Ultra-High Energy Particles with LOFAR

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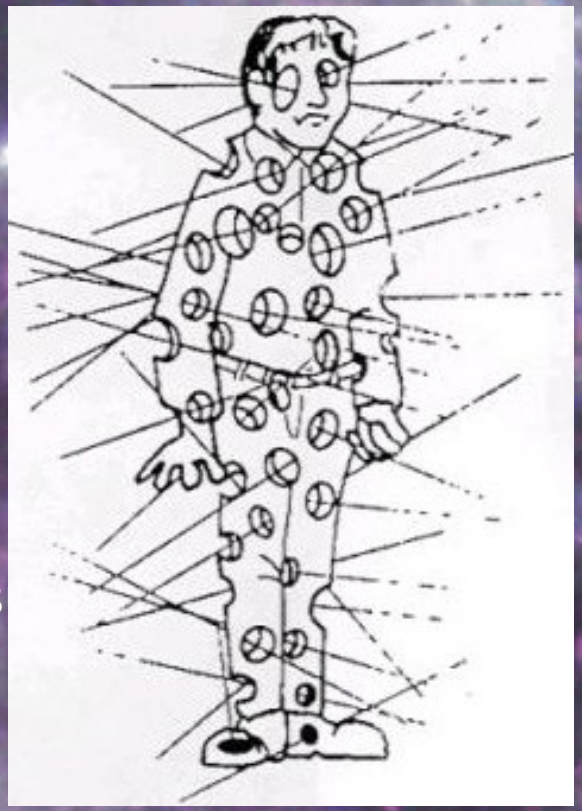

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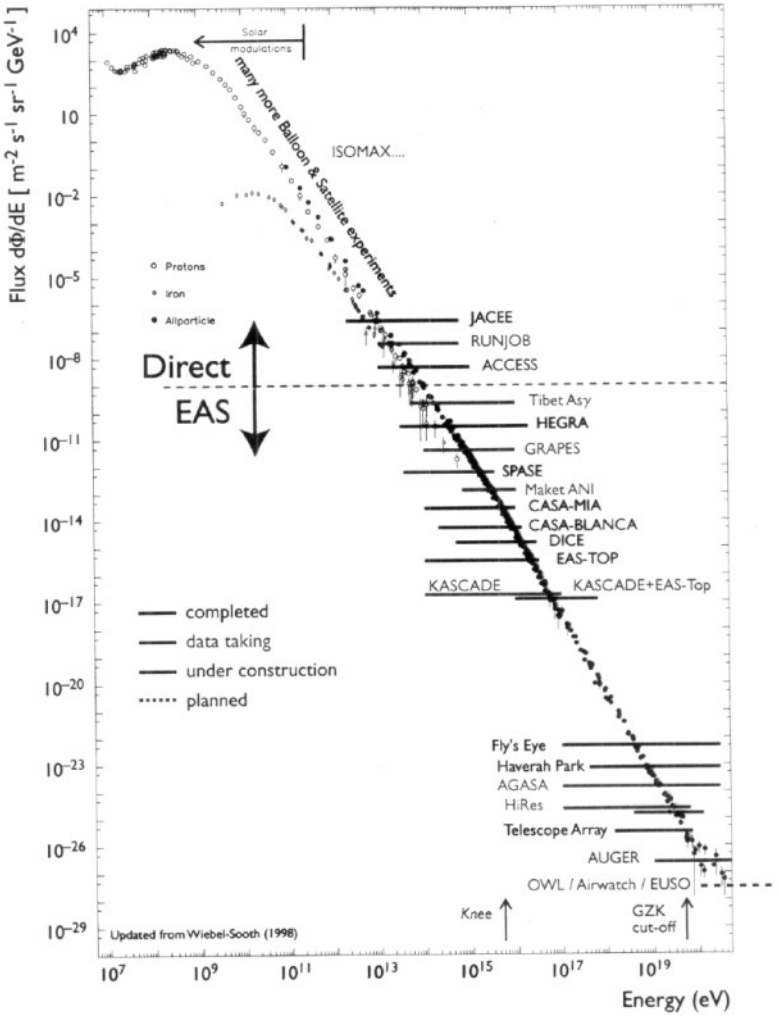
About 1 Million energetic particles will hit each of you during this talk

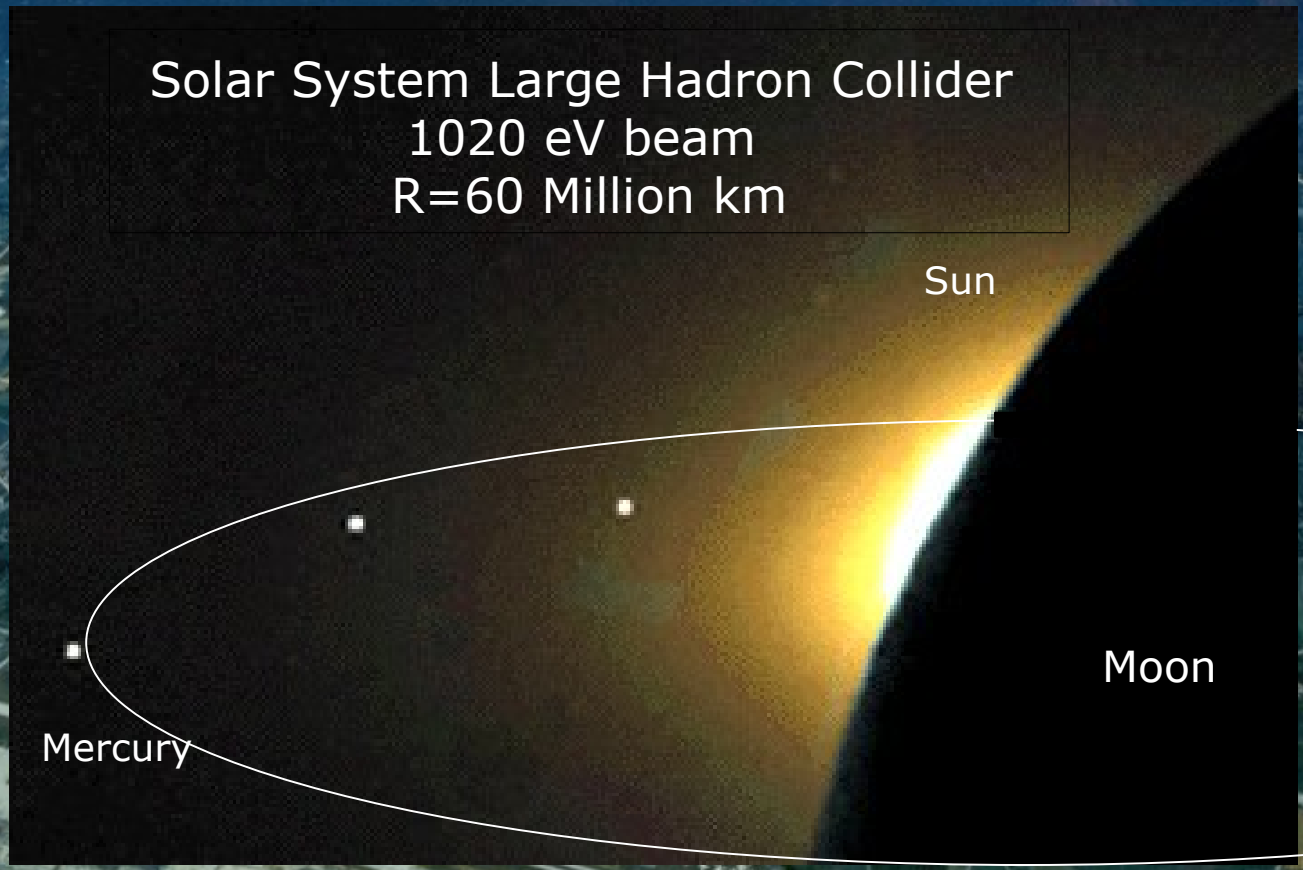
(there is a non-zero chance to mutate into a dinosaur)

What we (don't) know about UHECRs



- We know:
  - their energies (up to 1020 eV).
  - their overall energy spectrum
- We don't know:
  - where they are produced
  - how they are produced

CERN Large Hadron Collider
7×1012 eV beams
R=4.3 km



Potential Sources

- Hillas plot: Gyro radius has to fit source size!

$$R_{gyr} = \frac{E_{CR}}{eB}$$

- Galactic < 1017eV
  - Supernovae
  - neutron stars & stellar black holes
- Extragalactic >1018 eV
  - Supermassive black holes
  - Gamma-Ray bursts
  - Intergalactic shocks
  - Top-down: decay of primordial

1 EeV = 1018 eV

Radio Images of Cosmic Accelerators

Cygnus A

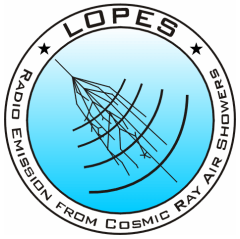
Cas A

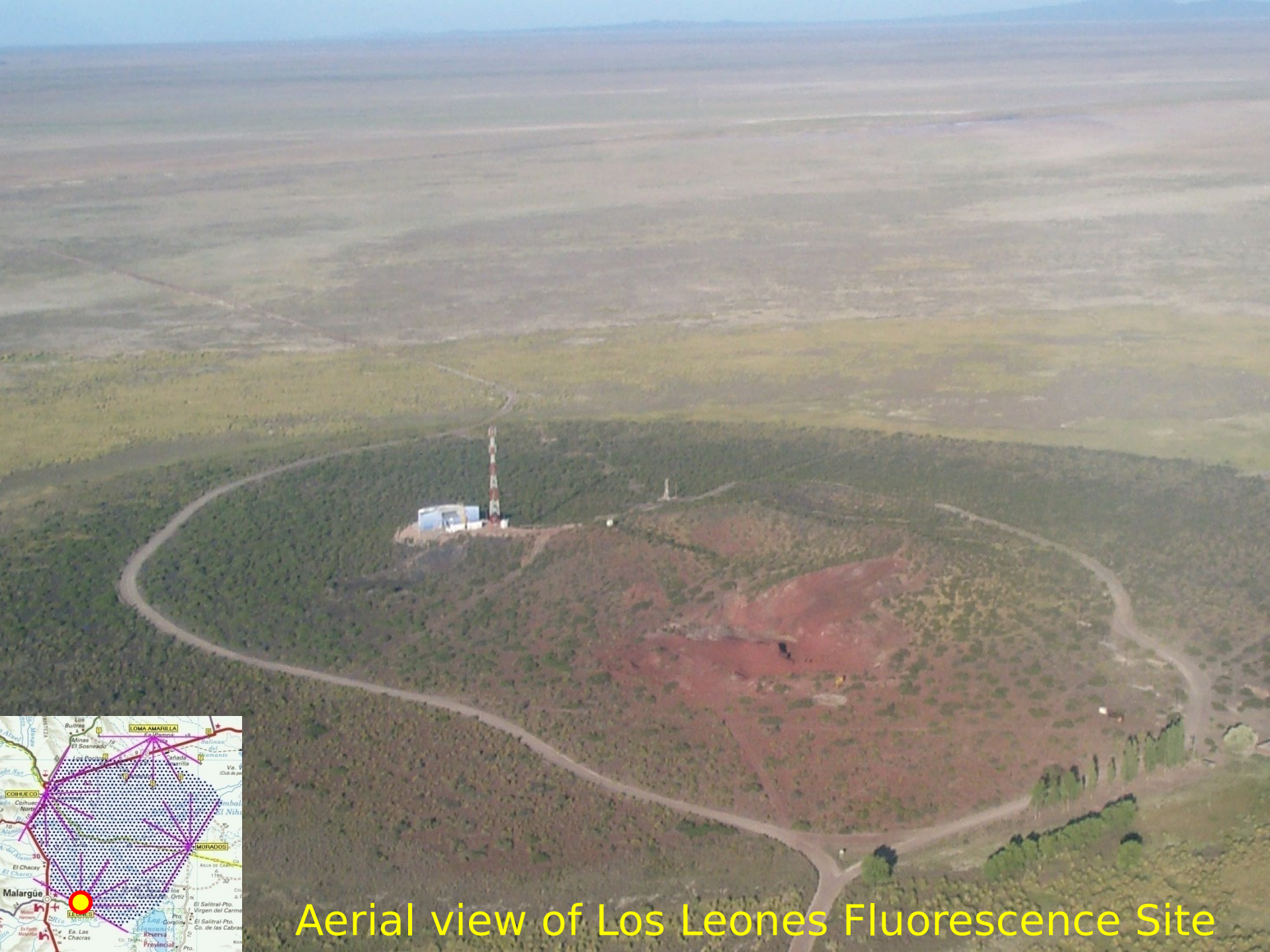
NRAO/AUI

Fornax A

1.4 , 5, & 8.4 GHz

The Pierre Auger Observatory

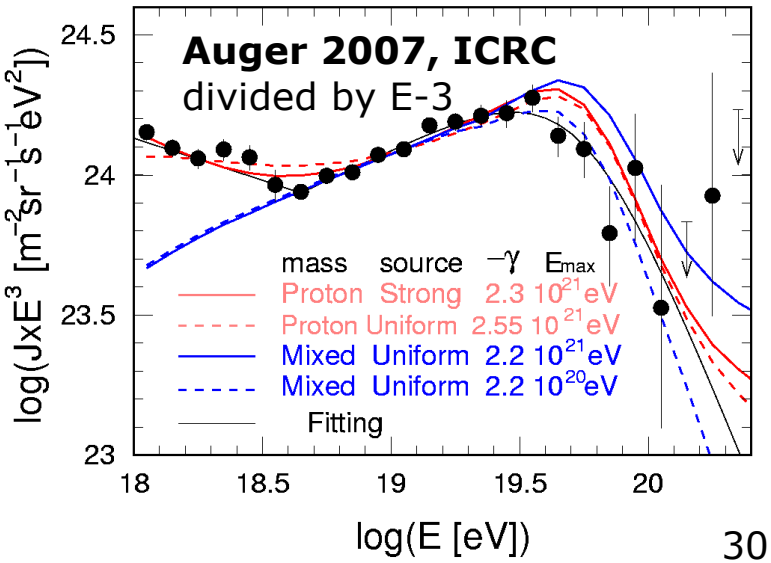




Aerial view of Los Leones Fluorescence Site

Tanks aligned seen from Los Leones

Auger: UHECR Spectrum



- Reliable energy spectrum up to >1020 eV from surface detectors (SD)
- Evidence for a suppresion above 1019.6 eV
- Interaction of UHECRs with cosmic microwave background ("GZK cut-off")?

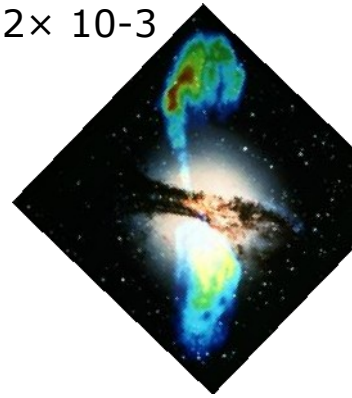
⇒ UHECRs are extragalactic

30 expected for E-2.6, 2 seen

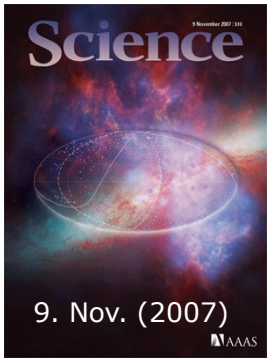
Auger: Clustering of UHECRs

New data confirms correlation with AGN clustering. Chance probability: 2× 10-3

The beginning of “charged particle astronomy”!



AUGER Collaboration (2007), Science



Early CR Radio Experiments

The 76-m Lovell Telescope at Jodrell Bank

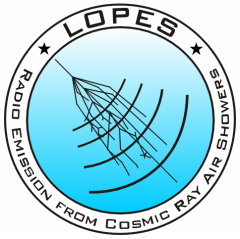
- Blackett & Lovell (1940): Propose radar reflection of CRs (and L. builds big dish).
- Jelley et al. (1965), Spencer (1969): Detect and measure CR

See also: Gorham et al. (2003), Beresnyak A. R. et al. (2005)

Astroparticle Physics: Radio Detection of

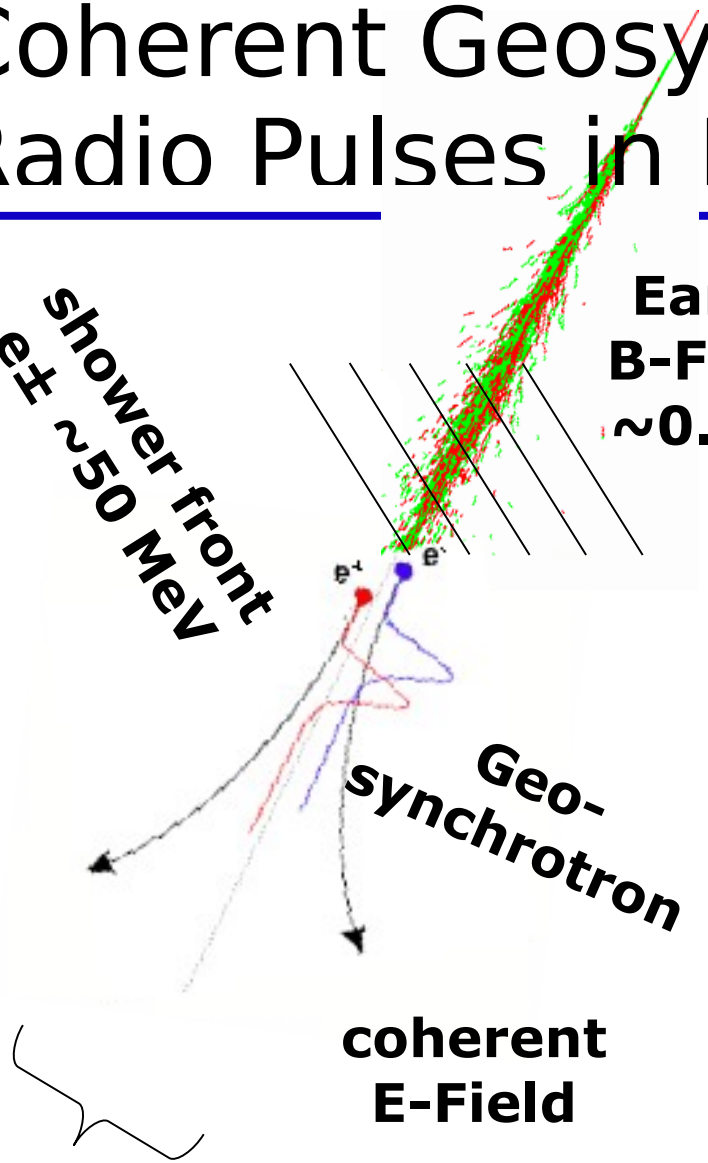
- Cosmic Rays in atmosphere:
  - Geosynchrotron emission (10-100 MHz)
  - Radio fluorescence and Bremsstrahlung (~GHz)
  - Radar reflection signals (any?)
  - VLF emission, process unclear (<1 MHz)
- Neutrinos and cosmic rays in solids: Cherenkov emission (100 MHz - 2 GHz)
  - polar ice cap (balloon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

LOFAR Cosmic Ray KSP: Main Motivation



- Exploring the sub-second transient radio sky:
  - Extensive Air showers as guaranteed signal
  - Radio flashes from the moon (UHECR and other?)
  - Identify and understand other sporadic signals (“RFI”, lightning, SETI, astrophysical sub-ms pulses, e.g. giant pulses)
- Develop the techniques to work on

Coherent Geosynchrotron Radio Pulses in Earth

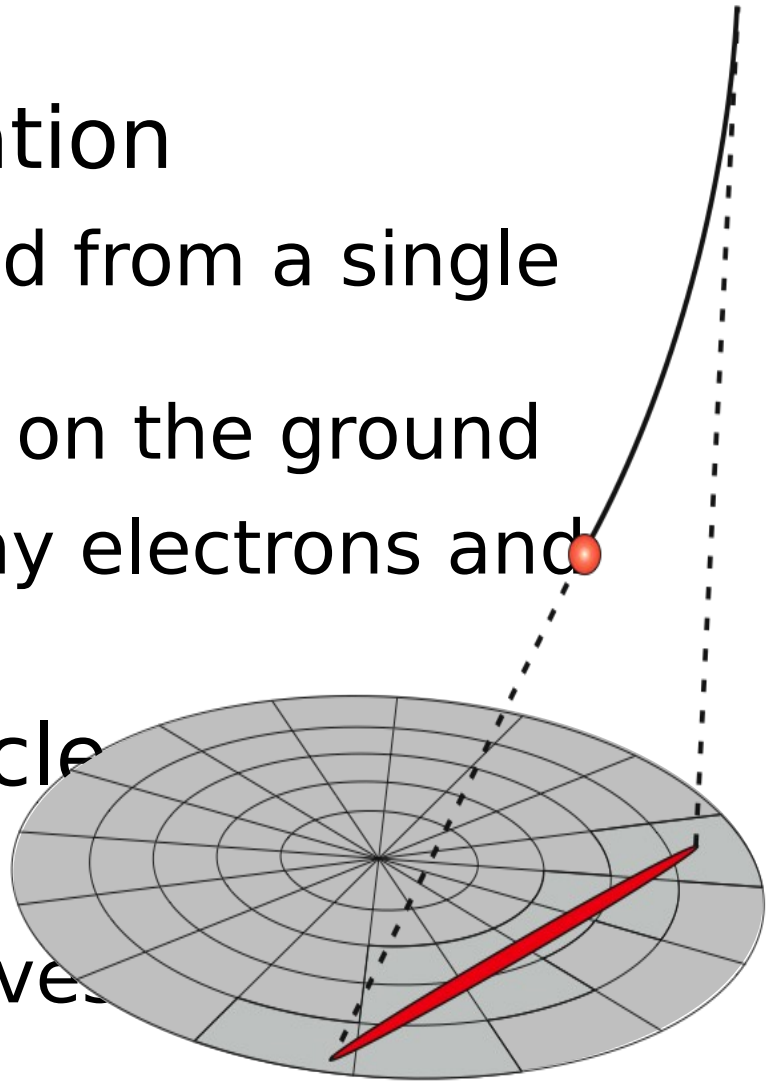


- UHECRs produce particle showers in atmosphere
- Shower front is ~2-3 m thick ~ wavelength at 100 MHz
- e± emit synchrotron in geomagnetic

Falcke & Gorham (2003), Huege & Falcke (2004,2005)
Tim Huege, PhD Thesis 2005 (MPIfR+Univ Bonn

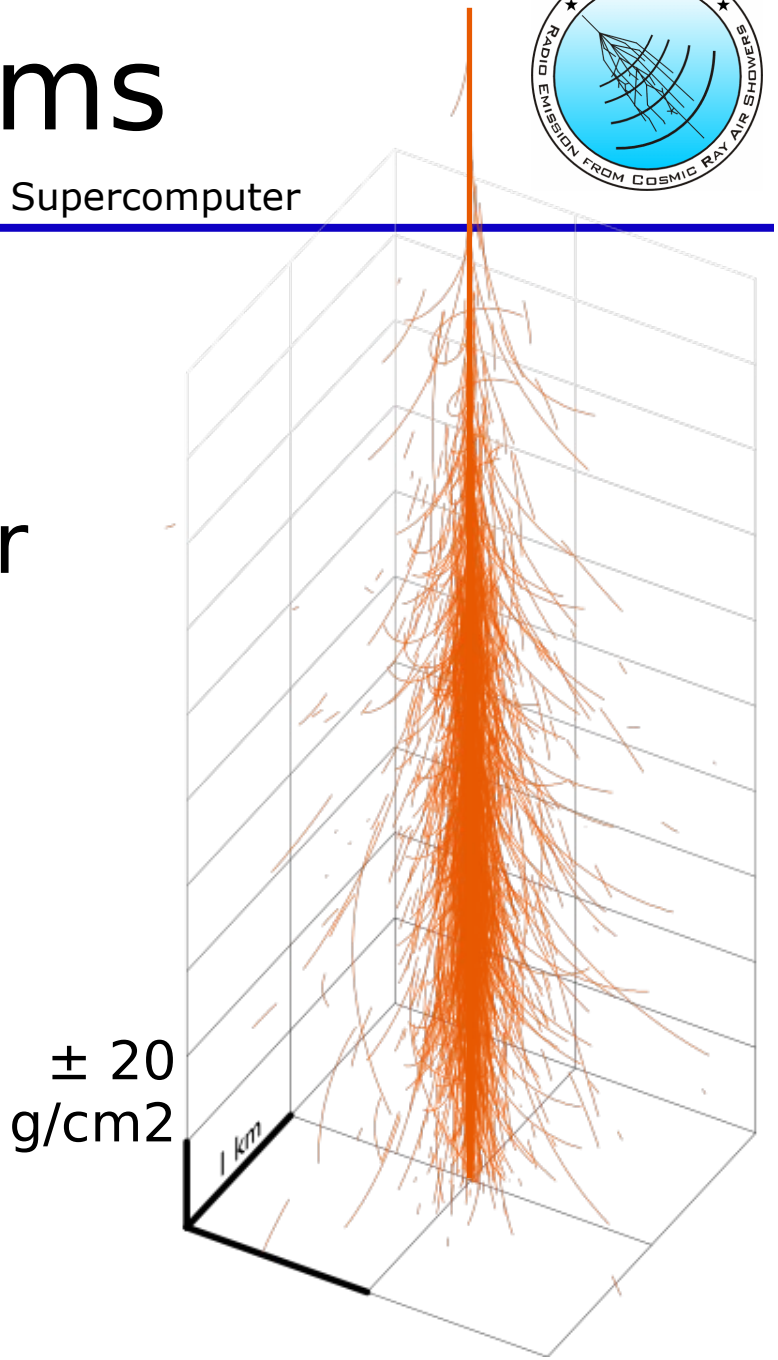
Monte Carlo Simulations

- Monte Carlo simulation
  - Calculate electric field from a single particle at different positions on the ground
  - Add pulses from many electrons and positrons
- Separation of particle and radiation codes
  - Intermediate step saves time

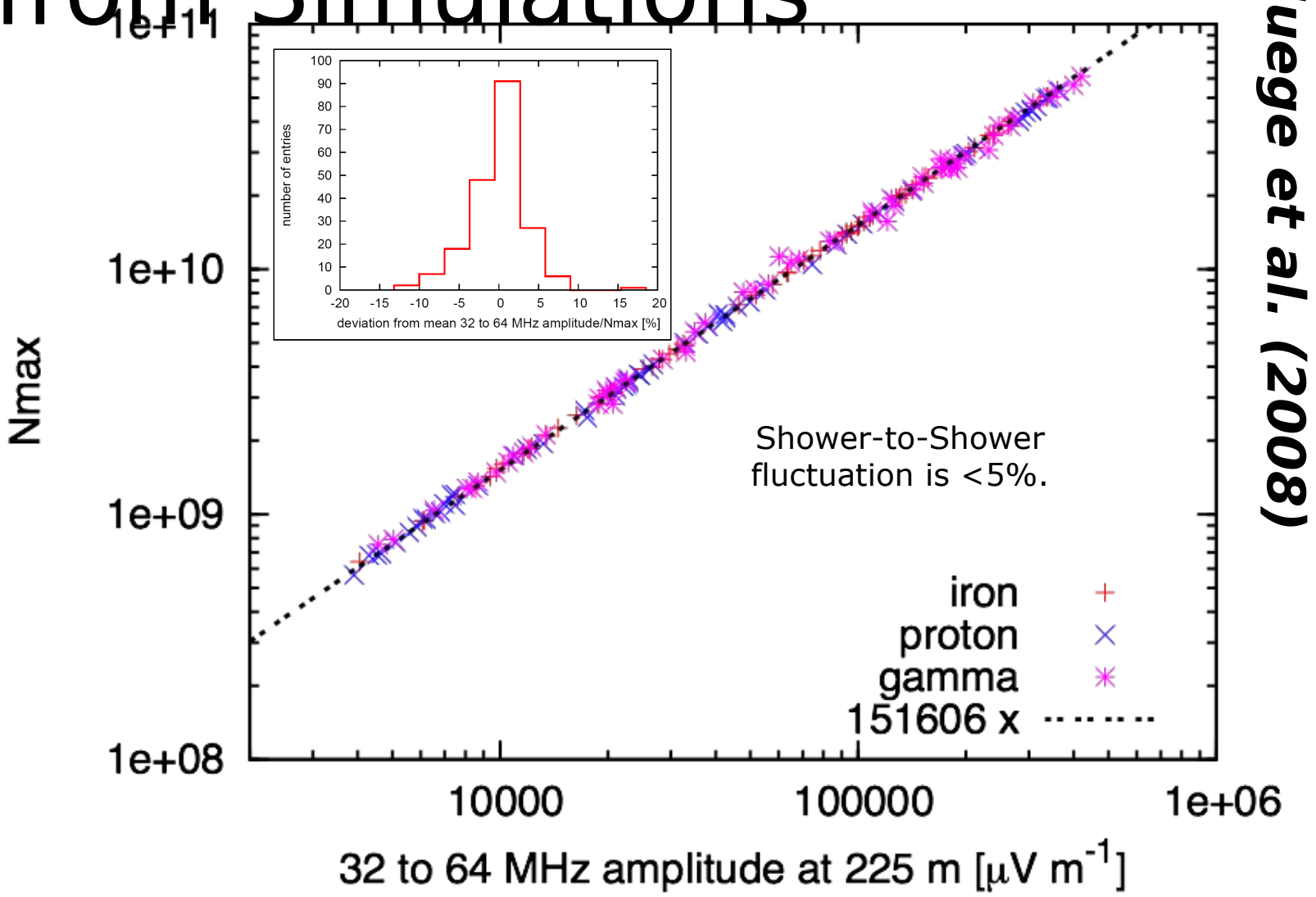


Corsika histograms

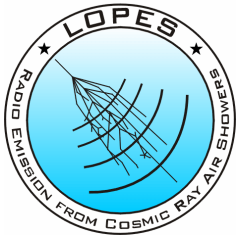
- Corsika simulations with 50 slices at equidistant shower depths
- Record e+/e– characteristics:
- Energy
- Lateral distance
- Arrival time
- Momentum angles



Extraction of Energy & *N*max from Simulations

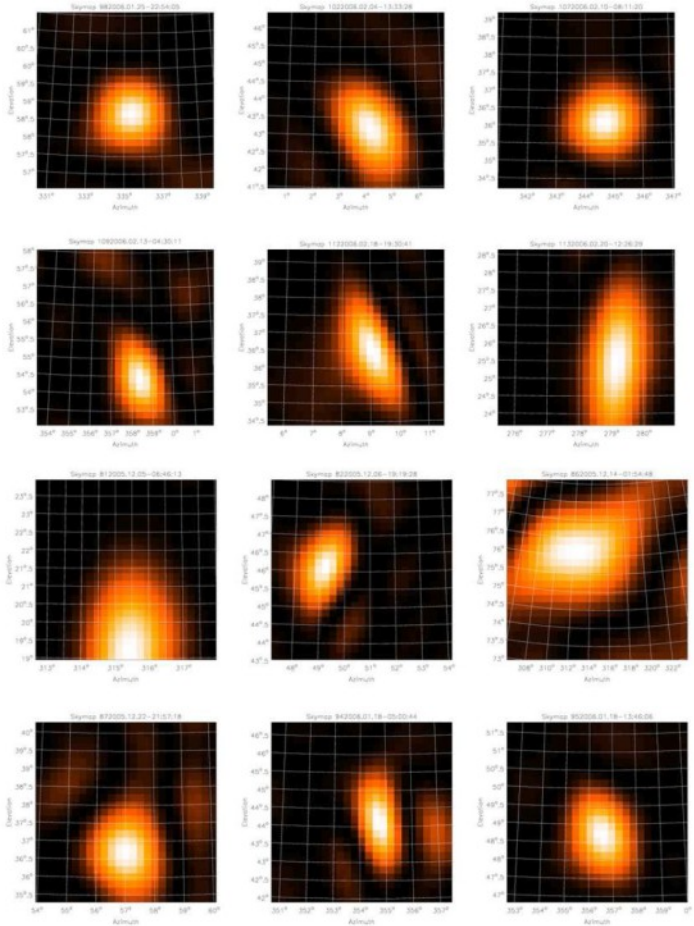


LOPES: LOFAR Prototype Station



Imaging of CR radio pulses with LOPES

A. Nigl 2007, PhD



Horneffer, LOPES30 event

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

Cross Calibration of LOPES10 and KASCADE

UHECR Particle Energy

B-field

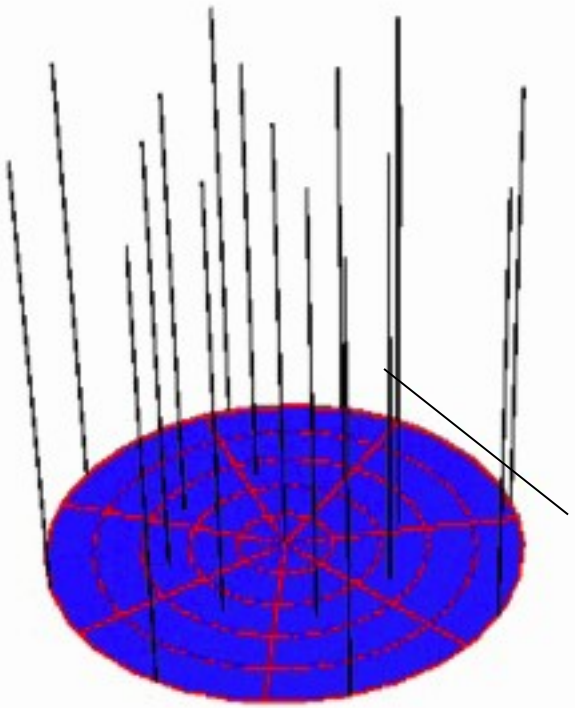
Distance

$$\varepsilon_{est,E_p} = (12 \pm 1.8)\left[\frac{\mu V}{m\ MHz}\right](1 + (0.1 \pm 0.03) - \cos(\alpha))\cos(\theta)$$
$$\times \exp\left(\frac{-R_{SA}}{(200 \pm 45)m}\right)\left(\frac{E_p}{10^{17}\,eV}\right)^{(0.91 \pm 0.07)}$$

Horneffer-Formula 2008

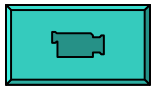
Phased Array Beam Steering

- LOFAR low-band element receives radiation from all directions.
- Phased Arrays have a virtual steerable "focal surface" which can be



Phased Array Beam Steering

- Curving the virtual "focal surface" allows near-field imaging.
- Offline processing allows one to scan an entire volume at all frequencies and time ranges.
- ⇒ Search for fast and unpredictable bursts.



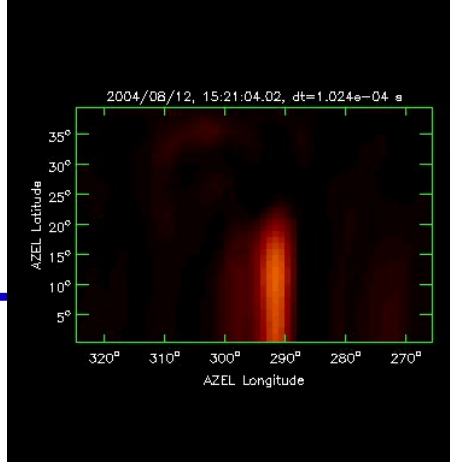
Nanosecond Radio Imaging in 3D

Actual 3D radio mapping of a CR burst
No simulation!

- Off-line correlation of radio waves captured in buffer memory
- We can map out a 5D image cube:
  - 3D: space
  - 2D: frequency & time

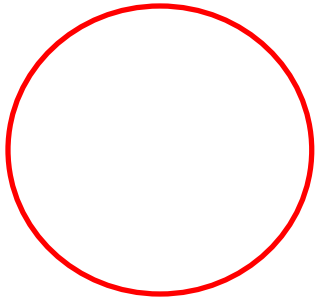
Bähren, Horneffer, Falcke et al. (RU Nijmegen)

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

Thunderstorm events



Buitink et al. (LOPES coll.) 2007, A&A

Thunderstorm Events

- CORSIKA simulations with thunderstorm electric fields
- Electrons and positrons are accelerated and deflected (“Electron rain”)
- This can lead to increased radio emission

⇒ The shower is modified in thunderstorms not the radio emission

CORSIKA air shower simulation with thunderstorm electric fields

Positron “Rain”

Buitink et al. (LOPES coll.) 2007, (ICRC)

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CORSIKA air shower simulation with thunderstorm electric fields

Buitink et al. (LOPES coll.) 2009, (PhD)

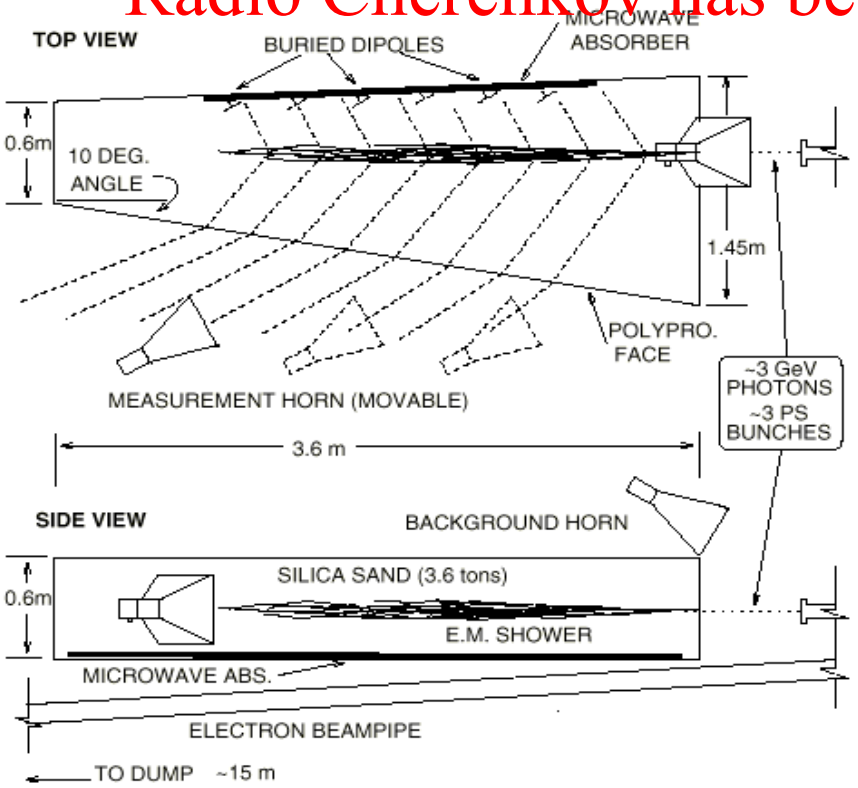
Ultra-High Energy (Super-GZK) Neutrino Detections

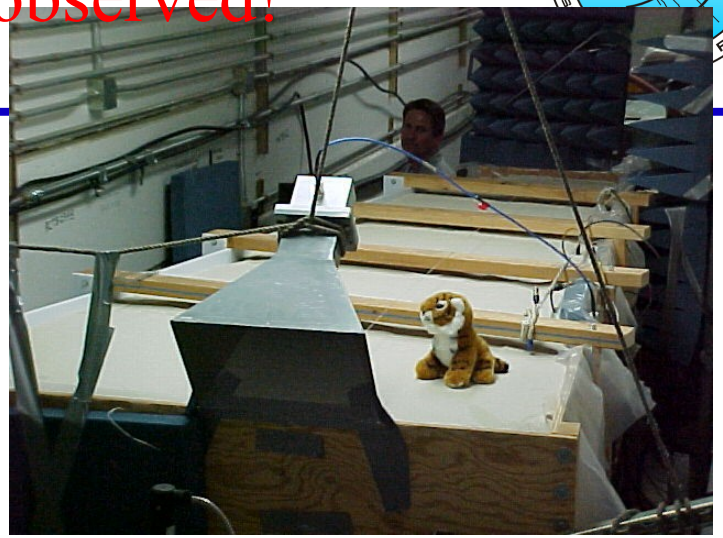
- Ultra-high energy particle showers hitting the moon produce radio Cherenkov emission in the regolith.
- The moon

radio from
neutrinos hitting the moon

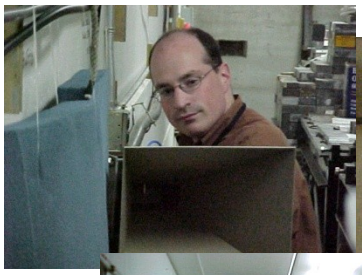
from Gorham et al. (2000)

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

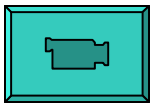




From Saltzberg, Gorham, Walz et al PRL 2001



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



UHECR Limits of LOFAR with improved

Singh et al. (2008)

UHE Neutrino Limits

Singh et al. (2008)

Westerbork Synthesis Radio Telescope (WSRT) – NuMoon

- WSRT Observations:
  - PuMa II (pulsar) backend
  - 4 frequency bands between 113 and 175 MHz
  - sampling with 40 MHz
  - RFI filtering
  - Ionosphere correction
  - 47.6 h observations

Future Radio Observations

10% SKA &
current LOFAR

10% SKA &
originally planned LOFAR

**1 year
original**

1 year
10% SKA

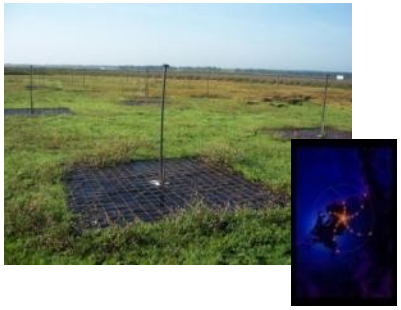
LPM effect taken
into account!

νMoon Collaboration: Scholten, Falcke, Singh, Buitink, Stappers, de Bruyn, Strom

KSP Organization

- Main Groups
  - RU Nijmegen, KVI Groningen
  - Association with FZ Karlsruhe theory group
  - Collaboration with LOPES and Radio@Auger groups
  - Open for further input ...
- Personpower
  - Currently: 4 staff, 2 PostDocs, 1 SW Developer
  - 2009: + 3 PhDs + 2 PostDoc + Developer

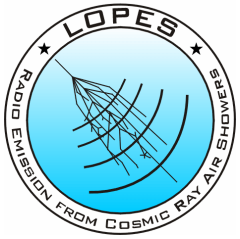
Cosmic Rays in the Radio



νMoon

S. Lafebre

Summary & Conclusions



- The LOFAR CR KSP will ..
- ... explore the fastest time scales in LOFAR (down to 5ns) and develop novel techniques in radio astronomy
  - Real-time triggering
  - Transient Buffer-Board (TBB) utilization
  - 3D all-sky imaging on buffered data (1sec observation needs 1TB of data to be processed...)
  - Transient signal extraction
- ... detect airshowers from UHECRs