Observations of the Ultra-High Energy Sky at the Pierre Auger Observatory

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for the Pierre Auger Collaboration

TeVPA 2010
Paris, France
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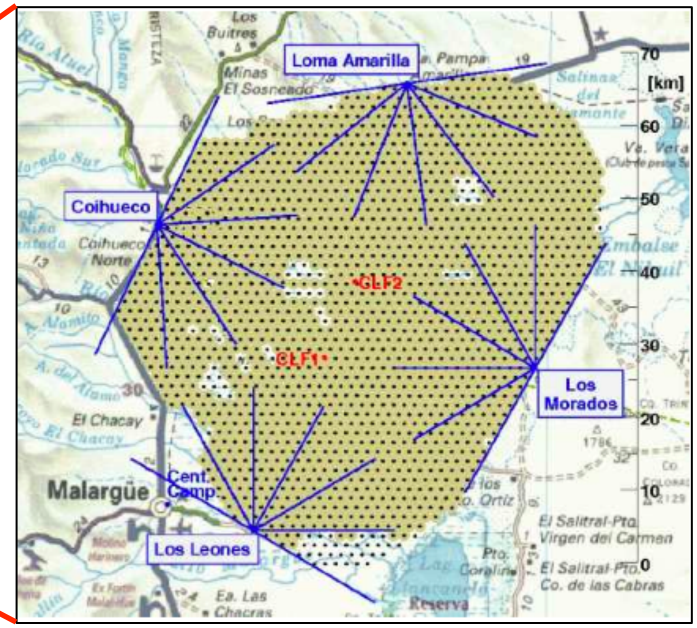
Pierre Auger Observatory

Collaboration: 18 countries, >450 scientists

Southern Observatory
Malargüe, AR
Completed – 2008



- 1 600 ground stations
- Area: 3 000 km^2
- 27 (6 × 3 + 9 × 1) fluorescence telescopes overlook array
- Optimized for $E > 3\times10^{18}$ eV

Pierre Auger Observatory

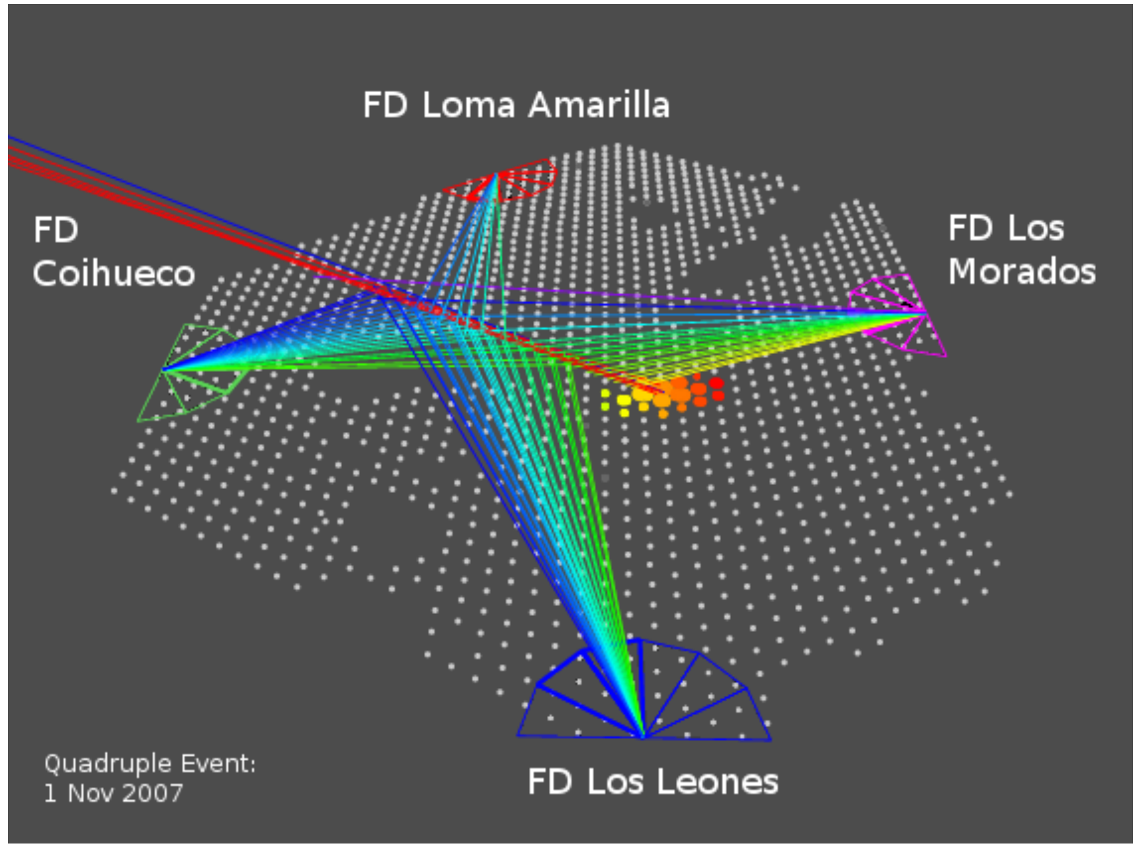
Northern Observatory: Planned for Lamar, CO

Details in *New Journal of Physics* **12** (2010) 035001

- 4 400 ground stations; 20 000 km^2
- Optimized for $E > 3\times10^{19}$ eV

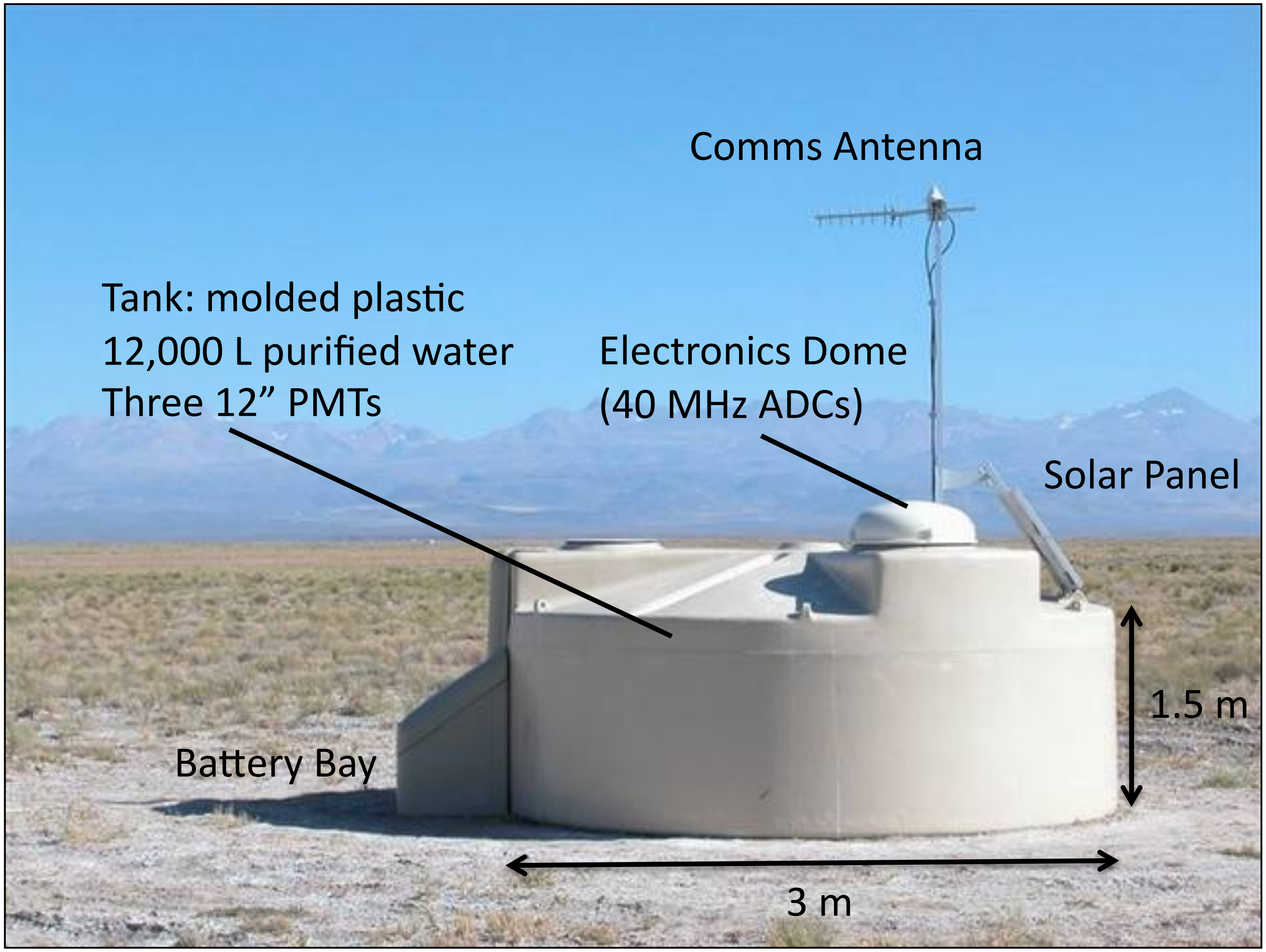
Hybrid Detection of Air Showers

- Surface Detector (SD)
  - Water Cherenkov tanks
  - Detect air shower particles at ground
  - Sensitive to *lateral distribution* of particles
  - 100% duty cycle
  - Energy: model-dependent
- Fluorescence Detector (FD)
  - Observe faint UV emission in air due to passage of charged particles
  - Sensitive to *longitudinal development* of shower
  - Direct, calorimetric energy measurement
  - 10% - 15% duty cycle
  - Atmospheric monitoring required

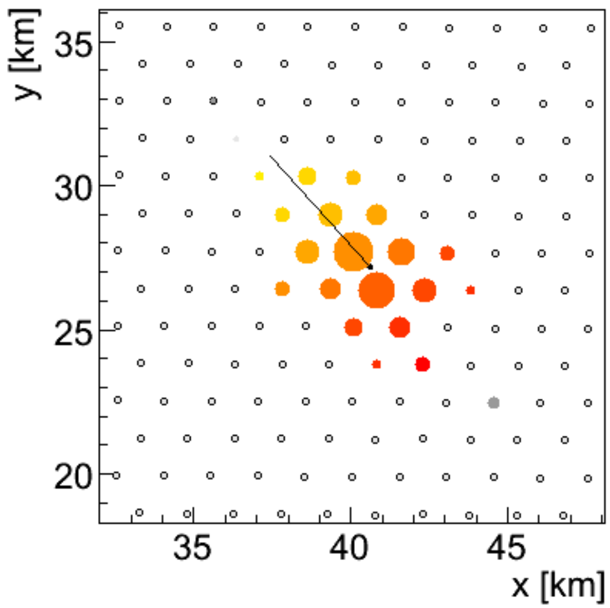


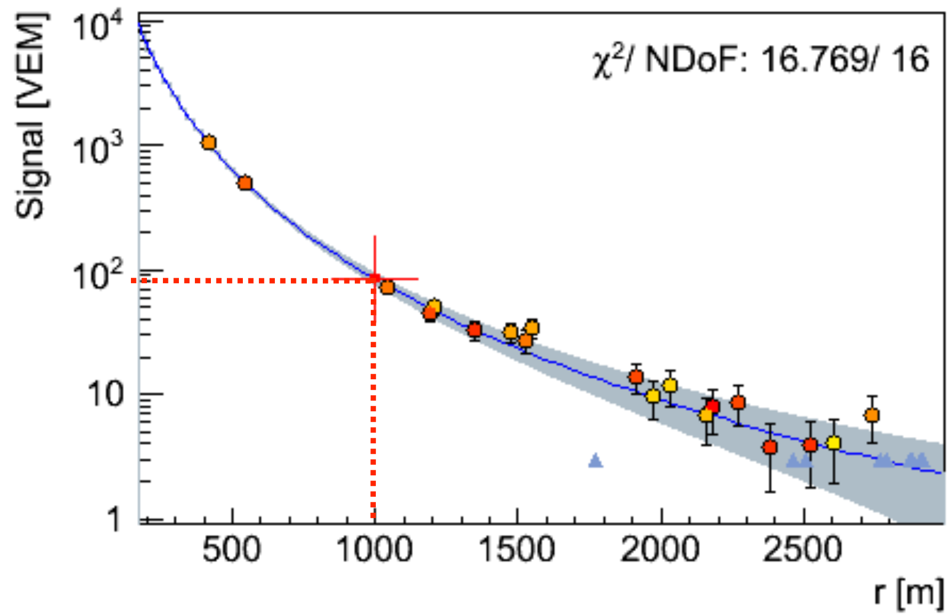
- Four FDs overlook surface array: each FD views 180° in azimuth and 2° – 30° (60°) in elevation; provide calibration for SD

Water Cherenkov Station



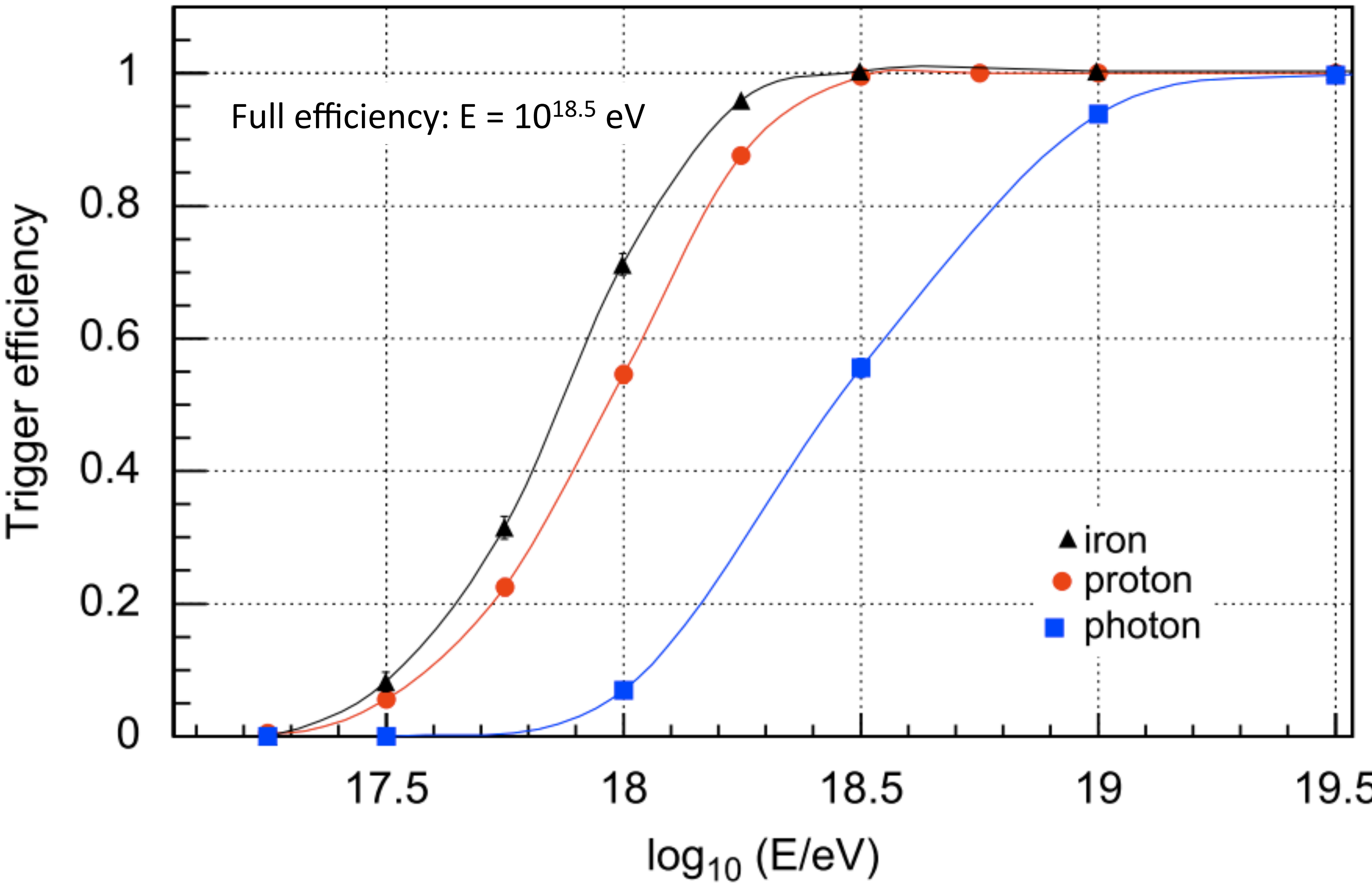
Surface Detector Operation





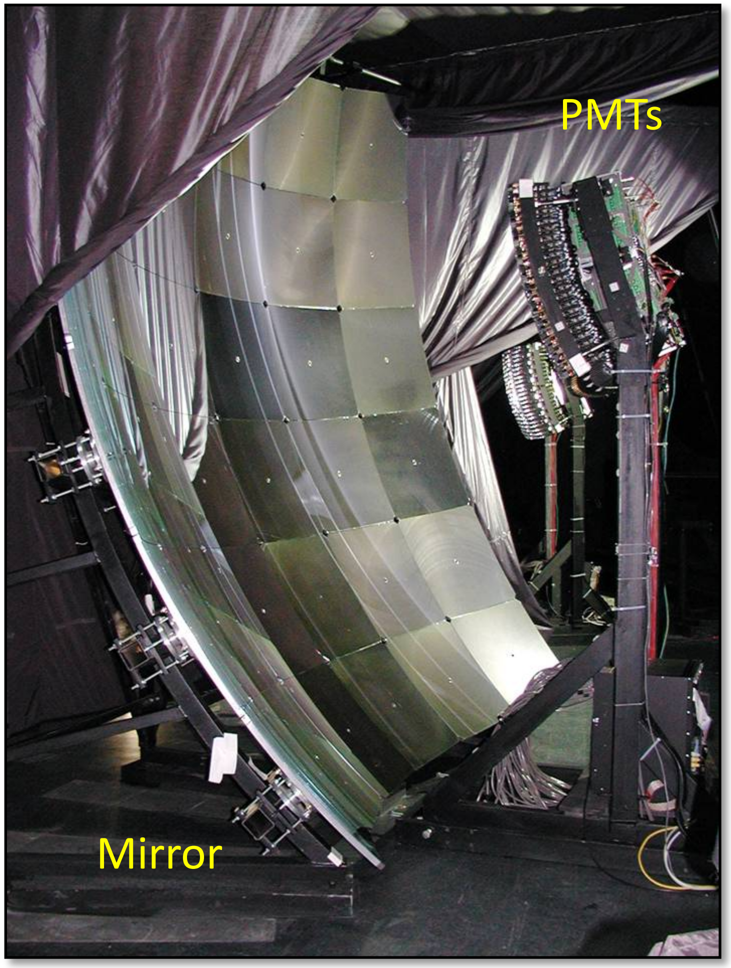
- Topological trigger – minimum 3 tanks ToT
- Arrival direction: hit timing; < 1° resolution
- Energy: particle density 1000 m from core, S(1000)
- Composition: signal time width, shower curvature

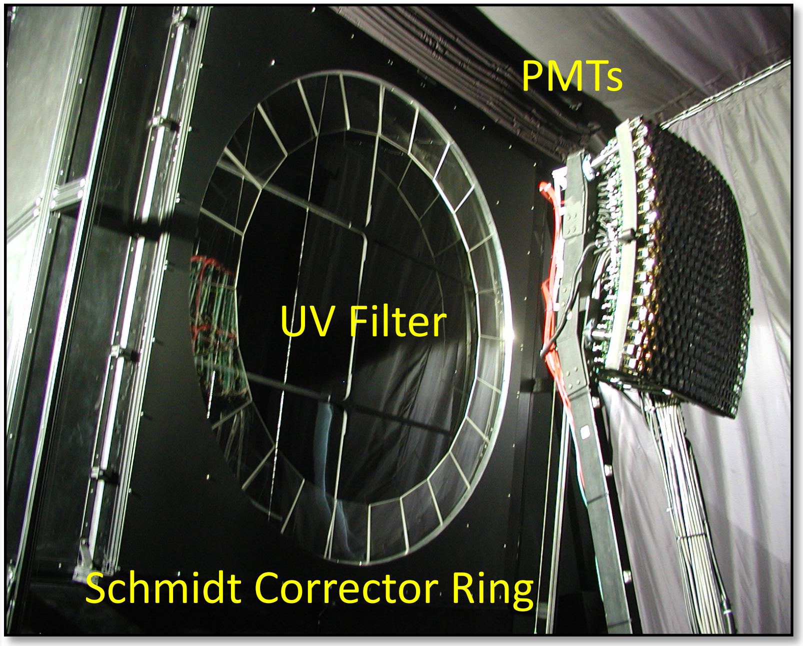
Surface Detector Efficiency

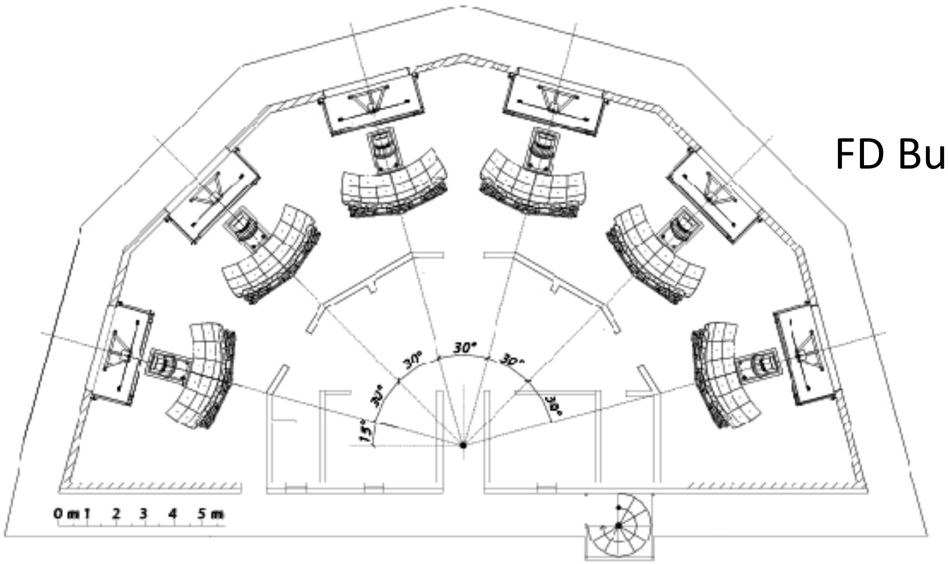


J. Abraham *et al.*, NIM **A613** (2010) 29

Fluorescence Telescopes

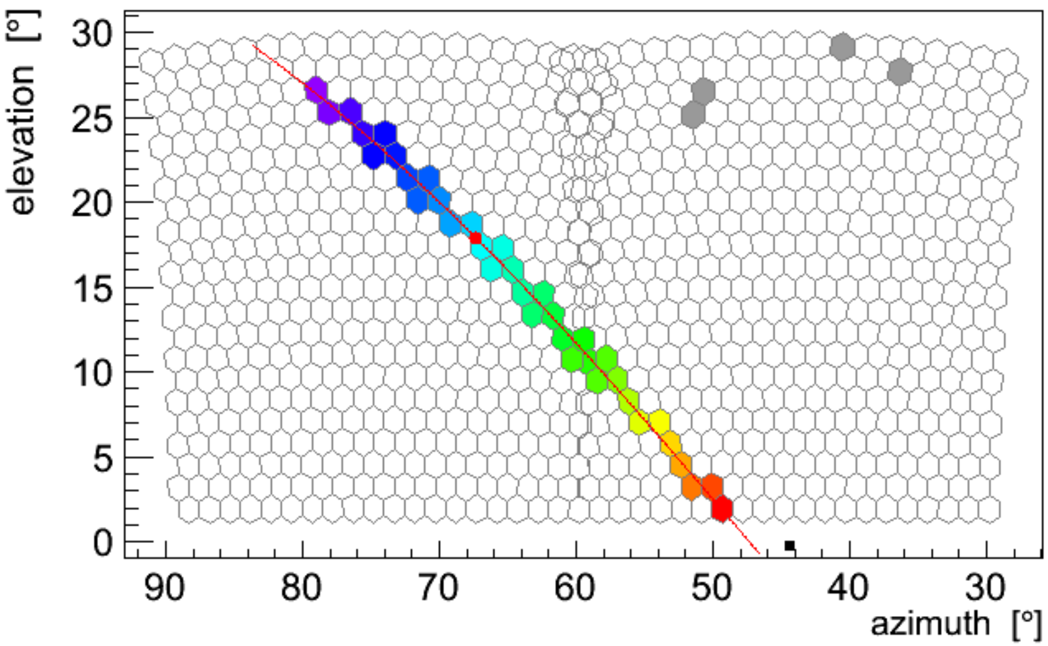


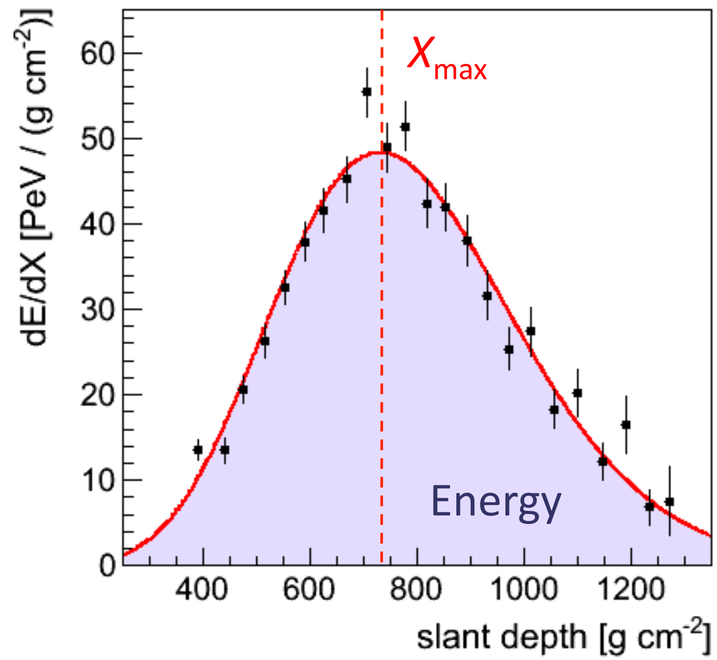




FD Building

Fluorescence Detector Operation





- Arrival direction: track angle + hit times + station time: 0.6° res.
- Energy: from longitudinal profile: $E = \int (dE / dX)\, dX$
- Mass Composition: from slant depth of shower maximum, X_{max}

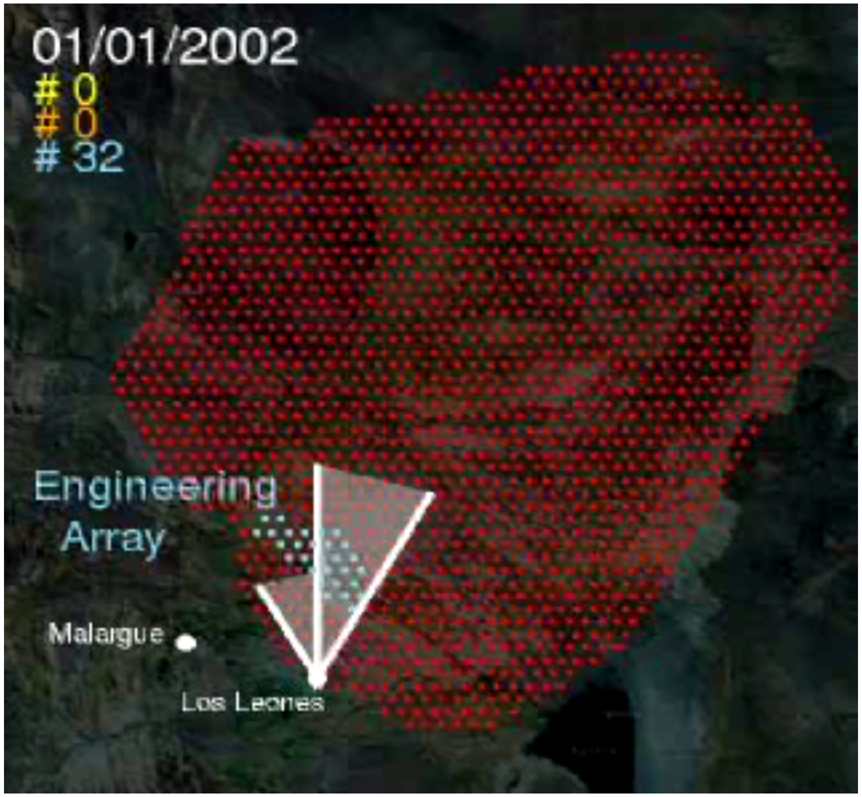
$$\sigma_E / E \approx 8\% \qquad \Delta_{sys} \approx 22\%$$

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

Complications: Deploying the Detector

- Unlike many detectors (such as IceCube), Auger has not conducted extended "science runs" in a single configuration

Deployment Evolution

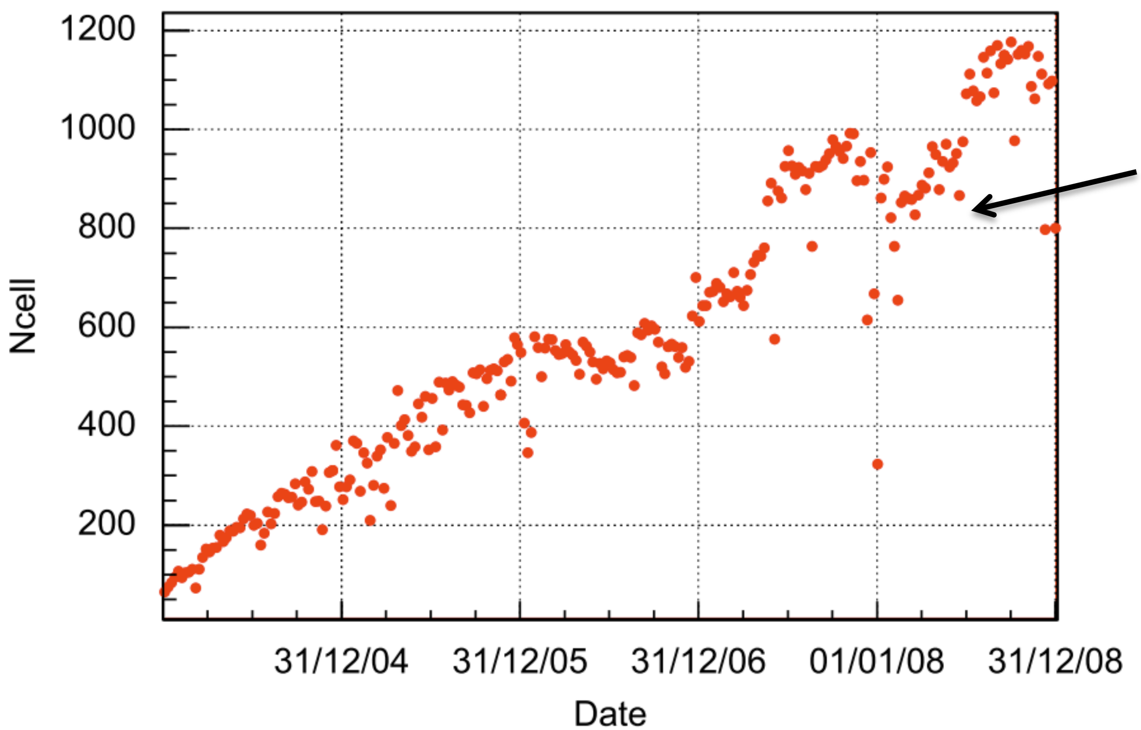


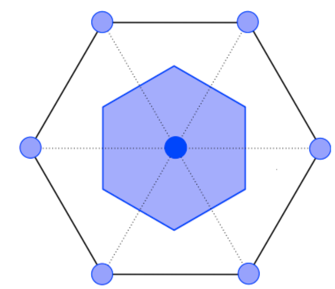
From C. Lachaud, Laboratoire APC, Université Paris 7

- The detector was operated continuously during deployment (2004 – 2008). This introduced a non-negligible time dependence into quantities that depend on the detector configuration (e.g., exposure)

Calculating Surface Detector Exposure

- Single station trigger state is monitored with 1-second resolution





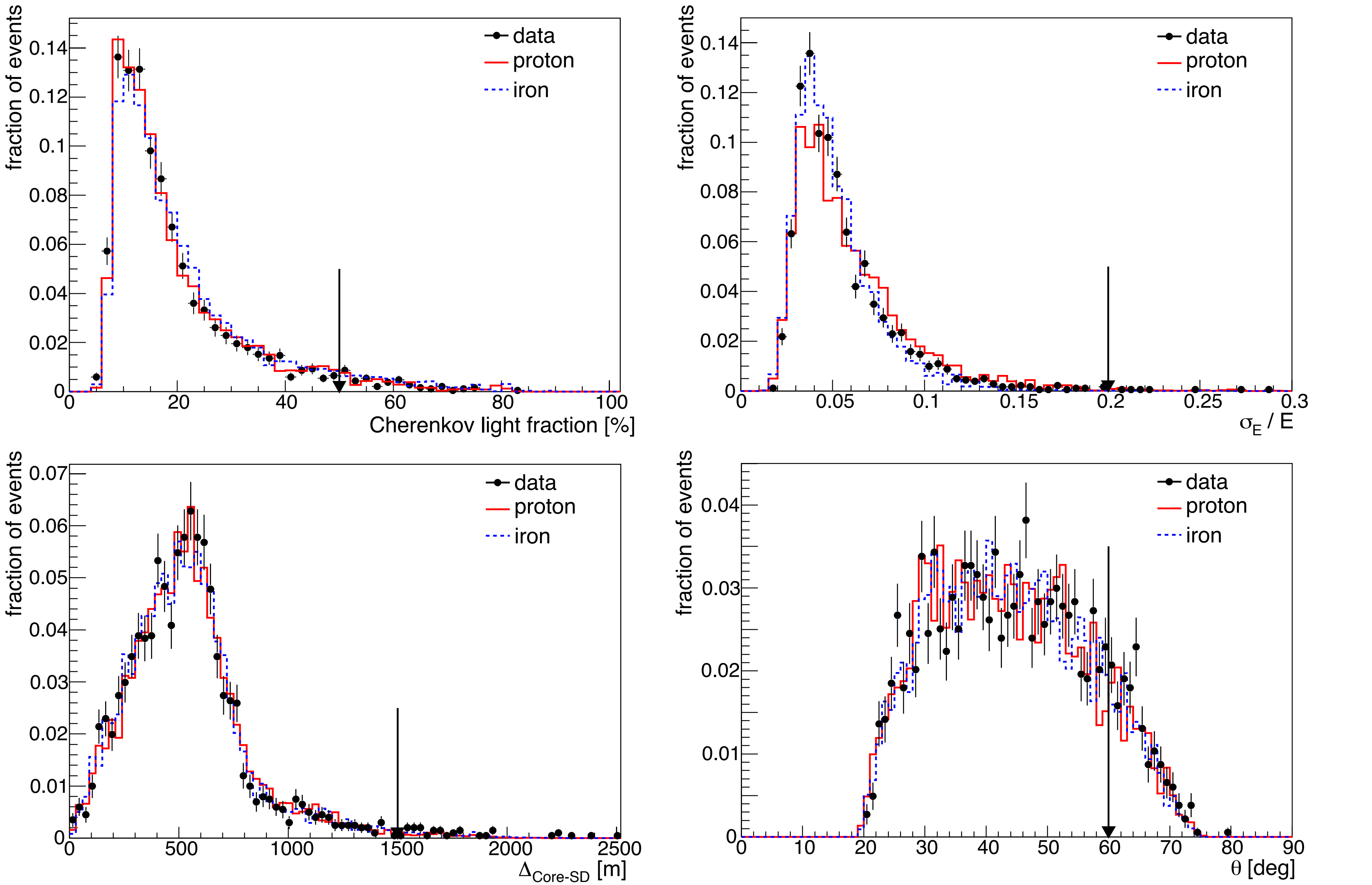
- Full trigger efficiency above $10^{18.5}$ eV means instantaneous aperture is *simple* to get: geometric acceptance = single-station acceptance × number of active hexagons

- Below $10^{18.5}$ eV, trigger probability is measured from data (> 10^6 events) as a function of signal S and zenith θ. Upward-fluctuation biases are corrected using Monte Carlo

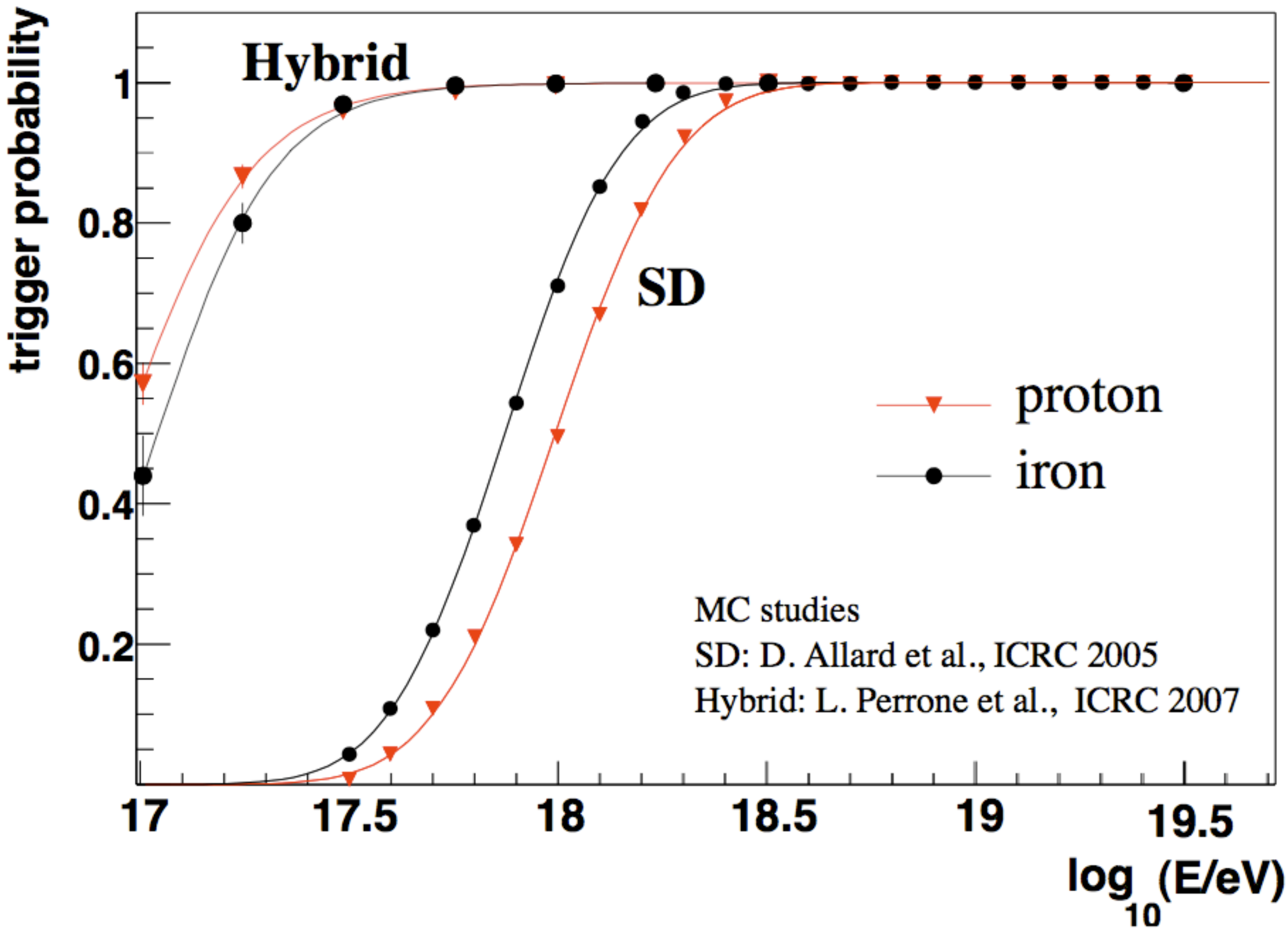
Modeling the Hybrid Detector State

- FD uptime affected by weather, DAQ efficiencies, and failures
- Time-dependent FD state is recorded at pixel level (10 min resolution):
  - True variance, baseline, threshold
- Real weather conditions from site measurements:
  - Cloud coverage (5 min/1 hour)
  - Aerosol density (1 hour)
  - *T*, *p*, *u* profiles (monthly models)
- Time-dependent MC with fast CONEX simulations
  - FD state from offline databases
  - SD state from active station list

Checks: Hybrid Data vs Simulation

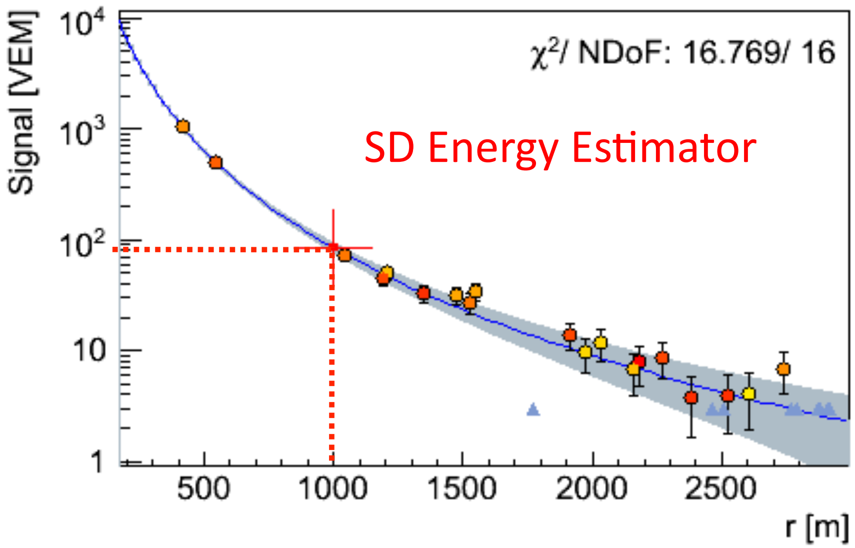


Hybrid Detector Efficiency



- Composition dependence of hybrid exposure: <10% above 10^{18} eV

“Golden” Hybrid Energy Calibration



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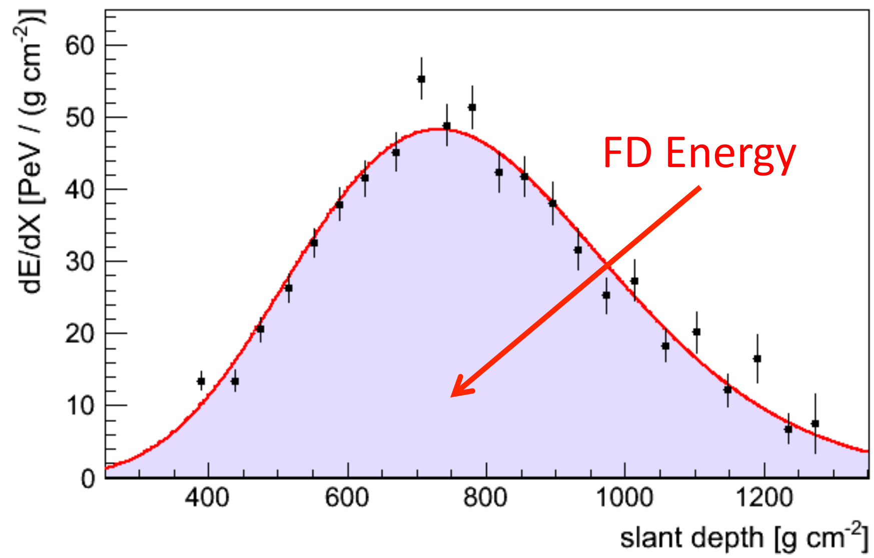

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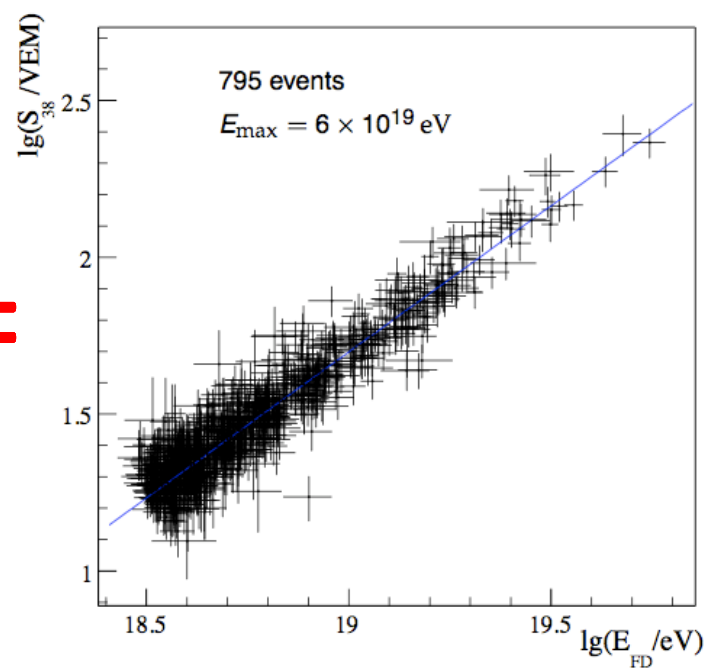


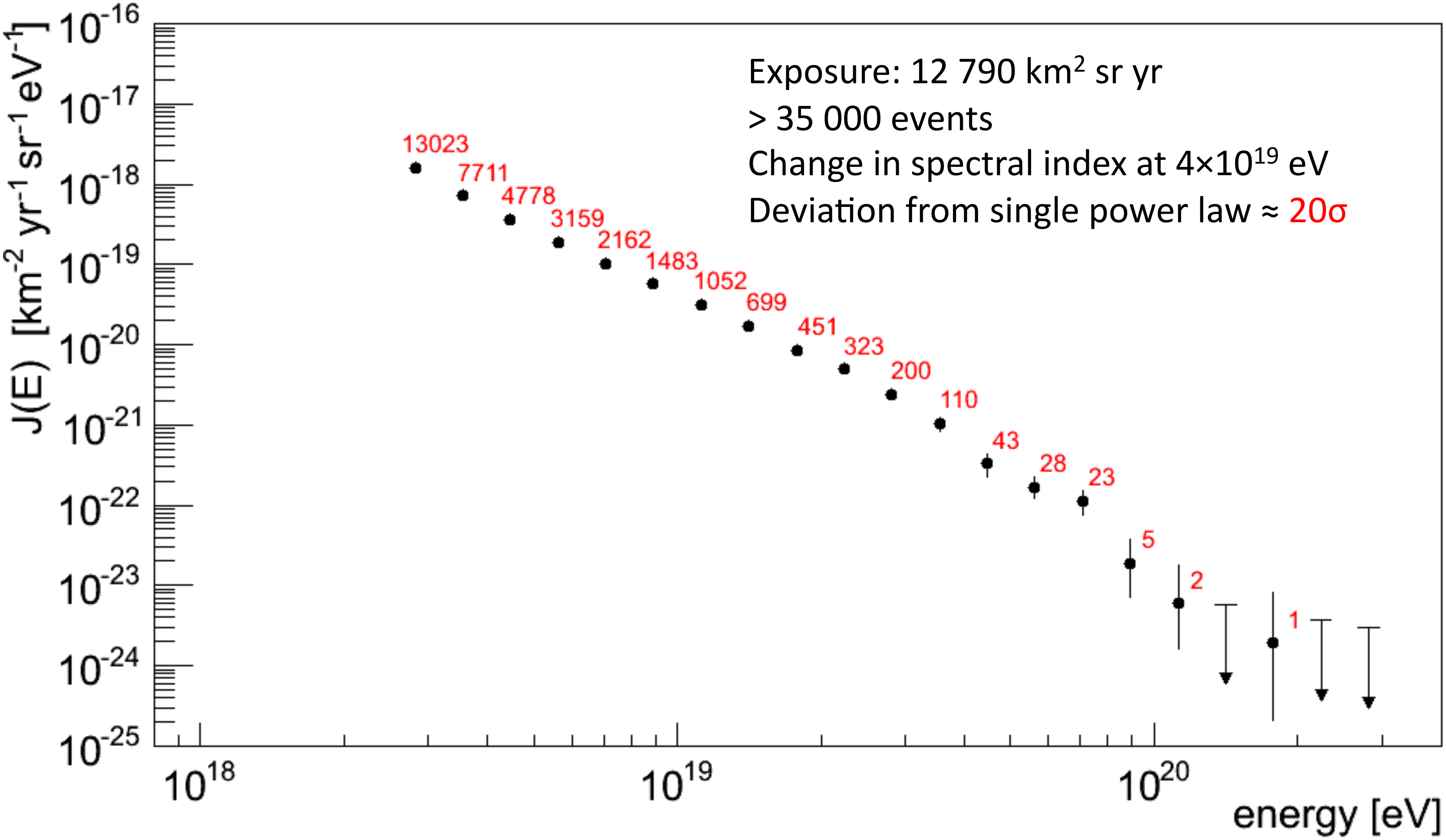
FD-SD Energy Calibration
(17% resolution)

C. DiGiulio, ICRC 2009
arXiv:0906.2189

Results:
Energy Spectrum

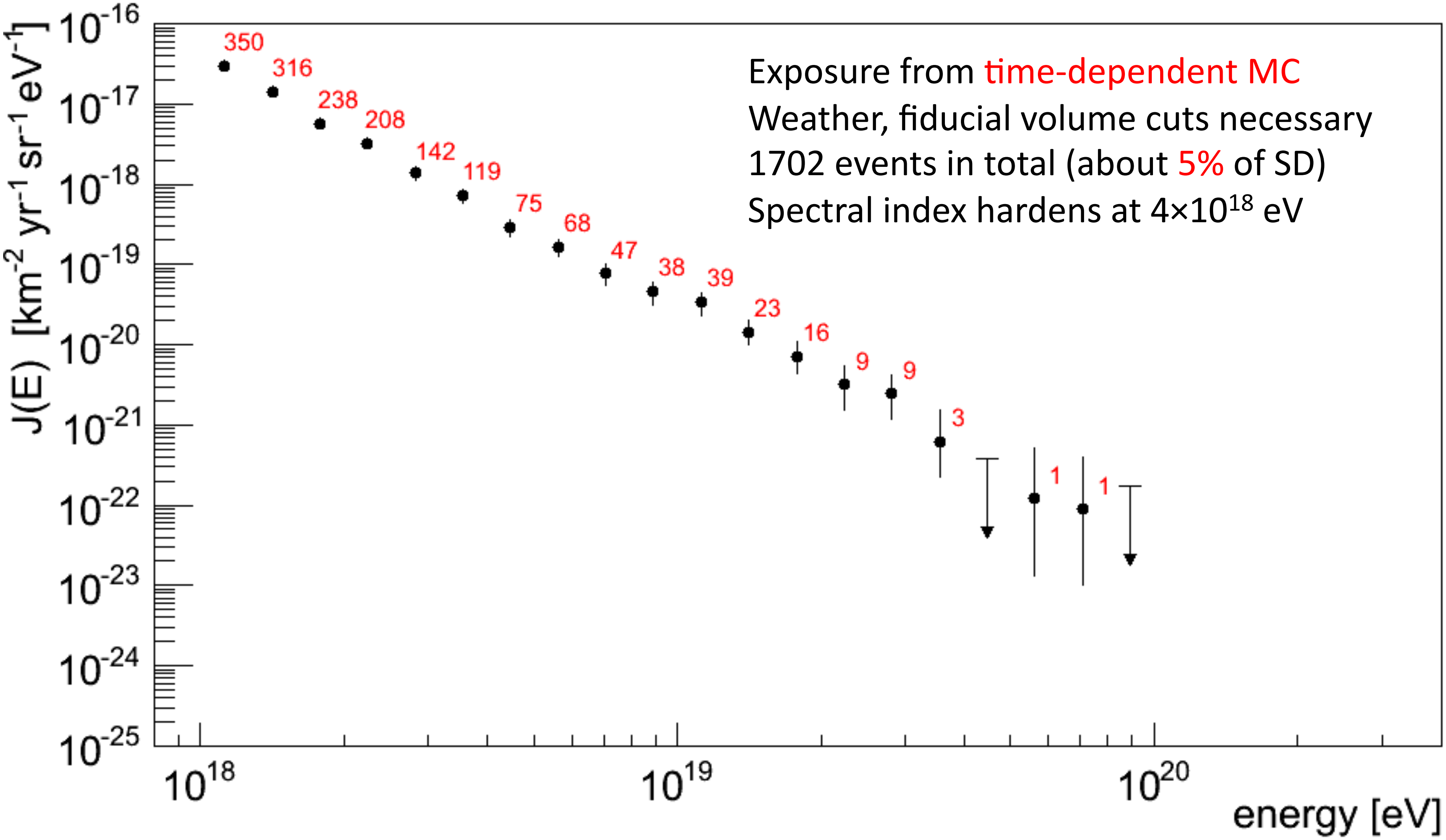
Energy Spectrum: SD

Jan 2004 – Dec 2008



Energy Spectrum: Hybrid

Jan 2004 – Mar 2009



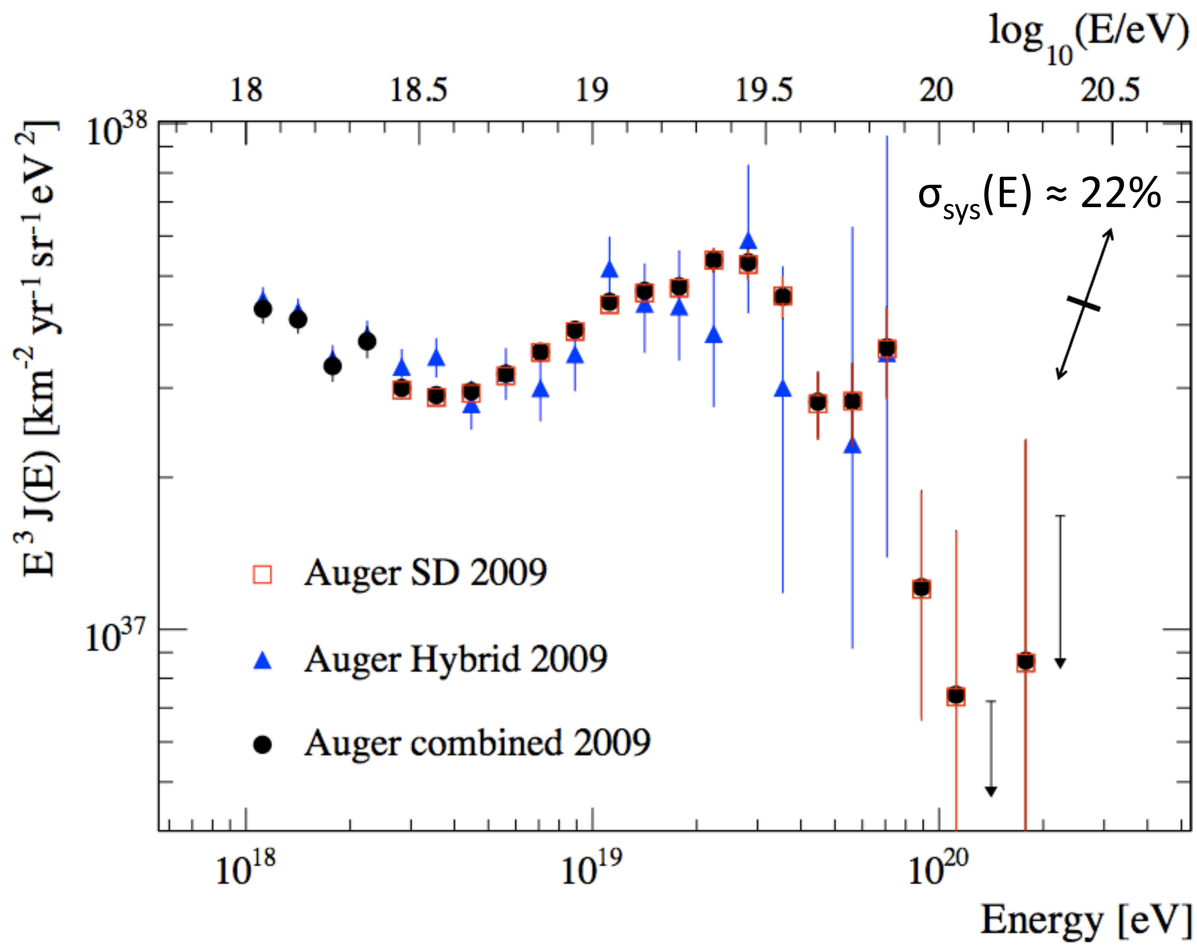
Exposure from time-dependent MC

Weather, fiducial volume cuts necessary

1702 events in total (about 5% of SD)

Spectral index hardens at 4×10^{18} eV

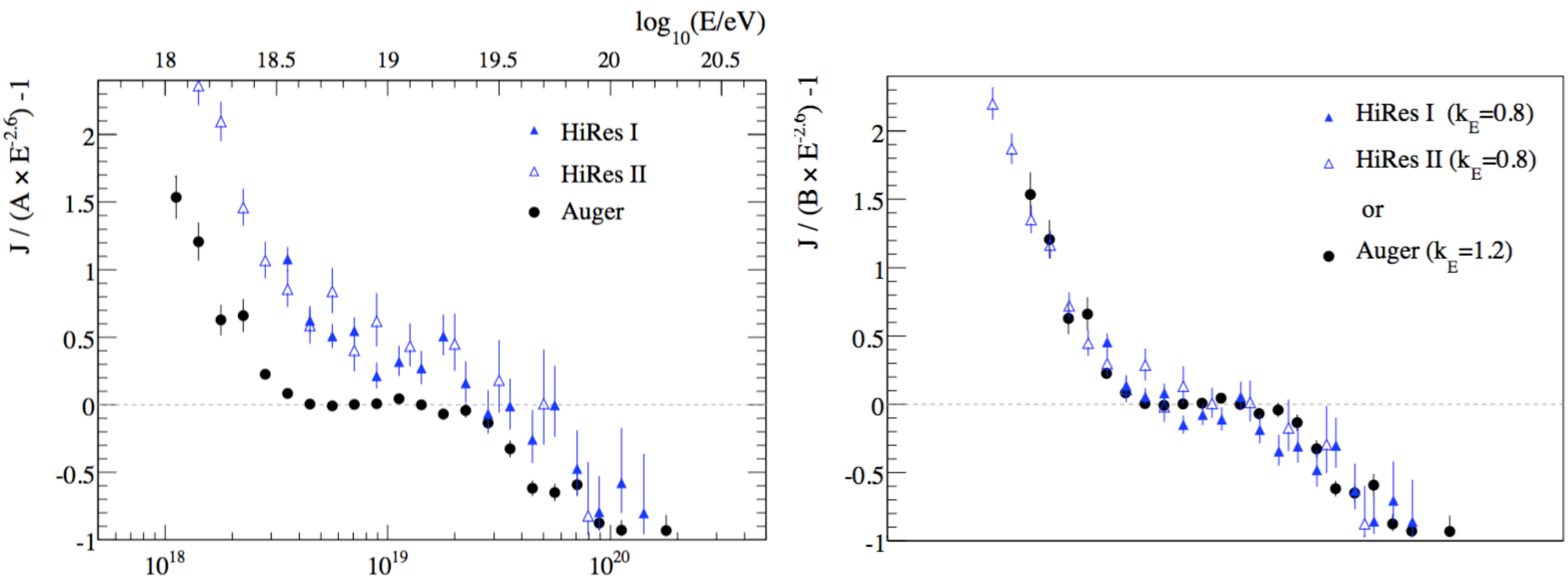
Combined Energy Spectrum



Details: J. Abraham *et al.*, Phys. Lett. B **685** (2010) 239

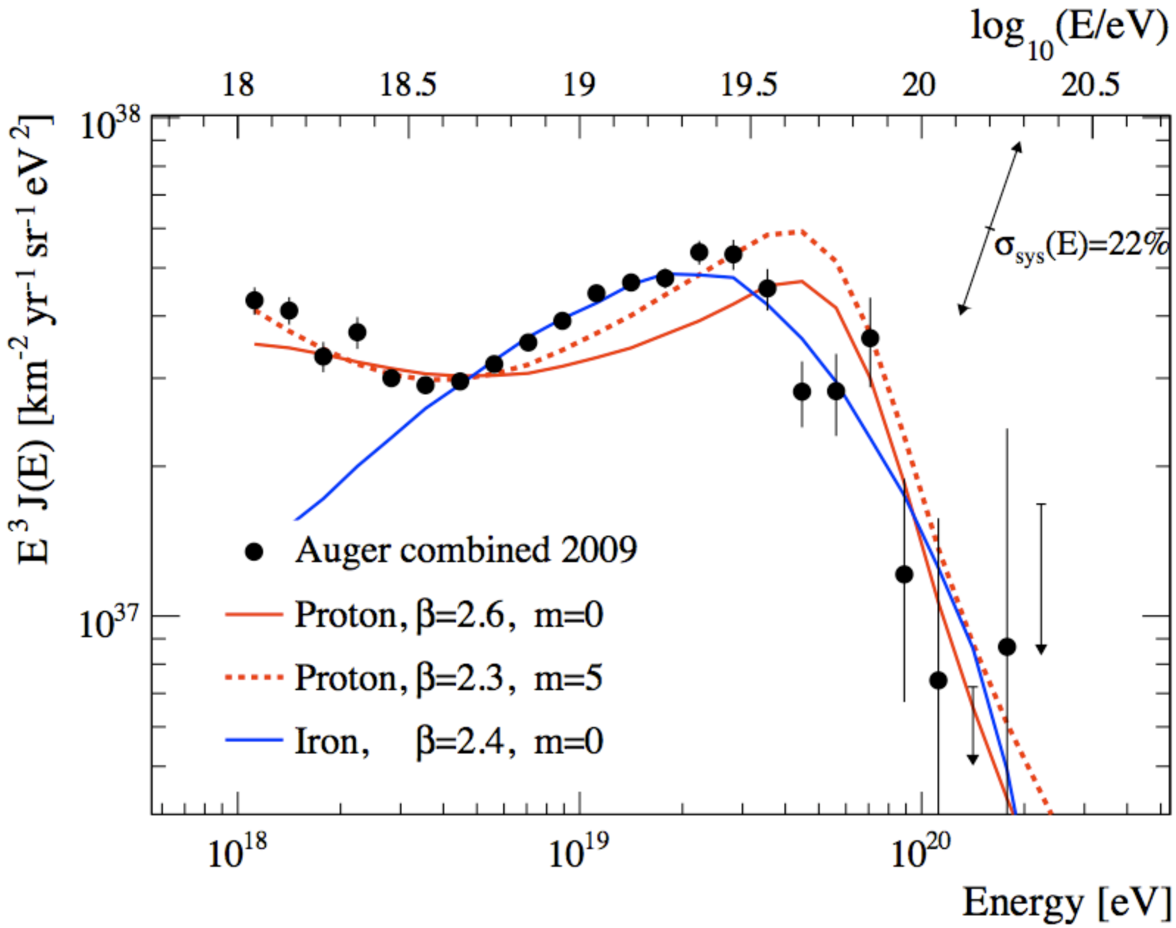
- Hybrid + SD: extension of energy spectrum to 10^{18} eV
- Hybrid/SD scale factors estimated with ML technique
- Corrected for event migration due to energy resolution (low energies)

Comparison to Other Measurments



- Auger + HiRes detectors: significant change in spectral index above $E = 4\times10^{19}$ eV, where GZK suppression of proton flux is expected
- Details: *PRL* **100** (2008) 101101; *PRL* **101** (2008) 061101
- Scaling energies by ±20% brings spectra into alignment

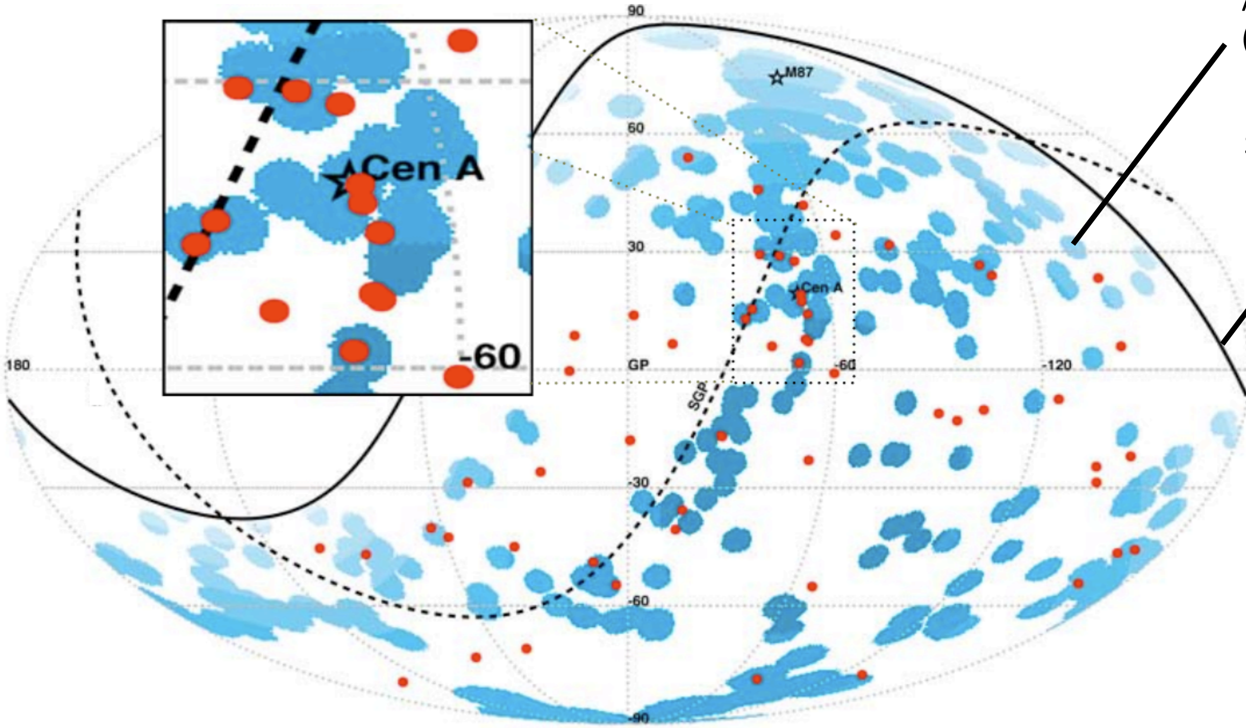
Simple Astrophysical Scenarios



- Source model: $E^{-\beta}$ injection spectrum, sources evolve like $(1+z)^m$

Results:
Arrival Direction Anisotropy

Anisotropy

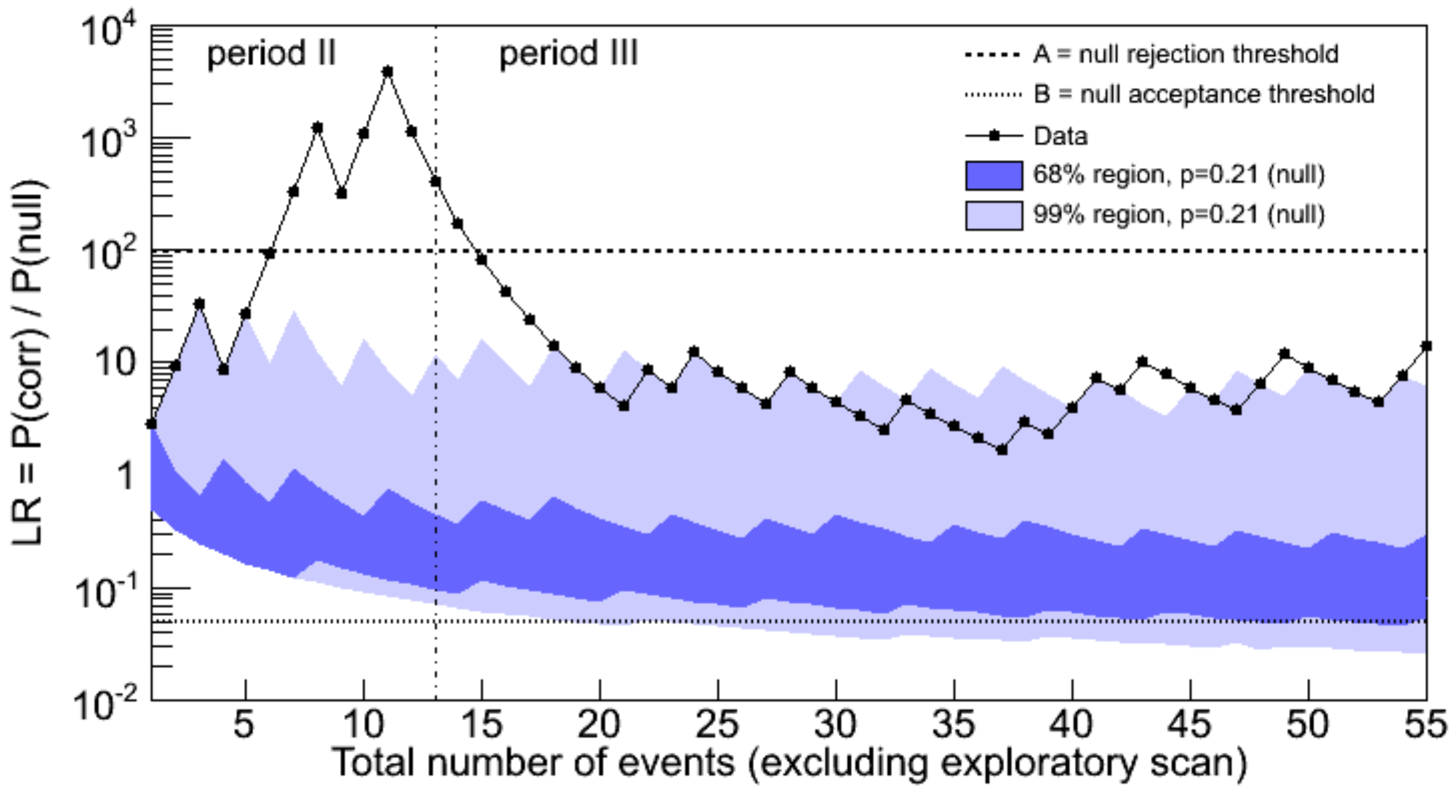


- SD events compared to nearby AGNs: Science **318** (5852) 938
- VCV Quasar + AGN catalog used
- VCV is biased and incomplete; statistical studies are possible, but interpretation of correlations is less clear

- Test parameters: $\Delta\Psi \leq 3.1°$, $E_{SD} \geq 56$ EeV, $z \leq 0.018$ ($D \leq 75$ Mpc)

Progress of the Correlation

- Correlation confirmed at >99% after *a priori* sequential trial (period II)

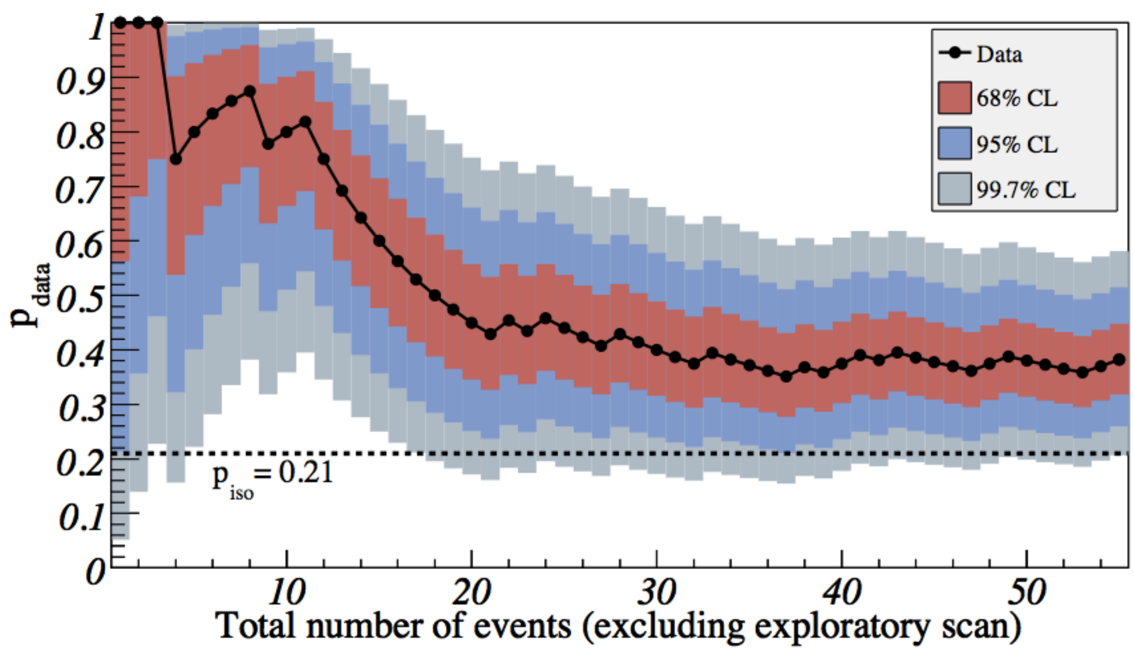


k = 21 (12)
N = 55

- Since publication (period III): significance has decreased, though full dataset still disfavors the null hypothesis of chance correlations

Correlation Probability Evolution

- Has signal disappeared, or stabilized? We will continue to follow up with more data

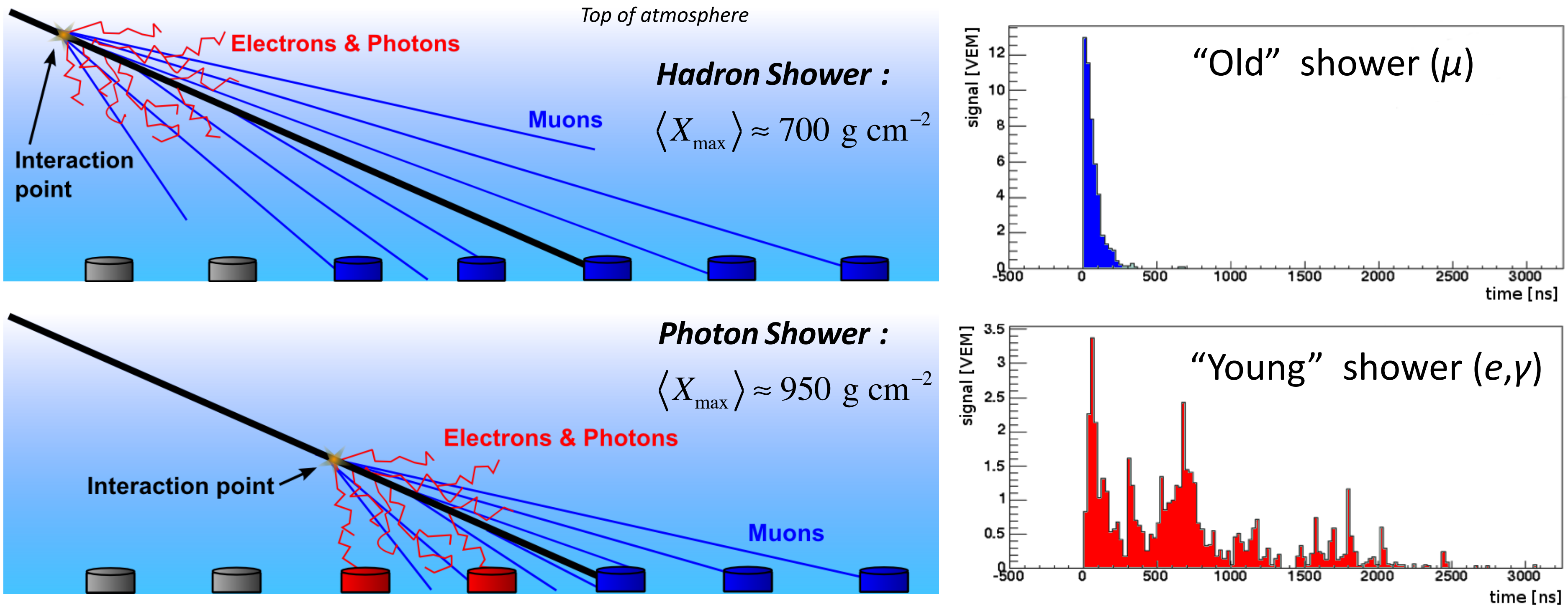


- Other, more complete object catalogs checked: 2MRS, Swift-BAT, and HIPASS
- Arrival direction anisotropy above 55 EeV also consistent with local sources (Cen A) at level of few percent

- Arrival directions and energies used in these studies will be made publicly available (manuscript submitted to Astropart. Phys.)

Results:
Particle Composition

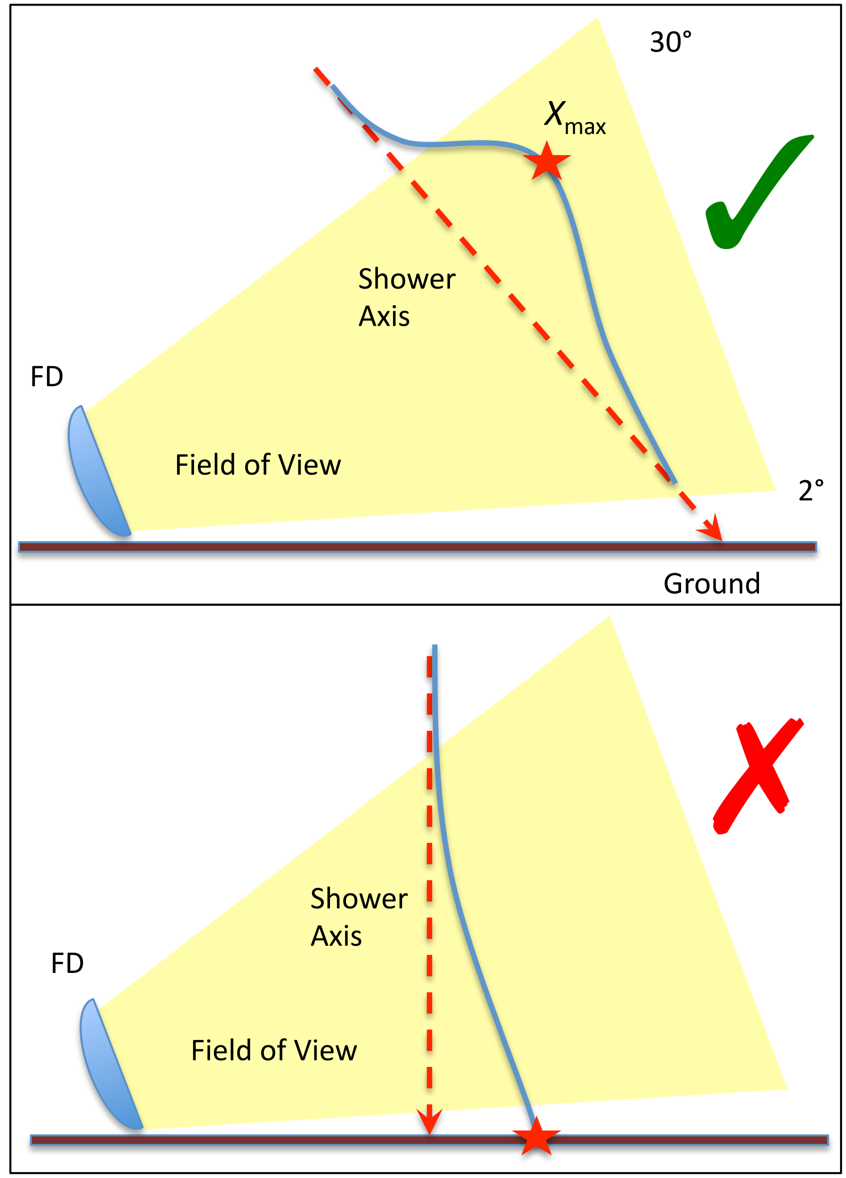
SD Event Tagging: Photons



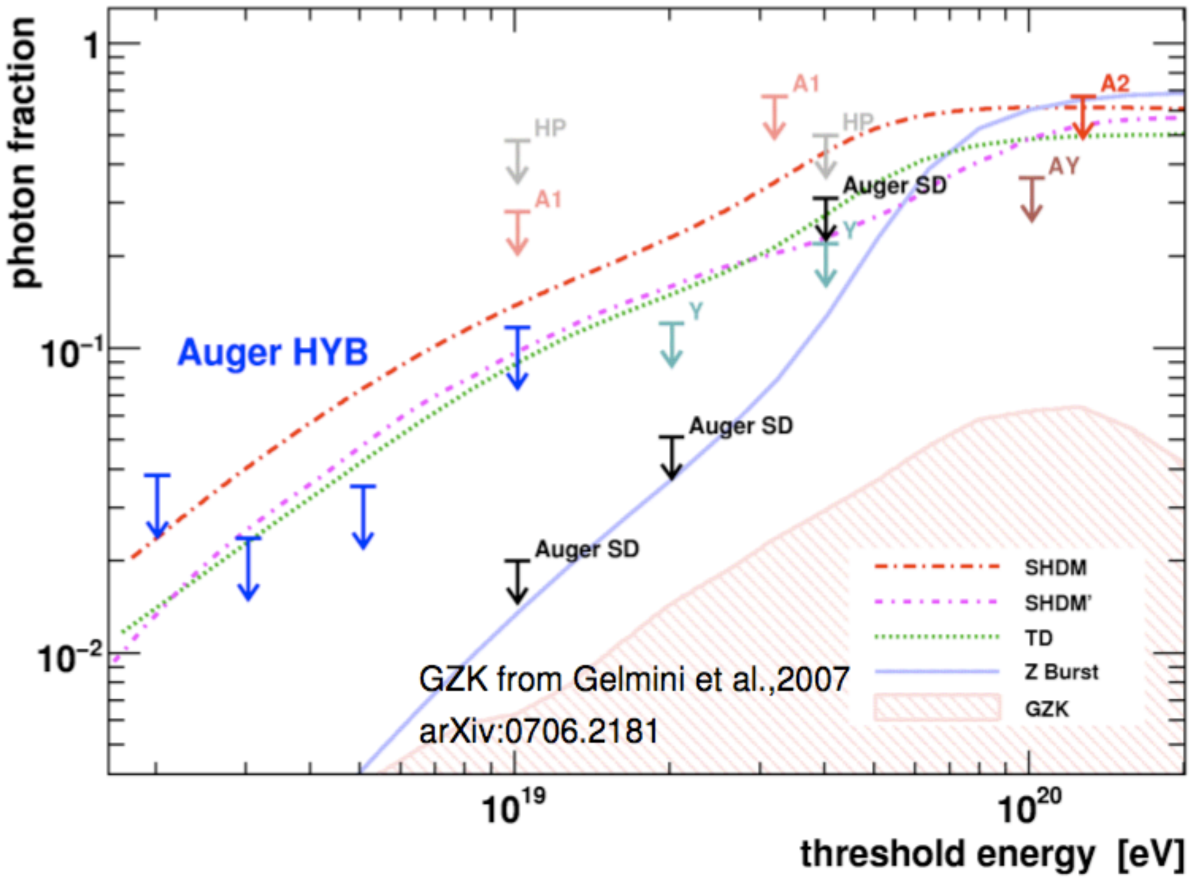
- γ showers develop deep in atmosphere (+200 g cm^{-2} w.r.t. hadrons)
- EM particles in shower do not have time to range out before reaching ground level. Showers look "young":
  - Large scatter in particle arrival times; large *risetime* in signal trace
  - Shower front has smaller radius of curvature w.r.t. "old" hadronic shower
  - Details in Astropart. Phys. **29** (2008) 243

Hybrid Event Tagging: Photons

- Hybrid mode: search for showers with unusually deep X_{max} using FD telescopes
- Strong geometry cuts: X_{max} contained in field of view
- Profile/fiducial volume cuts: vertical and distant showers rejected to remove trigger and reconstruction biases
- Atmospheric cuts to remove distorted profiles (read: cloud removal)
- Details: J. Abraham *et al.*, Astropart. Phys. **31** (2009), 399



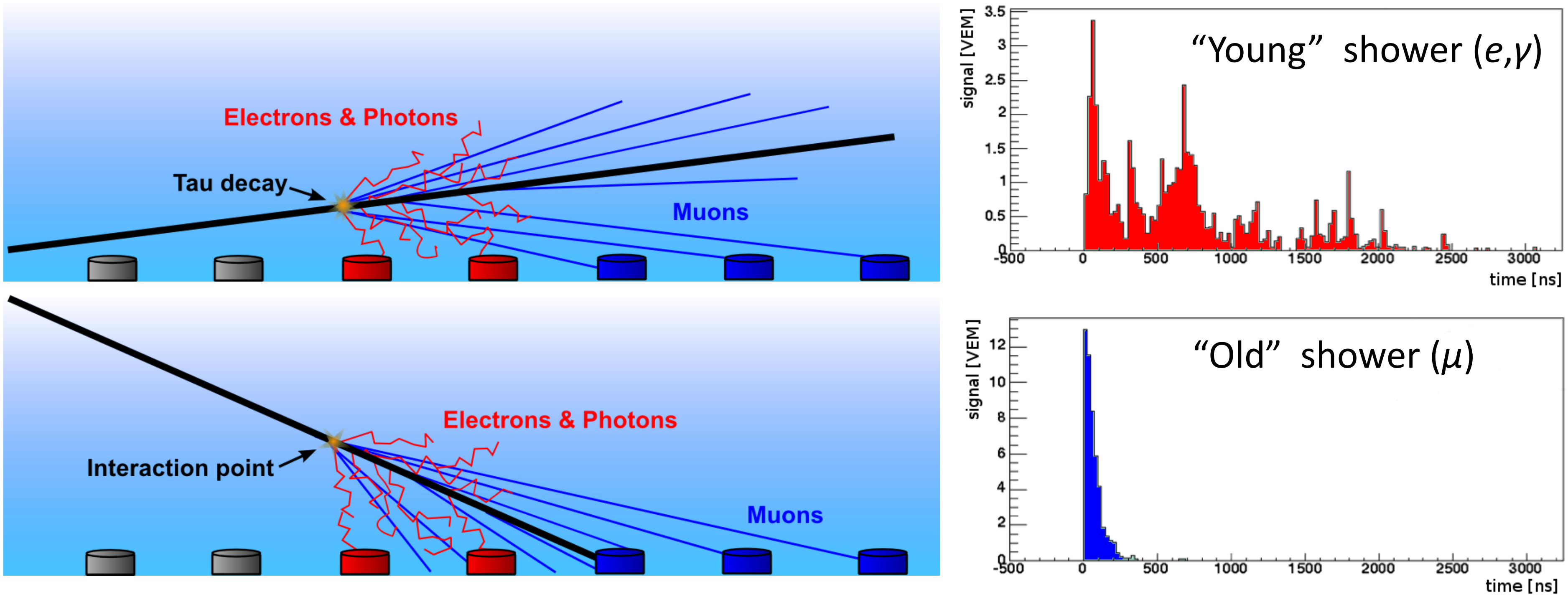
Photon Upper Limits: SD + Hybrid



J. Abraham *et al.*, Astropart. Phys. **31** (2009) 399

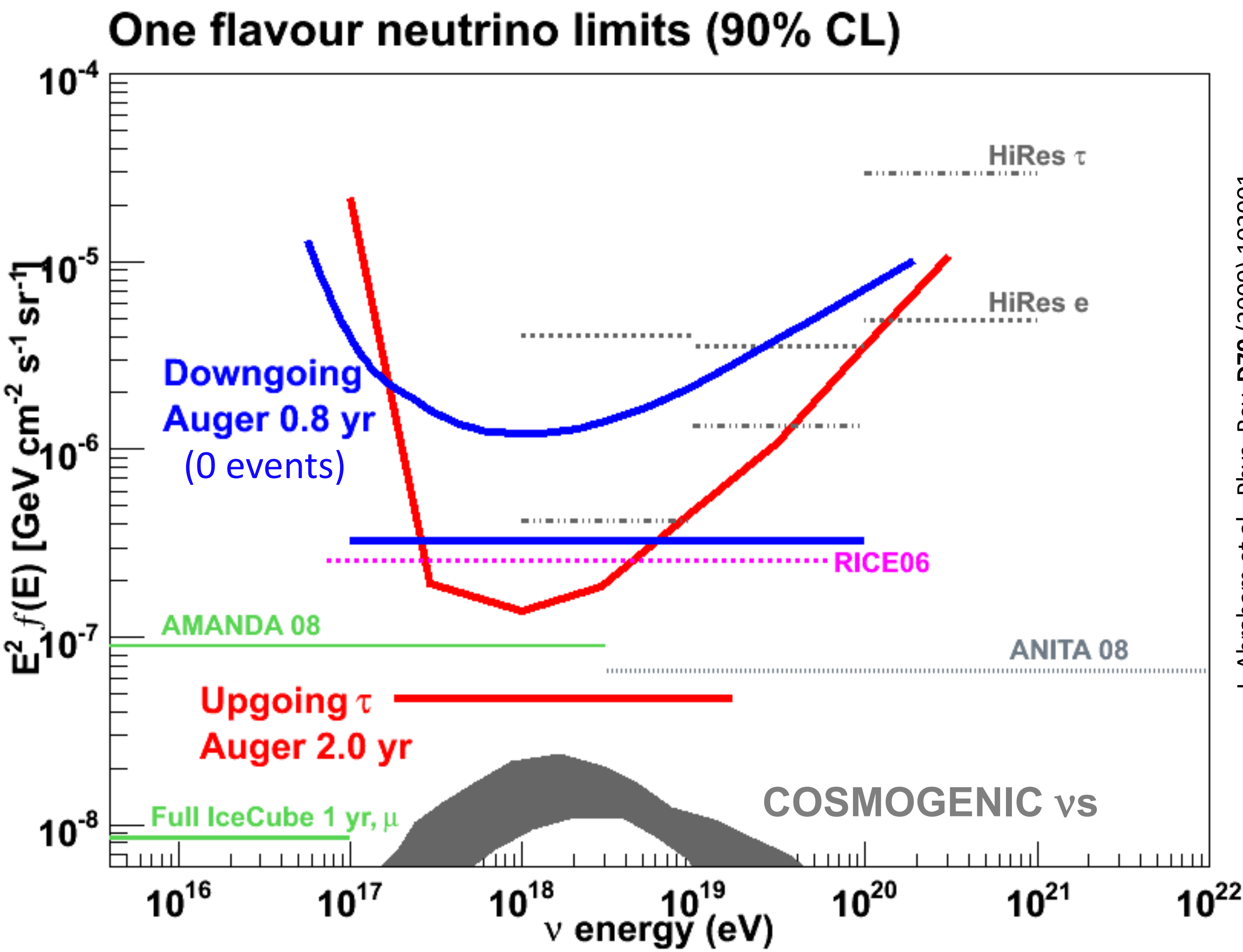
- All top-down production models strongly constrained
- GZK photons: 0.1% (95% C.L.) accessible after 20 years of Auger South SD? If Auger North built, can be reached in 10 years (arXiv:0906.2347)

SD Event Tagging: Neutrinos



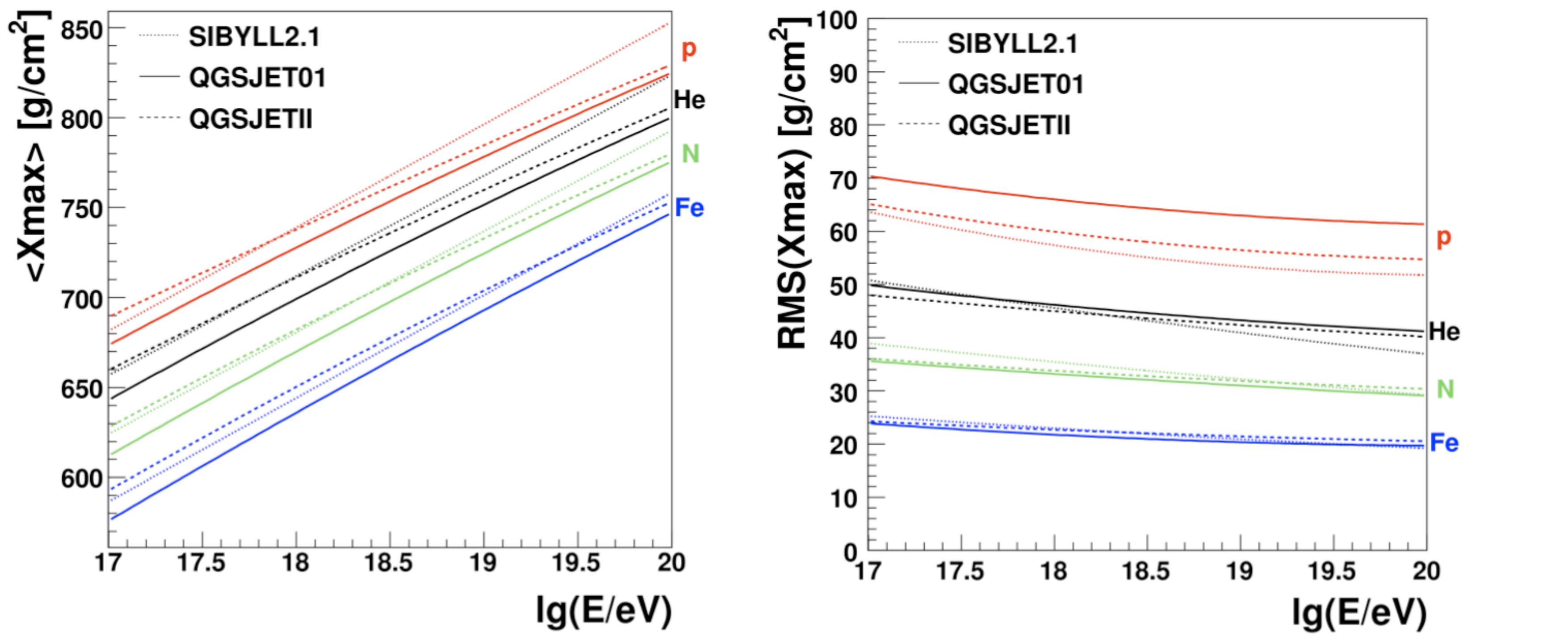
- Neutrino Showers:
  - Deep, very inclined (36,000 g cm^{-2}): elongated shower footprint
  - Start as broad signals, narrowing as EM particles range out
  - Upgoing events: earth-skimming ν_τ
  - Downgoing events: all flavors, CC + NC interactions
  - Details: J. Abraham *et al.*, Phys. Rev. **D79** (2009) 102001

Single-Flavor Neutrino Upper Limits



J. Abraham et al., Phys. Rev. **D79** (2009) 102001

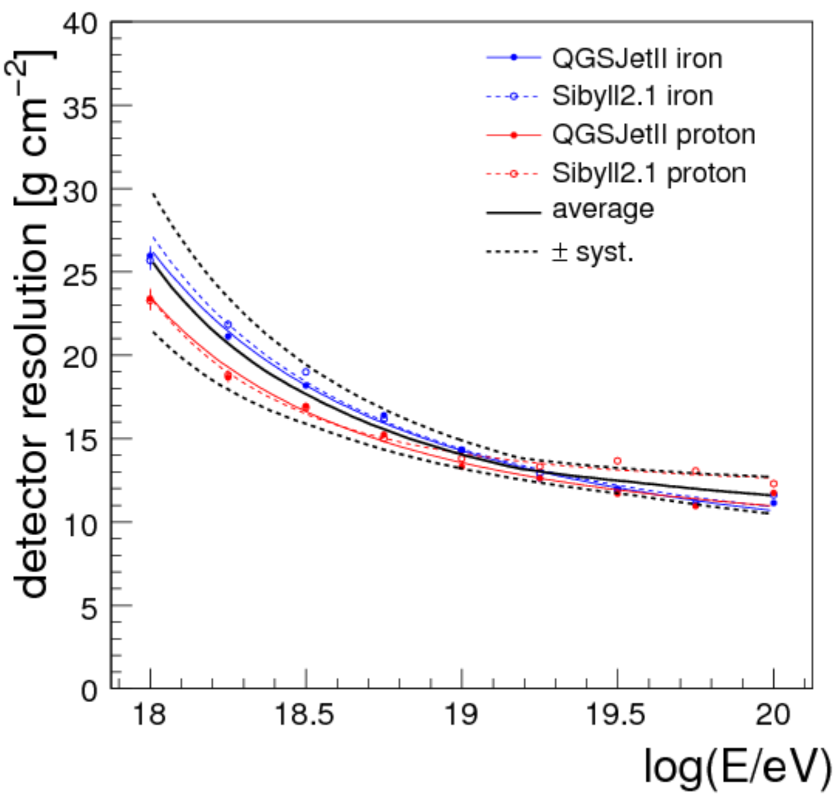
Composition of Charged Cosmic Rays

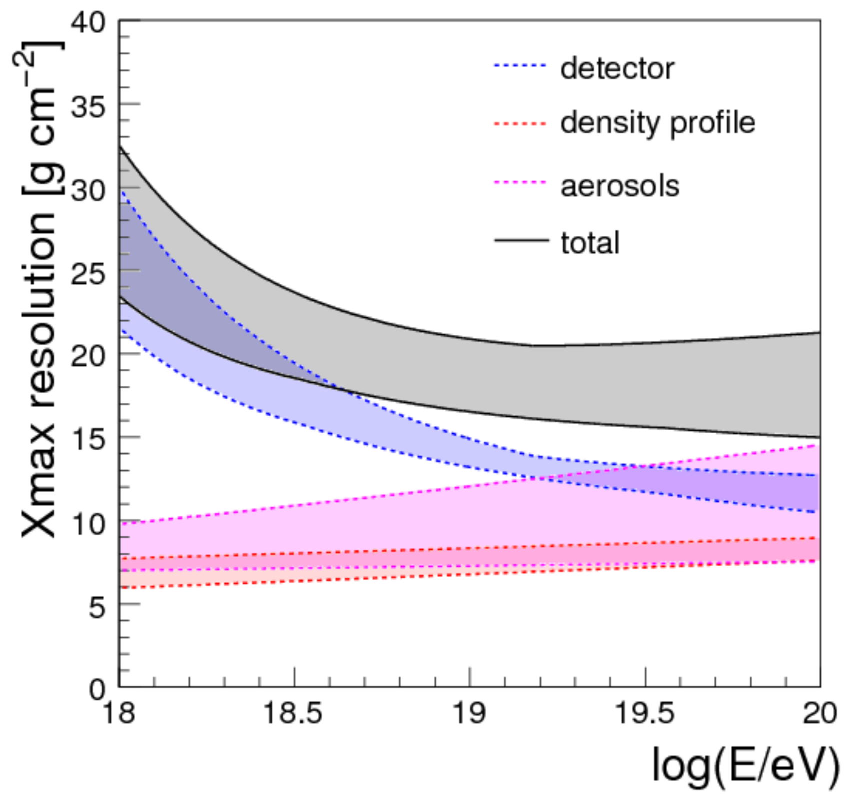


- Mass discrimination of charged cosmic rays using X_{max} from hybrid data
- Challenge: large shower-to-shower fluctuations; difficult to identify single events
- Solution: use statistics of the X_{max} distribution of many showers:
  - Protons: large energy/nucleon: deep $\langle X_{max} \rangle$, wide X_{max} distribution
  - Iron: small energy/nucleon: shallow $\langle X_{max} \rangle$, narrow X_{max} distribution

Complications: Detector Effects

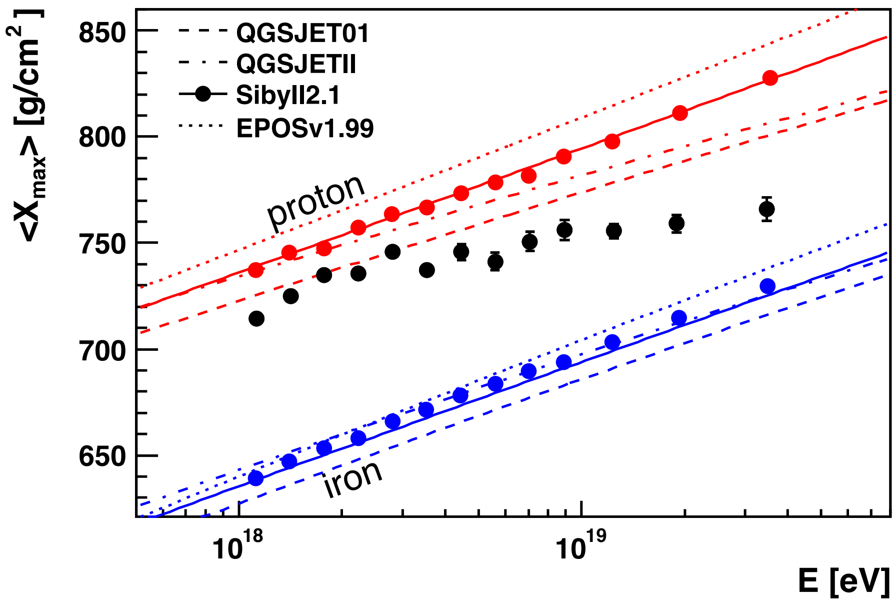
- Fiducial volume cuts are necessary (similar to photon analysis)

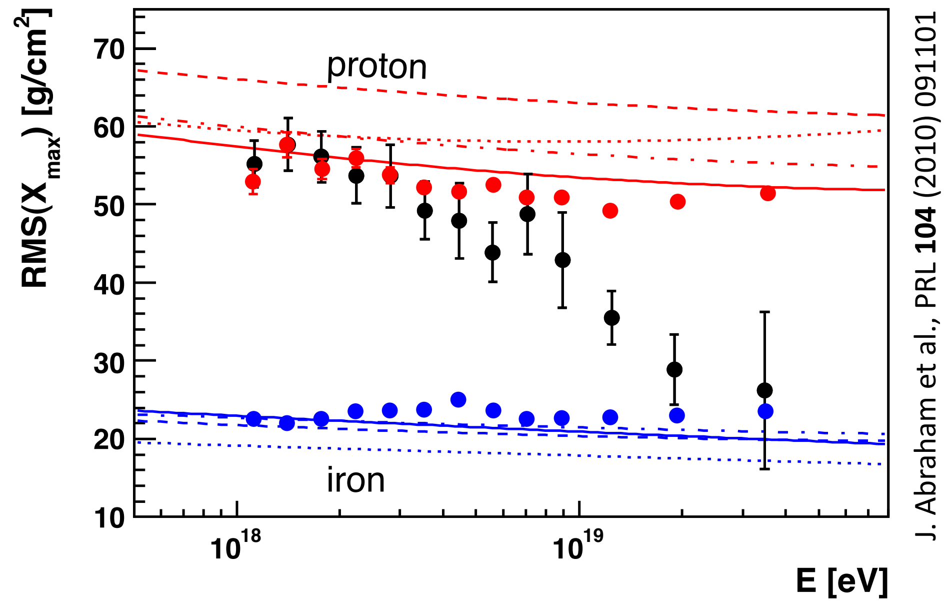




- X_{max} resolution changes as a function of energy and must be estimated with full Monte Carlo (verified w/ stereo data)

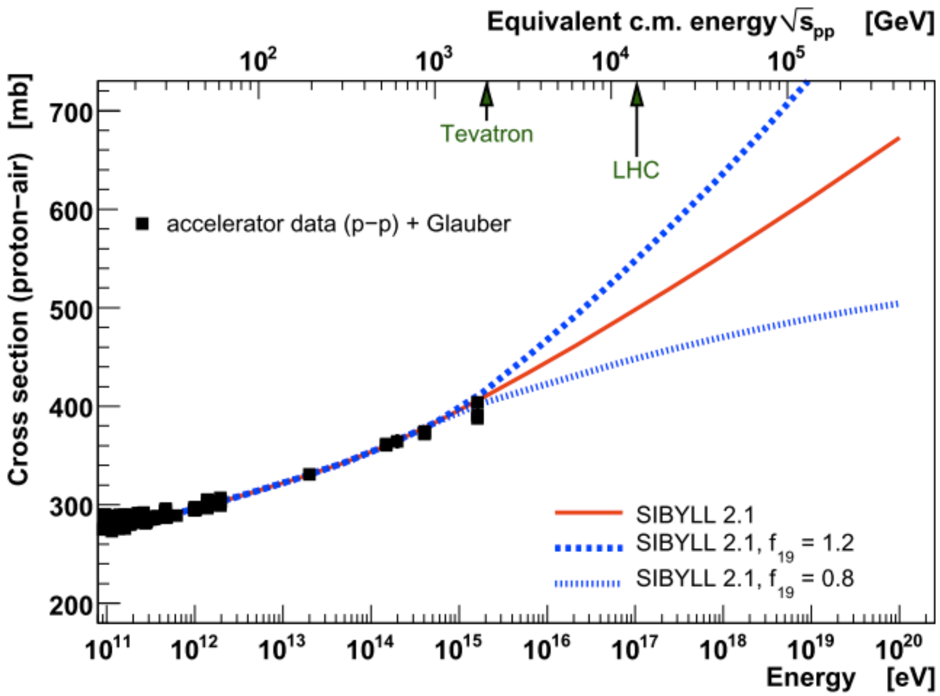
Charged Particle Composition with FD

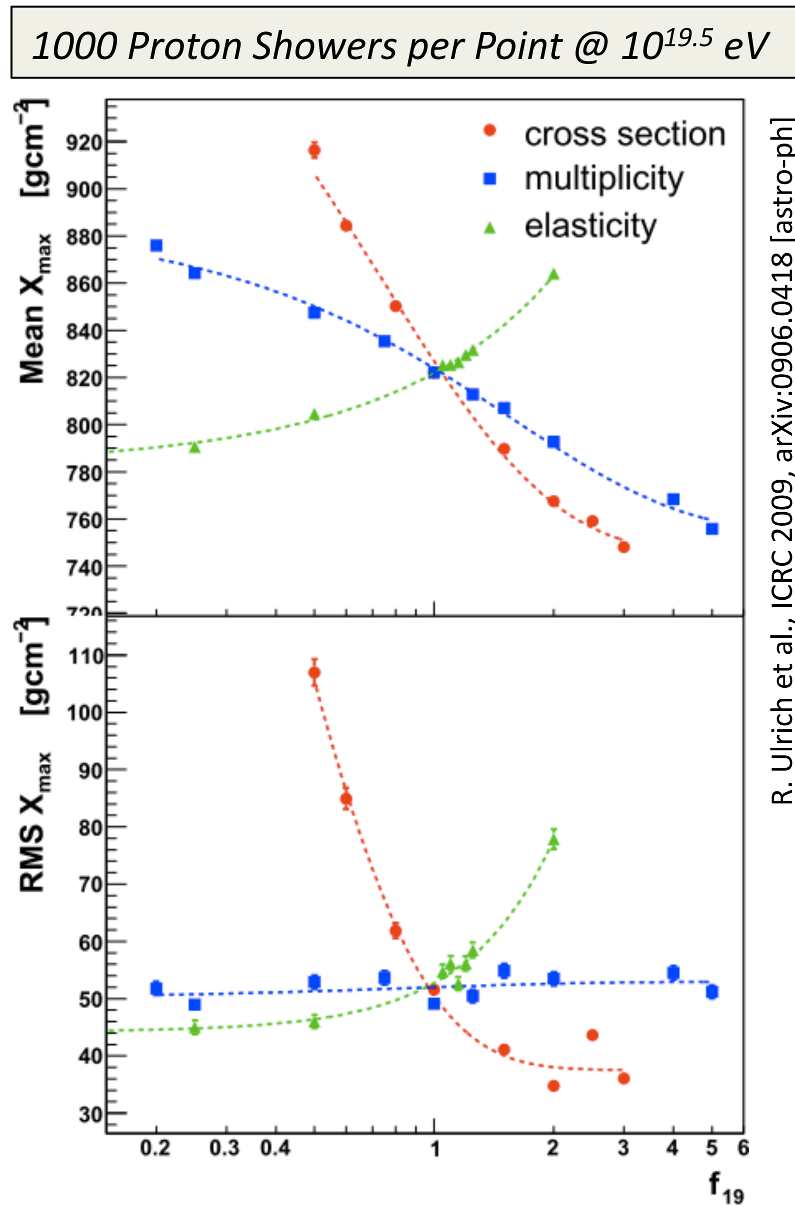




- Mean estimated with anti-bias cuts
- RMS has been resolution-corrected
- Both mean and RMS of X_{max} distribution seem to favor increasingly heavy composition

Are Cosmic Rays Actually Heavy?





- The X_{max} distribution can be altered by tuning the details of hadronic interactions
- Mean X_{max} is easy to change; width of the distribution is less sensitive

Coming Attractions

Low Energy Extensions; New Techniques

High-Elevation Auger Telescopes (HEAT)

- Increase elevation coverage to 60°
- Reduce hybrid threshold to 10^{17} eV

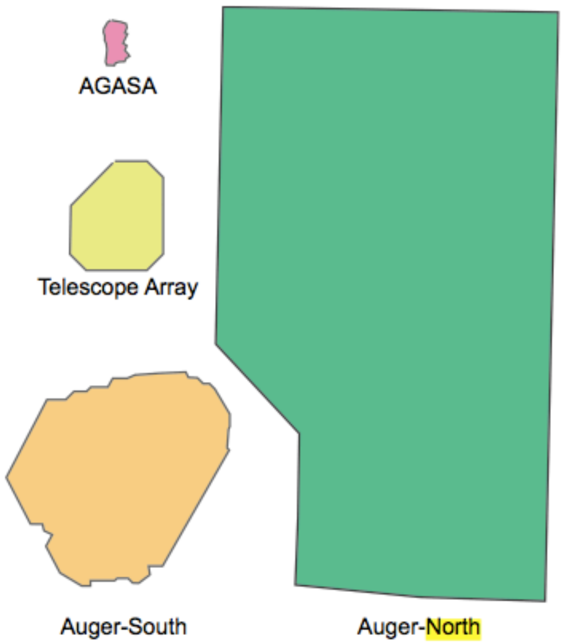
Auger Engineering Radio Array (AERA)

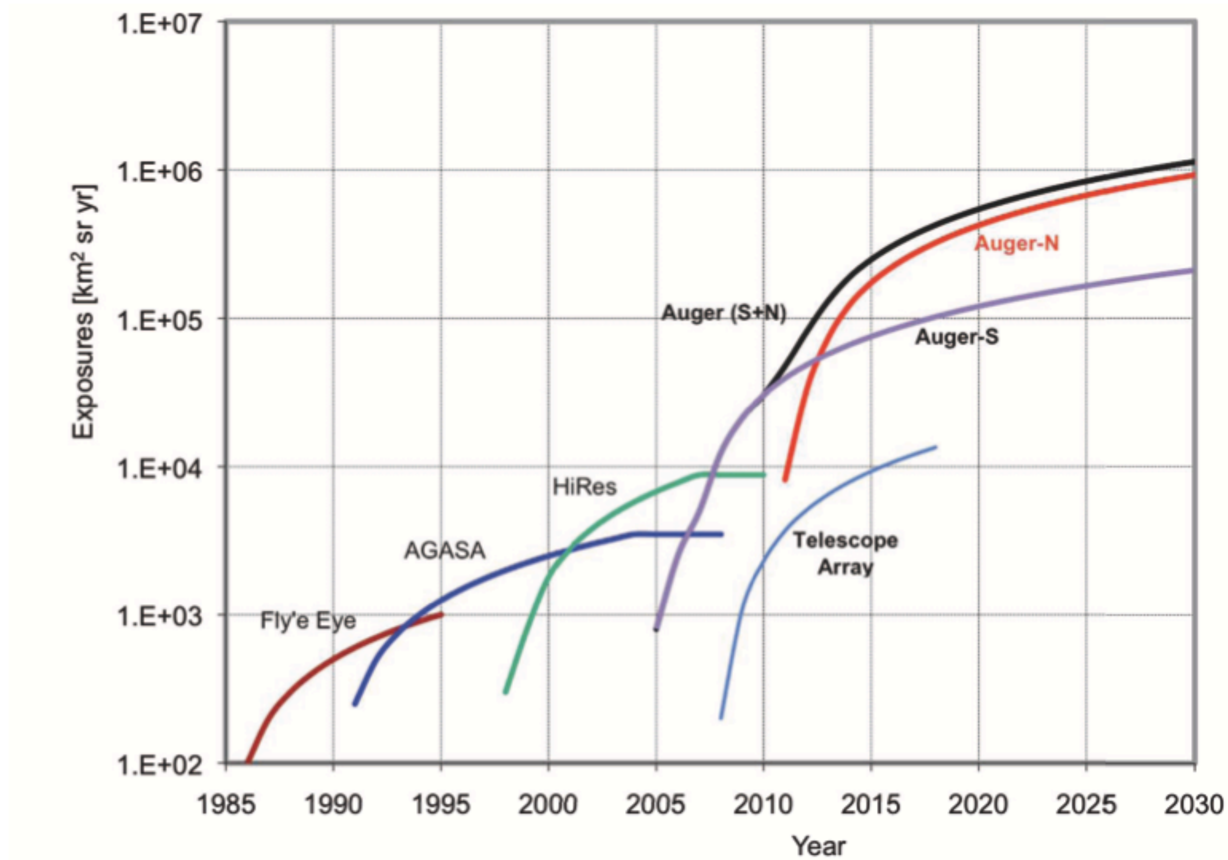
- Air shower development with 100% uptime
- Antennae deployed to cover 24 km^2

Auger Muons and Infill for the Ground Array (AMIGA)

- 30 square-meter muon counters
- Buried 3 m underground
- Lower SD energy threshold to 10^{17} eV
- First direct muon measurements in Auger

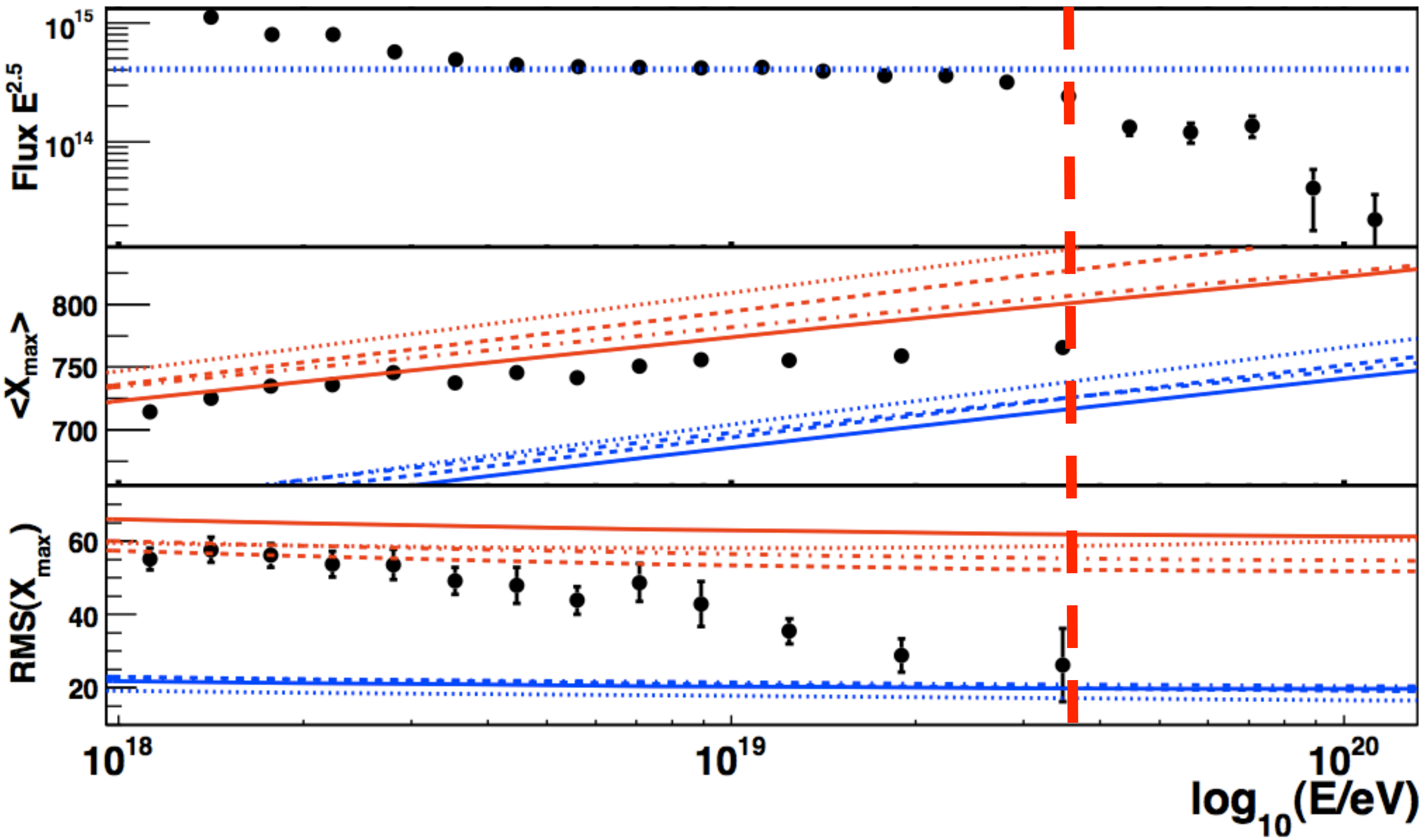
Focus on the Highest Energies





- Events over 60 EeV with Auger South: < 30 / yr
- Events with Auger South + North: ~200 / yr

High Energy is Important!



From R. Ulrich, APS 2010, Washington D.C.

Conclusions

- The Pierre Auger Observatory southern site is complete and recording data with an annual exposure of 7000 km^2 sr yr

- Results:
  - Changes in the spectral index at $10^{18.6}$ eV and $10^{19.6}$ eV
  - Apparent trend toward heavy nuclear composition; could be due to poor understanding of hadronic interactions
  - Upper limits set on neutrino and photon flux, ruling out top-down models of cosmic ray production
  - Arrival direction anisotropy investigated with large statistics, weakening previous claim of significant clustering

- Future work:
  - Extension of measurements to 10^{17} eV at southern site
  - Badly needed jump in high-energy statistics with northern site