Radio Detection of Cosmic Particles with the SKA

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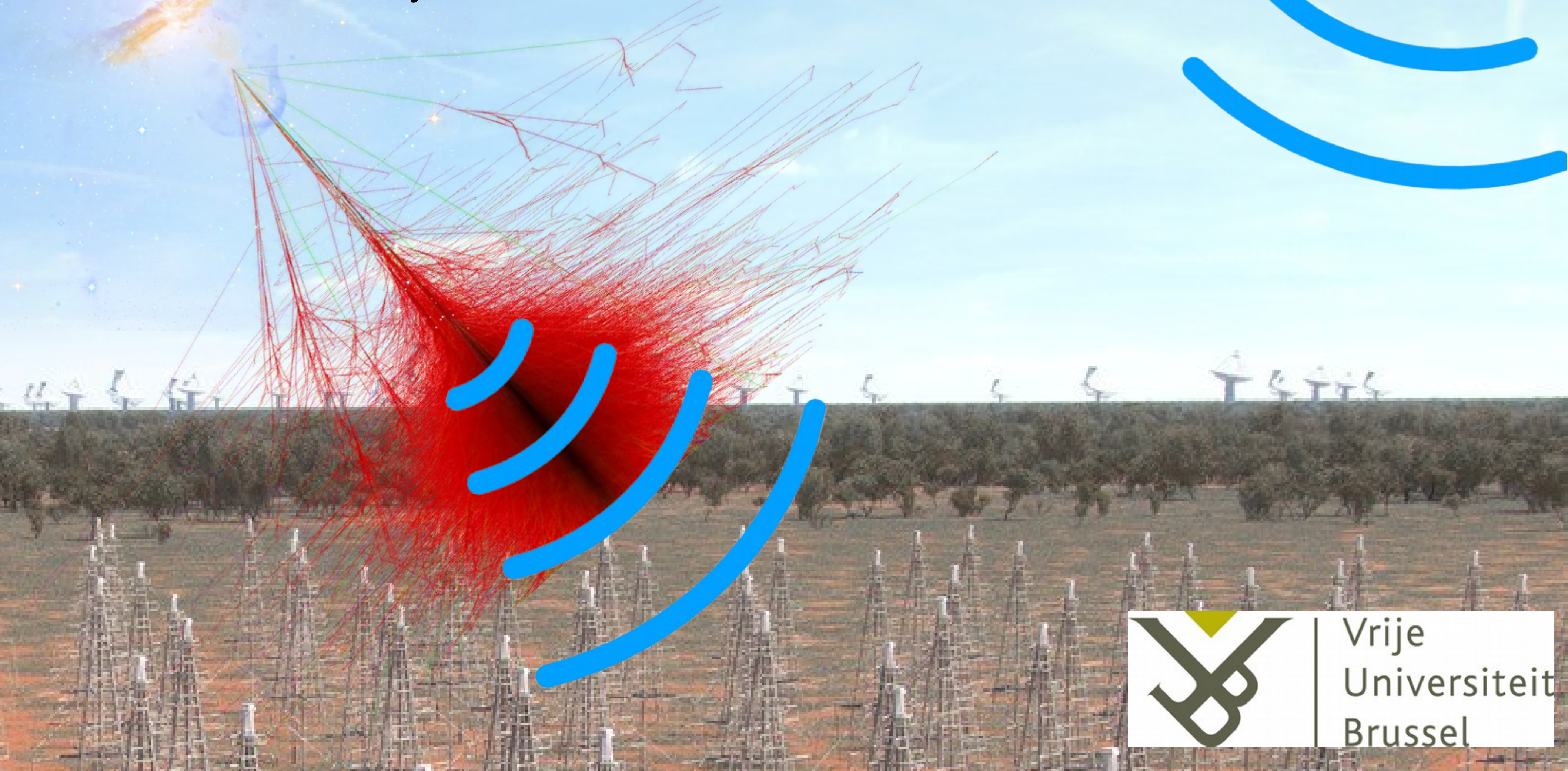
For the SKA Focus Group on High Energy Cosmic Particles
EWASS Greece, July 2016



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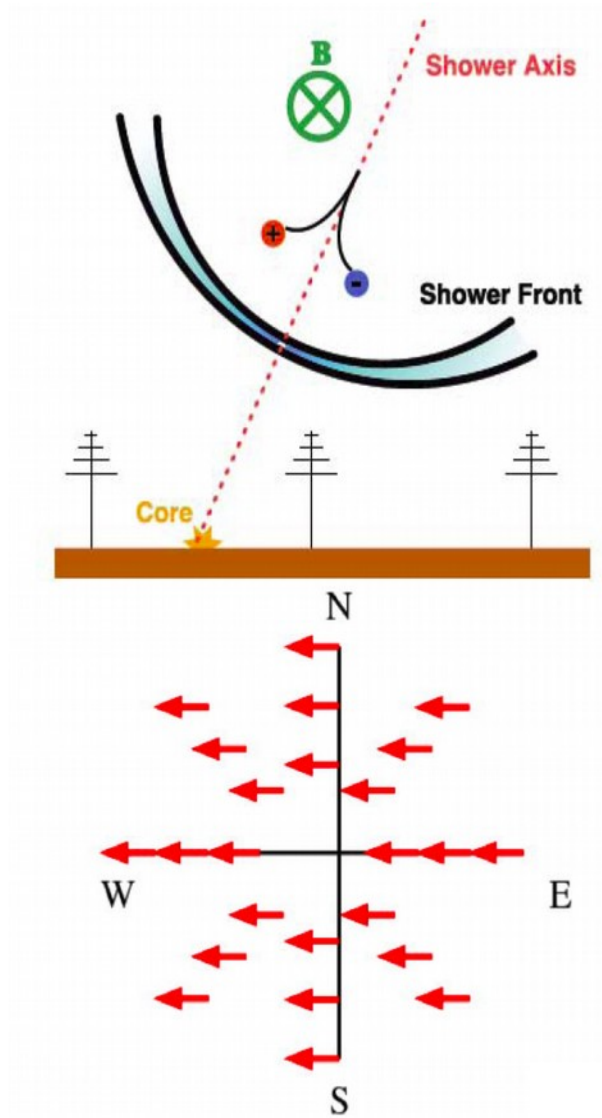
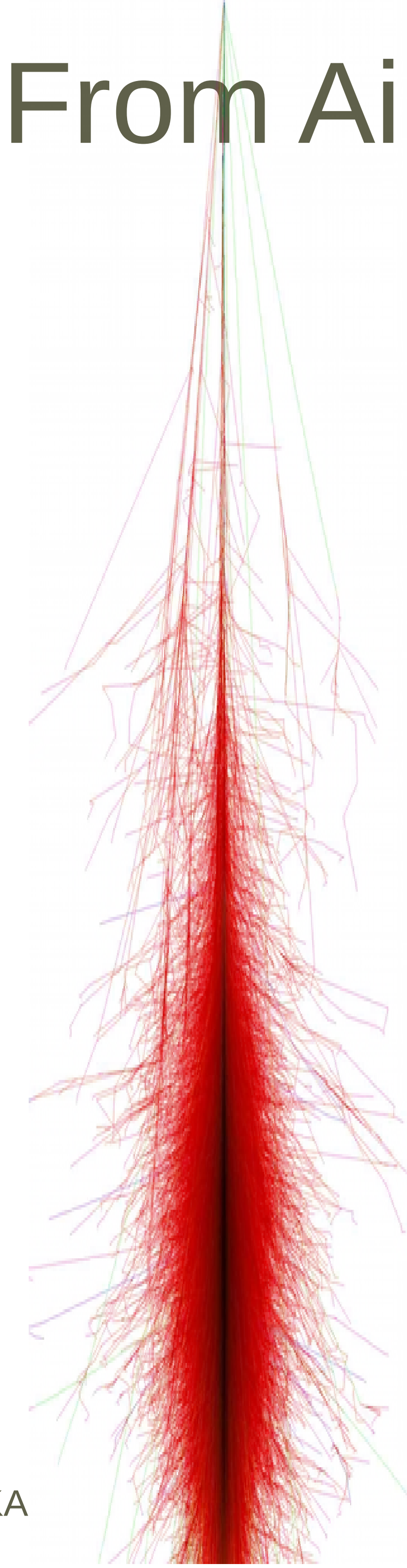
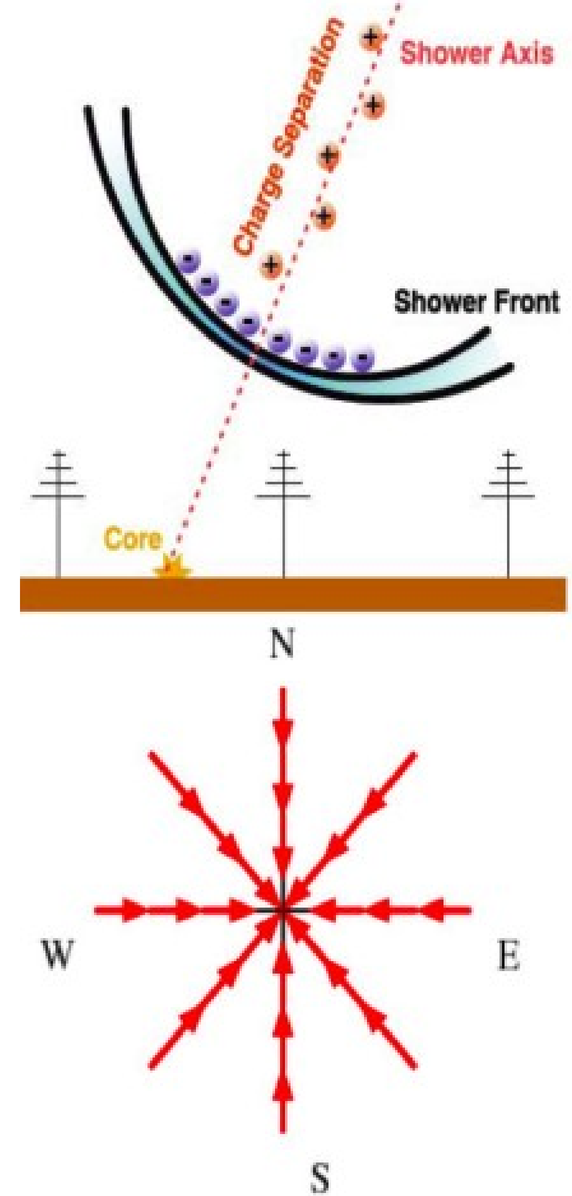
Radio Emission From Air Showers

Geomagnetic Emission

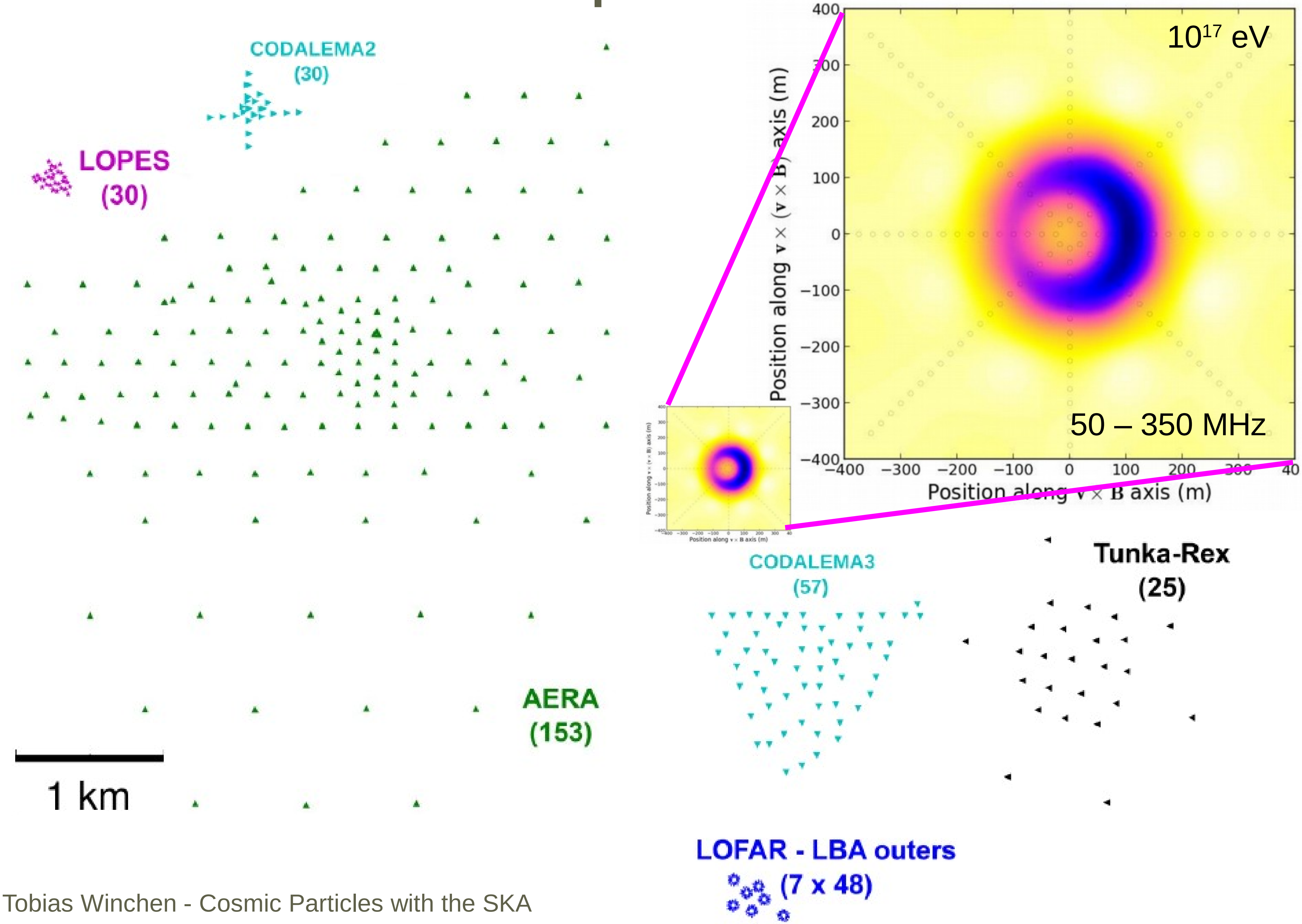




Charge Excess



Current Radio Experiments



Radio is Ready for Astrophysics

LETTER

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A large light-mass component of cosmic rays at 10^{17}–$10^{17.5}$ electronvolts from radio observations

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M. J. Bentum[3,15], G. Bernardi[16,17], P. Best[18], A. Bonafede[19], F. Breitlin
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D. J. Schwarz[43], M. Serylak[30], J. Sluman[3], O. Smirnov[17,44], B. W. Sta
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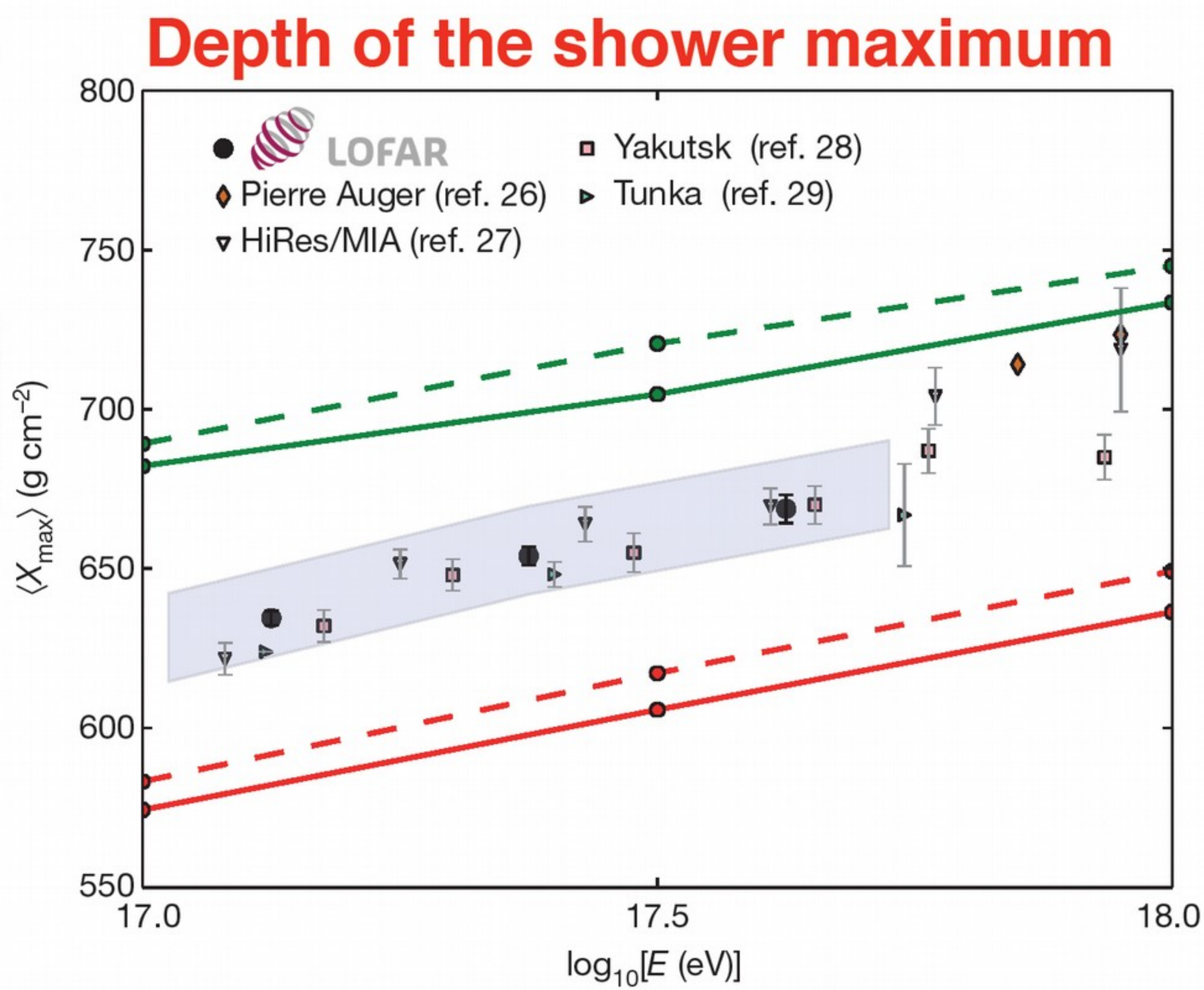
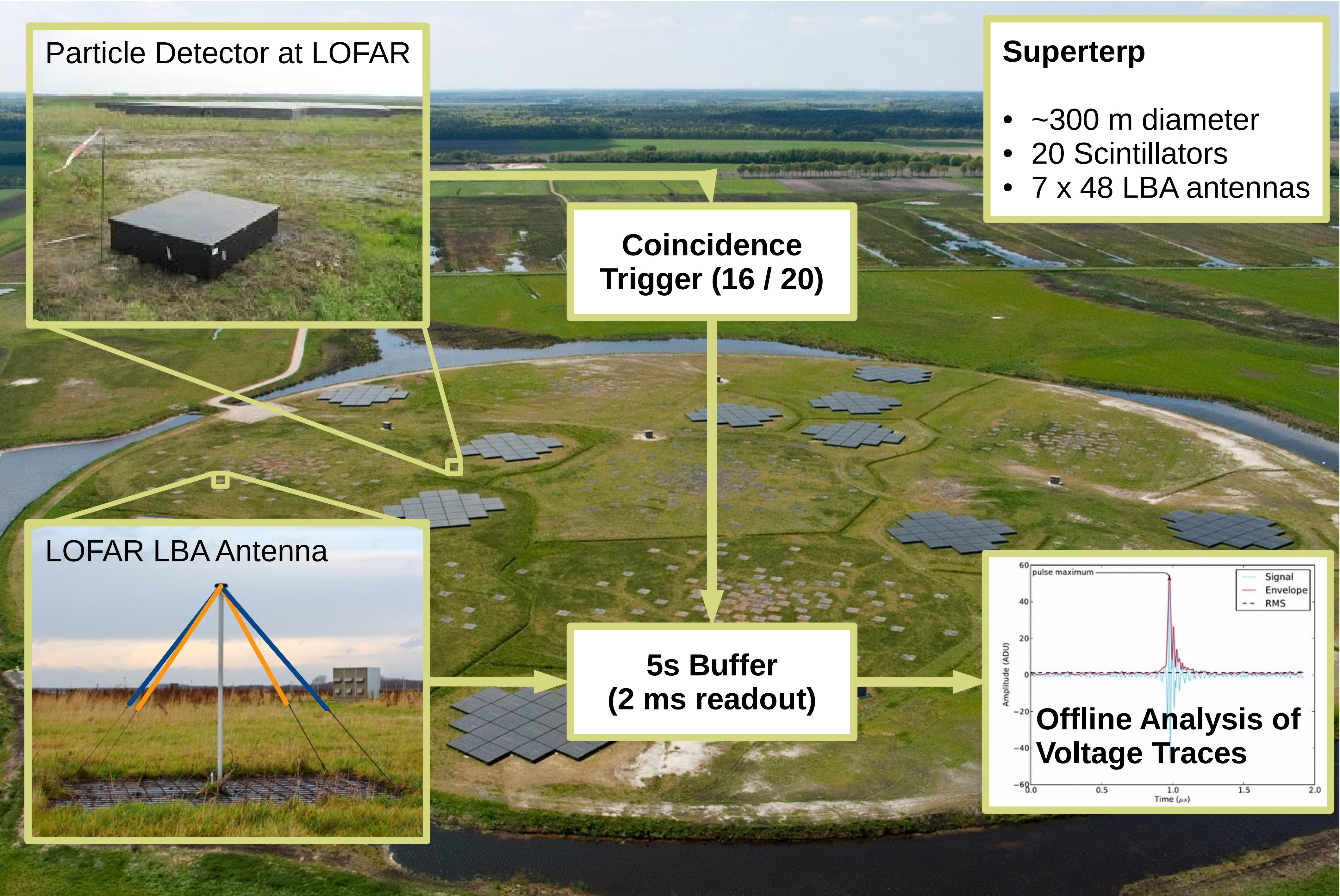
Cosmic rays are the highest-energy particles found in nature. Measurements of the mass composition of cosmic rays with energies of 10^{17}–10^{18} electronvolts are essential to understanding whether they have galactic or extragalactic sources. It has also been proposed that the astrophysical neutrino signal[1] comes from accelerators capable of producing cosmic rays of these energies[2]. Cosmic rays initiate air showers—cascades of secondary particles in the atmosphere—and their masses can be inferred from measurements of the atmospheric depth of the shower maximum[3] (X_{max}; the depth of the air shower when it contains the most particles) or of the composition of shower particles reaching the ground[4]. Current measurements[5] have either high uncertainty, or a low duty cycle and a high energy threshold. Radio detection of cosmic rays[6–8] is a rapidly developing technique[9] for determining X_{max} (refs 10, 11) with a duty cycle of, in principle, nearly 100 per cent. The radiation is generated by the separation of relativistic electrons and positrons in the geomagnetic field and a negative charge excess in the shower front[6,12]. Here we report radio measurements of X_{max} with a mean uncertainty of 16 grams per square centimetre for air showers

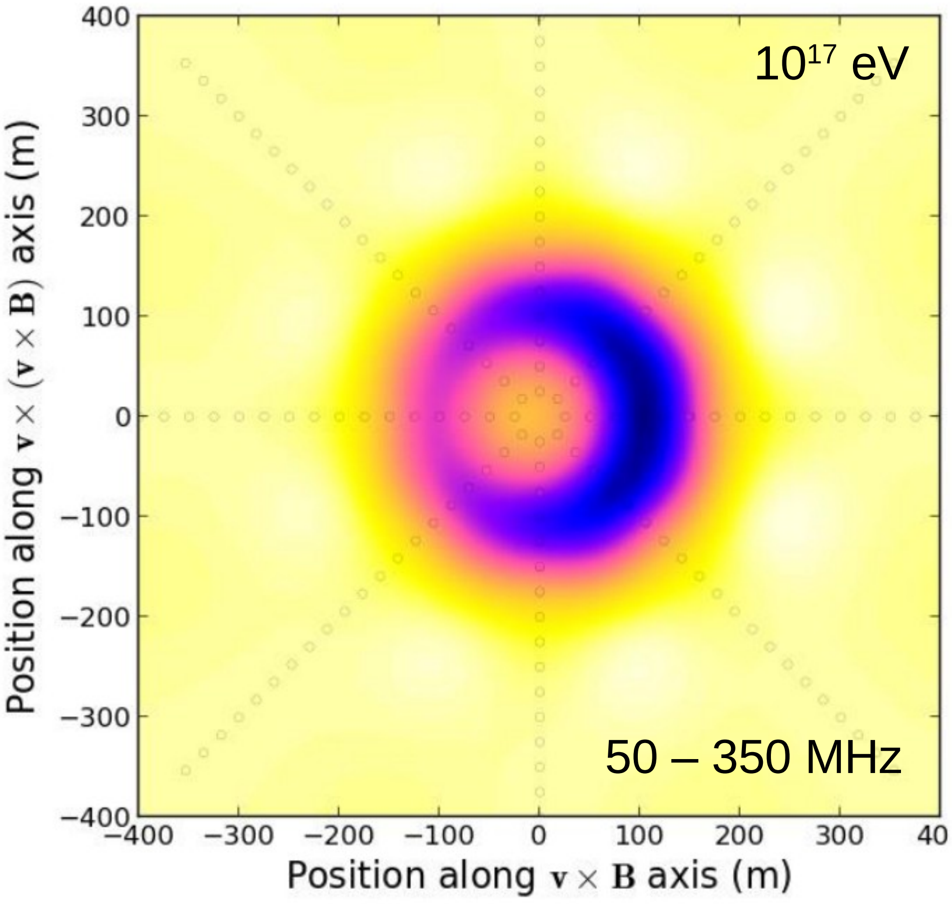


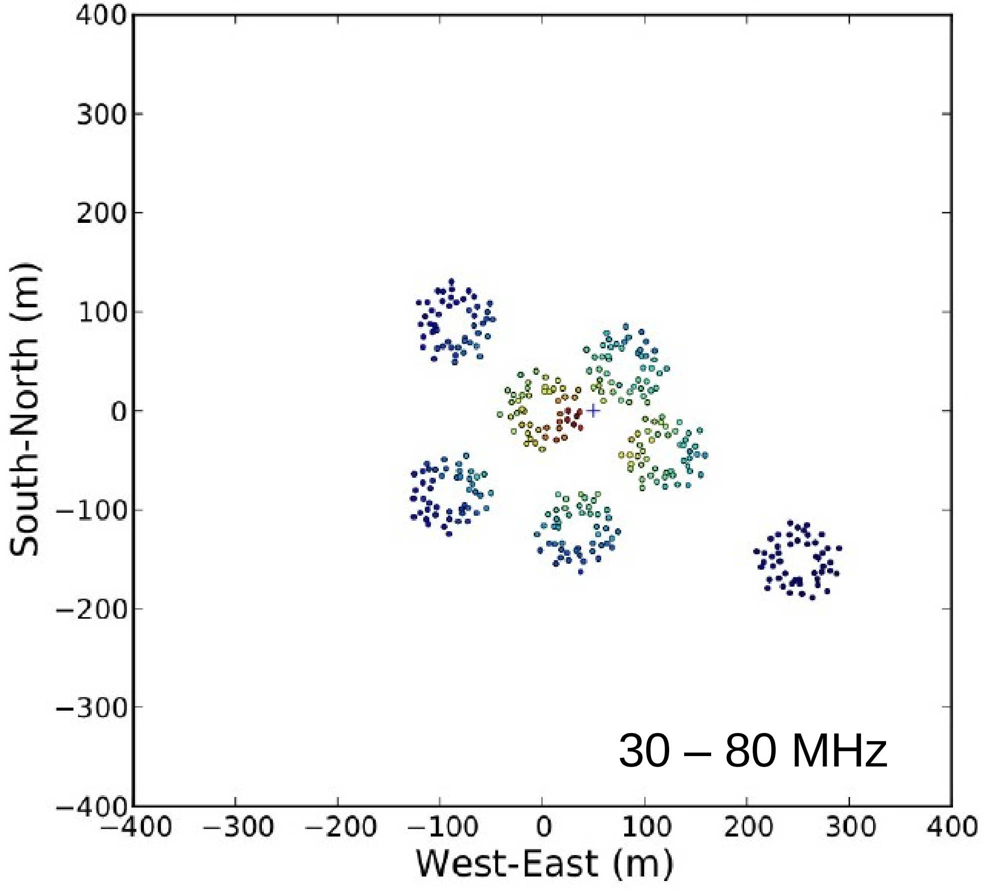
published
in **nature**

Air Shower Detection with LOFAR

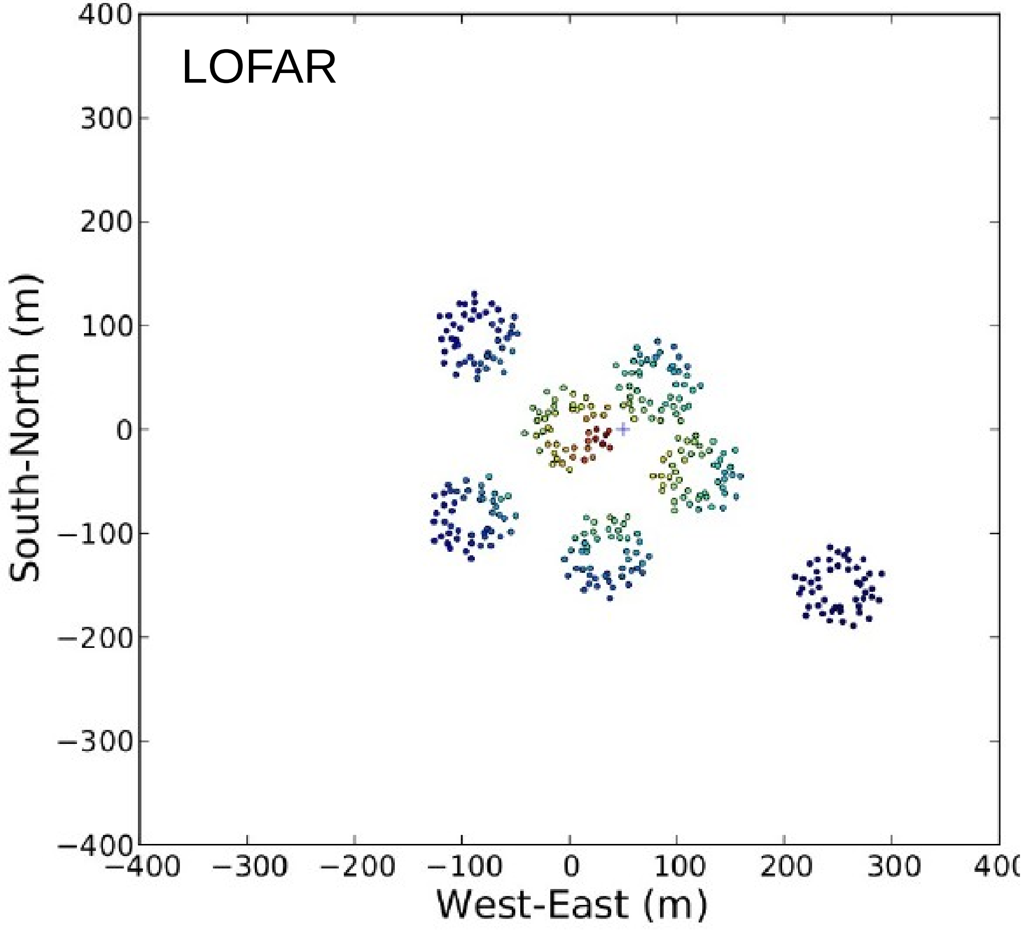


High Precision with LOFAR

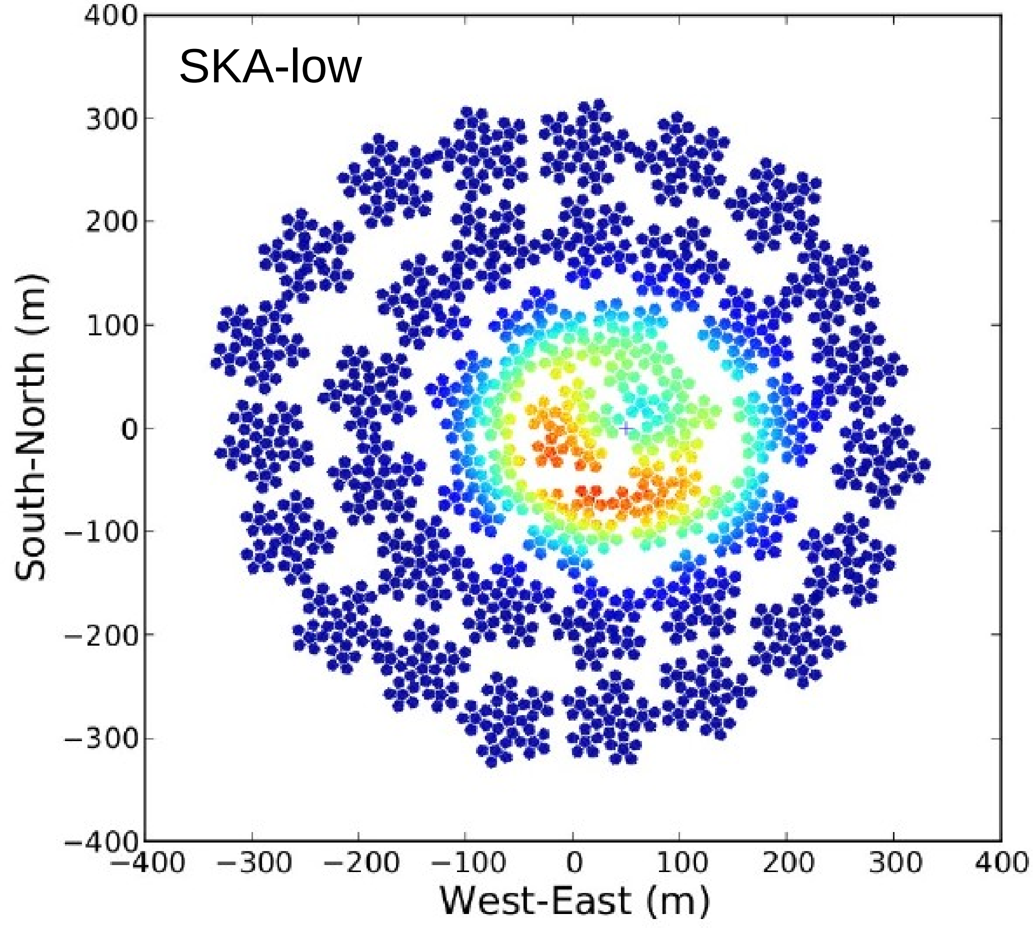




Ultimate Precision with the SKA

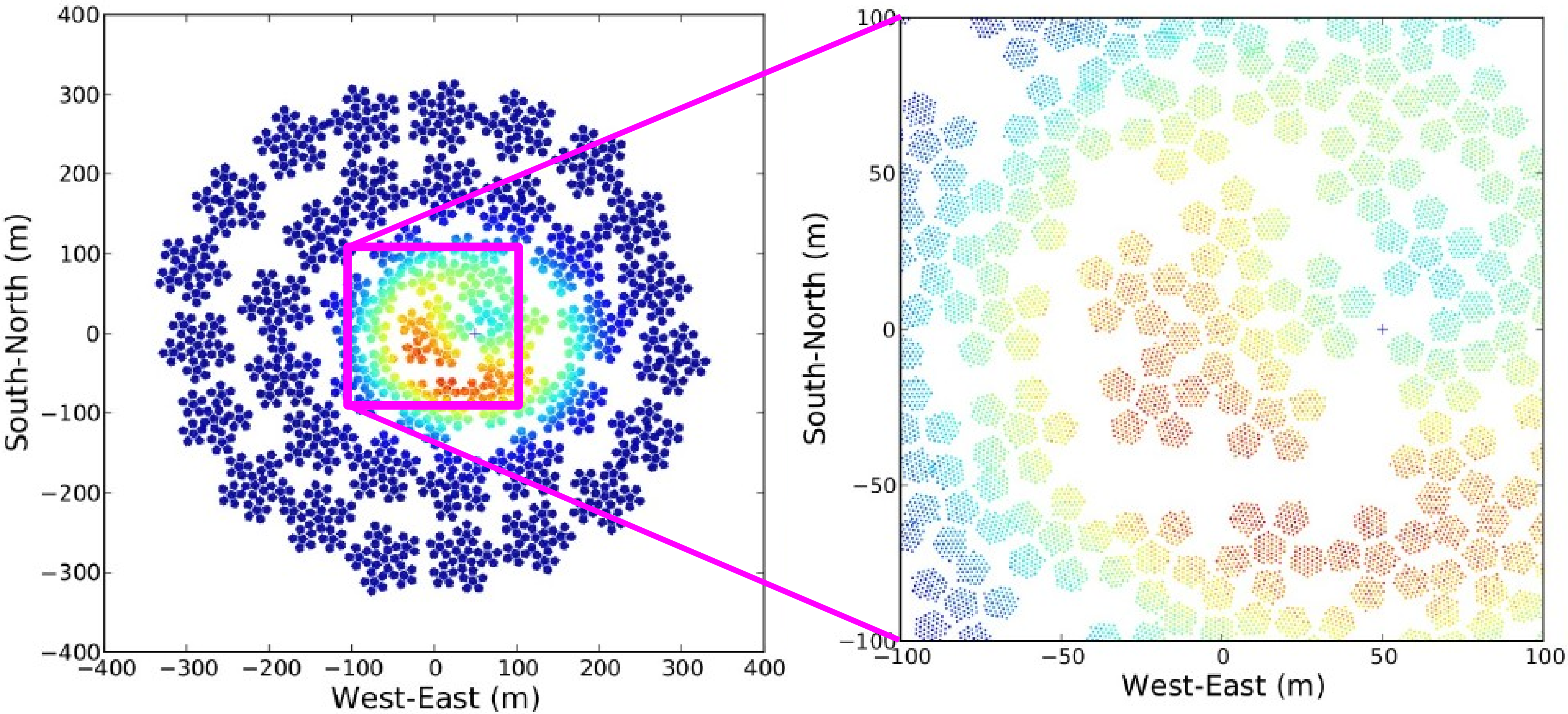


30 – 80 MHz
7x 48 Antennas



50 – 350 MHz
70 000 Antennas

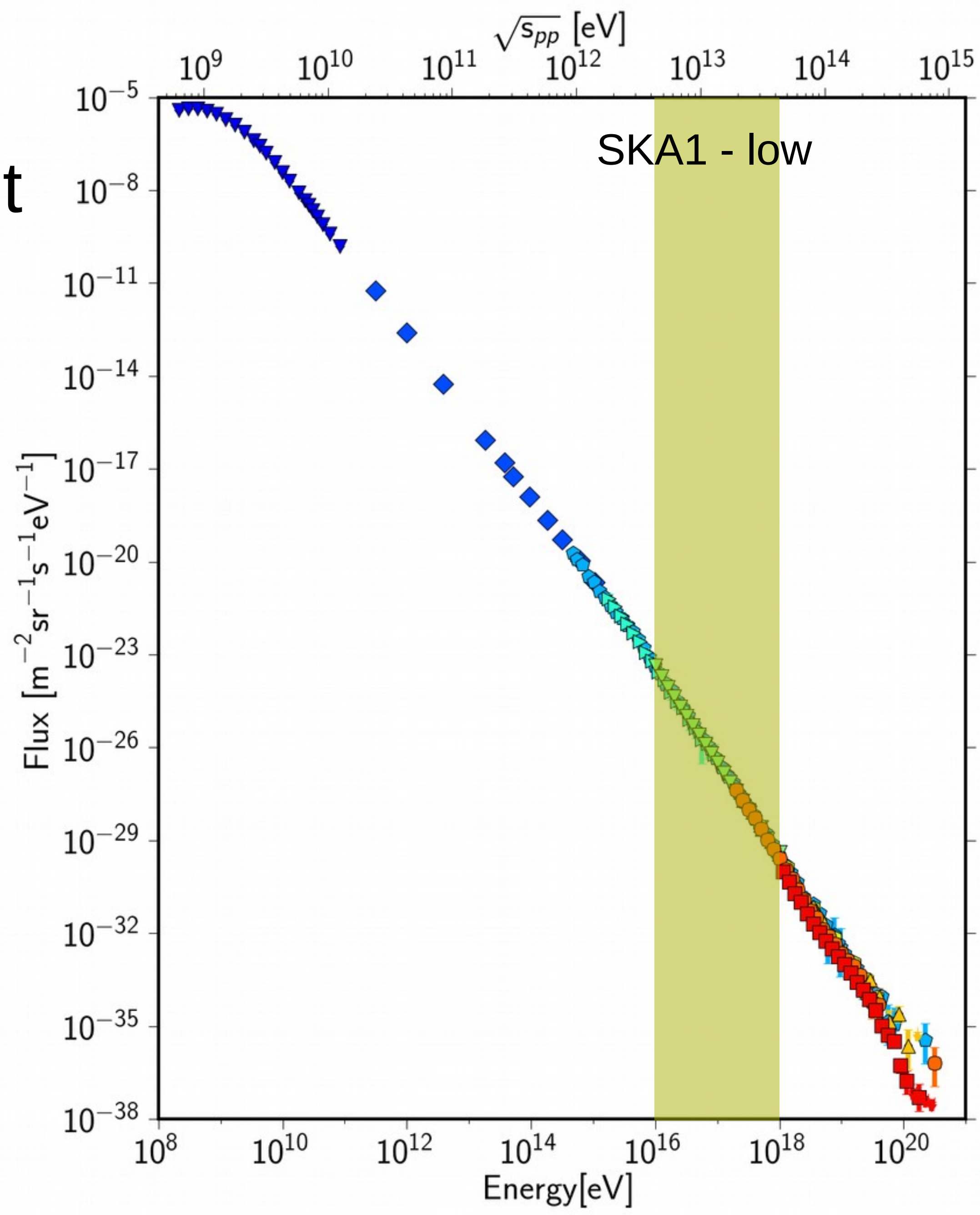
Ultimate Precision with the SKA



High density of antennas
+ Increased bandwidth
= Measure rich details of individual air shower

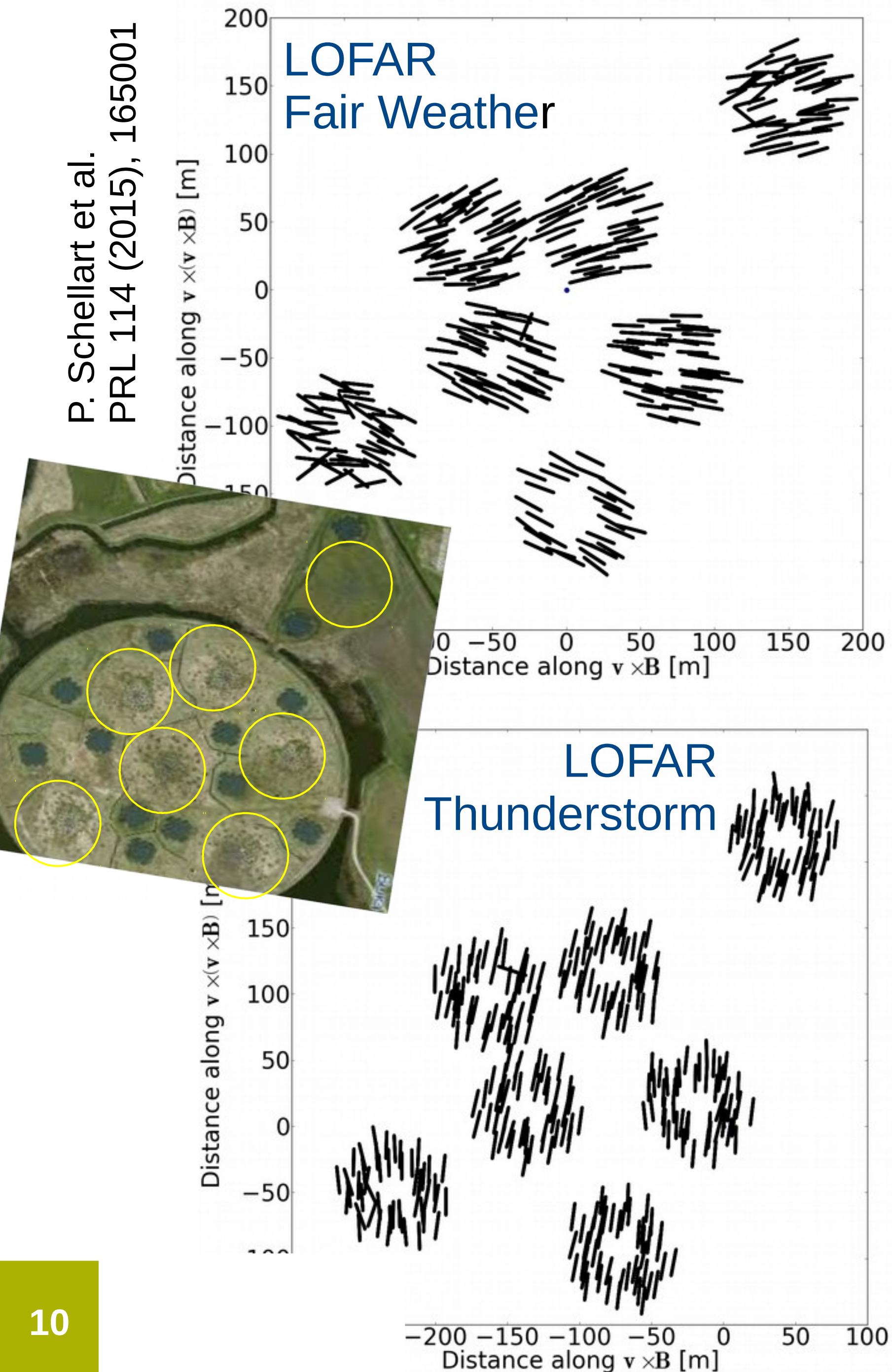
Science Potential: Astrophysics

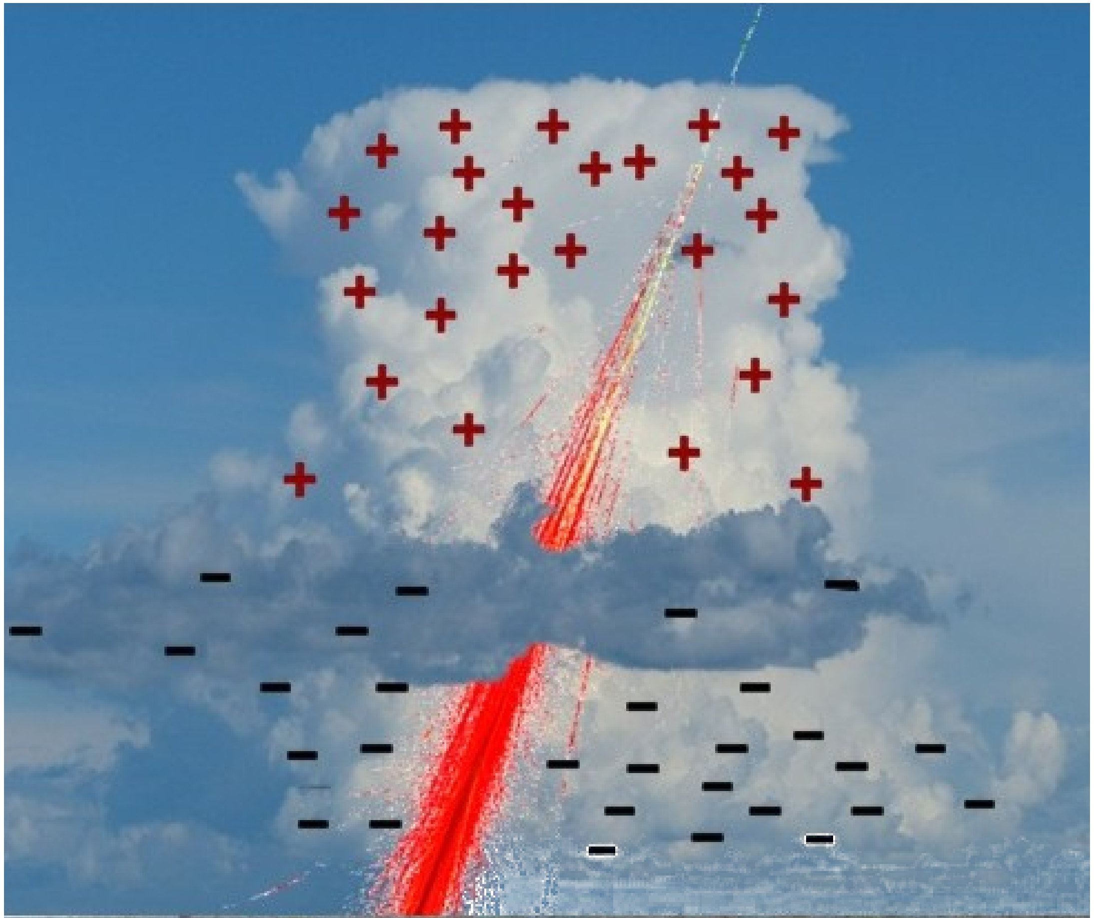
- Unprecedented precise composition measurement
- Increased duty cycle
- Increased energy range
- Will help to answer:
  - Which cosmic rays are galactic, which are extragalactic?
  - What are the sources of cosmic rays?
  - How are they accelerated?



Science Potential: Thunderstorms

P. Schellart et al.
PRL 114 (2015), 165001

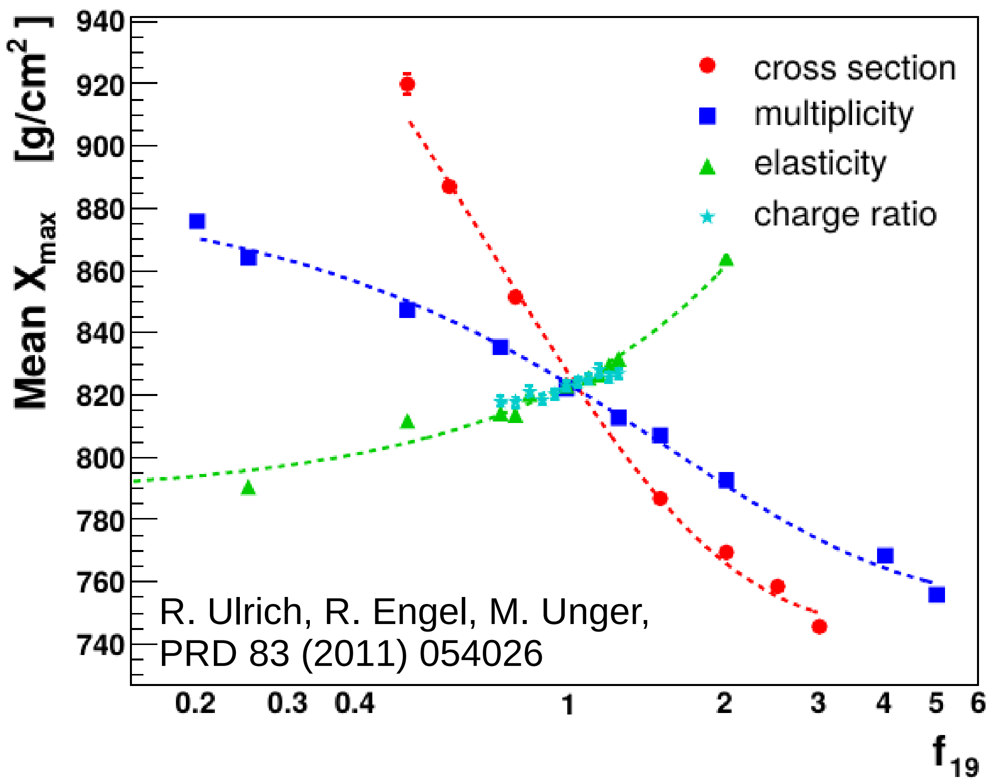


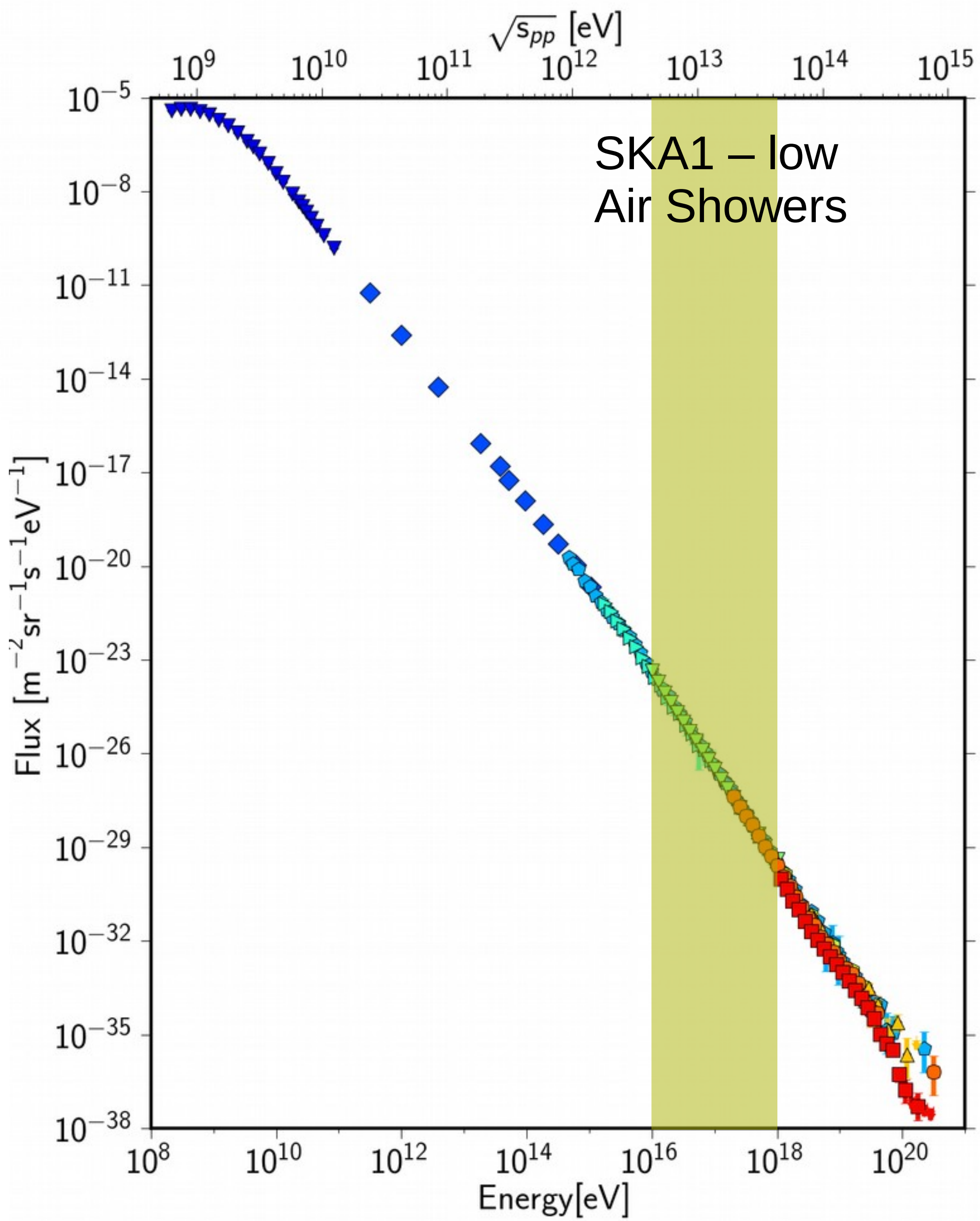


- Determine E-Field profile in thunderclouds
- Is lightning initiated by cosmic rays?

Science Potential: Particle Physics

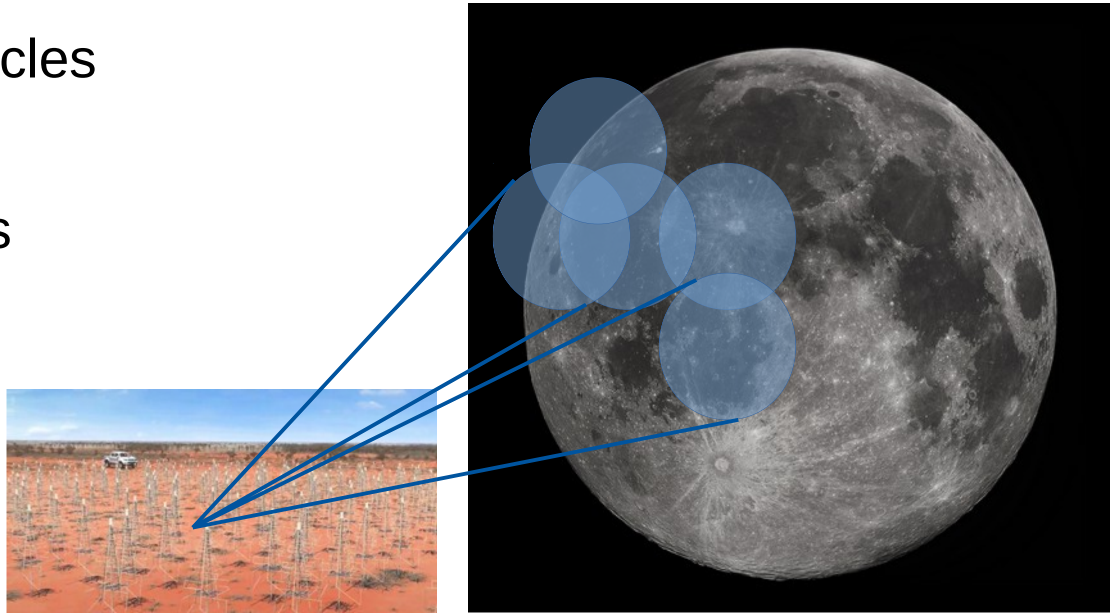
- pp center-of-mass energy 4 – 40 TeV

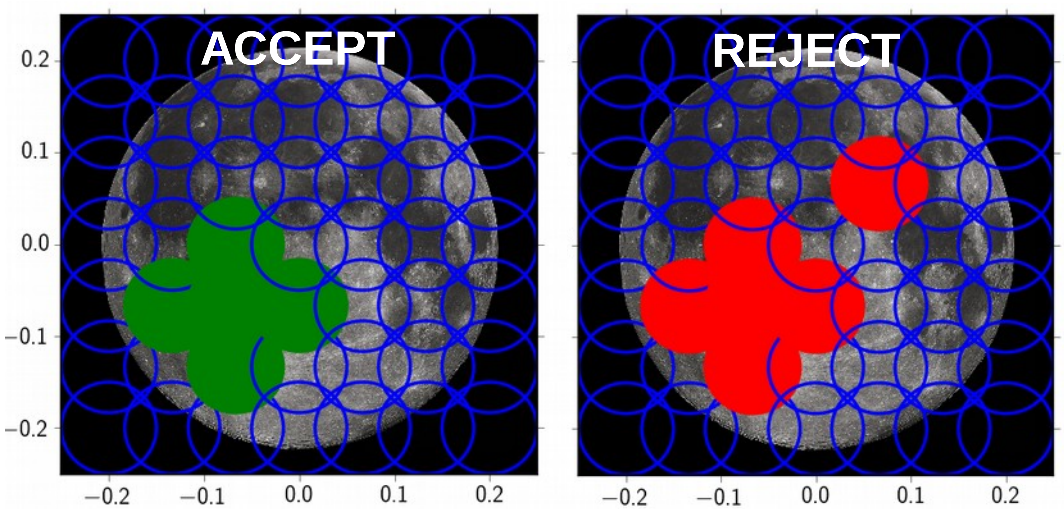




ZeV Scale with Lunar Observations

- Search for extreme energetic particles
- Form multiple beams on the Moon
- Search for ns pulses in time-series
- Anti coincidence to suppress RFI
- Analyze Faraday rotation and dispersion to check lunar origin
- Previous searches at Parkes, Westerbork, Lovell, ATCA, …





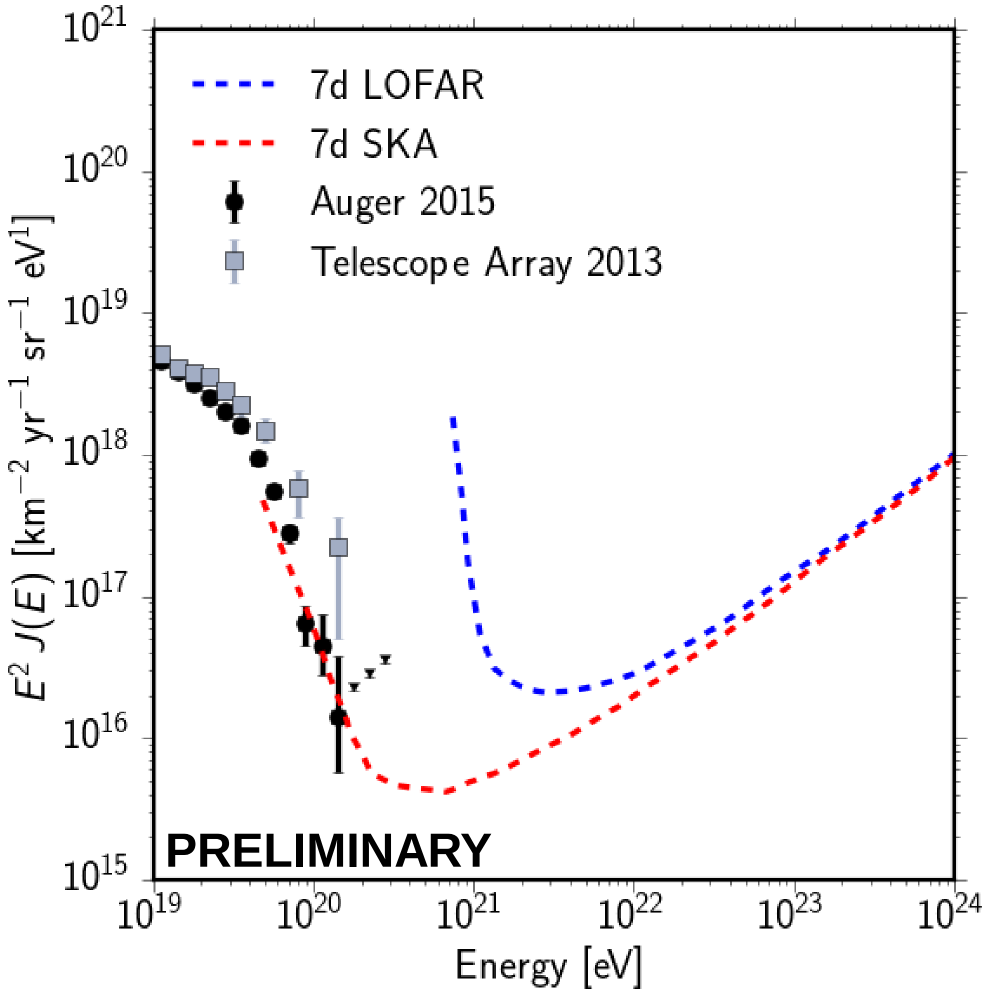
Challenges

- Data rate

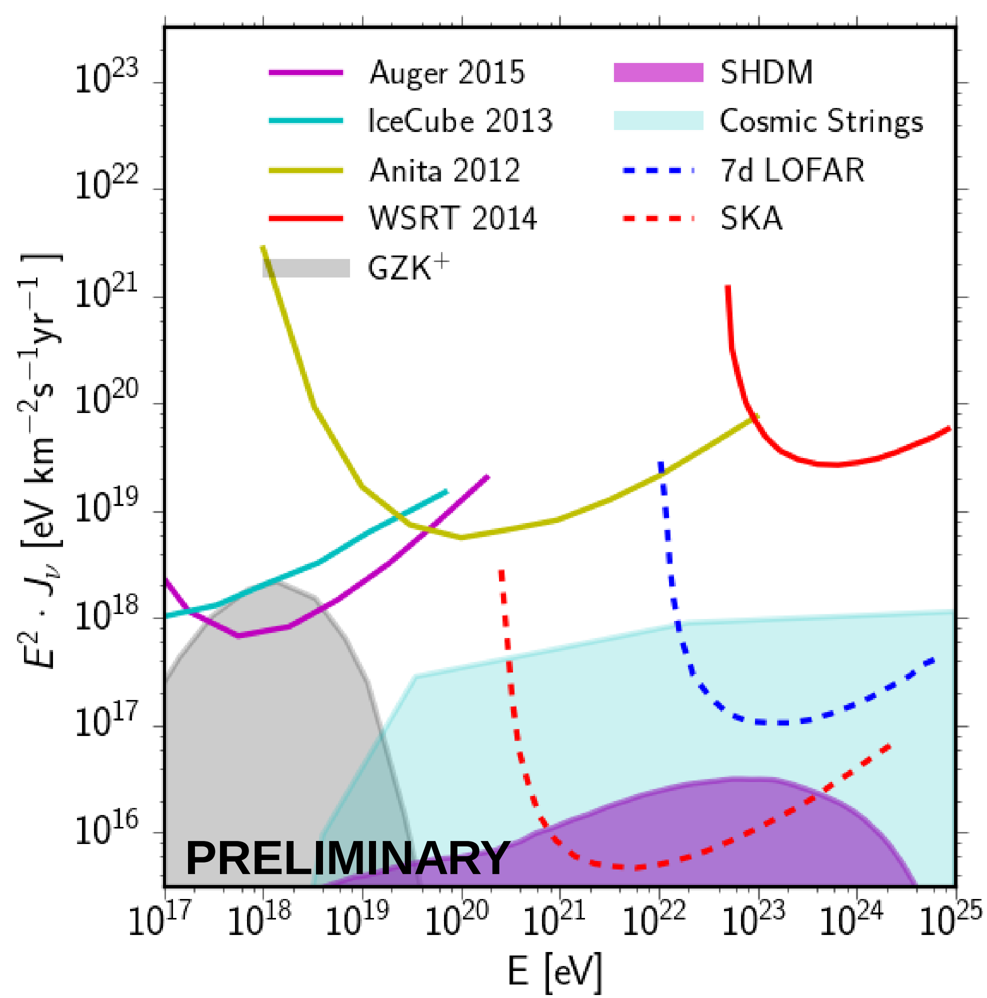
  → Trigger required
- Recover ns time resolution
- Analyse ns traces in real time
- LOFAR Lunar mode currently under development

Science Potential Lunar Showers: Astrophysics and New Physics

COSMIC RAYS

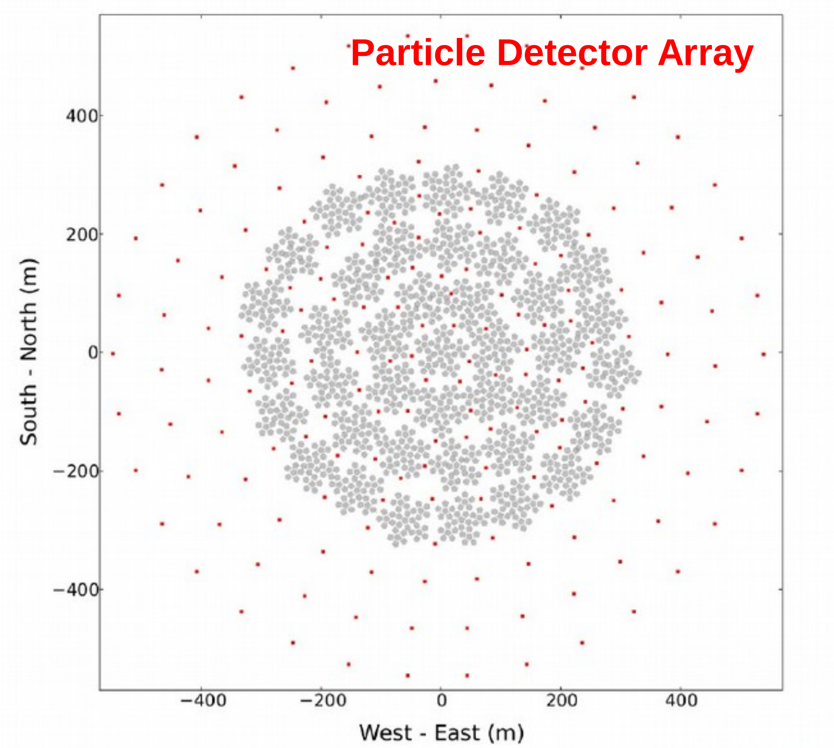


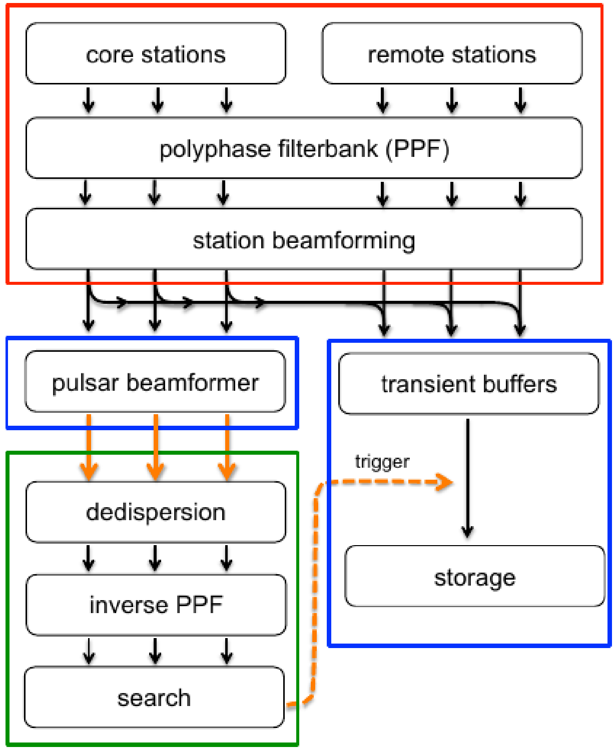
NEUTRINOS



What is Needed?

- Air showers:
  - Station buffers with trigger
    (available in baseline design)
  - Particle detector array
- Lunar showers:
  - Fast realtime analysis of
    nano second time traces
    → Dedicated computing power
    → Tap into data stream
  - Antenna buffers with trigger
- Engineering change proposals under review (stage 4 of 6)

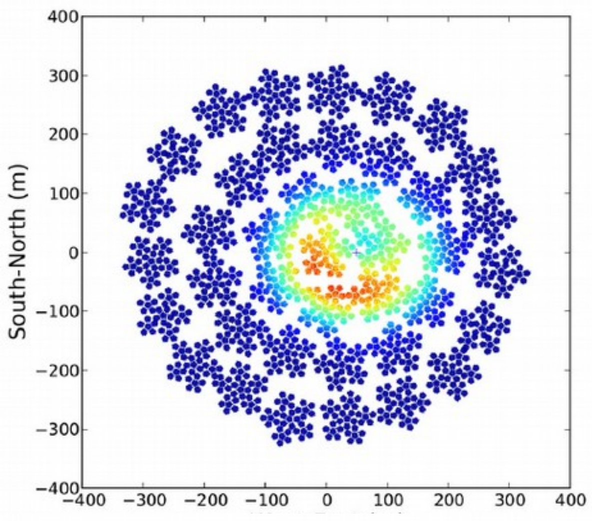


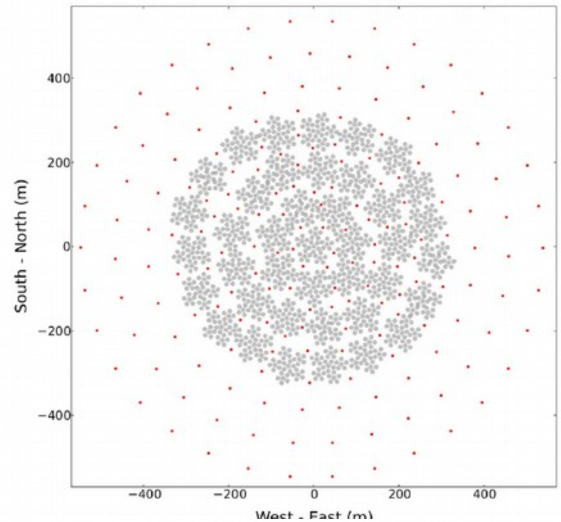


Conclusions

- SKA ultimate precision radio detector for cosmic ray physics
- Rich science Potential

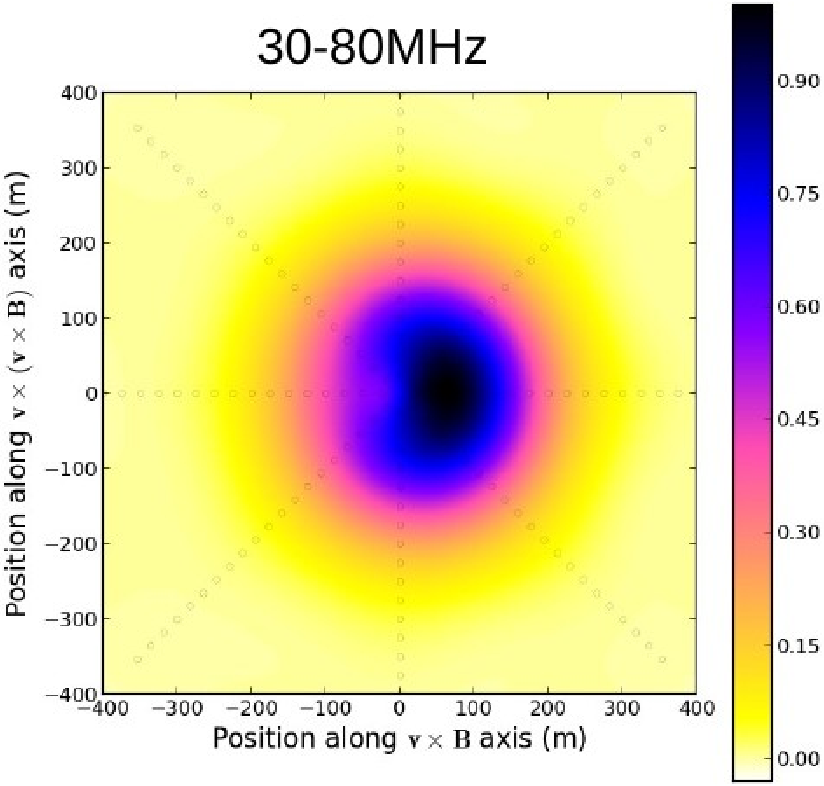
  Astrophysics / Thunderstorms / Particle physics / ...
- SKA focus group on high energy cosmic particles
- Requires small engineering changes that are currently under investigation
  - Particle detectors
  - Buffers
  - Online computing
- Experience with LOFAR
  - No disturbance of astronomy operations
  - Low-level diagnostics of antennas

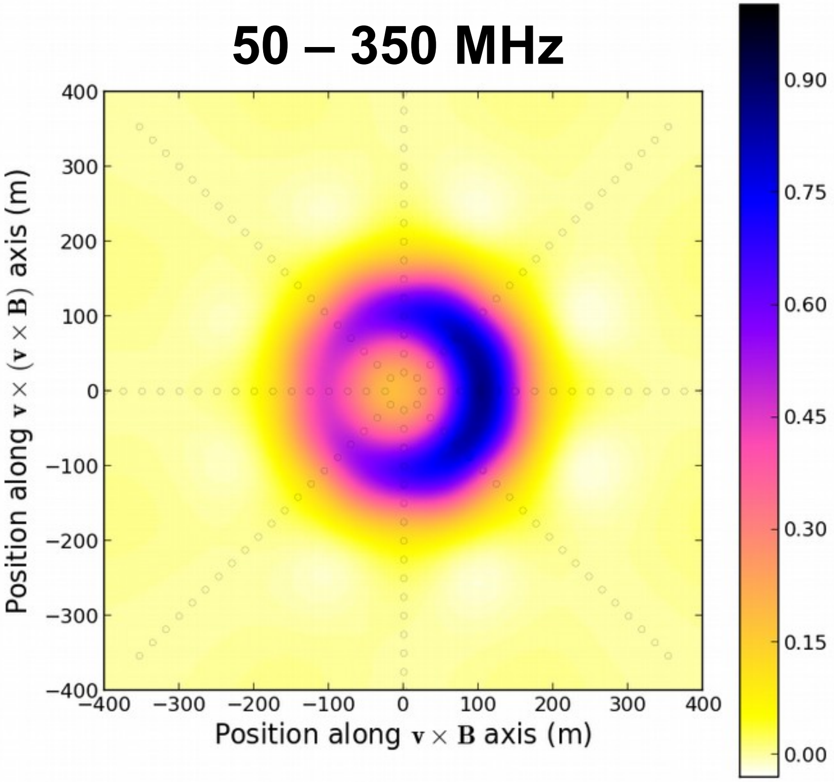




Backup

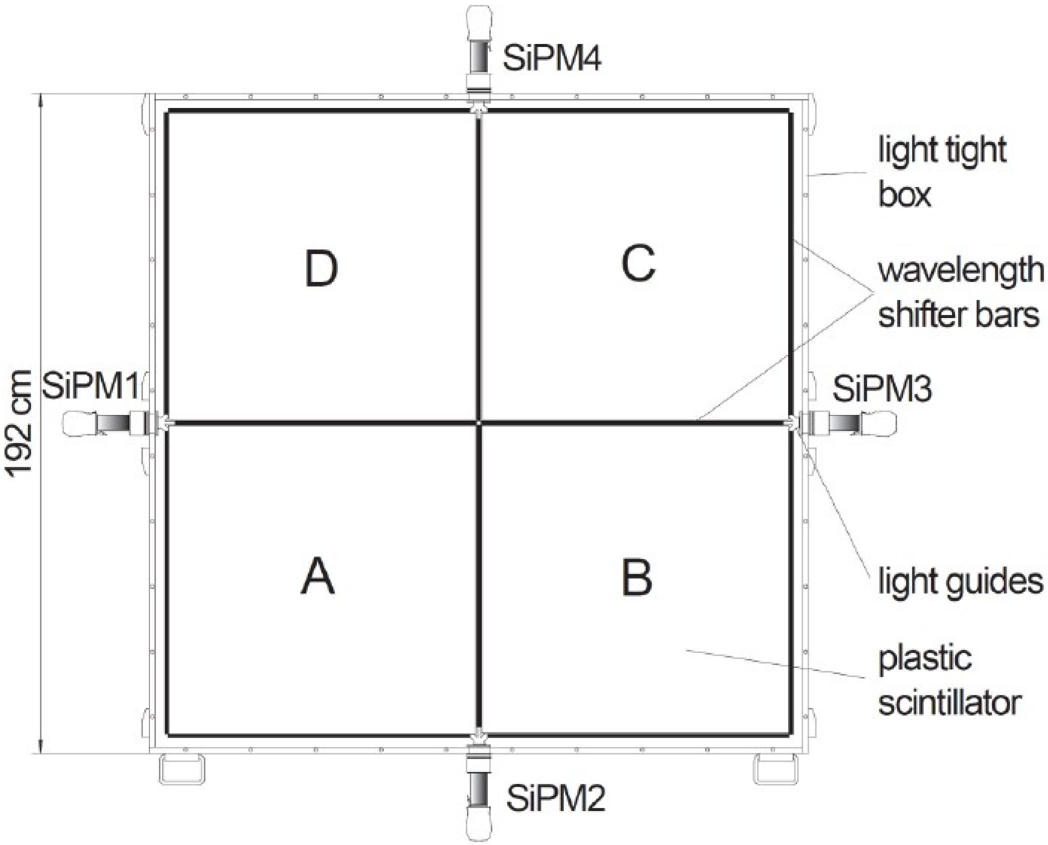
Shower Footprint





Energy: 10^{17} eV
Zenith: 36.87°

Particle Detector Details

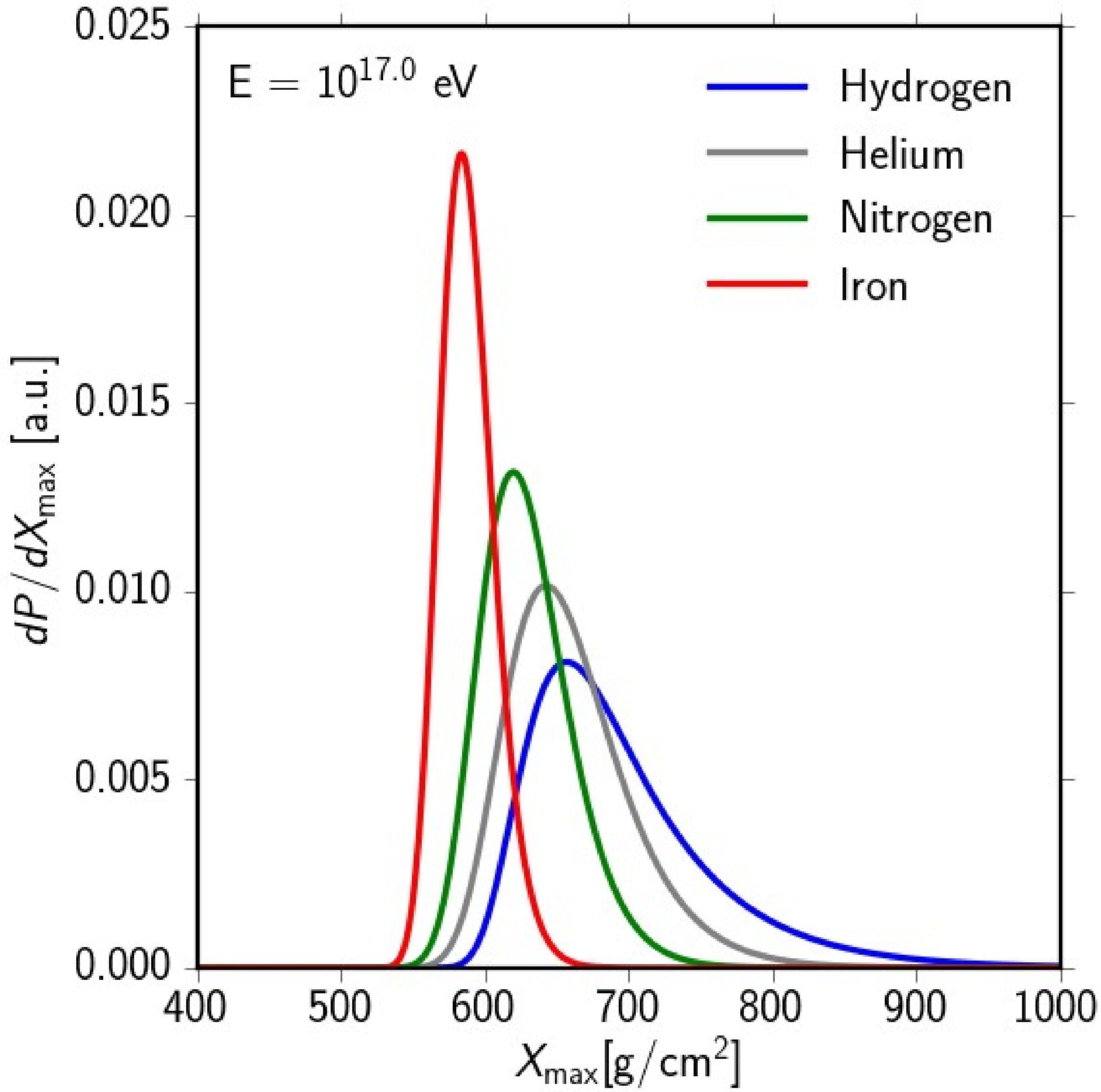


- 180 particle detectors of 3.6 m^2 area and 3 cm thickness may be available from KASCADE
- need 720 additional readout channels (4 per Scintillator), cf. 140,000 existing ones
- need 720 SiPMs, ensure RFI quietness
- possibly shield/bury part of detectors for muon separation

Buffer for Individual Antenna Signals

- 800 MHz sampling
- Aat least 8 bit, preferably 12 bit dynamic range
- Buffer depth determined by trigger latency (10 ms)
- 1.4 TeraBytes of buffer for 60,000 antennas
- In parallel with any other buffering activities (100% duty cycle)
- Read out 50 microseconds upon an external air shower trigger
- 7.2 GB per event for 60,000 antennas
- Estimate: 1 shower per minute at 10^{16} eV
  - 120 MB/s data stream small for SKA
  - But Poisson statistics results in bursts of 2.4 GiB/s for 3s every minute
  - Calculated: ~3% deadtime

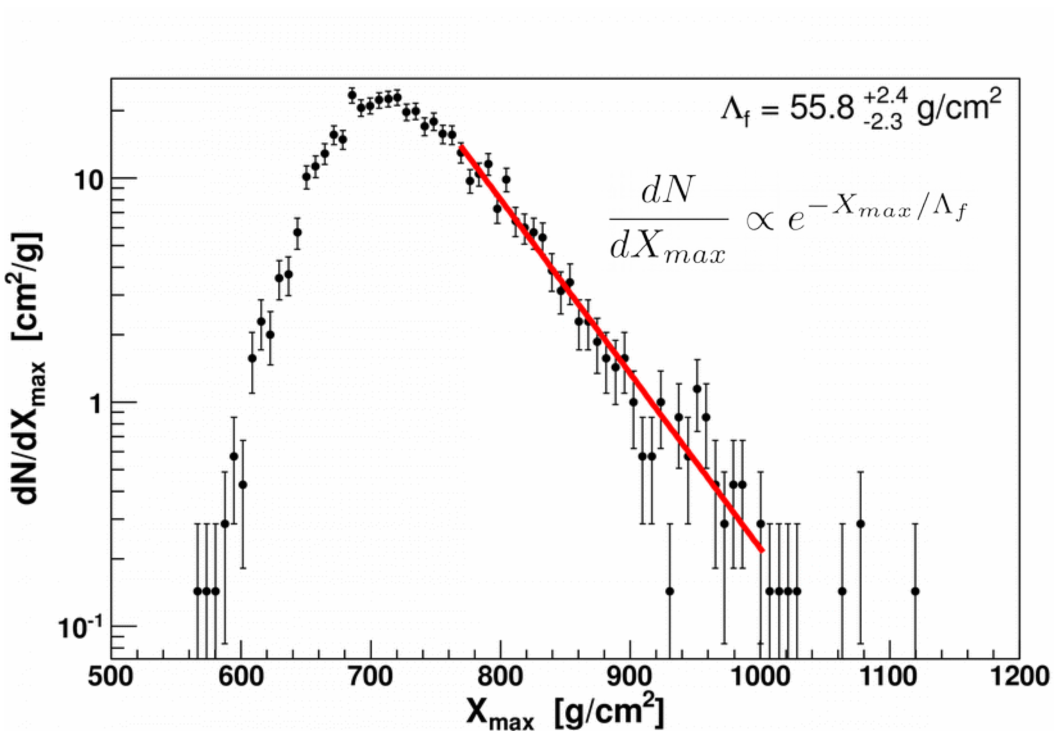
Depth of Shower Maximum

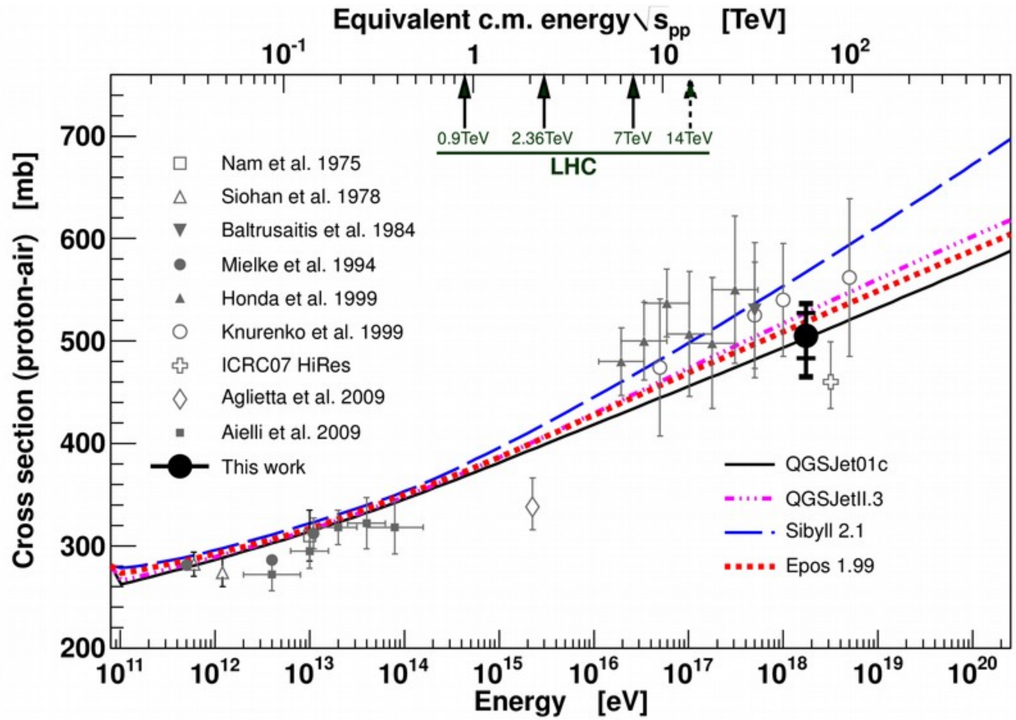


Proton – Air Cross-Section

Data of the Pierre Auger Observatory

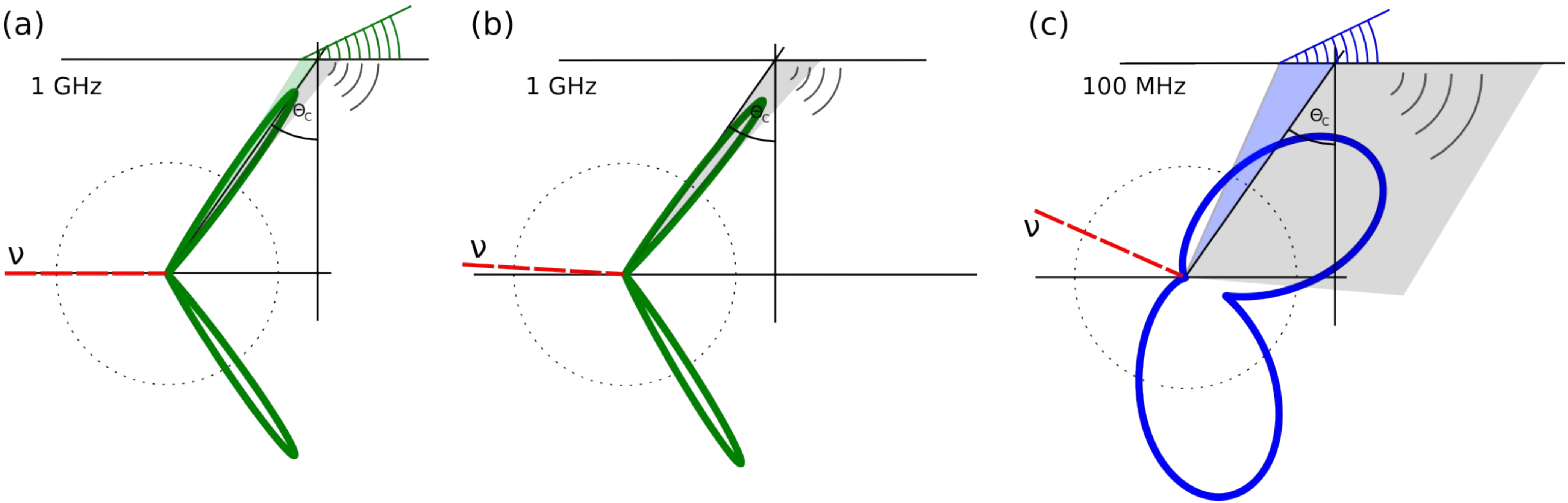
E = 10^{18} eV - $10^{18.5}$ eV,
center of mass energy: 57 TeV





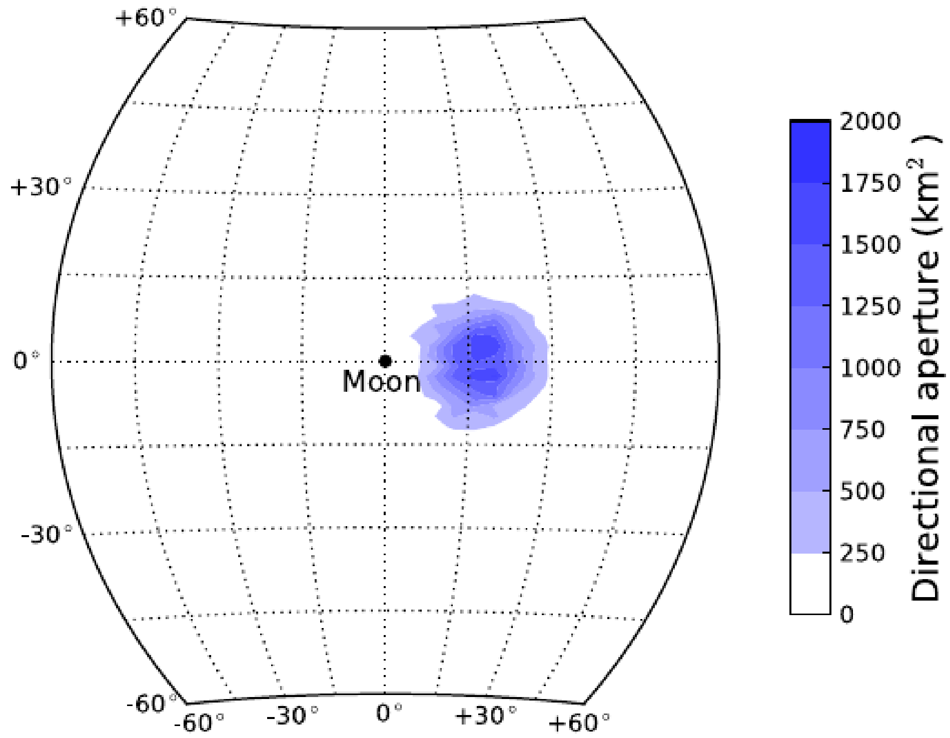
R. Ulrich et al., 32nd ICRC, 2011

Lunar Pulses

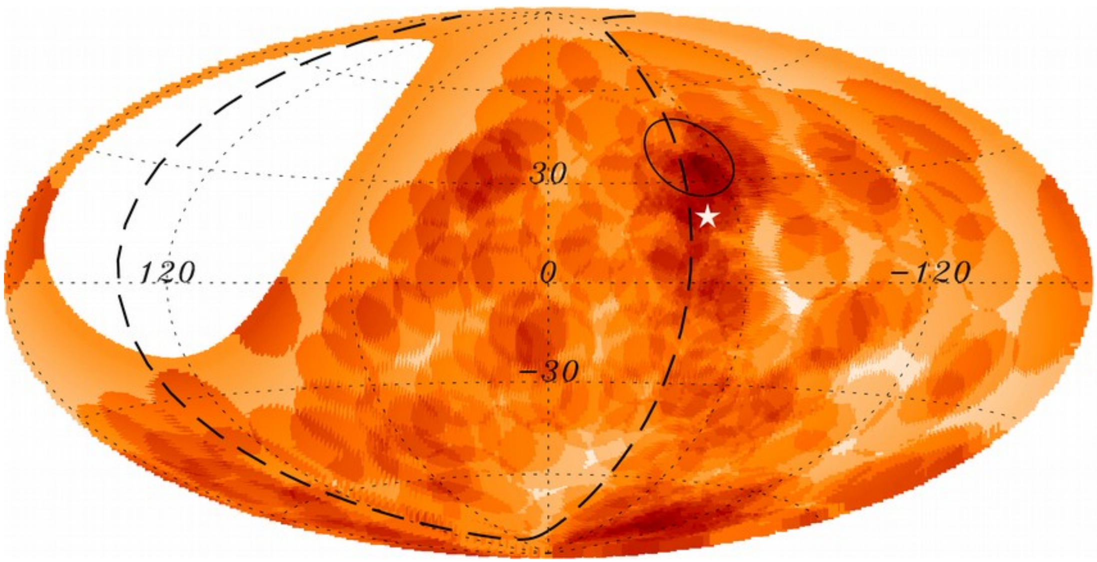


- Radiation emitted in Cherenkov cone
- Cherenkov angle == Angle of total reflection
- Upgoing shower required / rely on surface roughness
- Cherenkov cone is broader at low frequencies
- Also downgoing showers detectable
- Optimum in 100 - 200 MHz range (Scholten et al. 2006)

Angular Resolution of Lunar Mode



Cosmic Ray Excess at 15^{O} scales



Aab et al, ApJ 804 (2015), 15

- Limit observations to rim
- Possible Incident angles yield ~5^{O} resolution
- Explicit reconstruction should do better