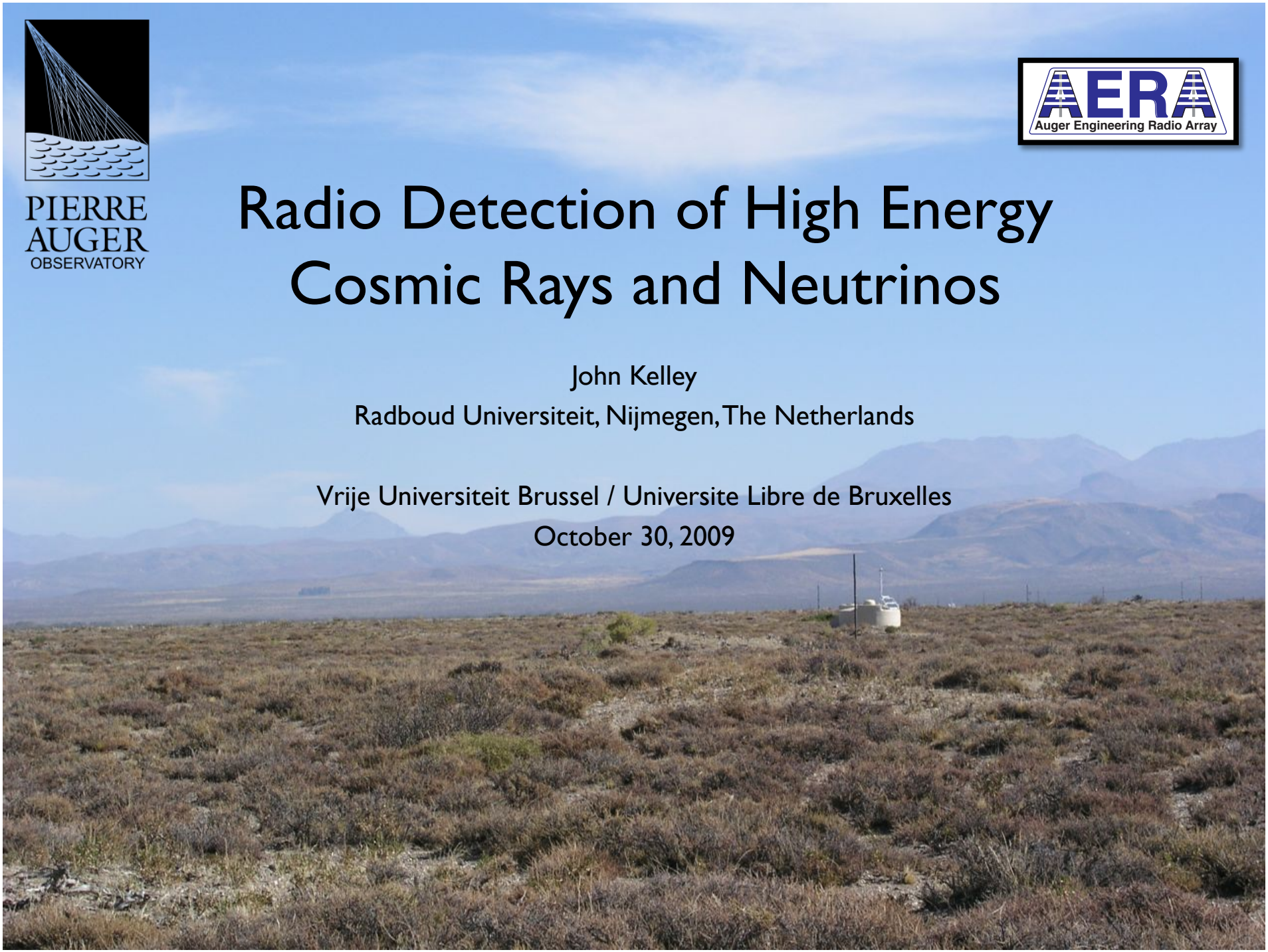


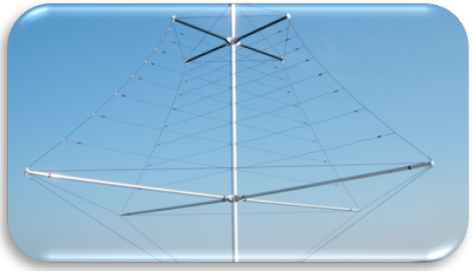
Radio Detection of High Energy Cosmic Rays and Neutrinos

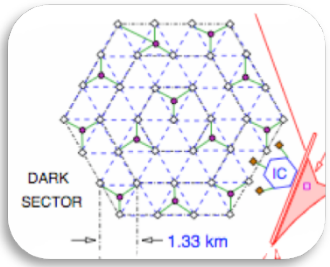
John Kelley
Radboud Universiteit, Nijmegen, The Netherlands

Vrije Universiteit Brussel / Universite Libre de Bruxelles
October 30, 2009

Outline

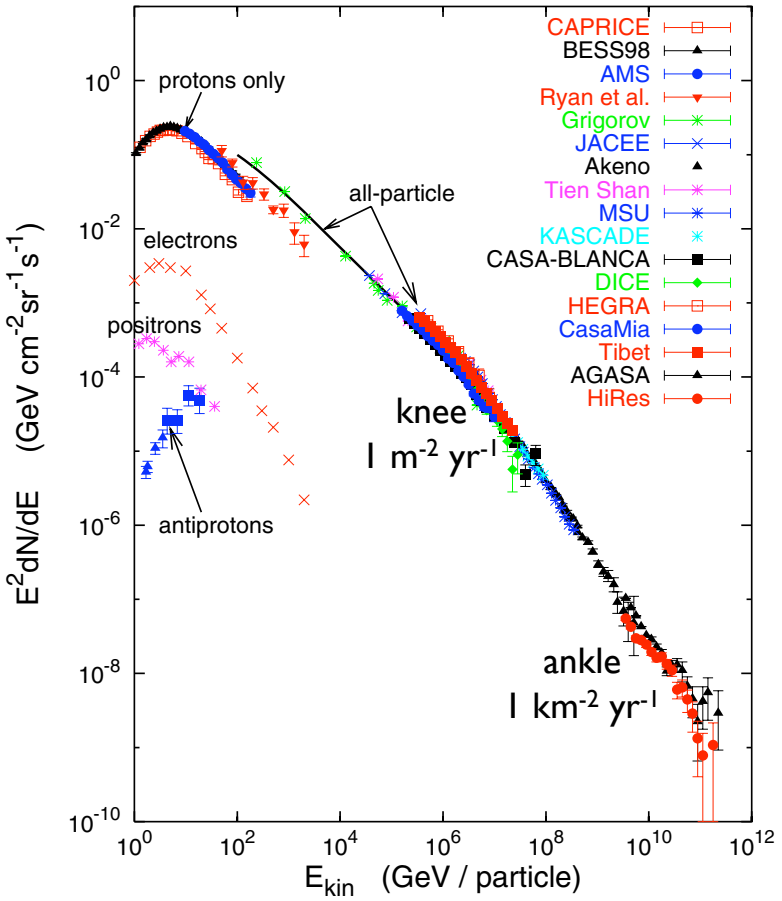
- Background and motivation
  - Open issues in cosmic ray physics
  - Latest results and their implications
- Radio air shower detection
  - Theory / simulation
  - Results from pioneer experiments
  - Next-generation detectors
- The neutrino connection
  - Cosmogenic neutrino flux
  - Radio neutrino detection
  - Next steps





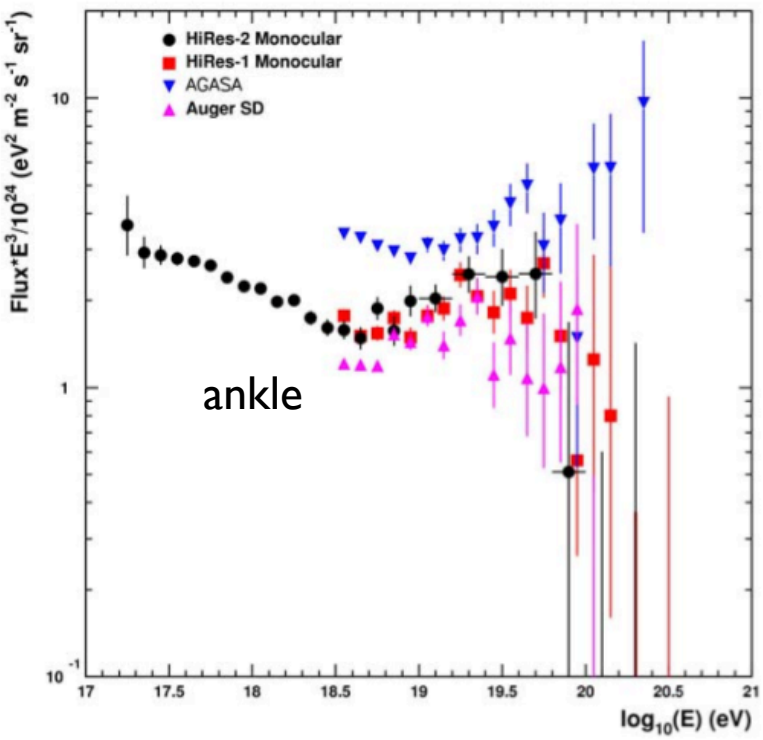
Cosmic Ray "Standard Model"

- Charged particles with steep power law spectrum (flux changes by 10^{30})
- Below "knee" (~10^6 GeV) mostly protons
  - gyroradius smaller than our Galaxy
  - shock acceleration in supernovae remnants (?)
- "Ankle": transition to extragalactic sources?



Gaisser 2004

Above Ankle:
Ultra-High Energy Cosmic Rays (UHECR)

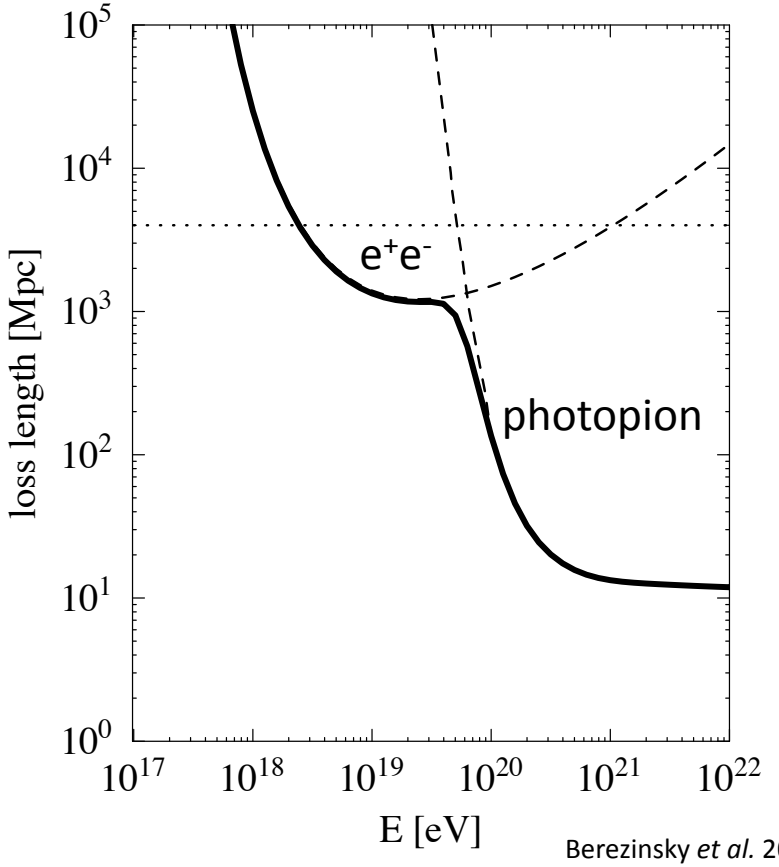


Sokolsky & Thompson 2007

- Highest energy particles known in the Universe
- Composition unknown
- Sources + acceleration mechanism unknown
  - presumably extragalactic
  - AGN? GRBs? Topological defects?
- Cutoff in spectrum or not?

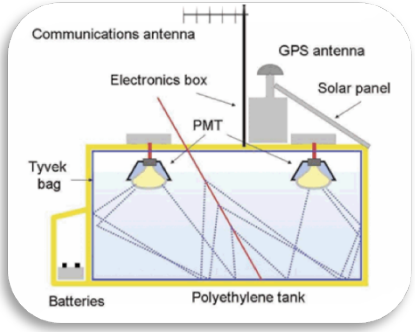
GZK Suppression

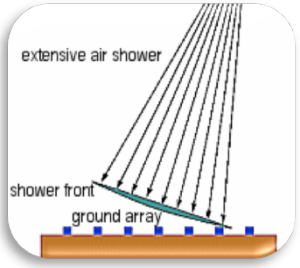
- Suppression expected above 50 EeV due to interaction with CMB photons (Greisen-Zatsepin-Kuzmin)
- Spectrum keeps going?
  - Sources unexpectedly close (not many candidates within 50 Mpc)
  - New physics (e.g. violation of Lorentz invariance)
  - Situation 4-5 years ago totally unclear

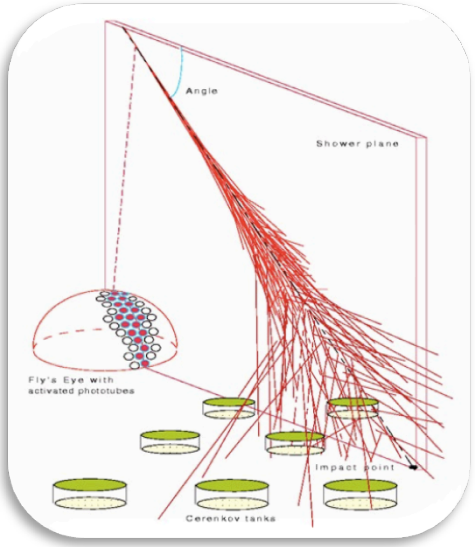


Berezinsky *et al.* 2007

Air Shower Detection



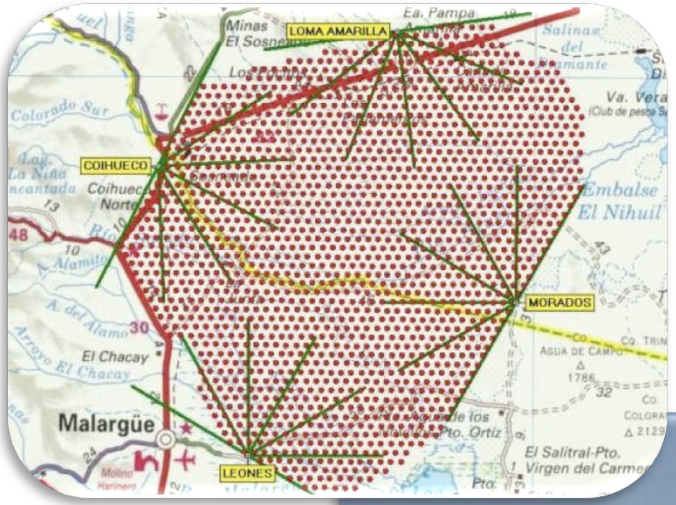




- Water (or ice) Cherenkov tanks
  - detect EM shower front on ground
  - spacing controls energy threshold
  - near-100% duty cycle
- Fluorescence telescopes
  - follow Nitrogen fluorescence as shower develops
  - good for calorimetry, measurement of shower maximum
  - requires monitoring of atmospheric conditions
  - duty cycle is ~10%

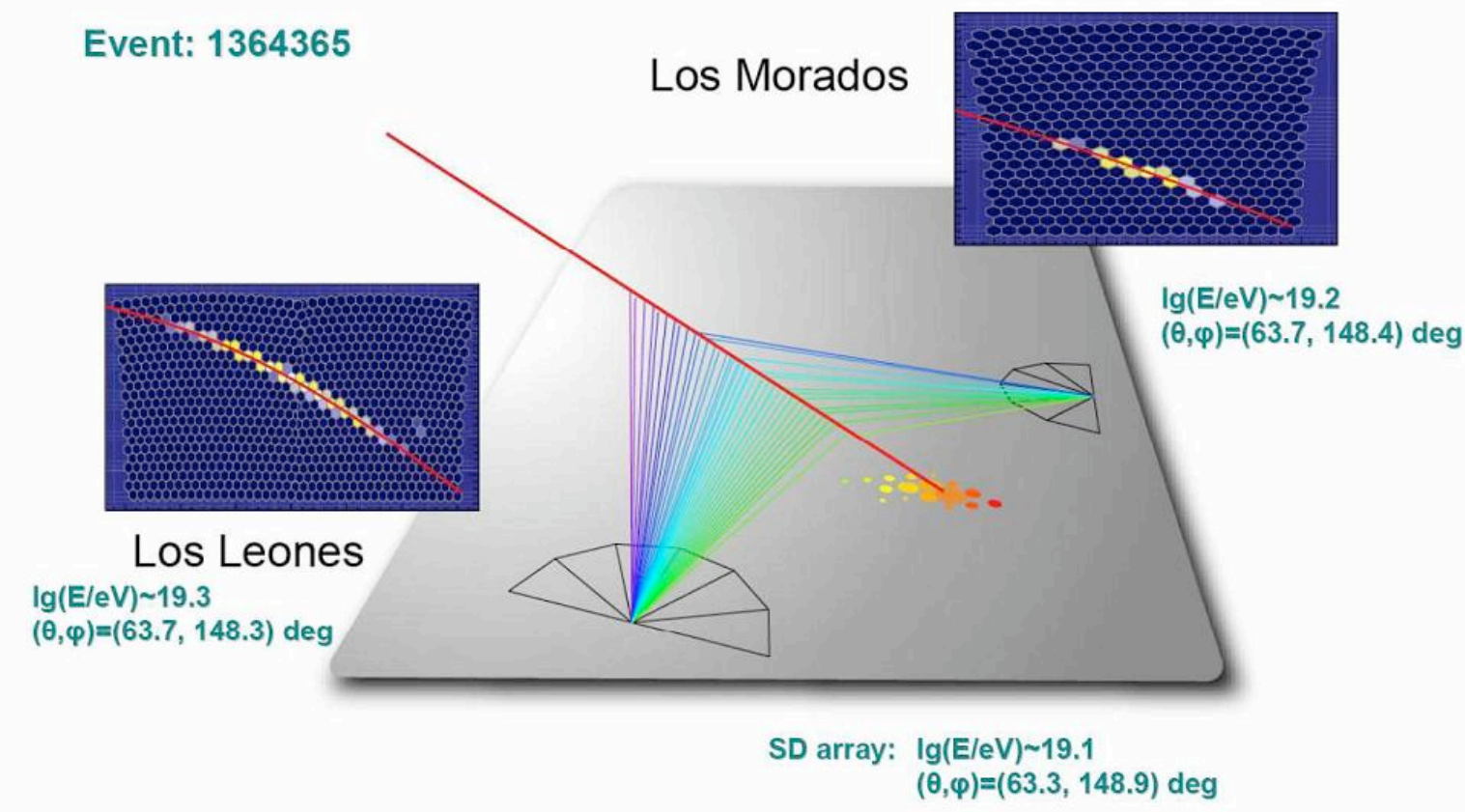
Pierre Auger Observatory

- Hybrid air shower detector
- Southern site (3000 km^2) in Argentina completed 2008
- Northern site (21000 km^2) planned for Colorado, U.S.A.

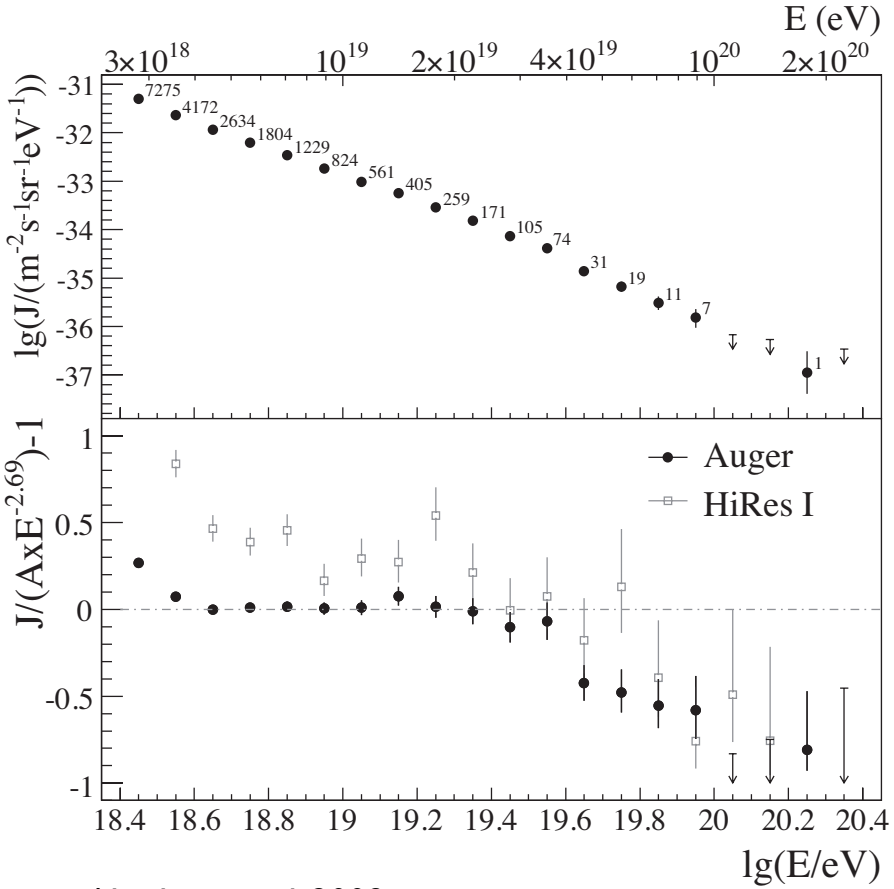


Auger South

Sample Hybrid Event



Latest Results: UHECR Energy Spectrum



Abraham *et al.* 2008

- Continuation of power law rejected at 6σ
- Confirms result by HiRes experiment (Abbasi *et al.* 2008)
- Suppression energy consistent with GZK onset

UHECR Anisotropy

- Extragalactic protons above 50 EeV or so should point back to sources (within a few degrees)

$$\theta(E,Z) \approx \left(\frac{L}{L_{\rm coh}}\right)^{0.5} \alpha \approx 0.8^\circ \left(\frac{10^{20}\,{\rm eV}}{E}\right)\left(\frac{L}{10\,{\rm Mpc}}\right)^{0.5}\left(\frac{L_{\rm coh}}{1\,{\rm Mpc}}\right)^{0.5}\left(\frac{B}{1\,{\rm nG}}\right) Z,$$

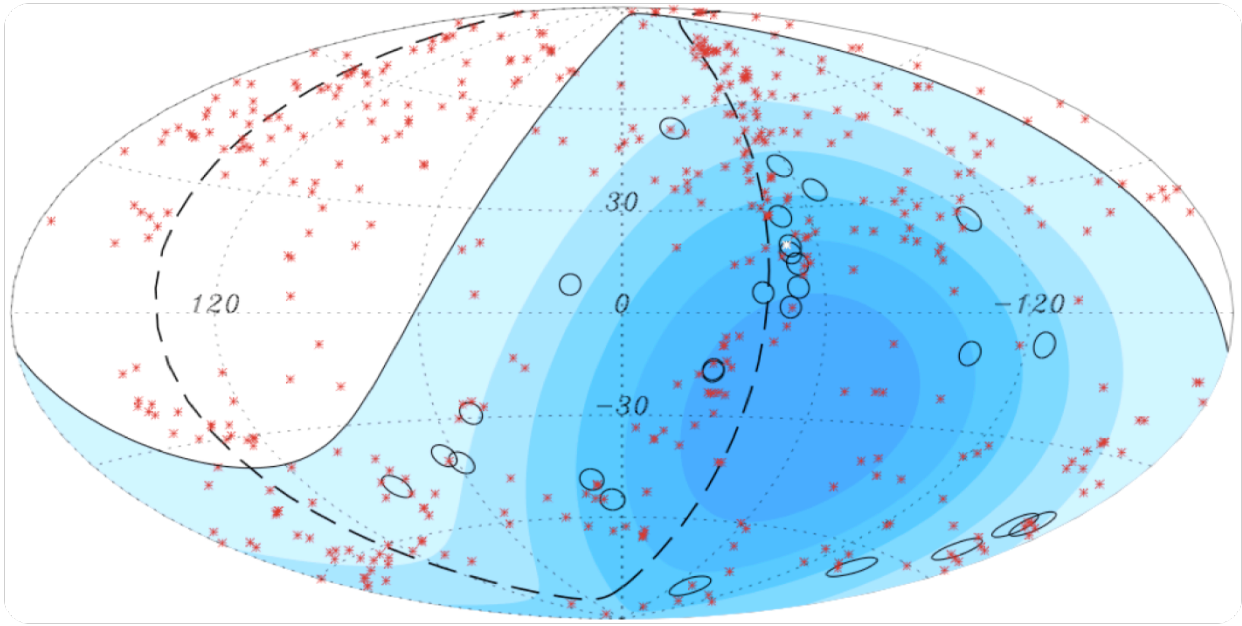
Hooper *et al.* 2008

- Pre-Auger: claims of excess from galactic center, BL-Lacs, etc.

- Anisotropy with low statistics is a tricky business

Anisotropy, cont.

Abraham *et al.* 2007



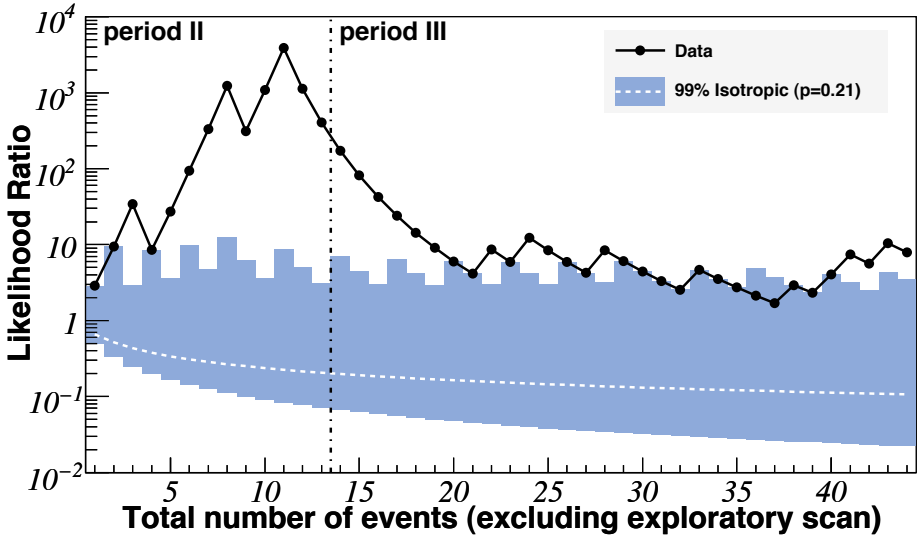
2007: 27 events above 55 EeV (ovals); 3.7σ correlation with nearby AGN (red crosses)

Isotropy rejected at 99% confidence level

Separate analyses: No correlation found with galactic center or BL-Lacs

Latest Results: Anisotropy

Hague *et al.* 2009 (ICRC)



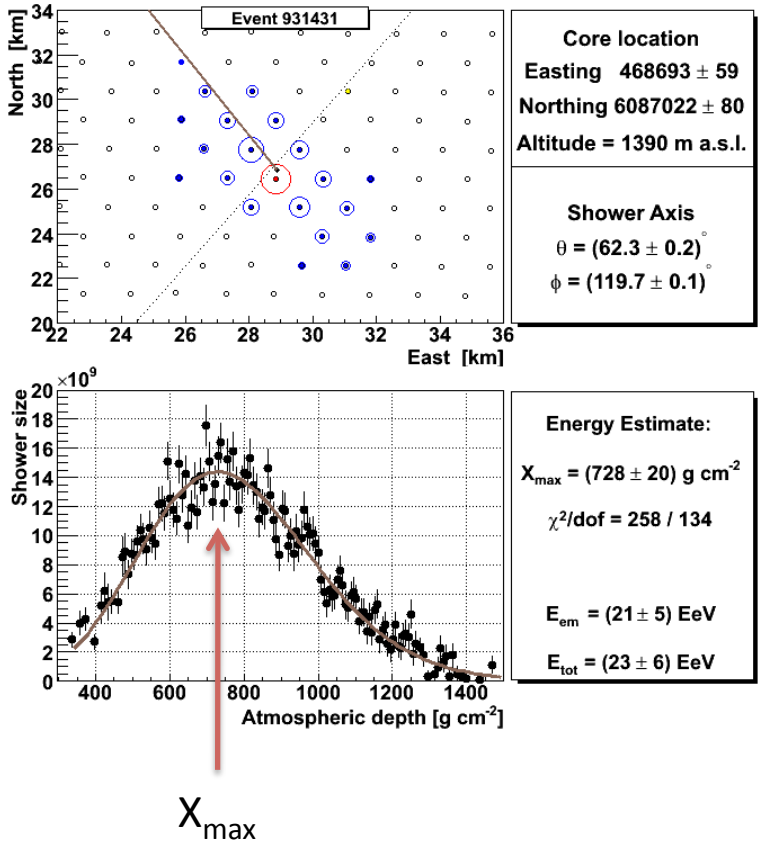
2009: correlation with AGN catalog weakens (39% correlate, 21% expected for isotropy — 3.4σ)

Period III only: 1σ correlation

Isotropy rejected at about same CL (99.4%)

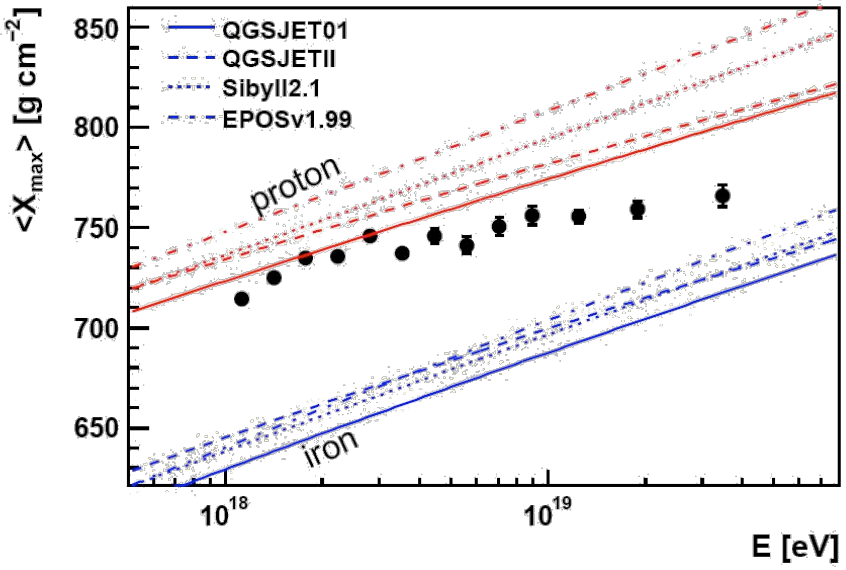
Composition

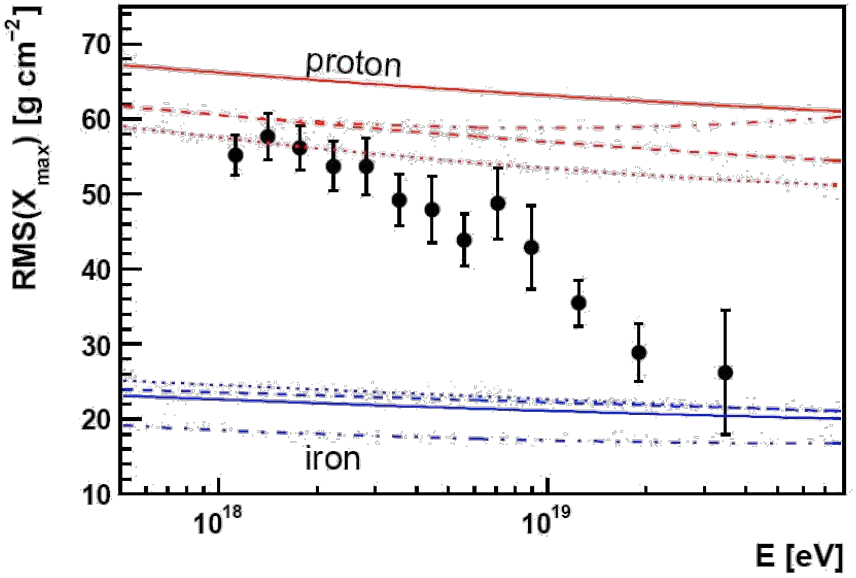
- Slant depth X_{max} (integrated density) of shower maximum in atmosphere
  - energy and composition-dependent
  - higher in atmosphere for heavier nuclei (interact, lose energy sooner)
- Shower-to-shower fluctuations of X_{max}
  - iron showers (~superposition of 56 proton showers of 1/56 energy) have fewer fluctuations



Latest Results: Composition

Bellido *et al.* 2009 (ICRC)





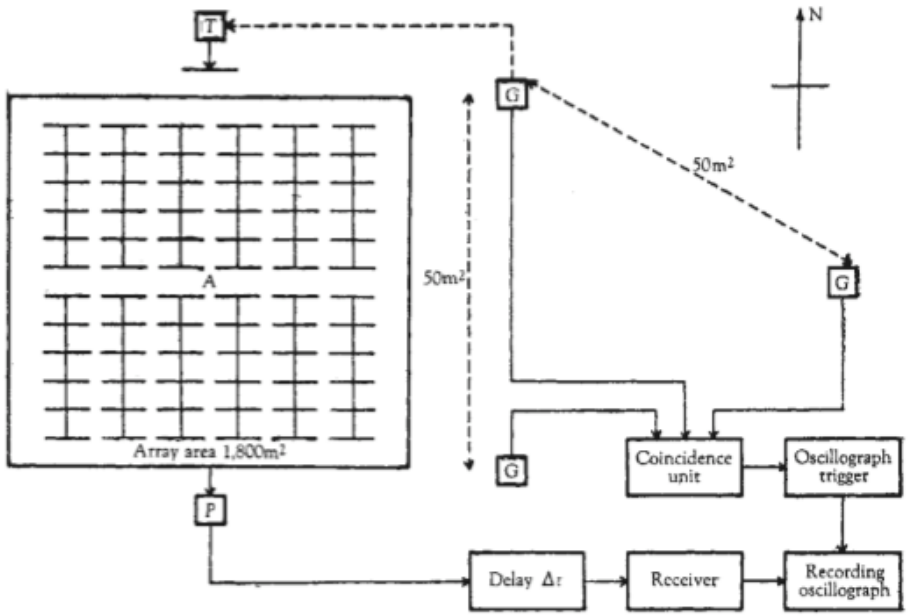
Both indicate composition getting heavier…
or protons behaving very differently than expected

Interpretation

- Tension between…
  - anisotropy results (small deflection) and heavy composition (large deflection)
  - Auger and HiRes results on composition (latter data look proton-like, but fewer statistics)
- GZK interpretation difficult if composition uncertain
- A calorimetric air shower detection method with a high duty cycle can help resolve this
- Need a technology that is scalable to even larger areas

Air Shower Radio Emission

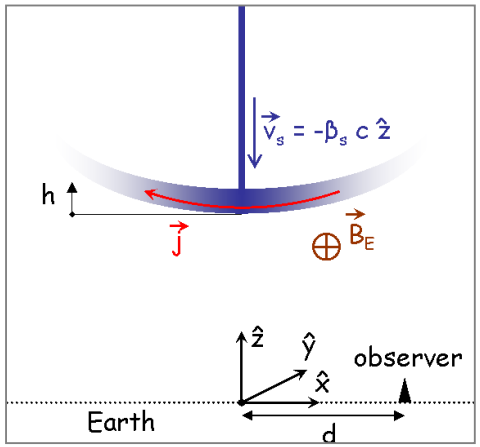
- Measured at 44 MHz by Jelley *et al.* in 1965
- Approach shelved in 1970s (technological limitations)
- High bandwidth receivers + fast digitizers: renewed interest



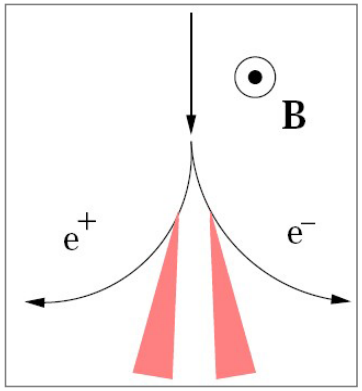
Jelley *et al.* 1965

Emission Mechanism(s)

- Cherenkov radiation from negative charge excess
  - proposed by Askaryan in 1962
  - verified at SLAC
- Separation of e^+, e^- in geomagnetic field
  - macroscopic: transverse current
  - microscopic: synchrotron emission
- For air, geomagnetic emission expected to dominate
  - other way around for dense media (like ice)

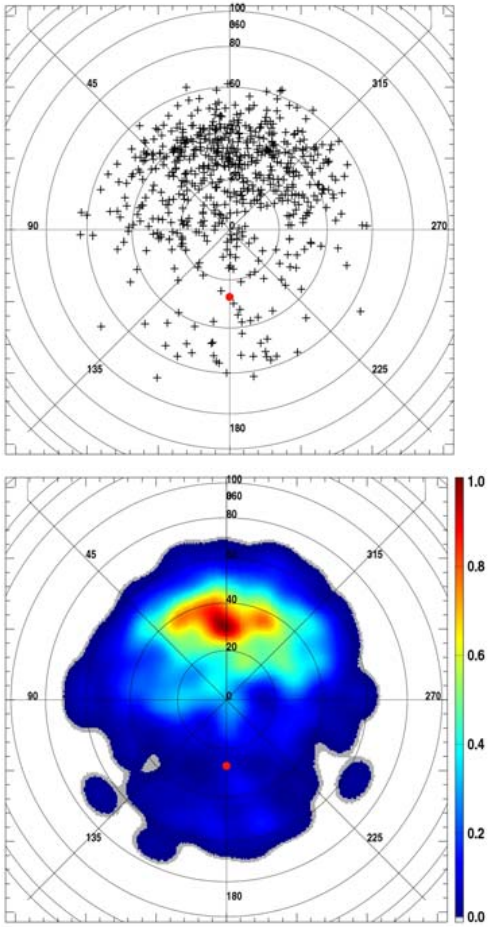


see e.g. Kahn & Lerche, Werner & Scholten



see e.g. Falcke & Gorham, Huege *et al.*

Geomagnetic Origin



Ardouin *et al.* 2009

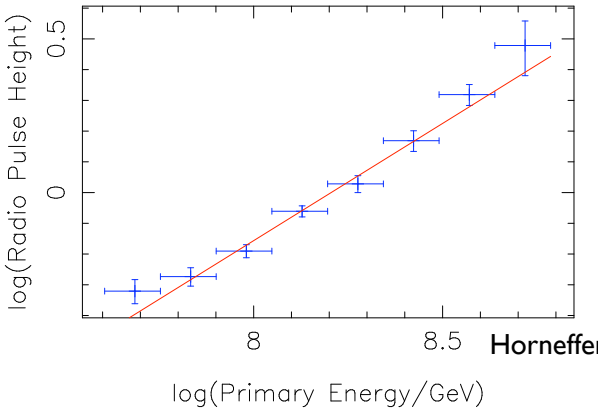
- Simplification: geomagnetic origin implies

$$\vec{E} \propto \vec{v} \times \vec{B}$$

- Asymmetry confirmed with LOPES, CODALEMA experiments

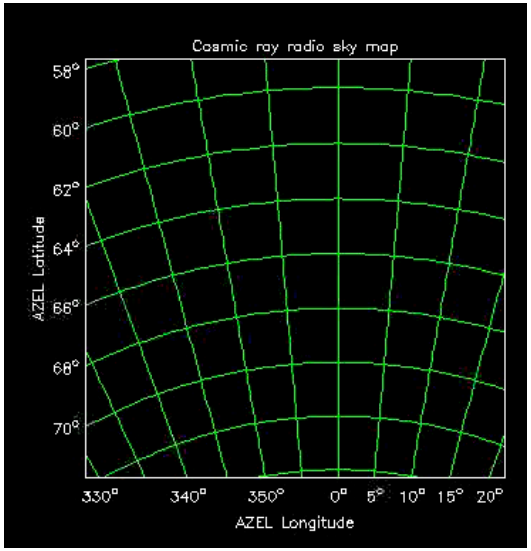
Coherence and Imaging

- Radiation is coherent below ~100 MHz
  - E field ~ primary energy



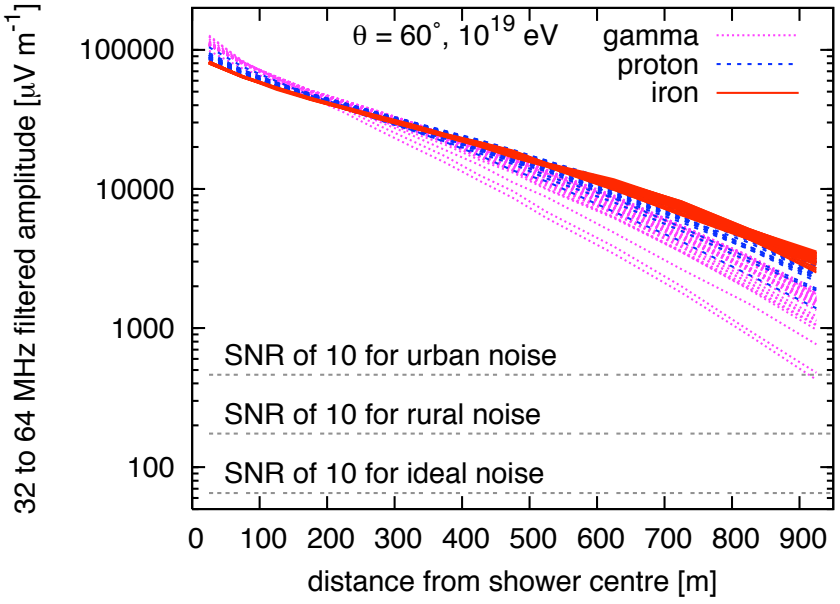
Horneffer *et al.* 2006

- Offline beam-forming!
  - image radio pulse in 5D: space, time, and frequency
  - angular resolution ~ 1°



Composition

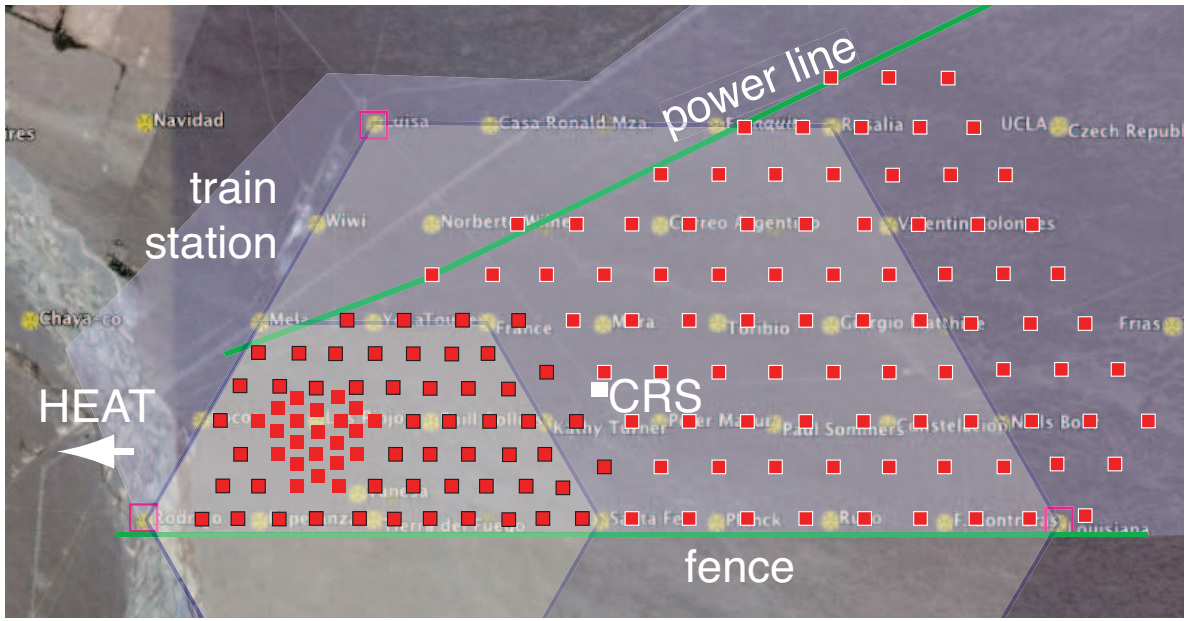
- Primary composition by:
  - lateral distribution
  - reconstruction of X_{max} by shower front curvature
- Simulations only at this point: need larger array, more events!



Huege *et al.* 2008

AERA

- AERA: Auger Engineering Radio Array
- 20 km^2 extension to southern site (at infill array)
- Phase I: 25 stations, early 2010 (total: 150)



Radio Detection Station

- Autonomous, solar power
- LPDA antenna, 30-80 MHz bandpass
- Local digitizer and trigger
- Coincidence via central DAQ

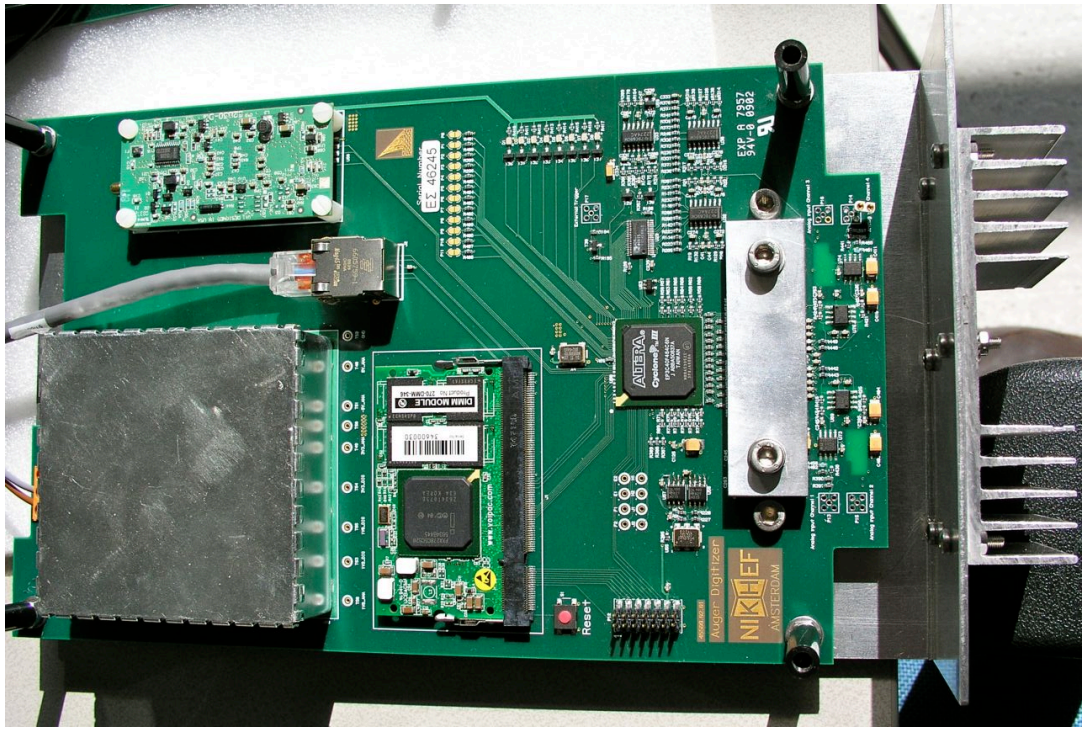
Digital Electronics

GPS receiver (timestamping)

Cyclone III FPGA (triggering & readout)

Ethernet (to comms)

DC/DC conv. (shielded)

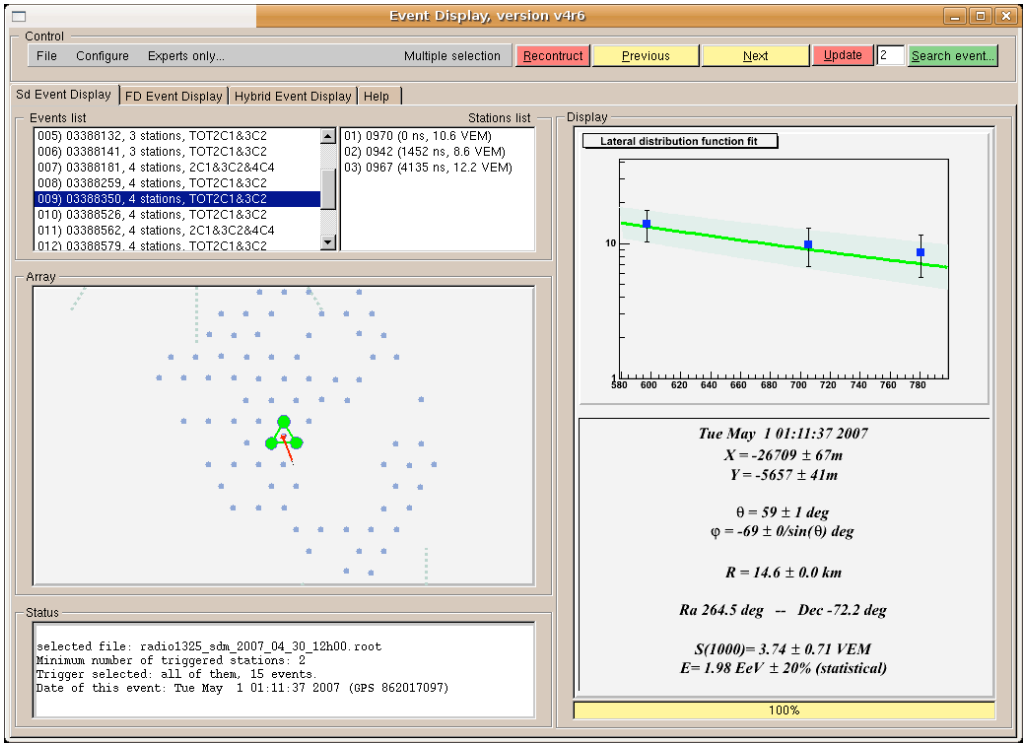


4 channel, 200 MHz ADCs w/heatsink (passive)

XScale-based PC board (running Linux)

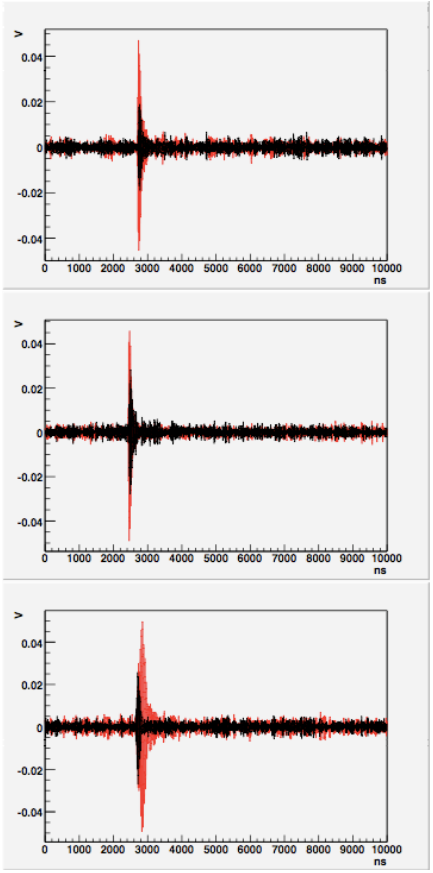
serial interface

Sample Event



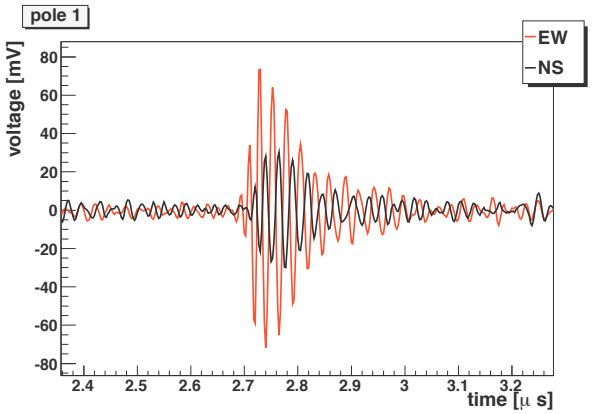
Auger SD display (E ~ 2 EeV)

radio signal (3 antennas x 2 polarizations)

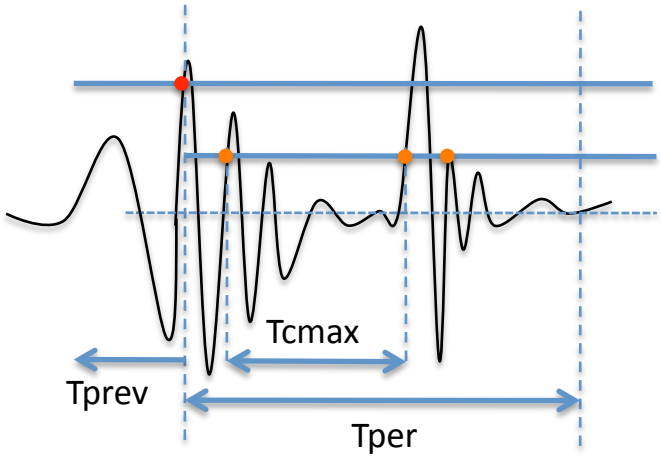


Self-Triggering

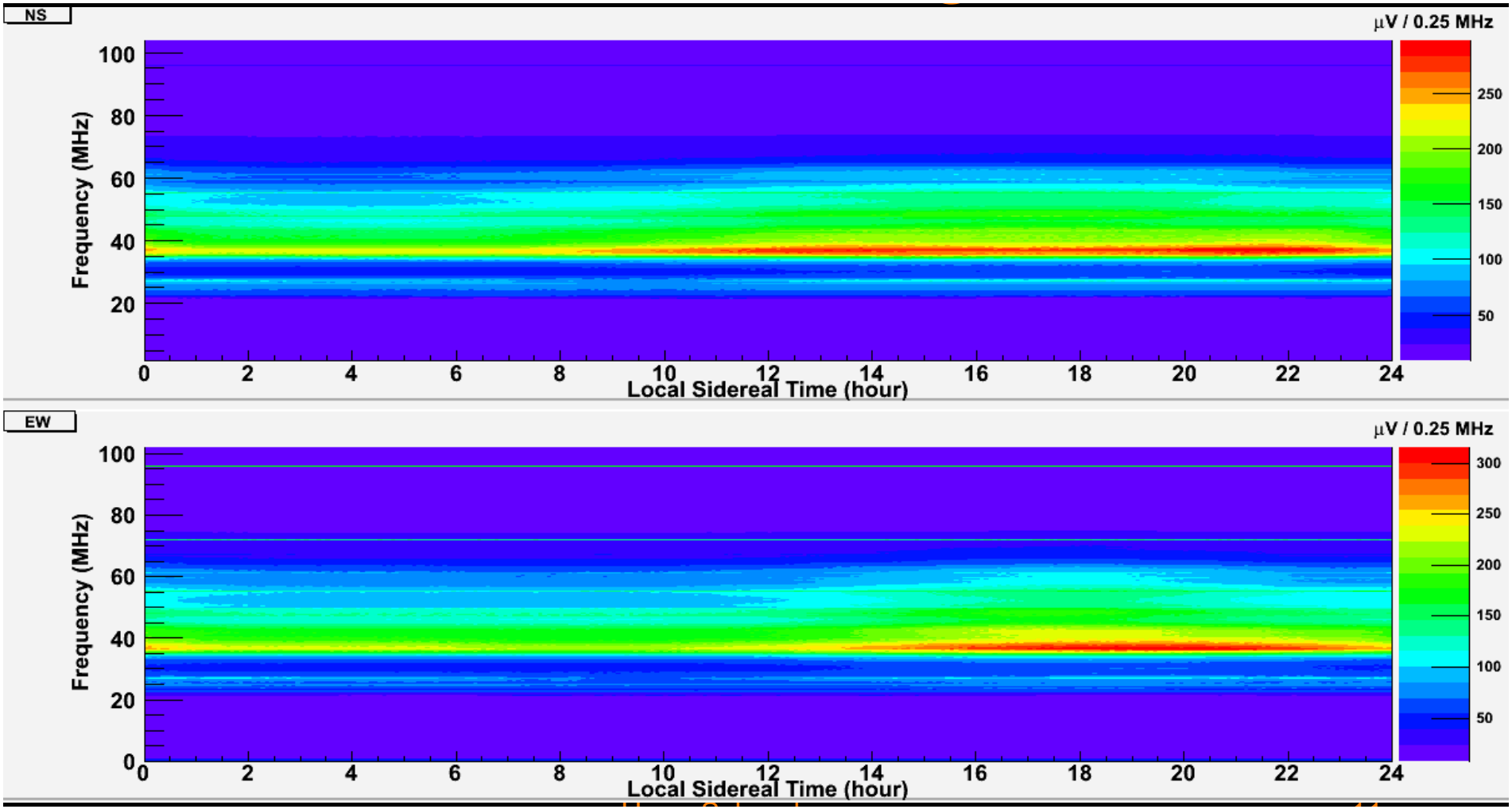
- Technological challenge: impulsive RFI
- Current algorithms focus on time-domain analysis
- New techniques under development:
  - power detection circuit
  - periodic veto (e.g. 50 Hz)
  - wavelet filtering



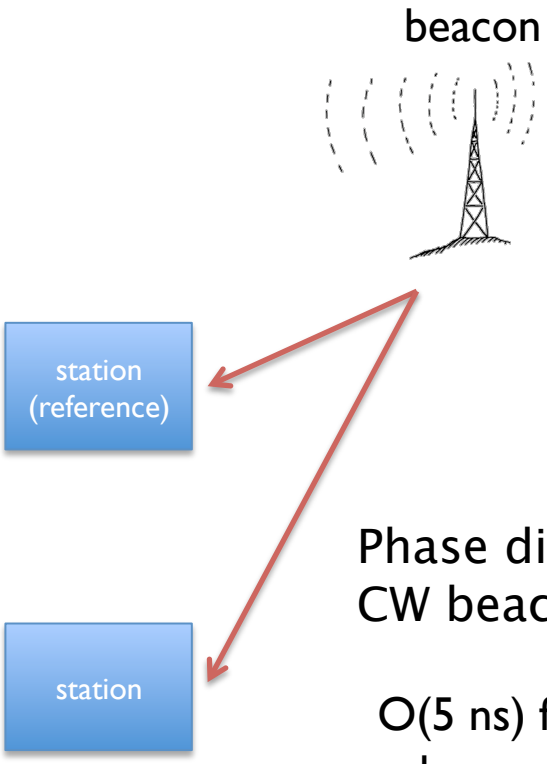
BW-limited pulse



Calibration Techniques (I)



Calibration Techniques (II)

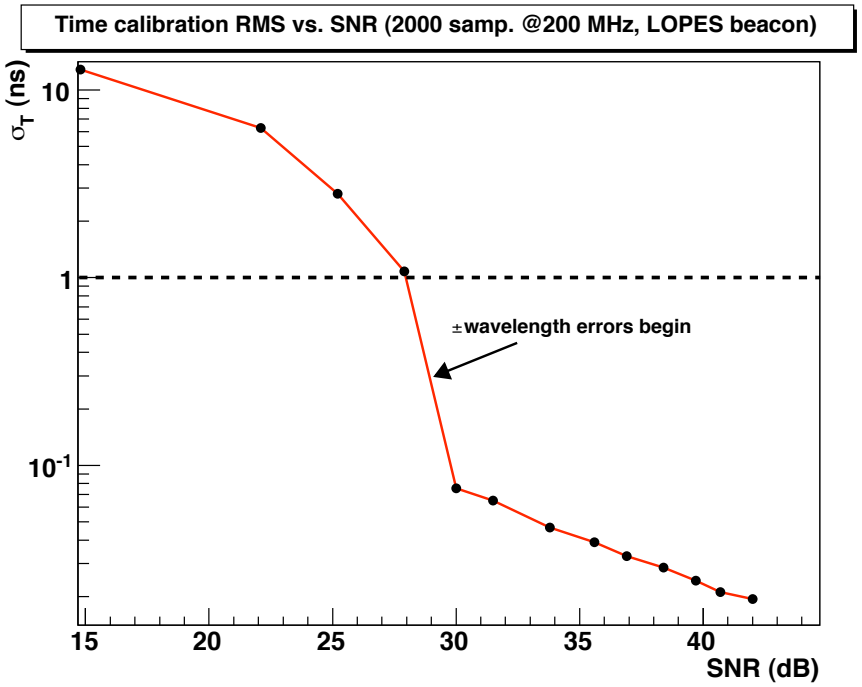


Phase difference from CW beacon (2+ freq.)

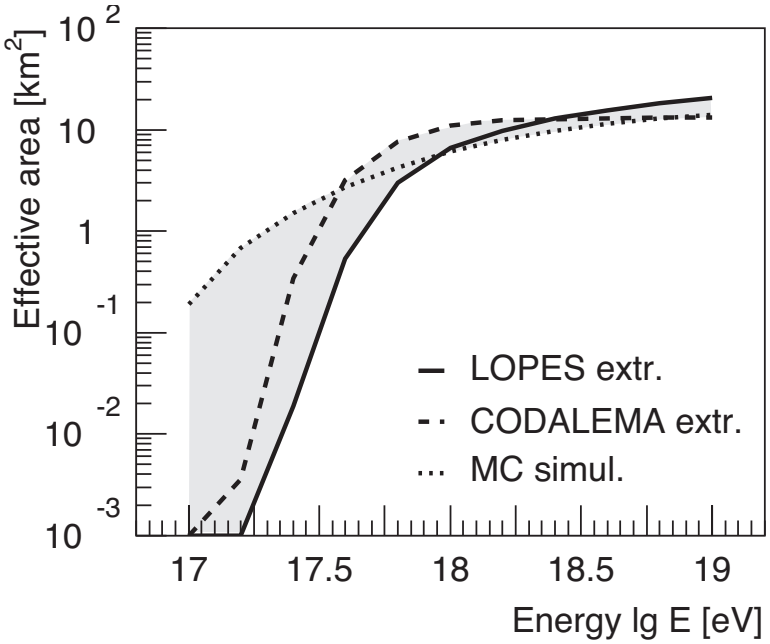
O(5 ns) from GPS to sub-nanosecond timing

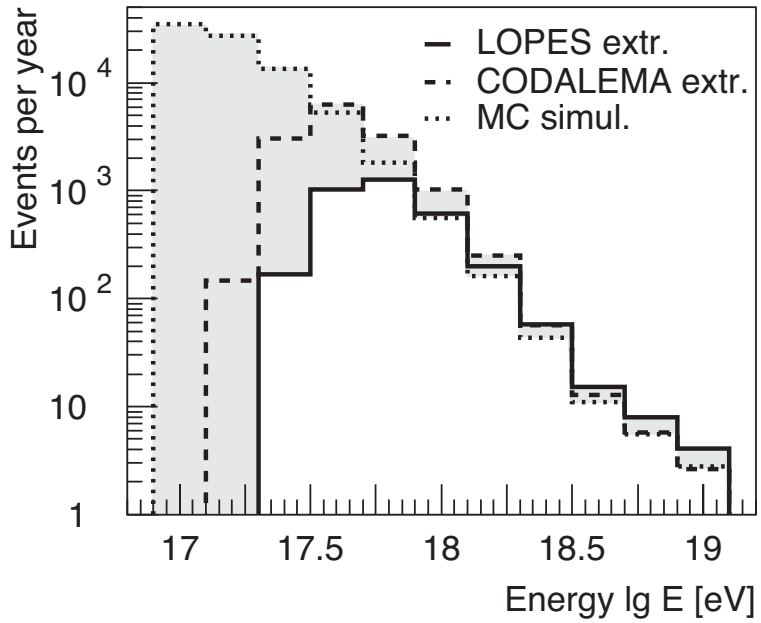
Also: solar flares, lightning

simulated timing error



Event Rates





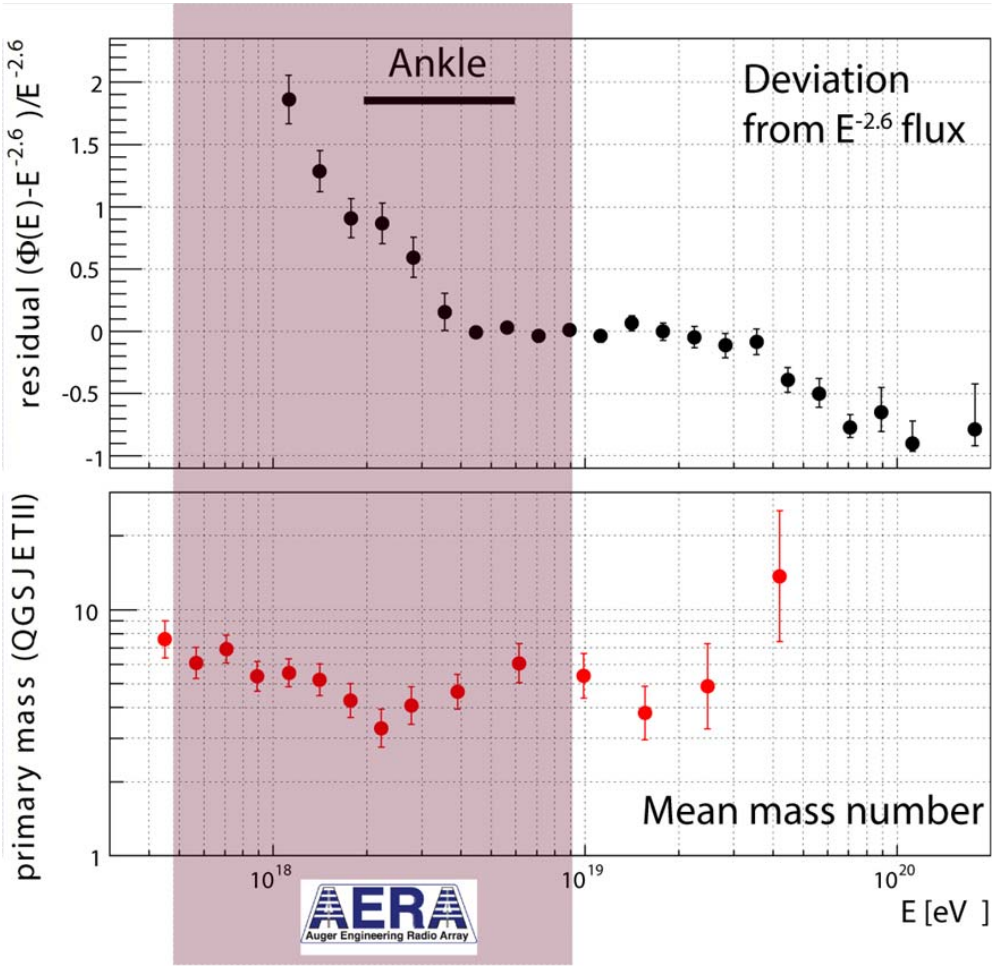
Conservative energy threshold: log(E / eV) ~ 17.2

5000 events / year with $E > 3 \times 10^{17}$ eV
800 events / year with $E > 1 \times 10^{18}$ eV

AERA Science Program

- Detailed calibration of radio signal
  - self-triggering + coincidences other Auger components
  - full understanding of all RF mechanisms
- Resolution of radio technique
  - energy, direction, composition
- Composition of ankle region
  - galactic to extra-galactic transition
  - super-hybrid measurements

AERA Physics



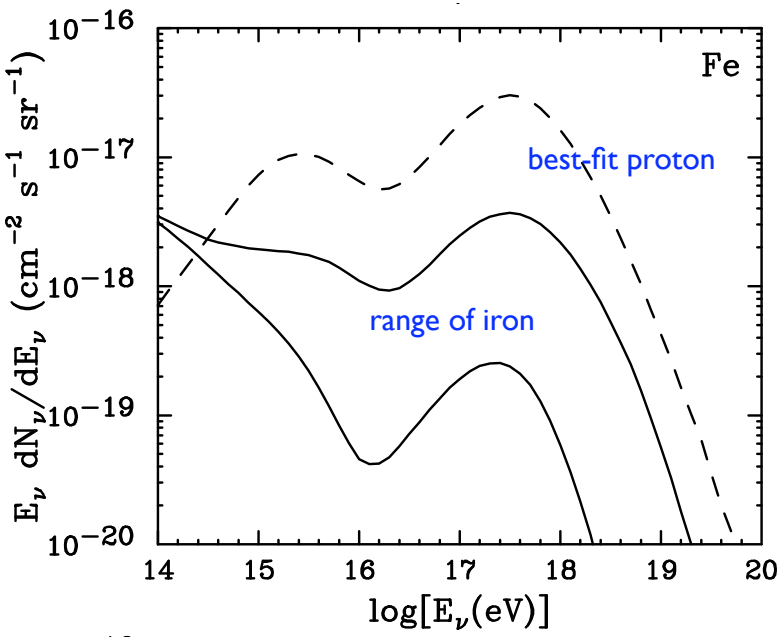
The Neutrino Connection

- Trans-GZK protons lose energy via CMB photopion production
- Also produces UHE neutrinos!

$$p\gamma \rightarrow n\pi^{+} \rightarrow n\mu + \nu_{\mu}$$

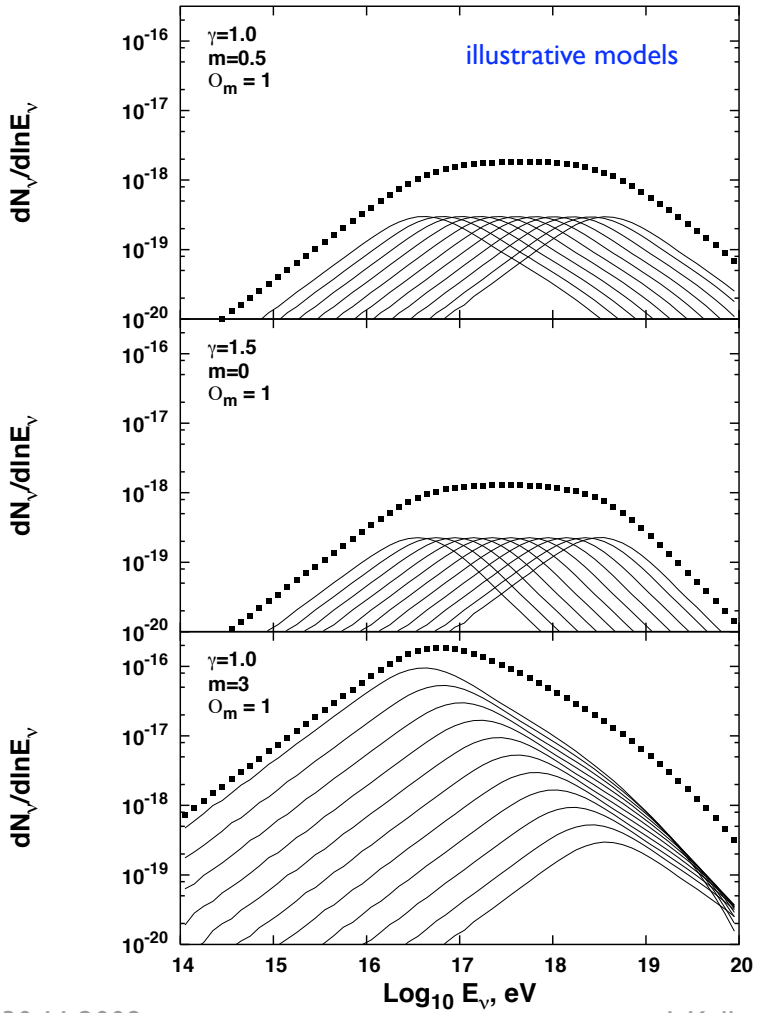
- Nuclei will tend to photodisintegrate first (reduced flux)

GZK neutrino flux



Anchordoqui *et al.* 2007

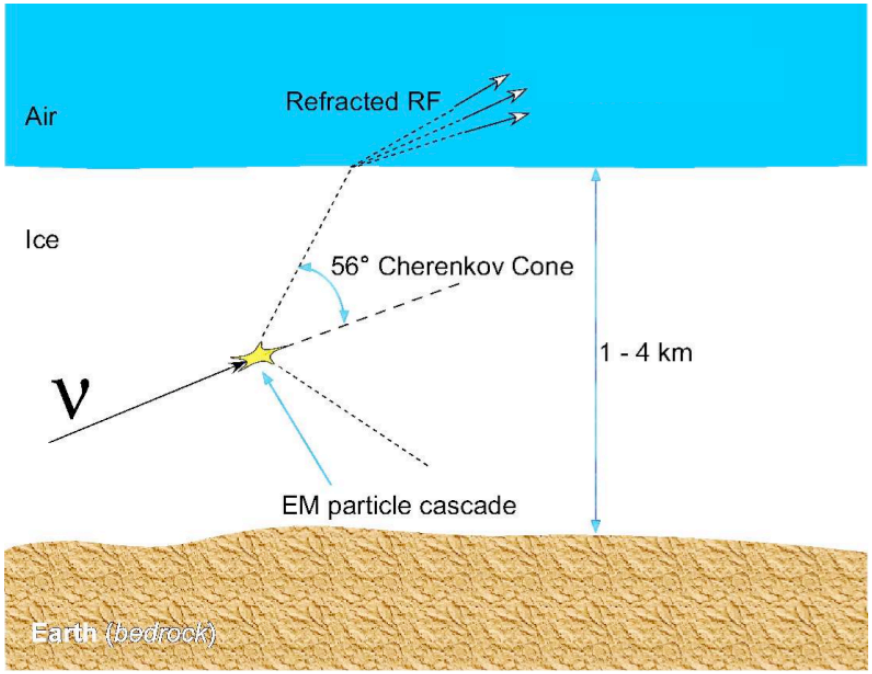
GZK Neutrino Flux



Seckel & Stanev 2005

- UHECR measurements probe only local universe
  - may be dominated by single close source (e.g. Cen A)
  - difficult to disentangle source evolution, source spectrum
- GZK neutrino flux measurement:
  - composition
  - source evolution
  - source spectrum

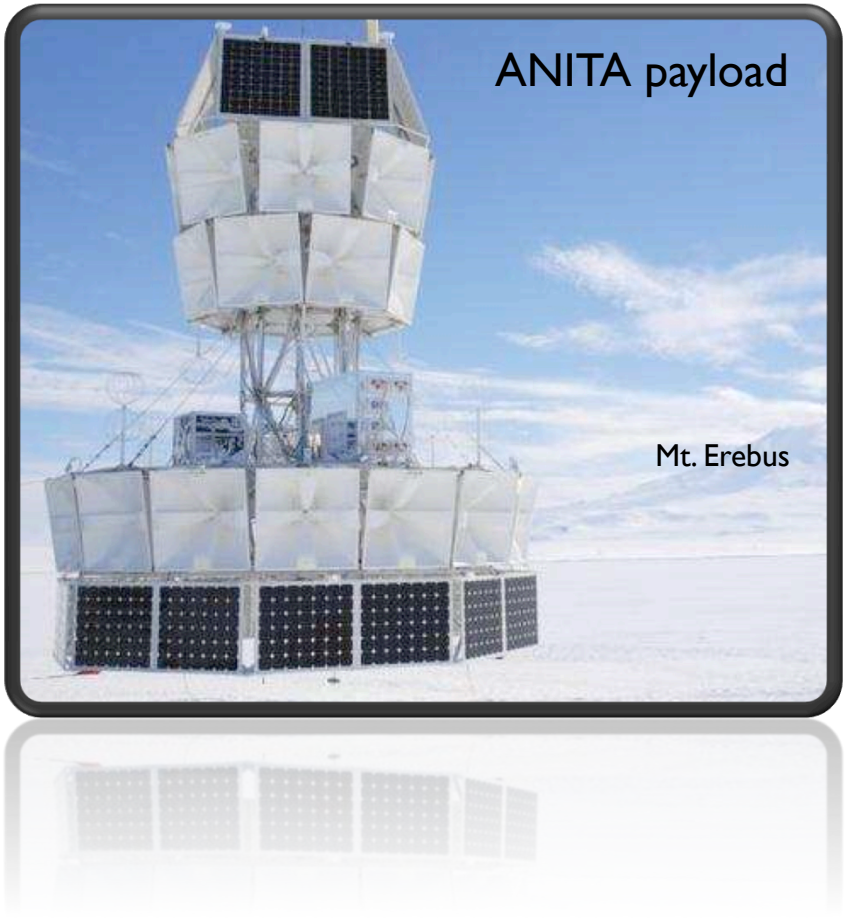
Askaryan Emission

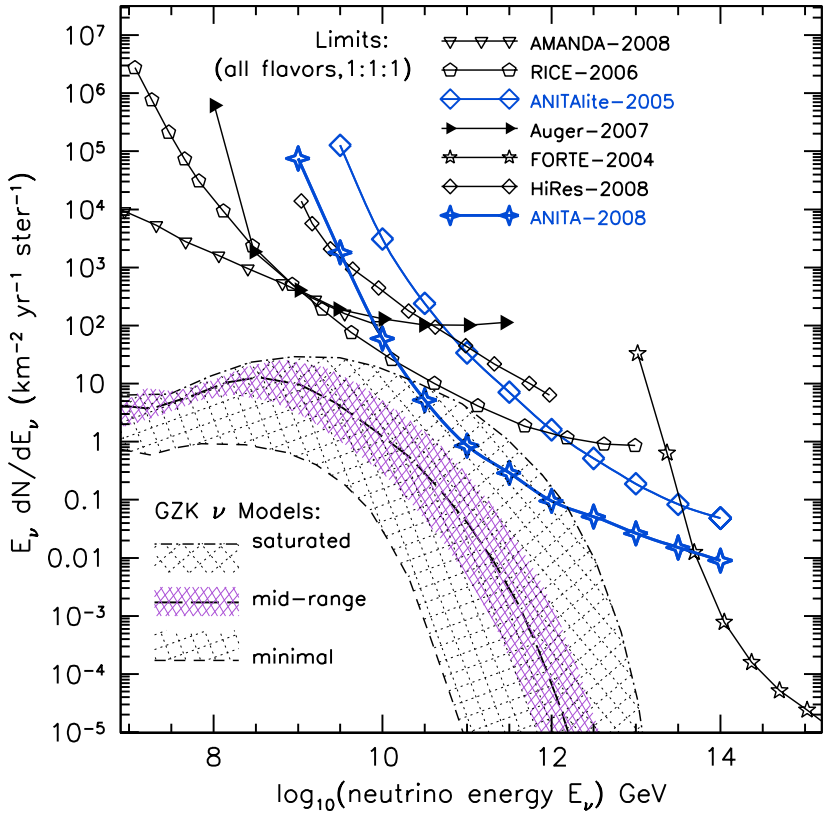


Kowalski *et al.* 2007

- Coherent radio pulse from charge excess (60-1000 MHz) in neutrino-induced showers
- Radiation characteristics confirmed in sand, salt, and ice
- Low fluxes: even e.g. IceCube is too small — but again, radio is scalable
- Cold ice is exceptionally RF-transparent

ANITA

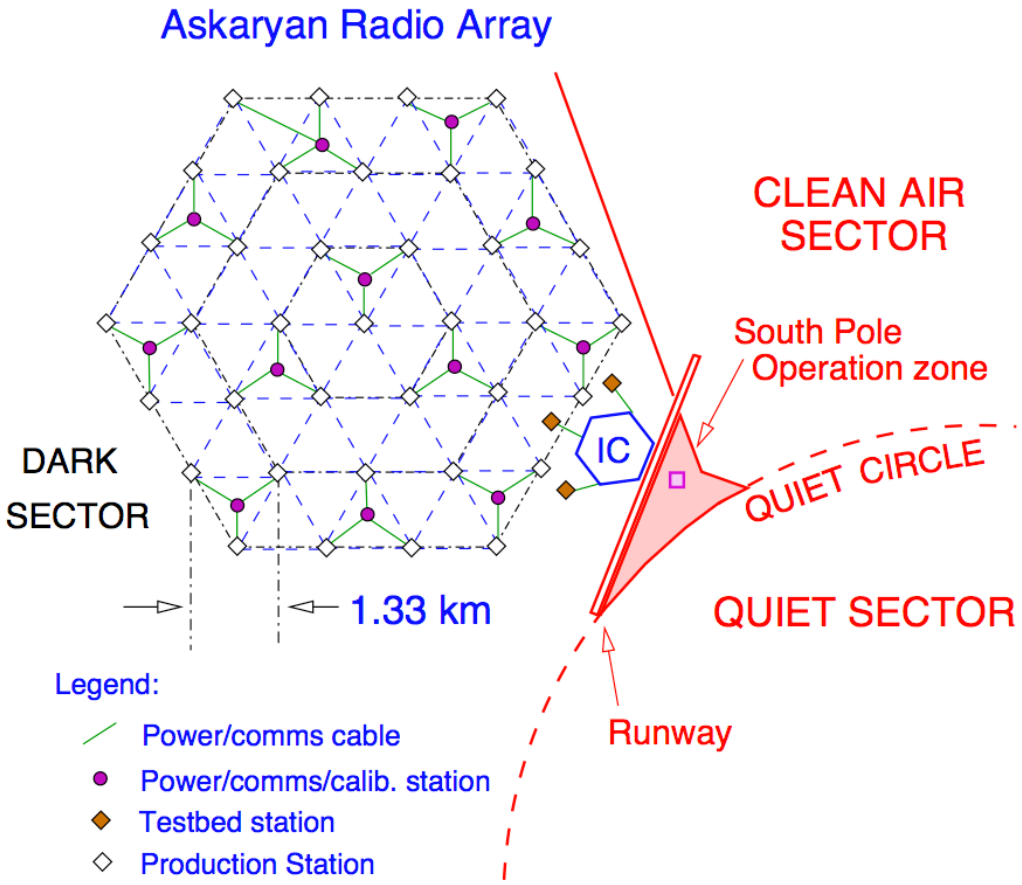




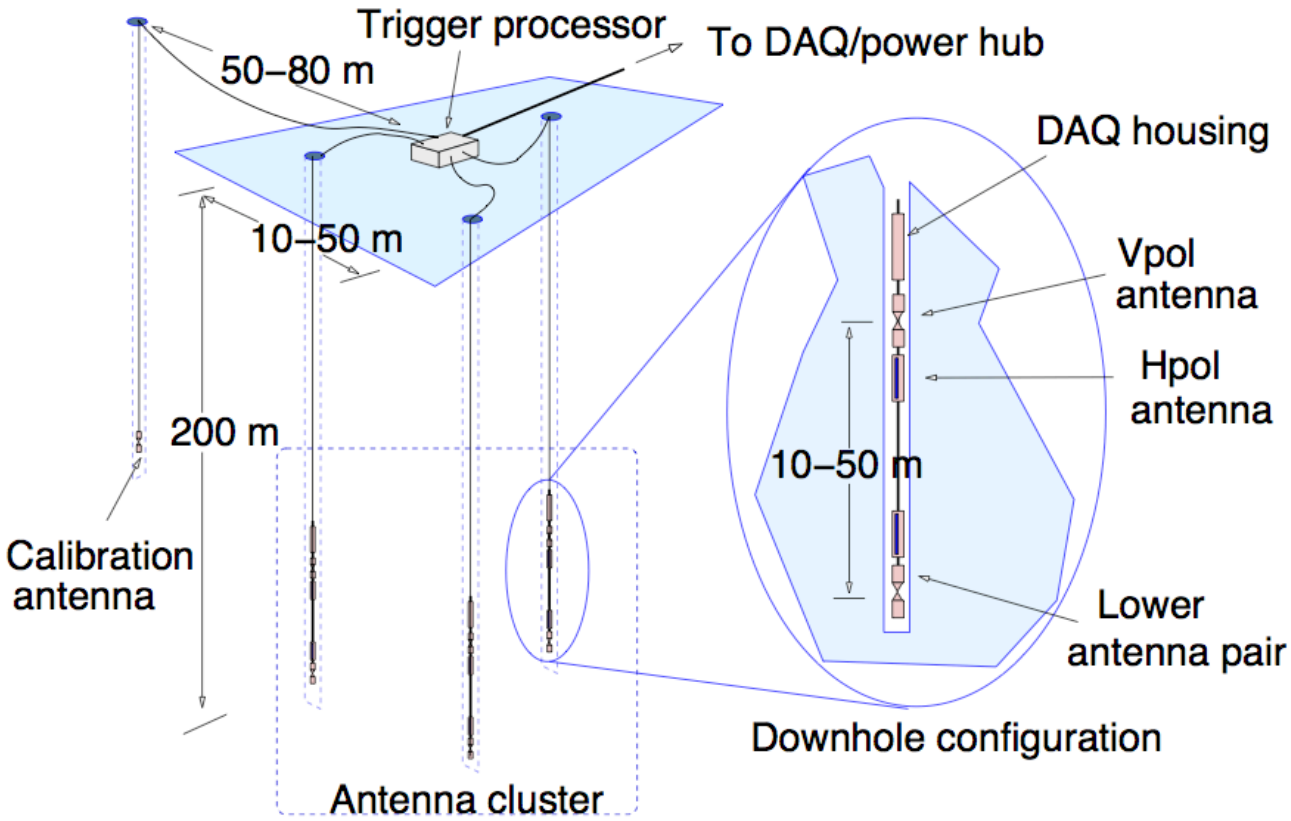
Gorham *et al.* 2009

Askaryan Radio Array

- RF extension of IceCube
- GZK rates from 1-25 events / year
- Possible cross-calibration with IceCube

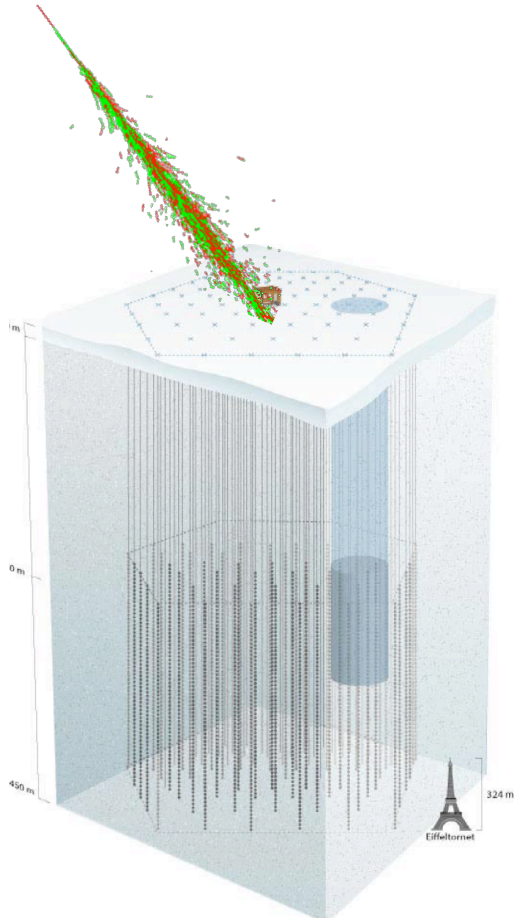


In-Ice ARA Cluster



ARA + Surface Radio Array

- Hybrid in-ice and surface radio stations
  - Hardware, triggering techniques are very similar
  - GZK detection + air shower physics
  - Super-hybrid radio + IceTop + IceCube
  - Veto for IceCube (downgoing neutrino searches)
  - Neutrinos from inclined air showers?

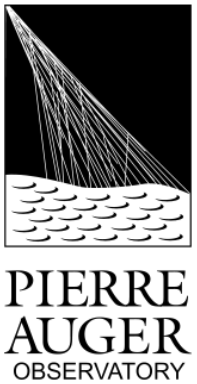


Summary

- Latest results from Auger: spectral cutoff clear, but anisotropy, composition still unclear / surprising
- Will likely need both new air shower techniques (even larger arrays) and multi-messenger measurements (neutrinos) to fully understand UHECRs
- Fortunate confluence: radio techniques may be the future for both

The Pierre Auger Collaboration

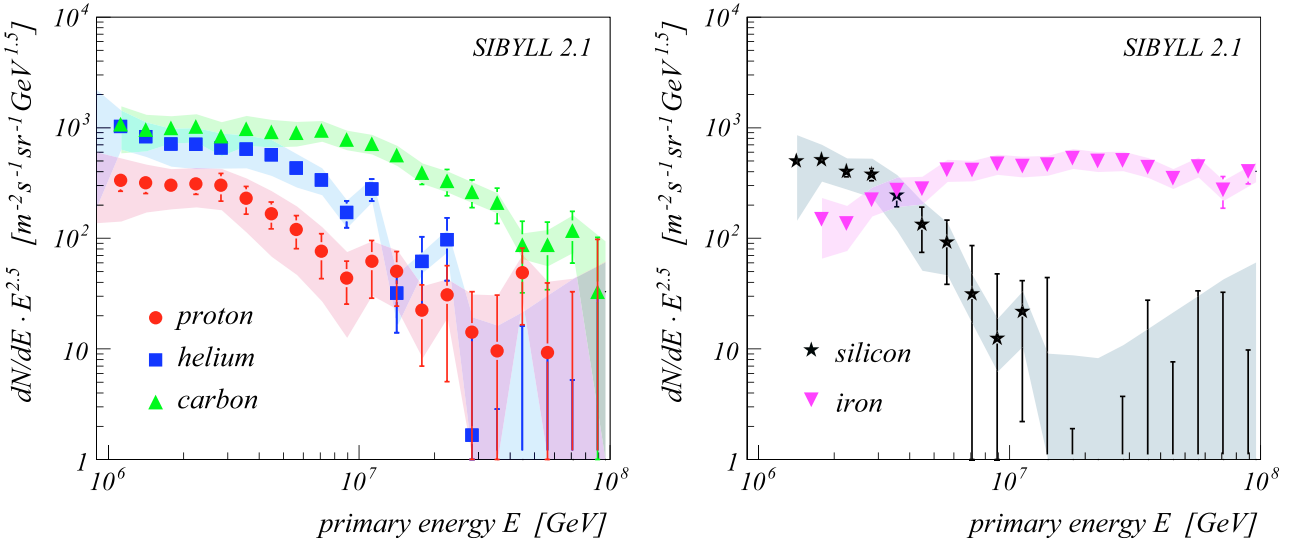
Czech Republic	Argentina
France§	Australia
Germany§	Brazil
Italy	Bolivia*
Netherlands§	Mexico
Poland§	USA
Portugal	Vietnam*
Slovenia	
Spain	*Associate Countries
United Kingdom	§ Radio Working Group



Thank you!

Between Knee and Ankle

Antoni *et al.* 2005



Composition gets heavier

- expected if Galactic cutoff rigidity-dependent
- transition to iron?
- composition analysis tricky
  (unfolding dependent on hadronic models + simulation)