Radio detection of extensive air shower

Bärnfels
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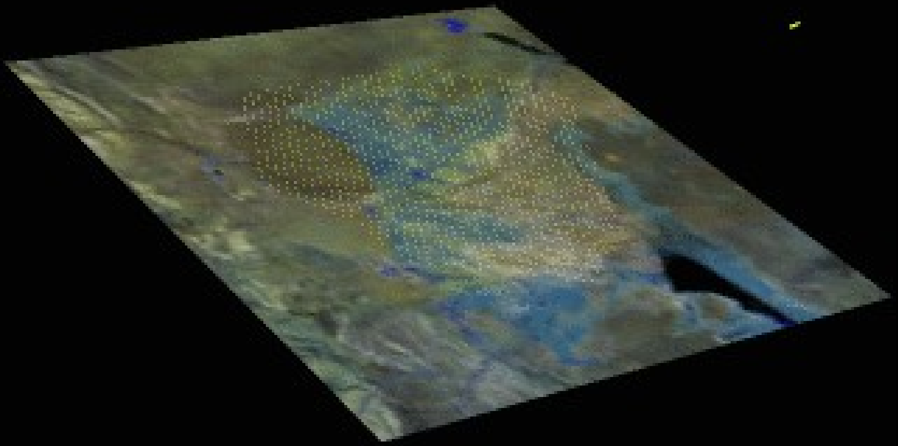
Julian Rautenberg

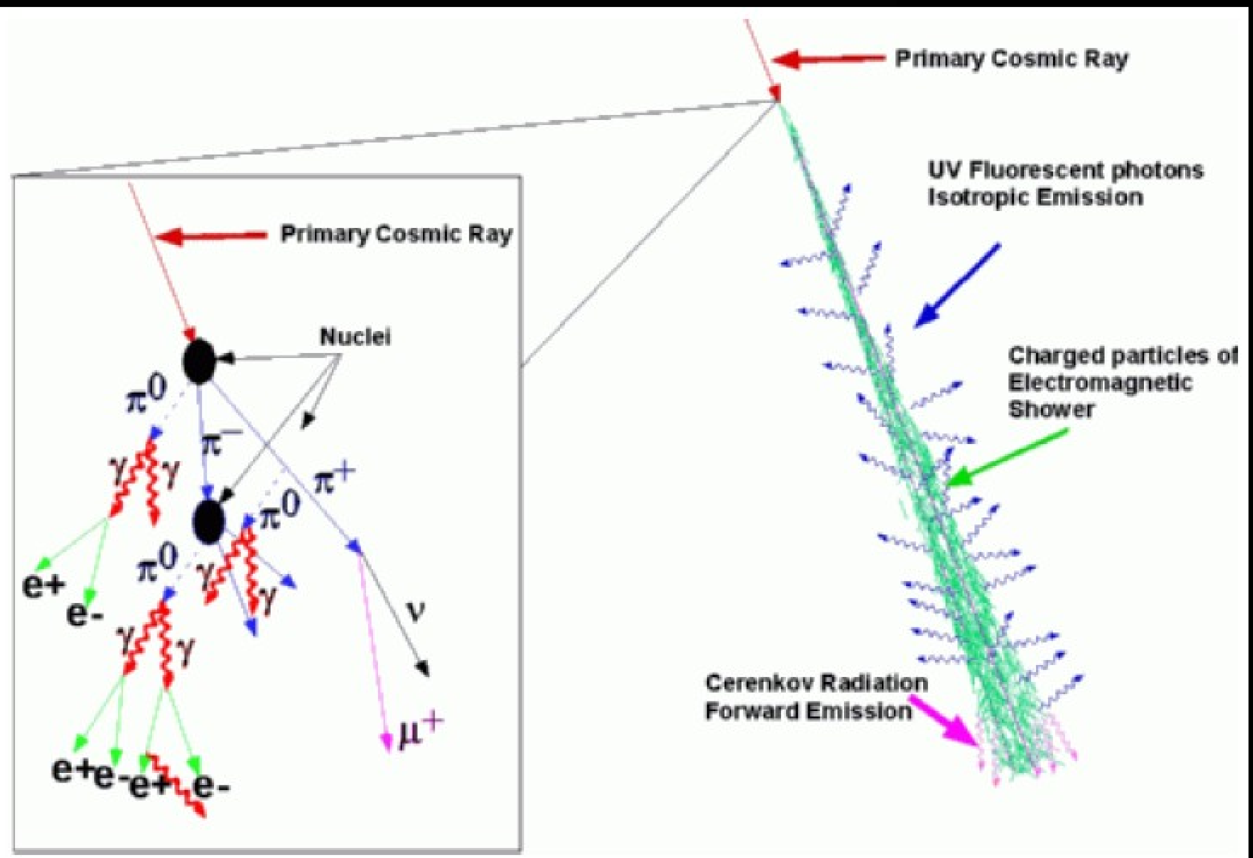
Bergische Universität Wuppertal

Outline

- Physics of radio-emission of EAS
- Radio-detection of EAS
- Pierre Auger Observatory measuring cosmic rays
- AERA at PAO
  - Layout
  - Components
  - Software
- Summary

Extensive Air Shower

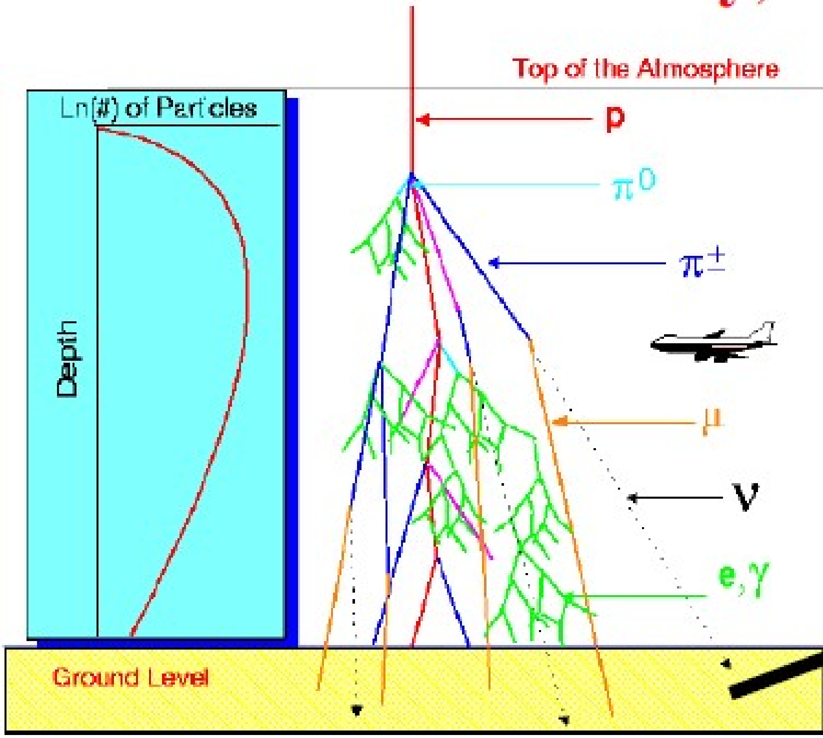




- Hadronic interaction
- Electromagnetic Cascade:
  - Isotrope fluorescence light
  - Focused Cerenkov light
- Disc of particles approaching ground
- Some reache ground (muons)

Surface Detector Arrays

1961: Linsley, towards highest energies



Extensive Air Showers

measured by ground array

Linsley, Scarsi, Rossi, PRL 1961:

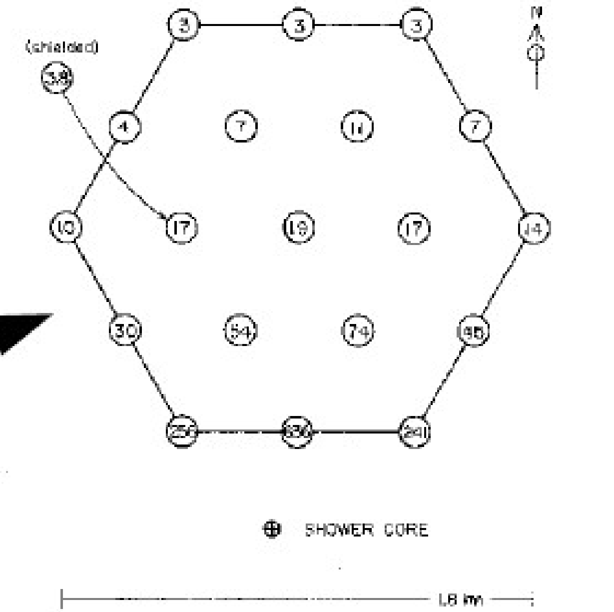


FIG. 1. Diagram of the Volcano Ranch 2-km² array, showing the location of the shower axis and measured densities in particles/m² for this event. No. 39 565. The shielded detector was located very near the indicated main detector.

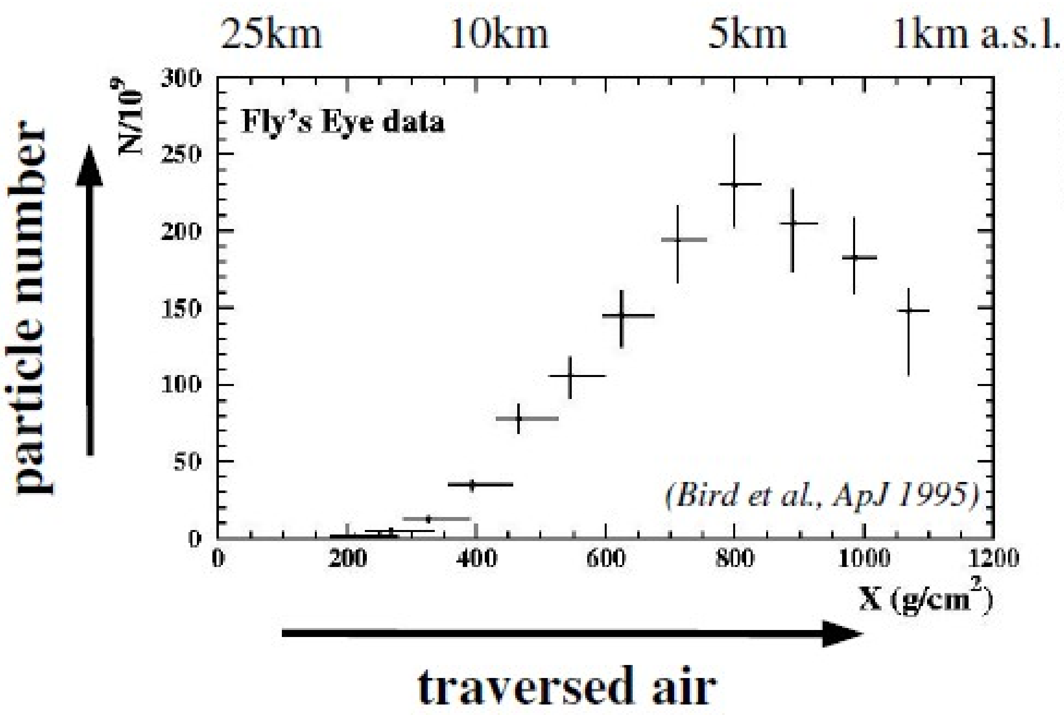
Linsley (checking for rattlesnakes)

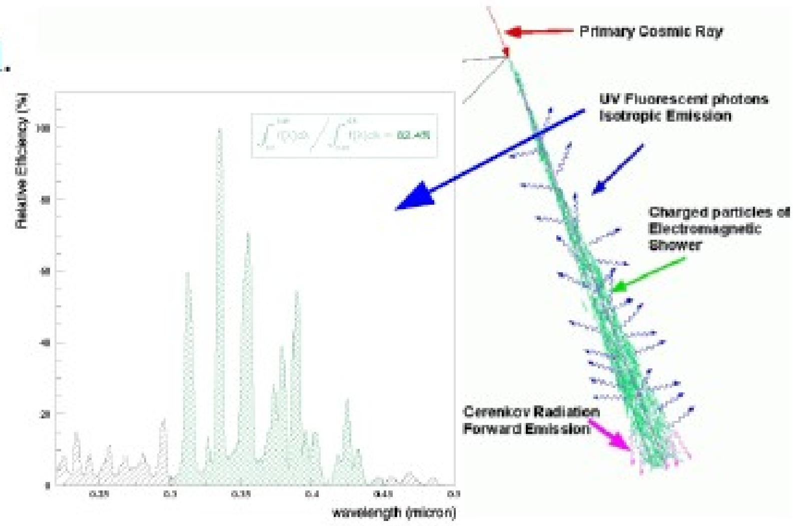
- 19 scintillation counter (~3 m^2) on ~2 km²
- **N > 5x10^9 => E > 10^{19} eV**

➔ extragalactic origin likely !

Fluorescence Detector

15 Oct 1991: Fly's Eye event





- UV fluorescence light ~ N_{ch}
- observation of shower profile (in clear nights)

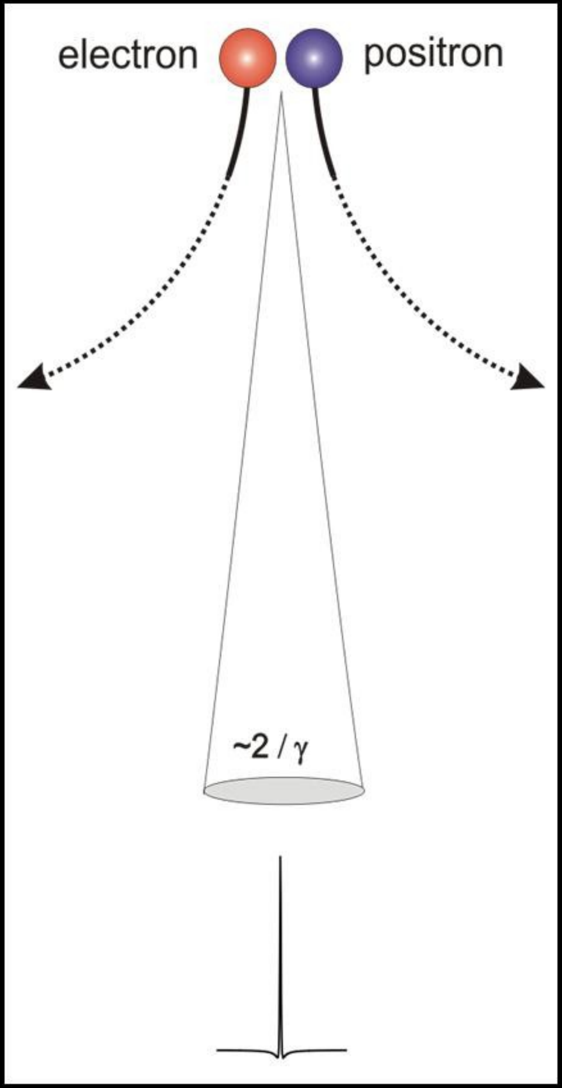
- >200 billion particles at maximum !!
- integration => $E \sim (3.2 \pm 0.9)\ 10^{20}$ eV
- X_{max} ~ 815 ± 60 g cm^{-2} => type? *anything ...*

➔ **there are „super-GZK" events!**

Fly's Eye, Utah (successor: HiRes)

Radio detection theory: Geo-synchrotron

- In the shower electron-positron pair-production
- Charge bended in Earth magnetic field radiate — geo-synchrotron radiation
- At wave-length larger than shower-disc coherent emission
- Emission is focused in beam-direction
- Foot-print size depends on distance to shower maximum
- Frequency spectrum rather smooth



Falcke & Gorham A.Ph. (2003)
Huege & Falcke, A&A (2005)

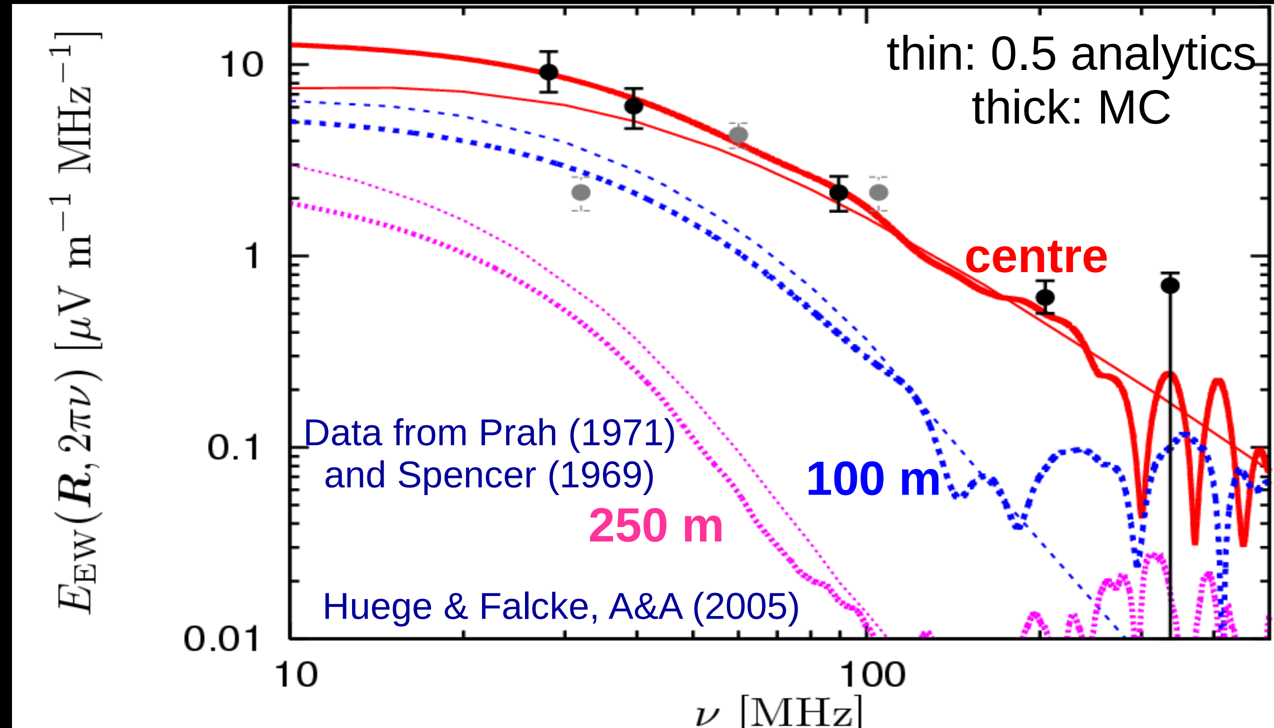
Geo-synchrotron simulation: REAS1

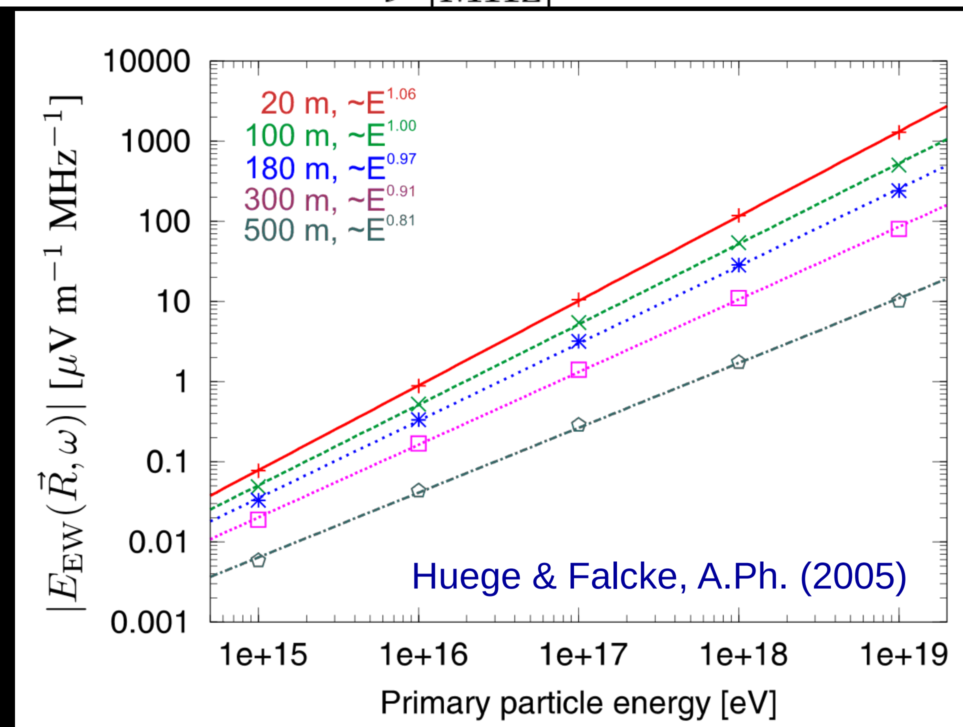
analytic parametrisation
of emission model

vertical, 10^{17} eV shower

steeper decrease
in Frequency for larger
distances from core

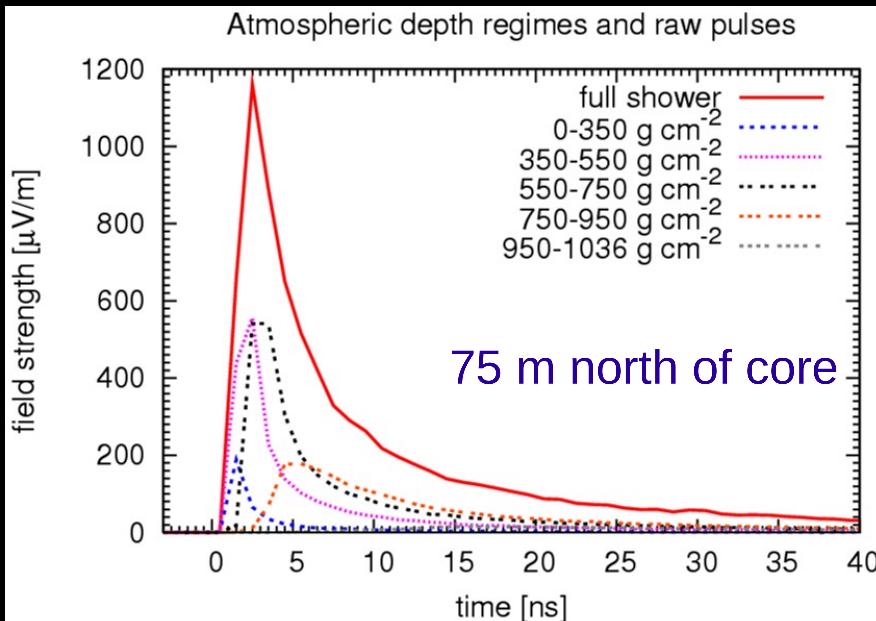
Field-strength
close to proportional
to primary particle energy

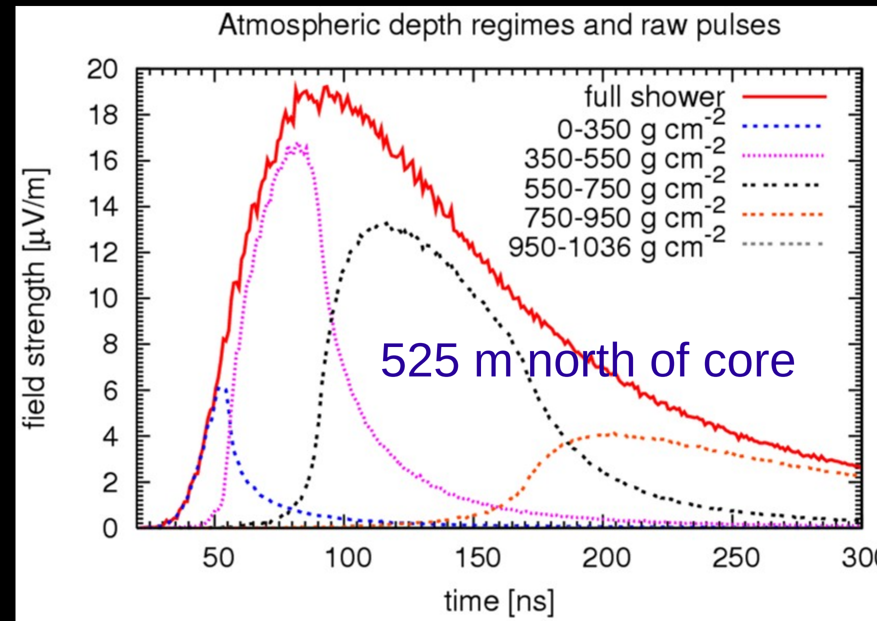


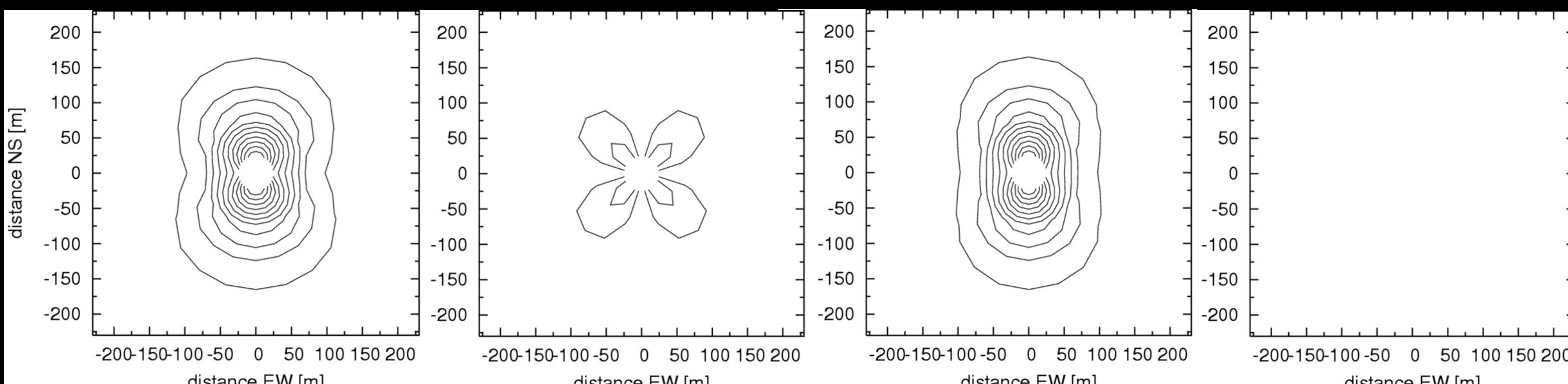


Geo-synchrotron simulation: REAS2

vertical 10^{17} eV p-induced shower, 60 MHz







Huege, Ulrich, Engel, A. Ph. (2007)

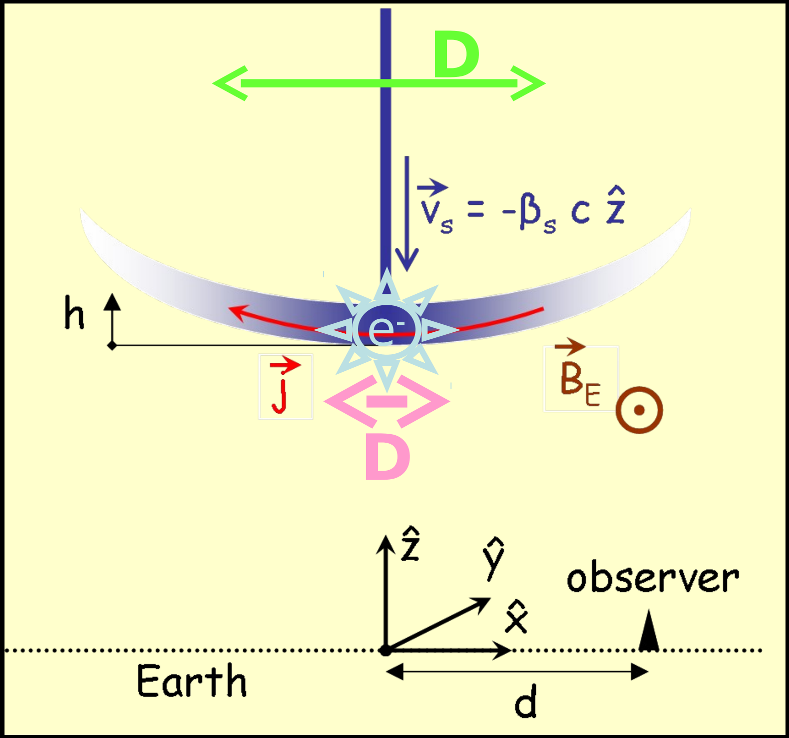
Macroscopic Model – Olaf Scholten et al.

Transverse current — Dominant

Moving Dipole — ~15 %

Static Dipole — ~2 %

Charge Excess — >25 %

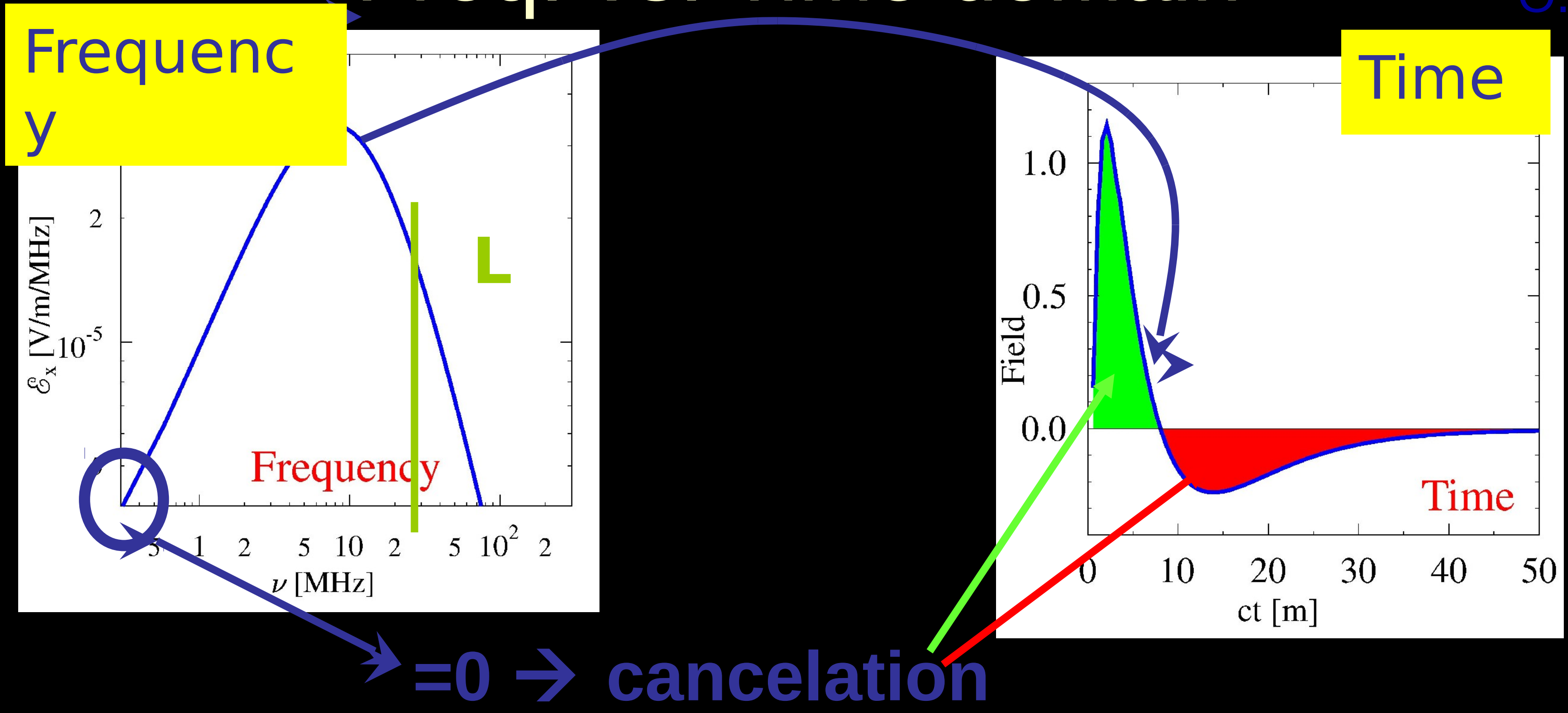


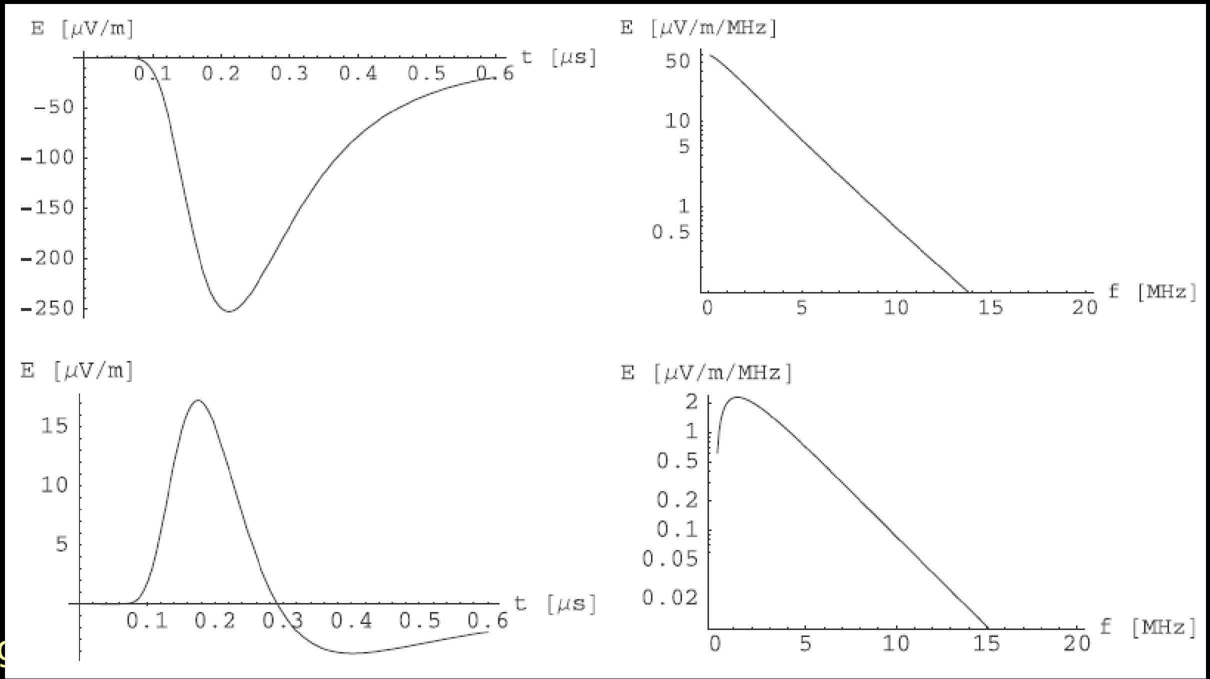
Charge-excess described by Askaryan:

- Radiation from moving net charge usually reffered to as Askaryan effect, important in dense media
- Radiation from **change** in net charge

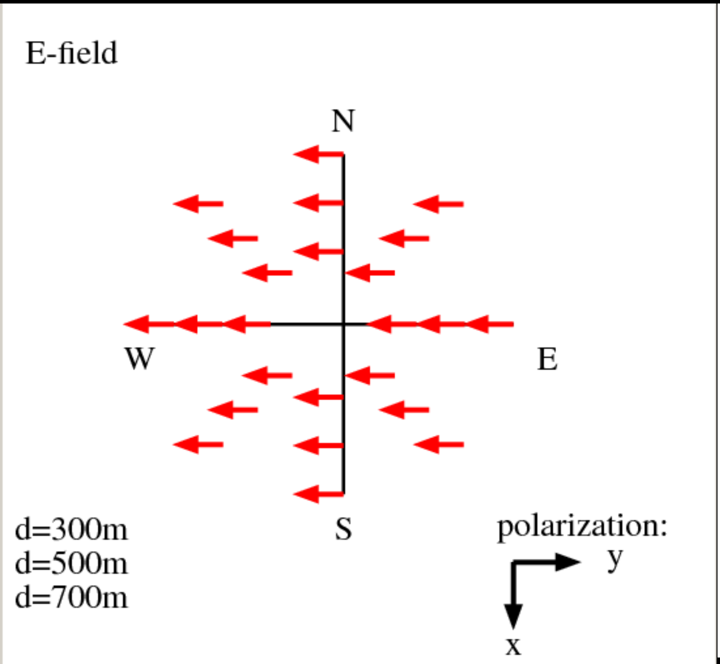
Freq. vs. Time domain

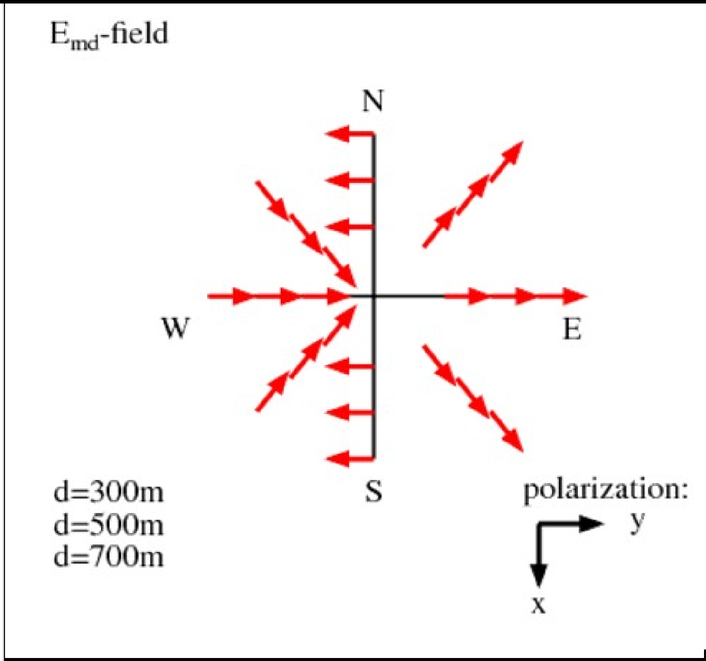
O. Scholten



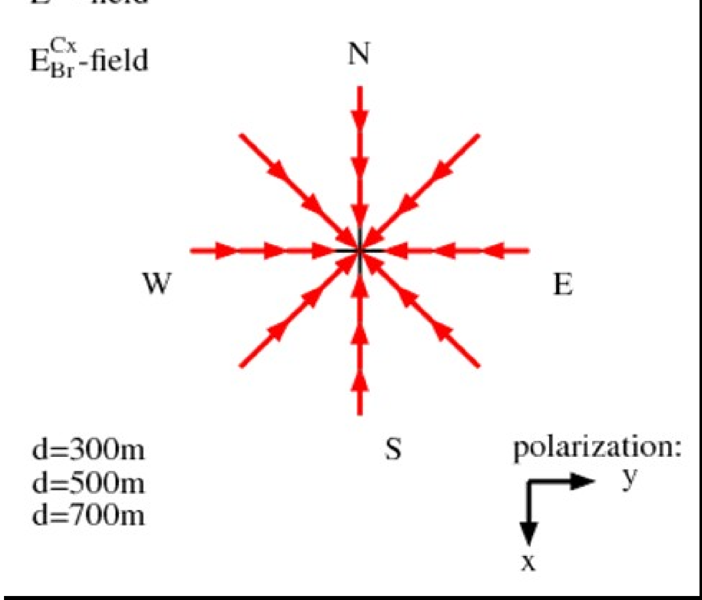


Polarization: key to emission mechanism





O. Scholten



Moving dipole polarization:

Depending on observer position.

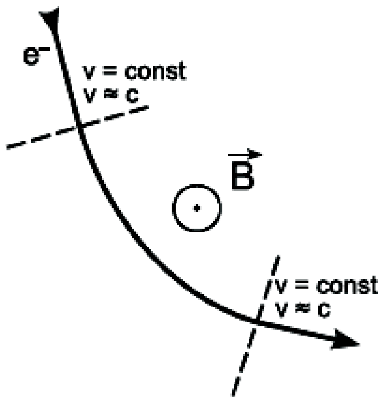
Charge excess polarization:

Depending on observer position. Pointing inwards

End-point contribution in REAS3

REAS2

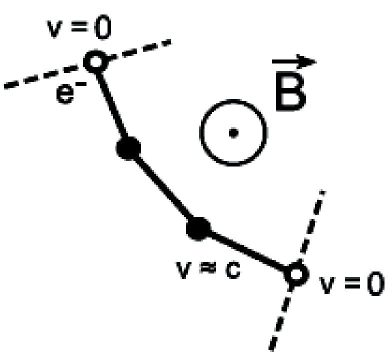
- Continuous radiation processes along the tracks, not at the end or the beginning of track
- e^-/e^+ with v≈c before and after being tracked analytically in the B-field



REAS3

T. Huege

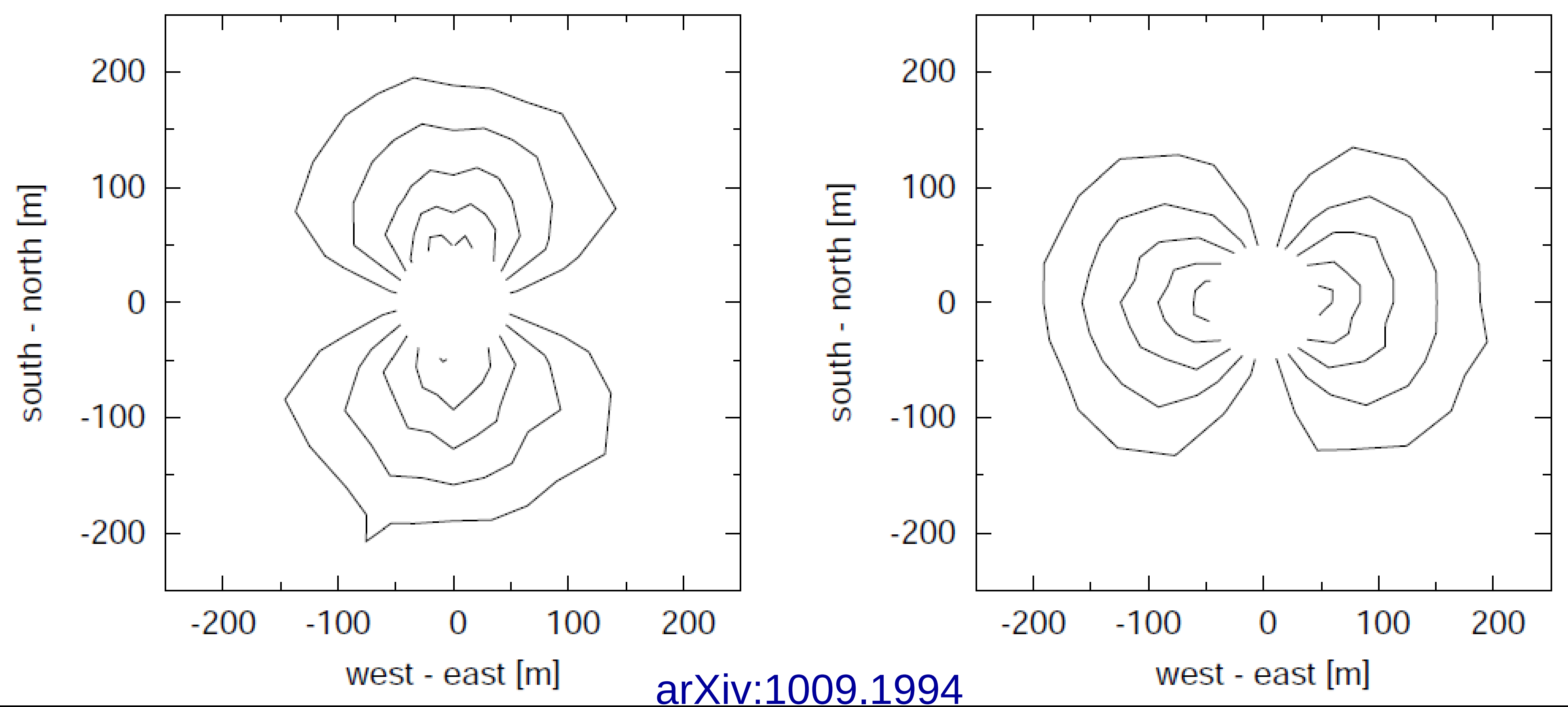
- Straight track fragments joined by "kinks"
- Variation of $\vec{v}$ in kink: discrete radiation process
- e^-/e^+ with $\vec{v}=0$ before and after being tracked analytically ⇒ radiation due to creation/annihilation is considered



arXiv:1007.4146

REAS3 varying charge access

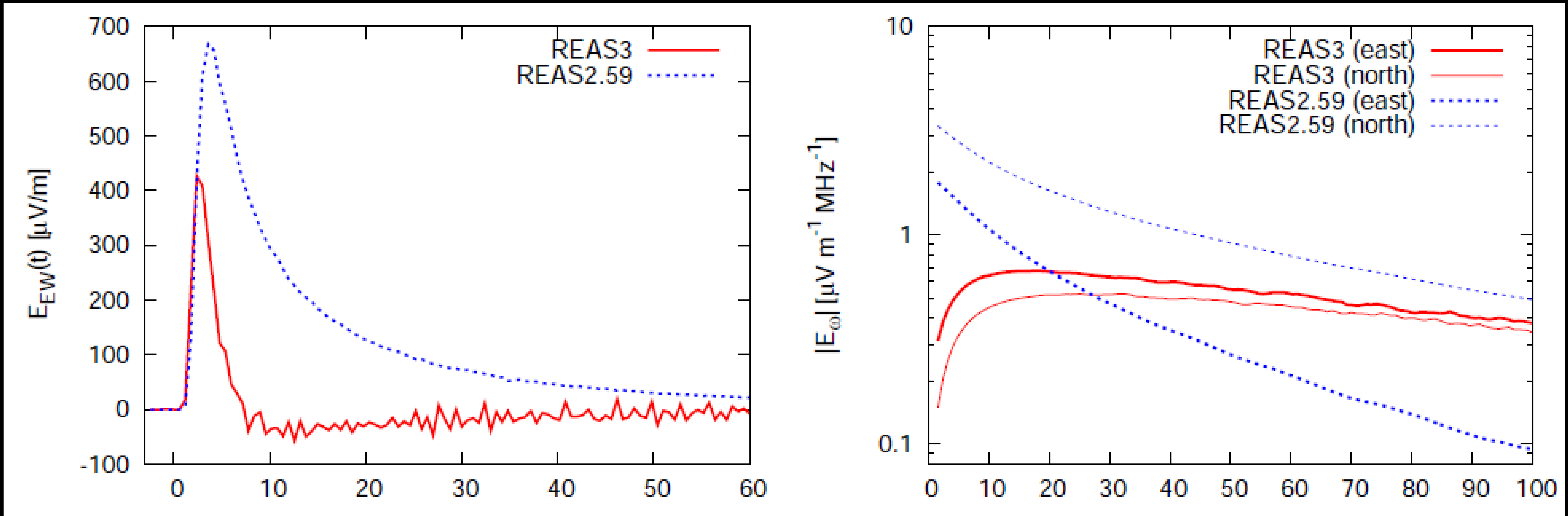
- Component in simulation has polar-type polarization-pattern



arXiv:1009.1994

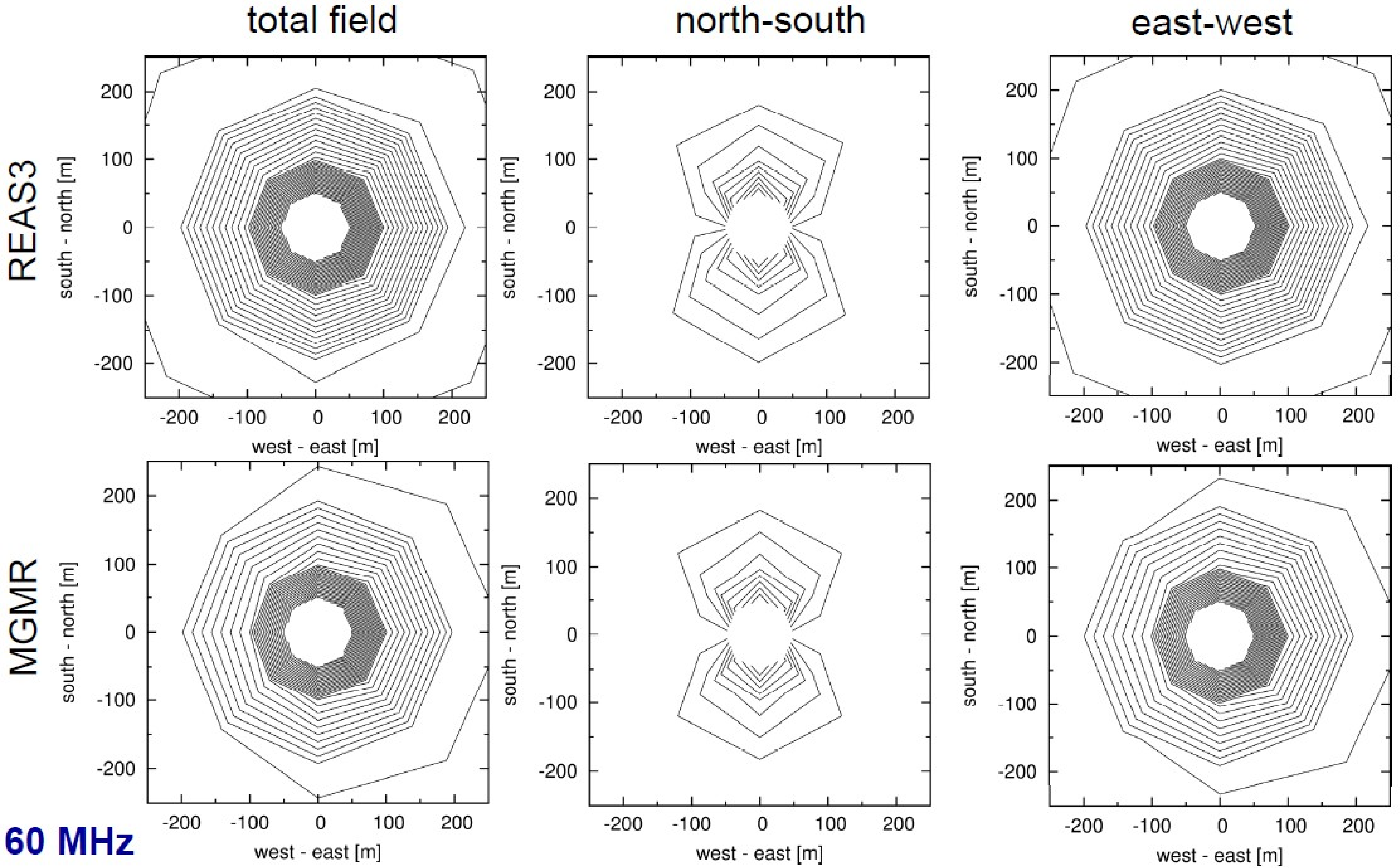
REAS3:

- Comparison of end-point contributions
  - vertical air shower with a primary energy of 10^{17} eV
  - observer distance of 100m
  - geomganetic angle 90°, horizontal magnetic field of 0.23G

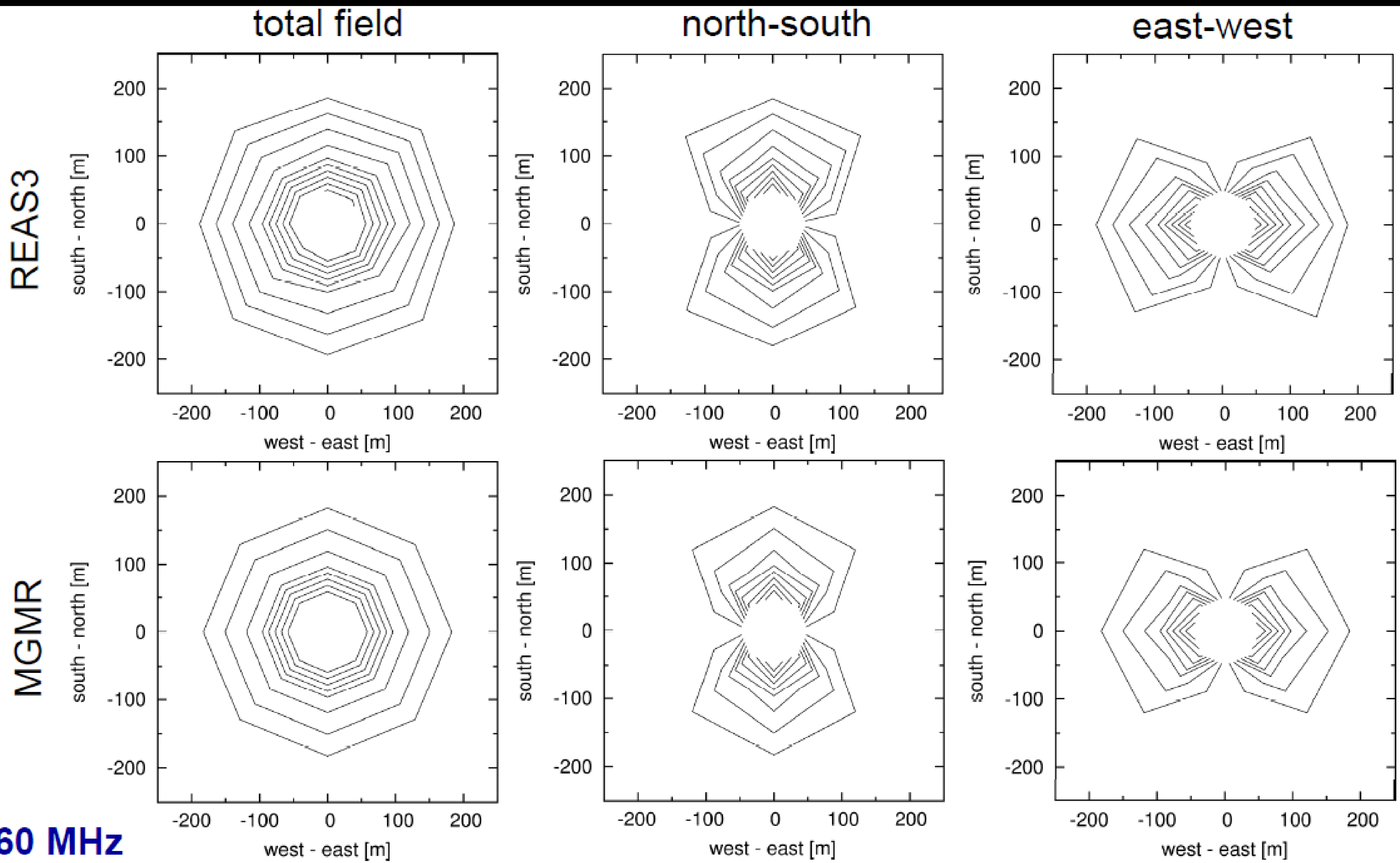


arXiv:1009.1994

Footprint comparison



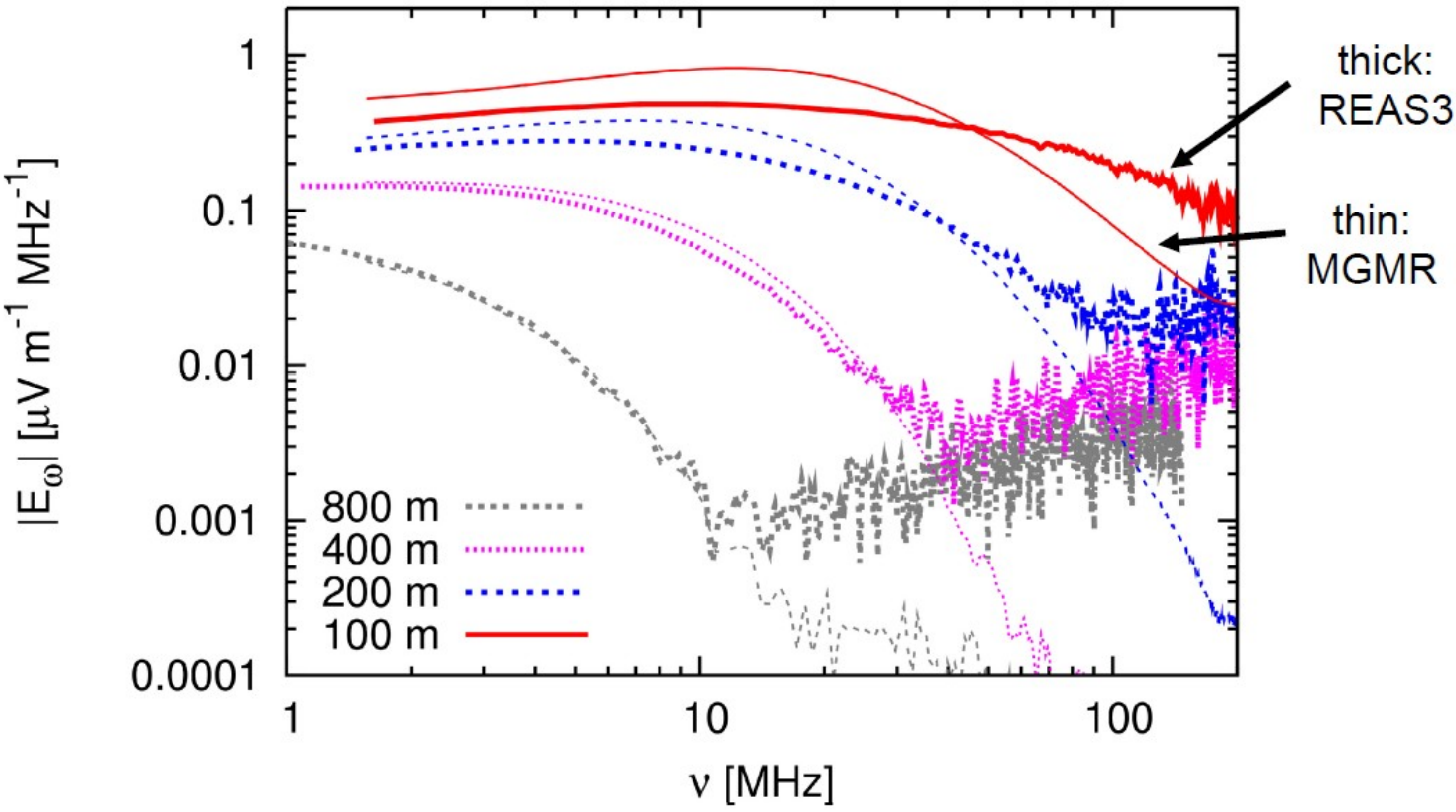
Radio ohne Erdmagnetfeld

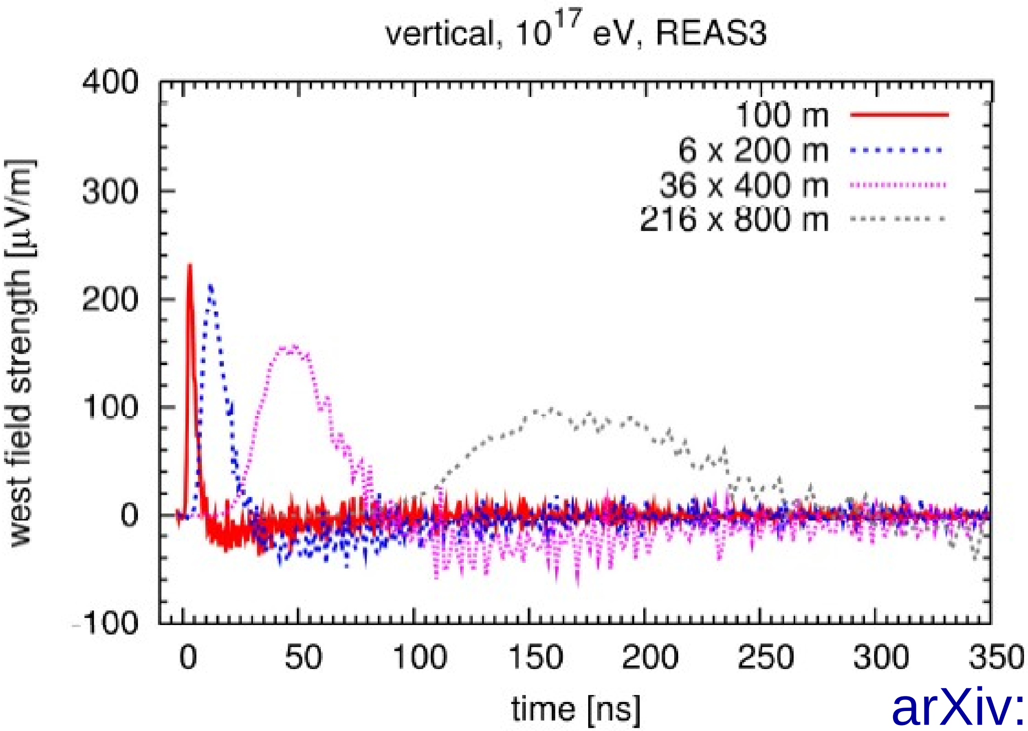


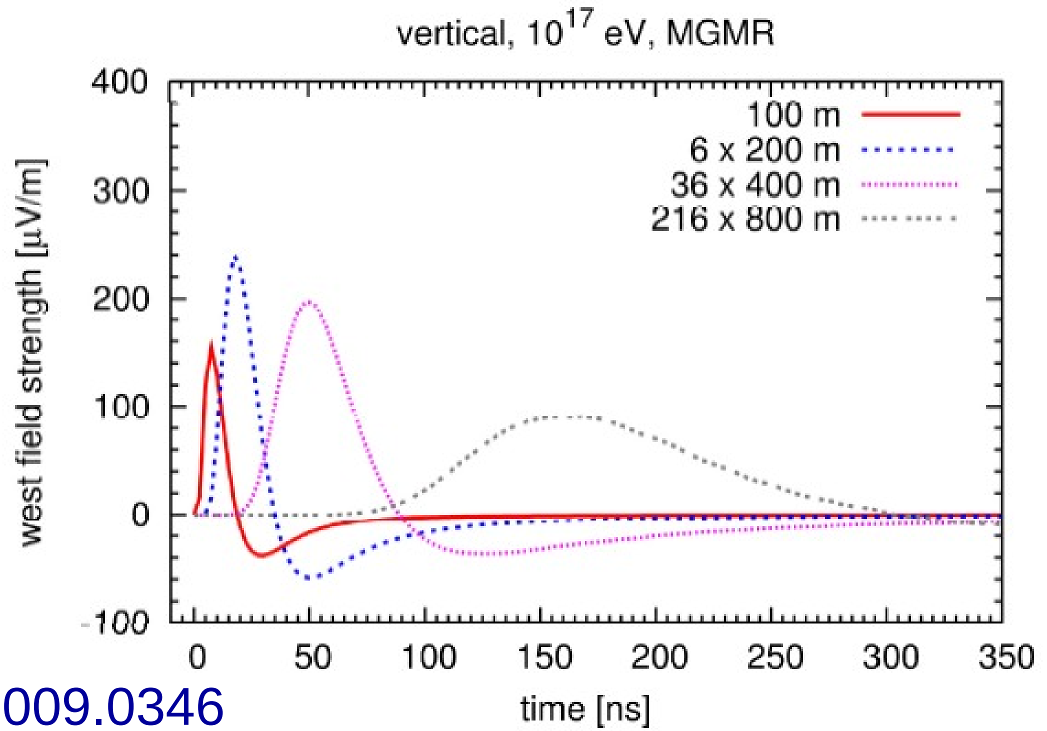
60 MHz

Comparison:

MGMR
-
REAS3







arXiv:1009.0346

Historical: Radio emission models

Year	Authors	Type	Regime	Comment
1961/65	Askaryan	Cherenkov	frequency	charge excess
1966	Kahn & Lerche	Cherenkov & geomagnetic	frequency	transverse currents, dipole
1967	Colgate	geomagnetic	both	electromagnetic pulse
1967	Allan	geomagnetic	*time*	Feynman approach
1969	Fuji & Nishimura	Cherenkov & geomagnetic	frequency	combine approaches with *cascade theory*
1969	Castagnoli et al.	Cherenkov & geomagnetic	frequency	combine approaches with *Monte Carlo*
...	...	...	...	...

T. Huege

The High Energy Universe observed with Radio

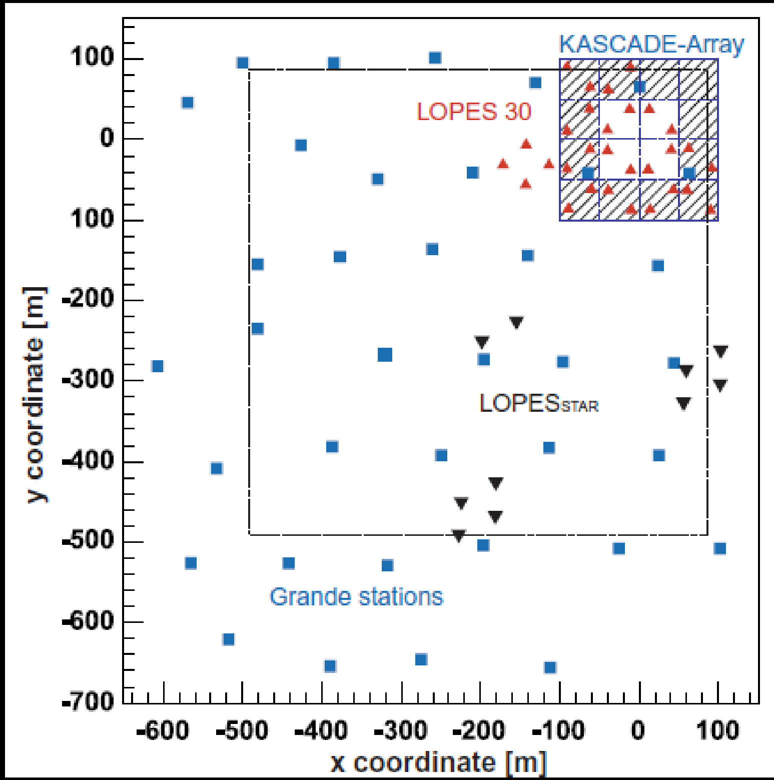
- Prospect: cost-effective, large-scale detector
- Particles: Charged CR, Gamma Rays, Neutrinos
- Targets: Air, Solids, Moon
- Theory: Geo-synchrotron, Askaryan
- Experiments:
  - Air : (Geo-synchrotron) LOPES, CODALEMA, AERA @ AUGER, LOFAR, R-ICETOP, 21CMA
  - Solids: (Askaryan) ARIANNA, ANITA, ICERAY, RICE, AURA, ARA, RAMAND, SALSA
  - Moon: (Askaryan) LUNASKA, NuMoon (WRST/LOFAR/SKA), LORD, GLINT, RAMHAND

here: Radio-detection of extended air shower (EAS)

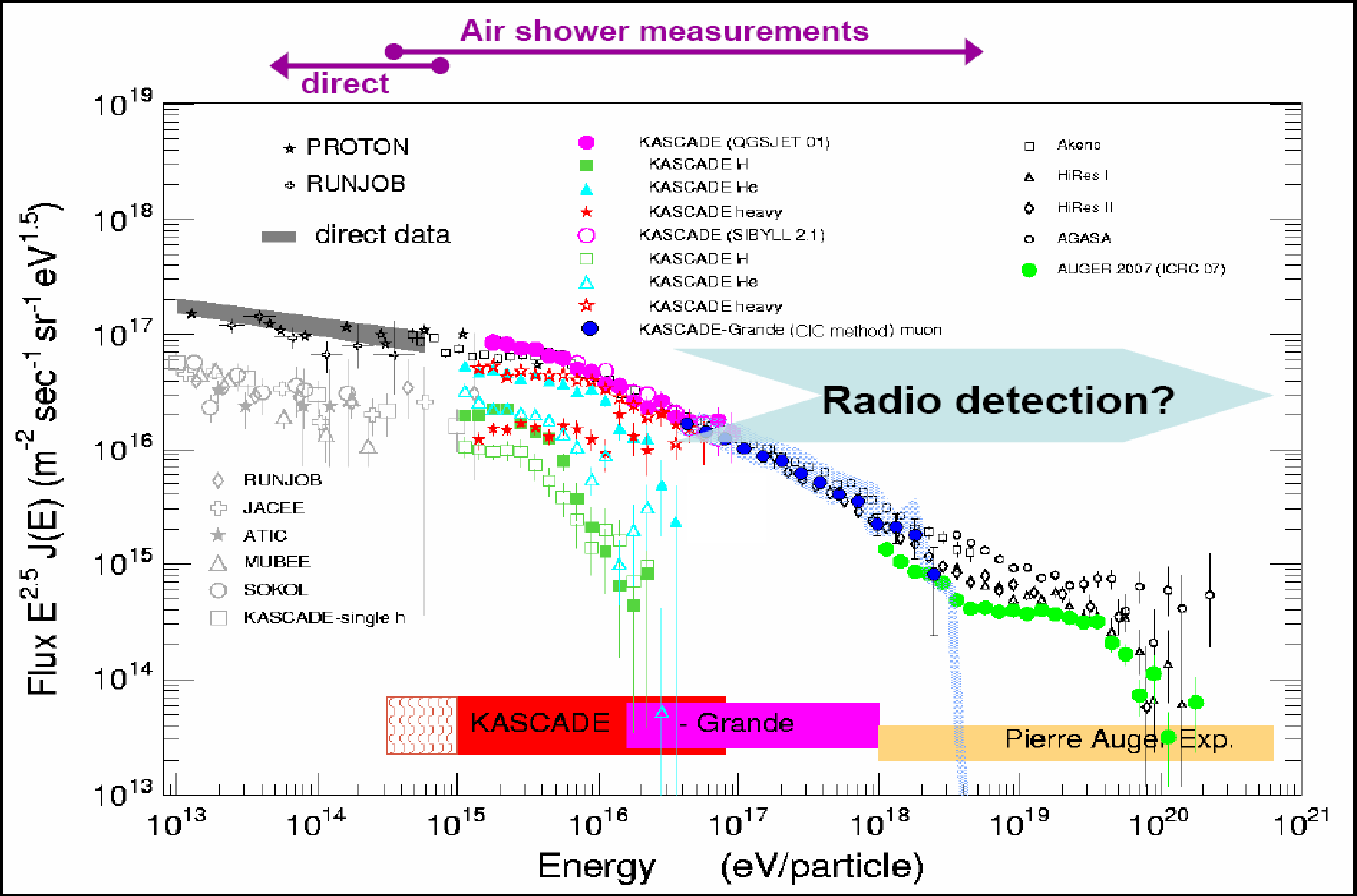
Experimental results: LOPES

- 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 physics-triggered**

understand radio-emission of extended air shower

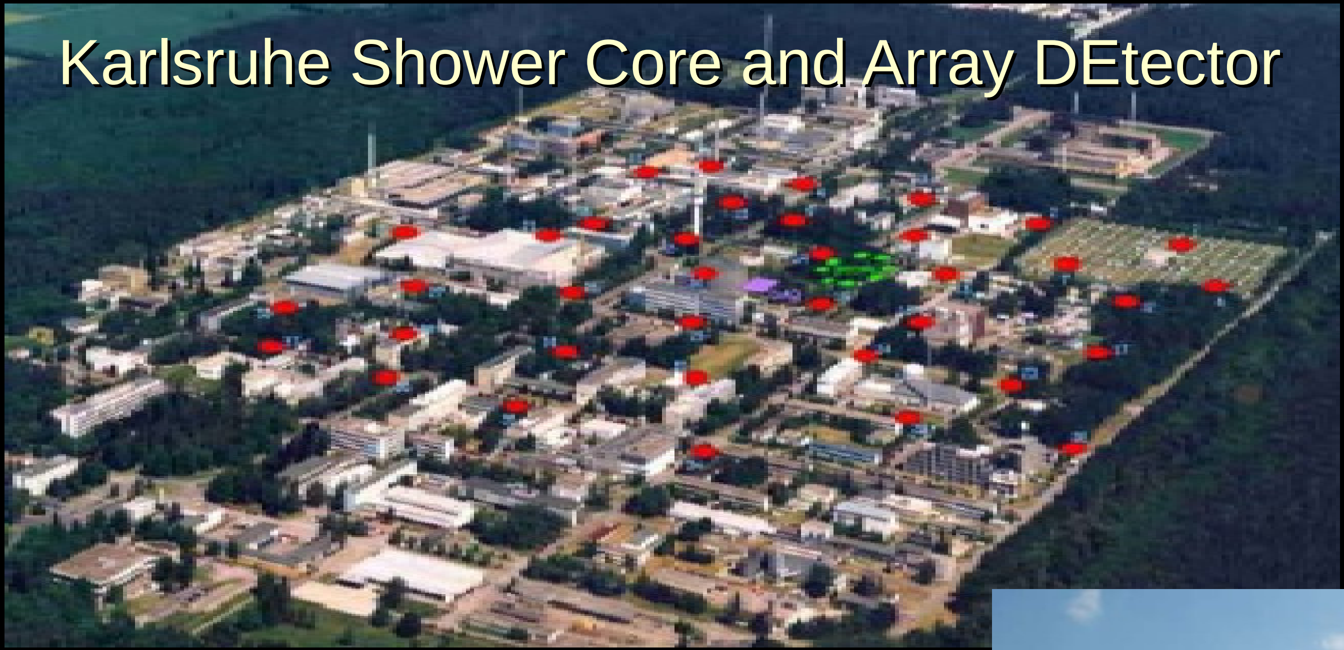


Cosmic rays: spectrum



energy-range from KASCADE-Grande
balance shower-rate and signal-height

KASCADE-Grande & LOPES



Air-shower at
100 TeV – 1 EeV

well calibrated

Inverted V-shape short dipole

40 — 80 MHz

10, later 30 channels

mainly EW-polarisation

triggered by KASCADE

LOPES Collaboration

ASTRON, The Netherlands
H. Butcher, G.W. Kant, W. van Capellen, S. Wijnholds

Univ Wuppertal, Germany
D. Fuhrmann, R. Glasstetter, K.H. Kampert, J. Rautenberg

Max-Planck-Institut für Radio-astronomie, Bonn, Germany
P.L. Biermann, J.A. Zensus

Istituto di Fisica dello Spazio Interplanetario, Torino, Italy
E. Cantoni, P.L. Ghia, C. Morello, G.C. Trinchero

Soltan Institute for Nuclear Studies, Lodz, Poland
P. Łuczak, F. Marcin, J. Zabierowski

Dipartimento di Fisica Generale dell'Universita, Torino, Italy
M. Bertaina, A. Chiavassa, F. Di Pierro, G. Navarra*

Dept of Astrophysics, Nijmegen, The Netherlands
L. Bähren, S. Buitink, H. Falcke, J.R. Hörandel, A. Horneffer, J. Kuijpers, S. Lafèbre, A. Nigl, K. Singh

LOPES
RADIO EMISSION FROM COSMIC RAY AIR SHOWERS

National Inst of Physics and Nuclear Engineering Bucharest, Romania
I.M. Brancus, B. Mitrica, M. Petcu, A. Saftoiu, O. Sima, G. Toma

IK, KIT, Germany
W.D. Apel, J.C. Arteaga, A.F. Badea, K. Bekk, J. Blümer, H. Bozdog, K. Daumiller, P. Doll, R. Engel, M. Finger, A. Haungs, D. Heck, T. Huege, P.G. Isar, H.J. Mathes, H.J. Mayer, S. Nehls, J. Oehlschläger, T. Pierog, H. Rebel, M. Roth, H. Schieler, F. Schröder, H. Ulrich, A. Weindl, M. Womm

www.astro.ru.nl/lopes

IPE, KIT, Germany
T. Asch, H. Gemmeke, M. Helfrich, O. Krömer, L. Petzold, Ch. Rühle, M. Scherer, A. Schmidt

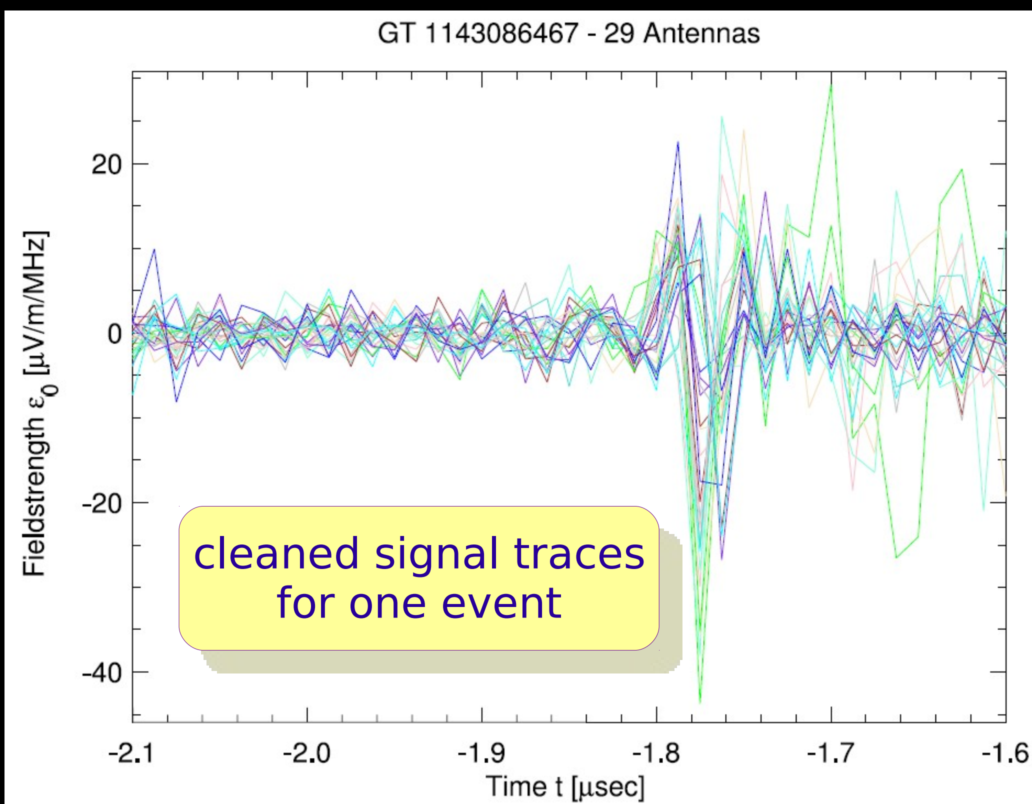
IEKP, KIT, Germany
F. Cossavella, V. De Souza, D. Huber, D. Kang, M. Konzack, K. Link, M. Ludwig, M. Melissas, N. Palmieri

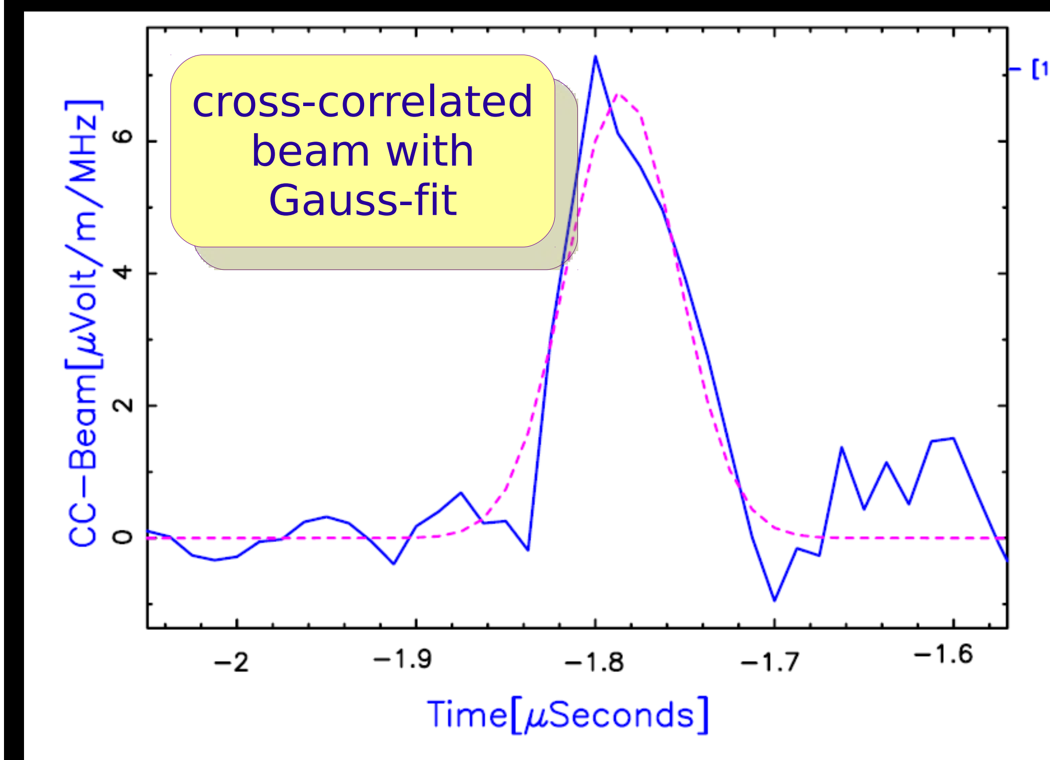
Universität Siegen, Germany
P. Buchholz, C. Grupen, D. Kickelbick, S. Over

LOPES: Cross-correlation

- beam-forming by adding signals with different time-offsets
- time-offsets determine geometry

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





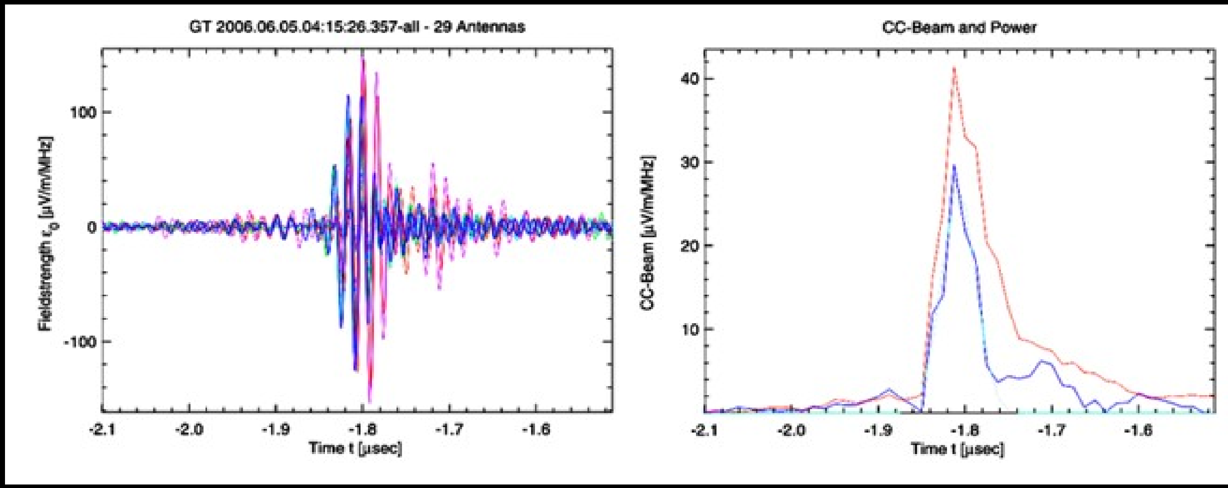
LOPES: beam-forming

time-offset for cross-corelation:

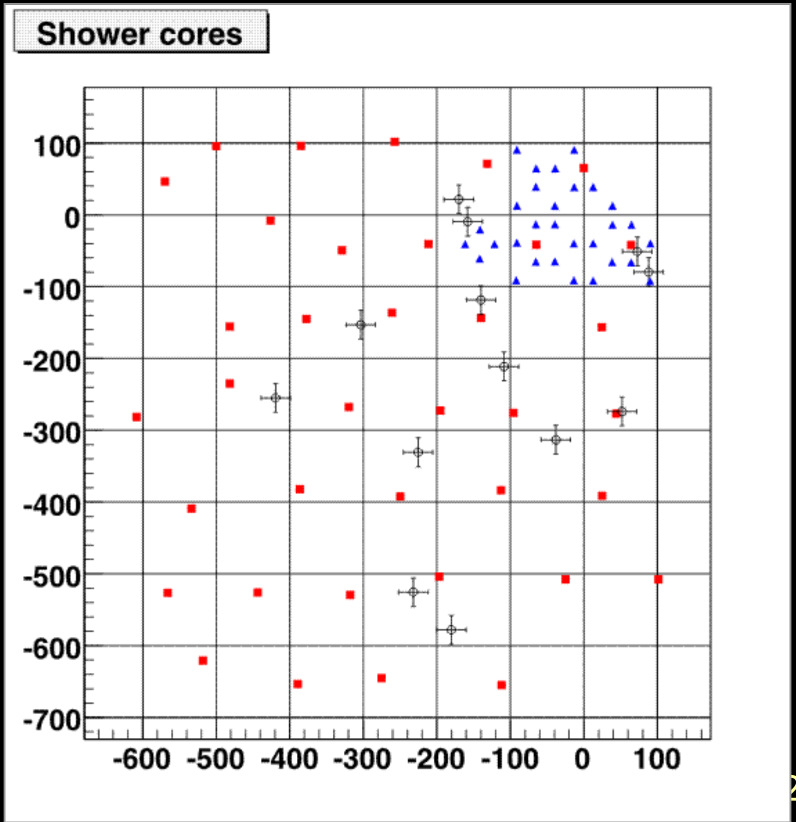
- oriantation of plane
- curvature for focus

Heino Falcke, Andreas Horneffer, Lars Bären

LOPES-30 EW polarised



- Jan-Jul 2006
- High energy, $N_\mu > 10^5$
- High inclination, θ > 50°
- beam-forming
- KASCADE-Grande reconstruction (316 events)
- 161 well radio-reconstructed
- 14 clear, coherent signals



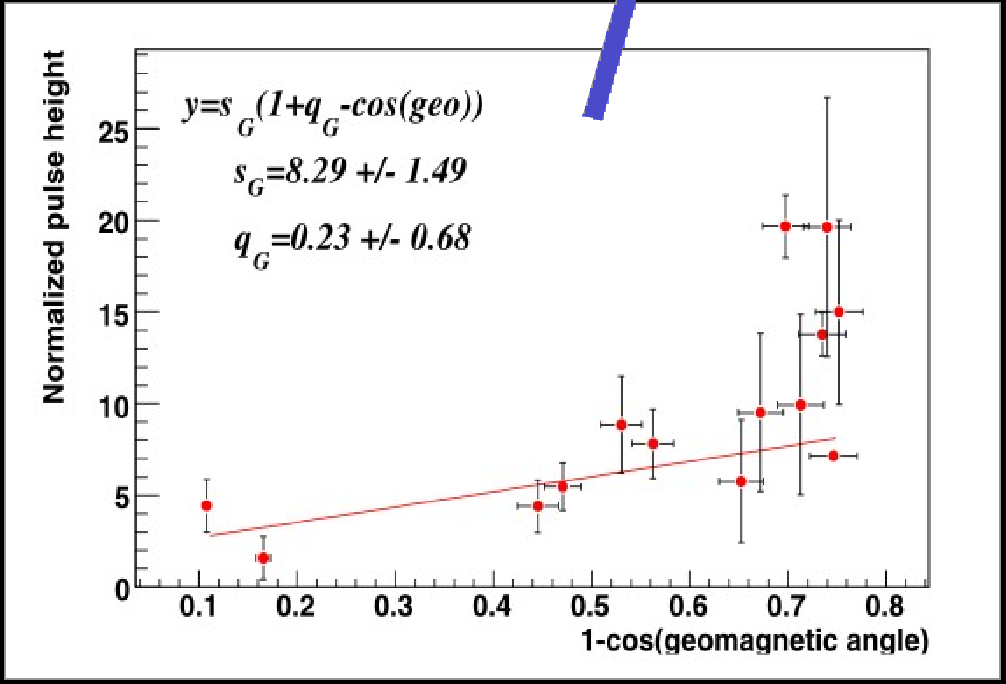
LOPES: pulse-height correlation

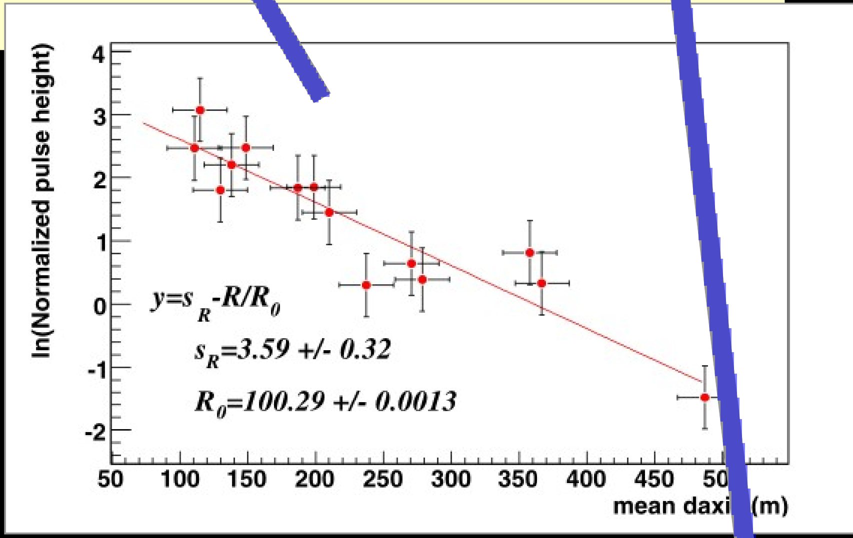
$$\varepsilon_{est\text{-}EW} = A \cdot (1+B-\cos\alpha) \cdot \cos\theta \cdot \exp(-R/R_0) \cdot (E/10^{17}\,\mathrm{eV})^{\gamma}$$

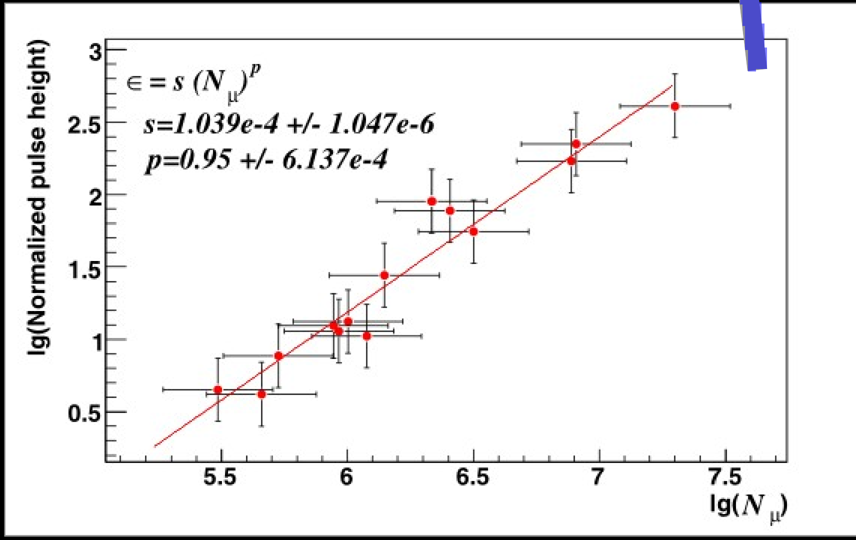
A = 10.9 ± 1.1 B = 1.16 ± 0.02

R_0 =202 ± 64 m γ = 0.94 ± 0.03

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







LOPES: lateral distribution

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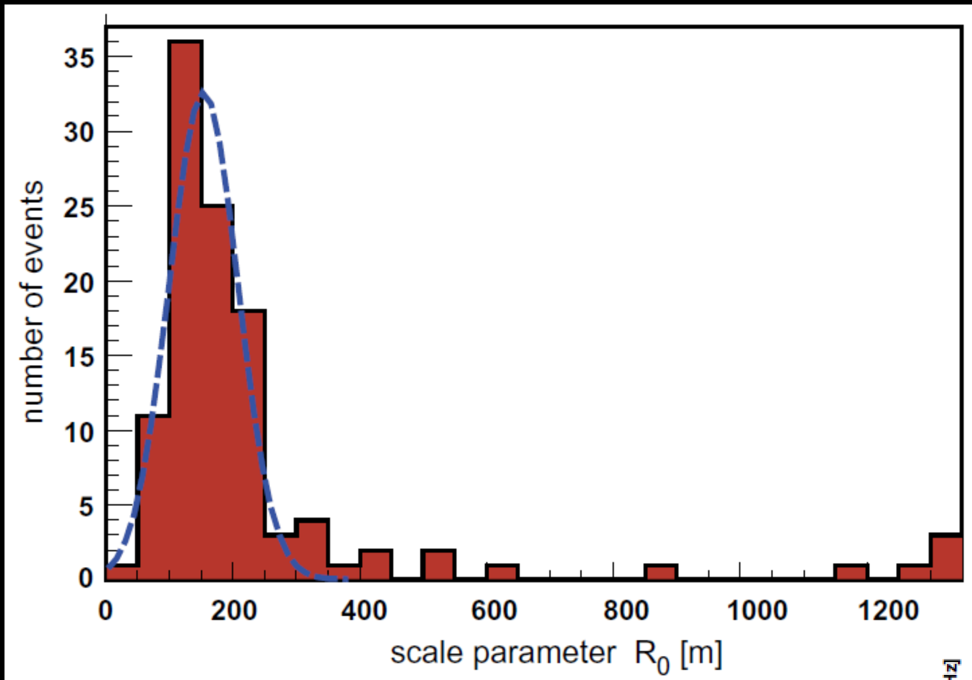
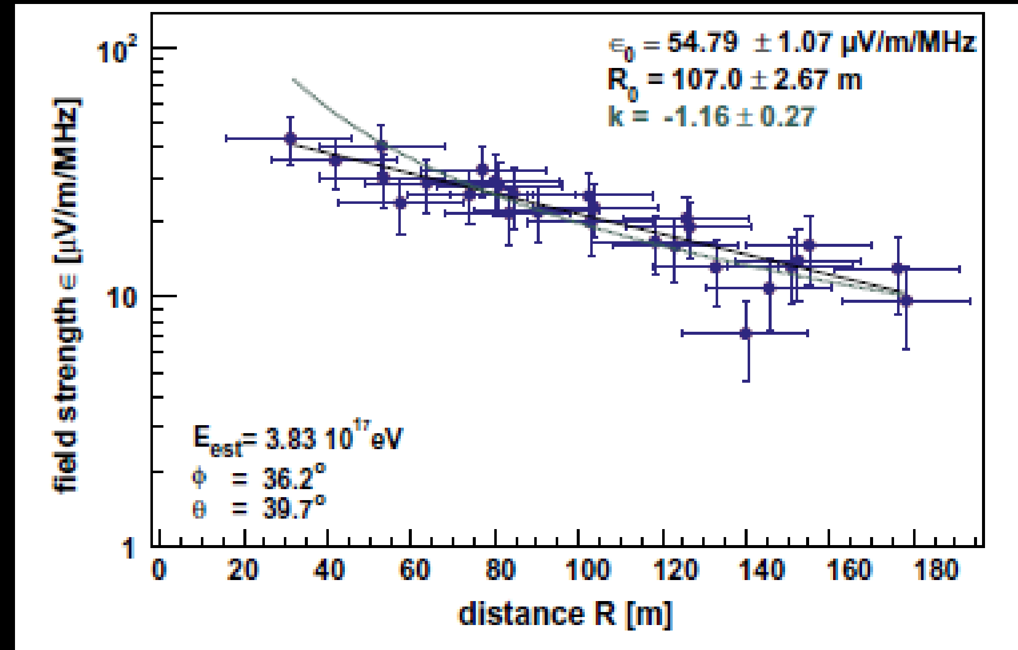
Lateral distribution of the radio signal in extensive air showers measured with LOPES

W.D. Apel[a], J.C. Arteaga[b,1], T. Asch[c], A.F. Badea[a], L. Bähren[d], K. Bekk[a], M. Bertaina[e], P.L. Biermann[f], J. Blümer[a,b], H. Bozdog[a], I.M. Brancus[g], M. Brüggemann[h], P. Buchholz[h], S. Buitink[d], E. Cantoni[e,i], A. Chiavassa[e], F. Cossavella[b], K. Daumiller[a], V. de Souza[b,2], F. Di Pierro[e], P. Doll[a], R. Engel[a], H. Falcke[d,j], M. Finger[a], D. Fuhrmann[k], H. Gemmeke[c], P.L. Ghia[i], R. Glasstetter[k], C. Grupen[h], A. Haungs[a], D. Heck[a], J.R. Hörandel[d], A. Horneffer[d], T. Huege[a], P.G. Isar[a], K.-H. Kampert[k], D. Kang[b], D. Kickelbick[h], O. Krömer[c], J. Kuijpers[d], S. Lafebre[d], P. Łuczak[l], M. Ludwig[b], H.J. Mathes[a], H.J. Mayer[a], M. Melissas[b], B. Mitrica[g], C. Morello[i], G. Navarra[e], S. Nehls[a,*], A. Nigl[d], J. Oehlschläger[a], S. Over[h], N. Palmieri[b], M. Petcu[g], T. Pierog[a], J. Rautenberg[k], H. Rebel[a], M. Roth[a], A. Saftoiu[g], H. Schieler[a], A. Schmidt[c], F. Schröder[a], O. Sima[m], K. Singh[d,3], G. Toma[g], G.C. Trinchero[i], H. Ulrich[a], A. Weindl[a], J. Wochele[a], M. Wommer[a], J. Zabierowski[l], J.A. Zensus[f]

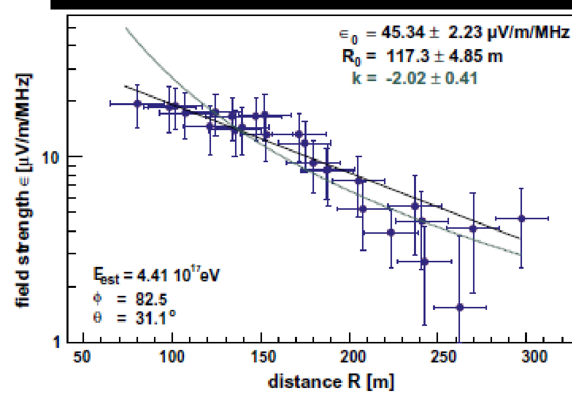
LOPES: lateral distribution

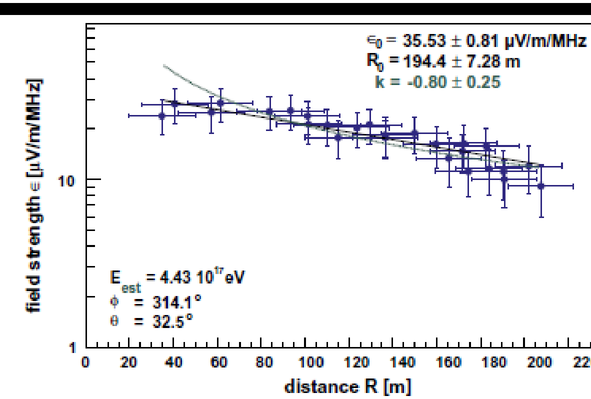


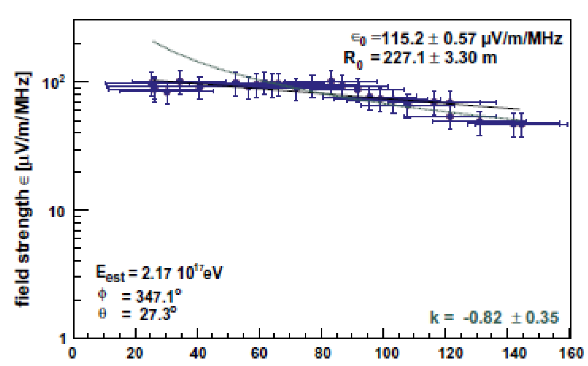


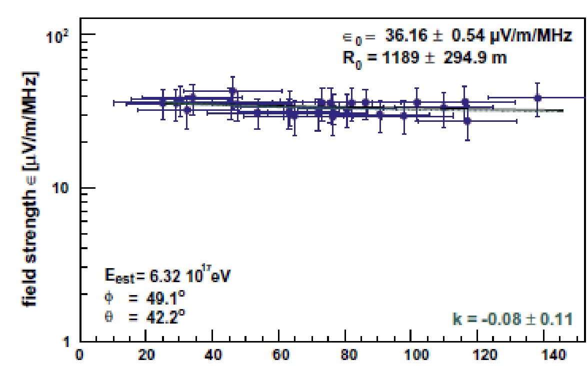
Some are very strange,
flat close to core
or even flat at all

Amplitude estimator fails?

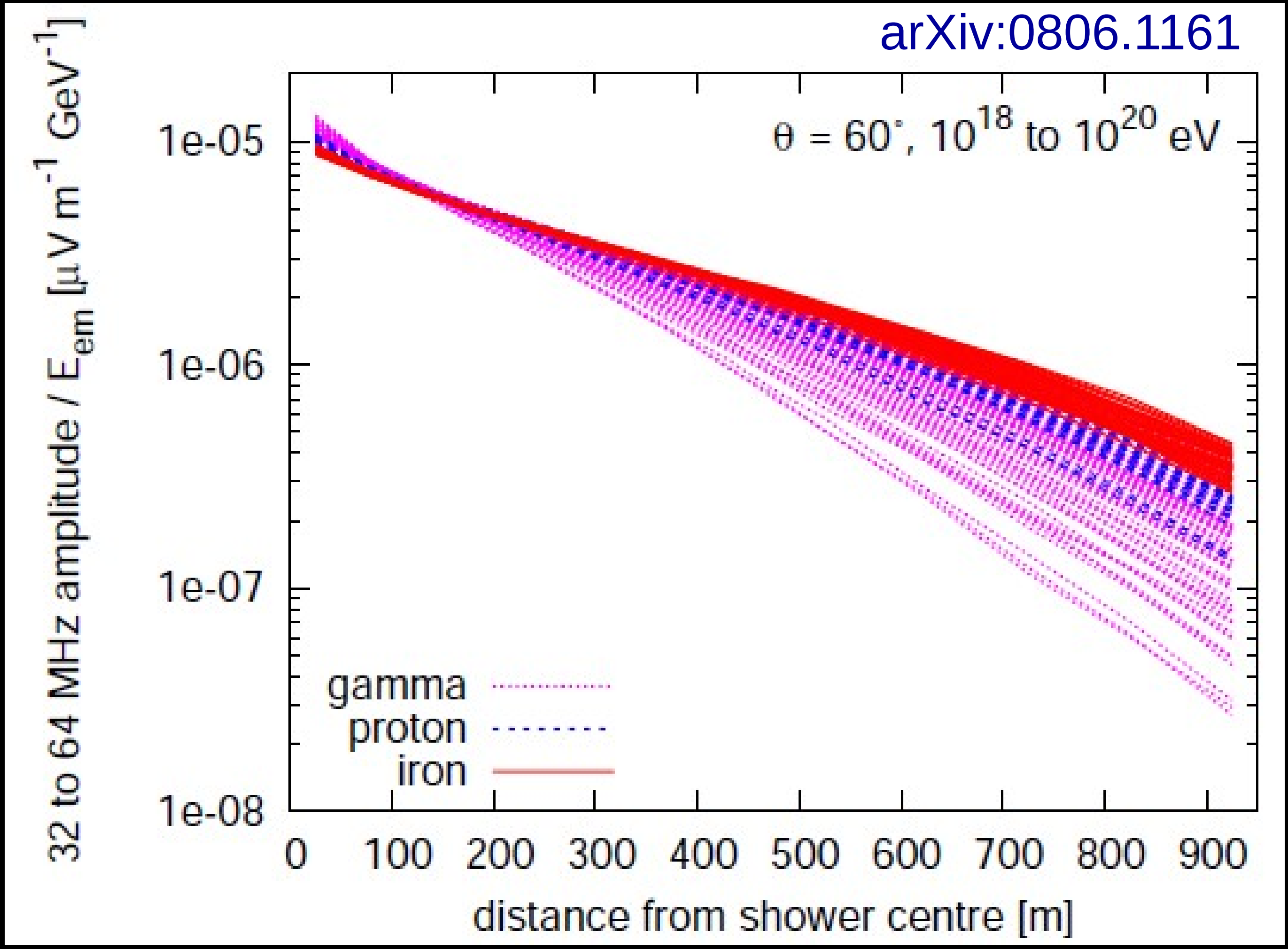




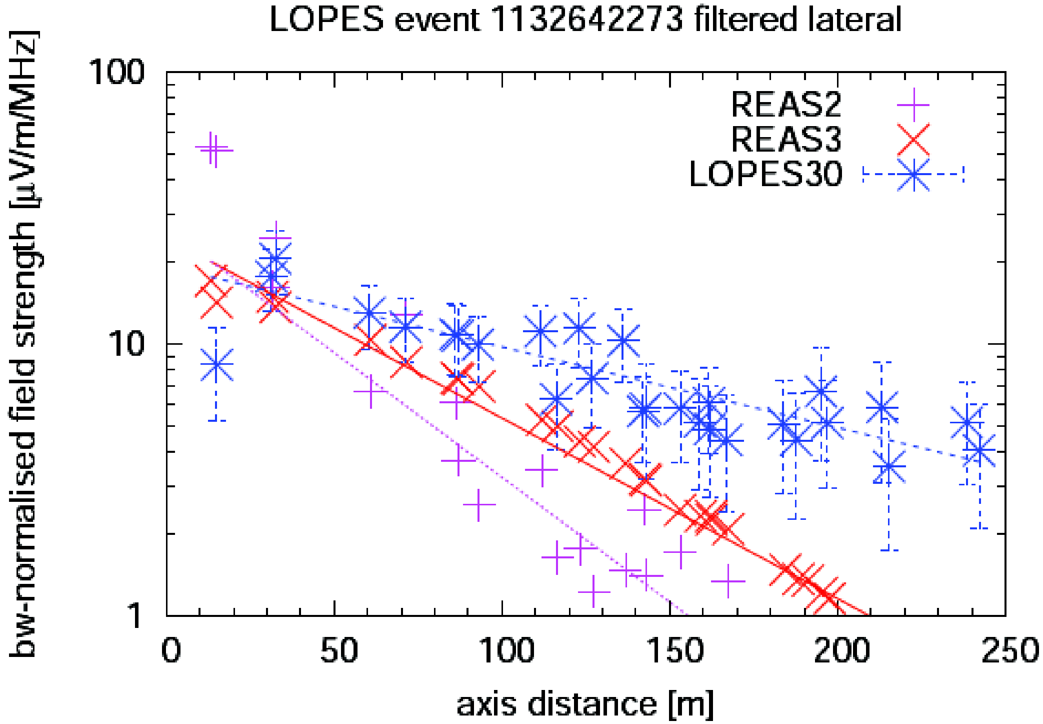


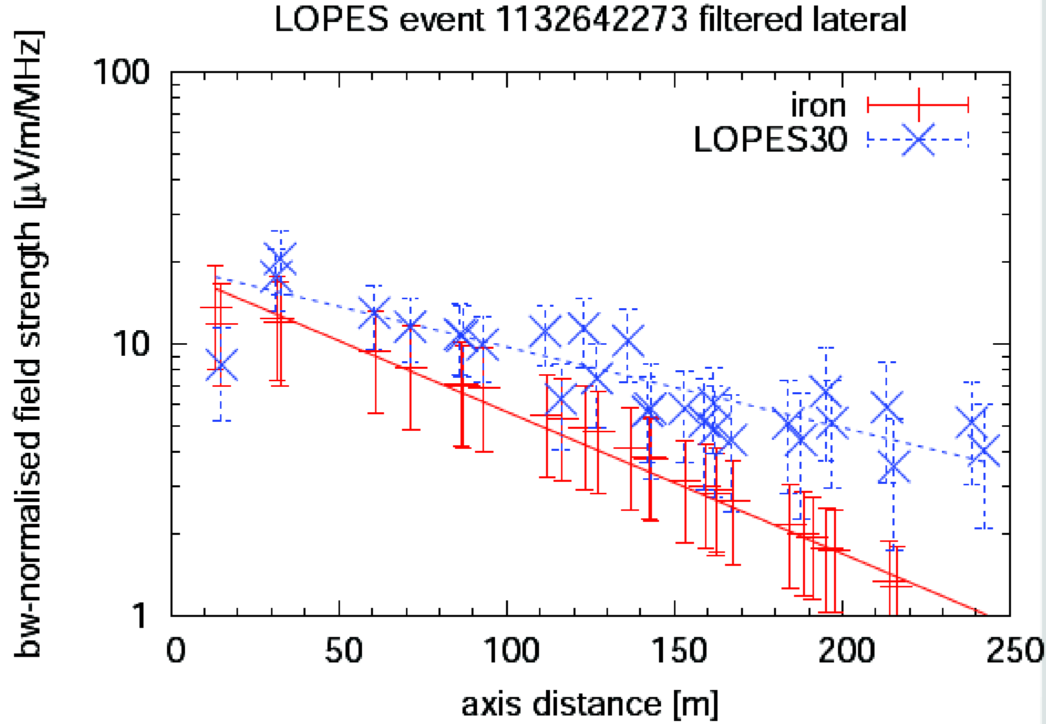


Composition with Radio

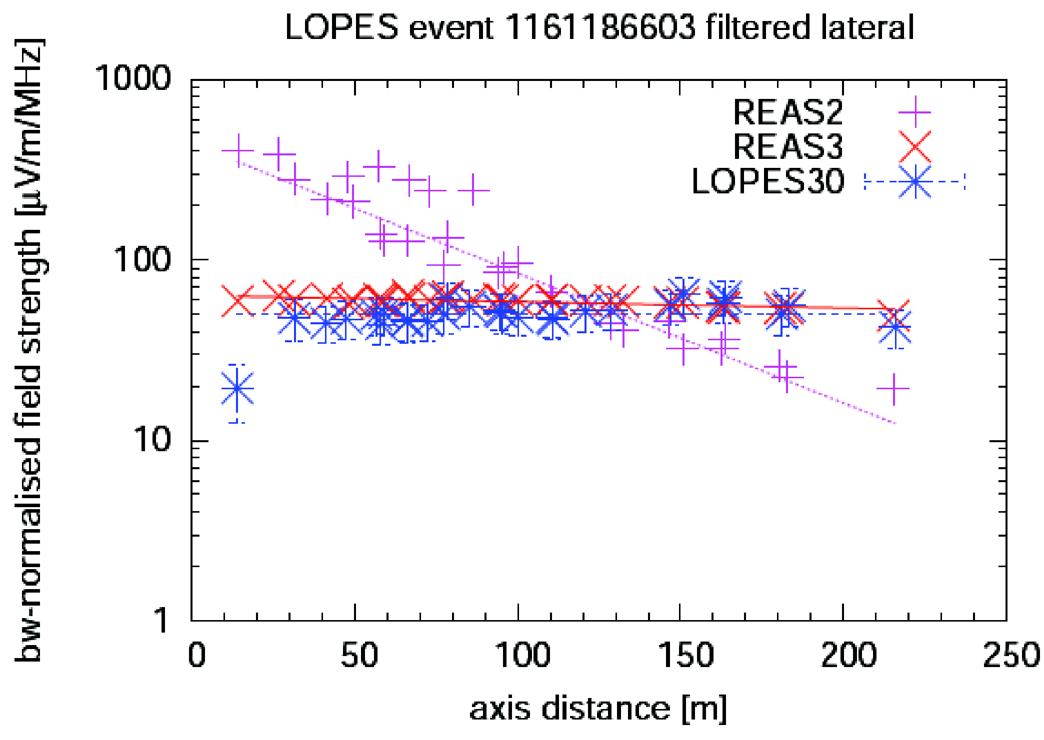


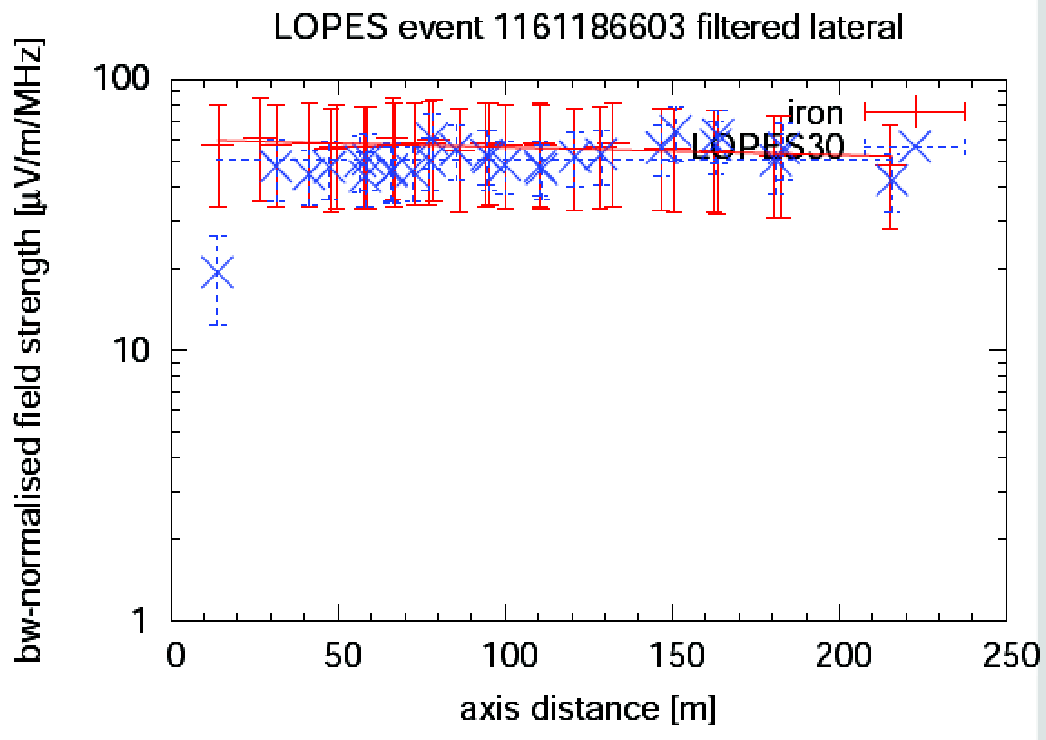
- Measure energy at ca. 175 m
- Composition sensitivity at larger distances

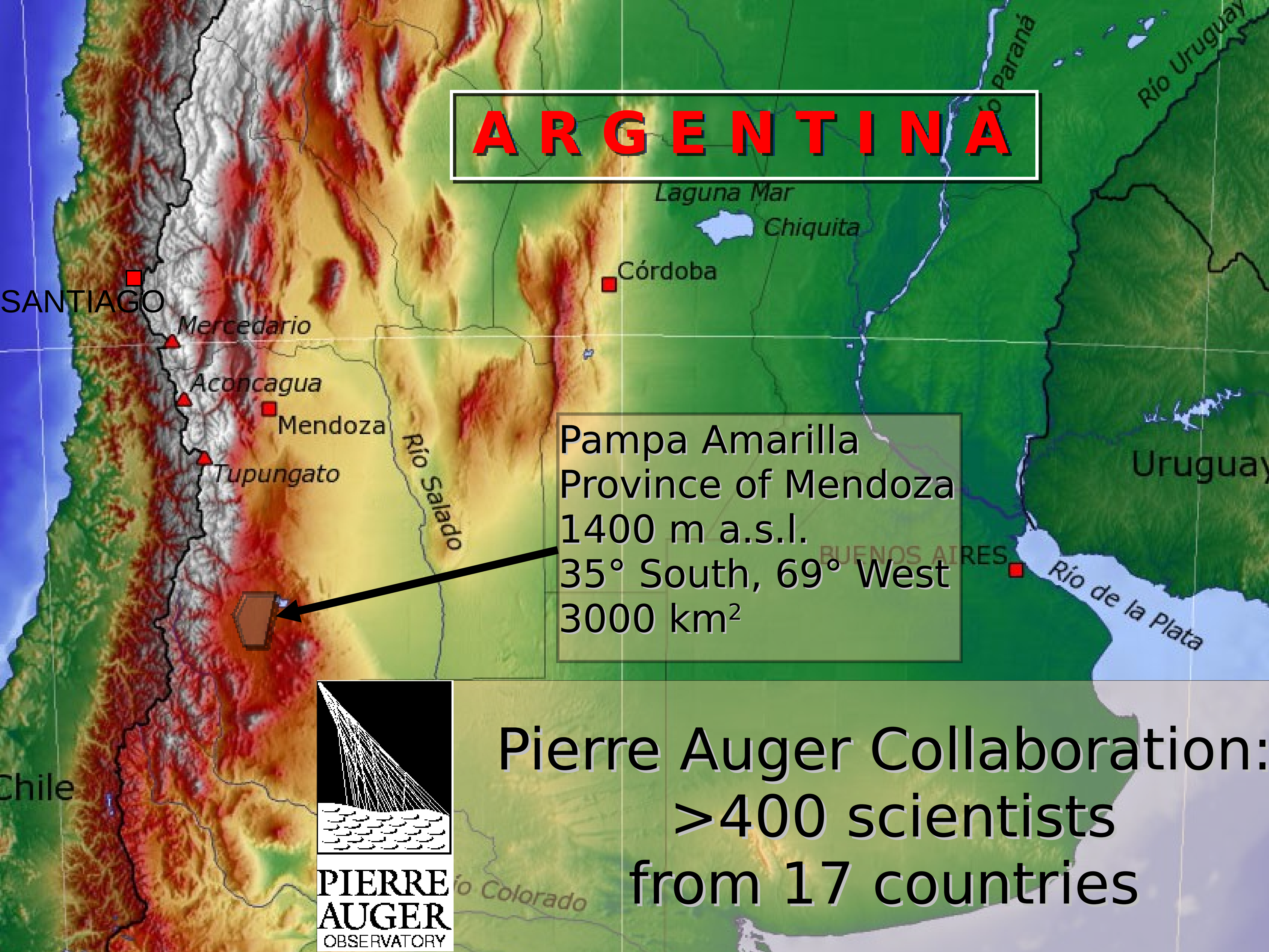

LOPES event 1132642273 filtered lateral
REAS2
REAS3
LOPES30
bw-normalised field strength [µV/m/MHz]
axis distance [m]
100
10
1
0
50
100
150
200
250


LOPES event 1132642273 filtered lateral
iron
LOPES30
bw-normalised field strength [µV/m/MHz]
axis distance [m]
100
10
1
0
50
100
150
200
250

Proton

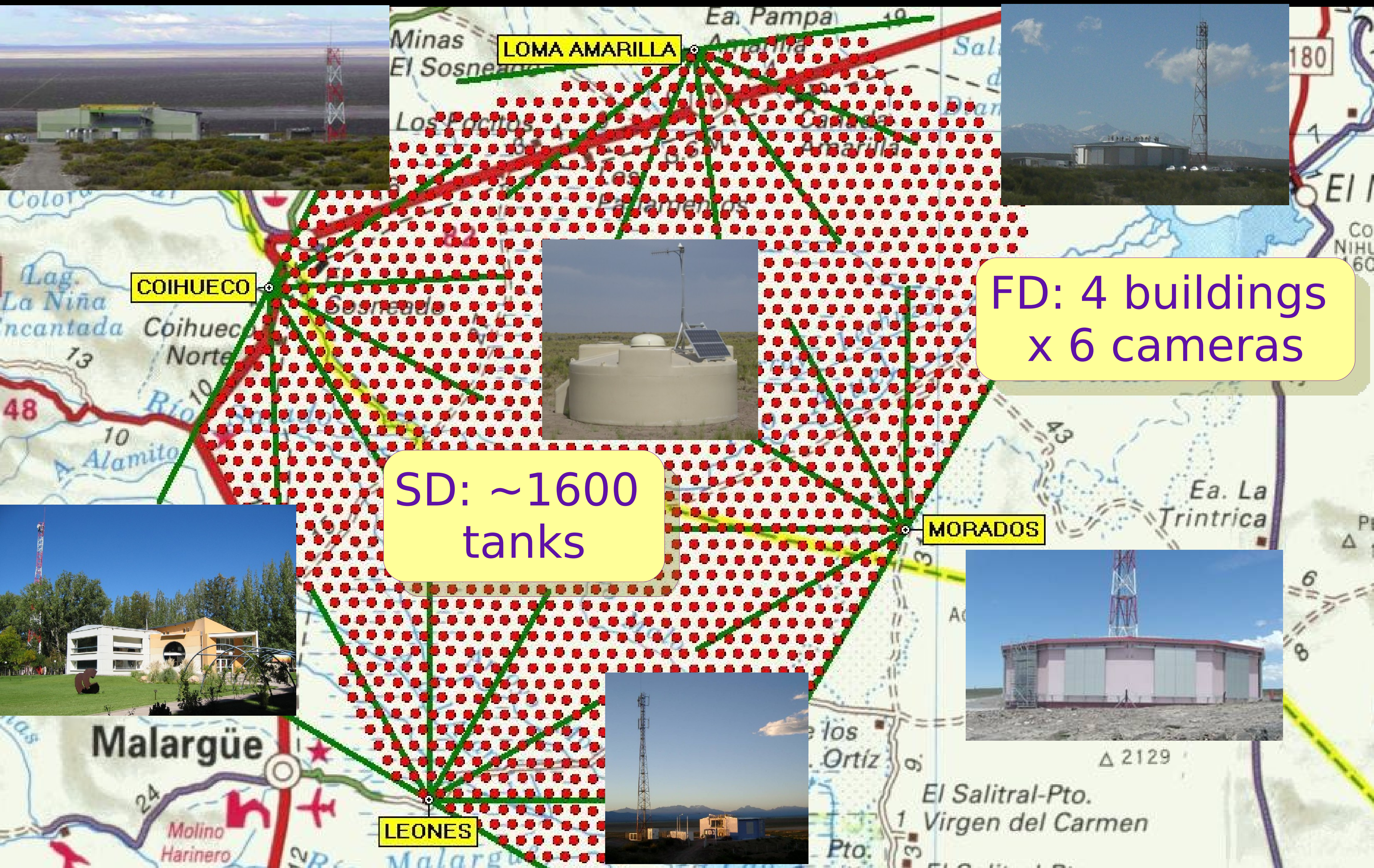

LOPES event 1161186603 filtered lateral
REAS2
REAS3
LOPES30
bw-normalised field strength [µV/m/MHz]
axis distance [m]
1000
100
10
1
0
50
100
150
200
250


LOPES event 1161186603 filtered lateral
iron
LOPES30
bw-normalised field strength [µV/m/MHz]
axis distance [m]
100
10
1
0
50
100
150
200
250

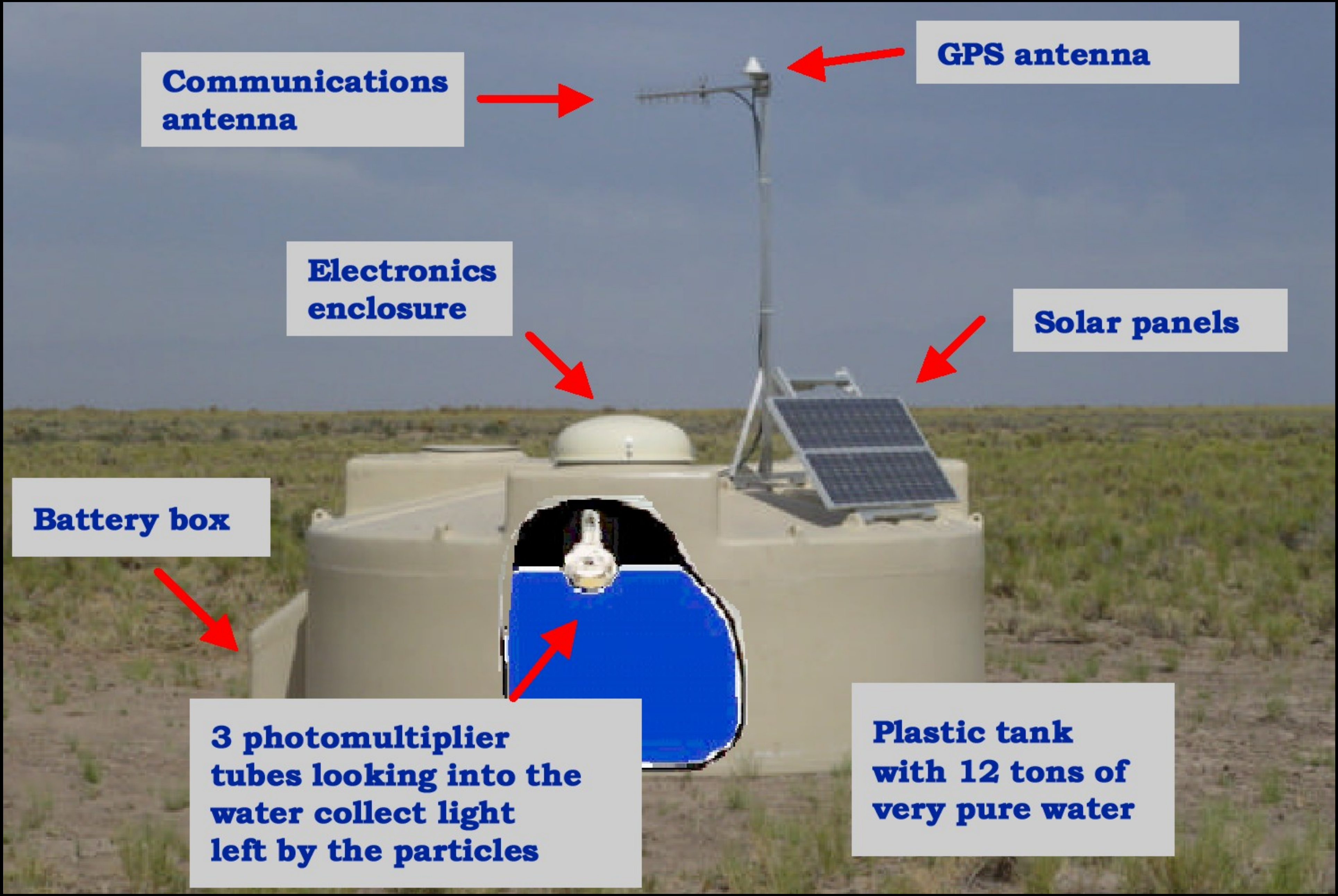

ARGENTINA
Laguna Mar
Chiquita
Córdoba
Río Paraná
Río Uruguay
SANTIAGO
Mercedario
Aconcagua
Mendoza
Tupungato
Río Salado
Pampa Amarilla
Province of Mendoza
1400 m a.s.l.
35° South, 69° West
3000 km²
BUENOS AIRES
Uruguay
Río de la Plata
Chile
PIERRE
AUGER
OBSERVATORY
Pierre Auger Collaboration:
>400 scientists
from 17 countries

Pierre Auger Experiment in Argentina

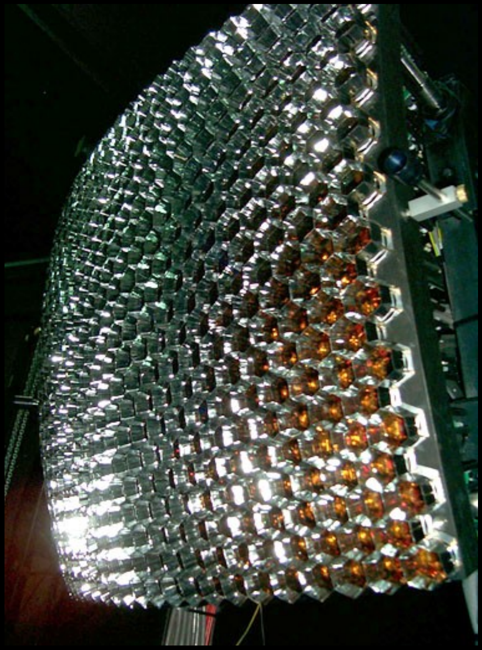
Hybrid detection: surface- (SD) / fluorescence-detectors (FD)

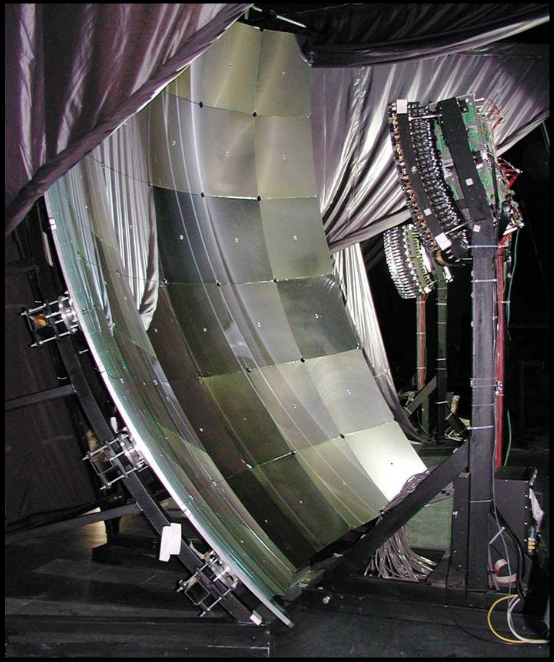


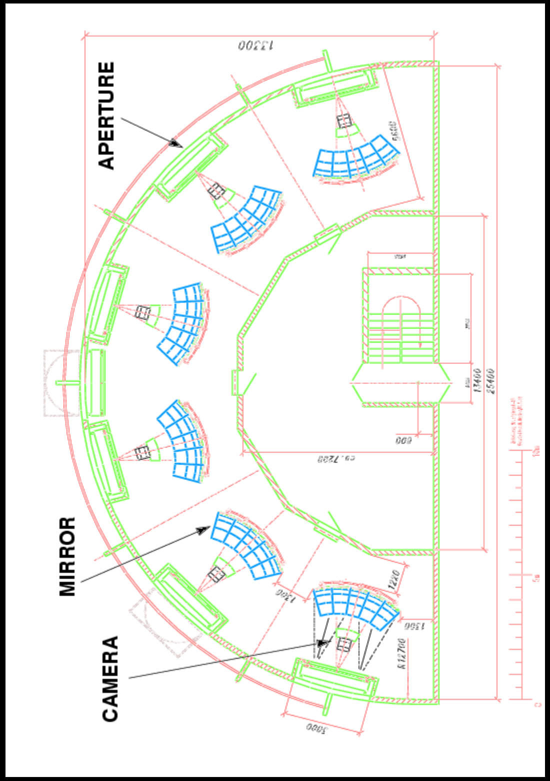
Pierre Auger Observatory: Surface detector



Fluorescence-Detectors



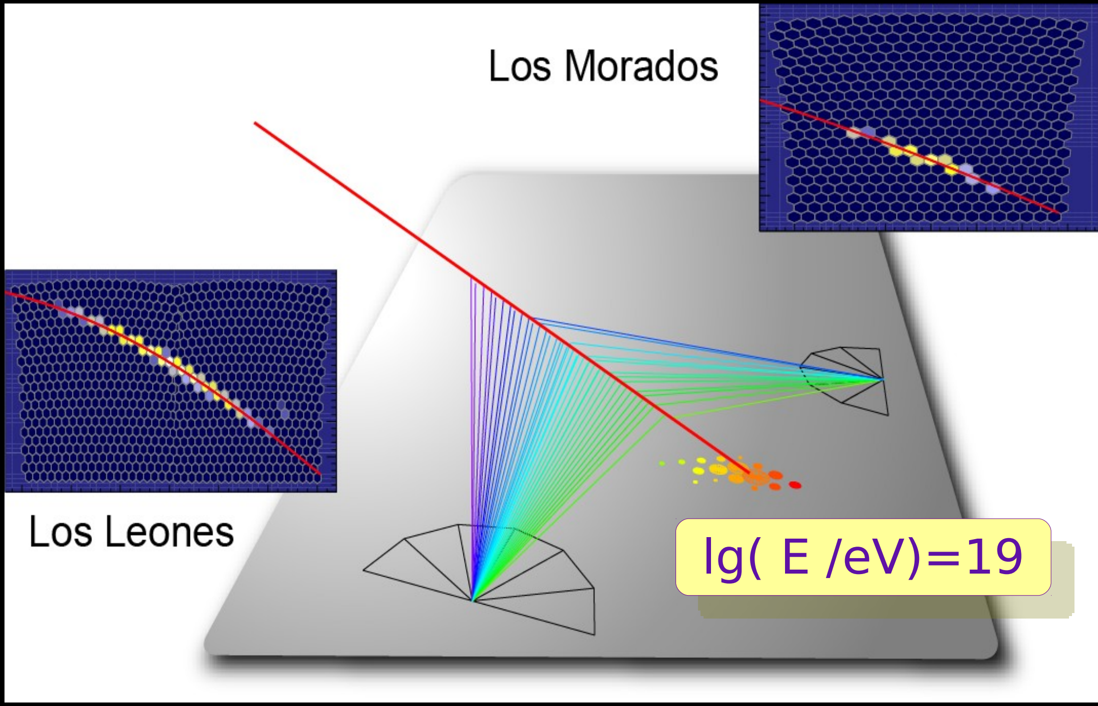




Camera with Schmidt-optics and 440 PMTs

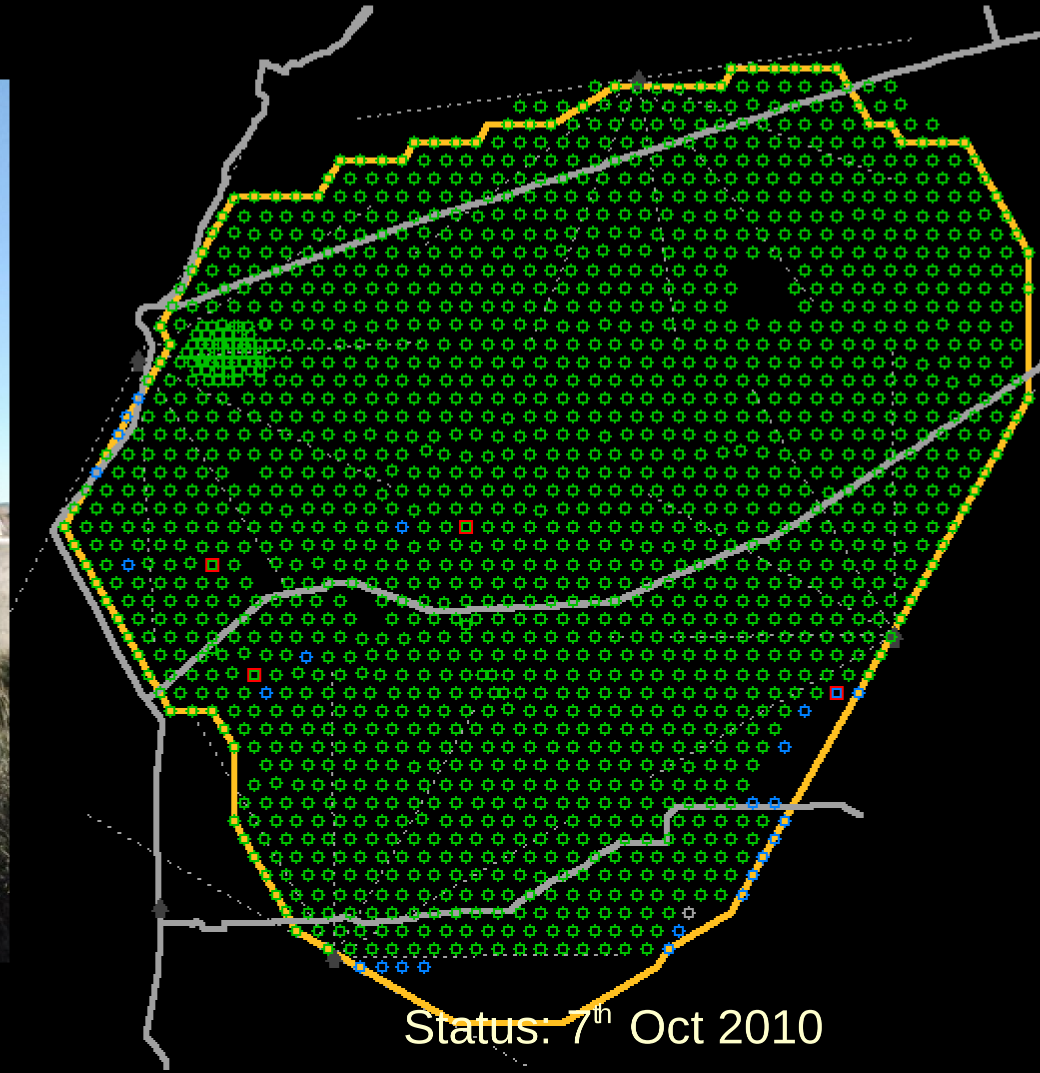
30° x 30° field of view

only active in clear, moon-less nights



Pierre Auger Observatory: status

- 4th fluorescence building first light in April 2007
- Last tank has been deployed on Friday 13th June 2008



Status: 7th Oct 2010

Radio at Pierre Auger Observatory

2 main motivations to go to PAO:

Pampa Amarilla is radio-quiet

Best EAS-detector, i.e. for high energies $E>10^{18}$ eV

(But magnetic field anomaly and rather high altitude)

Auger established a Radio Detection R&D Task Force

Sep. 2006 data acquisition started with up to 4 test-setups

After some problems (autonomy, power, ground-loops):

Data exists now for three different data formats

EAS have been measured *--- they are in the data!*

Radio Auger: People

http://augerradio.org/wiki/moin.cgi/who_we_are

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Edit (Text) Edit (GUI) Comments Info Add Link Attachments More Actions:

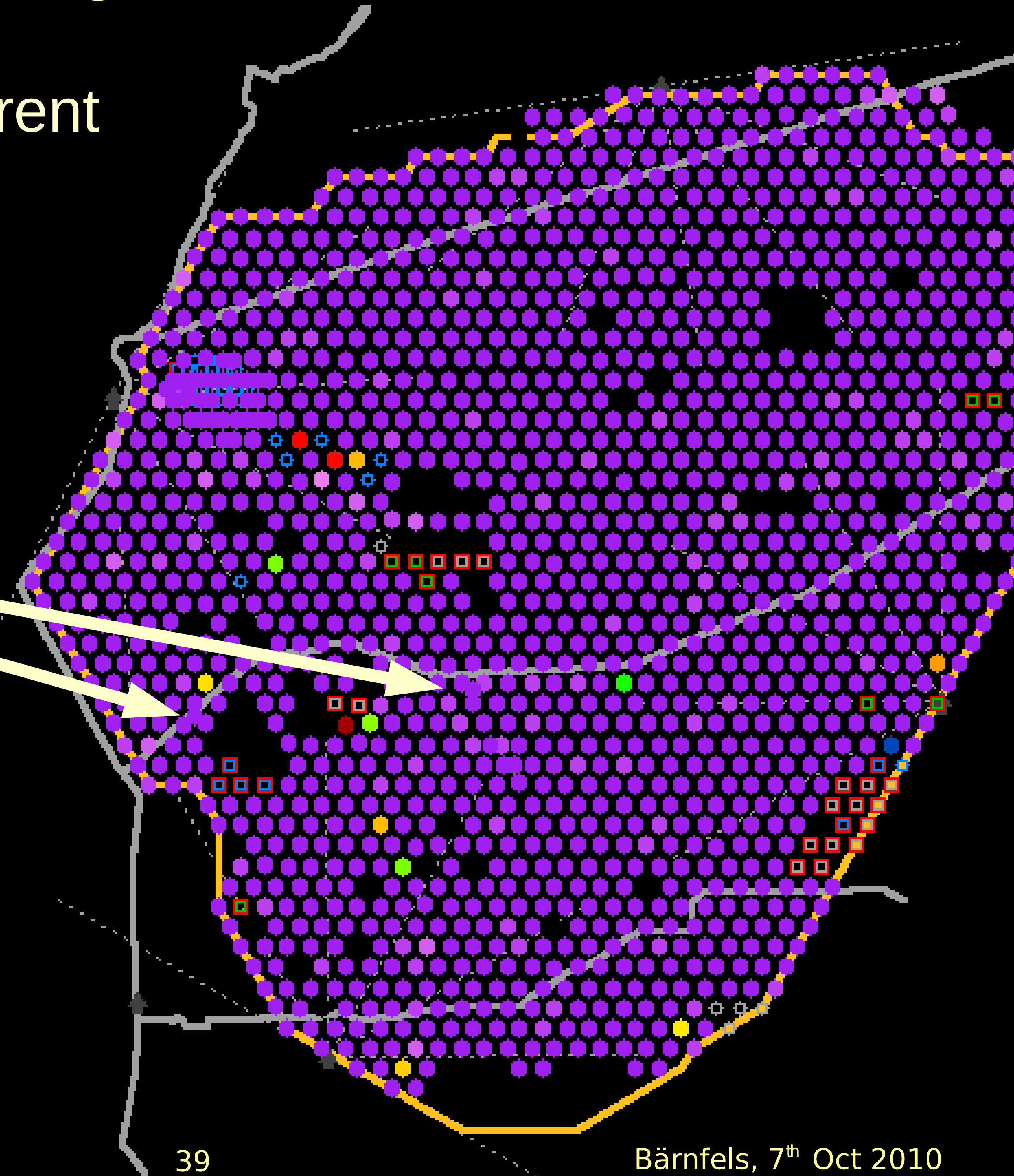
Ordered list of scientists, engineers, and students ranked according to location of home institute

Update July 11, 2007

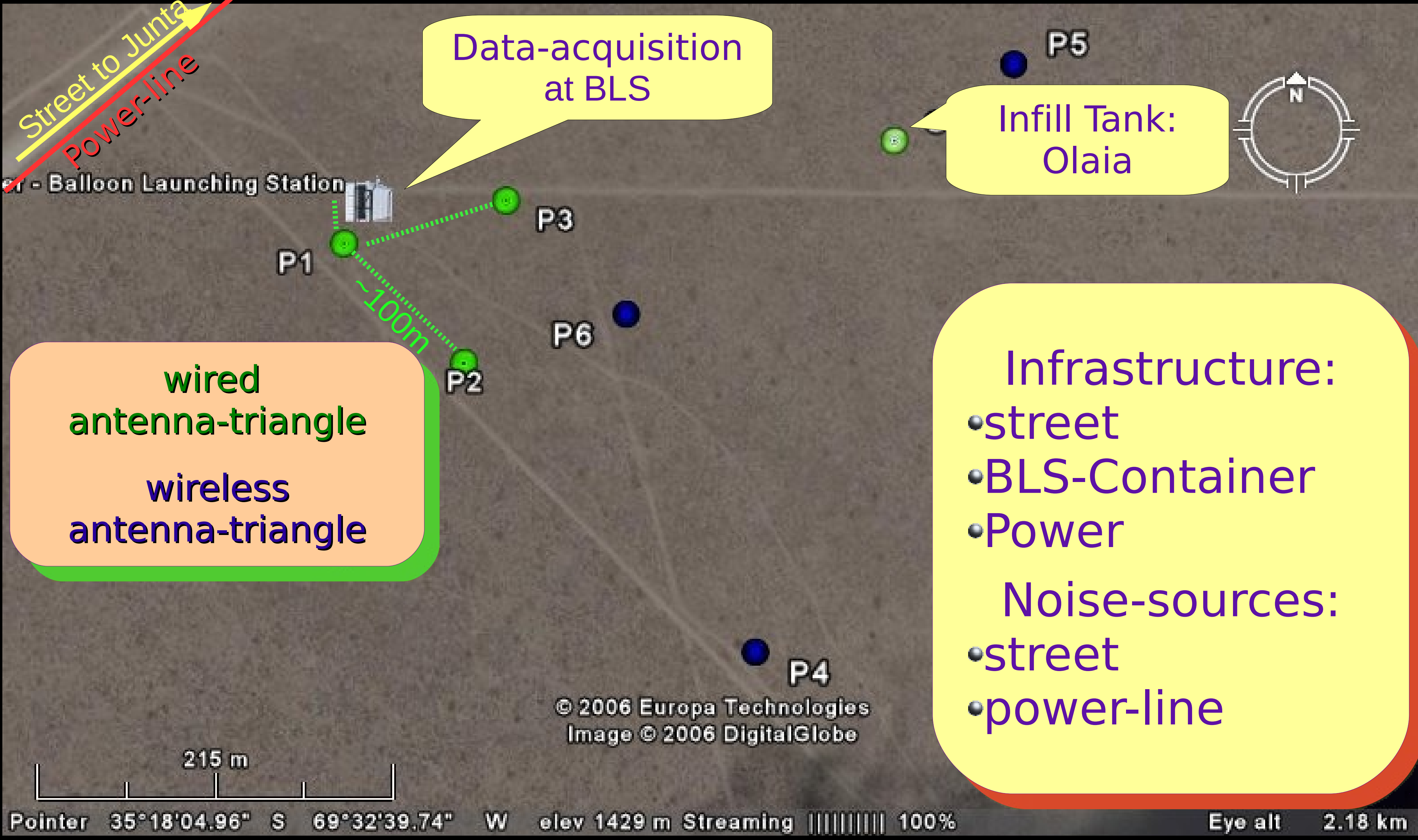
- Aachen, III Physikalisches Institut A o
- Bonn, MPI für Radioastronomie, **P. B**
- Catania, INFN Sezione di Catania, **R**
- Columbus OH, Department of Physic
- Dwingeloo, ASTRON, **H. Falcke**
- Grenoble, LPSC, **C. Berat, J. Chau**
- Groningen, KVI, **S. Harmsma, R. Me**
- Karlsruhe, FZK-IK, **J. Blümer, A. Ha**
- Karlsruhe, FZK-IPE, **T. Asch, H. Ger**
- Karlsruhe, IEKP of the University of K
- Leeds, University of Leeds, **P.D.J. C**
- Lodz, Soltan Institute of Nuclear Stud
- Nantes, SUBATECH, **S. Acounis, D**
- Nijmegen, NIKHEF and IMAPP of the
- Orsay, IPN, **E. Parizot, T. Suomijärv**
- Orsay LAL, **A. Cordier, S. Dagoret-**
- Paris, APC, **S. Collonges, B. Cour**
- **Paris, LPHNE, A. Letessier-Selvo**
- Siegen, Department of Physics of the University of Siegen, **T. Backer, I. Fleck**
- Wuppertal, Department of Physics of the University of Wuppertal, **J. Auffenberg, K.-H. Becker, K.-H. Kampert, J. Rautenberg**

Radio at Auger: 2 test-sites

- measurements at different locations in the field
  - accessibility
  - power provided
  - noise
- additional SD-tanks to lower energy-threshold
- about 1 Event with $E>10^{18}$ eV



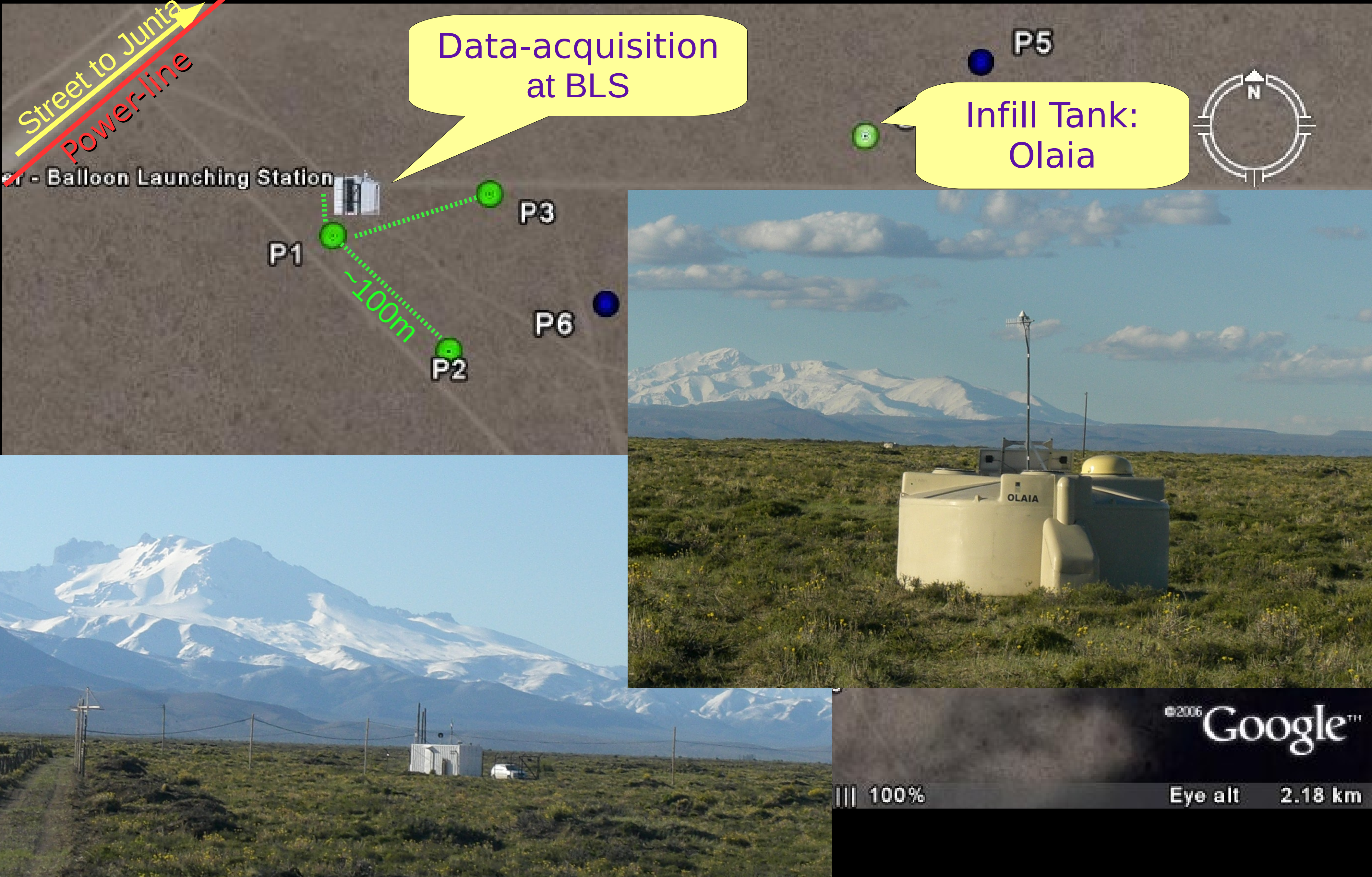
Auger test-site at Ballon-Launching Site:



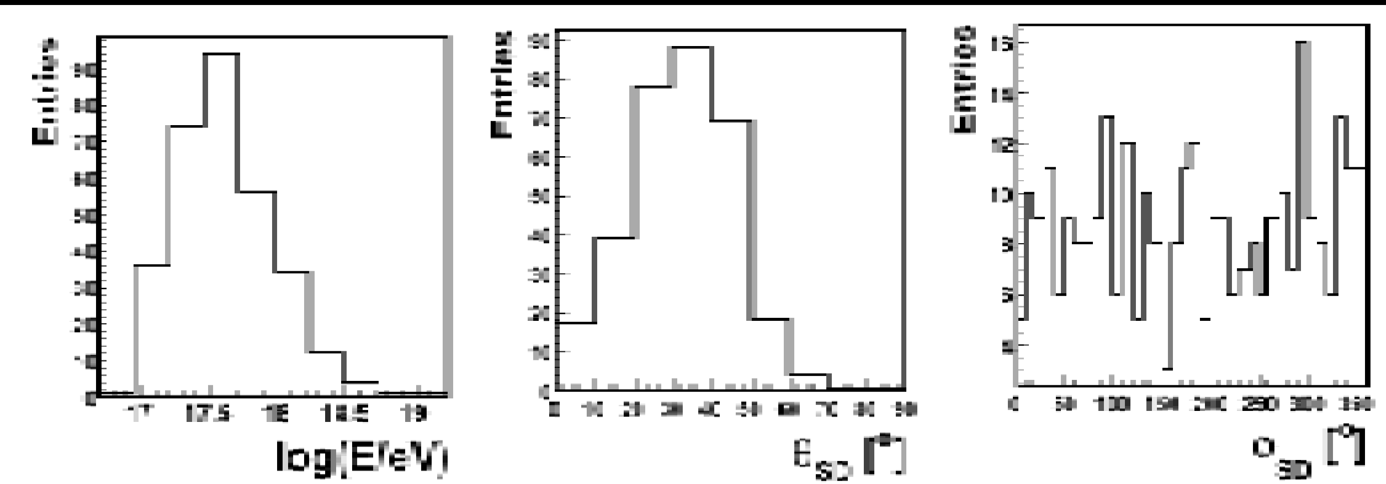
Infrastructure:
- street
- BLS-Container
- Power

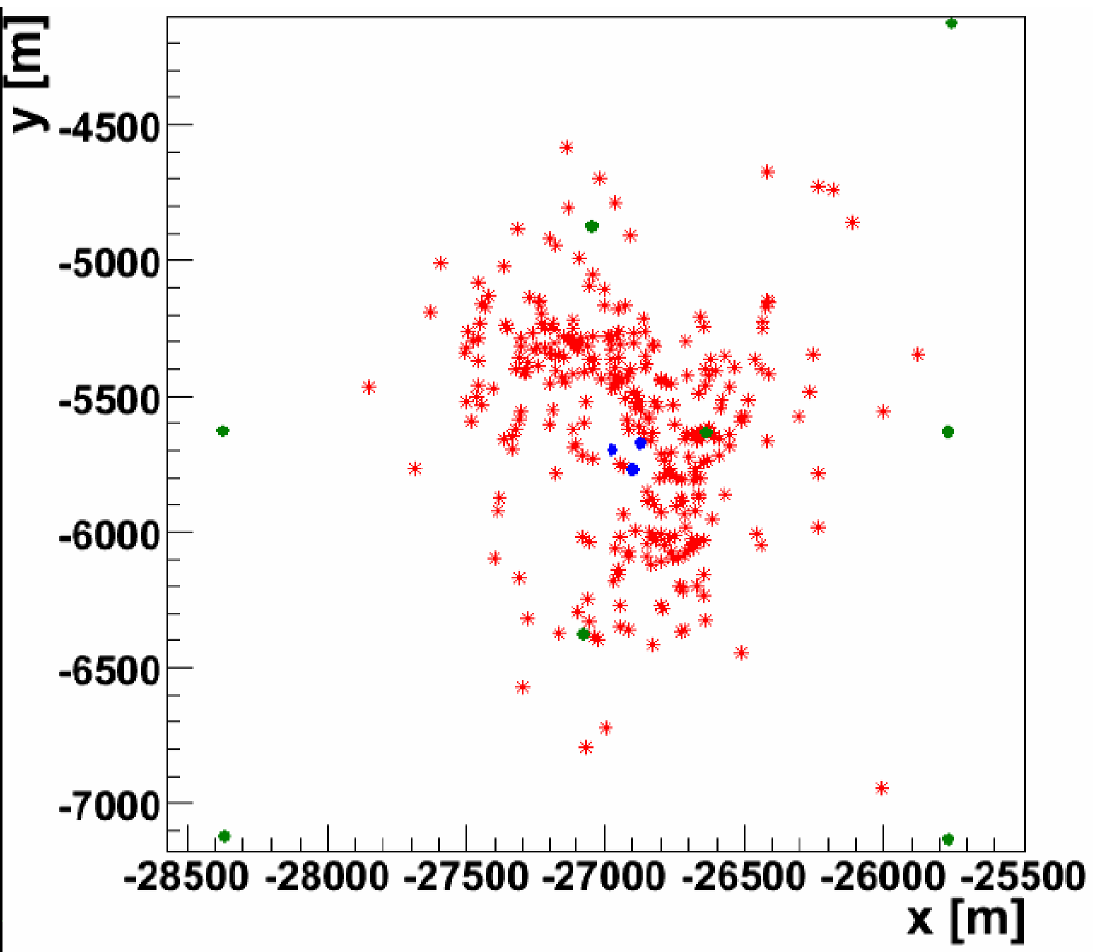
Noise-sources:
- street
- power-line

Auger test-site at Ballon-Launching Site:



Auger coincident events

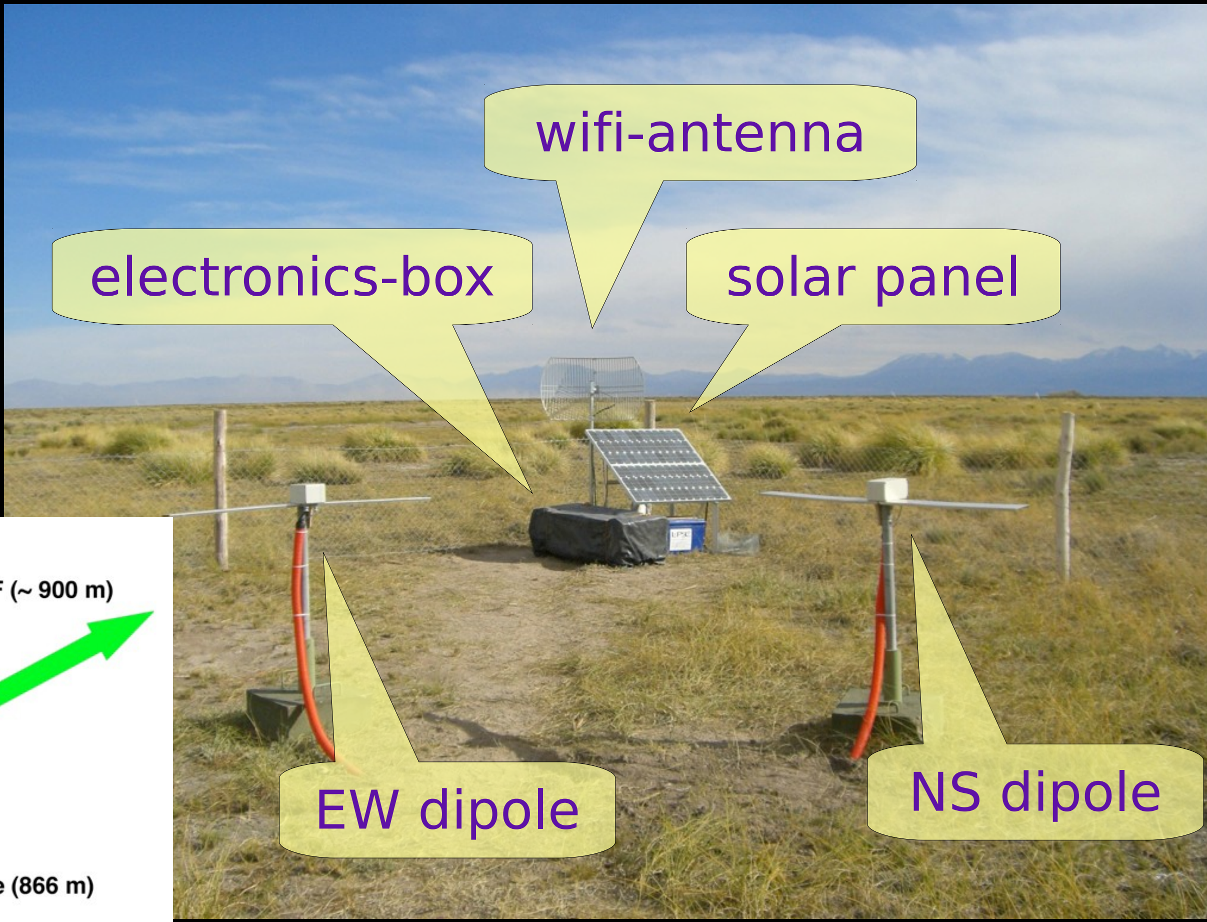


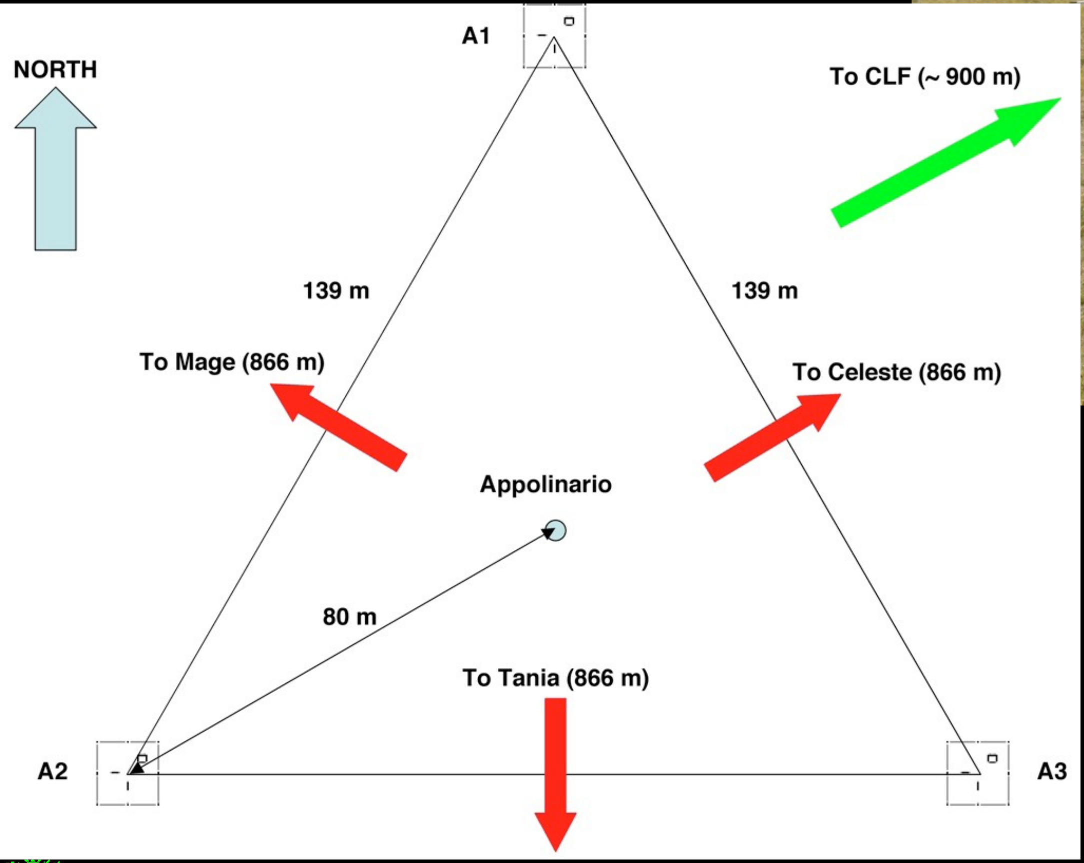


- Externally (Szintillator) triggered events
- 313 events in coincidence with Auger (GPS-time matching)
- up to 1.5 km distant
- energy-threshold ~ 0.4 EeV

Auger test-site at Central Laser Facility:

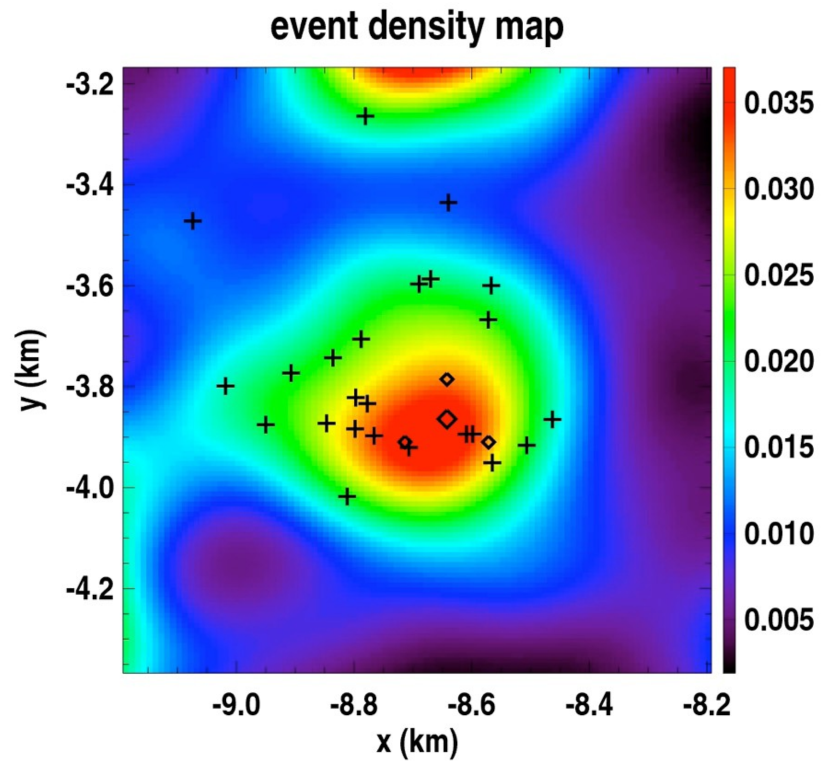
- CLF more radio-quiet
- difficult accessible

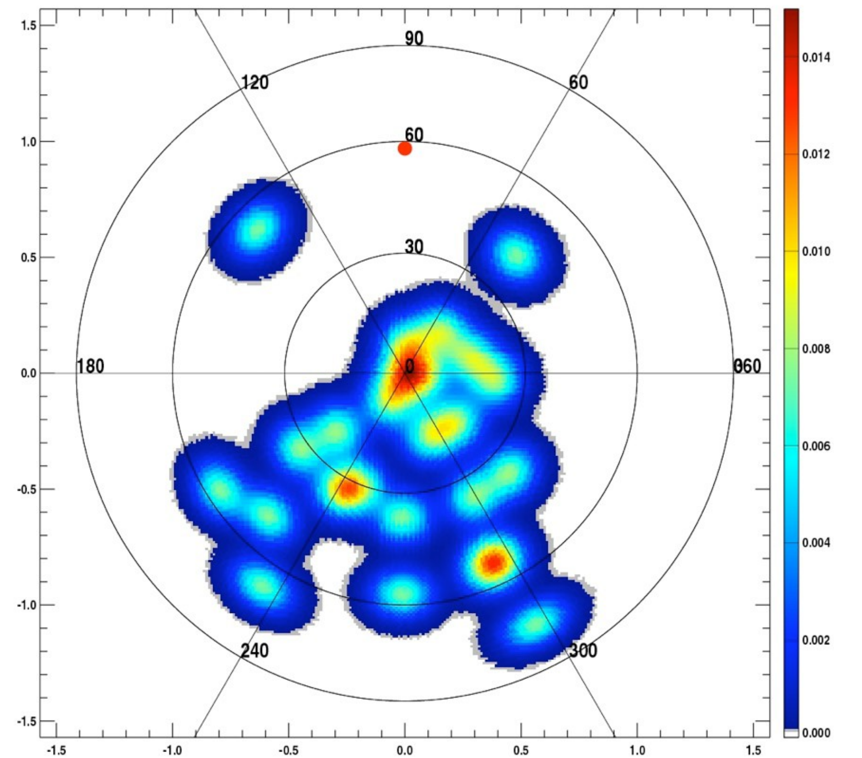




CLF: event analysis

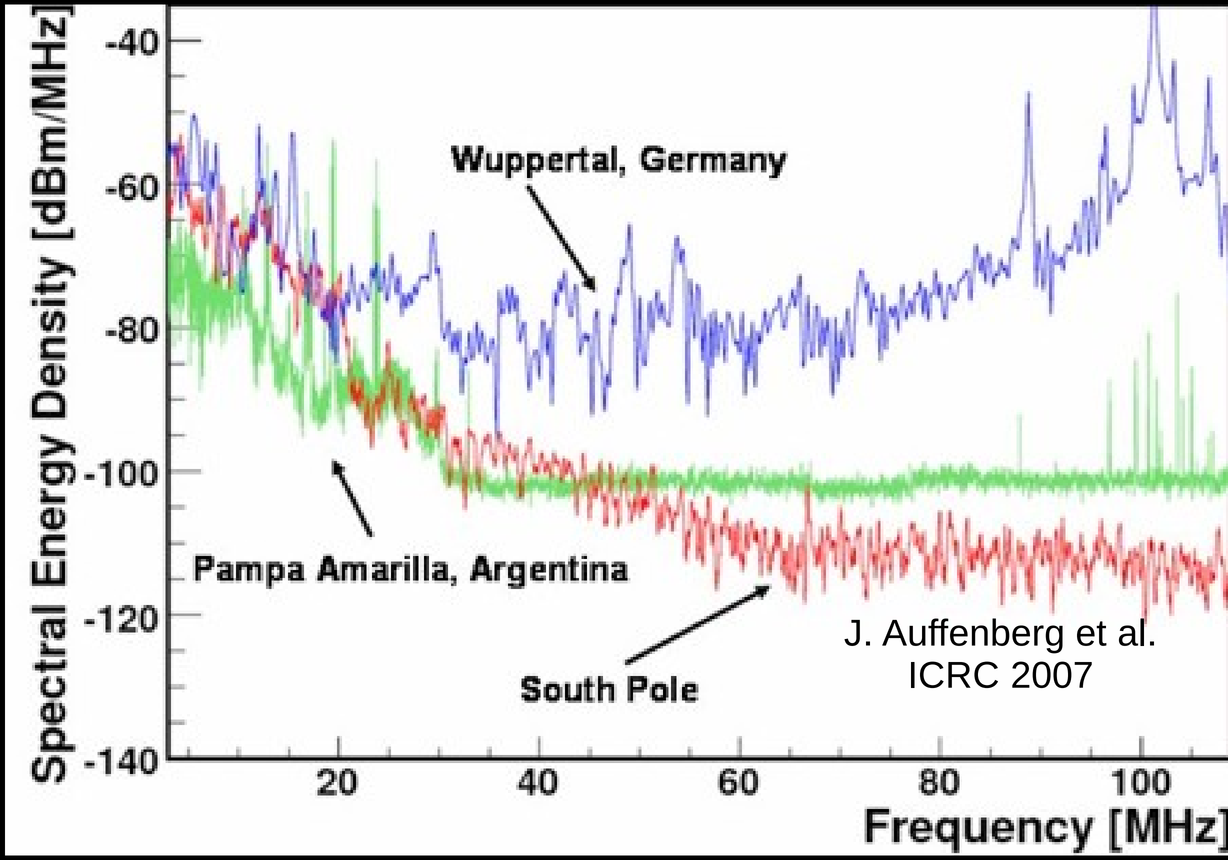
- 25 coincidences with Auger matched by time-stamp
- autonomous DAQ!
- No 3-fold event:
  - dead time
  - variable noise rate
- Auger-events:
  - compatible with Auger density-map
  - show south predominance





Background

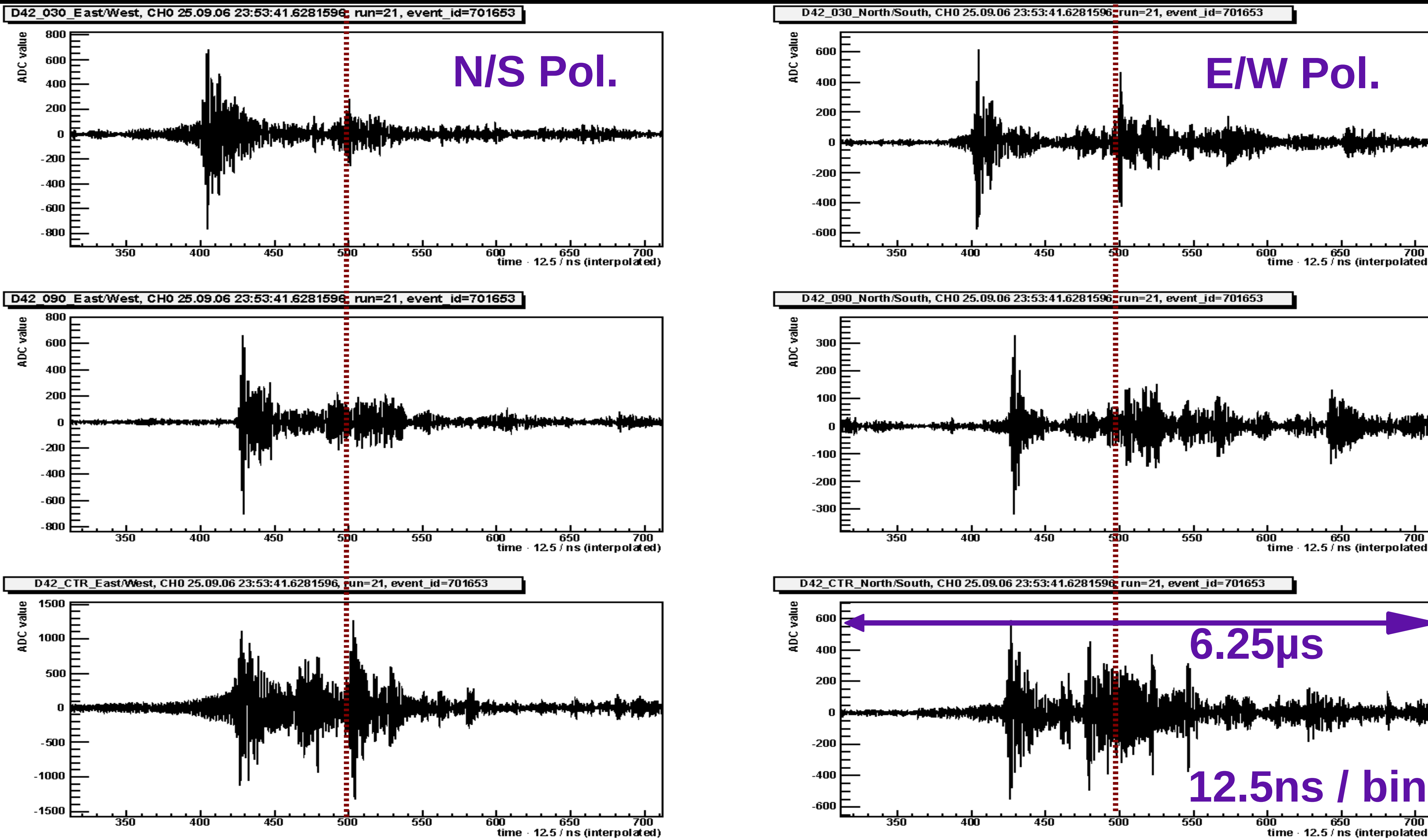
- BG measured with simple monopole
- Below 30 MHz strong rise of galactic noise
- In addition day-night ionospheric variation
- narrow-band emitters above 80 MHz



Transient background

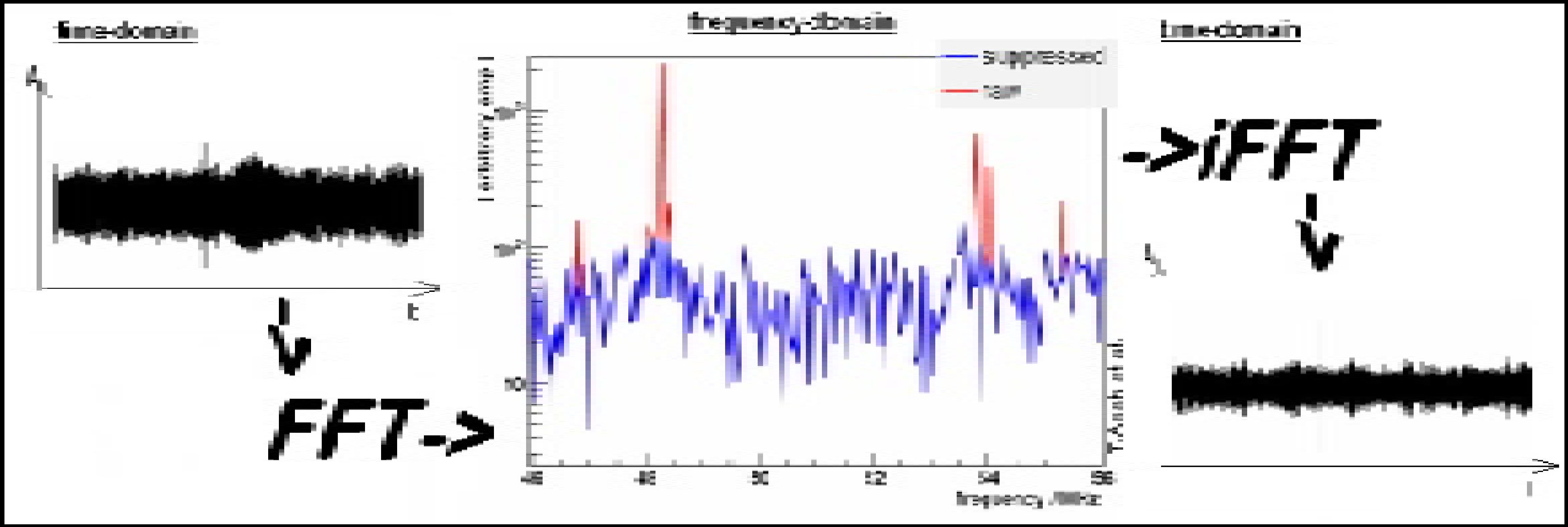
trigger at ~ bin 500

Coincidence: 16 bins



Intelligent trigger: cut-off filter

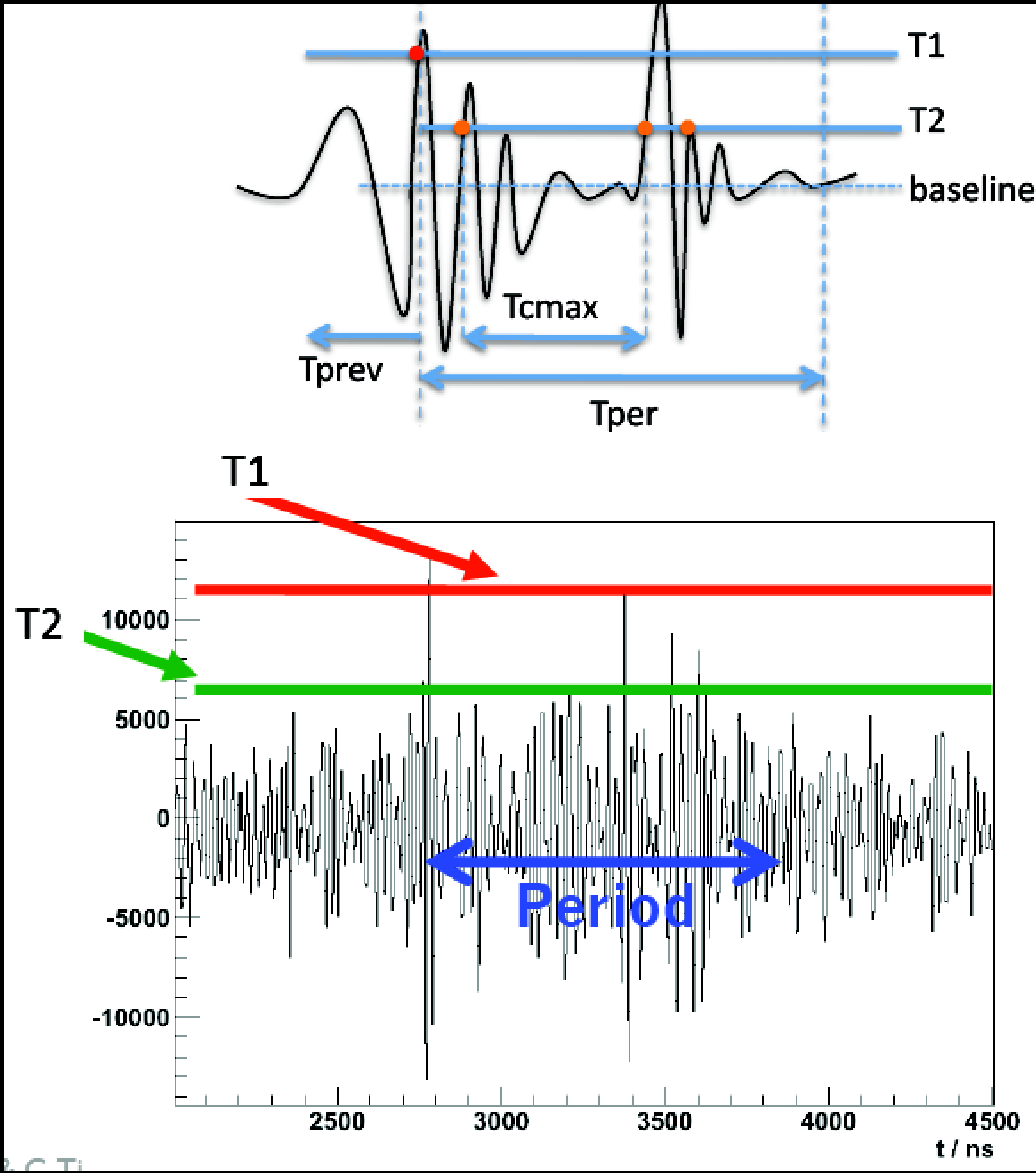
- Narrow band noise emitters: cut out in frequency domain



- radio-emission of shower: smooth in frequency
- but for triggering needed online
- cut-off too complicated: calculate mean, cut backwards

Intelligent trigger: shape analysis

- Try to remove multiple spikes by shape analysis
- Crossings of two threshold levels in defined time intervals



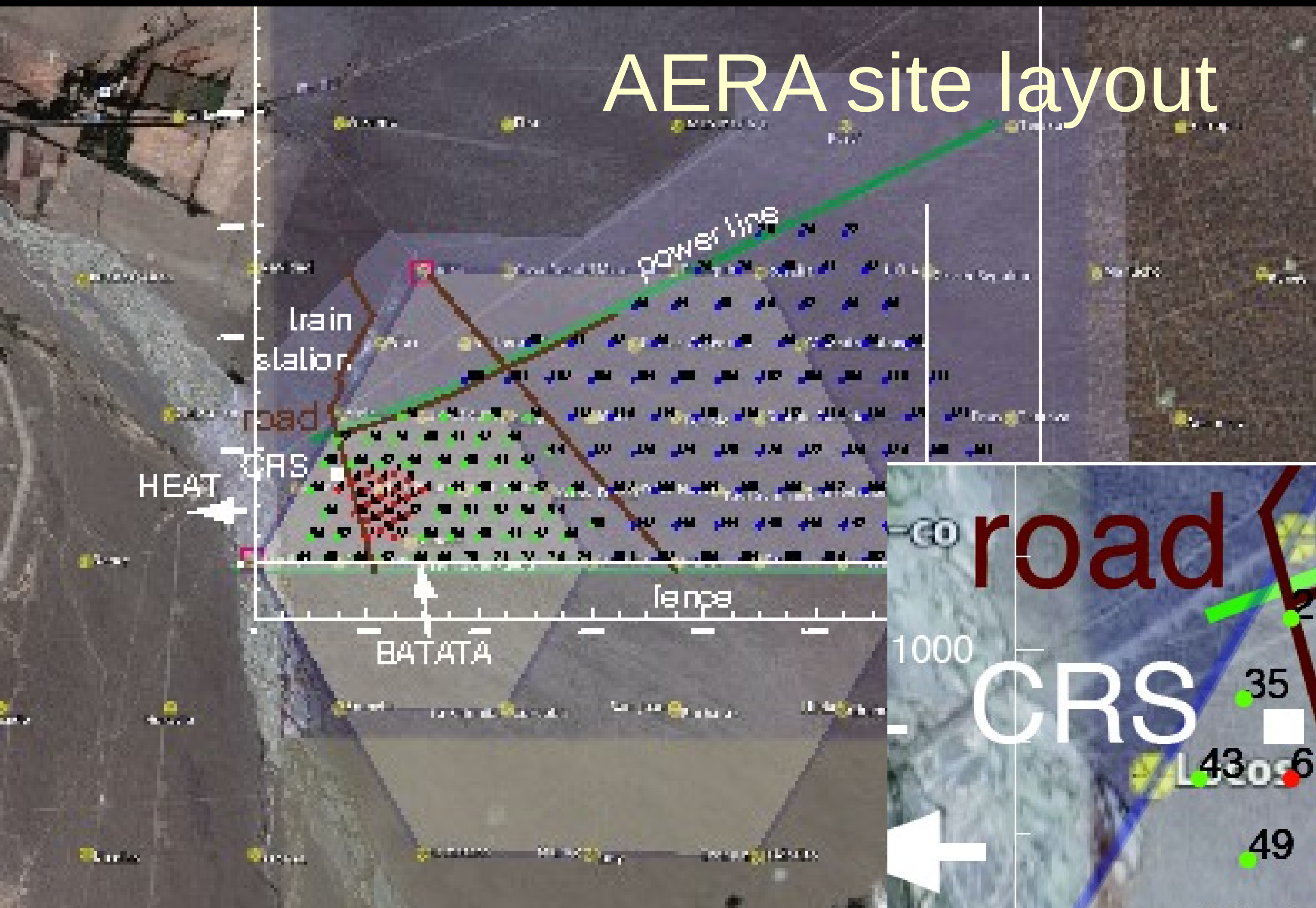
Radio Auger: Phase 2

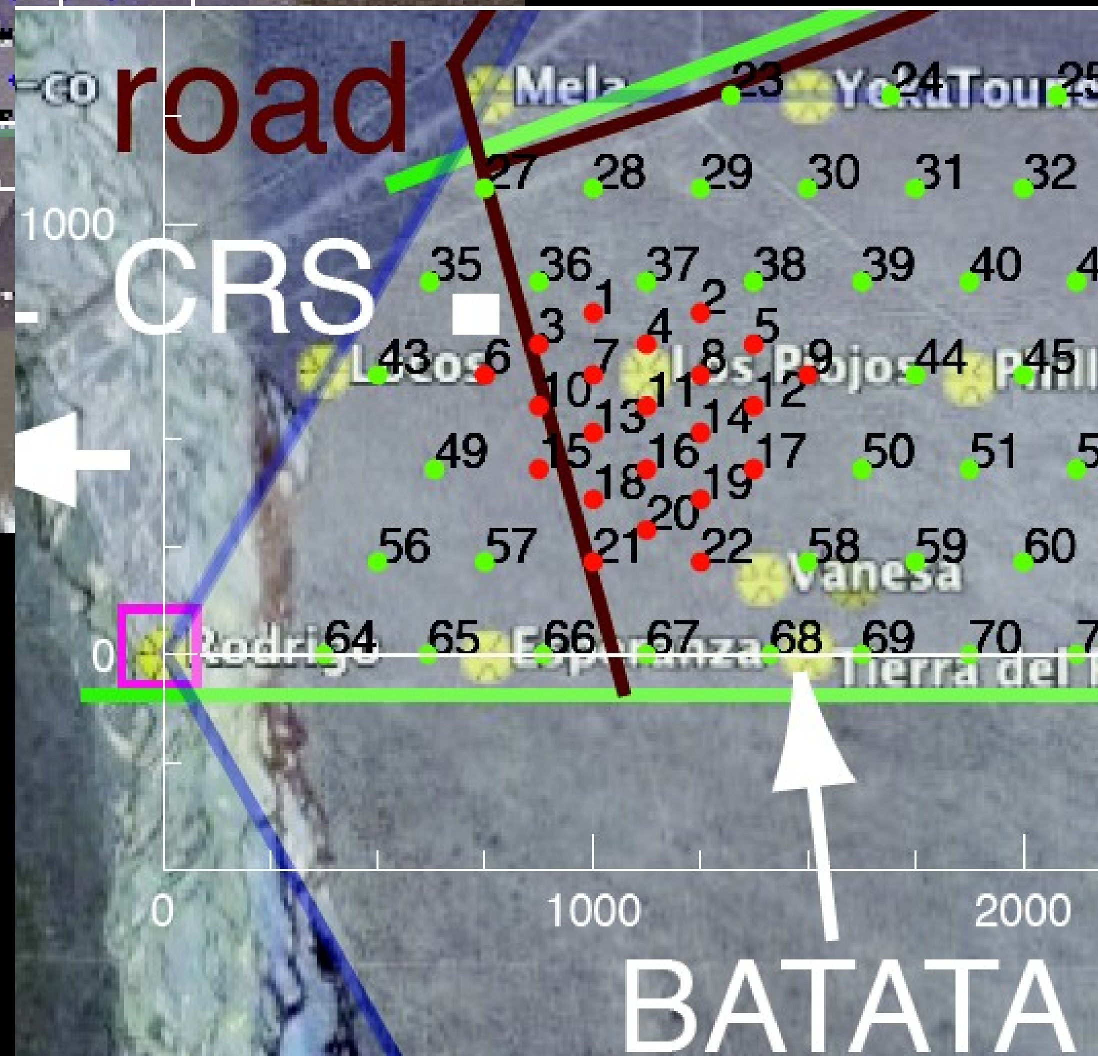
- Phase 1a (2007): 3 double-pol. antenna, baseline ~ 100 m, hardware and trigger problems
- Phase 1b (2008): up to 10 antenna, baseline ~ 400 m, advanced hardware and trigger strategies
- Phase 2 (>2009): ~ 140 antenna, 20 km² baseline ~ 150-380 m, self-trigger, autonomous detector, enhancement area close to Coihueco (AMIGA, HEAT)

autonomous radio detection (at $E>10^{18}$ eV)

super-hybrid detector (surface, fluorescence, radio)

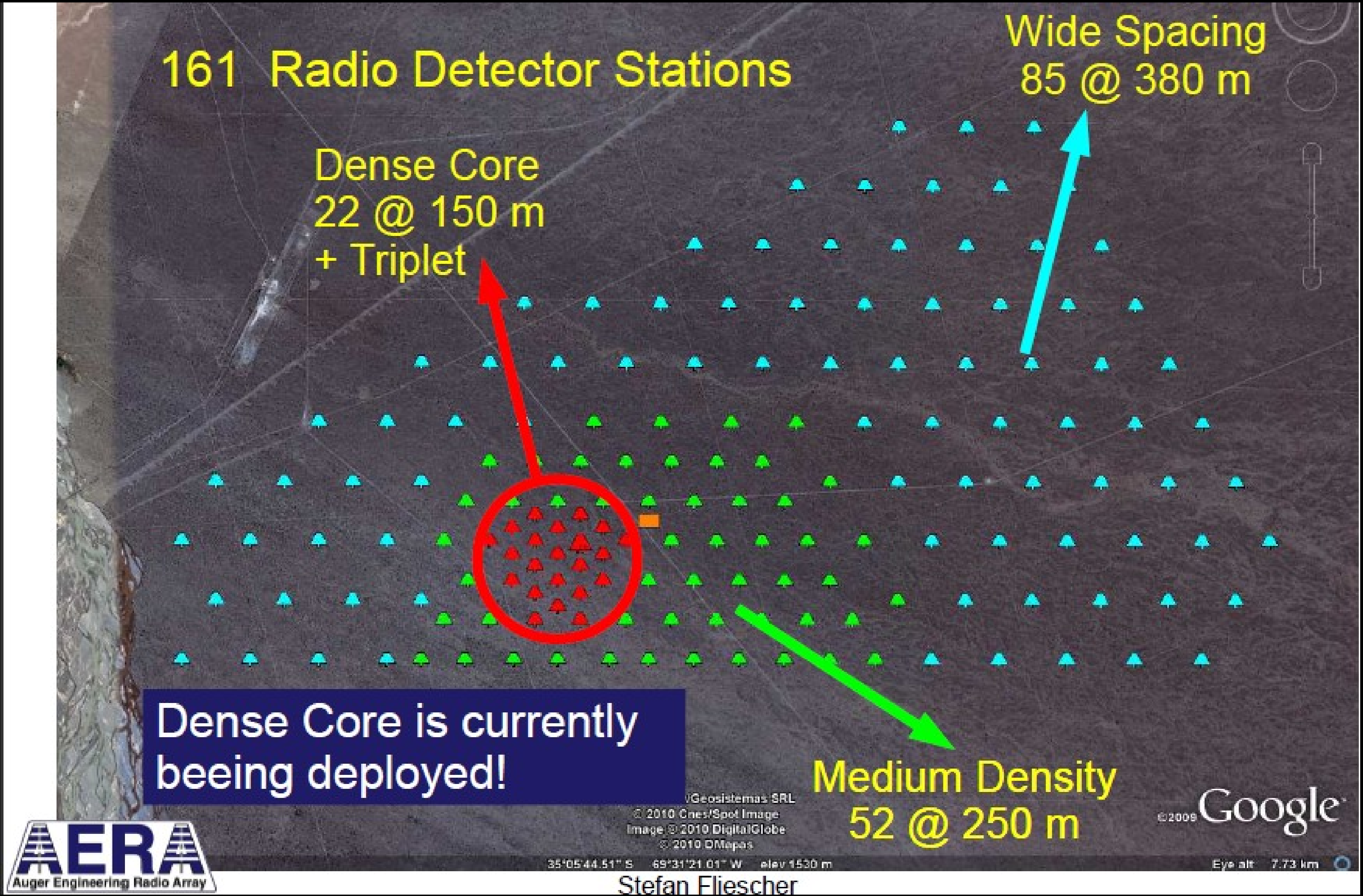
AERA site layout



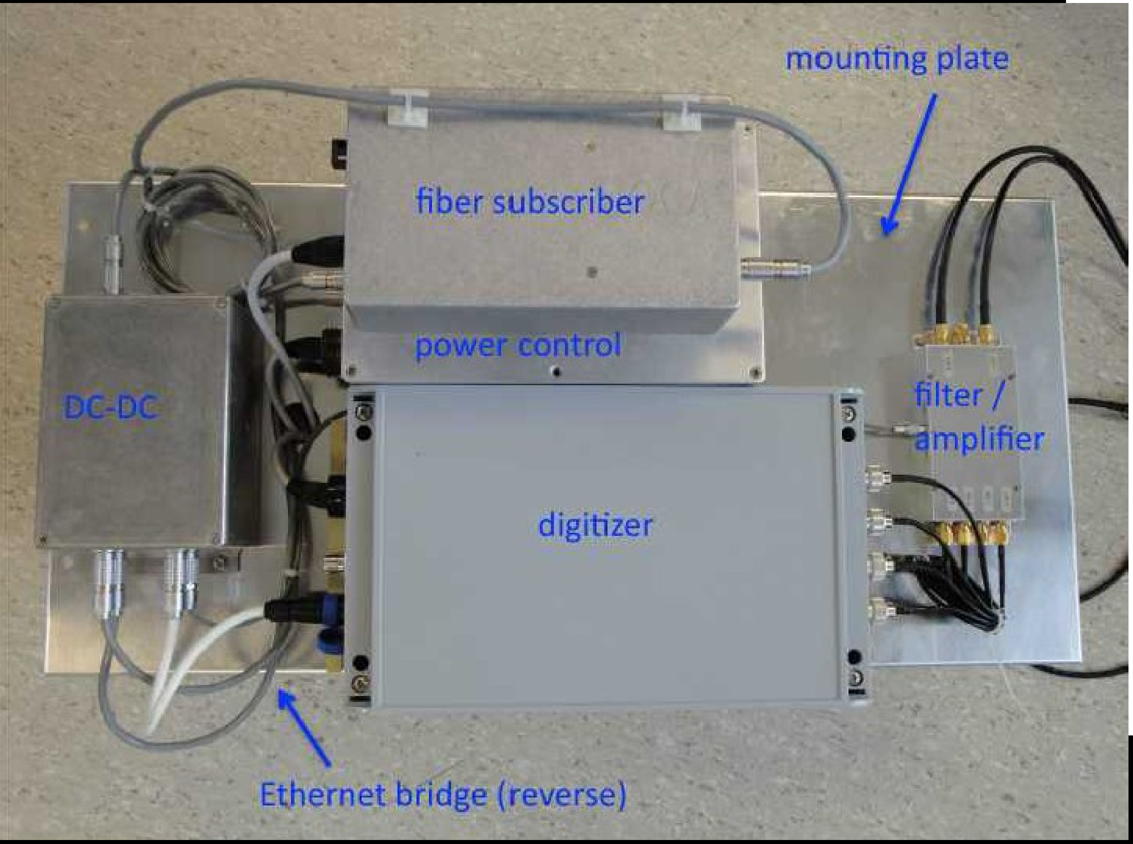


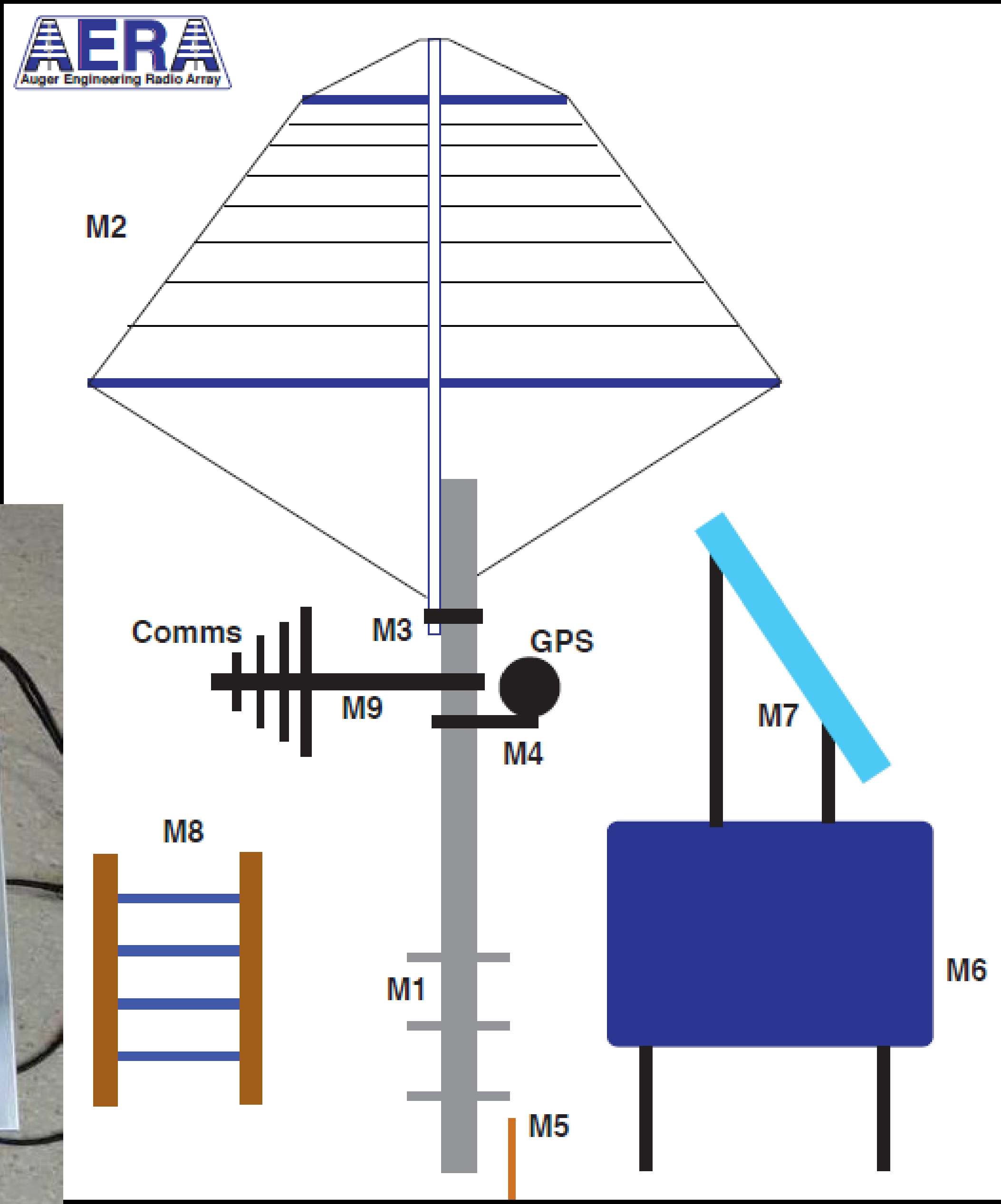
Co-located with Auger enhancements:

- HEAT
- AMIGA (Infill)


161 Radio Detector Stations
Wide Spacing
85 @ 380 m
Dense Core
22 @ 150 m
+ Triplet
Dense Core is currently
beeing deployed!
Medium Density
52 @ 250 m
Google
AERA
Auger Engineering Radio Array
Stefan Fliescher

- LPDA Antenna
- GPS-Antenna
- Comm-Antenna
- Solar Panels
- Electronic Box





Test of Antennas at Nancay

Antenna Test:

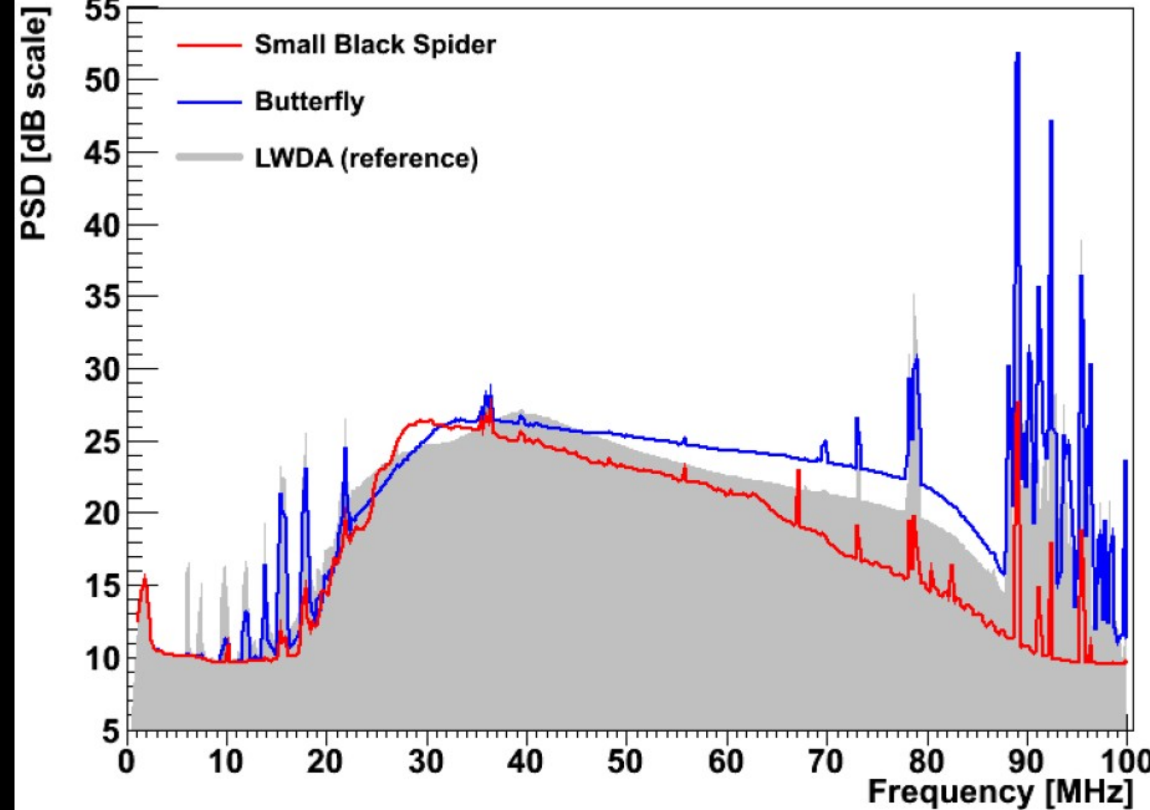
- Galaxy visible ?
- Variation of galactic signal with time ?
- Intermodulation ?

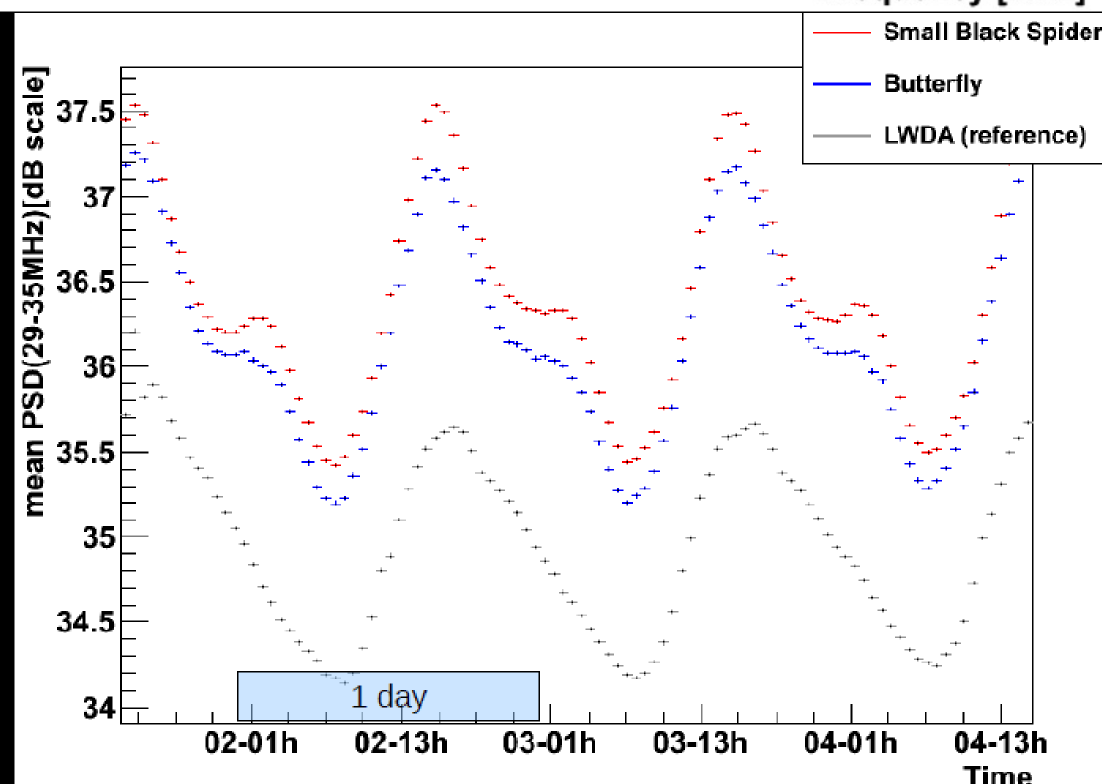
Test bench with:

- Small Black Spider
- Butterfly
- LWDA

Test of Antennas at Nancay

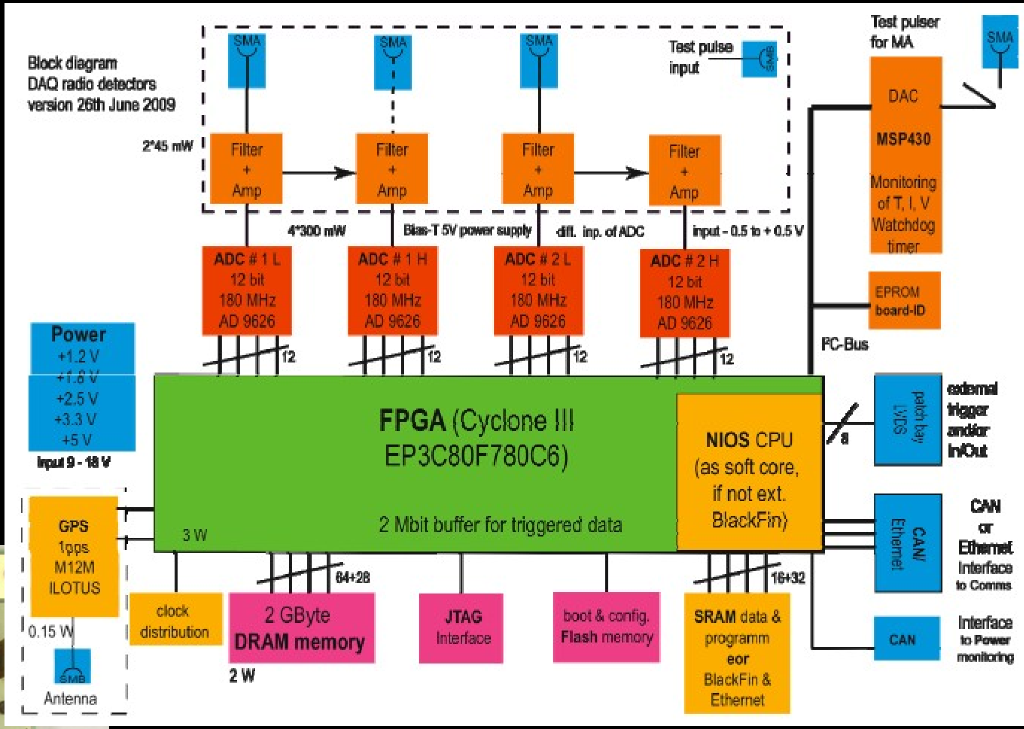
- Broad Band: ~28 to ~80 MHz
- Galactic Back-Ground clearly visible

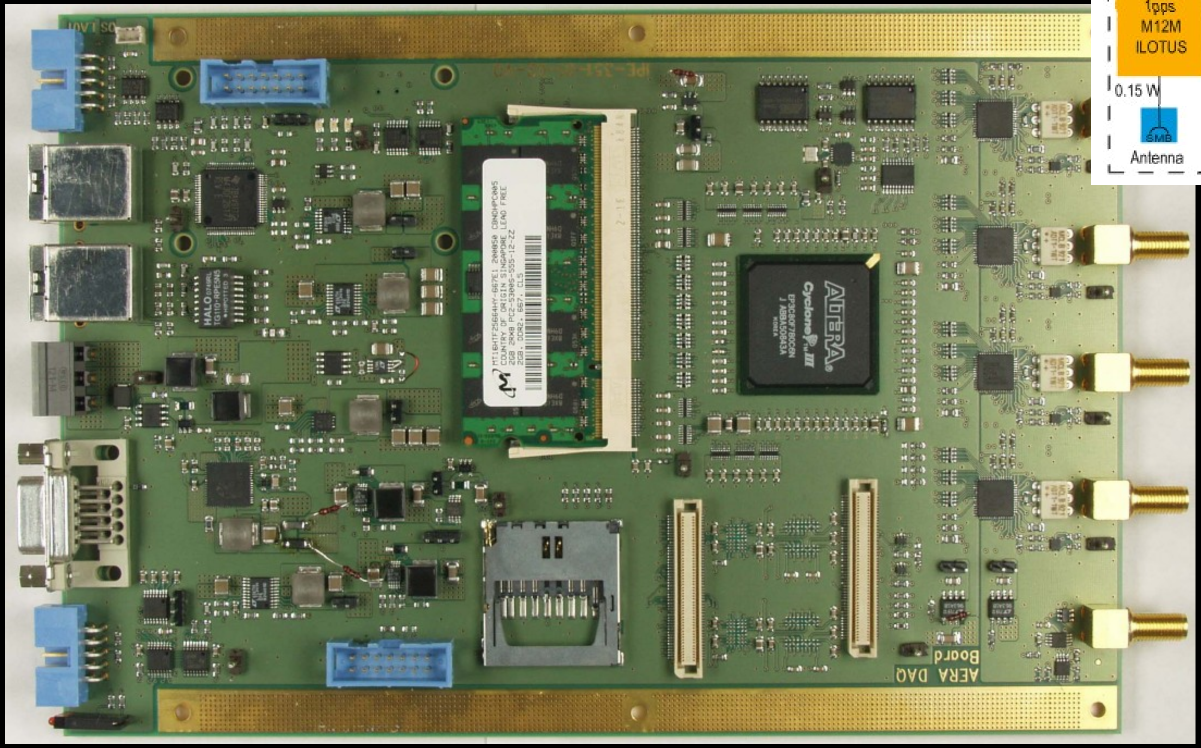




Digital Front-End Cards

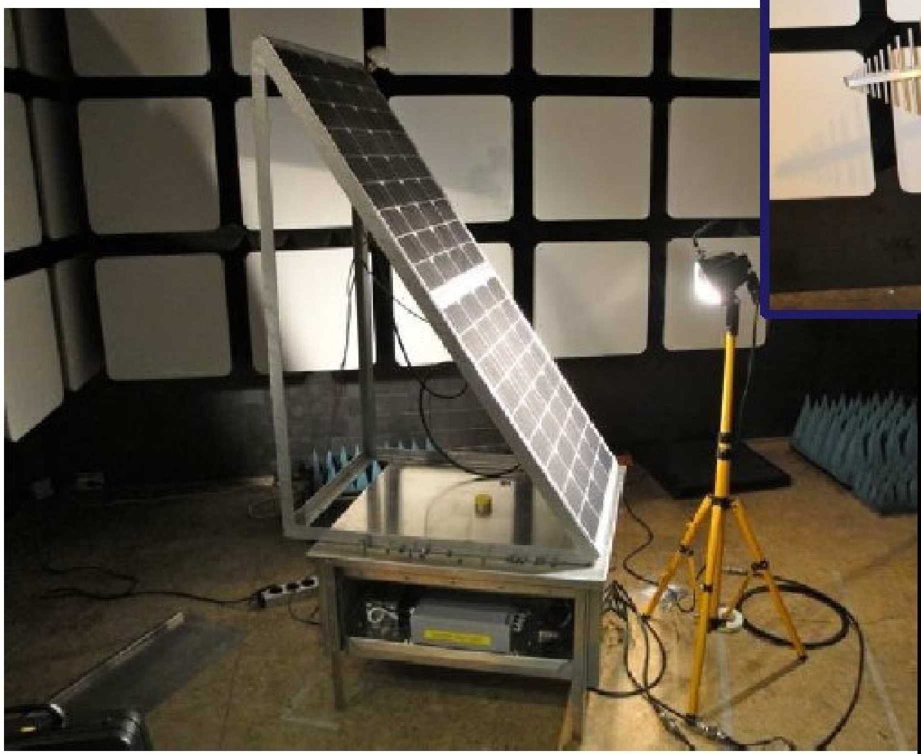
- Cyclone FPGA
- Soft-Core NIOS
- Lot's of communications
- 2 high/low gain channels





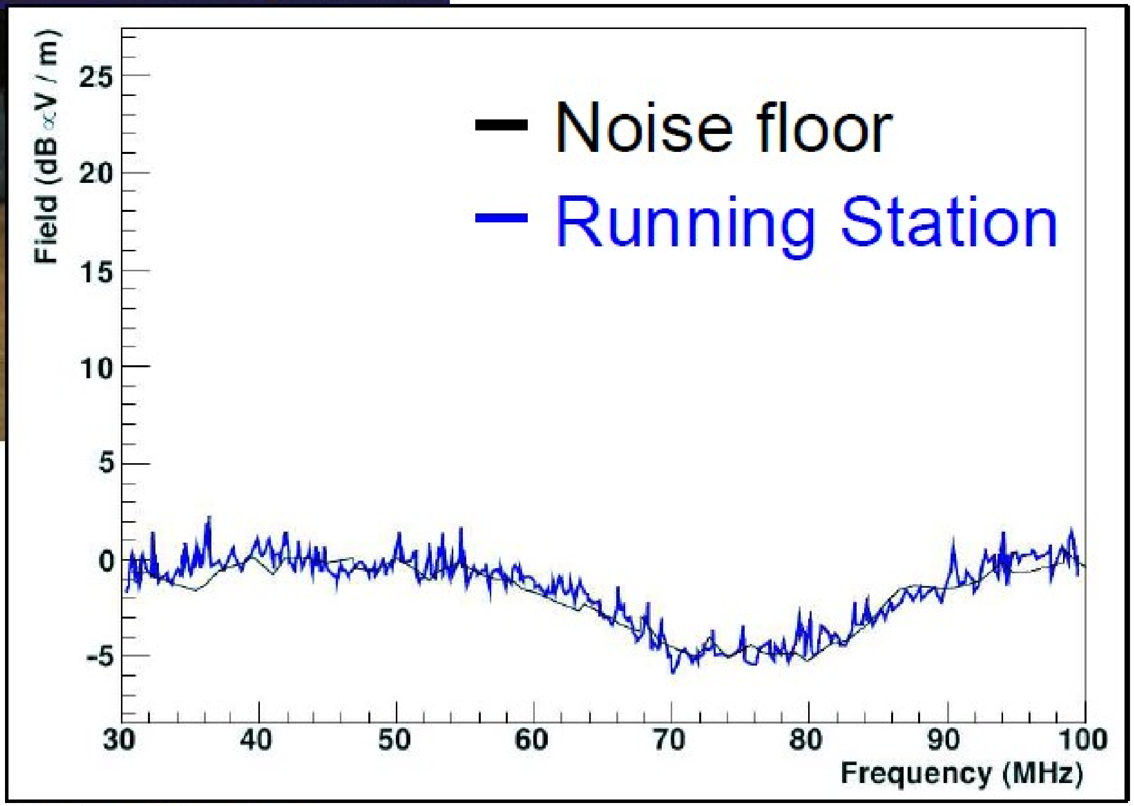
Test of Assembled Hardware Components

EMC Testing Chamber



'Radio Quietness' of the hardware:

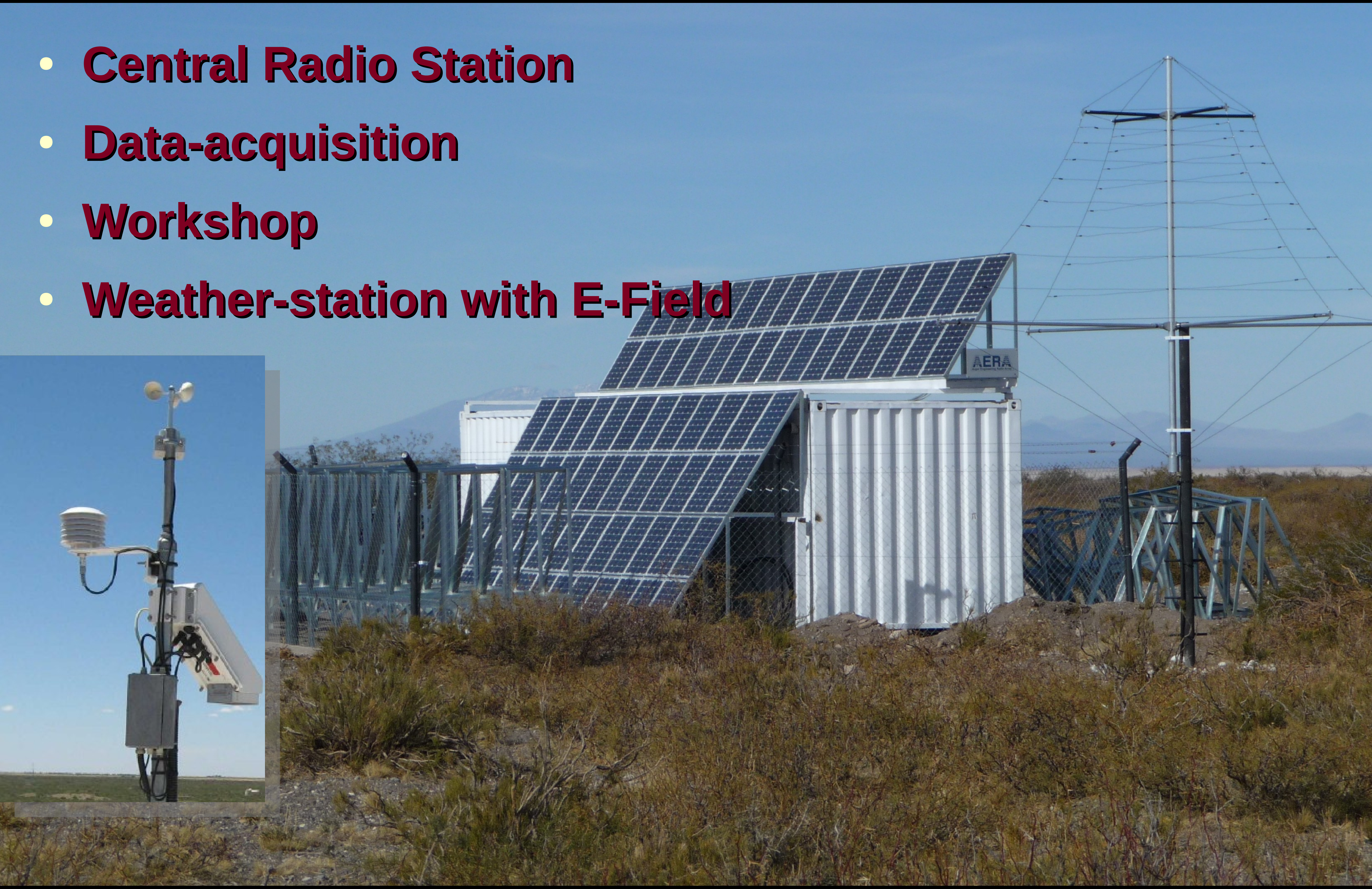
- Shielded box
- Carefully selected items



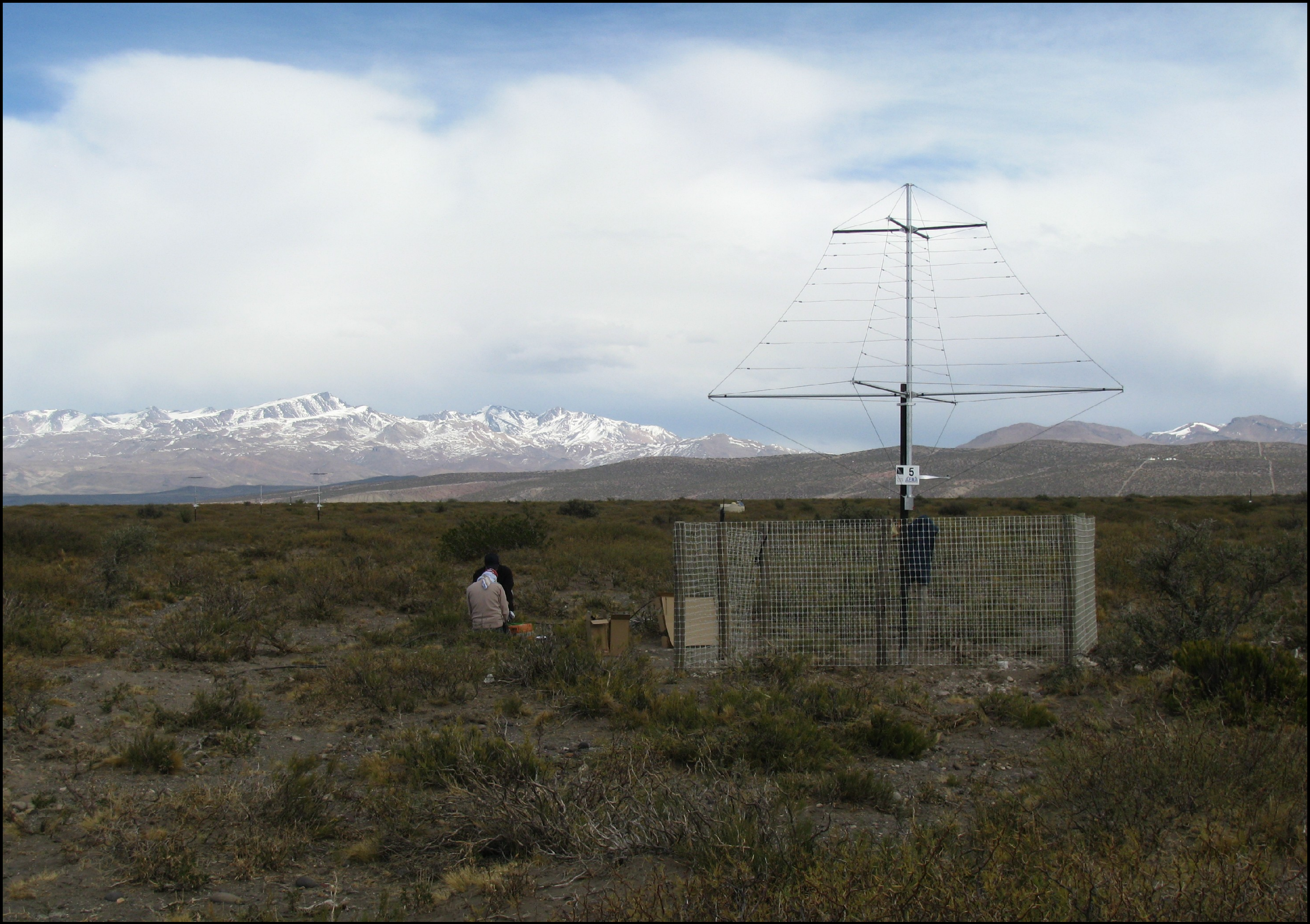
Stefan Fliescher

AERA
Auger Engineering Radio Array

- **Central Radio Station**
- **Data-acquisition**
- **Workshop**
- **Weather-station with E-Field**



- **Communication for first 25 Station via fibre**


5

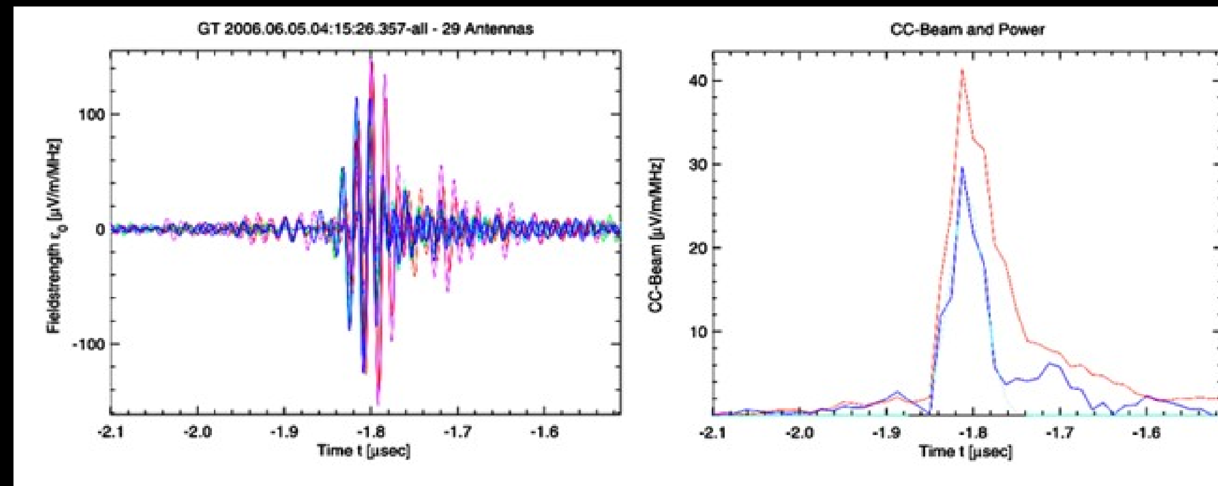
Antenna installation finished

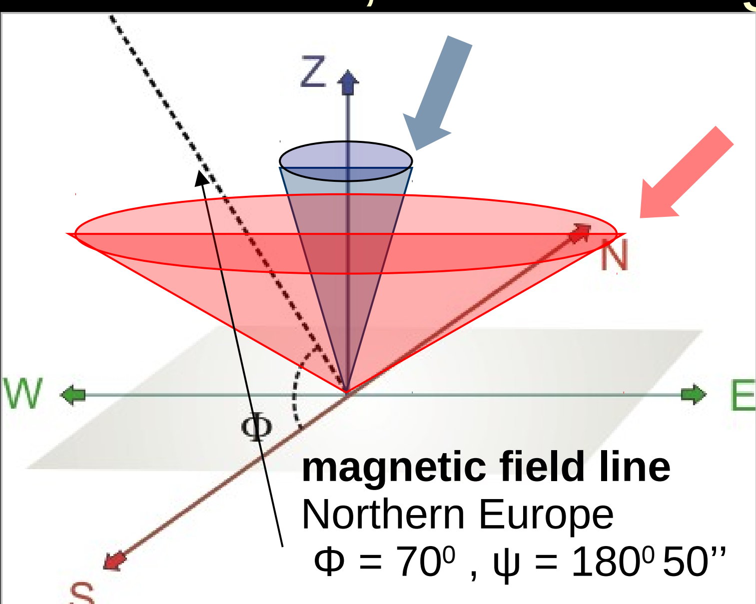
Summary

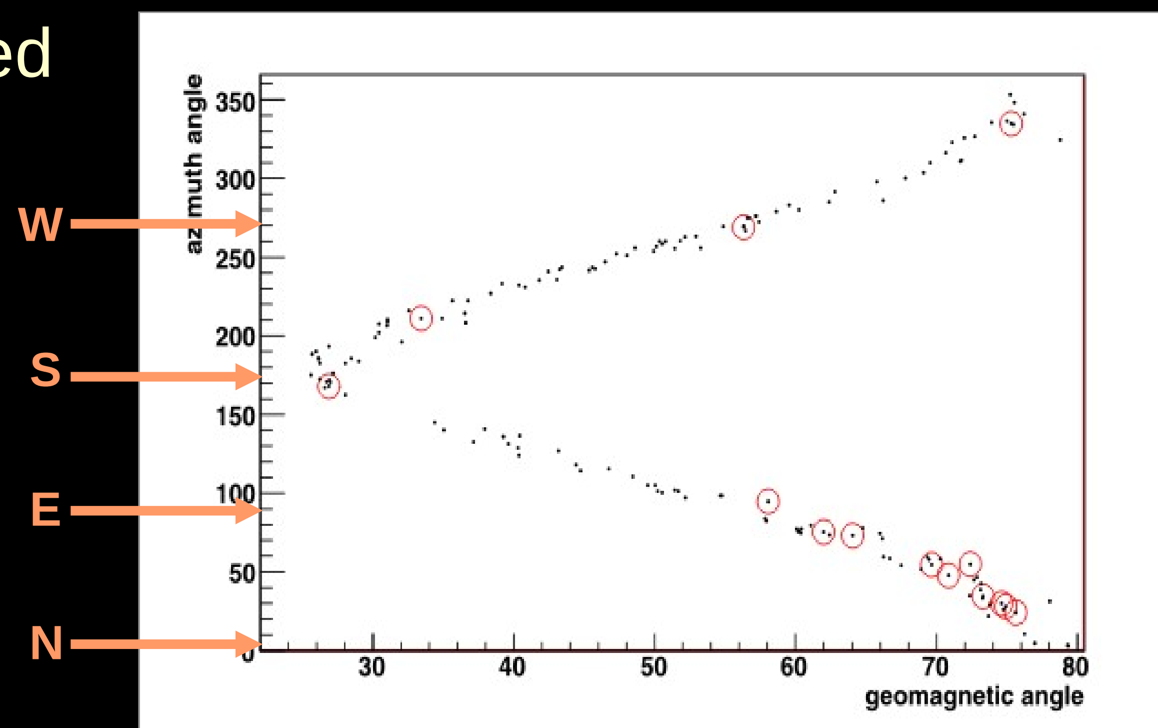
- Radio-emission of extended air shower described by geo-synchrotron effect
- LOPES-measurements to understand general amplitude-dependence, LDF and polarisation
- Auger started R&D in radio-quite Pampa Amarilla, measure at $E>10^{18}$ eV, super-hybrid
- Need intelligent self-trigger
- Construction for 20 km² array with ~160 antenna ongoing
- First 25 Stations ready

LOPES-30 EW polarised

- Jan-Jul 2006
- High energy, $N_{\mu}>10^5$
- High inclination, $\theta > 50°$
- beam-forming
- KASCADE-Grande reconstruction (316 events)
- 161 well radio-reconstructed
- 14 clear, coherent signals







Transient background

- Power-line producing Spikes?