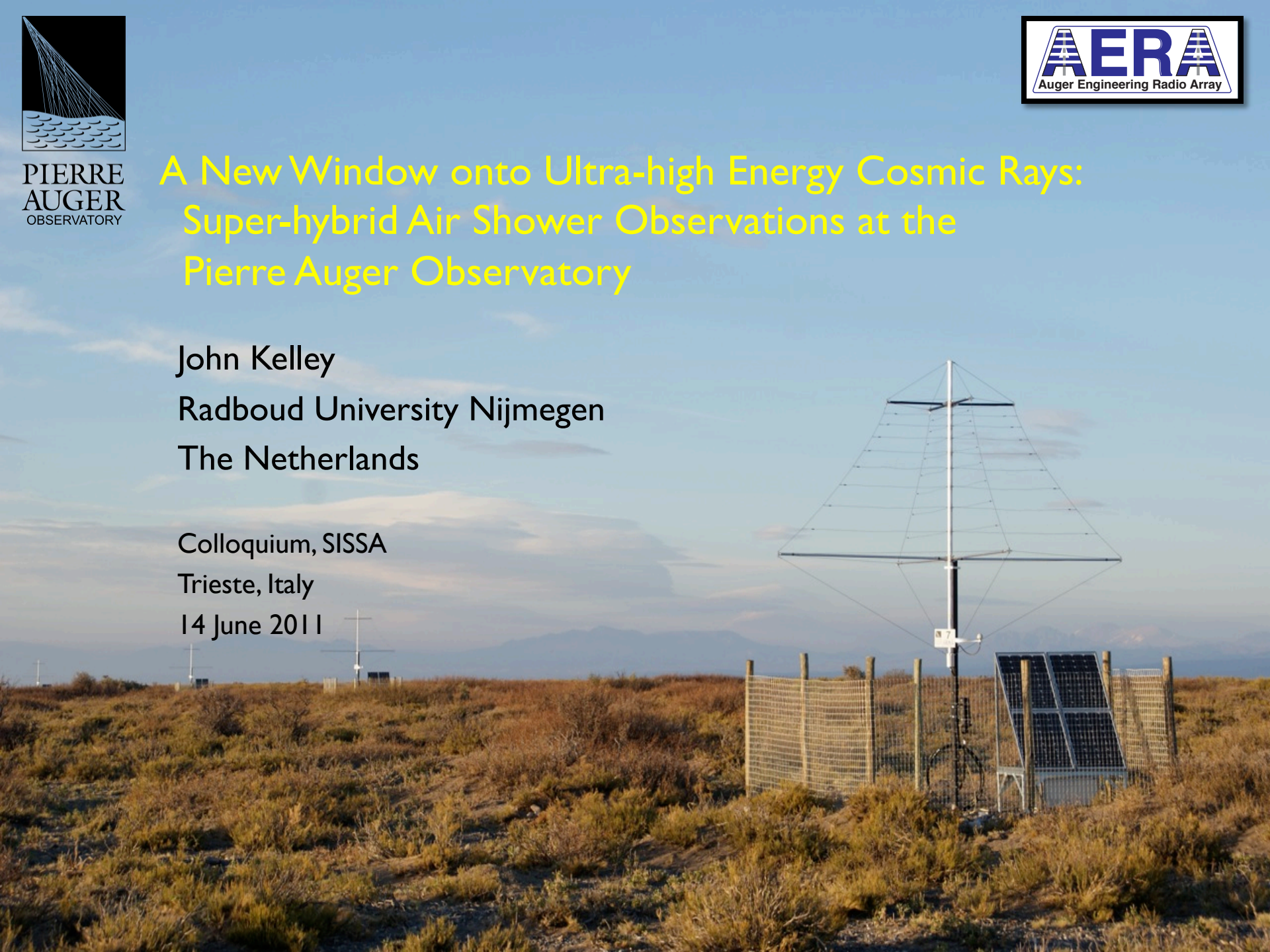
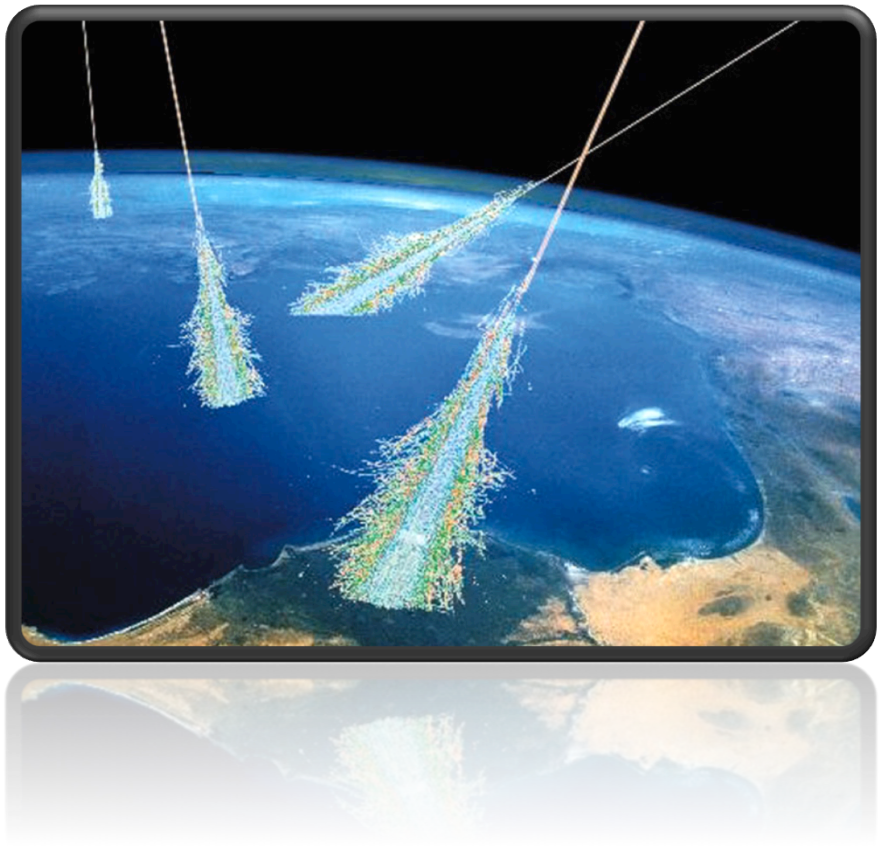
A New Window onto Ultra-high Energy Cosmic Rays: Super-hybrid Air Shower Observations at the Pierre Auger Observatory

John Kelley
Radboud University Nijmegen
The Netherlands

Colloquium, SISSA
Trieste, Italy
14 June 2011



Ultra-High Energy Cosmic Rays (UHECR)



- Highest energy particles known in the Universe
- Composition unknown
- Sources + acceleration mechanism unknown
  - Astrophysical acceleration or decay of exotic particles?

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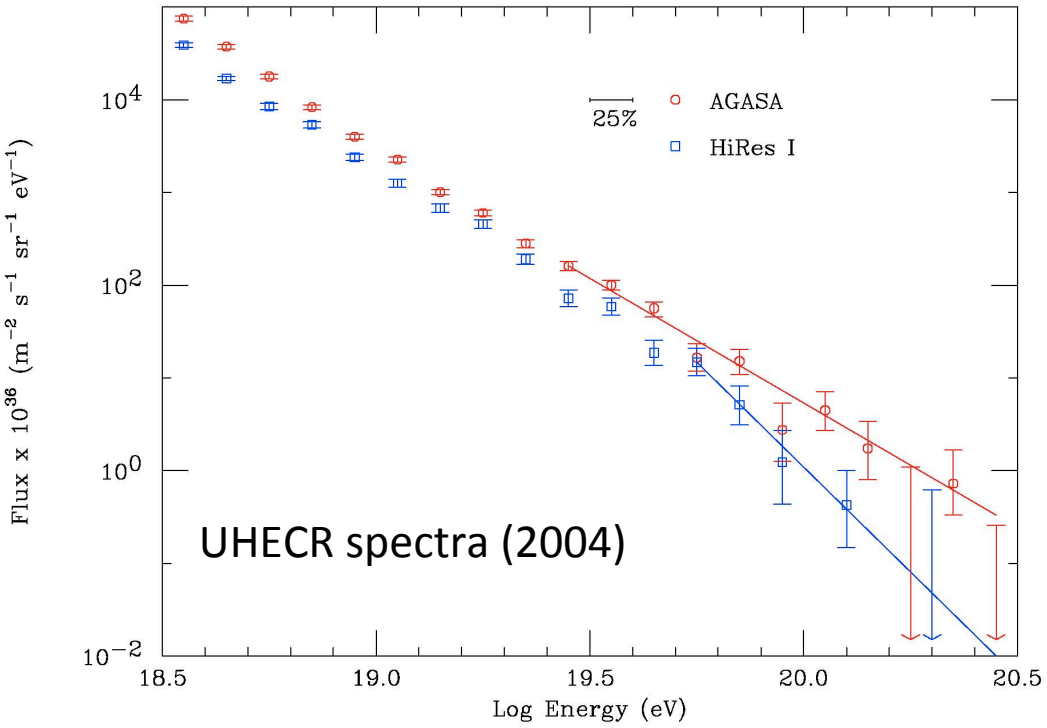


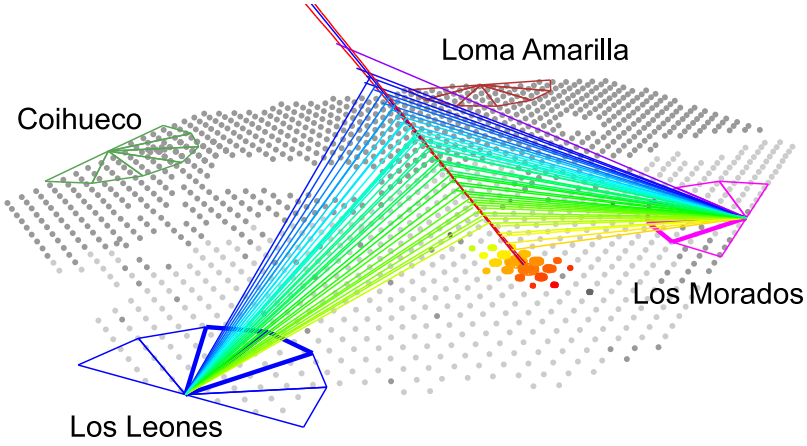
- Highest energy particles known in the Universe
- Composition unknown
- Sources + acceleration mechanism unknown
  - Astrophysical acceleration or decay of exotic particles?
- Cutoff in energy spectrum or not?
  - Expected from interactions with CMB (GZK effect)
  - no cutoff... Lorentz violation?

Pierre Auger Observatory

- Hybrid cosmic ray air shower detector
- Southern site (3000 km^2) in Argentina completed 2008
- Energy threshold:
  - $E > 10^{18}$ eV full array
  - $E > 10^{17}$ eV infill array

Auger South

Data and Observables



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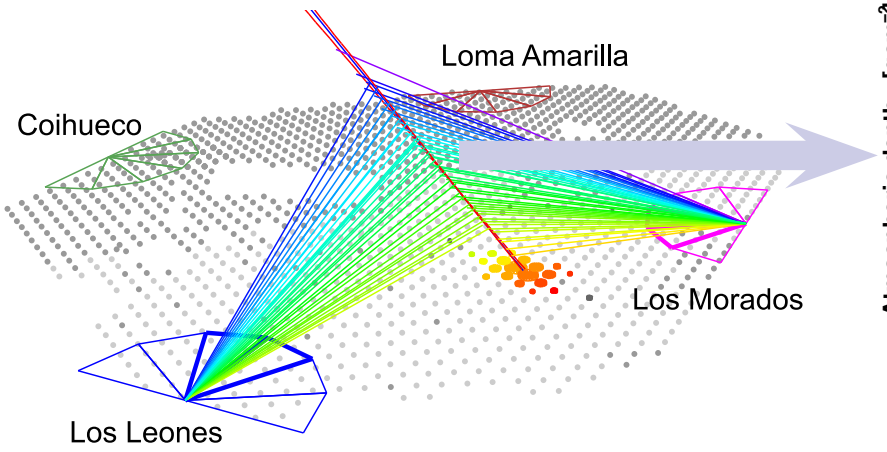
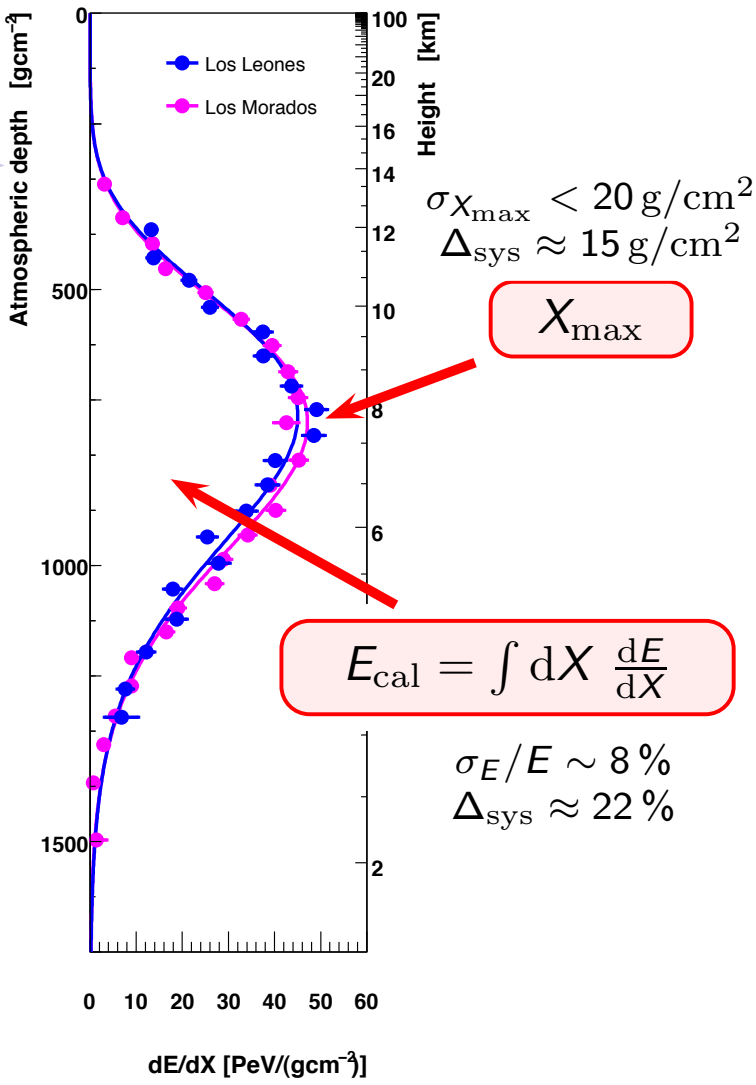




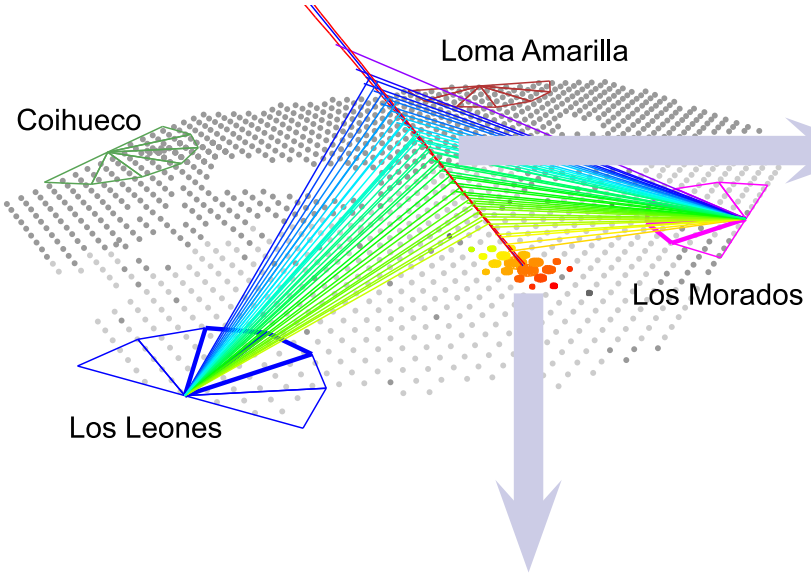
$\sigma_{X_{\max}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

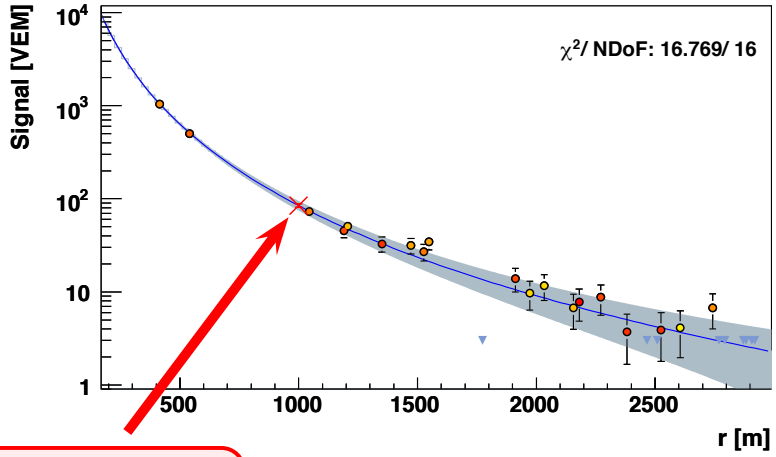
$X_{\max}$

$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$

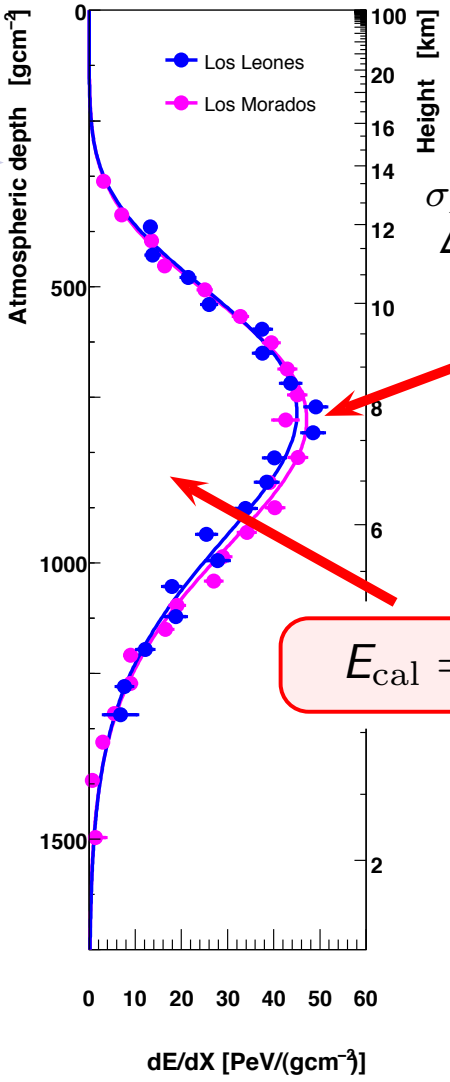
Data and Observables





S_{1000}

$E_{\mathrm{surface}} = f(S_{1000}, \theta)$



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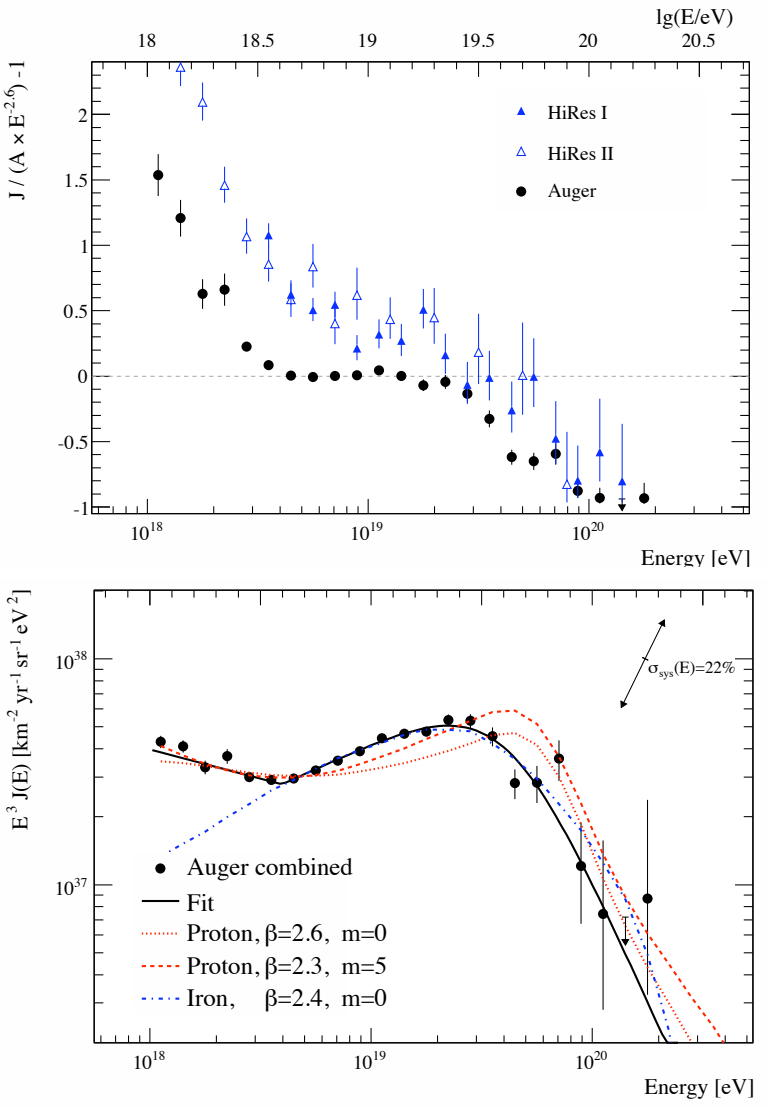
courtesy R. Ulrich
APS 2010

UHECR Energy Spectrum after Auger



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- 2008: Continuation of power law rejected at 6σ (confirms HiRes)
- Suppression energy consistent with GZK onset (limits on LV)
- 2009: combined FD + SD spectrum
  - protons with strong source evolution?
  - iron with another component below ankle?
- Difficult to rule out non-GZK causes
  - source cutoff?

UHECR Anisotropy

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

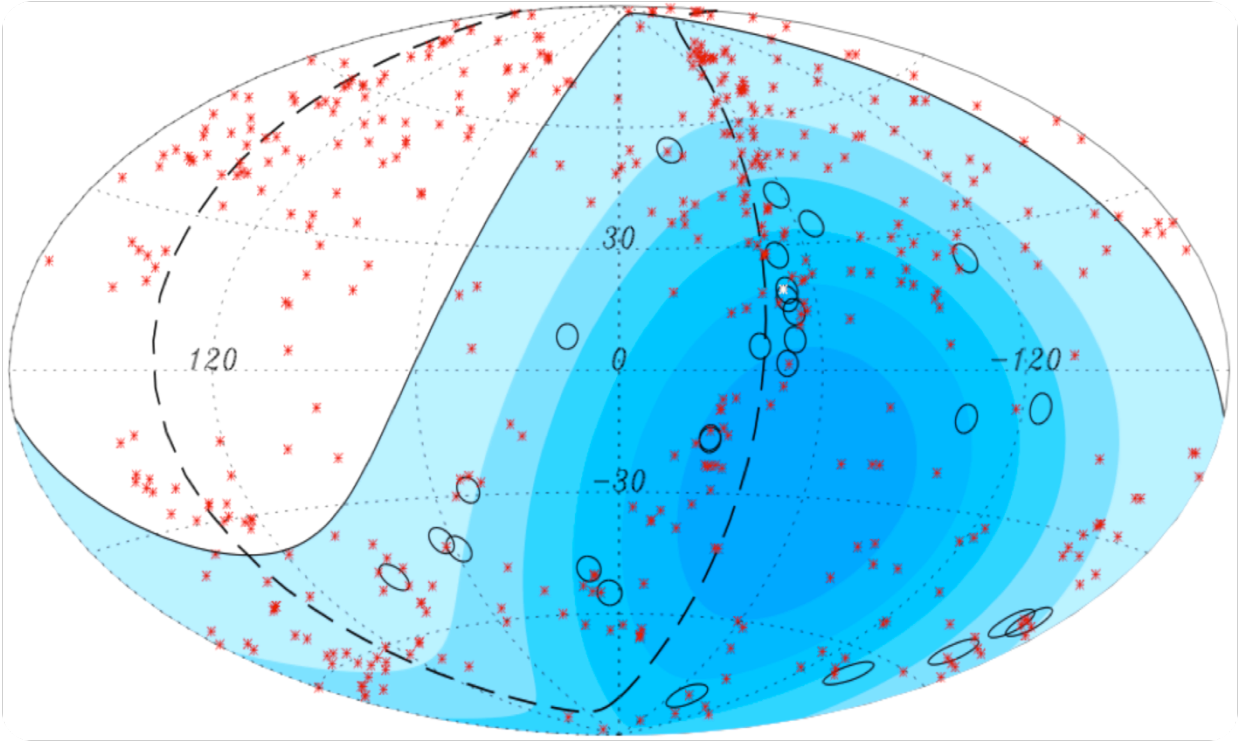
$$\theta(E,Z) \approx \left(\frac{L}{L_{\rm coh}}\right)^{0.5} \alpha \approx 0.8^\circ \left(\frac{10^{20}\,{\rm eV}}{E}\right)\left(\frac{L}{10\,{\rm Mpc}}\right)^{0.5}\left(\frac{L_{\rm coh}}{1\,{\rm Mpc}}\right)^{0.5}\left(\frac{B}{1\,{\rm nG}}\right) Z,$$

Hooper *et al.* 2008

- Pre-Auger: claims of excess from Galactic Center, BL-Lacs, etc.

- Anisotropy with low statistics is a tricky business

Arrival Directions (2007)



Abraham *et al.* 2007

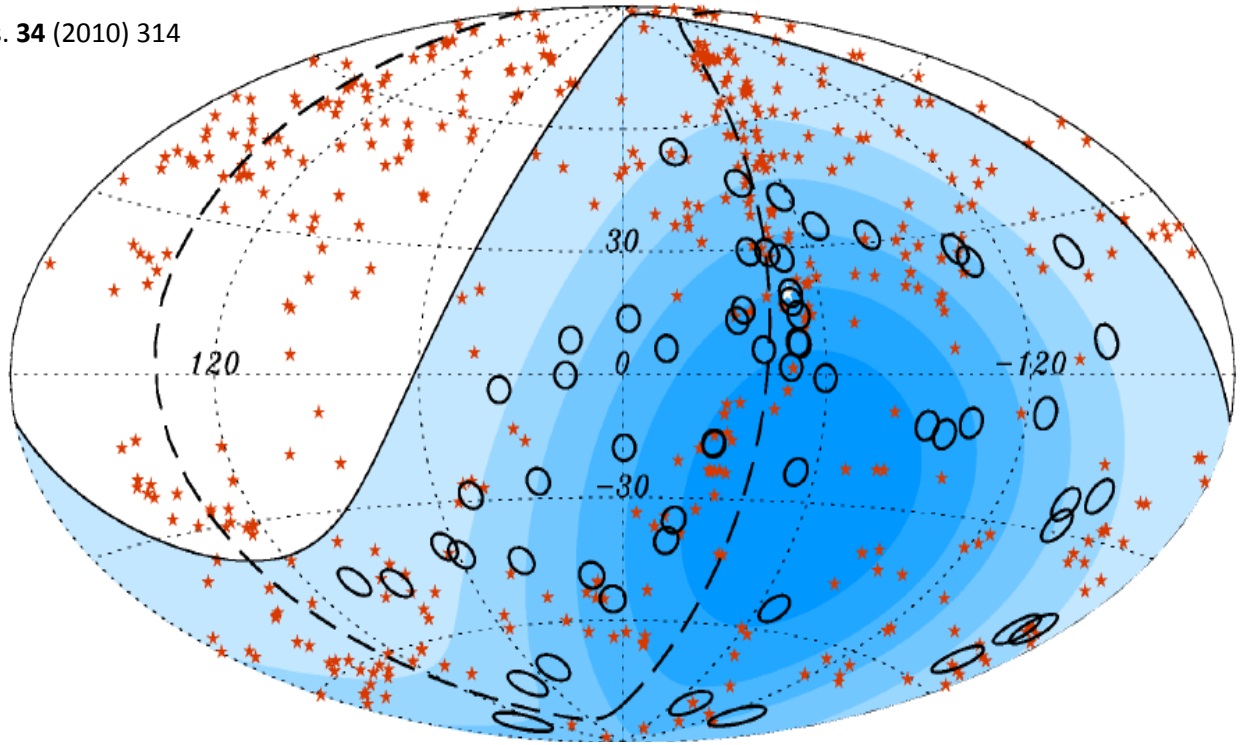
2007: 27 events above 55 EeV (ovals)

Excluding data from exploratory scan: 9 of 13 events correlate with nearby AGN in VCV catalog (69%; 21% expected for isotropy)

P-value for isotropic hypothesis: 0.0002 (3.7σ)

Arrival Directions: Update

Astropart. Phys. **34** (2010) 314



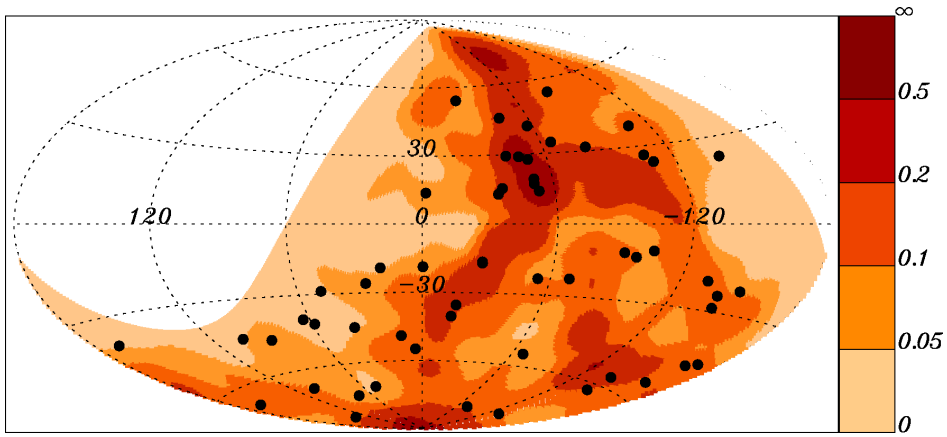
2009: 69 events above 55 EeV

Correlating fraction has decreased: now 21 of 55 (38%)

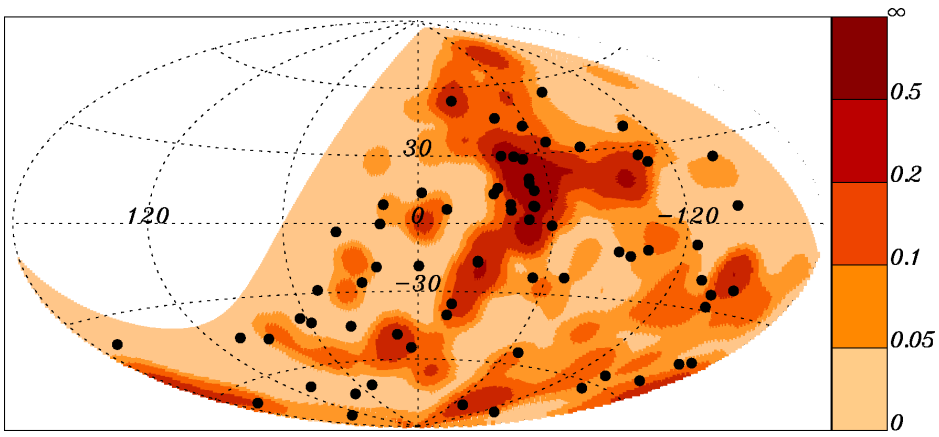
P-value of isotropic hypothesis: 0.003 (3.0σ)
To reach 5σ: ~4 more years of data

A posteriori Investigations: flux-weighted density maps

2MRS galaxy survey



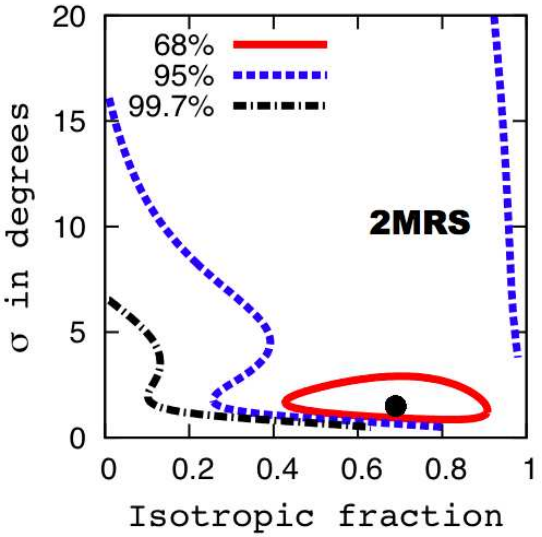
Swift-BAT X-ray AGN

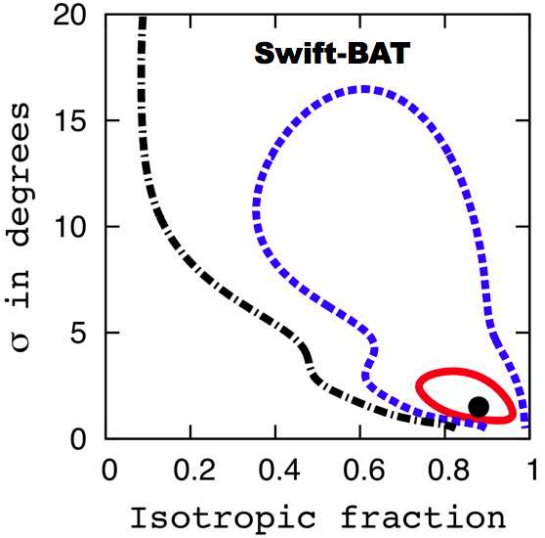


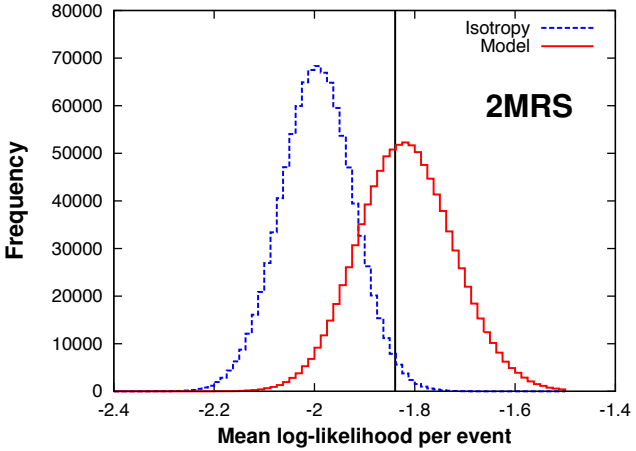
$$F(\hat{\mathbf{n}}) = \frac{\varepsilon(\hat{\mathbf{n}})\mu(\hat{\mathbf{n}})}{I}\left[\frac{f_{\rm iso}}{\Omega} + (1-f_{\rm iso})\frac{\phi(\hat{\mathbf{n}})}{\langle\phi\rangle}\right]$$

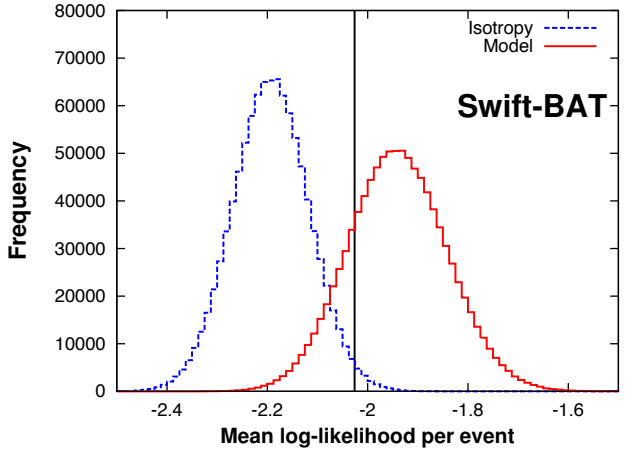
$$\phi(\hat{\mathbf{n}}) = \sum_{i=1}^{N_{\rm cat}} w(z_i)\, e^{-\frac{d(\hat{\mathbf{n}}_i,\hat{\mathbf{n}})^2}{2\sigma^2}}$$

Results (Excluding Exploratory Data)



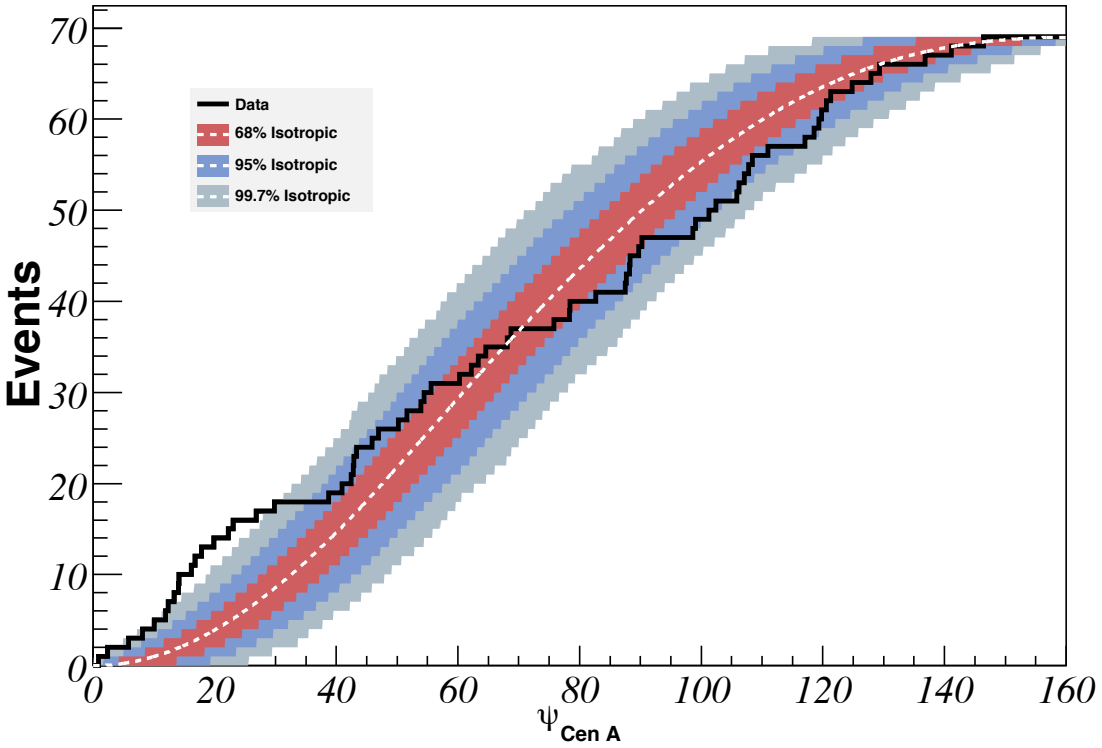






Centaurus A Region

- Cen A: closest AGN (3.7 Mpc)
- Largest CR overdensity within 4° of Cen A core
- Region also contributes to flux-weighted models
- Investigations ongoing

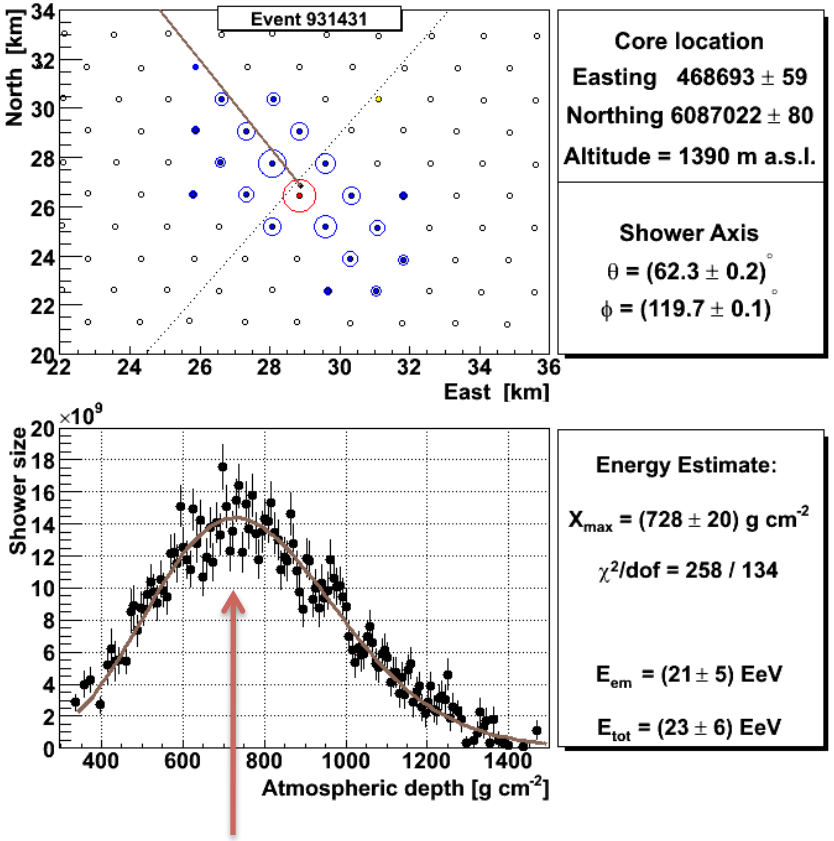


Composition

- 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)

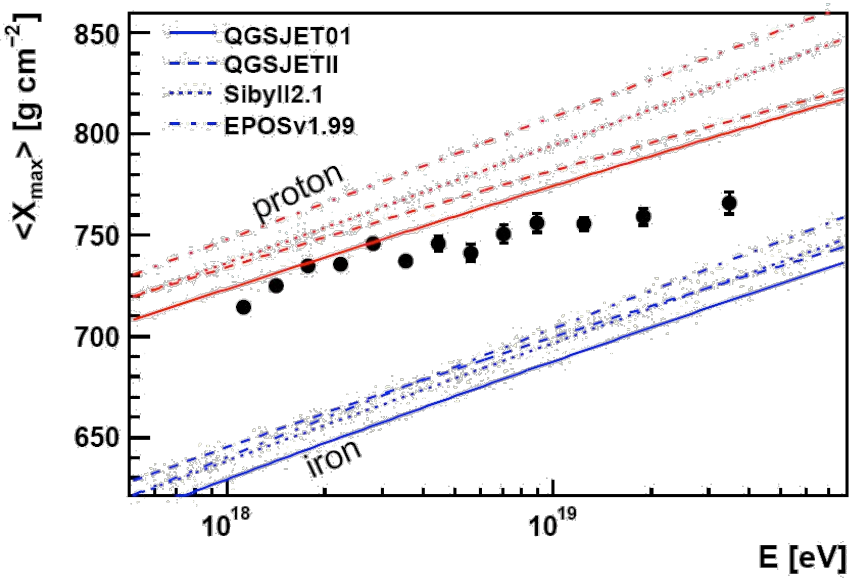
- Shower-to-shower fluctuations of X_{max}
  - iron showers (~superposition of many single-nucleon showers) have fewer fluctuations

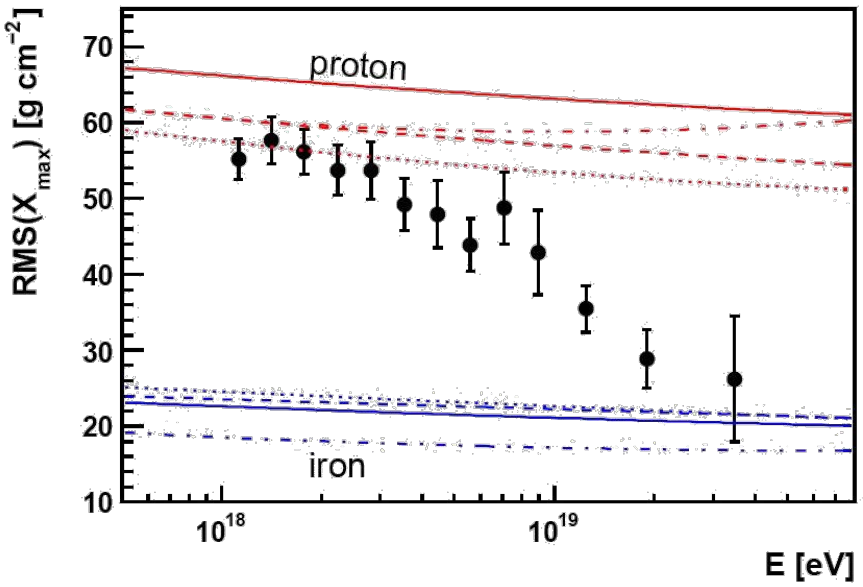
- Can also be used for UHE photon searches



Latest Results: Composition

Phys. Rev. Lett **104** (2010) 901101





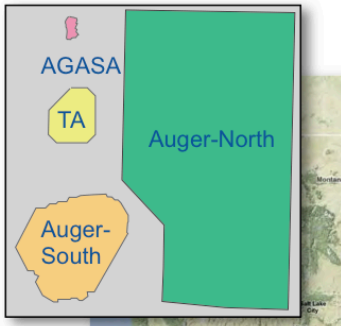
Both indicate composition getting heavier…

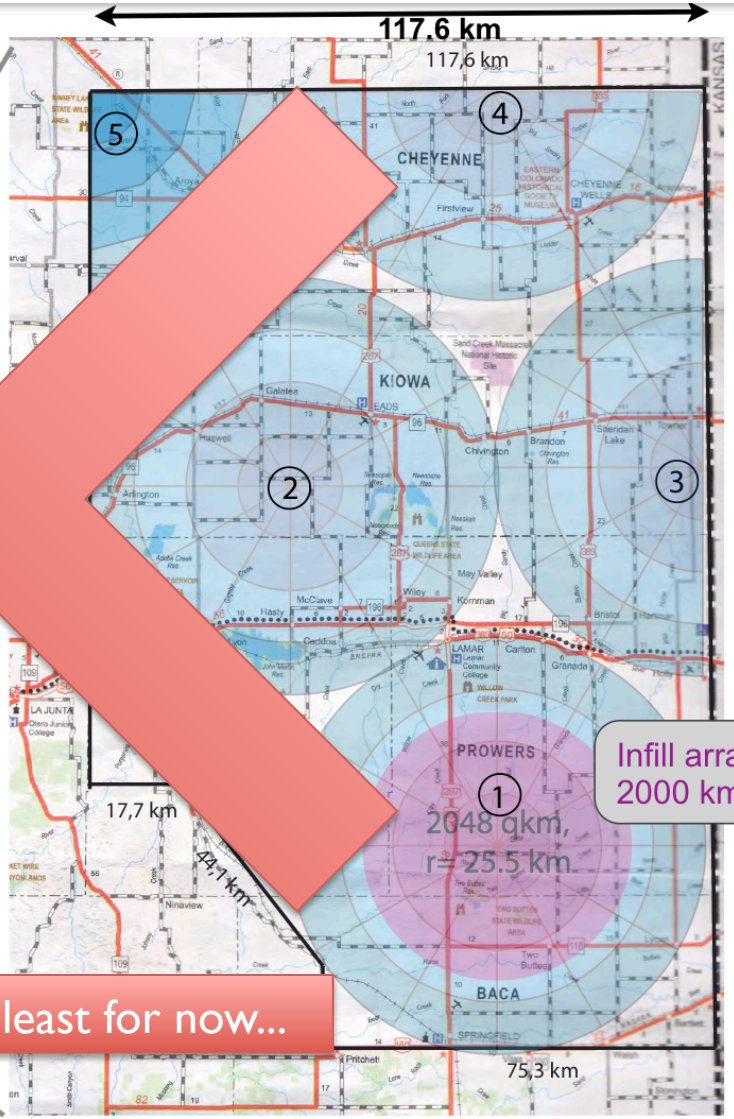
or protons behaving differently than expected?
(see e.g. Ulrich *et al.*, arXiv:0906.3075)

Need hybrid measurements at highest energies!

Auger North

- **Optimized for science and costs**
- **Surface array with 4000 [illegible]ons:**
  20,000 km² with
  √2-mile = 2.3 km grid
- **Infill array with 400 statio[illegible]**
  2,000 km² with
  1-mile = 1.6 km grid
- **39 fluorescence telescopes**

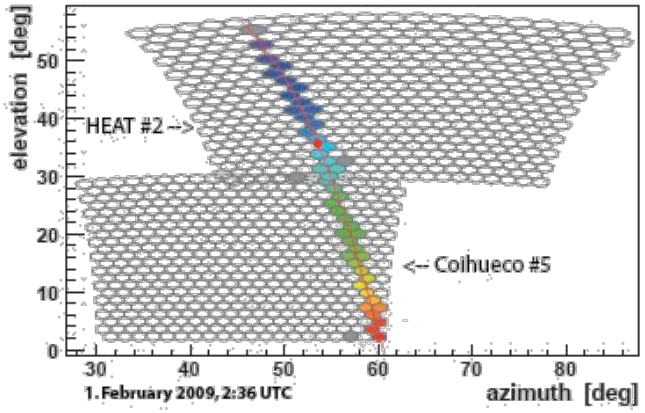


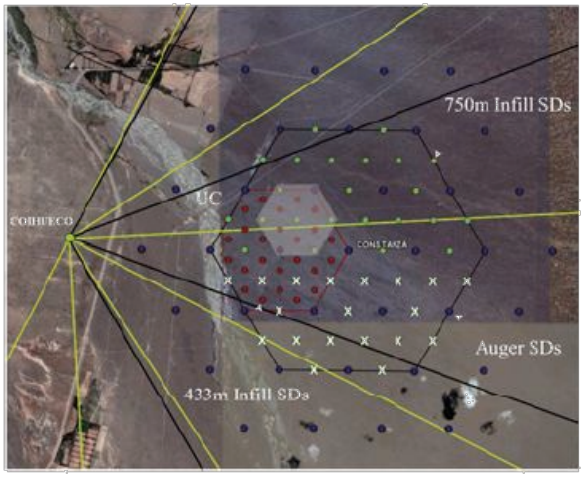


at least for now...

Enhancements at Auger South

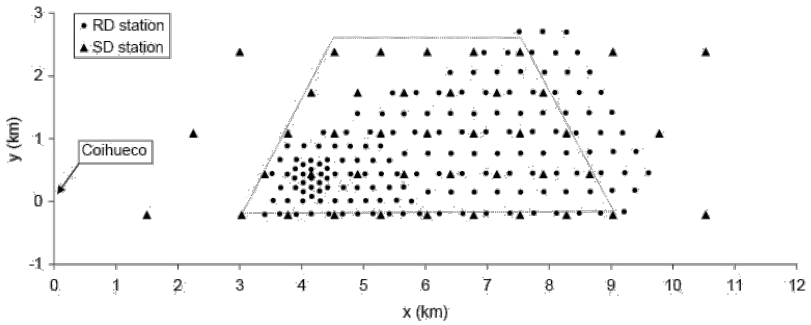
HEAT: High Elevation Auger Telescopes





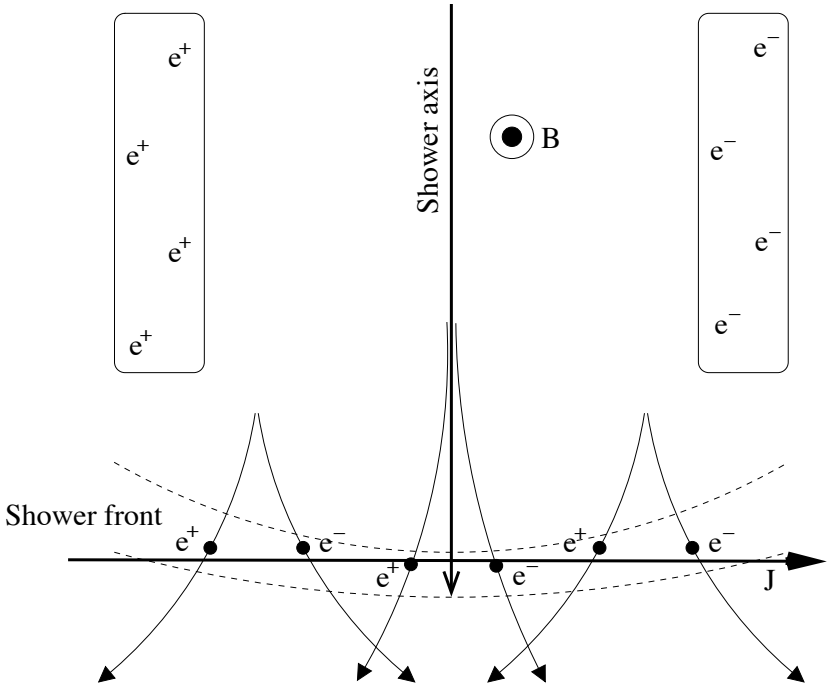
AMIGA: Auger Muon and Infill Ground Array

AERA: Auger Engineering Radio Array

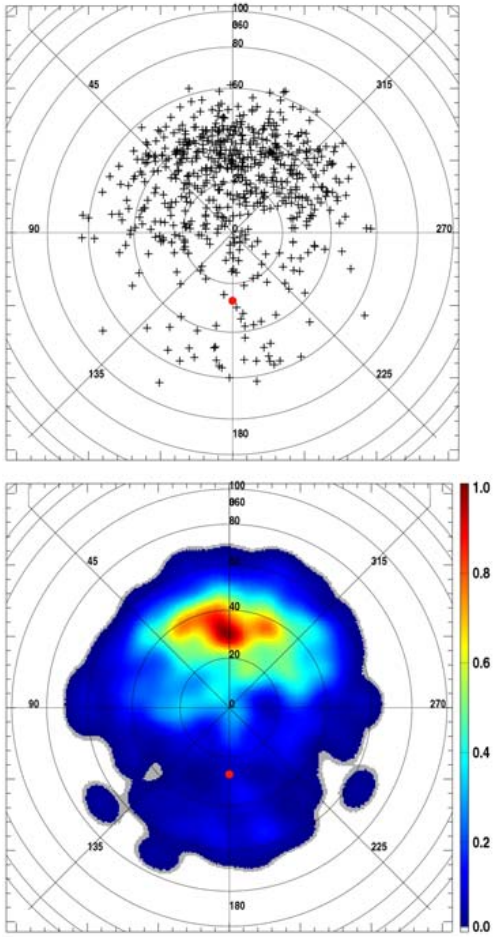


Radio Emission from Air Showers

- Separation, acceleration of e^+, e^- in geomagnetic field
  - secondary: charge excess, moving dipole
- Broadband radio pulse (width ~50 ns)
- Interesting because of high duty cycle and access to shower development
- Hybrid measurement all the time!



(Primarily) Geomagnetic Origin



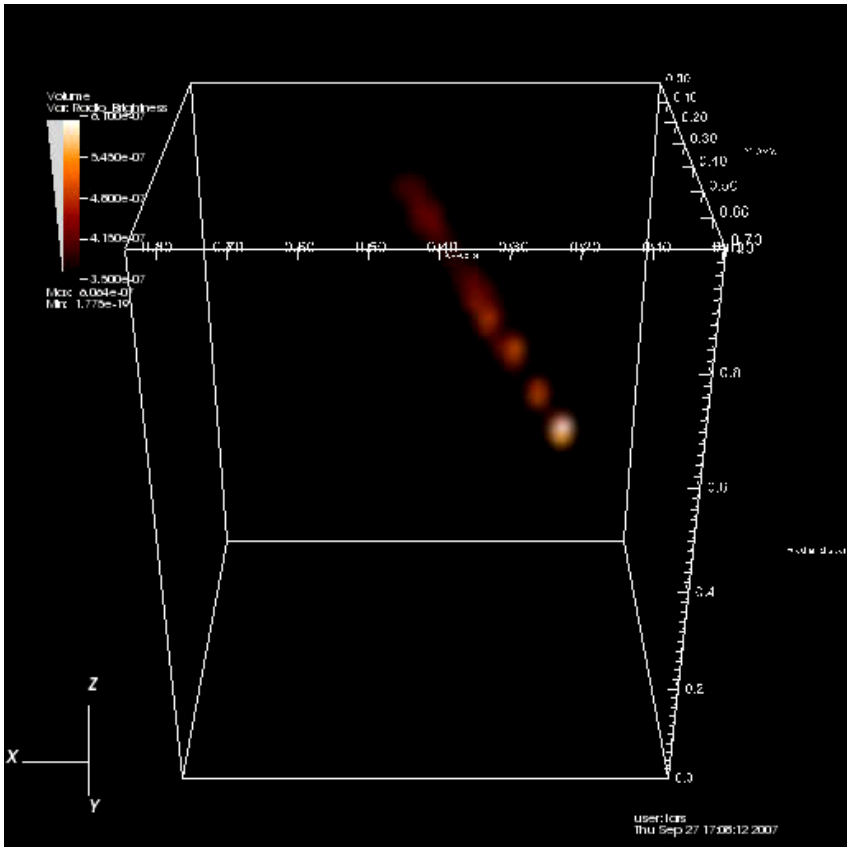
- Simplification: geomagnetic origin implies

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

- Asymmetry confirmed with LOPES, CODALEMA experiments
- Full story is actually more complicated...

Ardouin *et al.* 2009

3D Localization of Emission

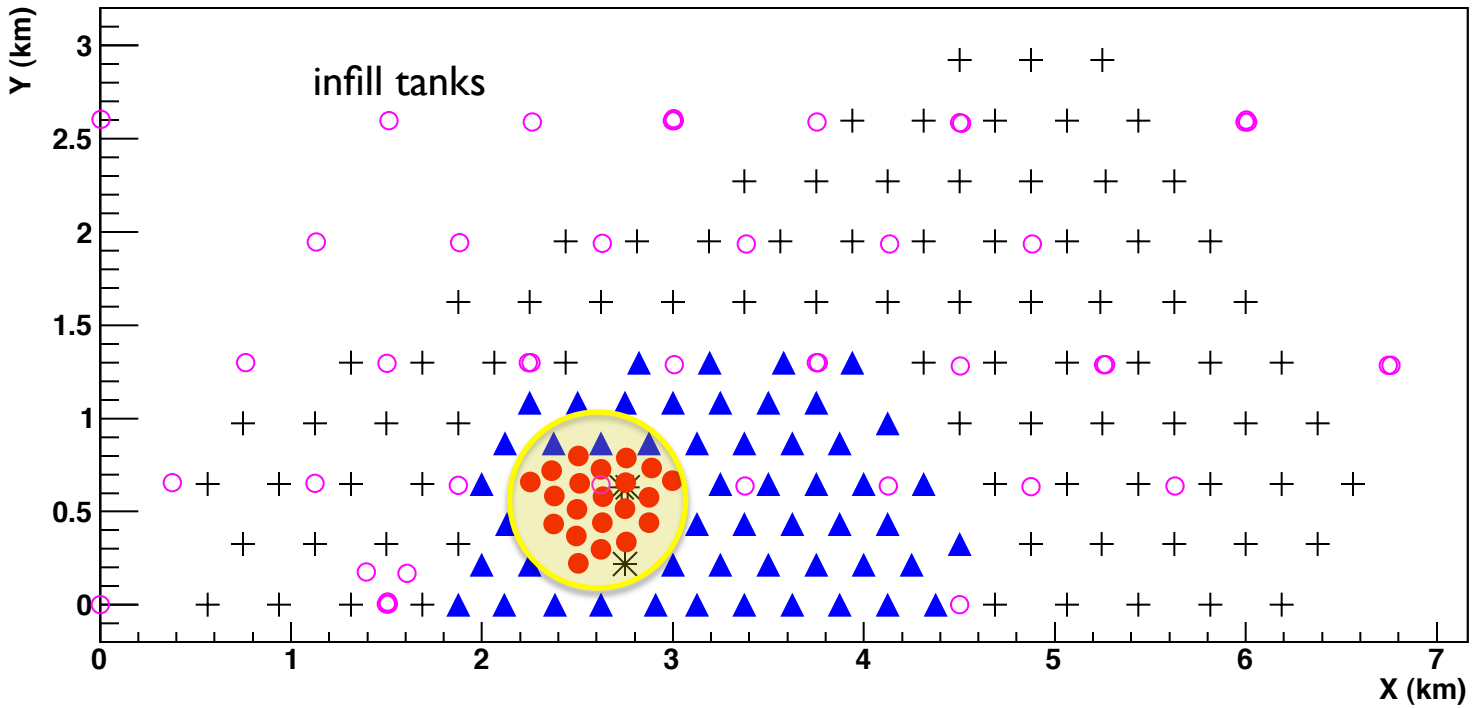


Sample LOPES radio flash triggered with KASKADE

Technique works... but can one build a large, autonomous array?
Is it suitable for the next generation ~10000 km^2 detector?

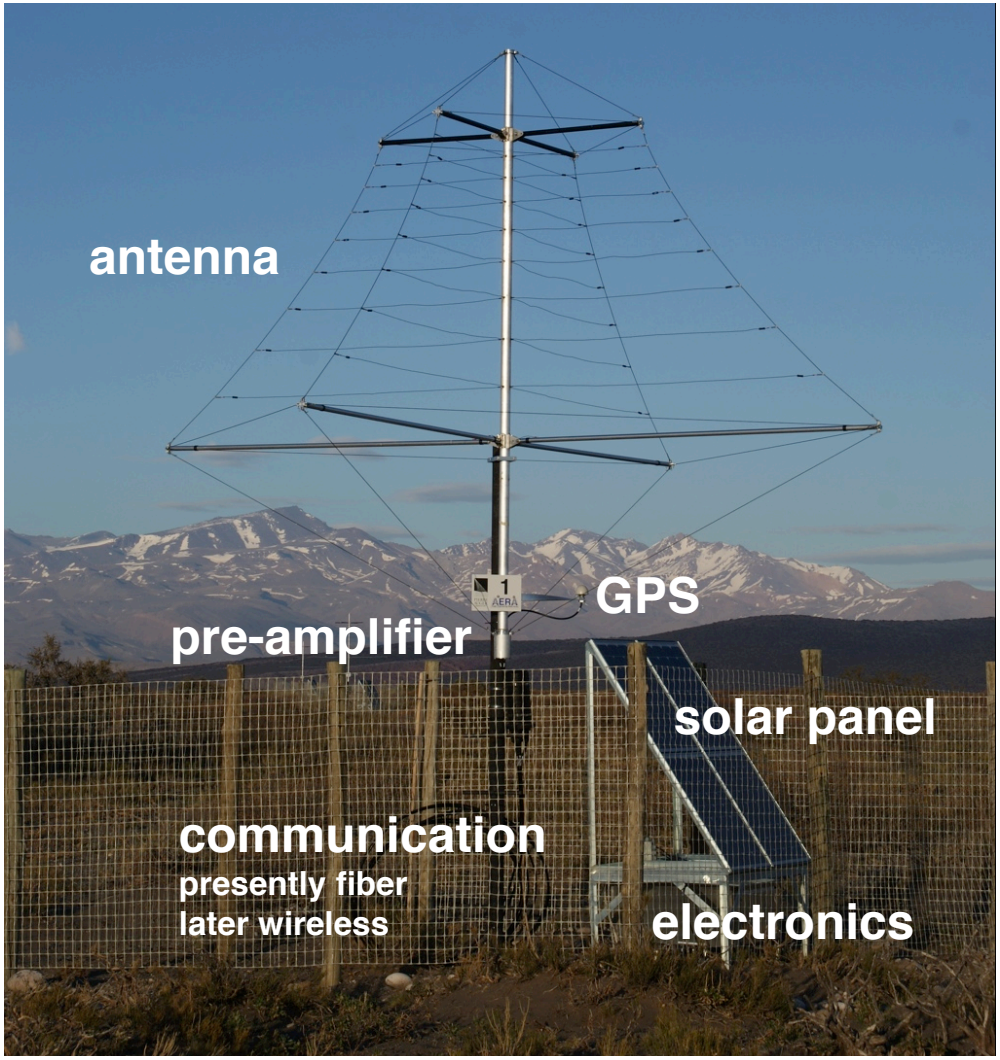
Auger Engineering Radio Array

HEAT



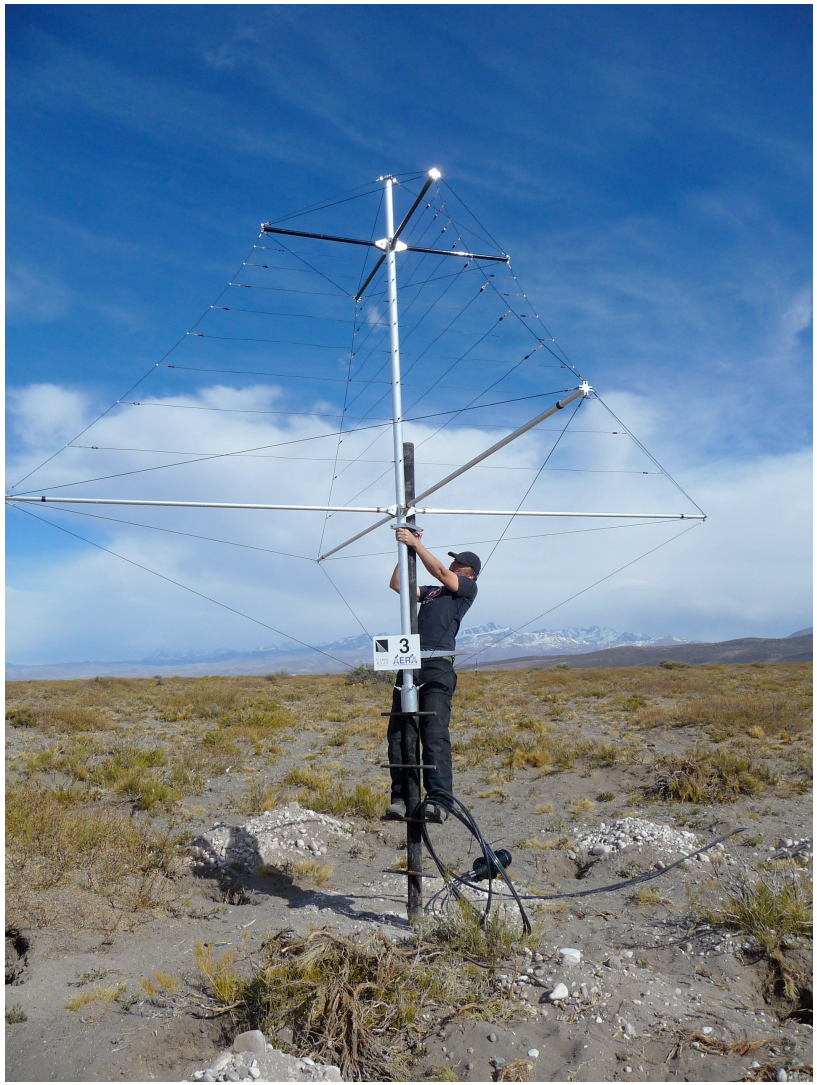
- 20 km^2 extension to southern site: 160 radio detector stations
- 2010: deployed dense core (21 stations)

AERA Station

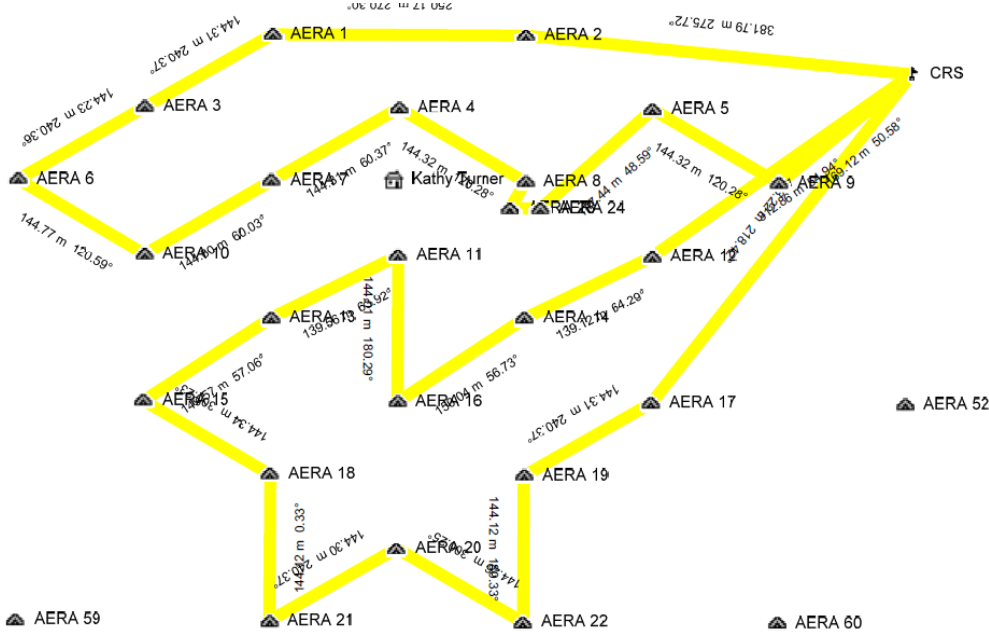


Stage 1 Deployment: Antennas

- Log-periodic dipole antennas
- Wideband: 30-80 MHz
- Two polarizations; aligned to magnetic north to within 1°



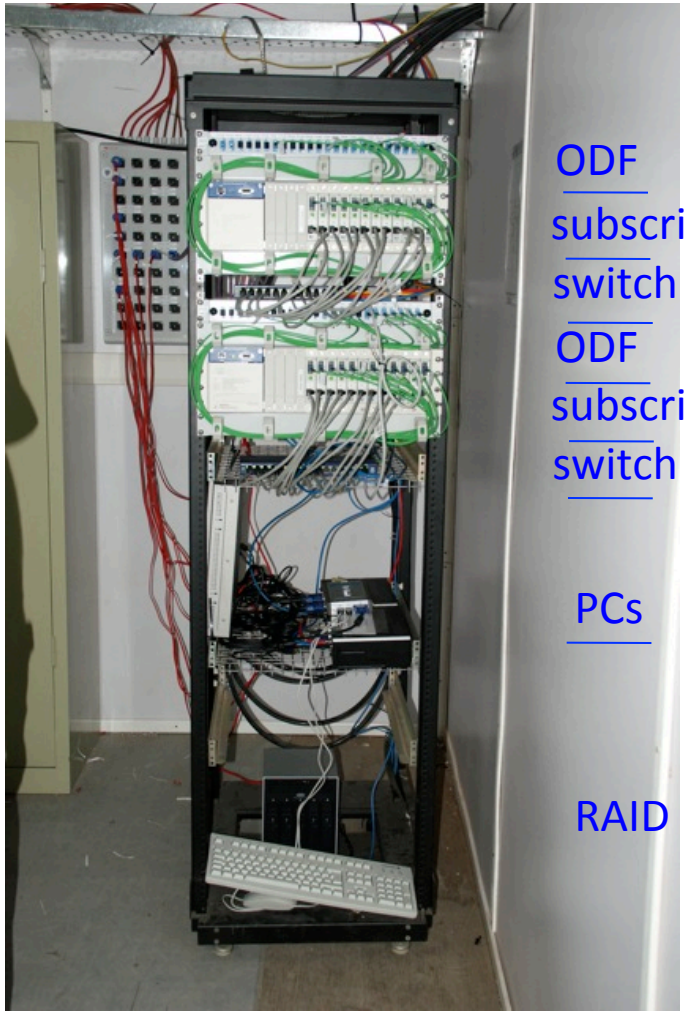
Stage 1 Deployment: Optical Fiber



Stage 1 Deployment: Stations

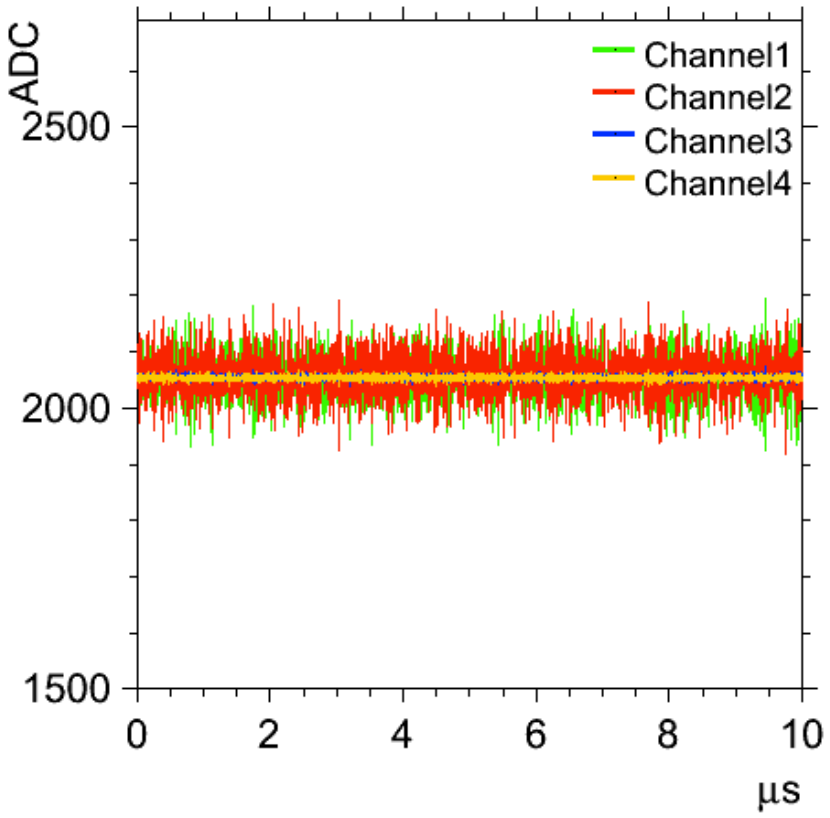
Sept 2010

Stage 1 Deployment: Central Container

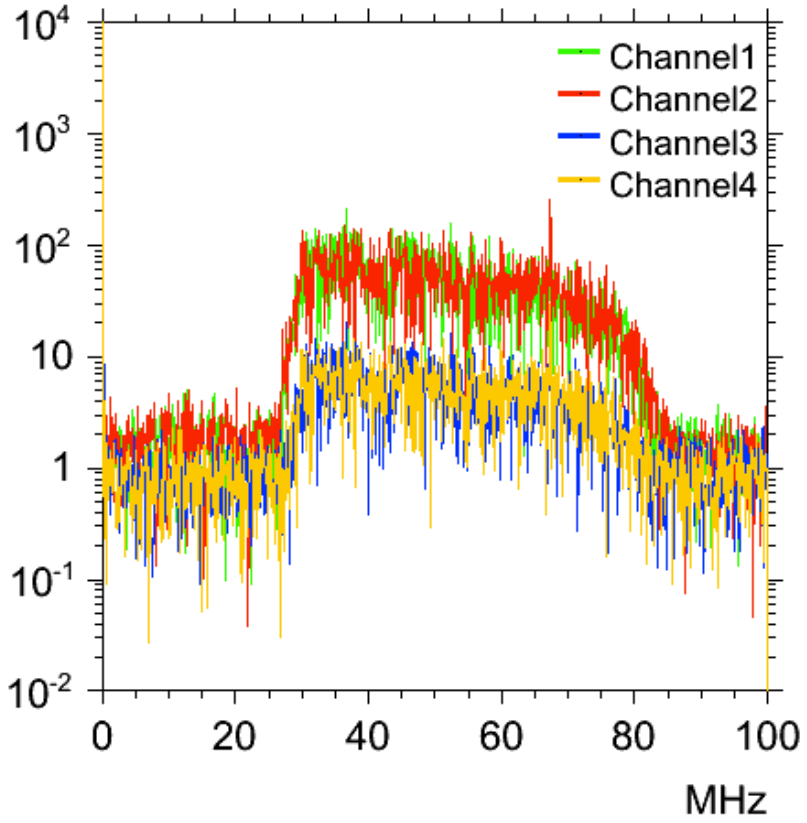


Sample Untriggered Data

2 polarizations, high- and low-gain

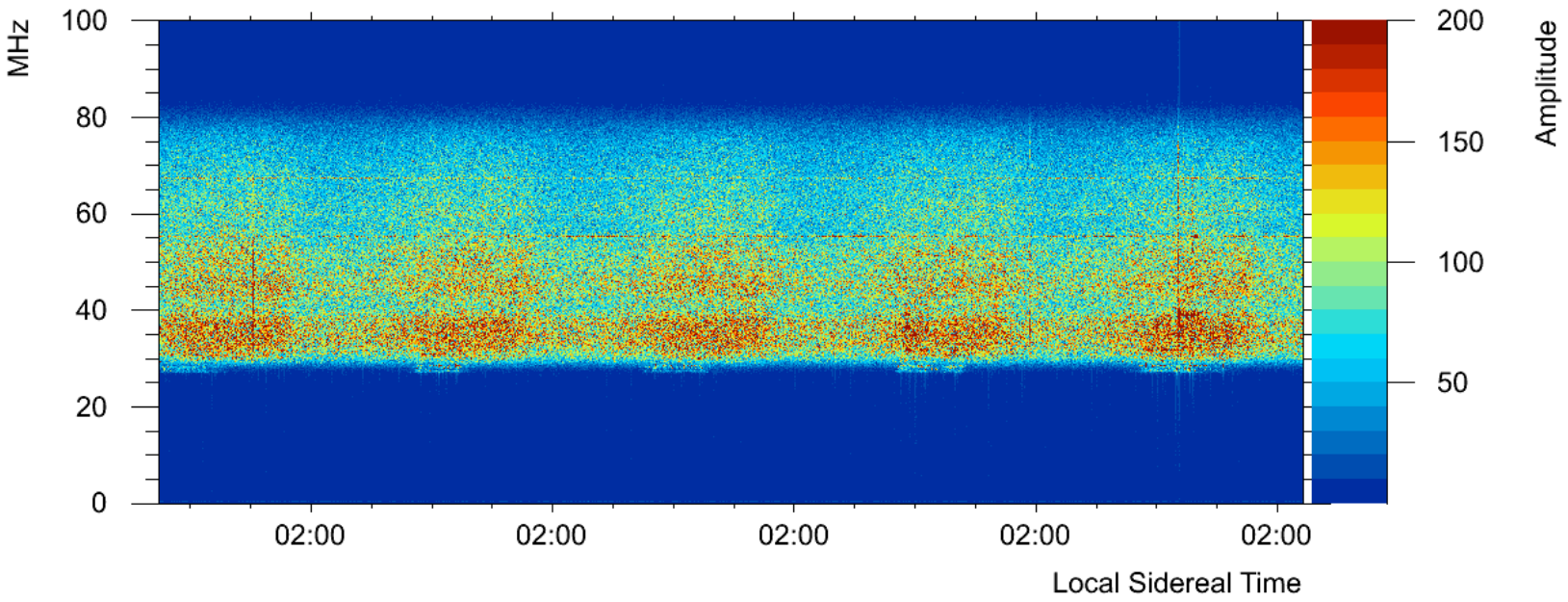


After Fourier transform



Observation of Galactic Background

NS Channel, one station 10 s traces, Oct 8th - Oct 13th



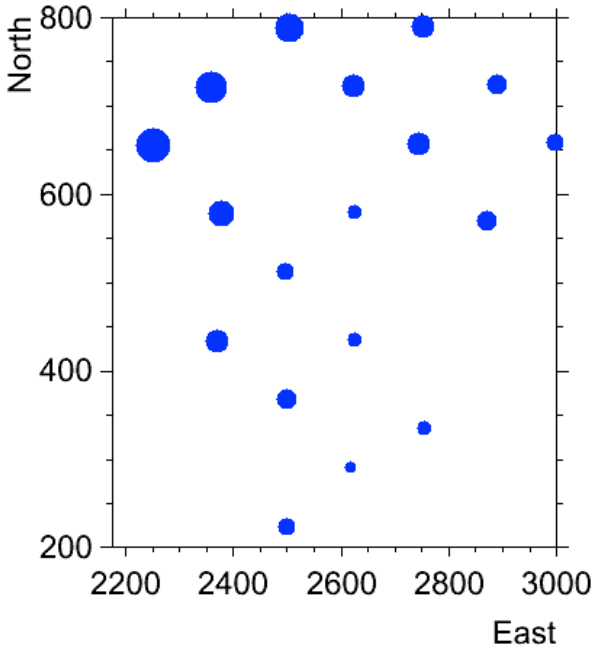
Rise of Galactic Center: LST 10:10
Maximum: LST 17:45
Set of Galactic Center: LST 01:15

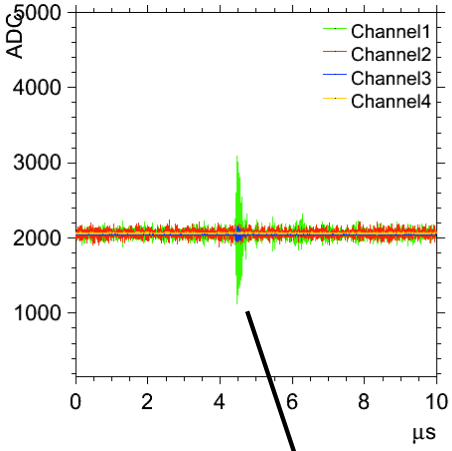
Self-Triggered Events

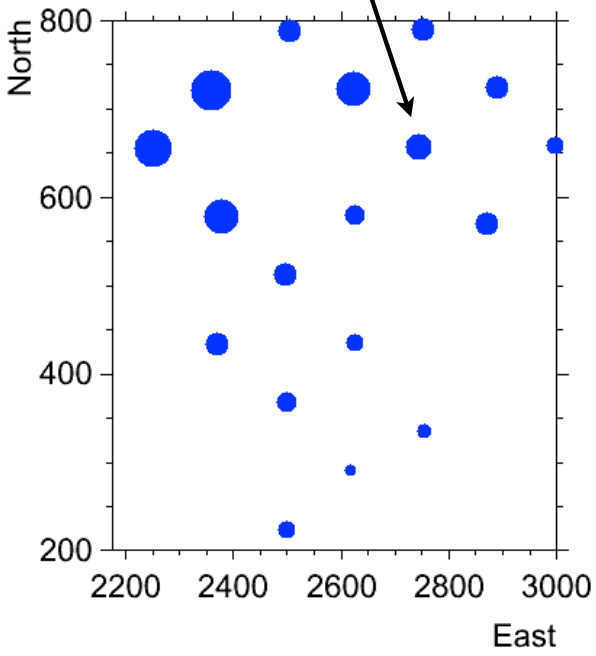
Largest pulses

(sometimes saturation of ADC)
from close-by source
steep drop-off in pulse height
mostly from northwest direction

Very large pulses:
2200 ADC counts





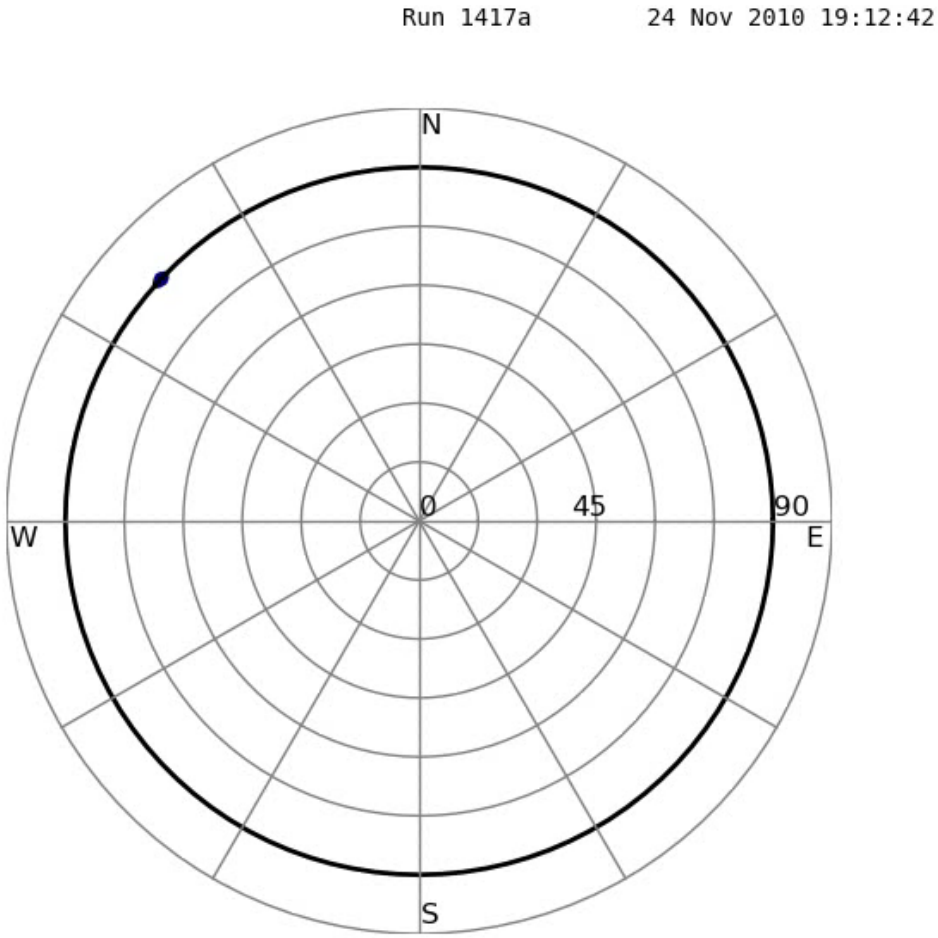


Skyplot of Reconstructed Events

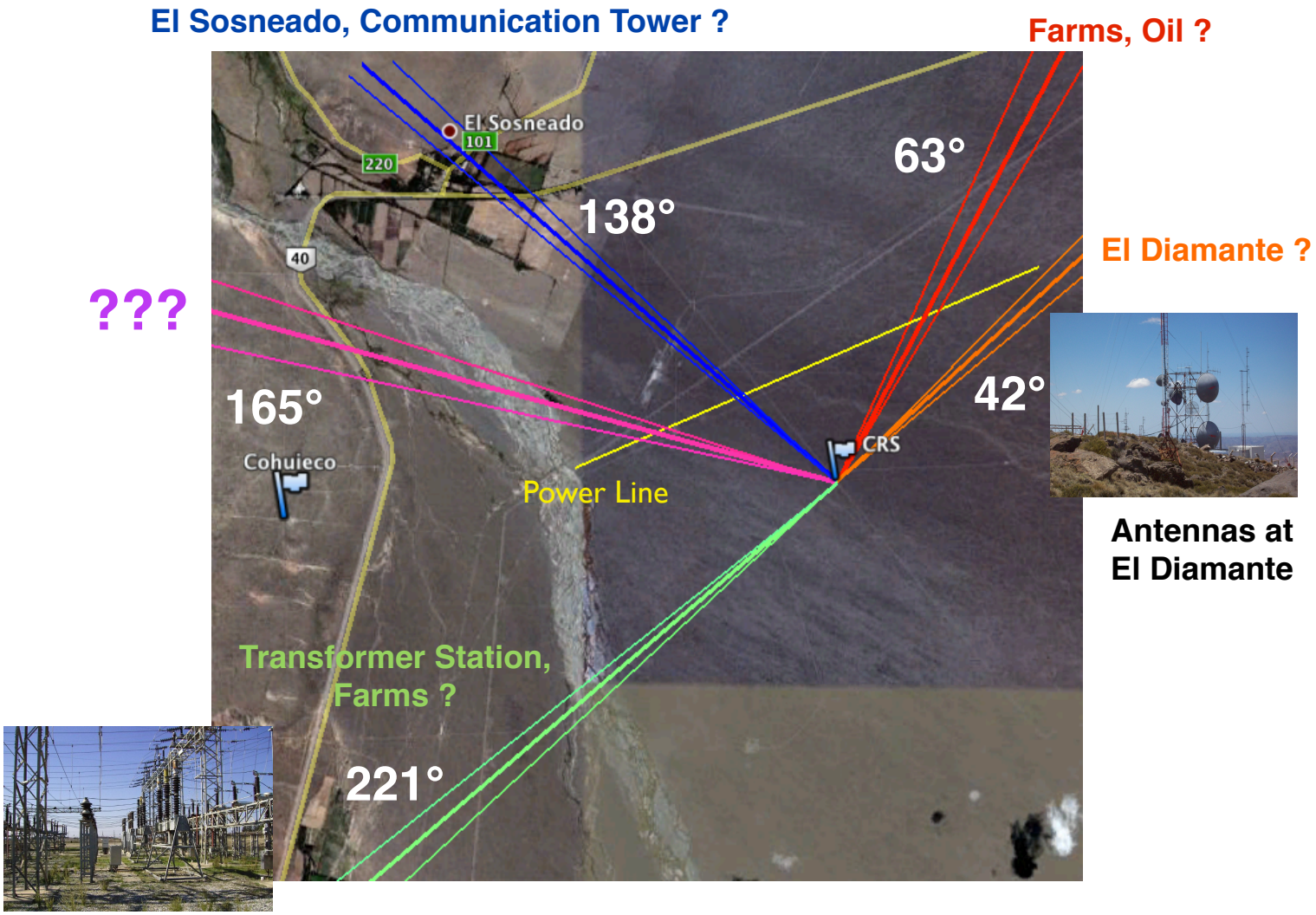
Station trigger: ~5σ Galactic noise, pulse shape requirements (~200 Hz)

L3 trigger: 3 neighboring stations in coincidence

99k events in 30.5 hours (0.9 Hz)

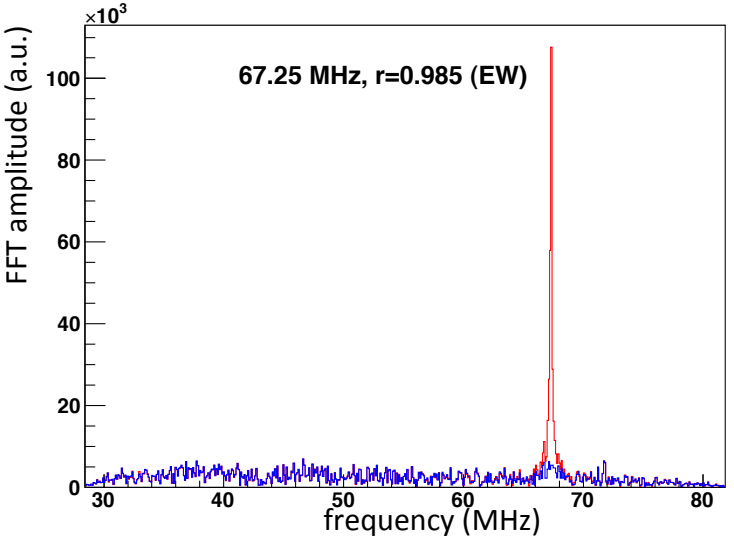


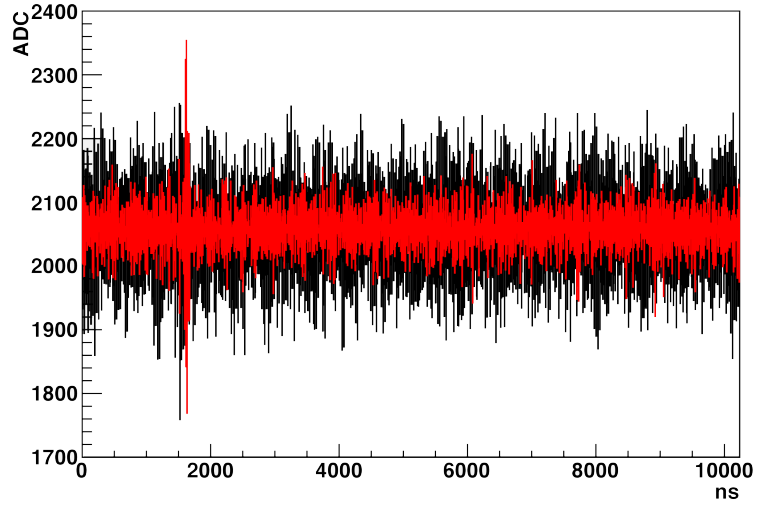
Direction of Noise Sources



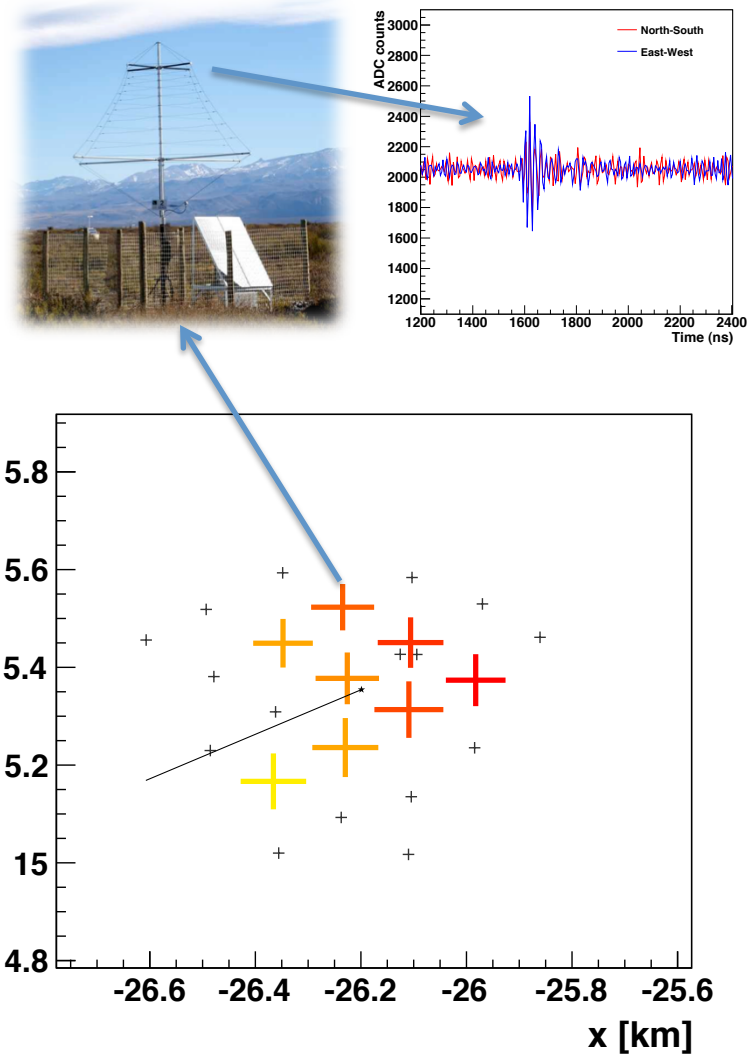
Noise Management

- Trigger rates in hardware and software are limited, so...
- Veto horizontal sources via directional reconstruction in level 3 trigger
- Veto repeating (50 Hz) events
- Digital narrowband filters to improve signal-to-noise





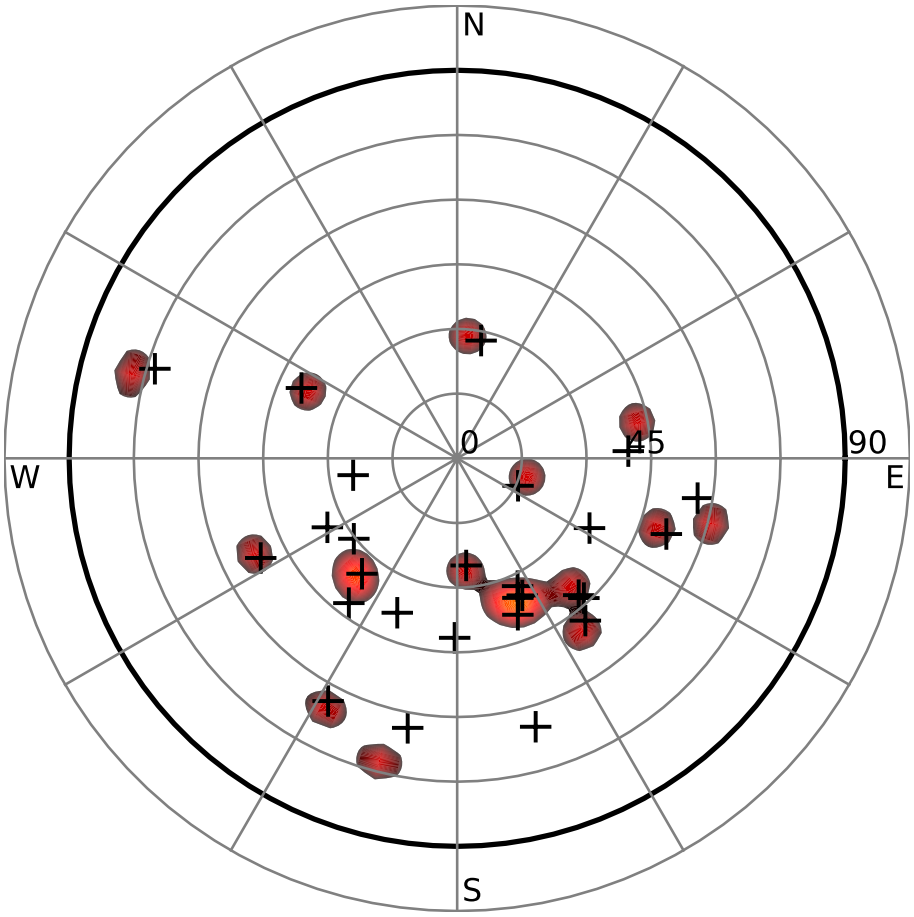
Hybrid Self Triggered Cosmic Rays

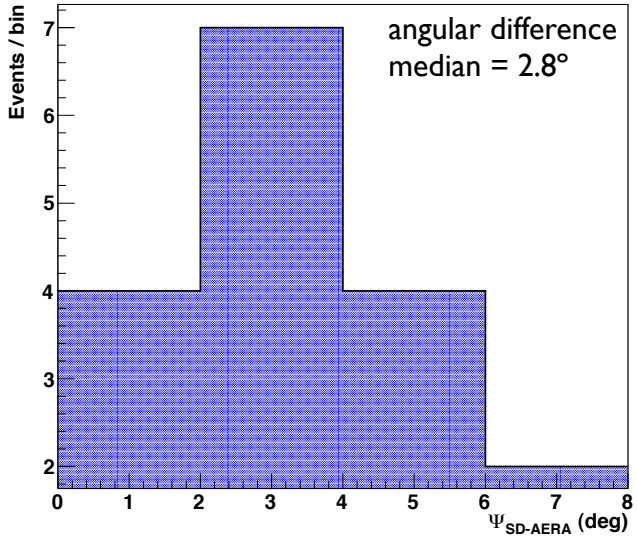


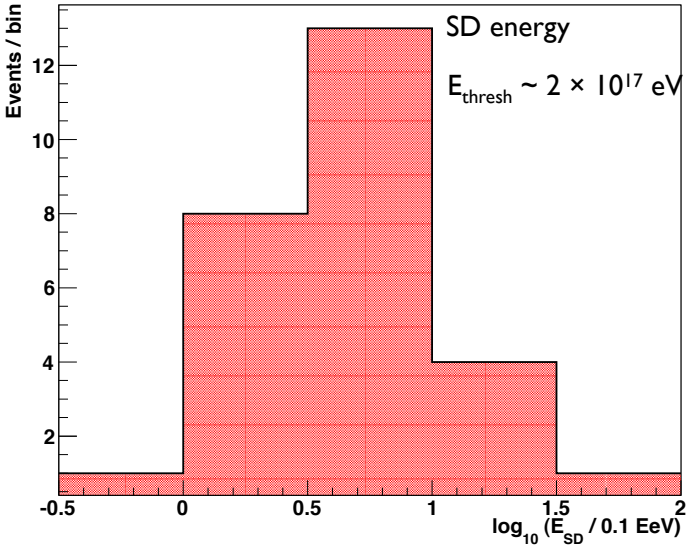
- First hybrid cosmic ray detections in mid-April
  - coincidences with SD!
- First super-hybrid event at end of April
  - radio, SD, and FD

Hybrid Events (as of 2 June)

27 events: 0.3 to 0.9 per day

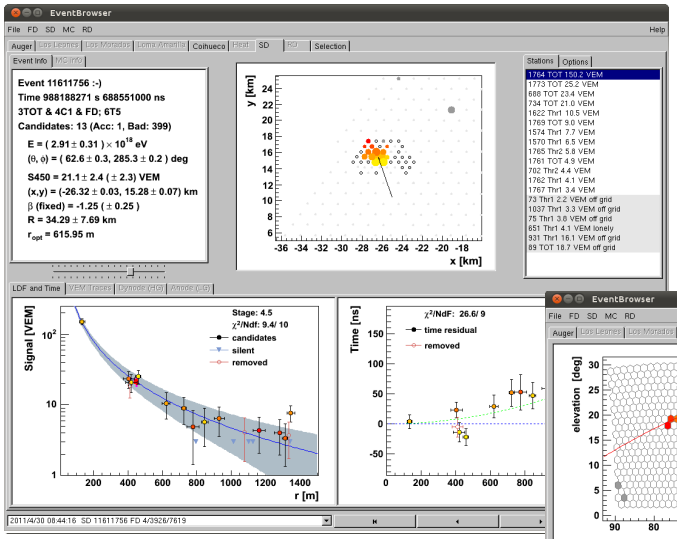




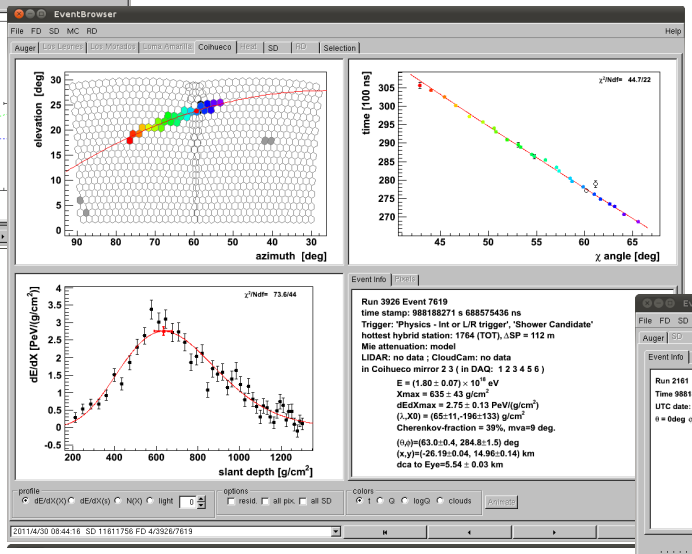


First Super-Hybrid Event

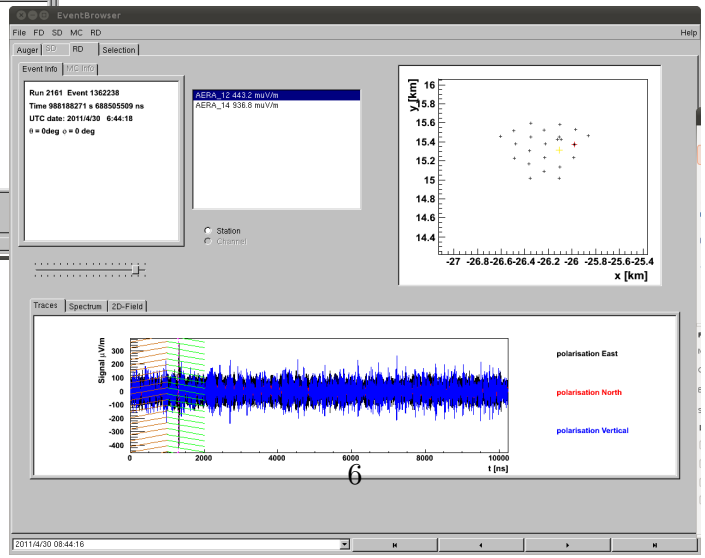
Surface detector



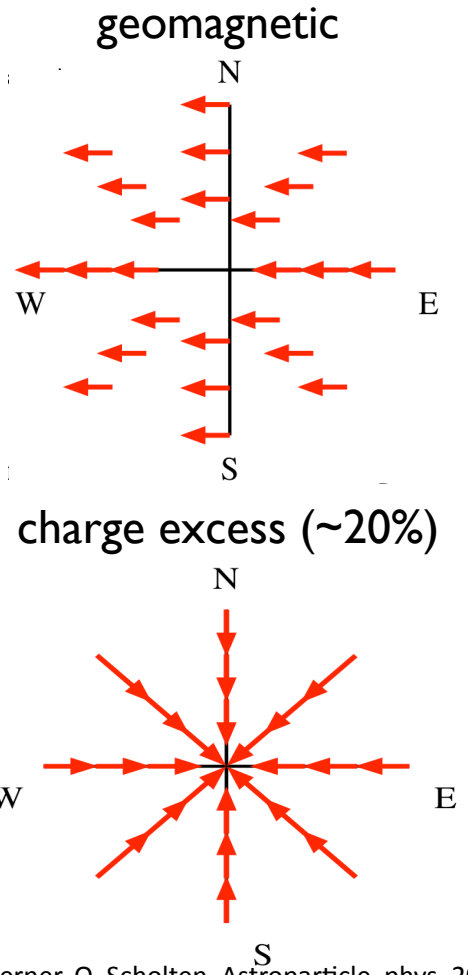
Fluorescence



AERA



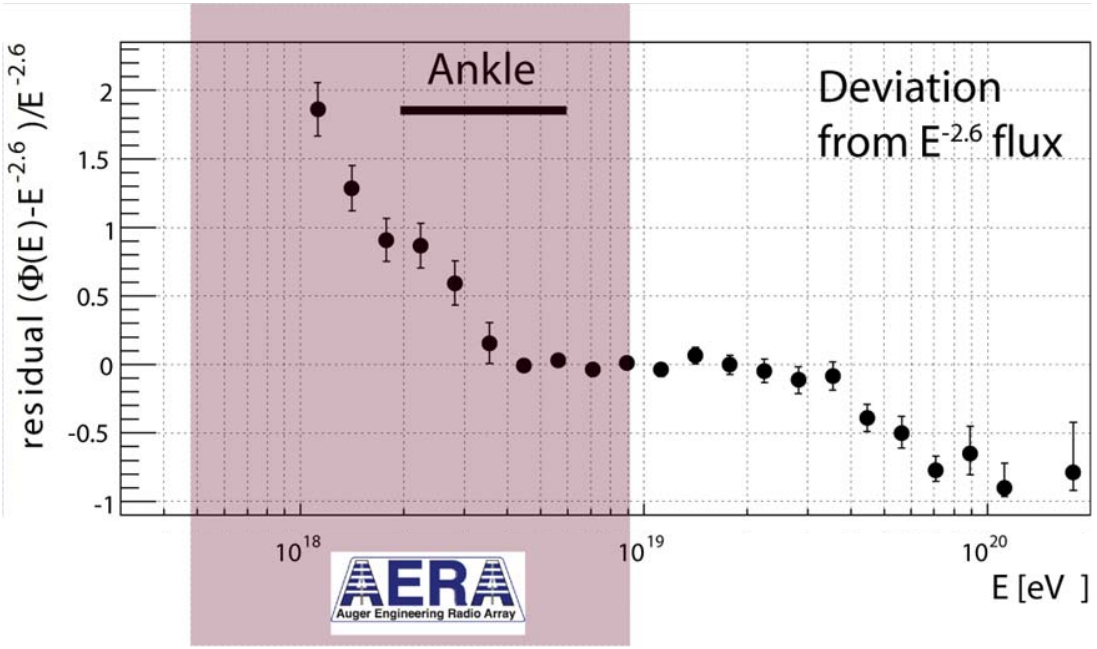
Next Steps



K. Werner, O. Scholten, Astroparticle phys, 2008

- Disentangle sub-dominant emission mechanisms
  - polarization is the key
- Multi-dimensional LDF
  - improved directional reconstruction
  - shower parameters (energy, shower maximum)
  - cross-check with SD, FD

AERA Physics Program



1. Full understanding of all radio emission mechanisms
2. Potential of radio technique for primary energy and mass determination
3. Composition of ankle region; understanding Galactic to extra-galactic transition
4. ... scale up!

Summary

- Pierre Auger UHECR results (and remaining questions)
  - suppression in spectrum (GZK or intrinsic to source?)
  - suggestive anisotropy results (really AGN? role of Cen A?)
  - composition getting heavier (compatible with anisotropy?)

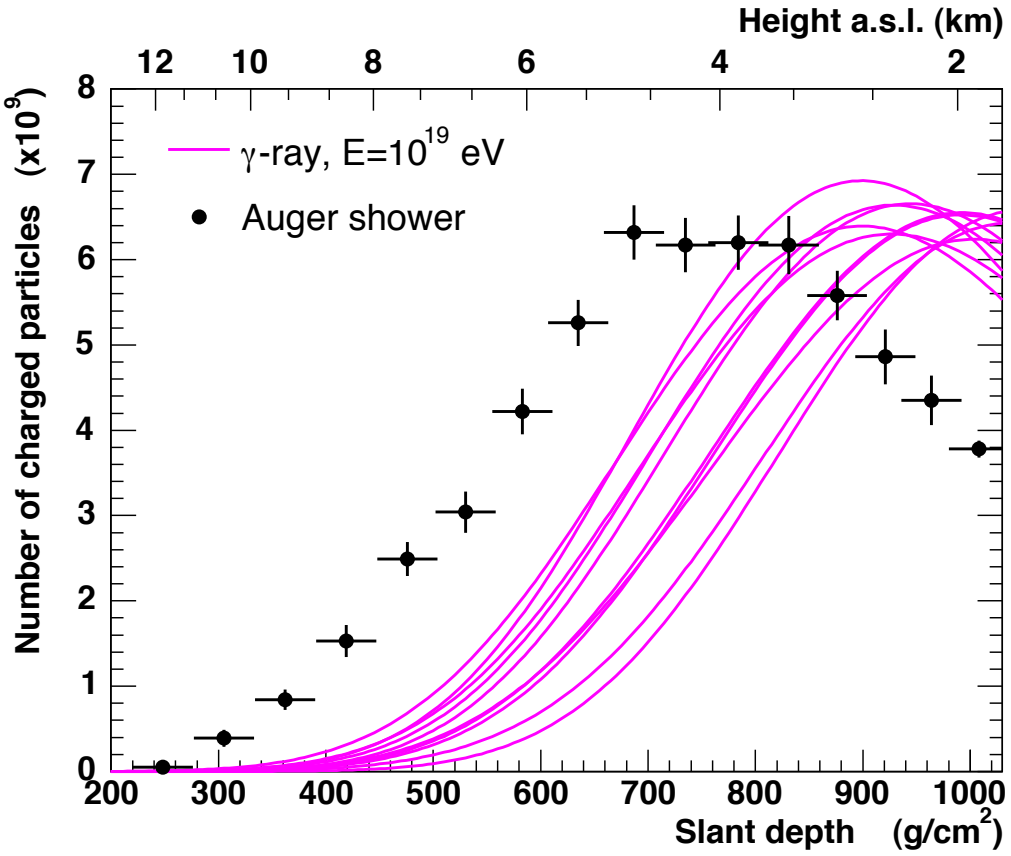
- Radio detection is maturing
  - delay in Auger North... but new technologies under development
  - super-hybrid observations underway

- Updates on many analyses at ICRC... stay tuned!


Thank you!

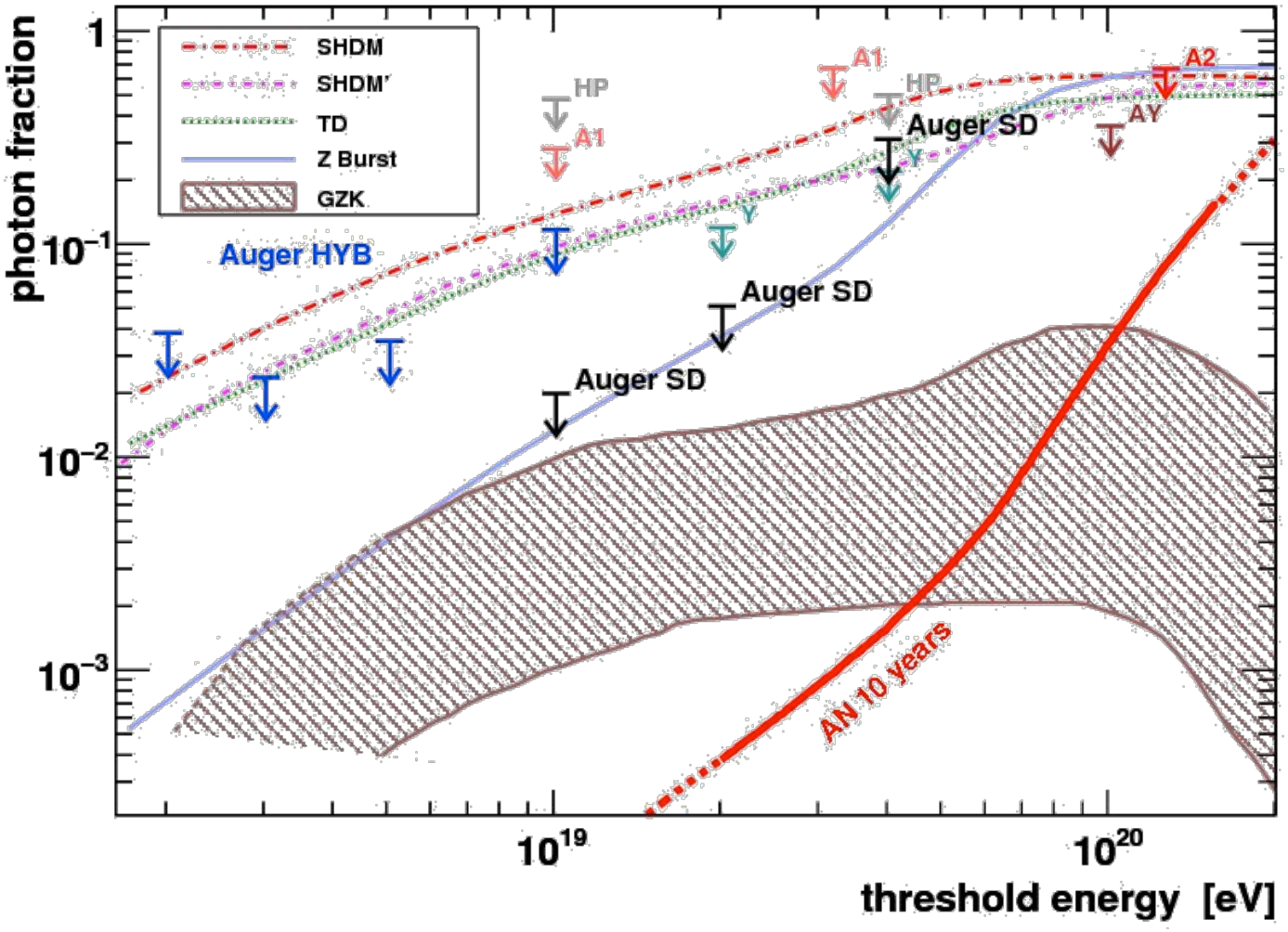
UHE Photon Searches

- Auger can detect primary UHE photons!
  - $E > 10^{18}$ eV ($\lambda < 10^{-24}$ m)
  - $D_{att} \sim 10$ Mpc
- Air shower development lower in atmosphere than p, Fe
- Predicted by many top-down CR models, some VLI scenarios

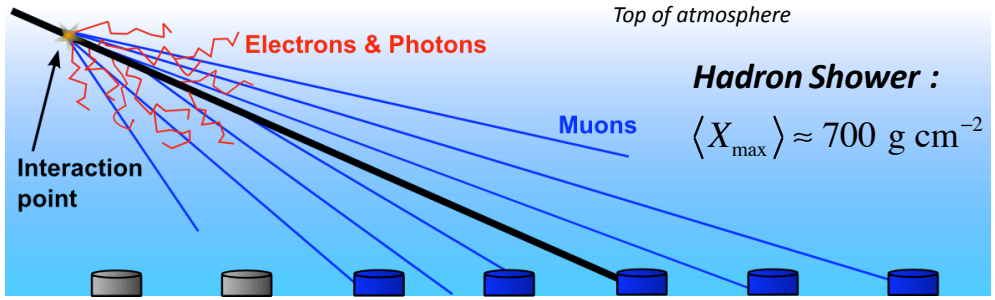


UHE Photon Upper Limits

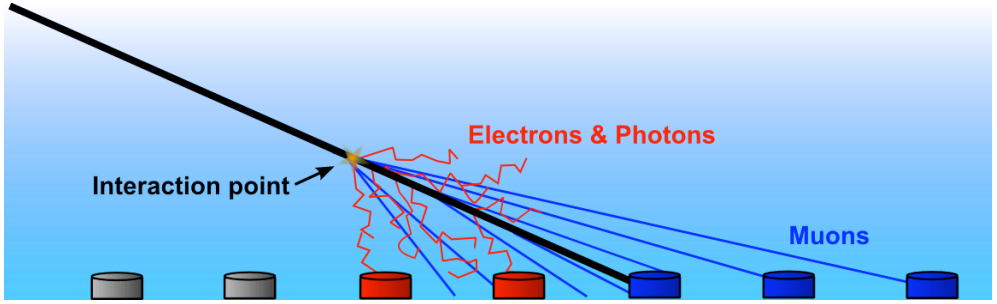
strongly constrain top-down models



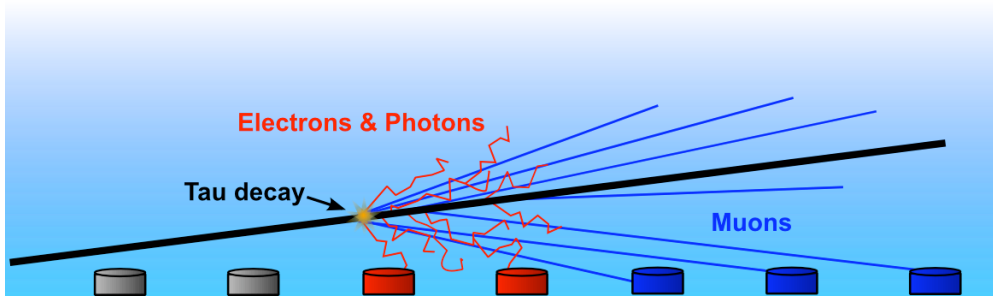
Neutrino Detection via Air Showers



"normal" inclined shower:
only muons left



neutrino-induced shower:
young EM component
(broad signals in tanks)



tau decay from Earth-skimming ν_τ:
dense target, but only one flavor

Limits on Diffuse Neutrino Flux