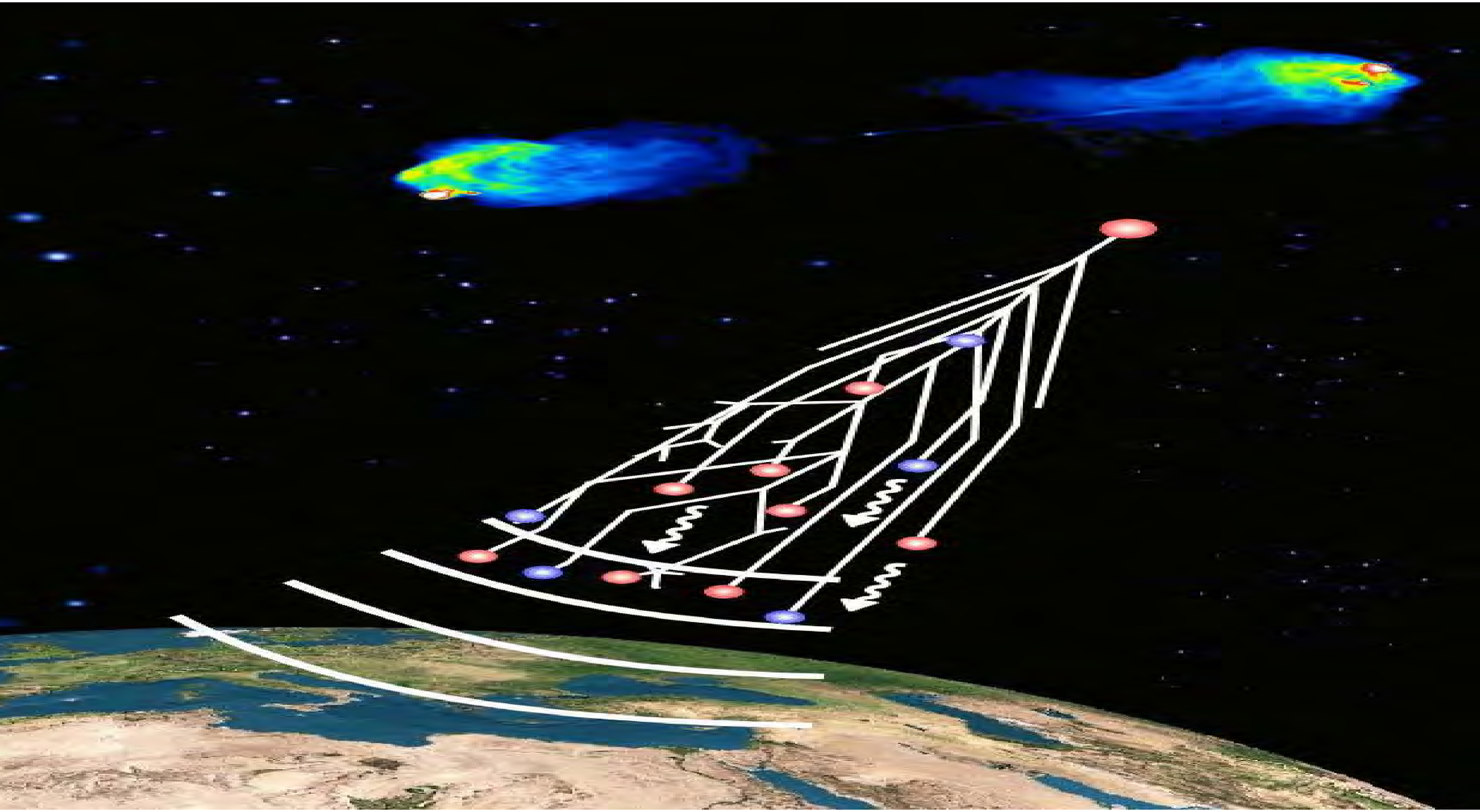
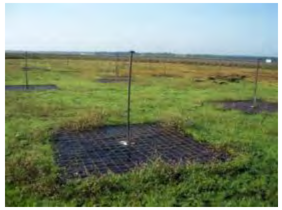
Radio Detection of High-Energy Cosmic Rays

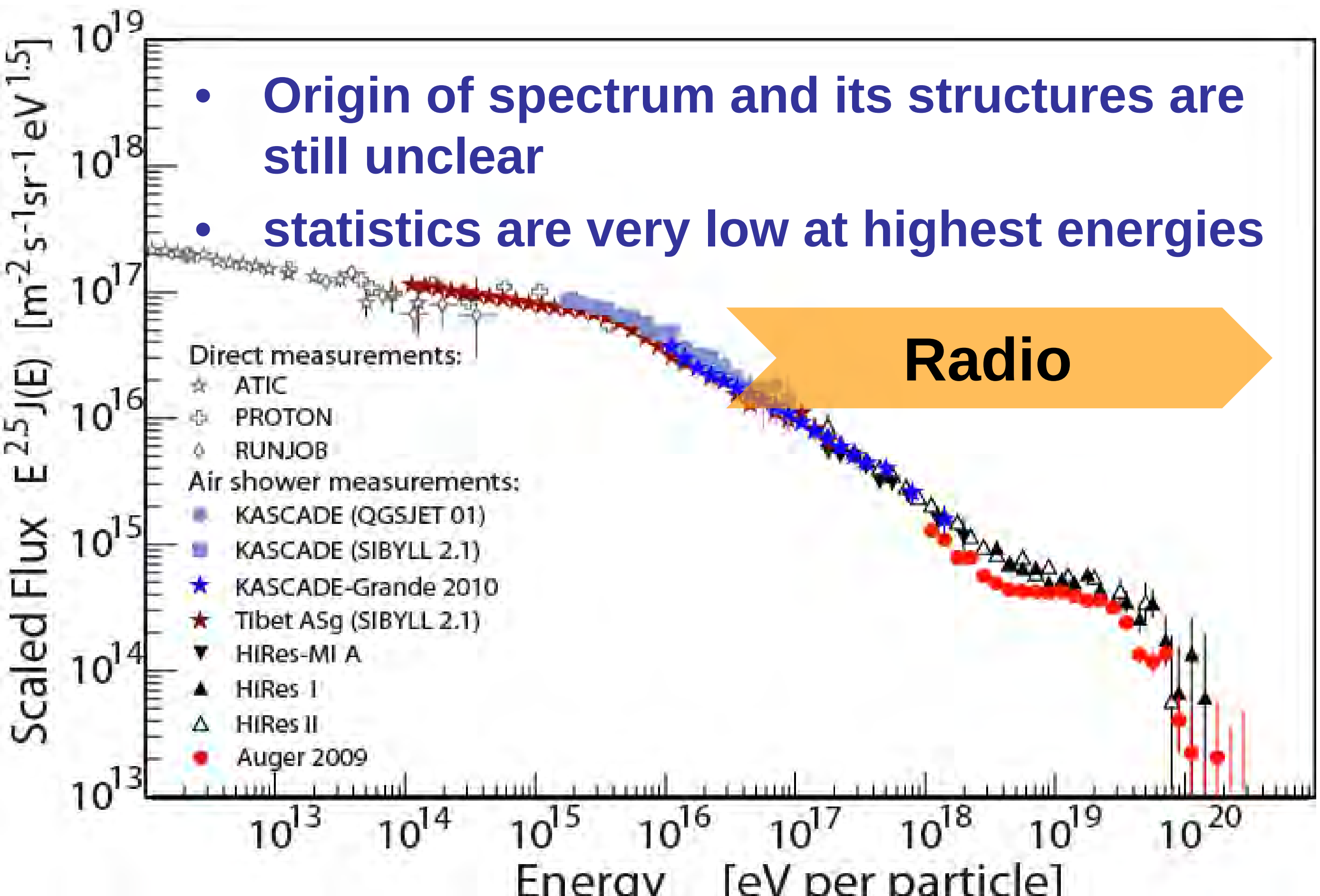


Motivation: Cosmic Rays

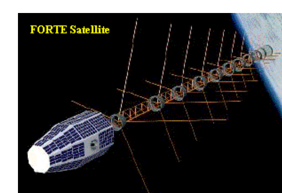




- Origin of spectrum and its structures are still unclear
- statistics are very low at highest energies



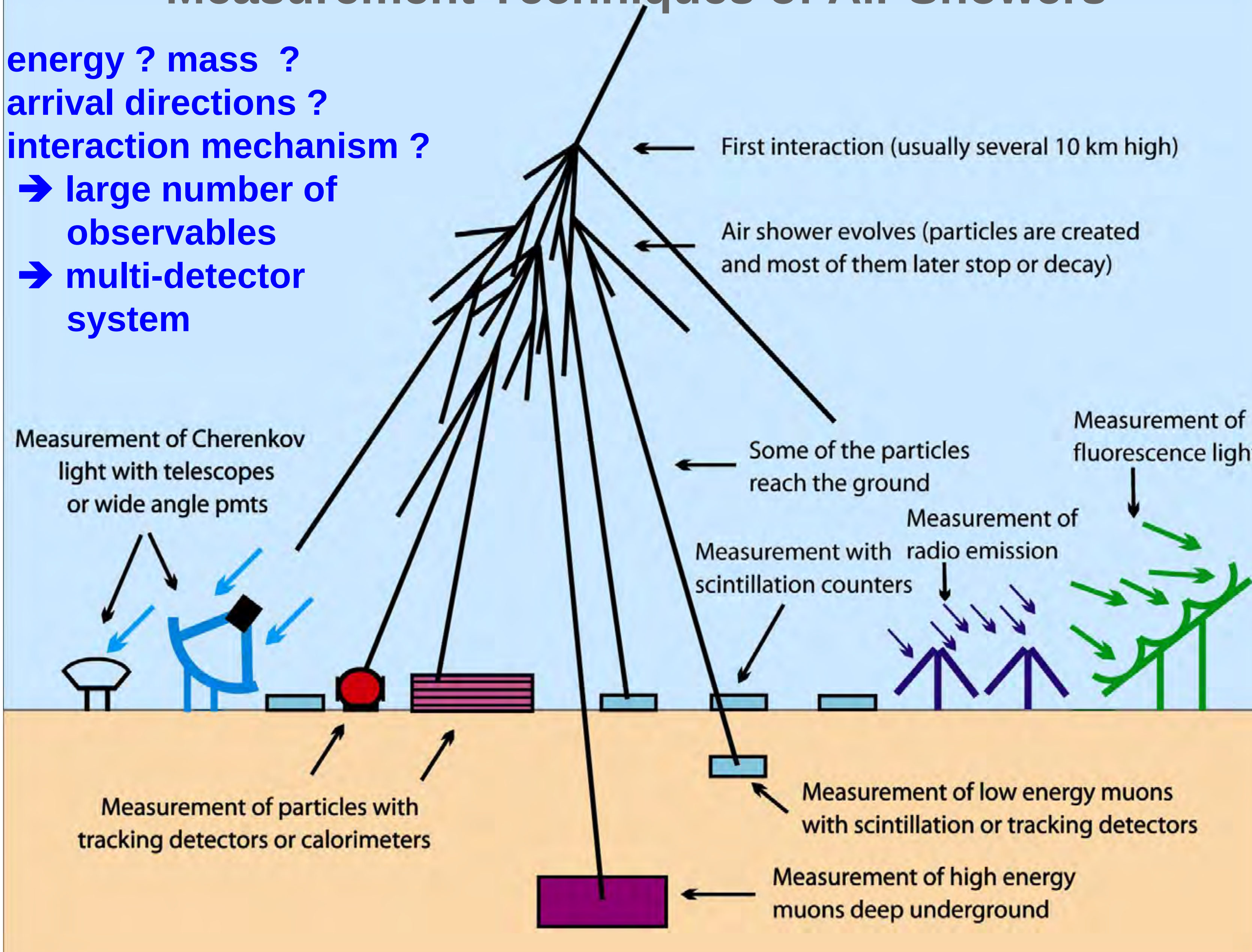




Measurement Techniques of Air Showers

energy ? mass ?
arrival directions ?
interaction mechanism ?

- ➔ **large number of observables**
- ➔ **multi-detector system**

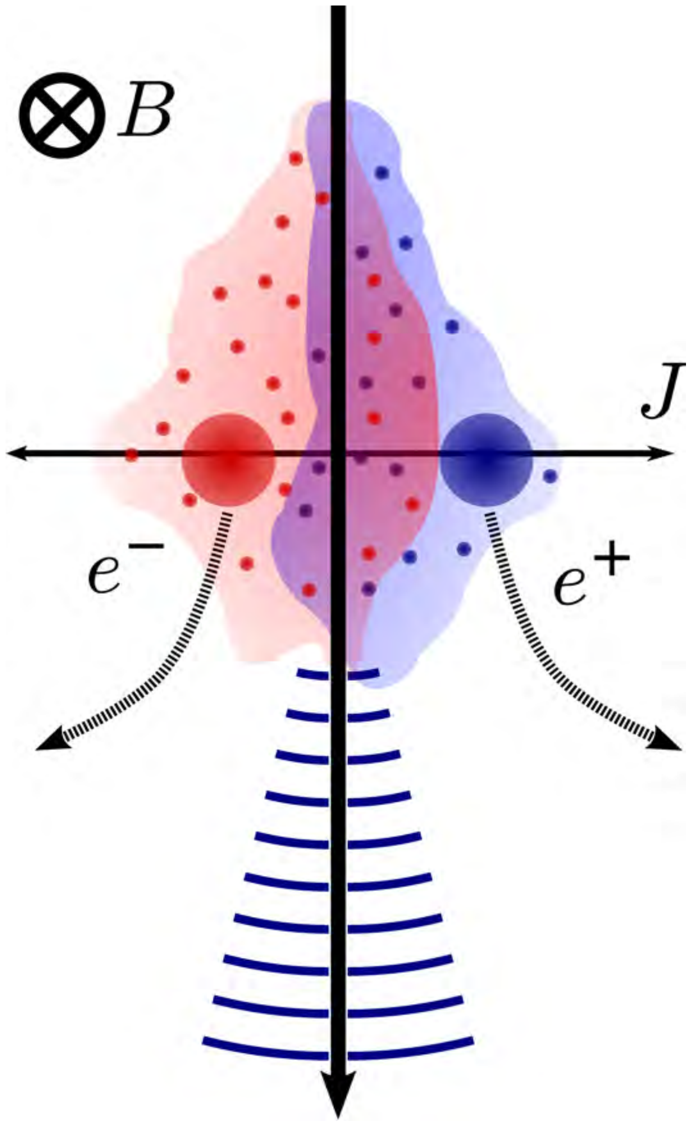


Radio from Air Showers

Detection principle:

-Geomagnetic deflection of electrons and positrons
-Time-variation of number of charged particles
-Time-variation of charge excess radiation
-and possibly more (refraction index)

➔ lead to coherent emission in atmospheric air showers (initiated by UHECR)
- MHz frequency range !
- µV/m-range amplitude
- few ns duration



“Way of Success” of EAS radio detection technique

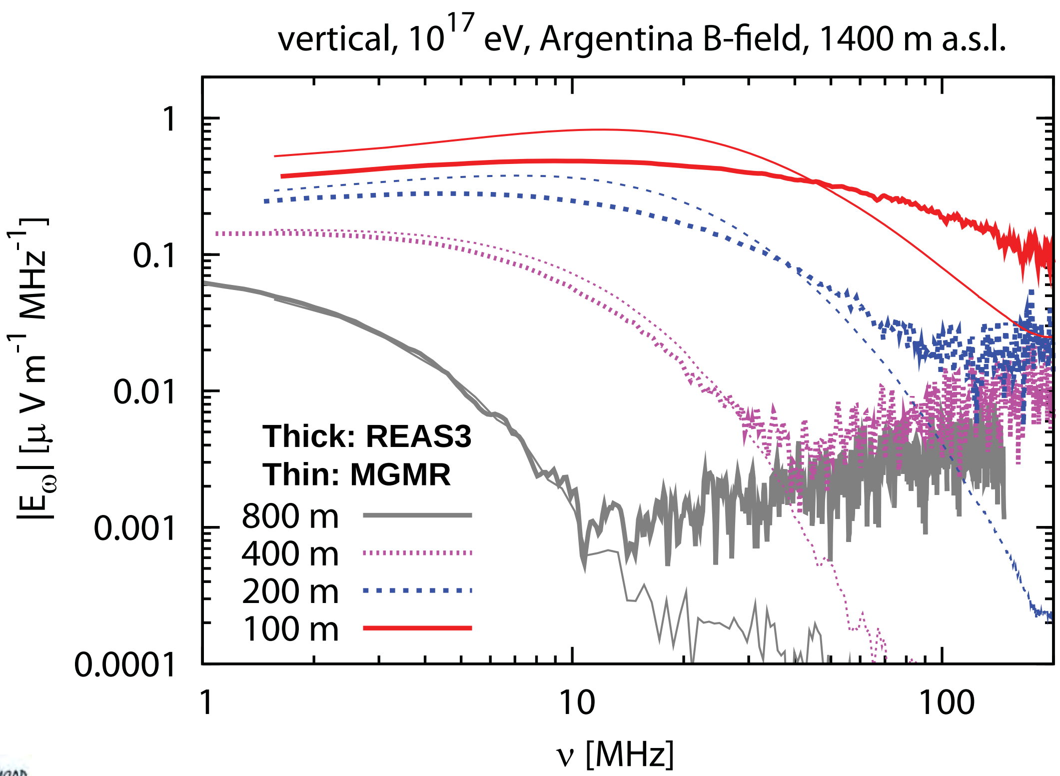
➔ The idea (70ies)
➔ proof-of-principle ➔ infancy test experiments
➔ engineering arrays ➔ hybrid CR physics
➔ stand-alone detection technique

1. Calibration (understanding) radio emission
   - Dependencies of radio signal
   - Fixing emission mechanism(s) = simulations
2. Capability of the radio detection technique
   - Sensitivity to energy, direction, composition
3. High-Energy Cosmic Ray Physics
   - Hybrid (superhybrid) measurements
   - Stand-alone measurements

Monte Carlo Simulations

Presently large progress in Theory and Simulation

-Very different approaches
-Large competition
-But also good co-operation



Present Models:

REAS3
MGMR
ZHAires
SELFAS
Konstantinov/Engel
…..

Huege, ARENA 2010, NIM A

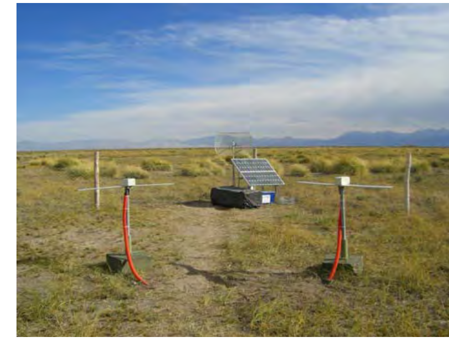
Radio from Air Showers

~3-4000 cosmic ray events unambiguously detected by

LOPES
CODALEMA
Radio Prototypes@Auger
AERA
TREND
ANITA
Radio@Tunka

(and of course the historical experiments, partly re-analyzed: MSU, Yakutsk, e.g.)

➔Now: do we understand the signals?

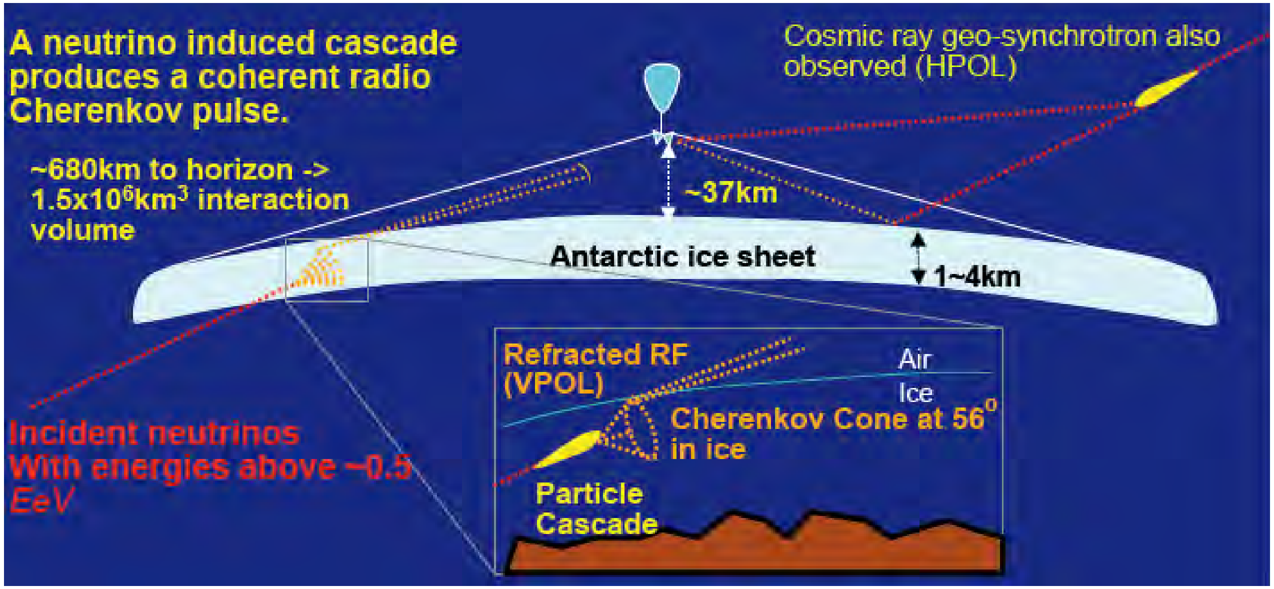


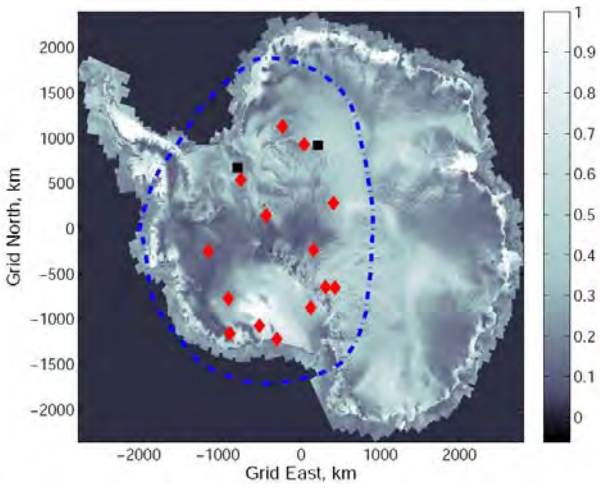
TREND :
The Tianshan Radio Experiment for Neutrino Detection

➔ using 21cm array in China
➔ first events detected

Olivier Martineau, IHEP February 2011
D.Ardouin et al, Astropart.Phys.34:717-731,2011

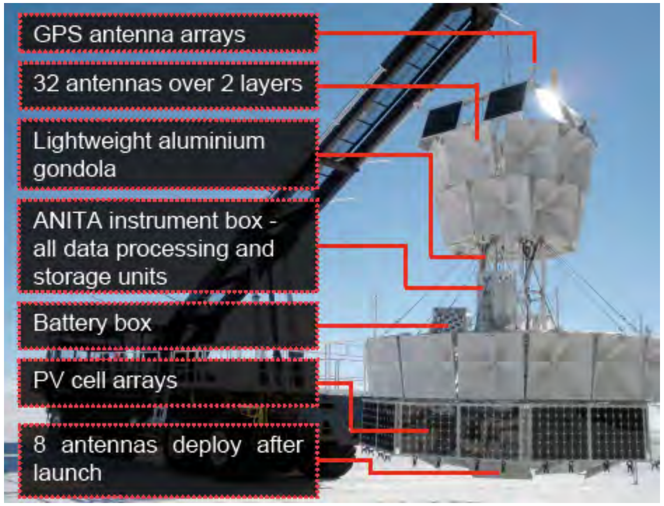
ANITA :
ANtarctic Impulsive Transient Antenna





Horn antennas 300MHz-1GHz
➔ 16 EAS candidates (Energy ~10^{19}eV)
➔ No neutrino candidate

➔2012 next (CR optimized) flight



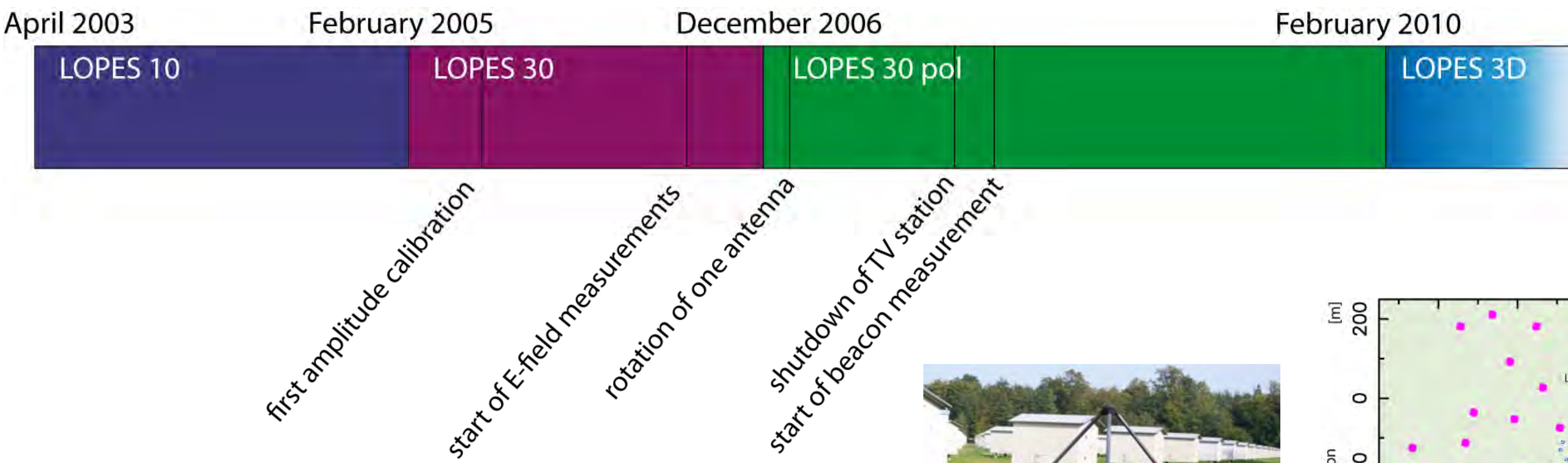
A.Romero-Wolf, ARENA 2010, Nantes
S.Hoover et al. - Phys.Rev.Lett.105:151101,2010.

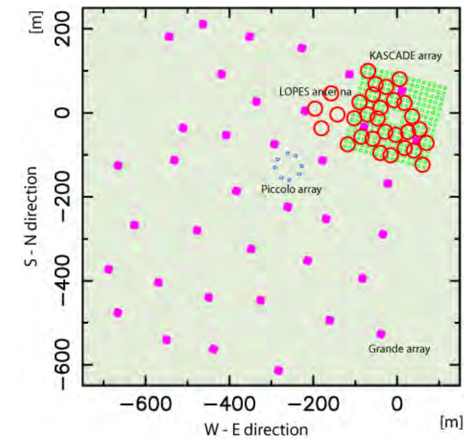
LOPES

LOPES collaboration:
-) KASCADE-Grande
-) U Nijmegen, NL
-) MPIfR Bonn, D
-) Astron, NL
-) IPE, FZK, D

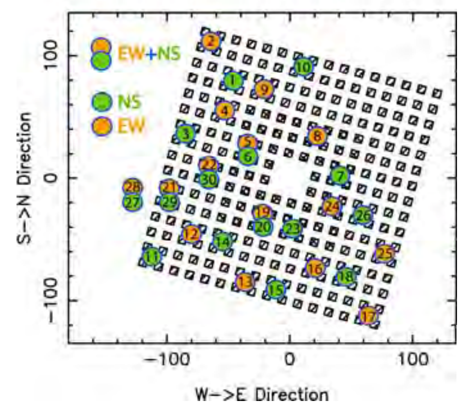
→Development of a new detection technique!

Evolution of LOPES



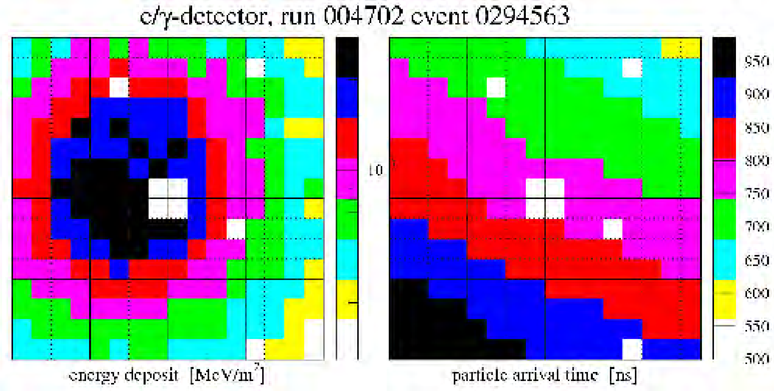


- **LOPES 10**
  - **„proof of principle“**
- **LOPES 30 east-west**
  - **calibration of signal**
- **LOPES 30 pol**
  - **polarization dependencies**
- **LOPES 3D**
  - **complete E-field-vector**

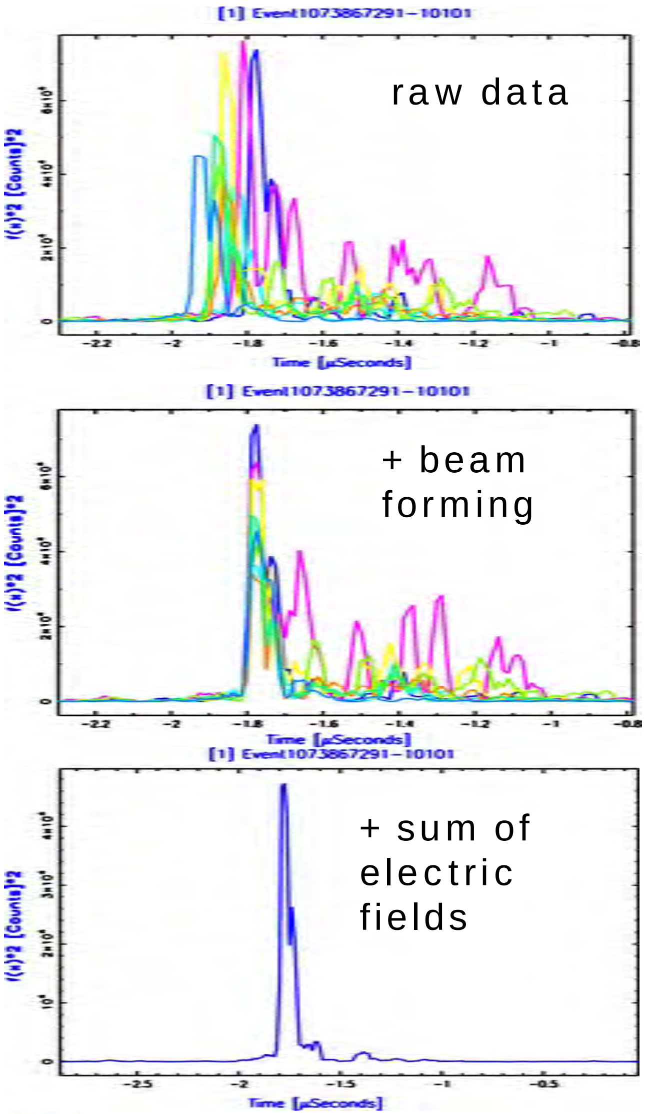


LOPES: Proof of principle

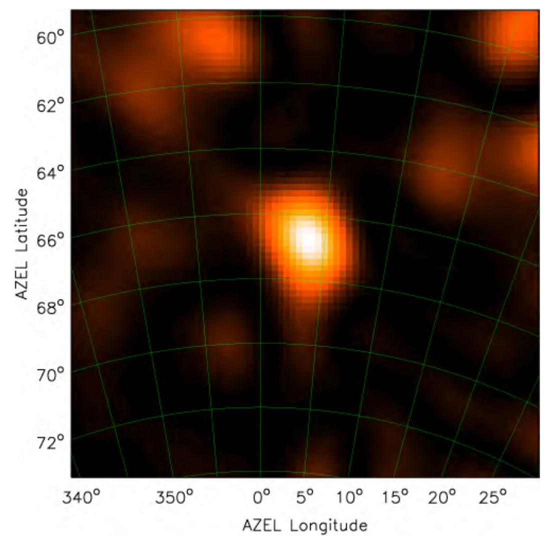
1. KASCADE measurement



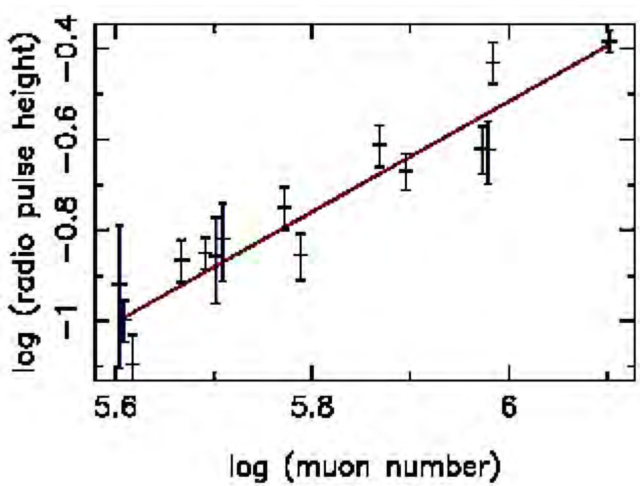
2. Radio data analysis



3. Skymapping



4. Many events



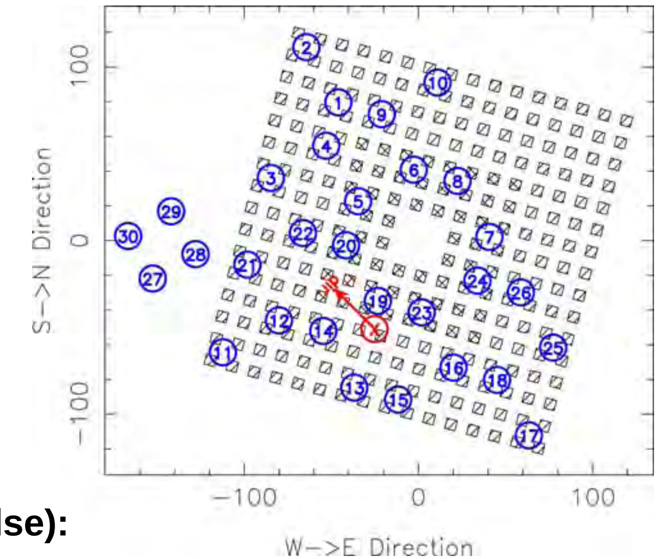
LOPES collaboration, Nature 425 (2005) 313

LOPES 30 event example

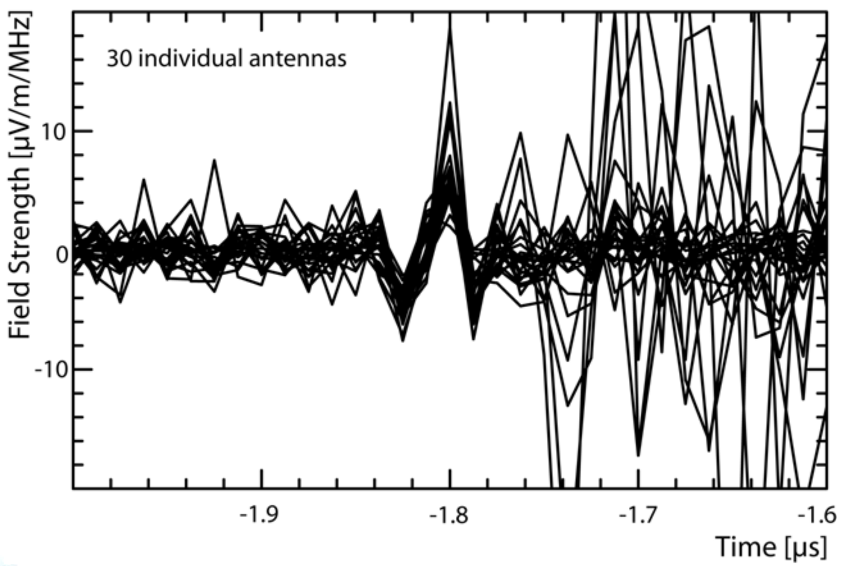
-radio reconstruction inclusive calibration factors of antennas
➔CC-beam value (per event)
➔Field strength (per antenna)

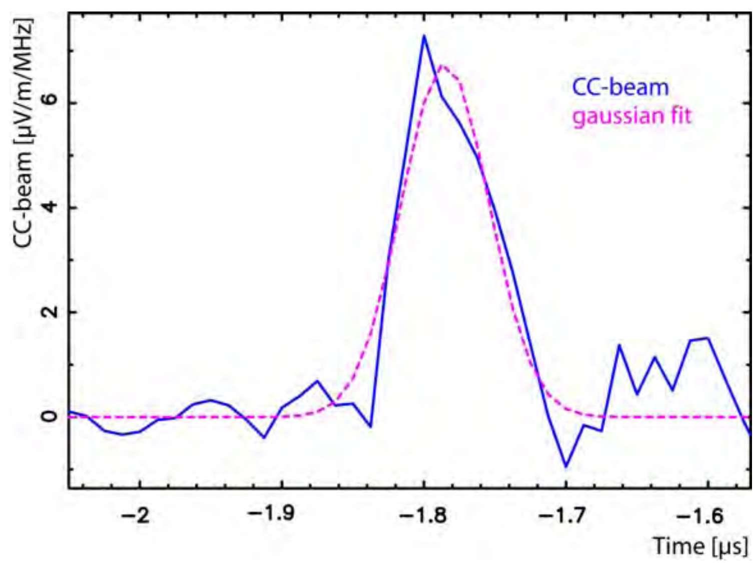
$$cc[t] = \pm\sqrt{\left|\frac{1}{N_{Pairs}}\sum_{i=1}^{N-1}\sum_{j>i}^{N} s_i[t]s_j[t]\right|}$$

(degree of correlation ➔ extract coherent pulse):

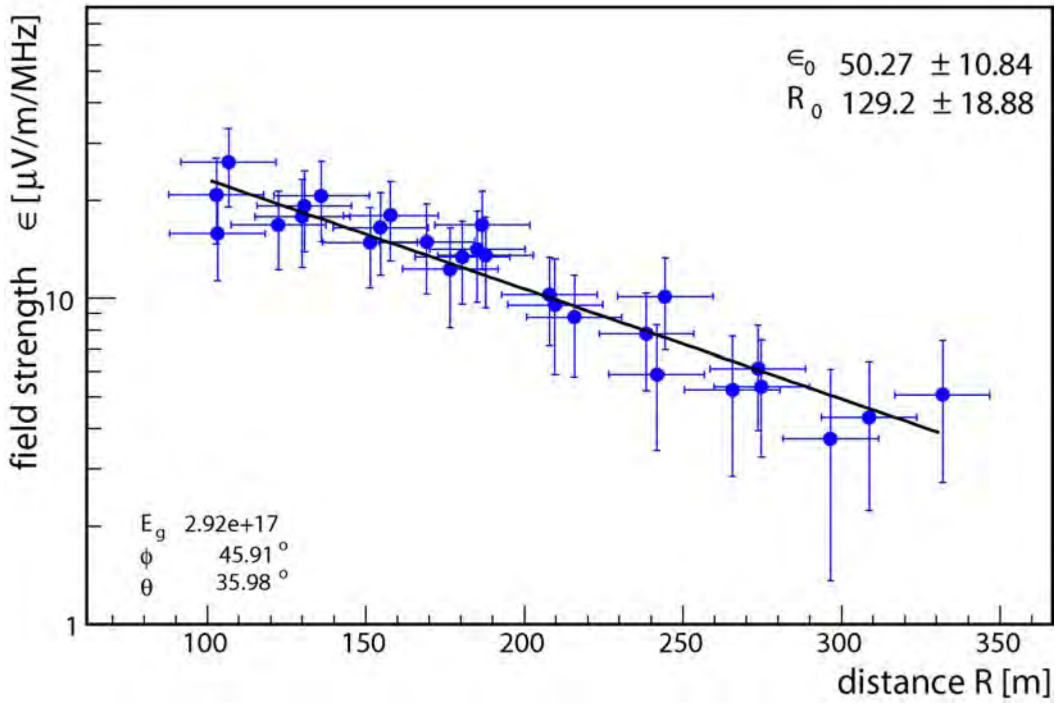


Event:
$\Phi = 15^o$ $\theta = 306^o$
core = in KASCADE
$lg(N_e) \sim 7.4$
$lg(N_\mu) \sim 6.0$
$E_0 \sim 1.6 \cdot 10^{17}$ eV





Lateral distribution

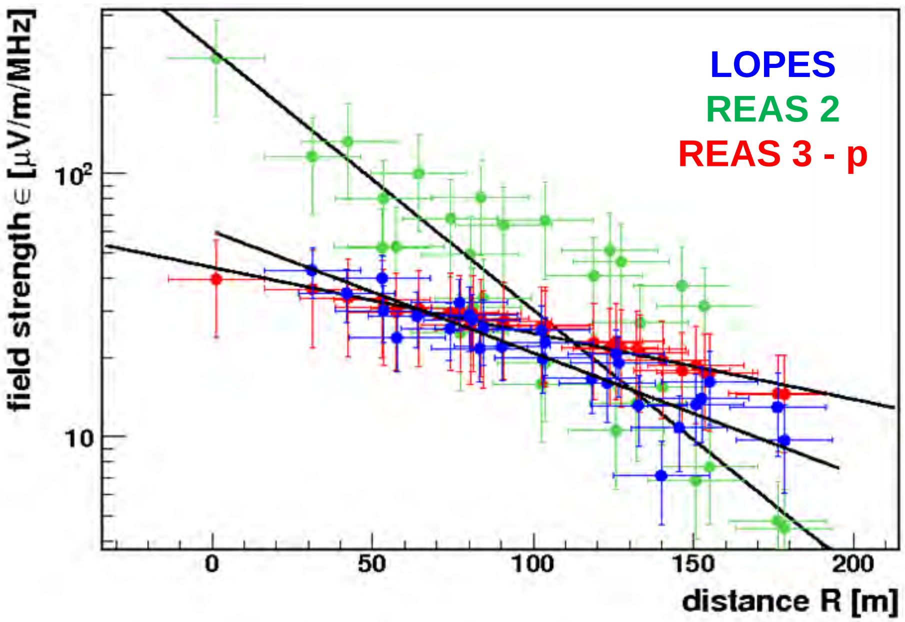


W.D. Apel et al. (The LOPES Collaboration), Astroparticle Physics 2010

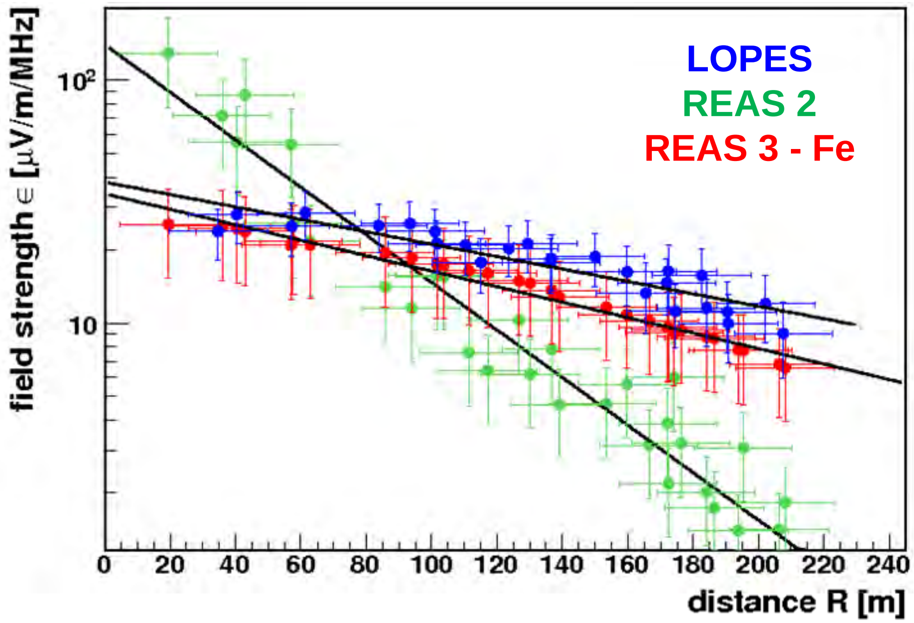
- **Field strength of individual antennas**
- **Fit with exponential function $\varepsilon(R)= \varepsilon_0 \exp -(R/R_0)$**
  - **80% exponential with R_0~100-200 m**
  - **20% total flat events or flat at small distances**

Lateral distribution
Comparison of data with simulations

event A



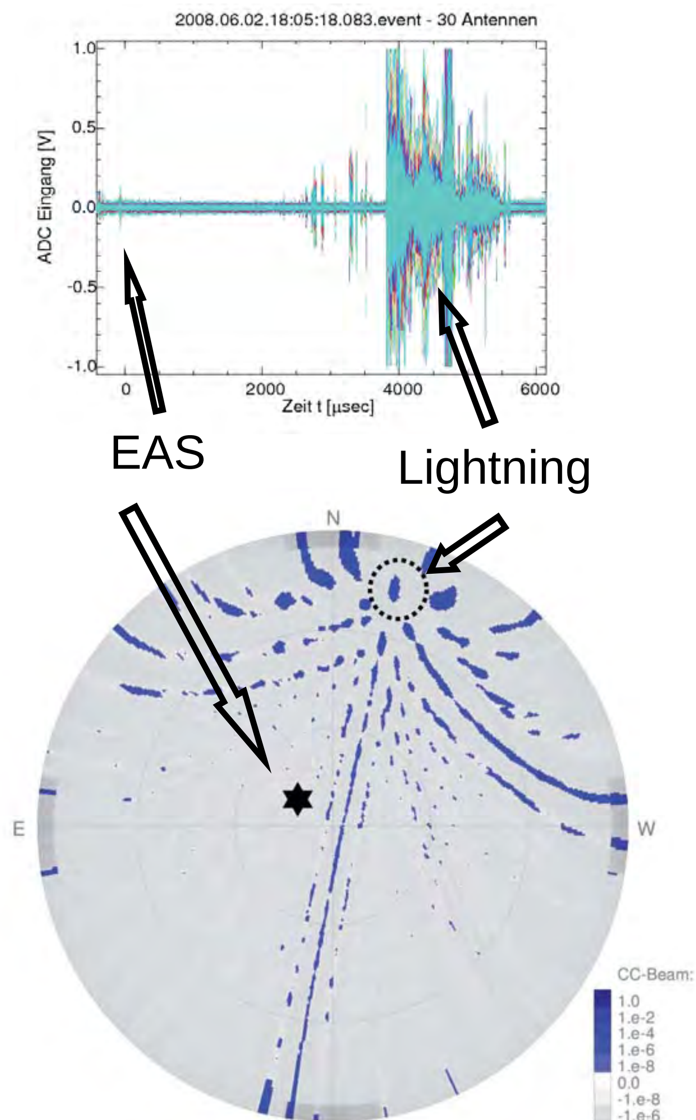
event B



- **Simulation of measured events**
- **REAS2 often too steep**
- **REAS3 fits well, explains also most flat events**

REAS3: Huege, Ludwig, Astroparticle Physics 2010
LOPES data: F.Schröder, PhD thesis, Feb 2011

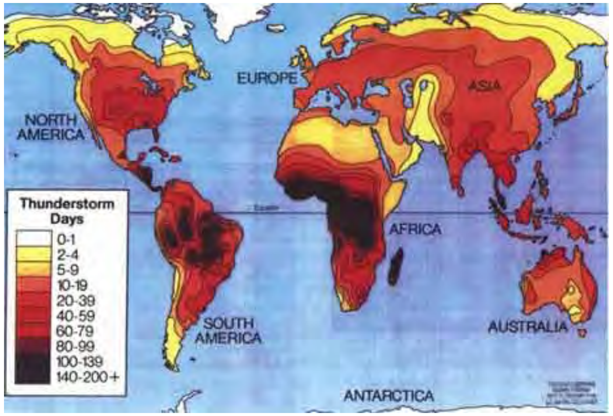
LOPES: Lightning vs. EAS



Cloud-to-cloud lightning

- **Problem: how lightning are initated?**
- **One solution: by EAS**

➔Radio good oportunity to measure lightning development



LOPES coll, accepted Advance Space Research (2011)

Connection particle array – radio array:

Radio detection technique is still in developing phase
hardware, software, analysis, emission mechanism(s?), … ➔
Calibration (understanding) radio emission
- **Dependencies of radio signal**
- **Understanding emission mechanism(s)**

Capability of the radio detection technique?

Sensitivity and resolution to

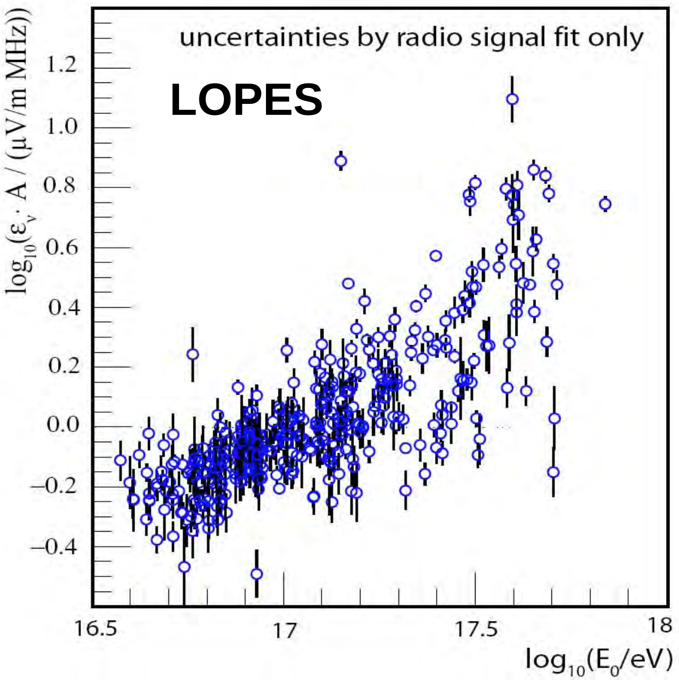
primary energy?
arrival direction?
composition ?

EAS radio detection for CR (and neutrino) measurements:

stand alone or hybrid technique?

Hybrid with particle arrays, not fluorescence technique (duty cycle).

Primary Energy



- **Radio-Emission seems coherent !**
- **Energy sensitivity via electric field strength**
- **Radio signal (electric field) scales with primary energy:**

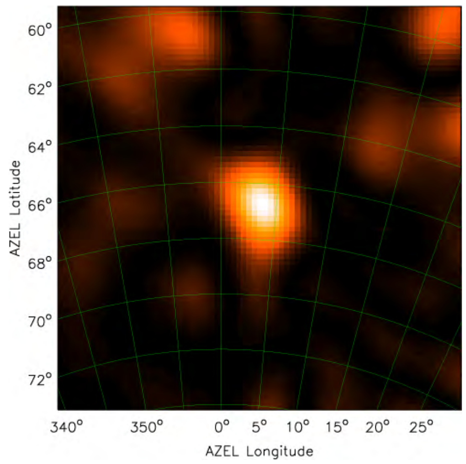
$$\varepsilon_\nu \sim E_0^{\approx 1}$$

➔**Power of electric field scales approximately quadratically with primary energy !**

- **Sensitivity and resolution** **$\Delta E/E \sim$ 20-25%**
- **Particle array: 10-20%**

➔ **is energy resolution really worse?**
Model dependence?
Emission mechanism?
Geometry of shower (polarization)?

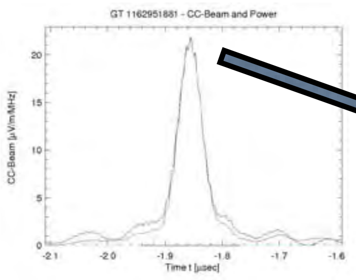
Arrival Direction



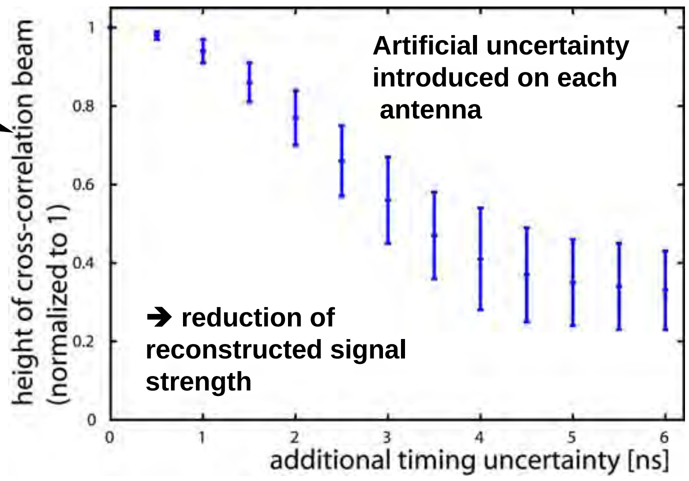
- sensitivity via pulse arrival time and phase
- systematic studies of direction resolution:
  KASCADE vs. LOPES: offset (1.3±0.8)°

➔ resolution better 1°

(by beam forming; Better with increasing field strength, but number of antennas?)



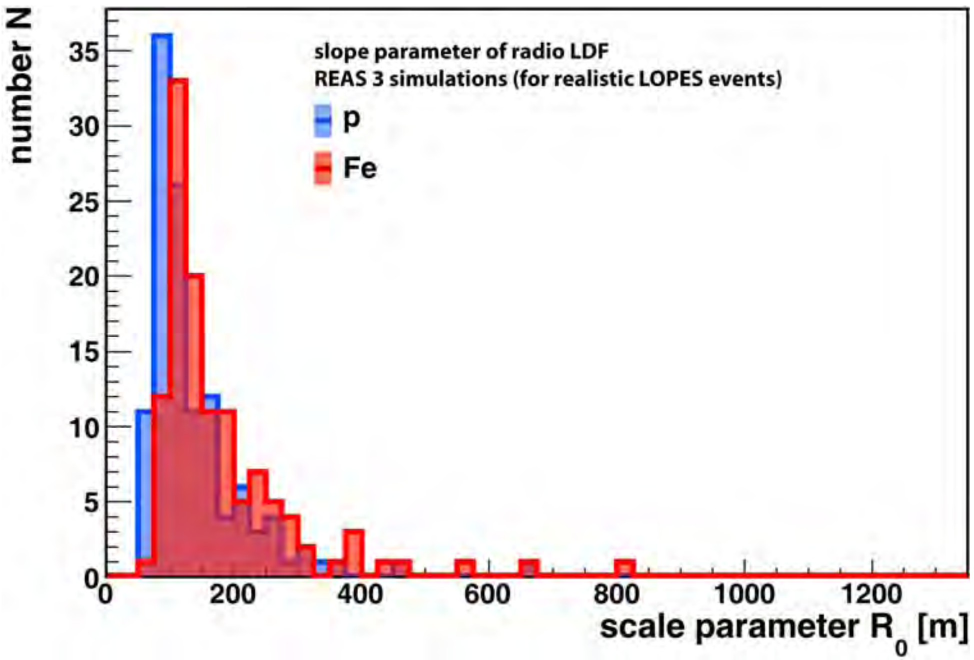
➔ ~1ns time resolution needed



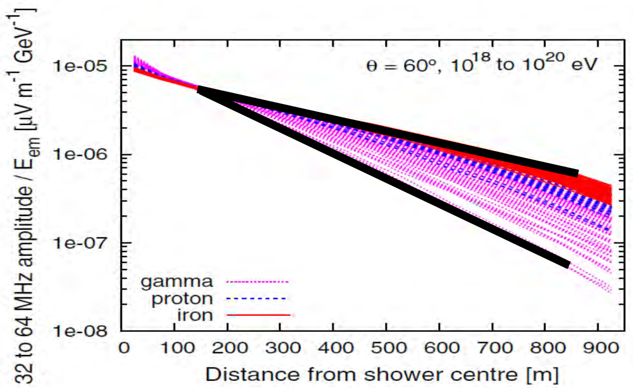
F.Schröder et al., NIM A 615 (2010) 277

- **Sensitivity and resolution** σ(direction) << 1°

Composition



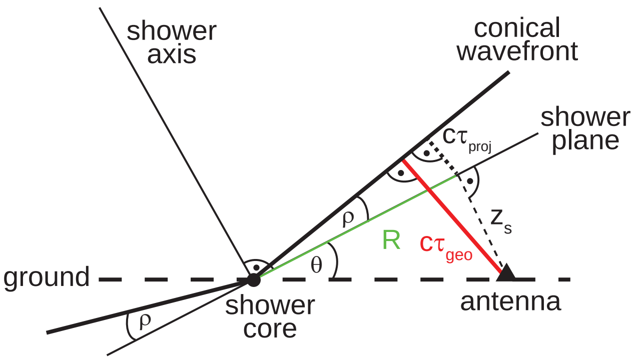
- Lateral distributions have composition sensitivity!
- model dependence?



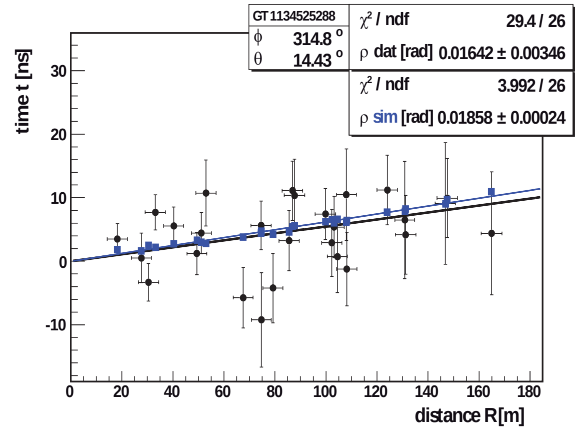
- Sensitivity and resolution ??
- Particle array: unknown (large) uncertainty (FD better)
  - ➔ by lateral sensitivity (pattern) ….seems possible
  - ➔ by longitudinal sensitivity:
    - pulse shape
    - wave front
    - frequency spectrum
    - ….

= Xmax (shower maximum) sensitivity needed!!

Composition II



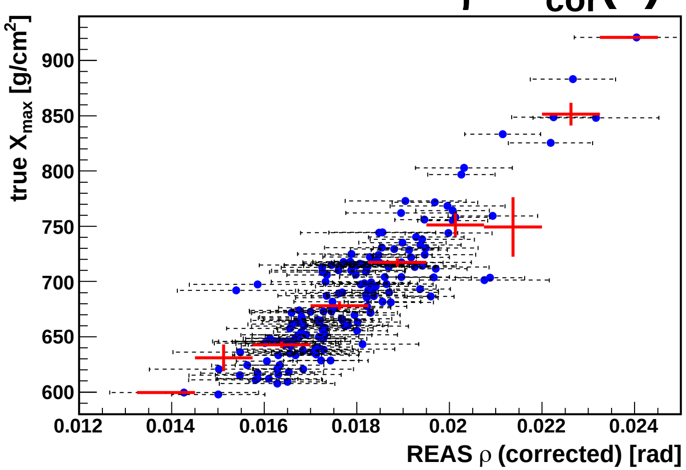
Cone parameter ρ,
geometrical delay τ_{geo},
lateral distance to shower axis R



Conical wave front good approximation in data and simulations!

- **wave front is conical and has composition sensitivity!**
- **model dependence?**
- **distance dependence?**

$X_{max} = const \cdot \rho \cdot f_{cor}(\theta)$



➔ **X_{max} (shower maximum) sensitivity is given**

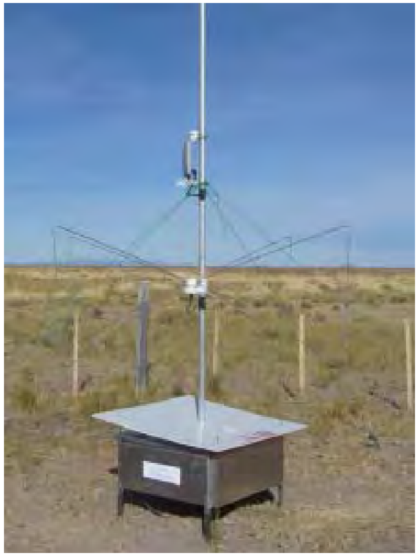
- **Resolution:**
  - **in REAS3: 30g/cm²**
  - **in LOPES: 200g/cm²**

F.Schröder, PhD thesis, Feb 2011

Present R&D studies

Self-triggered radio events observed at the Pierre Auger Observatory

See AERA talk later (B.Fuchs)

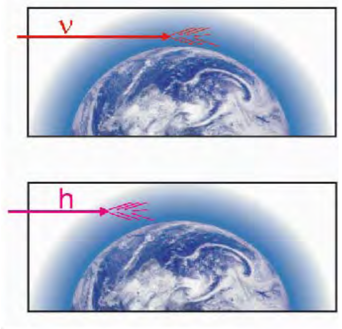


- **Optimizing Self Trigger Radio Detectors**
- **Antenna / Amplifier / Filter Design**
- **Electronics**
- **Data Communication**
- **Station layout**

Gemmeke et al, IEEE (2010)
Pierre Auger Collaboration, ICRC 2011

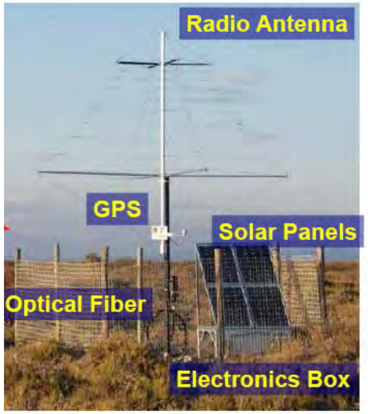
Next steps in R&D

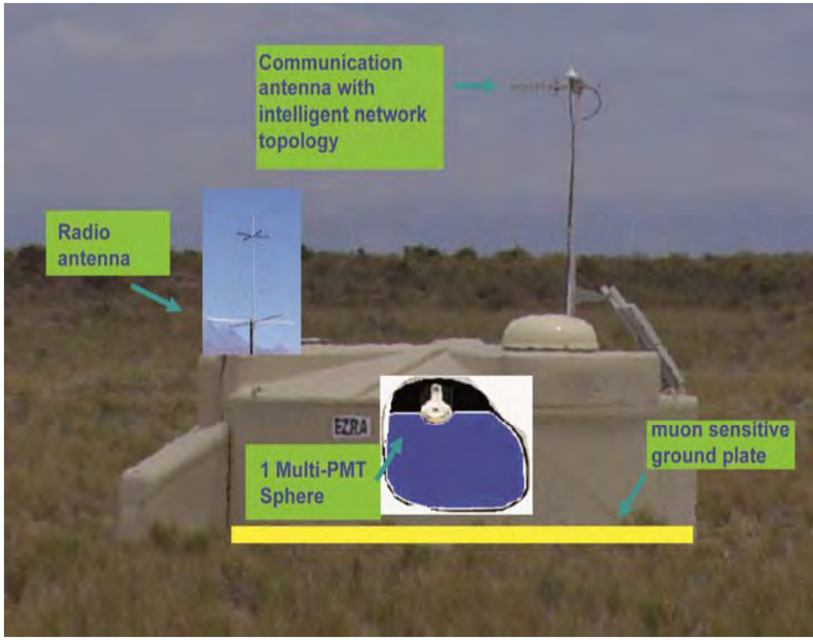
- **Horizontal sensitivity (for Neutrinos)**
- **Scalability of stations to hundreds of antennas**
- **Embedded radio detection in surface particle detectors**



>80º: sensitivity for neutrinos

>70º: 35% of the total solid angle: larger rate for charged cosmic rays





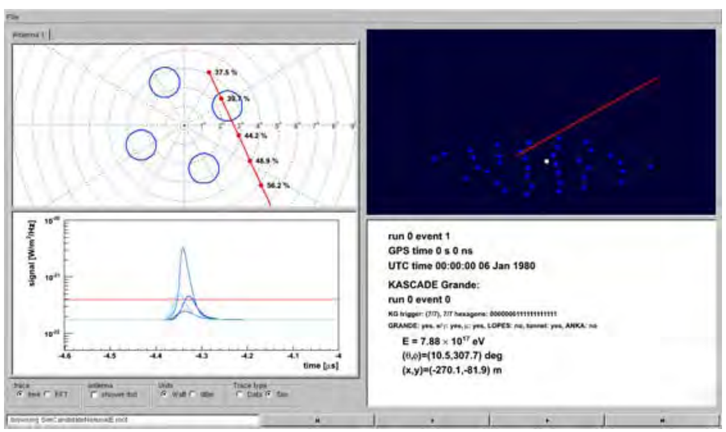
Workpackage of ASPERA „AugerNext“ innovtive R&D studies (second call)
➔ Start funding in 2011

EAS Radio detection: GHz range

See next ICRC!!

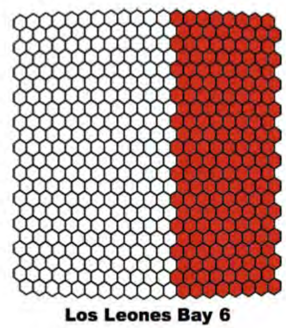
- **Signal might stem from molecular bremsstrahlung:**
  = incoherent, unpolarised, isotropic emission

e.g. CROME



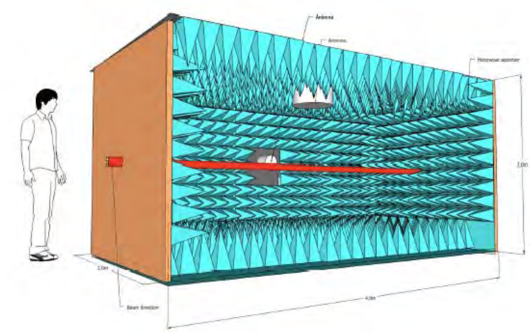
3 Setups using commercial satellite receivers triggered by KASCADE-Grande !

e.g. FDWave:



Replacing AugerFD PMTs by horn antennas
(V.Verzi, Roma)

e.g. AMY@Frascati:



850 MeV electrons
(V.Verzi, Roma)

More: AMBER, MIDAS, EASIER, . . .

➔ No EAS detection, yet

EAS Radio detection

- as new CR detection technique estblished $E_{threshold} \approx 10^{17}$eV
- successful and sensitive to
  - primary energy $\varepsilon \sim E_0^{\gamma}$ ($\gamma \approx 1$) $\Delta E/E \sim$ 20-25%
  - arrival direction beam forming resolution better 1º
  - composition LDF-slope; wave front $\Delta A/A$ still unknown
- still many question open to emission mechanism(s)

⇨ ***suitable for hybrid measurements ? yes!!***

As stand-alone technique? will see!!

Next: AERA@Pierre Auger Observatory / LOFAR / ANITA-CR optimization / TREND / IceCube surface Radio Array