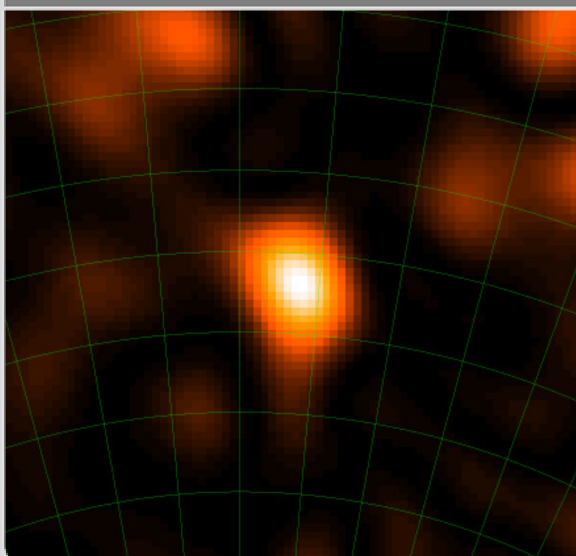
The LOPES experiment – recent results, status and perspectives

Tim Huege (KIT) for The LOPES Collaboration



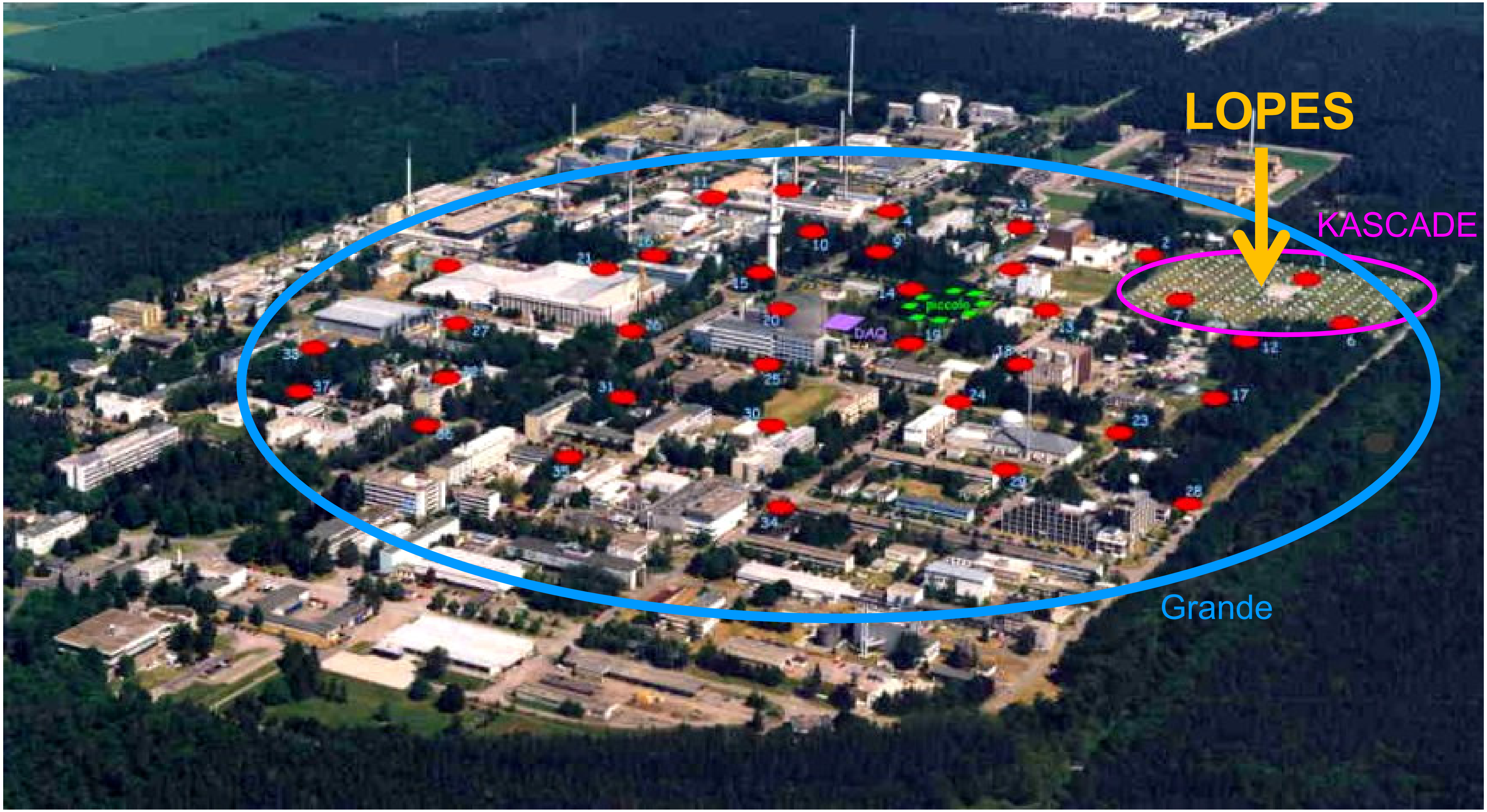
KIT – University of the State of Baden-Wuerttemberg and
National Research Center of the Helmholtz Association

www.lopes-project.org

The LOPES experiment

- digital radio interferometer measuring in the 40-80 MHz frequency window
- integrated with KASCADE-Grande experiment
  - provides the trigger for LOPES
  - provides the air shower geometry (core, direction)
  - provides high-quality per-event air shower parameters (N_e, N_μ, …) for study of radio emission systematics
- effective energy range ~$10^{16.7}$ eV to ~10^{18} eV

LOPES at KIT Campus North



The LOPES Collaboration

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LOPES
RADIO EMISSION FROM COSMIC RAY AIR SHOWERS

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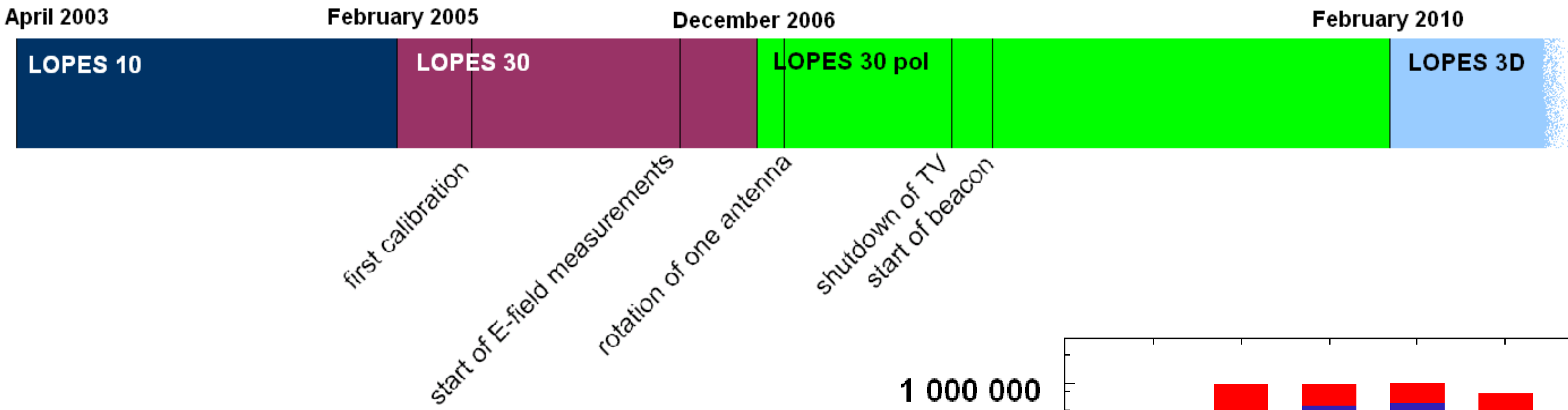
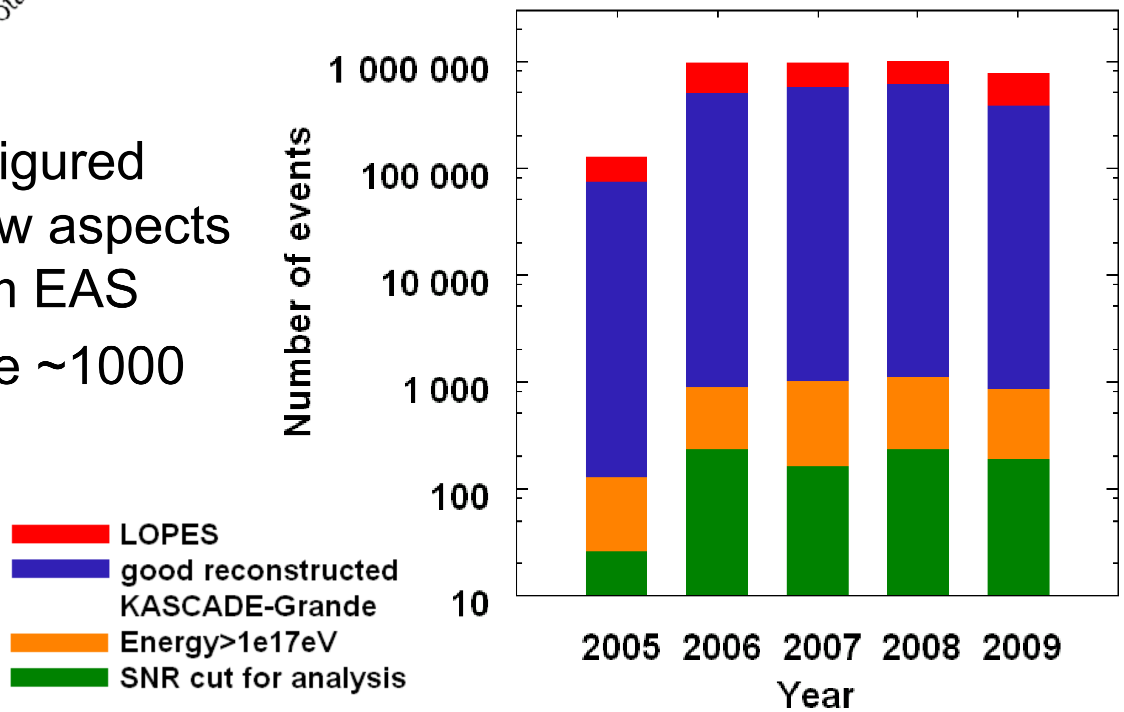
LOPES – an ever-evolving experiment

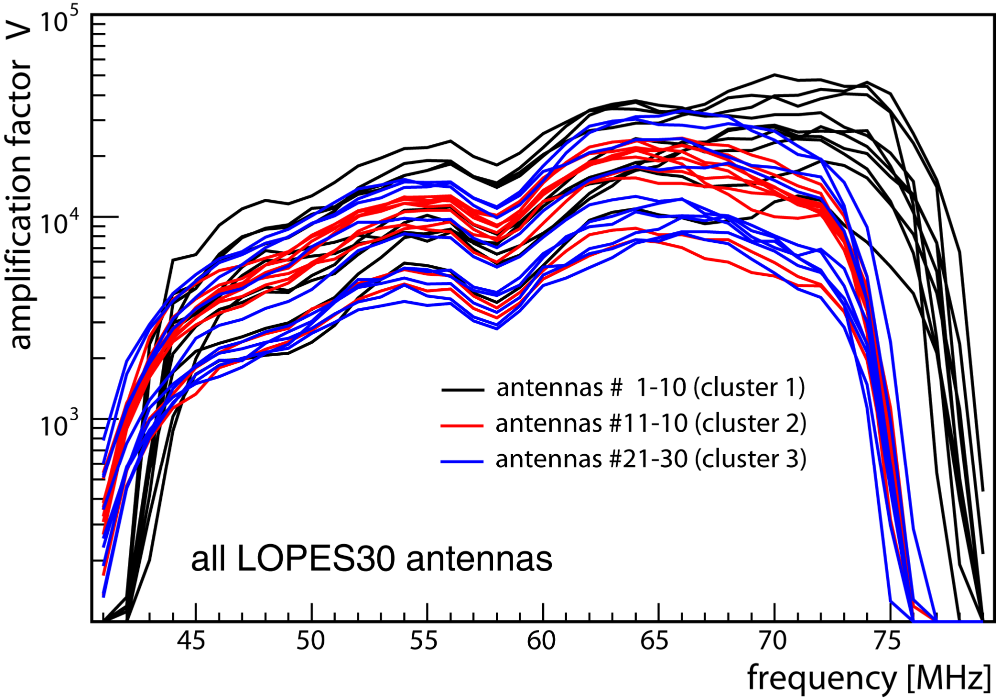


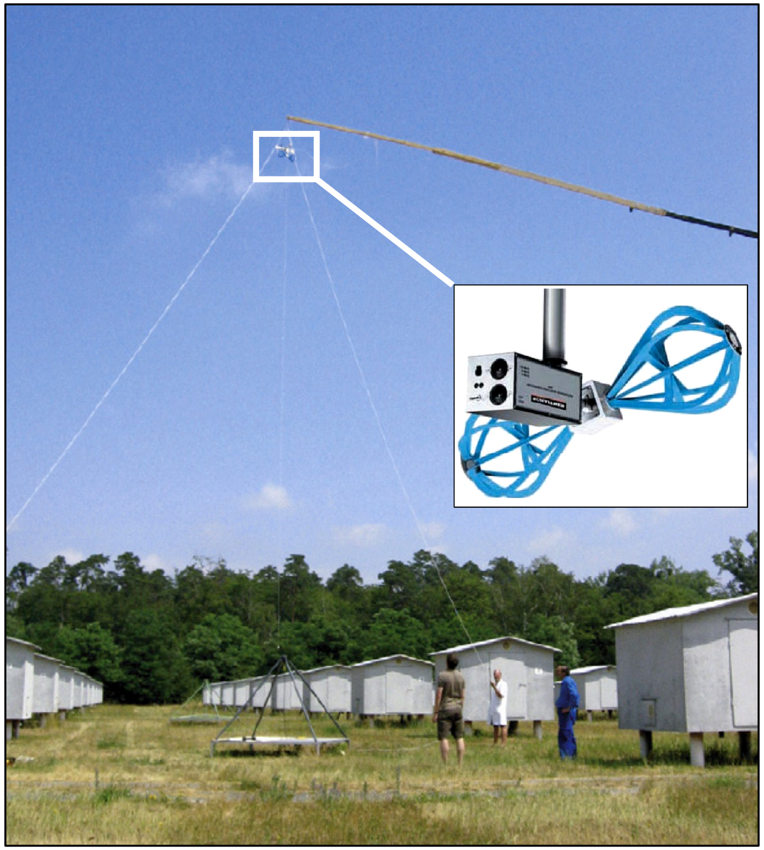
- LOPES has been re-configured several times to study new aspects of the radio emission from EAS
- after quality cuts, we have ~1000 events for analysis
- noisy environment requires sophisticated analysis procedure



The LOPES analysis pipeline

1. Amplitude calibration (absolute since LOPES 30)
   - absolute calibration of all 30 channels with an external reference source
   - systematic uncertainty 20% in power
   - good stability (~13%) over 2 years



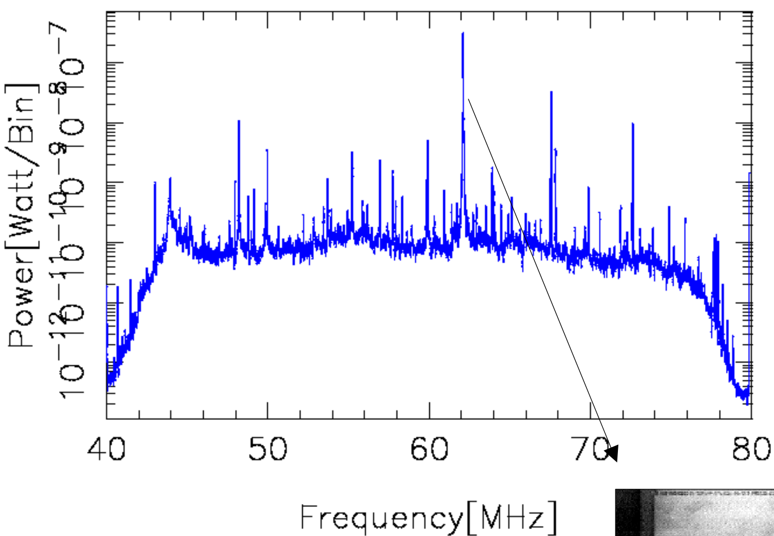


S. Nehls et al., NIM A 2008

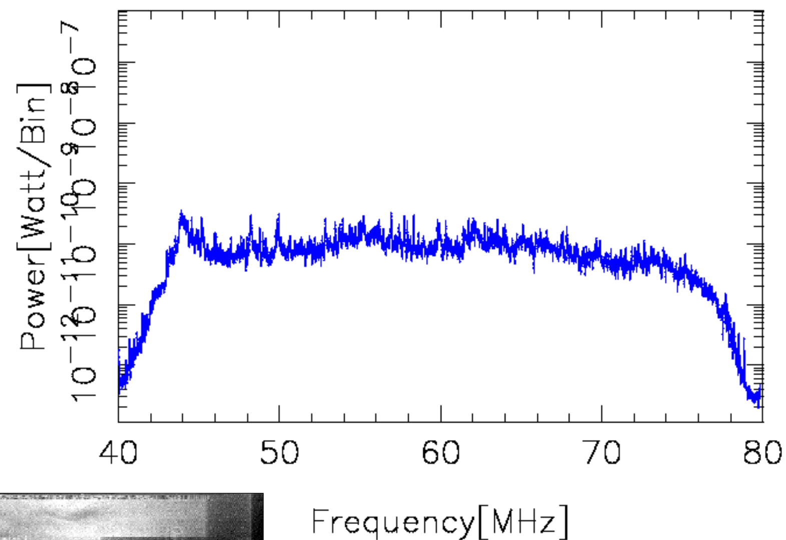
The LOPES analysis pipeline

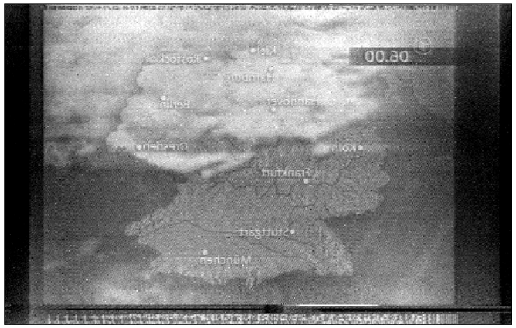
1. Amplitude calibration (absolute since LOPES 30)
2. Digital filtering of narrow-band radio frequency interference

before



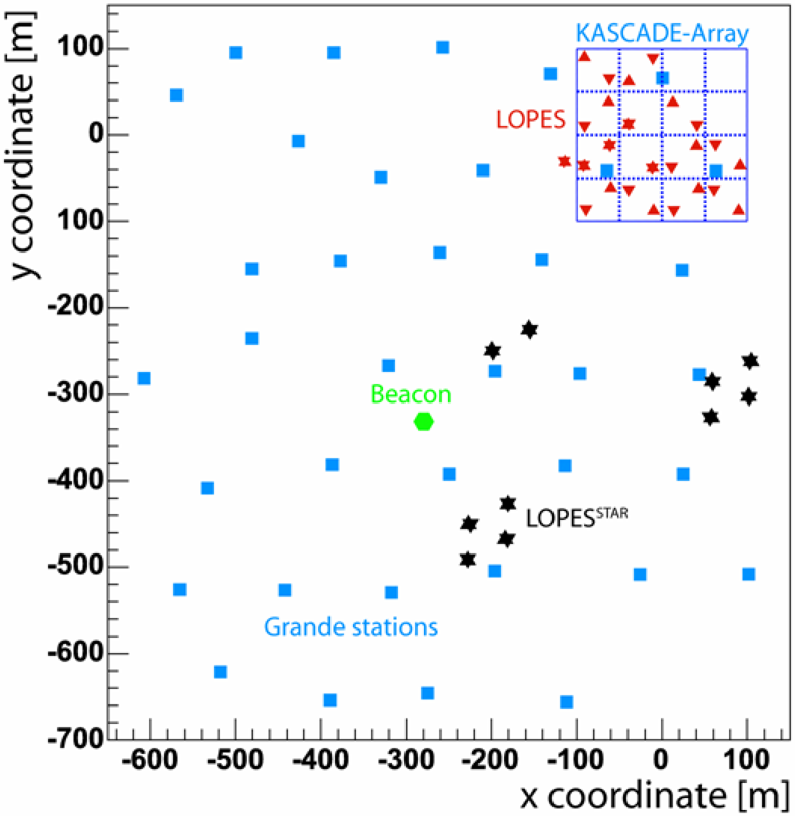
after





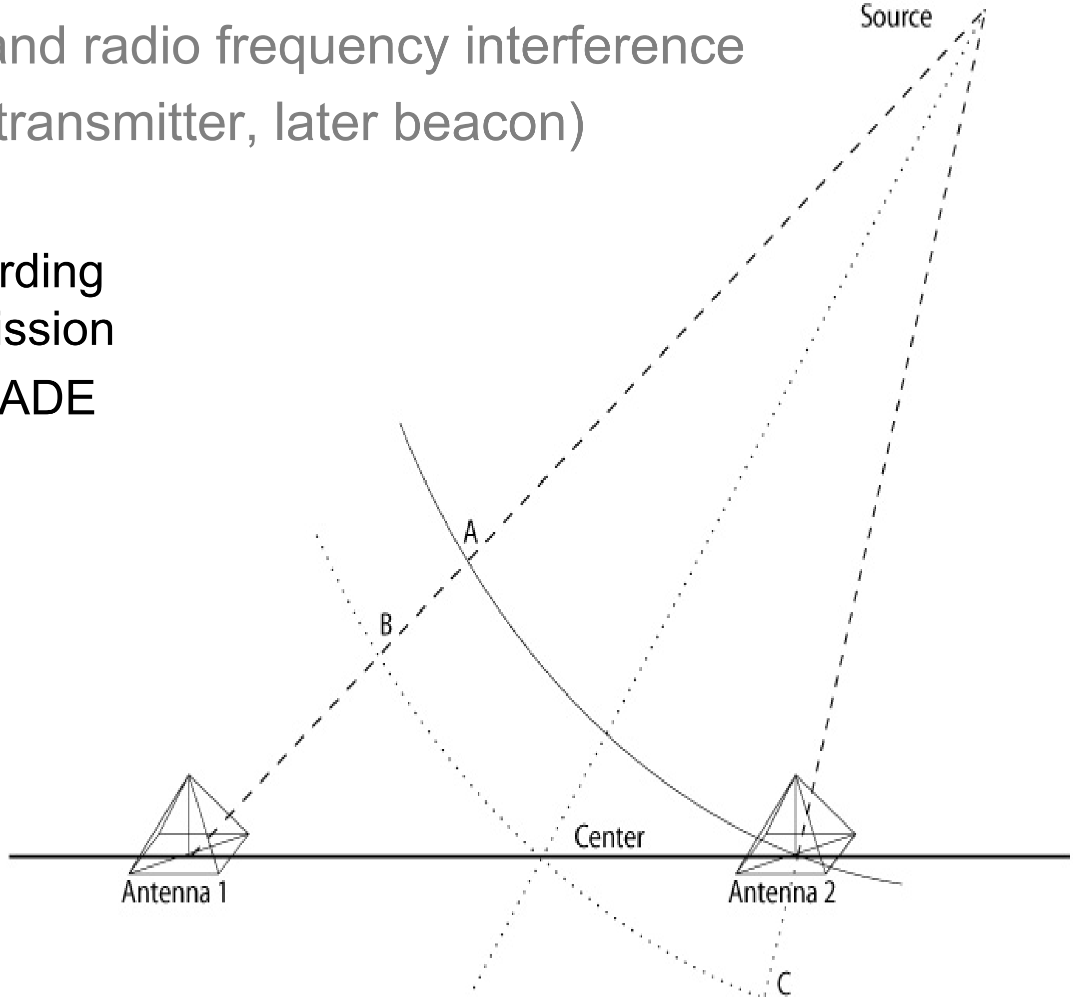
The LOPES analysis pipeline

1. Amplitude calibration (absolute since LOPES 30)
2. Digital filtering of narrow-band radio frequency interference
3. Time calibration (using TV transmitter, later beacon)
   - need very good time resolution for interferometry
   - using beacon transmitter, we achieve ~1 ns time resolution: F. Schröder et al., NIM A 2010



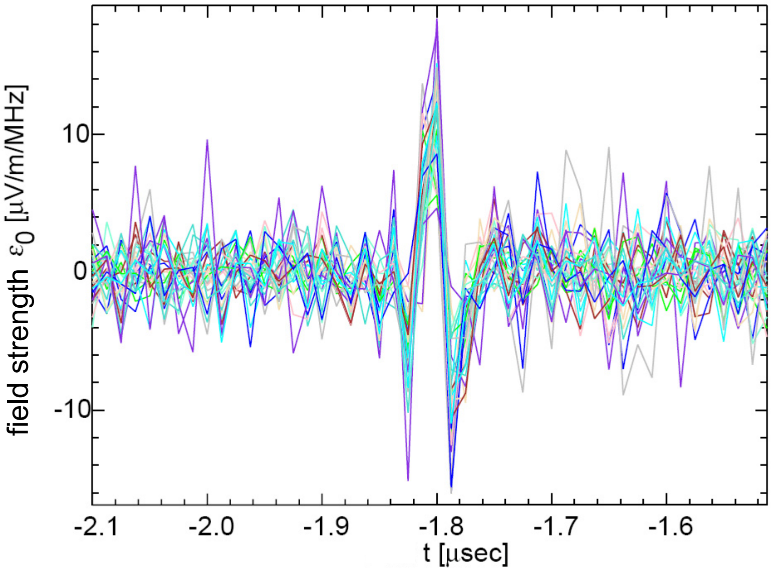
The LOPES analysis pipeline

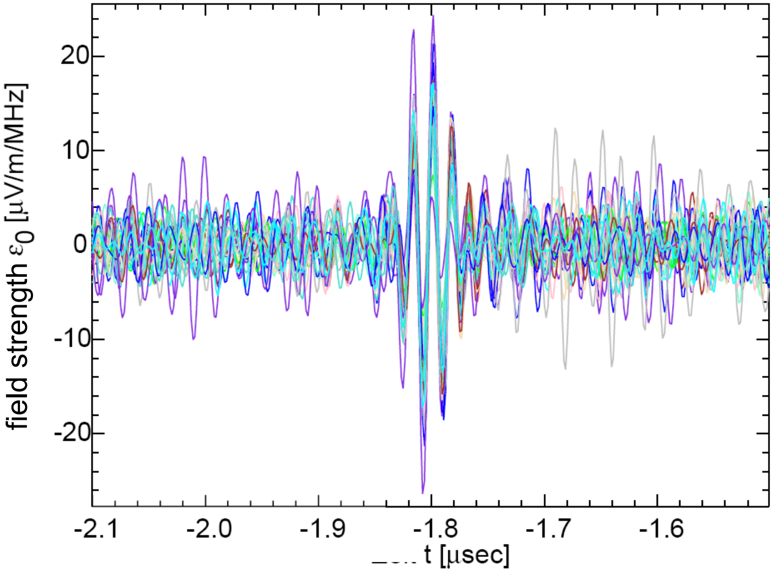
1. Amplitude calibration (absolute since LOPES 30)
2. Digital filtering of narrow-band radio frequency interference
3. Time calibration (using TV transmitter, later beacon)
4. Digital beam-forming
   - align antenna traces according to arrival time of radio emission
   - in first iteration use KASCADE direction as starting value



The LOPES analysis pipeline

1. Amplitude calibration (absolute since LOPES 30)
2. Digital filtering of narrow-band radio frequency interference
3. Time calibration (using TV transmitter, later beacon)
4. Digital beam-forming
5. Up-sampling of 2nd Nyquist zone data
   - in addition, deconvolute instrumental dispersion from pulses

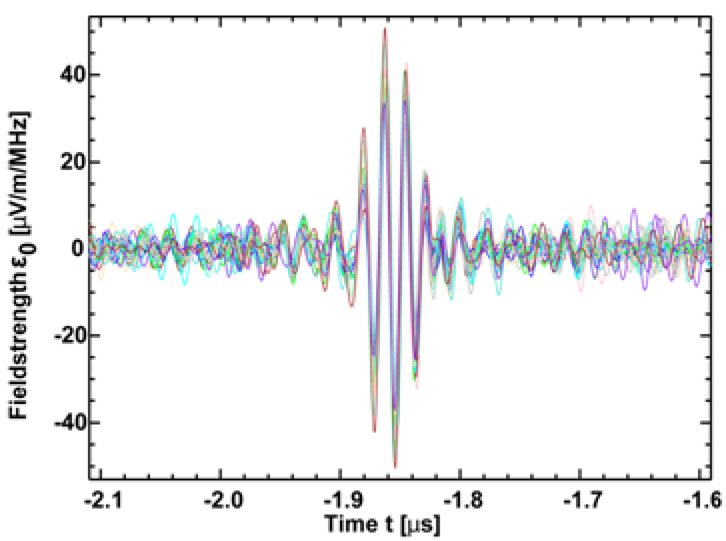


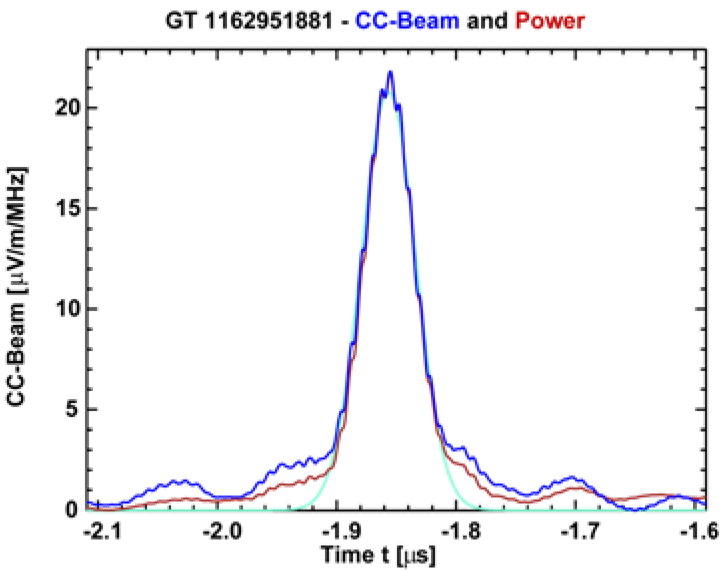


The LOPES analysis pipeline

1. Amplitude calibration (absolute since LOPES 30)
2. Digital filtering of narrow-band radio frequency interference
3. Time calibration (using TV transmitter, later beacon)
4. Digital beam-forming
5. Up-sampling of 2nd Nyquist zone data
6. Calculation of the cross-corelation beam, block-averaging and Gauss fit

$$CC(t) = \pm\sqrt{\left|\frac{1}{N_P}\sum_{i=1}^{N-1}\sum_{j>i}^{N} s_i(t)s_j(t)\right|}$$





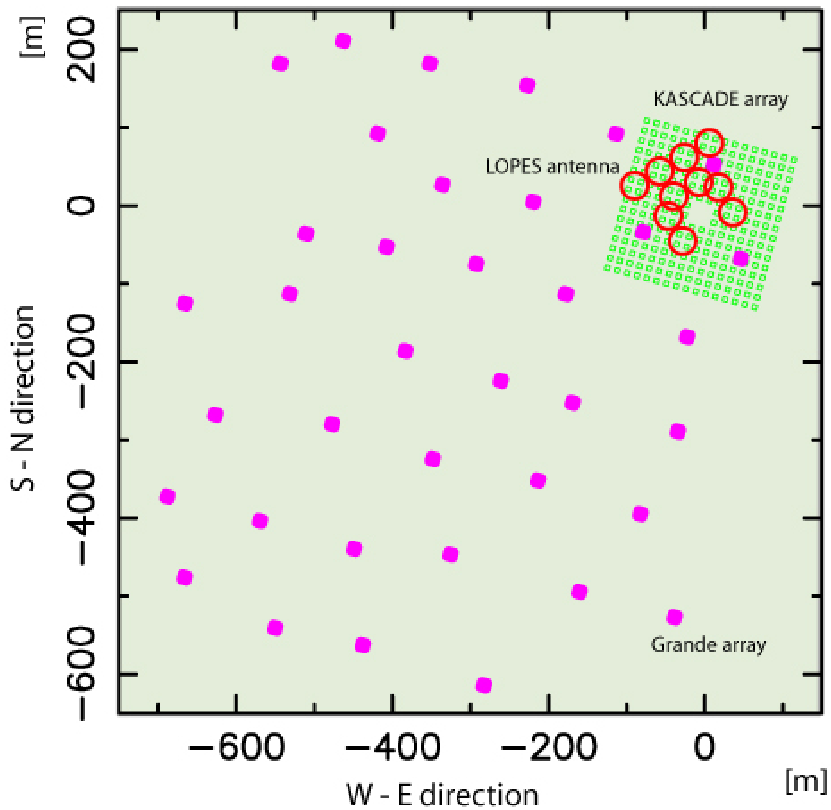
The LOPES analysis pipeline

1. Amplitude calibration (absolute since LOPES 30)
2. Digital filtering of narrow-band radio frequency interference
3. Time calibration (using TV transmitter, later beacon)
4. Digital beam-forming
5. Up-sampling of 2nd Nyquist zone data
6. Calculation of the cross-corelation beam, block-averaging and Gauss fit
7. Determination of radio pulse parameters
   - low S/N ratio: pulse height of block-averaged CC-beam
   - high S/N ratio: also pulse heights in individual antennas
8. Correlation of events with thunderstorm data
9. Application of quality cuts

LOPES 10

April 2003 | February 2005 | December 2006 | February 2010

LOPES 10 | LOPES 30 | LOPES 30 pol | LOPES 3D



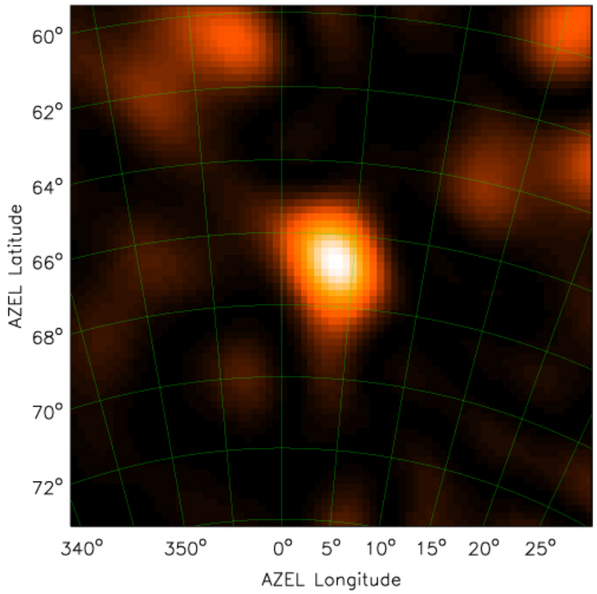
- 10 inverted-V dipole antennas
- east-west polarisation only

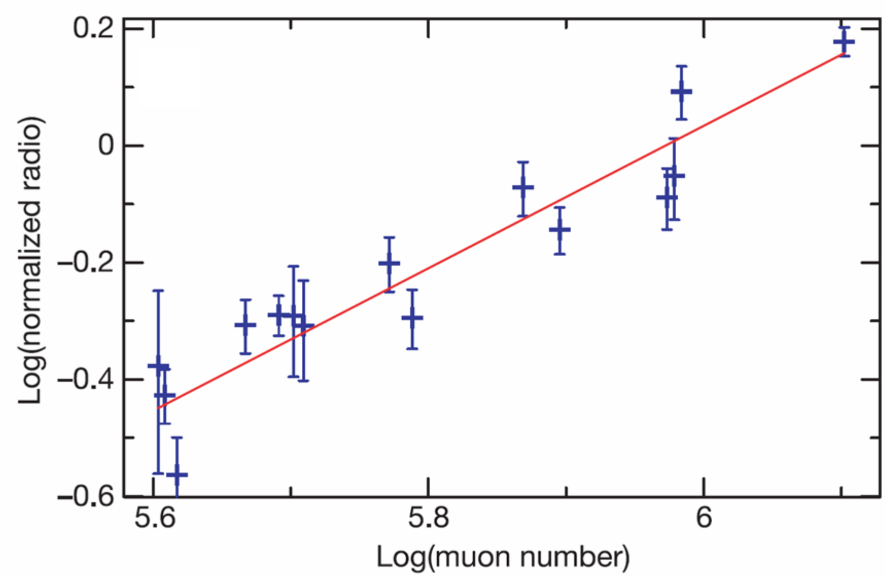
LOPES 10 proof of principle

April 2003 | February 2005 | December 2006 | February 2010

LOPES 10 | LOPES 30 | LOPES 30 pol | LOPES 3D

- H. Falcke et al. (The LOPES Collaboration), Nature 2005
  - successful coincident radio detection with KASCADE
  - confirm geomagnetic origin of radio signal
  - confirm coherent energy scaling of radio signal



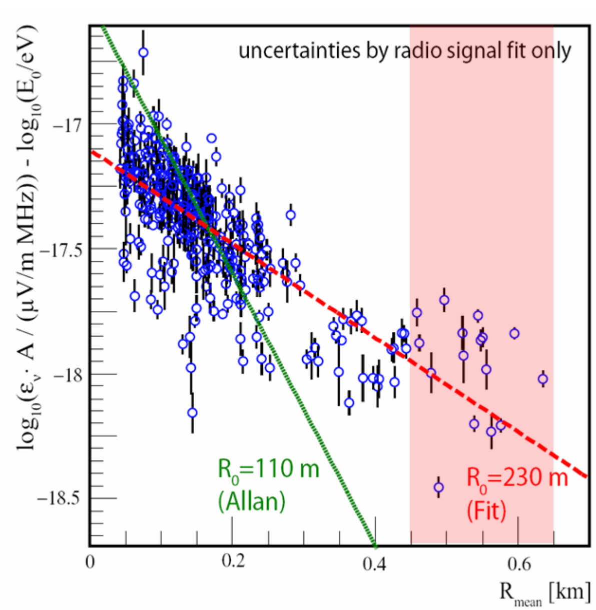


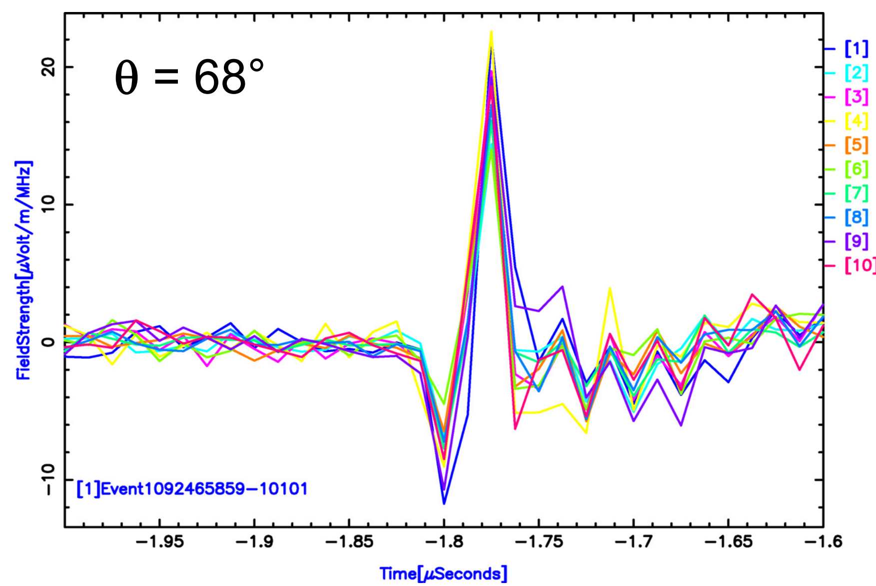
Further LOPES 10 results

April 2003 | February 2005 | December 2006 | February 2010

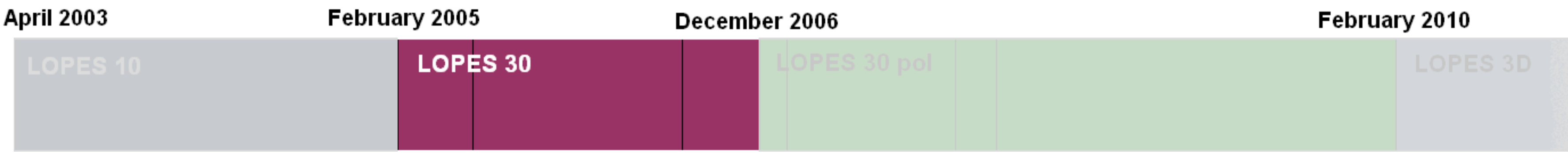
LOPES 10 | LOPES 30 | LOPES 30 pol | LOPES 3D

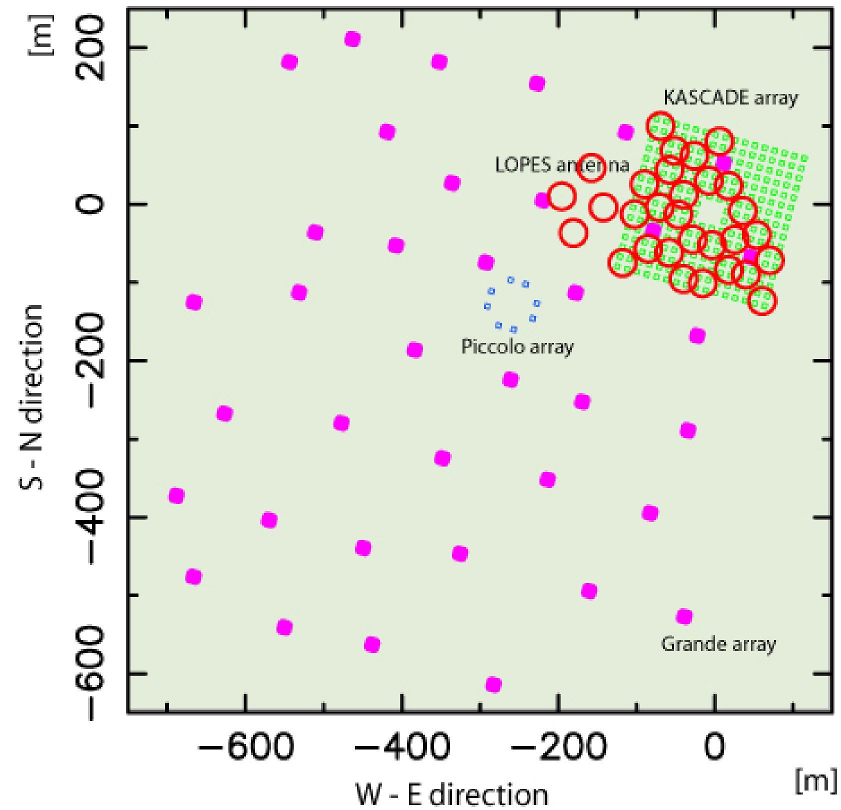
- W.D. Apel et al. (The LOPES Collaboration), Astroparticle Physics 2006
  - see events at >500 m lateral distance for E>10^{17} eV
  - exponential lateral distribution over multiple events: R_0 ~ 230 m
- J. Petrovic et al. (The LOPES Collaboration), Astronomy & Astrophysics 2007
  - LOPES sees very inclined air showers up to θ = 80° well – cf. talk Alexandra Saftoiu





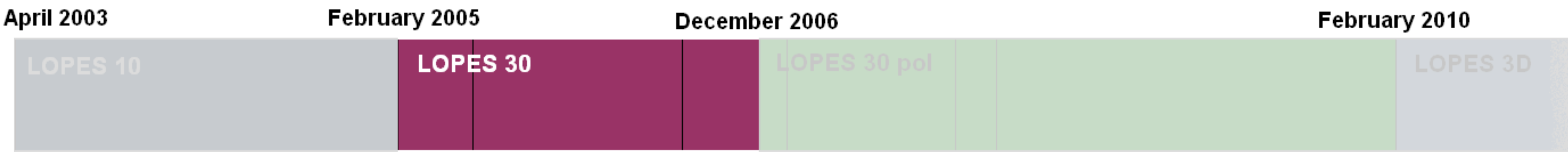
LOPES 30



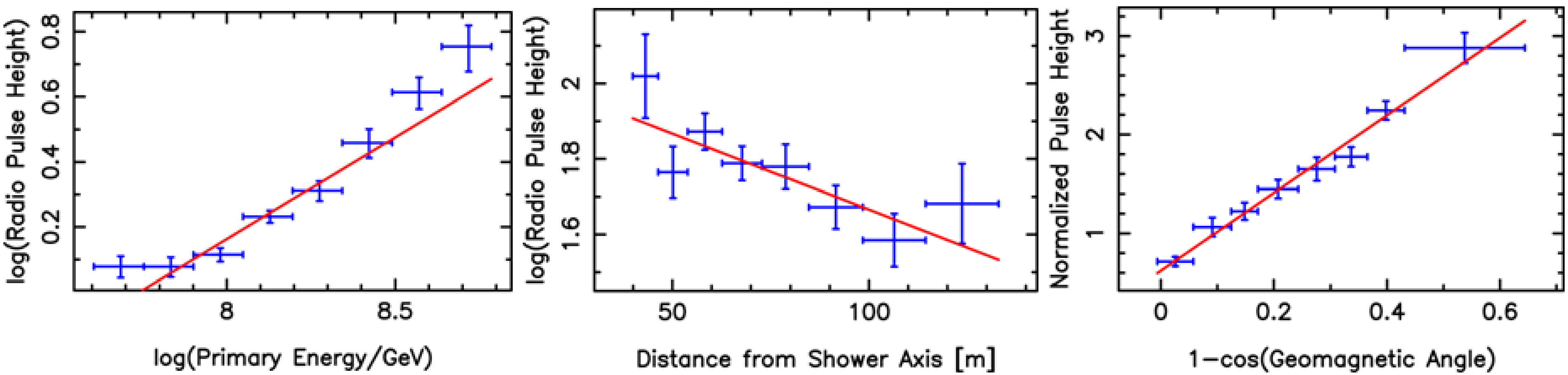


- 30 inverted-V dipole antennas
- east-west polarisation only
- absolute calibration (external source)
- monitoring of atmospheric E-field

Major LOPES 30 results



- A. Horneffer et al. (The LOPES Collaboration), ICRC 2007
  - parameterization of east-west signal (energy, distance, geomagnetic angle)



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

[µV / m MHz]

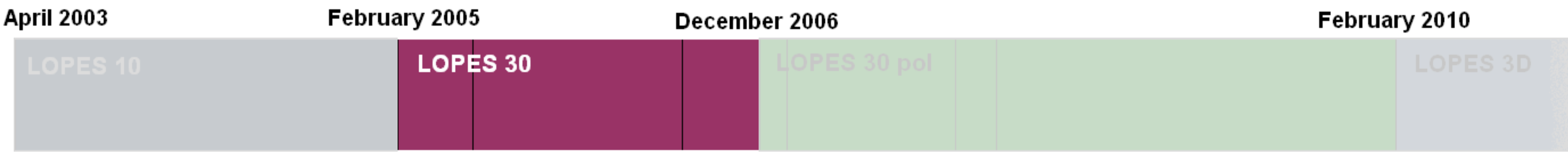
$A = 10.9 \pm 1.1$

$B = 1.16 \pm 0.02$

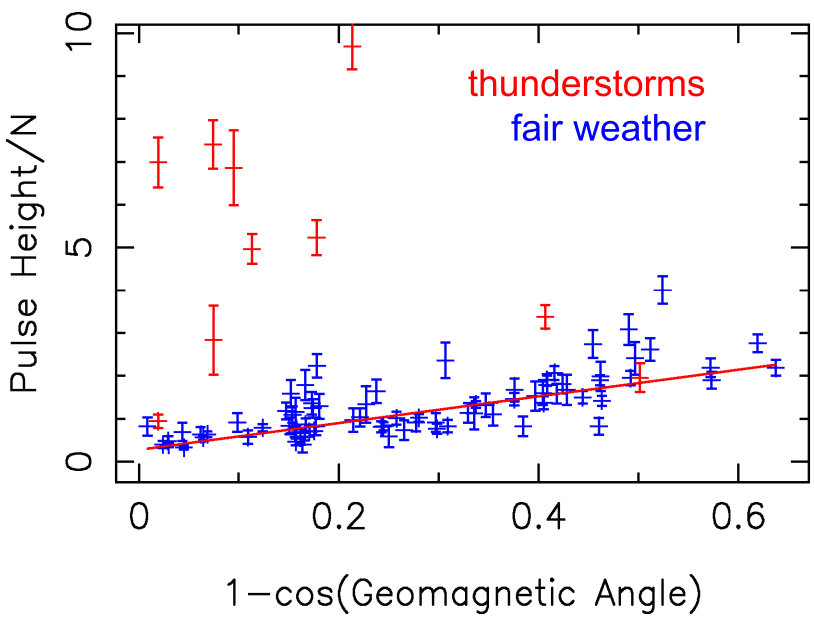
$R_o = 202 \pm 64$ m

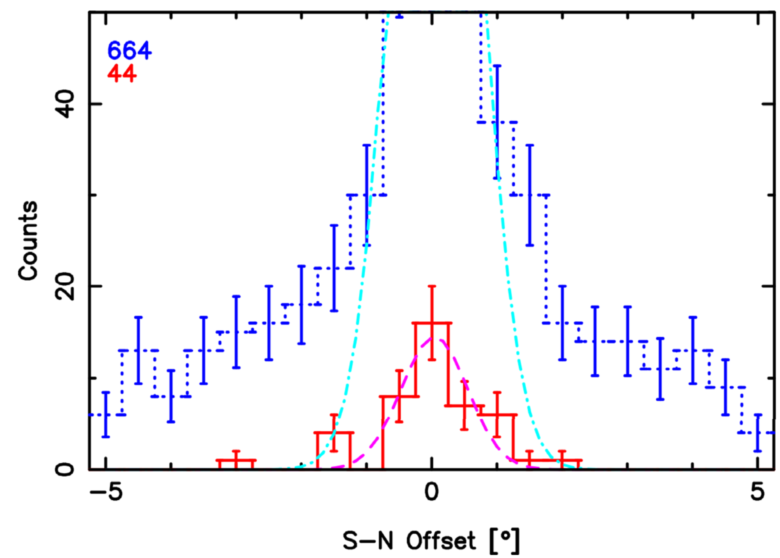
$\gamma = 0.94 \pm 0.03$

Major LOPES 30 results

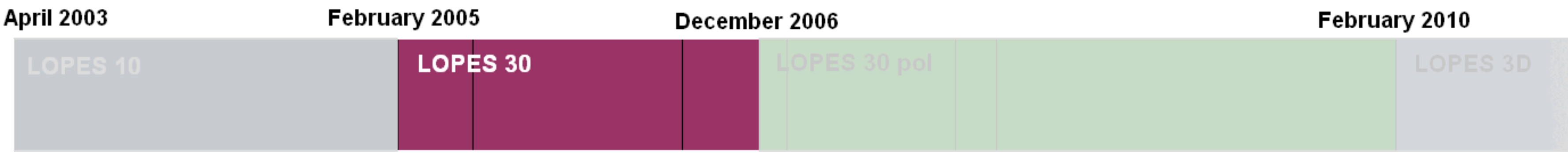


- S. Buitink et al. (The LOPES Collaboration), Astronomy & Astrophysics 2007
  - LOPES 30 detects amplified radio signals during thunderstorms
- A. Nigl et al. (The LOPES Collaboration), Astronomy & Astrophysics 2008
  - LOPES 30 has an angular resolution of <1.5°, better than 1° should be achievable

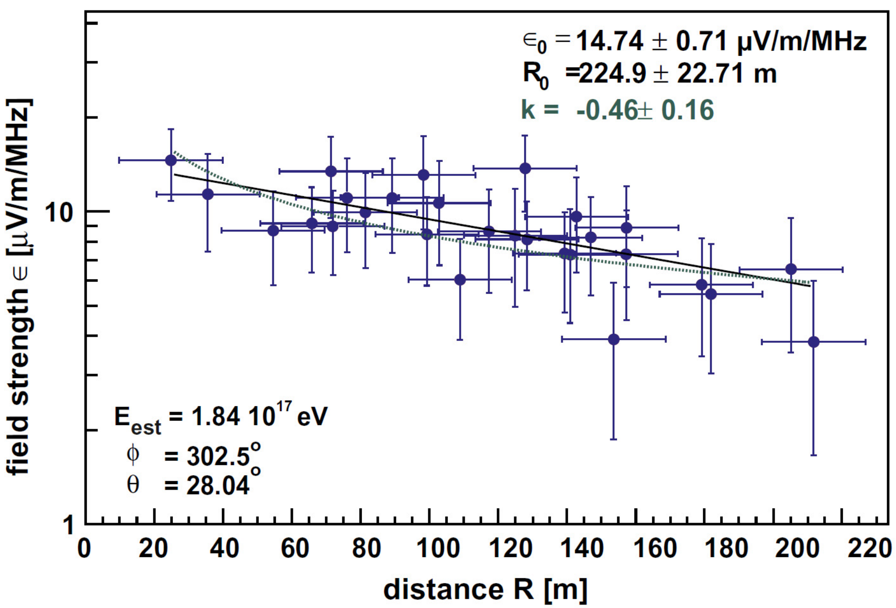


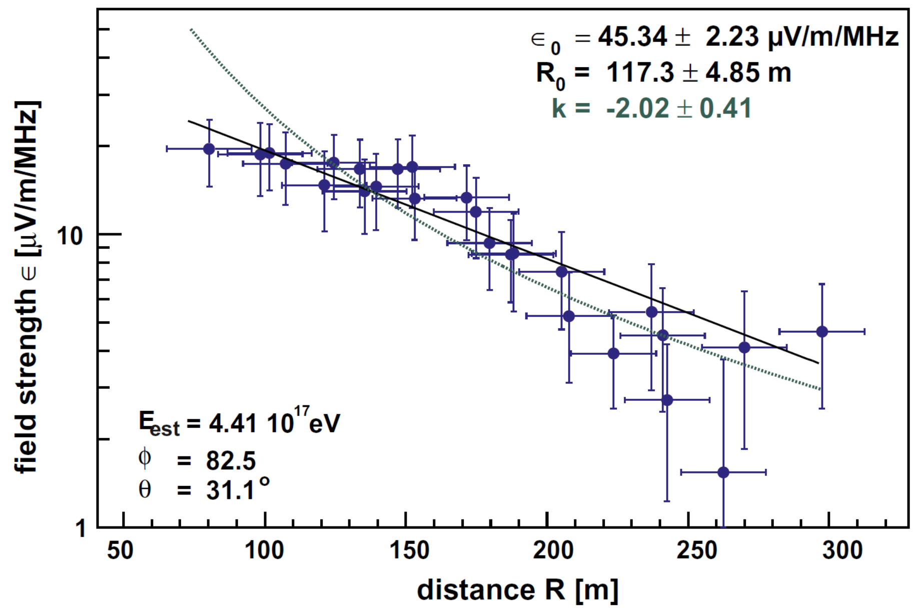


Major LOPES 30 results

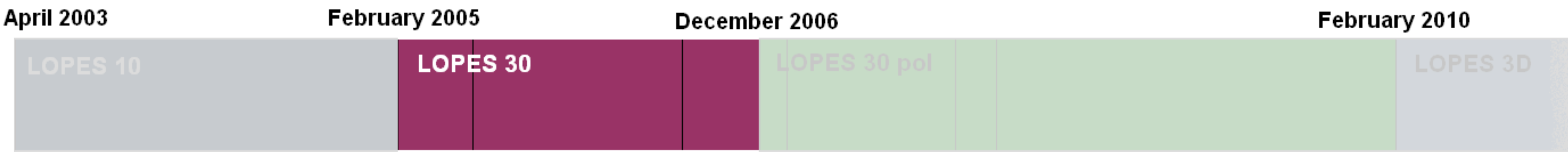


- W.D. Apel et al. (The LOPES Collaboration), Astroparticle Physics 2010
  - detailed per-event lateral distributions
  - ~80% well-fit by exponential, ~20% show flattening to core or flatness



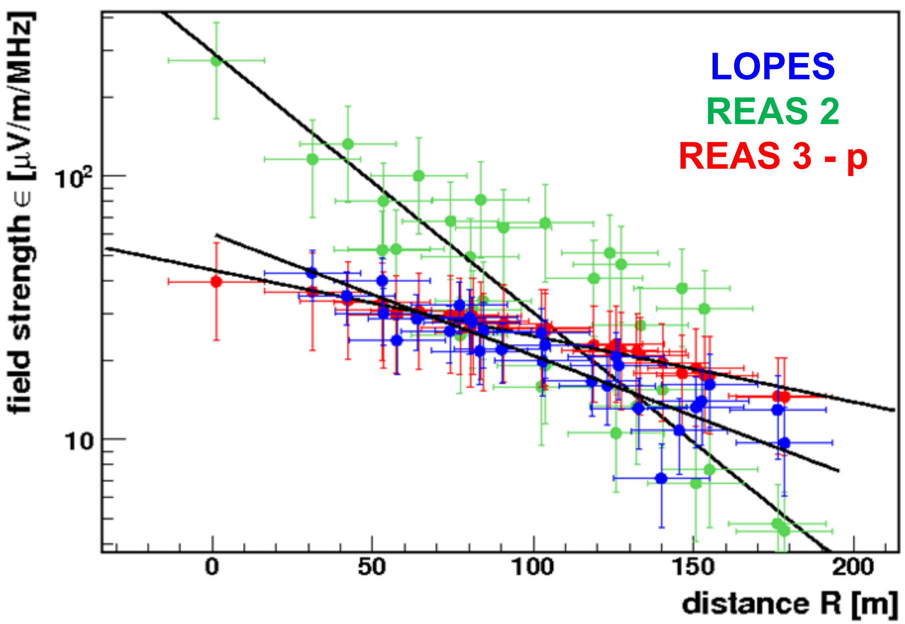


LOPES 30 comparison with REAS simulations

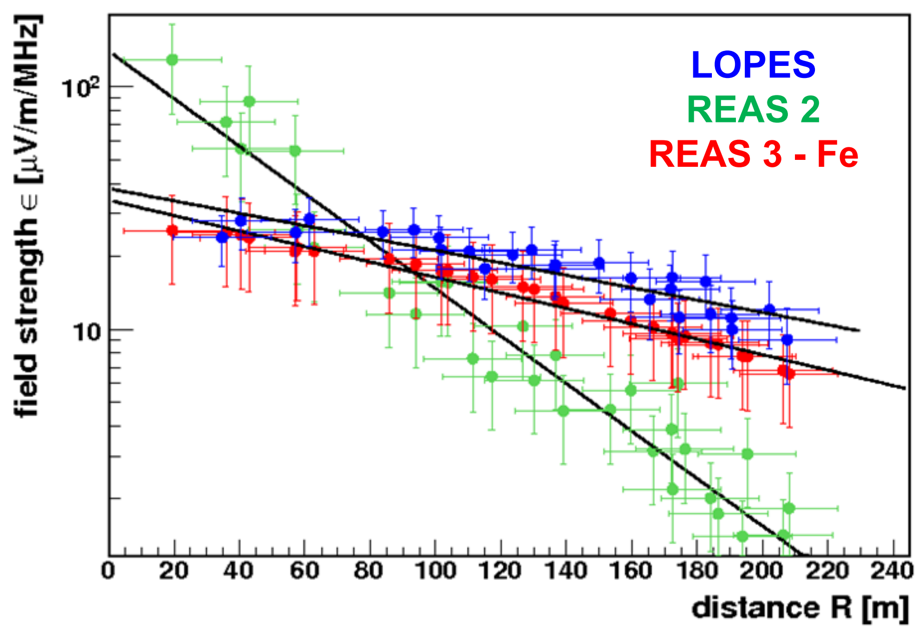


- superior parameter determination by KASCADE (energy, geometry)
- while REAS2 LDFs were too steep, REAS3 simulations often fit nicely

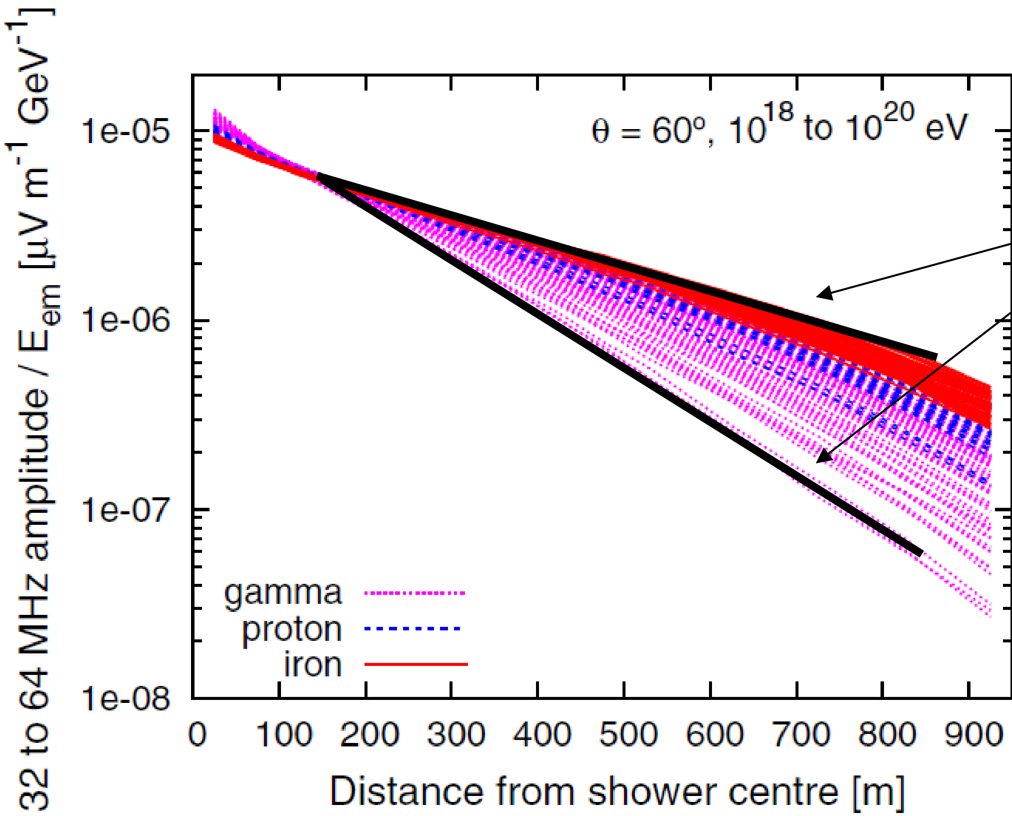
event A



event B



Theoretical expectation – radio Xmax sensitivity

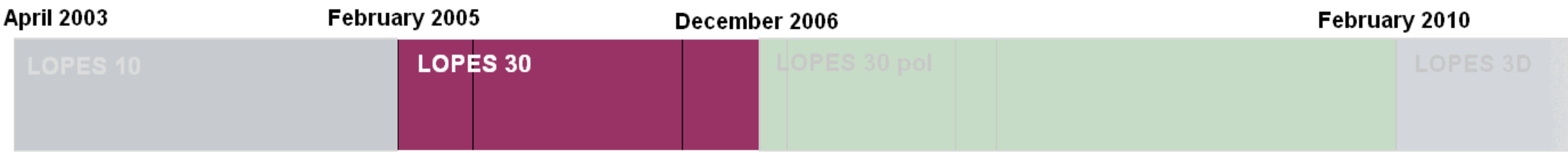


Xmax determination from lateral slope

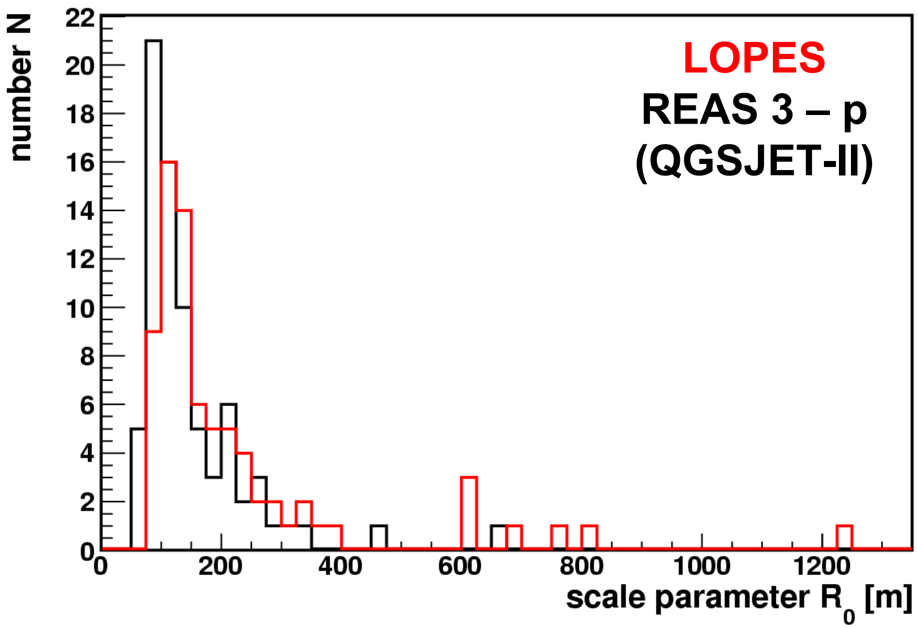
Fe – flat
p – steeper, fluctuating
γ – steepest, fluctuating

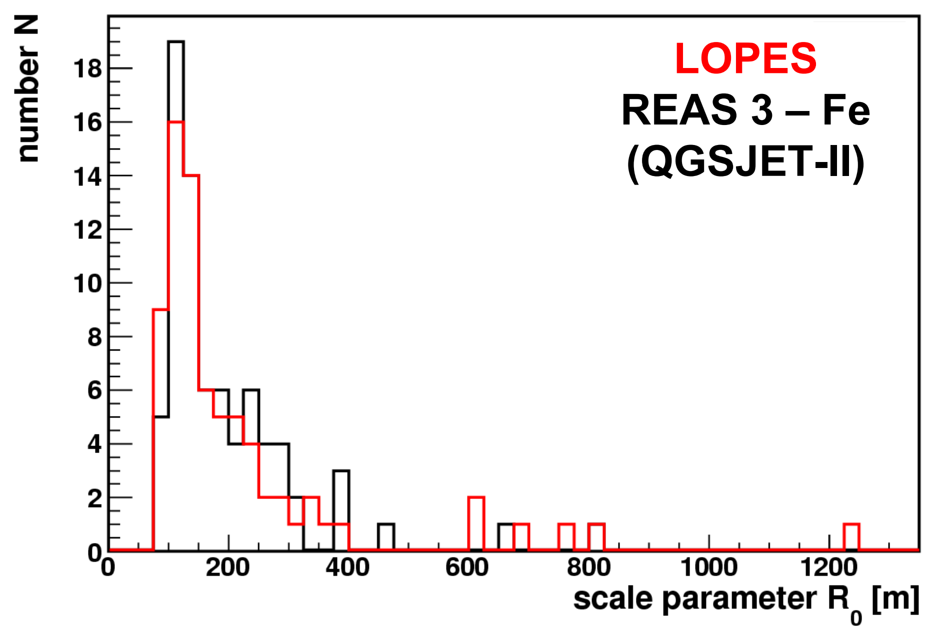
- Huege, Ulrich, Engel, Astroparticle Physics 2008

LOPES 30 comparison with REAS simulations



- REAS3 simulations do not reproduce extremely flat LDFs
- iron simulations fit better than proton simulations
- energy of events ~10^{17} eV

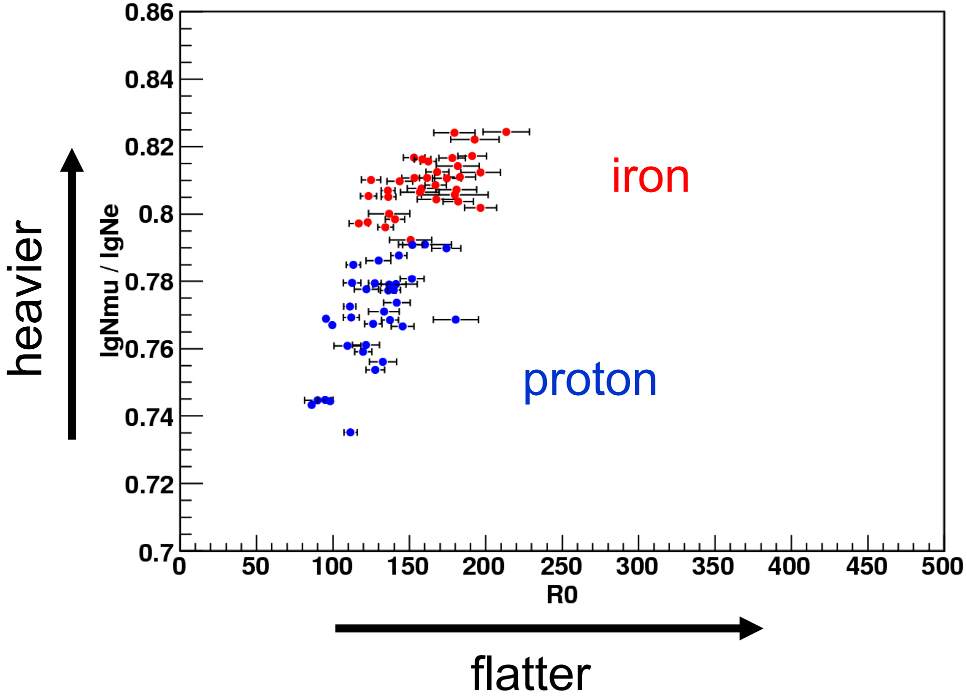




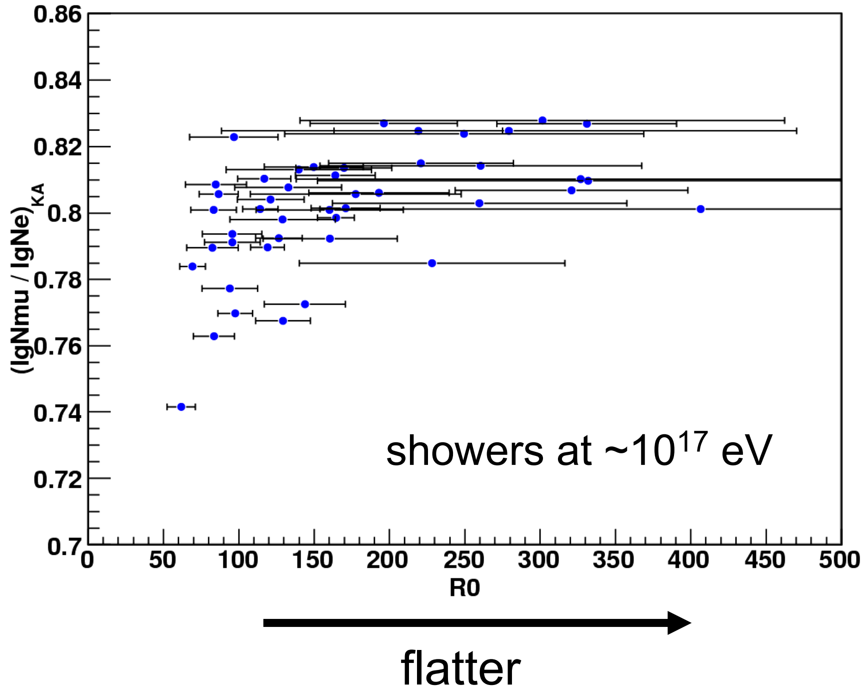
Outlook – Mass sensitivity of radio signals

- Do we see the expected increase of R_0 for heavy elements?
- Compare directly with REAS3 simulations!
- Can we use additional information like curvature, frequency spectra?

REAS3 simulation (QGSJET-II)

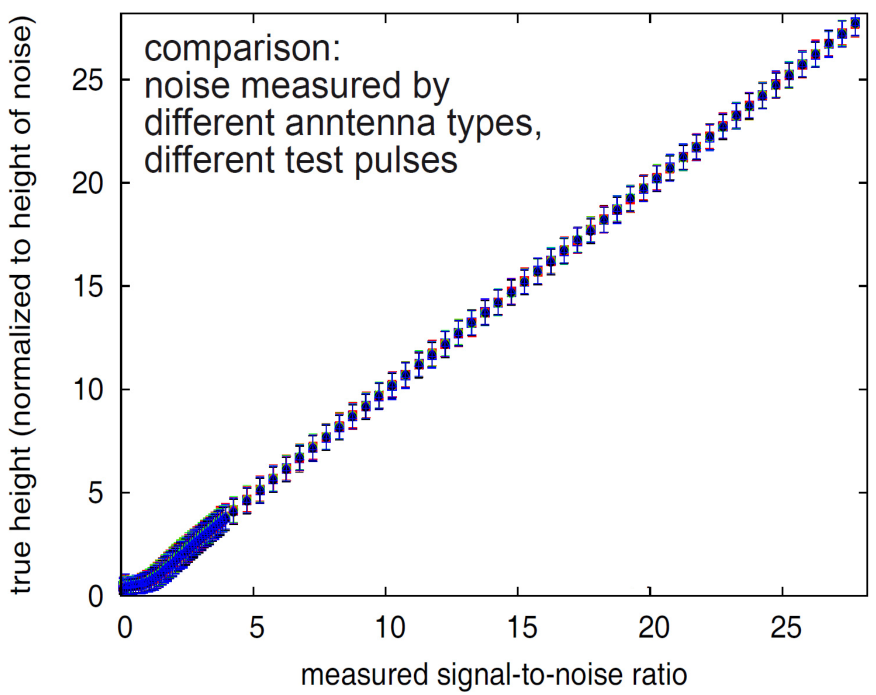


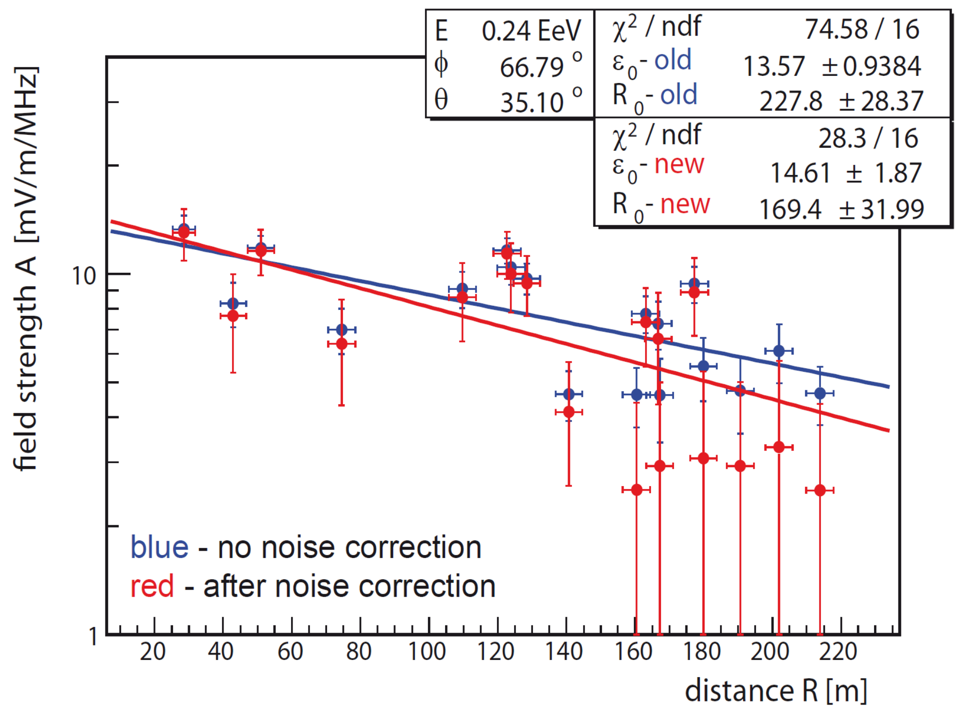
LOPES 30 east-west data



Outlook – Revised treatment of noise

- choose noise definition consistent with signal definition (envelope max.)
- for signals close to noise, correction reduces measured amplitudes
- can have a significant effect on the determined lateral slope parameter
- for further information, cf. poster by Frank Schröder

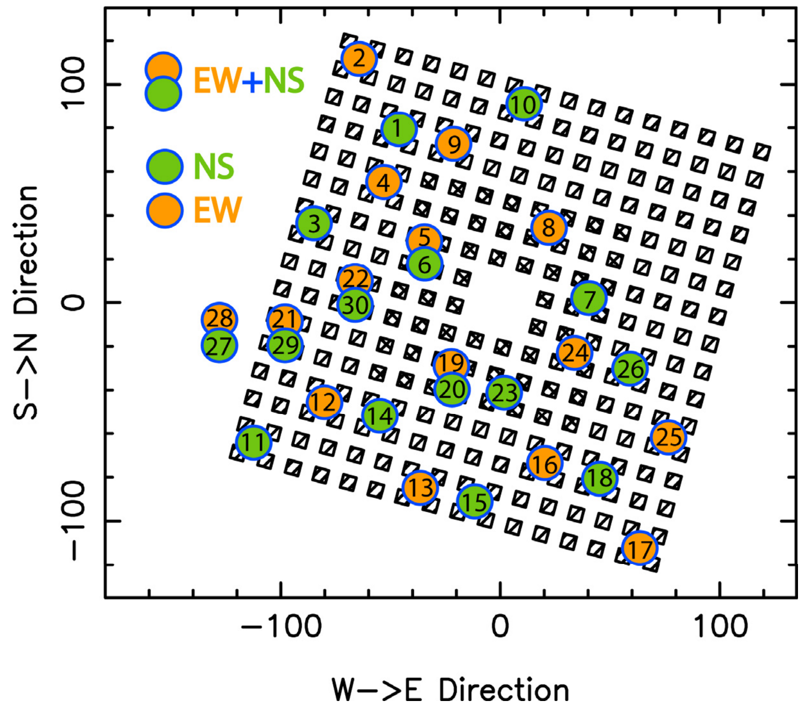




LOPES 30 pol

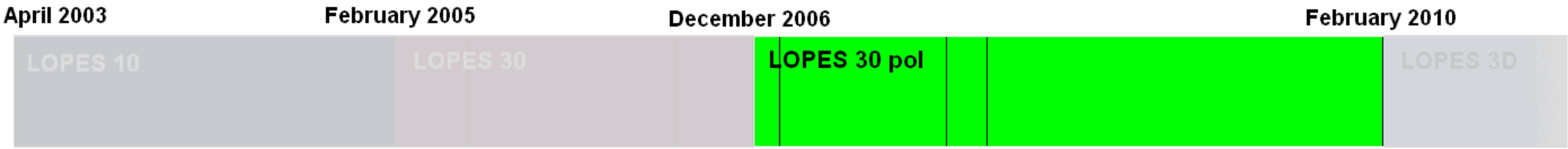
April 2003 | February 2005 | December 2006 | February 2010

LOPES 10 | LOPES 30 | LOPES 30 pol | LOPES 3D

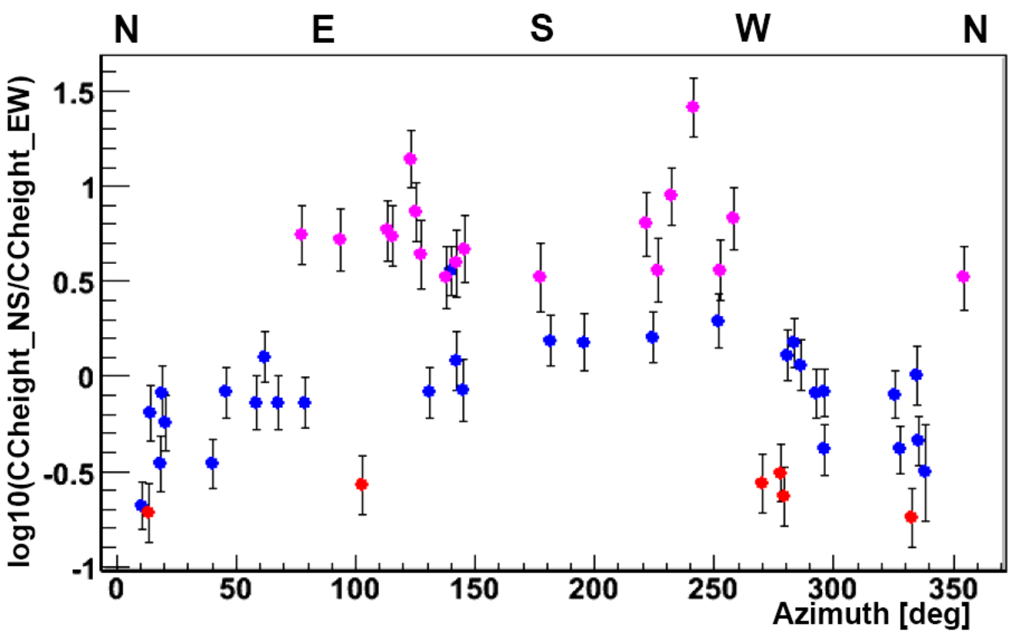


- 15 antennas east-west, 15 north-south
- at 5 locations both polarisations combined

Preliminary results of LOPES 30 pol



- Isar et al. (The LOPES Collaboration), ICRC 2009
  - to first order, data seem to follow a ***v*** x ***B*** polarisation pattern
  - no longer apply 1-cos(α) parameterisation used so far for east-west data
- analysis still in progress (cf. talk Saftoiu), hints for deviation from pure ***v*** x ***B***



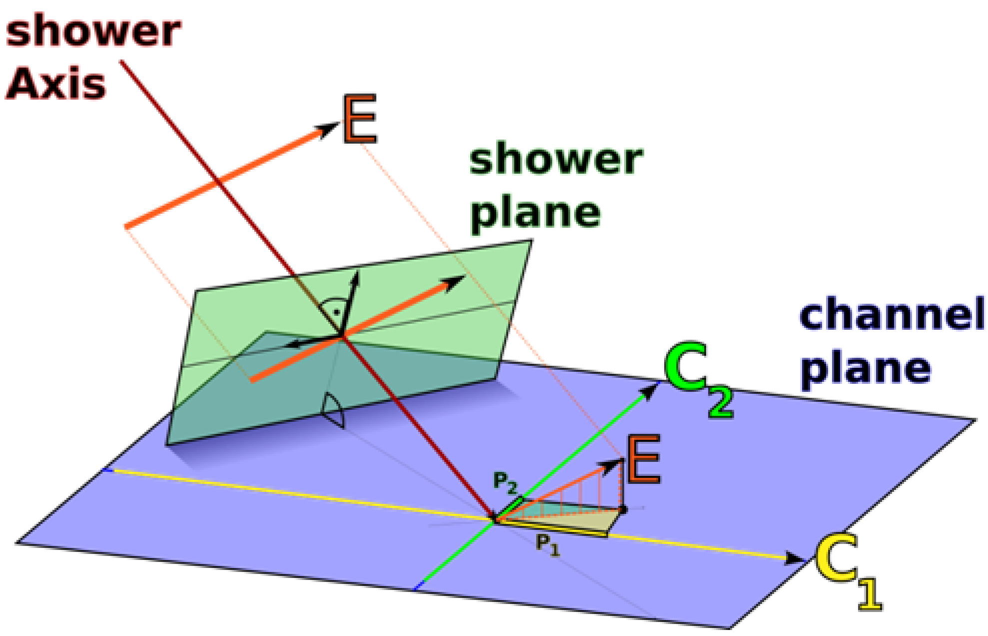
only EW detected

both detected

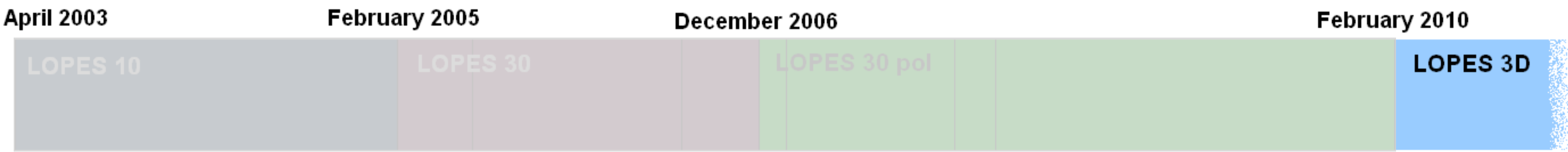
only NS detected

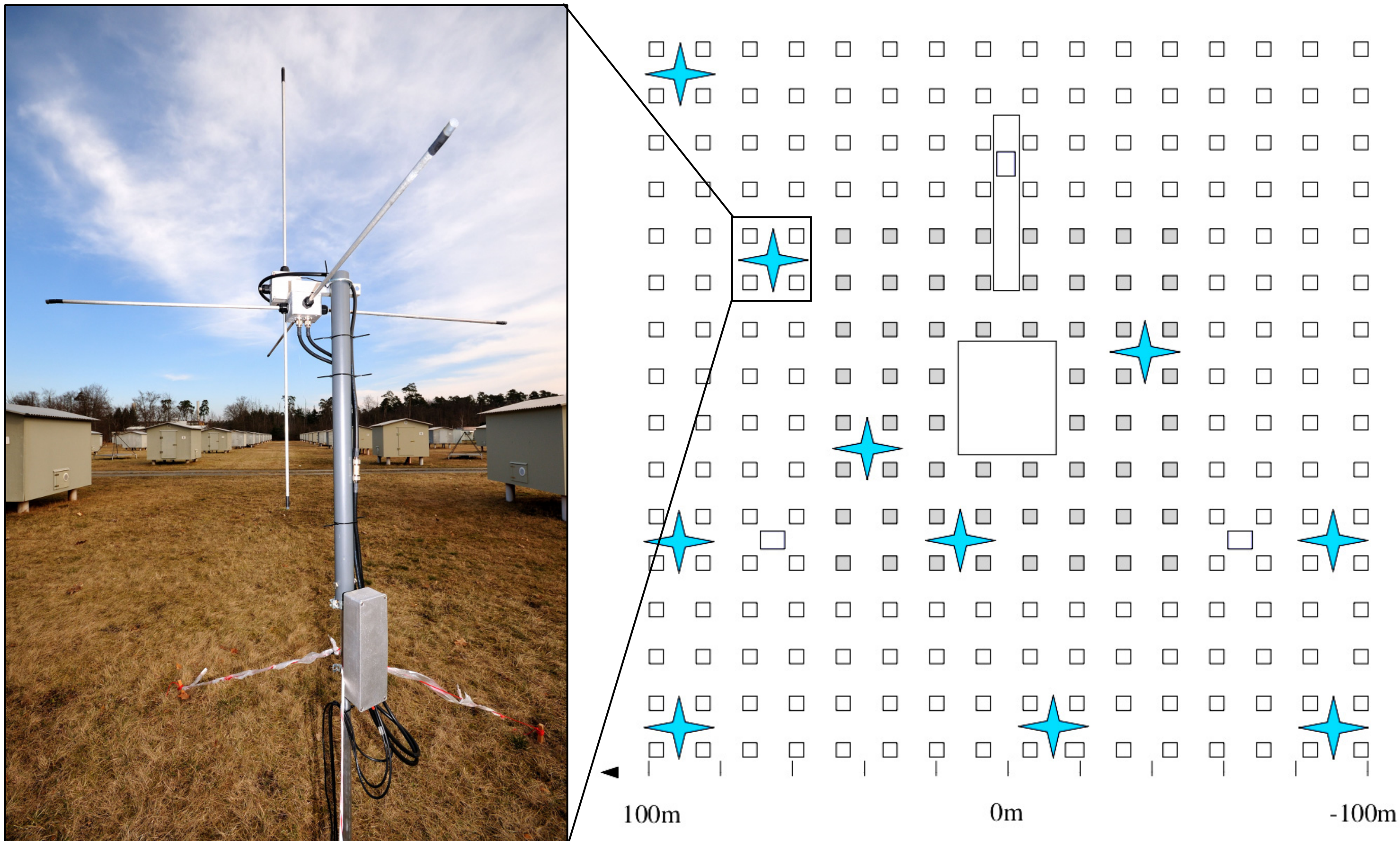
Potential of 3D measurements

- the electric field is a three-dimensional vectorial quantity
- current experiments only measure a 2D projection of the vector
- the potential of a true 3D measurement should be investigated
  - importance of vertical component for highly inclined air showers?
  - improved direction reconstruction?
  - consistent with simulations?
  - better self-trigger?
  - worth 50% more channels?



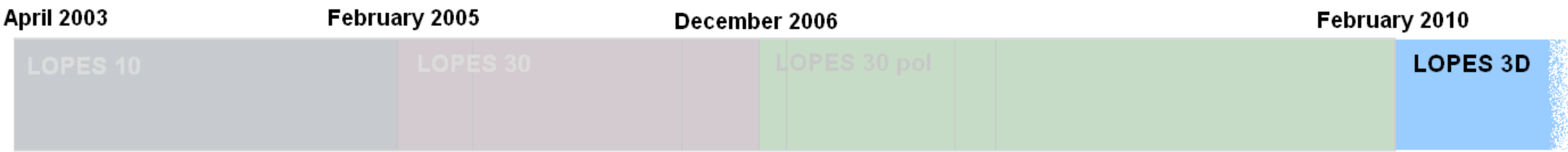
LOPES 3D



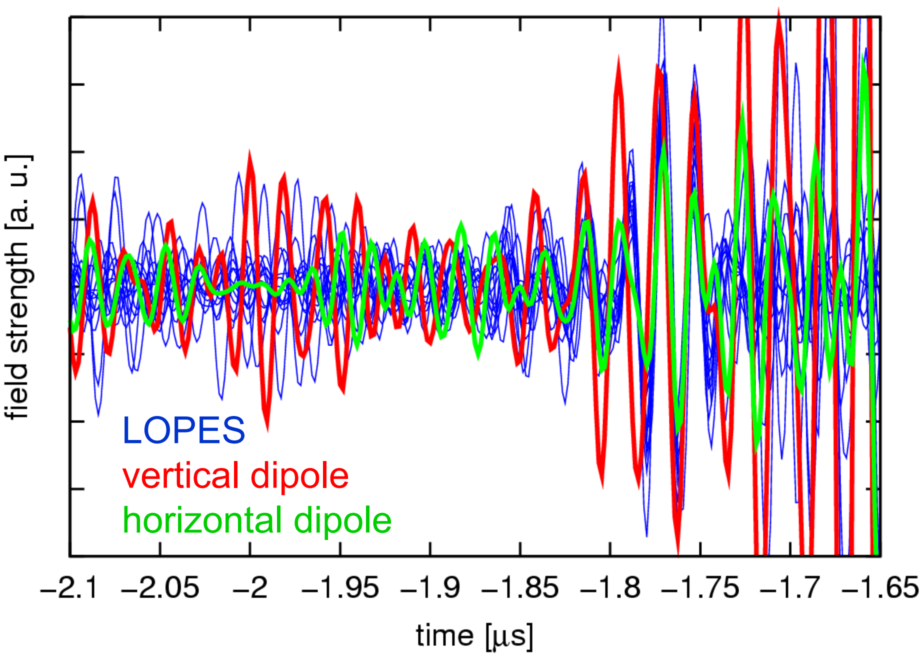


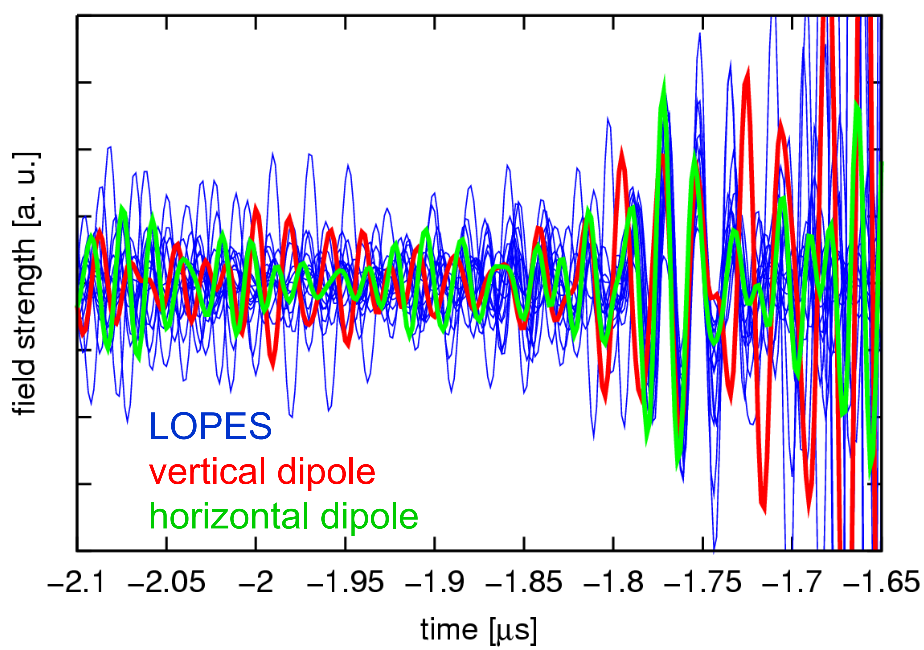
- 10 tripole antennas (NS, EW, vertical)
- kept readout from LOPES

LOPES 3D

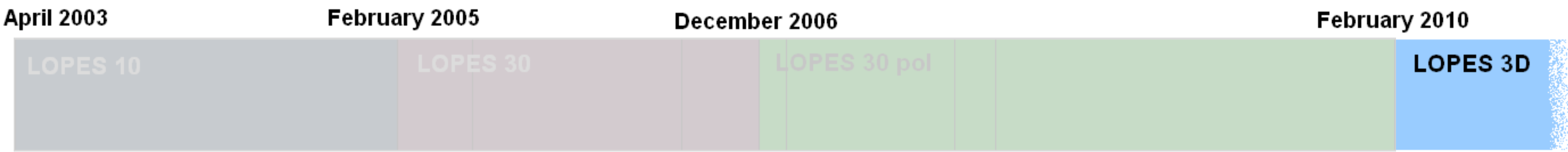


- decision for tripoles made after test measurements with one station
  - SALLAs plus dipole also saw pulses, but less homogeneous setup
- test measurements confirmed coherent signal in vertical polarization

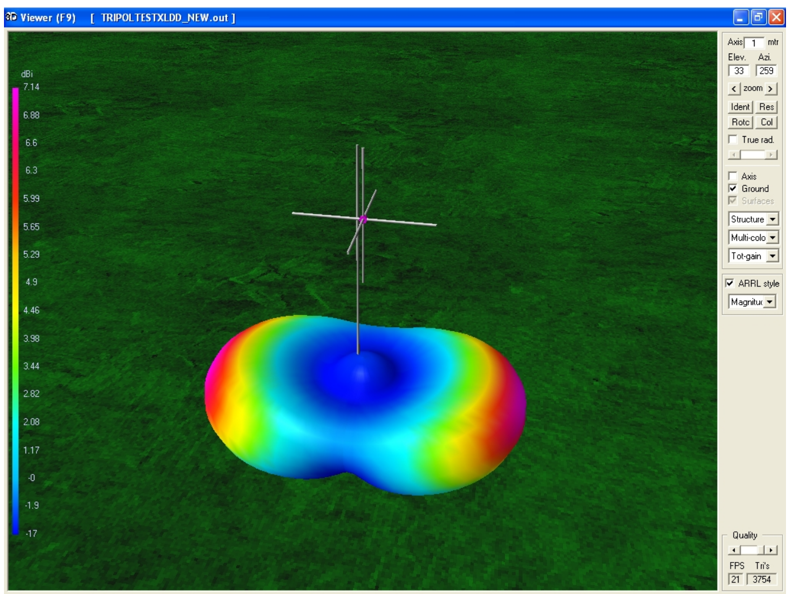


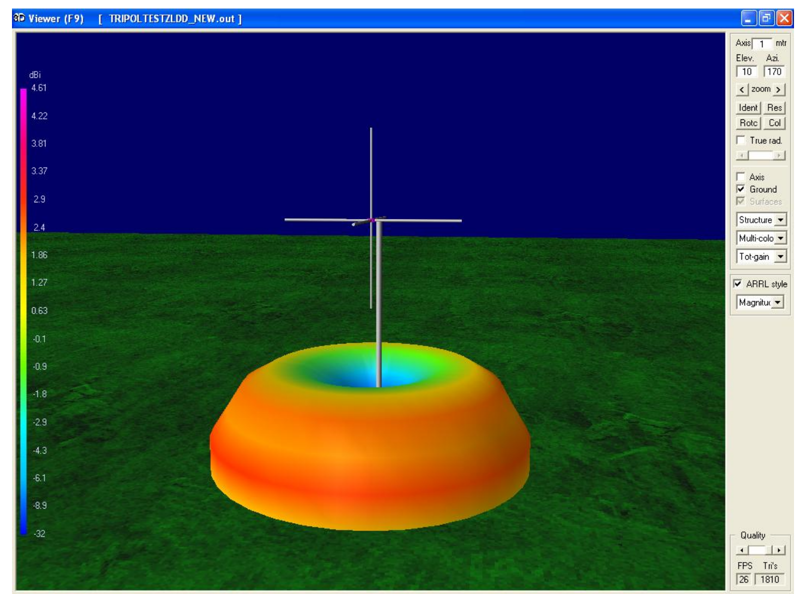


LOPES 3D



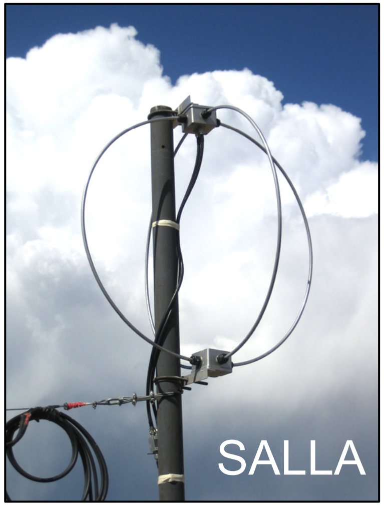
- complete: channel delays, antenna positions, reference phases, NEC2-simulated antenna characteristics
- pending: absolute calibration with external source
- stable data taking since May 2010

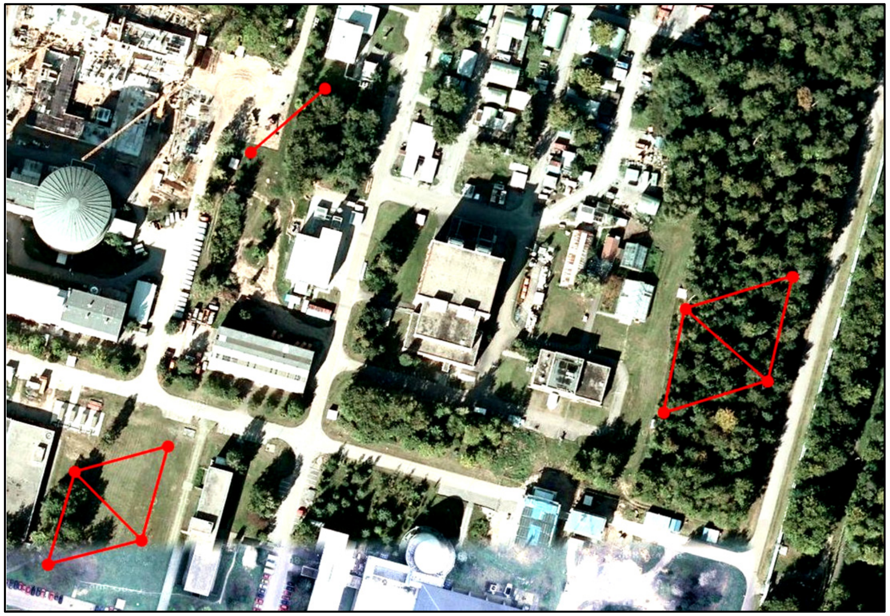




LOPES^{STAR}

- developments for radio detection on large scales (→ AERA at Auger)
  - LPDA and SALLA antennas
  - “low noise amplifiers” with low power consumption, filters
  - self-trigger using real-time digital RFI suppression, upsampling and enveloping in an FPGA
- data taking in coincidence with original LOPES array





Summary

- LOPES is an ever-evolving experiment
- unique point of LOPES: KASCADE high-quality per-event information
- many important results published
- analysis of LOPES data is ongoing
  - polarization properties of the radio signal
  - properties of the radio LDF (flattening, …)
  - detailed comparisons with simulations
  - composition sensitivity of radio emission
  - complete parametrization of results
- latest setup: LOPES 3D
  - determine potential of 3D measurements of electric field vector
  - in stable data taking since May 2010
- LOPES is an ideal R&D test-bed for large scale application

Karlsruhe Institute of Technology

Announcement for a
WE-Heraeus-Seminar

Wilhelm und Else Heraeus Stiftung

Radio Detection in Astroparticle Physics

A New Technique for Measuring Cosmic Particles of the Highest Energies

October 4^{th} to 6^{th} 2011, Bad Honnef, Germany

Topics

theory and experiments for
- radio detection in air
- radio detection in dense media

connections to other fields (thunderstorm physics, ...)

Format

40-minute in-depth expert lectures
poster sessions with poster prizes
selected audience (~65 participants)
full board sponsored by the WE-Heraeus-Stiftung

Organizers

Dr. T. Huege <tim.huege@kit.edu>
Dr. A. Haungs <andreas.haungs@kit.edu>
Prof. Dr. J. Blümer <johannes.bluemer@kit.edu>