The LOFAR Cosmic Ray KSP and associated pipelines.

C.W.James, Radboud University Nijmegen

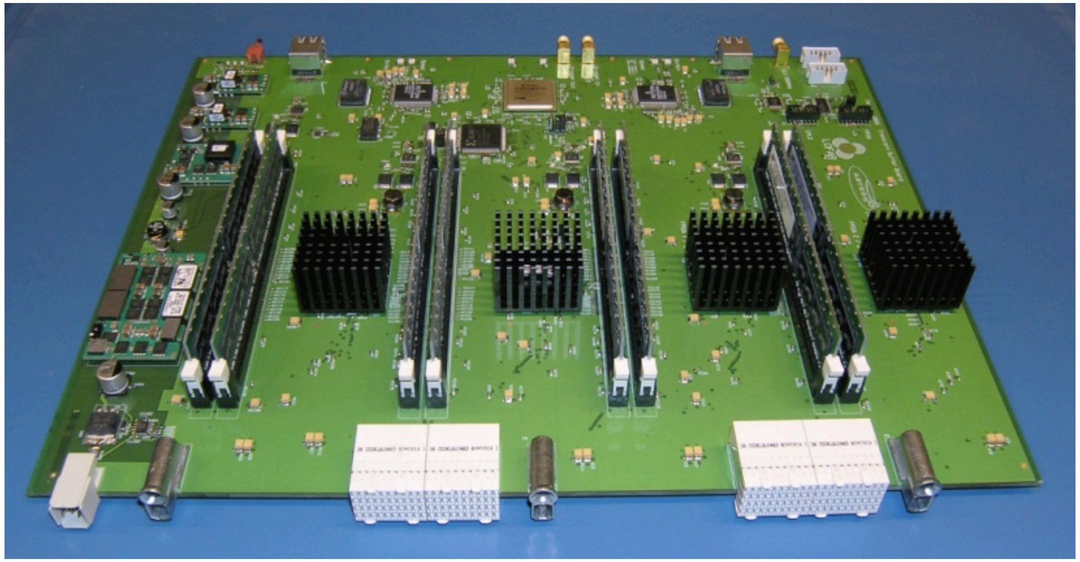
On behalf of the LOFAR CR KSP

Special thanks to H. Falcke, A. Horneffer, and A. Corstanje.

Outline

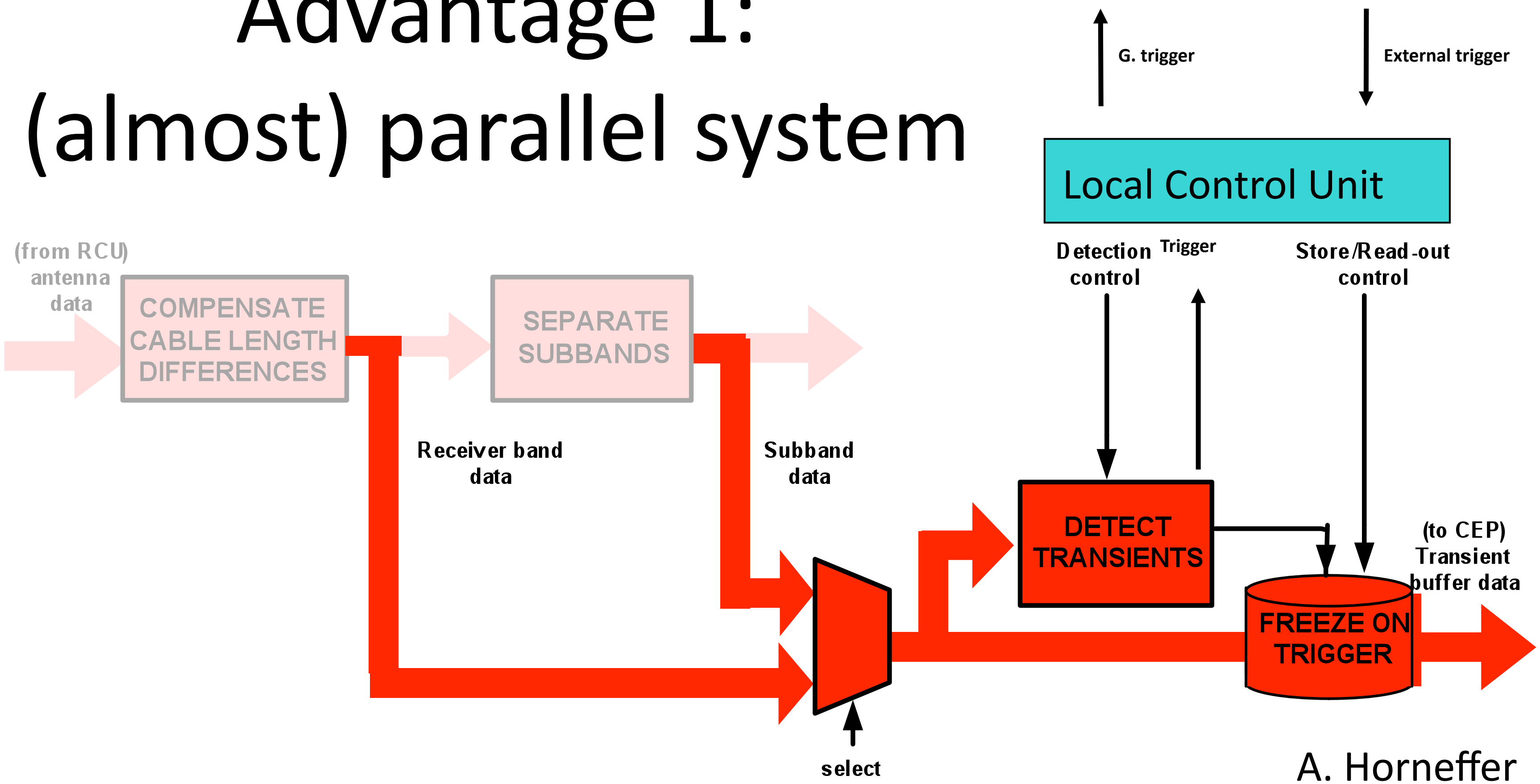
- Transient buffer boards (TBBs) and why they’re great.
- Cosmic rays – brief overview.
- Radio detection of cosmic rays
- The LOFAR VHECR mode
- LOFAR UHEP mode
- Other projects

LOFAR TBBs
(transient buffer boards)



- RAM buffers located at each station.
- Can record more data than can be sent back to CEP (raw voltages, 512 sub-bands)
  - LBA: filtered antenna voltages
  - HBA: filtered tile voltages (limited to tile beams)
- Enough space for 1.3 seconds of data on 200 MHz clock at 8 bits.

Advantage 1: (almost) parallel system

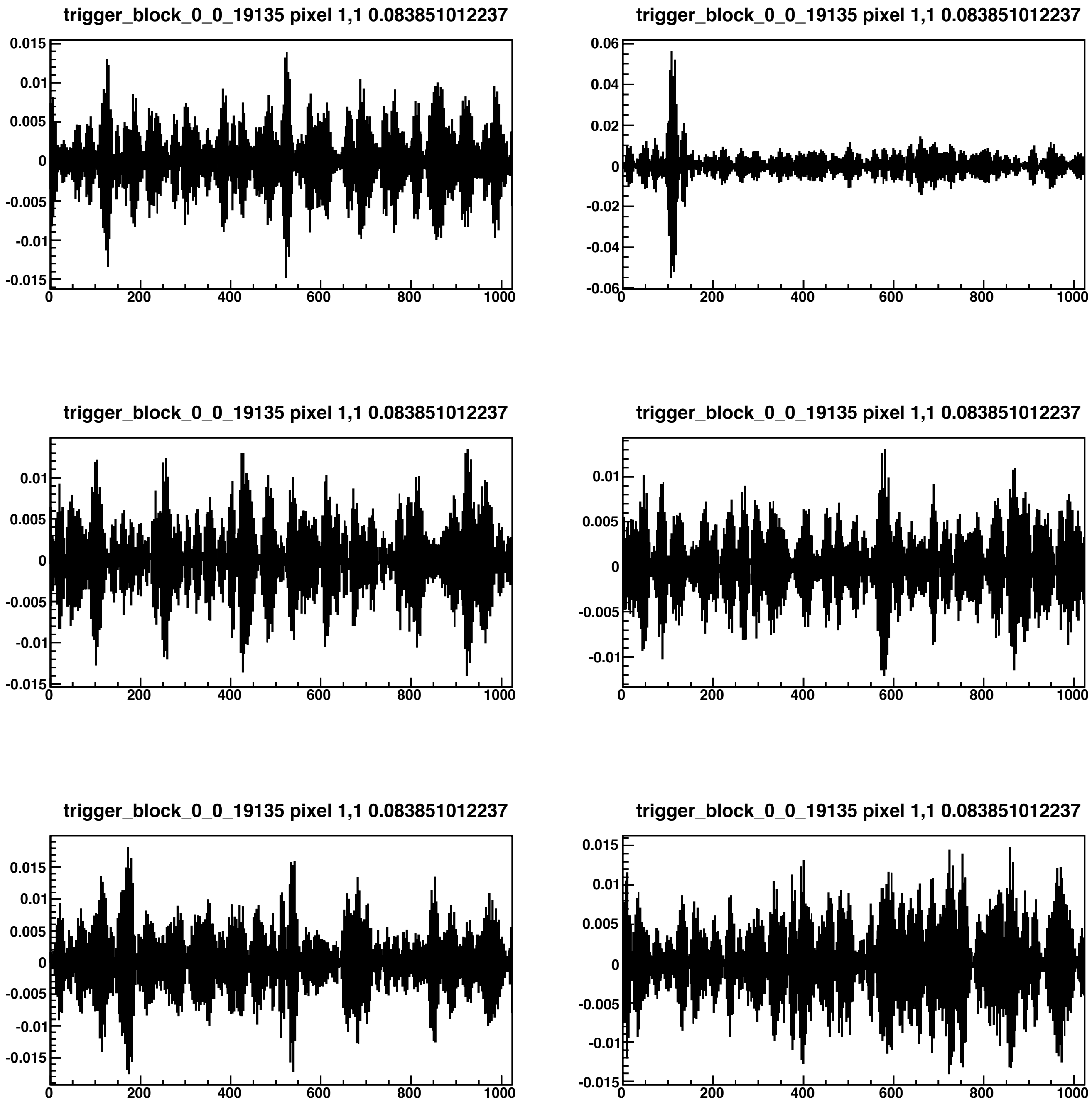


- Recording to TBBs independent of station beamforming, and what is going on at CEP
- Data can be recorded, stopped, and returned *independently.*

Courtesy M. Mevius

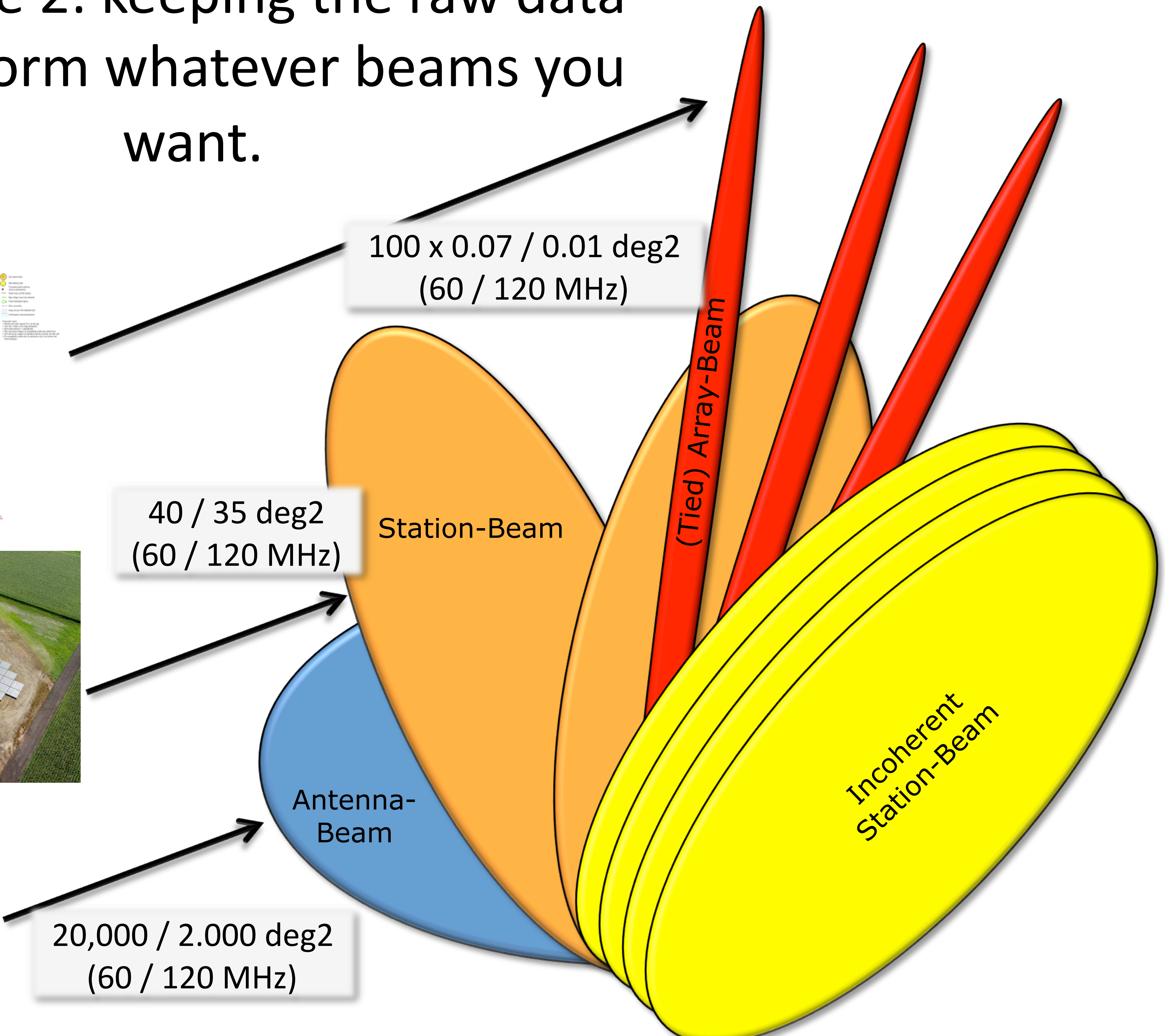
Example TBB data

- From HBA tile 0 from all six superterp stations
- Note different size scales
- Large pulse observed – but in only one station
- The nanosecond radio environment is strange!

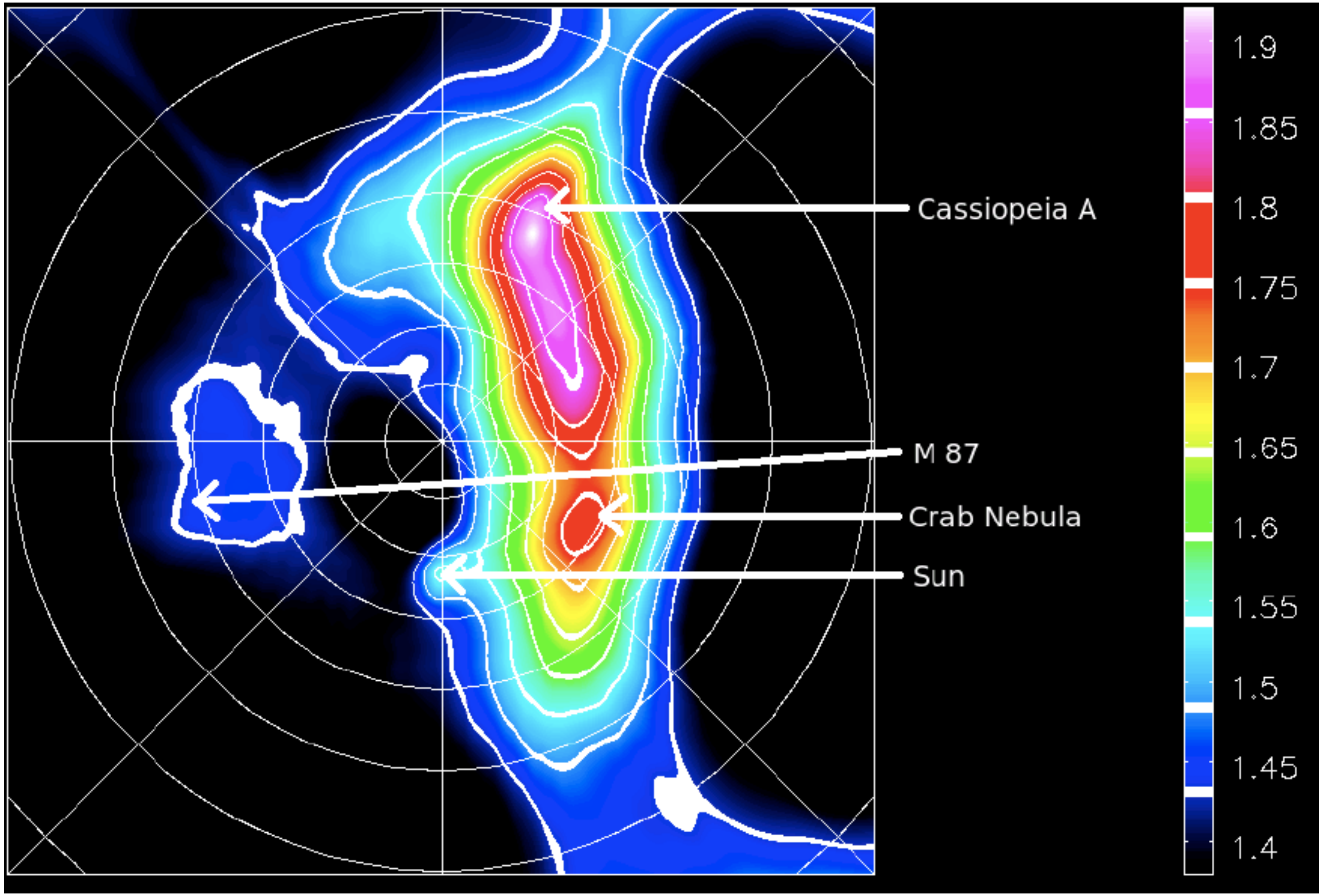


Courtesy of M. Mevius

Advantage 2: keeping the raw data lets you form whatever beams you want.



5ms All-Sky Imaging with LOFAR TBBs

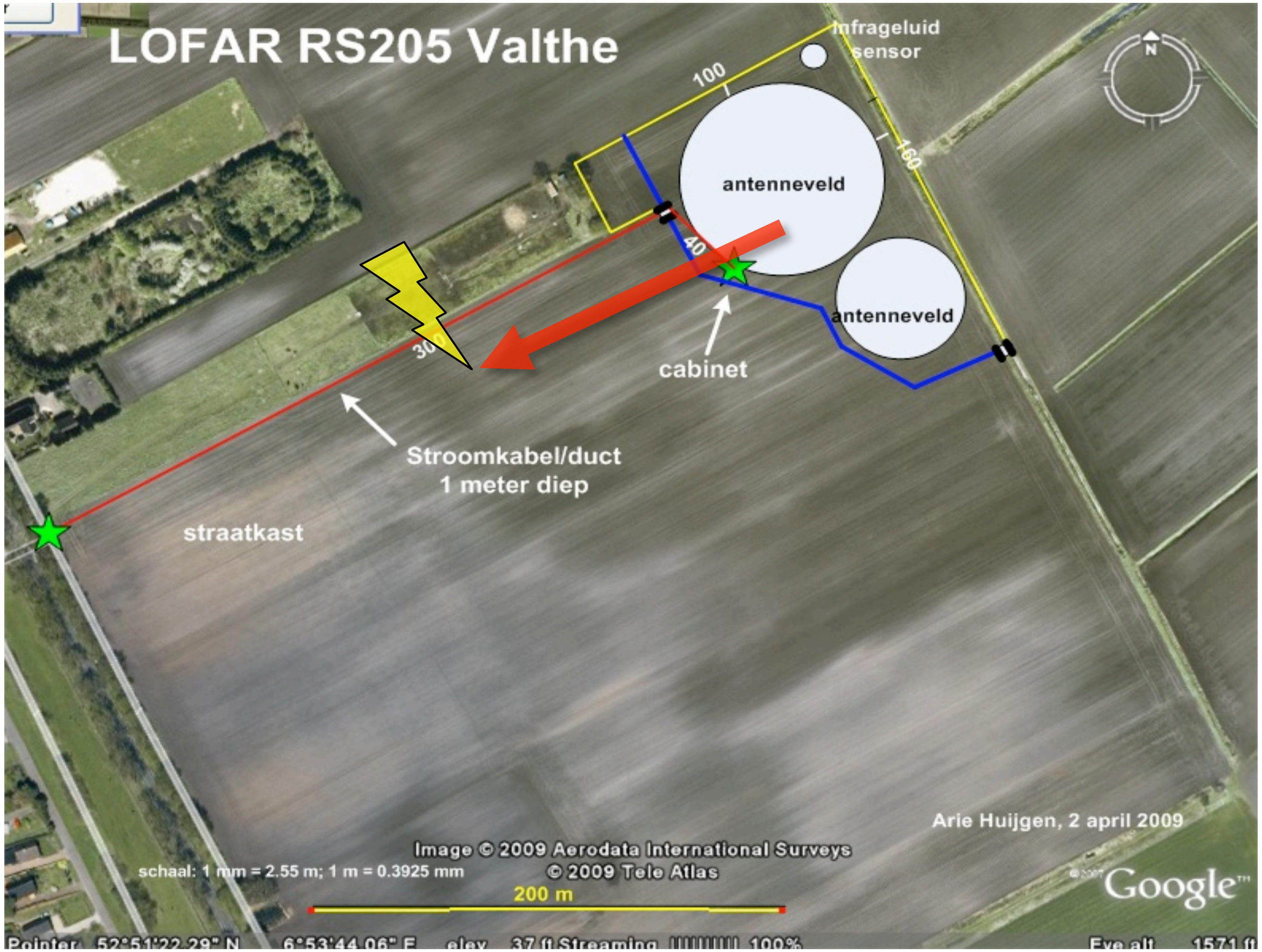


Single LBA station

S. Welles
L. Bähren
(Radboud)

Advantage 3:
full time resolution /bandwidth

- 5 ns timing: = 1.5m accuracy.
- E.g. nearfield source location.
- Also gives full (~100 MHz) bandwidth.



Disadvantages

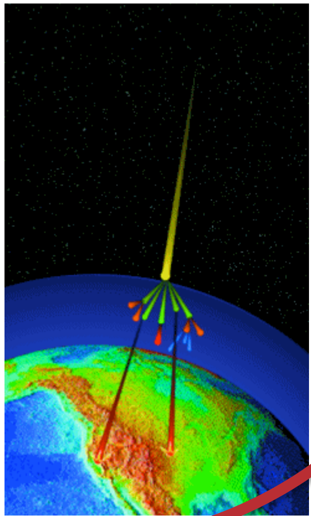
- Data not processed through station beamforming or CEP – must do it yourself!

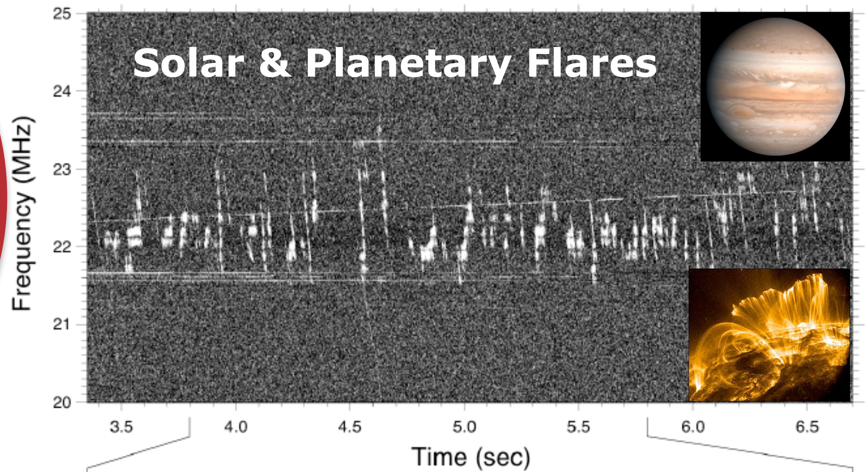
- Observation time is 1.3 seconds *max* for raw voltages.
  - what can you see in 1.3 seconds…
  - …which can't be seen in imaging mode…?
  - …and which can't be followed-up from pulsar (~dynamic spectrum) mode?

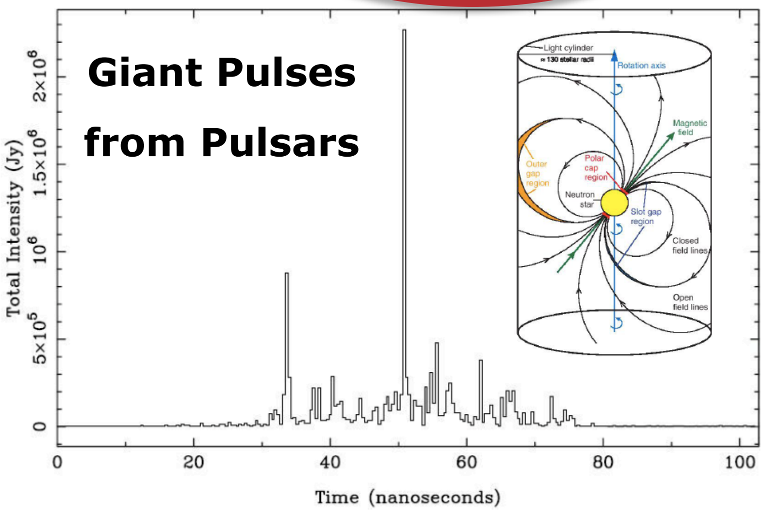
- Answer: once-off transients!

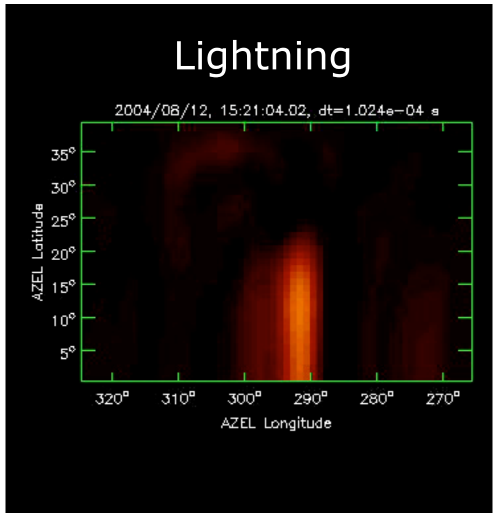
Cool things you can see with TBBs

cosmic rays



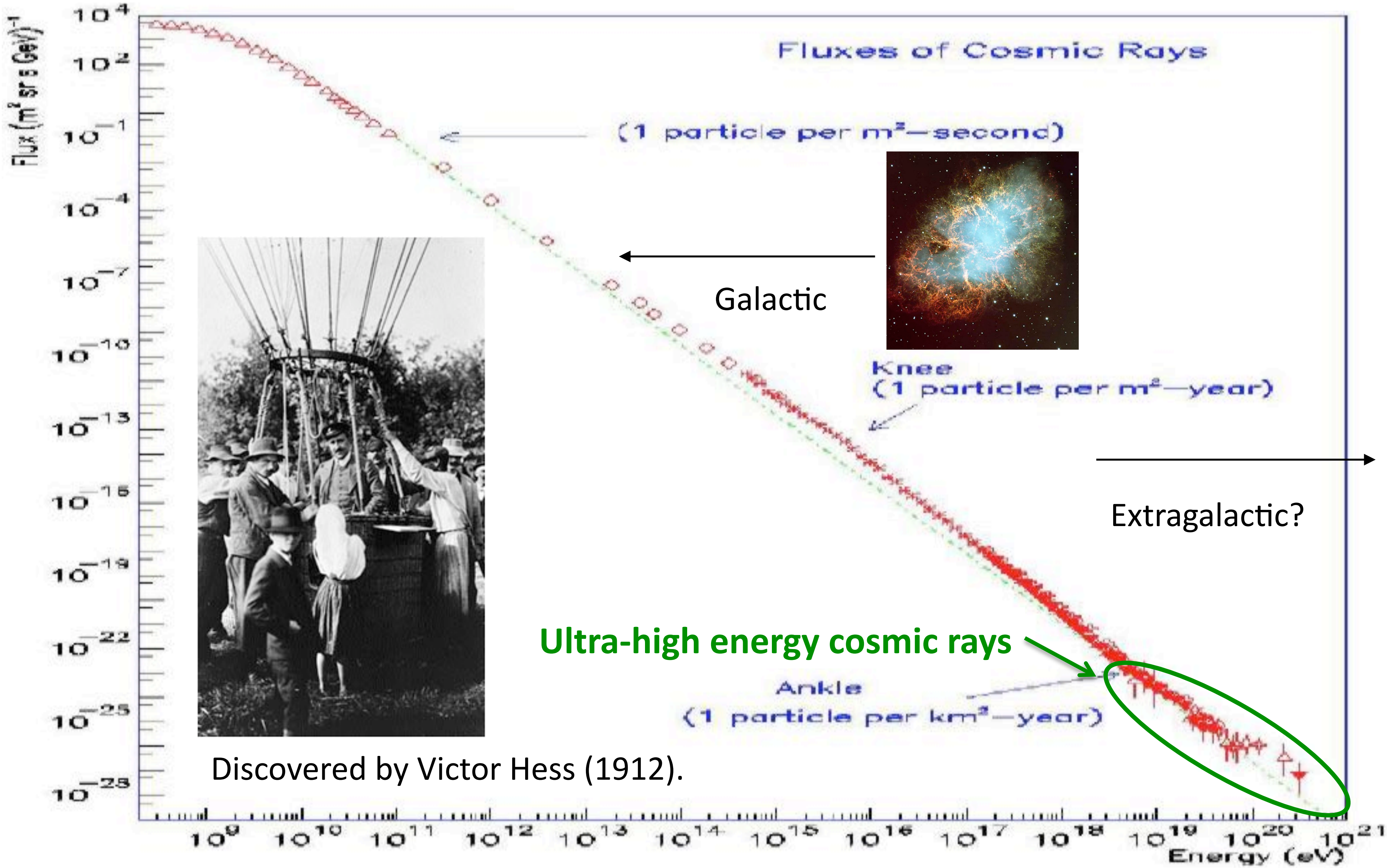






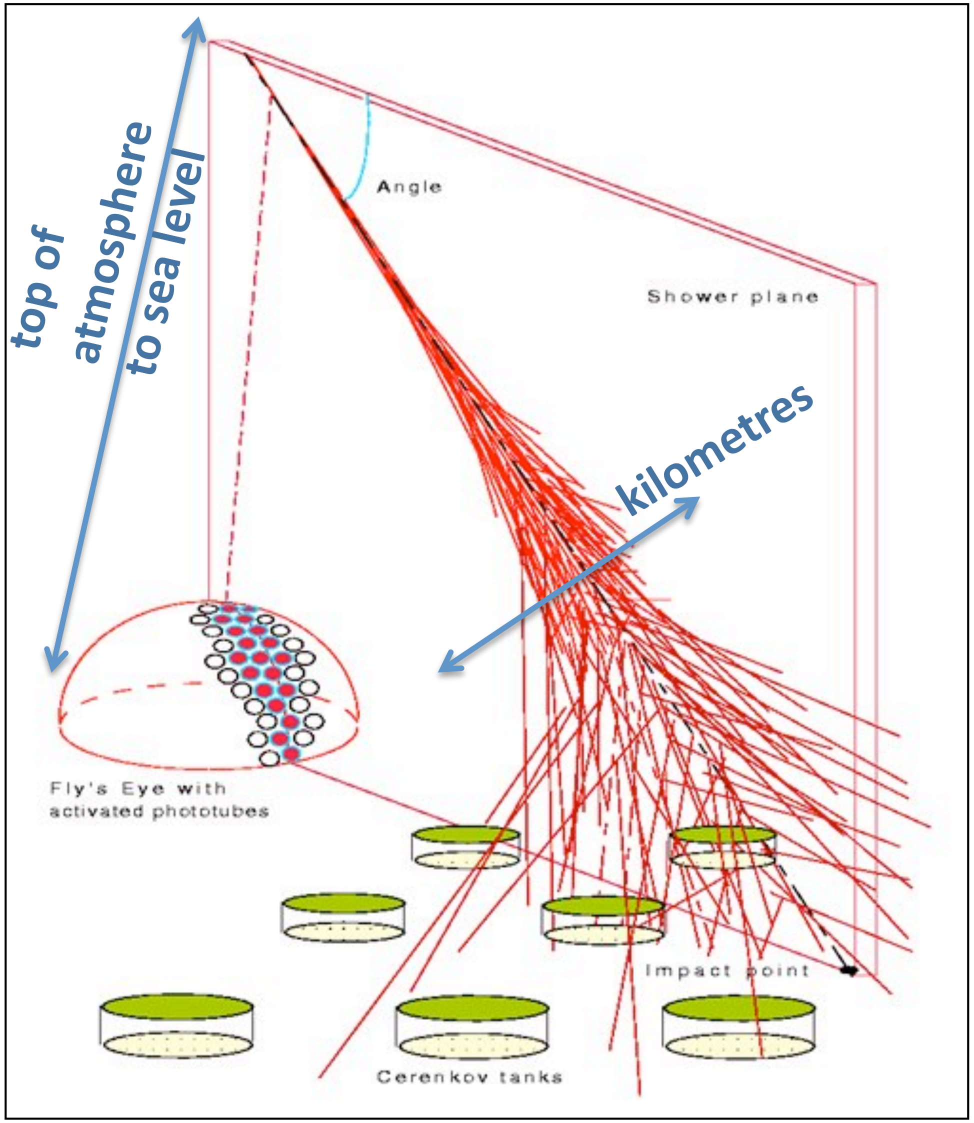
Cosmic Rays

High-energy particles (mostly protons) from space hitting the Earth's atmosphere.



Discovered by Victor Hess (1912).

Cosmic-ray detection at UHE (>~ 10^{18} eV)

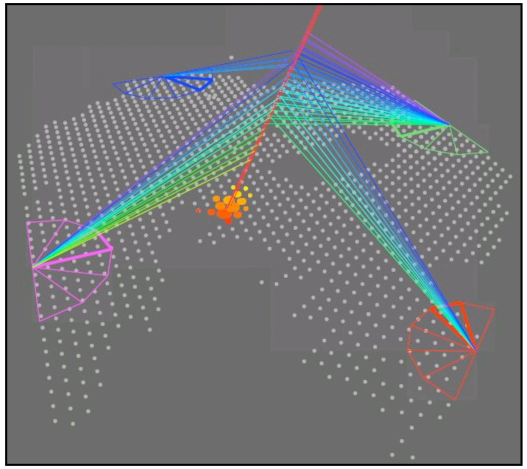


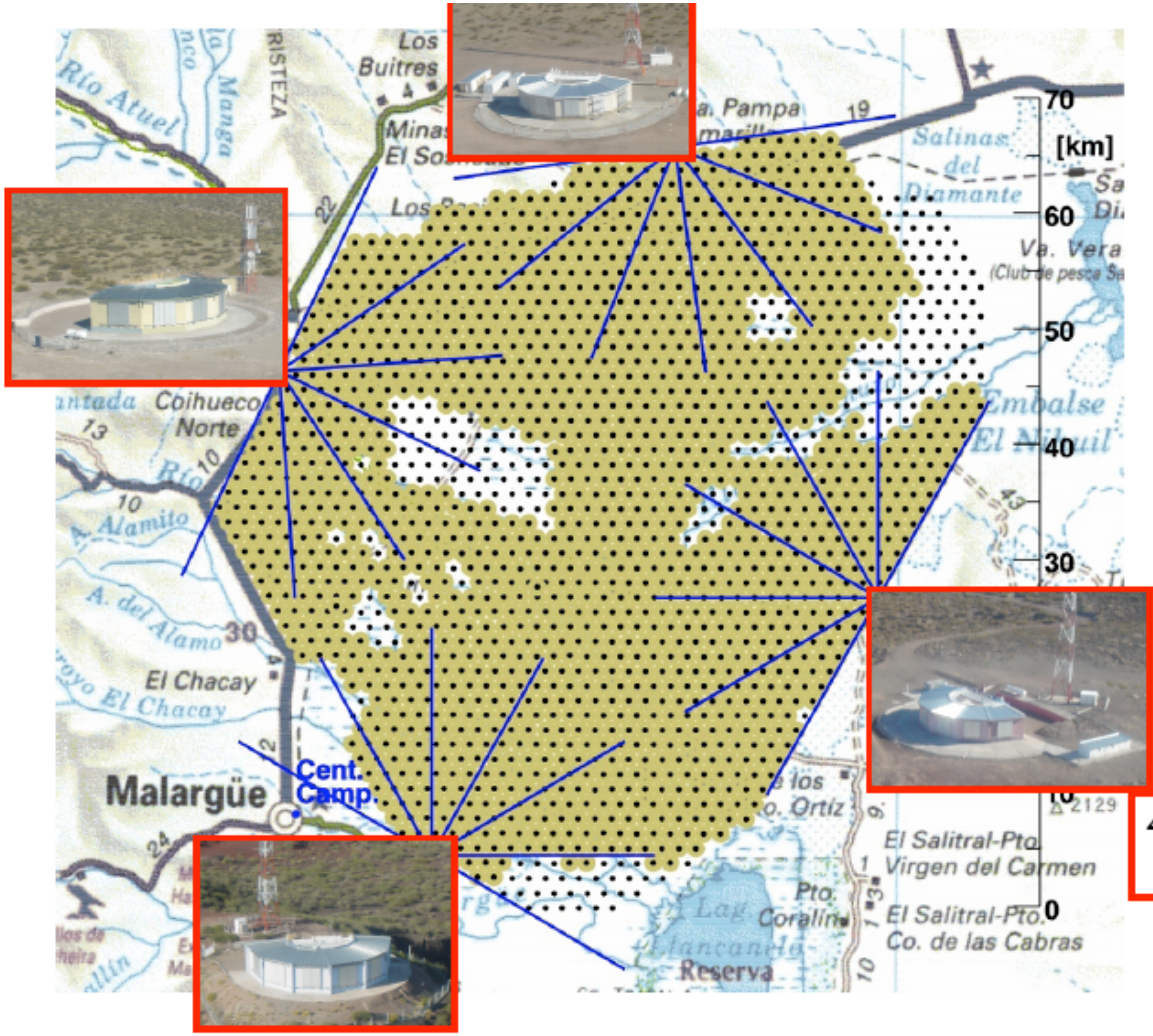
- Cosmic ray interaction (upper atmosphere)
- Cascade of secondary particles (may make it to ground level)
- Detect particles directly (e.g. water Cherenkov tanks)
- Observe nitrogen fluorescence with optical/near UV telescopes.

- Air fluorescence sees whole of shower energy
- Critical for determining energy spectrum
- Can only operate on dark, moonless, cloudless nights (10% duty cycle)

The Pierre Auger Observatory

- Near Malargue, Argentina
- 3000 km^2 effective area
- uses both air fluorescence and water Cherenkov detectors



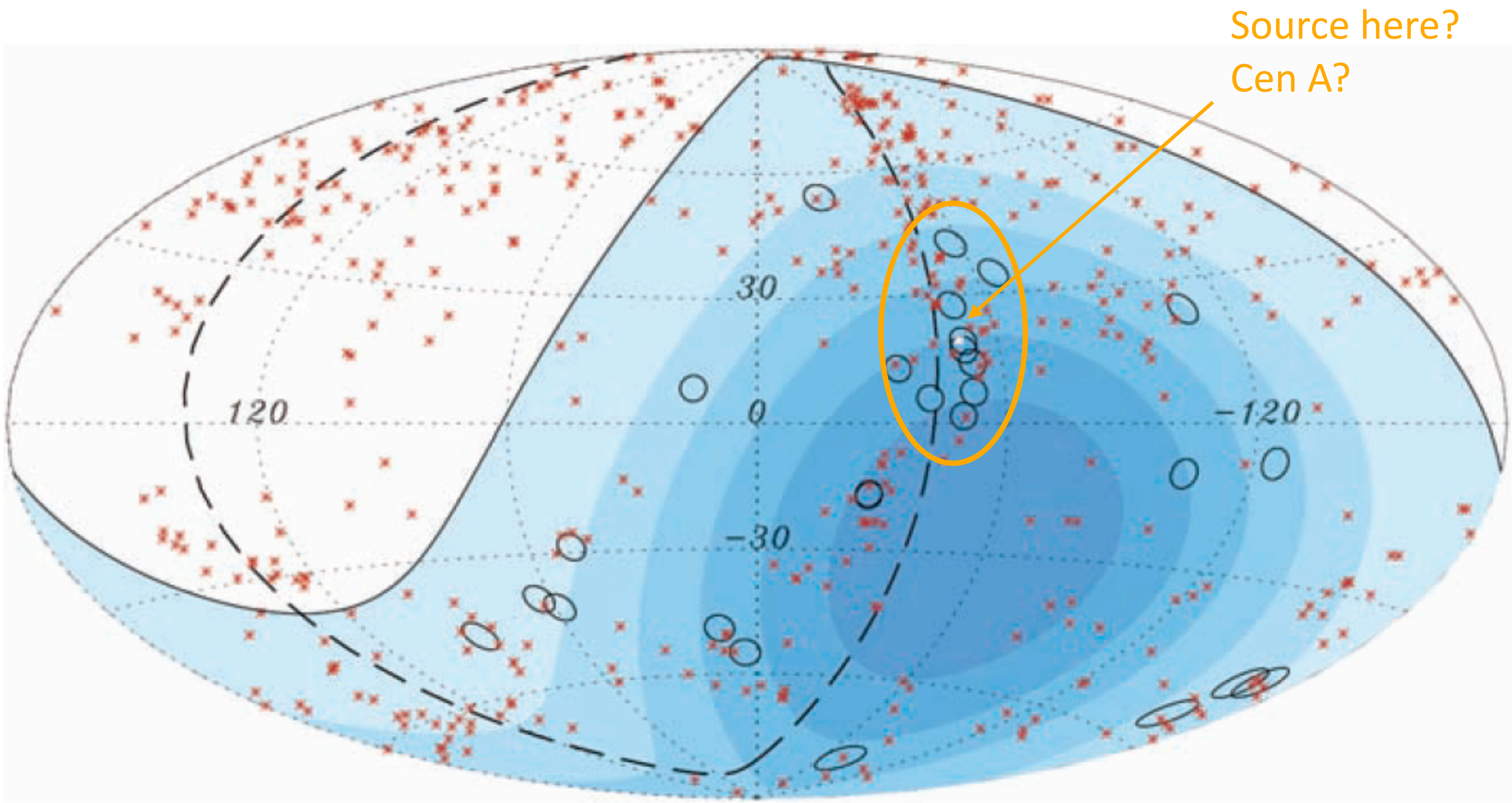


1600 surface detectors: water-Cherenkov tanks (triang. grid of 1.5 km)

4 fluorescence detectors (24 telescopes in total)

Measurement 1:– arrival direction

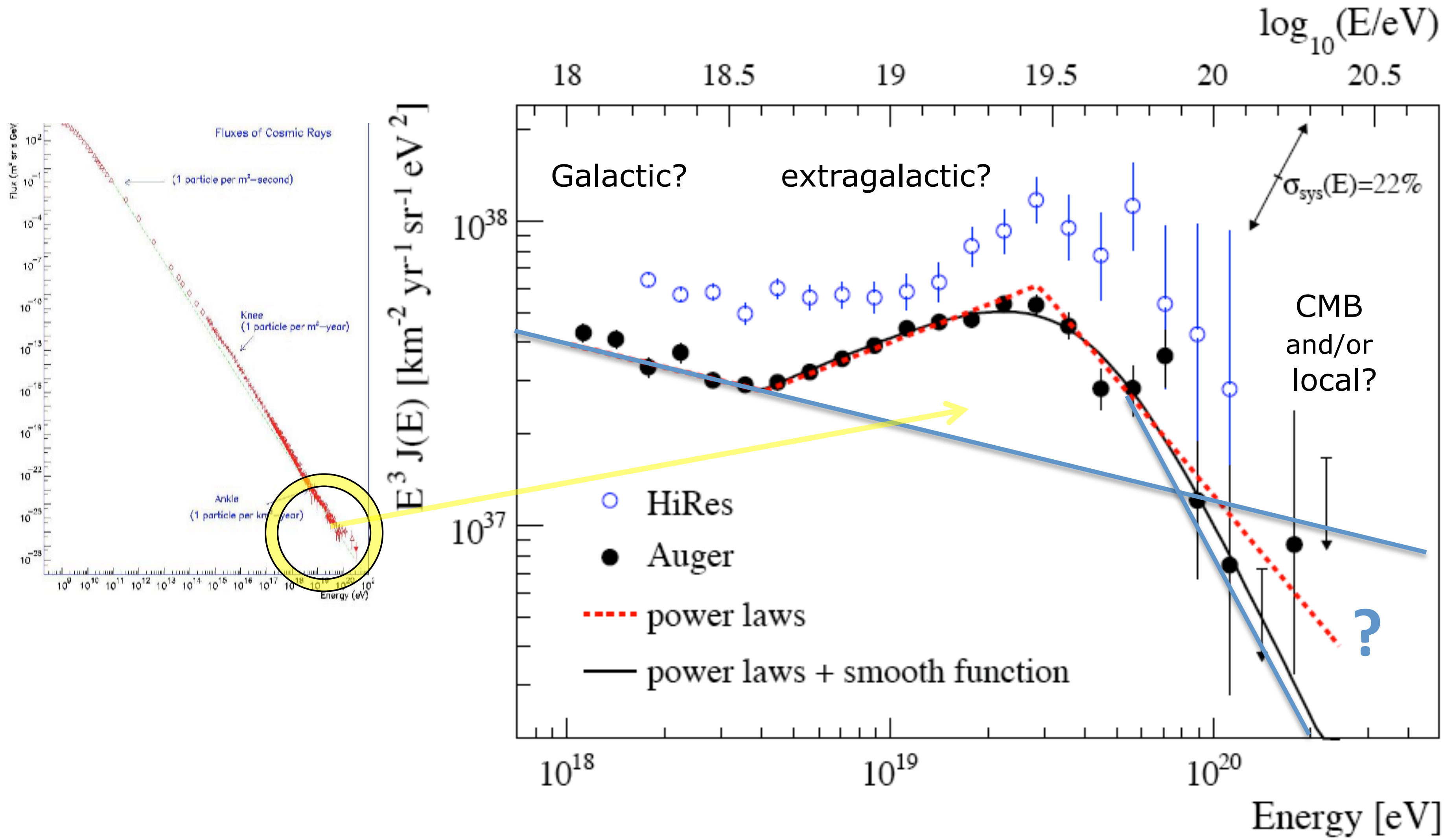
- Energies over 56 EeV (5.6 10^{19} eV) retain some directional information. (one full year's data: 27 'useful' events.) (Galactic coordinates)
- Correlation with nearby (<100 Mpc) AGN observed.



Blue shading – Auger exposure red – AGN 3^0 circles – UHE CR events

Auger collaboration, Science 318, 938 (2007)

Measurement 2: Cosmic Ray Spectrum



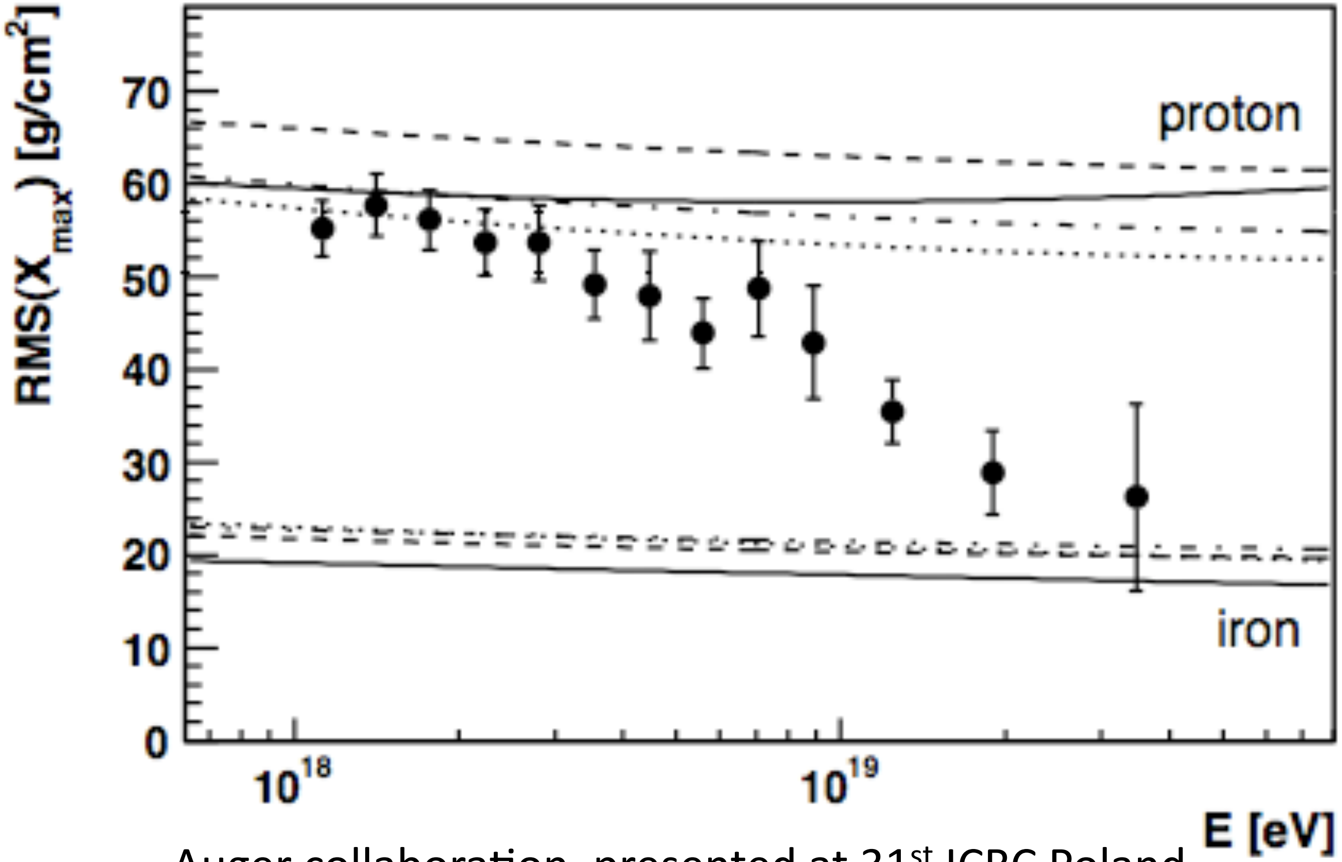
The Pierre Auger Collaboration, Physics Letters B (2010)

Measurement 3: Composition

- Protons and iron will reach us most easily from distant sources
- Simulations vs measurement of EAS height + fluctuations therein.
- Conclude: tendency towards iron composition at the highest energies.

Lines: different simulations for protons and iron
Points: Auger measurements

Variance in:
Atmospheric height where:
number of cascade particles is maximum



Auger collaboration, presented at 31[st] ICRC Poland

What we don't know about UHECRs

- ***where they're produced (maybe AGN)***
- ***how they're produced (Fermi 1st order acceleration?)***
- composition at UHE (protons vs iron?)
- what their maximum energy is (>10^{20} eV)
- anything about them beyond 100 MPc (~energy-loss horizon)

- **What can we do about it?**
  - Build larger cosmic ray detectors
  - Use new methods… radio telescopes!

Radio Detection of High Energy Particles

- 1: UHE particle interacts in matter.
- 2: Cascade of many secondary particles produced.
- 3: Charged particles accelerated on production, further interactions, and surrounding EM fields.
- 4: *Accelerating charged particles -> EM radiation!*
- 5: Radiation is coherent at frequencies comparable to the cascade dimensions.

$$p_{CR}/\pi^{\pm} + q_{atmo} \xrightarrow[\text{jet}]{} \pi^{+}, \pi^{0}, \pi^{-} \quad \text{(quark jets)}$$

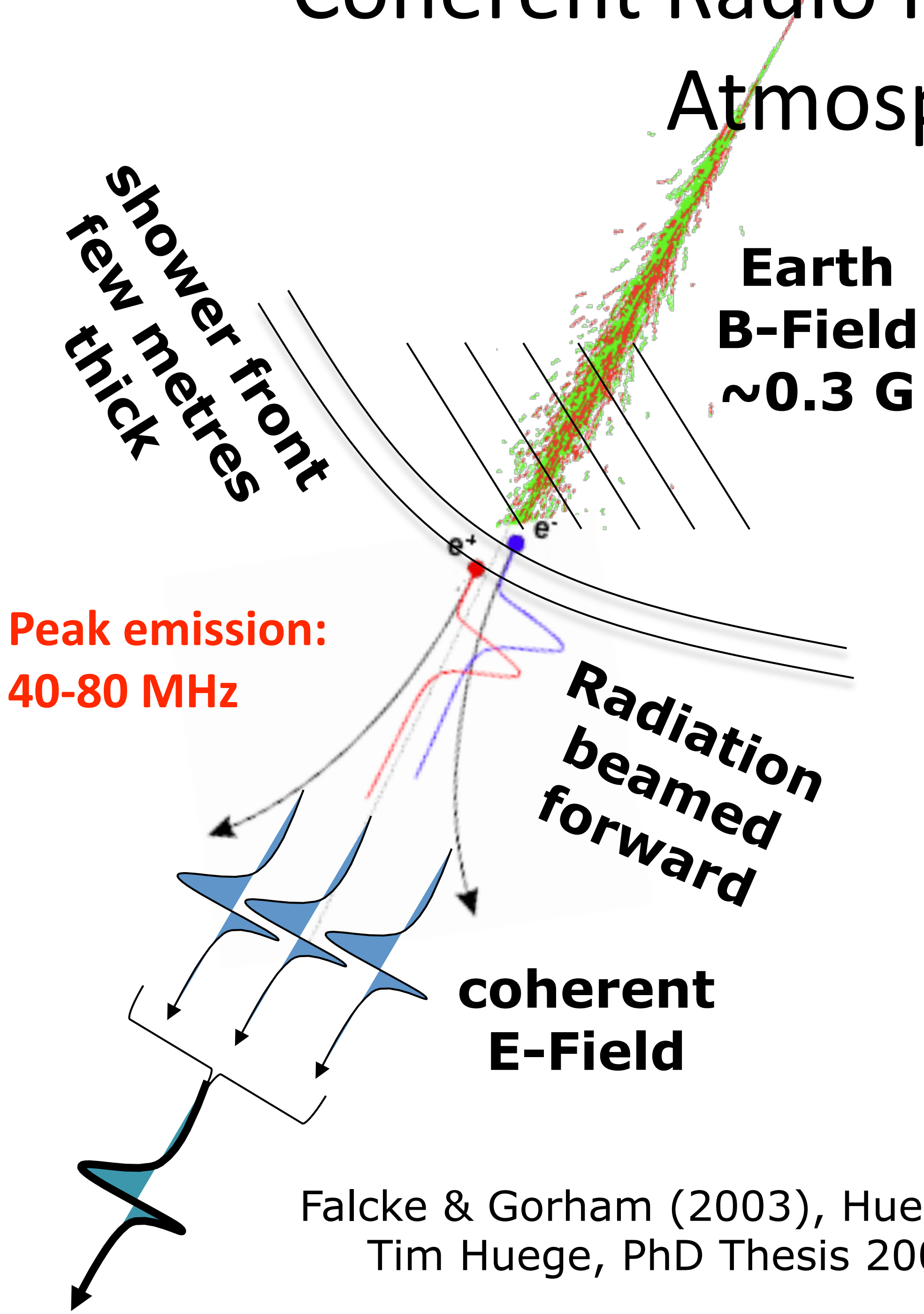
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu} \quad \text{(charged pion decay)}$$

$$\pi^{0} \rightarrow \gamma + \gamma \quad \text{(neutral pion decay)}$$

$$\gamma \xrightarrow[Z_{atmo}]{} e^{+} + e^{-} \quad \text{(pair production)}$$

$$e^{\pm} \xrightarrow[Z_{atmo}]{} e^{\pm} + \gamma \quad \text{(bremsstrahlung)}$$

Coherent Radio Pulses in Earth's Atmosphere



- Coherent emission:
- $E_{total}=N_e*E_e$

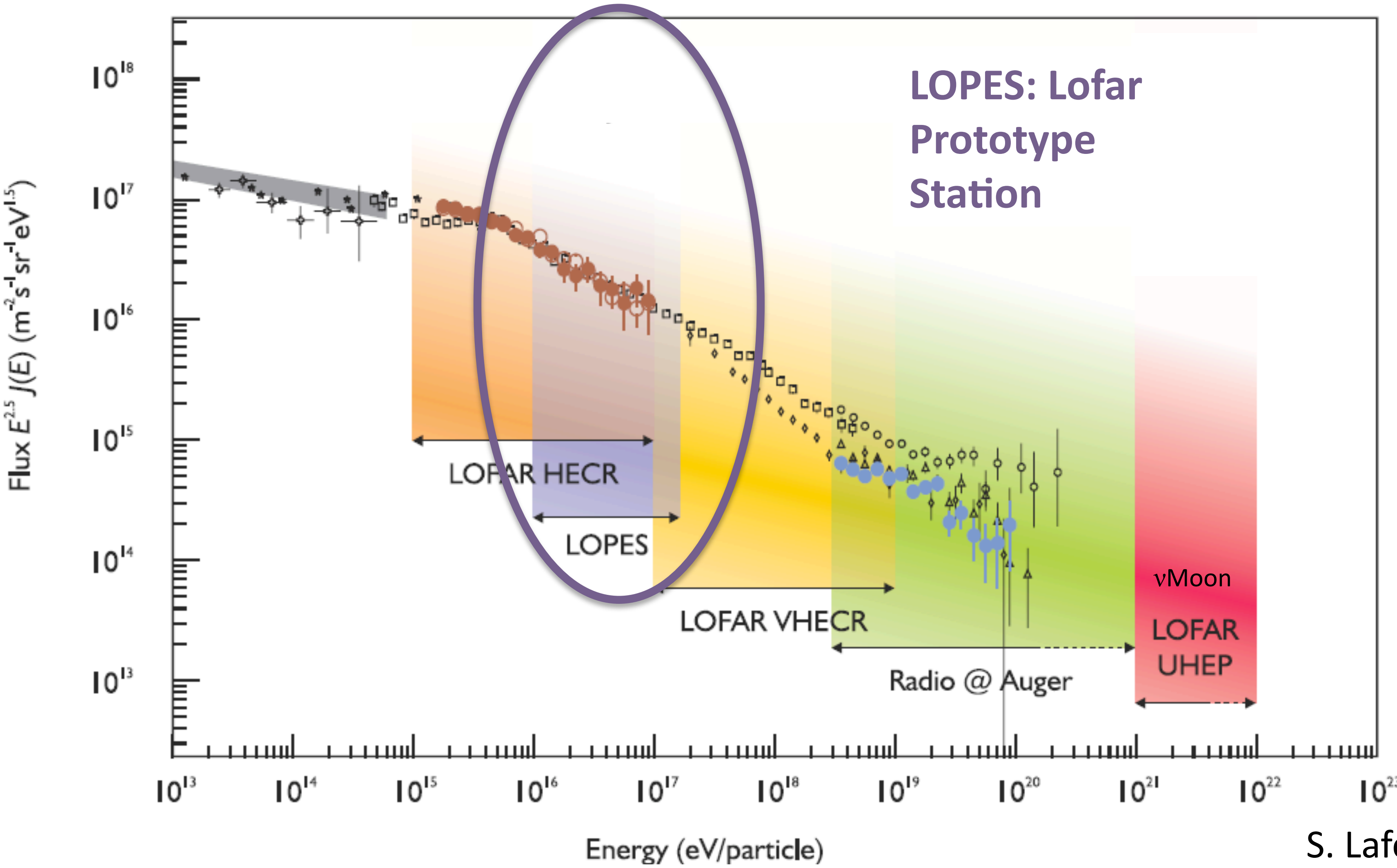
$\Rightarrow$ Power $\propto E_e^2 \propto N_e^2$

$\Rightarrow$ GJy flares on 20 ns scales

$\Rightarrow$ Need raw time-series data

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

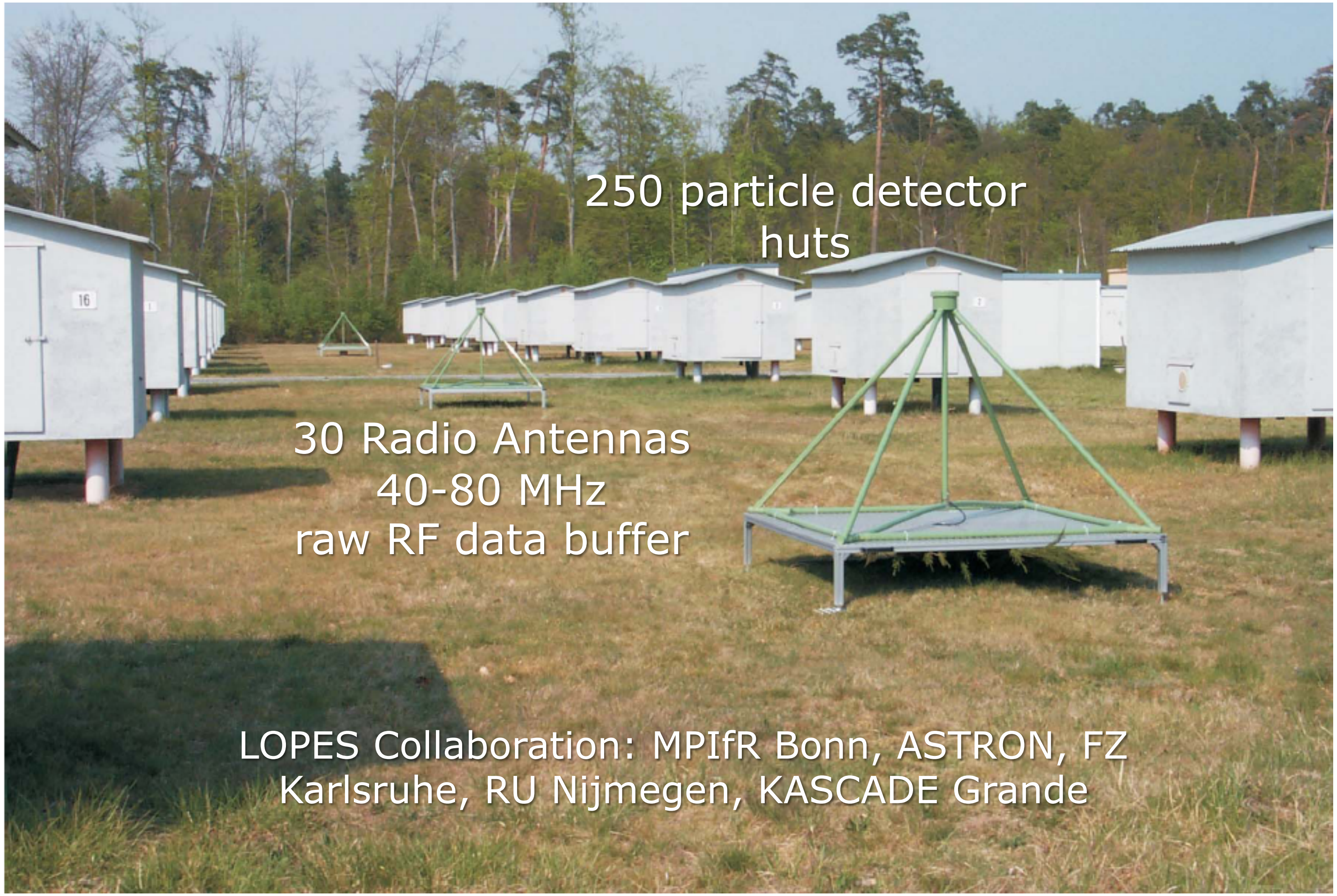
LOFAR CR KSP



S. Lafebre

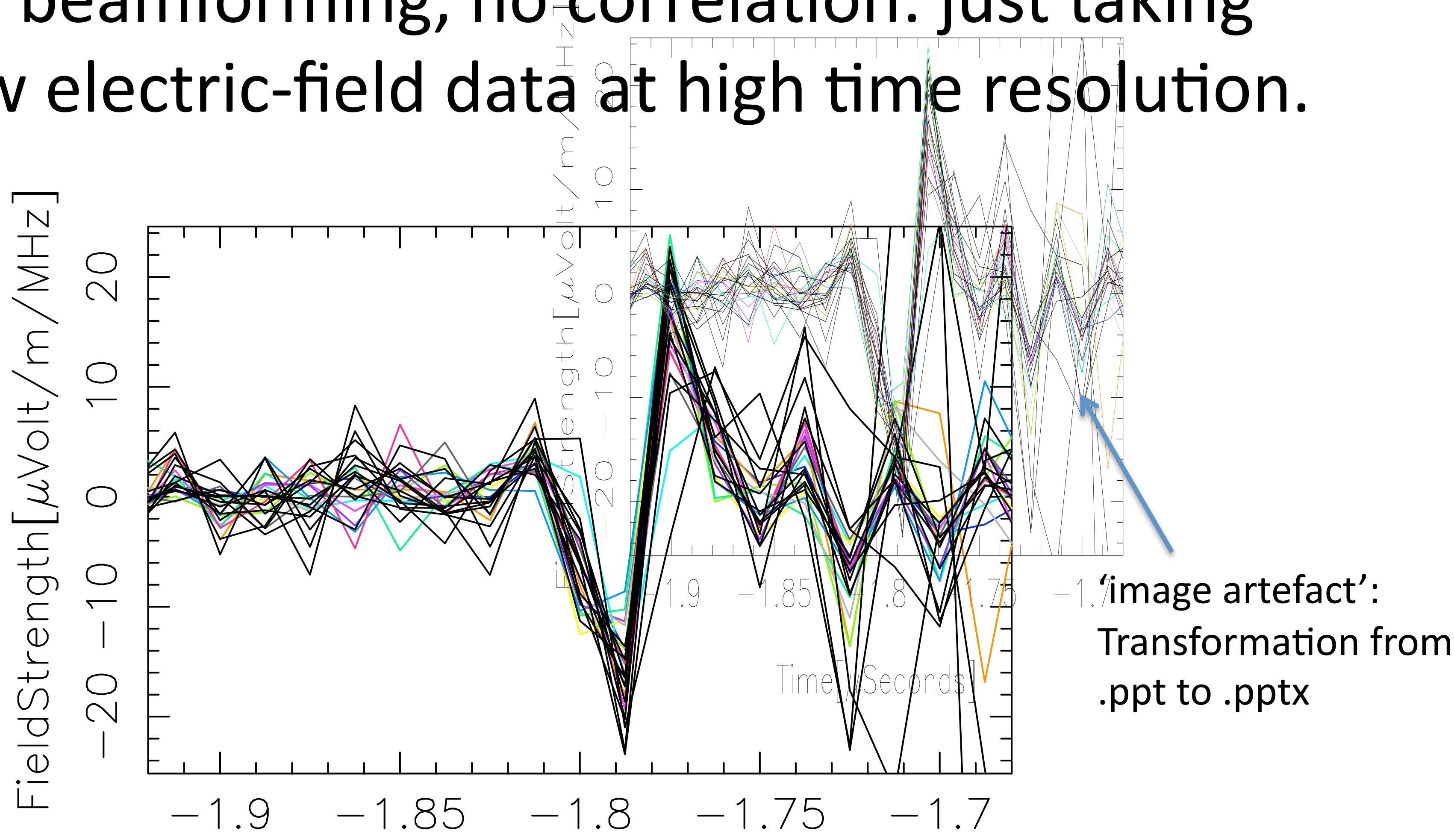
Low energies: higher sensitivity, less collection area.
High energies: need less sensitivity, more collection area.
Different projects cover much of the energy spectrum.

LOPES: LOFAR Prototype Station
(next to KASCADE particle detector, Karlsruhe)



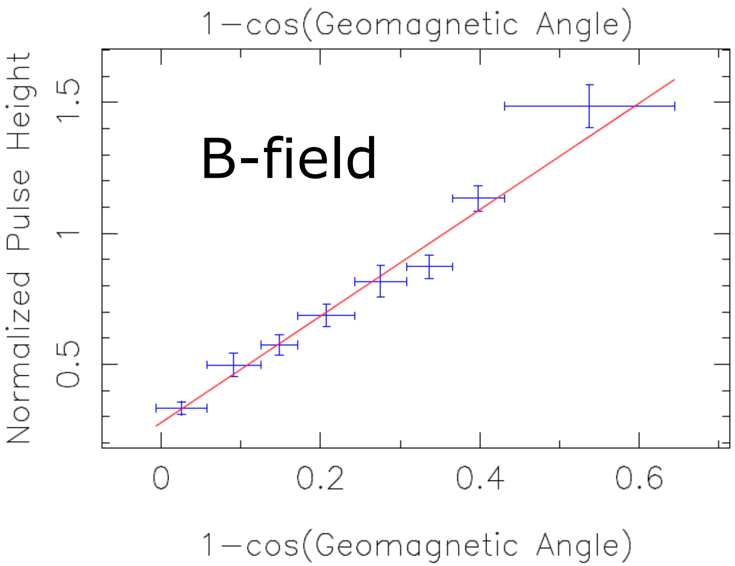
LOPES CR pulses

- No beamforming, no correlation: just taking raw electric-field data at high time resolution.

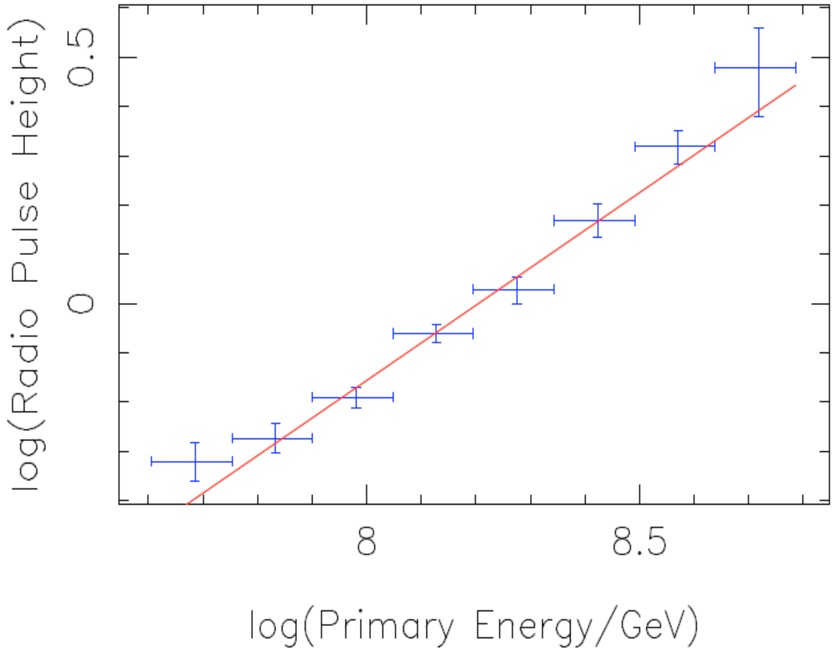


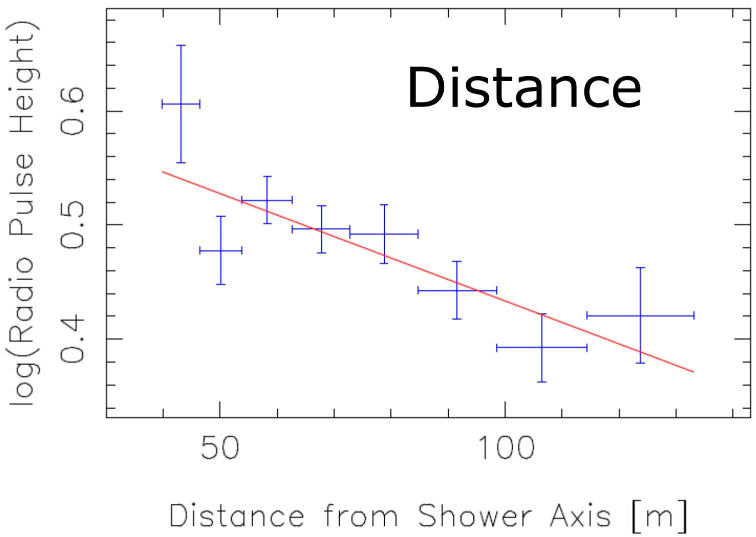
Time (hundreds of nanoseconds (80 MHz sampling)

Cross Calibration of LOPES10 and KASCADE



UHECR Particle Energy

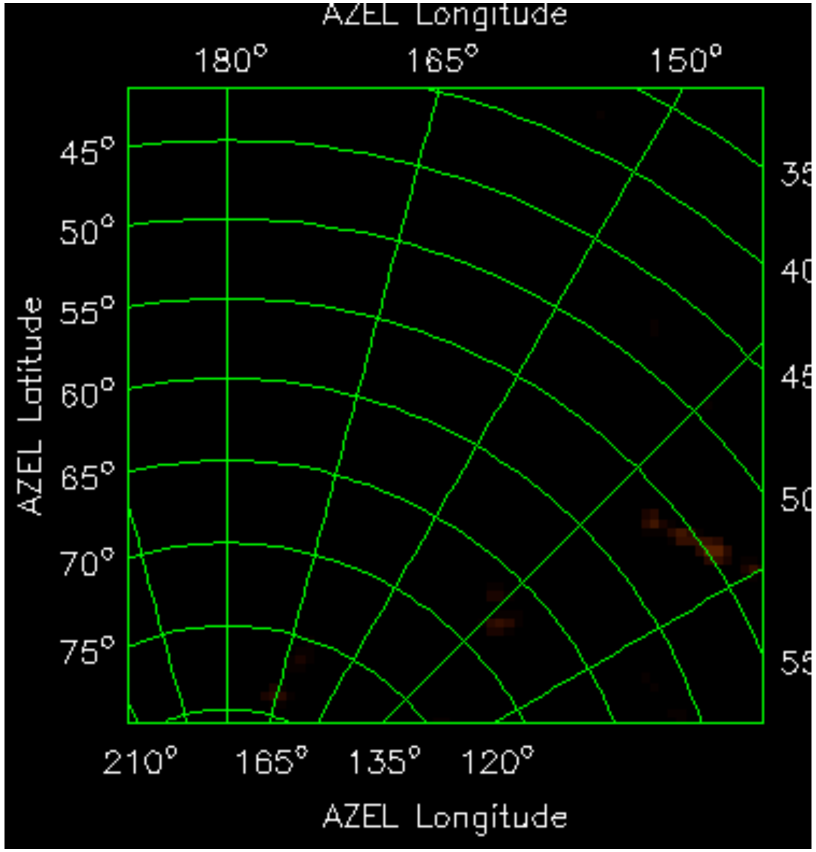


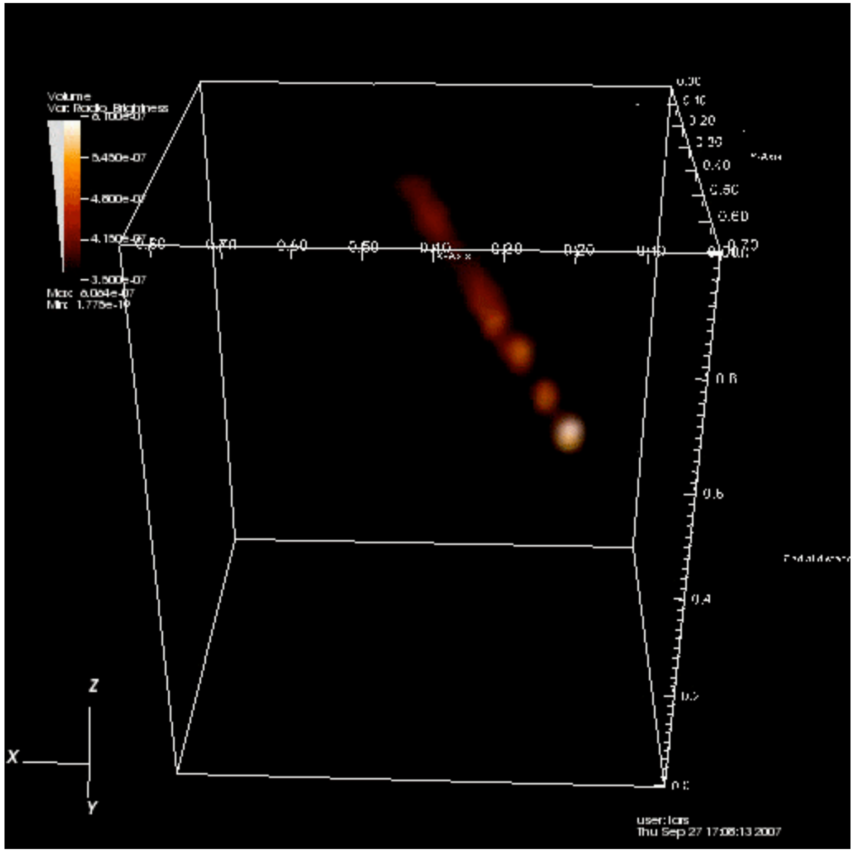


$$\varepsilon_{est,E_p} = (12 \pm 1.8)\left[\frac{\mu V}{m\ MHz}\right]\left(1 + (0.1 \pm 0.03) - \cos(\alpha)\right)\cos(\theta)$$
$$\times \exp\left(\frac{-R_{SA}}{(200 \pm 45)m}\right)\left(\frac{E_p}{10^{17}\, eV}\right)^{(0.91 \pm 0.07)}$$

Horneffer-Formula 2008

First cosmic ray images in 2 and 3D





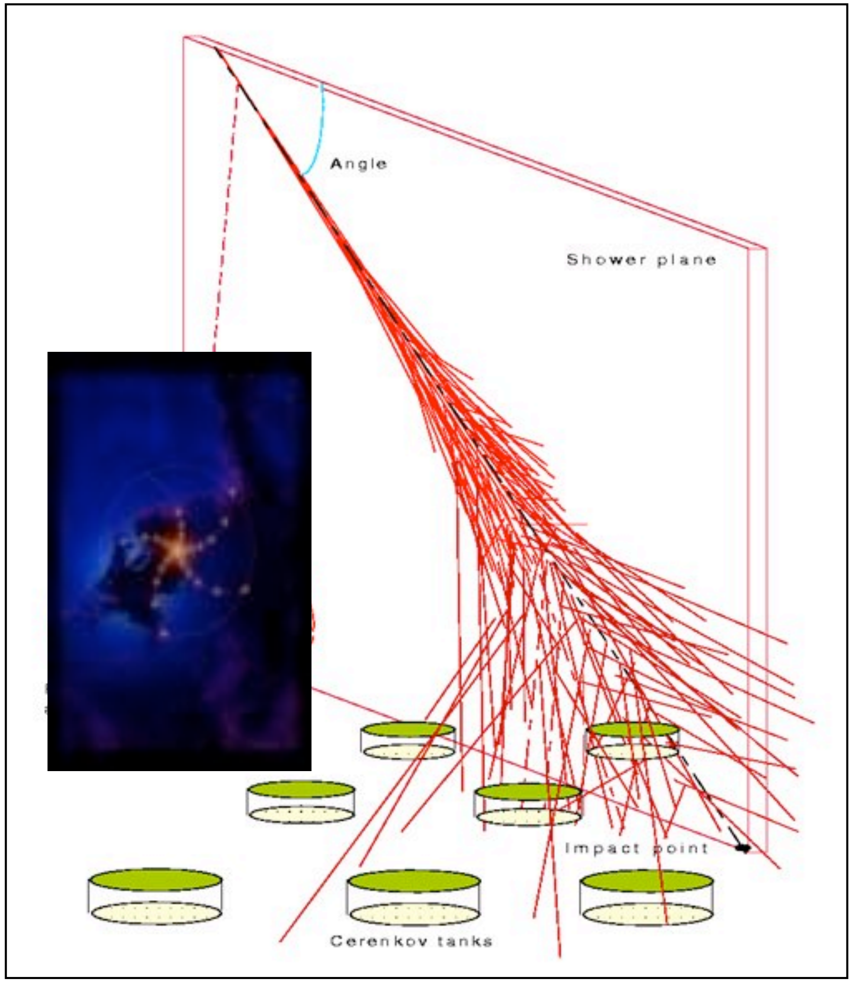
12.5 ns time resolution (!)

Rather limited by the size of LOPES – but never done before!

Radio detection works!

Why do we care?

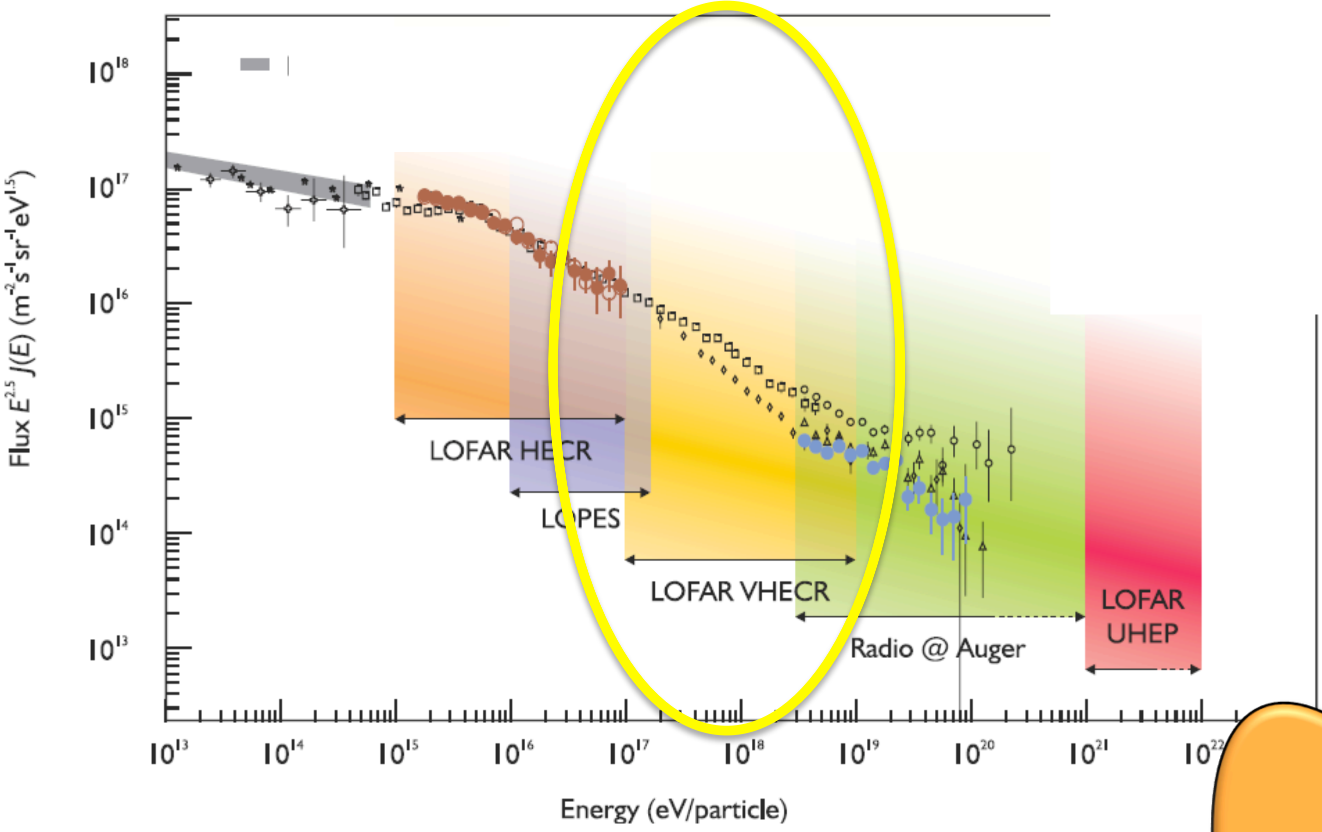
- Air fluorescence sees whole of shower energy
- Critical for determining energy spectrum
- Can only operate on dark, moonless, cloudless nights (10% duty cycle)



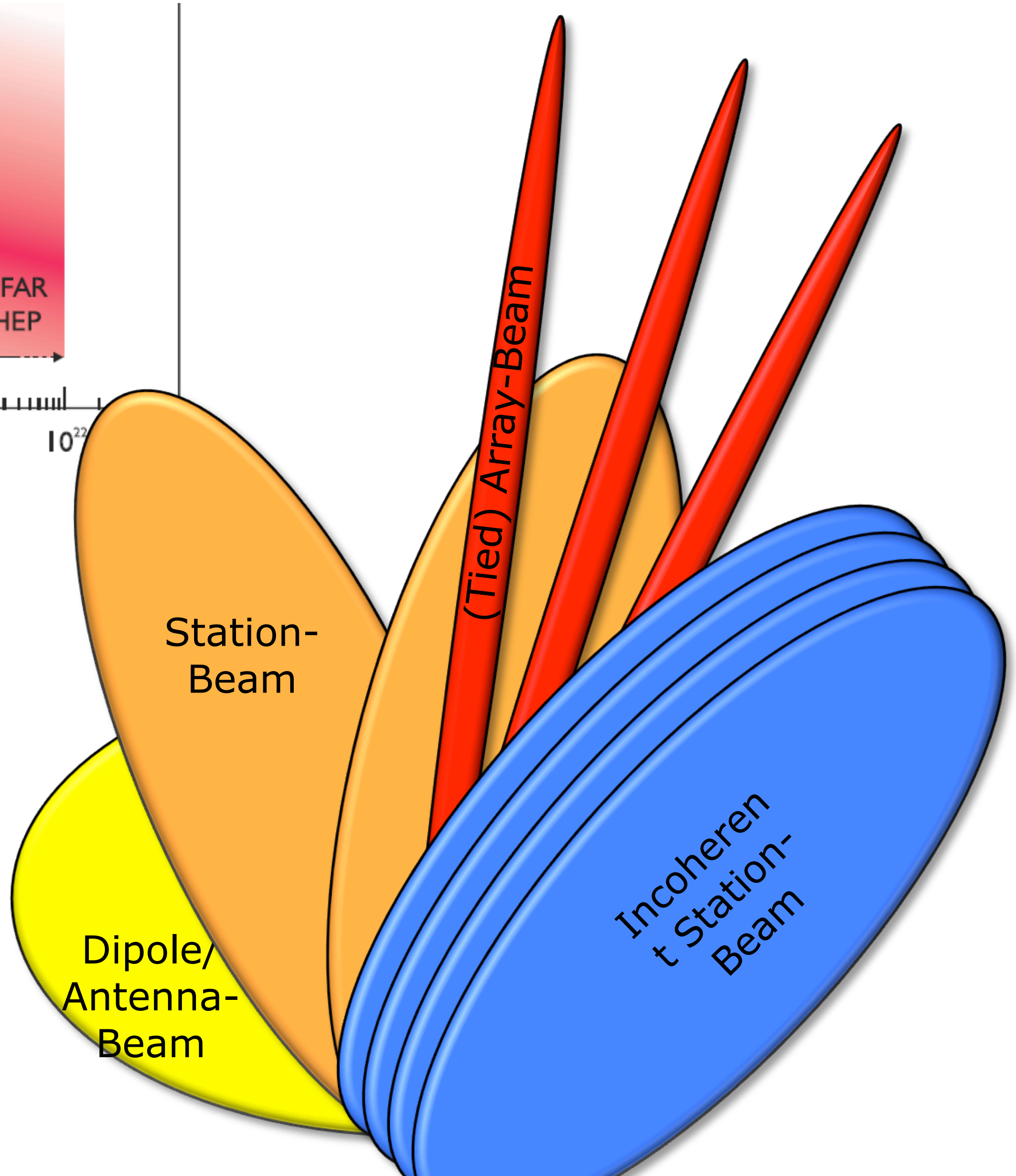
Radio detection can operate ~100% of the time and see the whole cascade!

LOFAR VHECR

Very-high-energy cosmic rays

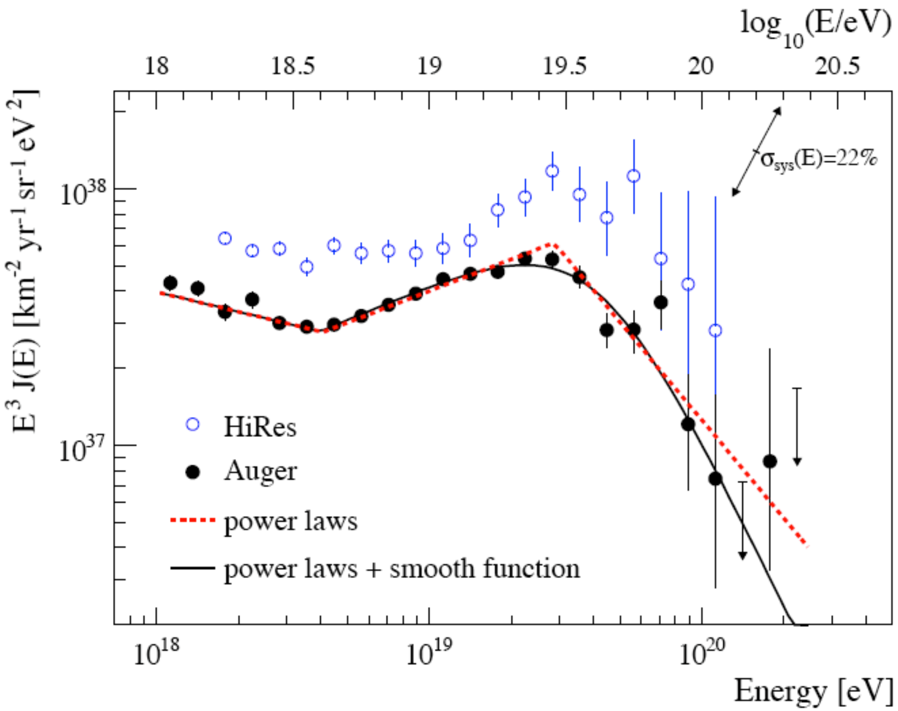


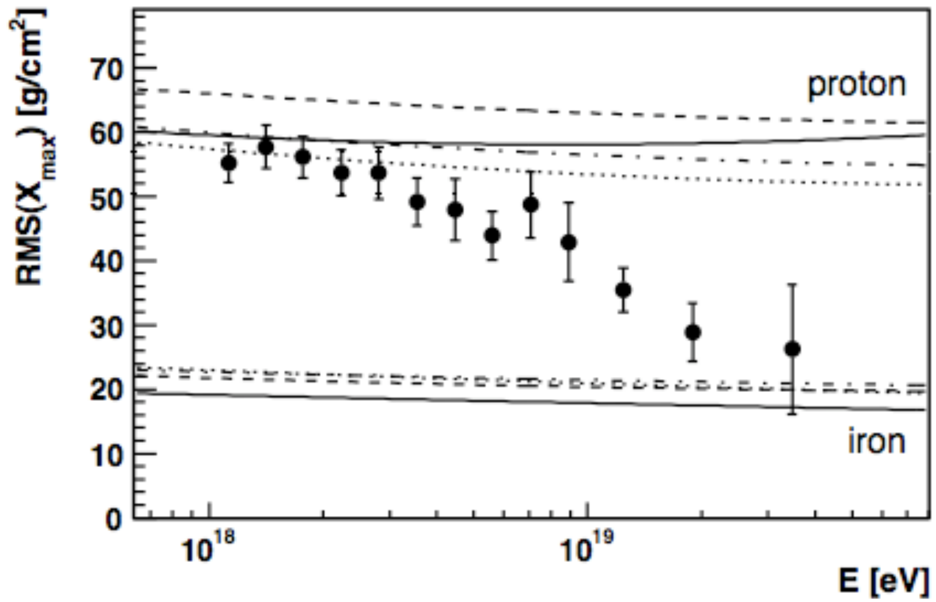
S. Lafebre



- Cosmic rays at these energies produce ‘very’ strong pulses
- These can be seen by individual dipoles!

VHECR Motivation: Improve these



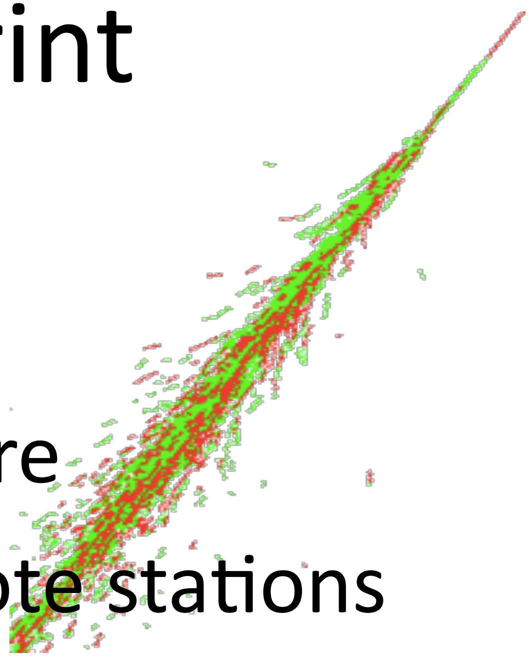


Get the maximum information per event

Fluoresence revolutionised VHECR detection – expect radio will too.

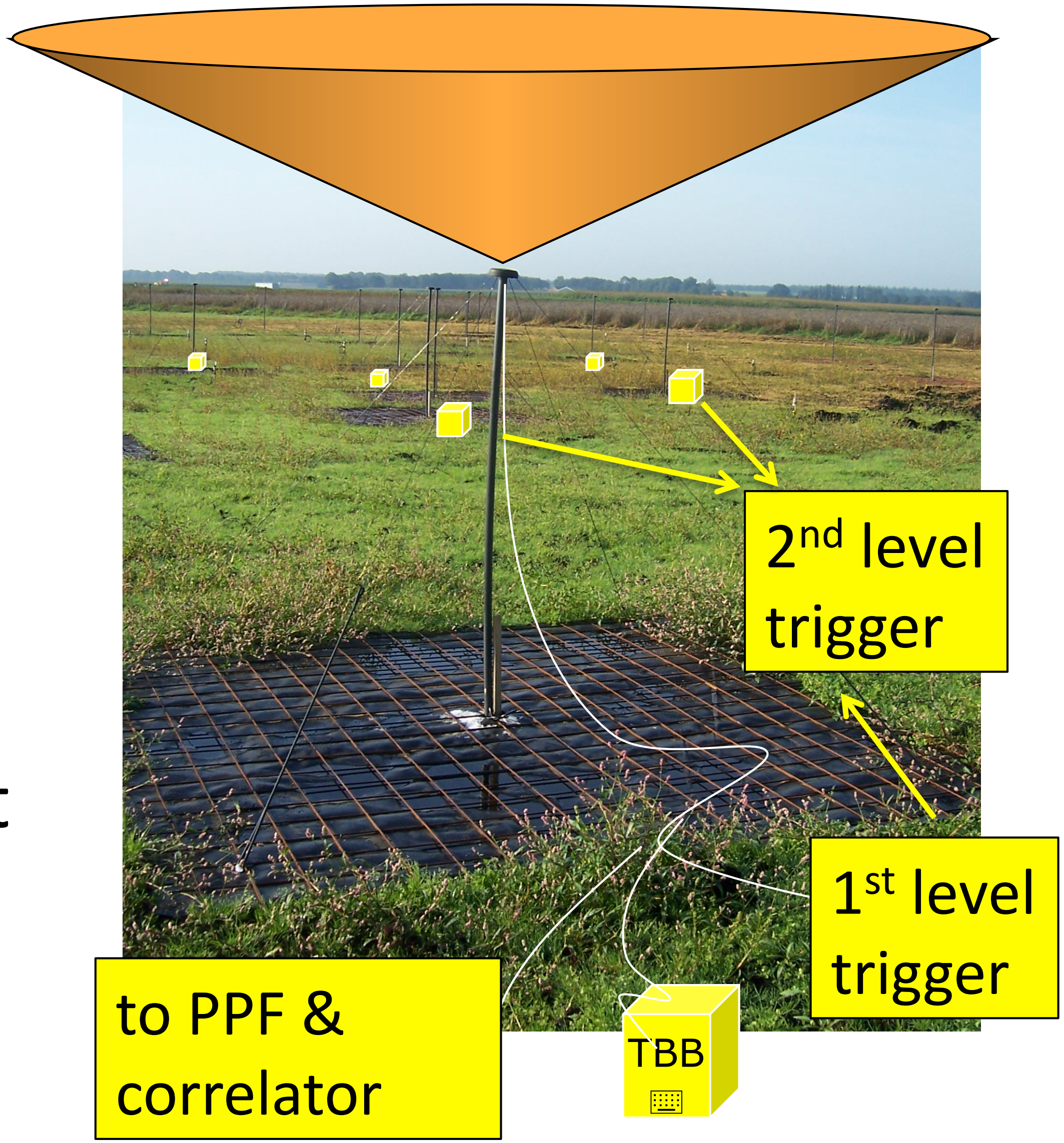
Cosmic-ray footprint

- Depends on energy.
- Few 100m to few km.
- Multi-station detection in the core
- Single-station detection for remote stations



VHECR detection at LOFAR

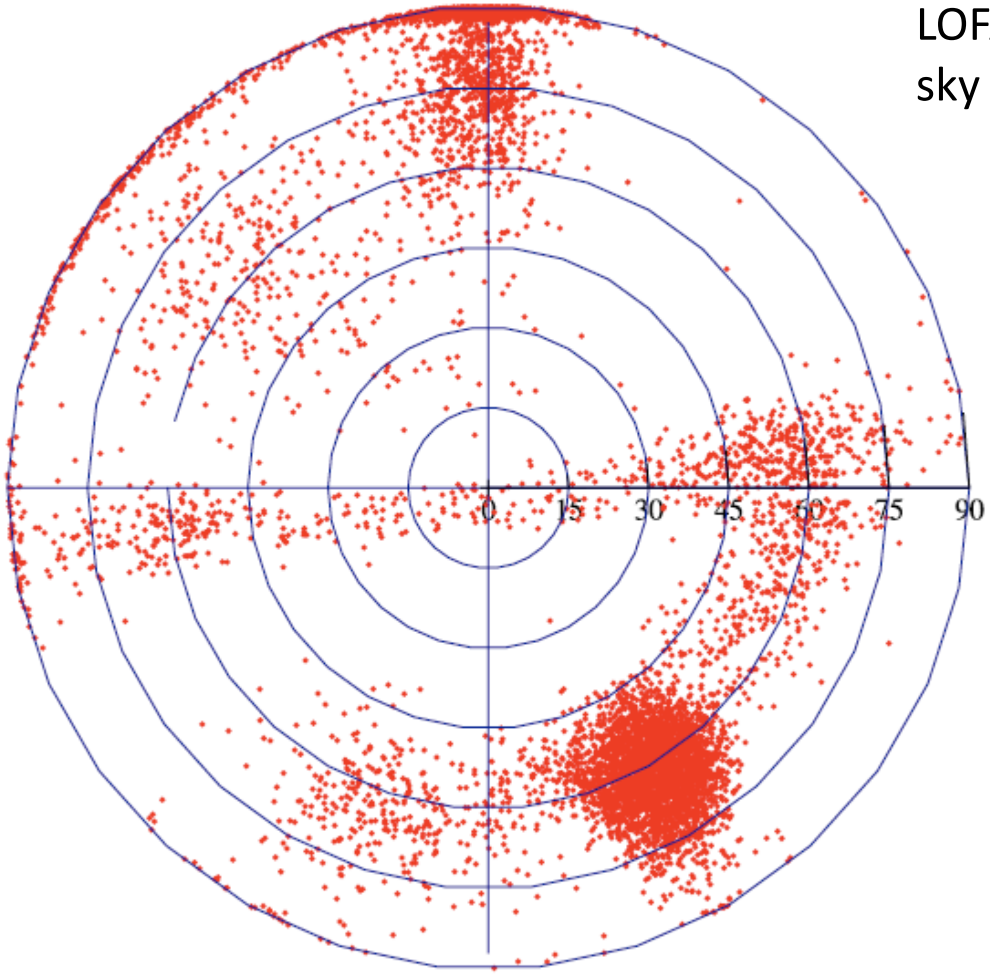
- Use LBA only
  - sees more of the atmosphere
  - pulses are stronger
- Run trigger algorithm on raw time series data
- Return TBB RAM buffers on likely event
- Does NOT interfere with LBA imaging!



Raw Event Data

- 1st level trigger – most triggers off short-duration, wide-band RFI.
- 2nd-level (station) trigger: returns few microseconds of data from each LBA antenna at a given station.
- Normal operating mode: return 1 station trigger every ~10 minutes (~25 Mb).
- Use 1st-level trigger data to look see what ~~crap~~ interesting RFI is out there!

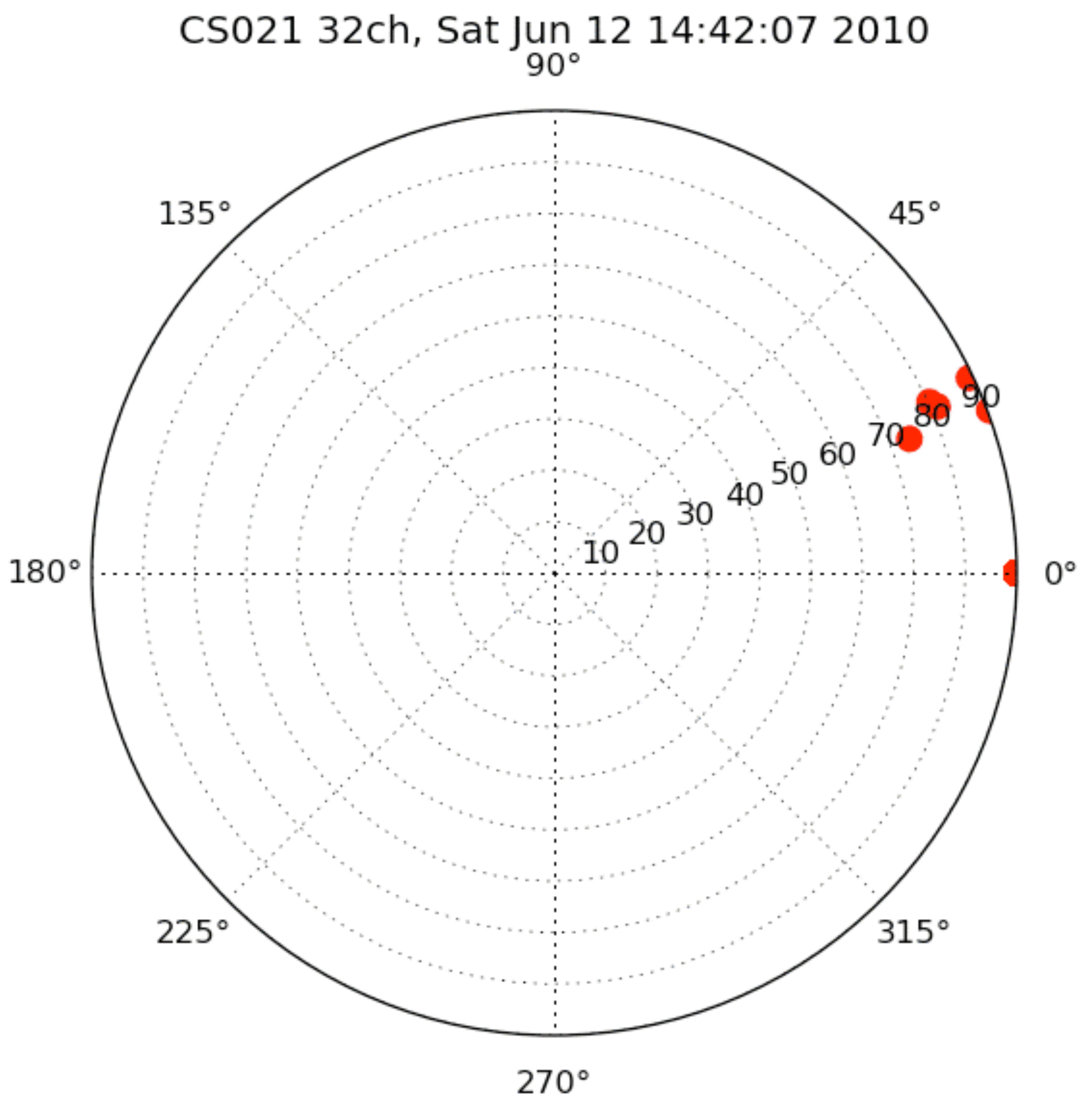
Station Pulse Triggers in a Day (Sky Distribution = far-field fit)



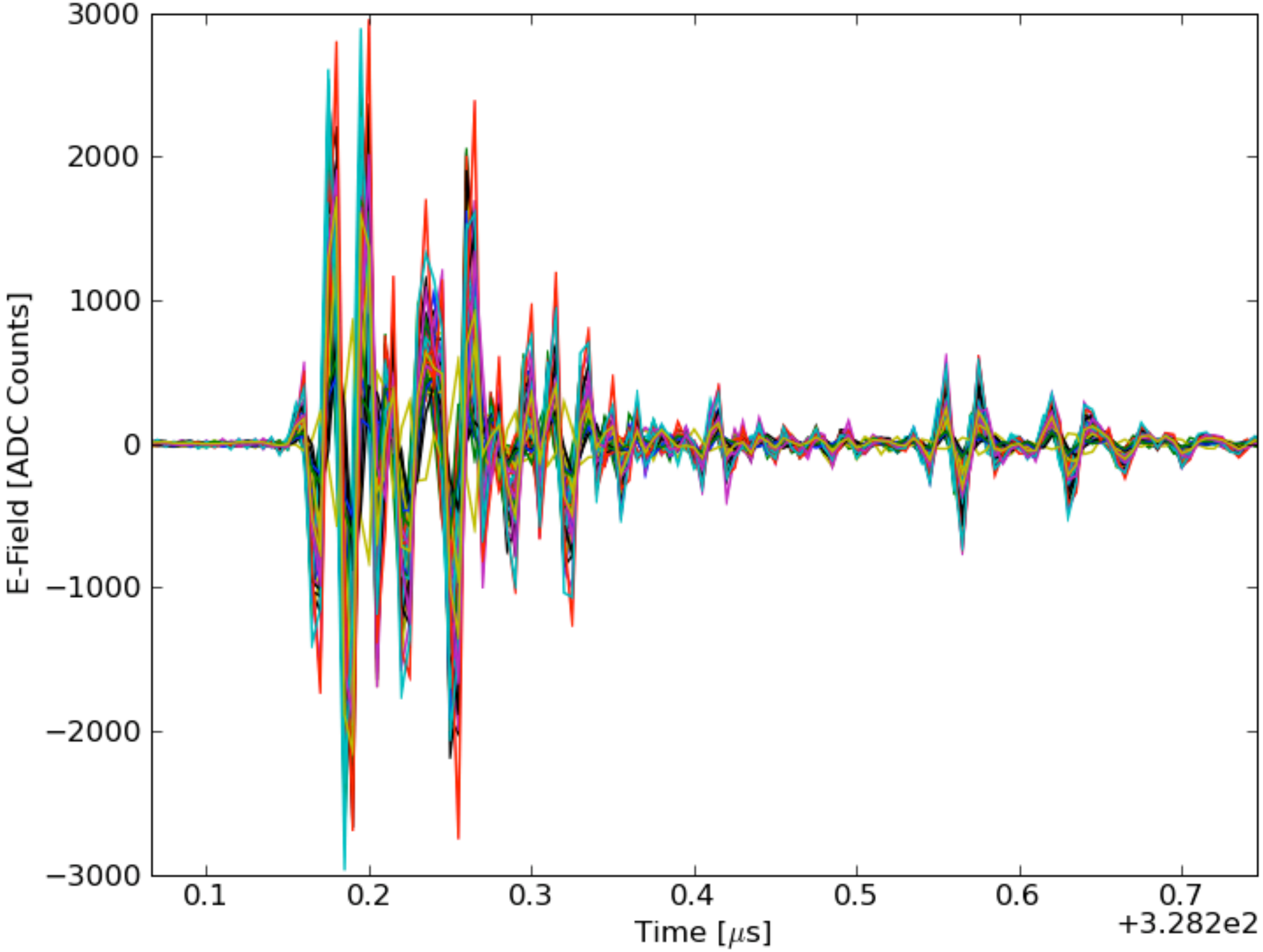
LOFAR low-band has all-sky visibility!

A. Corstanje (Radboud)

Queens Helicopter



Radio Triggered Event after station beam-forming

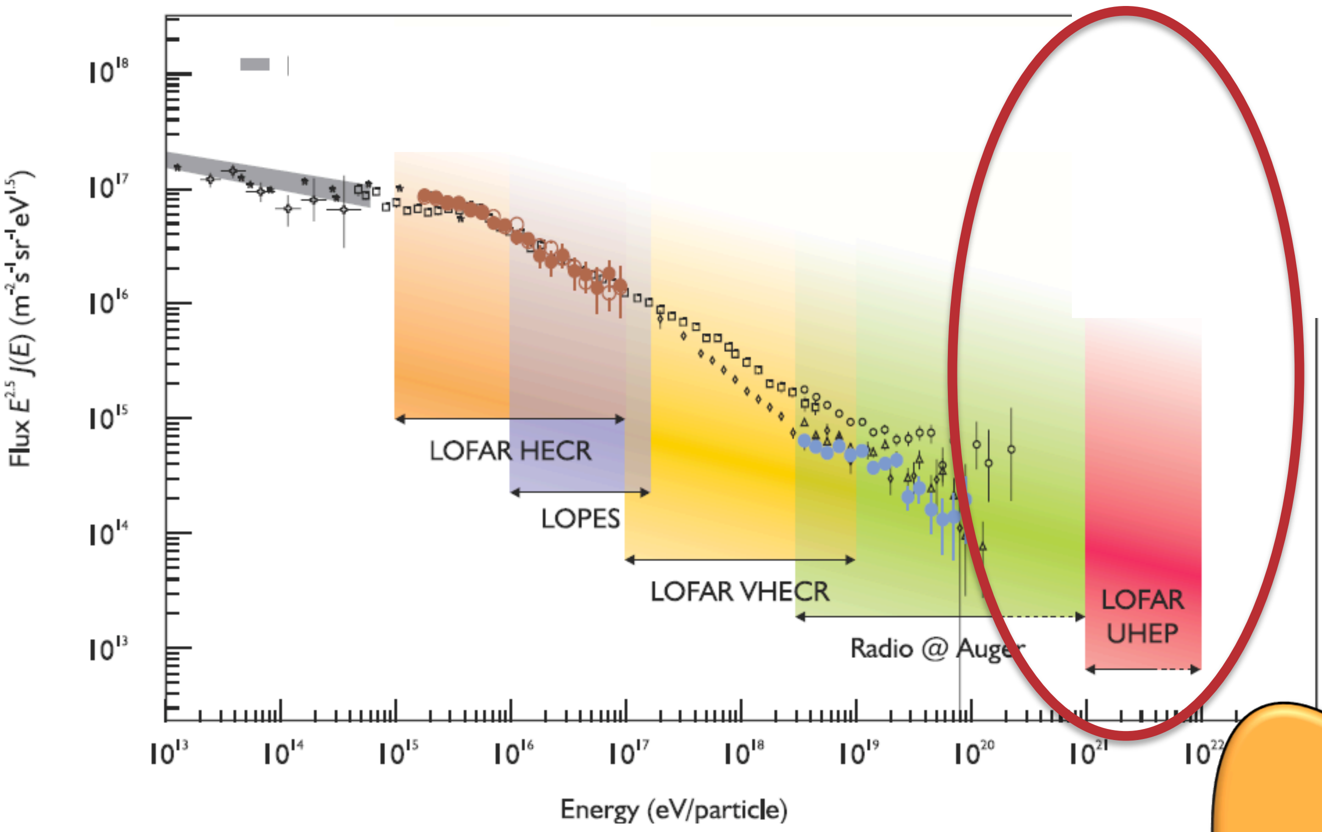


Cosmic ray data from LOFAR

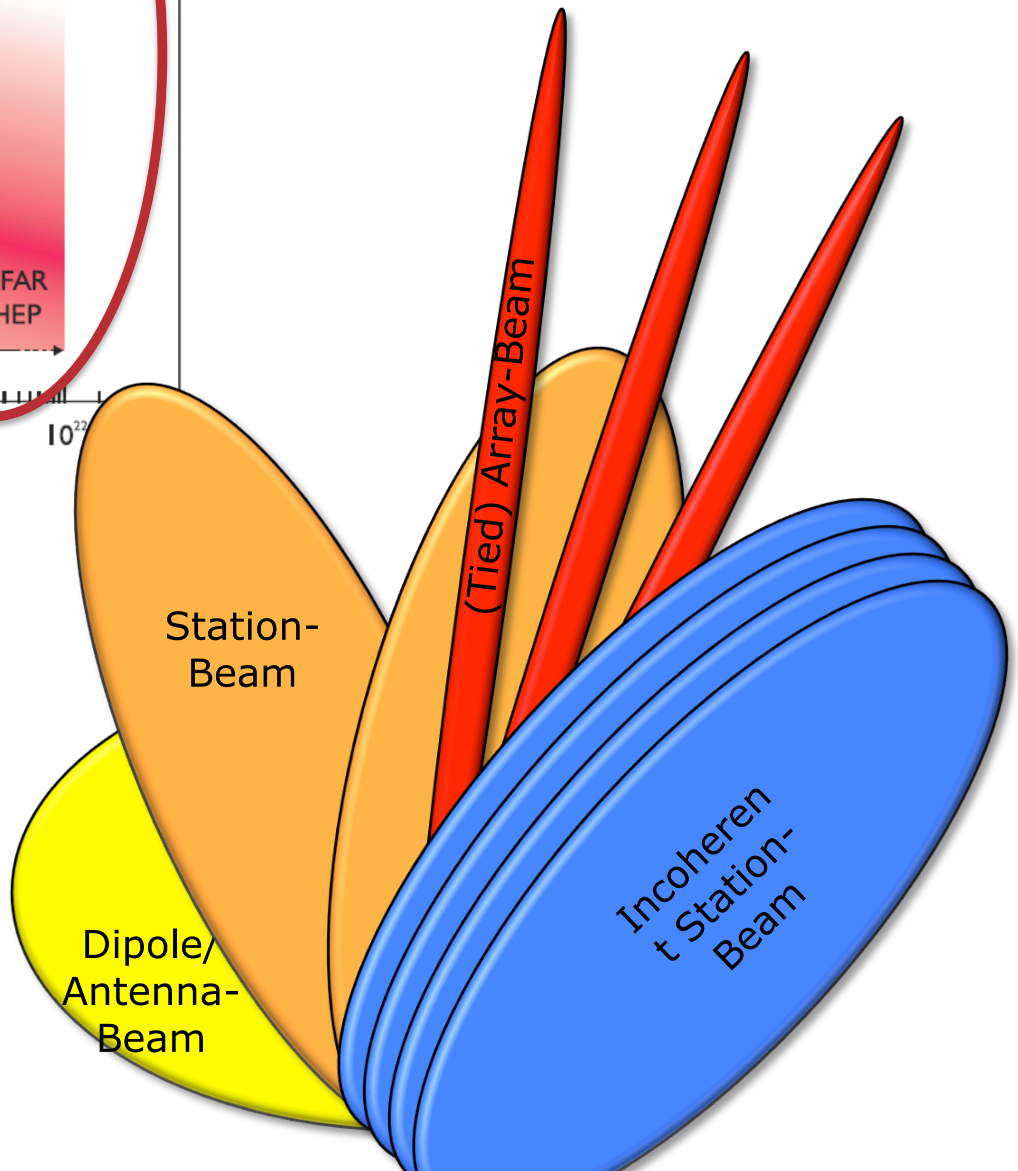
- Not yet! Requires further tuning of 1st- and 2nd-level trigger parameters
- Expectation:
  - Single-station triggers on remote stations.
  - Multi-station triggers over the core.
- Core triggers will allow resolved 3D images of a cosmic-ray air-shower.
- Requires the imaging pipeline – in 3D!
  - no ionospheric effects
  - Jones matrices constant over signal duration

LOFAR UHEP

Ultra-high energy **particle** mode

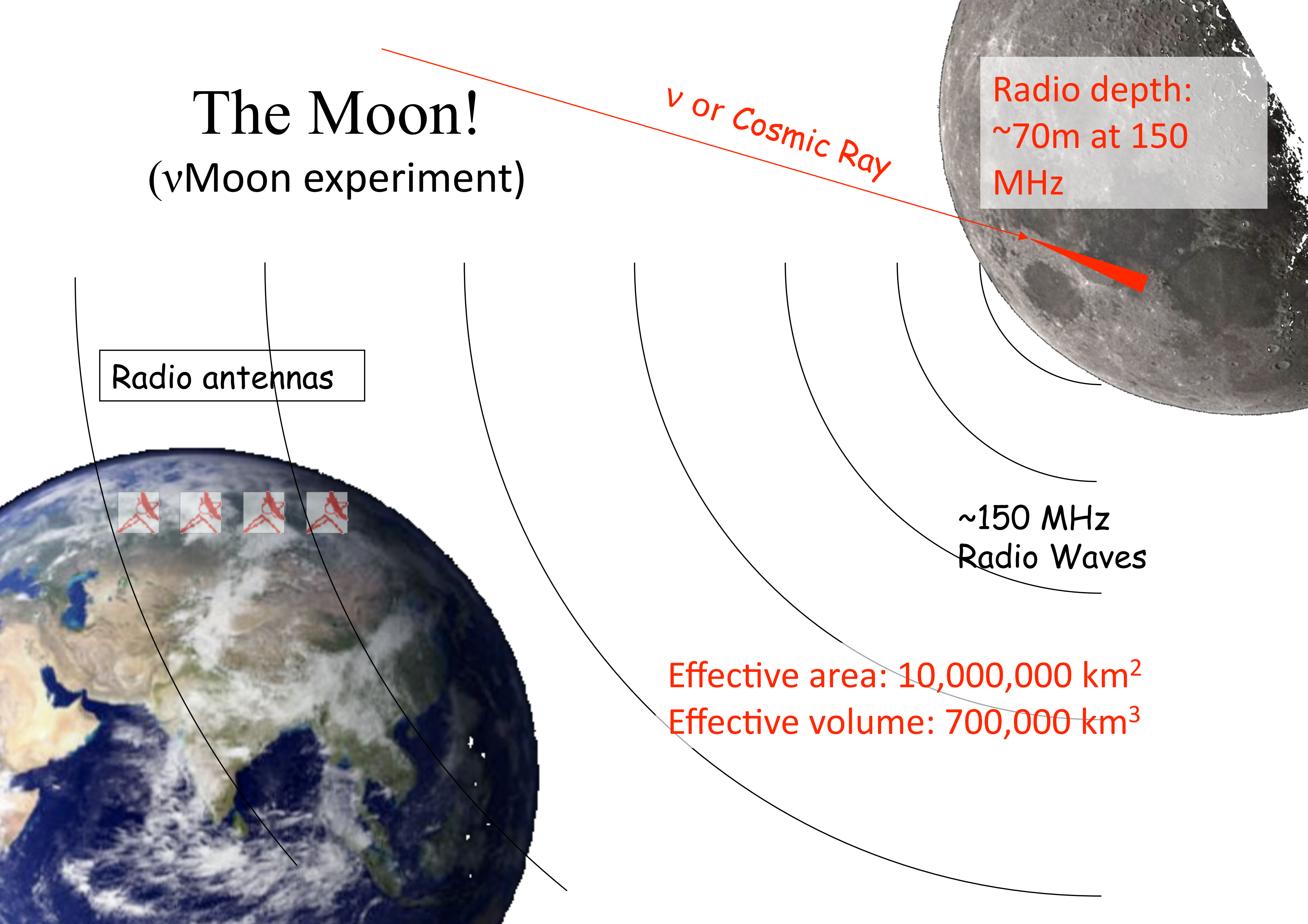


S. Lafebre

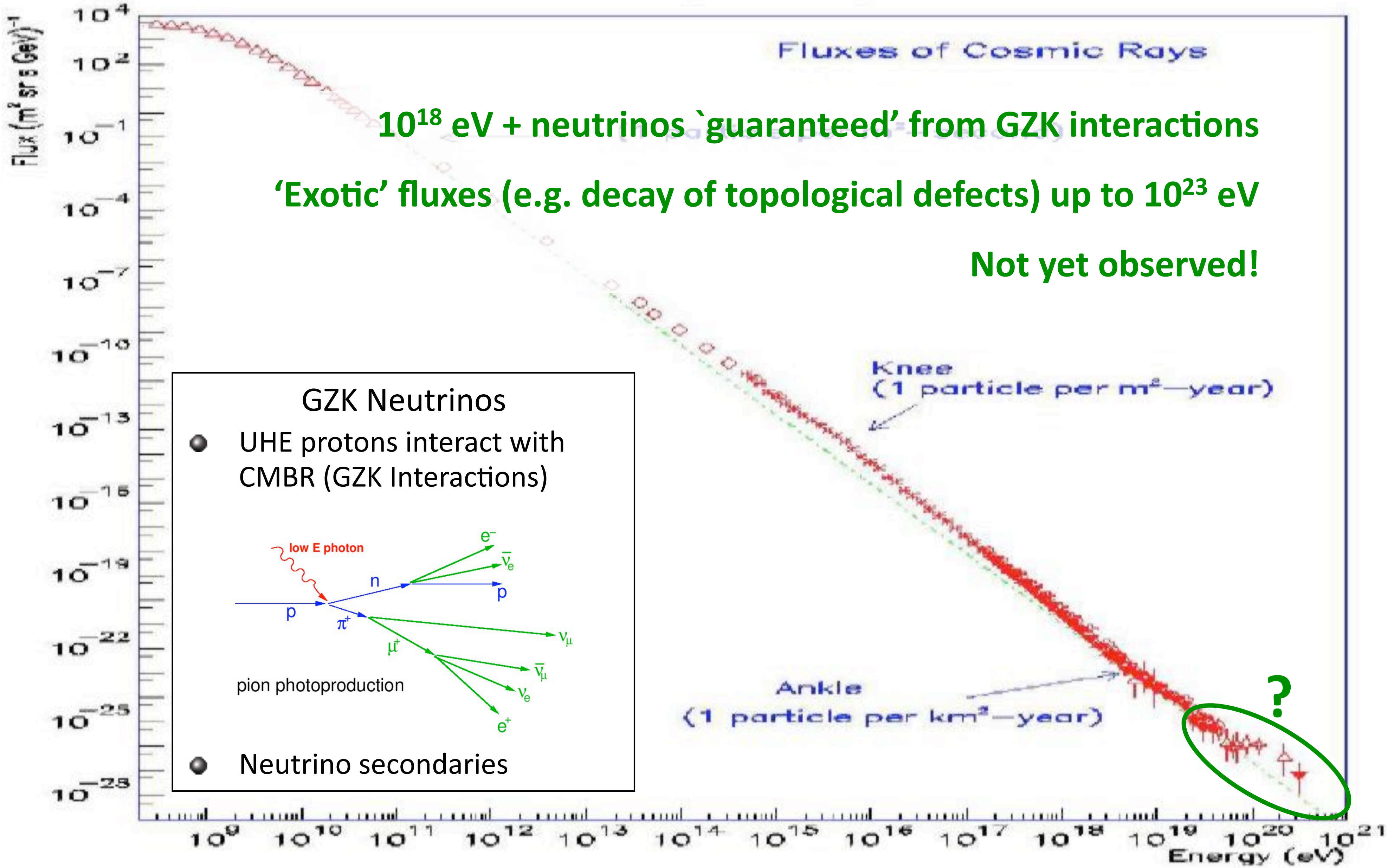


- -Extremely strong pulses!
- -Rare to nonexistent: atmosphere not a large-enough detection volume
- -What else can we use?

The Moon!
(νMoon experiment)



Neutrinos from the GZK effect



10^{18} eV + neutrinos `guaranteed' from GZK interactions

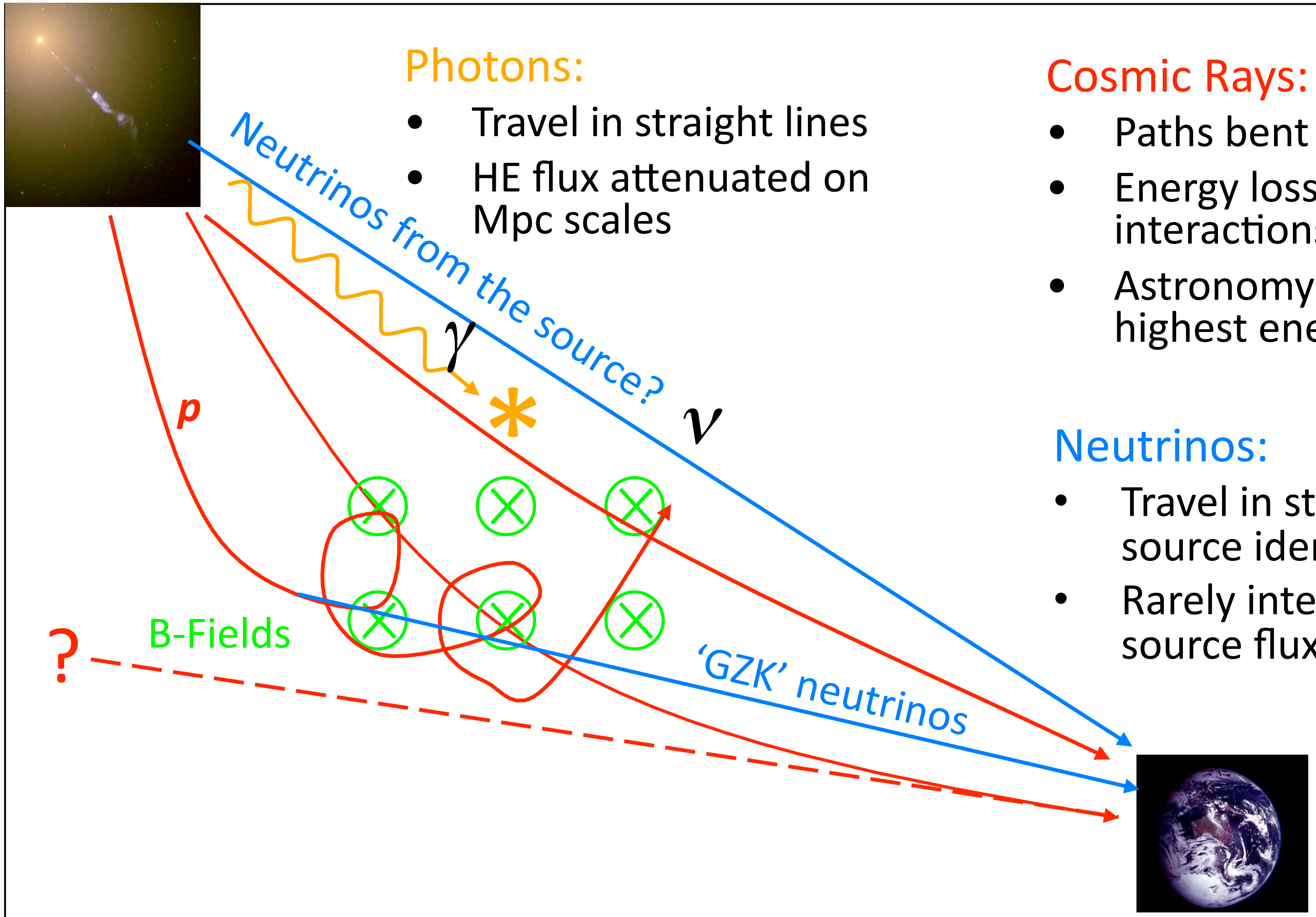
'Exotic' fluxes (e.g. decay of topological defects) up to 10^{23} eV

Not yet observed!

GZK Neutrinos

- UHE protons interact with CMBR (GZK Interactions)
- Neutrino secondaries

The 'Ideal Messengers'



Photons:

- Travel in straight lines
- HE flux attenuated on Mpc scales

Cosmic Rays:

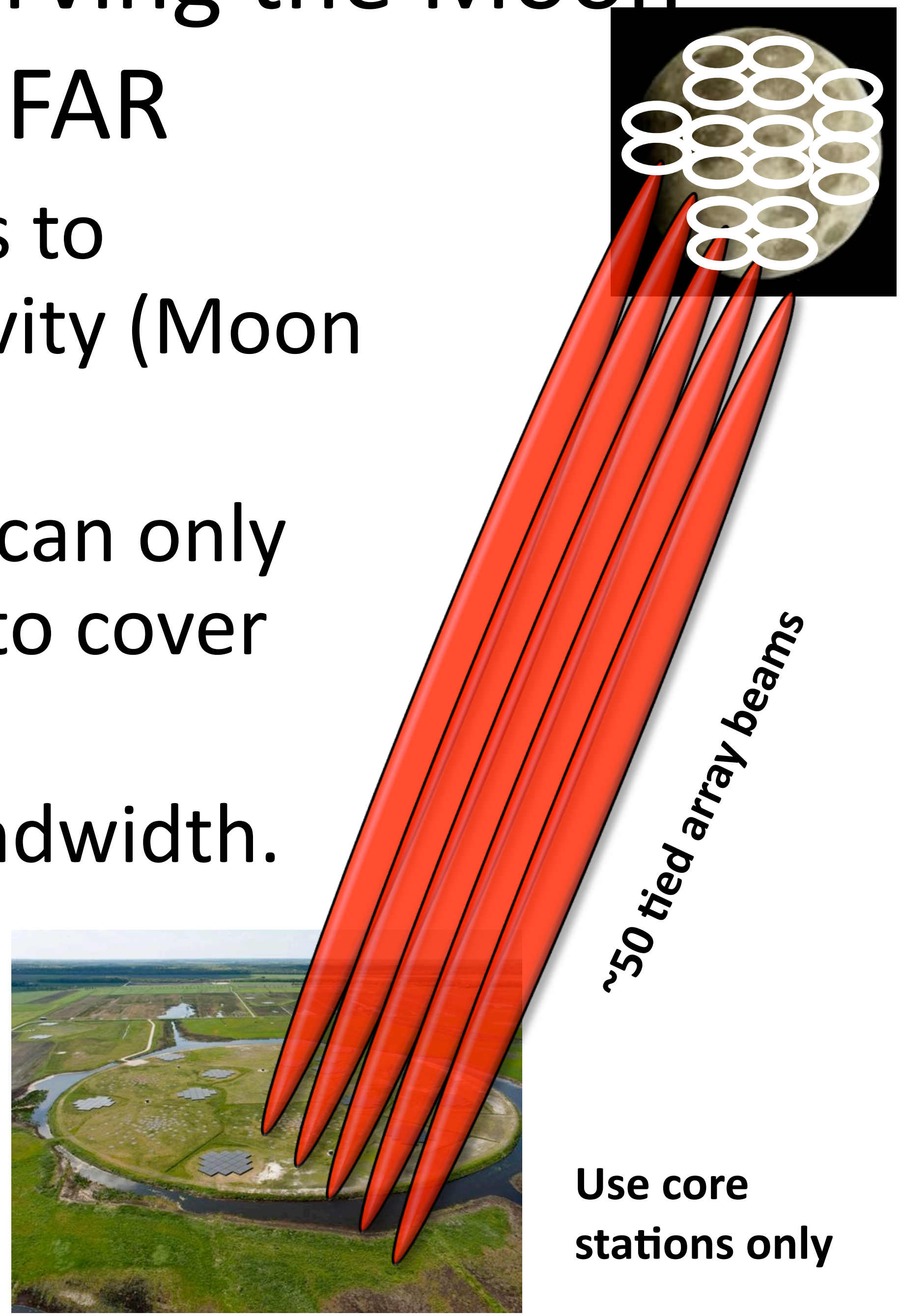
- Paths bent by B-fields
- Energy loss via GZK interactions
- Astronomy possible only at highest energies

Neutrinos:

- Travel in strait lines: allows source identification.
- Rarely interact: observed flux = source flux.

UHEP Mode – observing the Moon with LOFAR

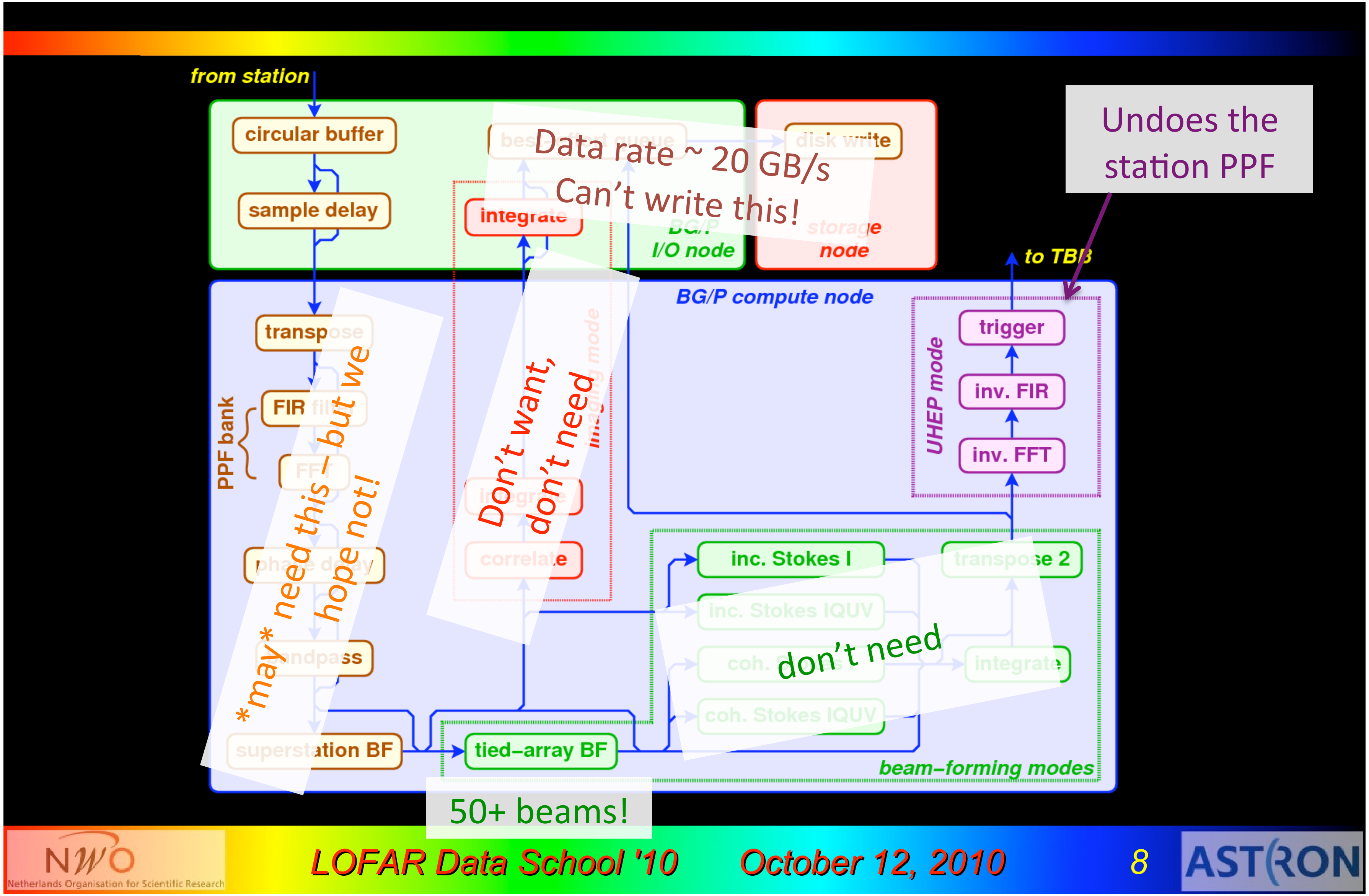
- Require tied-array beams to achieve sufficient sensitivity (Moon far away).
- Limit of ~50 tied beams: can only use the 18 core stations to cover the visible lunar surface.
- Can only use 48 MHz bandwidth.
- Raw data rate too high (O~20 GB/s)



TBBs and triggering

- The transient buffer boards (TBBs) contain the full bandwidth on all antennas.
- If we can capture the pulse on these, we will have x4 sensitivity (x2 bandwidth, x2 area)
- But how do we know when the pulses are in the TBBs? (length = 1.3 seconds)
- Real-time pulse search requirements:
  – tied beamforming 50+ beams
  – reconstructing the time-domain signal (5ns time res)
  – discriminating against RFI
  – searching for signals and triggering: in 1.3 seconds!
  – returning ~10-100 microseconds of data for each event from every antenna (inc international stations).

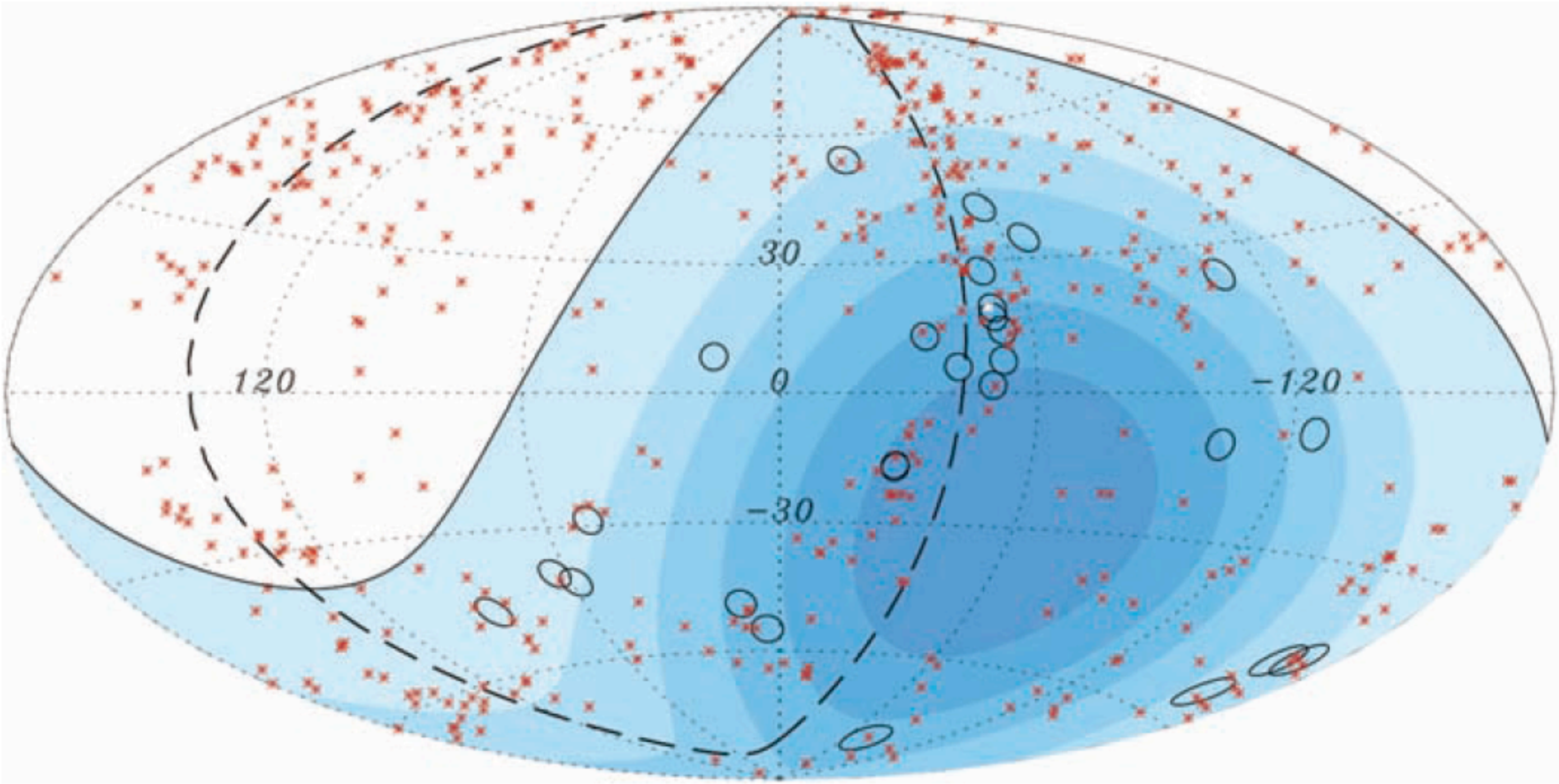
UHEP mode CEP Processing



Courtesy John Romein

UHEP motivation: improve this

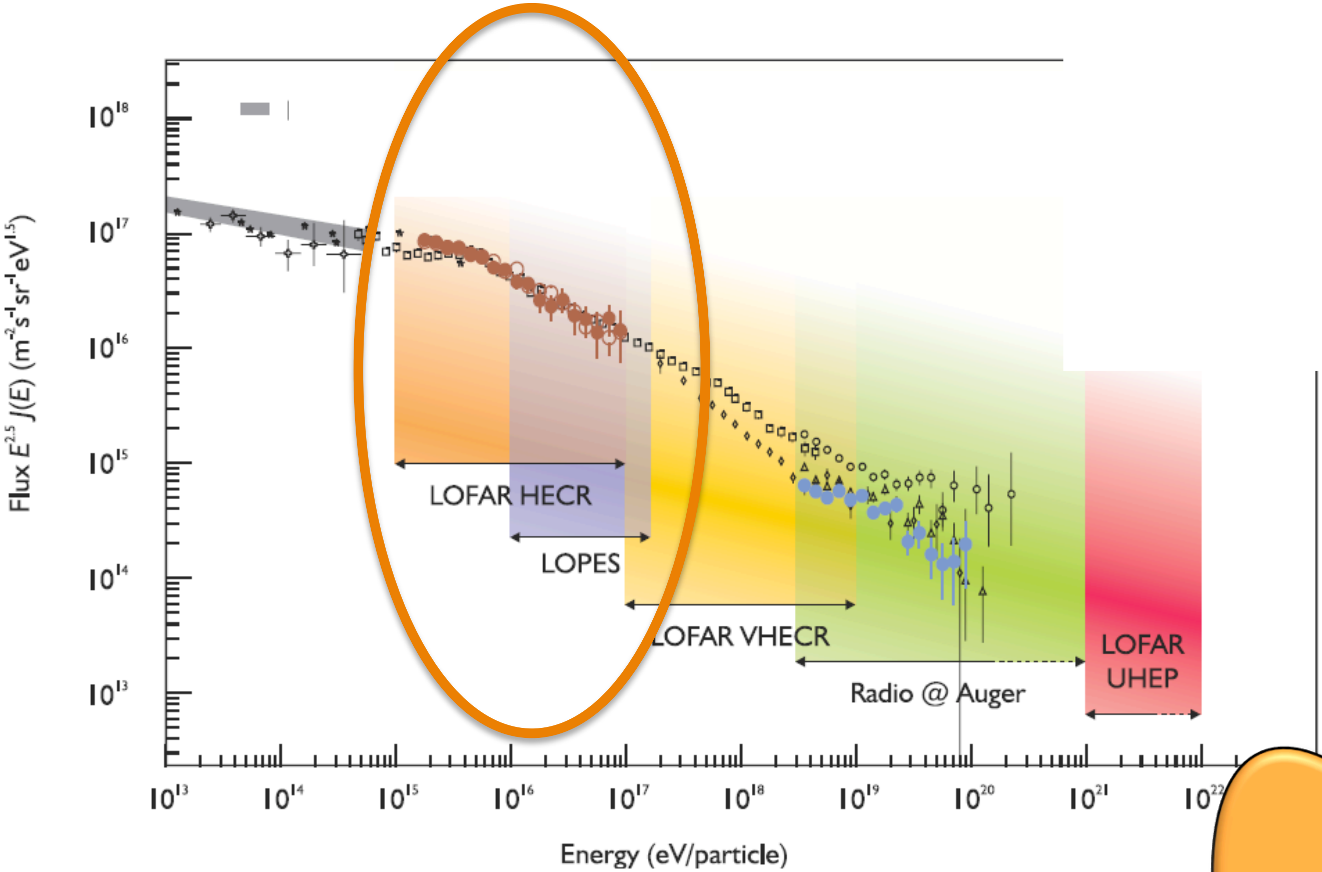
- *Single UHEP event would point back to the source of UHECR*
- *Provide information on CR production on cosmic timescales*



Blue shading – Auger exposure red – AGN 3^0 circles – UHE CR events

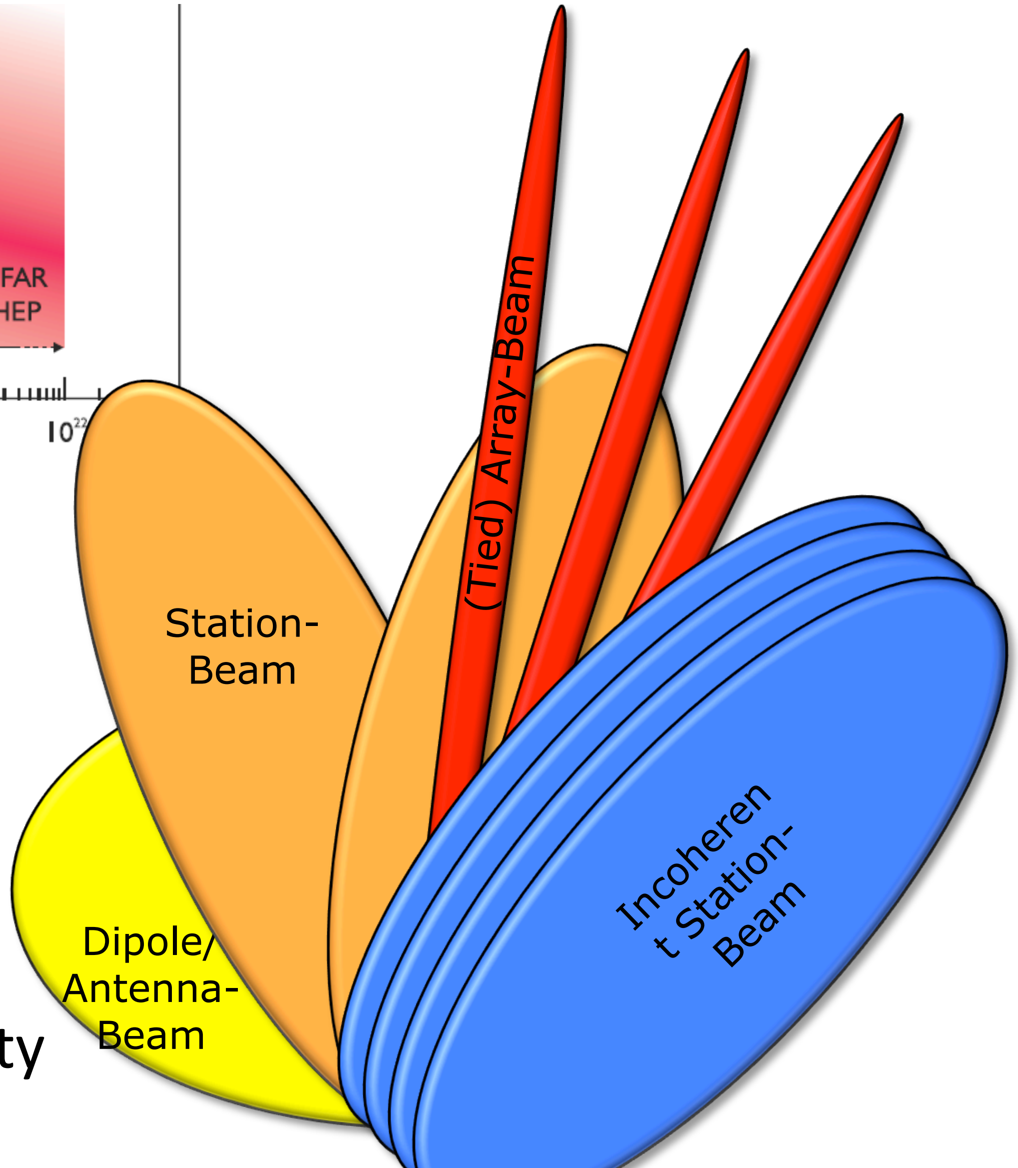
Auger collaboration, Science 318, 938 (2007)

LOFAR HECR



S. Lafebre

High-energy cosmic rays



-Weaker pulses can not be seen by individual antennas

- Requires station beamforming

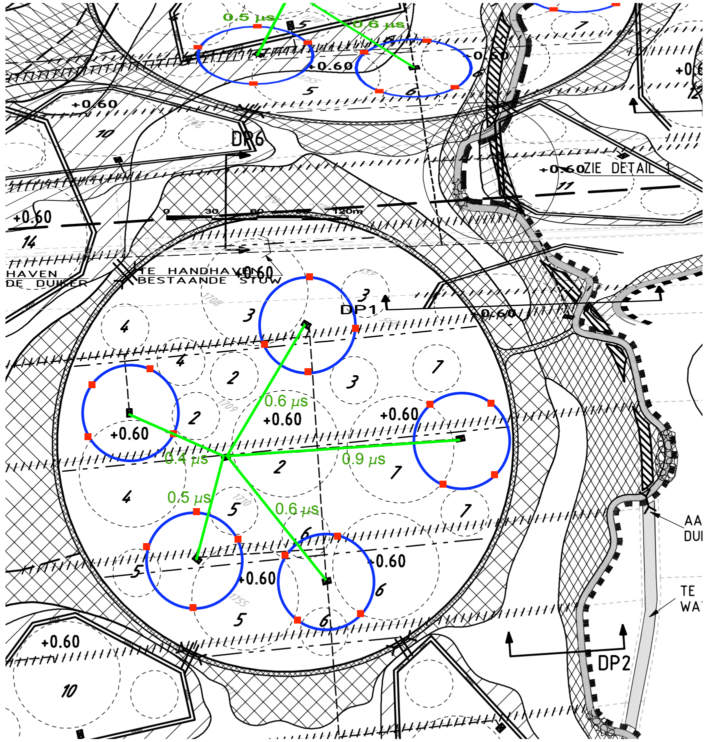
-Can *still* piggyback (we don't care about direction)

-Science case less strong: lower priority

LORA

LOFAR Radboud Air Shower Array

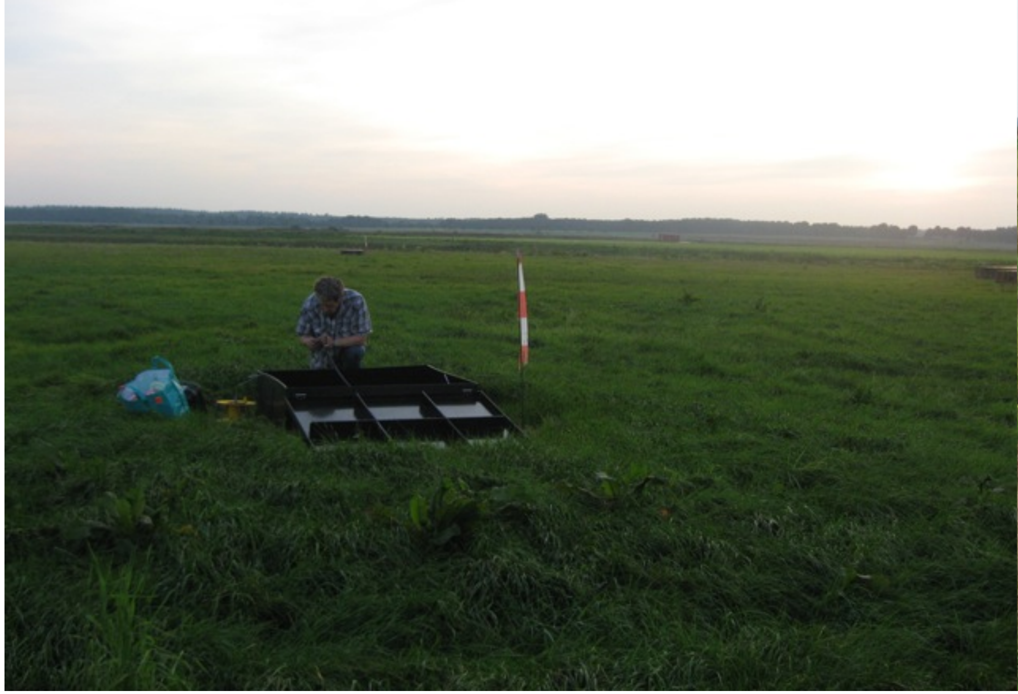
- small particle detector array for triggering and additional data – provide support for CR modes.
- 5 stations with 4 scintillators each
- around/inside the super-terp
  - electronics in LOFAR cabinets
  - layout matched to LOFAR
- status:
  - hardware and DAQ done
  - Working on detector calibration

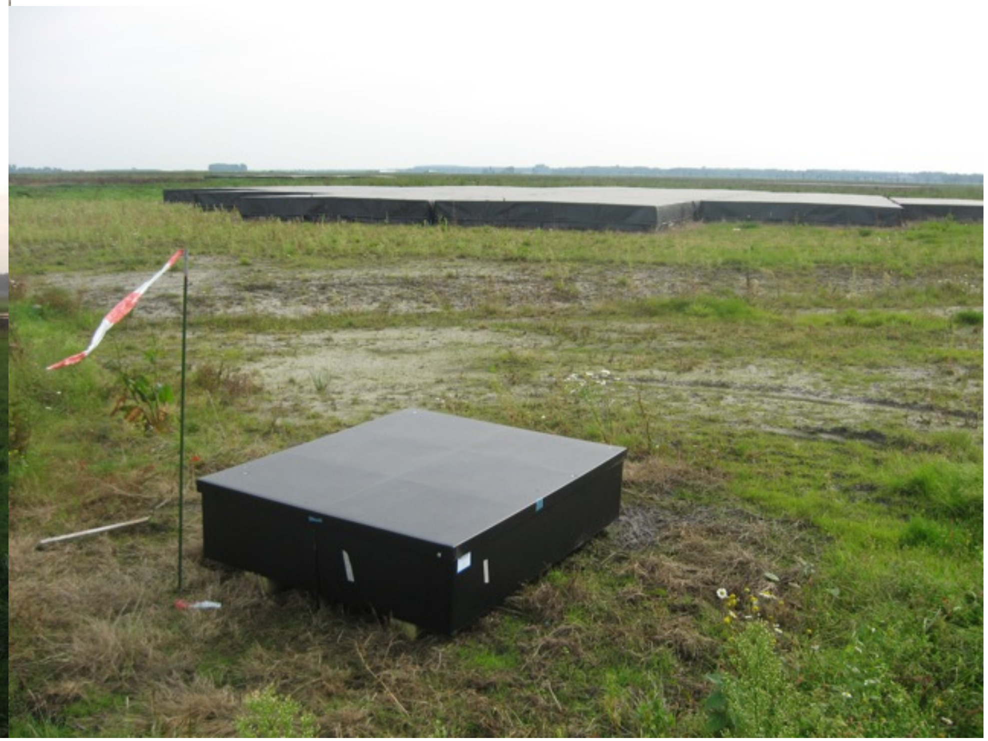


Worked on by S. Thoudam

LORA: 1st scintillator is now deployed

Pics thanks to J. Horandel





AERA: Auger Engineering Radio Array

LORA: small particle detectors, large radio telescope. AERA: reverse situation!

CR operations in practice

- VHECR: to run via ‘piggyback’ whenever a station uses the LBA antennas (not by specific time request). Users will not see this mode.
- UHEP: will require full LOFAR, special CEP mode by request – no piggybacking.
- CR triggered data:
  - <1ms per event only
  - archival form flexible
  - will contain mode-specific info on the trigger
  - are there other uses? Let us know!

Summary 1

- Always embed video in powerpoint.
- Don’t loan mac display adaptors to friends.
- Don’t run simulatios that last two days during a workshop

Summary 2

- TBBs in LOFAR enable new science.
- LOFAR is the first imaging radio telescope to consider cosmic ray detection in the design.
- Radio-detection of high-energy particles is a new field – we are learning as we go.
- Prospects very exciting: can we resolve the mystery of the highest-energy particles in nature?