The Dark Past and Bright Future of Radio Detection of UHECRs

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UCLA

IPMU

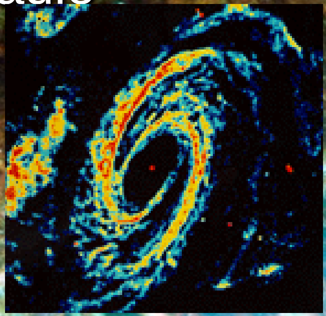
Japan, Dec 5 2013

Electromagnetic “Windows” into the Universe

Observational astronomy
Most likely the oldest of natural sciences

Stonehenge 2500 BC - 2000 BC

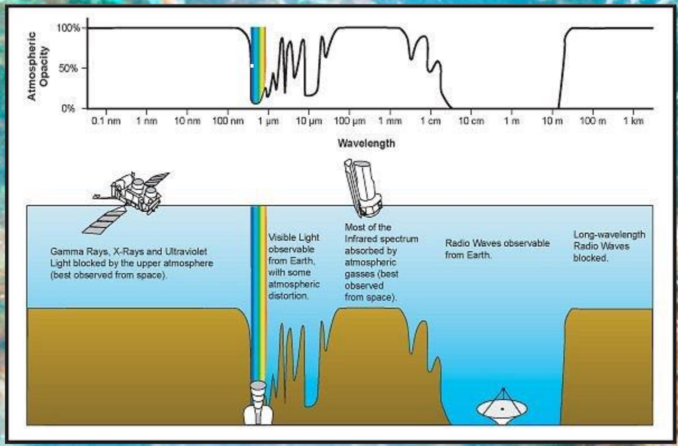
Radio



InfraRed

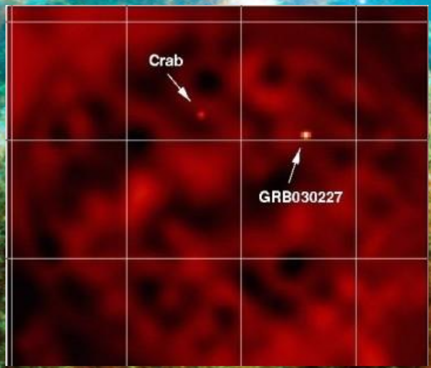
NGC 5746

Spitzer Space Telescope



Invention of the telescope in 1609 by **Galileo Galilei**

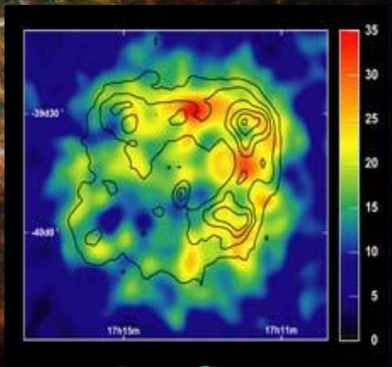
Gamma Ray and X-ray



Crab Nebula and GRB from February 27, 2003

INTEGRAL

High Energy Gamma Ray



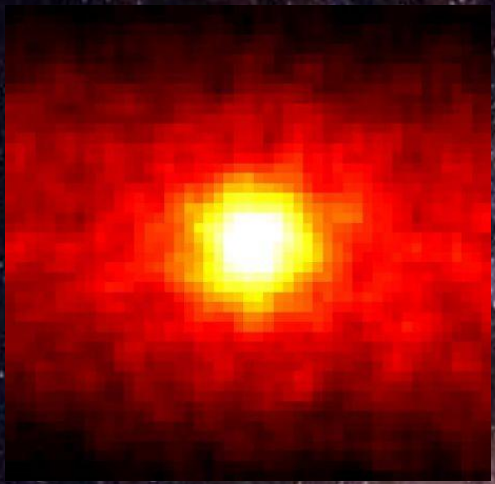
Supernova RXJ1713.73946

HESS

Crab Nebula, 1054 AD supernova
FORS Team, 8.2-meter VLT, ESO

Other messengers

Neutrinos

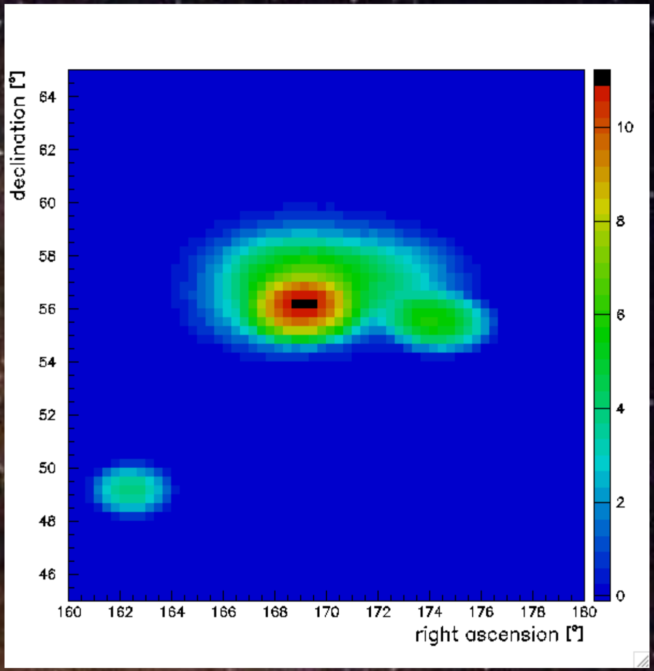


Neutrino image of the Sun by SuperK

Gravitons

LIGO

Cosmic Rays

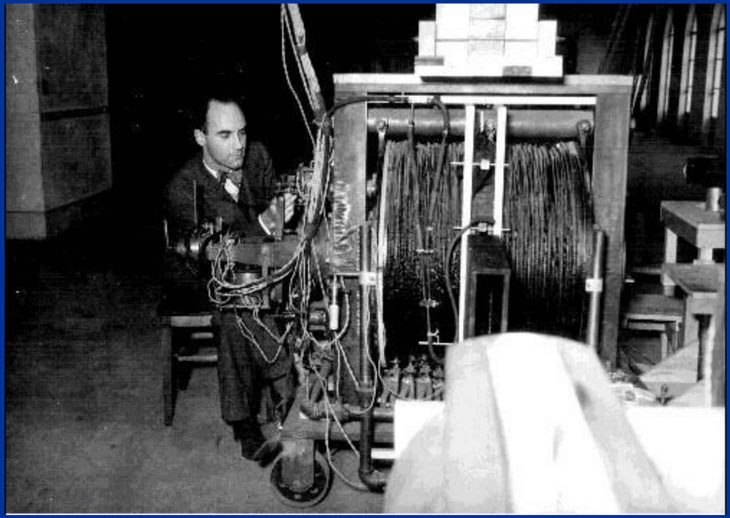


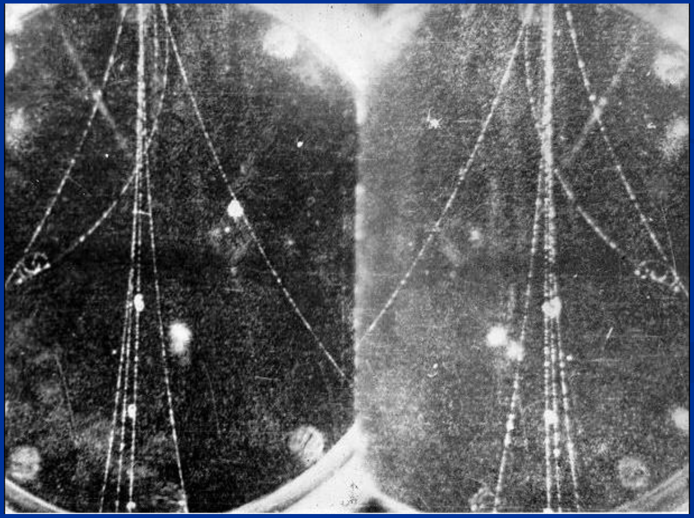
HiRes “Hottest” region

night sky near Sagittarius
red marks the primary stars

Cosmic Rays

- **1912 - Hess discovered “penetrating radiation" coming form space**
- **1929 - Skobelzyn explained simultaneous tracks in Wilson cloud chamber**
- **1932-1947 – positron, muon and kaon were discovered in cosmic rays**
- **1991 Fly’s Eye observed $3x10^{20}$ eV particle (energy of a fast baseball)**



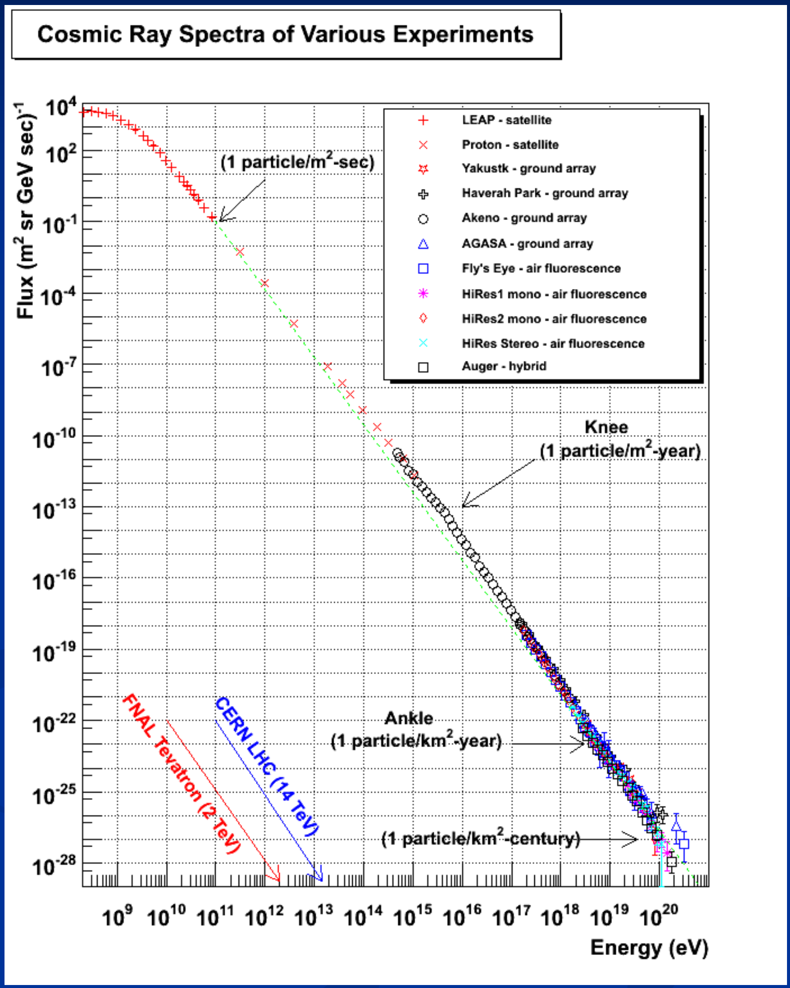


In days before accelerators, physicists climbed mountains to study high energy particles coming from space.

Some went even higher…

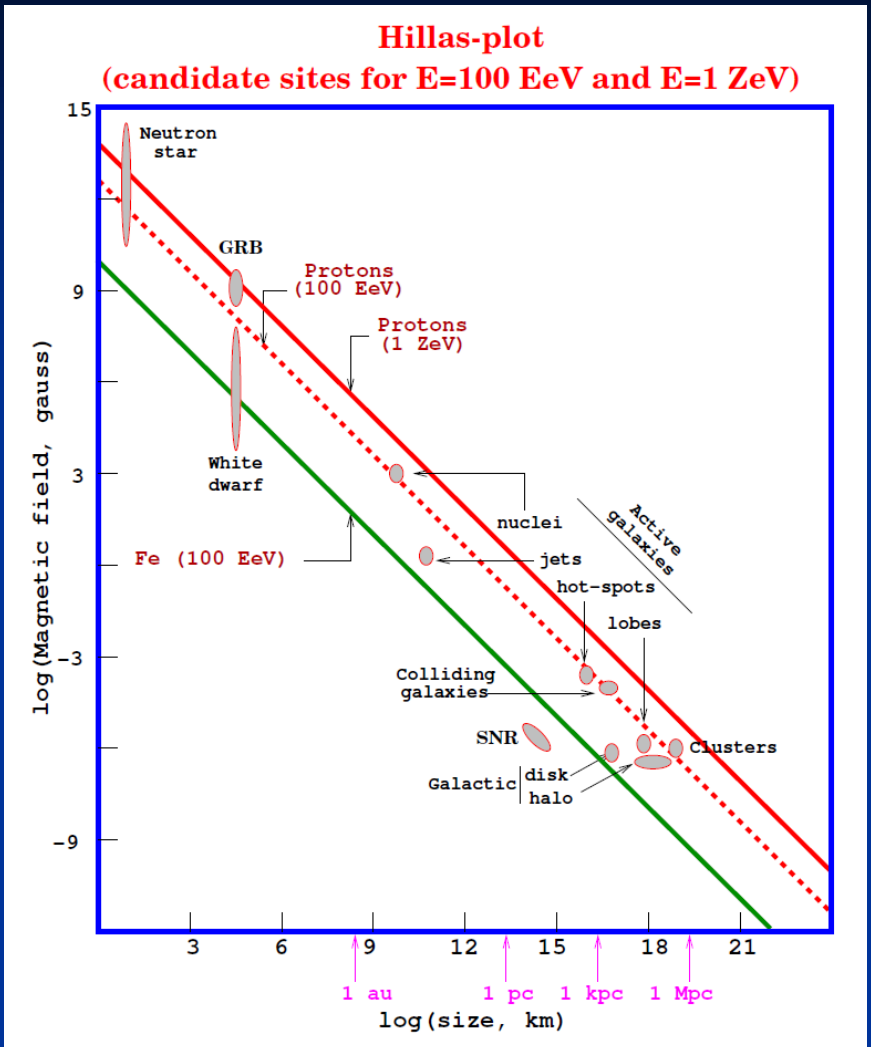
Why ultra-high energy cosmic rays?

- Non electro-magnetic "window" into the Universe
- The origin of the UHECRs is unknown
  - Nearby sources are excluded ?
  - Energy of particles coming from distant sources may be suppressed (GZK mechanism)
- Hyper-powerful particle accelerators can reveal new physics
- Charged particles are deflected by the magnetic field
  - Only highest energy particles can point back to their origin



Plot by W. Hanlon based on S. Swordy's plot

Candidate sources of the UHECRs

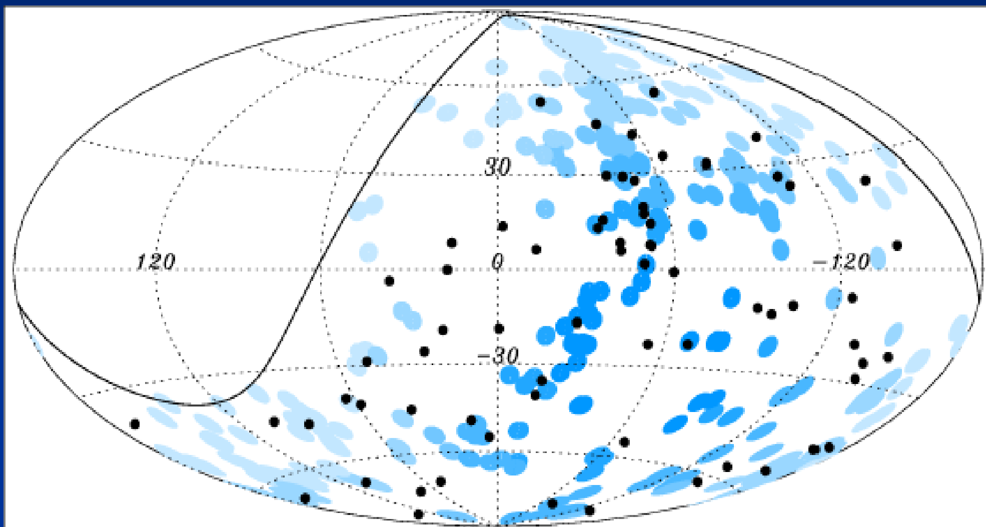


- Sources are:
  - Compact & highly magnetic
  - Large & moderately magnetic
- Light composition - extragalactic sources:
  - GRB - gamma-ray bursts
  - SNR – supernova remnants
- Heavy composition - galactic sources that are now extinct:
  - GRBs
  - Hypernovae
  - collapsars

- Z-bursts: $\nu + \bar{\nu} \rightarrow \mathrm{Z} \rightarrow \mathrm{hadrons}$
- AGNs converting dark matter into high energy protons (A. Grib, Yu. Pavlov, Grav.Cosmol.15:44-48,2009)
- Decay of super-heavy dark matter "X particles"
- Magnetic monopole decays

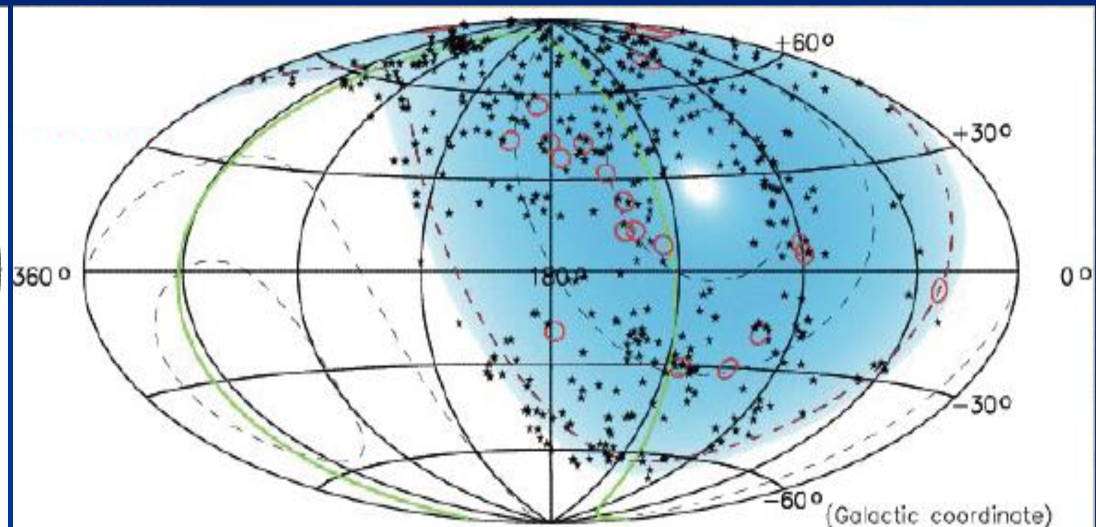
UHECR Astronomy

Auger



Black dots - 69 Auger events with E > 55 EeV
Blue - 3.1 degree circle around 318 AGNs from VCV catalog. Astroparticle Physics 34 (2010) 314

Telescope Array



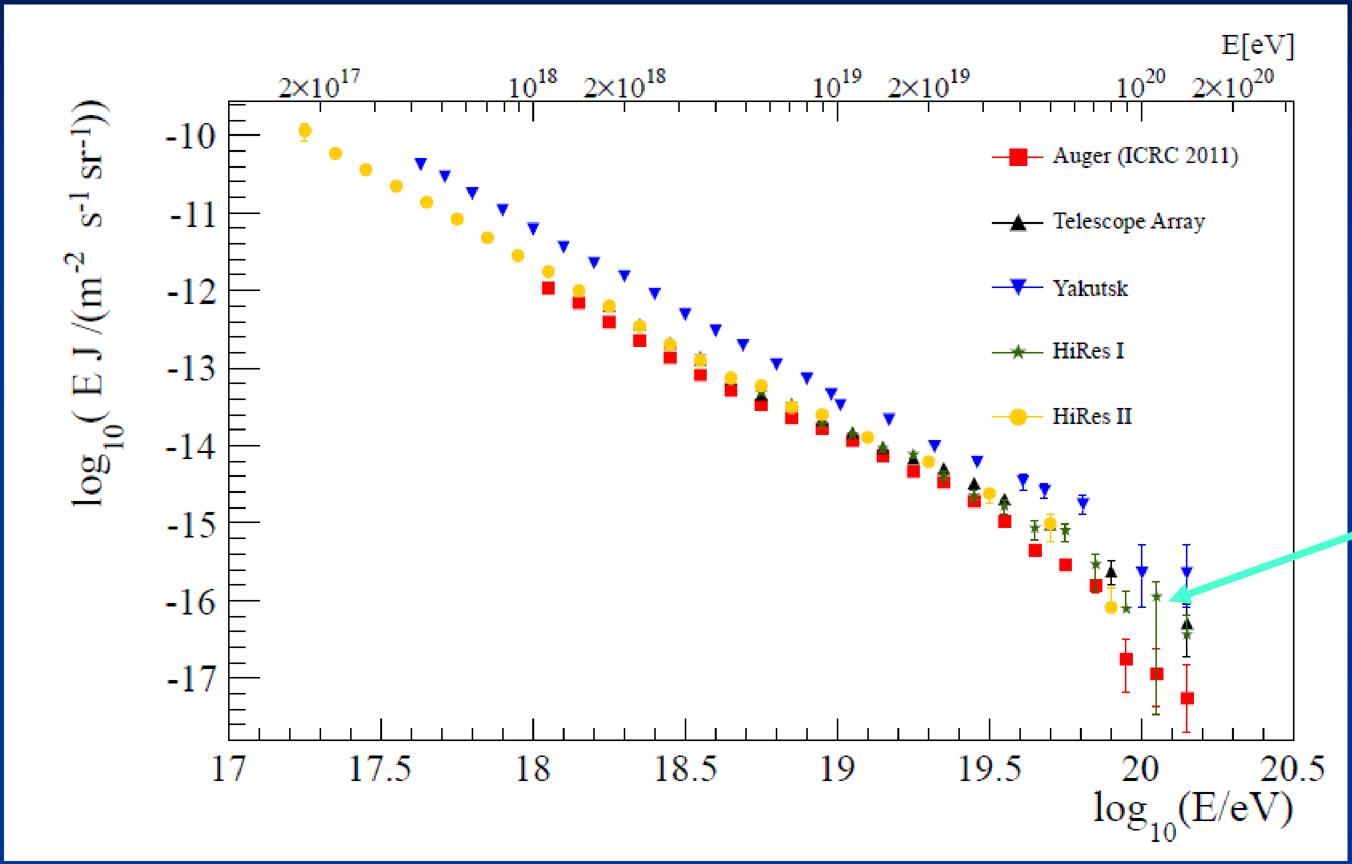
Red: 20 TA events with E > 57EeV in Galactic coordinates
Black: AGNs closer than 75Mpc, ICRC 2011

- A correlation with nearby AGNs reported by the Auger (*light composition*?)
- TA and earlier HiRes did not find any correlation

- Need 10 x more data at highest energies to identify sources

  => 10 x aperture of the existing detectors - space missions

Greisen–Zatsepin–Kuzmin (GZK) mechanism

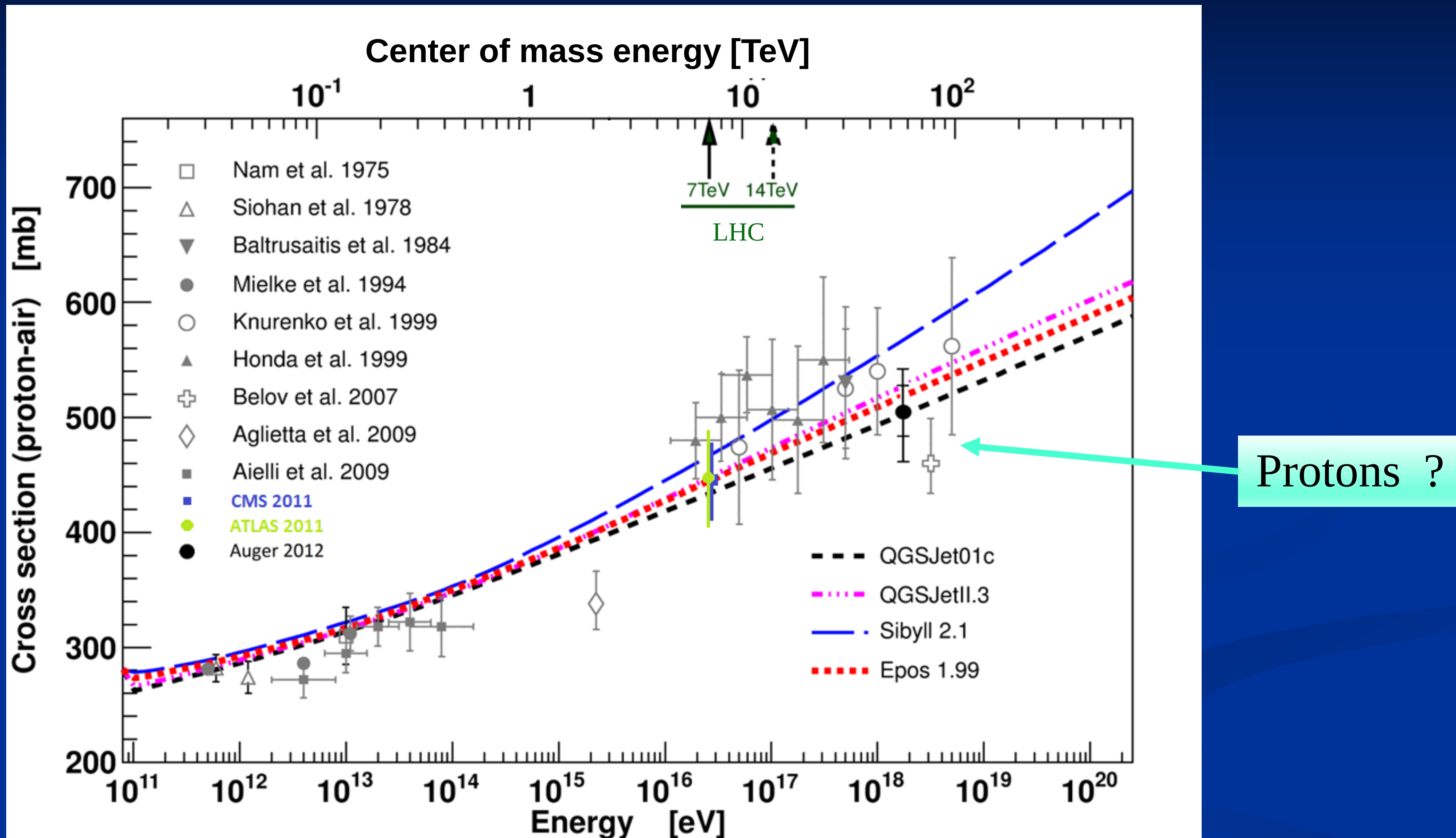


Dawson, Bruce R., et al., EPJ Web of Conferences **53**, 01005 (2013)

Protons – GZK feature
(should see UHE neutrinos)

Heavy – galactic sources
from the past
(no GZK neutrinos)

Particle interactions at ultra-high energies



***p*-air inelastic cross-section measured by accelerators and cosmic-ray experiments**

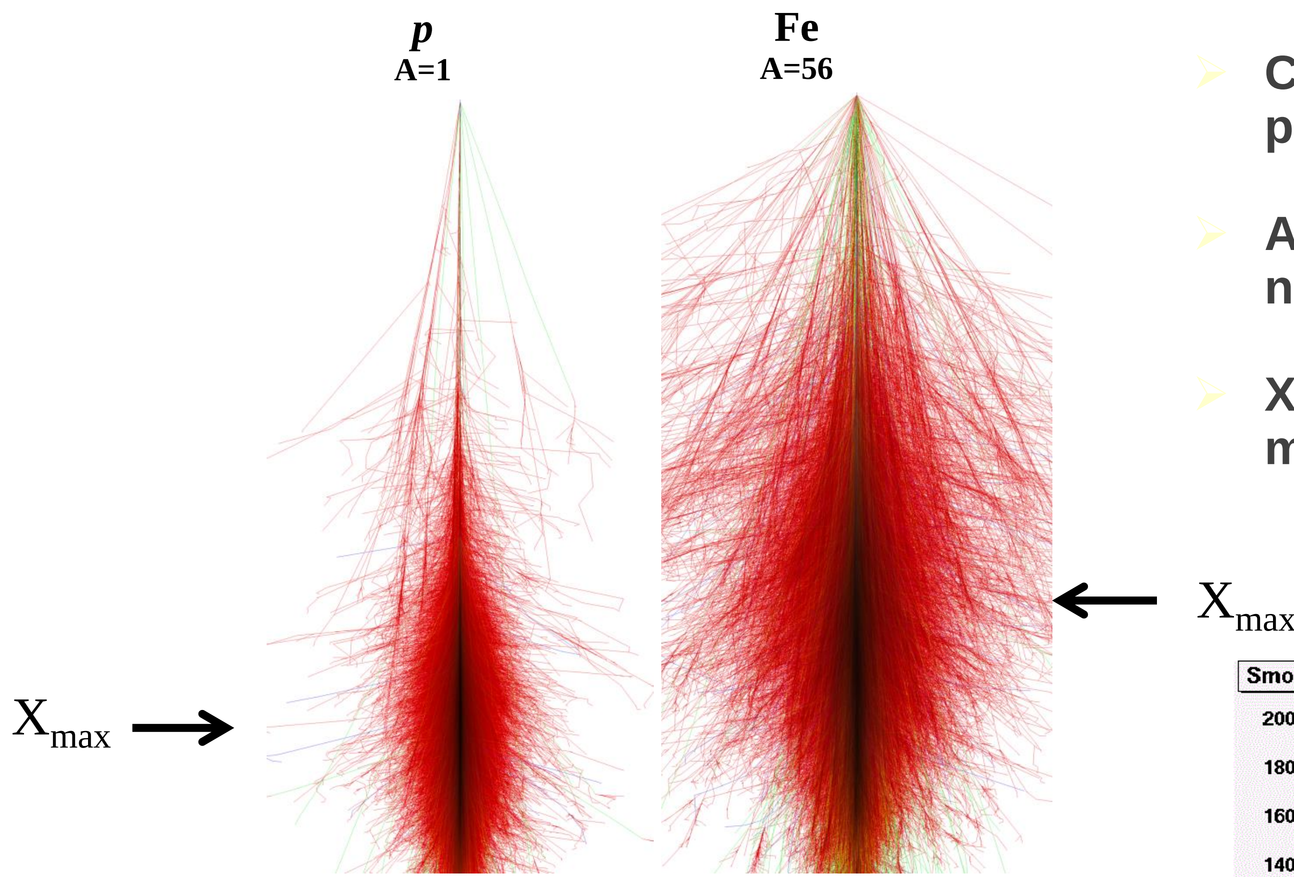
Color lines – different interaction models.

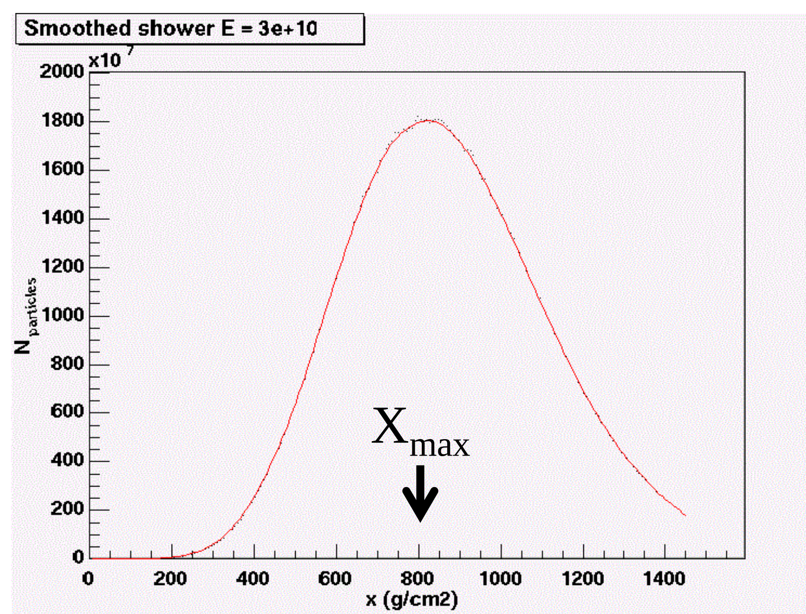
UHECR composition

- **Precise chemical composition measurements are needed to:**
  - **Identify UHECR sources**
  - **Learn about UHECR acceleration mechanism**
  - **Explain the GZK – like feature at the end of the spectrum**
  - **Interpret particle cross-section measurements at UHE**

Extensive air showers

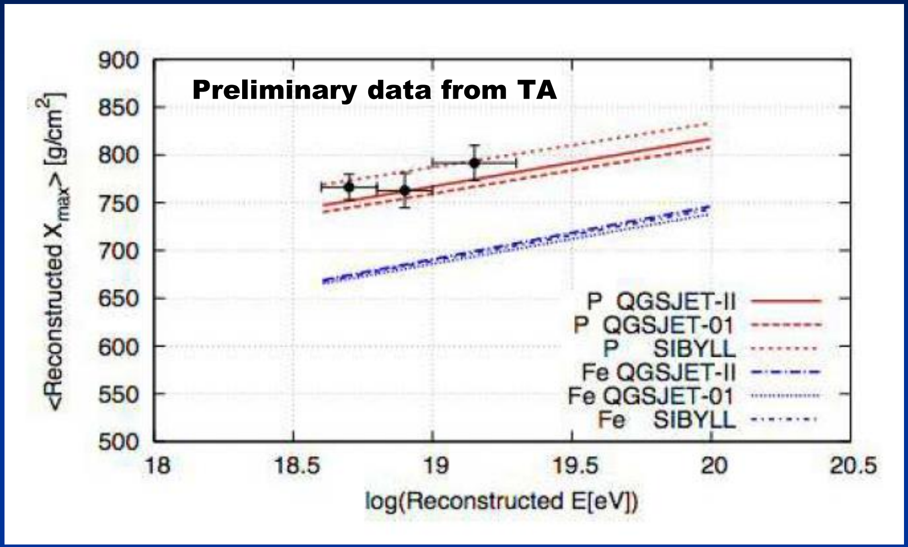
- Caused by high energy cosmic particles
- Air showers induced by heavier nuclei develop earlier
- X_{max} – depth of the shower maximum usually in g/cm^2



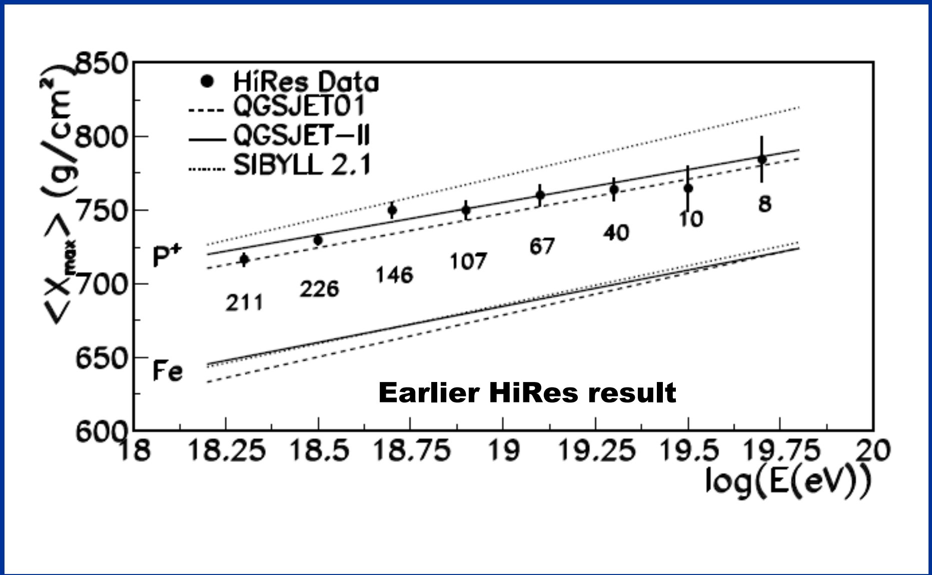


UHECR composition

$\langle X_{max} \rangle$ only analysis

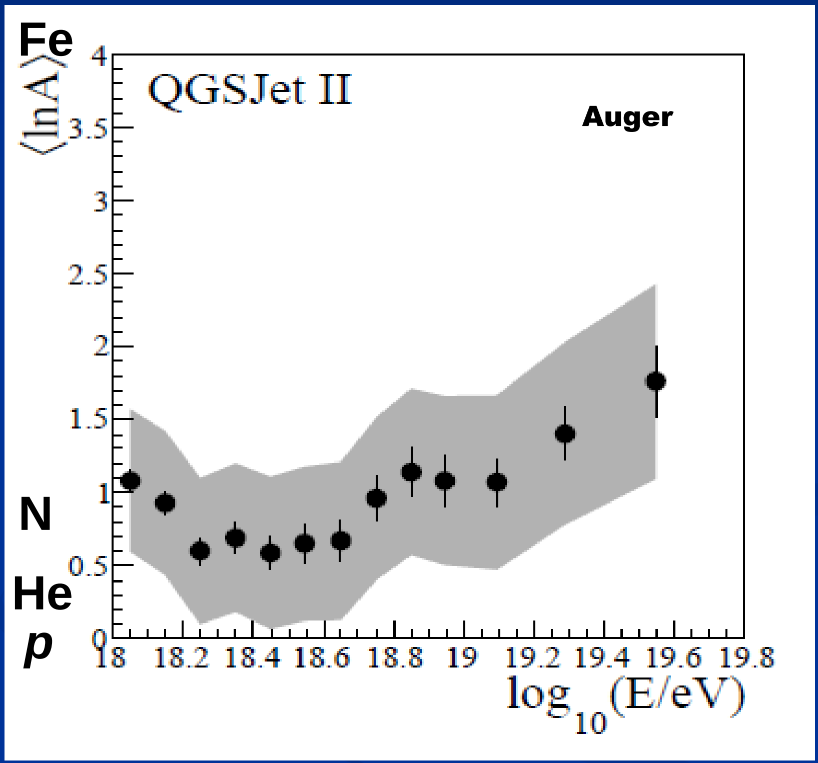


J. Matthews, Nuclear Physics B - Proceedings Supplements Volumes 212–213, March–April 2011, Pages 79–86



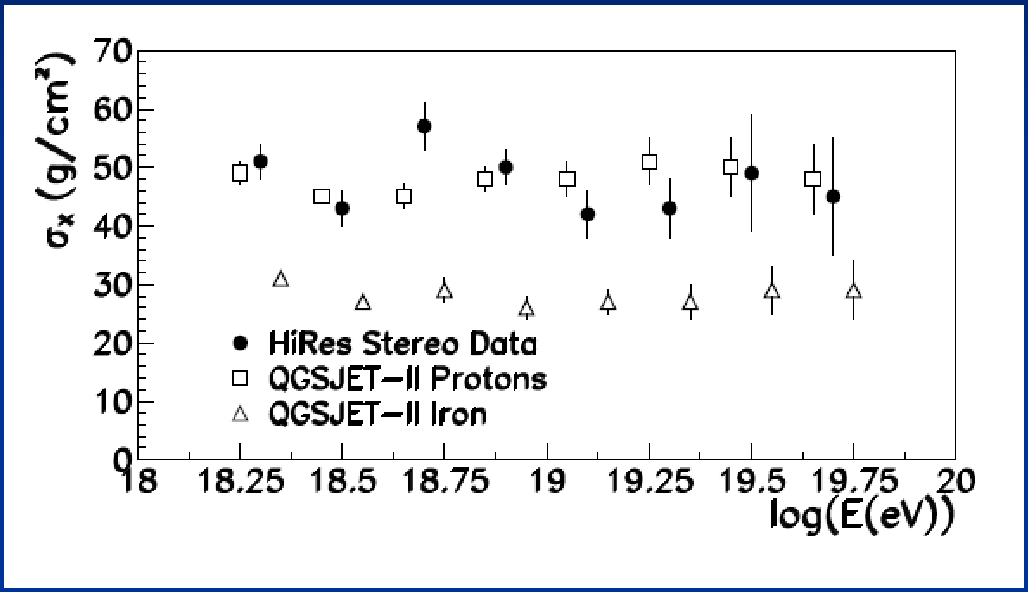
P. Sokolsky, Nuclear Physics B - Proceedings Supplements Volumes 212–213, March–April 2011, Pages 74–78

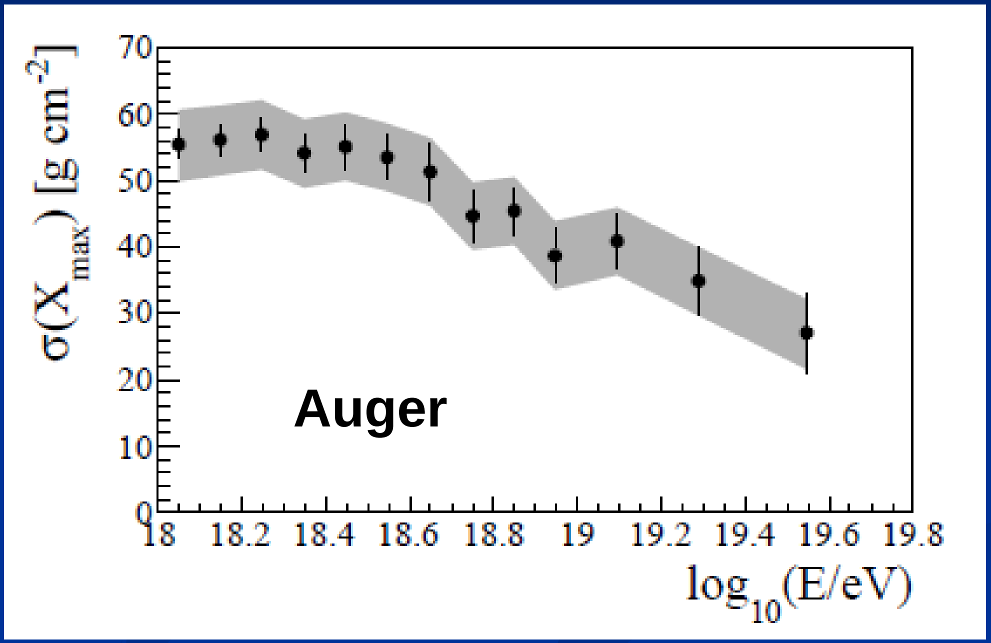
$\langle X_{max} \rangle$ and X_{max} dispersion analysis



Pierre Auger Collaboration, Jan. 2013, arXiv:1301.6637

X_{max} dispersion





Pierre Auger Collaboration, Jan. 2013,
arXiv:1301.6637

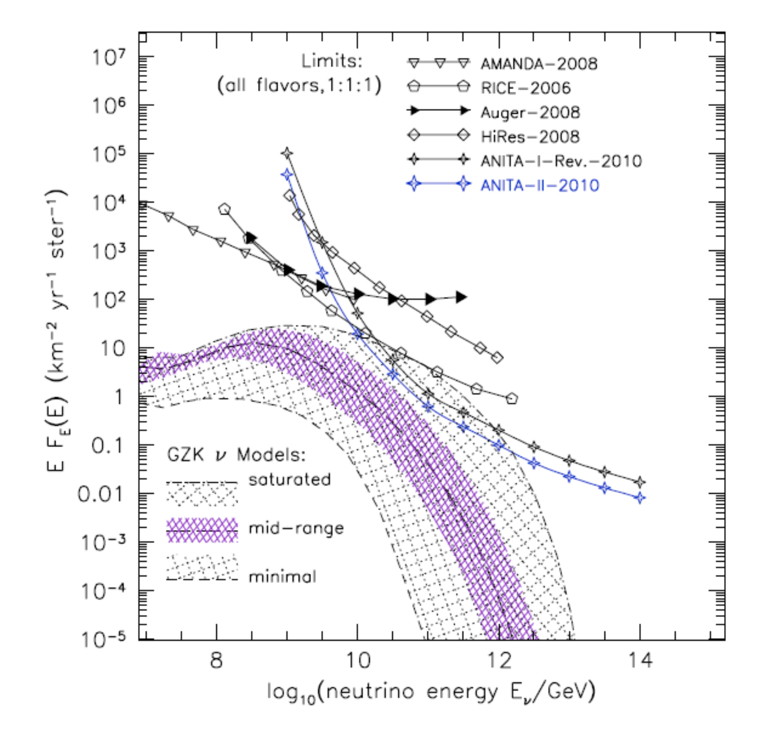
- **No agreement on dispersion of the X_{max} distribution is an indication of the detector bias?**

We need *different* data

No UHE neutrinos?

- ➢**Two ANITA flights did not discover UHE neutrinos above expected background:**
  - ➢**Lorentz invariance violation (LIV)**
  - ➢**New physics**
  - ➢**Heavy composition of UHECRs**

- ➢**IceCube recently reported 28 neutrino events up to 1.2 PeV**

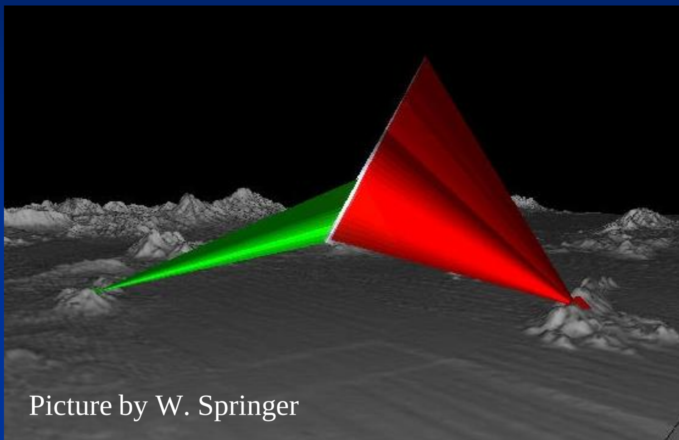


Phys. Rev. D 82, 022004 (2010)

1 V-pol event on background of 0.97 ± 0.42

Air fluorescence

Hires stereo air fluorescence detector in Dugway Proving Ground, Utah 1999-2006


Picture by W. Springer

Camera. 256 PMTs


HiRes building with two mirrors

UV 330-400 nm


PMT

$$e^- + N_2 \rightarrow {N_2}^{*+} + e^-(+e^-)$$

$$e^- + N_2 \rightarrow {N_2}^{*+} + e^-(+e^-)$$
$${N_2}^{*+} + e^- \rightarrow {N_2}^{*}$$

Pros:

- **Energy measurement is calorimetric**
- **Calibration is very well understood:**
- **Ionization loss => track length =>fluorescent emission**

Cons:

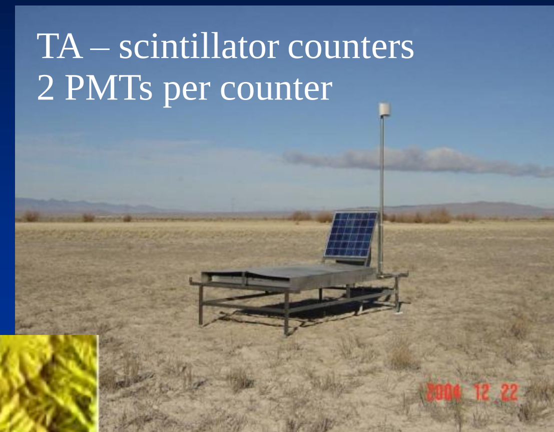
- **10% duty cycle**
- **Aperture is difficult to estimate:**
  - **Energy dependence**
  - **Atmospheric monitoring required (radiosondes, IR cloud monitoring etc)**


HiRes2 detector

Two detectors, 62 mirrors x 265 PMTs = 15872 PMTs

Ground counter arrays

PMT is still the King



Pros:

100% duty cycle

Exposure is easily estimated

Trigger efficiency is 100% for large showers

Self-calibration with atmospheric muons

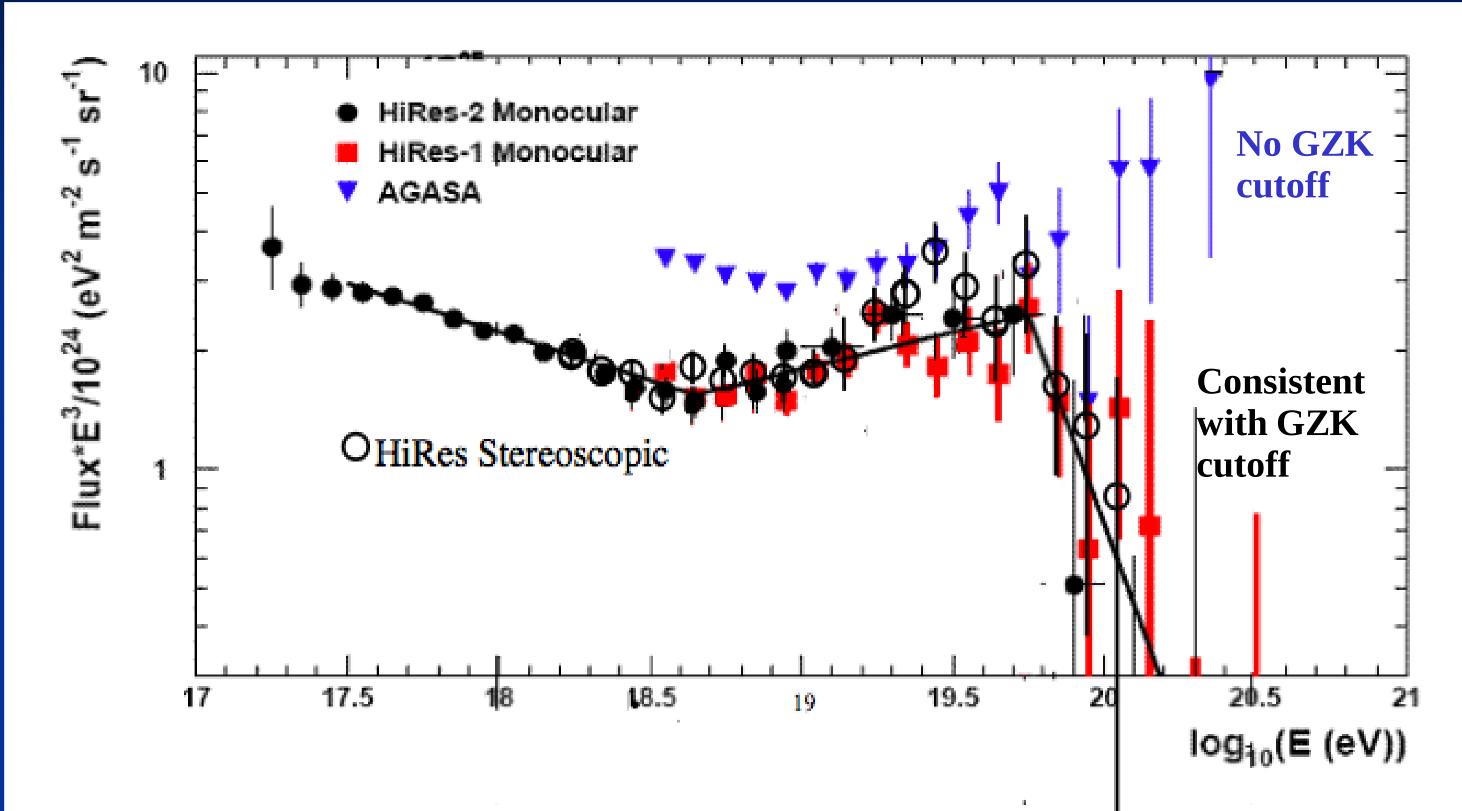
Cons:

Energy measurement relies on MC simulations

Hadronic interaction model extrapolated to ultra-high energy and rapidity.

Difficult to estimate uncertainties.

Early energy spectrum discrepancy

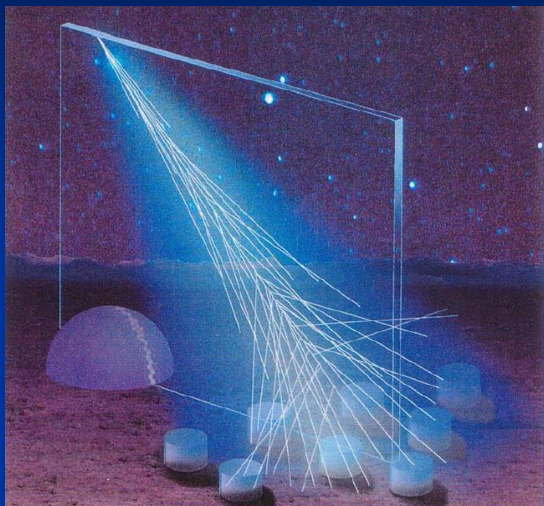


P.Sokolsy, Final Results from the HiRes

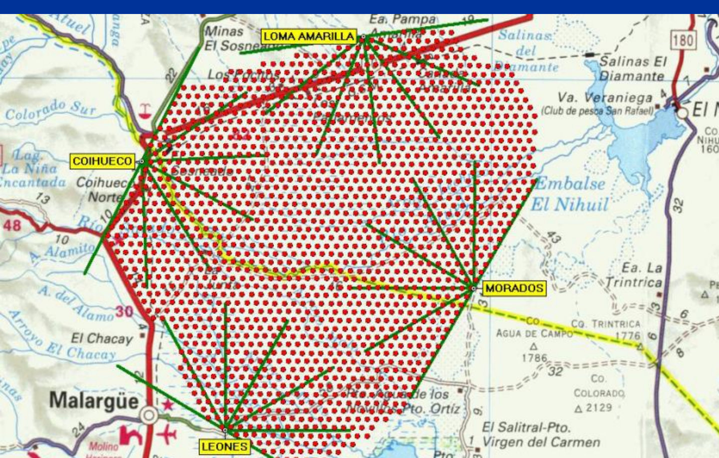
Combine observational techniques

Hybrid Cosmic Ray Detectors

Argentina



Auger hybrid detector.
1600 water tanks
4 air fluorescence telescopes

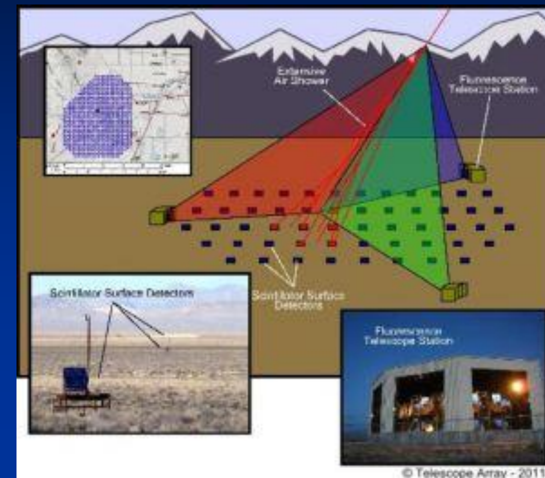


Best of both approaches:

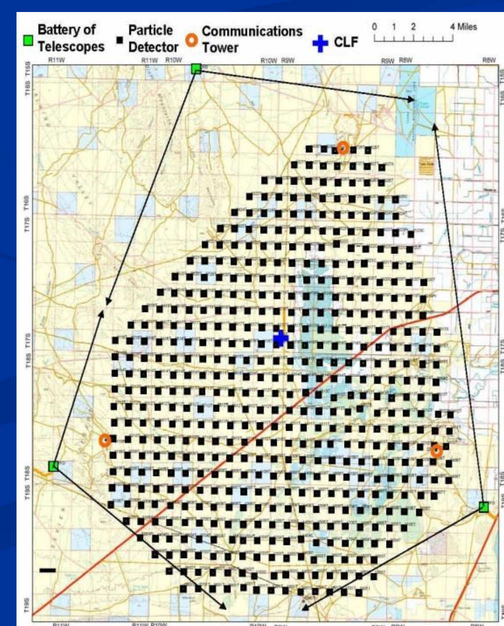
Energy is calibrated using FD

- **Statistics at UHE is still low**
- **Discrepancy in composition measurements**
- **Need a *different* technique**

Utah, USA

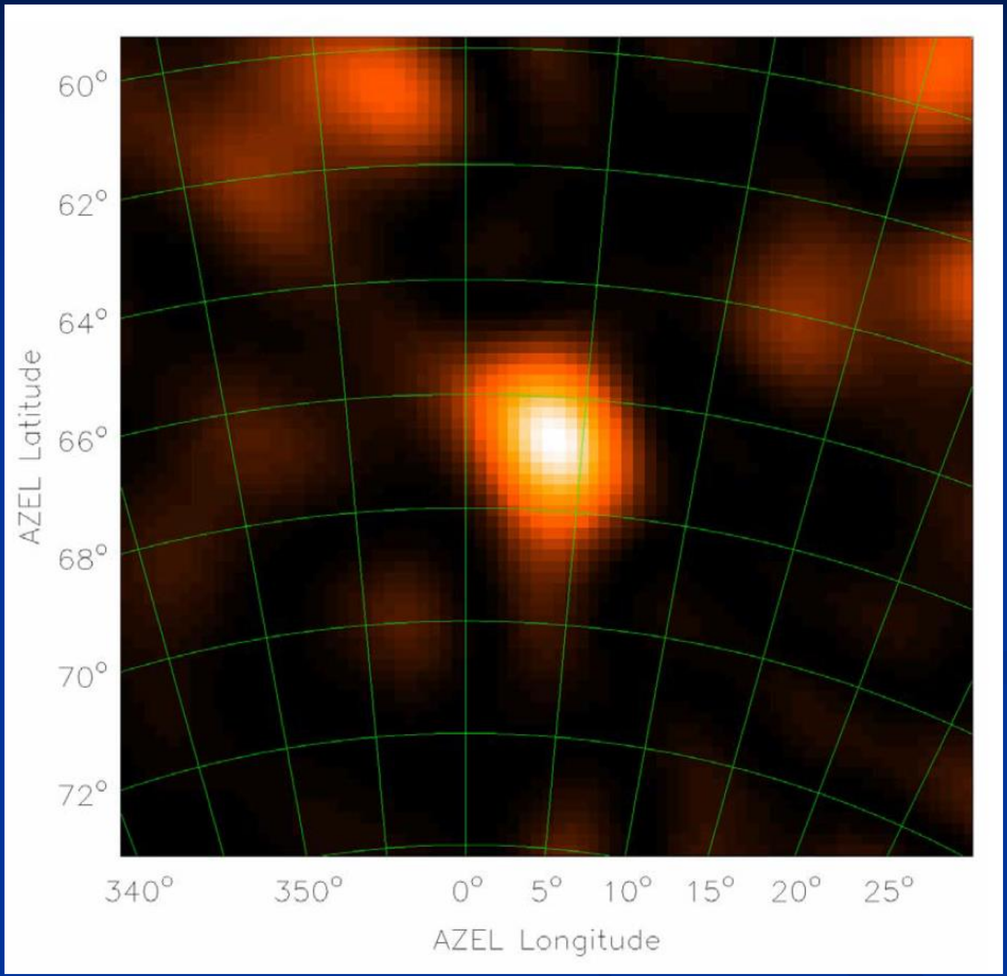


TA hybrid detector.
500 ground counters
3 air fluorescence telescopes
+ TALE – low energy extension



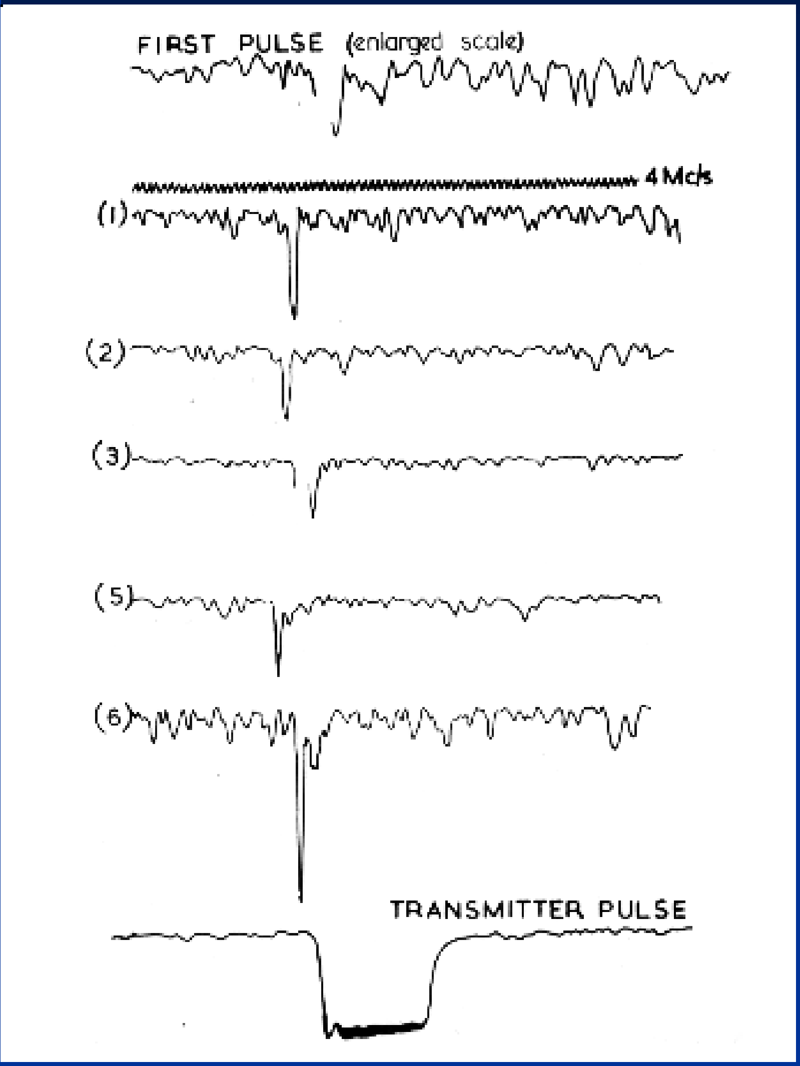
Radio is an attractive observational technique

- **100% duty cycle**
- **Not sensitive to atmospheric conditions**
- **Measurements are calorimetric**
- **Lower deployment and operational costs**



Radio map of an air shower.
12.5 ns integration time. 43-76 MHz.
Noise is due to sidelobes.
LOPES collaboration (2005).

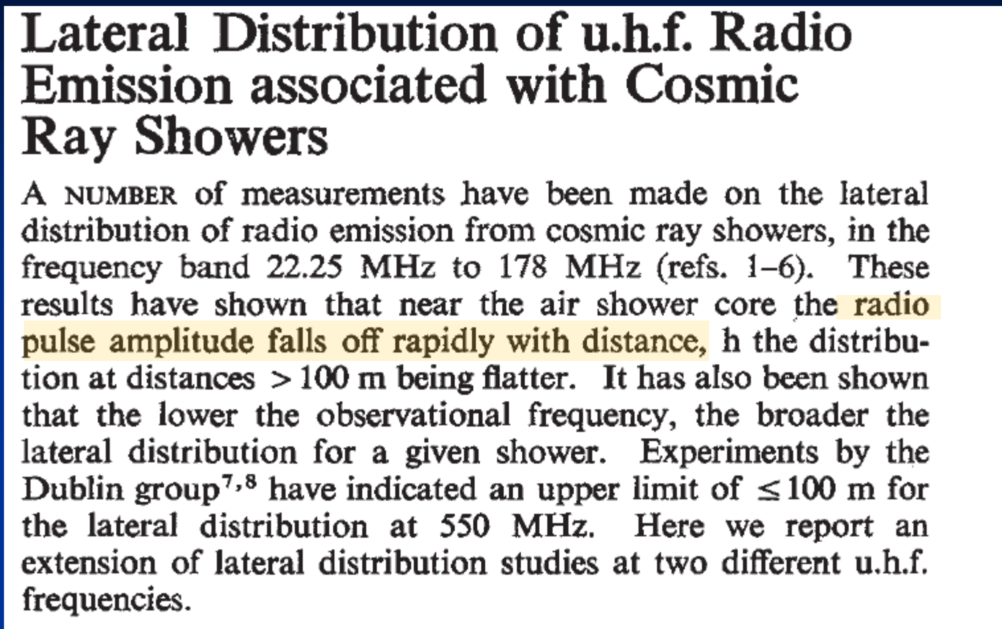
History of radio detection of UHECRs



Jelley et al. (1965)

- **Discovery:**
  - **Jelley et al. (1965) Jodrell Bank at 44 MHz**
- **Theory papers:**
  - **Colgate (1967)**
  - **Kahn & Lerche (1968)**
- **Activities around the world in late 60's & early 70's**
- **Radioastronomy moved to higher frequencies. UHECR work ceased (late 70's)**

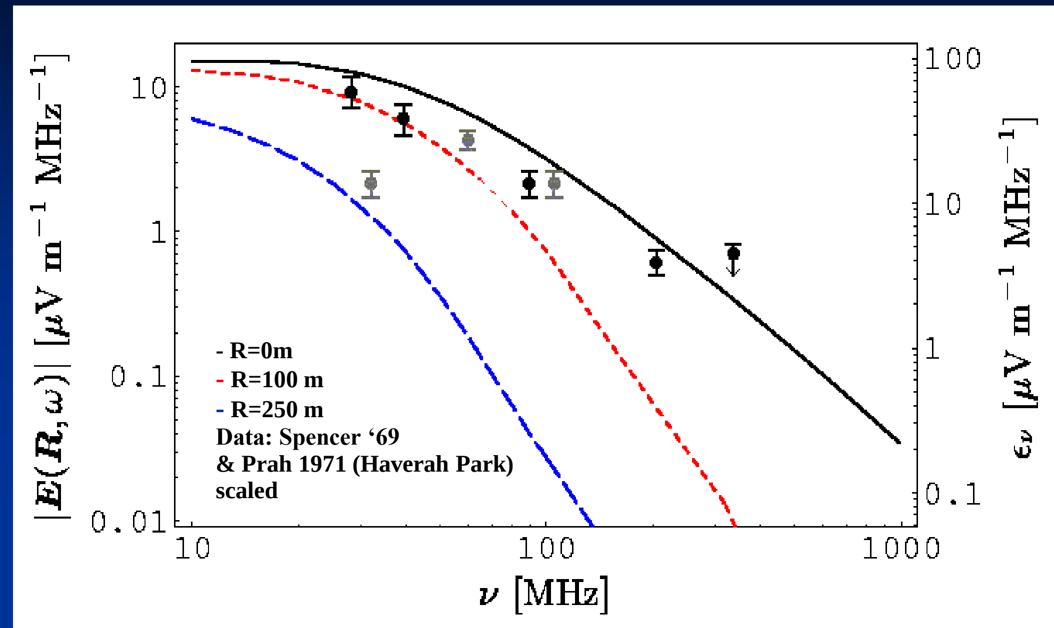
Early ground antenna measurements



Lateral Distribution of u.h.f. Radio Emission associated with Cosmic Ray Showers

A NUMBER of measurements have been made on the lateral distribution of radio emission from cosmic ray showers, in the frequency band 22.25 MHz to 178 MHz (refs. 1–6). These results have shown that near the air shower core the radio pulse amplitude falls off rapidly with distance, h the distribution at distances >100 m being flatter. It has also been shown that the lower the observational frequency, the broader the lateral distribution for a given shower. Experiments by the Dublin group[7,8] have indicated an upper limit of ≤100 m for the lateral distribution at 550 MHz. Here we report an extension of lateral distribution studies at two different u.h.f. frequencies.

D. Fegan & P.O'Neill, *Nature* (1973)



Huege & Falcke (**2003**) (semi-analytic solution)

$$\varepsilon_\nu = (1-66)\frac{\mu V}{m\mathrm{MHz}}\frac{E_p}{10^{17}\,\mathrm{eV}}\frac{\sin\alpha\cos\theta}{\sin 45^\circ\cos 30^\circ}e^{\frac{-R}{R_0(\nu,\theta)}}\left[\frac{50\,MHz}{\nu}\right]$$

1-5 Prah(1971), Sun(2001)

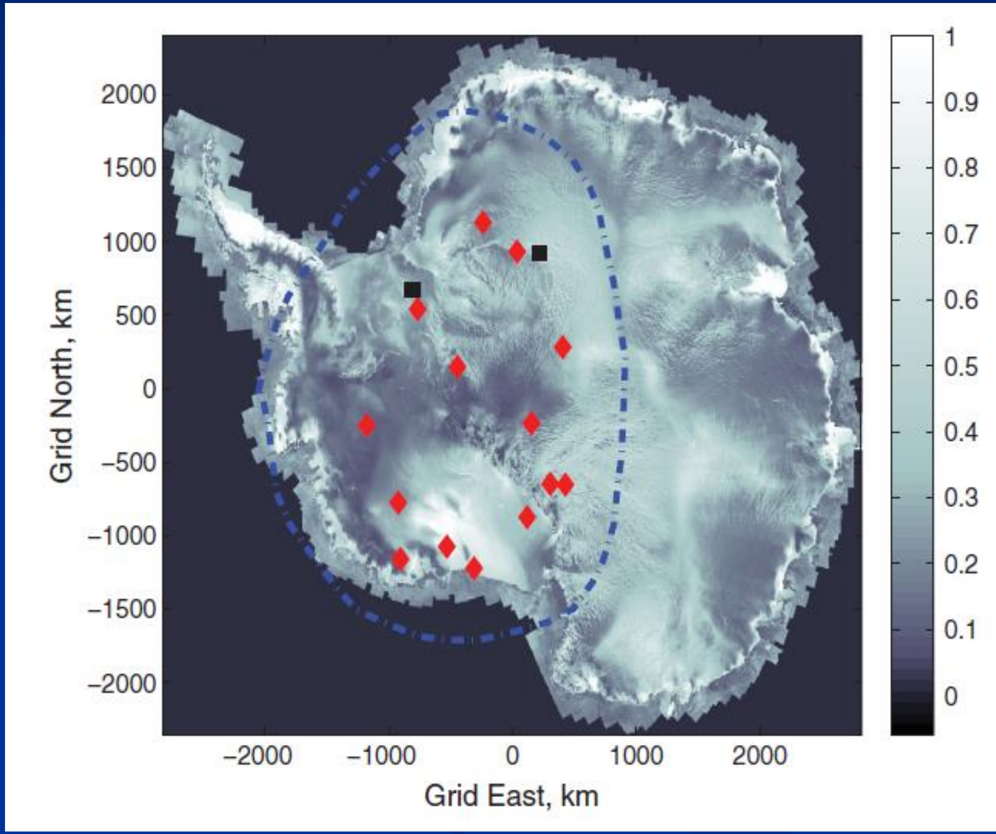
13 Allan, Wilson (1971)

66 LOPES (2008)

Two orders of magnitude uncertainty!
We need better measurements:
- **spectrum**
- **polarization**
- **polarity**

Reincarnation of radio technique

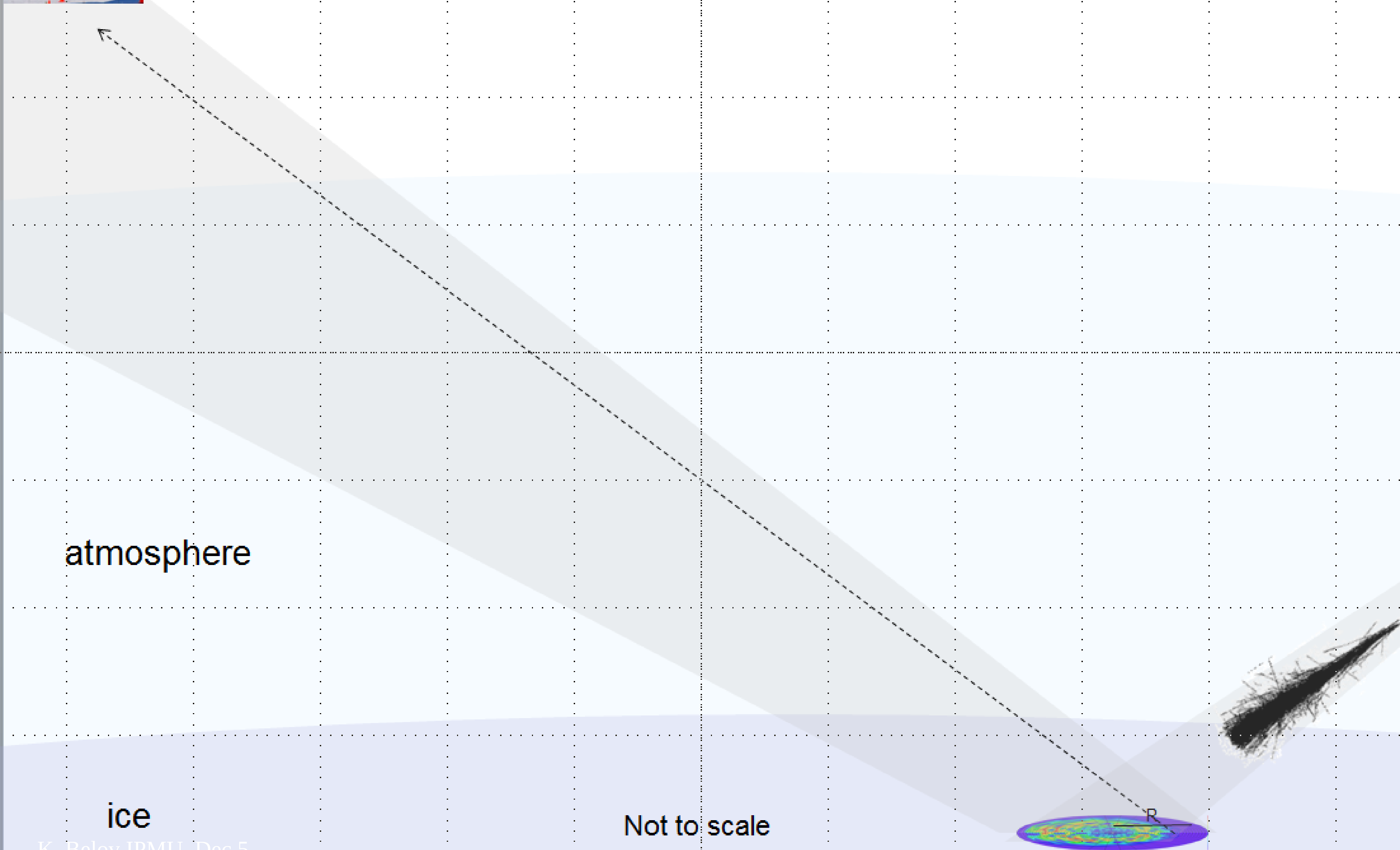
- **Engineering ground radio arrays:**
  - **LOPES**
  - **CODALEMA**
  - **AERA**



PRL 105, 151101 (2010)

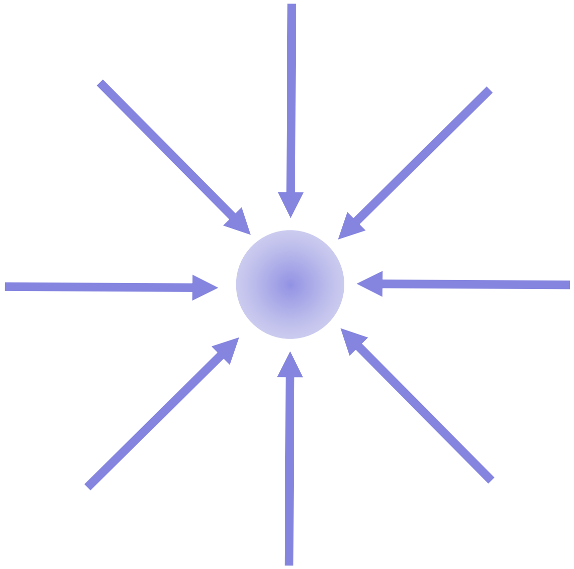
- **LOFAR**
- **ANITA UHECR discovery**
  - **16 non-base single events on background of 2**
  - **14 similar in shape and spectrum**
  - **H-pol and impulsive with very weak V-pol content**
- **Better understanding of RF emission from EASs**
- **New MC simulations based on first principles**

ANITA – a balloon-borne UHECR detector

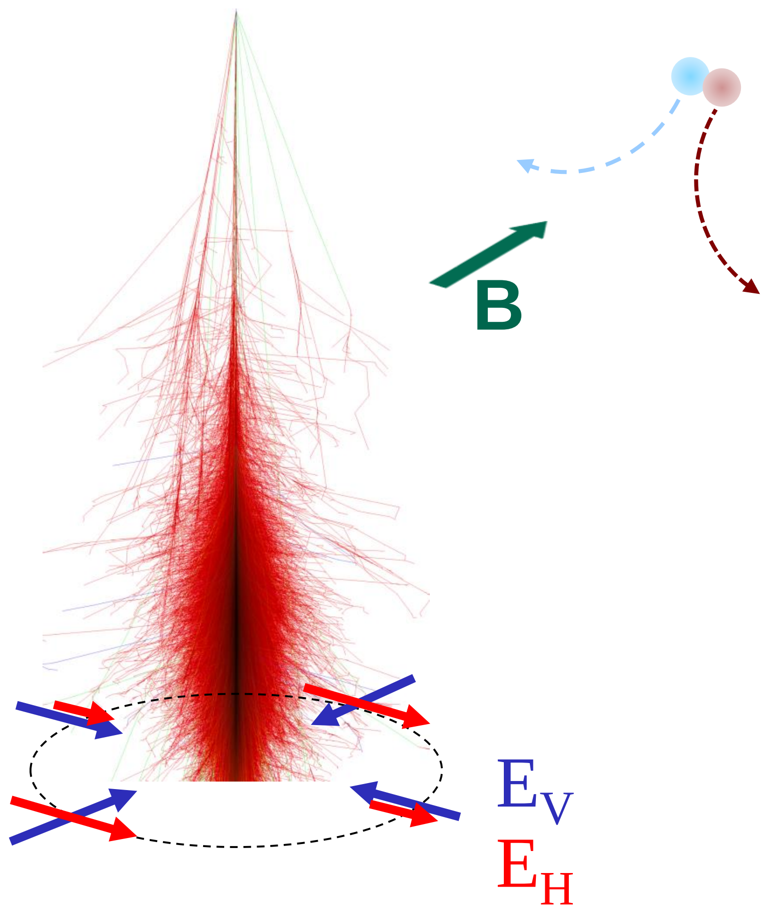


Anatomy of RF pulse from EAS

Polarization



Geosynchrotron effect. Polarization depend on observer location



Coulomb boost (Askaryan effect):

- Charge buildup in the medium
- Charge is moving towards the observer

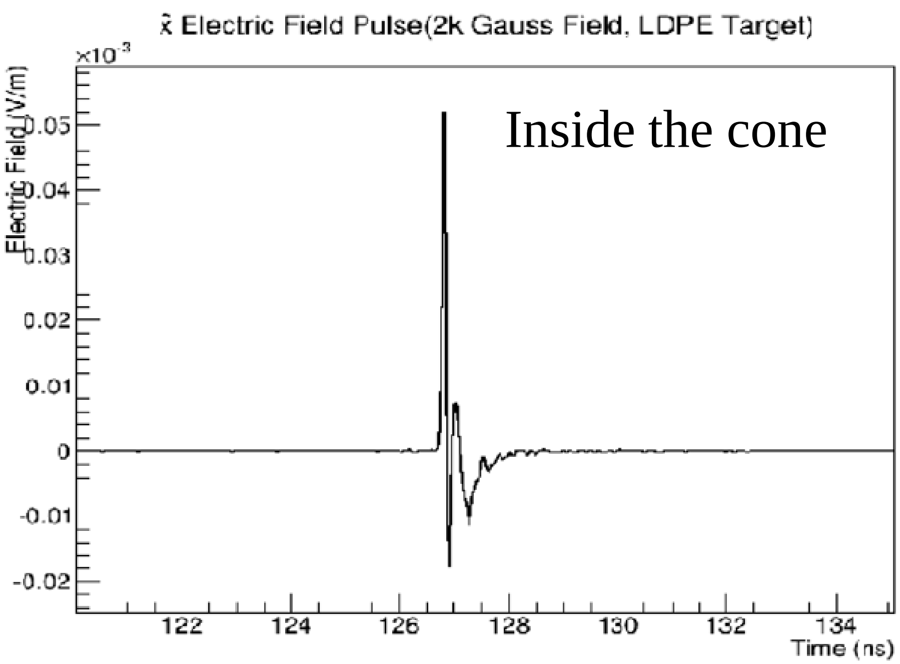
Vertical polarization of electric field

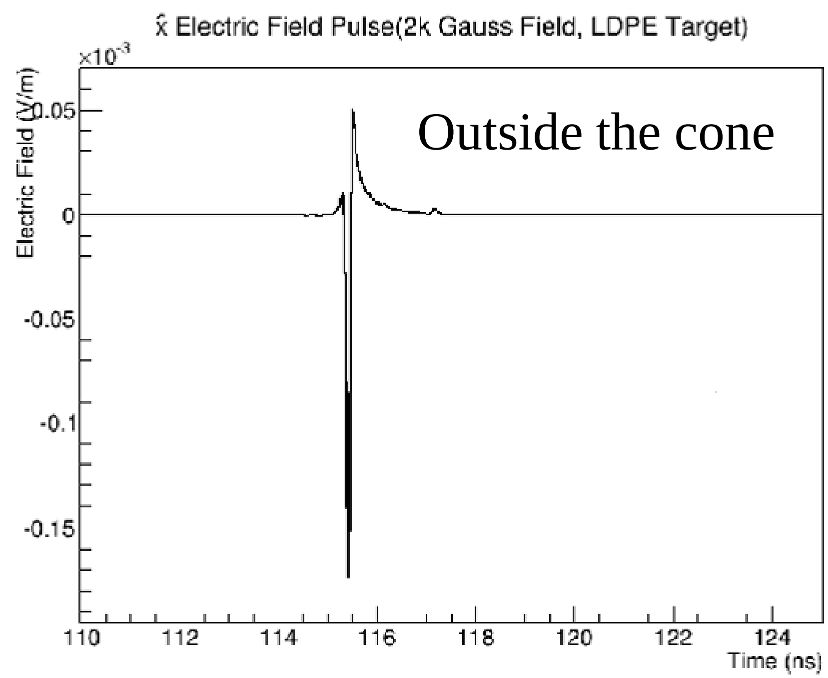
At the Cherenkov angle:

- Signal arrives coherently (flat spectrum)
- Shower develops instantly (relativistic amplification)

Anatomy of RF pulse from EAS
Polarity

Time is reversed inside the Cherenkov cone – electric field polarity is flipped





Plots by R. Hyneman

UHECR radio footprint

MC simulation based on first principles

- Emission from each particle track added coherently

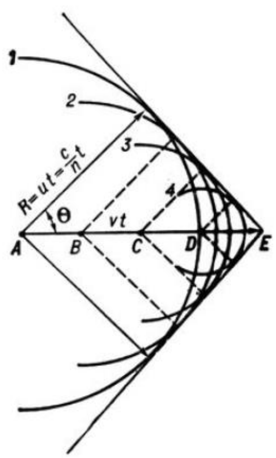
10^{19} eV primary cosmic proton

70^{o} zenith angle

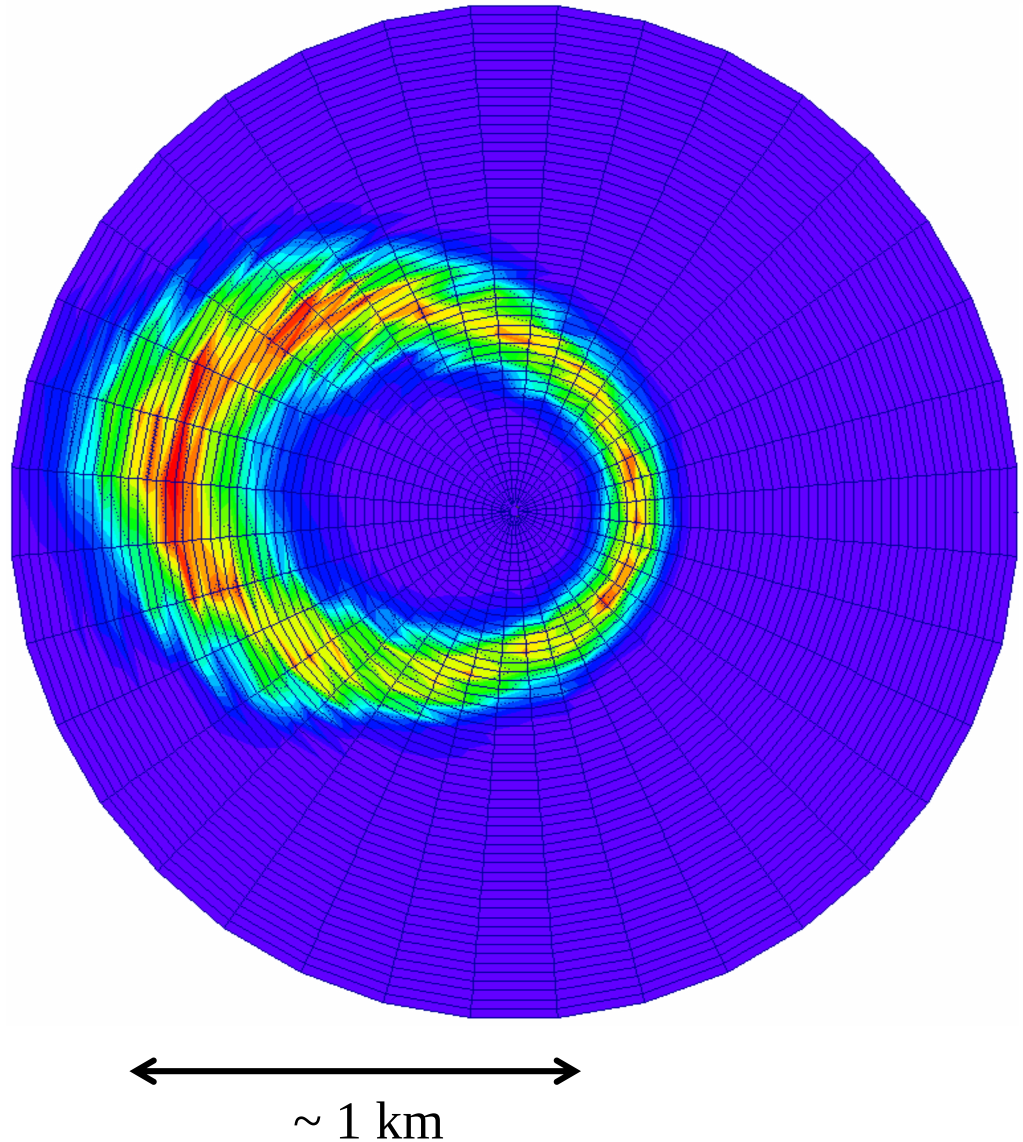
Horizontal component of electric field

200-1200 MHz frequency band

Relativistic amplification of the signal



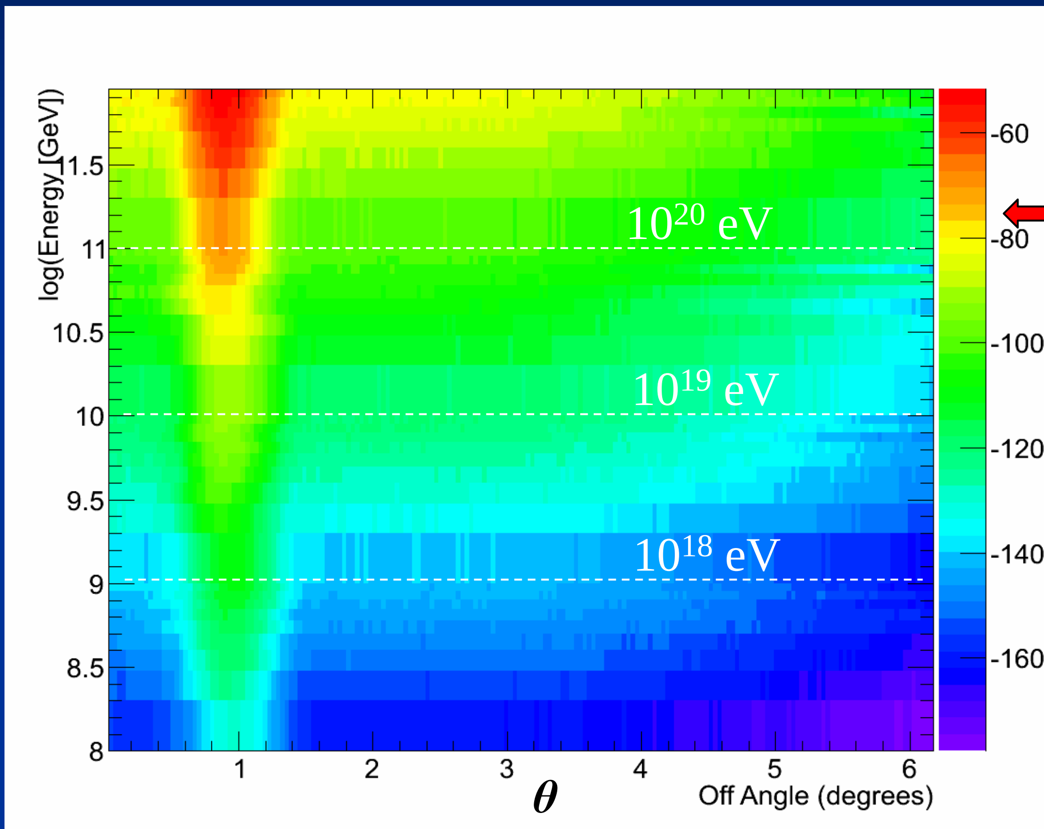
Time reversal inside the cone

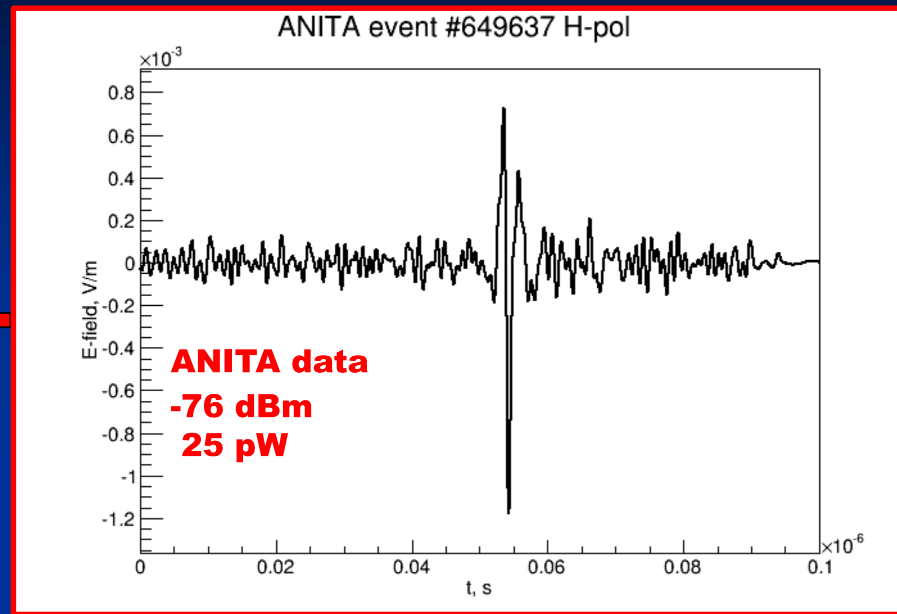


How to measure the energy with only one antenna hit?

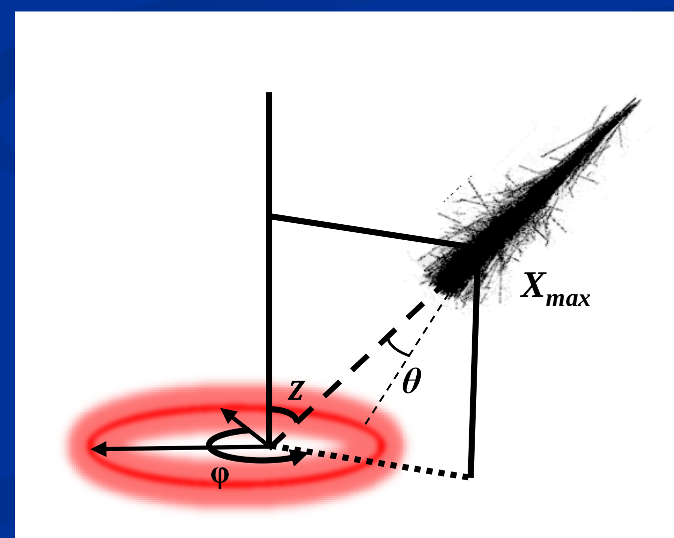
Total power in RF received by ANITA

ANITA event # 649637
MC simulations

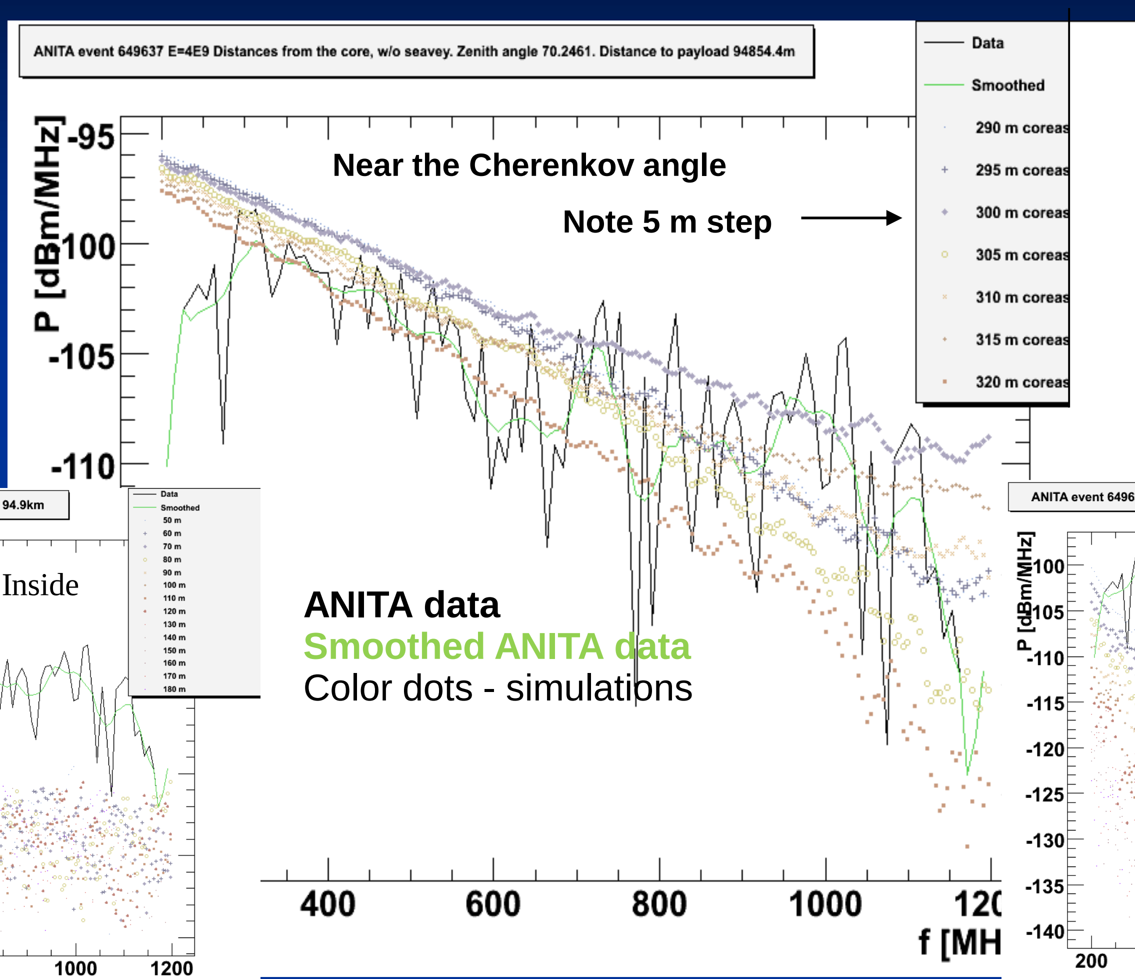


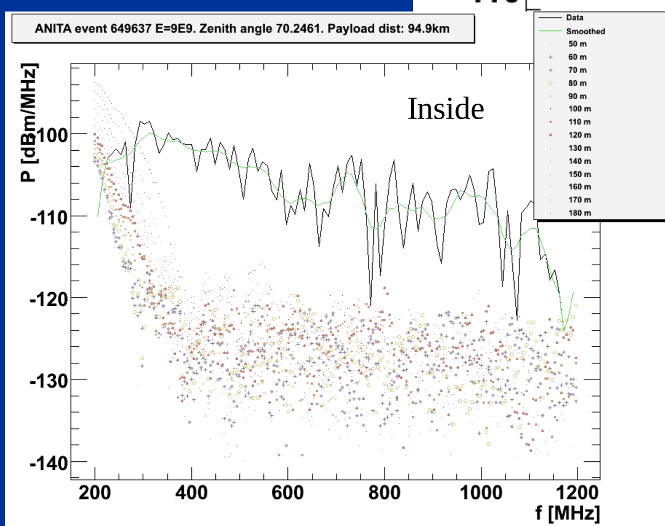


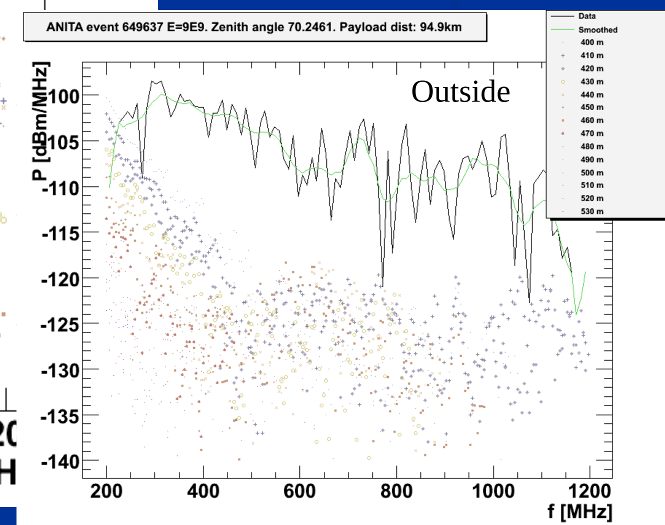
Plot by D. Urdaneta
Sophomore at UCLA



RF spectrum





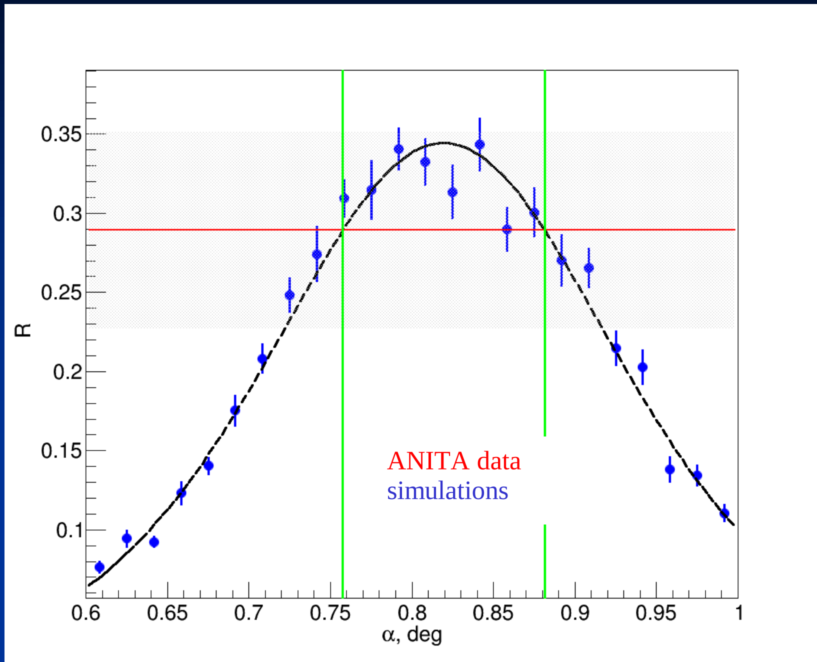


Plots by D. Urdaneta

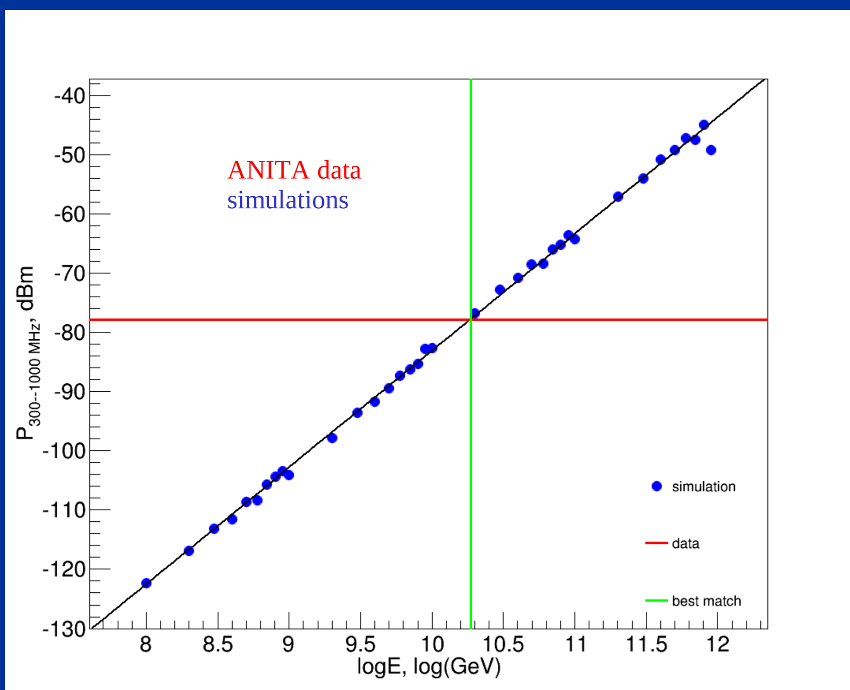
- Spectral ratio is a quantitative measure of the RF signal spectrum

$$R = \frac{P_{(650-1000)MHz}}{P_{(300-650)MHz}}$$

Spectral ratio analysis



Match the total power for observer at the reconstructed off angle



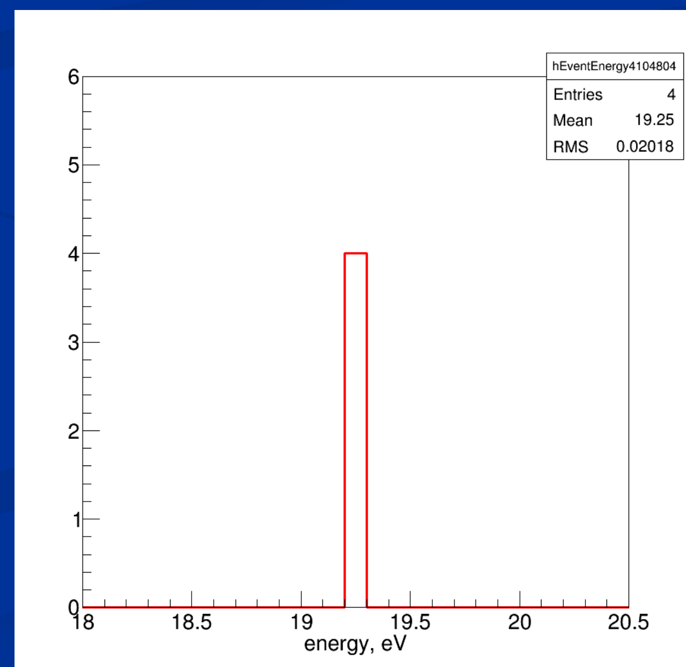
Spectral ratio:

$$R = \frac{P_{(650-1000)MHz}}{P_{(300-650)MHz}}$$

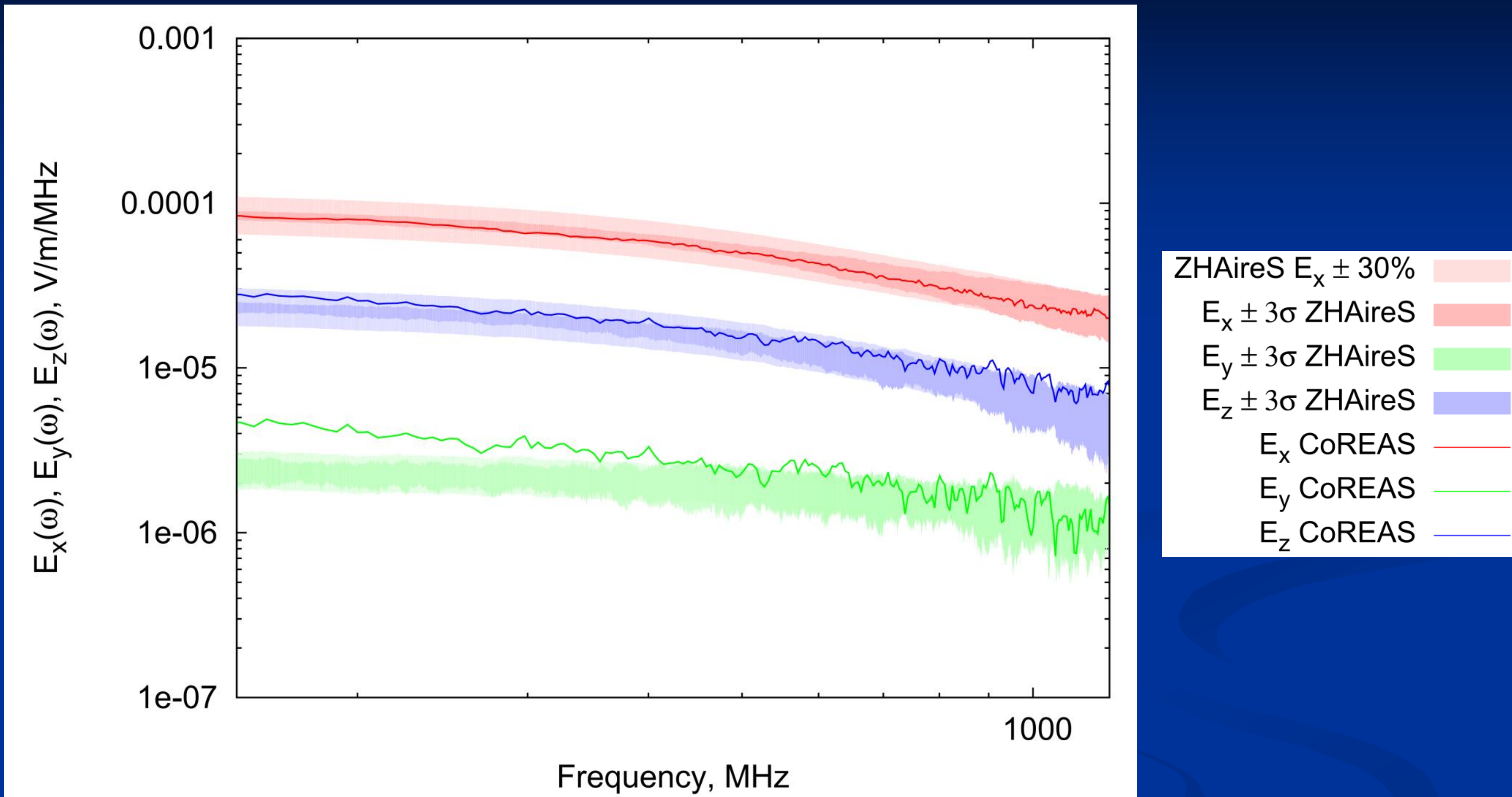
In case of degeneracy:

- **reconstructed energies are very close**
- **use average of two energies**

Reconstruct at several core azimuths



Current RF model uncertainty



Plot by V. Bugayov (Wash. U)

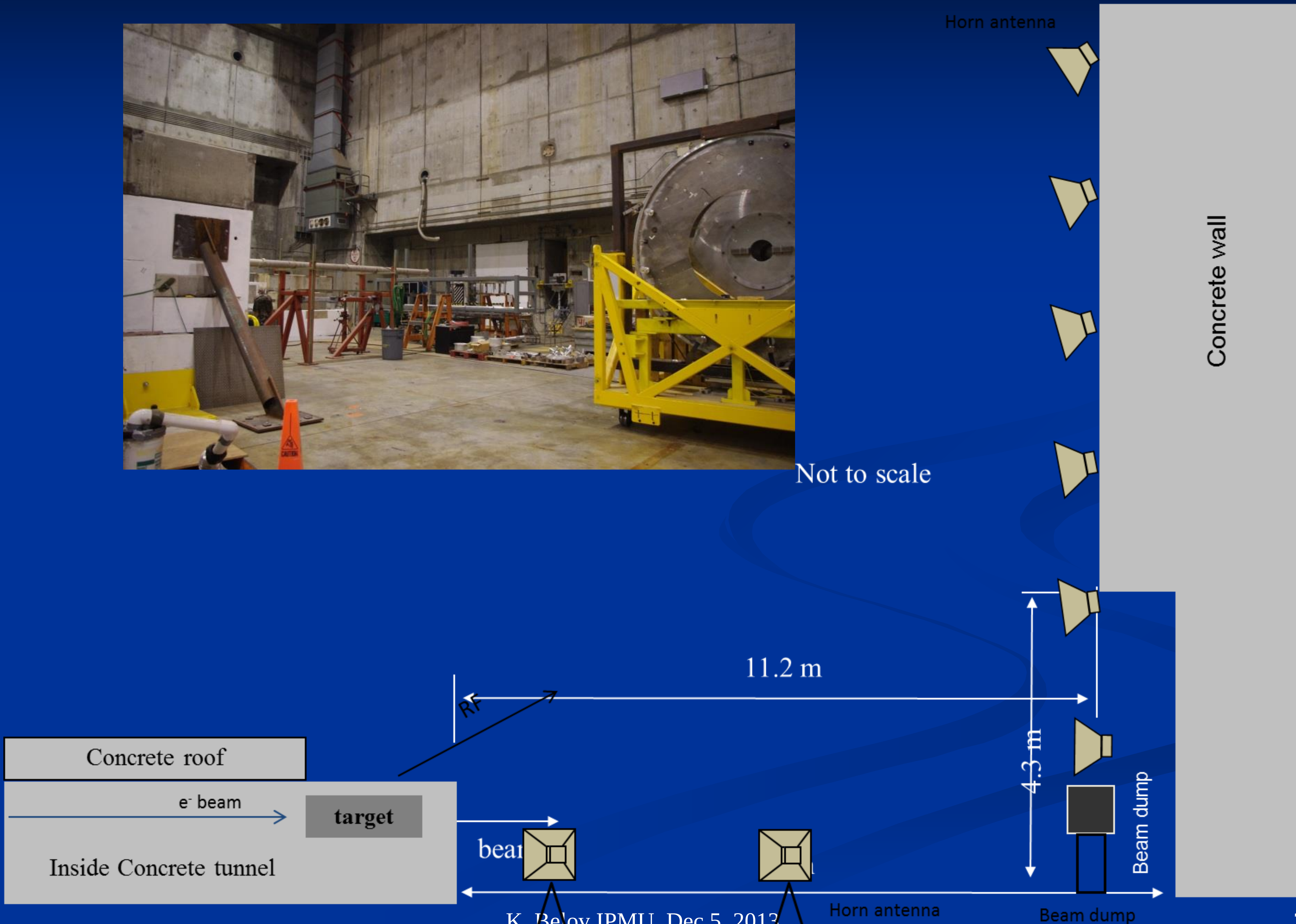
Very good agreement between CoREAS and ZHAireS

RF calibration

- Radio detection of the UHECRs relies on MC simulations
- Several Monte Carlo codes are under development now
  - Full MC: CoREAS, ZHaireS – no assumption about radio emission mechanism
  - Macroscopic models EVA, Dave Seckel’s model
- MC need to be validated by an experiment in controlled lab environment
- T-510 experiment at SLAC is scheduled for January 13-31, 2014

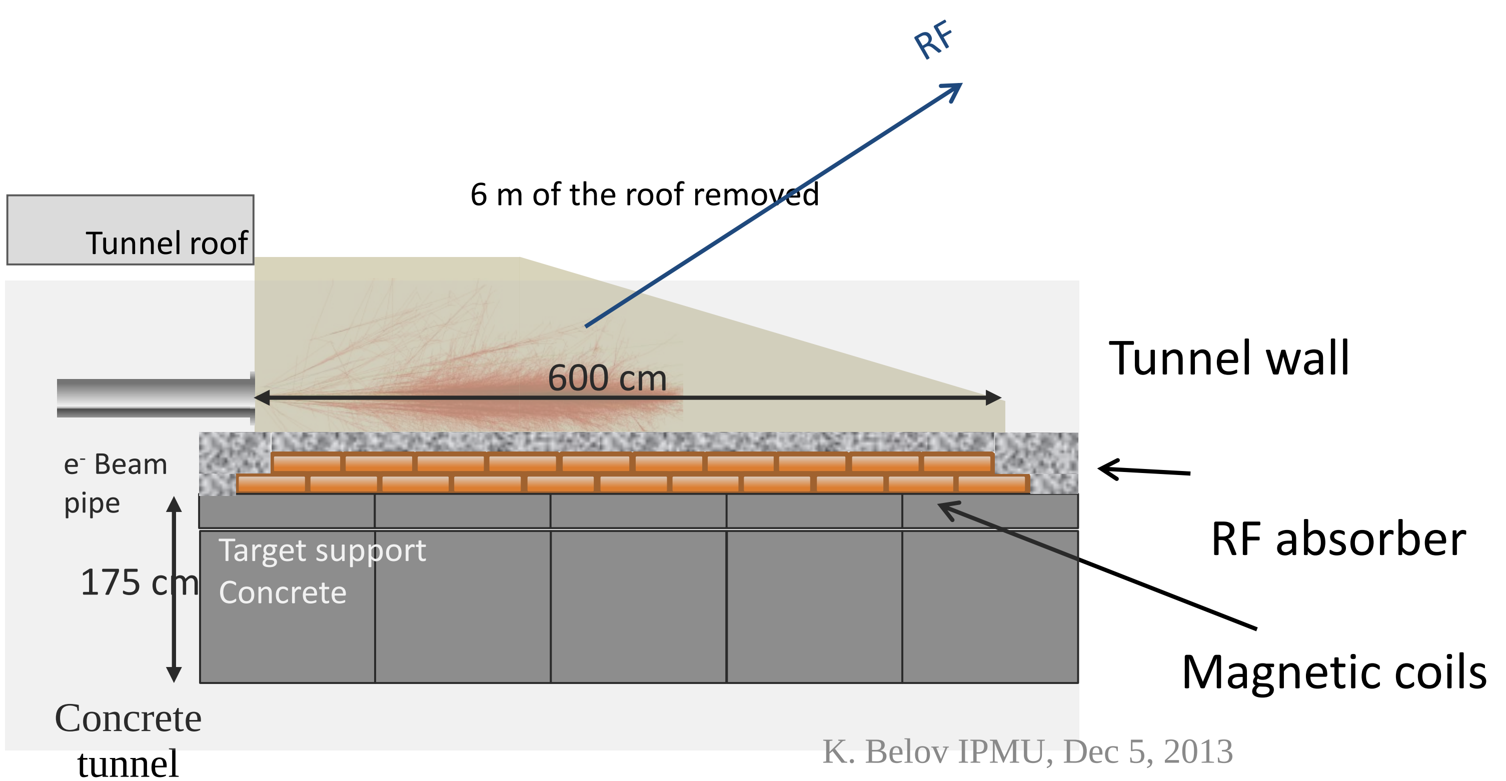
Geosynchrotron emission from extensive air showers.

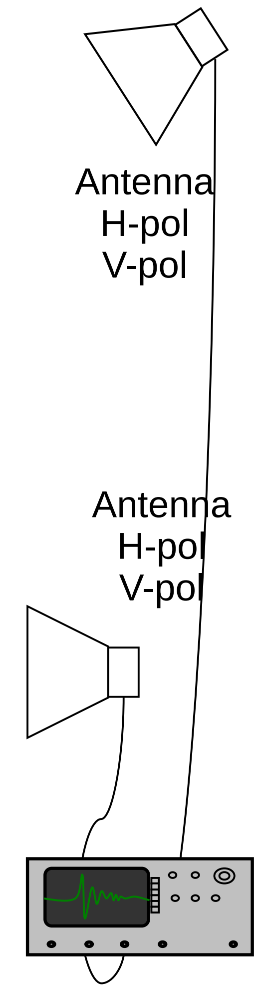
End Station A building at SLAC



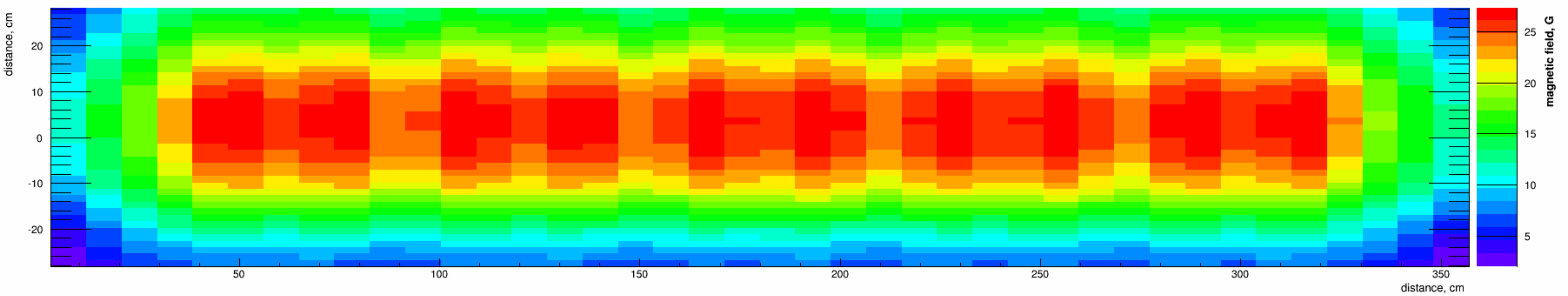
SLAC T-510

- 4-6 m long HDPE target
- 13 GeV electrons
- 0.15 nC charge



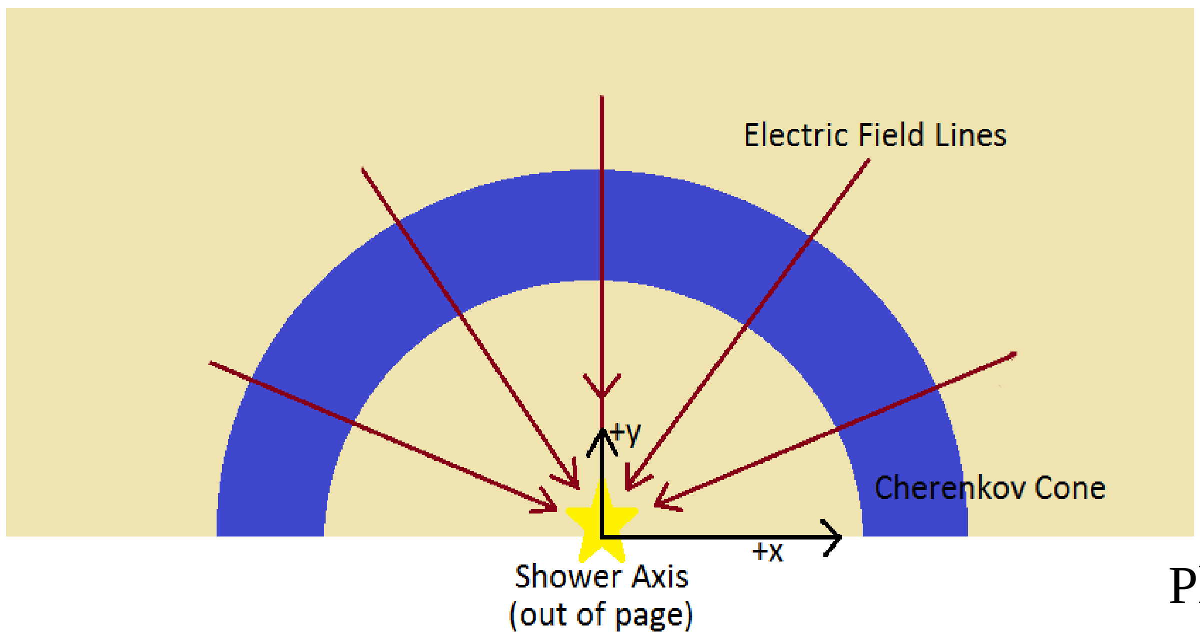


Magnetic coils

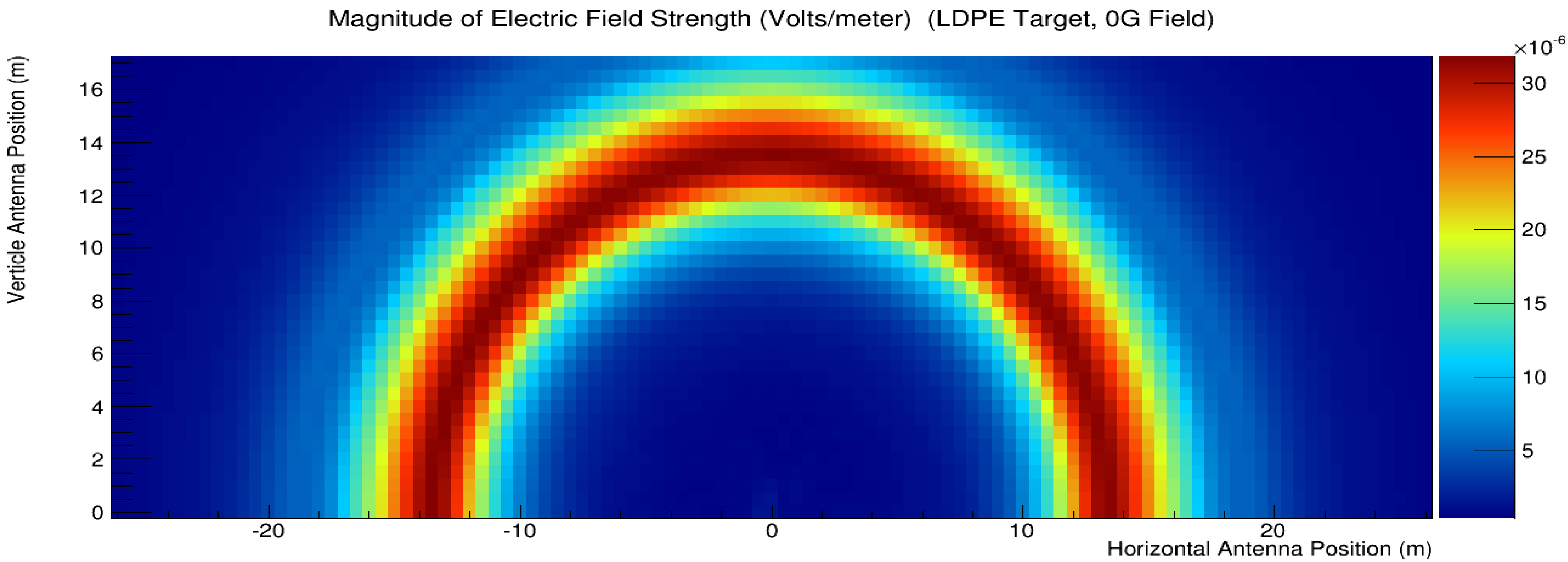


- 13 water cooled magnetic coils
- 700 A current
- ~ 400 kW power
- ~ 1500 G magnetic field

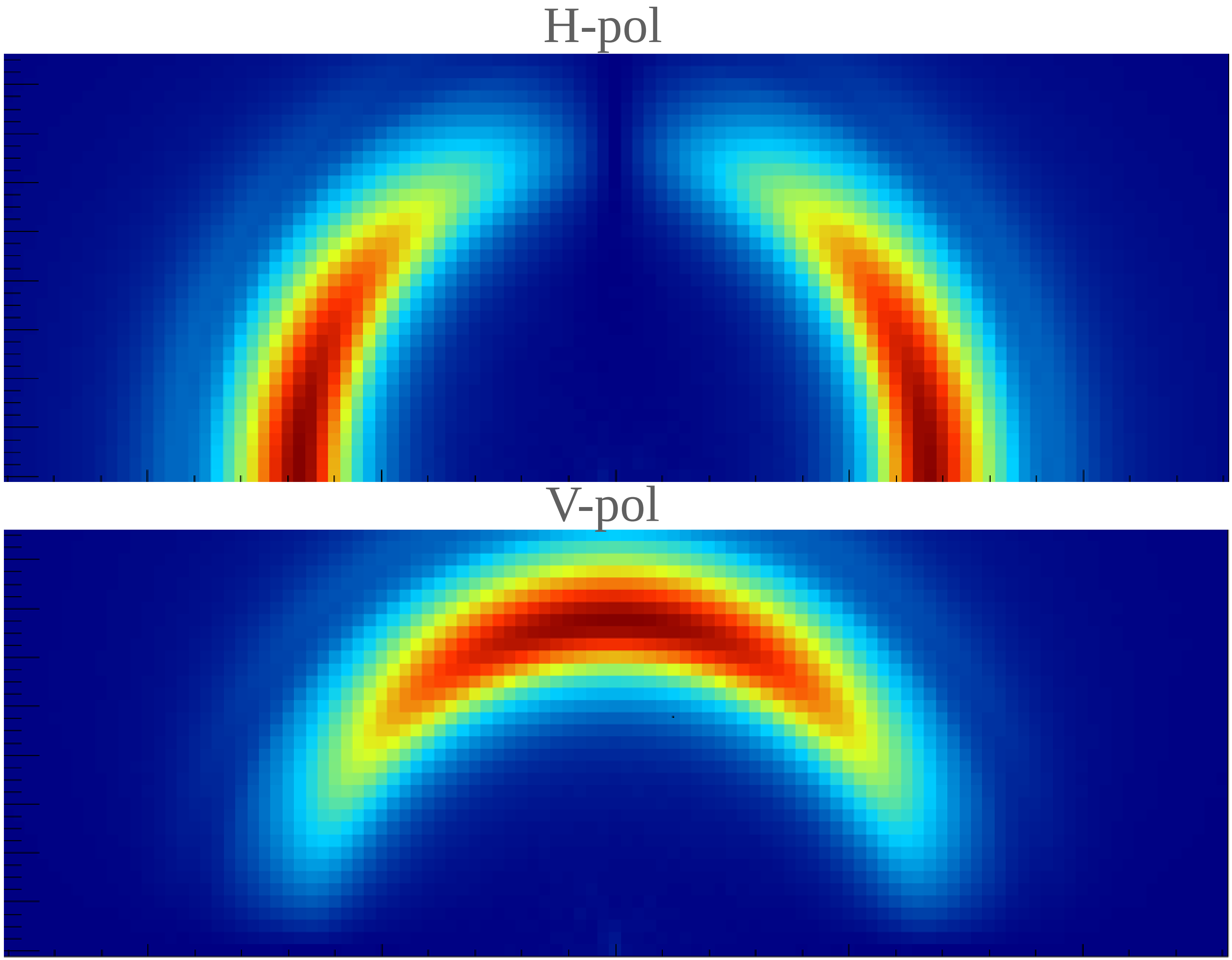
T-510 simulations. GEANT4 + ZHS



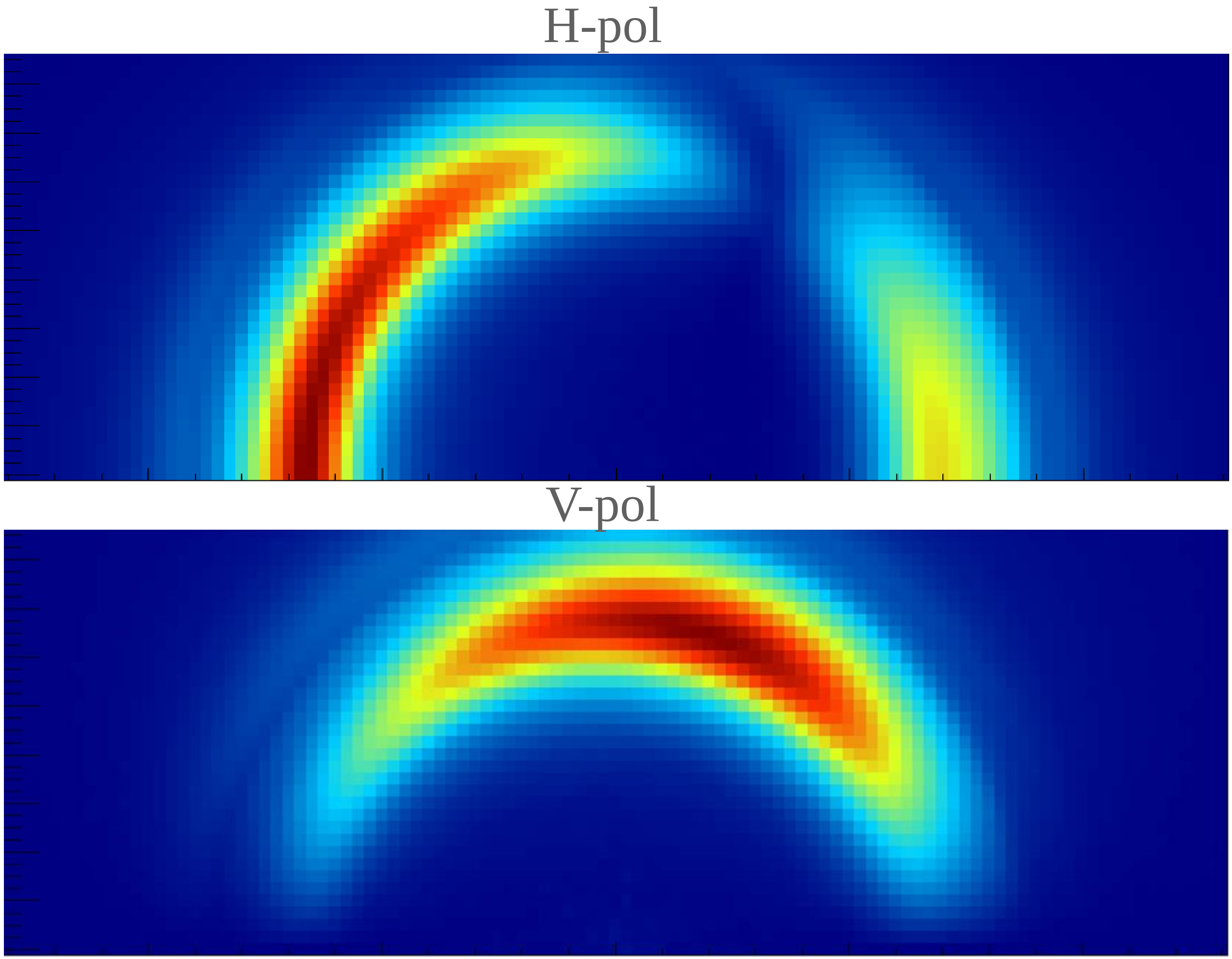
Plots by R. Hyneman



Magnitude of electric filed. No magnetic field.

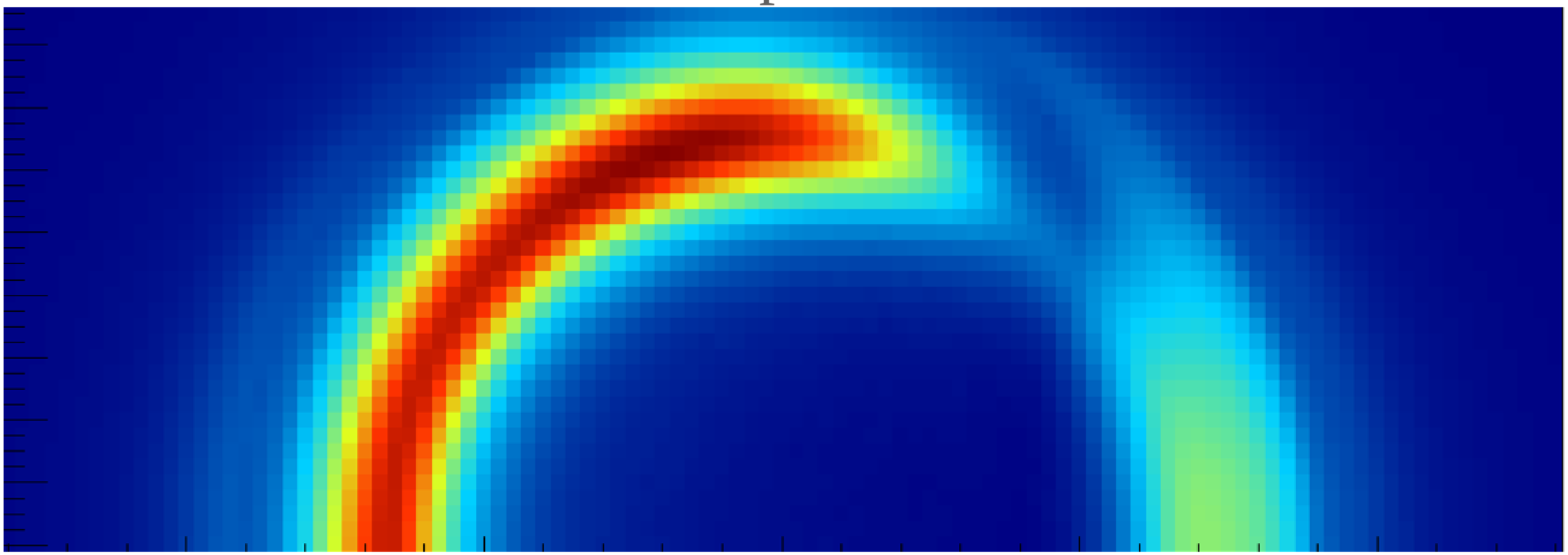


Magnitude of electric field. (LDPE target. 1000G magnetic field).

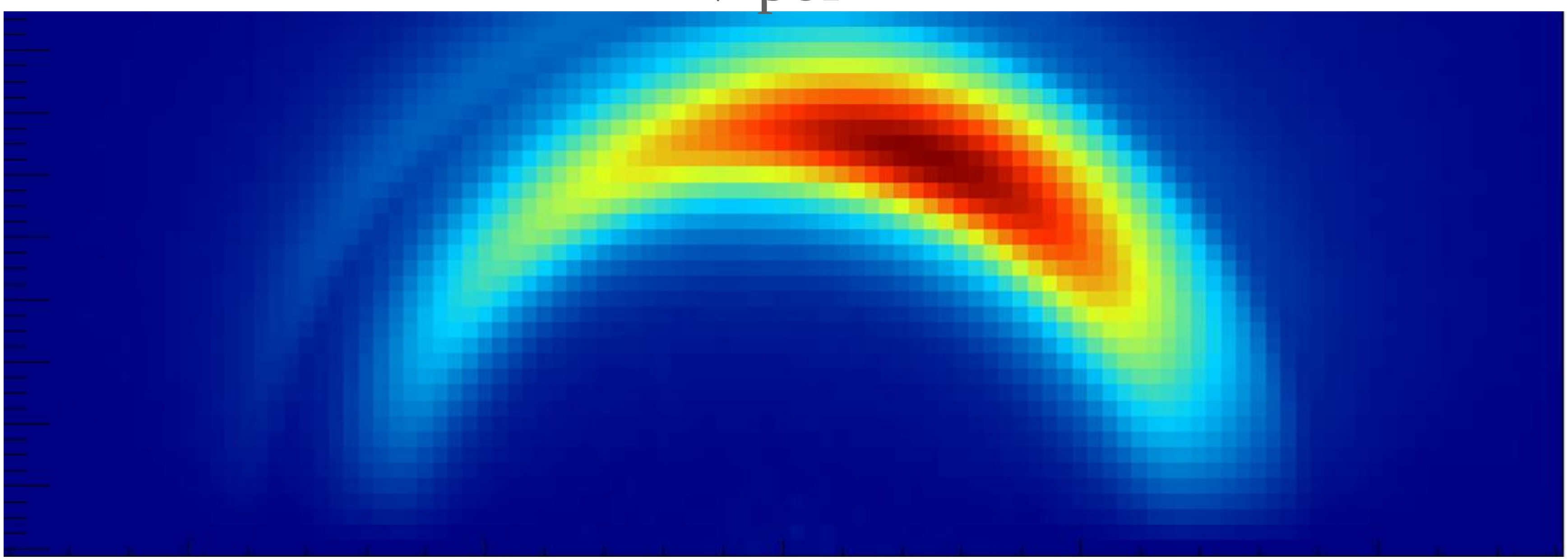


Magnitude of electric field. (LDPE target. 2000G magnetic field).

H-pol

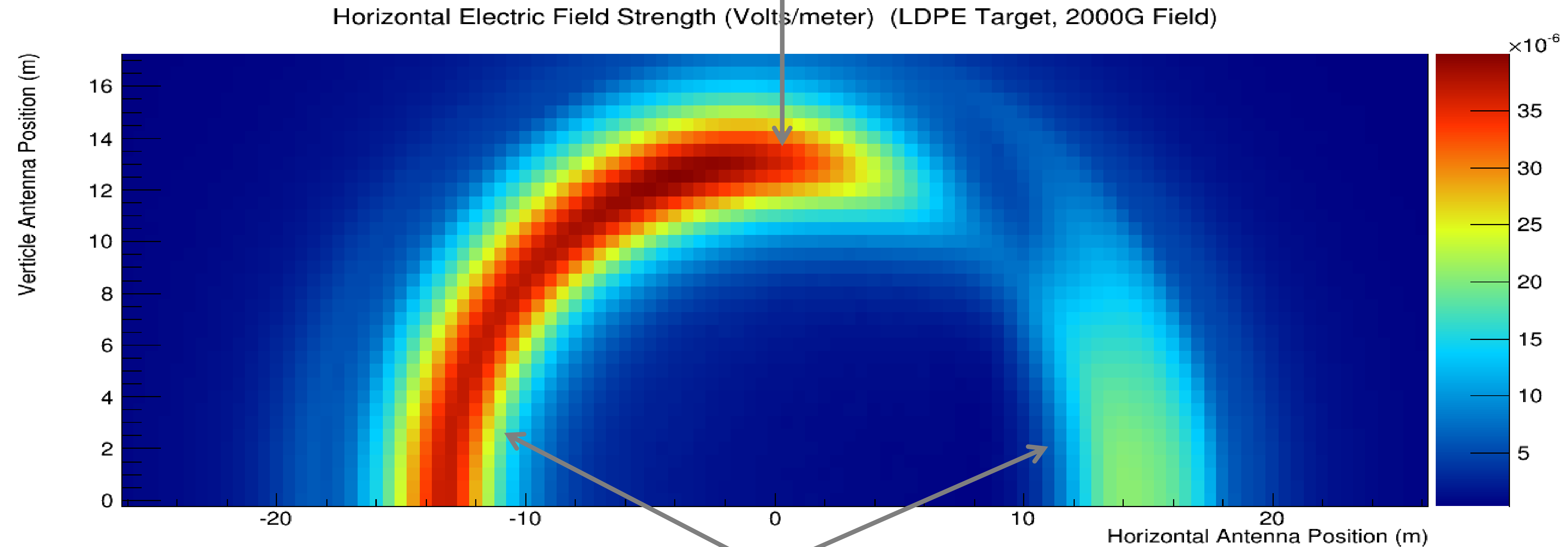


V-pol



H-pol component of E-field

Transverse current due to secondary electron/positron particle deflection in the magnetic field (Synchrotron Effect)

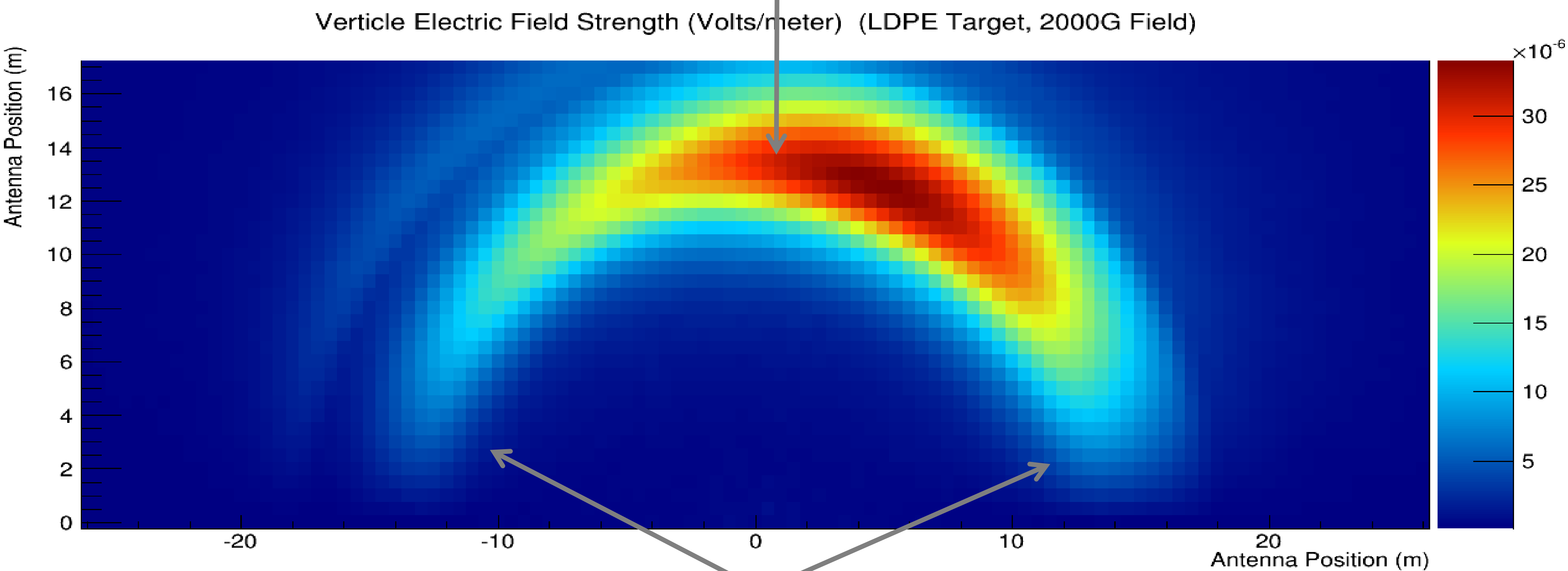


Coulomb boost

Relativistic amplification of the signal at the Cherenkov angle

V-pol component of E-field

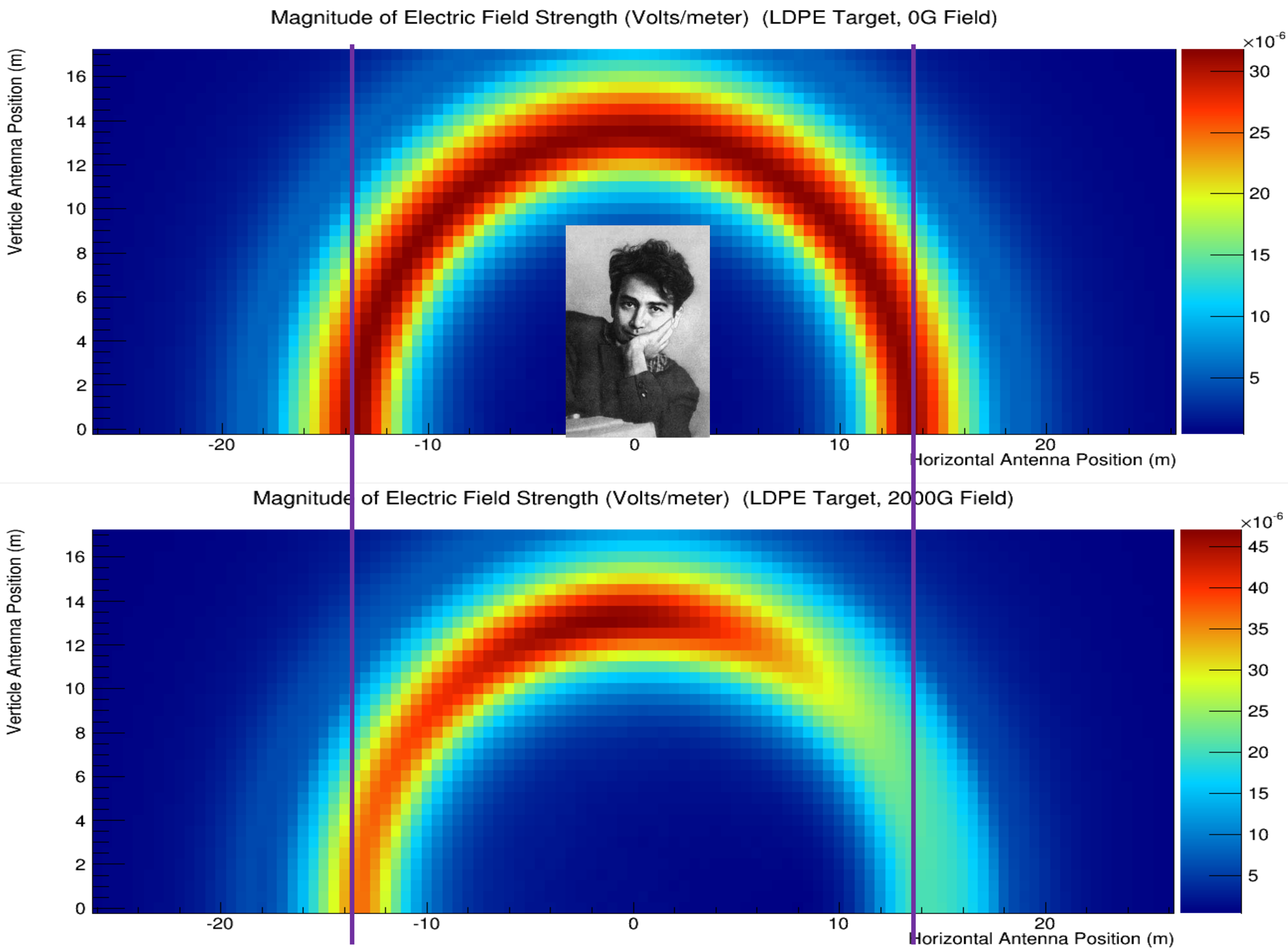
Coulomb boost



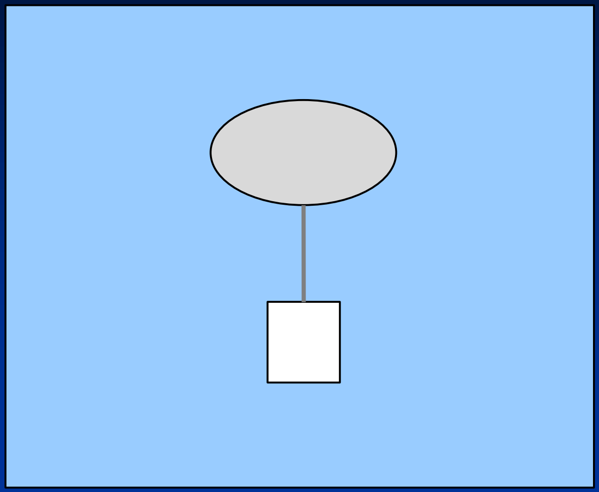
No emission

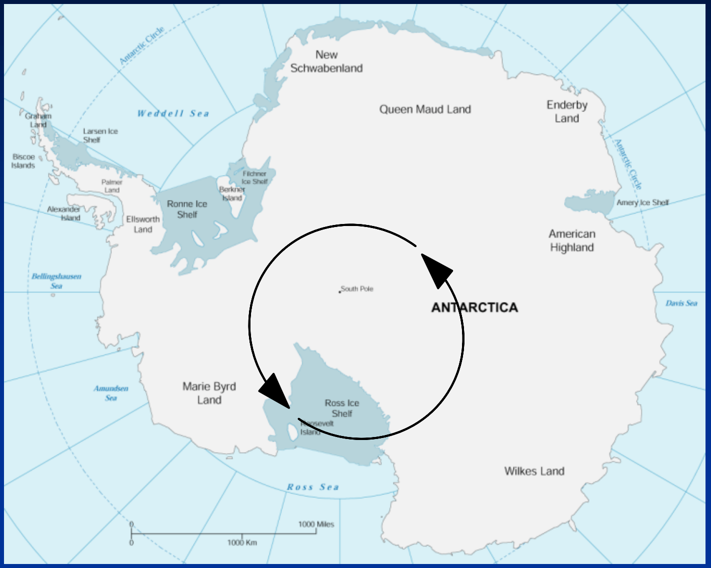
Relativistic amplification of the signal at the Cherenkov angle

Askaryan Effect



ANITA III – Dec 2014 – ?





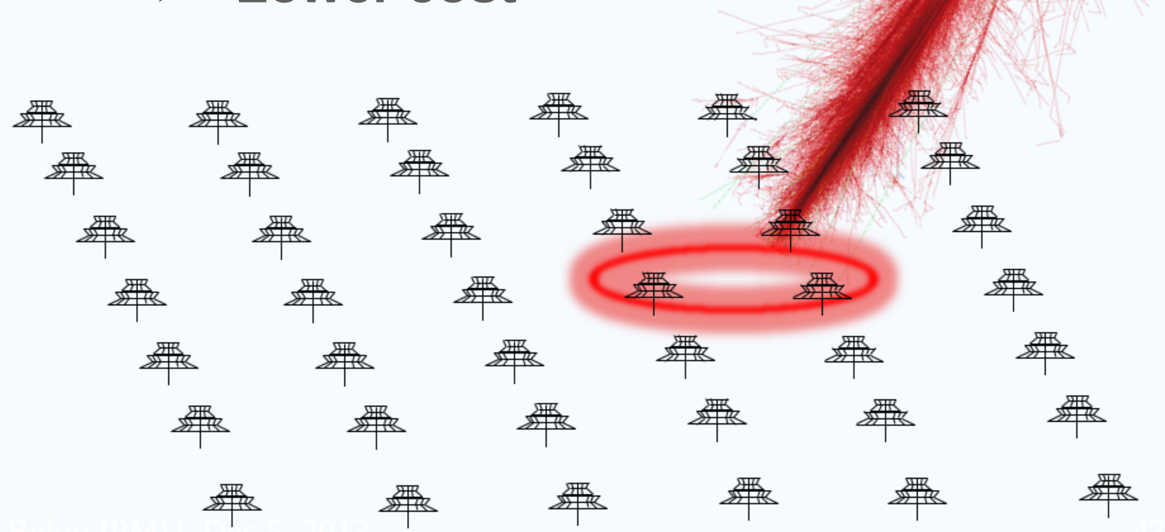
?

- H-pol trigger optimized for UHECRs
- V-pol trigger optimized for neutrino
- A dropdown lower frequency H-pol antenna
- New DAQ system

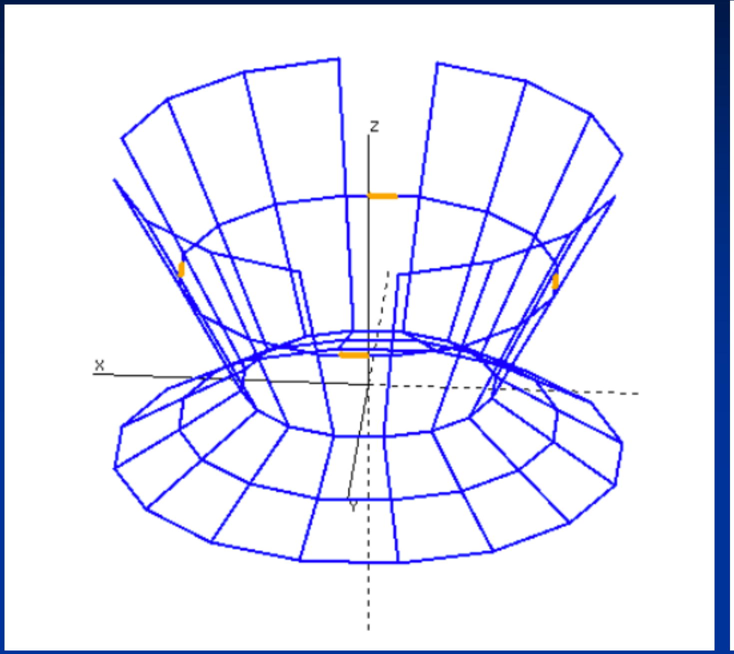
Balloon-borne (space) experiment vs ground array

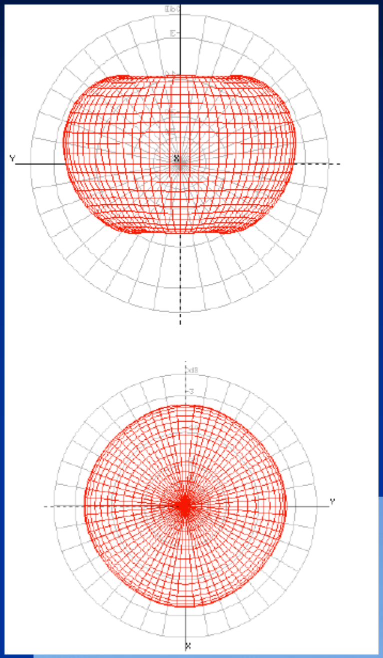
- **Large aperture**
- Equivalent to a single radio antenna
- Reflection effects:
  - Fresnel
  - Roughness
- RF propagation in the air
- Ionospheric dispersion

- Smaller aperture
- **RF footprint reconstruction**
  - Shower profile measurement
  - Pointing resolution up to 0.1º
- **Stronger signal**
- **Lower cost**



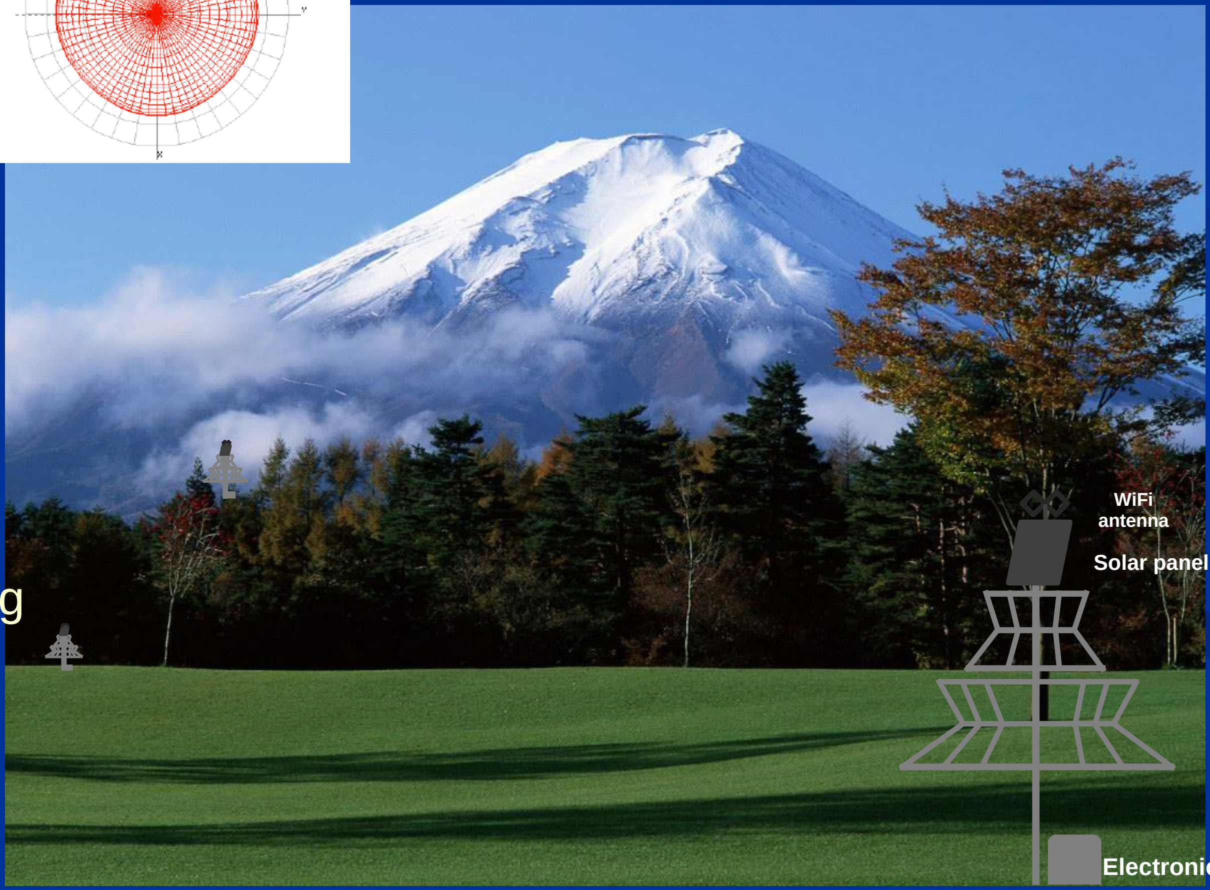
UHECR radio detection on the ground





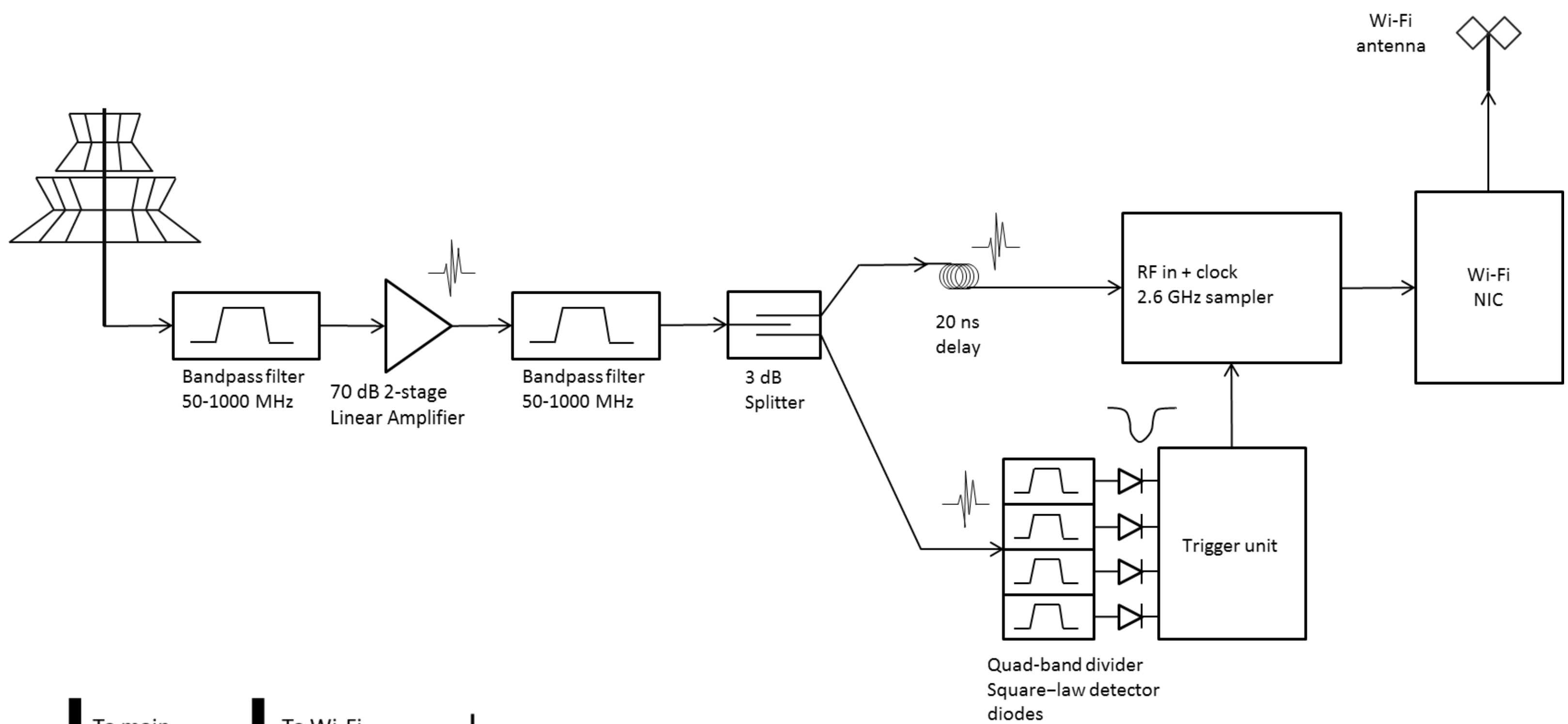
ALPHA prototype. Drawing by A. Romero-Wolf (JPL)

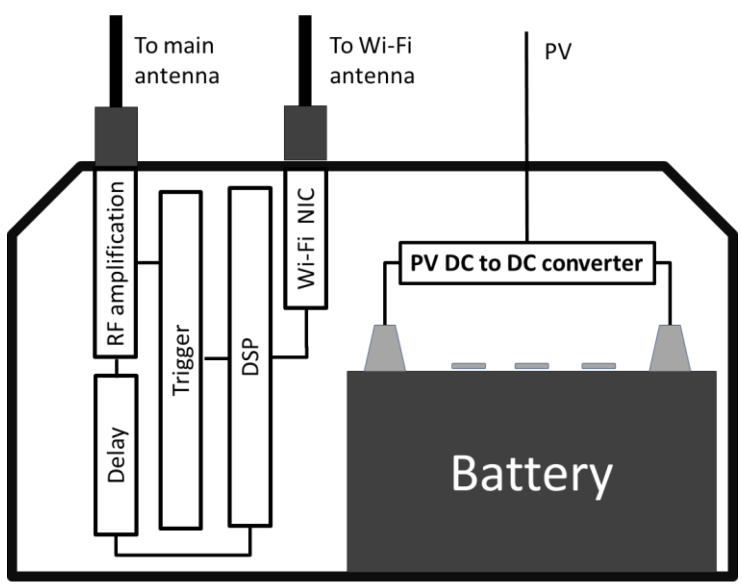
- Broadband radio antennas and DAQ
- Autonomous electronics with solar/wind/battery power
- WiFi communication



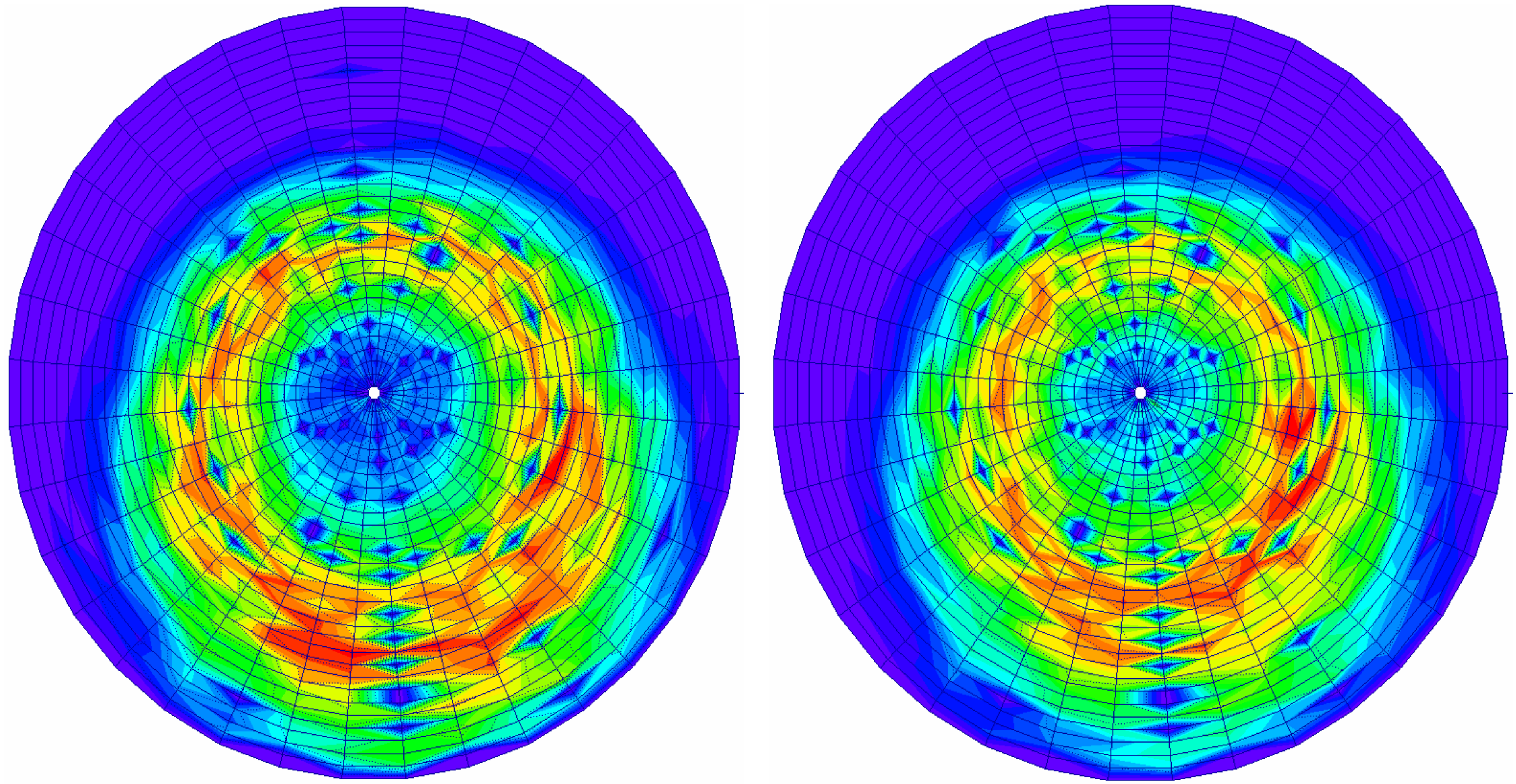
- A line of antennas at existing cosmic ray detector for calibration
- New reconstruction technique allows to increase antenna spacing and lower the deployment costs
- Light weight, low environmental impact

Broadband trigger circuit and electronics box





Xmax measurements using radio data

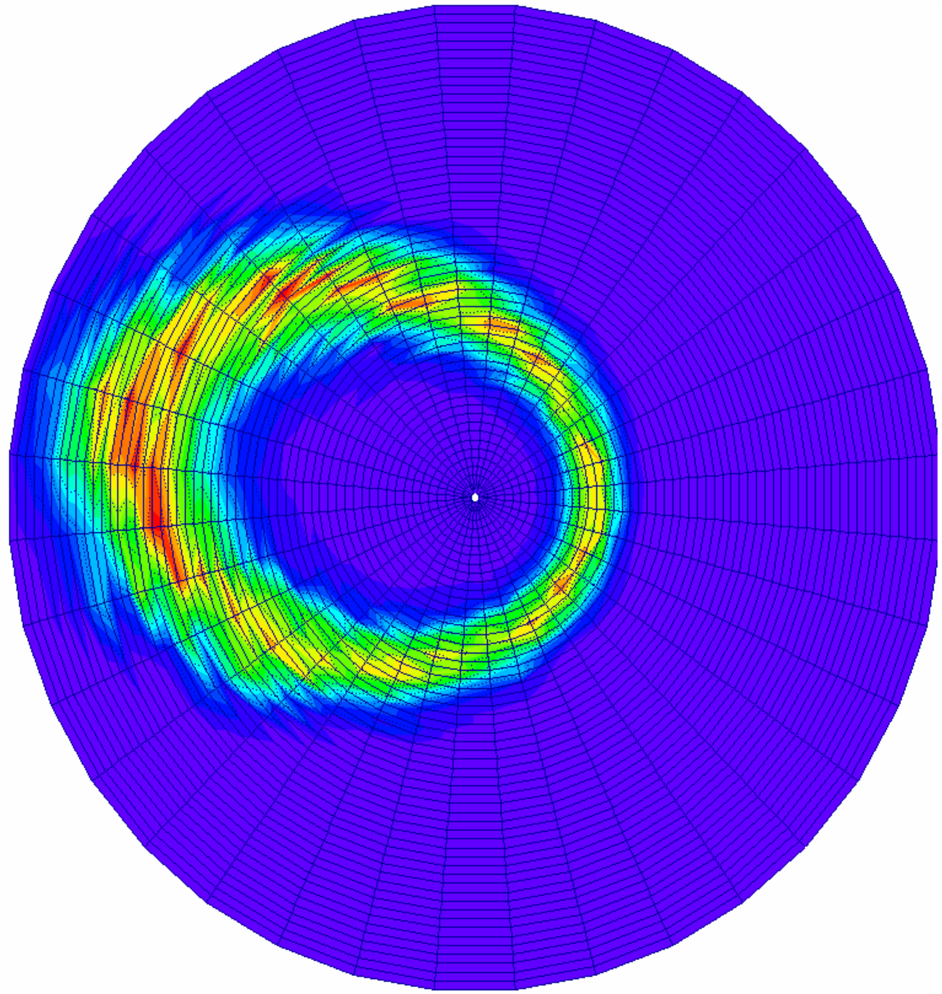


Xmax = 755 g/cm2

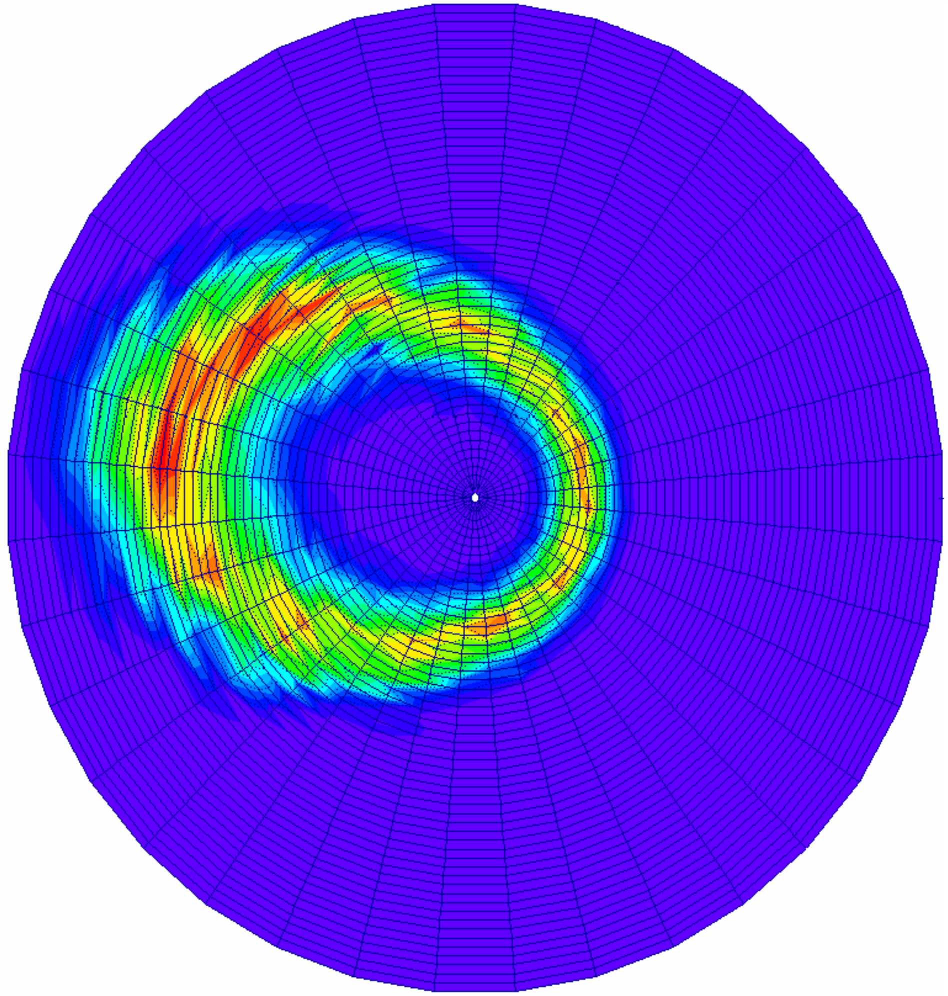
Xmax = 819 g/cm2

θ=55º

Xmax measurements using radio data



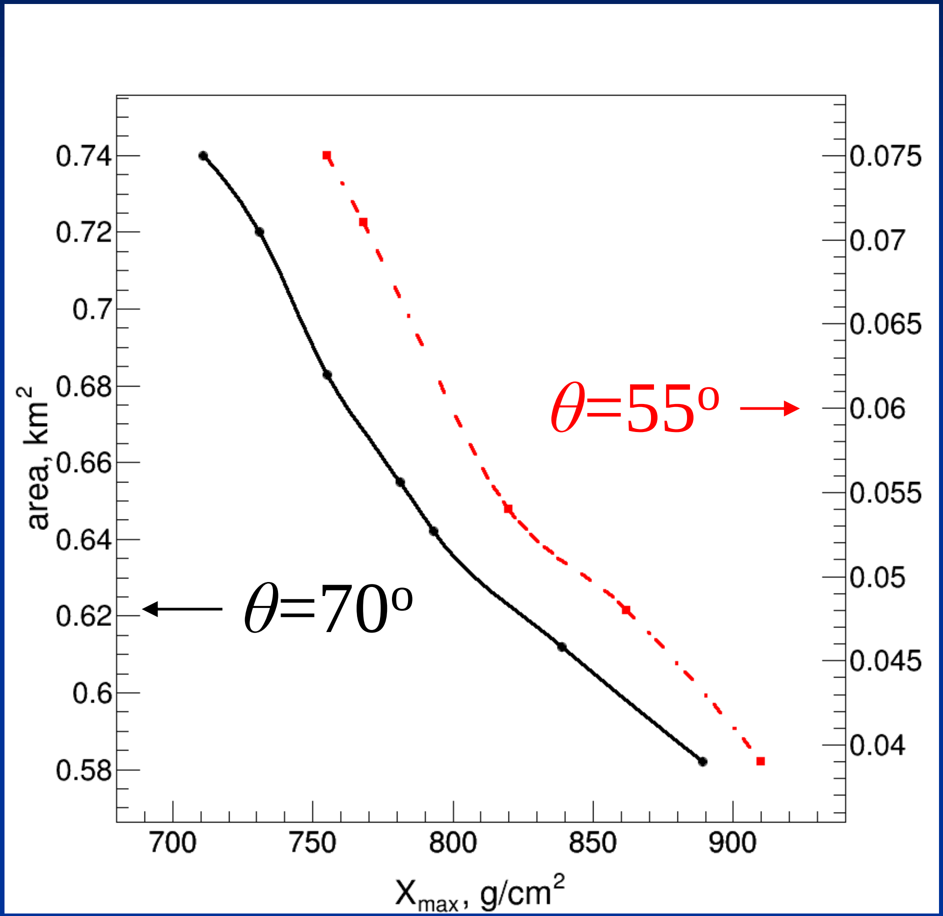
Xmax = 711 g/cm2



Xmax = 879 g/cm2

θ=70º

Cherenkov ellipse area



- **Zenith angle is measured by ellipticity**
- **Area determines the shower maximum**

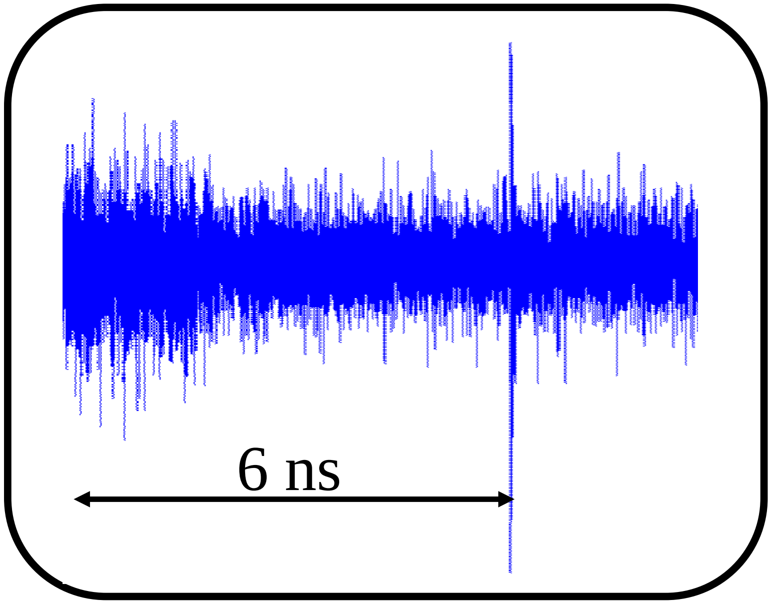
Resolution is improved by measuring:

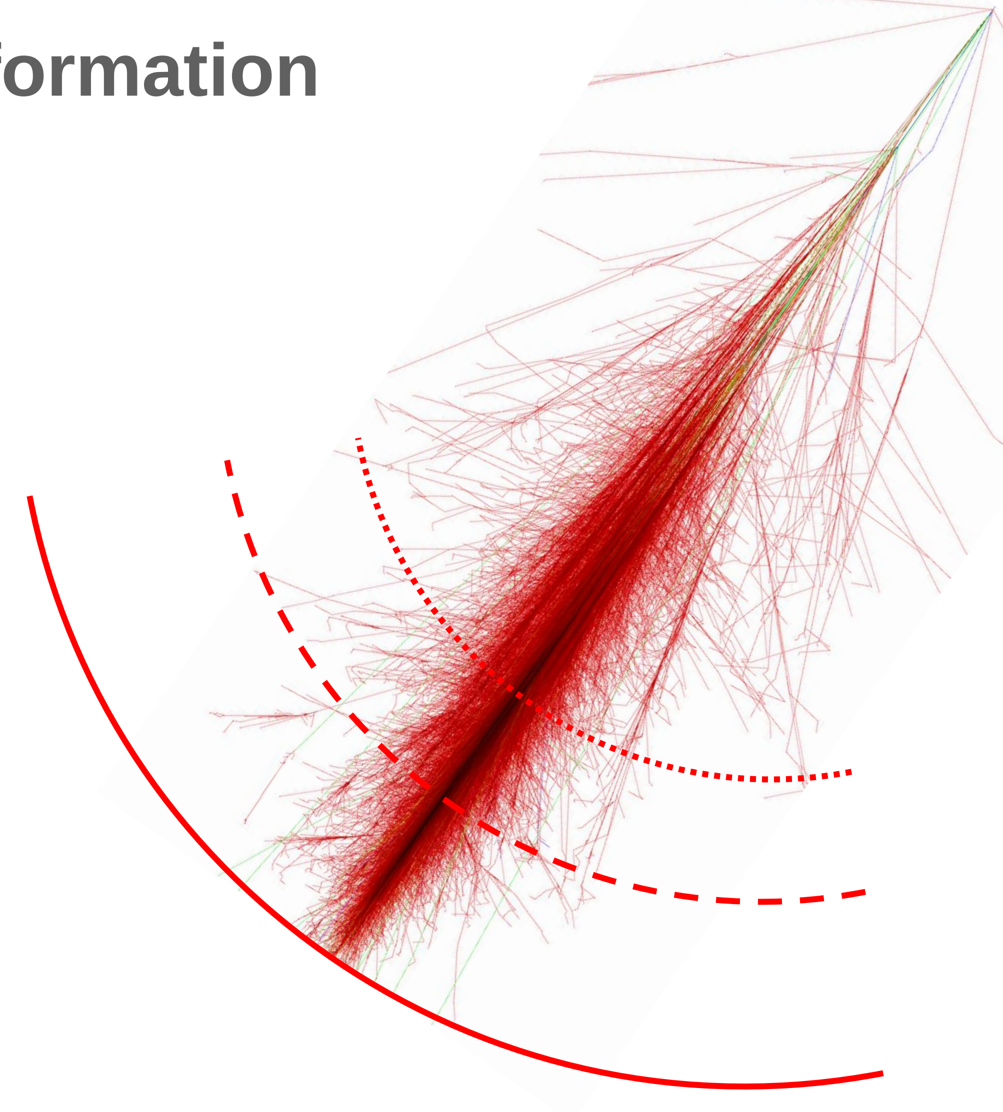
- **Spectrum (off angle)**
- **Polarity (inside or outside of Cherenkov cone)**
- **Polarization (azimuthal location)**

Few antenna hits are needed to reconstruct the Cherenkov ellipse

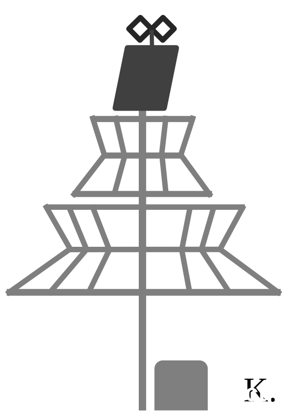
Timing information

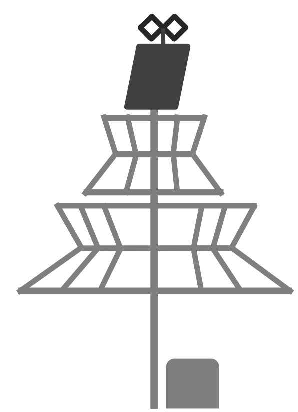
- Arrival direction reconstruction
- X_{max} reconstruction





- n =1.0003
- Trigger on muons
- 6 ns ~ 6 km
- Alternative external trigger (TA counter)





Neutrino-induced air showers

A tau neutrino interactions: tau lepton decay produces large footprint of particles up to 50km

Left: ground particle density from electron decay channel.

Right: pion decay channel

Bertou et al. 2001, astroph/0104452

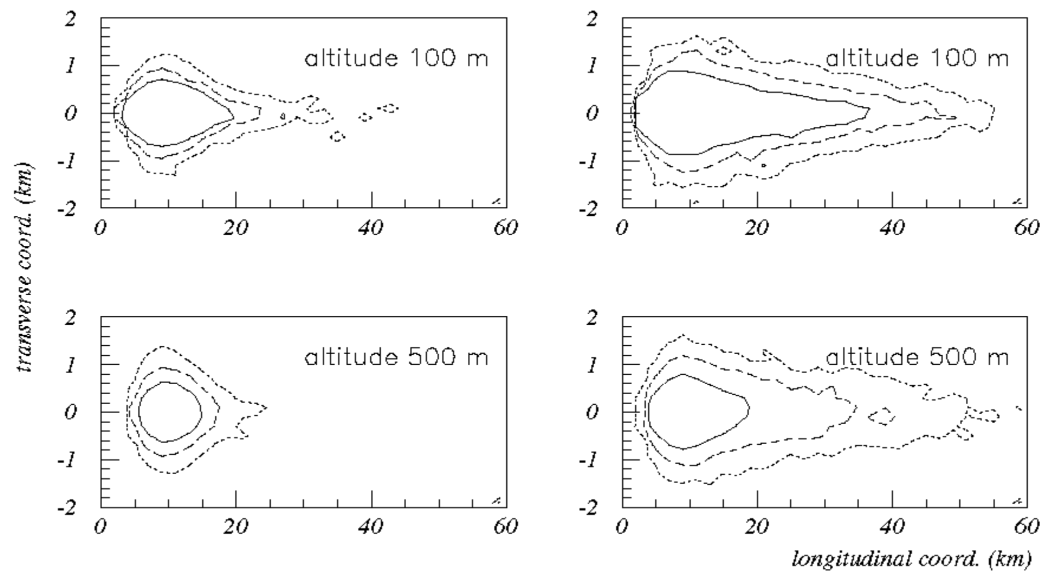
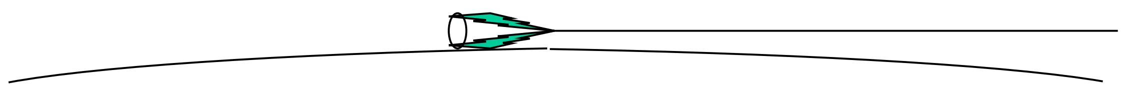


Figure 3. Ground spots of horizontal showers induced by a τ of 1 EeV. Lines are iso-density curves at the threshold of the tank local trigger (solid), at 0.3 (dashed) and at 0.1 (dotted). All of this data (even when below threshold) can be used if a global trigger could be generated from a set of local triggers. Left: τ decay into $e\nu_e\nu_\tau$; right: decay into $\pi\nu_\tau$



- 10^{19} eV - 0.2% chance of producing a shower along a 250 km track
- 0.5%at 10^{20} eV
- Radio wavefront curvature is different for cosmic ray interactions:
  - neutrinos will be interacting all along their track with equal probability
  - statistically closer & deeper in atmosphere

By P. Gorham

Conclusions

- **Radio detection of UHECRs emerges from the dark past into bright future - first measurement of UHECR flux using radio**
- **Energy, composition and particle cross–section can be measured with high resolution by a ground radio array**
- **Complimentary trigger discriminator for a space mission (EUSO-X):**
  - **to detect upward going showers (like tau-neutrino events)**
  - **golden set of hybrid CR events (air fluorescence + radio data)**
- **New data at highest energies will allow us to finally solve the mystery of the cosmic rays**
- **Can detect radio transients (RF emission from GRB bursts and other violent events)**
- **Opening a new window to Charged Particle Astronomy!**