LOFAR and Cosmic Rays

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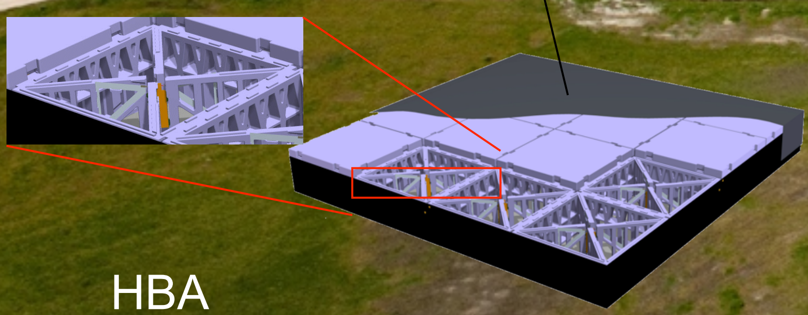
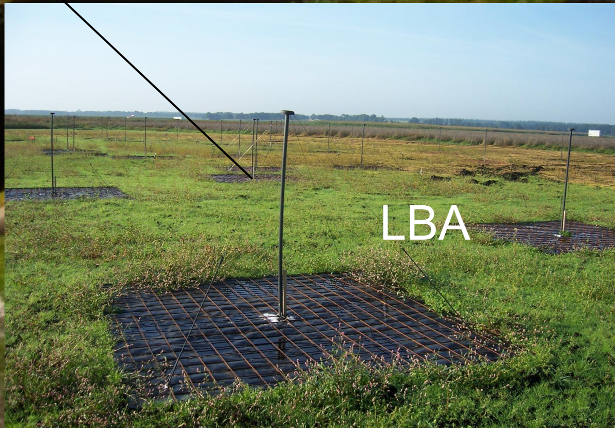
LOFAR Superterp
(6 stations)

terp (NL) = ‘hill’

37 operational stations
41 completed
7 still to go

- **Low-Band Antennas (LBA):**
  - 10-80 MHz
  - 48 crossed wire dipoles per station
- **High-Band-Antennas (HBA):**
  - 120-240 MHz
  - 48 tiles of 16 bow-tie antennas per station



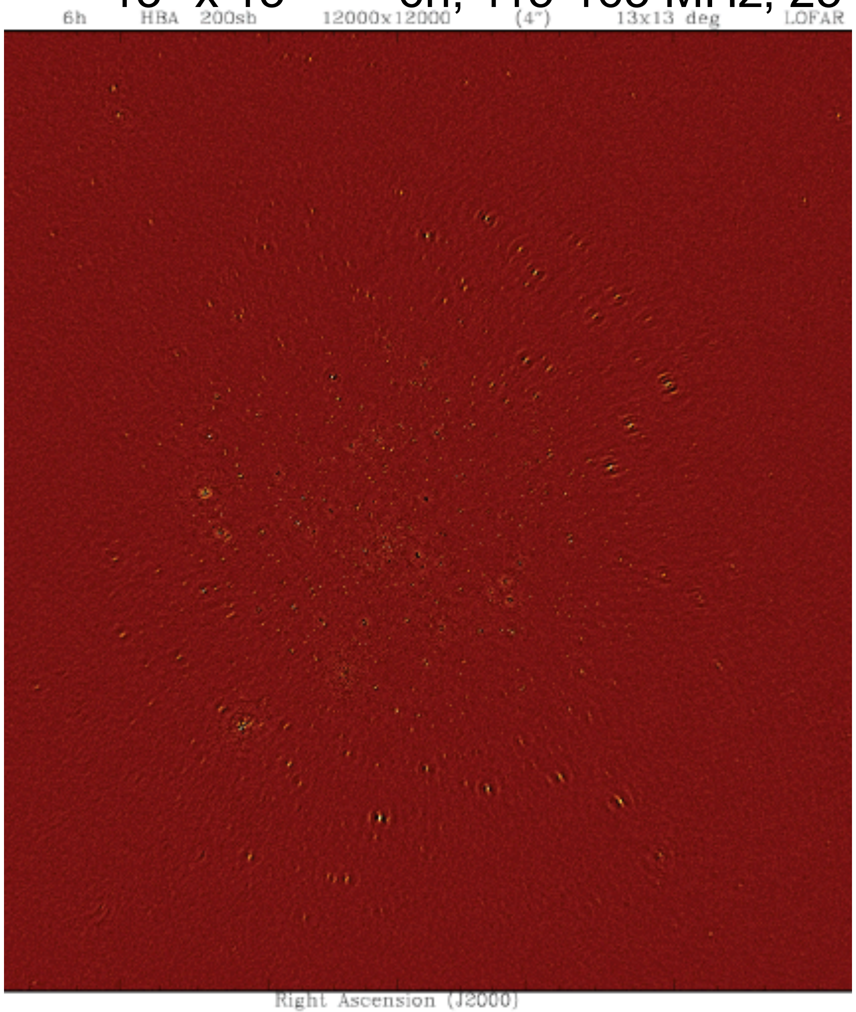


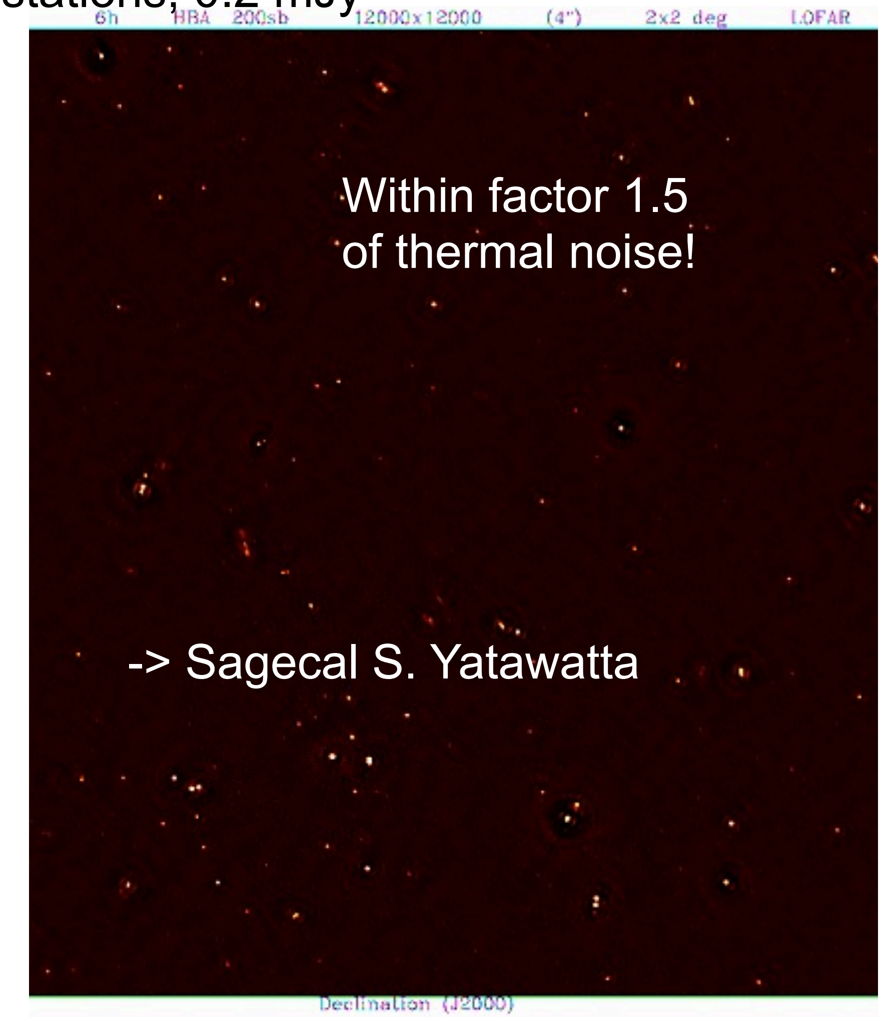
LOFAR Stations Across Europe

Deep EOR Imaging

de Bruyn,
Labropoulos, Jelic,
Yatawatta, et al.

13° x 13°   6h, 115-163 MHz, 25 stations, 0.2 mJy   2° x 2°

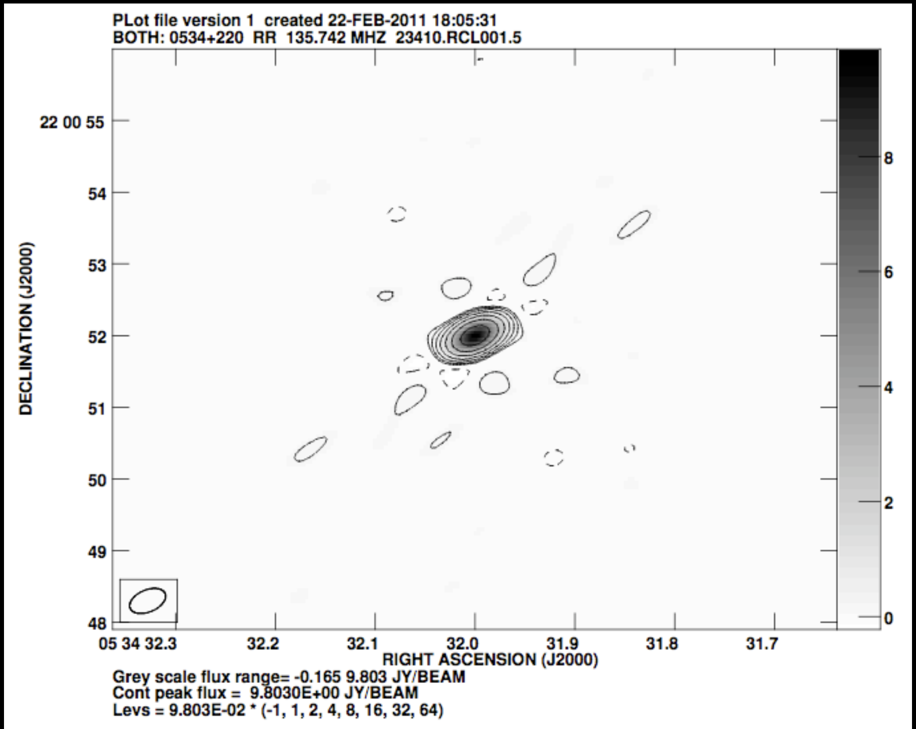


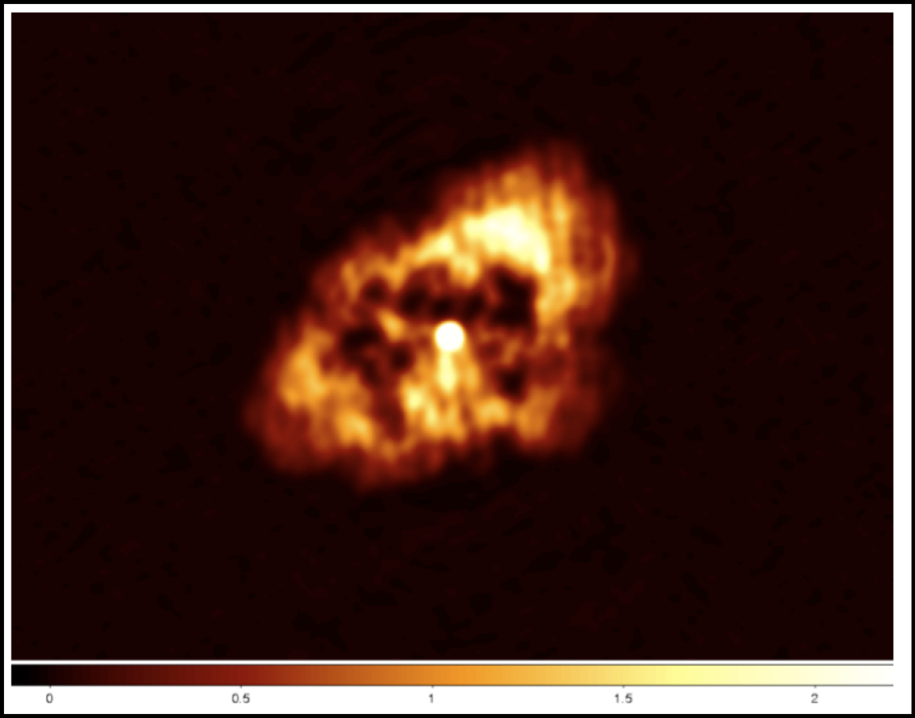


Taurus A with international baselines

1 Core station, 7 remote stations, 2 international stations

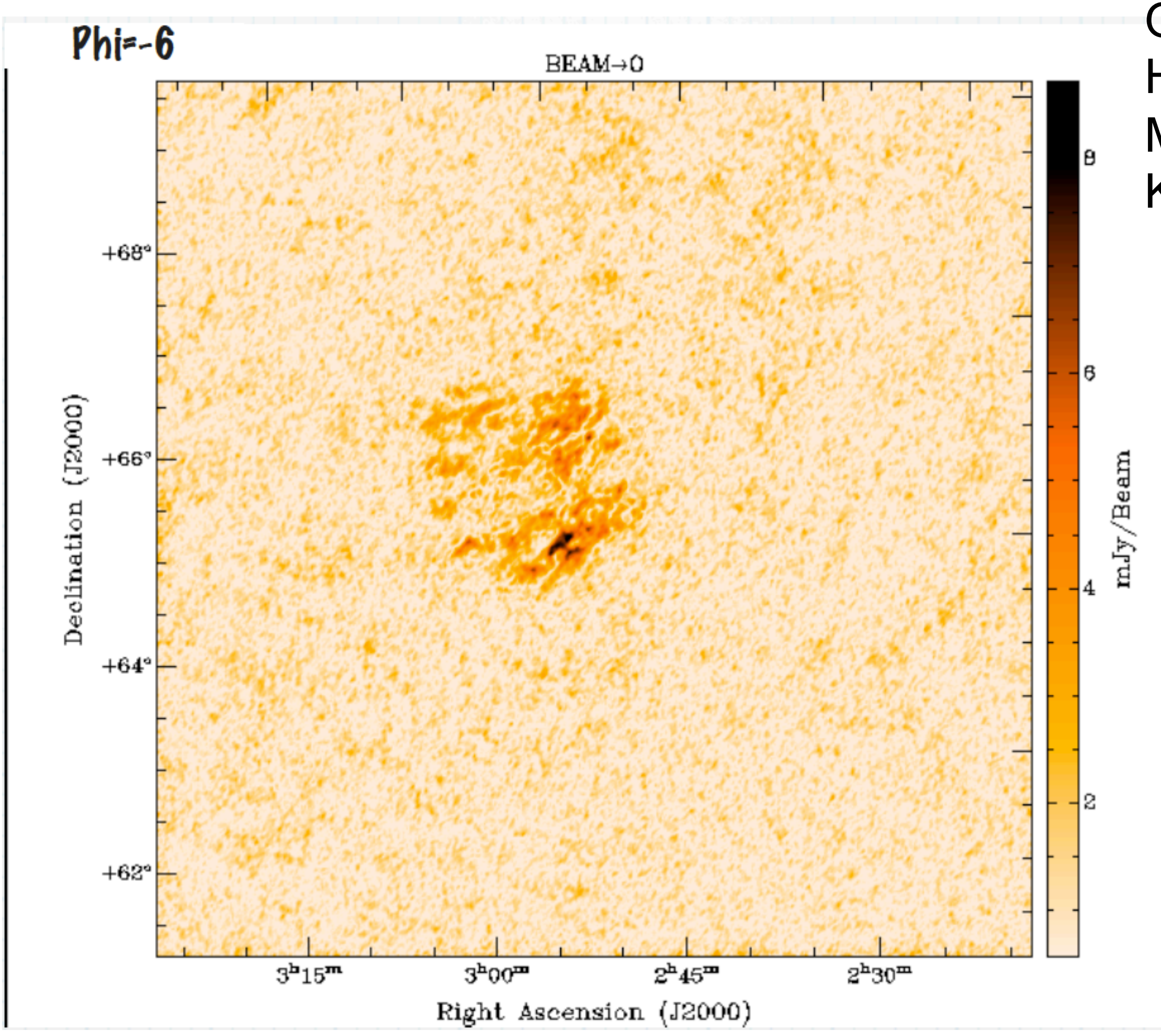
Detection of central source (Crab pulsar)





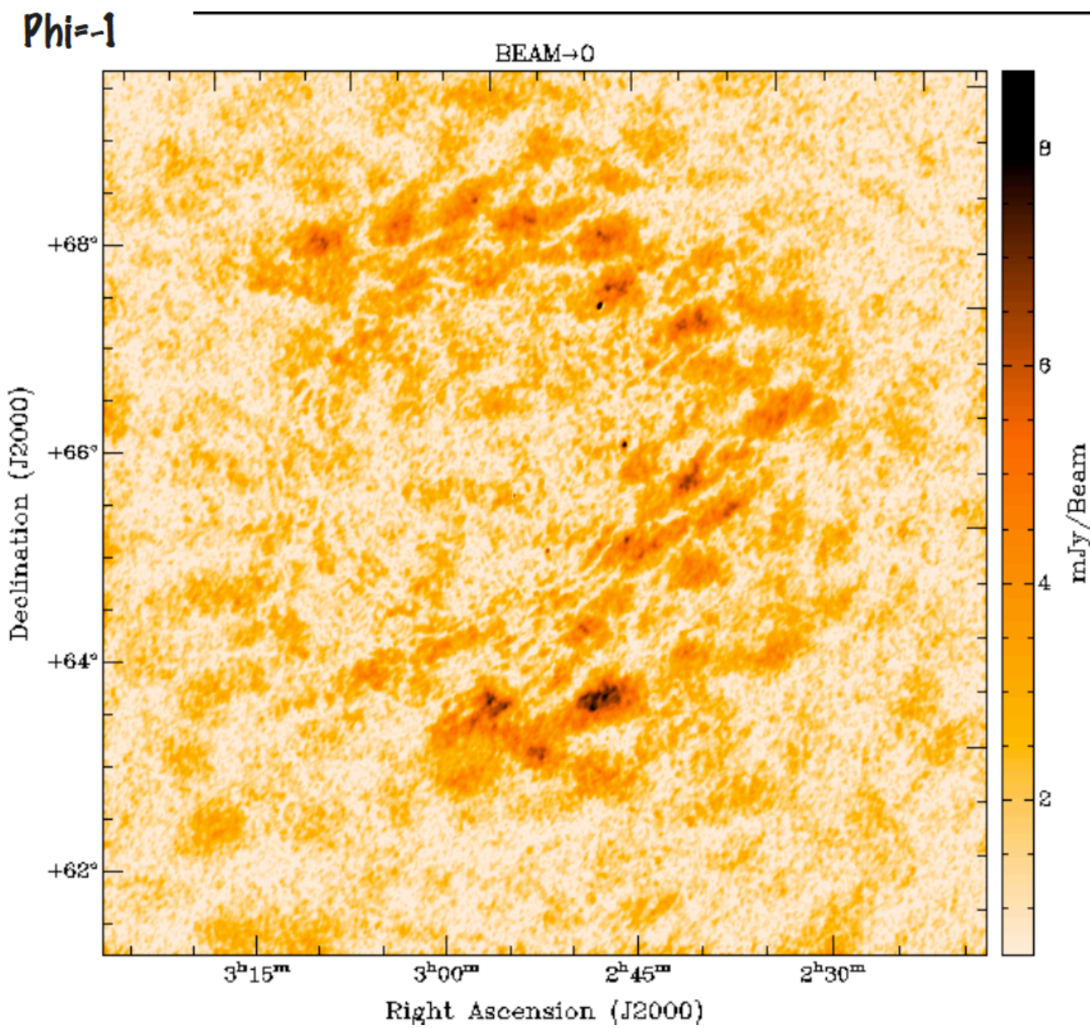
O. Wucknitz (Bonn)

Polarized structure in Fan Region with RM synthesis

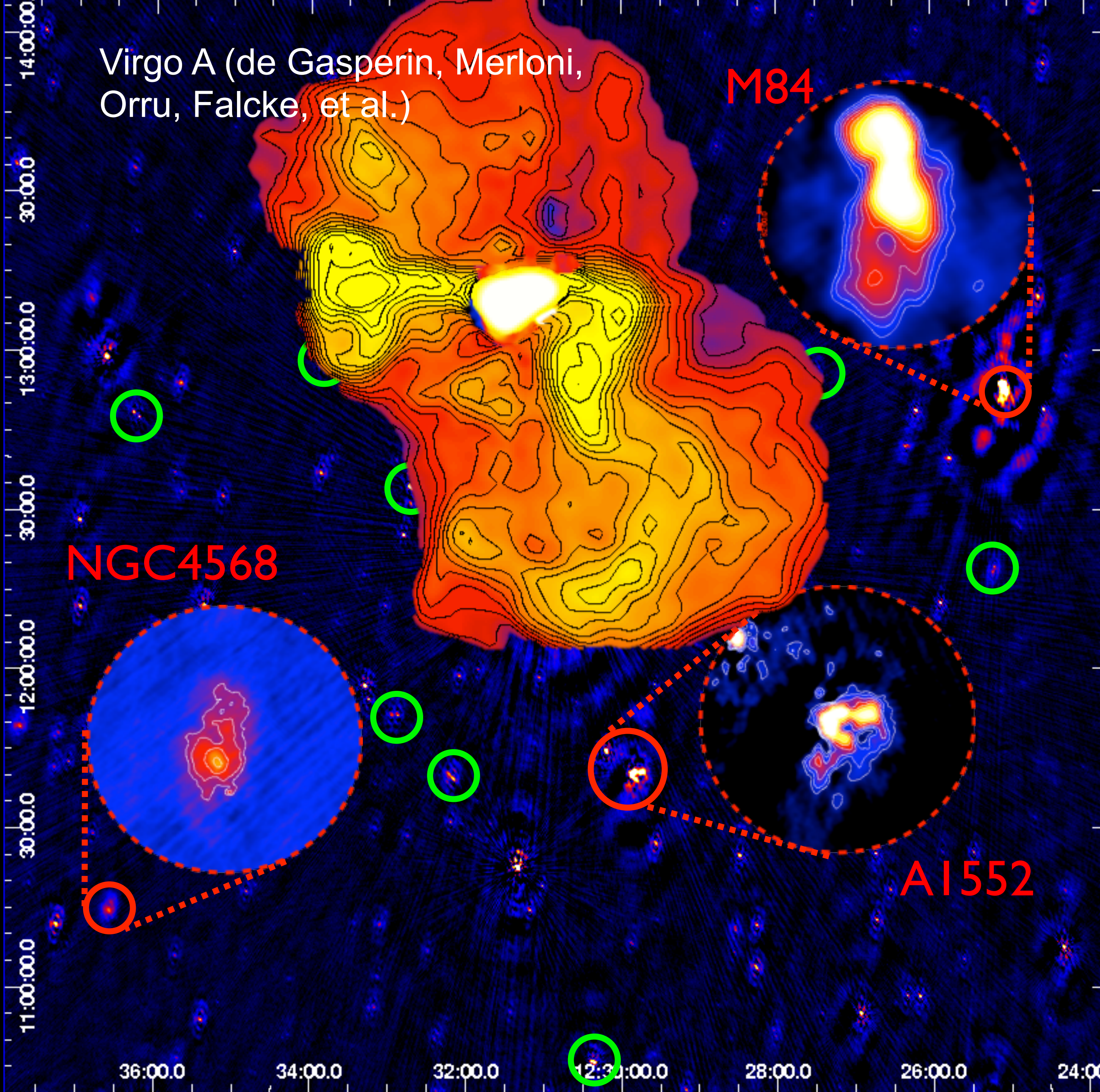


Orru, Haverkorn, Magnetism KSP, et al.

Polarized structure in Fan Region



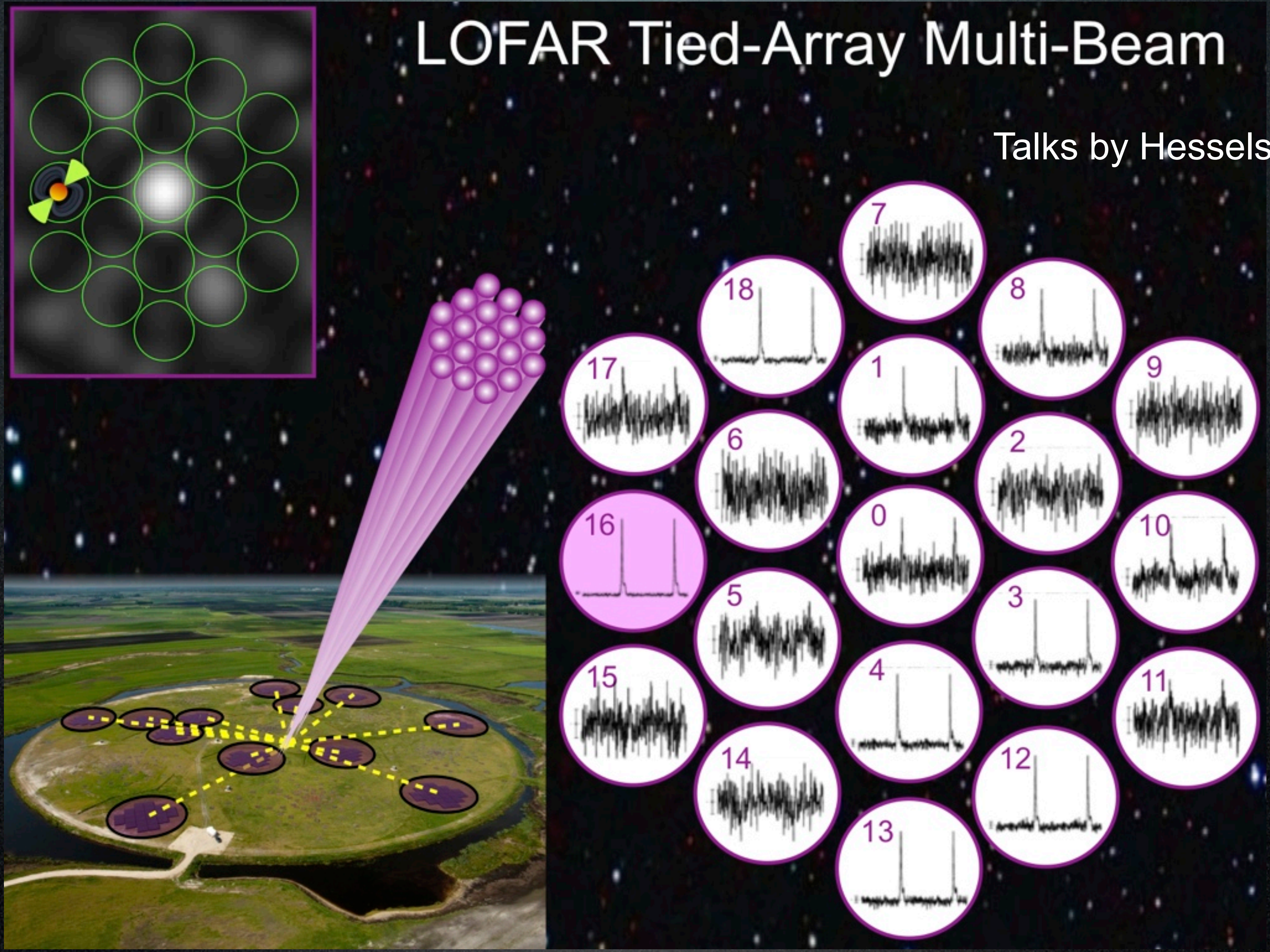
Orru, Haverkorn, Magnetism KSP, et al.



Virgo A (de Gasperin, Merloni,
Orru, Falcke, et al.)
M84
NGC4568
A1552
14:00:00.0
30:00.0
13:00:00.0
30:00.0
12:00:00.0
30:00.0
11:00:00.0
36:00.0
34:00.0
32:00.0
12:30:00.0
28:00.0
26:00.0

LOFAR Tied-Array Multi-Beam

Talks by Hessels



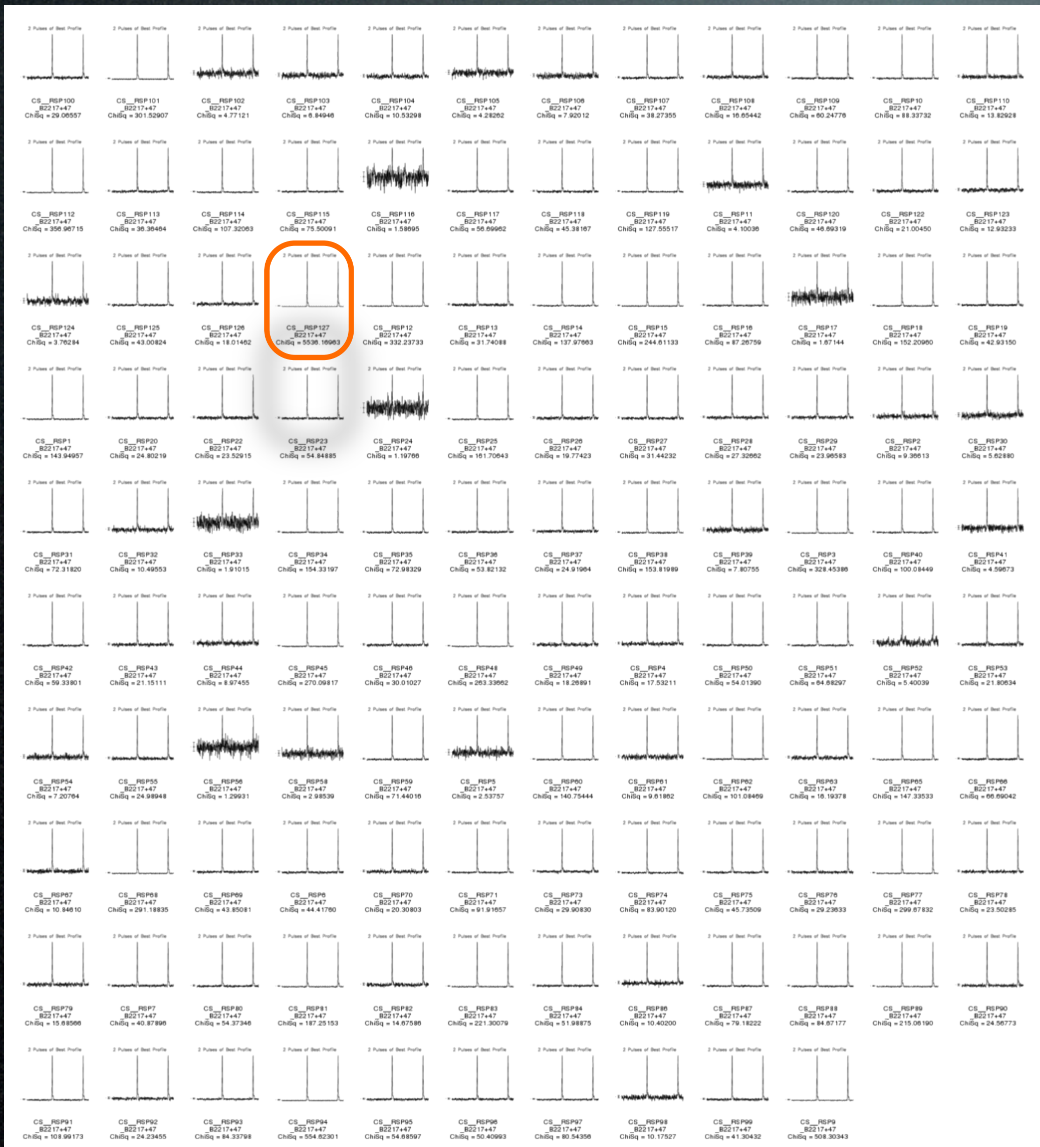
See Mol & Romein 2011 for multi-beam tied-array benchmarking results

Credit: Hessels, Stappers & Scaife

Data <12 hours old!!!

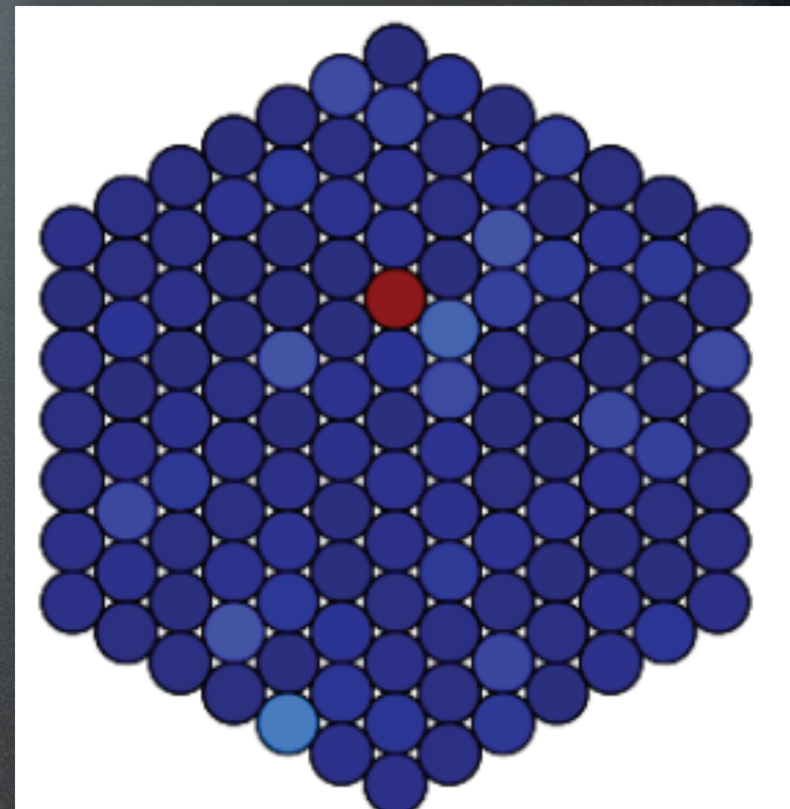
>100 beam Tied-Array!!

Talks by Hessels



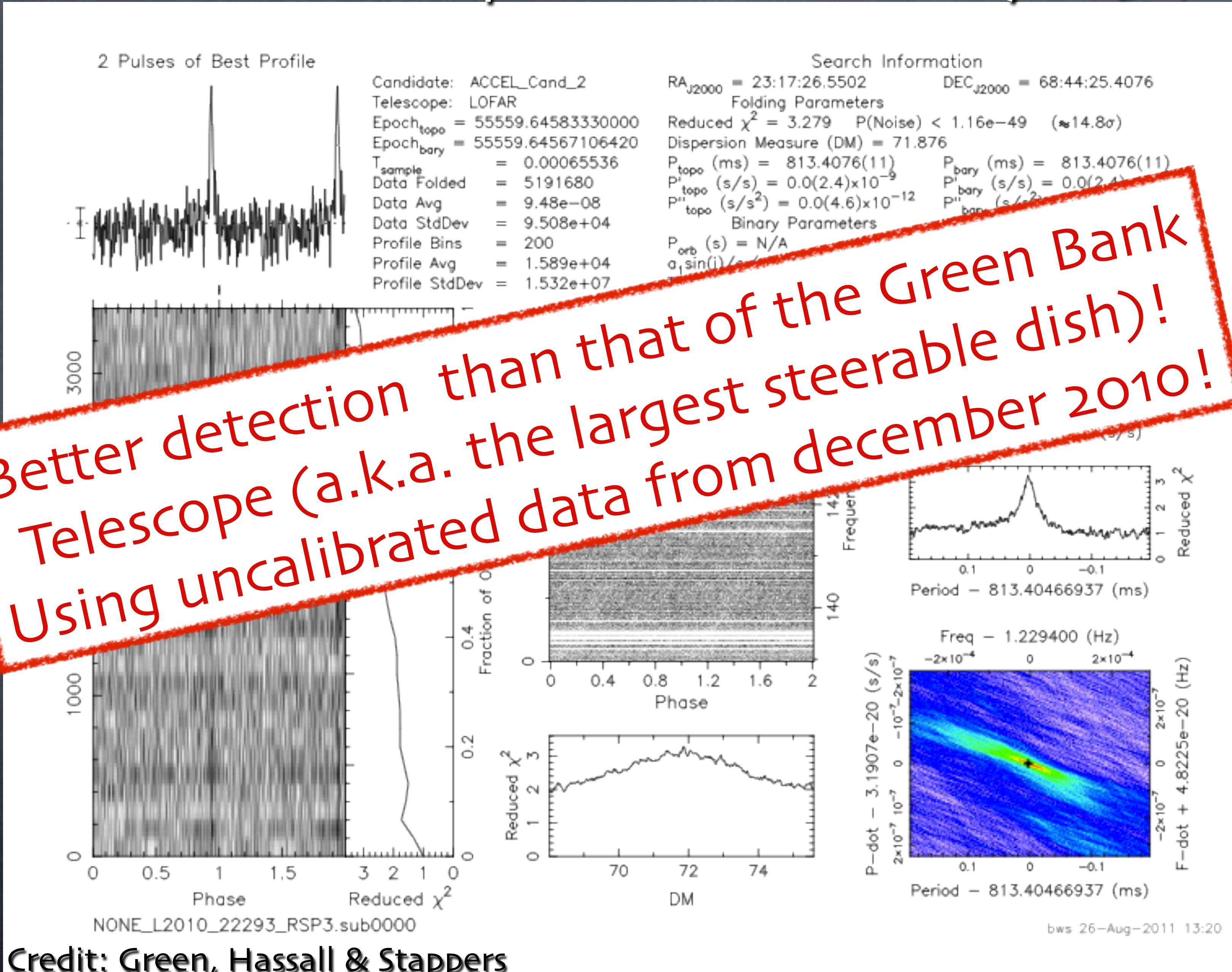
Credit: Alexov & Hessels

Pulsar in the center of FoV



Pulsar is 10x brighter in the correct beam!

Independent discovery J2317+68

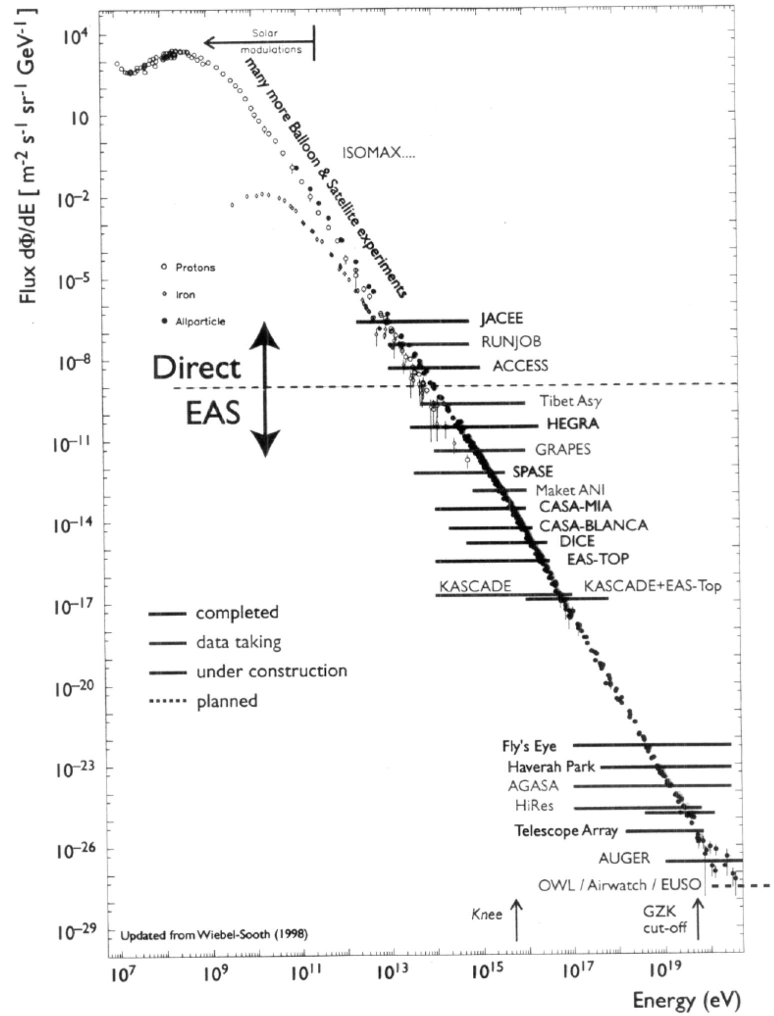


Better detection than that of the Green Bank Telescope (a.k.a. the largest steerable dish)!
Using uncalibrated data from december 2010!

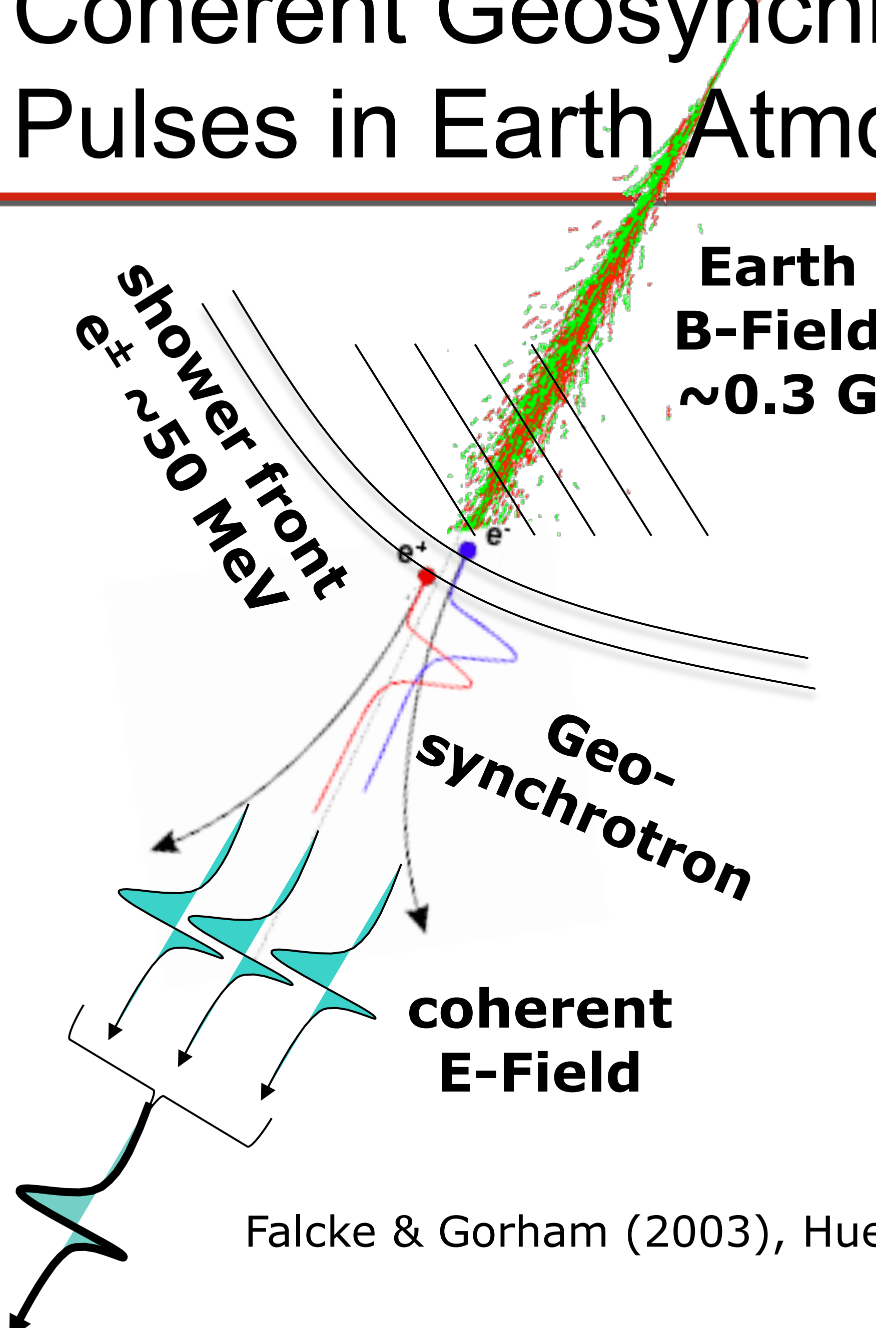
Credit: Green, Hassall & Stappers

Cosmic Ray Energy Spectrum

- Cosmic rays are very energetic particles (v~c) accelerated in the cosmos
- They reach energies beyond what can be achieved in accelerators (5 Nobel prizes for fundamental physics)
- The differential Cosmic Ray spectrum is described by an almost universal power law with a $E^{-2.75}$ decline.
- Low-energy cosmic rays can be directly measured.
- High-energy cosmic rays are measured through their air showers.
  - What are they made of?
  - Where do they come from?
  - What is the highest energy?



Coherent Geosynchrotron Radio Pulses in Earth Atmosphere



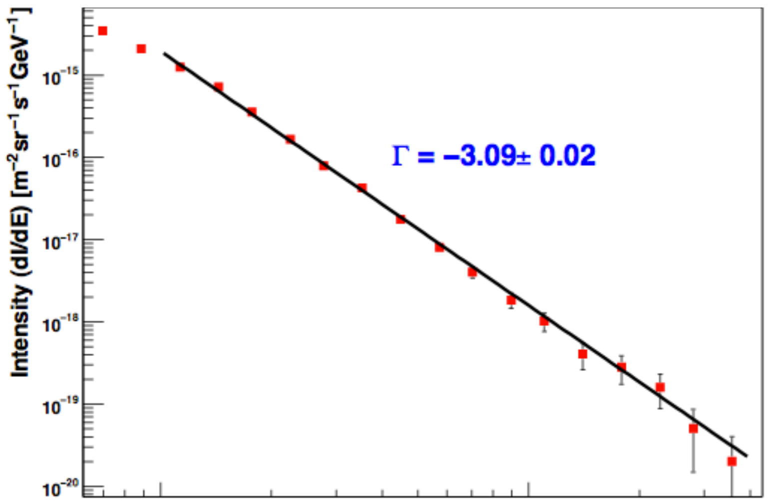
- UHECRs produce particle showers in atmosphere
- Shower front is ~2-3 m thick ~ wavelength at 100 MHz
- $e^{\pm}$ emit synchrotron in geomagnetic field
- Emission from all $e^{\pm}$ (N_e) add up coherently
- Radio power grows quadratically with N_e

⇒ $E_{total}=N_e*E_e$
⇒ Power $\propto E_e^2 \propto N_e^2$
⇒ GJy flares on 20 ns scales

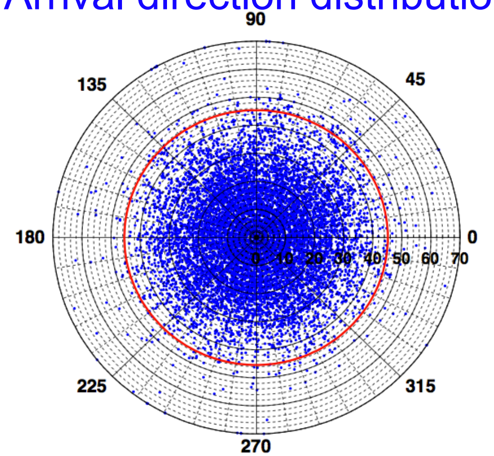
Falcke & Gorham (2003), Huege & Falcke (2004,2005)

LOFAR Radboud Air Shower Array

Talk by Satyendra Thoudam

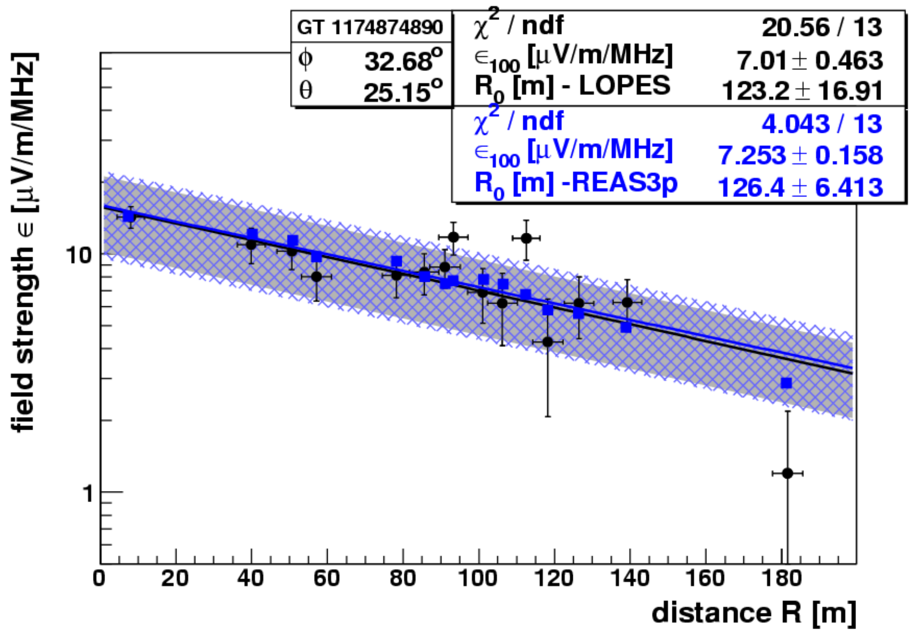


Arrival direction distributions

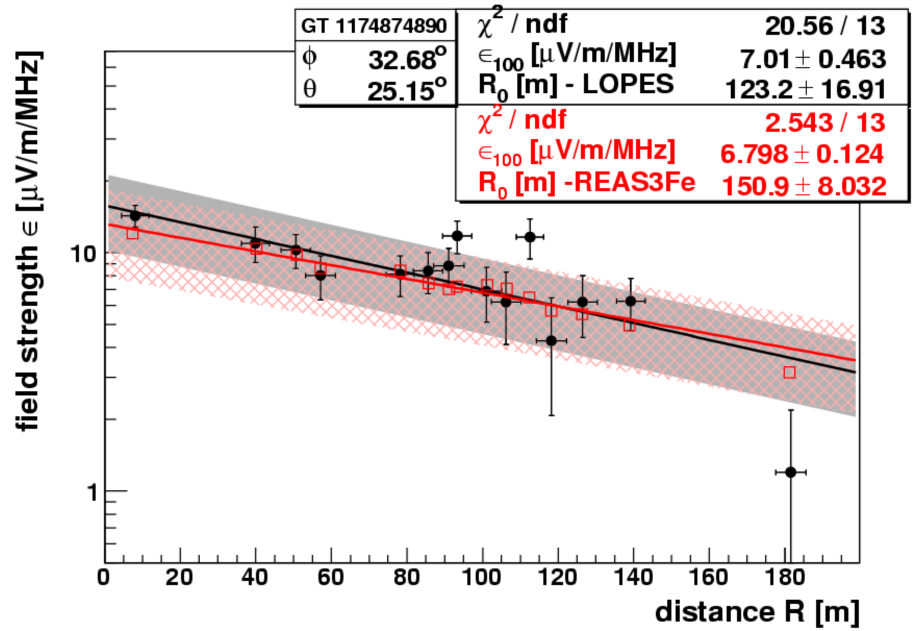


Individual events LOPES vs. REAS3

proton simulation



iron simulation

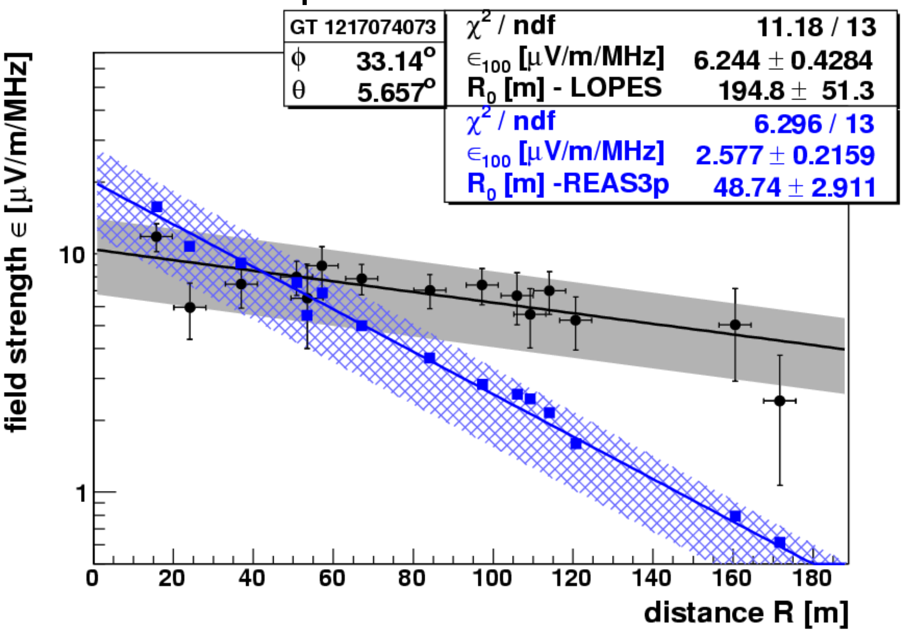


- roughly 40-50% show very good agreement

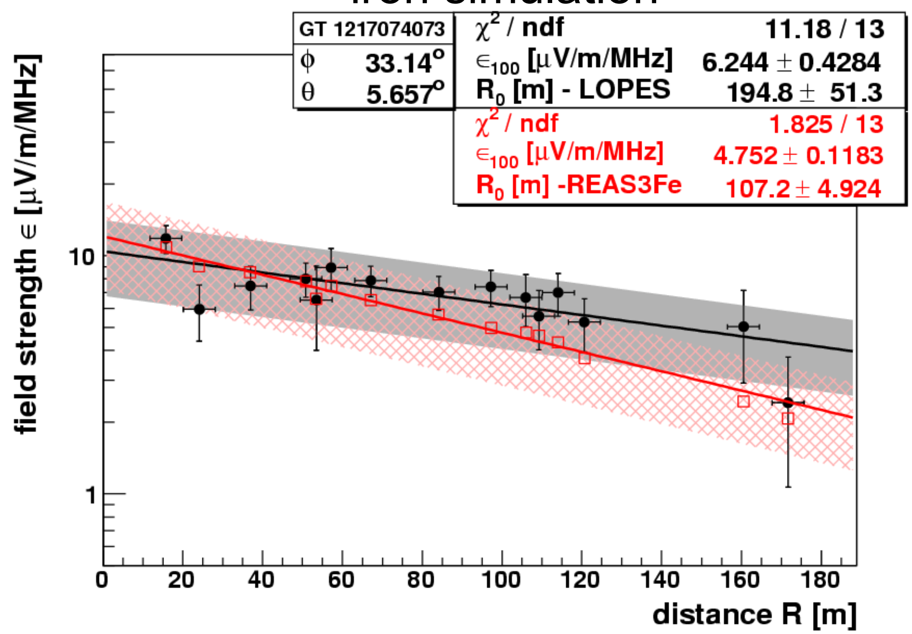
Huege, Ludwig, et al. (2011)

Individual events LOPES vs. REAS3

proton simulation



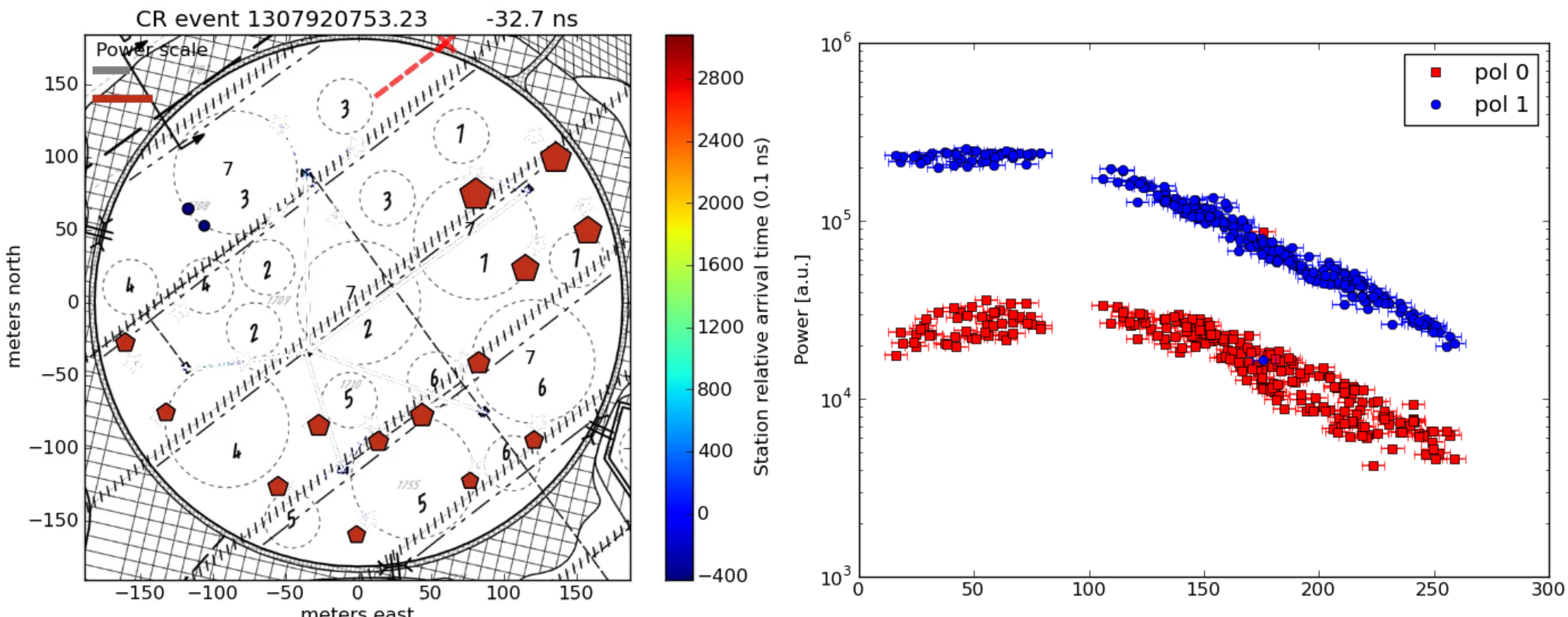
iron simulation



- roughly 10-20% show a deviation in slope (usually sim too steep)

Huege, Ludwig, et al. (2011)

Cosmic Rays seen with LOFAR



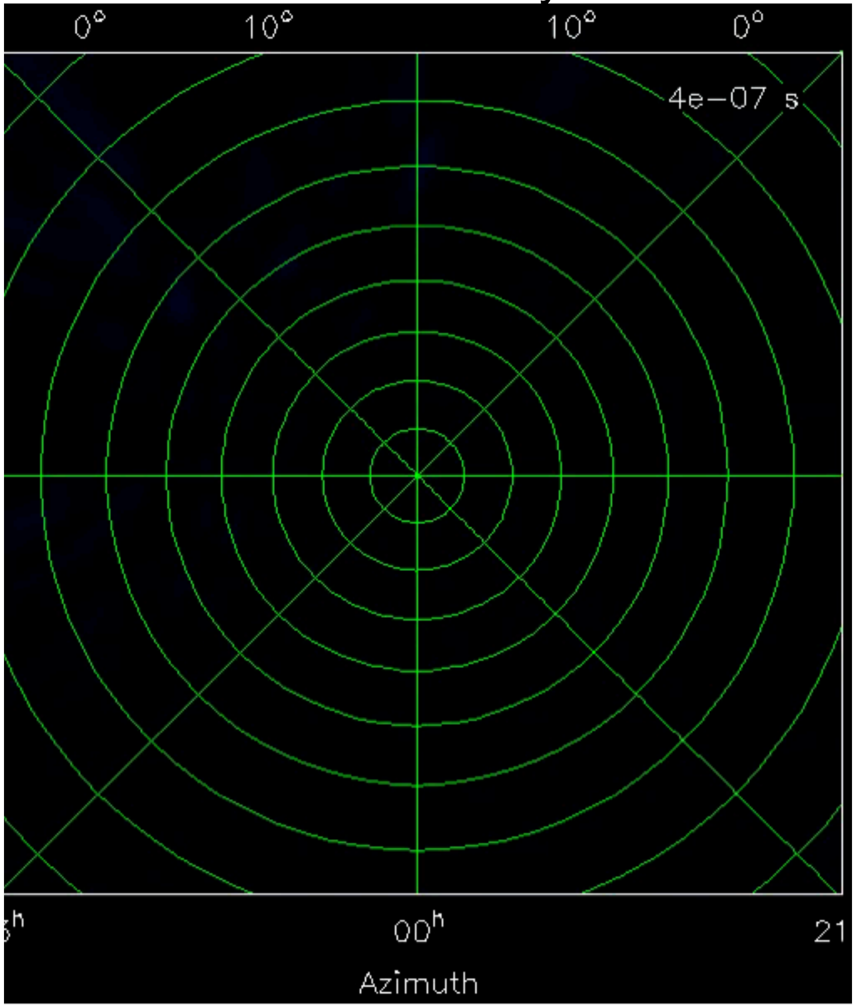
Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

Ter Veen, Corstanje, Nelles, Falcke, Schellart,
Hörandel, Satyendra, et al.

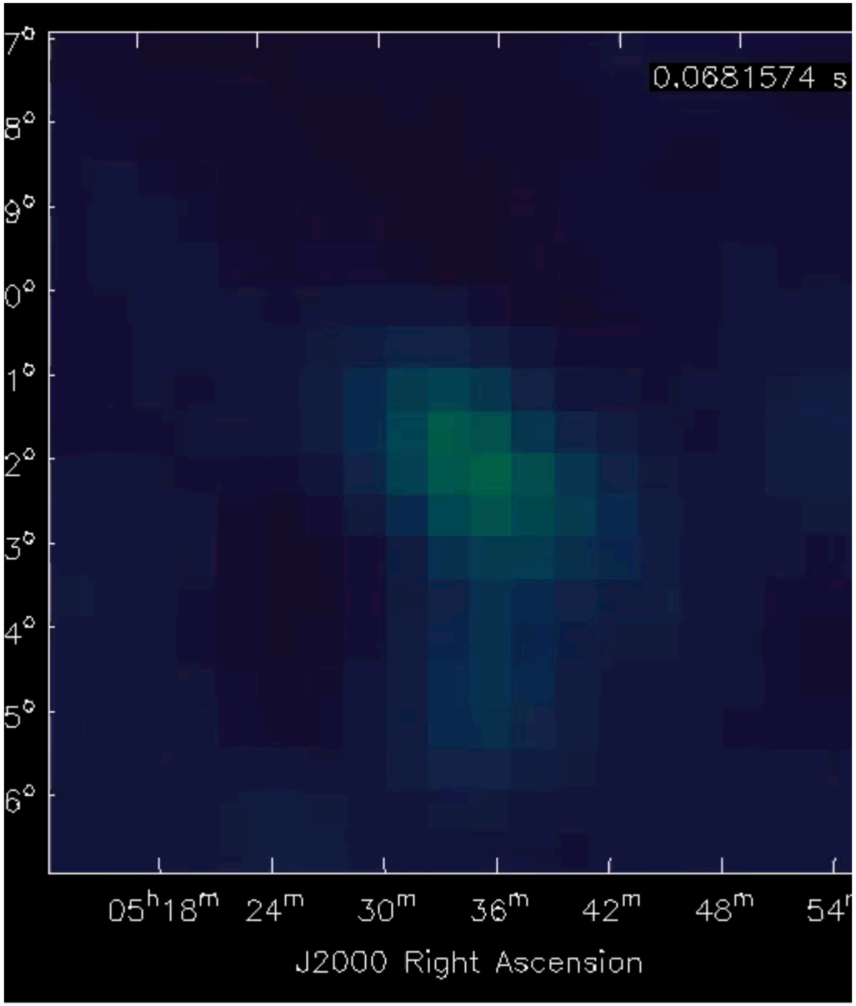
Most densely instrumented measurements of air shower radio emission!

TBB Imager

Cosmic Ray

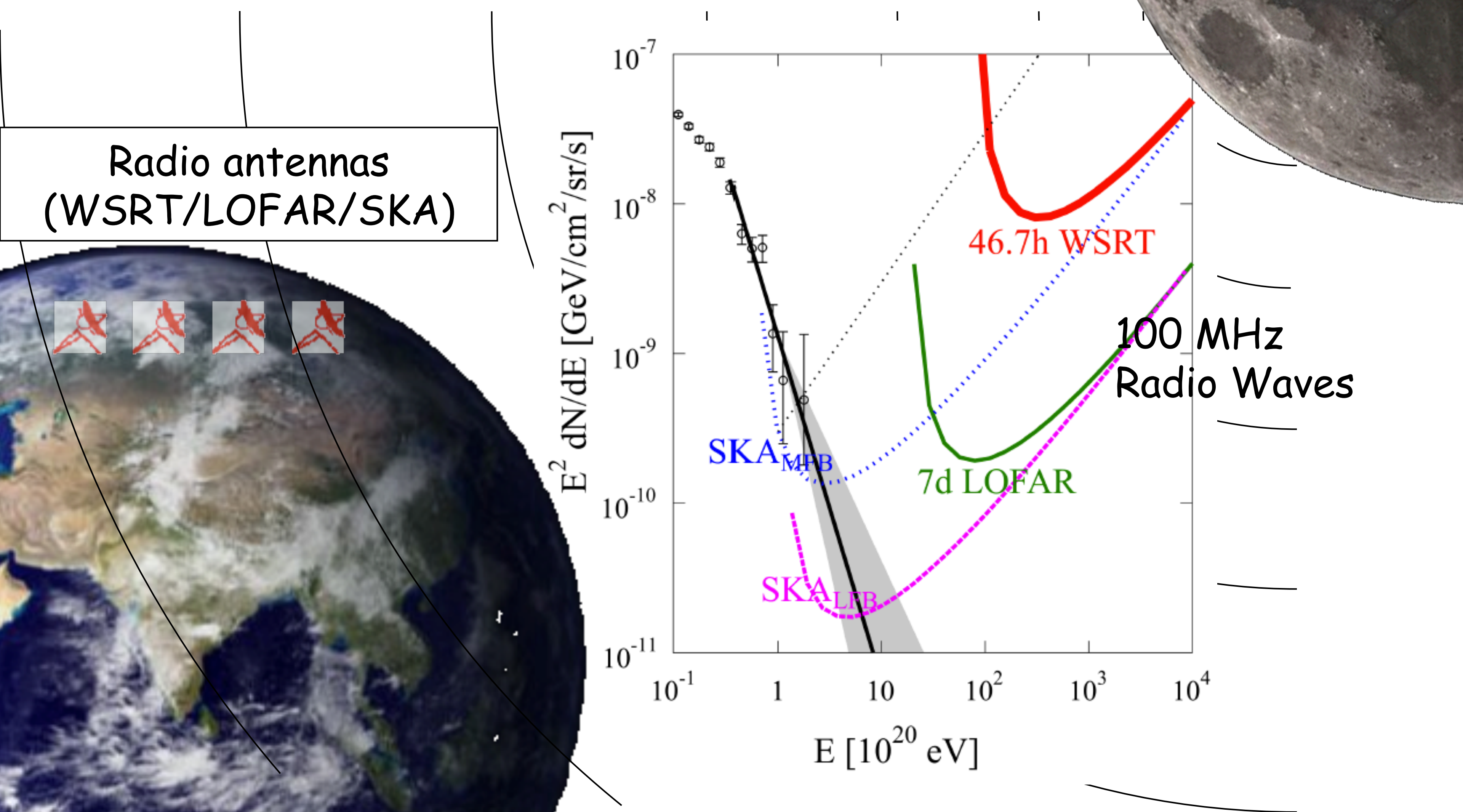


Giant Pulse

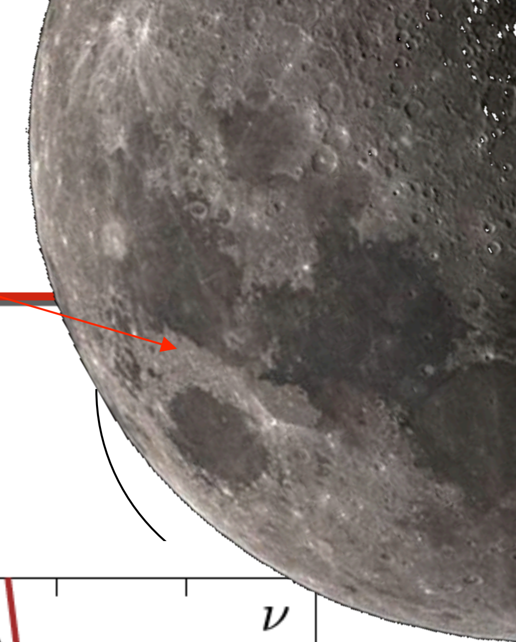


Schellart et al. (Radboud Univ)

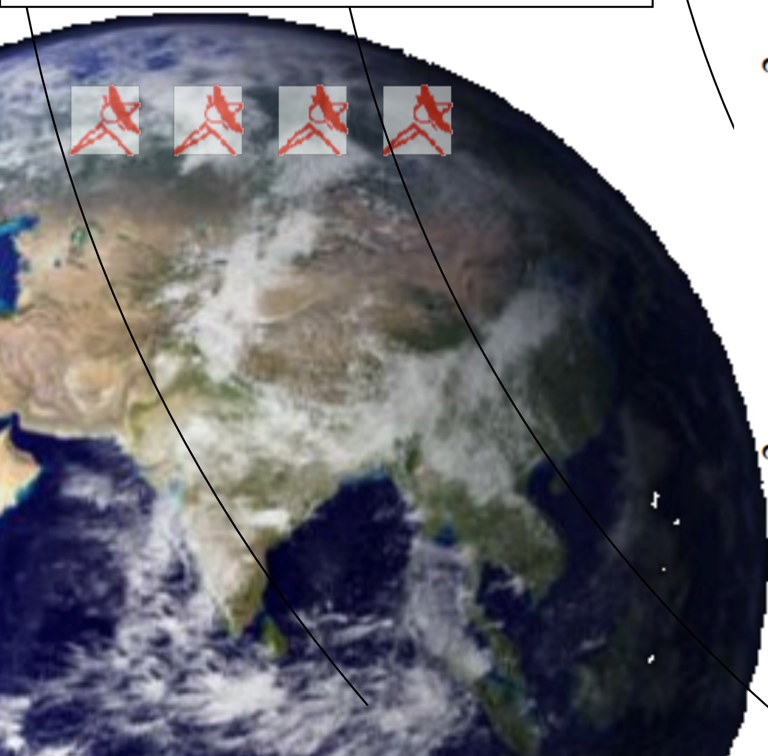
Cosmic Ray

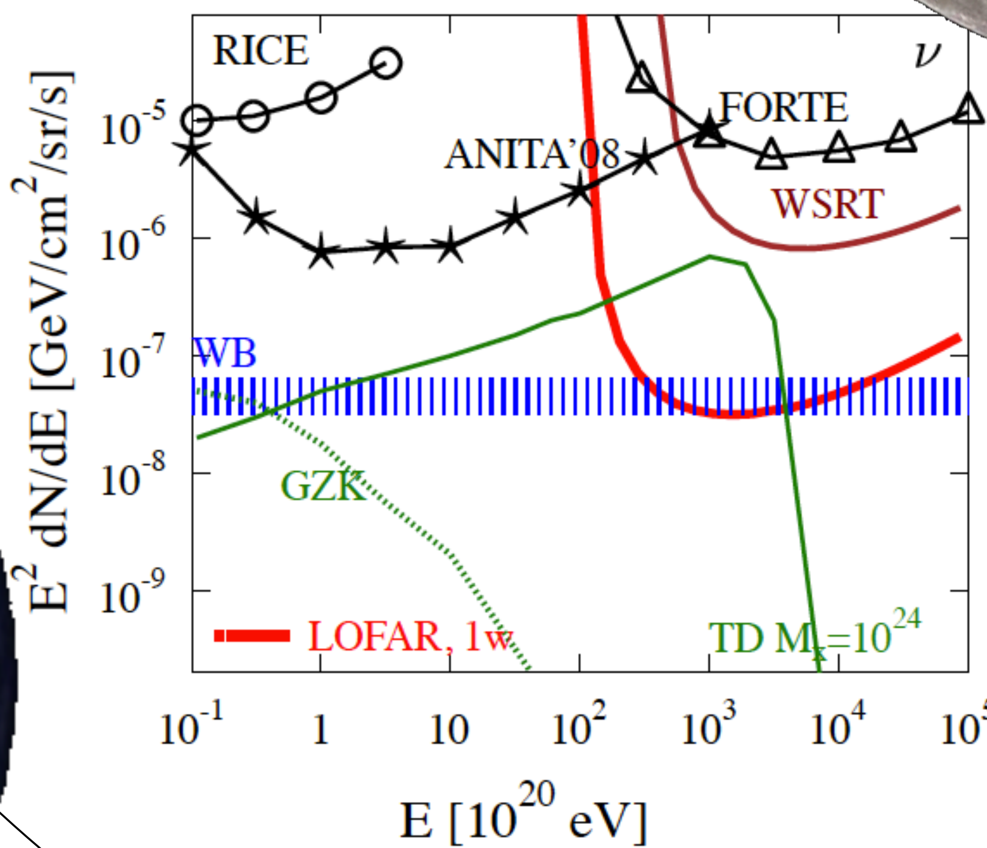

Radio antennas
(WSRT/LOFAR/SKA)
100 MHz
Radio Waves
E^2 dN/dE [GeV/cm^2/sr/s]
E [10^{20} eV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-1}
1
10
10^2
10^3
10^4
46.7h WSRT
7d LOFAR
SKA_{MFB}
SKA_{LFB}

Neutrinos

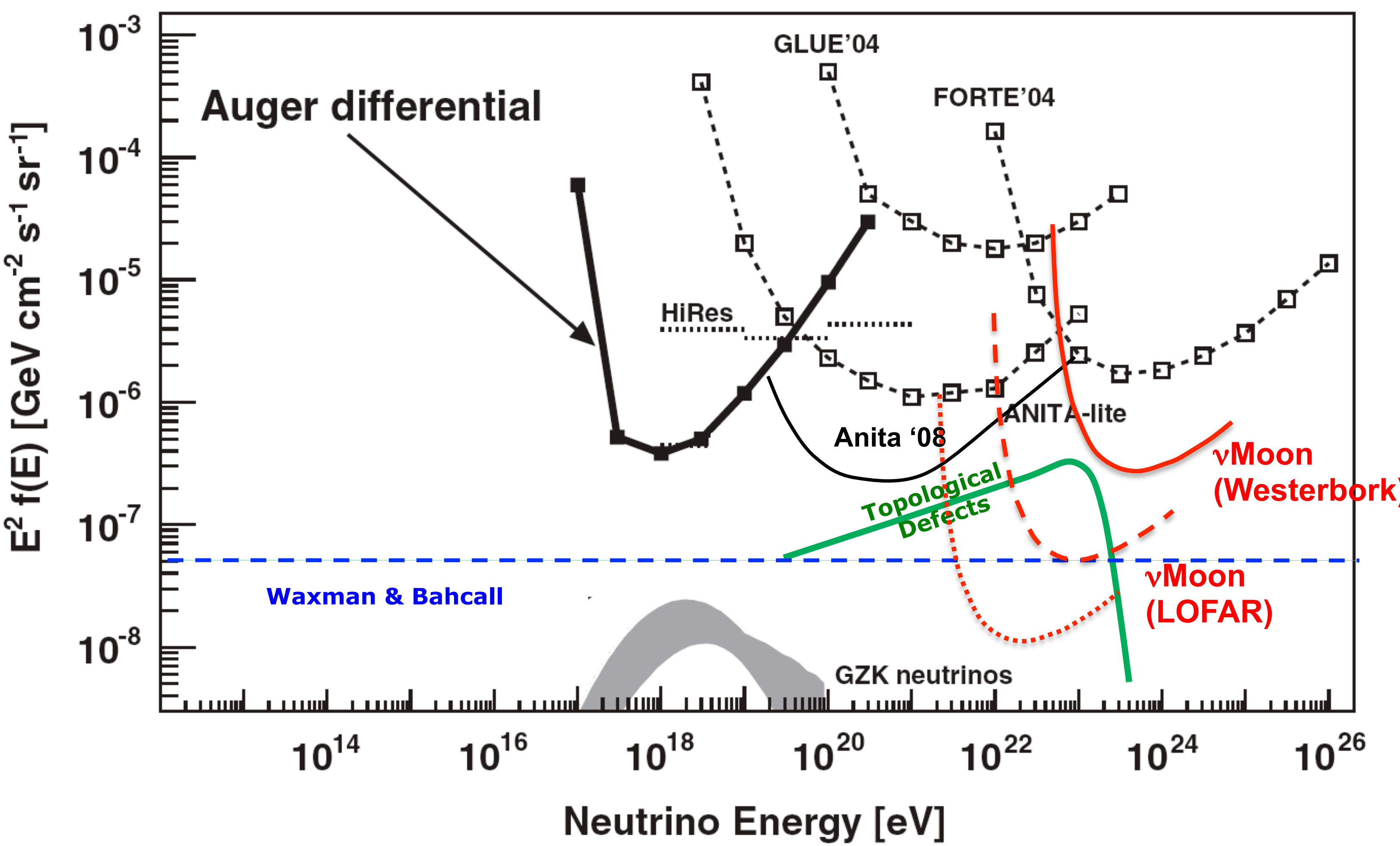


Radio antennas
(WSRT/LOFAR/SKA)





UHE World Neutrino Limits



Buitink et al. (2009), A&A - Scholten et al. (2010), Phys. Rev. Lett.

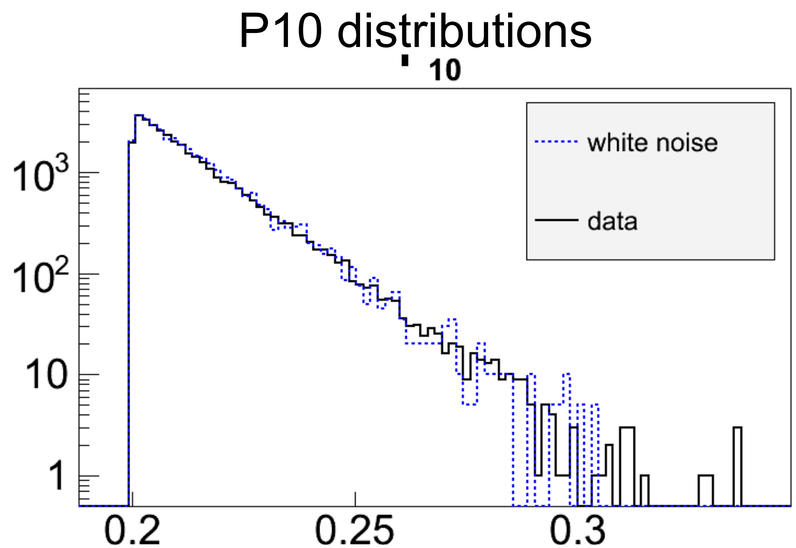
Summary

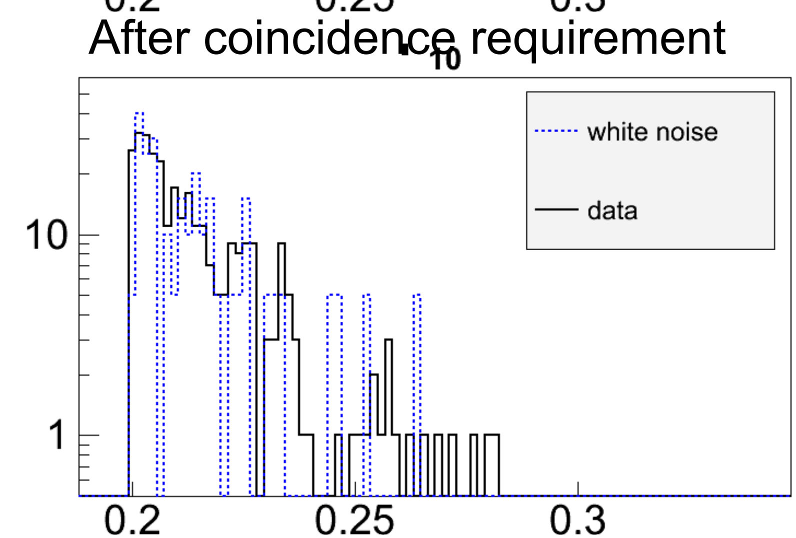
- LOFAR can do ns-timescale detection and imaging of radio flashes
- Radio detection of CRs has matured into a serious technique

⇒ **Direct detection of CR air showers with LOFAR works**:
  - Investigate composition of CRs (synergy LOFAR & AUGER)
- **Search for radio pulses from UHECRs hitting the moon**:
  - Best UHECR and neutrino limits beyond 10^{21} eV for LOFAR
- SKA will detect particles >10^{20} eV, be most sensitive detector

⇒ **Also: Hunting FRATs (fast radio transient at t<1s)**
  - Lightning, radio flares from planets, stars, neutron stars, black holes, and extraterrestrials (SETI) …
  - Ready to explore **the unknown** – stay tuned

NuMoon – Cosmic Rays hitting the Moon (Mevius)





- No pulses other than Gaussian noise were found in 5 minutes of data

- Next steps:
  - Repeat analysis on full bandwidth data
  - More stations (tied array mode)
  - Point one or more beams to the Moon, to check for differences
  - Investigate short time structure of others sources?
  - Implement simple trigger (@TBBS or CEP)