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Detecting High Energy Cosmic Rays with LOFAR

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for the LOFAR-CR Team

LOFAR CR-KSP: Main Motivation

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- 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 with TKP)
- Develop the techniques to work on raw time series data (transient buffer board & tied-array beam) in near field and far-field.

Cosmic Rays

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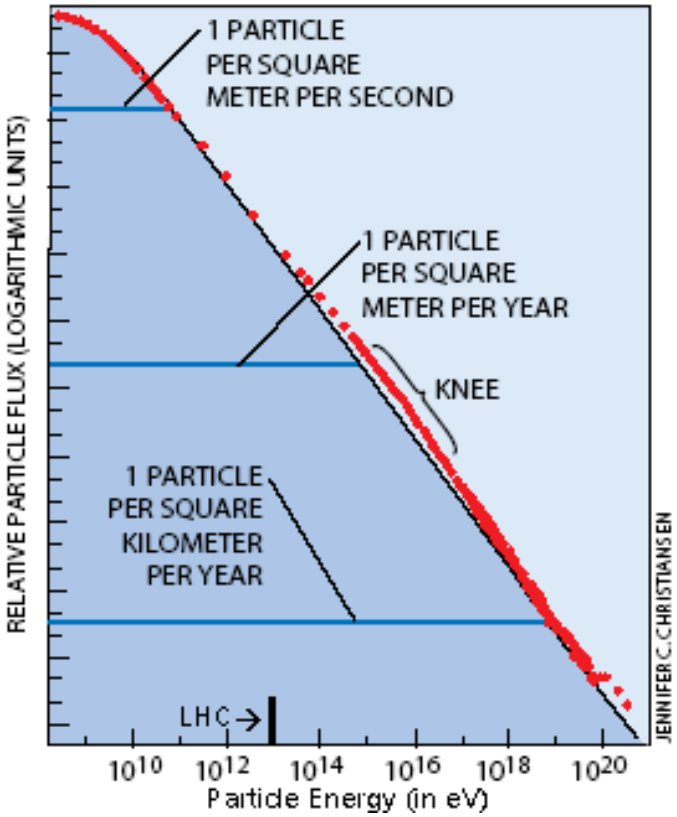
- High energy particles
- Dominated by hadrons (atomic nuclei)
- Similar in composition to solar system
- Broad range in flux and energy
- Different energy regimes:



$<10^{7}$ eV	Modulated by solar wind
$<5 \cdot 10^{14}$ eV	Direct detection possible
$>5 \cdot 10^{14}$ eV	Indirect detection (air showers, moon)

Sources of Cosmic Rays

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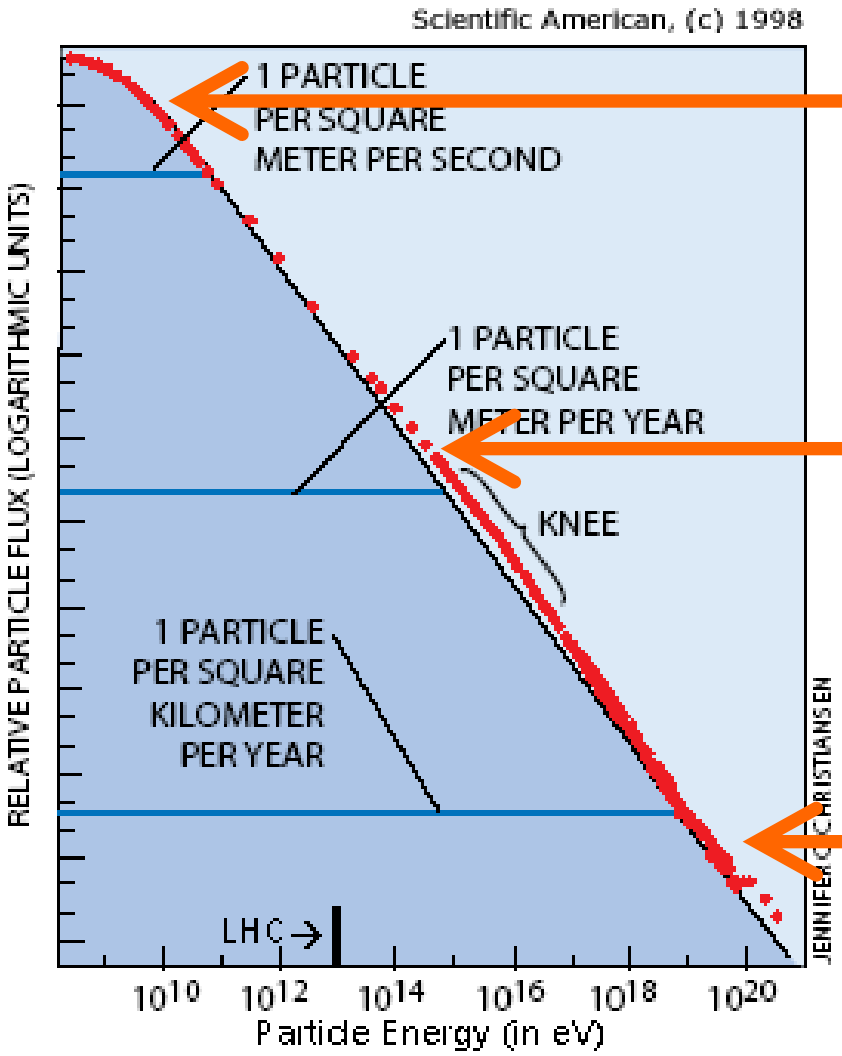

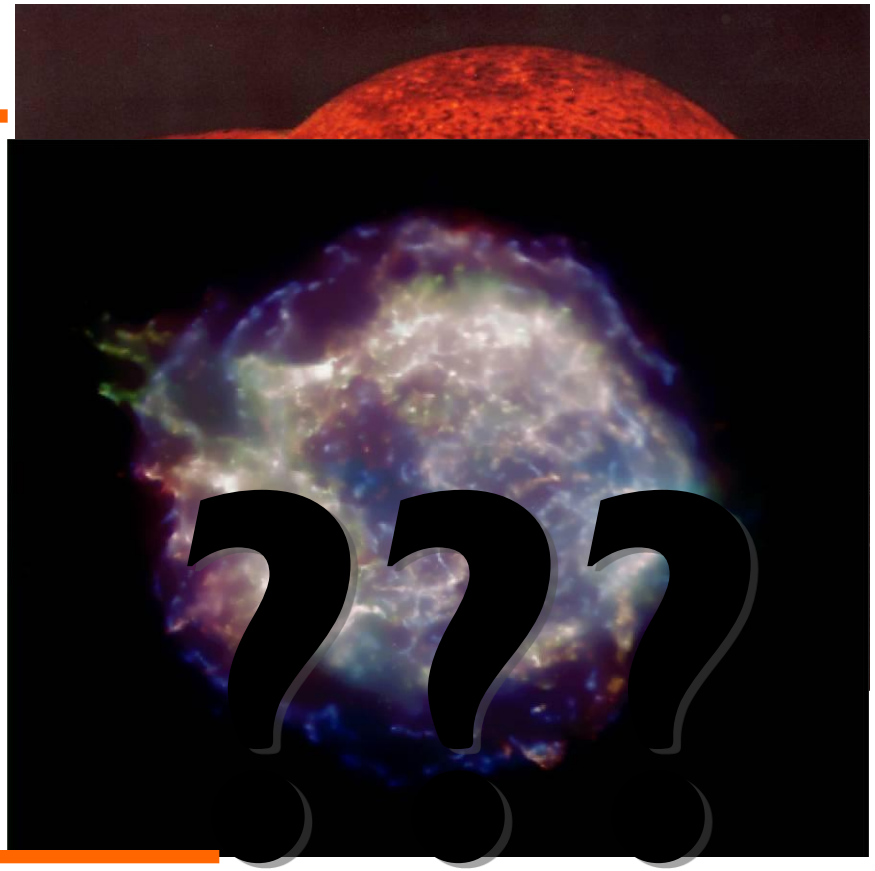

Unknown Sources!

Sources of Cosmic Rays

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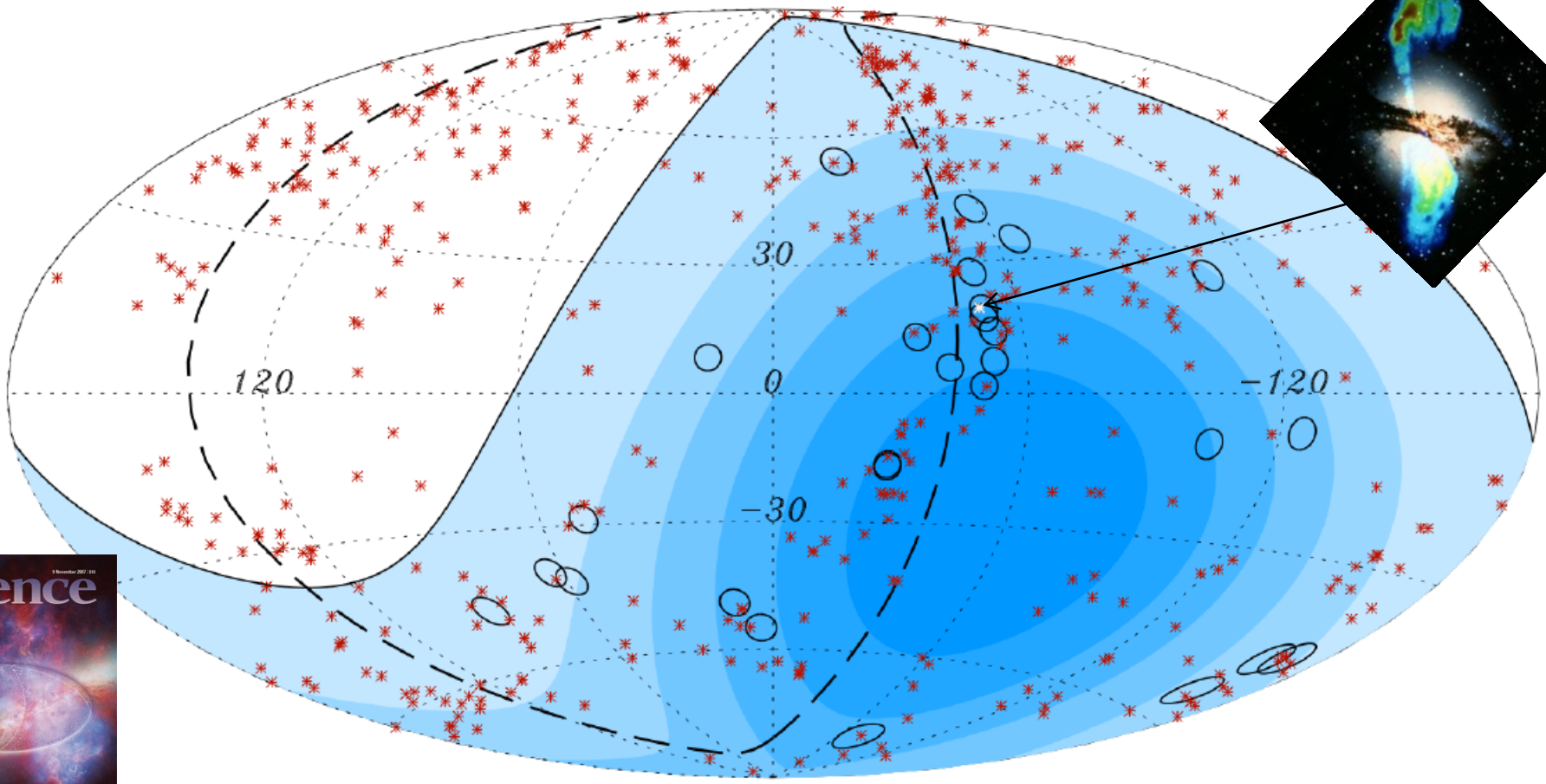
- Correlation with AGN clustering at $E>5.7 \cdot 10^{19}$ eV



AUGER Collaboration (2007), Science

Detection: Particle Cascades

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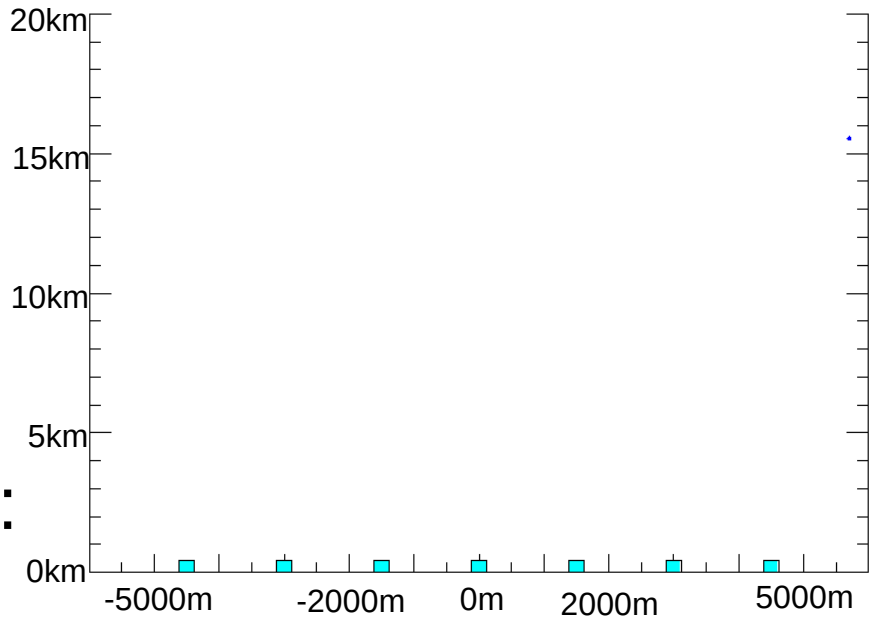
- High energetic cosmic rays interact with nuclei in a medium (air, rock, etc.)
- In a cascade many secondary particles emerge
- Classical detection methods:
  - Air fluorescence
  - Particle detector arrays



- These cascades also emit radio waves
  - **Air Showers**: Geo-synchrotron radiation
  - **In solids/rock**: Cherenkov radiation
- Coherent emission produces short (≤10 ns) radio pulses.

LOFAR-CR Energy Ranges

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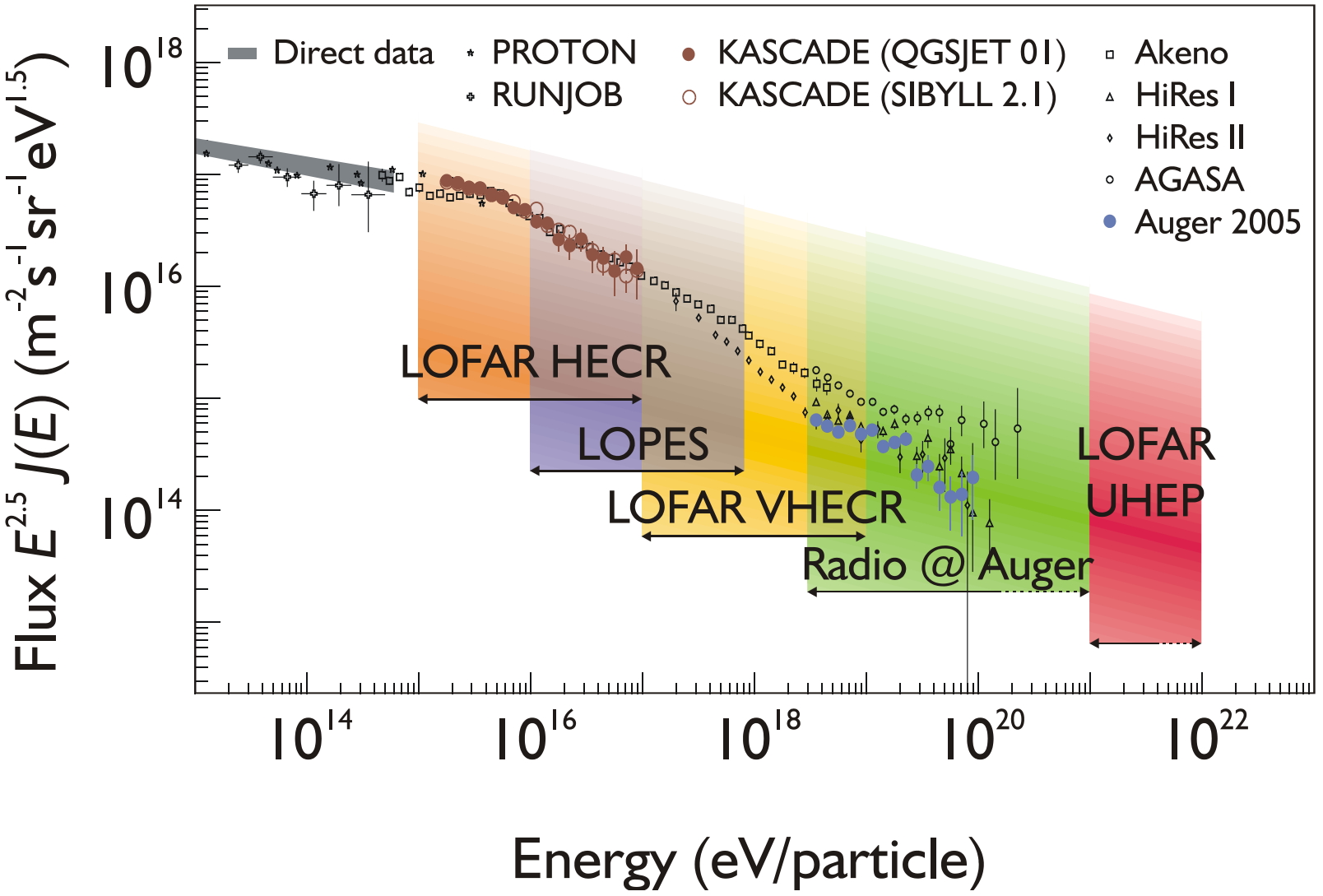

LOPES

(**LO**FAR **P**rototyp**e** **S**tation)

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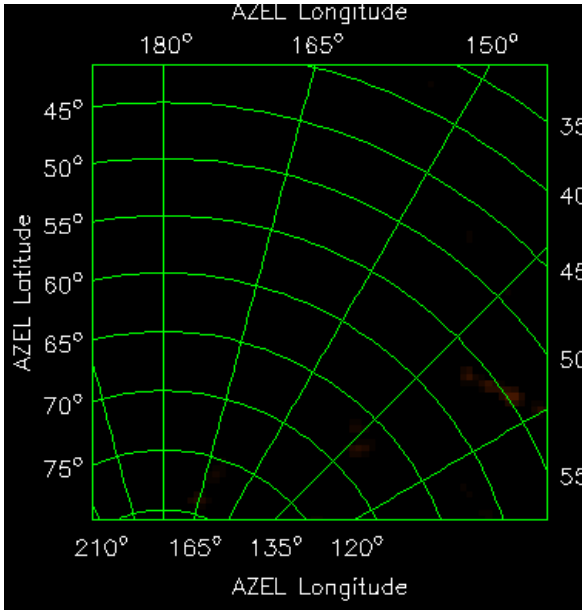
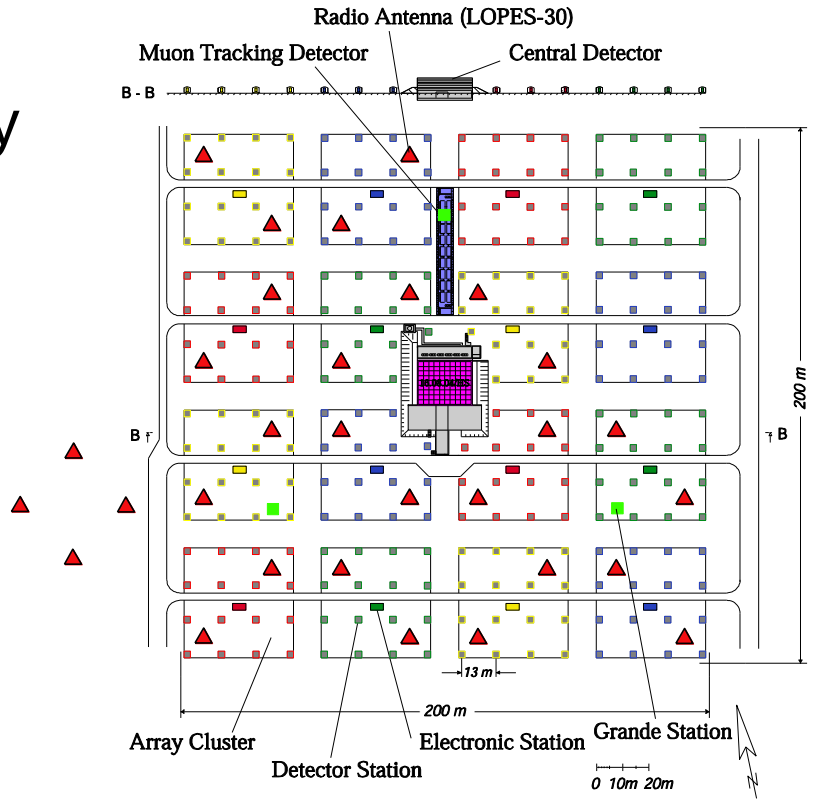
- Prototype of a LOFAR station
- Set up inside an air shower array
- Frequency range of 40–80 MHz
- Triggered by particle detectors
- Detection of air showers with LOFAR technology





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

LOFAR for Air Showers

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- designed as an astronomical telescope not an air shower detector:
  - “small” stations with lots of antennas in a small area
  - different baselines between stations
- consequences:
  - low effective area for the number of antennas
  - **high sensitivity**
  - **very good calibration**
- this makes LOFAR an unique tool to study air showers:
  - Develop the method (triggering, reconstruction)
  - Understand the emission process
  - Air shower physics (new particles?)
  - Change galactic→extragalactic cosmic rays

Radio Signature of Air Showers

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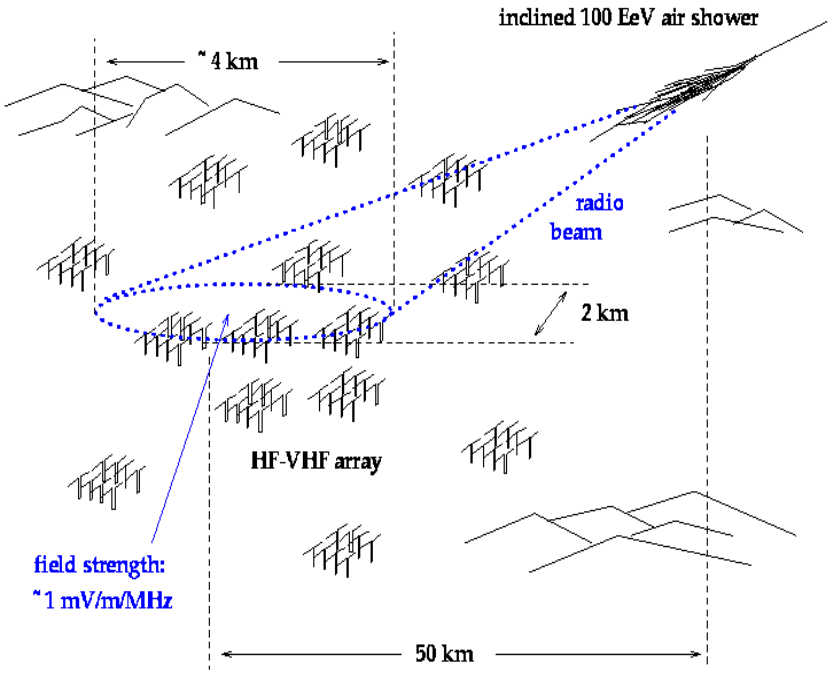
- random arrival times and directions
  - can ignore (man made) pulses from the horizon
- broad-band, short time pulse (~10ns)
- limited illuminated area on the ground
  - depending on primary energy
- curvature of radio front
  - similar (but not identical) to point source in few km height
- coincident with other air shower signs
  - e.g. particle front



LOFAR Queens Helicopter

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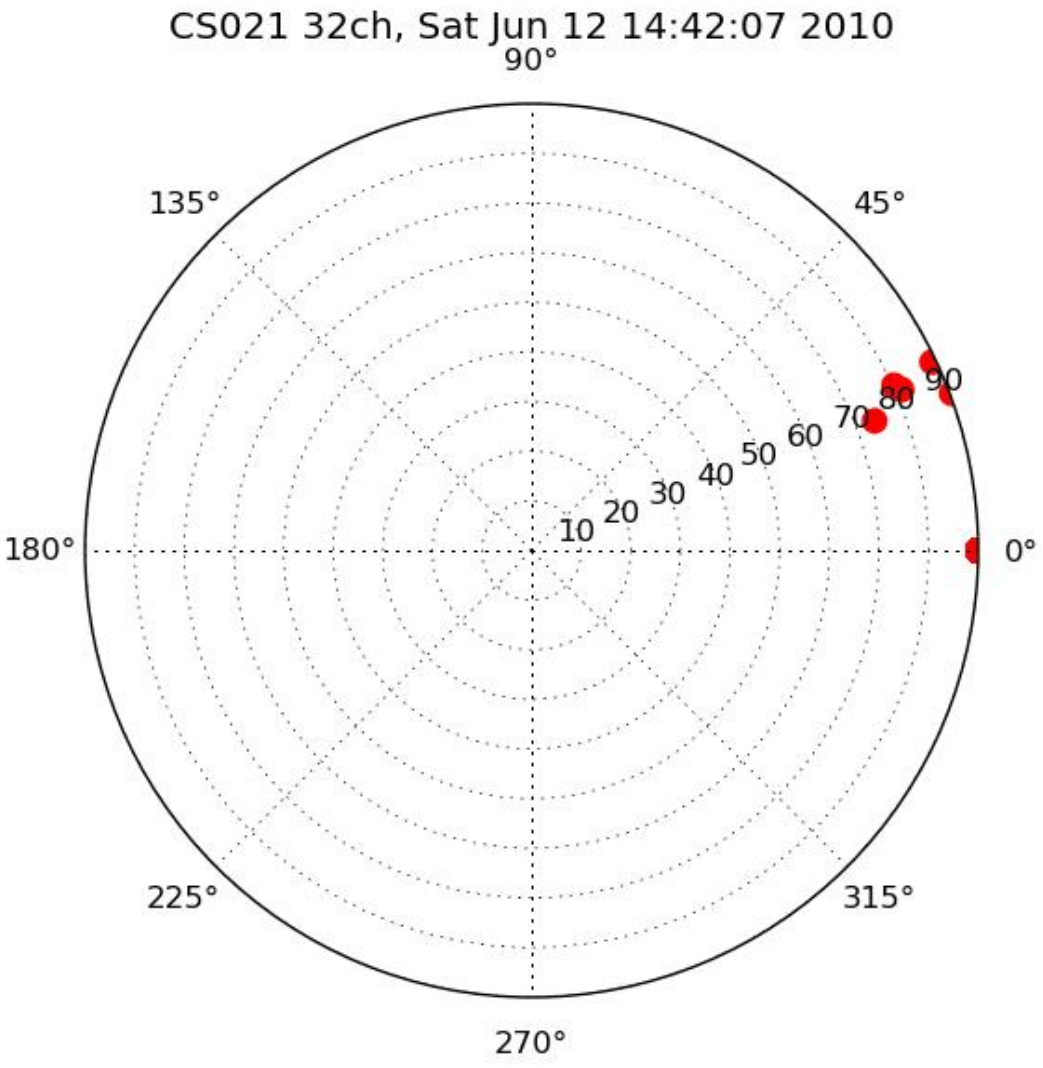

LOFAR Triggered Pulse

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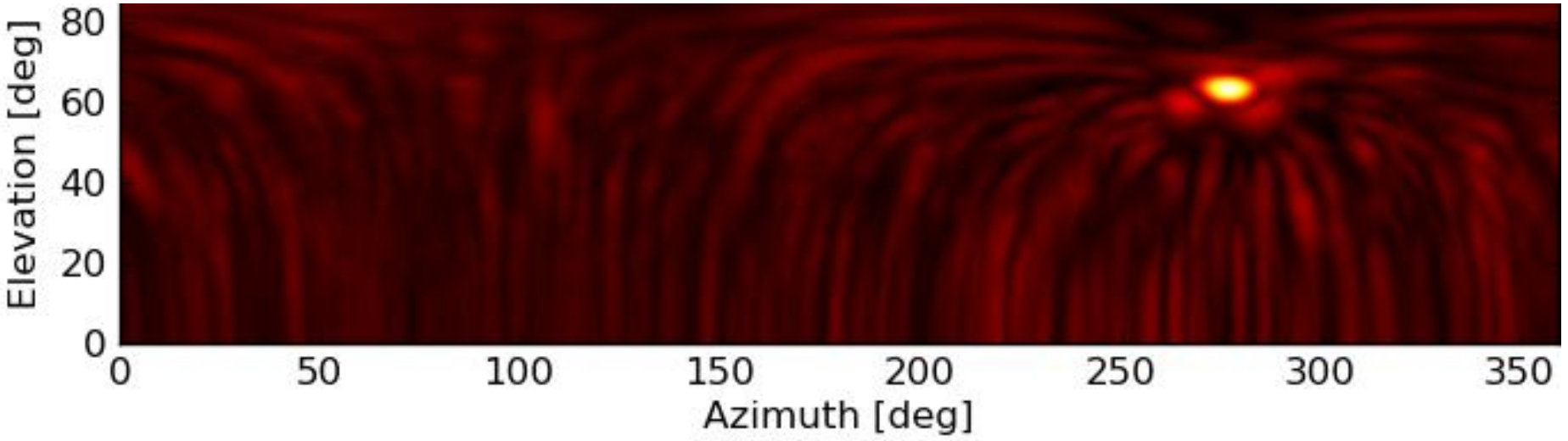

Ultra-High Energy Particle Detection

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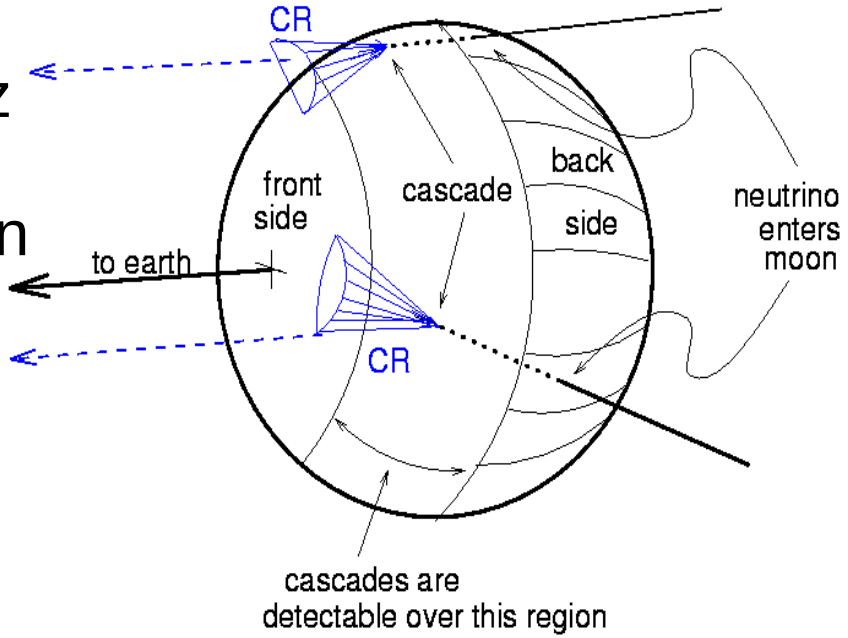
- Particle showers inside the moon produce Cherenkov radio emission
- In the Cherenkov cone the emission maximum is in the GHz range
- At long wavelengths the emission is more omni-directional
- This increases the effective detection volume
- LOFAR can detect the radio pulses in a tied-array beam
- And use the TBB data for exact pinpointing afterwards.



from Gorham et al. (2000)

Neutrino-Sensitivity

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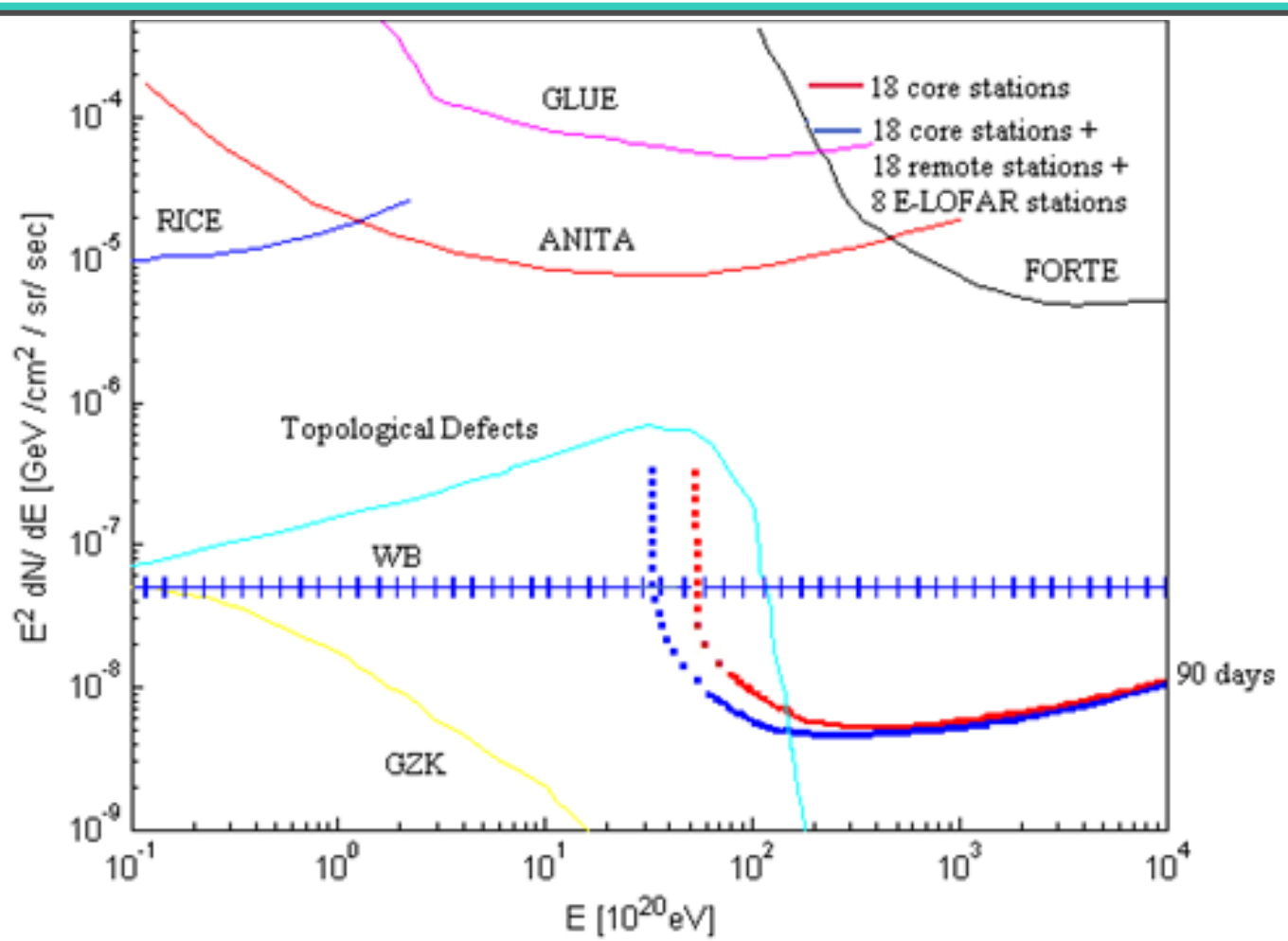

- Non-detection will disprove some theories

UHE-CR Sensitivity

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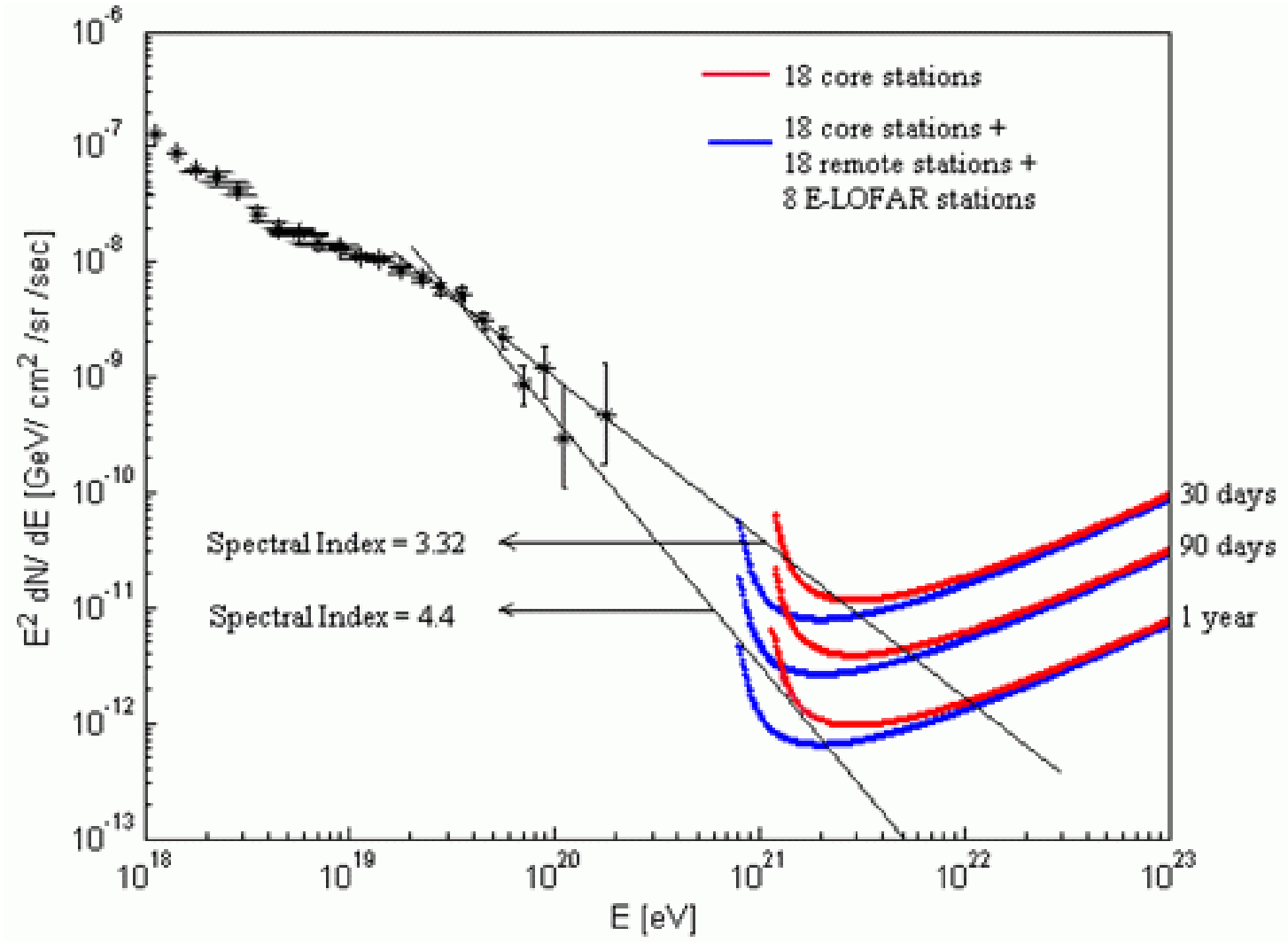

Summary

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- UHE-CRs that hit the Earth or the Moon produce nanosecond radio flashes in:
  - Air showers in the Earths atmosphere
  - Particle cascades in the lunar regolith
- LOPES has proven that LOFAR can measure air showers
- Its high sensitivity and excellent calibration make LOFAR an unique tool for this measurement
- At low frequencies the radio-Cherenkov emission from the moon becomes nearly omni-directional
- This allows LOFAR to detect particles above 10^{21} eV with unprecedented sensitivity