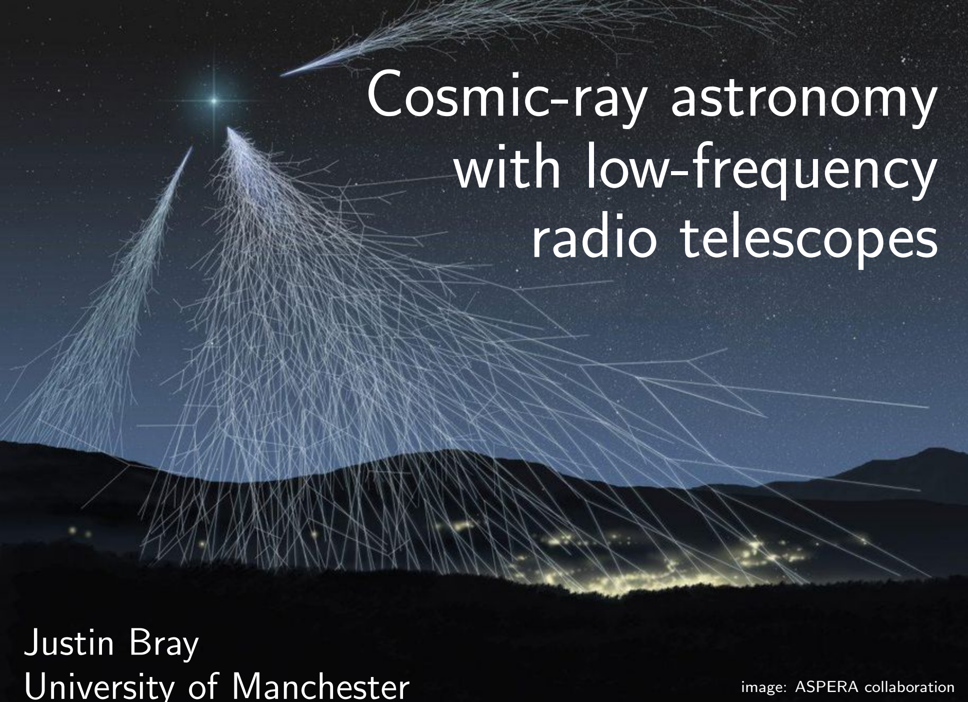
Cosmic-ray astronomy with low-frequency radio telescopes

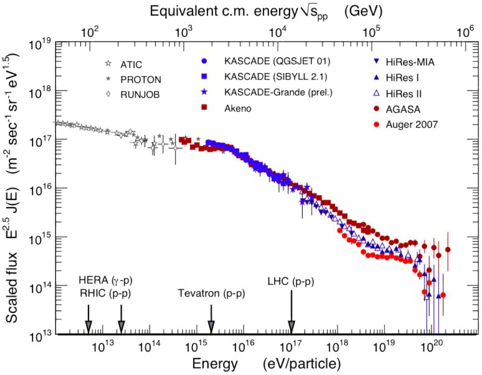


Justin Bray
University of Manchester

image: ASPERA collaboration

- **Cosmic rays**
- Cosmic-ray **detectors**
- **Radio** cosmic-ray detectors
- Radio **telescopes** as cosmic-ray detectors
  - atmospheric detection
  - lunar detection

Cosmic rays



R. Engel

What are cosmic rays?

- bare nuclei (p-Fe)
- high energies ($\rightarrow 10^{20}$ eV)
- rare ($\rightarrow 0.01/\text{km}^2/\text{yr}$)

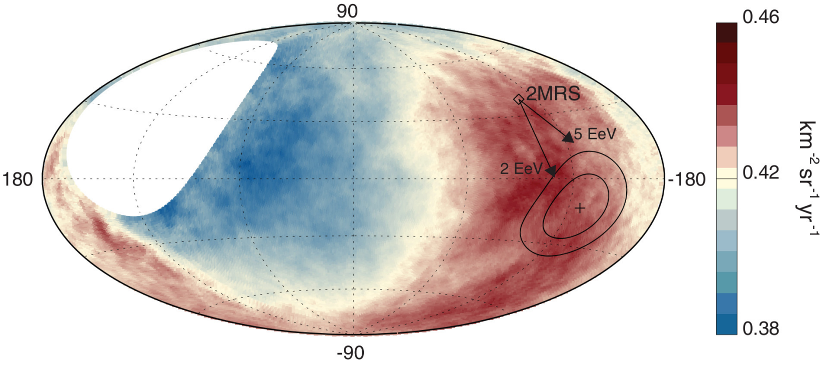
Observables:

- arrival direction
- energy/spectrum
- composition

Depend on:

- source
- propagation

Observables: arrival direction



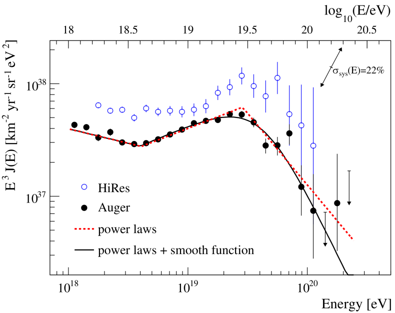
Aab et al. (Pierre Auger Collaboration) 2017, Science, 357, 1266

Dipole anisotropy (energy $>$ 8 EeV):

- 6.5% amplitude; 5.2σ significance
- *not* aligned with Galactic Centre
- $\sim$aligned with 2MRS dipole

Strong evidence for extragalactic origin.

Observables: energy/spectrum



Abraham et al. (Pierre Auger) 2010, PLB, 685, 239

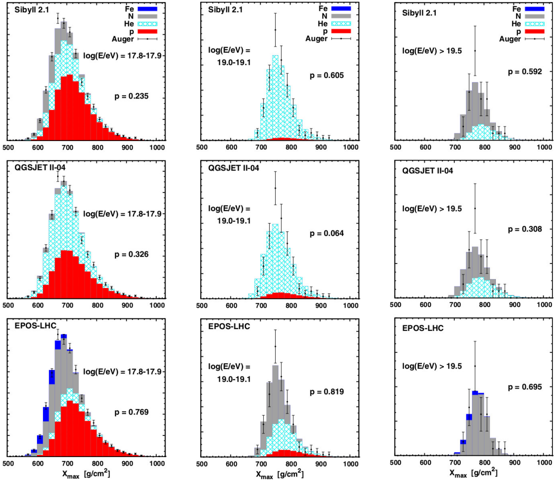
Spectral cut-off: $E \gtrsim 5 \times 10^{19}\,\mathrm{eV}$

- GZK effect: interactions with CMB photons
- or coincidence: max. energy from sources

Ankle: $E \sim 4 \times 10^{18}\,\mathrm{eV}$

- transition between galactic and extragalactic sources
- or recycling of cosmic rays in galactic magnetic field

Observables: composition



$10^{17.8}$ eV $\quad$ 10^{19} eV $\quad$ $> 10^{19.5}$ eV

Aab et al. (Pierre Auger Collaboration) 2014, PRD, 90, 122006

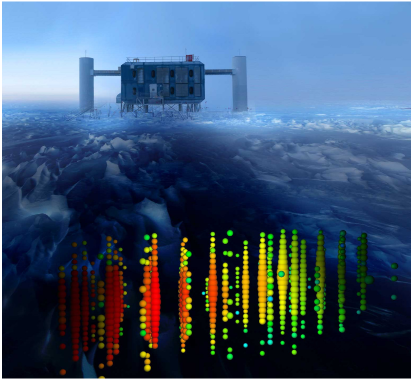
Composition becomes heavier at higher energies, but with large model uncertainties.

Depends on:

- seed population of high-energy particles
- acceleration efficiency in source
- attenuation during propagation
- photodisintegration to lighter species

Cosmic-ray detectors

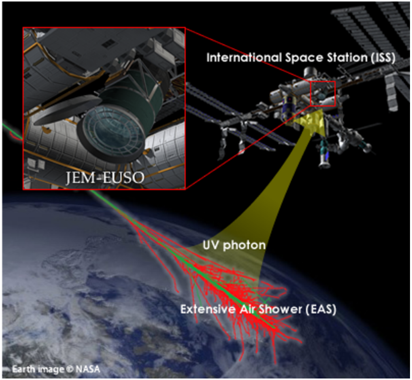
instrumented volume



Aperture depends on instrumented volume.

Threshold and precision depend on array density.

remotely-monitored volume



Aperture depends on volume in field of view.

Threshold and precision depend on sensitivity and distance.

Detection channels

Particle detectors, e.g.:

- KASCADE
- Tunka
- Telescope Array
- Pierre Auger
- HAWC

Cherenkov, e.g.:

- HESS
- MAGIC
- VERITAS

Radar, e.g.:

- TARA
- Jodrell Bank

Nitrogen fluorescence, e.g.:

- HiRes
- Pierre Auger
- Telescope Array

Acoustic, e.g.:

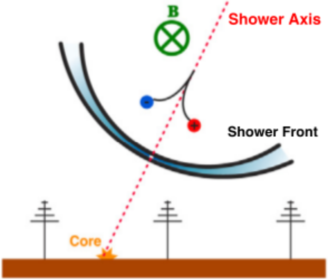
- ACORN
- SAUND
- AMADEUS

Radio, e.g.:

- LOPES
- CODALEMA
- Tunka-REX
- AERA

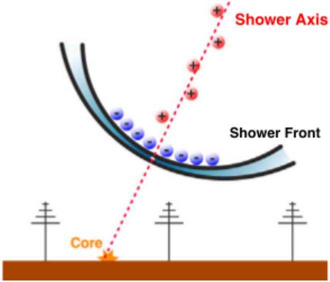
Radio emission from particle cascades

geomagnetic emission



H. Schoorlemmer

Askaryan emission



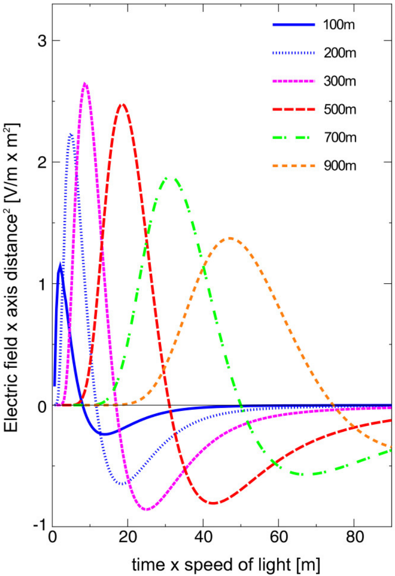
K.D. de Vries et al.

Geomagnetic emission is typically dominant ($\sim$ 90%) in atmosphere, but depends on field strength & orientation.

Discriminate with polarisation.

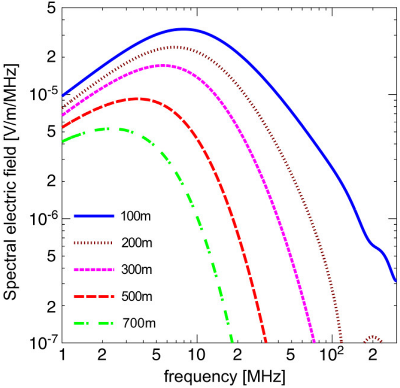
Coherence at scales of front thickness or width (0.1–100m).

Radio emission from particle cascades



Spectrum determined by loss of coherence.

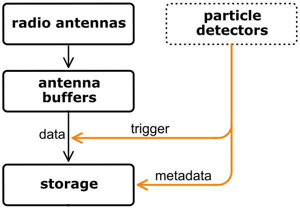
Greatest coherence and intensity close to cascade axis (or θ_c).

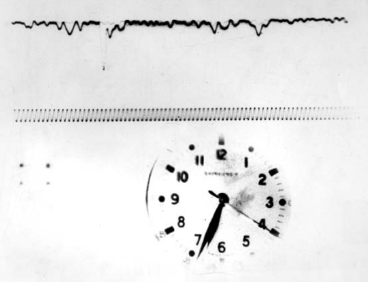


Huege 2016, Phys. Rep. 620, 1

Radio cosmic-ray detectors

Porter (1967)





Spencer & Rapley (2018)

Real-time detection in radio is difficult (RFI!).

Normal procedure: use particle detectors to trigger storage of buffered radio data.

Radio at the International Cosmic Ray Conference

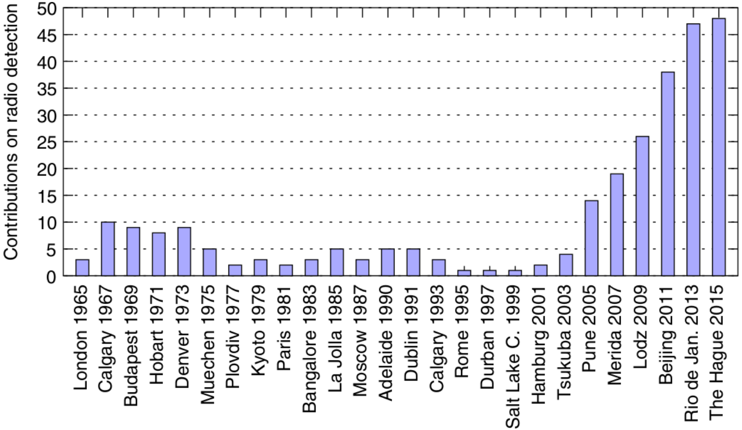


figure: T. Huege

Radio telescopes as cosmic-ray detectors

Rather than building an array of antennas to study cosmic rays, why not use an existing one?

Aperture-array radio telescopes have an all-sky field of view.

Antenna-level buffers can be commensal with other observations.

Just need (preferably) a co-located array of particle detectors.

Array layout & scale

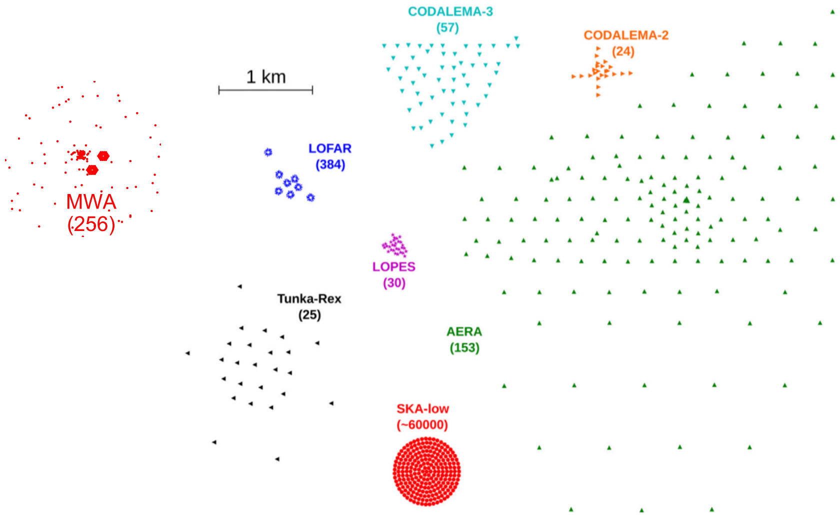
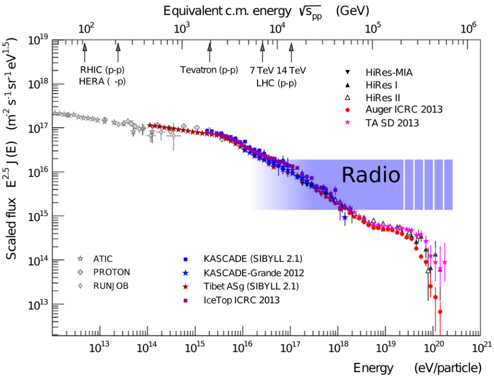


figure: A. Zilles

Radio telescopes as cosmic-ray detectors

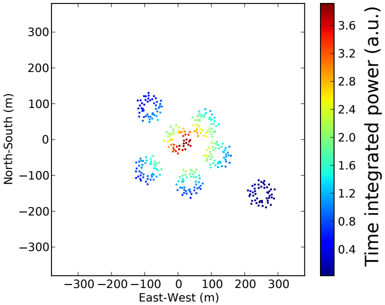


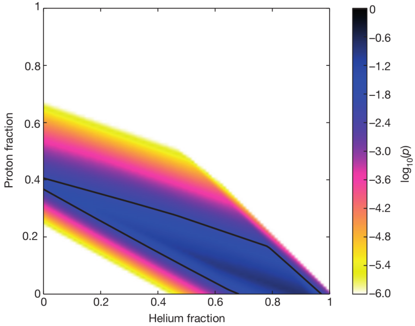
Extents of radio arrays and per-antenna sensitivity set cosmic-ray energy range to which they are sensitive: 10^{17}–10^{19} eV

Radio **telescopes** have particularly dense antenna arrays, so their strength is **precision** measurements of cosmic rays.

Cosmic-ray work with LOFAR

Operating with LBA-outer and 20 particle detectors (LORA).





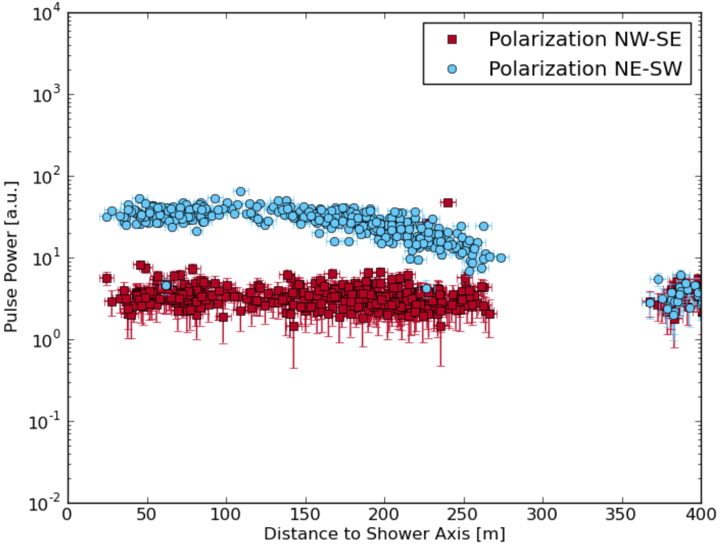
Buitink et al. 2016, Nature, 531, 70

Detected radio footprint
→ reconstruct $X_{\max}$ parameter

Reconstructed $X_{\max}$ values
→ determine composition

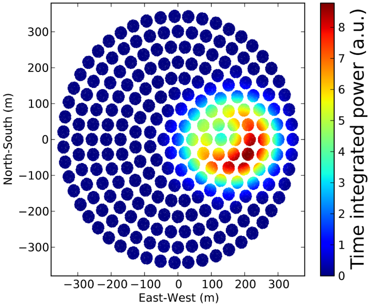
LOFAR $X_{\max}$ resolution: 16 $\mathrm{g\,cm^{-2}}$

Cosmic-ray work with LOFAR



Nelles et al.

Toward cosmic-ray work with SKA-LOW



Projected X_{max} resolution $\lesssim 10\,\mathrm{g\,cm^{-2}}$ (Zilles, 2017)

Doesn't need most of the SKA-LOW signal pipeline!

image: N. Patra

First particle detector deployed at MWA/SKA-LOW site.

Lunar particle detection with radio telescopes

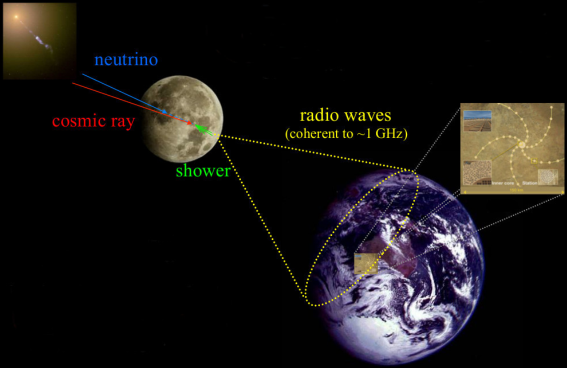


image credit: Ron Ekers

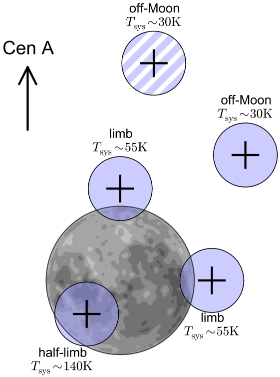
Huge area: $\sim 10^5$ km^2

High threshold: $\sim 10^{20}$ eV

Experimental challenges:

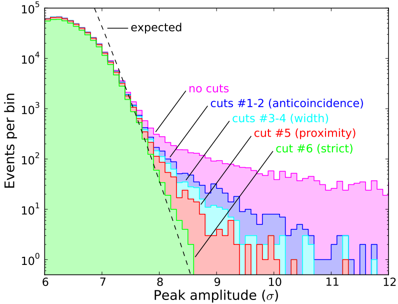
- ns-scale pulse detection
- RFI rejection
- ionospheric dedispersion
- moon in the beam

Lunar particle detection with radio telescopes



Bray et al., Phys. Rev. D 91, 063002 (2015)

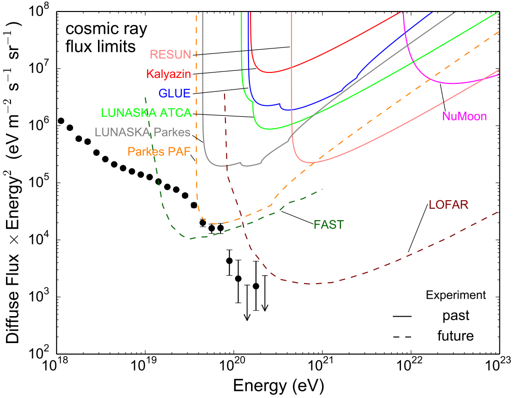
pointing configuration



Bray et al., Astropart. Phys. 65, 22 (2015)

$$\mathcal{E}_{\min} = 0.0053\ \mu\text{V/m/MHz}$$

Lunar particle detection with radio telescopes



Bray (2016); James et al. (2016); Winchen et al. (2018; prelim.)

No detections yet.

Ongoing work with:

- LOFAR (Winchen et al.)
- FAST (James et al.)
- SKA-LOW (HECP group)

One of these could achieve a detection, possibly more energetic than any cosmic rays detected thus far.

Summary

There's a bewildering variety of instruments for detecting cosmic rays and related particles.

Low-frequency radio telescopes are one of them.

LOFAR, detecting cosmic rays in the atmosphere, is currently measuring their composition with exceptional precision.

SKA-LOW will improve dramatically on this.

Radio telescopes also have the potential to detect cosmic rays interacting on the moon, at the very highest energies.

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Thanks for listening.