# Radio detection of Cosmic Rays in the GHz band at the Pierre Auger Observatory

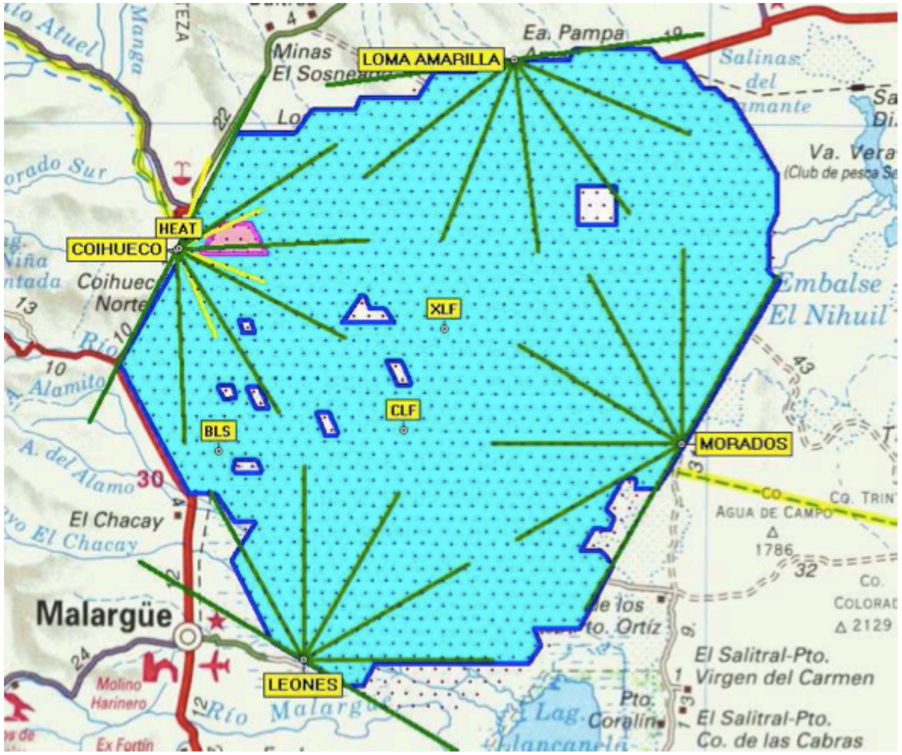
Imen Al Samarai[1]
On behalf of the Pierre Auger Collaboration[2]

1 Institut de Physique Nucléaire d'Orsay
2 Pierre Auger Observatory, Province of Mendoza, Argentina

# Outline

- Pierre Auger Observatory
- Microwave emission
- Microwave detectors at the Pierre Auger Observatory
- Status and Results
- Future enhancements

# The Pierre Auger Observatory




- $3000\ km^2$ in *pampa Amarilla*, Argentina
- Surface detector (SD)
  - 1660 water Cherenkov detectors, triangular grid, 1500 m spacing
  - 100% duty
- Fluorescence detector (FD)
  - 27 optical telescopes in 5 buildings
  - ~ 13% duty cycle

- Data taking started in 2004
- Detector completed in 2008

**Data and results**

- High quality data in stable and continuous operation
- Measurements of the UHECR above 1 EeV with unprecedented sensitivity

# Measurement of air showers with radio detection

## Aims of the radio detection

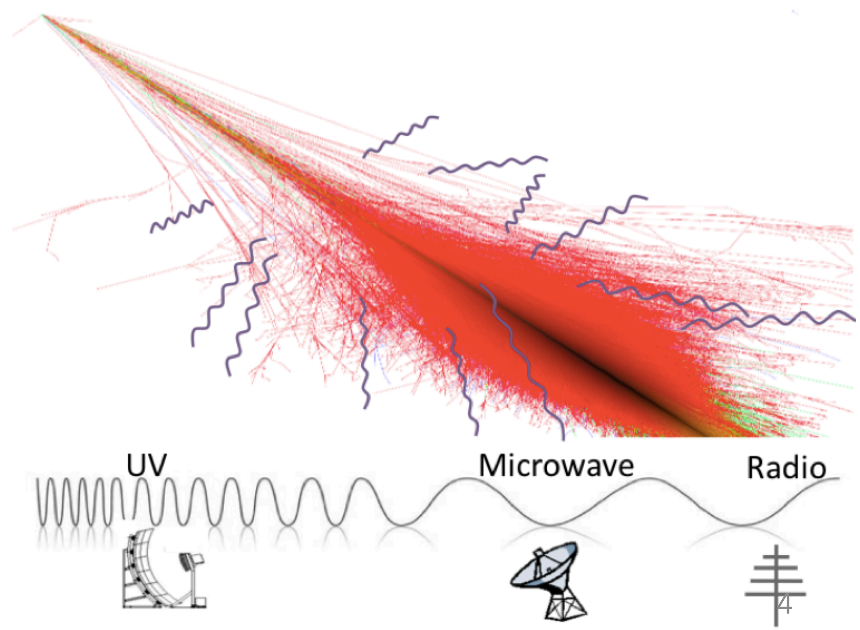
- Enhance the capabilities of the observatory in determining the UHECR mass composition
- Study the requirements for a very large aperture detection system in the next generation of air shower arrays

## Electromagnetic waves from air showers

- Several emission processes
- Different λ ranges

Advantages of the radio detection

- High duty-cycle
- Cost-effective approach



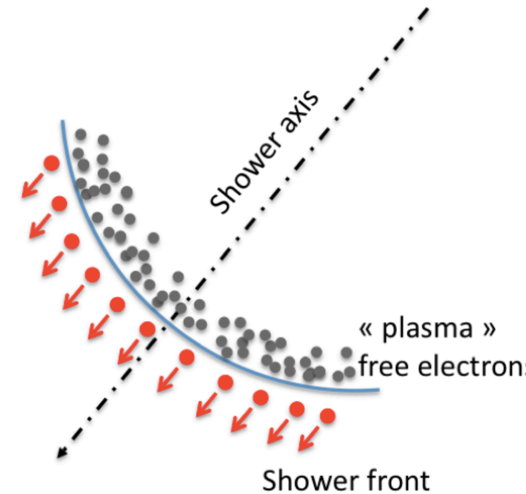
# Microwave emission

## Molecular Bremsstrahlung Radiation (MBR)

- EAS charged particles → Ionization → plasma
- Free electrons interact with air molecules

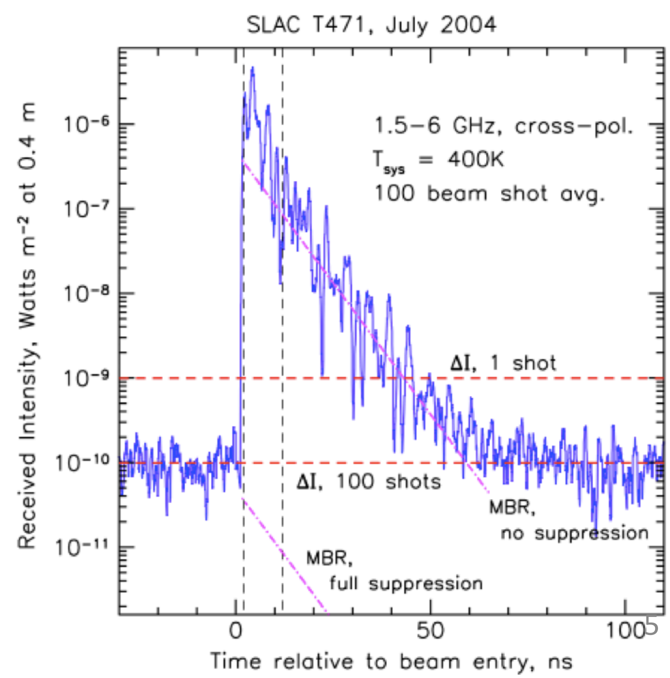
→ Bremsstrahlung emission in microwave regime

- Unpolarized and isotropic emission
- Scaling with no. of secondary charged particles




## Initial beam measurements

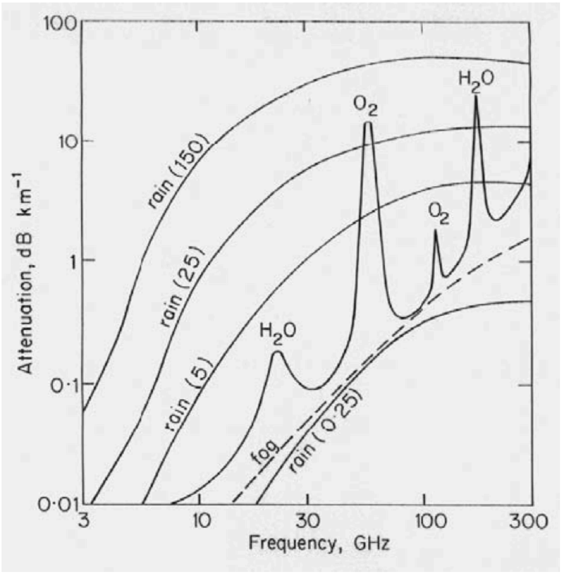
- SLAC T471 experiment - Gorham et al. Phys. Rev. D78 (2008)
- GHz emission observed from electro-magnetic cascades in anechoic chamber



# Microwave emission

## Potential for an FD-like detection technique

- Observation of the shower longitudinal development
- Nearly 100% duty cycle
- Low background and limited atmospheric effects: microwave absorption ≤ 0.05 dB/km
- Low cost (TV satellite) → Ability to cover large area




## Several issues to be clarified

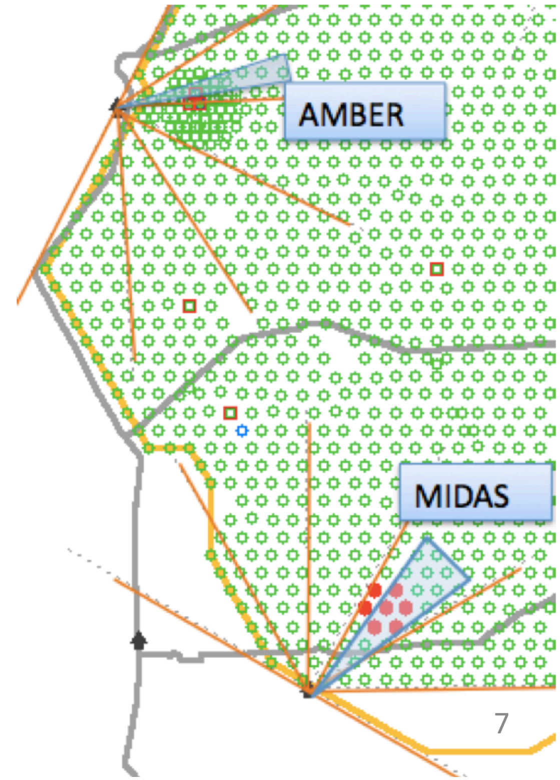
- Spectral intensity of this microwave radiation (MBR yield)
- Scaling with the primary energy (linear or quadratic ?)
  → New generation of experiments: Amy@Frascati, Maybe@Argonne

# Detector prototypes at the Pierre Auger Observatory

**First approach**

Parabolic dish reflector, instrumented with an array of antenna horns

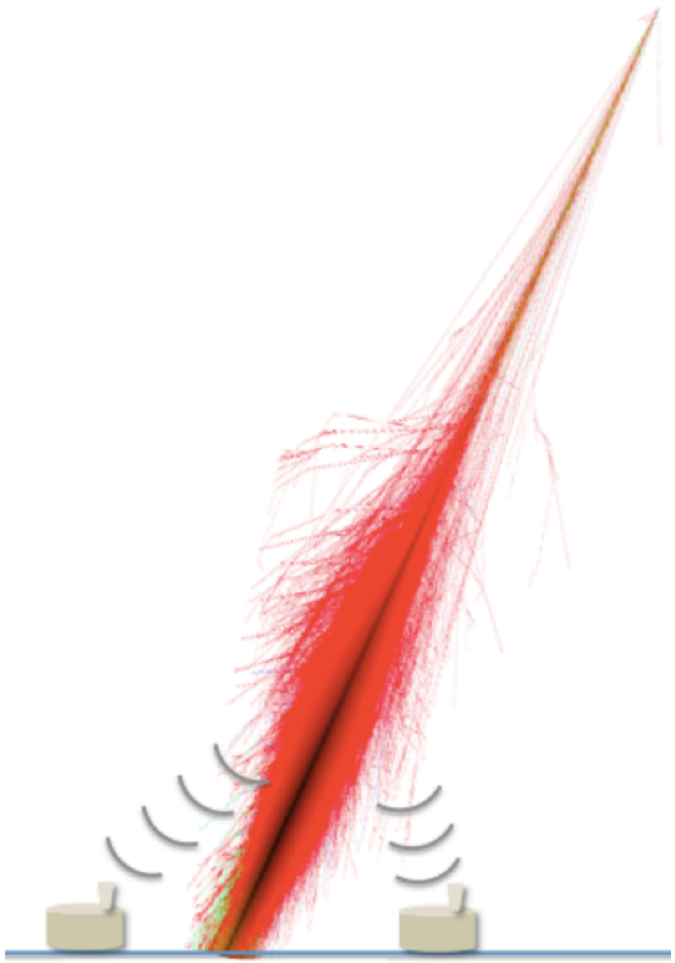
- Effective area ~ 10 $m^2$
- Several kilometers (O(10km)) from the shower.
- Configuration similar to fluorescence telescopes.



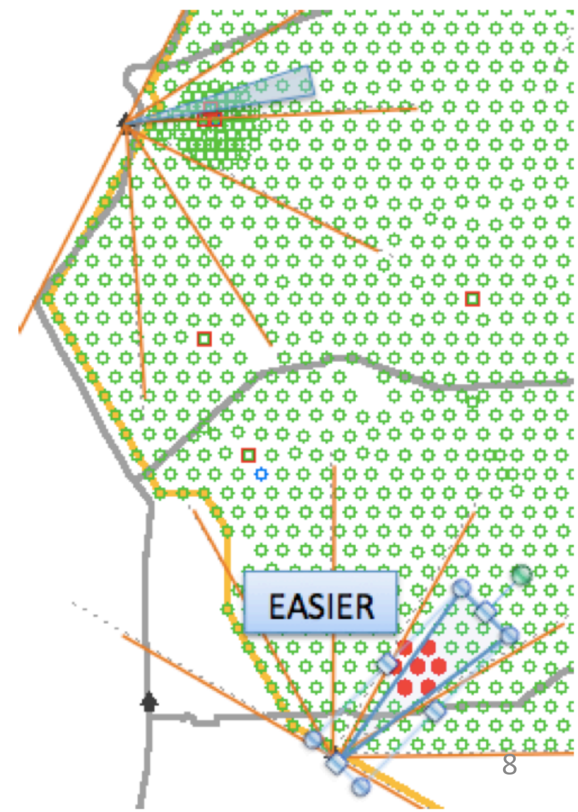
# Detector prototypes at the Pierre Auger Observatory

**Second approach**

Feed horns located on each surface particle detector



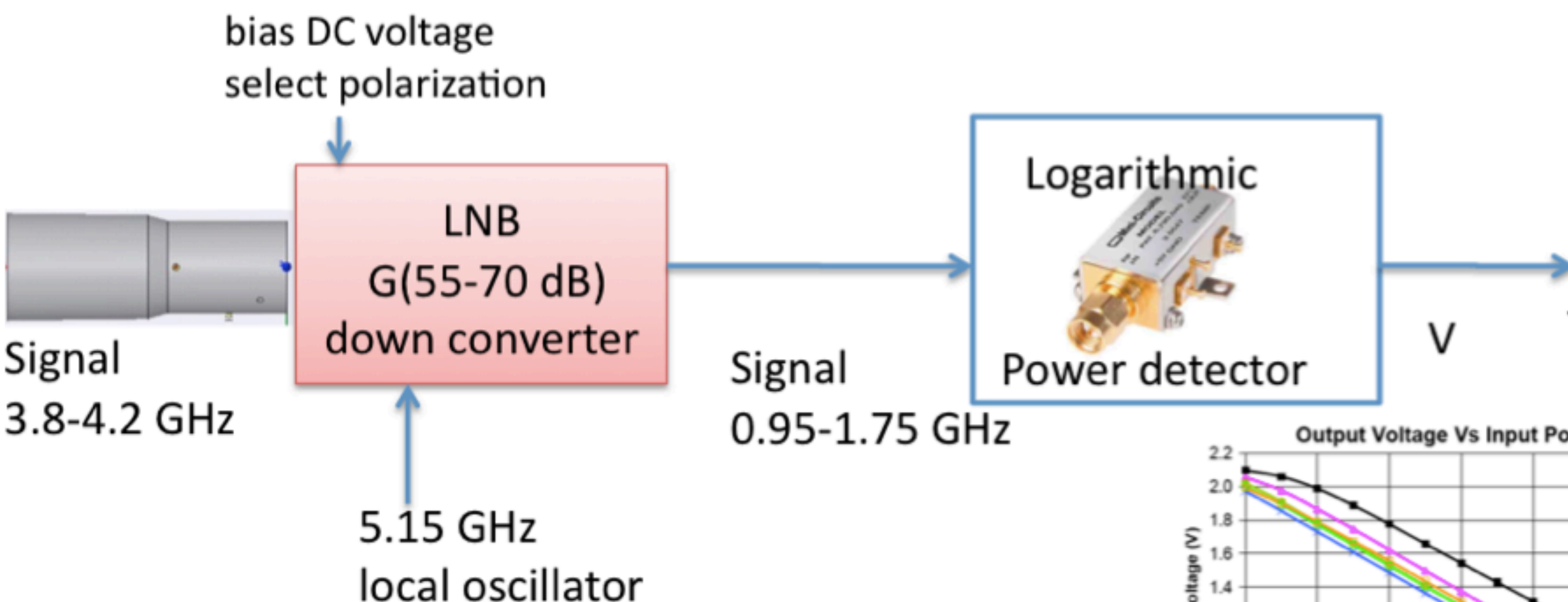
- Small effective area (O(0.003m$^2$)) large field of view (60°)
- Within ~ 3 km from the maximum of the shower development.
- radio signal compressed in time.

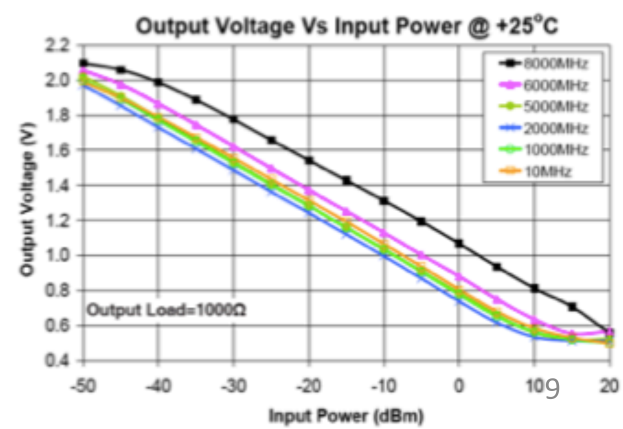


# Signal treatment

**Available satellite communication hardware**

- in the C-band (3.4 GHz−4.2 GHz)
- in the Ku-band (10.7 GHz−12.7 GHz)



# AMBER: Air-shower Microwave Bremsstrahlung Experimental Radiometer

## AMBER receiver

- 2.4m off-axis parabolic reflector, optical axis 30° in elevation
- 4 dual polarized dual band feed horns (C-band and Ku-band),
- 12 single polarization C-band horns (FoV) of 7◦ × 7◦.

## External trigger

- Wait for an SD trigger
- Perform a fast geometrical reconstruction of the SD events
- Calculate the time at which the shower crossed the FOV→read corresponding data
- Recording a long trace (150 μs) to overcome the uncertainty of the method

# AMBER: Air-shower Microwave Bremsstrahlung Experimental Radiometer

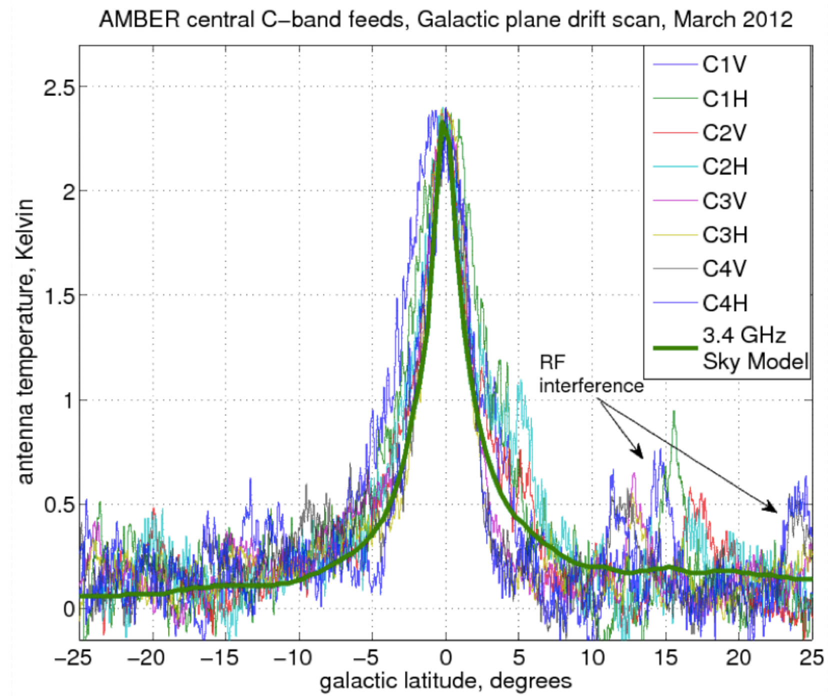
**Calibration method :**

Calibration of seperate components :

- The power detector using a network analyzer
- The gain and noise figure of the LNB using Y-factor measurement
- The dish calibrated separately using a Y-factor measurement using RF absorber foam and a calibrated LNB

*Complementary calibration :*

- Sun transit scan to validate the expected optical performance
- Microwave signal emitted by the galactic plane



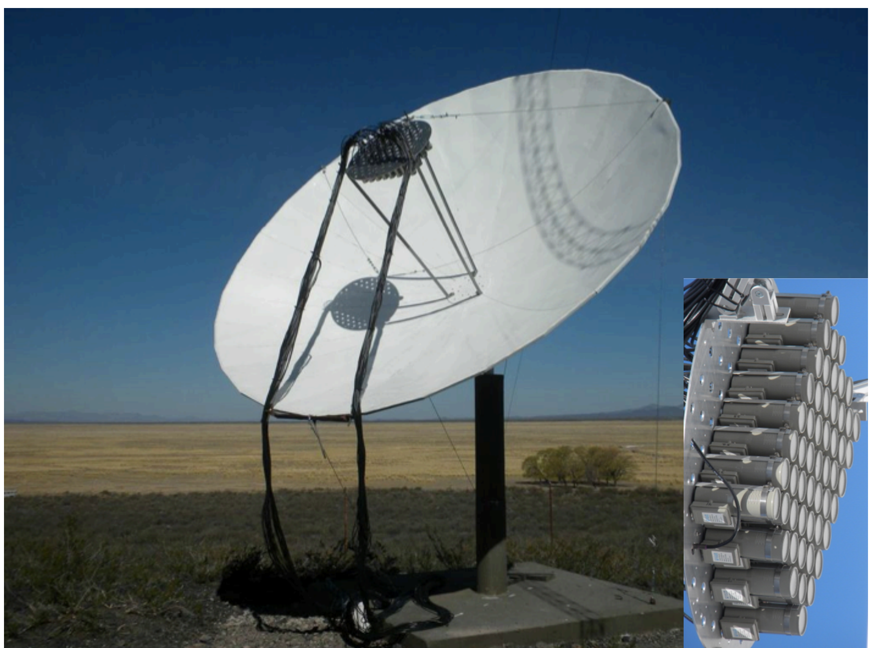

*Temperature elevation during the crossing of the Galactic Plane in the AMBER field of view*

**Status**

- More than 18 months of data, coincidence analysis with the SD is ongoing
- Upgrade of the camera → improve the sensitivity by 40%
- FOV to be extended to 17°

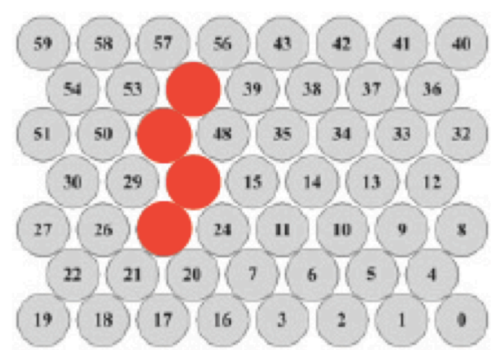
# MIDAS: Microwave Detection of Air Showers

**MIDAS receiver**
- 4.5 m parabolic reflector
- 53 pixel camera
- C-band feeds, $1.\ 3^{\circ} \times 1.3^{\circ}$
- total FOV of $20^{\circ} \times 10^{\circ}$



**Self-triggering system**
- *First Level Trigger*:
  - At the pixel level
  - Issued if the running sum on 1μs exceeds a certain threshold
  - FLT rate kept at 100 Hz
- *Second Level Trigger*:
  - pixels (at least 4) with FLT
  - time coincidence
  - Compatibility with an EAS pattern topology

→ Accidental SLT rate = $3.10^{-4}$ Hz



# MIDAS: Microwave Detection of Air Showers

**Calibration**

Sun transit for absolute calibration → Tsys= 65 +/-3K

**3 months of data taking in Chicago**

→ No clear event candidate was found

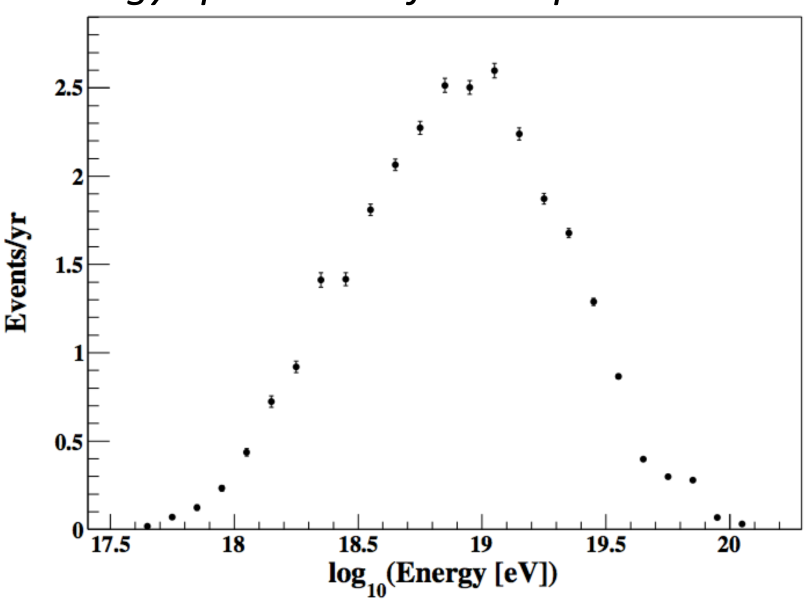
→ Exclusion of a microwave signal with quadratic scaling with the air shower energy

→ Linear scaling hypothesis : realistic simulation of the MIDAS detector yields a total of ≃ 30 events per year

**Status**

- Now installed at the Pierre Auger Observatory
- Data taking since 2013
- Data analysis is ongoing

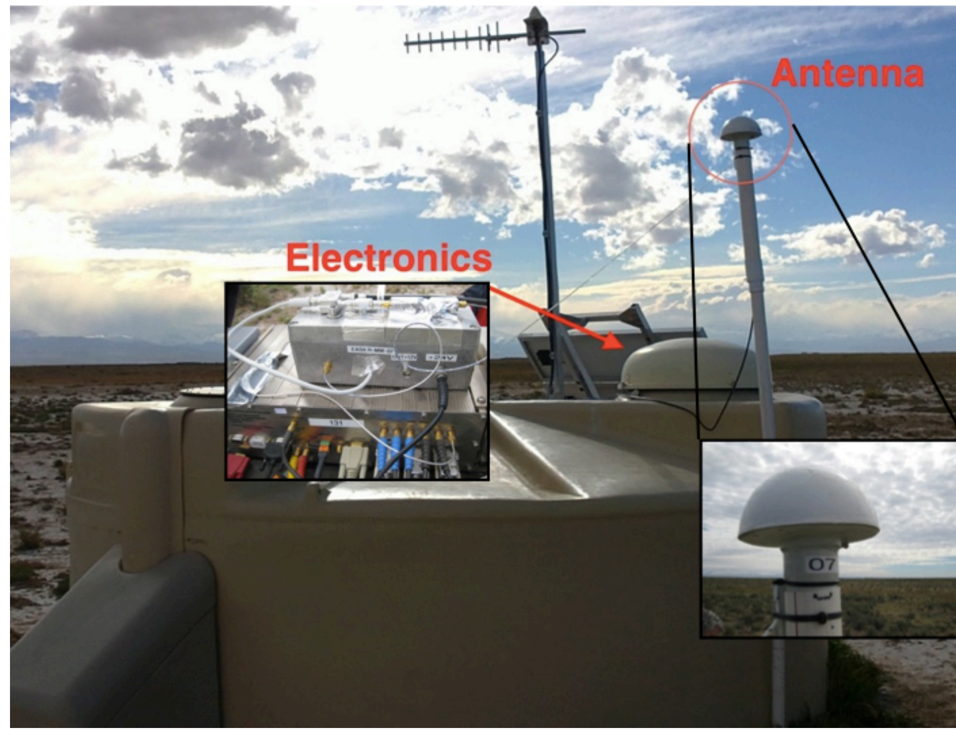
*Energy spectrum of the expected events*



# EASIER: Extensive Air Shower Identification using Electron Radiometer

**EASIER antenna system**

- Upward-facing feedhorns mounted directly above a SD station
- FoV ~ 60°, low Tsys
- Trigger from local surface detector station
- Digitization with the existing Flash ADC at 40 MHz, Auger DAQ
- 61 stations equipped in April 2011

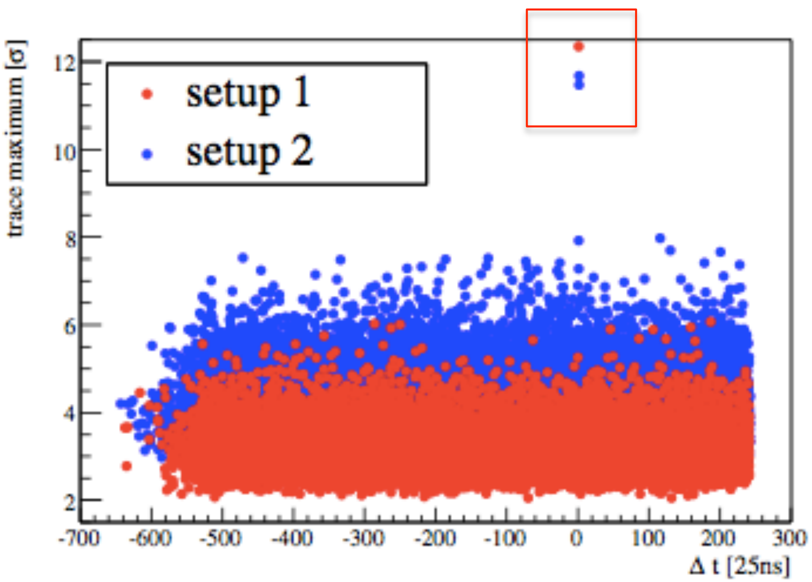


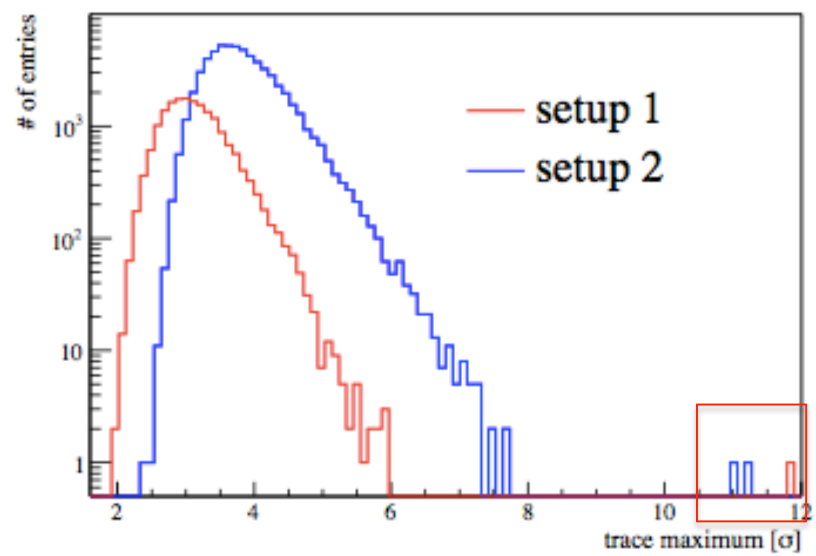
# EASIER: Extensive Air Shower Identification using Electron Radiometer

- Recording of 3 unambiguous radio signals in coincidence with air showers detected by the SD array

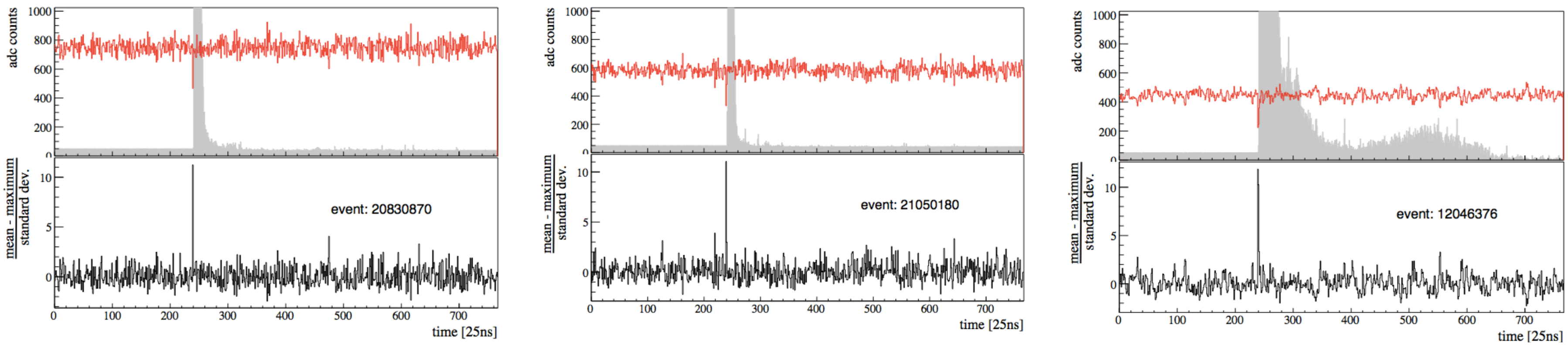
→ Signal Max > 10 times the trace fluctuations

→ Located one or two bins (25 to 50ns) before the start time of the particle signal



# EASIER: Extensive Air Shower Identification using Electron Radiometer




| Auger Id | 12046376 | 20830870 | 21050180 |
|---|---|---|---|
| station | 342 | 429 | 306 |
| date | 2011/06/30 | 2013/01/03 | 2013/02/07 |
| energy [eV] | $(1.32 \pm 0.12)\times10^{19}$ | $(1.71 \pm 0.1)\times10^{19}$ | $(2.56 \pm 0.41)\times10^{18}$ |
| zenith [°] | $29.7 \pm 0.3$ | $55.2 \pm 0.1$ | $47.4 \pm 0.5$ |
| azimuth[°] | $343.4 \pm 0.8$ | $33.8 \pm 0.1$ | $289.4 \pm 0.6$ |
| Distance to axis [m] | $136 \pm 40$ | $268 \pm 11$ | $193 \pm 15$ |
| $\Delta$t to trigger | 1 | 2 | 2 |
| radio maximum [sigma] | 11.86 | 11.23 | 11.05 |
| polarization | E-W | E-W | E-W |
| time length [time bins] | 2-3 | 1 | 1-2 |

# EASIER: Extensive Air Shower Identification using Electron Radiometer

- Short distance from the antenna to shower axis, and short pulse favors a beamed emission
- The East-West orientation of the antenna that detected the radio signals might point to a geomagnetic origin
- Simulations do not allow the rejection of a coherent emission

→ **3 candidates rejected**

# EASIER: Extensive Air Shower Identification using Electron Radiometer

## Limits on an isotropic emission

- Selection of stations with distance to shower core > 300m
- Noise estimation from first bins [0,150]
- Trace maxima selected around particle signal start (bin 242)

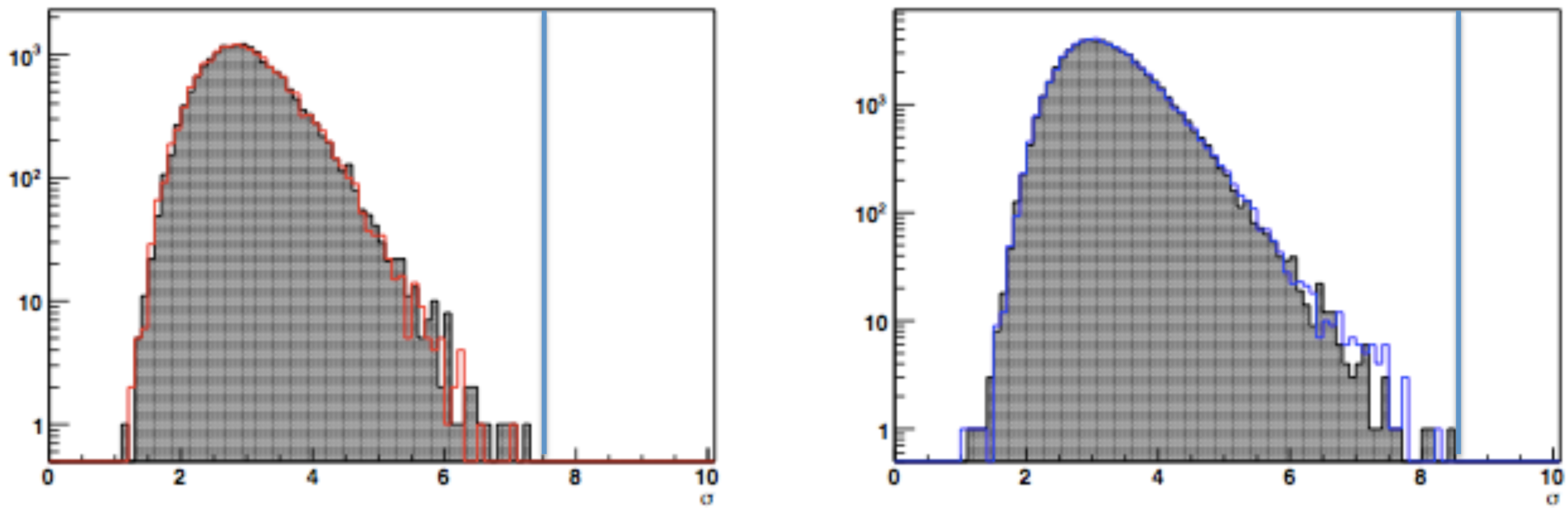


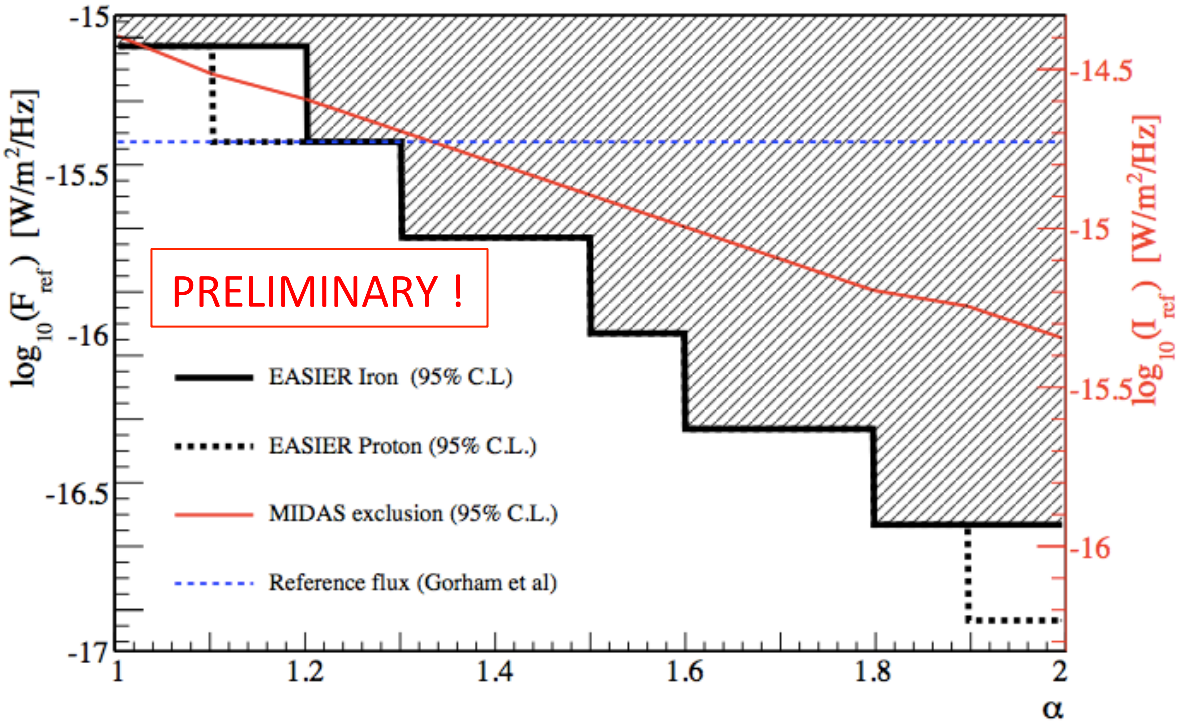

Figure 5.23: Distributions of the maximum in the window [0-150] in black and in color are represented the distributions of the maximum in the interval [230-380].

→ **No event found**

# EASIER: Extensive Air Shower Identification using Electron Radiometer

Limits on an isotropic emission

$$F(t) = F_{ref} \cdot \Gamma \cdot \frac{\rho}{\rho_0} \cdot \left(\frac{d}{R(t)}\right)^2 \cdot \left(\frac{N(t)}{N_{ref}}\right)^{\alpha}$$




- $\alpha$ =2 full coherent emission
- $\alpha$ =1 non-coherent emission

**$F_{ref} \lesssim 8\times10^{-16}$ W/m²/Hz with $\alpha \geq 1$**

*Romain Gaior PhD thesis*

# EASIER: Extensive Air Shower Identification using Electron Radiometer

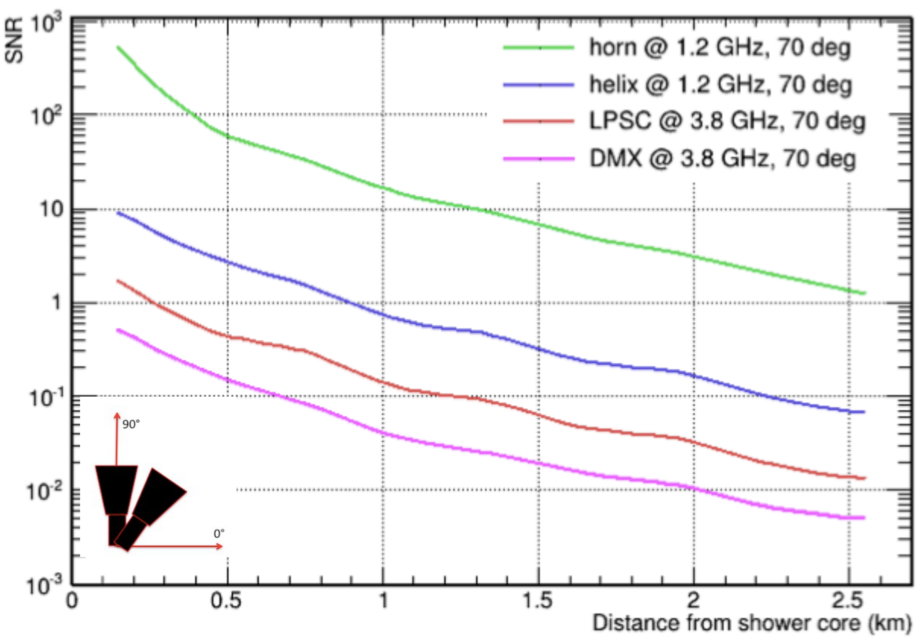
**Future developments :**

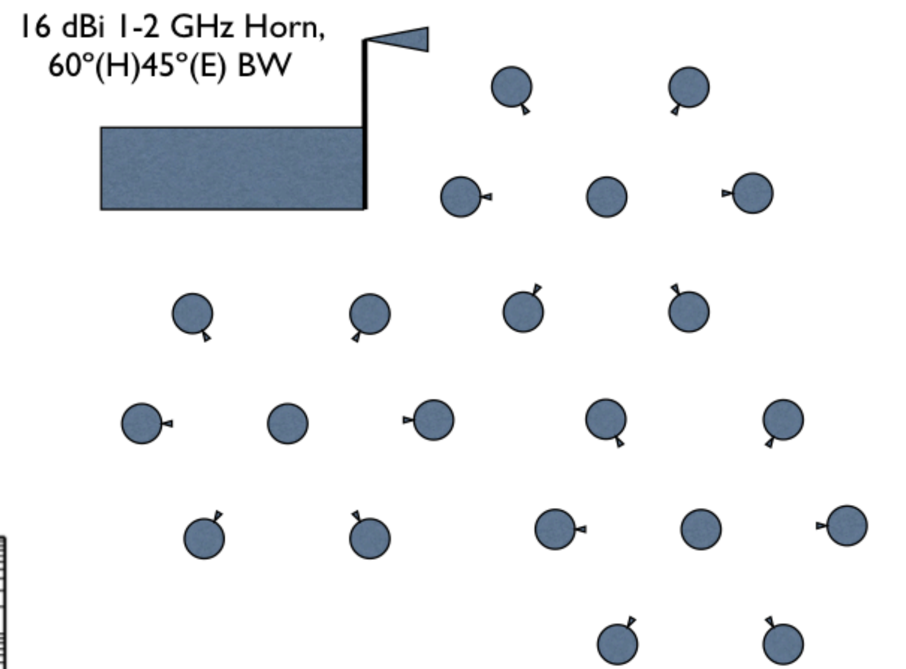
- Shift detection range to 1.2 GHz central frequency
- Incline the antennas

**In progress :**

→ Equip prototype hexagones with helix antennas and horn antennas

SNR = <$S_{max}$> (W) / $P_A$ (W).




# Conclusion

- 3 prototypes microwave detection of air showers are running with stable data taking
- First three unequivocal radio signals detected in the GHz range by EASIER in coincidence with air showers detected by Auger SD
- Emission mechanism ratherly due to time compression and/or geomagnetic effect

## Future enhancements

- In EASIER, further studies will be focused on the search for a fainter but longer signal and from more distant air showers
- Recent installation of MIDAS, the ongoing analysis of the AMBER data and its future upgrade will help in disentangling the origin of the emission process.