PeVatron Search Using Radio Measurements of Extensive Air Showers at the South Pole

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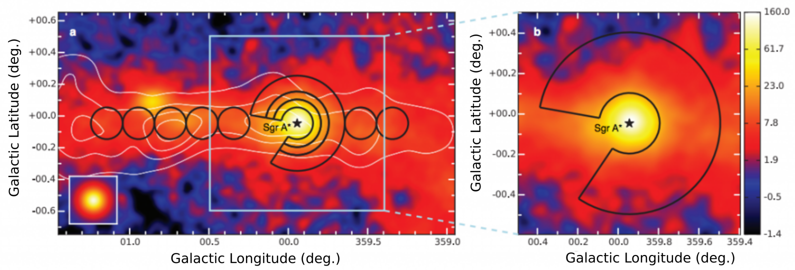
The Galactic Center

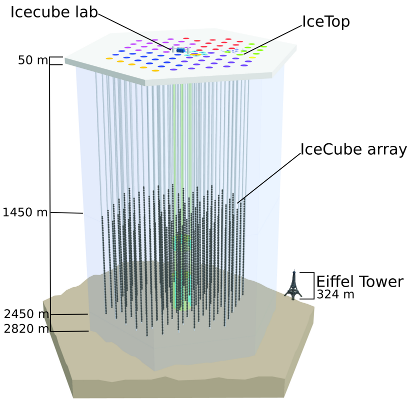
- H.E.S.S. has seen evidence for the existence of a PeVatron at the center of our galaxy [1].
- Extending the TeV gamma ray spectrum to PeV energies.
- Are PeV gamma rays produced from the Galactic Center? Can we search for them?



[1] A. Abramowski et al. Acceleration of petaelectronvolt protons in the Galactic Centre. Nature, 531:476, 2016

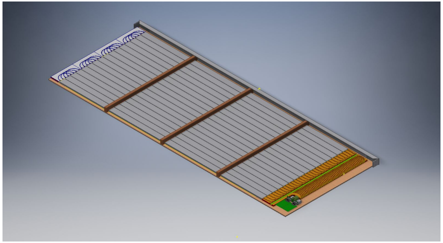
Possible experimental location

- IceCube Neutrino Observatory has a full exposure to the Galactic Center.
- Already has a cosmic-ray detector setup: IceTop
- IceTop consists of ice-Cherenkov tanks.
- Future enhancement with scintillators.
- Also a large surface array as part of IceCube-Gen2.
  (further details about IceCube-Gen2: *Claudio Kopper, High Energy Neutrinos, Plenary session*)
- Possibly a radio antenna array with an area of 1km^2.



IceTop tanks

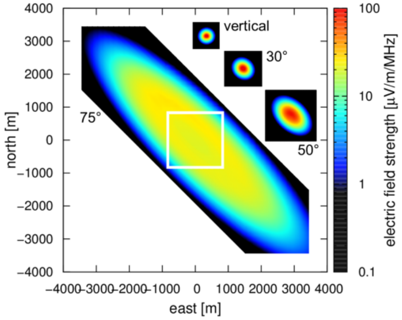
radio antenna
[eg. LOFAR]



Scintillator panels

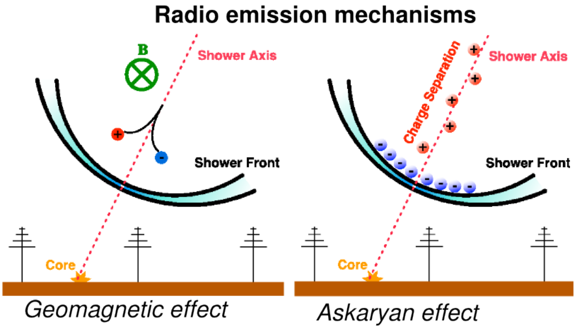
- Will help in measuring different components of the cosmic-ray air shower (electromagnetic and muonic).
- We can **search for PeV gamma rays from the Galactic Center** (by combining the particle detectors with **radio antennas**).

- PeV gamma rays hitting the atmosphere will produce air showers which can be detected on the ground.
- The Galactic Center lies at around 61 degrees inclination at the South Pole (always visible).
- Difficult to effectively reconstruct such events using particle detectors.
- Higher probability to capture such events with the help of radio detection techniques.
- Radio signal from inclined shower leaves a large footprint on the ground.
- We can use the scintillator array/IceTop tanks to trigger the antennas.



[T. Huege, A. Haungs]

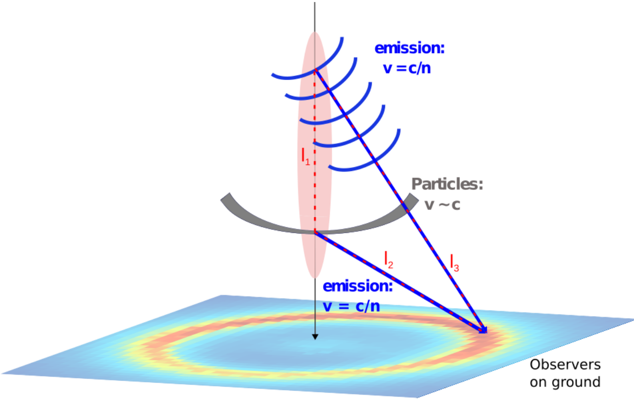
- The electromagnetic component of the air shower can be detected with radio technique.
- Radio component is a first order energy estimator (quasi-calorimetric).
- Using hybrid techniques (radio + particle detectors) we get a better understanding of the air shower (helps in estimation of electron/muon ratio).
- Inclined air showers give a large elliptical radio footprint.



[T. Huege]

Cherenkov ring formation in radio signals

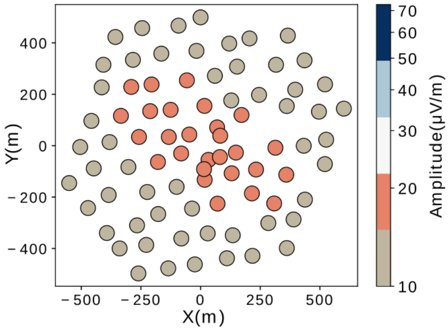
- Collimation of the electromagnetic waves due to the refractive index of air.
- Causes time compression of the signal in certain distances.
- Can be seen only at certain frequency ranges.
- Has sensitivity to Xmax.



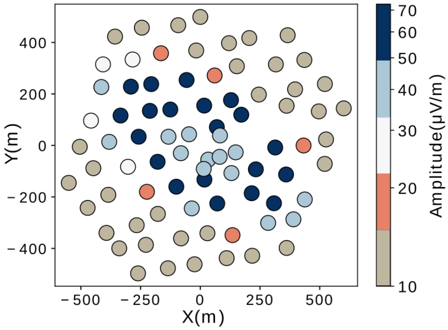
[A. Zilles]

Footprint of 10 PeV shower

Radio simulations (CoREAS) of photon primary with one antenna per IceTop station.



10 PeV, zen = 61°
(30-80 MHz)

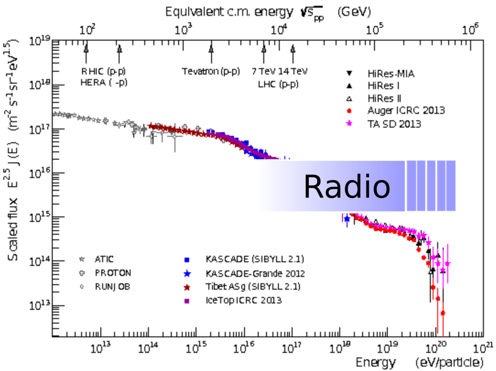


10 PeV, zen = 61°
(50-350 MHz)

Cherenkov ring is visible if we go to higher frequencies. We get stronger signals at these frequencies.

Status of radio detection

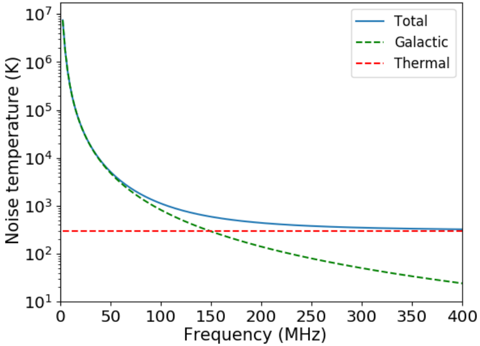
- So far, the energy range thought to be accessible with radio detection technique is $\gtrsim 10^{16}$ eV.
- At lower particle energies, radio signals become weak and are overwhelmed by background especially at 30-80 MHz (well studied bandwidth).
- So it is crucial to look for the bandwidth where we can lower the energy threshold for the detection of PeV gamma rays.



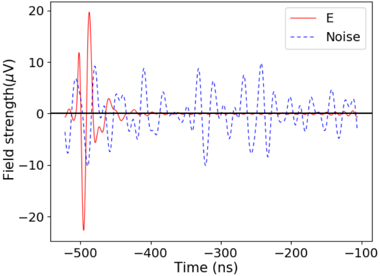
[T. Huege]

Noise

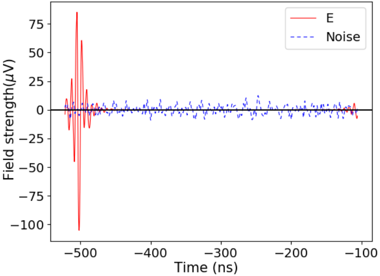
- At 30-80 MHz bandwidth, the signal from a 10 PeV shower will get dominated by the Galactic noise background.
- Galactic noise model adapted from H.V. Cane, thermal noise of $\sim 300K$ added.
- Noise temperature can be related to power delivered to the antenna by $P = kT\delta\nu$.



- Comparing the signal in one antenna (shower with E=10 PeV, 61°) with a random time trace of noise.
- At higher frequencies, there is a better chance to see the signal above the noise.
- SNR $= \frac{S^2}{N^2}$; S = max of the Hilbert envelope, N = rms noise
- SNR $>$ 10 is the limit for detection that is shown by other radio experiments.



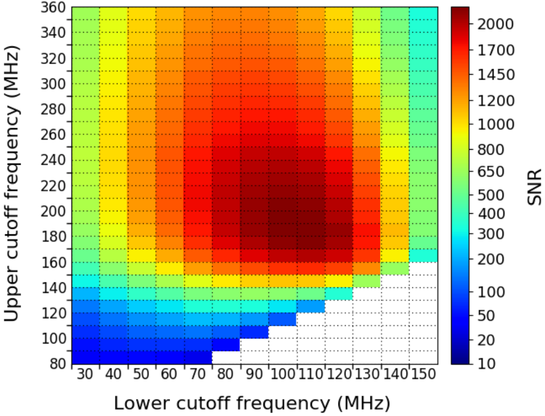
30-80 MHz (SNR $\approx$ 35)



50-350 MHz (SNR $\approx$ 1055)

Scanning the bandwidth

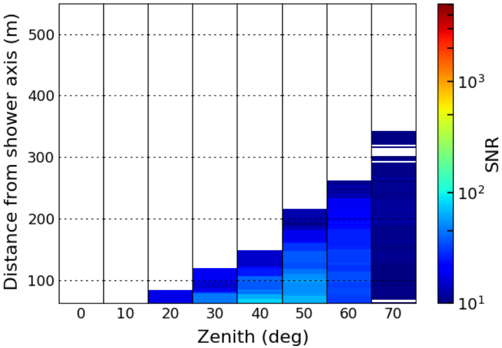
10 PeV gamma primary with 61° inclination: A typical station at the Cherenkov ring (distance to shower axis ≈ 107 m).



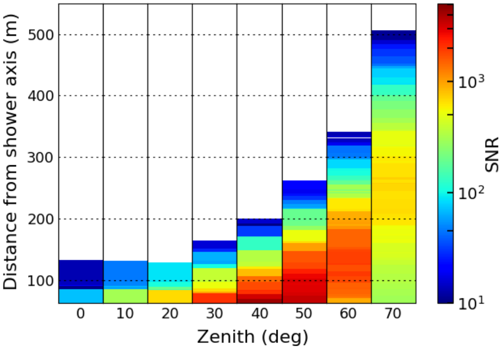
The region in red shows the bandwidths with a high level of signal-to-noise ratio

Dependence on zenith angle

10 PeV photon with different zenith angle: Showers with antennas located at each IceTop station and with core at the center.



30-80 MHz

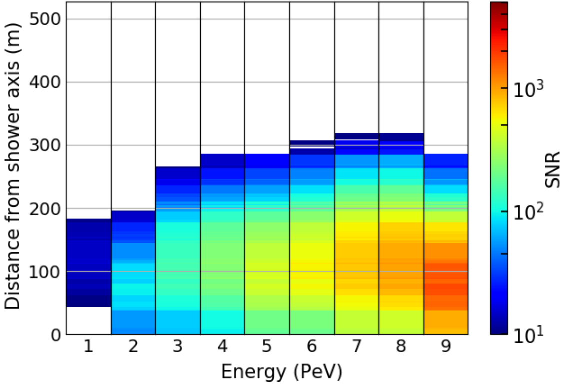


100-190 MHz

All antennas where SNR becomes < 10 have been set to white.

Energy threshold

61 degree photon showers



100-190 MHz

The threshold can be lowered to 1 PeV if we go to the optimum frequency bandwidth and have an antenna spacing of $\approx$ 125 m.

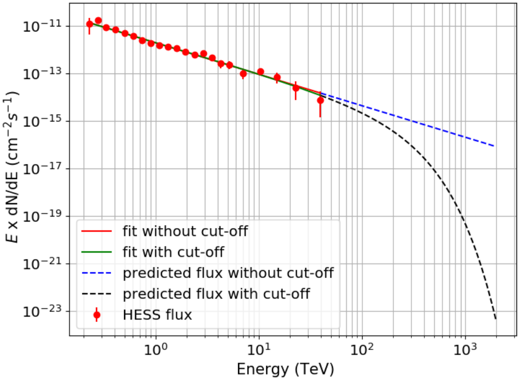
Summary

- Combining radio and particle detectors can help in obtaining a better reconstruction of the air showers.
- For inclined arrival direction radio antennas will help in measuring the electromagnetic part of the shower.
- We can search for PeV gamma rays from the Galactic Center with such a setup.
- A high level of SNR is obtained at frequencies like 100-190 MHz.
- Utilizing this we can lower the energy threshold down to 1 PeV for gamma rays coming from a zenith angle of 61° (direction of the Galactic Center at the South Pole).

Backup

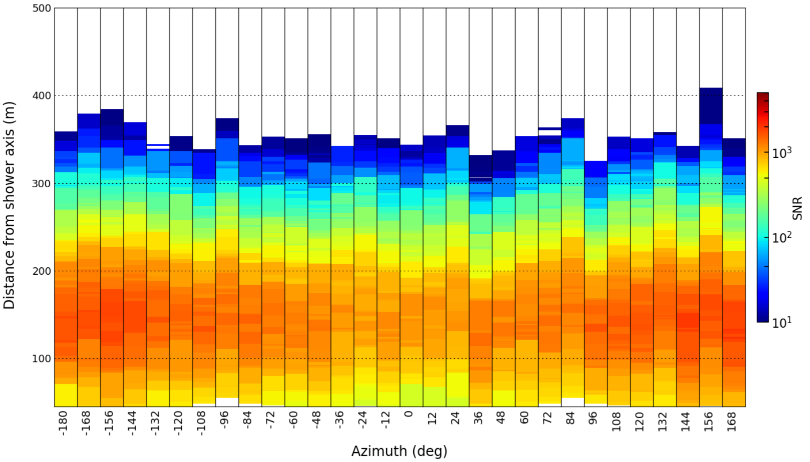
Expected number of events

- $E^{-2.3}$ fit to the H.E.S.S. spectrum without cut-off gives $\approx$ 23 events per year for an array of 1 km^2 area.
- Fit with cut-off at 116 TeV $\Rightarrow$ no events will be detected.



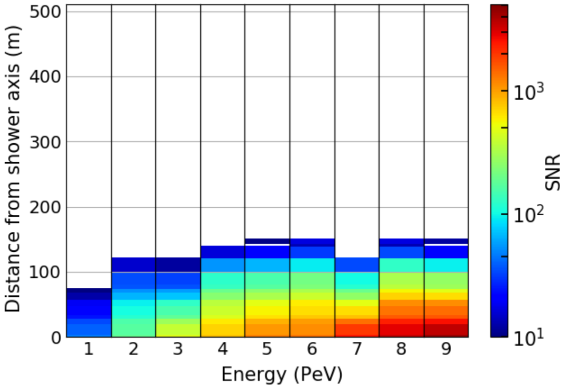
Dependence on azimuth

10 PeV photon showers of 61° inclination



≈ 50% change in the SNR when the azimuth changes (but same order of magnitude).

40 degree photon showers

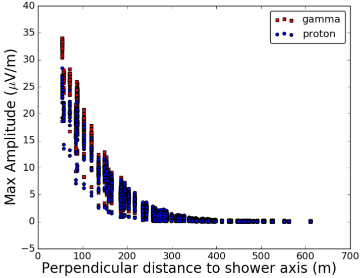


100-190 MHz

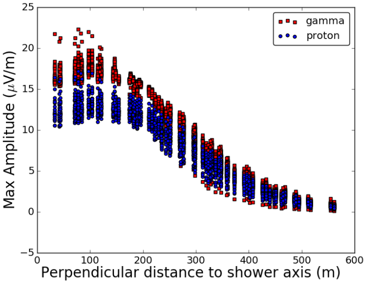
It is possible to lower the threshold for these zeniths if we have antennas within 100 m distance from the shower axis.

Lateral distribution of the radio component

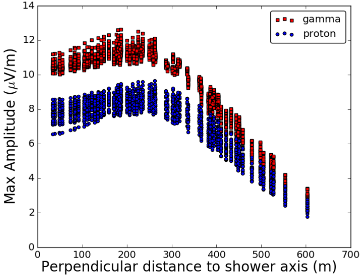
- Gamma showers have more electromagnetic component, resulting in higher amplitude in the radio profile.
- We can see a clear separation in the radio profile of gamma and proton at higher zenith angles.



10 PeV, zen $= 40^\circ$
(30-80 MHz)

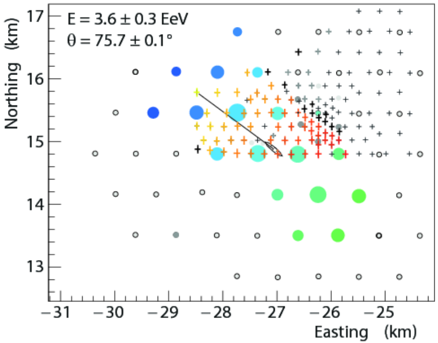


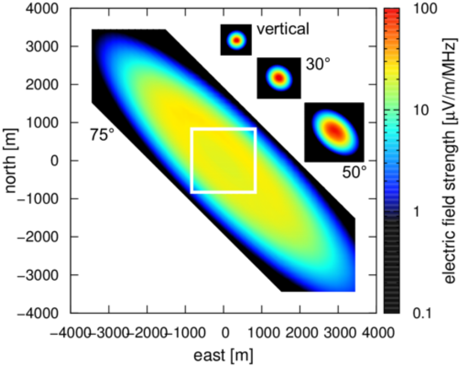
10 PeV, zen $= 61^\circ$
(30-80 MHz)



10 PeV, zen $= 70^\circ$
(30-80 MHz)

- Auger Engineering Radio Array (AERA) has shown that highly inclined showers can be detected using radio arrays.
- Leave a large footprint on the ground.





The footprint of an inclined shower in AERA