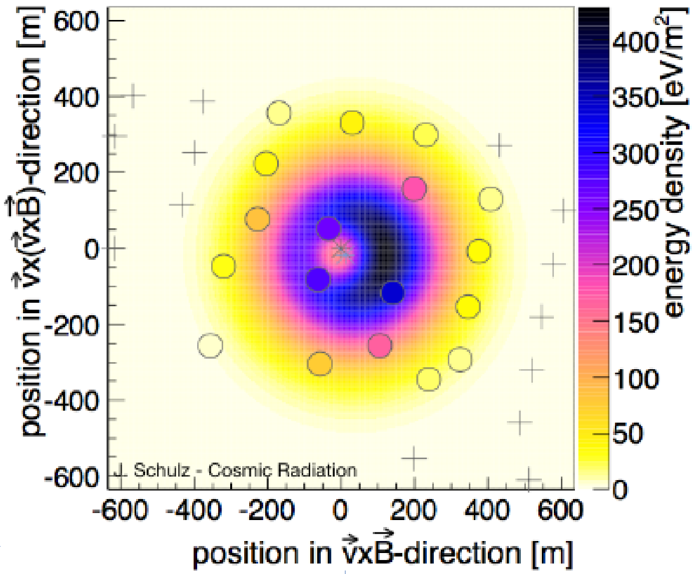


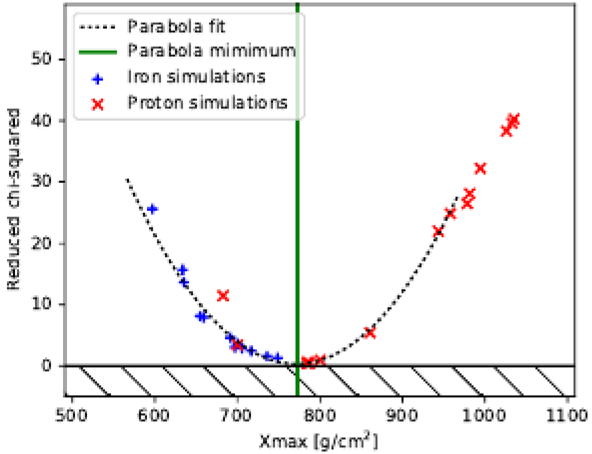




AERA: Composition fitting MC





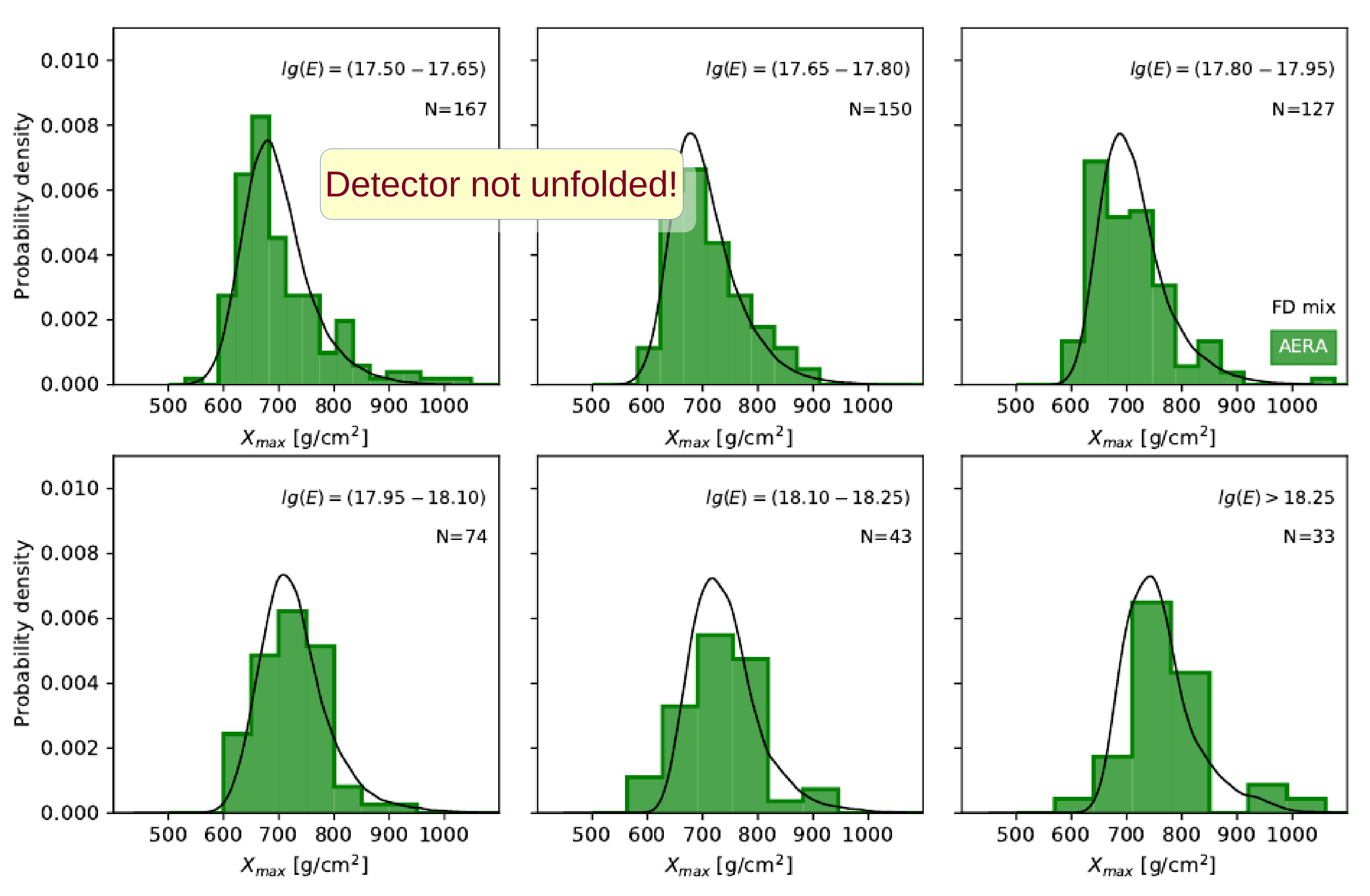


Footprint depends on distance to X_{max}

For each measured shower (geometry) generate many showers
→ fluctuating X_{max} and mixed composition

Phys. Rev. Lett. 132, 021001 (2024)
Phys. Rev. D 109, 022002 (2024):

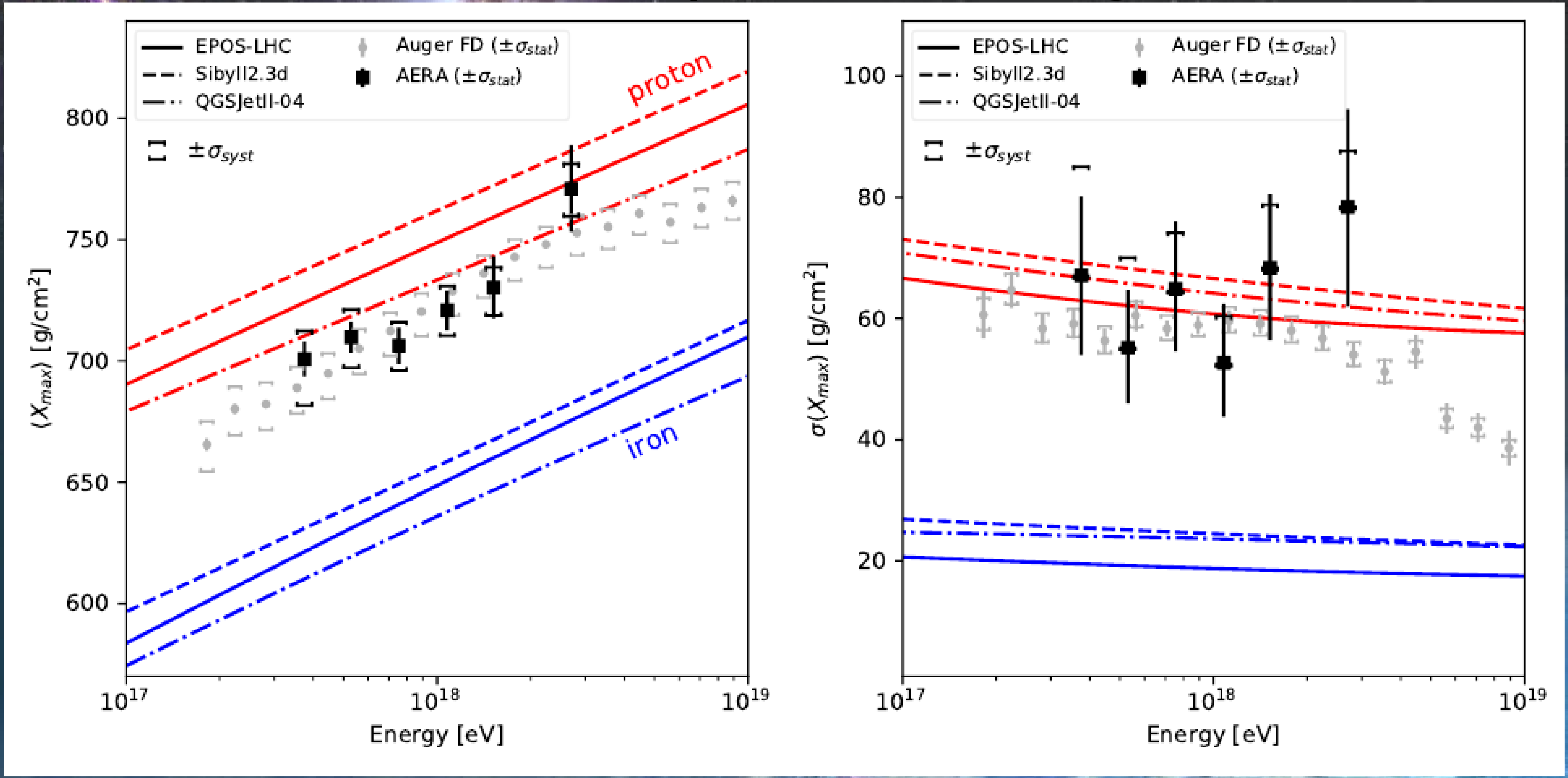
AERA: Composition fitting MC



Comparison to FD measurment!

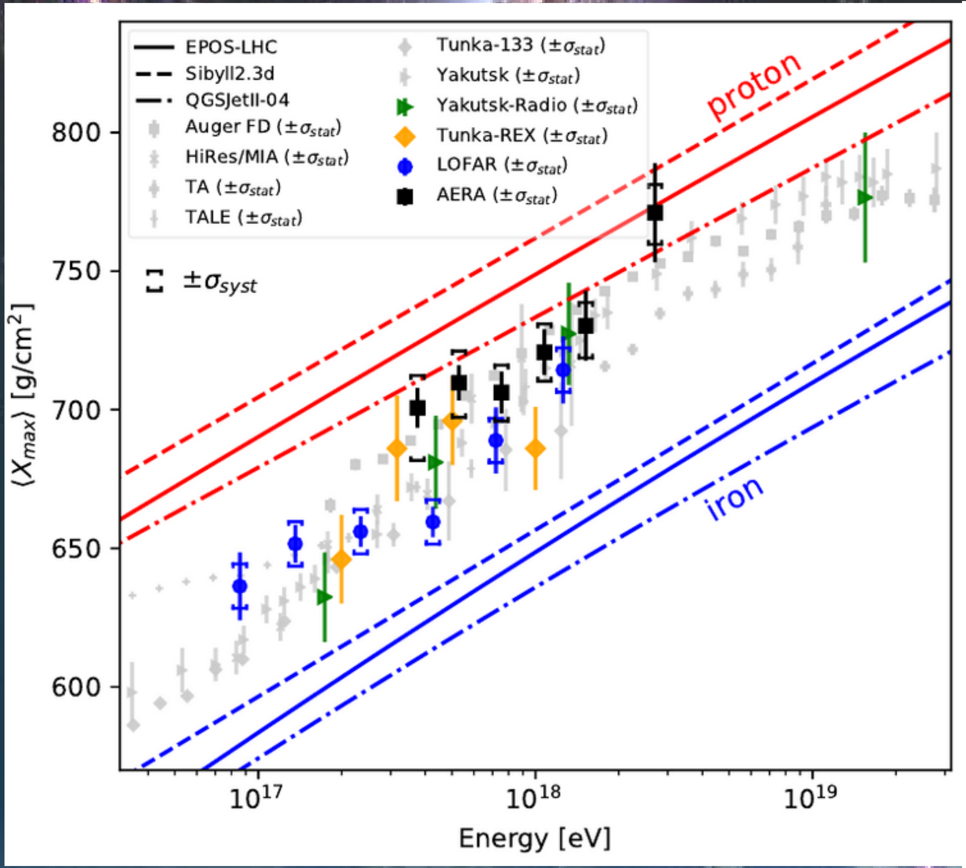
~600 showers after quality and anti-bias cuts!

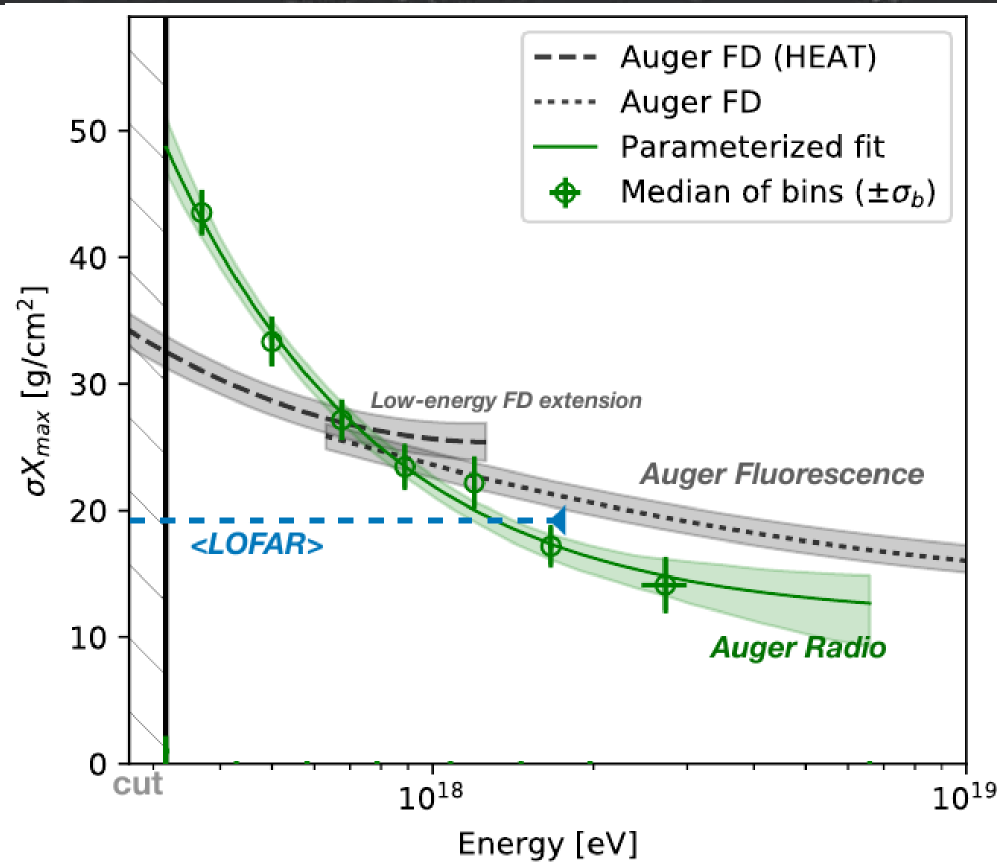
AERA: Composition fitting MC



Phys. Rev. Lett. 132, 021001 (2024)
Phys. Rev. D 109, 022002 (2024):

AERA: Composition fitting MC





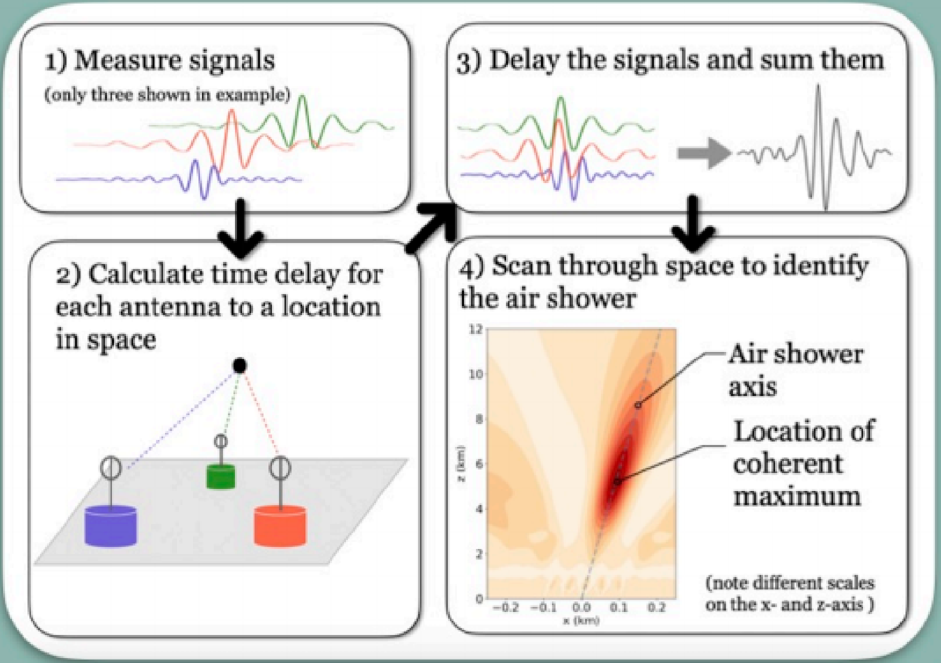
At higher energies promising resolution!

Phys. Rev. Lett. 132, 021001 (2024)
Phys. Rev. D 109, 022002 (2024):

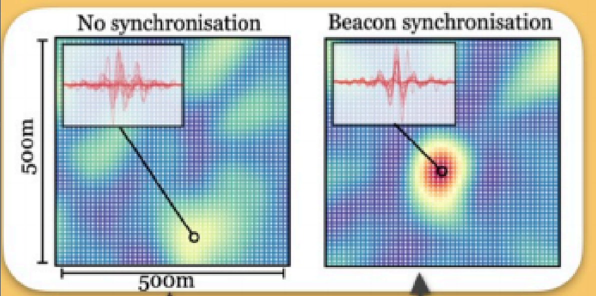
Xmax with Interferometry

Method

There have been several attempts to apply radio interferometry [4,5,6] for estimating air showers parameters. Below the basic steps are shown for scanning the atmosphere to find coherent emission from an air shower according to the method published in [1,2].



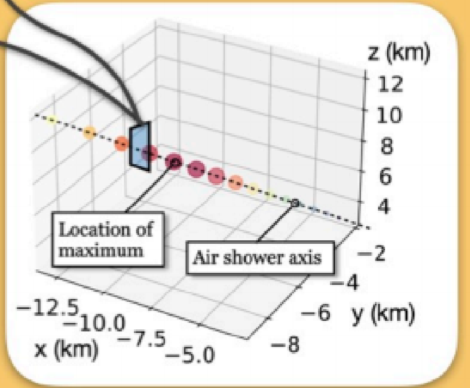
Reconstruction of an air shower

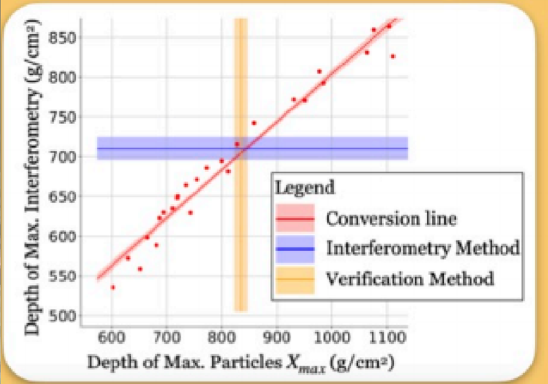


1) Apply beacon synchronisation and locate the air shower axis in a plane perpendicular to initial guess of the axis.

2) Reconstruct air shower properties:

a) track the axis
b) fit axis with a straight line,
c) find location of maximum of the coherent sum on



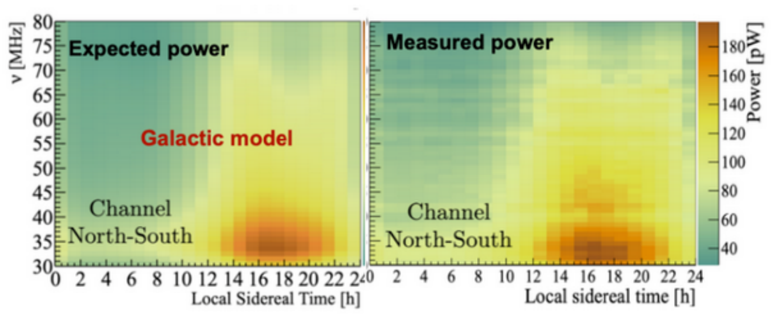


3) Relate the location of maximum from the interferometry to the location of the maximum of the air shower by generating a conversion line using air shower simulations.

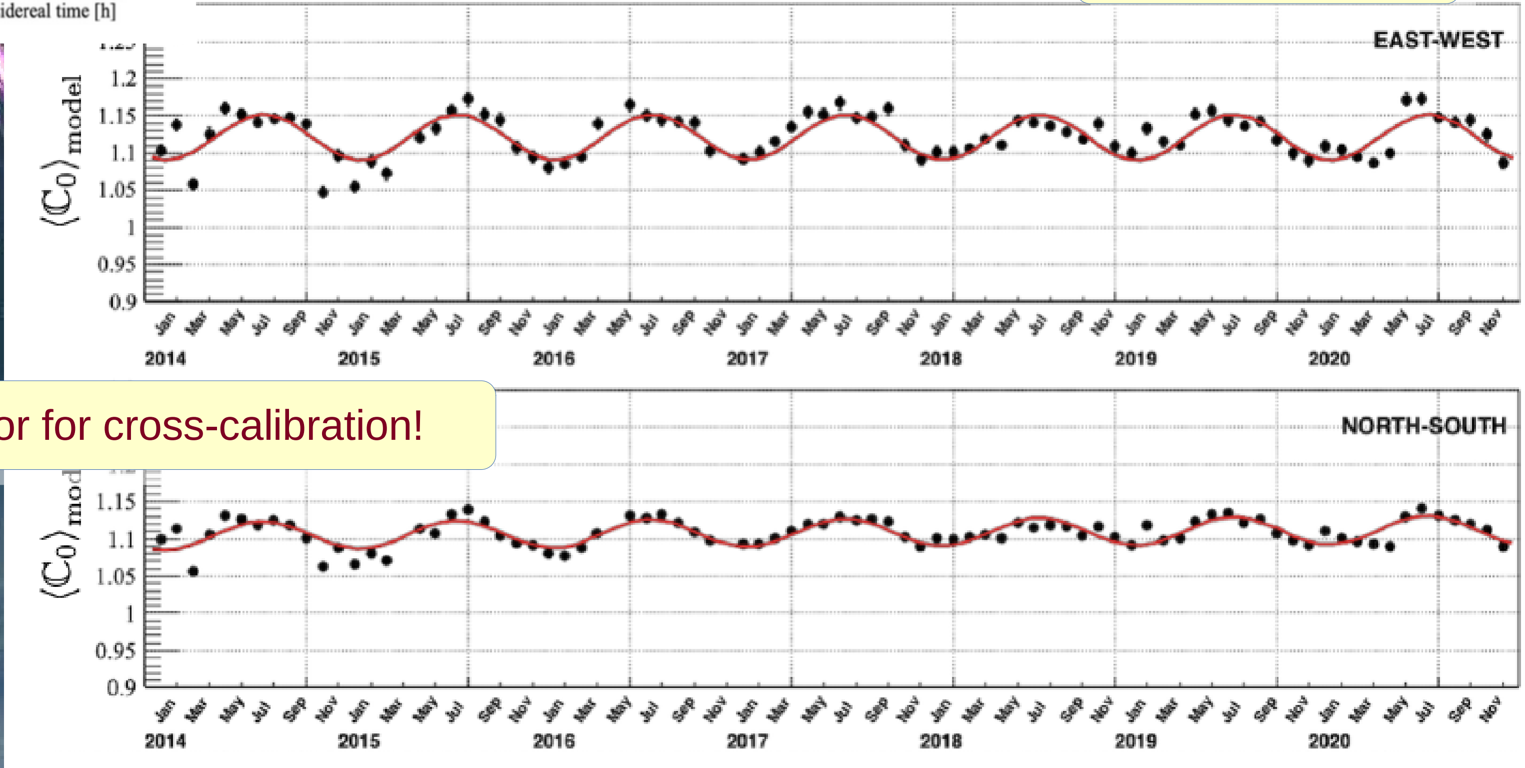
PoS(ICRC2023)380 H.Schoorlemmer for the Pierre Auger Collaboration

AERA: Calibration & Aging

Fit strength of Galactic noisefrom periodic triggered events
Compare to models for Galactic noise
Long-term stability 0.32 ± 0.51% per decade



UHECR 2024



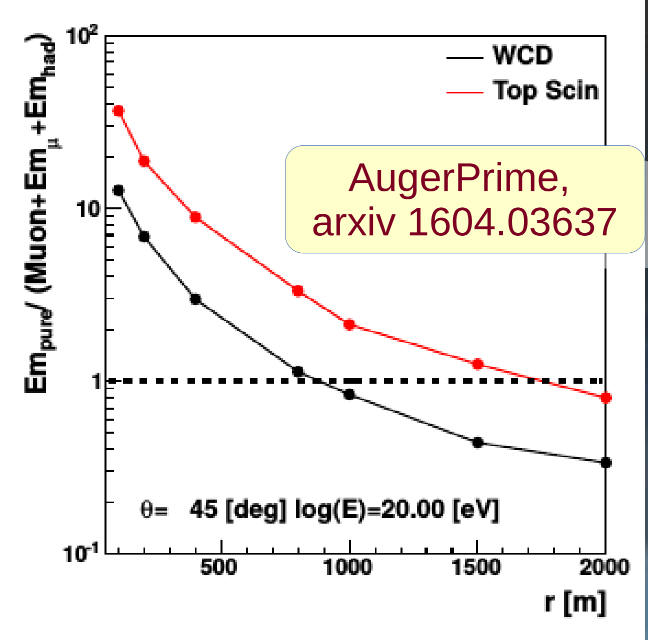
No Aging! Optimal detector for cross-calibration!

Pierre Auger Observatory: Radio+WCD

Radio for inclined showers

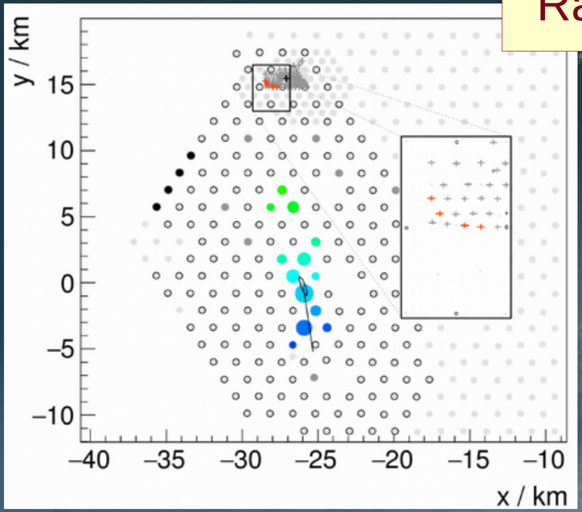
Radio as perfect EM and
WCD at large zenith angles as perfect muon detector

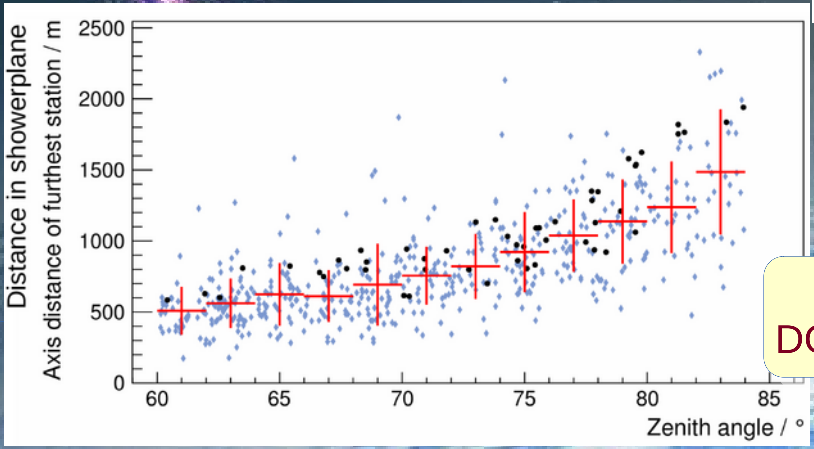
Proof: Radio at large zenith angles works!



AugerPrime,
arxiv 1604.03637

Radio footprint > particle footprint





A. Aab et al JCAP10(2018)026
DOI 10.1088/1475-7516/2018/10/026

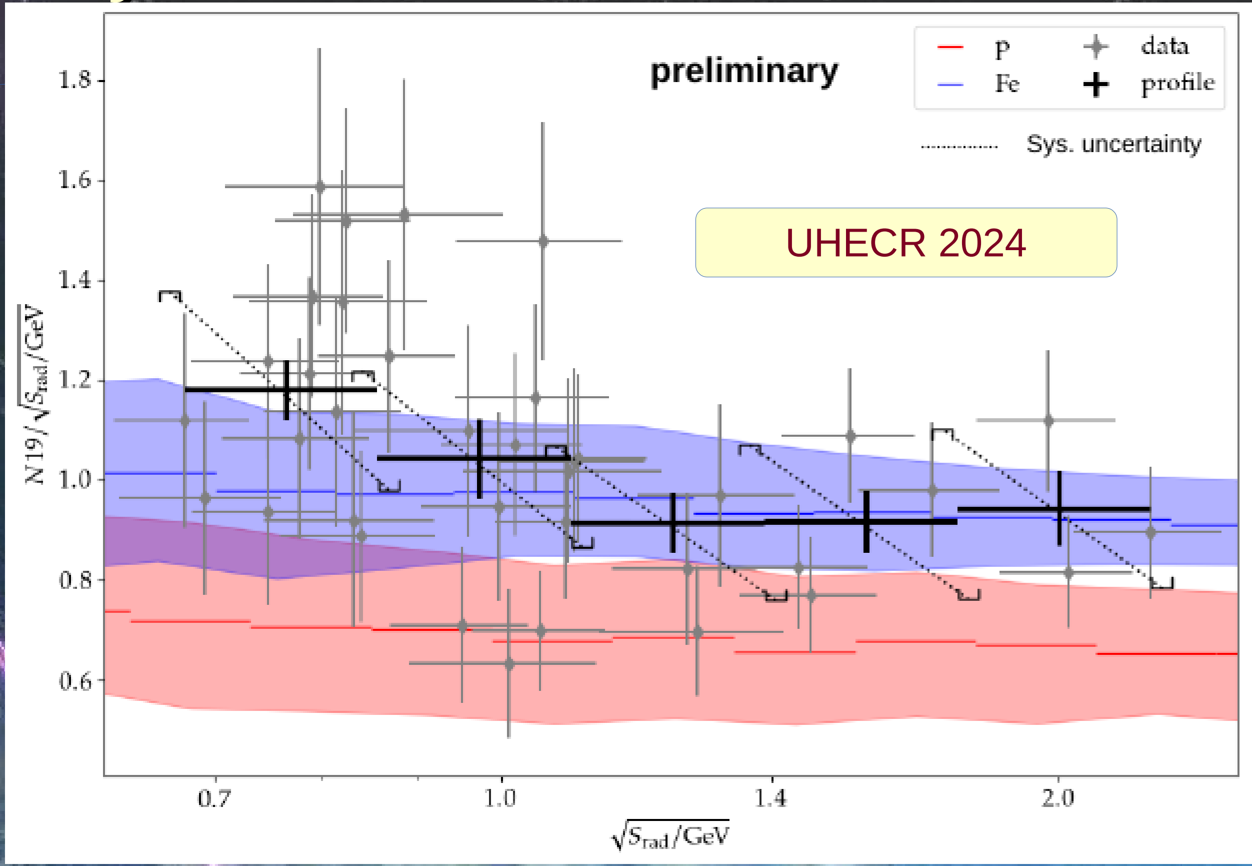
Pierre Auger Observatory: Radio+WCD

Muon number measured with the WCD

Energy estimation with AERA

Data period (Auger Phase 1): 26.06.2013 – 31.08.2021

37 high-quality events with WCD energies between ~4 to 12 EeV



Strongest cut: EEM > 4 EeV (enforces full efficiency of the WCD for inclined air showers)

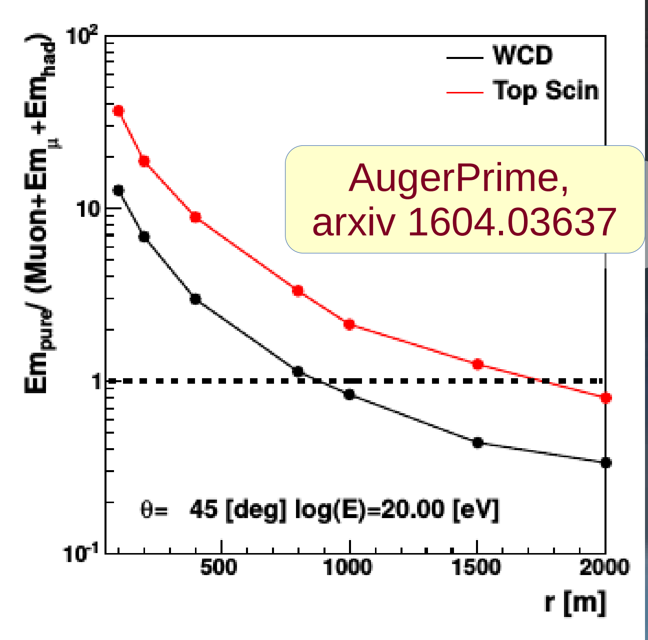
Systematic uncertainties: 10% on N19, ~28% on Srad (~14% on EEM)

Pierre Auger Observatory: Radio+WCD

Radio for inclined showers

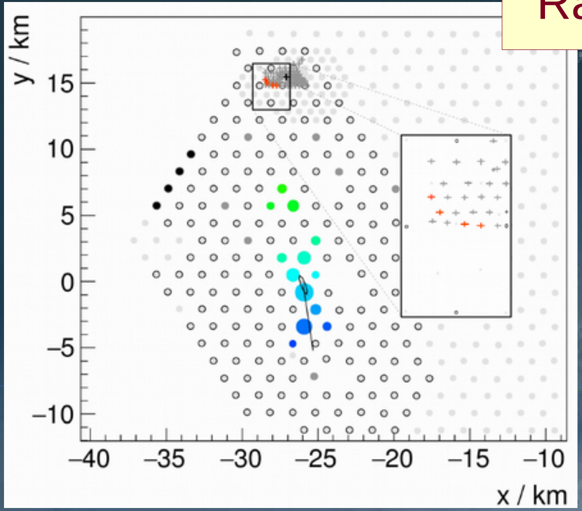
Radio as perfect EM and
WCD at large zenith angles as perfect muon detector

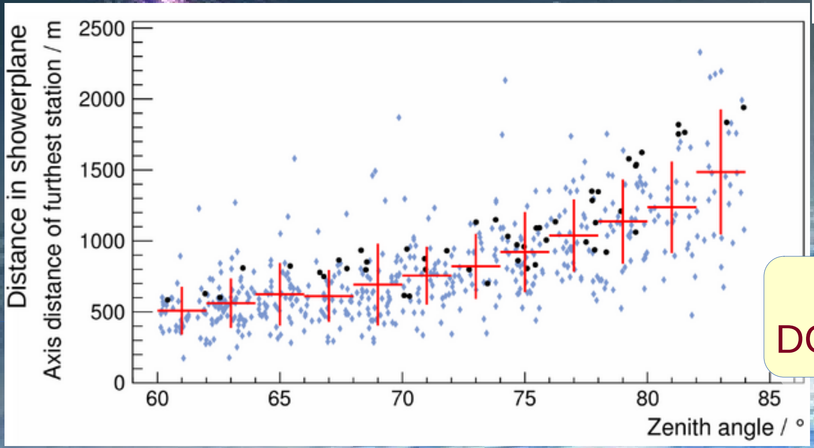
Proof: Radio at large zenith angles works!



AugerPrime,
arxiv 1604.03637

Radio footprint > particle footprint





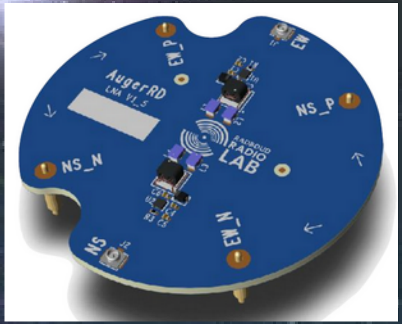
A. Aab et al JCAP10(2018)026
DOI 10.1088/1475-7516/2018/10/026

Proof: Radio at large zenith angles works!

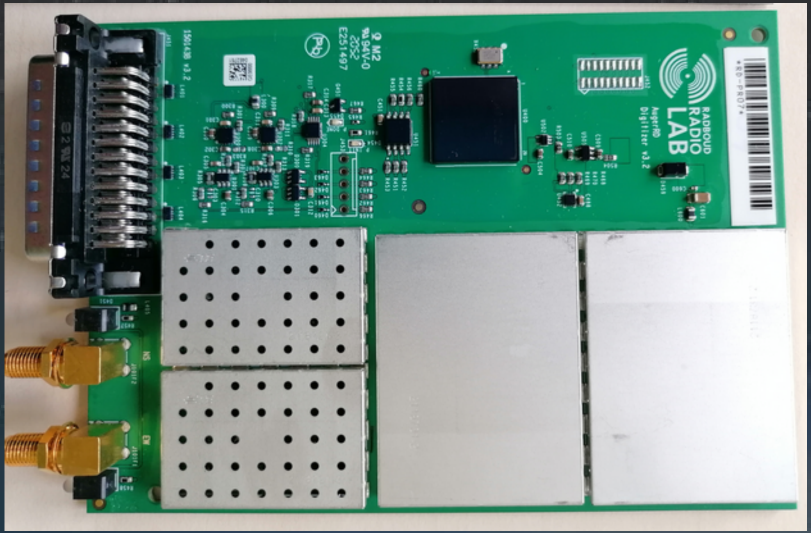
That came out of this: 1660 Stations with radio!

AugerPrime Radio Extension

SALLA Antenna based on development for AERA
2012 JINST 7 P10011 20



LNA with 18.2 dB gain in 30 – 80 MHz, 0.2 W

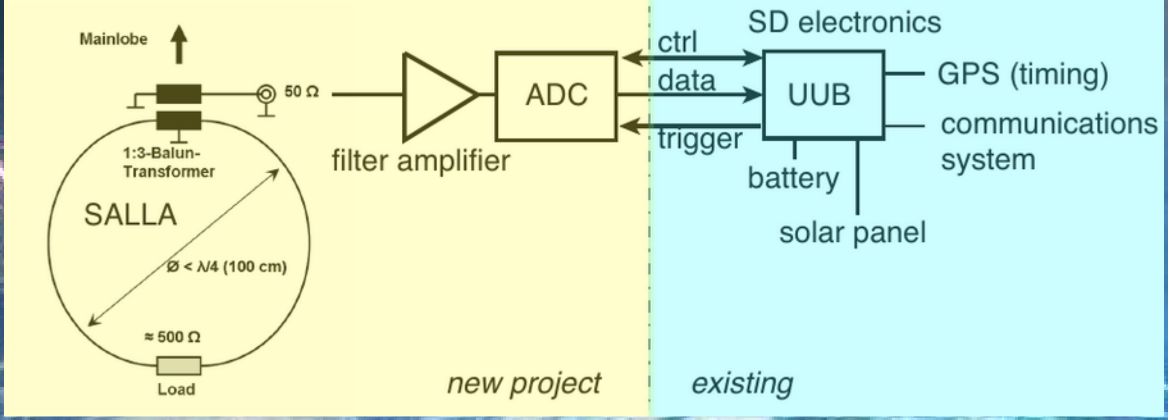


Front-end electronic board, 2.4 W

Filter-amplifier and 2x 250 MHz 12 bit ADC

Connected to digital port of UUB

Mechanical structure to mount on SD-clams



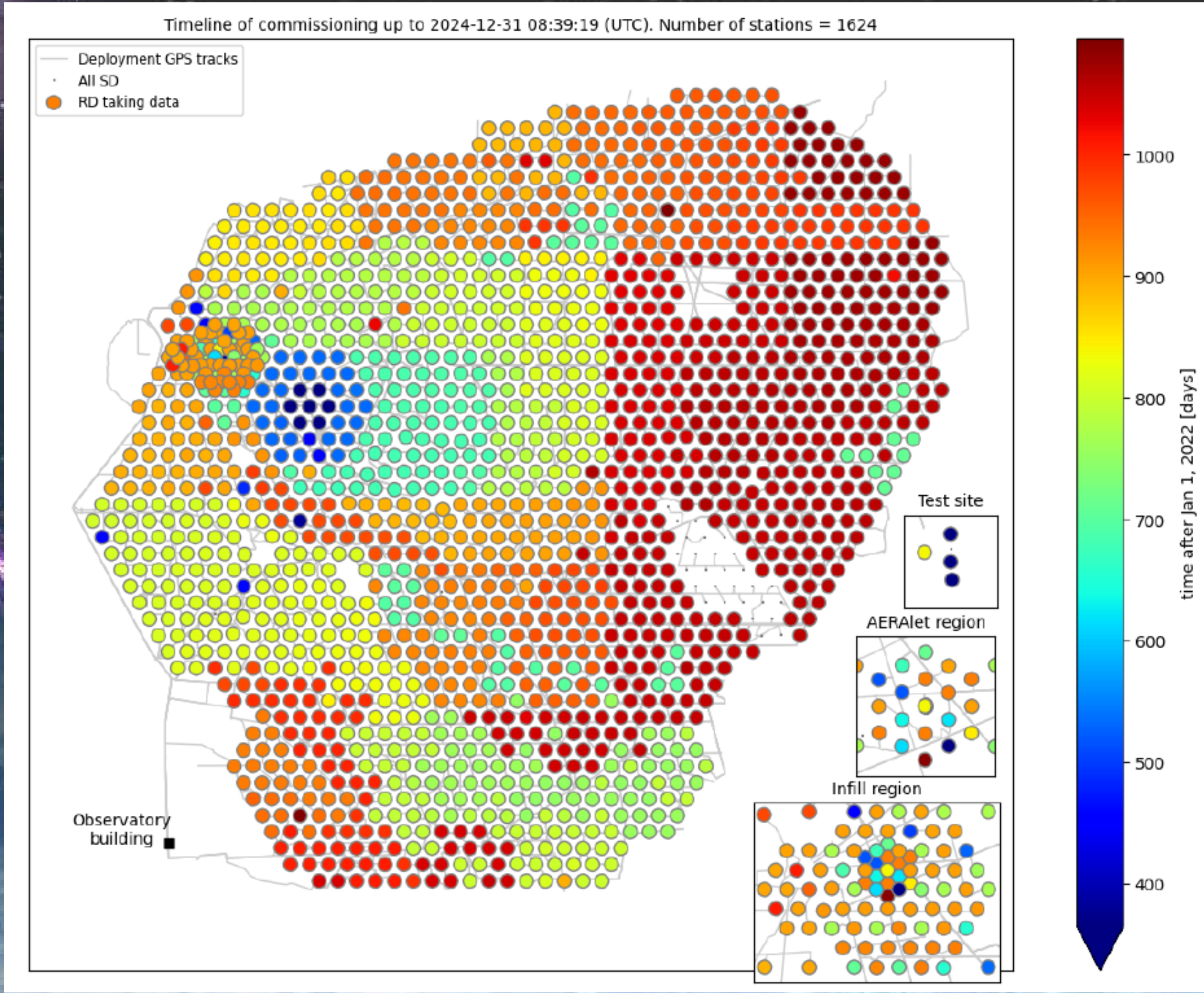
AugerPrime Radio Extension

First Hexagon (7 stations) installed in Nov’19

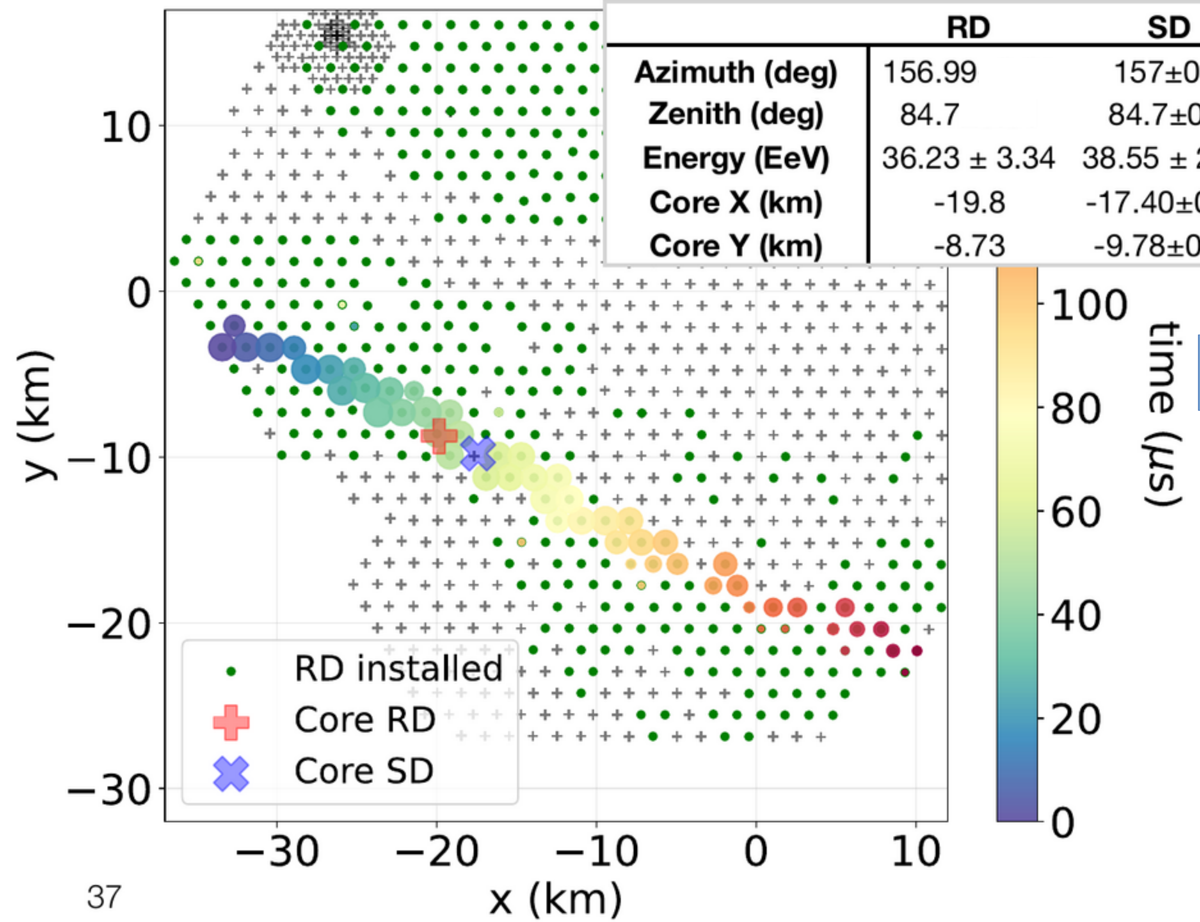
Deployment of mechanical structure & antenna

Production of electronic ready & tested with June’23

Deployment finished Nov’24



AugerPrime Radio Extension: large event!

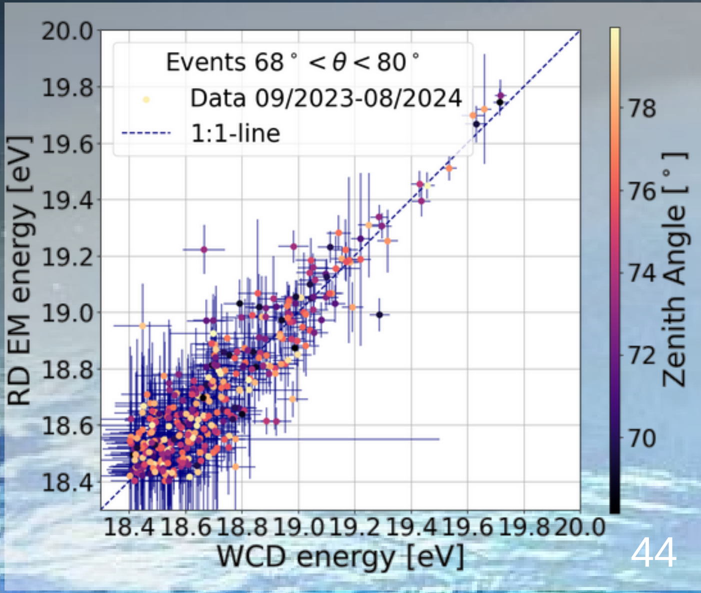


	RD	SD
Azimuth (deg)	156.99	157±0.1
Zenith (deg)	84.7	84.7±0.1
Energy (EeV)	36.23 ± 3.34	38.55 ± 2.92
Core X (km)	-19.8	-17.40±0.88
Core Y (km)	-8.73	-9.78±0.45

Largest Radio CR detector (deployment ready 2024-10)

First promising data

Full reconstruction working
Good agreement with SD



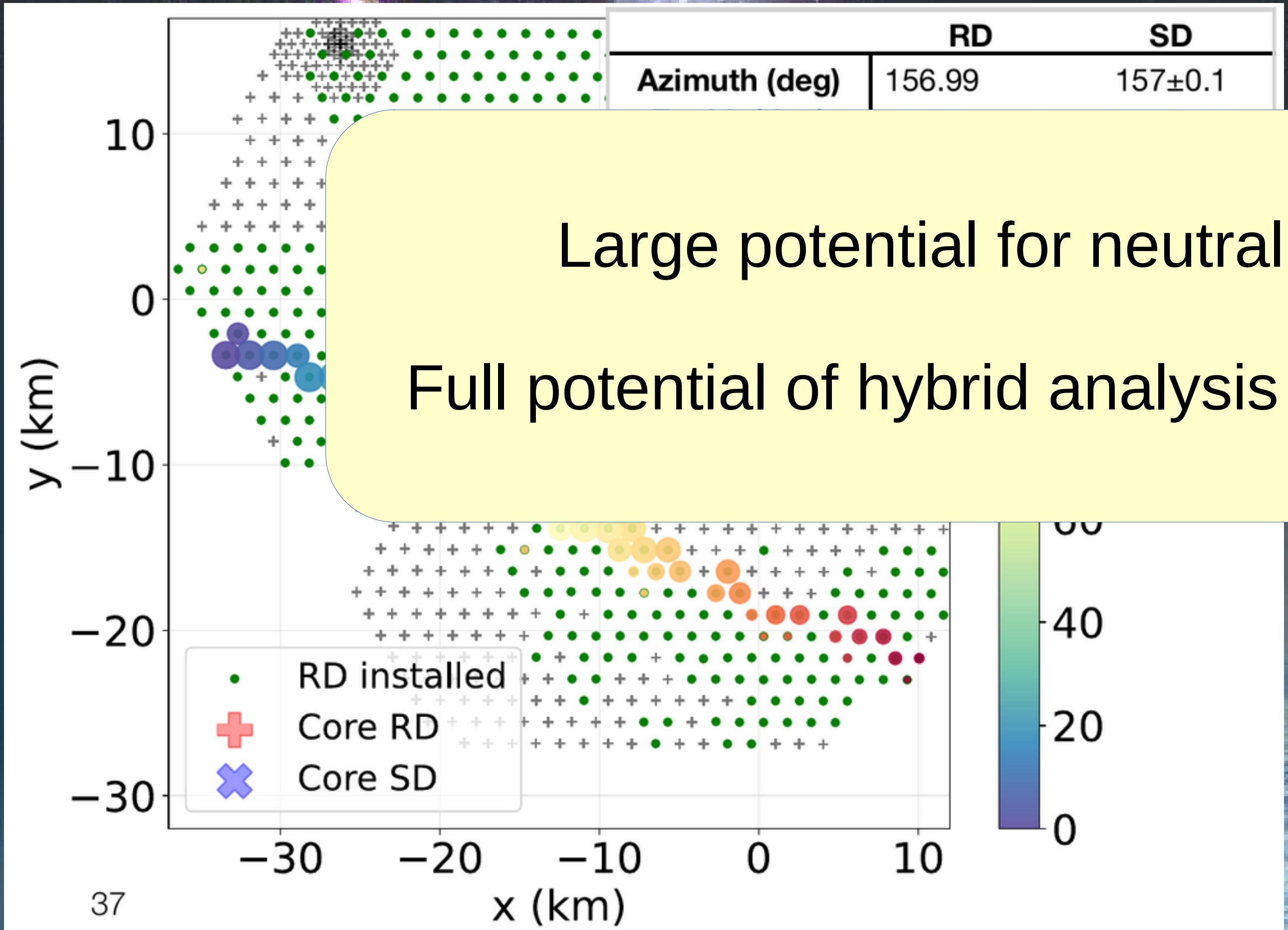
AugerPrime Radio Extension: large event!

Largest Radio CR detector (deployment ready 2024-10)

First promising data

on working

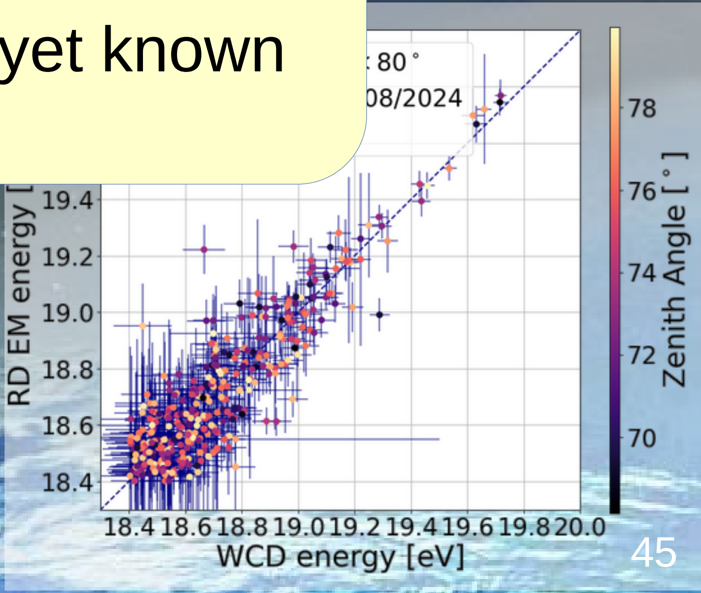
with SD



	RD	SD
Azimuth (deg)	156.99	157±0.1

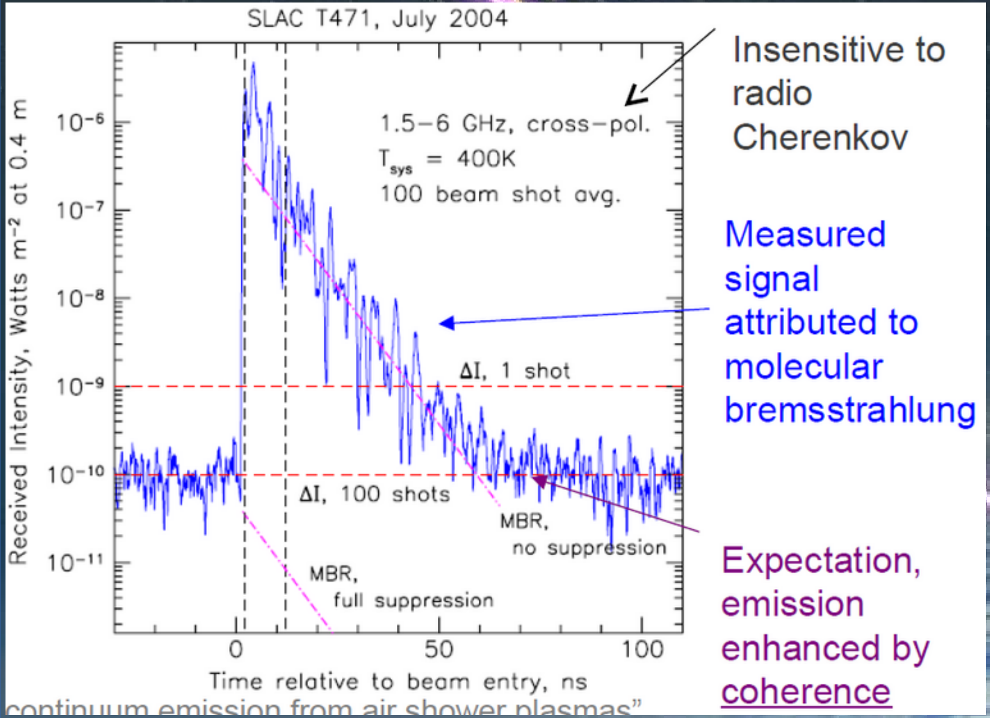
Large potential for neutral particles

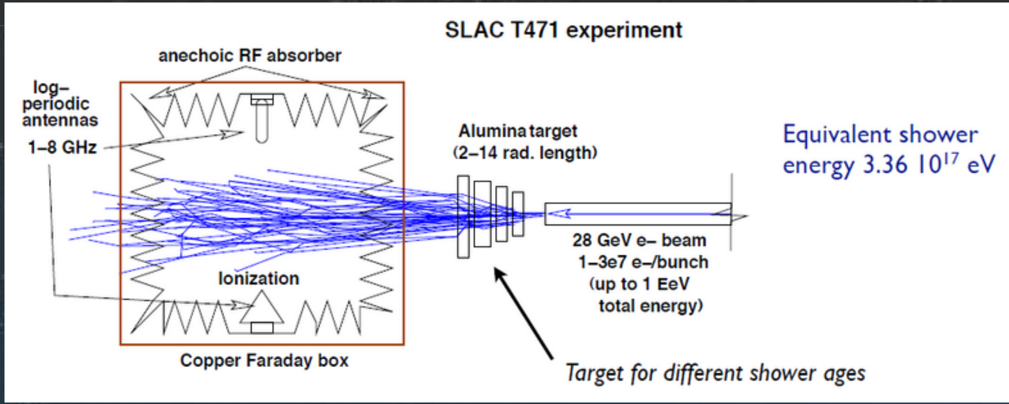
Full potential of hybrid analysis not yet known



Radio emission at GHz

Accelerator measurement Gorham et al.:
“Observations of microwave continuum emission from air shower plasmas”
Phys. Rev .D. 78, (2008)





Molecular Bremsstrahlung

Isotrope emission like fluorecence, but about to 100% duty cycle

Started extensive search AMBER, EASIER, MIDAS, CROME; MAYBE, AMY

First c-band events presented at UHECR 2012 by EASIER and CROME

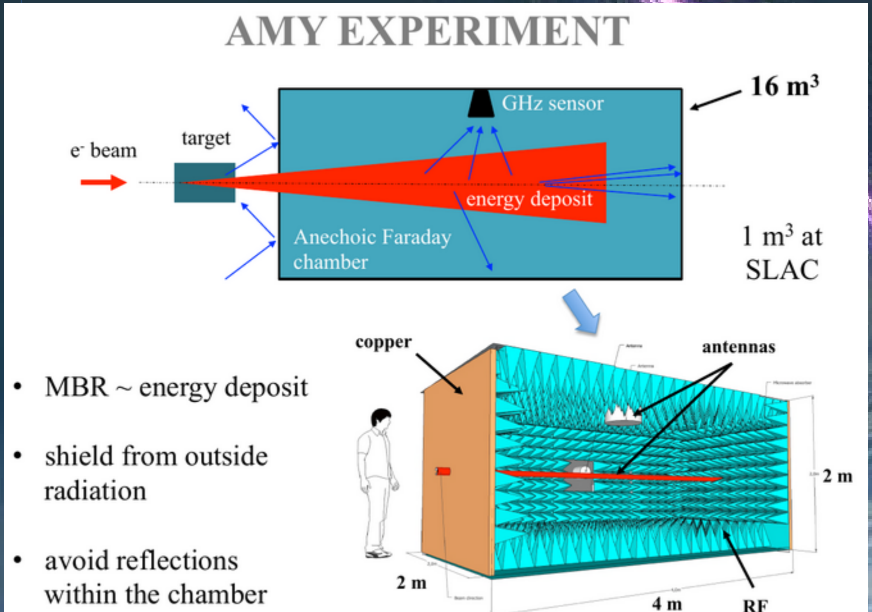
Radio emission at GHz

follow-up experiments to measure GHz „Molecular Bremsstrahlung“: AMY

Detected signal too small for EAS detection (ARENA 2014)
Experimentally challanging because of reflections and RFI sources.

The Air Microwave Yield (AMY) experiment - A laboratory measurement of the microwave emission from extensive air showers

J. Alvarez-Muñiz[1], M. Blanco[2], M. Boháčová[3], B. Buonomo[4], G. Cataldi[5], M. R. Coluccia[5,6], P. Creti[5], I. De Mitri[5,6], C. Di Giulio[7], P. Facal San Luis[8], L. Foggetta[4], R. Gaïor[2], D. Garcia-Fernandez[1], M. Iarlori[9], S. Le Coz[10], A. Letessier-Selvon[2], K. Louedec[*10], I. C. Mariş[2], D. Martello[5,6], G. Mazzitelli[4], M. Monasor[8], L. Perrone[5,6], R. Pesce[11], S. Petrera[9], P. Privitera[8], V. Rizi[9], G. Rodriguez Fernandez[7], F. Salamida[12], G. Salina[7], M. Settimo[2], P. Valente[4], J. R. Vazquez[14], V. Verzi[7], C. Williams[8]

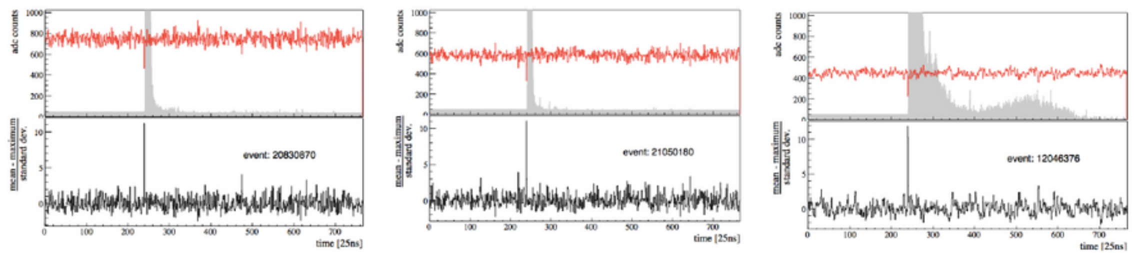


- 3 succesful tests at the BTF
- Interpretation of cross-pol signal unclear (Cherenkov, MBR, …?)
- Strong coherence induced by LINAC
- If MBR, the yield in air-shower should be lower
- Density flux (at 4.7 X_0) ~ 5×10^{-17} W/m²/Hz

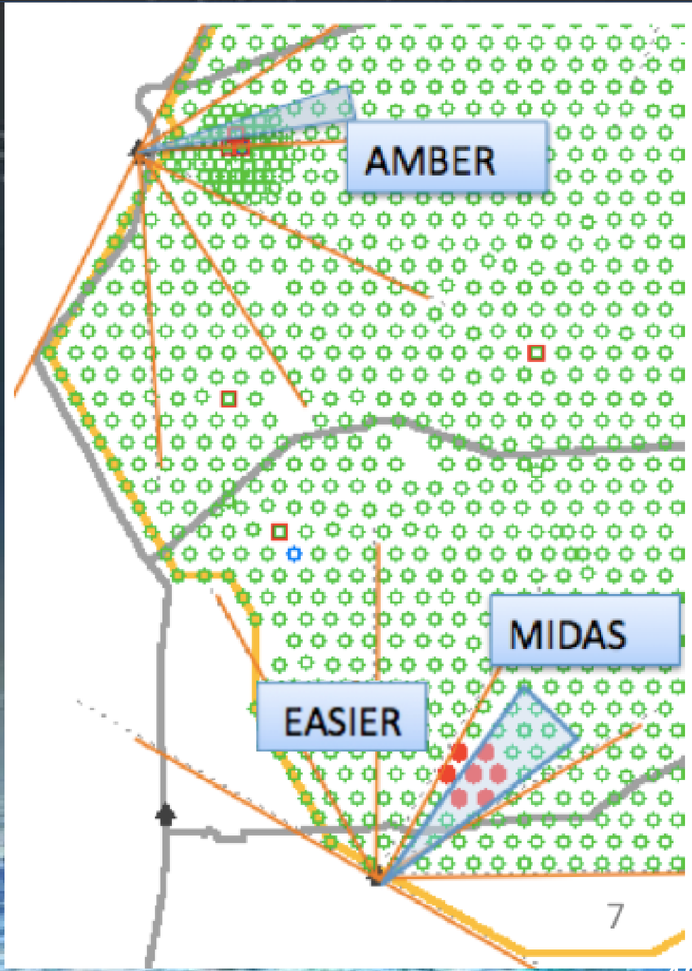
Radio emission at GHz @ Auger

Three setups:
AMBER (P. Gorham)
MIDAS (P. Privitera)
EASIER (A. Letessier-Selvon)

Events observed by EASIER:



Auger Id	12046376	20830870	21050180
station	342	429	306
date	2011/06/30	2013/01/03	2013/02/07
energy [eV]	$(1.32 \pm 0.12)\times10^{19}$	$(1.71 \pm 0.1)\times10^{19}$	$(2.56 \pm 0.41)\times10^{18}$
zenith [°]	29.7 ± 0.3	55.2 ± 0.1	47.4 ± 0.5
azimuth[°]	343.4 ± 0.8	33.8 ± 0.1	289.4 ± 0.6
Distance to axis [m]	136 ± 40	268 ± 11	193 ± 15
Δt to trigger	1	2	2
radio maximum [sigma]	11.86	11.23	11.05
polarization	E-W	E-W	E-W
time length [time bins]	2-3	1	1-2



Radio at GHz: CROME

Cosmic-Ray Observation via Microwave Emission

5 vertical tilted radio antennas

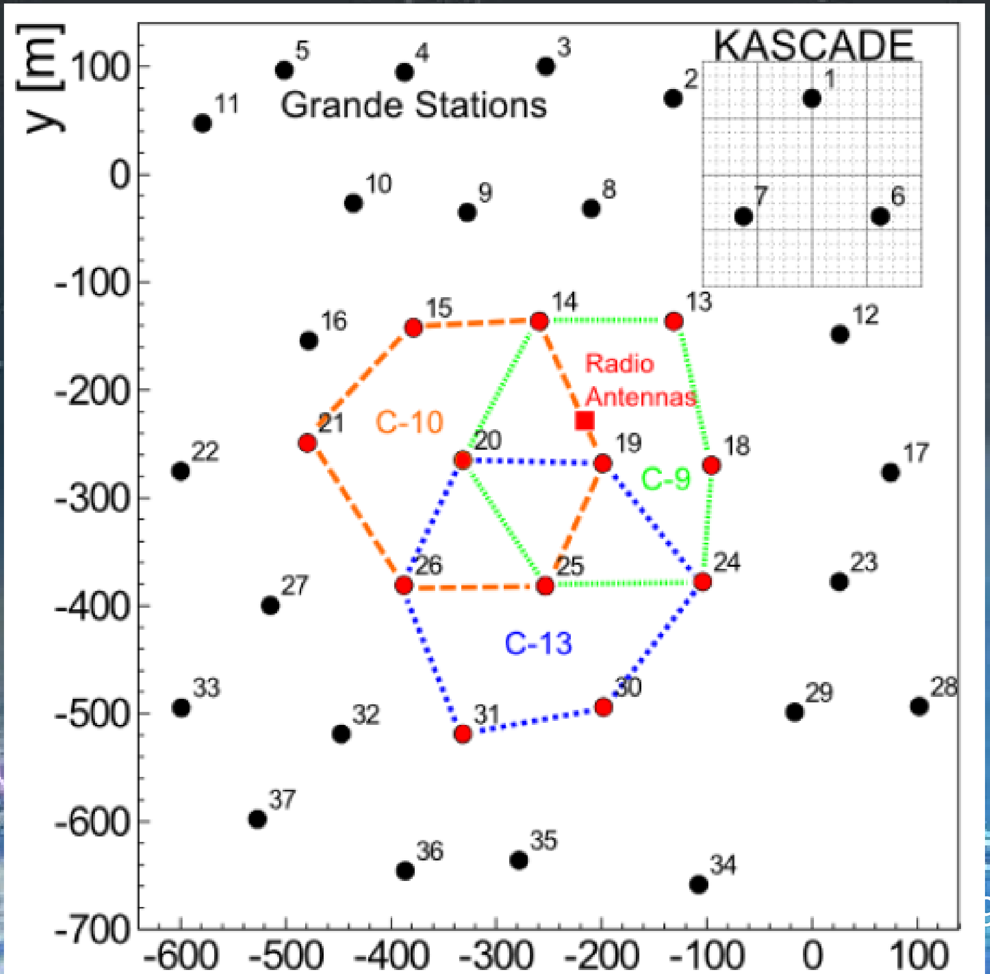
Diameter: 0.9 - 3.4m

Frequency range:
1.1 - 1.8 GHz, 3.4 - 4.2 GHz, 11 GHz

100% duty cycle

Ext. triggered by KASCADE-Grande:
- 12 out of 12 surrounding KG-stations
- 800 trigger/day

KG reconstruction:
- 0.8° for the arrival direction
- 6 m for the core position
- 20% for the energy

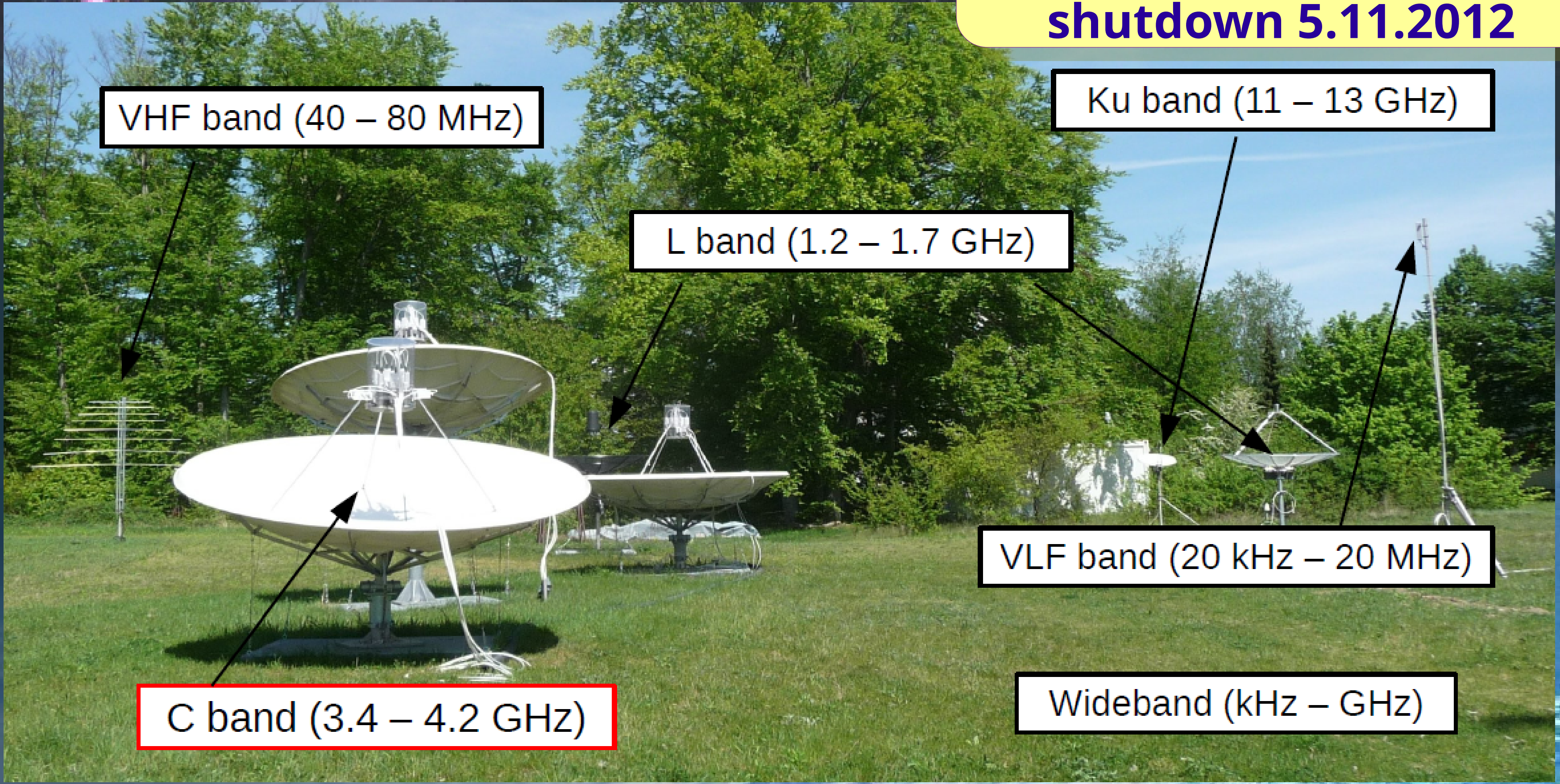


Radio at GHz: CROME

5 vertical tilted radio antennas

Diameter: 0.9 - 3.4m

30 events in c-band
KASCADE-Grande
shutdown 5.11.2012



Radio at GHz: CROME

T. Huege et al., ARENA 2012 proc.

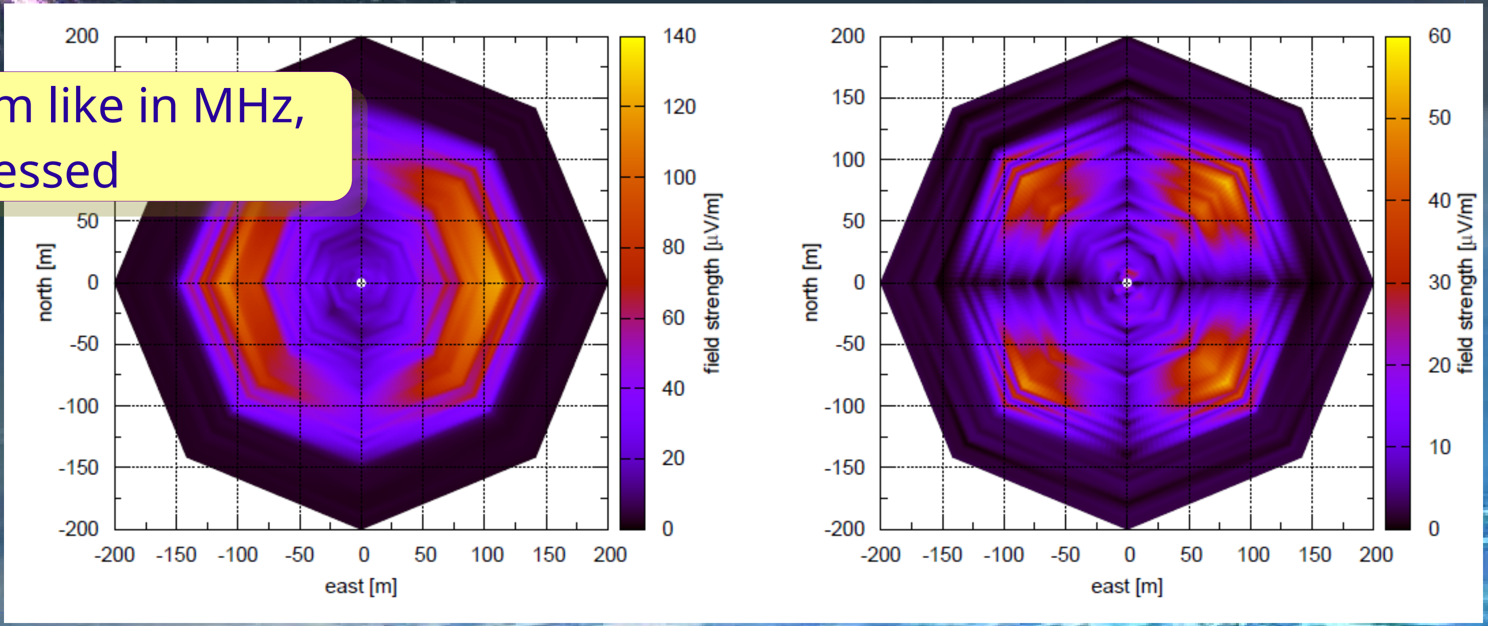
REAS 3.1, including end-point formalism and realistic refractive index

direct in CORSIKA, no histogramming

Cherenkov-like time compression due to refractive index gives shorter (higher frequent) & higher pulses

On sea-level 120m radius for vertical shower

Same emission mechanism like in MHz, only time-compressed



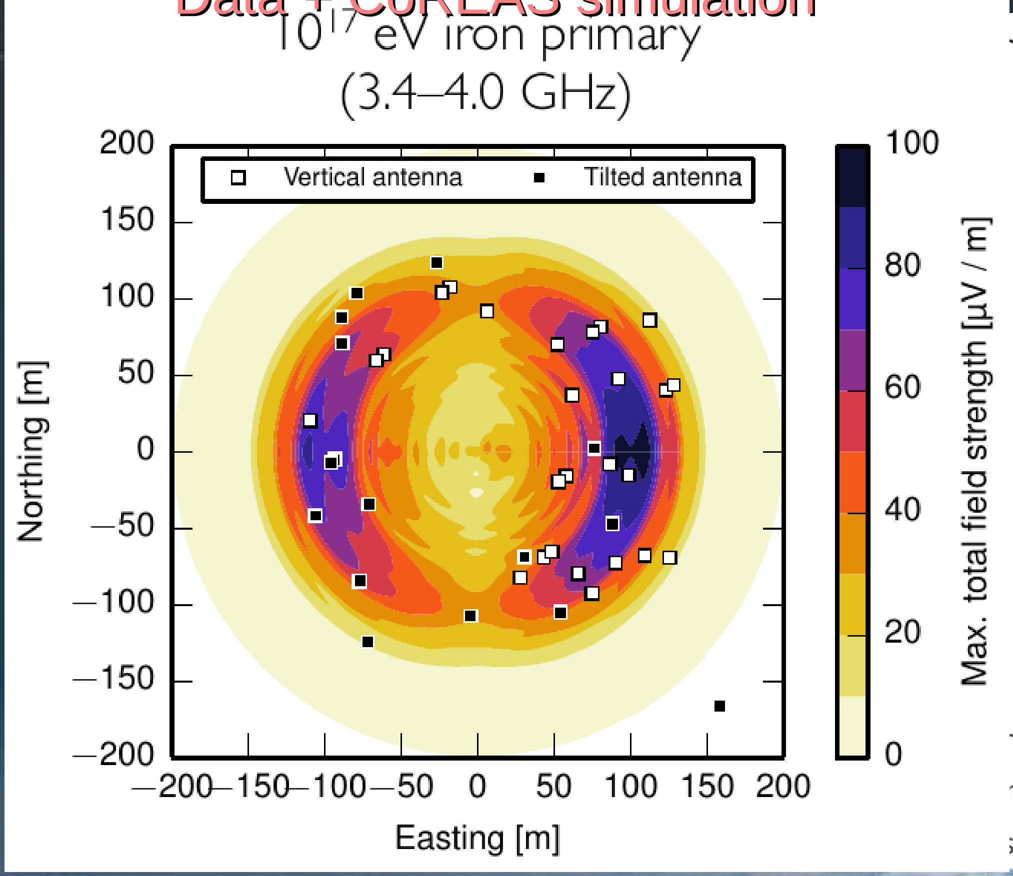
Radio at GHz: CROME

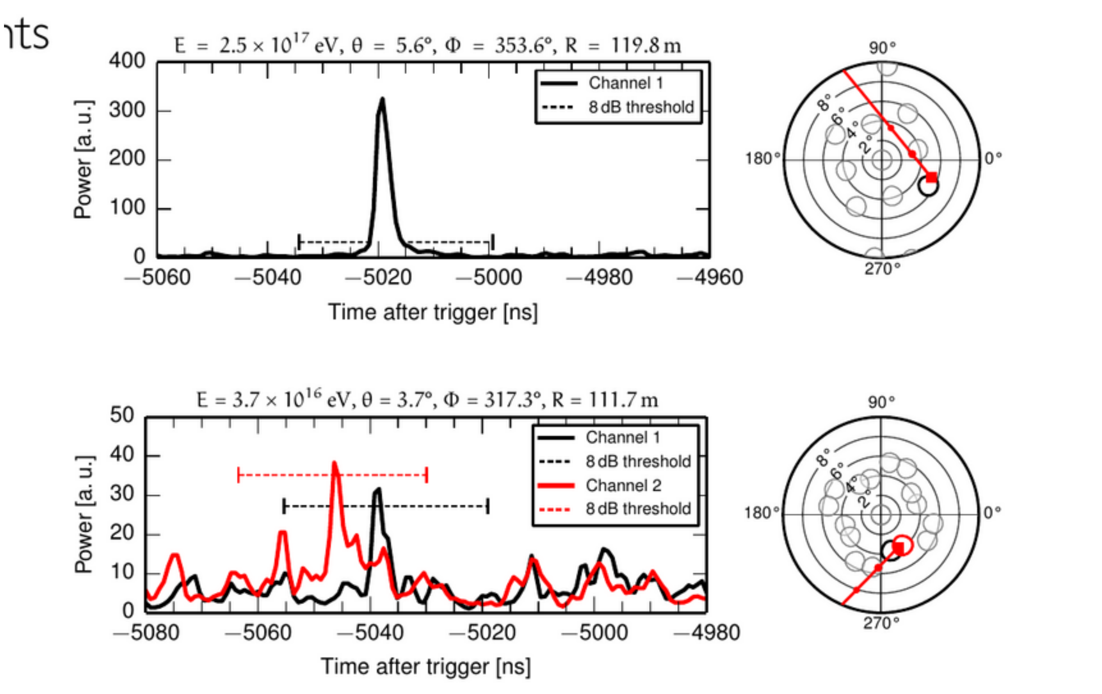
5 vertical tilted radio antennas

Diameter: 0.9 - 3.4m

30 events in c-band
KASCADE-Grande
shutdown 5.11.2012

Data + CoREAS simulation





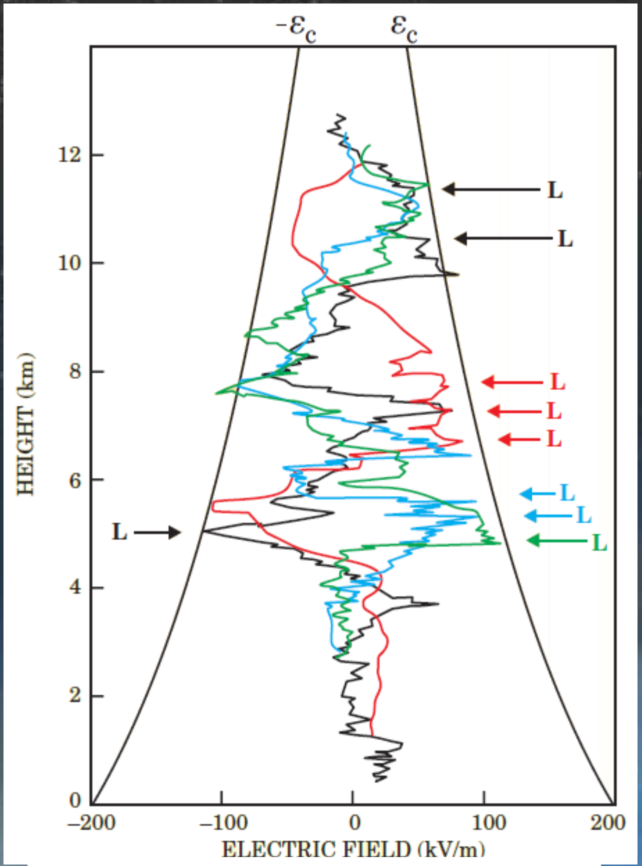
ion properties:

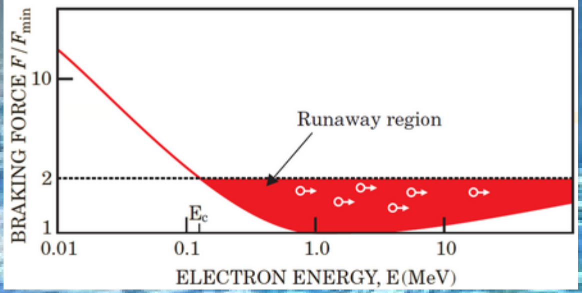
- rt pulses (~5 ns)
- stly single-receiver (only two stereo events)
- emission seems forward-directed
- signals originate from >2 km

Atmospheric E-Fields

- Very hard to parametrize the complex structures inside (thunder)clouds
- Fair weather ~ 100 V/m on ground level, thunderclouds with extends of several km up to ~ 100 kV/m
- Balloon soundings by Stolzenburg et al. found several layers with interchanging field polarity and variation on rather short time scale
- Clear influence of lightnings on field development
- Free electrons from ionization can be accelerated and induce current pulse
- Produce large number of slow thermal electrons, but can ionize molecules themselves
- Runaway breakdown:

$$\mathcal{E}_c \approx 100 - 150\ \mathrm{kV/m}$$

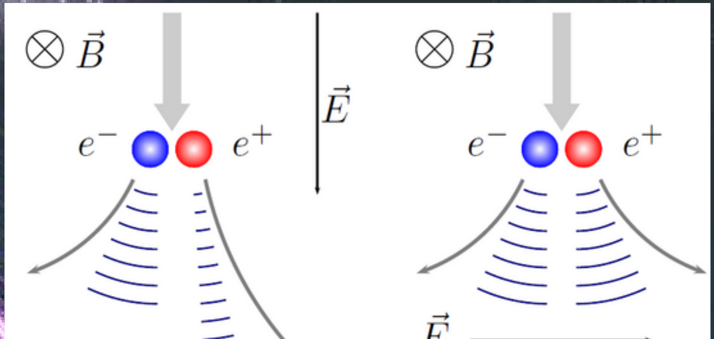




Atmospheric E-Fields and Radio Emission

Strong atmospheric fields have significant influence on radio emission due to charge separation and acceleration of ionization electrons (Charman, 1967)

Effect similar to magnetic field



LOPES, Adv. Space Res. 48 (2011) 1295

Parallel:

Accelerate only one particle type
→ asymmetry in the trajectory

Perpendicutar:

Electric force in same/ opposite direction of Lorentz force
→ amplification or attenuation

Change in polarization pattern: superposition of particle responses to magnetic & electric field

Altered amount of radially polarized emission due to increased charge excess contribution

Publications for experimental observations (not complete):
Mandolesi, N., Morigi, G., & Palumbo, G. (1974, J. Atmos. Terr. Phys., 36, 1431)
LOPES (Astron. & Astroph. 467 (2007) 385-394)
LOFAR (Phys. Rev. Lett. 114 (2015), 165001)

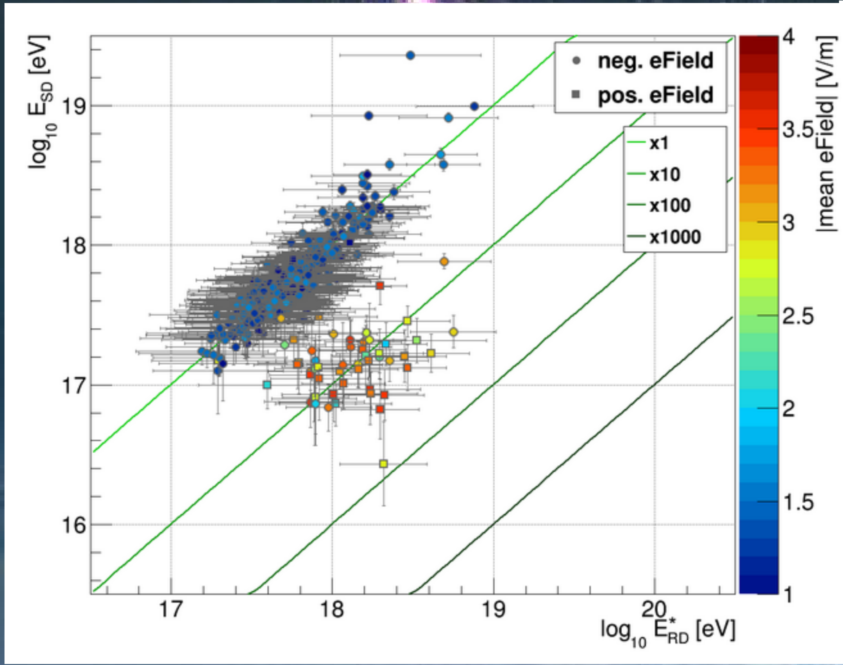
Atmospheric E-Fields: Radio EAS Events

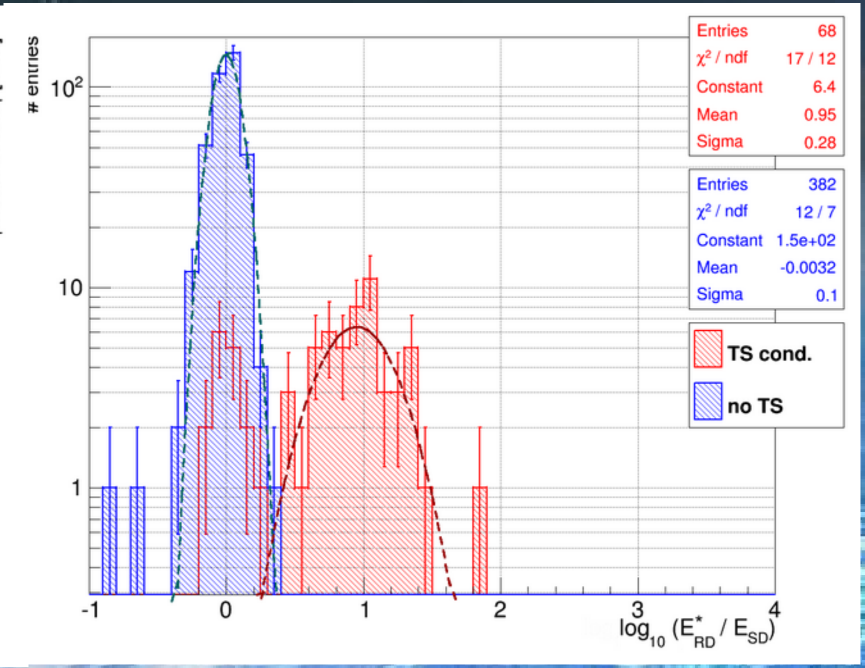
Mean amplification by one order of magnitude

Many events would normally be below detection threshold

TS cond. outliers most likely due to mis-identifaction

No obviouse correlation with E-Field strength or polarity





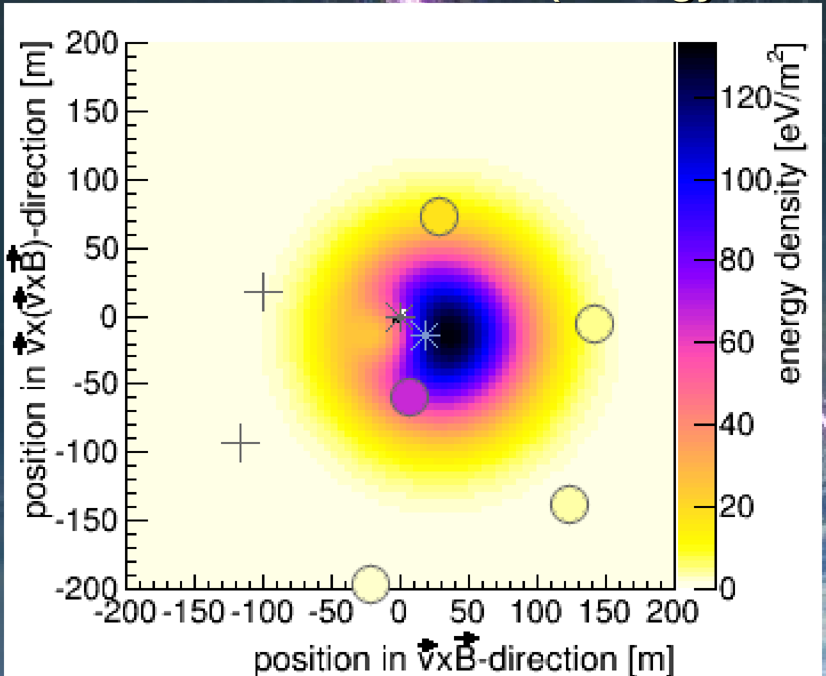
Atmospheric E-Fields: Radio EAS Events

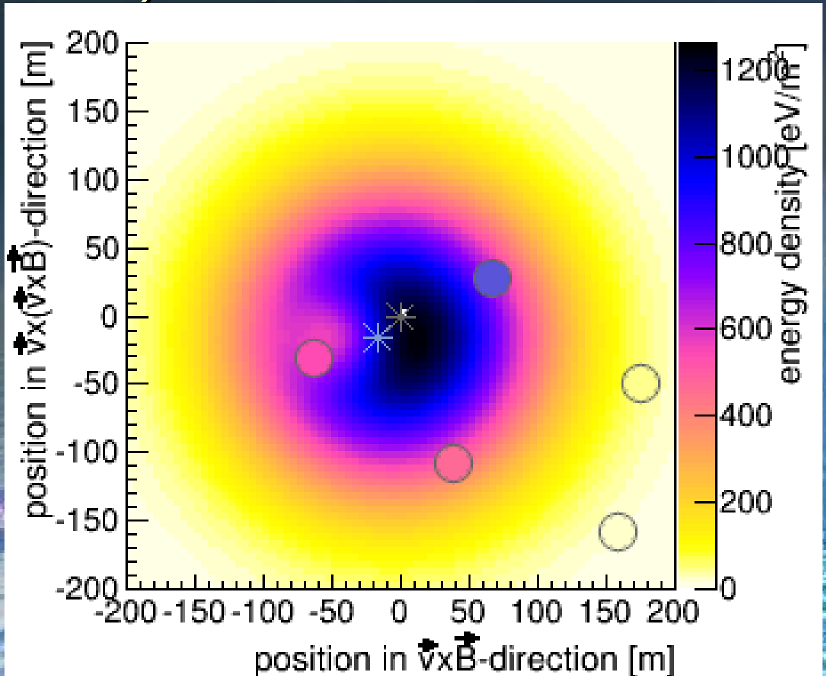
Twin events with & w/o E-Field, criteria Δlog(E)<0.1, Ω<5°

One measured during normal, one during TS conditions

Signifcant increase in size of footprint (note different color scale)

Low number of available pairs in this analysis, but promising approach for systematical detector studies (energy resolution, …)





Atmospheric E-Fields: Lightning events

Atmospheric E-Fields: Lightning events

LOFAR simulating e-Fields to match Radio-signals observed

https://doi.org/10.1029/2019JD031433

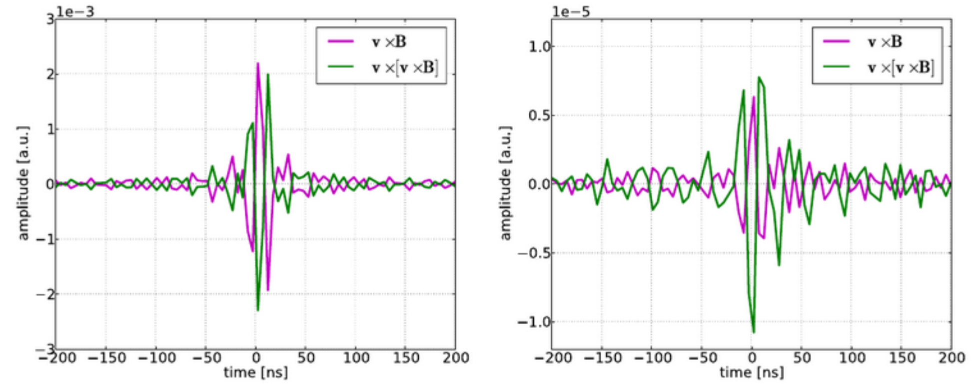
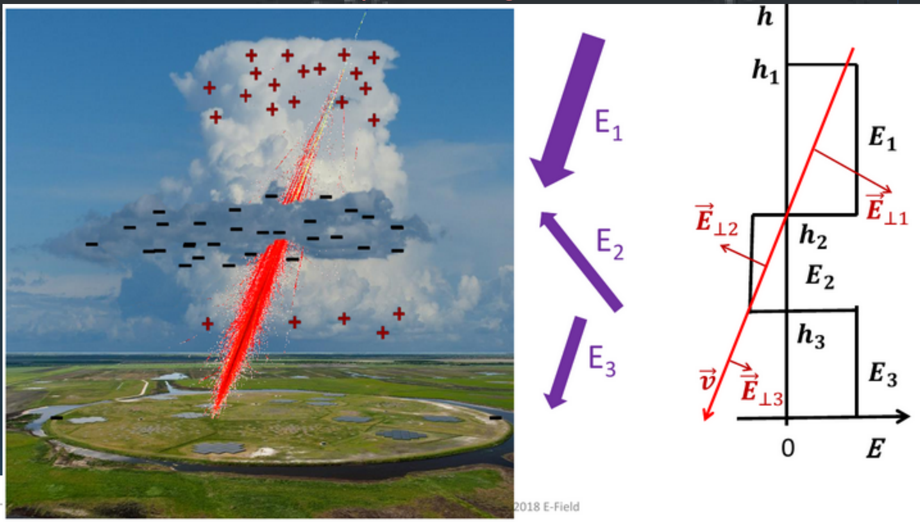
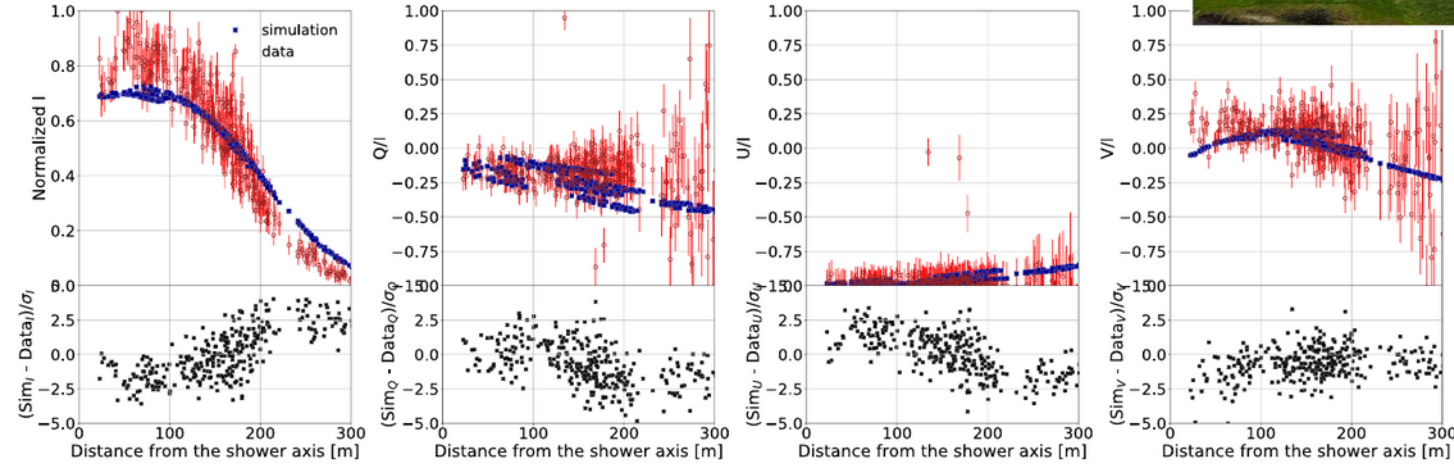


Figure 1. The simulated radio pulse, including the effects of the band-pass filter, (left) is compared to measured pulse (right) for the two polarization directions of an antenna from Event #8. The vertical scale of the model calculation is in arbitrary units (left) and the digitizer units (right) for the measurement.



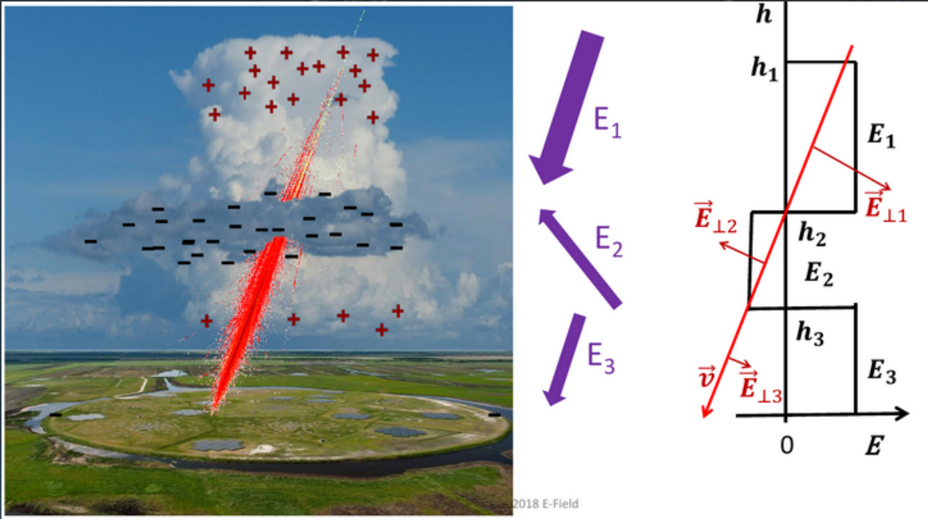


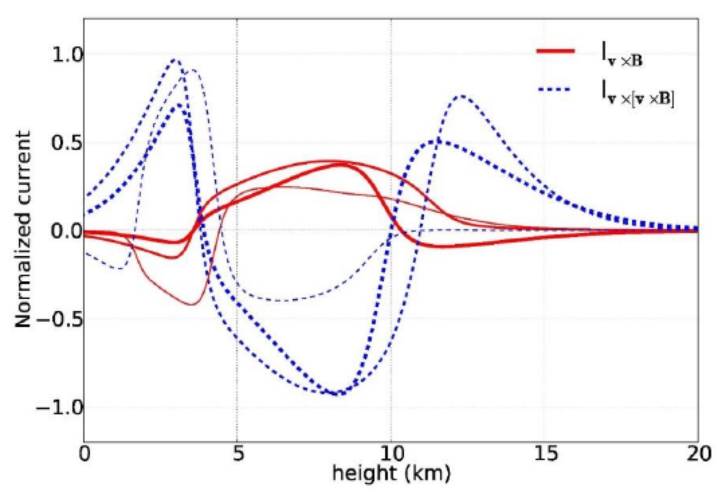
Atmospheric E-Fields: Lightning events

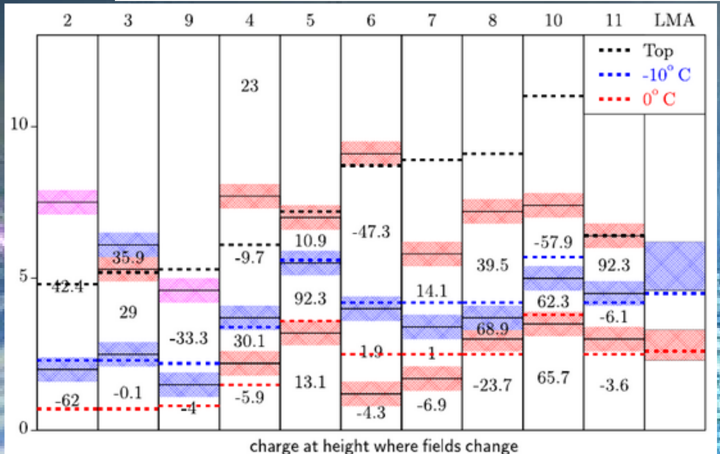
LOFAR simulating e-Fields to match Radio-signals observed

https://doi.org/10.1029/2019JD031433

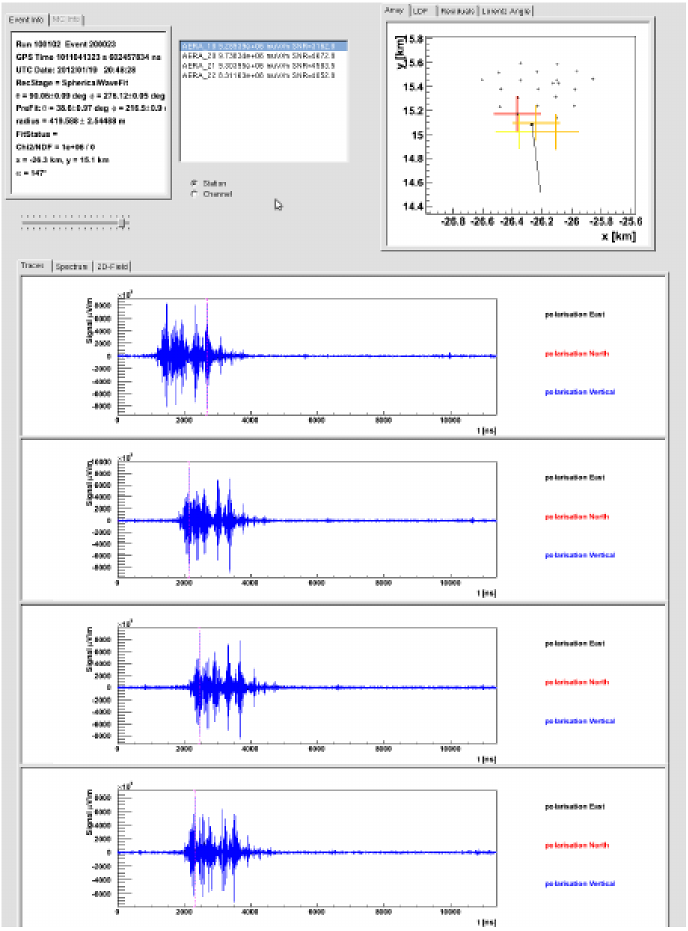
Calculation	I			II			III		
Energy (eV)	1.4×10^{17}			4.6×10^{16}			$\mathbf{4.0 \times 10^{16}}$		
Layer	1	2	3	1	2	3	**1**	**2**	**3**
h (km)	13.3	7.9	2.8	16.7	9.3	2.8	**7.6**	**3.3**	**1.6**
E (kV/m)	14	14	103	41	17	104	**15**	**107**	**42**
α (°)	156	-125	101	104	-109	104	**-103**	**119**	**-109**
$X_{\max}$ (g/cm^2)	526			634			**743**		
$X_{\max}$ (km)	7.3			5.9			**4.7**		
χ^2_{3D}	3.02			3.36			**3.36**		
χ^2_C	4.41			4.14			**3.15**		
f_r	8.2			13.3			**8.4**		

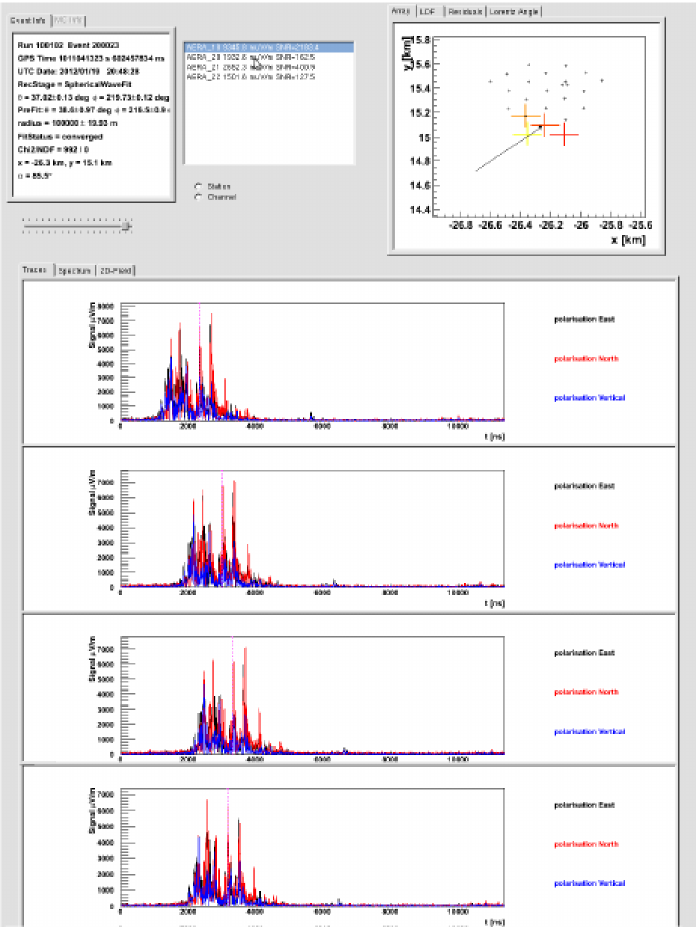


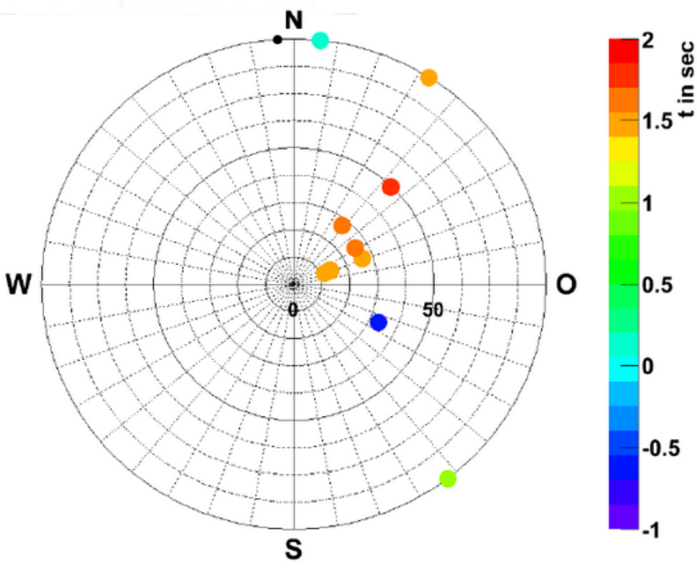




Atmospheric E-Fields: AERA Lightning events

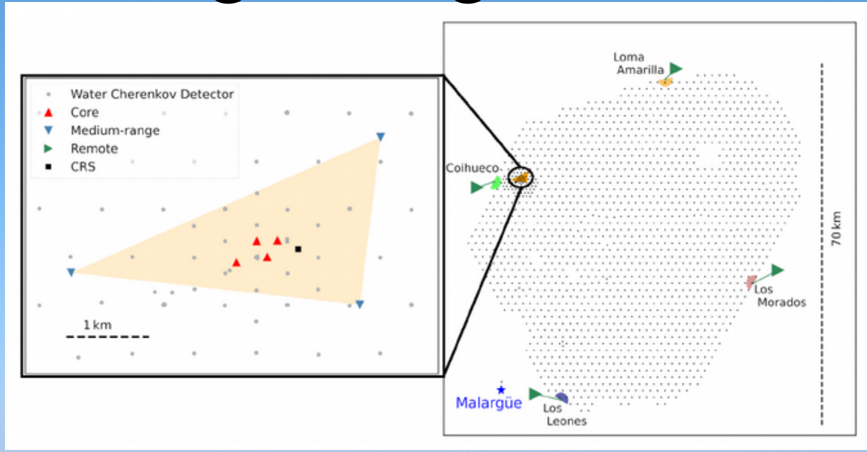






PoS ICRC2015 (2016) 678

BOLT: Broadband Observatory of Lightning and TGFs



Configuration: 3 clusters:

- Core: 4 stations, ~ 100 m
- Medium-range: 3 stations, ~ 2 km
- Remote: 4 stations, Auger scale

Main challenge:

- Readout of > 1 sec traces
- Upto 4 GB
- Network limitation to 20 min

Radio Detection developed
since the renaissance
since 2003

AugerPrime RD
is an impressing
new tool
for discoveries

Be prepared for surprises!