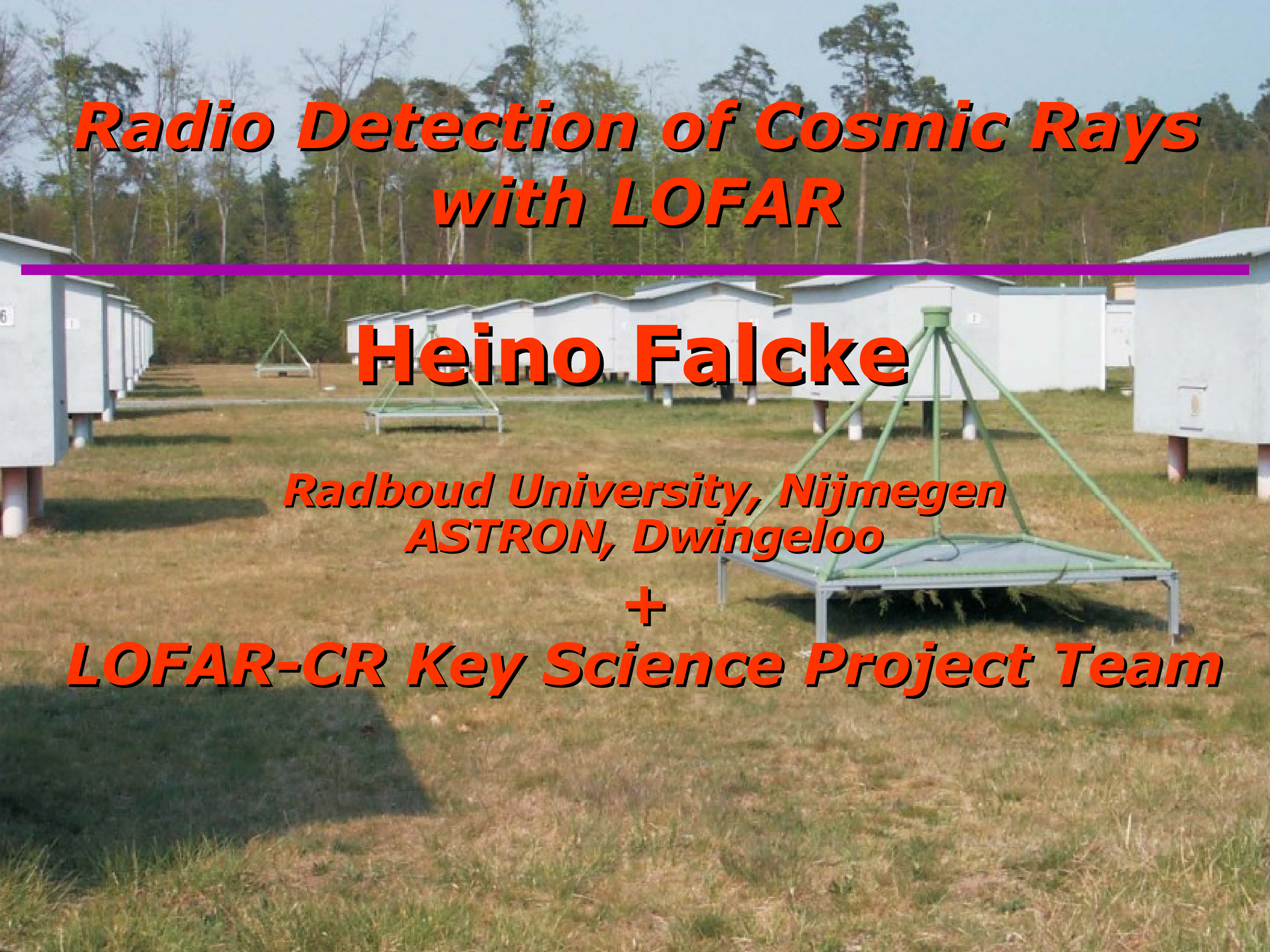
Radio Detection of Cosmic Rays with LOFAR

Heino Falcke

Radboud University, Nijmegen
ASTRON, Dwingeloo

+

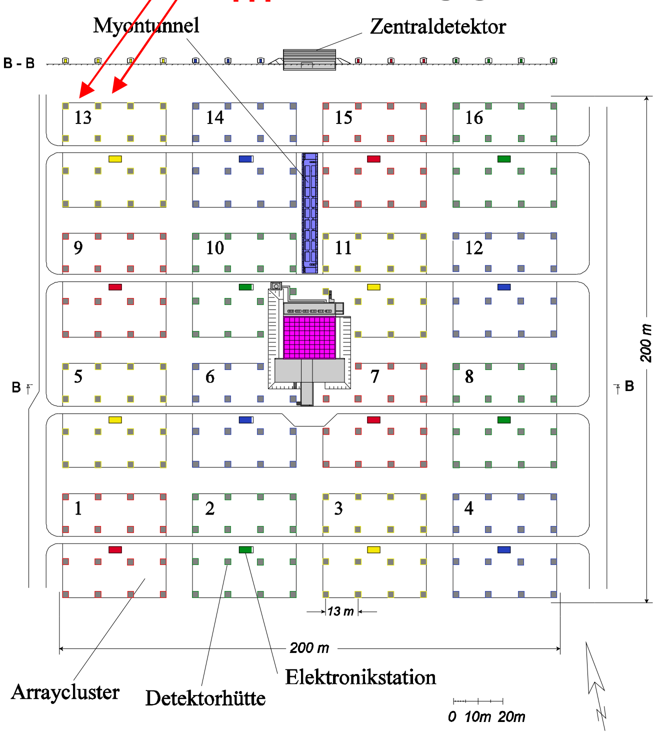
LOFAR-CR Key Science Project Team



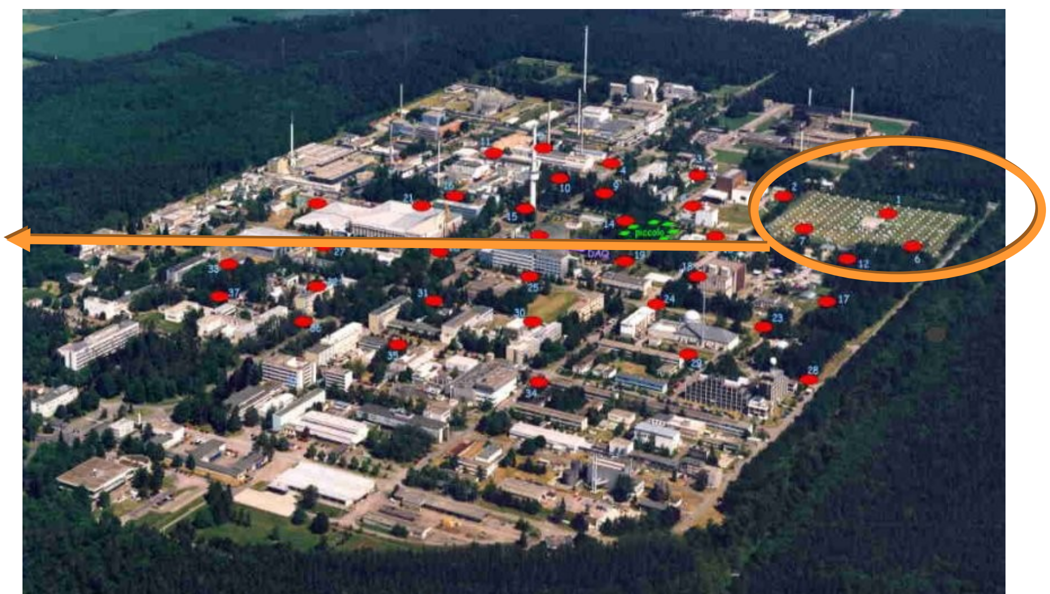
LOPES@KASCADE-Grande

...

KASCADE



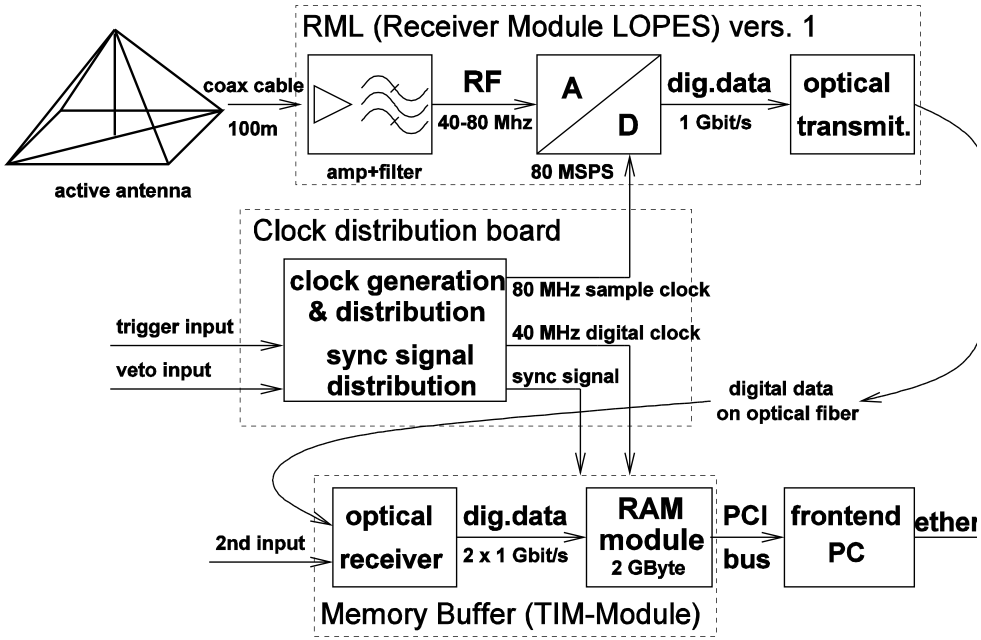
The red dots show the location of new particle detectors: expansion of KASCADE to KASCADE Grande



KASCADE Grande

Hardware of LOPES10

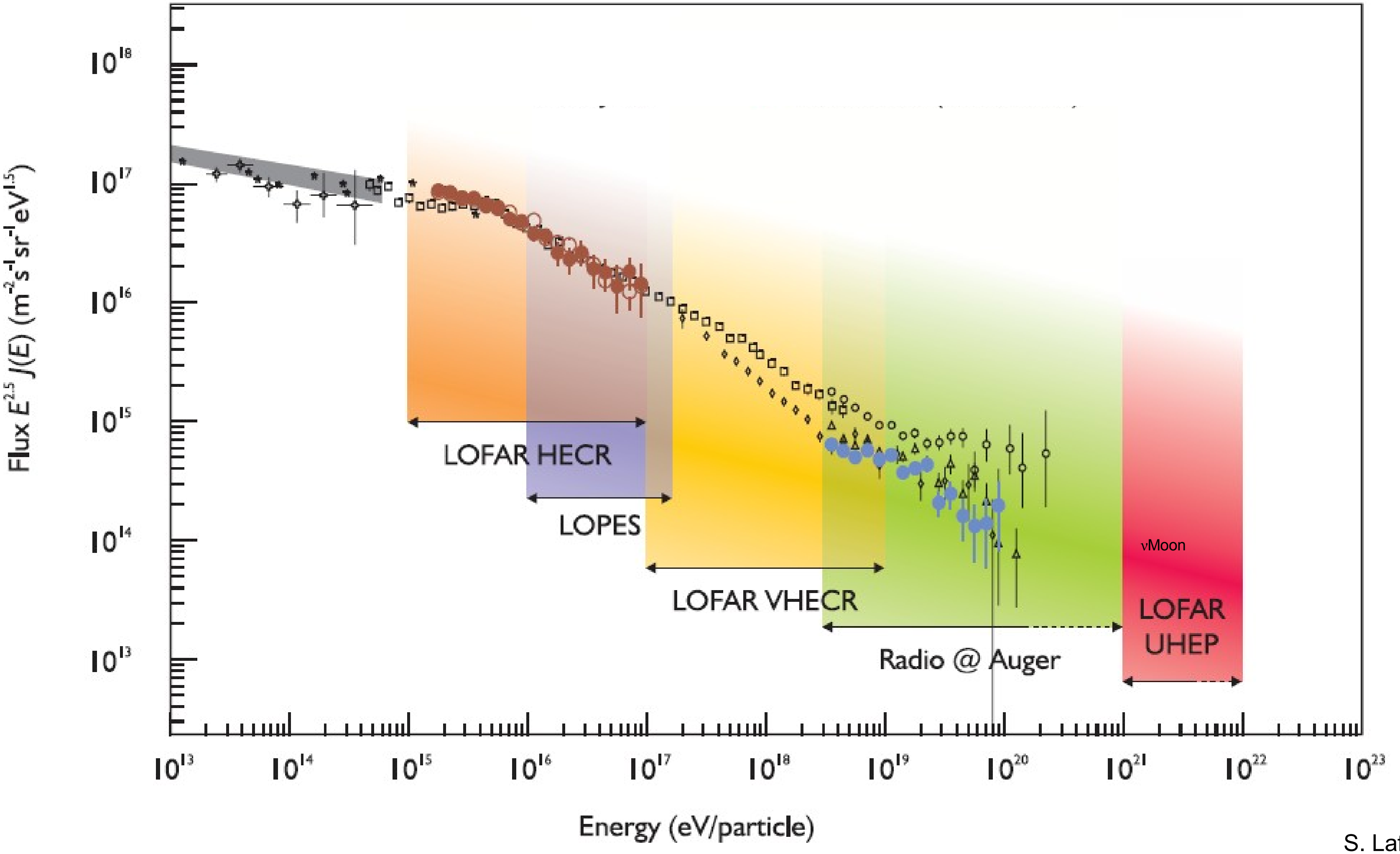
LOPES-Antenna



Horneffer 2004, PhD

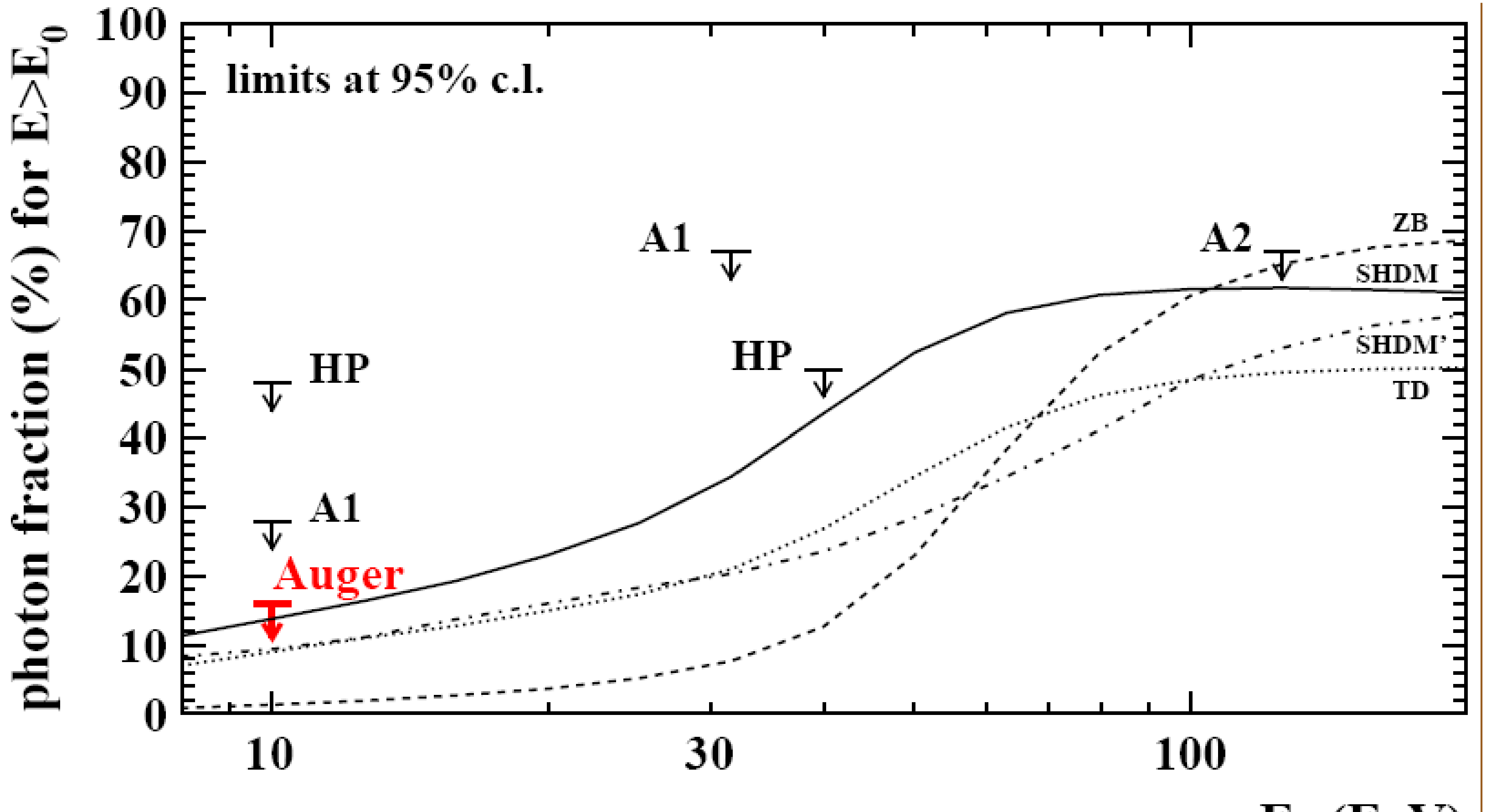

Radio at AUGER ….
van den Berg, KVI

Science Questions: Spectrum



S. Lafebre

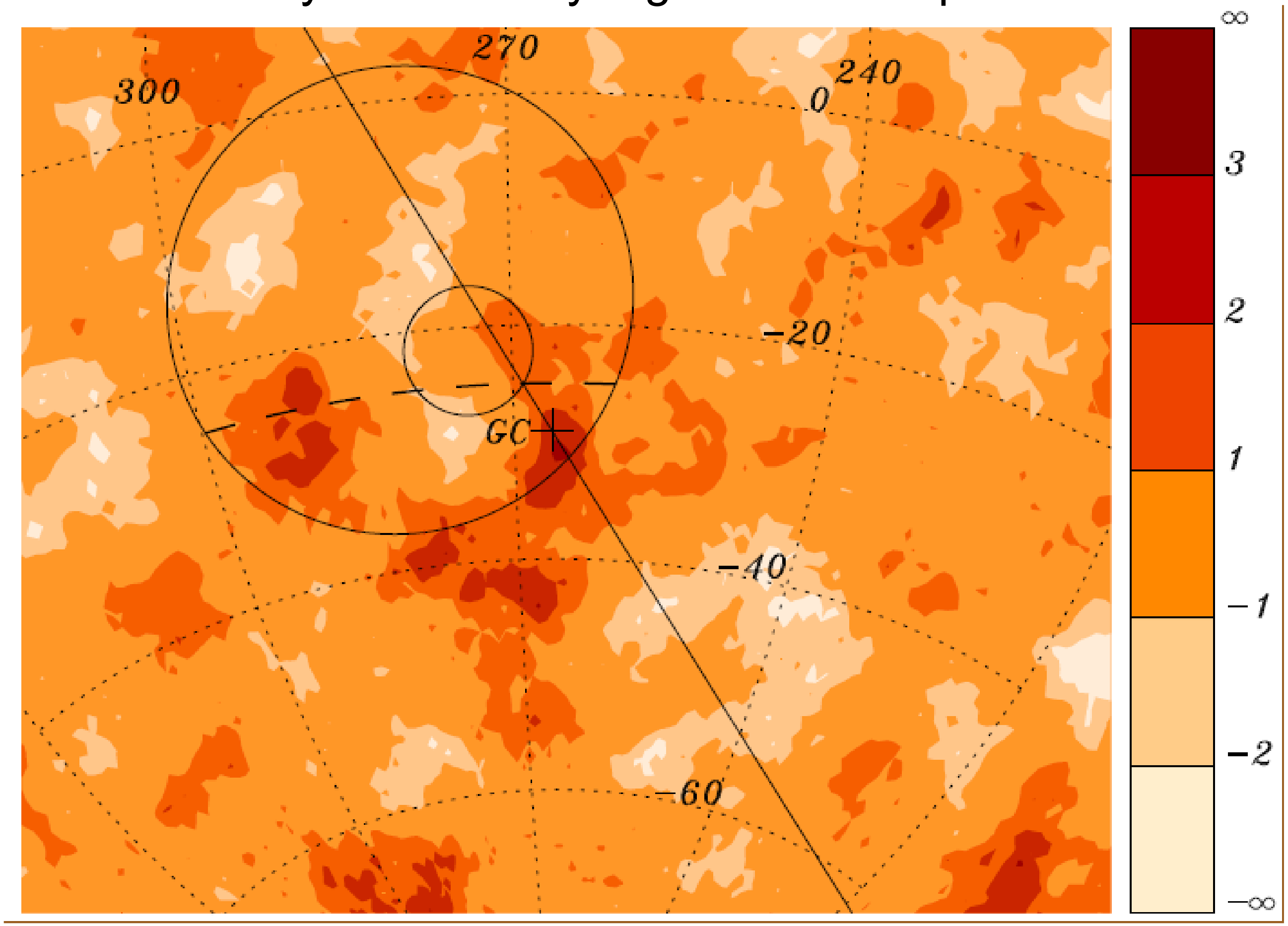
Science Questions: Composition



Auger Collaboration, Astropart. Phys. (2007)

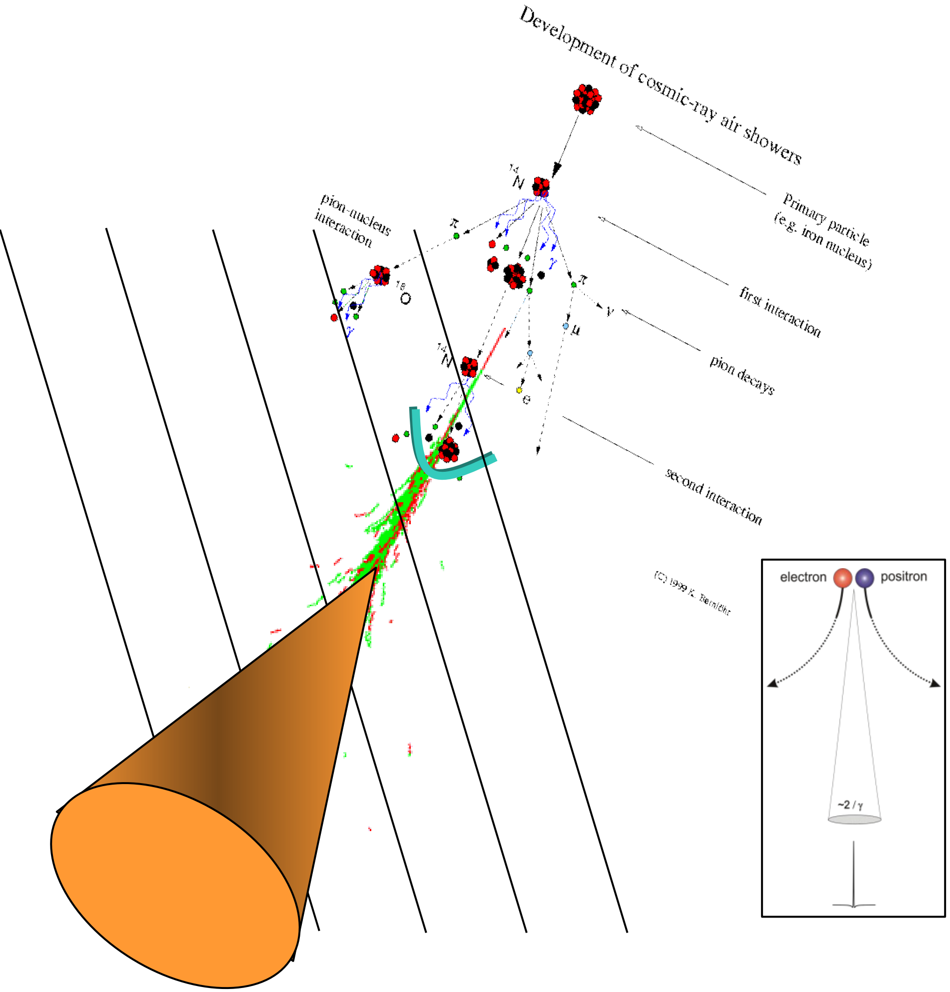
Science Questions: Clustering

Cosmic Ray Overdensity Significance Map at ~10^{18} eV



Auger Collaboration, Astropart. Phys. (2007)

Radio Emission from Extensive Air Showers (EAS)



- Cosmic Ray Air Showers produce radio pulses as electrons rush through the geomagnetic field via “geosynchrotron”.
- This is well detectable for showers above 10^{17} eV.

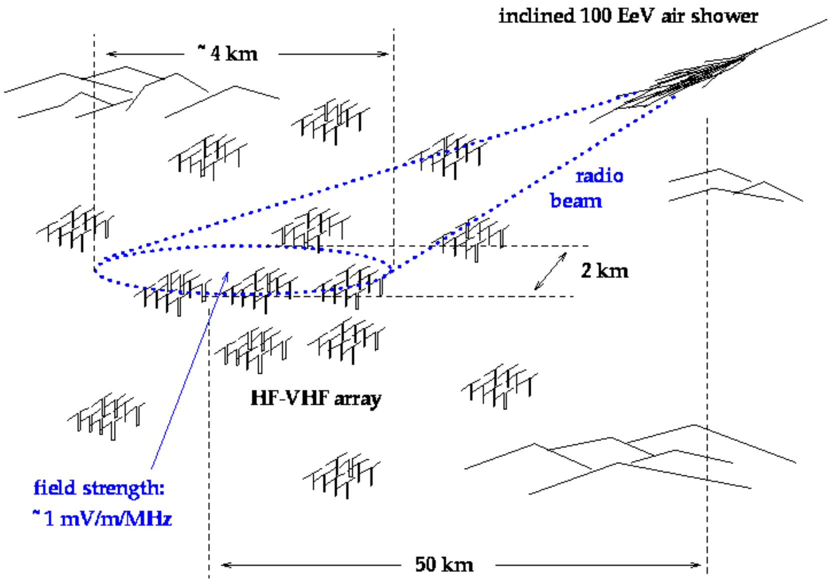
  (see Falcke & Gorham 2003; Huege & Falcke 2004; Allen 1973)

Astroparticle Physics: Radio Detection of Particles

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

Advantages of Radio Emission from Air Showers

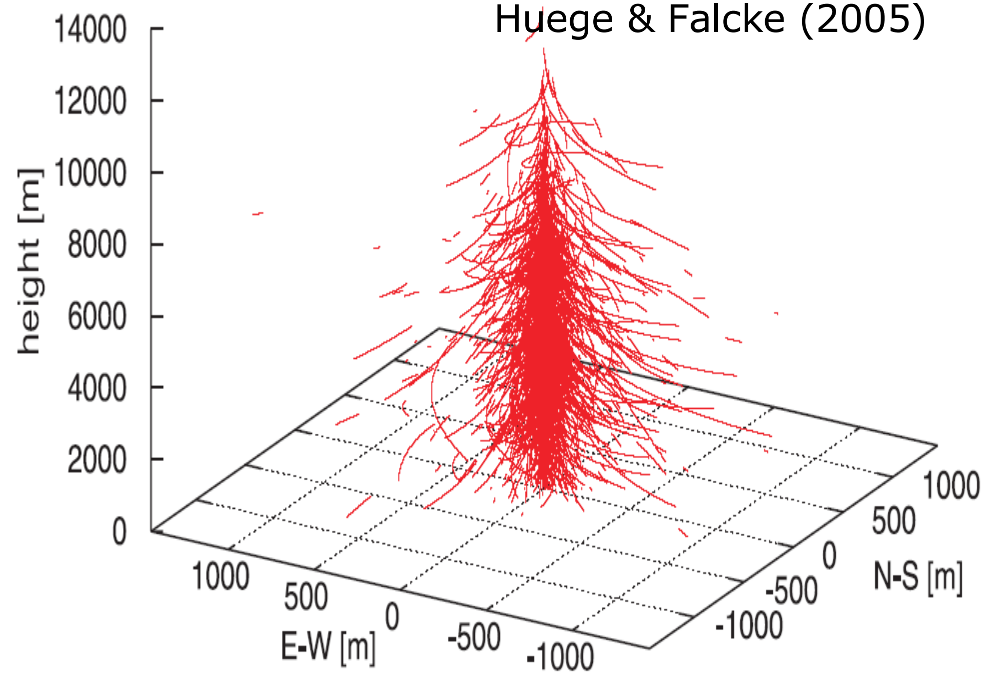
- High duty cycle (24 hours/day minus thunderstorms)
- Low attenuation (can see also distant and inclined showers)
- Bolometric measurement (integral over shower evolution)
- Also interesting for neutrinos
- Potential problems:
  - Radio freq. interference (RFI)
  - size of footprint
  - correlation with other parameters unclear
  - only practical above ~10^{17} eV.



Monte Carlo Simulations

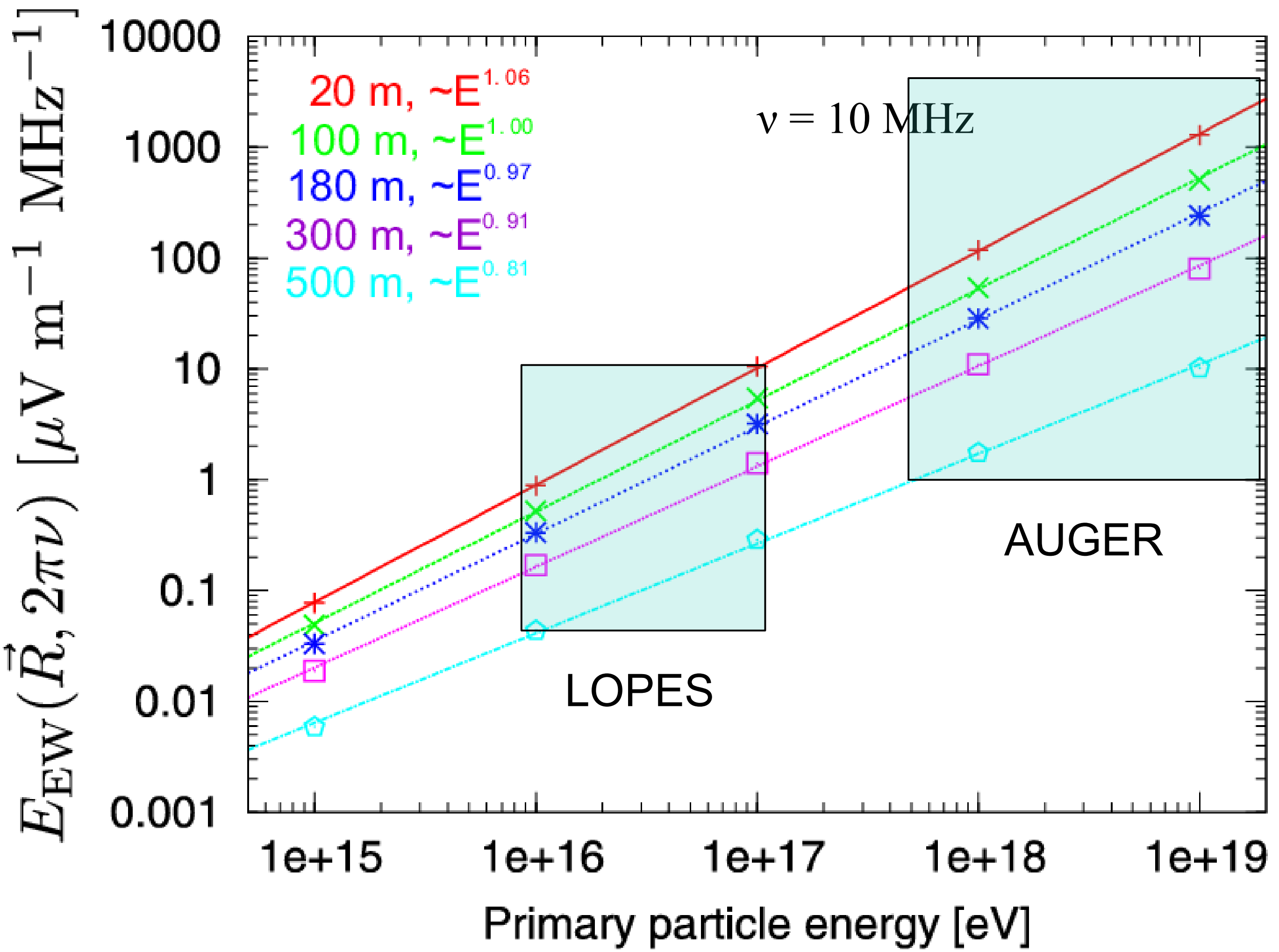
- time-domain MC
- no far-field approximations
- Maxwell Equations
- full polarisation inf.
- thoroughly tested
- Coupling to CORSIKA

Huege & Falcke (2005)



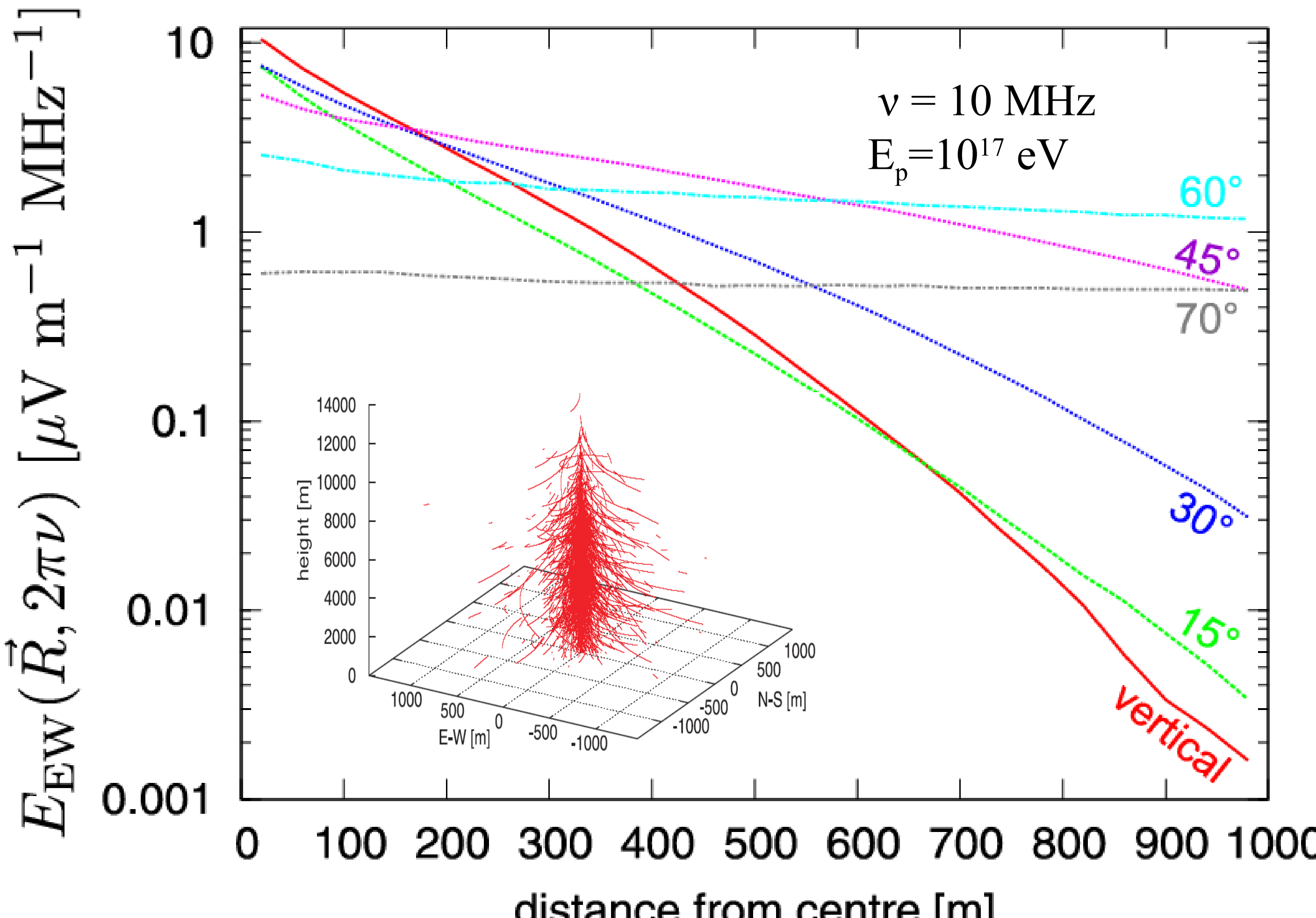
- Now:
  - Library of simulations produced on LOFAR Stella with CORSICA (S. Lafebre)
  - >3000 showers simulated (in progress)
  - Parametrization & coupling to radio code

Results: Scaling with E_p



- for 10 MHz
- nearly linear scaling
- Slightly flatter at higher distances
- Radio is bolometric

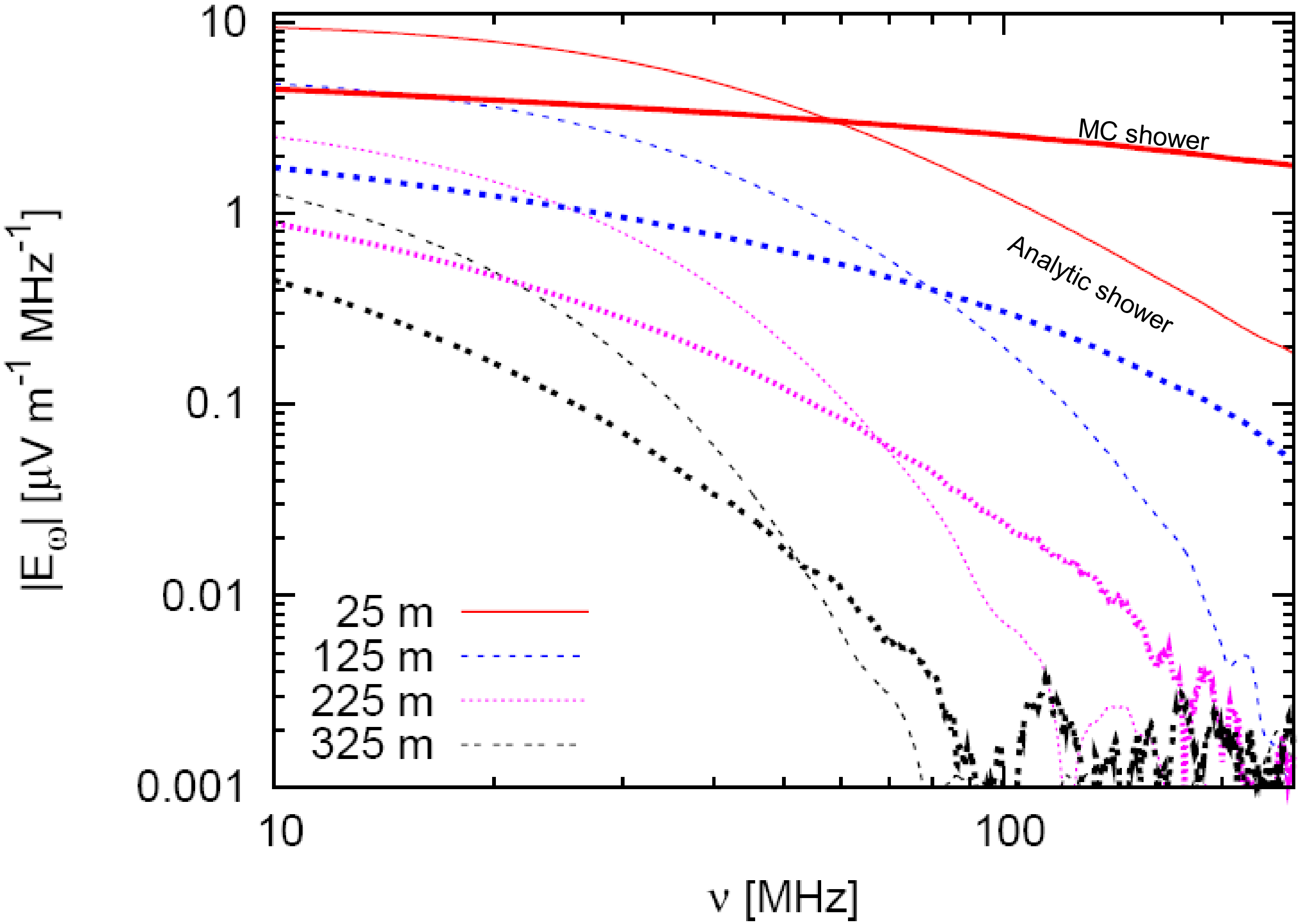
Radio Monte Carlo: Zenith Angle Dependence



- flattening with zenith angle
- Inclined showers can be seen to large distances

Huege & Falcke (2005)

Radio Monte Carlo: coupled to airshower code



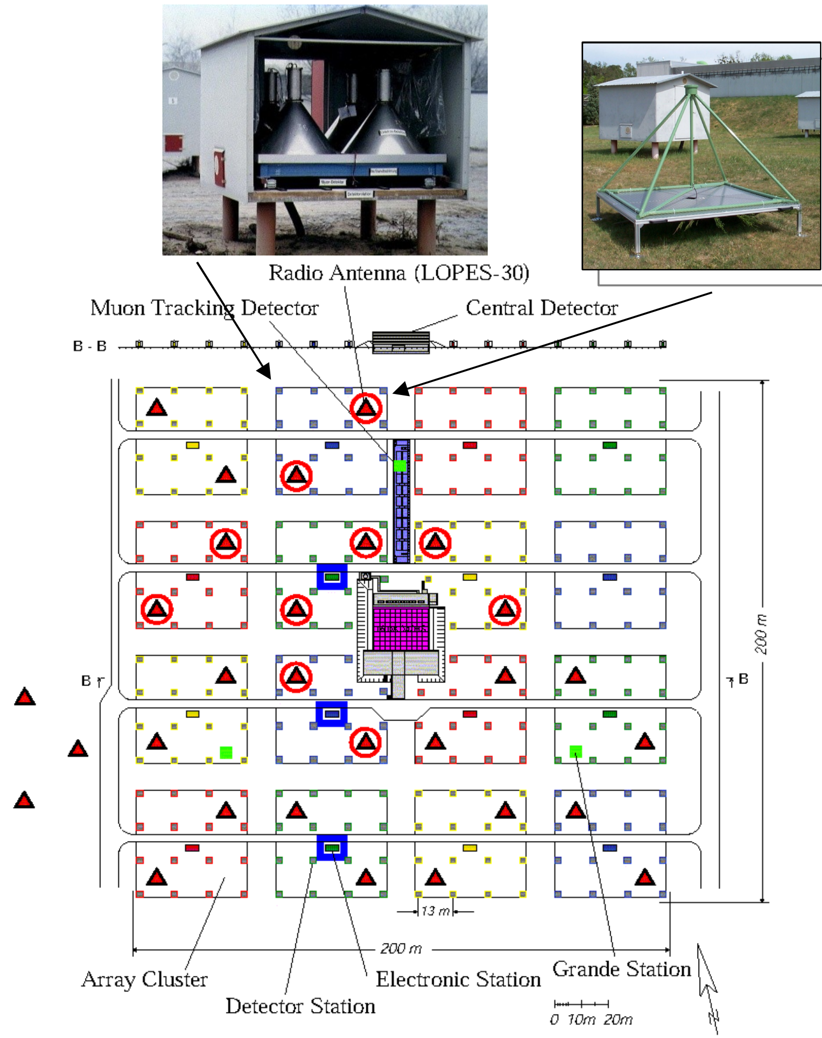
Huege et al. (2006)

- Thin lines: analytic showers
- Thick lines: MC showers

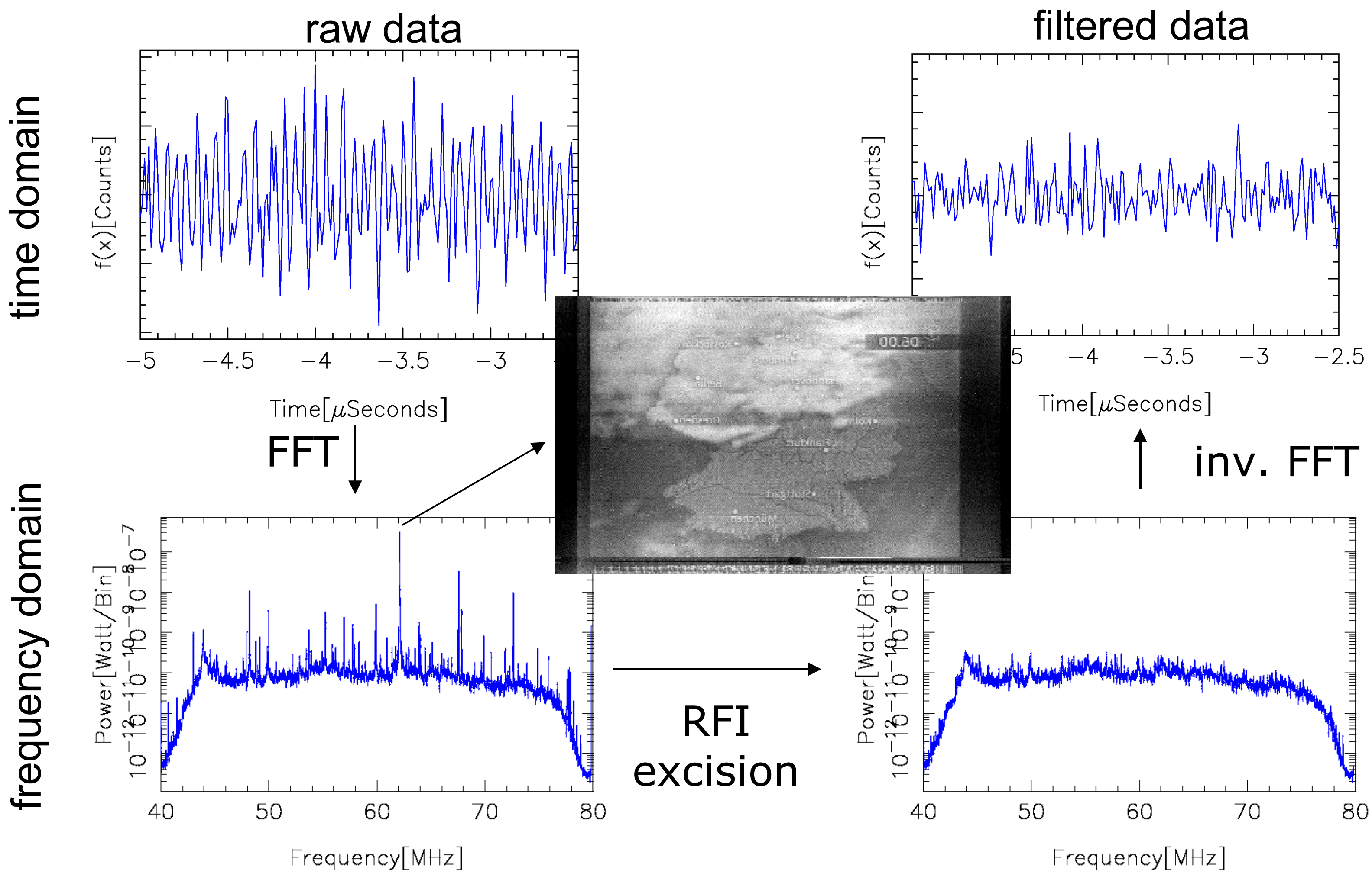
⇒Spectra extend to higher frequencies

LOPES:
LOFAR PrototypE Station

- 10 antenna prototype at KASCADE
  (all 10 antennas running)
- triggered by large event (KASCADE) trigger
  (10 out of 16 array clusters)
- offline correlation of KASCADE & LOPES
  (not integrated yet into the KASCADE DAQ)
- KASCADE can provide starting points for LOPES air shower reconstruction
  - core position of the air shower
  - direction of the air shower
  - size of the air shower
- Now: 30 antennas have been installed and take data
- Software and data archive on multi-TB raid system
- >1 Million events in database



Digital Filtering

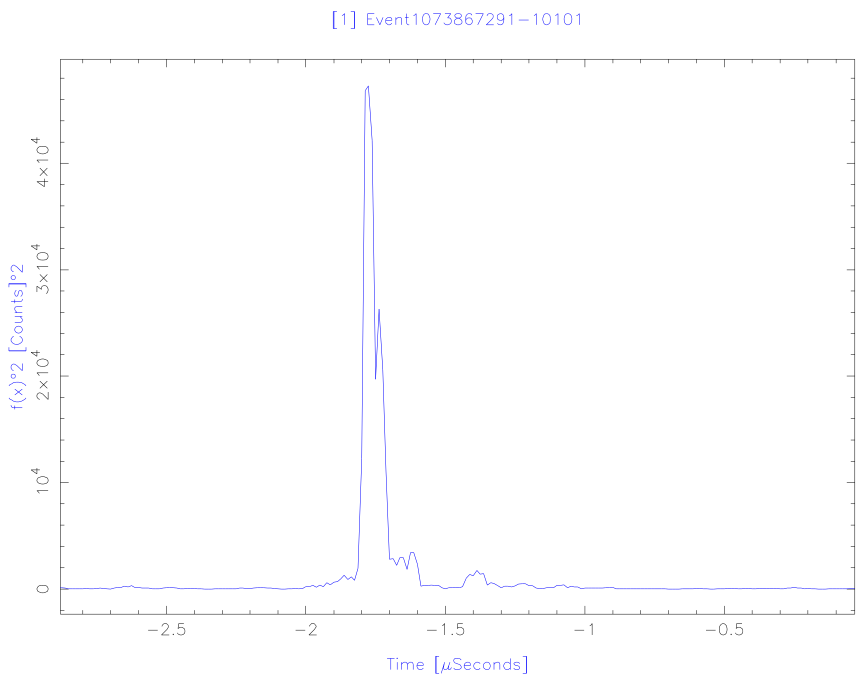


January 2004: First detection of CR radio pulse by LOPES

- Strong coherent radio pulse coincident with air shower
- All-sky radio-only mapping
  - Imaging (AZ-EL) with time resolution of 12.5 ns
  - Total duration is ~200 ns
  - No cleaning was performed, side lobes still visible
  - Location of burst agrees with KASCADE location to within 0.5°.

⇒ First detection of Cosmic Ray radio pulse in "modern times", with highest temporal and spatial resolution ever achieved.

⇒ Shows direct association of radio with shower core



Falcke et al. (LOPES collaboration) 2005, Nature, 435, 313

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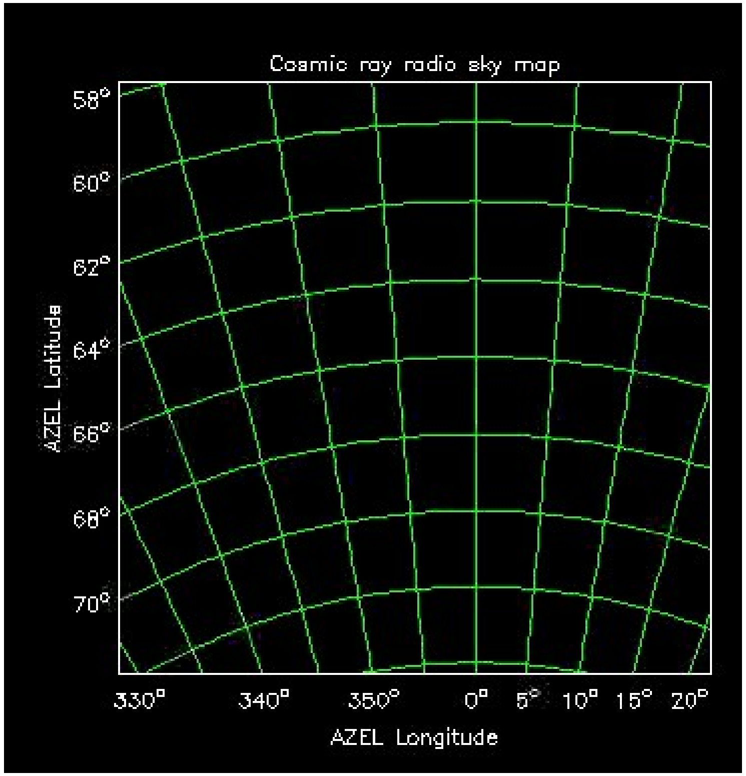
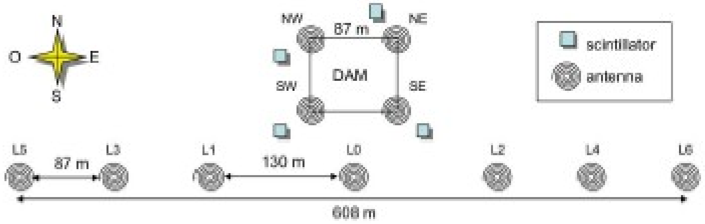
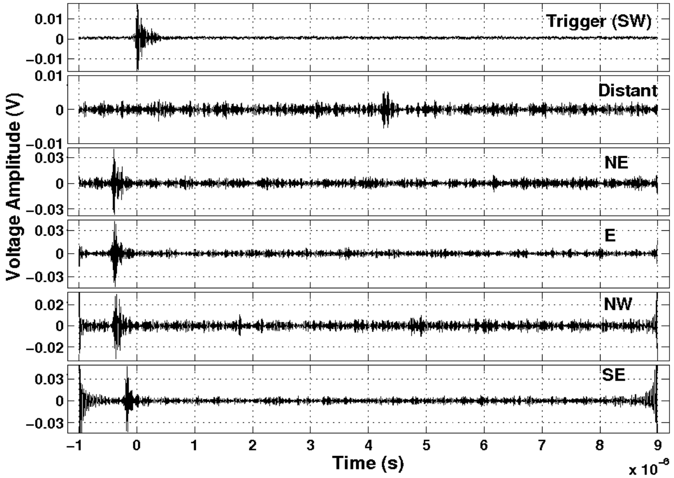


Falcke et al. (LOPES collaboration) 2005, Nature, 435, 313

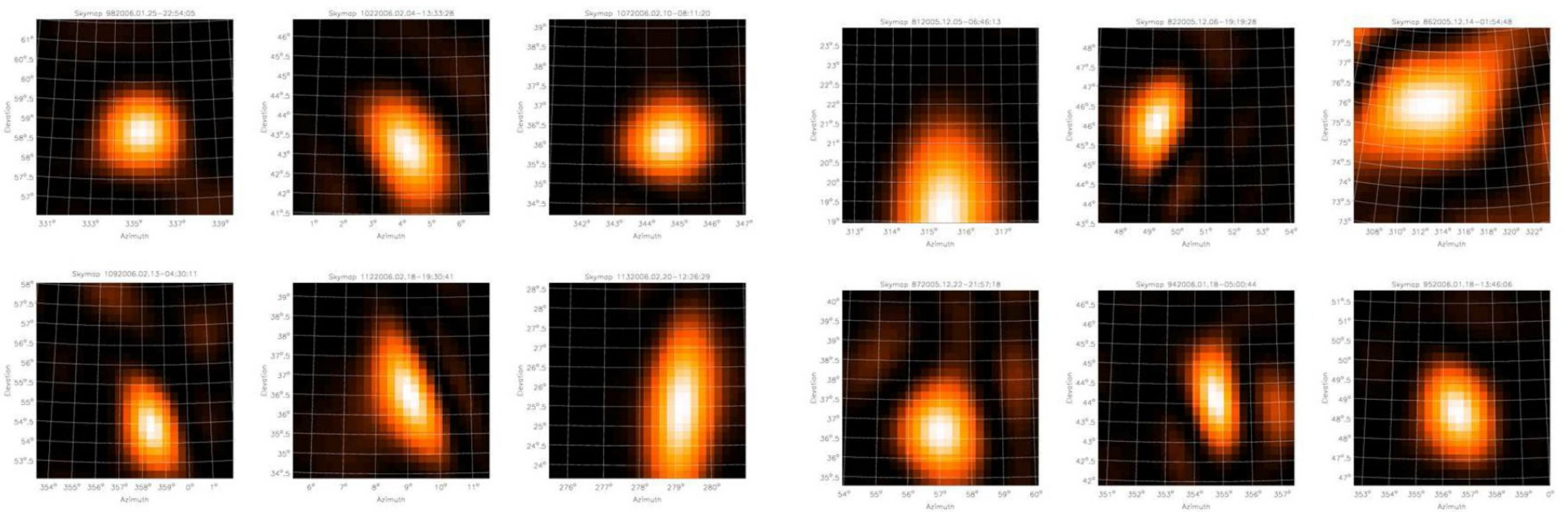
Detections Confirmed by Codalema (Nancay Observ.)



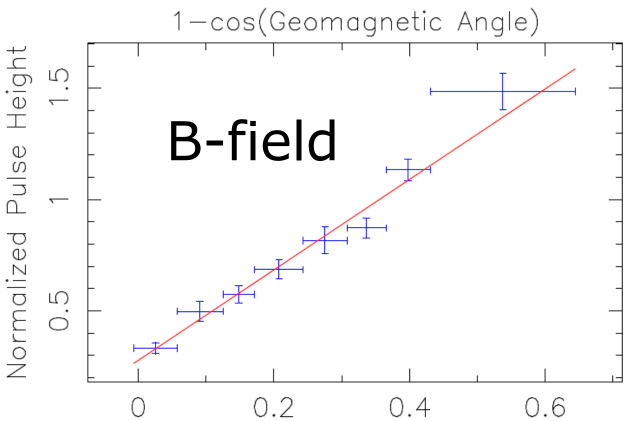


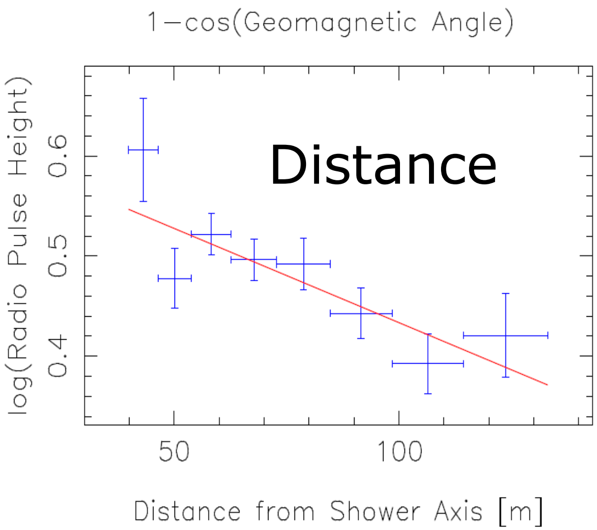
Ardouin et al. (2005)

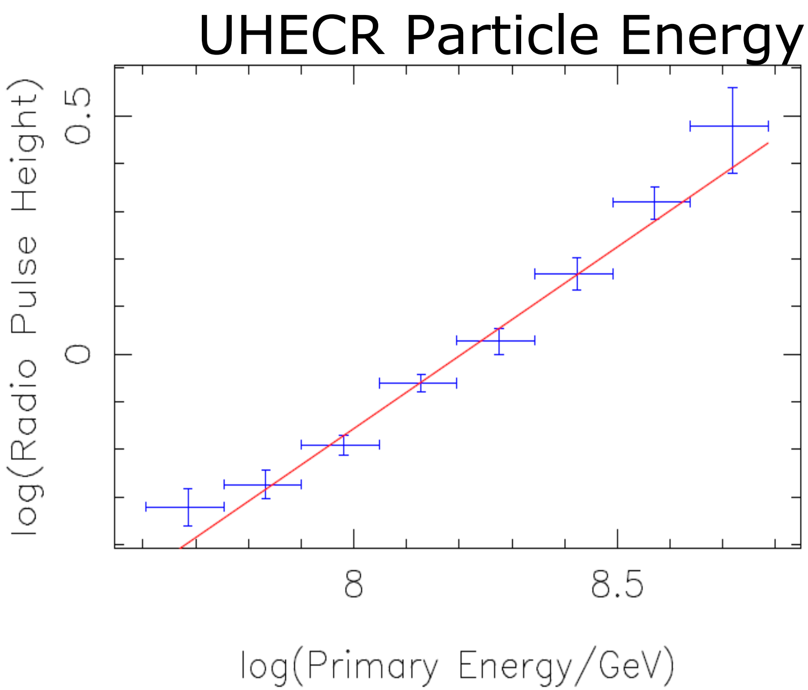
More events …


Skymap 982006.01.25-22:54:05
Skymap 1022006.02.04-13:33:28
Skymap 1072006.02.10-08:11:20
Skymap 812005.12.05-06:46:13
Skymap 822005.12.06-19:19:28
Skymap 862005.12.14-01:54:48
Skymap 1092006.02.13-04:30:11
Skymap 1122006.02.18-19:30:41
Skymap 1132006.02.20-12:26:29
Skymap 872005.12.22-21:57:18
Skymap 942006.01.18-05:00:44
Skymap 952006.01.18-13:46:06
Elevation
Azimuth

Calibration of CR Radio Signal with LOPES10

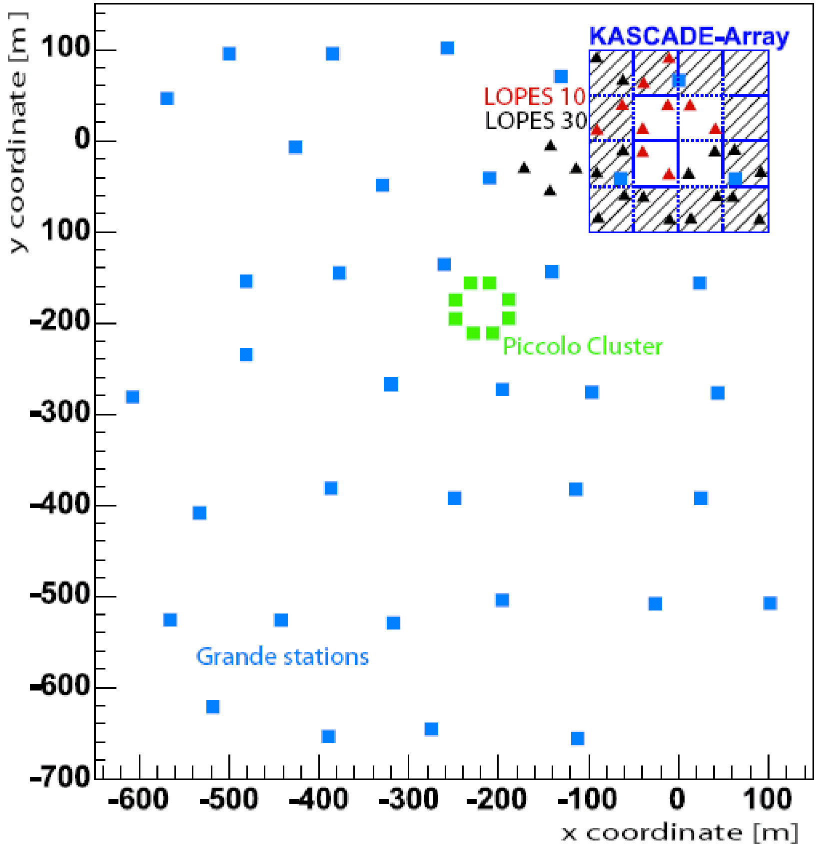




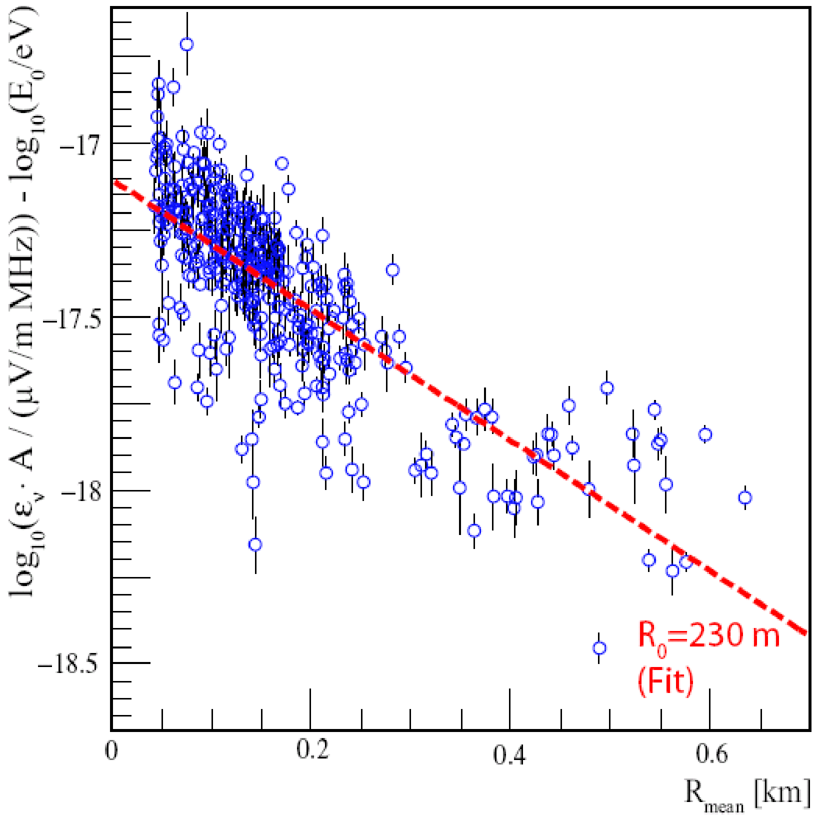


Horneffer 2006, PhD

LOPES & KASCADE Grande

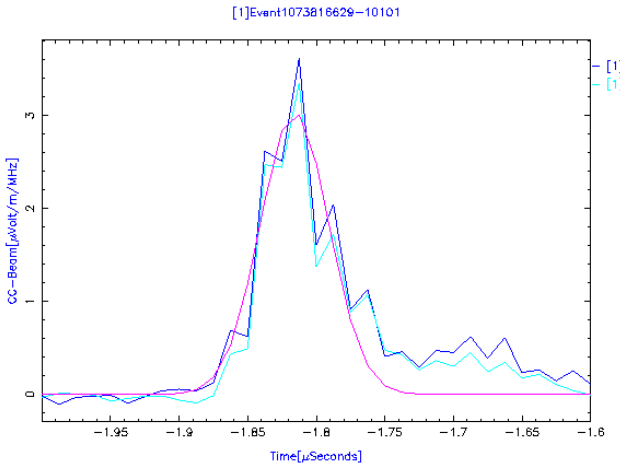


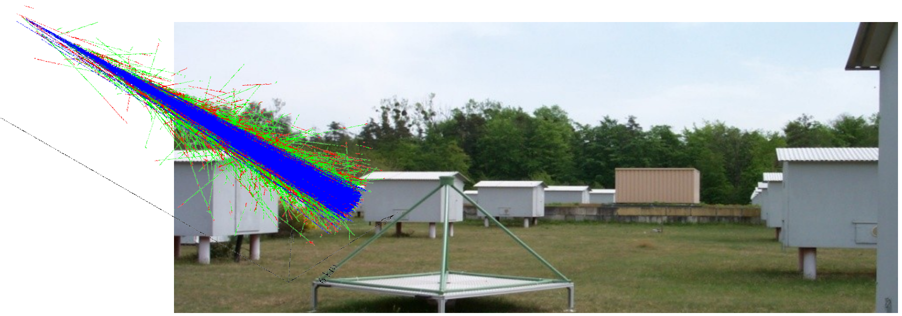
(not corrected for geomagnetic angle)

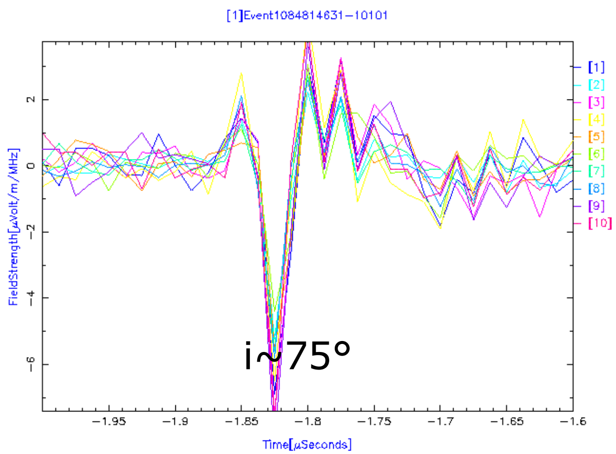


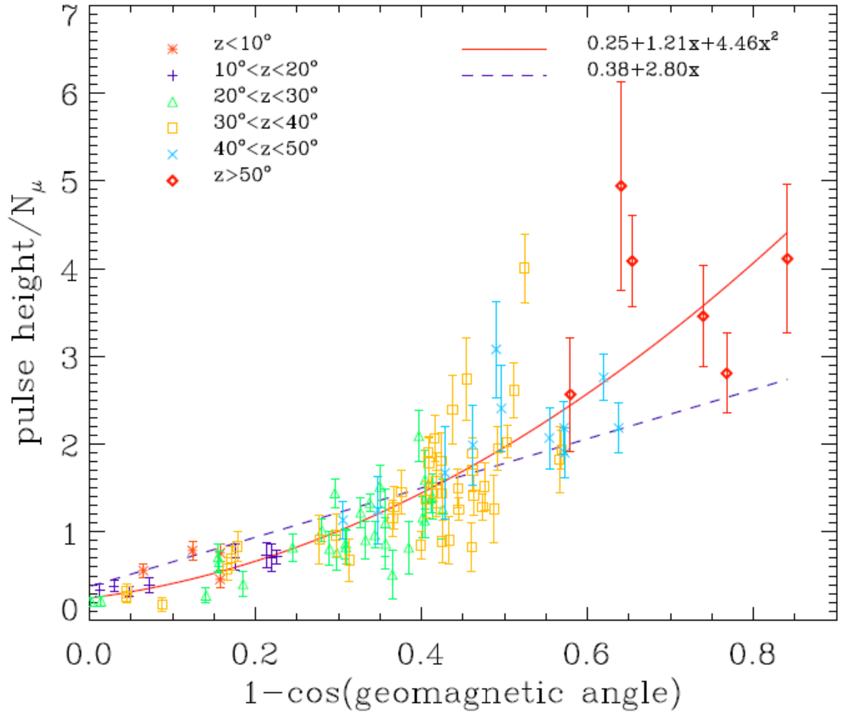
Haungs et al. 2006; Badea et al. 2005; Apel et al. (LOPES coll.), Astropart.Phys. 2006

Inclined Showers (i=50-90°)









Coherent airshower signal over 250 ns …

J. Petrovic et al. (LOPES Coll.), A&A, subm.

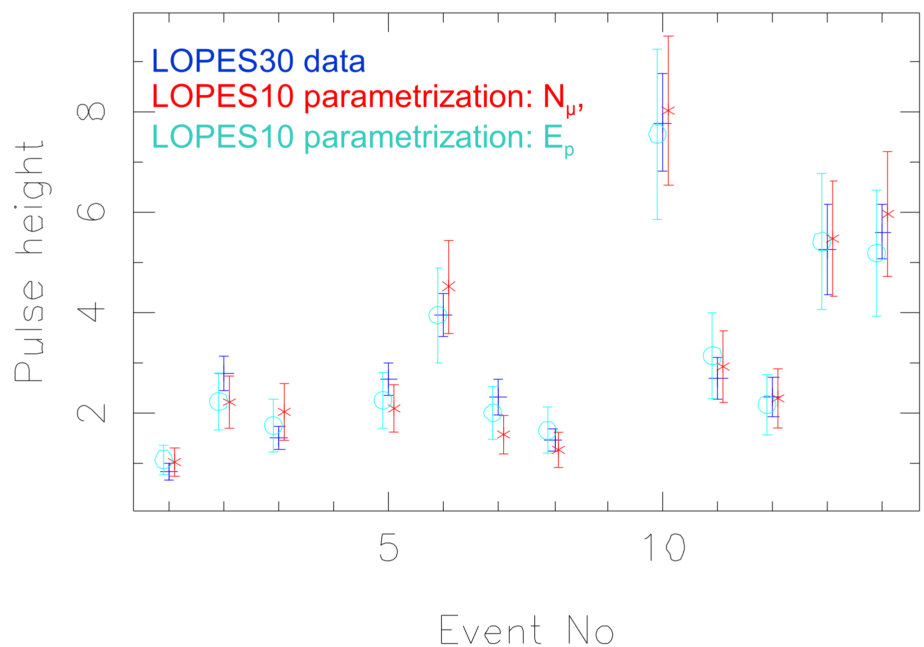
Parametrization & absolute Calibration

$$\epsilon_{\mathrm{est}} = (6.5 \pm 1.1) \left[\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\right] \times (1 + (0.1 \pm 0.02) - \cos\alpha) \cos\theta$$
$$\times \exp\left(\frac{-\mathrm{R_{SA}}}{(200 \pm 70)\,\mathrm{m}}\right) \left(\frac{\mathrm{E_p}}{10^{17}\mathrm{eV}}\right)^{(0.94 \pm 0.06)}$$

preliminary!

Horneffer 2006, PhD thesis

based on new absolute flux calibration and one (NS) polarization

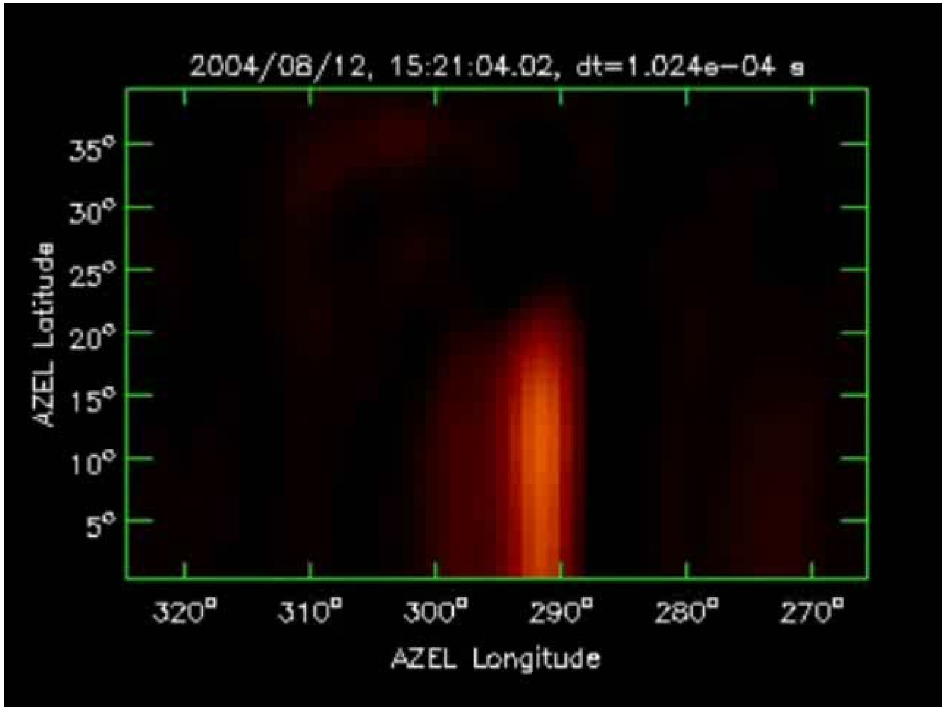


Terrestrial Transients: Lightning with ITS

Actual time span: 25 ms, 0.1ms/frame

Playing time: 31 sec

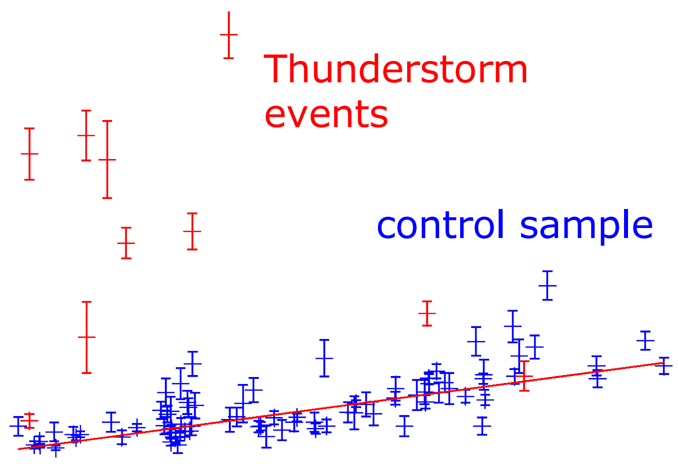
Frequency: 23-26 MHz



Bähren/Falcke (ASTRON)

Thunderstorm Events

- Does the Electric field of the atmosphere influence CR radio signal?
- For E>100 V/cm E-field force dominates B-field:
  - Fair weather: E=1 V/cm
  - Thunderstorms: E=1 kV/cm
- Select thunderstorm periods from meteorological data:
  - ⇒ Clear radio excess during thunder storms
  - ⇒ B-field effect dominates under normal conditions
  - ⇒ >90% duty cycle possible



Buitink et al. (LOPES coll.) 2006, A&A, subm.

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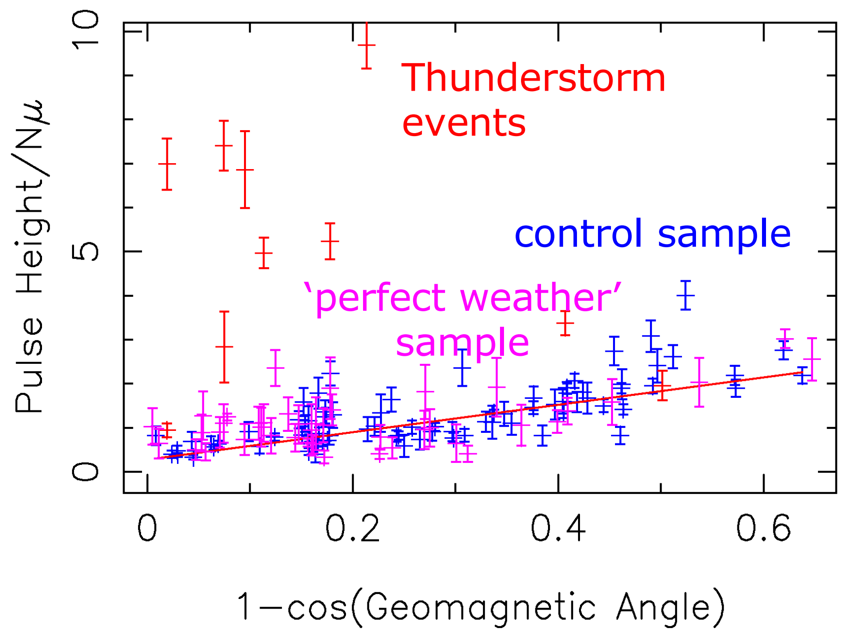
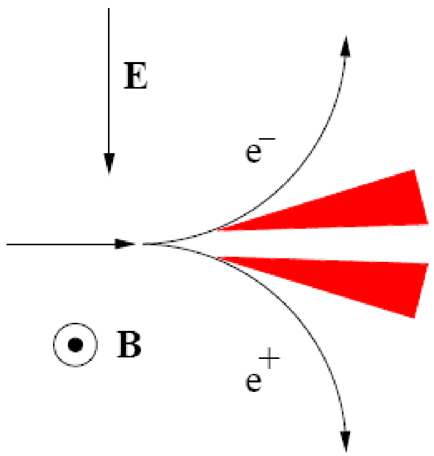
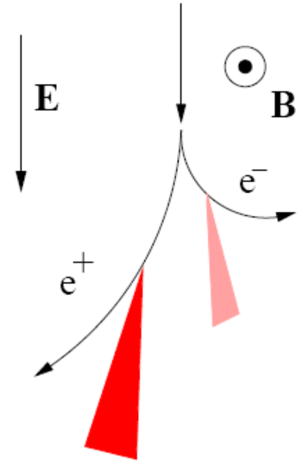


Buitink et al. (LOPES coll.) 2006, A&A, subm.

Interpretation: electric acceleration of secondary $e^{\pm}$

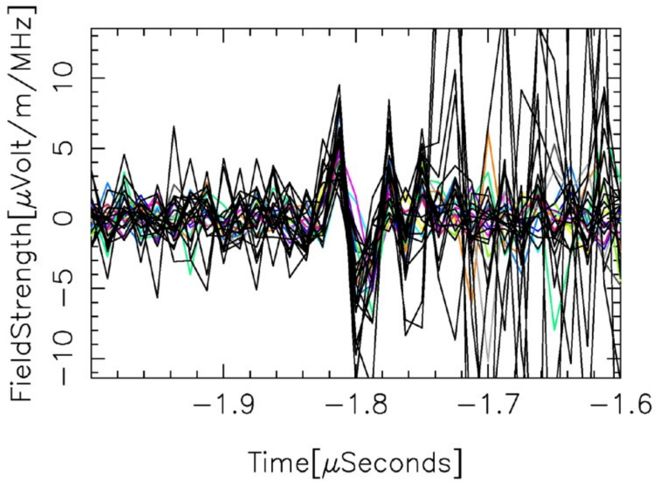
- Electric fields have two main effects depending on geometry:
  - Additional curvature of $e^{\pm}$ (similar to B-field)
  - Linear amplification of $e^{\pm}$ (higher energy)
- Both effects can in principle give amplification factors of radiation of several tens under thunderstorm conditions!
- Detailed MC under way.

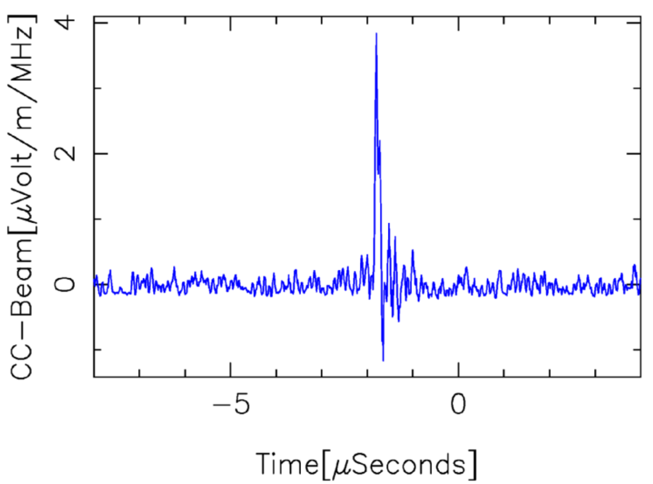


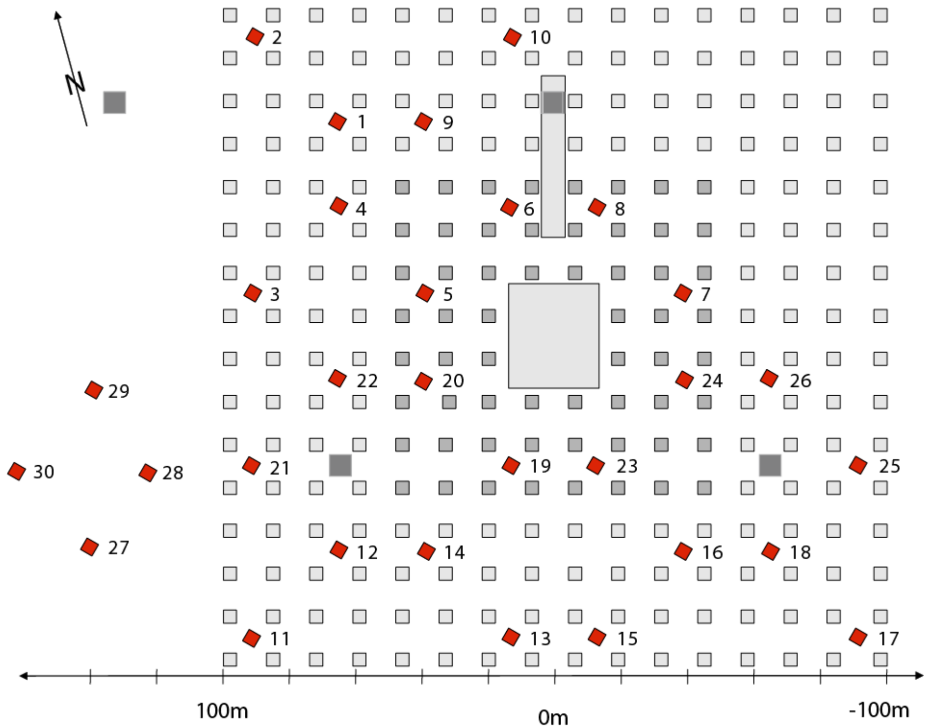


Buitink et al. (LOPES coll.) 2006, A&A, subm.

First Event with LOPES30





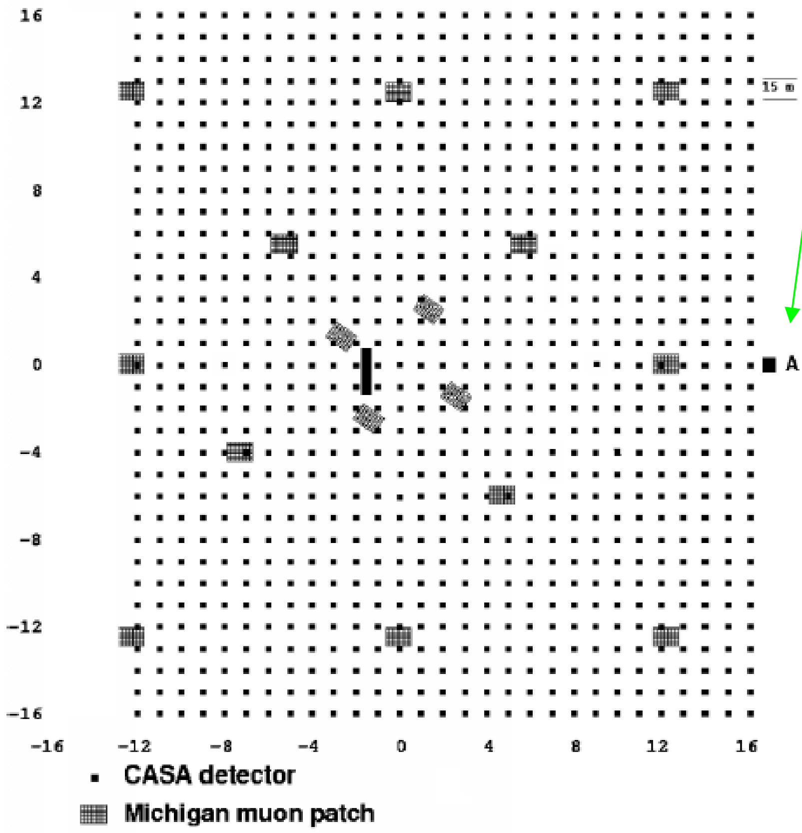


Recent Radio Experiments

EAS-Top (Gran Sasso)

CASA/MIA (Utah)

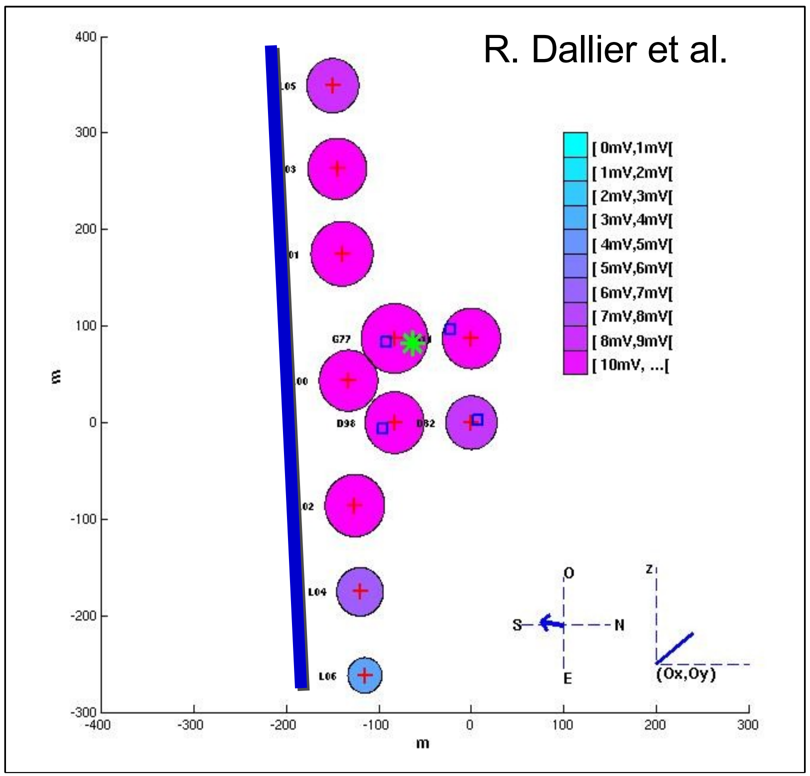
Single 8 bit Antenna

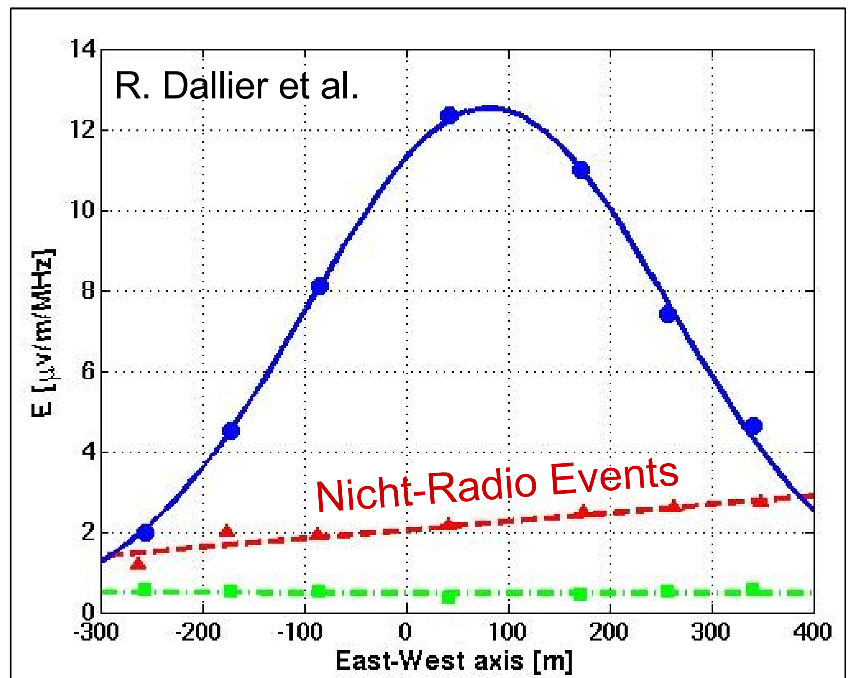


Green et al. (2002)

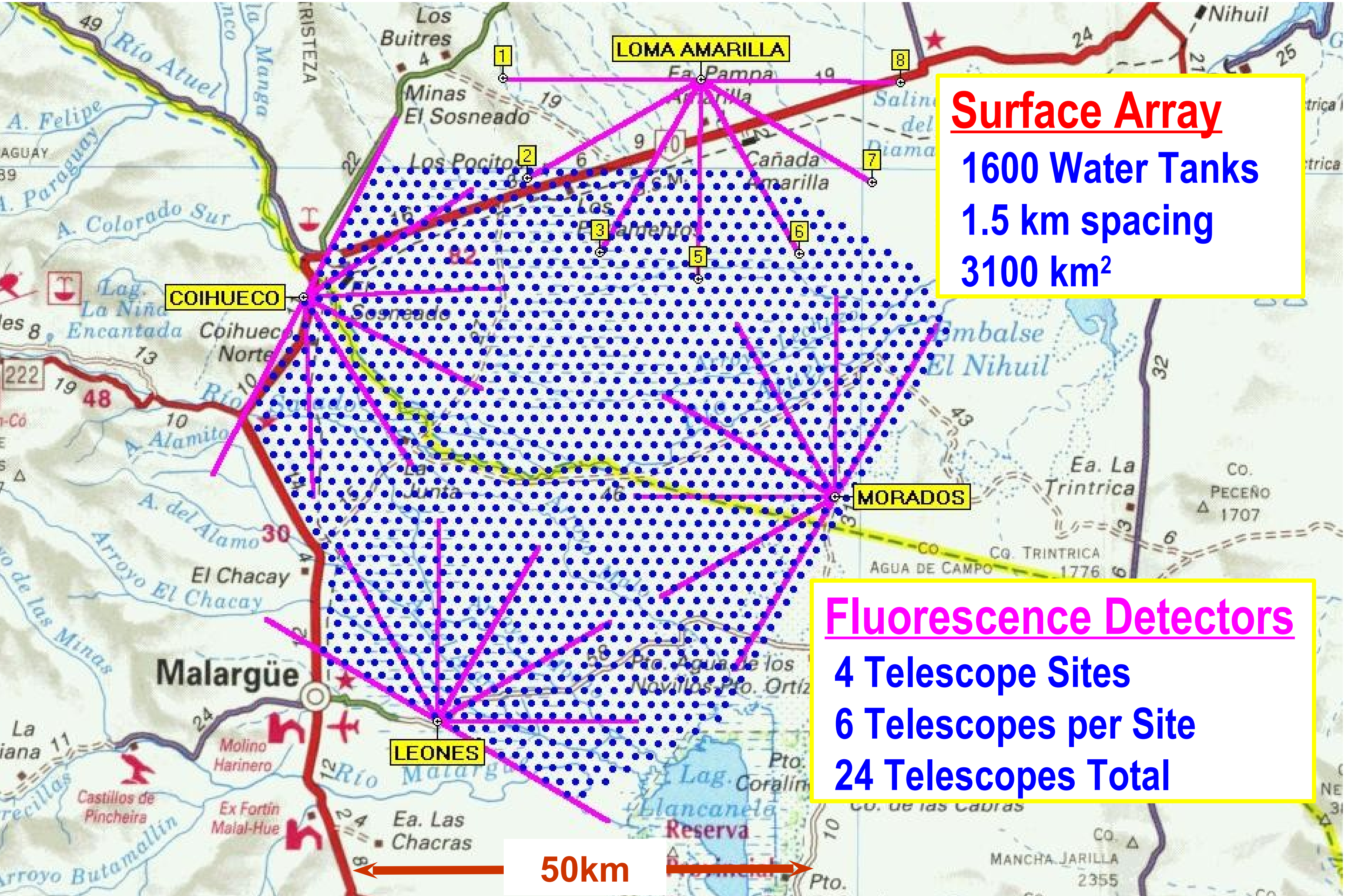
CODALEMA Results

- Lateral dependence of radio signal measured
  - Nearly exponential decay – as expected from Geosynchrotron
- Good calibration of radio signals – but no reliable air shower parameters

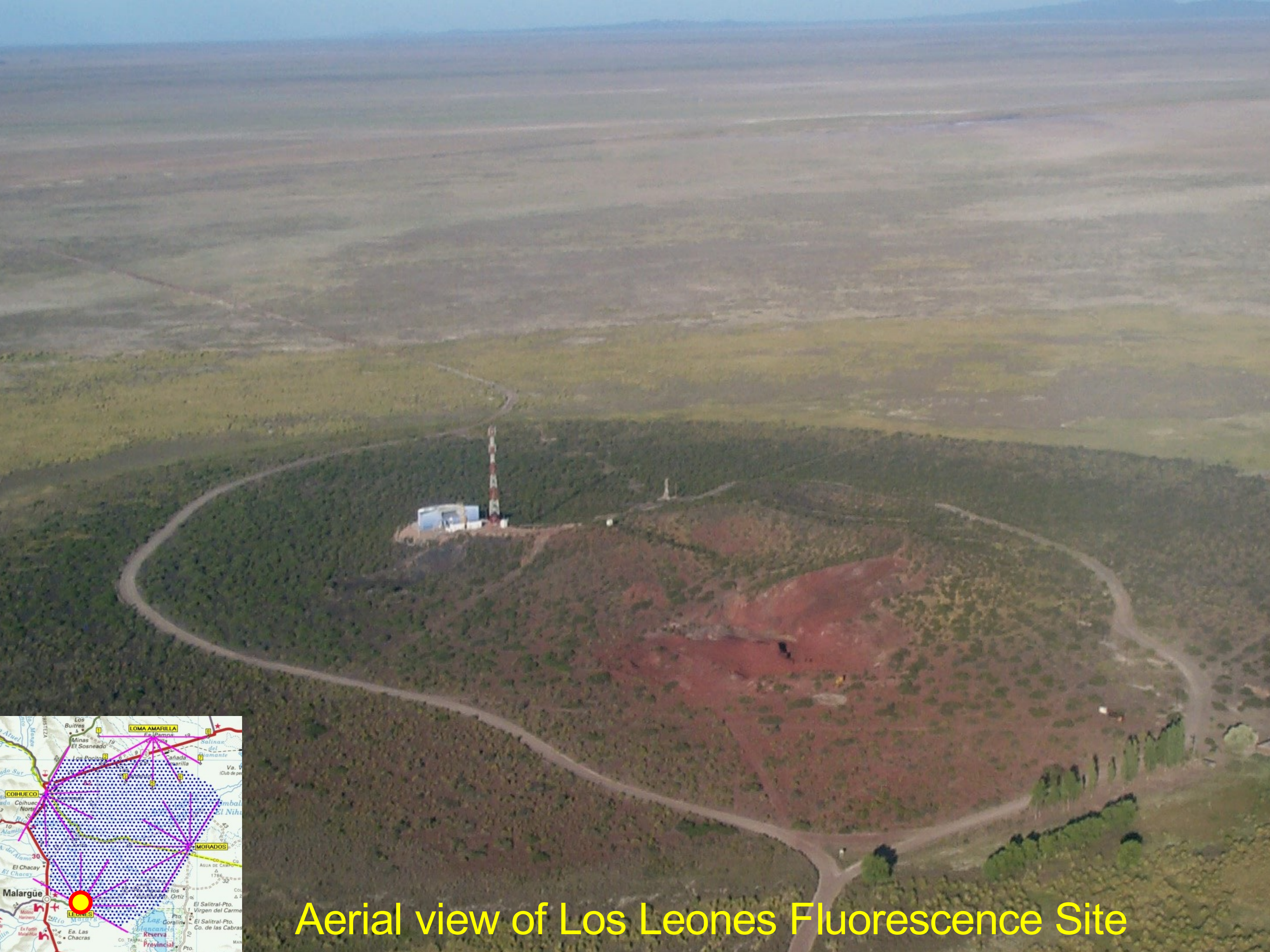




Southern-Auger in Argentina

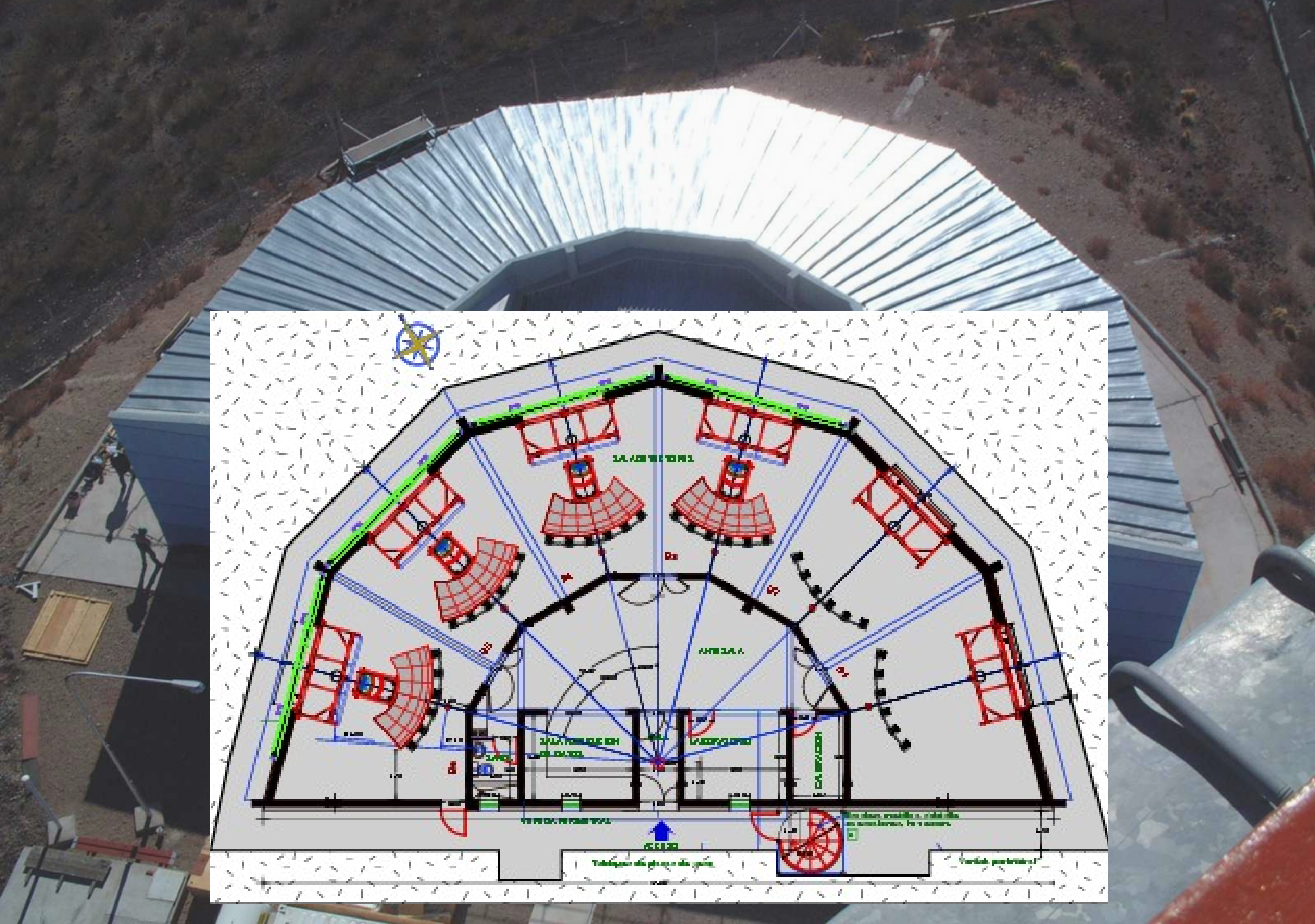


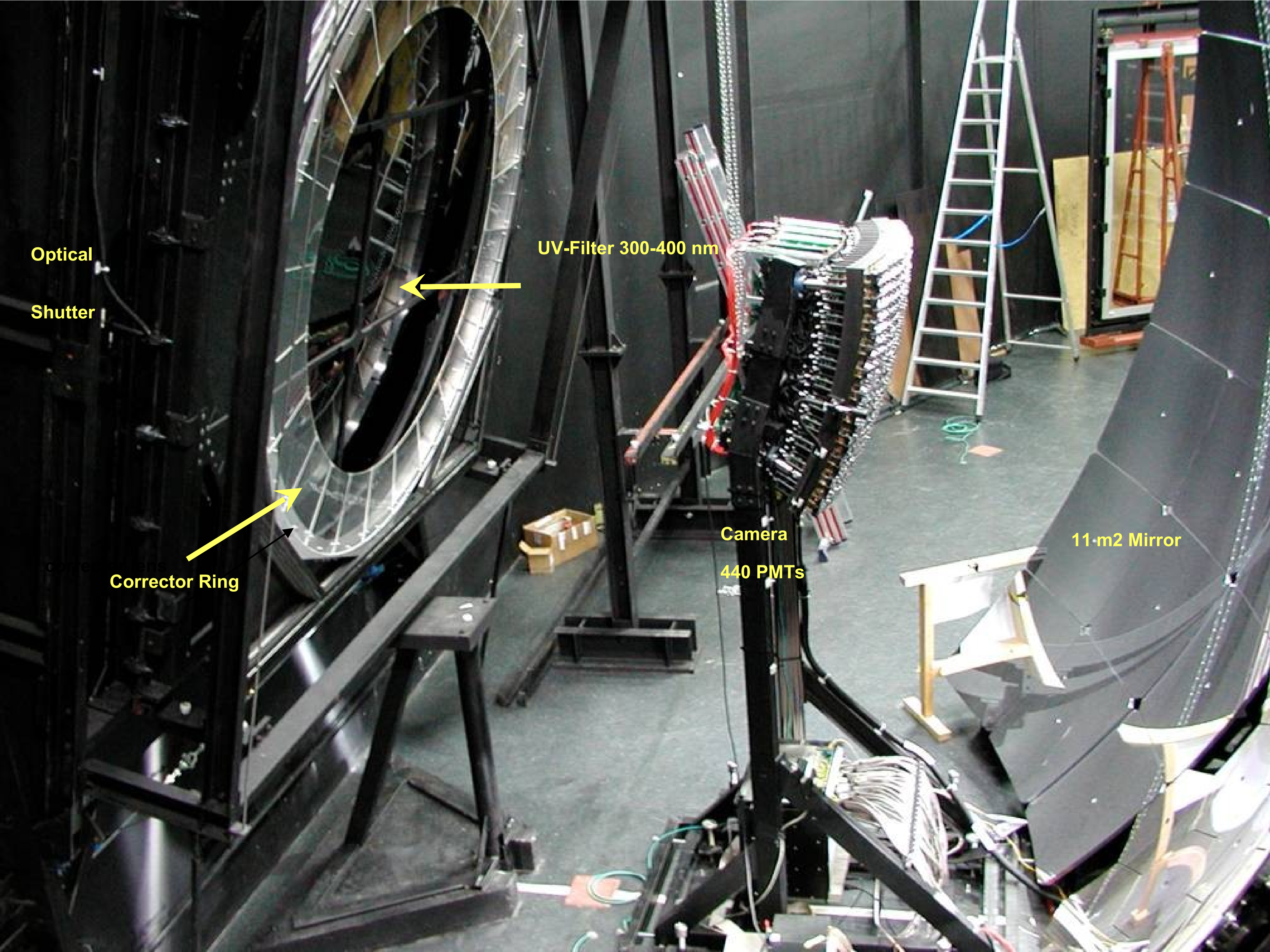
Auger in the Netherlands …



Aerial view of Los Leones Fluorescence Site

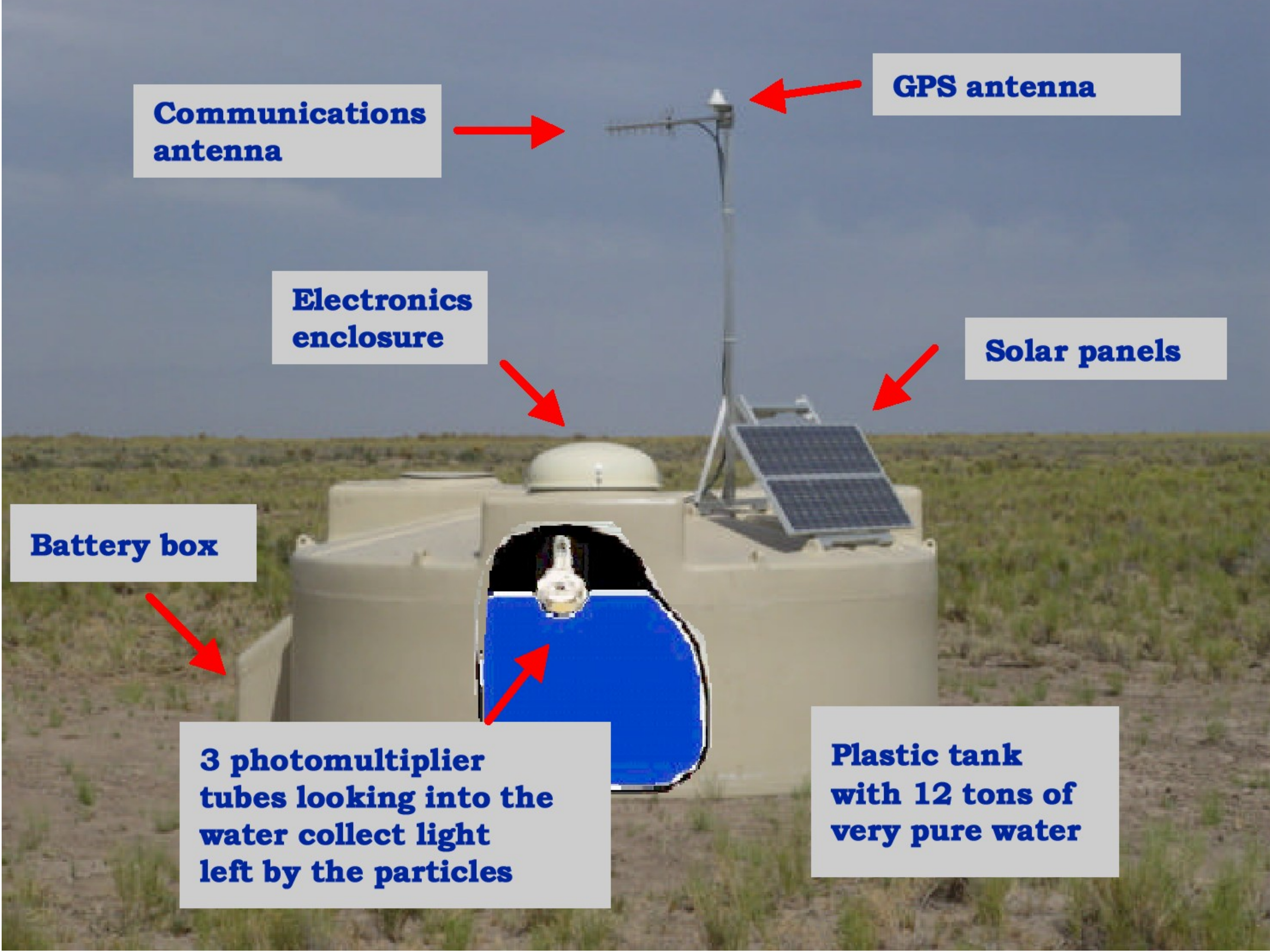
Six Telescopes looking at 30o x 30o each




Optical
Shutter
UV-Filter 300-400 nm
Corrector Ring
Camera
440 PMTs
11-m2 Mirror

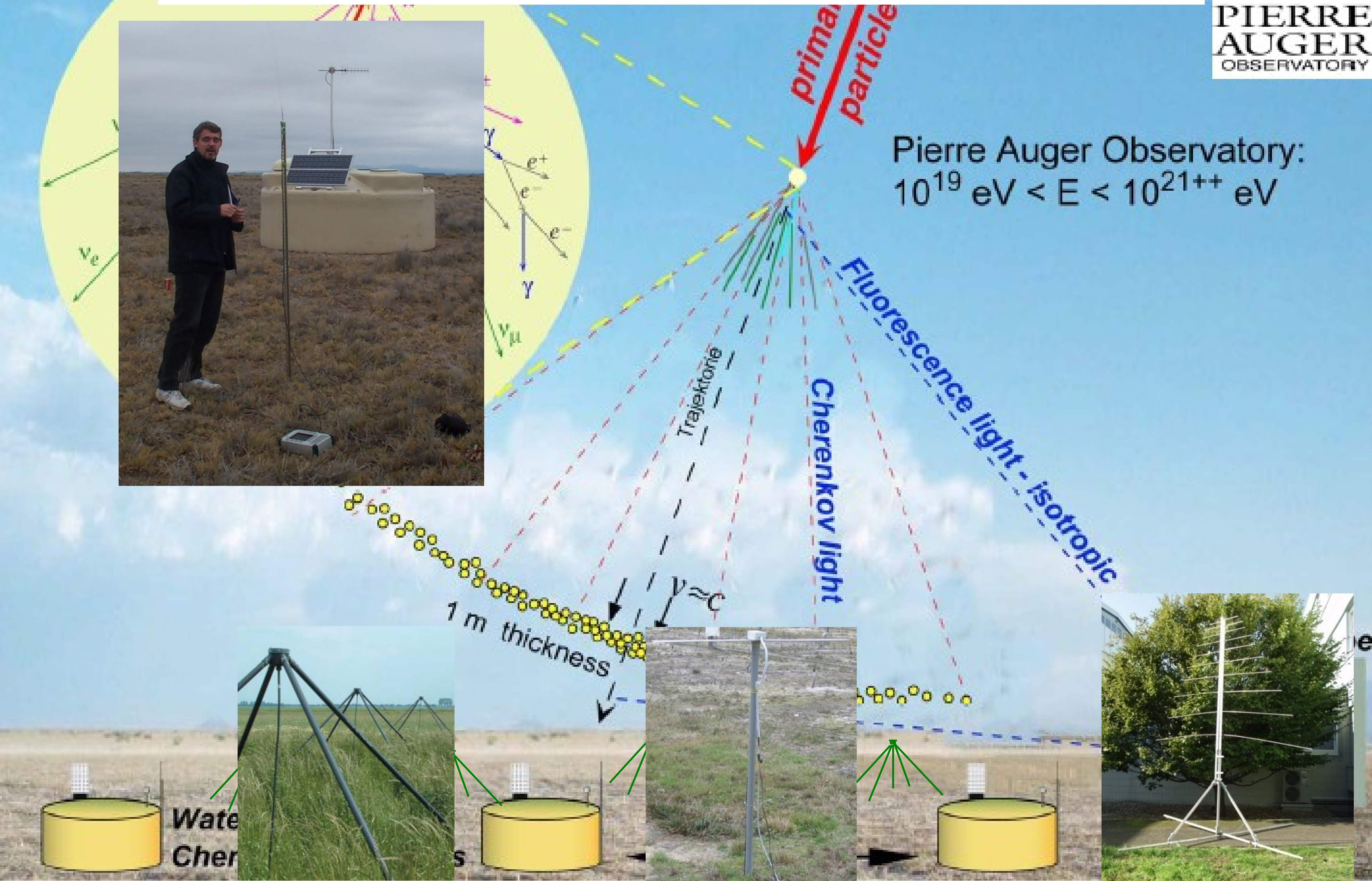
Tanks aligned seen from Los Leones

Real water tank under operation at Malargue


GPS antenna
Communications antenna
Electronics enclosure
Solar panels
Battery box
3 photomultiplier tubes looking into the water collect light left by the particles
Plastic tank with 12 tons of very pure water

Next step: Radio @ AUGER

First on-site tests starting this fall!



Why Radio at Auger …

- Triple-detection (radio, fluorescence, partilcles) of CR events to nail down energy scale and systematics
- Radio+surface detector to get composition with ~100% duty cycle (factor 10 more than fluoresence+surface)
- Radio interferometry gives precise localization – improve clustering statistics by factor 10 and do „CR astronomy“.

Radio Fluorescence: What is it?

- Microwave Molecular Bremsstrahlung Radiation (MBR) in EAS
  - Only a small fraction of the available energy budget for secondary isotropic radiation is used up by optical fluorescence.
  - MBR is simply a subsequent radiative process resulting from the cooling of the EAS plasma.
  - Some (isotropic) emission expected in GHz range

Stokes/Gorham

Accelerator Experiments

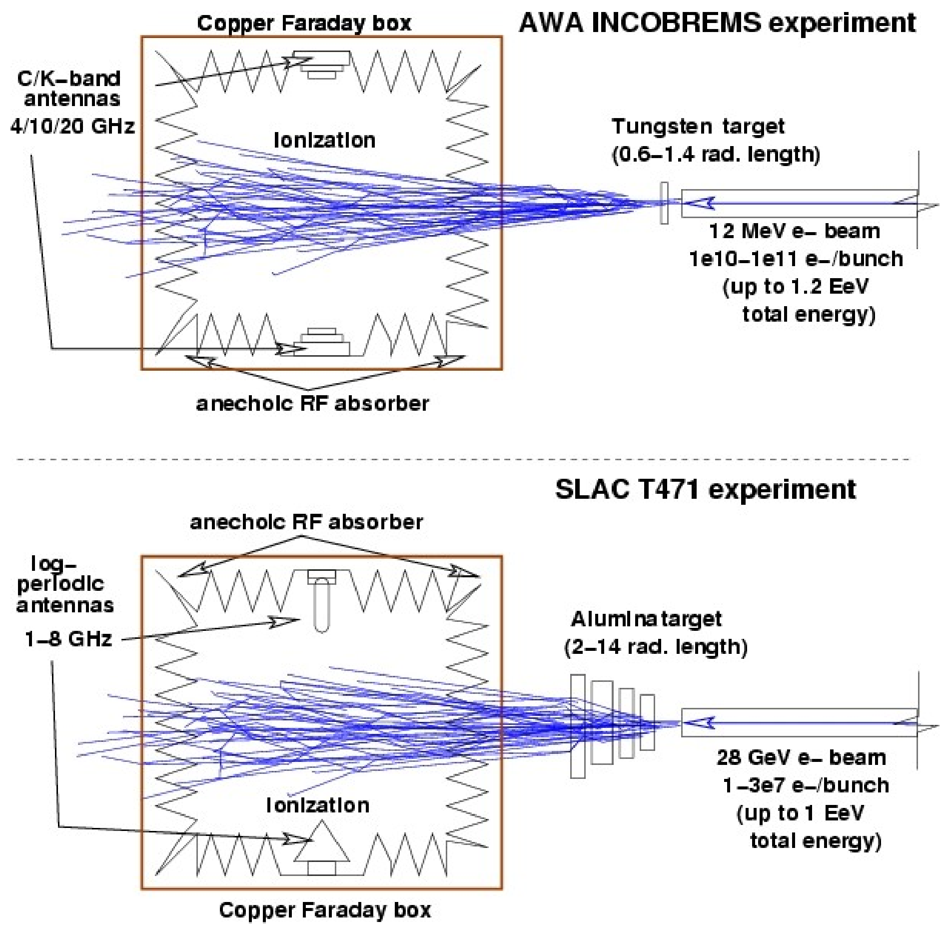
- AWA INCOBREMS
  - Jun 2003

    12 MeV e$^-$ beam

    1.2 EeV/pulse
- SLAC T471
  - July 2004

    28 GeV e$^-$ beam

    1 EeV/pulse



Stokes/Gorham

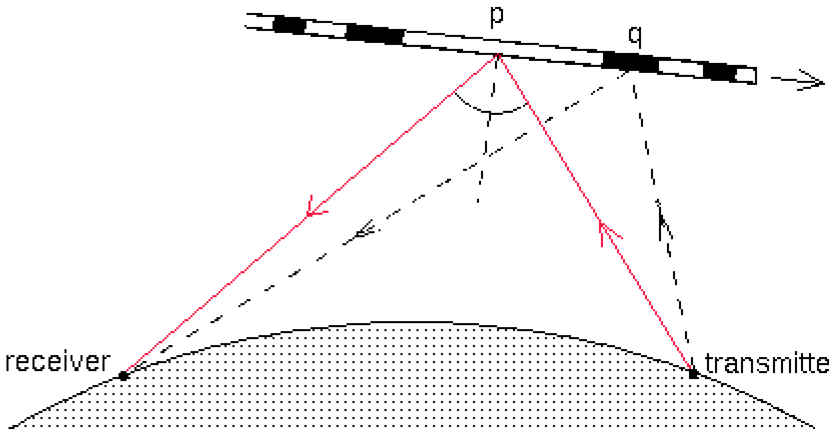
AMBER: Air-shower Microwave Bremsstrahlung Experimental Radiometer

- Single, four pixel telescope currently deployed at the University of Hawaii campus.
- No conclusive results yet
- LOFAR transient buffer boards will allow to search for low-frequency isotropic emission.

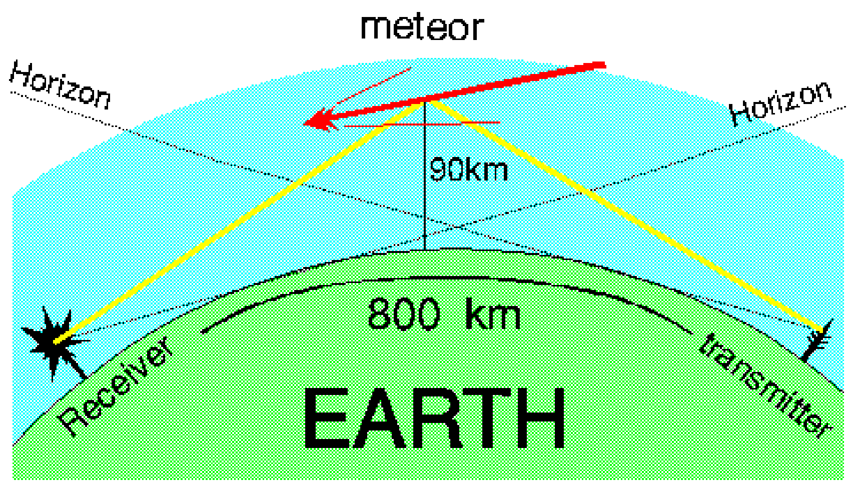
Stokes/Gorham

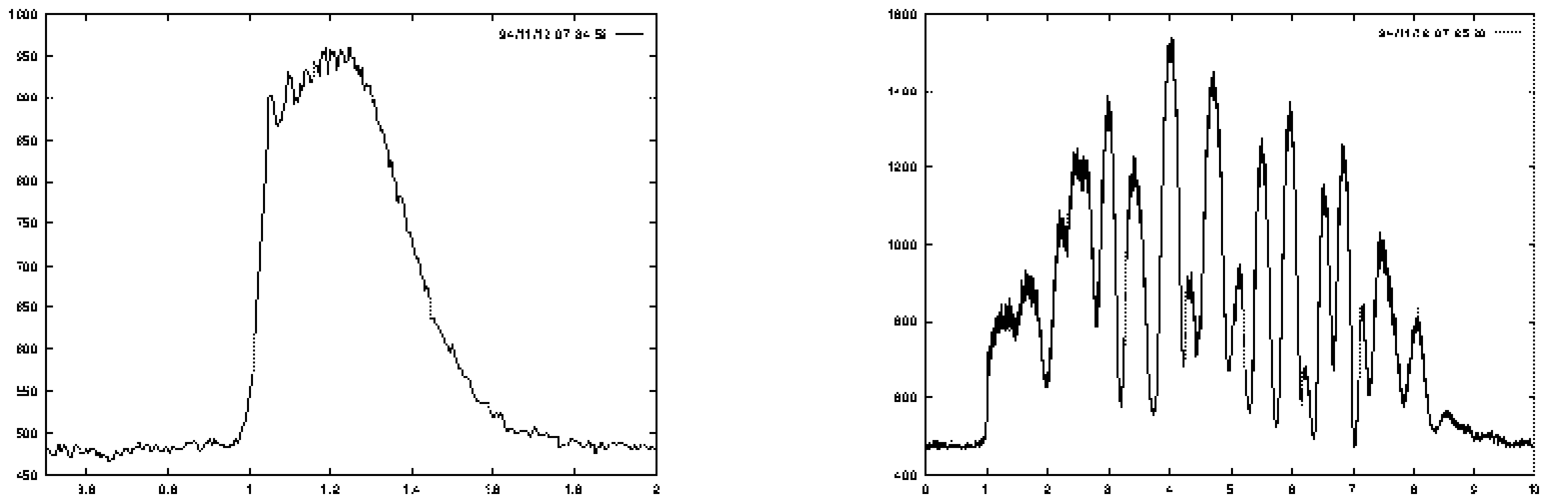
Radar detection of ionization trails: useful for CRs?

P. Gorham



Multipath effects in scattering geometry



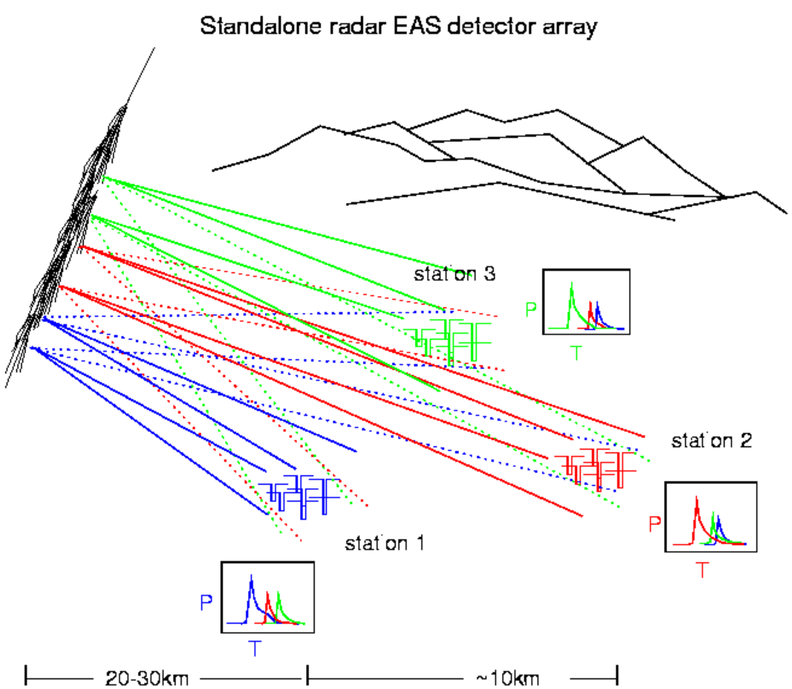


Overdense reflections showing varying degrees of interference

Radar array as a standalone EAS detection system

P. Gorham

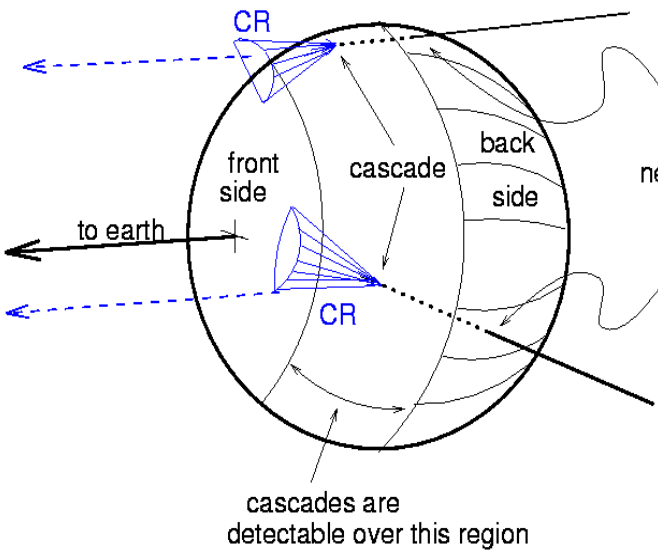
- EAS measurement requires at least 7 parameter estimation:
  - Xm,Ym,Zm, theta, phi, Eo, dE/dx
- A 3-station radar system, all with transmit/receive capability gives:
  - Complex amplitude for each direct echo
  - Each station gets two additional complex amplitudes from bistatic echoes
  - Minimum of 18 measured quantities at high SNR
  - ranges to ~10m on 10km baselines => mrad angles
  - range, rates:
    - ~20 km @ 1e19 eV, 10 per day
    - ~60 km @ 1e20 eV, 2 per day
  - Cost: ~$200K per station (?)
- Issues:
  - Complicated range-coding
  - strong ground-echoes from other stations
  - Ground clutter at large ranges
  - Lifetime of ionization trail at low altitudes!
- Investigate Passive Radar!



Ultra-High Energy Neutrino Detections

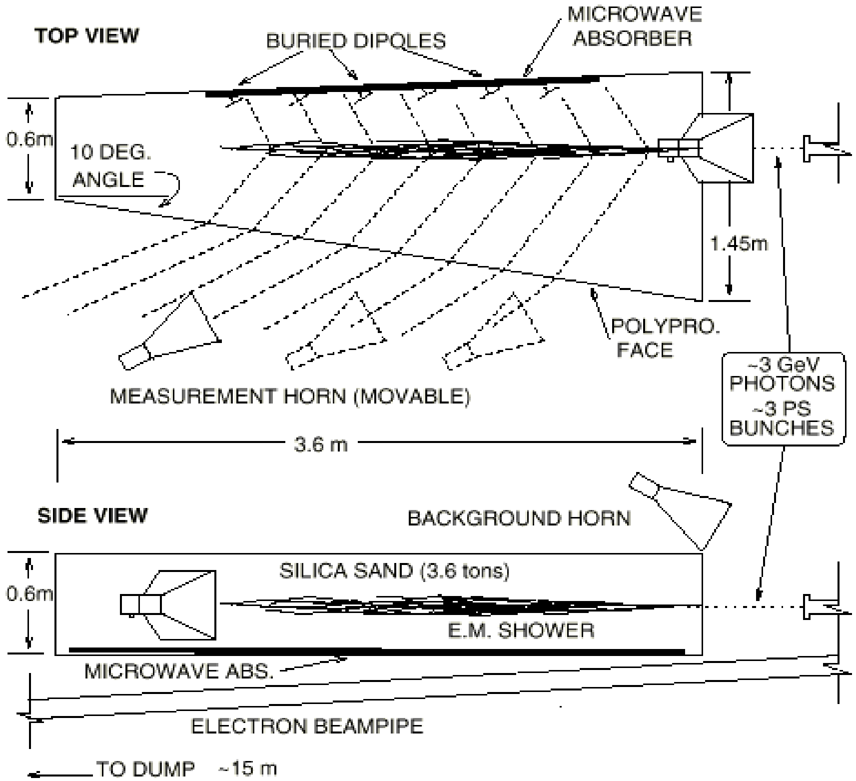
- Ultra-high energy particle showers hitting the moon produce radio Cherenkov emission (Zas, Gorham, …).
- This provides the largest and cleanest particle detector available for direct detections at the very highest energies.
- In the forward direction (Cherenkov cone) the maximum of the emission is in the GHz range.
- Current Experiments:
  - ANITA
  - GLUE
  - FORTE
  - RICE

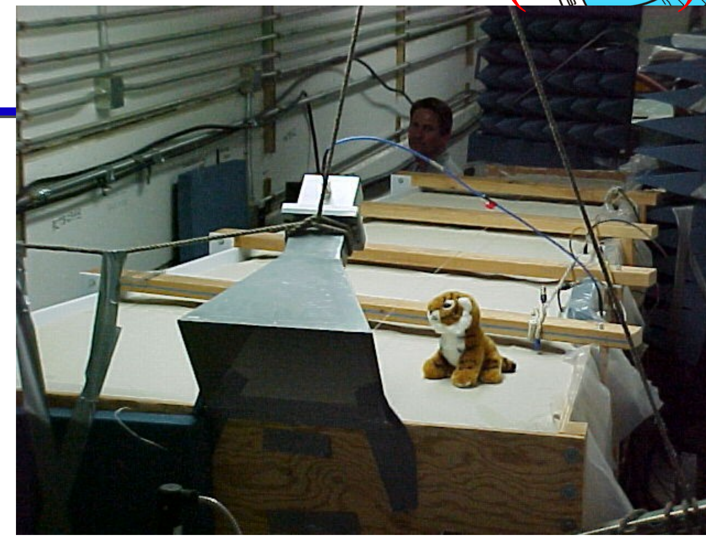
radio from
neutrinos hitting the moon



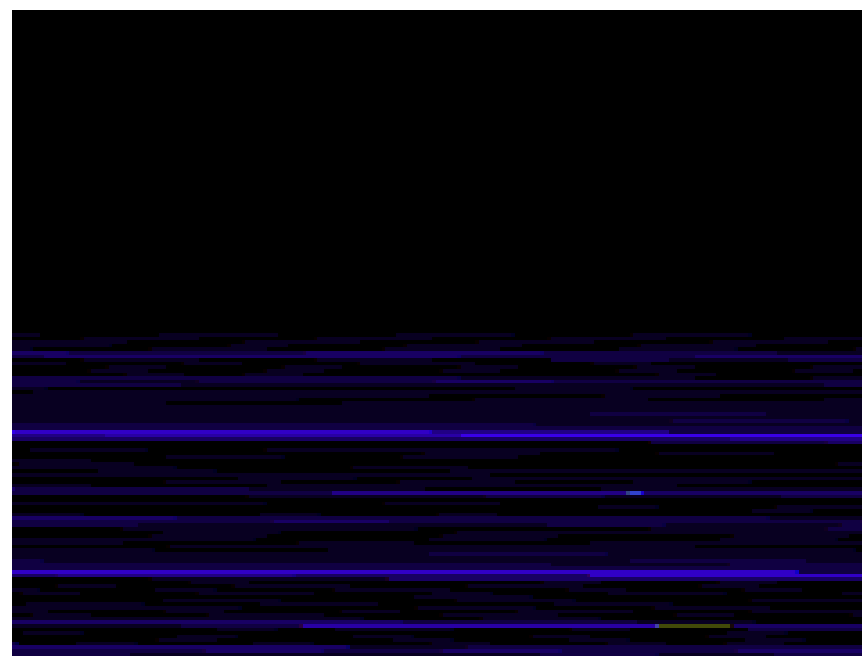
from Gorham et al. (2000)

Radio Emission from Showers in Dense Media: Radio Cherenkov has been observed! (2000)



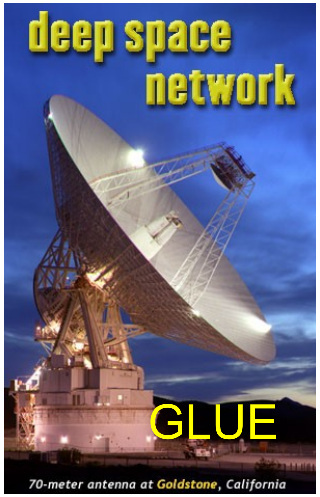


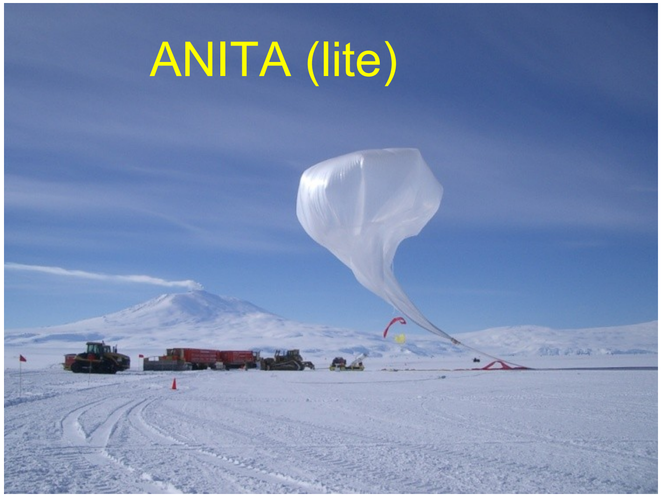
From Saltzberg, Gorham, Walz et al PRL 2001

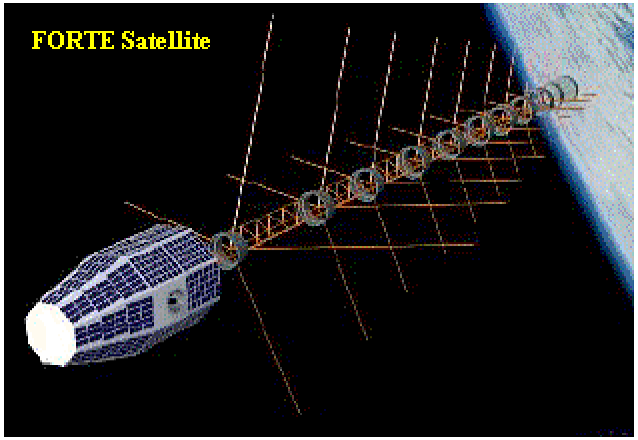


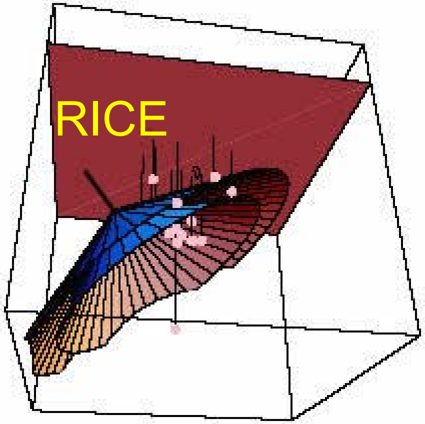
- Use 3.6 tons of sand
- Repeated with ice for ANITA experiment

Radio Neutrino Experiments









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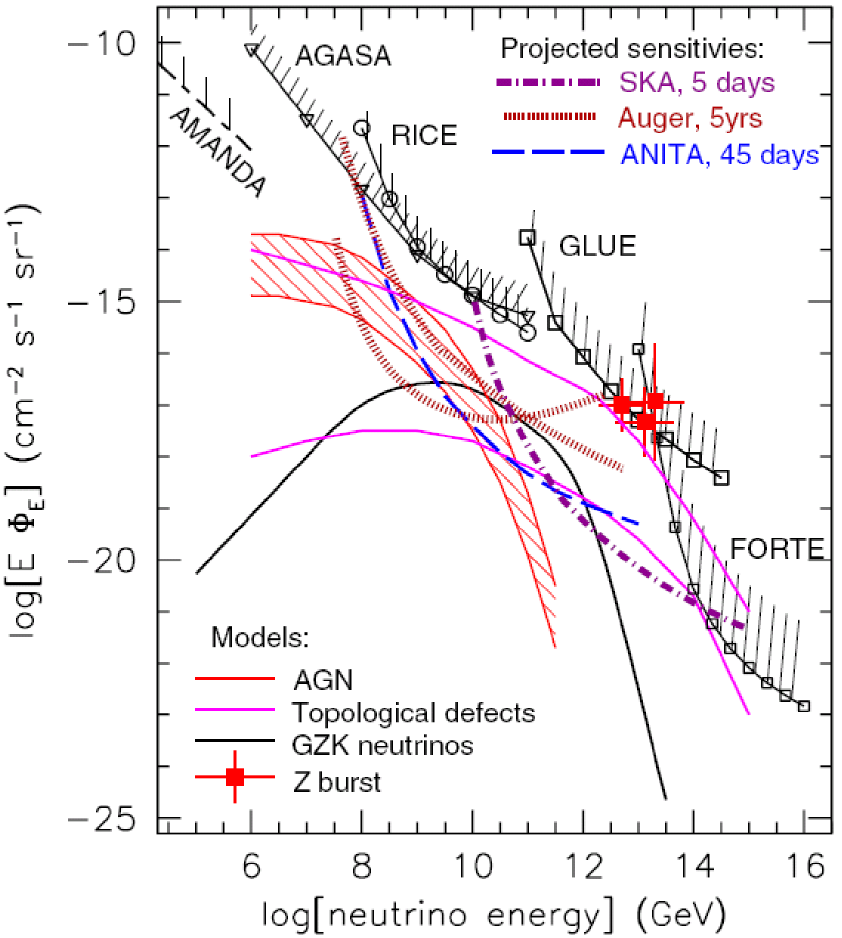
Neutrino limits

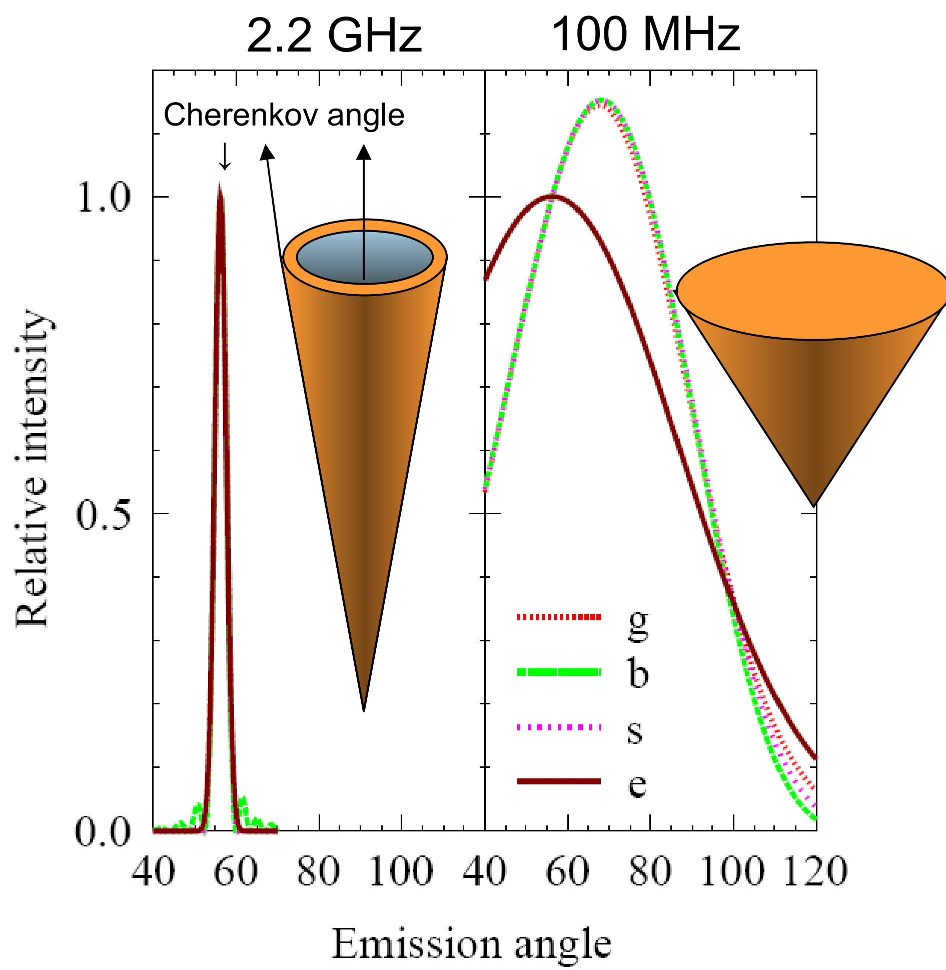


Falcke, Gorham, Protheroe (2005), SKA book

Radio Observations of the Moon: Different Frequencies

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

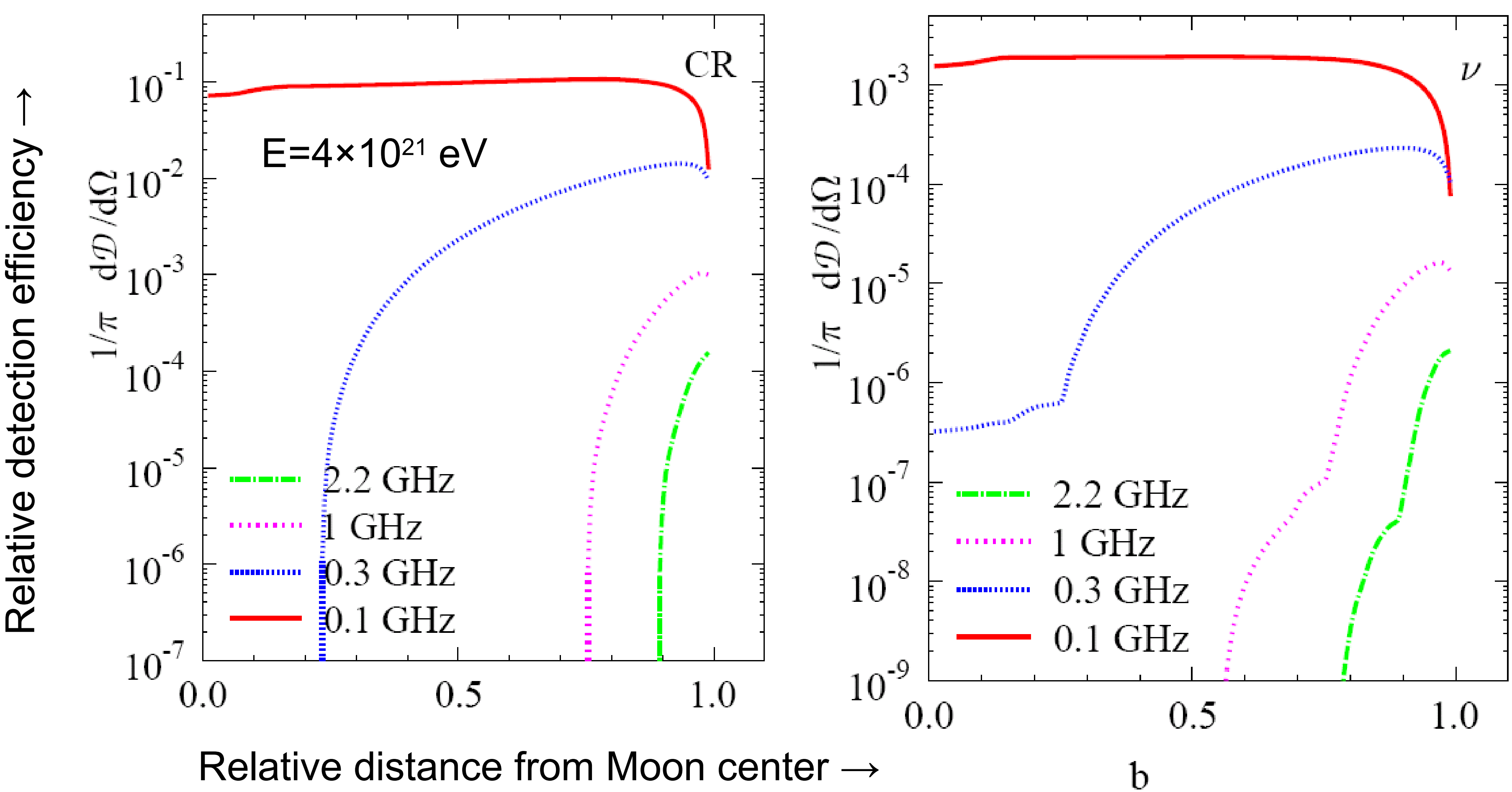
Angular spread of emission



Scholten, et al. (2006, in press)

Radio Observations of the Moon: Detection Efficiencies

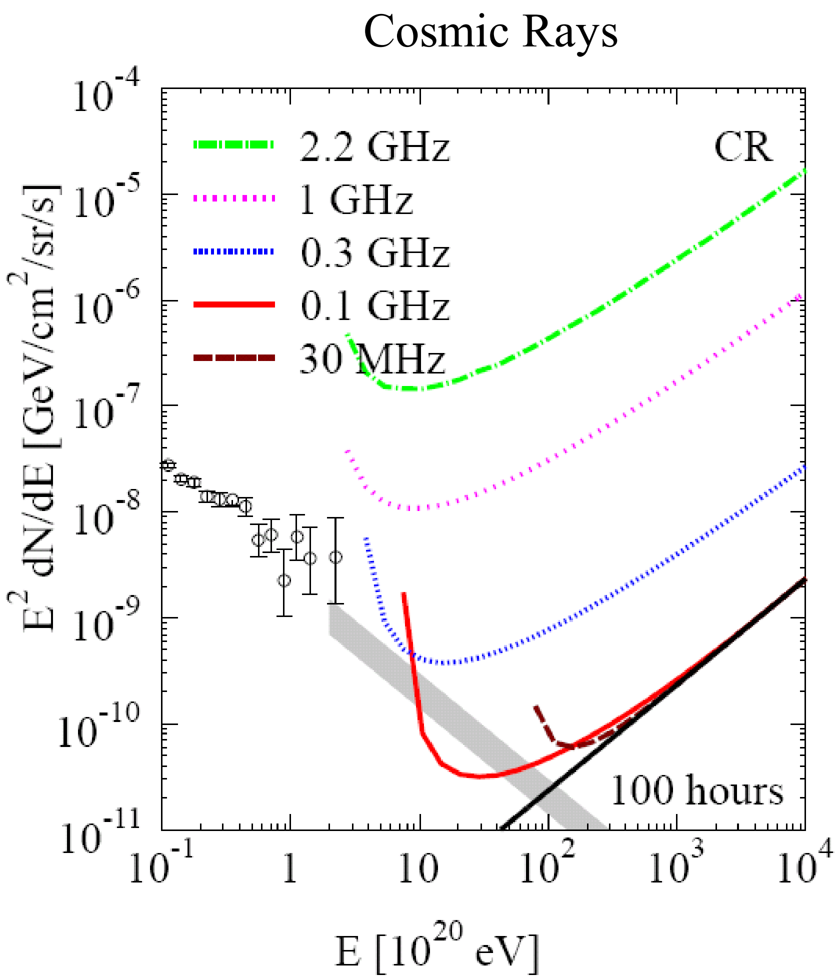
Cosmic Rays | Neutrinos



νMoon Collaboration: Scholten, Bacelar, Braun, de Bruyn. Falcke, Stappers Strom (KVI+ASTRON)

Radio Observations of the Moon: Different Frequencies

- Low frequencies are radiated into larger solid angle…
- … but need higher particle energies
- Low-frequency observations (100-300 MHz) of the moon may give best limit on super GZK Cosmic Rays!



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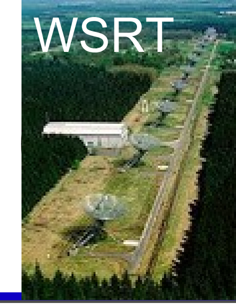
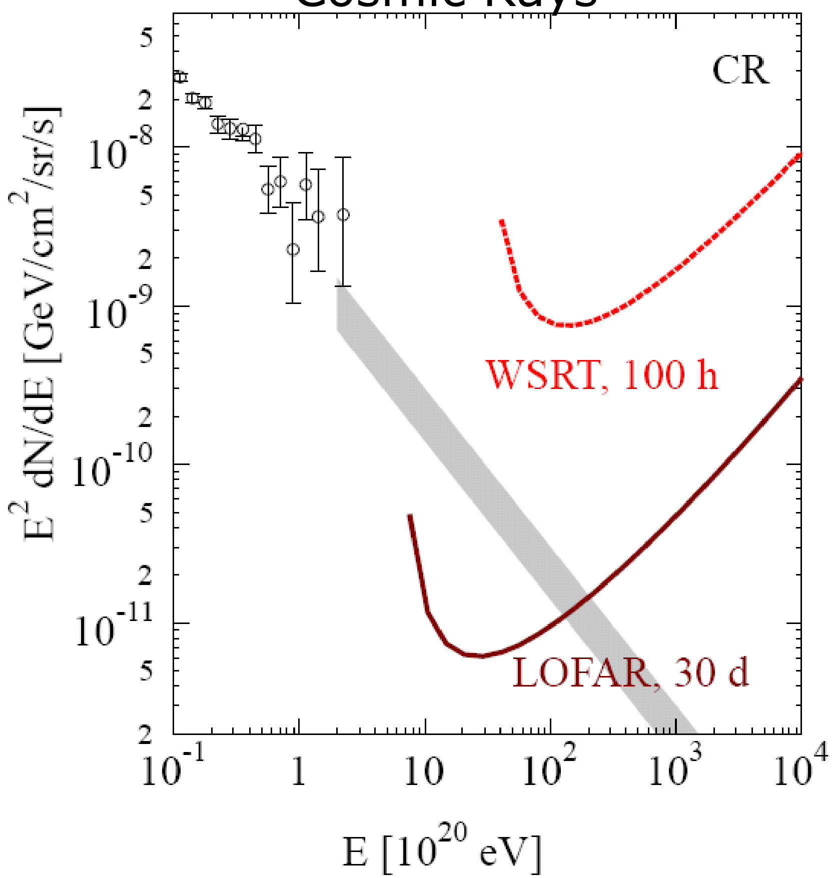
Low-Frequency Observations of the Moon: Sensitivity

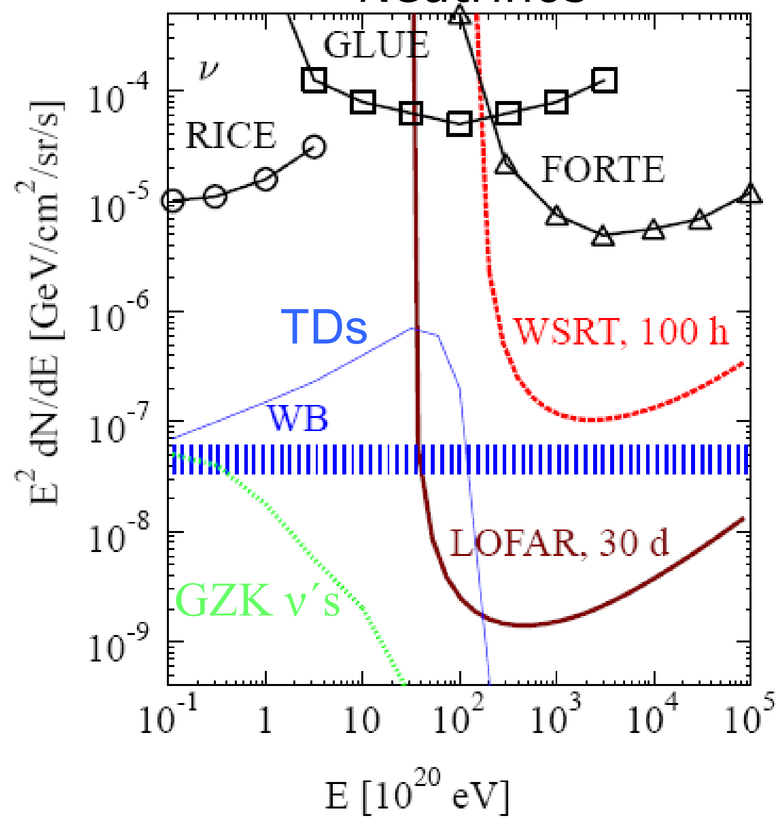


WSRT experiment has started! 500hrs granted

Cosmic Rays



Neutrinos



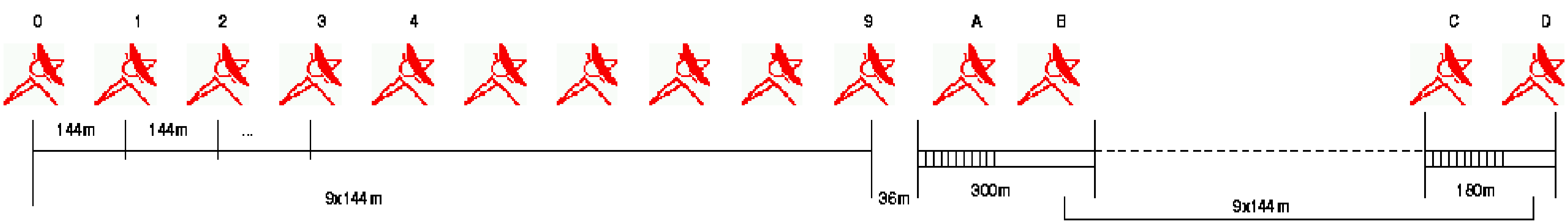
Scholten et al. (NuMoon Collab.) 2006, in press

Westerbork (WSRT) Experiment

Westerbork Synthesis Radio Telescope

Basic Properties:

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



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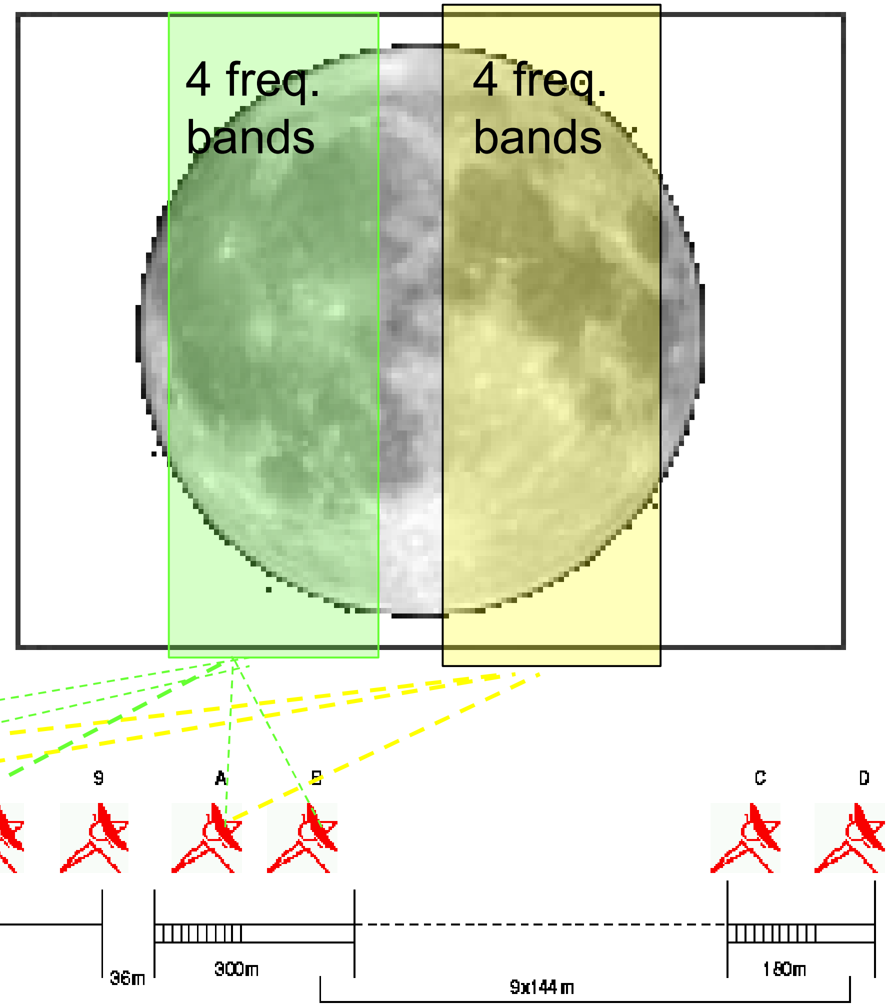
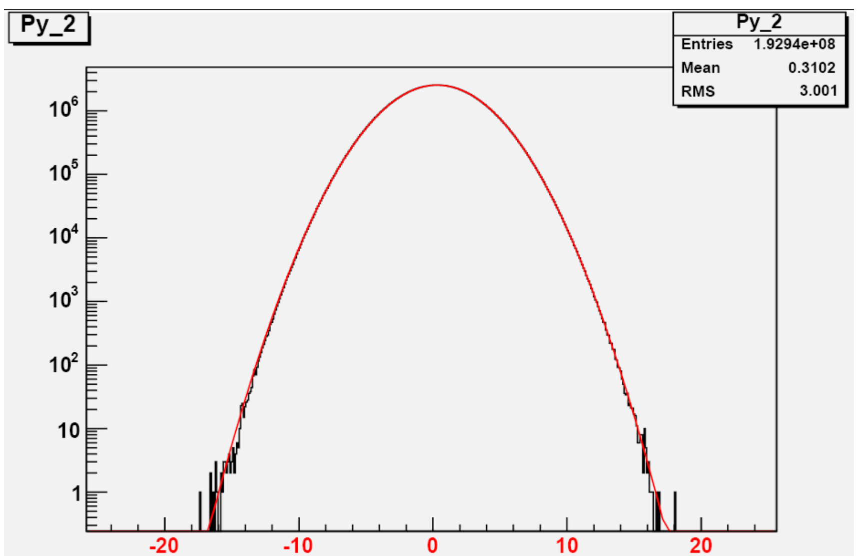
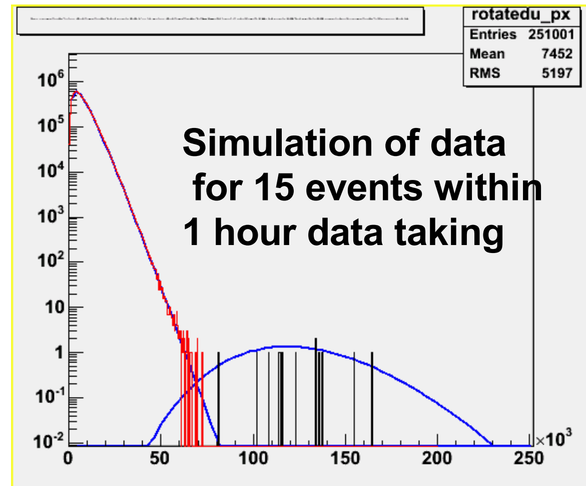
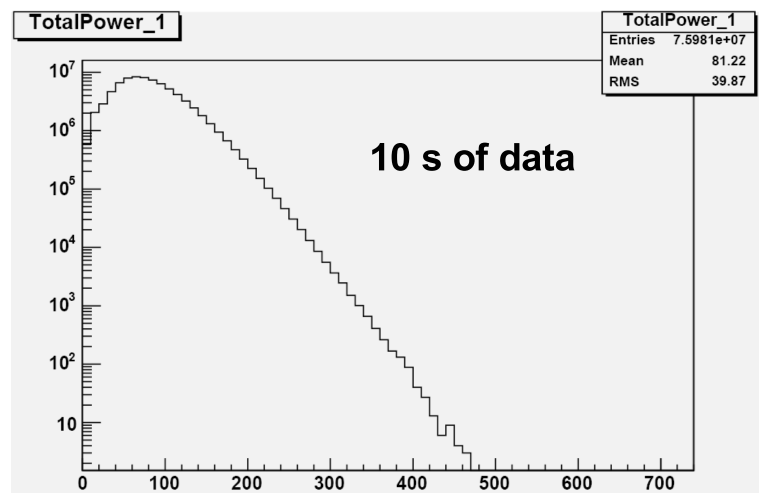


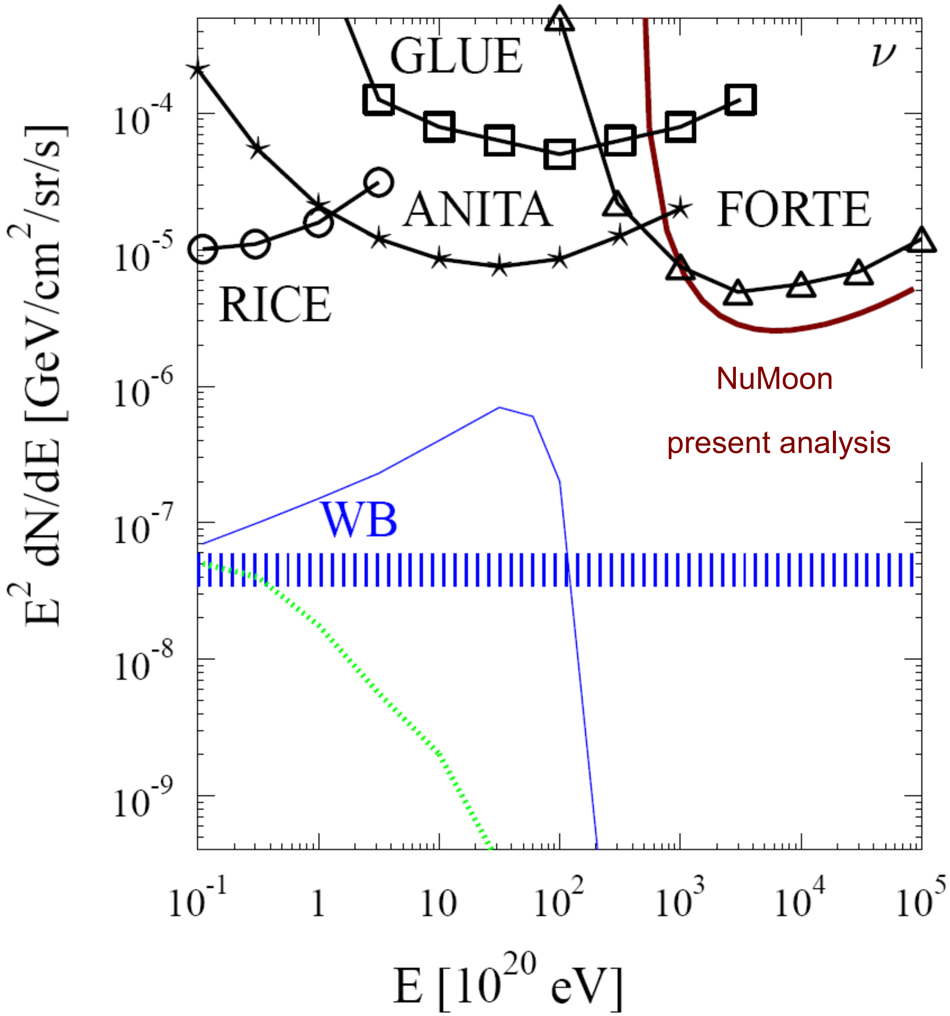
First Data Products: Noise Distribution & Power Spectra

Noise is Gaussian down to 10^{-7}





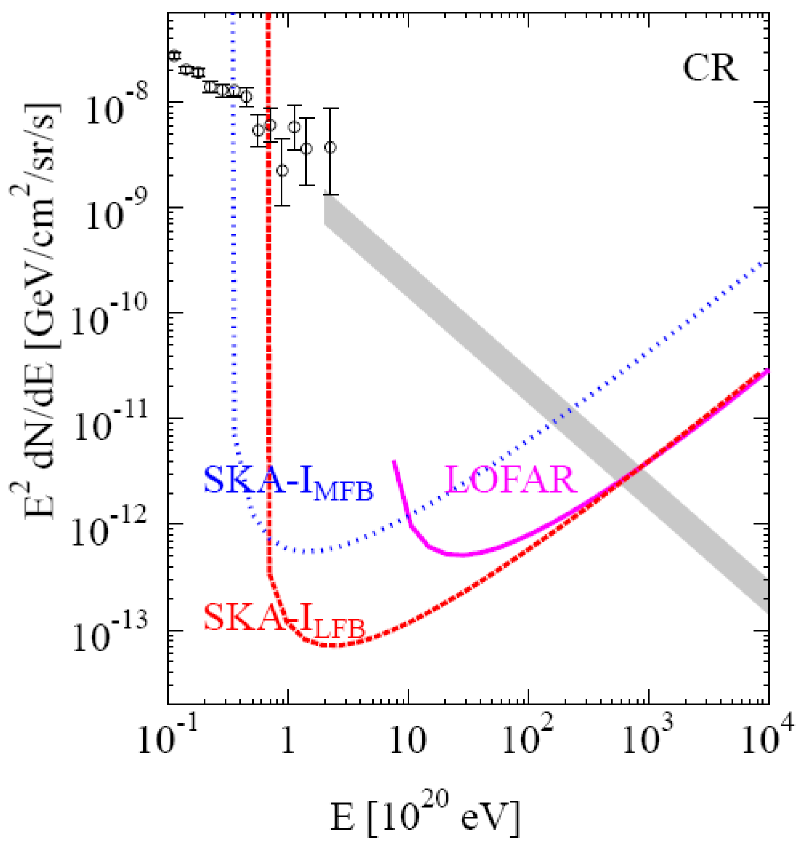



GLUE
ν
ANITA
FORTE
RICE
NuMoon
present analysis
WB
E^2 dN/dE [GeV/cm^2/sr/s]
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-1
1
10
10^2
10^3
10^4
10^5
E [10^20 eV]

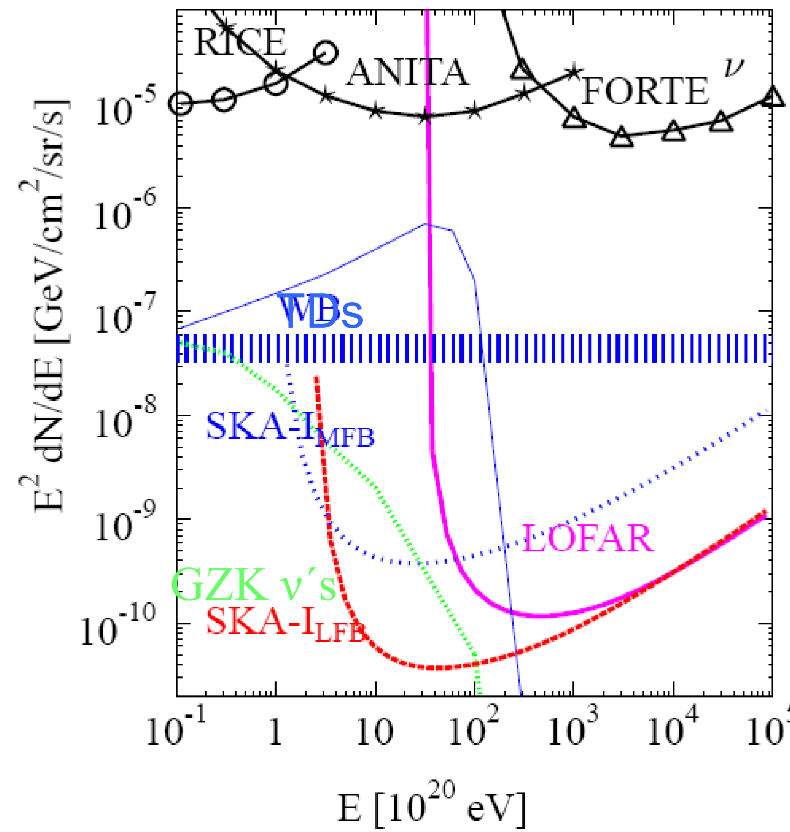
Low-Frequency Observations of the Moon: SKA

1 year, 10% SKA

Cosmic Rays

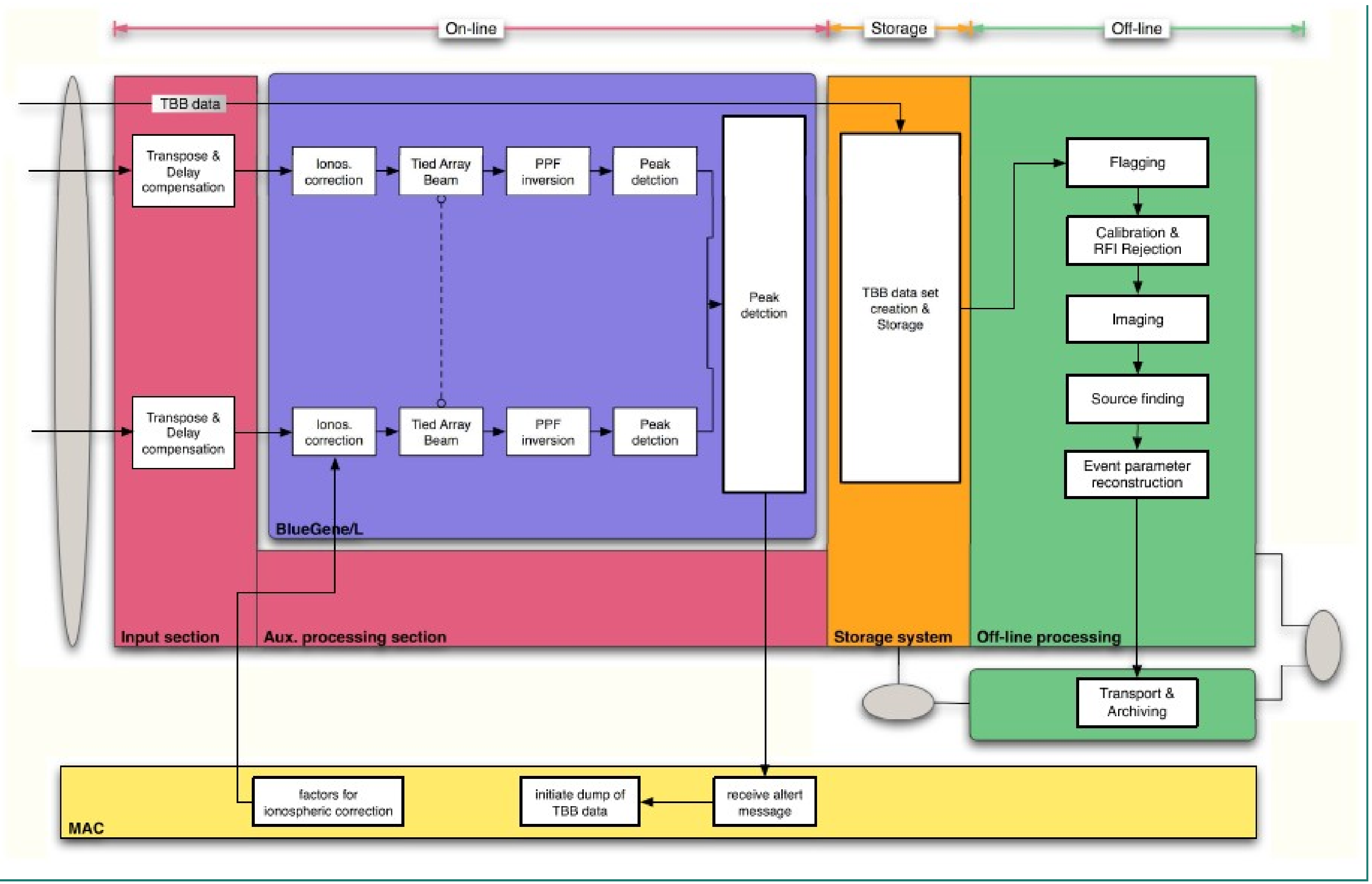


Neutrinos



Scholten 2006, SKA book

LOFAR NuMoon pipeline



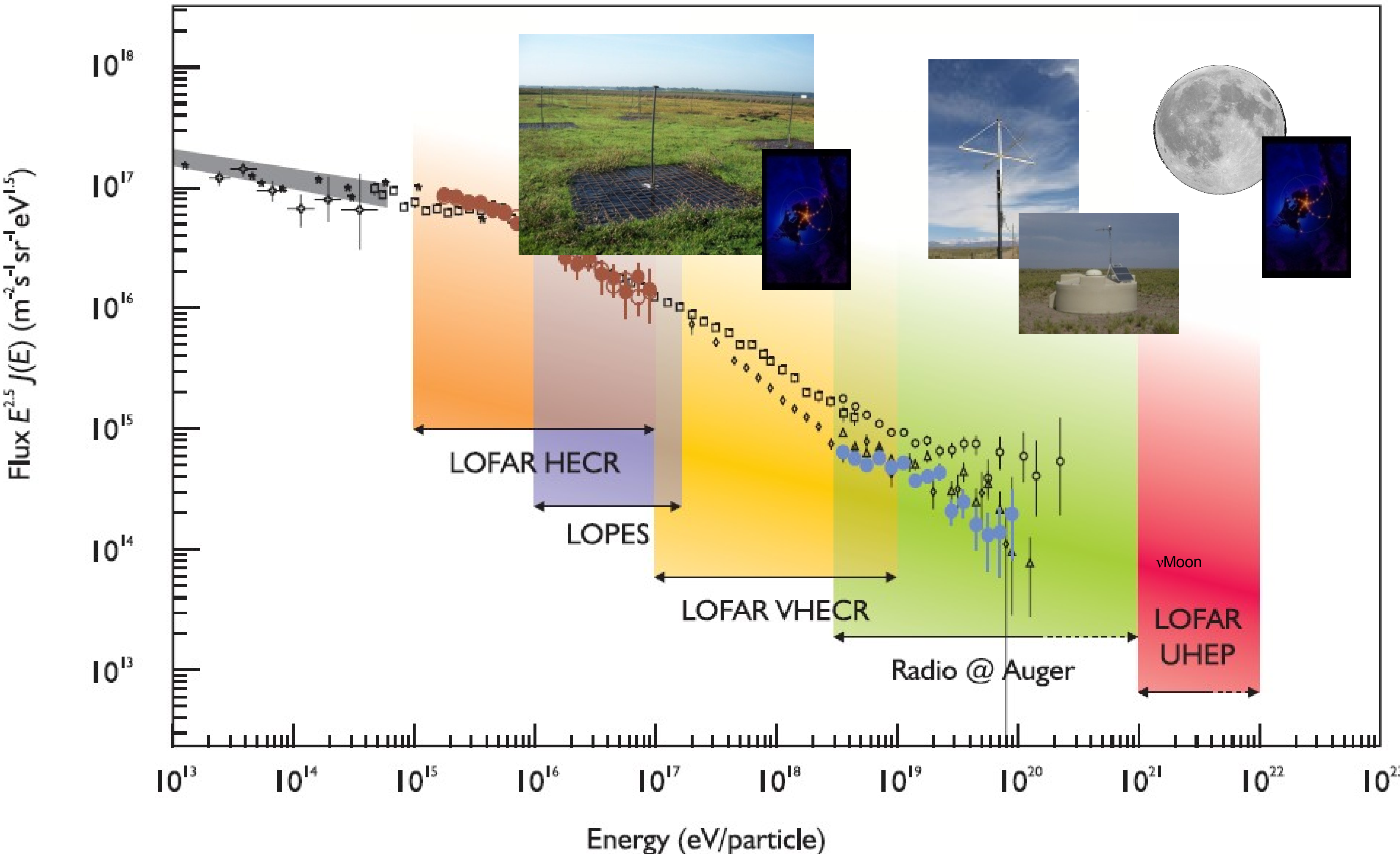
Members of KSP

NAME	AFFILIATION	FUNCTION
Bähren, L. (Lars), PhD	RU	
Buitink, S. (Stijn), PhD	RU	
Falcke, Prof. dr. H.D.E. (Heino)	ASTRON & RU	spokes-person
Hörandel, PD dr. J.R. (Jörg)	RU (as of June 1)	
Haungs, Dr. A. (Andreas)	FZK-IK, Karlsruhe (assoc. memb.)	
Horneffer, Dr. A. (Andreas), Post-Doc	RU (co-PI, inst. rep. LOPES)	
Huege, Dr. T. (Tim), Post-Doc,	FZK-IK, Karlsruhe (assoc. memb.)	
Kuijpers, Prof. dr. J. (Jan)	RU	PI (inst. rep. RU)
Lafèbre, S. (Sven), PhD	RU	
Nehls, S. (Steffen), PhD	FZK-IK, Karlsruhe (assoc. memb.)	
Nigl, A. (Andreas), PhD	RU	
Petrović, Dr. J. (Jelena), Post-Doc	NIKHEF (assoc. memb.)	
Scholten, Dr. O. (Olaf)	KVI, Groningen (inst. rep. KVI)	
Singh, K. (Kalpana), Post-Doc	RU	
Timmermans, Dr. C. (Charles)	NIKHEF/RU	
Van den Berg, Dr. A.M. (Ad)	KVI, Groningen	

Conclusion

- Radio detection of CRs is an exciting field nowadays.
- Geosynchrotron effect allows direct radio detection of EAS (near and far/inclined)
  - Emission process is well-behaved and direct measure of energy
  - LOFAR will become a unique and sizable CR detector at 18^{eV} with excellent energy and position accuracy
- Radio at Auger will give nature (composition) and origin (“CR astronomy”) of CRs at GZK energies
- LOFAR observations of the Moon:
  - low-frequencies preferred for highest energies
  - 3 orders of magnitude improvement over existing facilities
  - Unrivalled for super-GZK particles ($>10^{21}$ eV)

Cosmic Rays in the Radio

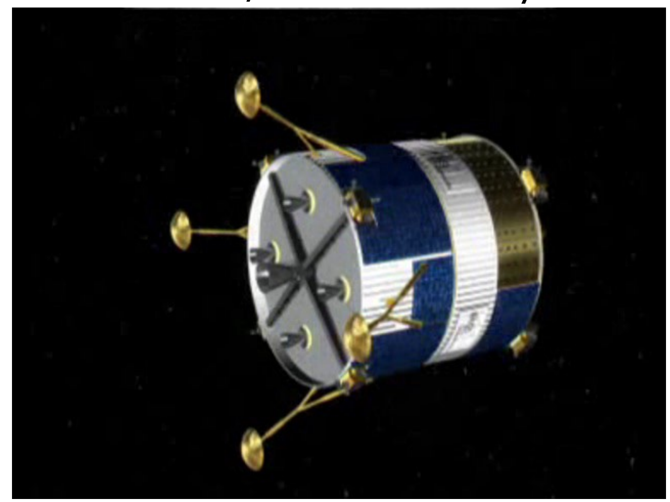


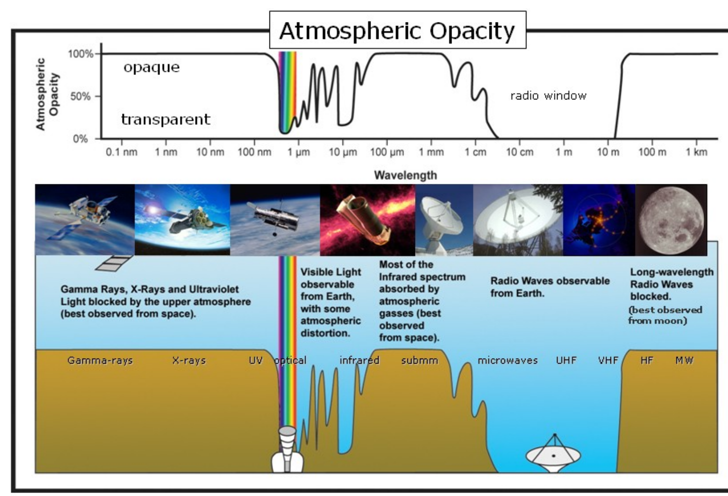
S. Lafebre

LOFAR on the Moon

- Below 10-30 MHz the atmosphere blocks radio emission.
- Man-made interference completely swamps all signals.
- No astronomy has ever been done in this long-wavelength regime.
- The only location where this can be explored is the far-side of the moon.
- A single Ariane V could bring a ~400m LOFAR telescope to the moon!
- Consider this as a lunar infrastructure for exploration and diverse applications …

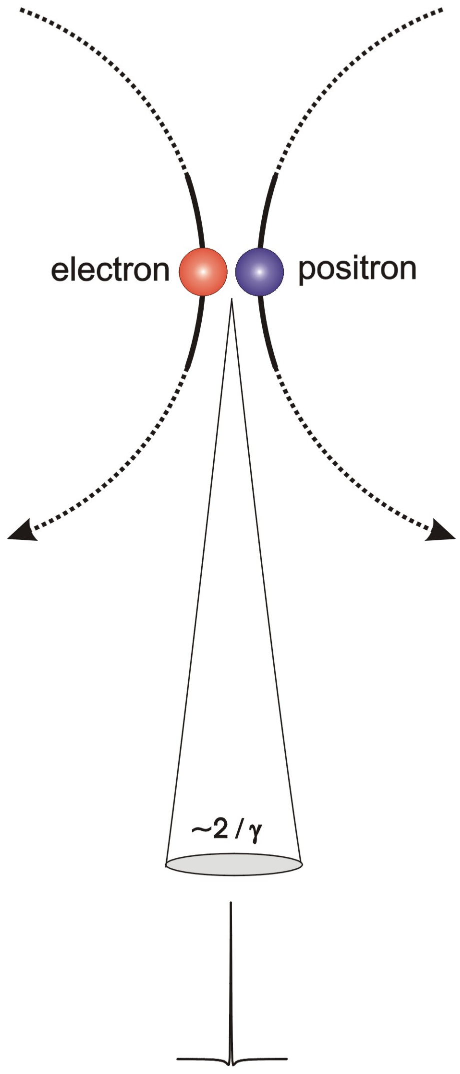
EADS/ASTRON study





Radio Emission from CRs: Modelling Geosynchrotron

- Idea: geosynchrotron emission
  - electron-positron pairs gyrating in the earth's magnetic field: radio pulses
  - coherent emission at low frequencies
- earlier:
  - back-on-the-envelope calculation (Falcke & Gorham 2003)
  - detailed analytic calculation (Huege & Falcke 2003)
  - Monte Carlo simulations based on analytic parameterizations of air shower properties (Huege & Falcke 2004,2005)
- currently:
  - Parametrization based on CORSIKA Monte Carlo simulations.



Southern-Auger in Argentina