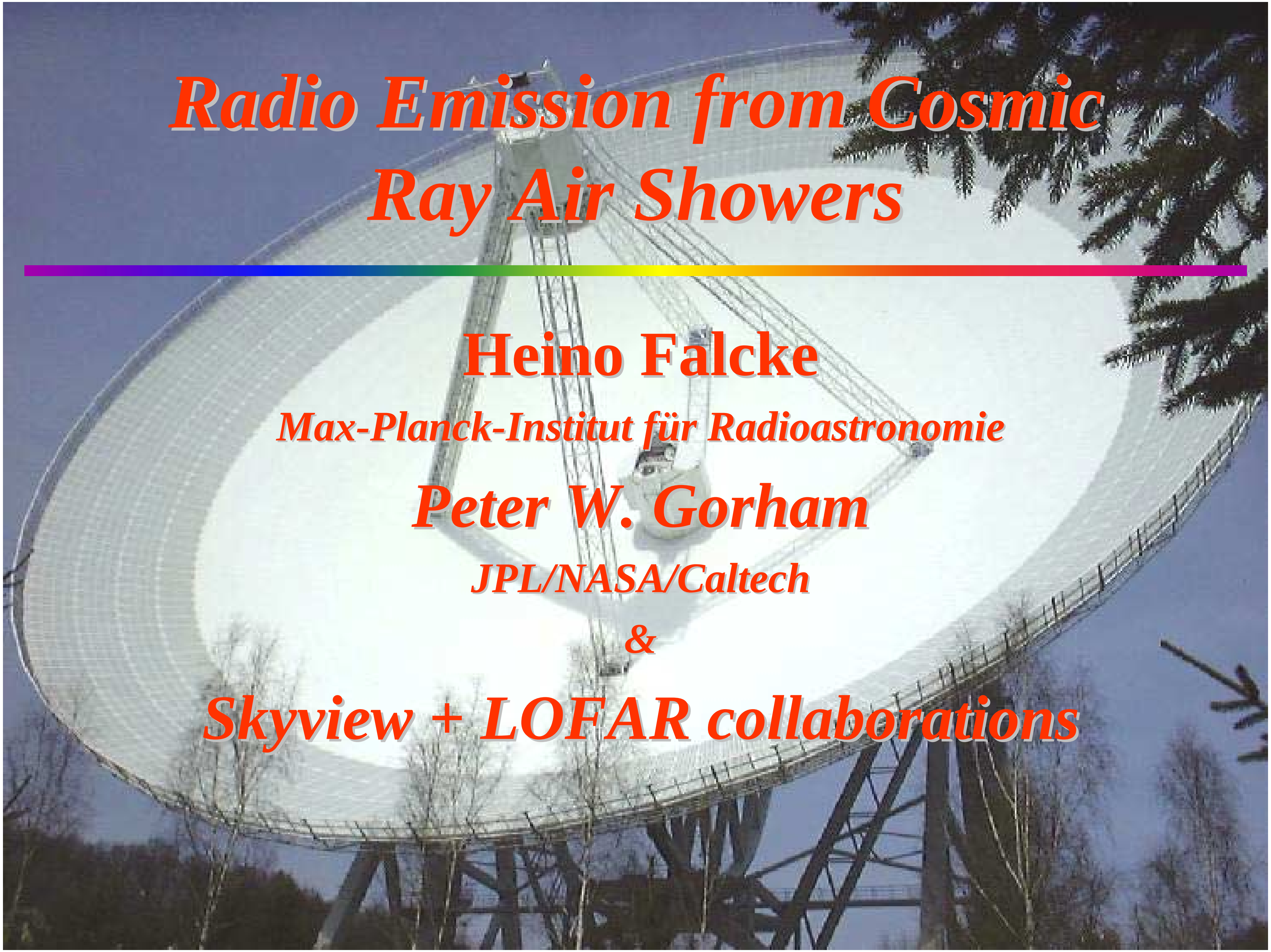

Radio Emission from Cosmic Ray Air Showers

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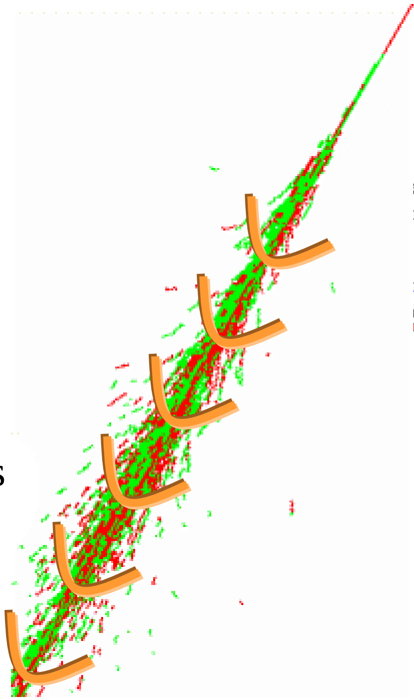
&

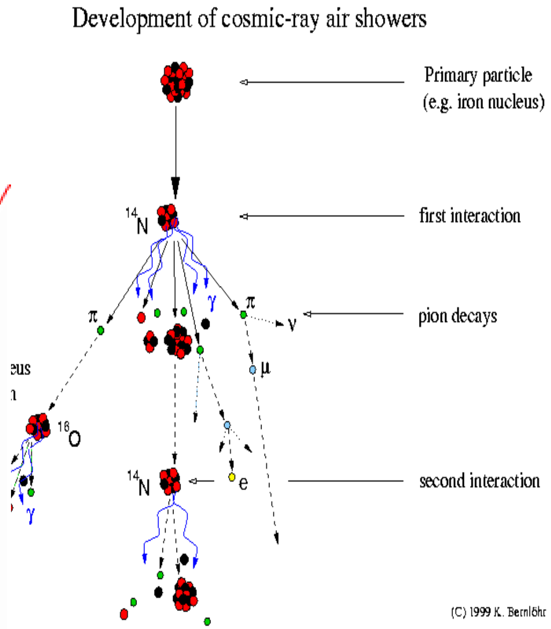
Skyview + LOFAR collaborations

A (very) Brief History of Cosmic Rays

Victor Hess, 1912:
- discovered cosmic rays in balloon flights, through discharge of Leyden jars

Pierre Auger, 1938:
- Research in Giant Air Showers showed energies of primary particles above 10^{16} eV-- truly unimaginable for the time!





- 1960's: Cosmic rays with energies of $>10^{19}$ eV detected - how are they made??
- Greisen, Zatsepin, Kuzmin (GZK): there should be a limit at $\sim 5 \times 10^{19}$ eV

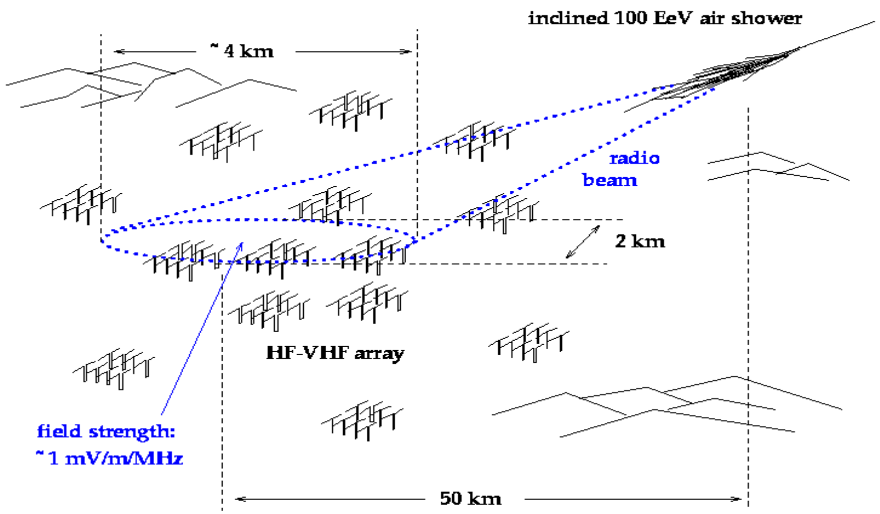
Radio Emission from Air Showers: History

- First discovery: Jelley et al. (1965), Jodrell Bank at 44 MHz
- Firework of activities around the world in the late 60ies & early 70ies
- In the late 70ies radio astronomy moved to higher frequencies and also CR work ceased

Jelley et al. (1965)

Advantages of Radio Air Showers

- Particle detectors on ground only measure a small fraction of electrons or muons produced
- Height of cosmic ray interaction depends on energy
- Energy calibration is greatly improved by additional information (e.g., Cerenkov)
- Radio could
  - Observe 24hrs/day
  - See evolution of shower
  - Coherent emission reveals shape



Radio measurements are usually triggered by particle detectors

Radio-Emission from Air Showers: Current Activities

- Work ceased almost completely in the seventies (interference)
- Radio-experiment at CASA/MIA arrays (Rosner & Suprun 2001) failed because of man- and self-made interference
- An isolated group at Gauhati University (India) is observing regularly at 2-220 MHz
- Monte Carlo air shower radio code developed by Dova et al.
- RICE – Searching radio emission from neutrino induced showers in ice at the AMANDA site in Antarctica
- Search for radio emission on the moon (neutrinos; Alvarez-Muniz & Zas 2000; Gorham et al. 1999)

Radio Properties of Airshowers: Radio Amplitude – Empirical Results

$$\mathcal{E}_\nu = K \frac{E_p}{10^{17}\ \mathrm{eV}} \sin\alpha \cos\theta \exp\left(-\frac{R}{R_0(\nu,\theta)}\right) \quad \mu\mathrm{V}\ m^{-1}\ \mathrm{MHz}^{-1}$$

Allan (1971)

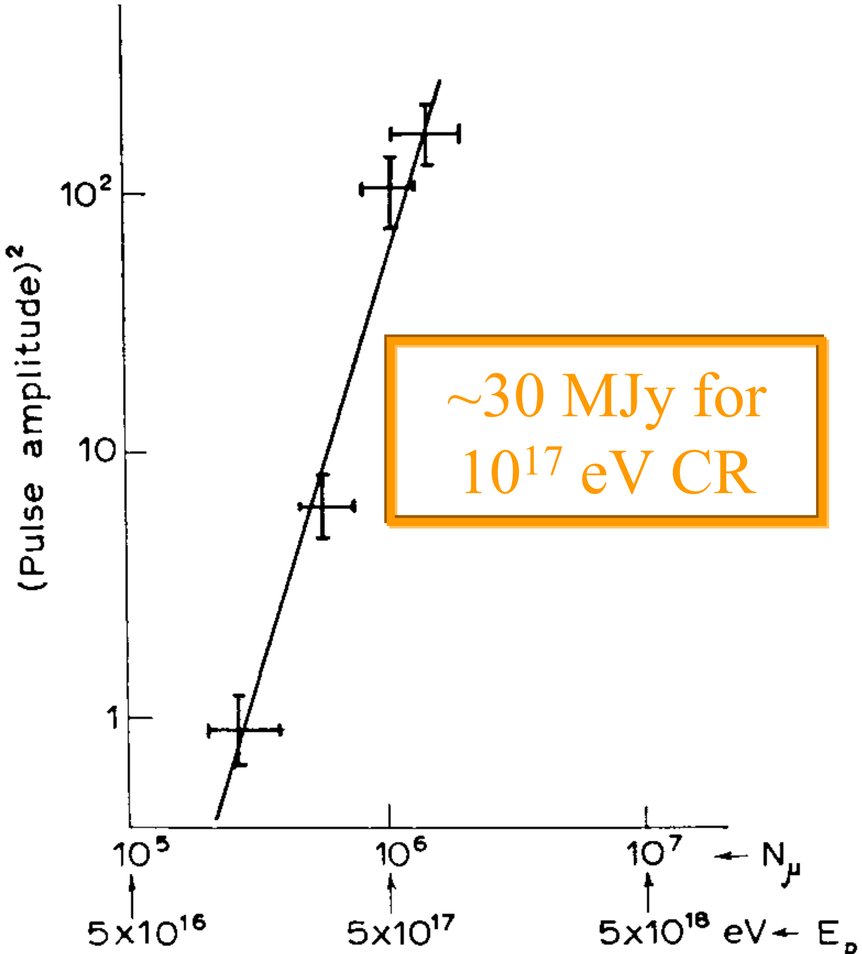
- Constant K~15, R_0~ 110m, spectrum flat from ~40-100 MHz?
- $S_\nu = \varepsilon_0 c\, \mathcal{E}_\nu^2/\mathrm{MHz} \Rightarrow S_\nu = 26.5\ \mathrm{MJy}\ (\mathcal{E}_\nu / 10\ \mu\mathrm{V\ m^{-1}\ MHz^{-1}})^2$
- R is distance from shower axis, relation corresponds to ~1 degree half-angle emission cone
- Here α is geomagnetic angle, θ is zenith angle, but not measured past ~50 deg.
- This relation is based on near field measurements: *Fresnel zone* for shower radio emission extends several tens of km, most data is from D~5-7 km!

Radio Properties of Airshowers: Energy Dependence of Amplitude

- Experimental results suggest a quadratic dependence of radio flux on particle energy.
- Particle number: $N_e \sim E_\mathrm{p}/\mathrm{GeV}$
- Coherent radiation:

$$\mathcal{E} \propto N_e \propto E_\mathrm{p} \ \& \ S_\nu \propto \mathcal{E}^2 \Rightarrow S_\nu \propto E_\mathrm{p}^2$$

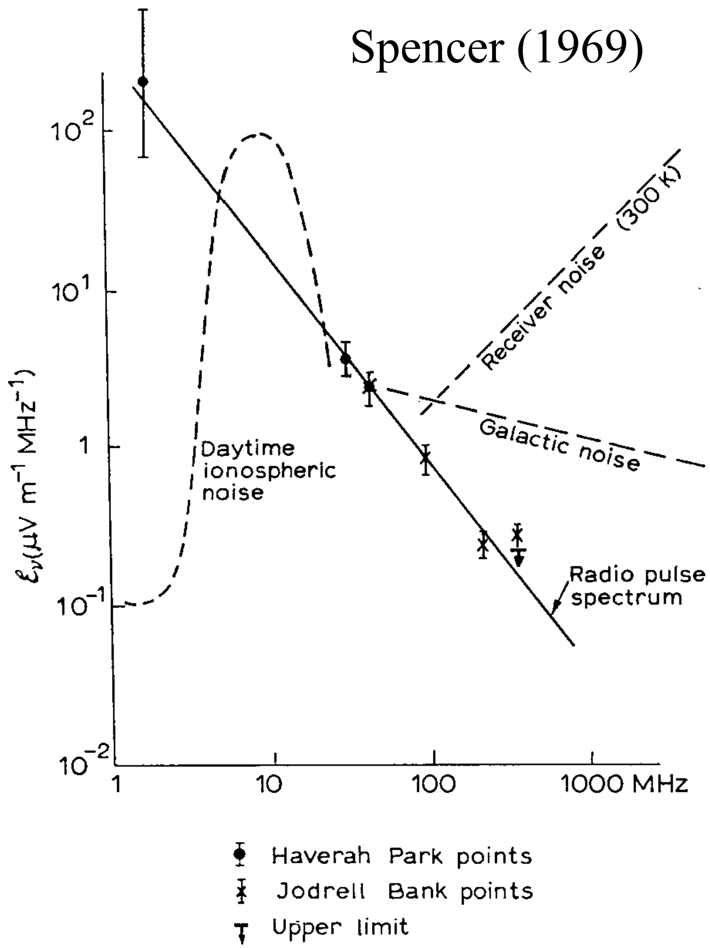
- Shower height is energy dependent → 2nd order effects?



Vernov et al. (1968)

Radio Properties of Airshowers: Frequency Spectrum

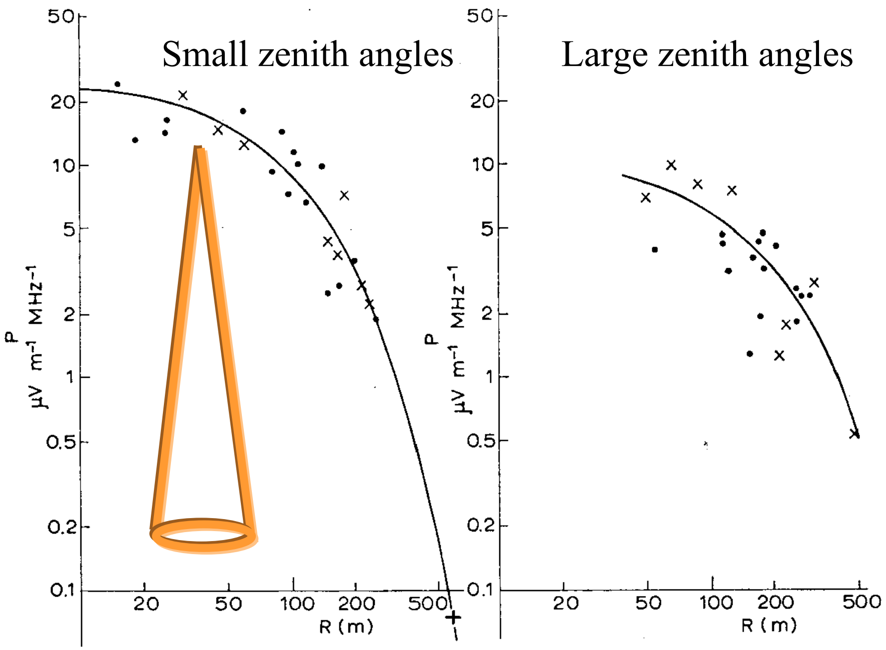
- Measurements at four frequencies between 44 and 408 MHz (Spencer 1969)
- Spectrum decreases as $\mathcal{E} \propto \nu^{-1}$ or $S_\nu \propto \nu^{-2}$
- May continue down to 2 MHz (Allan et al. 1969).
- Noise level favors 40-50 MHz observations



Radio Properties of Airshowers: Spatial Extent

- The particles move as a flat (2-3 m thick) pancake around a central core through the atmosphere.
- The radio emission falls off steeply beyond a characteristic distance from the shower core (R_0=50-500m)⇒beaming

Haverah Park



Amplitude normalized to $E_p = 10^{17}$eV

Radiation Mechanism: Coherent Synchrotron!?

- The characteristic energy where electrons disappear through strong ionization losses is 30-100 MeV, i.e. γ~60-200.
- Geomagnetic field is 0.3 Gauss
- Electrons will „gyrate“ along a small arc
- Electrons are in a thin layer of 2 meters thickness, i.e. less than a wavelength at 100 MHz
- Coherent emission can be produced (gives N^2 enhancement), beamed into propagation direction

Radiation Mechanism: Coherent Geo-Synchrotron!?

$$P_q = \frac{2q^2\ddot{\vec{r}}^{\,2}}{3c^3} \qquad \ddot{\vec{r}} = \frac{e}{\ldots}\vec{v}\times\vec{B}$$

Lorentz boost

$$\Rightarrow P_q = \frac{2q^2}{3c^3}\gamma^4\frac{q^2 v_\perp^2 B^2}{\gamma^2 m^2 c^2}$$

$$\Rightarrow P_q = \frac{2q^4}{3c^5 m^2}\gamma^2 v_\perp^2 B^2$$

$$q = N\cdot e;\ m = N\cdot m_e$$

$$\Rightarrow \boxed{P_q = N^2 P_e}$$

- Synchrotron emission in geomagnetic field is unavoidable
- Synchrotron power is given by the Poynting vector (charge & accel.)
- Acceleration is due to the Lorentz force
- N electrons act coherently as one particle of charge N · e and mass N · m

$\Rightarrow$ Power is increased by N^2 (amplitudes add coherently)

Radiation Mechanism: Coherent Synchrotron!?

$$P_e = \frac{2e^4}{3c^5 m_e^{\ 2}} \gamma^2 v_\perp^2 B^2 \ \& \ P_q = N^2 P_e$$

$$B = 0.3G \quad \gamma = 60 \quad \mathrm{N_e} = 10^8 E_{p,17}$$

$$\mathrm{A} = \pi(10\,\mathrm{km} \cdot 0.5°)^2$$

$$\nu_\mathrm{c} \sim \frac{3e}{4\pi m_e c} \gamma^2 B \sim 4.5\,\mathrm{GHz}$$

$$S_\nu = N_e^2 P_e A^{-1} \nu^{-1} \left(\frac{\nu}{\nu_\mathrm{c}}\right)^{1/3} f\left(\frac{\lambda}{\Delta z_{shower}}\right)$$

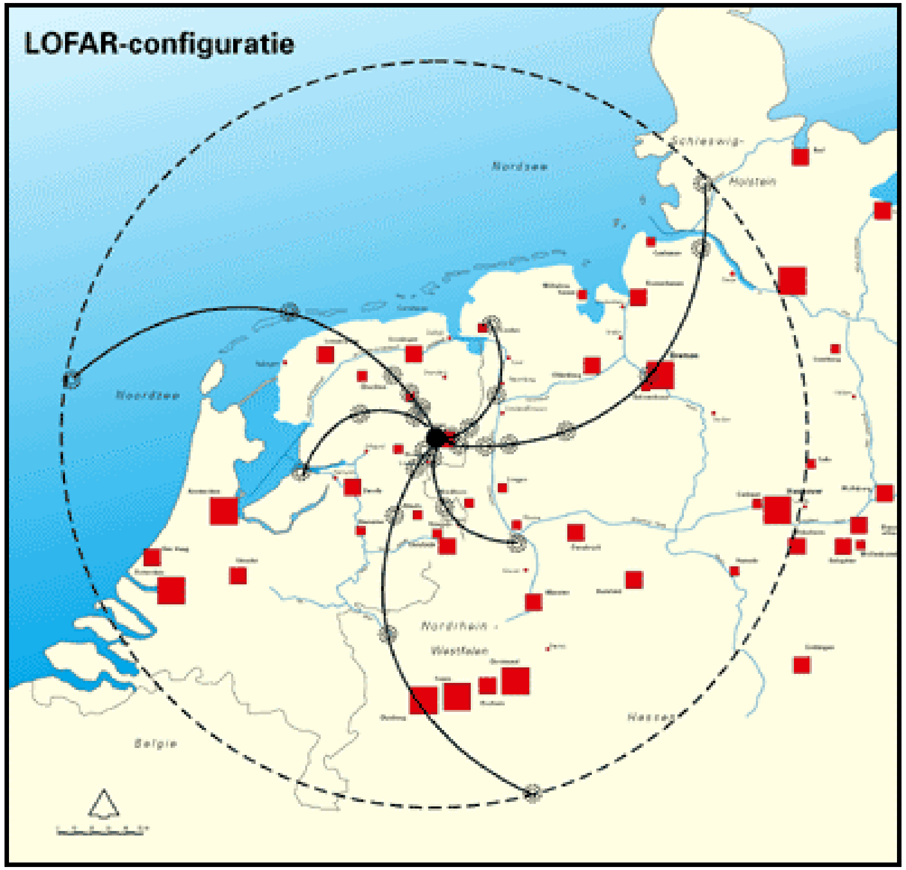
$$S_\nu (100\,\mathrm{MHz}) \sim 40\mathrm{MJy} \cdot E_{p,17}^2$$

Kahn & Lerche (1968), Allan 1971, Falcke & Gorham (2001)

- Synchrotron emission in geomagnetic field is unavoidable
- $\Delta z \sim \lambda$ @ 100 MHz $\Rightarrow$ coherence and amplification
- Plug in characteristic values for air showers.
- At the characteristic frequency coherence is not achieved due to finite thickness (decreasing spectrum)
- Predicts correct properties

LOFAR – a new window to the universe

- Low-Frequency Radio Array connected by high-speed internet (10 Tb/sec!)
- Monitors almost entire sky
- Astrophysics: B-fields, Cosmic Ray acceleration, stars, transients, AGN, ...
- monitors ionosphere & interf.
- Will certainly see meteorites and air showers!
- With 15 Mio. Nfl first phase fully funded, 30 M€ promised, completion 2006.



LOFAR – System Characteristics

Instrument type	Earth rotation synthesis array
Low frequency range	10 – 90 MHz
High frequency range	110 – 220 MHz
Number of receptors	13365 dual polarised dipoles for the 10 – 90 MHz range 213840 dual polarised dipoles for the 110 – 220 MHz range
Number of clusters	1485
Number of interferometric stations	Between 60 and 165
Number of digital beams in one frequency channel for a remote station	Between 2 and 8
Instantaneous sky coverage remote station	1 steradian at 20 MHz using 8 beams
Digitised Bandwidth	32 MHz
Spectral range transported from remote stations	Between 2 and 4 MHz
Number of spectral channels	4096
Polarization	full Stokes
Baseline range	Between 100 m and ~400 km
Spectral resolution	1 kHz
Integration time of correlator	Down to 1 ms

LOFAR

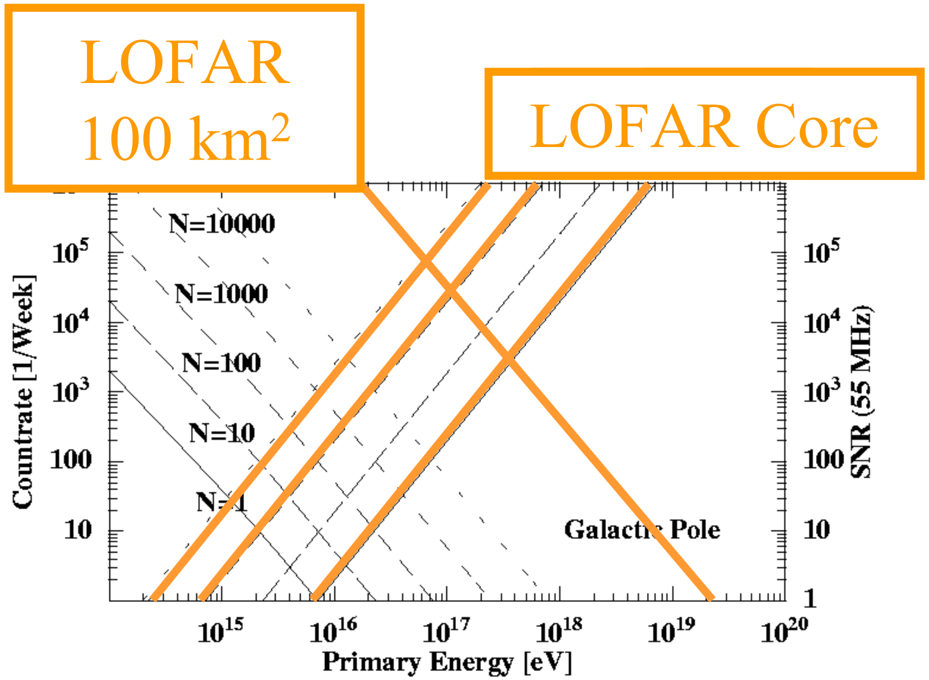
- 10^2 stations with 10^2 dipoles/antennas each, connected to a central computer supercluster
- Low-Tech „Hardware“
- “Next Generation” computing and internet (Lucent, KPN)
- No mechanical steering – beam is digitally synthesized
- Radically new telescope concept which is ideally suited for astroparticle-physics (radio air showers).

LOFAR

- LOFAR collaboration:
  - **ASTRON (NL)**
  - **MIT (USA)**
  - **Naval Res. Lab. (USA)**
  - Smaller groups in Australia, Canada, UK
- Astroparticle aspect is a relatively new baby:
  - MPI für Radioastronomie, Bonn
  - JPL, Pasadena (Goldstone)
  - Skyview collaboration

LOFAR Performance

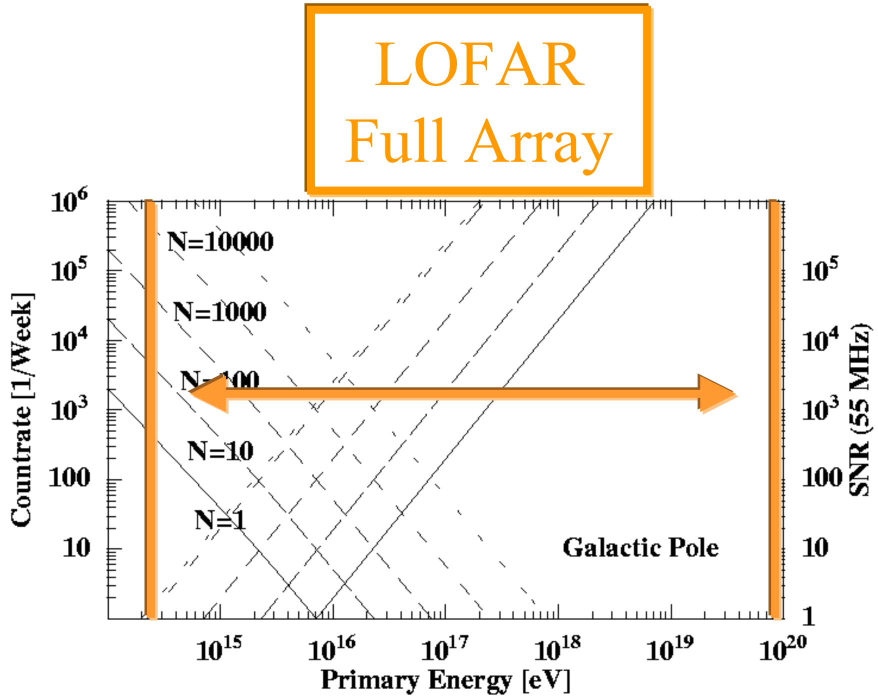
- Cosmic rays above 10^{17} eV are easily detected by radio antennas
- Cosmic ray energy is limited by Galactic radio background and effective area.



densely packed array

LOFAR Performance

- The full LOFAR array will measure CRs from $2 \cdot 10^{14}$ eV to 10^{20} eV with baselines varying from 1 m to 300 km → unique
- LOFAR will be an ideal multi-purpose air shower detector (almost) „for free“ – if we know how to use it
- Combine with Skyview to obtain a highly competitive giant air shower array in the northern hemisphere!



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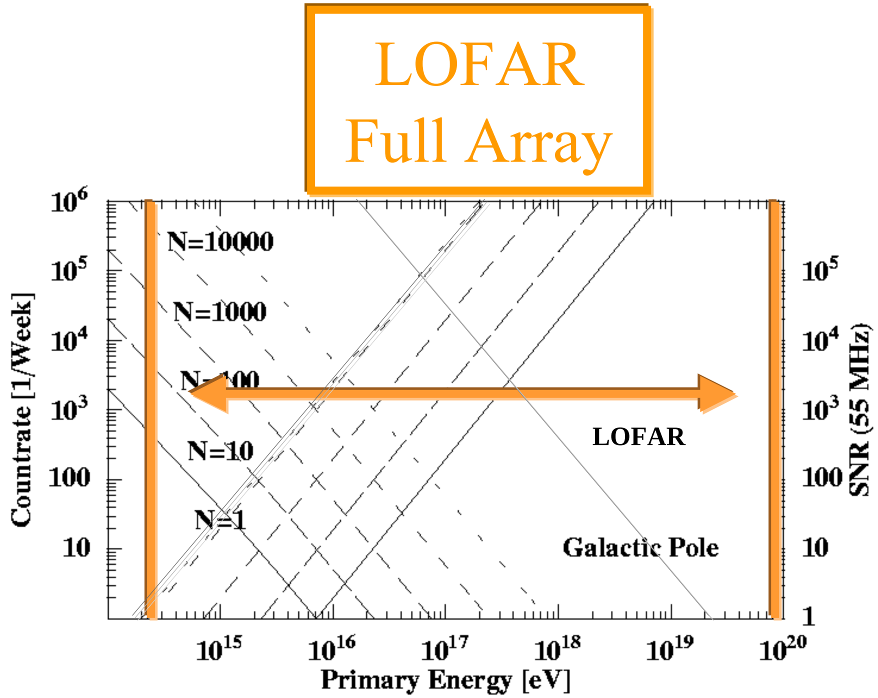


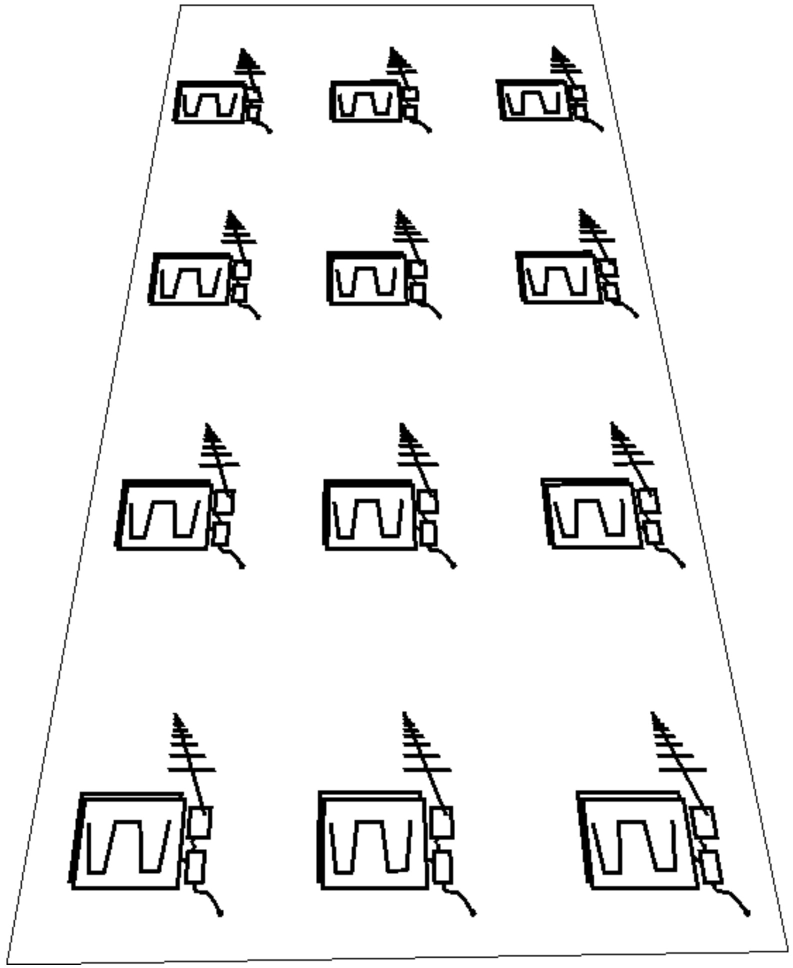
densely packed array

LOPES

- What to do until 2006?
- We need to study radio emission from EAS and calibrate the method with conventional arrays.

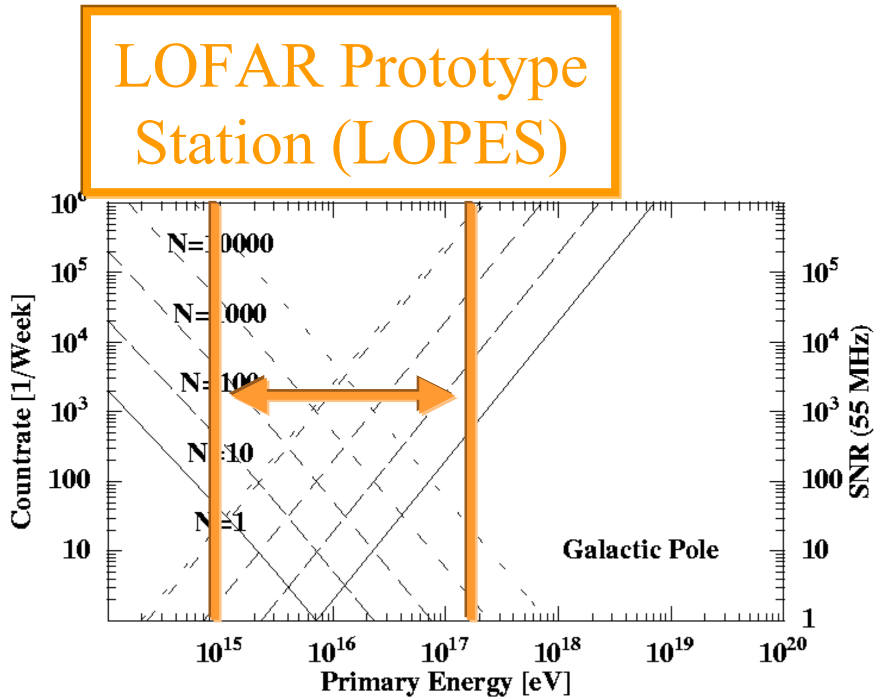
⇒ Build a single LOFAR prototype station (LOPES) in conjunction with Kascade, Coral, Skyview prototype, ...

- Need about 100 dipoles
- Reasonable cost:
  Cost=x · 10^5 €, x=1-3



LOFAR Prototype Performance

- 100 dipoles will measure CRs around the knee from 10^{15} eV to 10^{17} eV and study radio properties of air showers.
- With this knowledge we can add astroparticle capabilities to LOFAR and develop „software telescope“ technology.
- Test for Auger & Skyview



densely packed array

Scientific Goals of LOPES/LOFAR

- Understand radio emission from air showers (polarization, spectrum, energy dependence, evolution)
- Study composition of UHECR from 10^{15} to 10^{20} eV (Galactic/Extragalactic)
- Path length of 10^{18} eV neutrons is 10 kpc $\Rightarrow$ Galactic neutron astronomy!
- Probe parameter space for unexpected air shower properties (multiplets, patchiness).
- Search for isotropic radio emission $\Rightarrow$ would extend LOFAR to $10^{21.5}$ eV (super-GZK particles)!
- Also: Search for ultra-high energy neutrinos (moon, air)

Conclusion

- The new generation of software telescopes will revolutionize low-frequency radio astronomy.
- LOFAR will come and it will (unexpectedly) be a premier instrument to measure (UHE)CRs.
- LOPES will be an important stepping stone.
- Ideal: Joint development with SKYVIEW
- Provides a golden opportunity for the vibrant German astroparticle community to use the LOFAR project for astroparticle physics!