THE PIERRE AUGER OBSERVATORY:
RECENT RESULTS AND FUTURE PLANS

Inés Valiño (IGFAE)
for the Pierre Auger Collaboration

III Jornadas CPAN

Barcelona, 2 Nov 2011

Primary objective of the Pierre Auger Observatory

"Measure the properties of cosmic rays above 10^{18} eV

with unprecedented statistics and quality"

Energy

- Cutoff at the end of the spectrum (GZK effect)? Second knee? Ankle?

Arrival direction

- Where the UHECRs come from? Is the UHECRs flux isotropic?.....

Composition

- What are the UHECRs? Are they mainly proton? Iron?...

Other important goals....

Search for UHE neutrinos and photons

- Observatory has the capability to detect showers induced by ν and γ

Particle physics at 10^{19} eV

- Check for hadronic interaction models, measuring $\sigma_{p\text{-}air}$ in air showers

Other physics

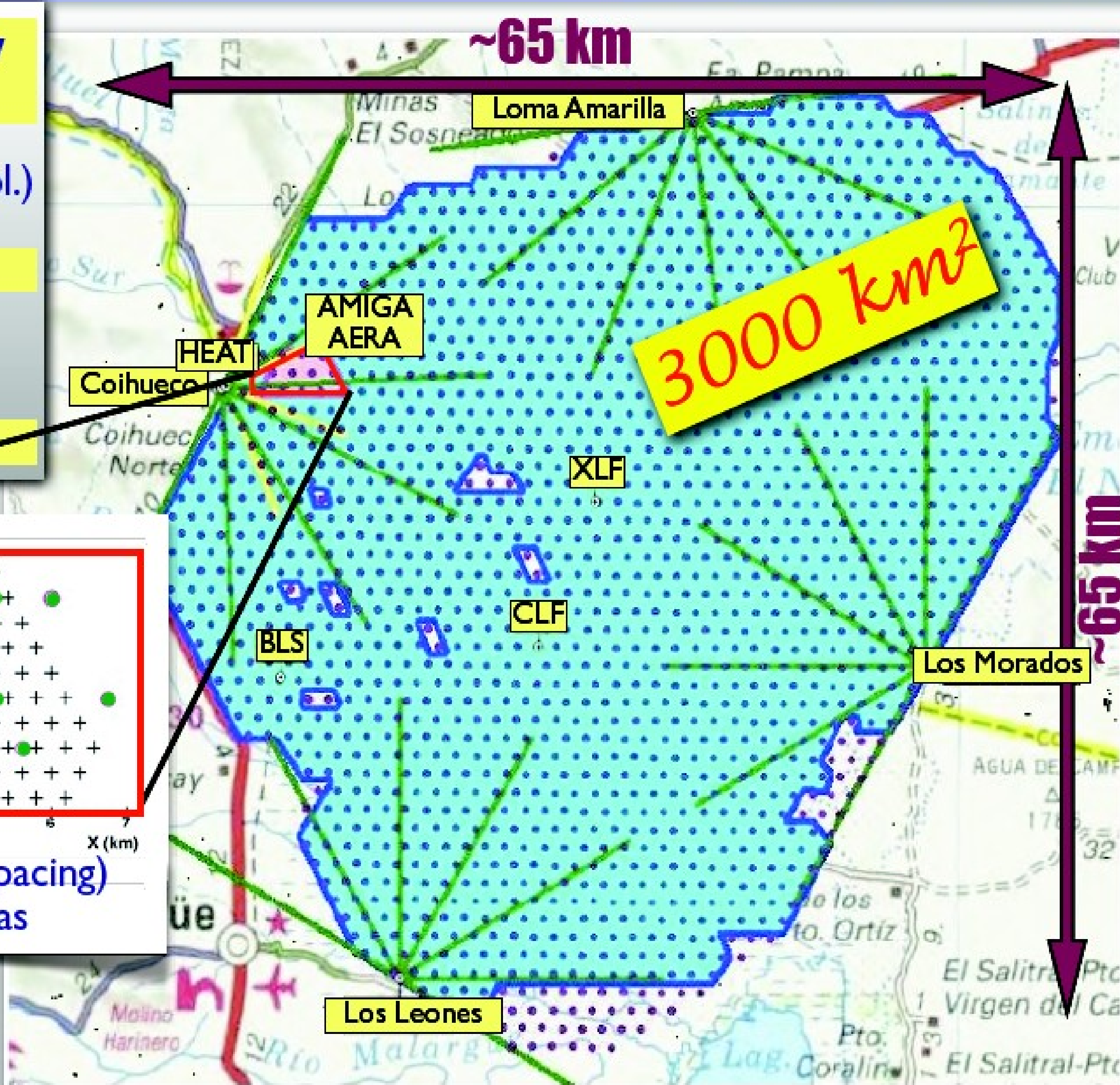
- Solar, enviroment, atmospheric physics...

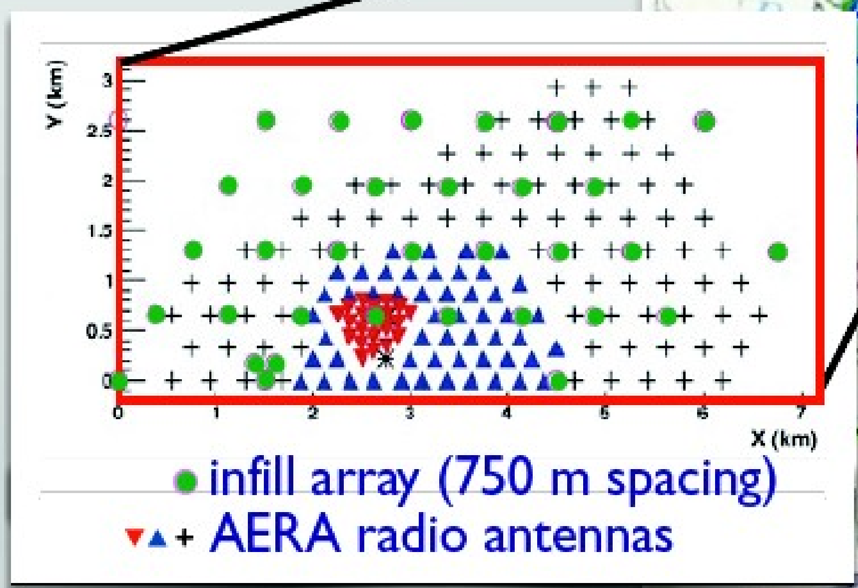
Pierre Auger Observatory in Argentina

1660 Water-Cherenkov tanks
1.5 km standard grid
0.75 km infill-grid (53/61 depl.)

27 telescopes
in 4+1 buildings at the periphery

3000 km² area

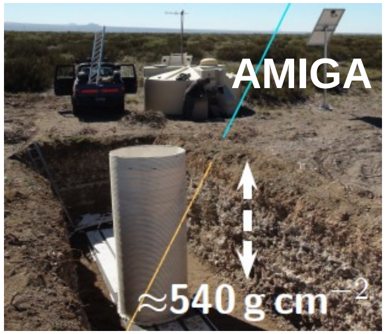




Near future....

Auger extension to lower energies:

- AMIGA: denser array (infill) and buried muon counters
- HEAT: 3 additional FD telescopes looking "higher" in the sky



Auger extension with new detection techniques:

- AERA: radio antennas (MHz) in the infill region
- R&D Ghz antennas: AMBER, MIDAS, EASIER, FDWave

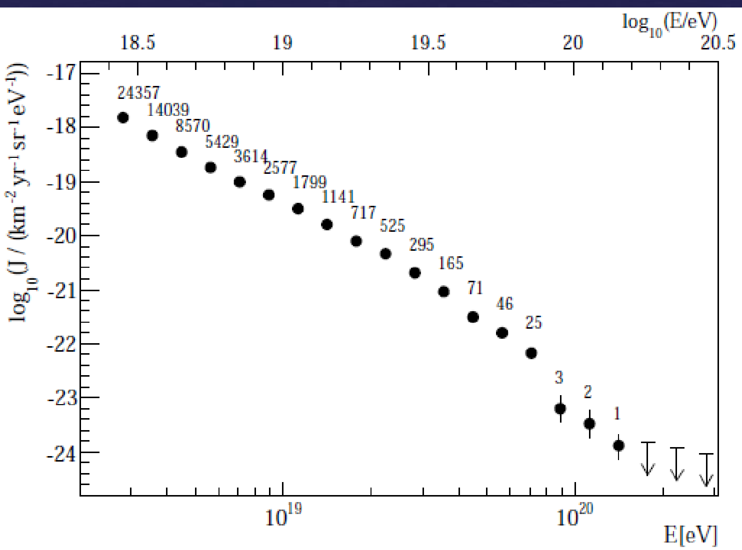
Pierre Auger enhances: arxiv:1107.4807

ASTROPARTICLE PHYSICS RESULTS:

energy spectrum, anisotropies, composition

Arxiv:1107.4809; 1107.4805; 1107.4804

Energy Spectrum ($\theta<60^0$)



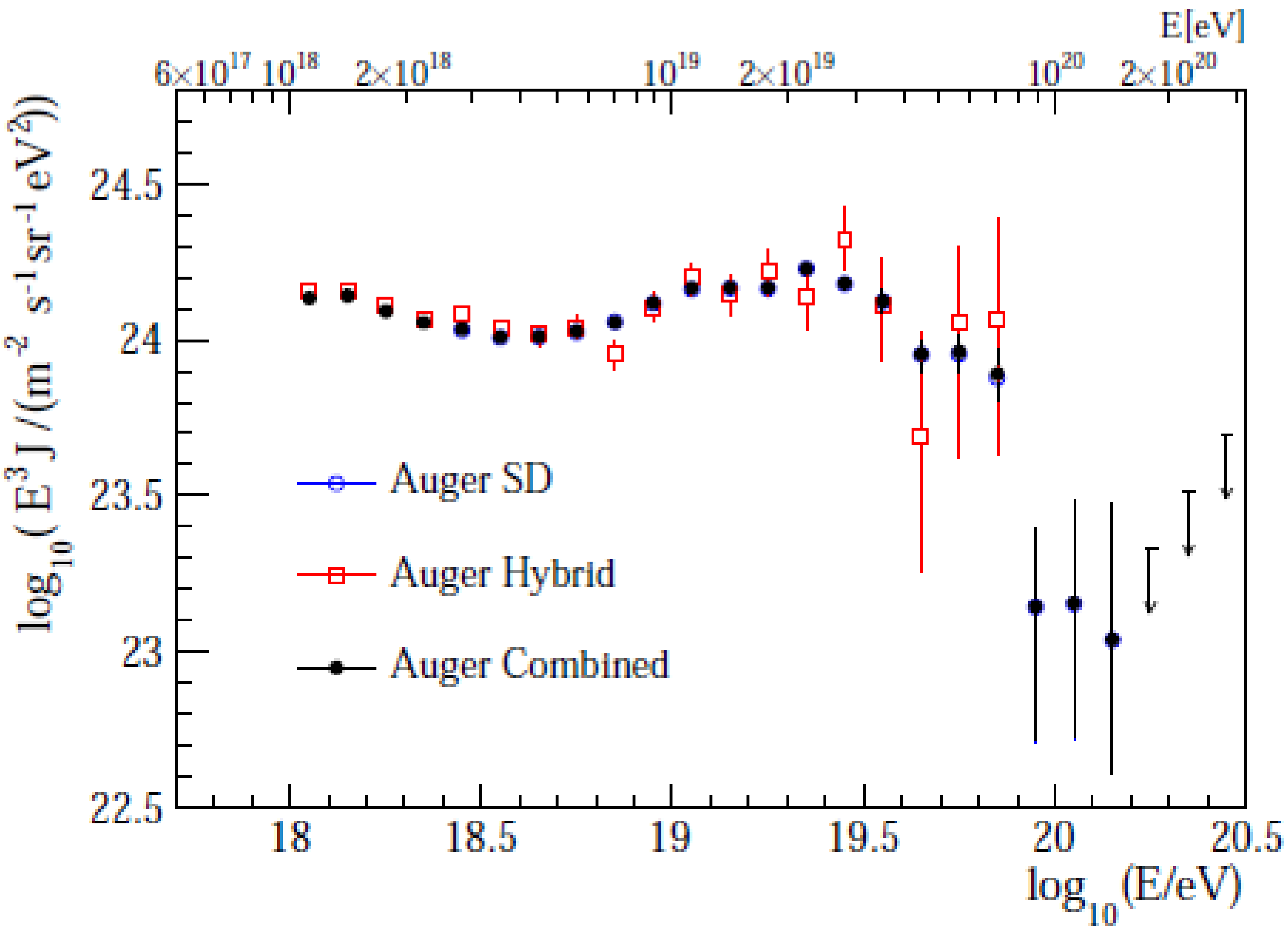
Spectrum with Surface Detector

- Calibrated with FD energy
- No corrected for energy resolution: ~16% (~12%) at 1 (10) EeV
- Systematic uncertainty in exposure ~ 3%

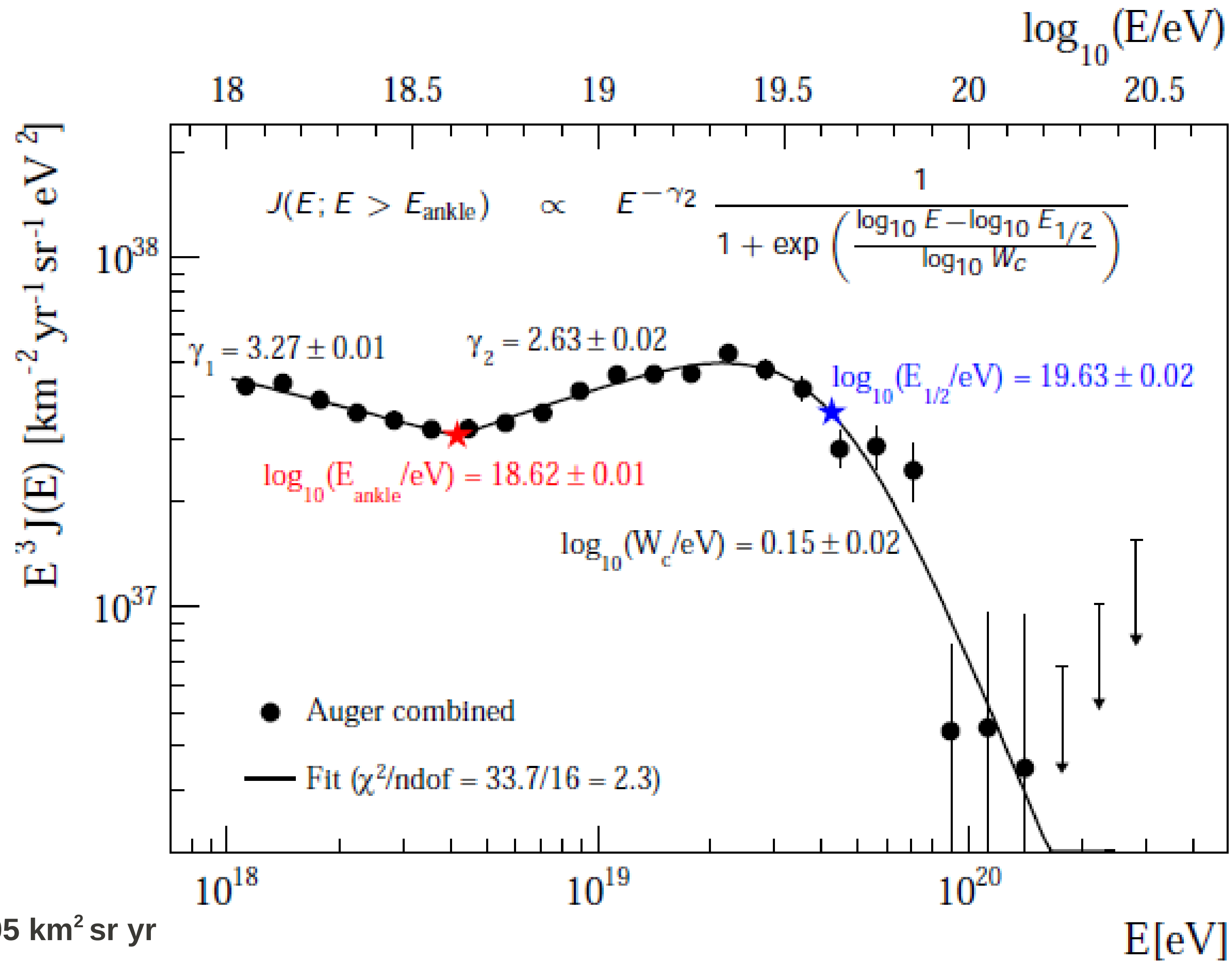
Combined energy spectrum:

SD and Hybrid (SD+FD)

- Good agreement SD and Hybrid
- Common systematic 22% uncertainty on energy-scale



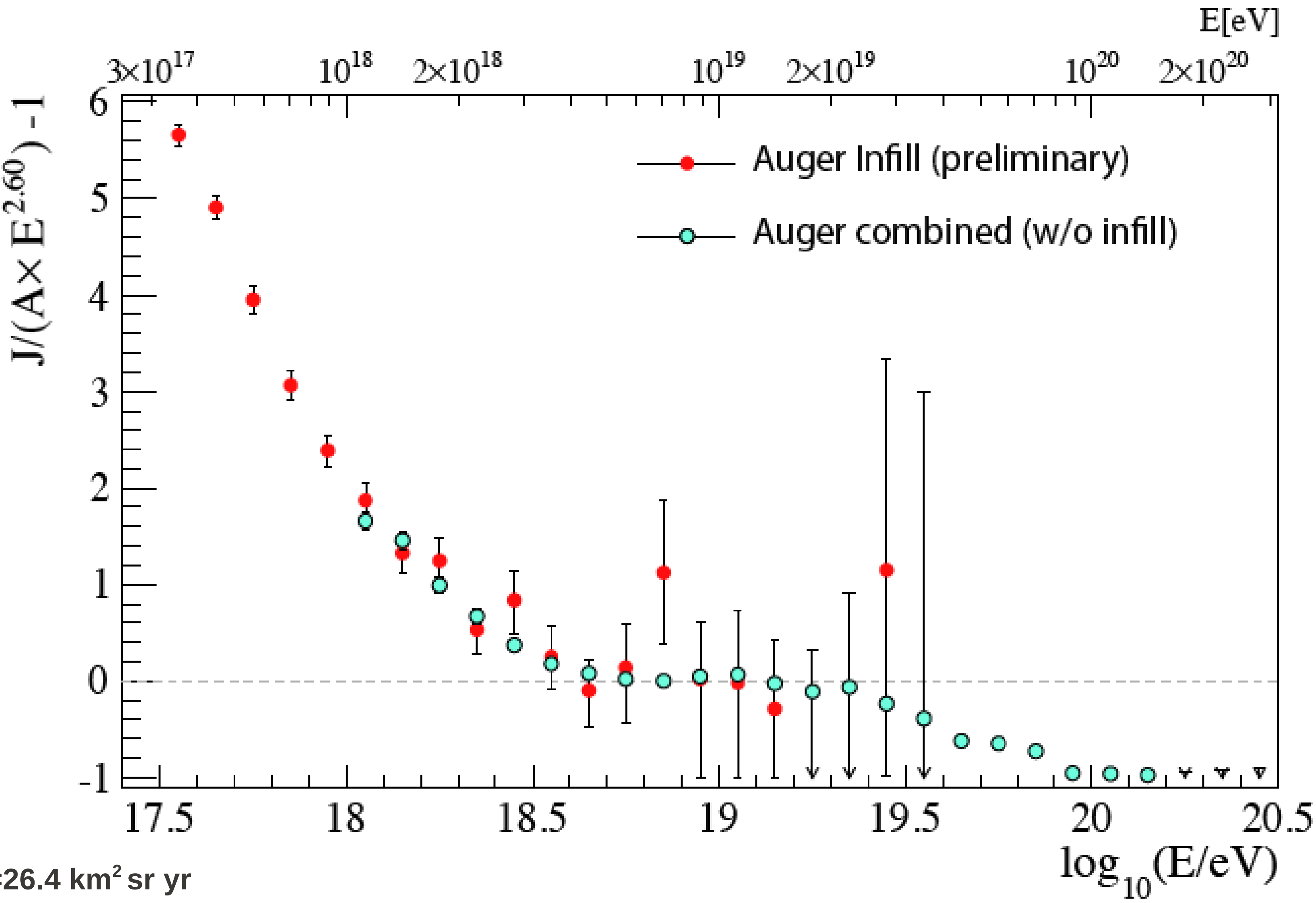
Fitting the combined Energy Spectrum



Exposure = 20905 km^2 sr yr

Precise measurement of spectral features

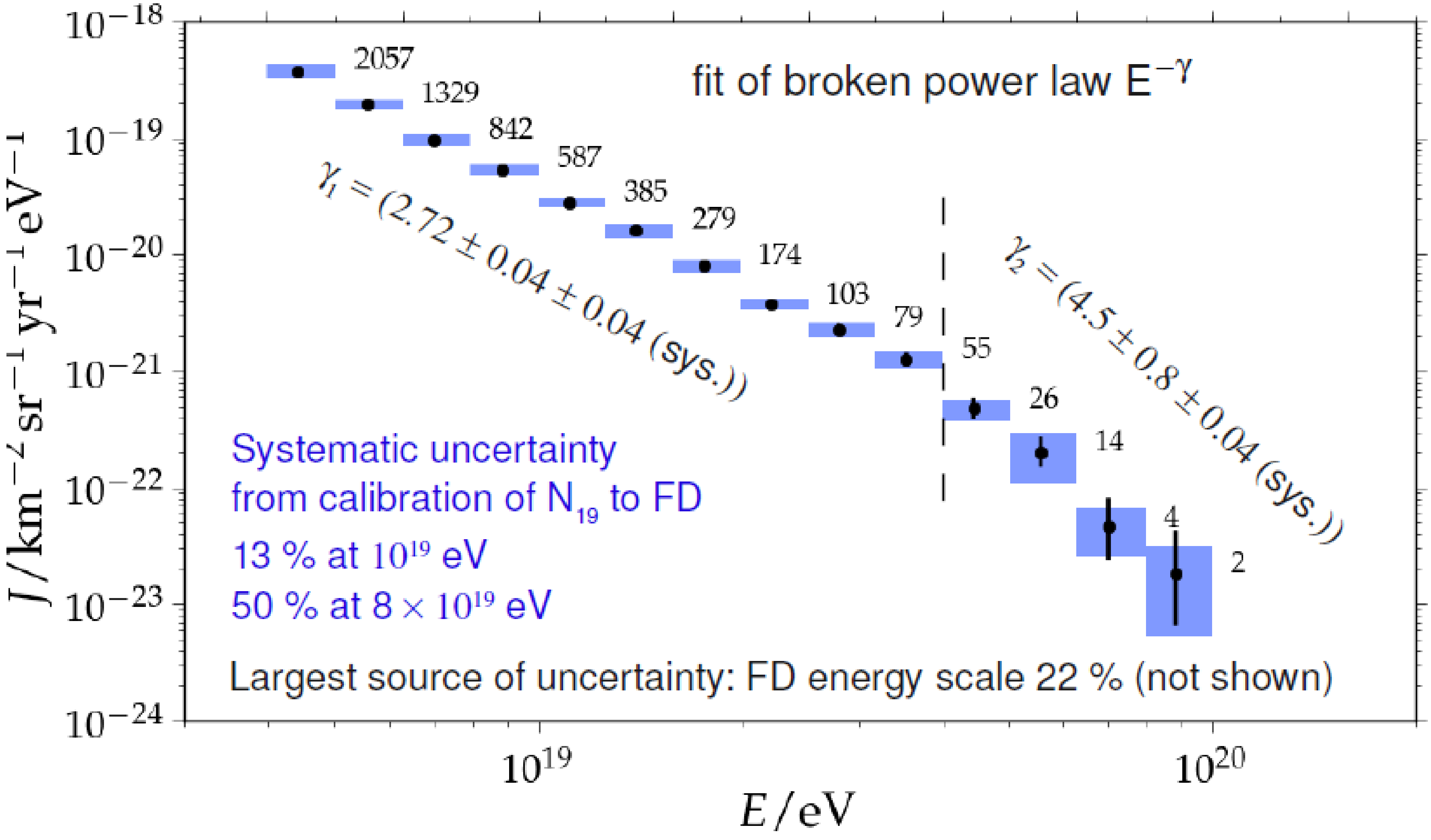
Preliminary Infill Spectrum



Exposure =26.4 km^2 sr yr

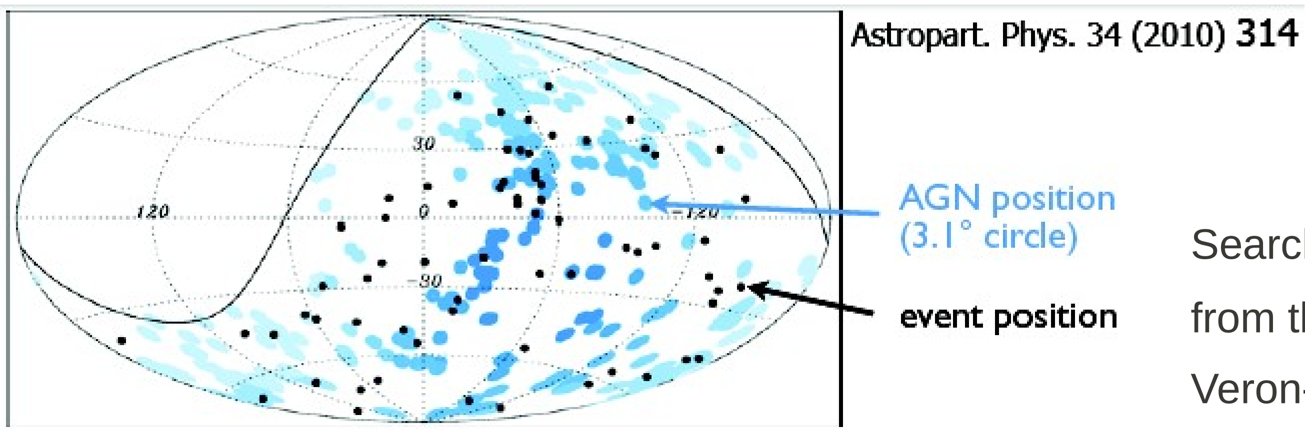
Infill is fully efficient at 3x10^{17} eV and $\theta < 55^0$

Inclined SD Spectrum ($\theta > 60^0$)

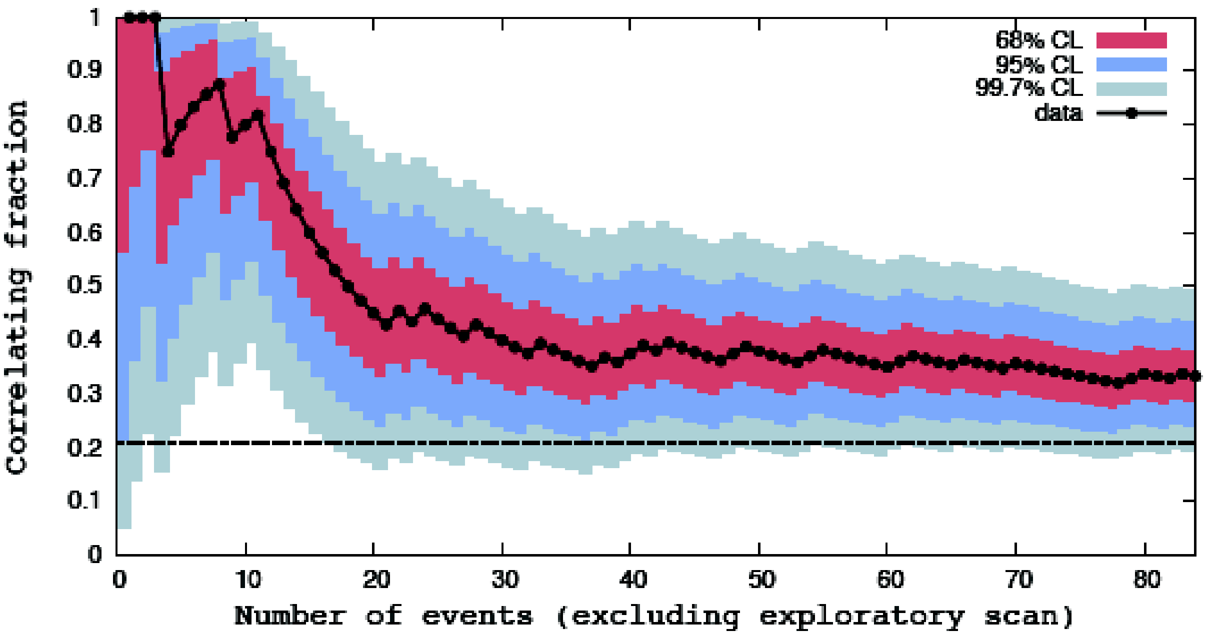


Good agreement with vertical SD spectrum

Update on correlation with VCV-AGN



Search for correlation with the AGNs from the 12th edition of the Veron and Veron-Cetty catalogue



Prescription:

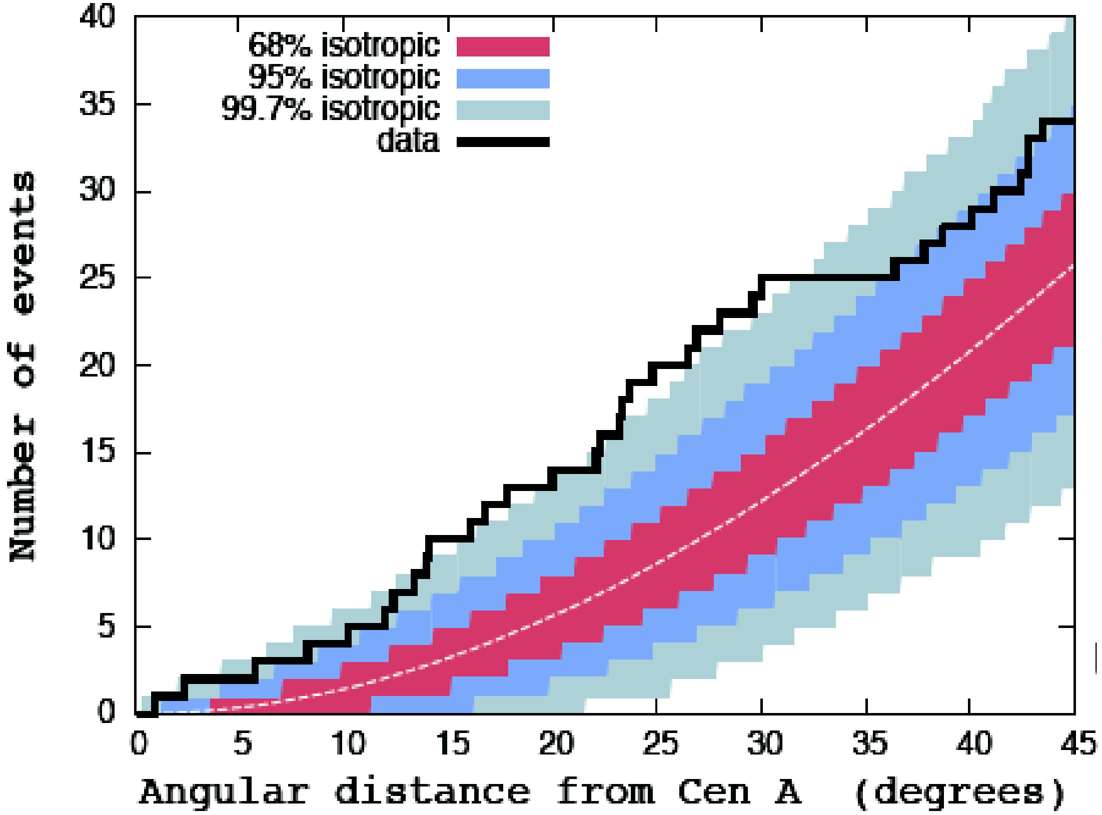
D_{max} = 75 Mpc, E_{min} = 57 EeV, $\Theta = 3.1^0$

Update up to June 2011:

28/84 correlate → (33±5)% correlation

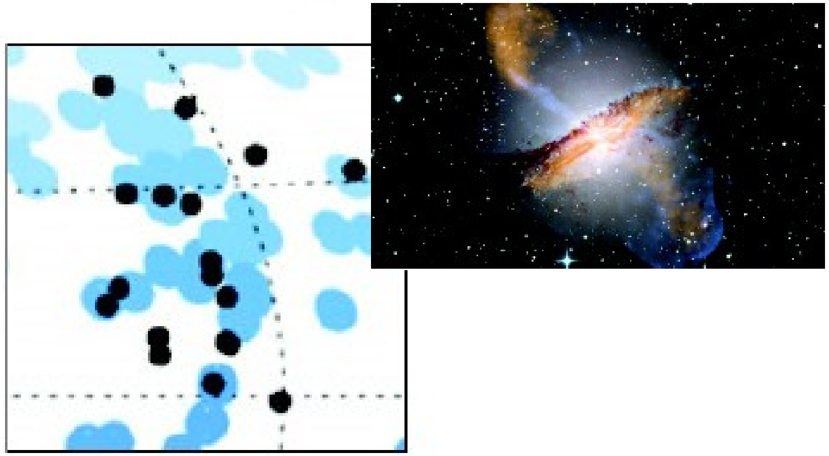
vs 21% expected from isotropy (P=006)

Update on correlation with CenA



High Energy Centaurus A (NGC 5128) excess

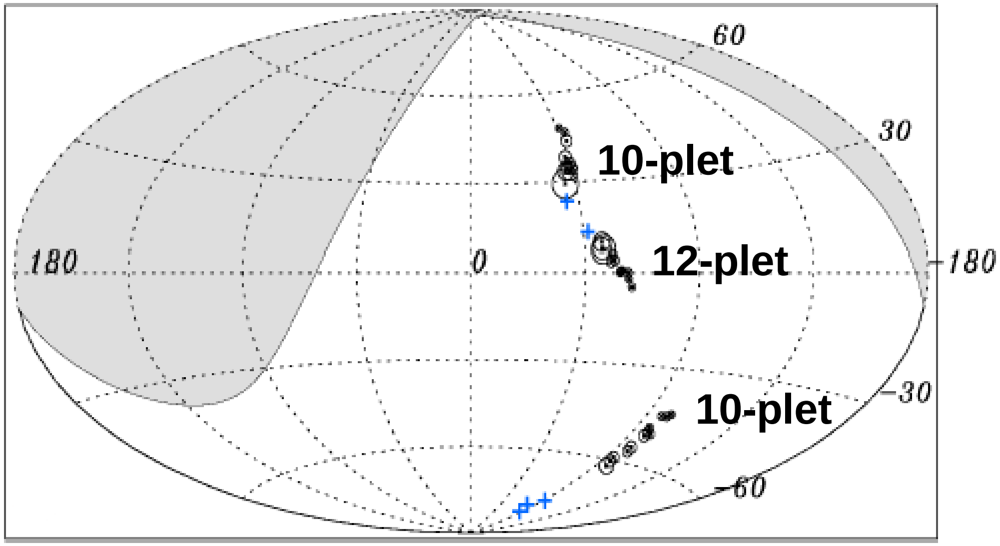
update up to June 2011



- Most significant excess in a 24^{0} window
- 19 observed events / 7.6 expected
- KS test yields 4% isotropic probability but significance for the excess region can only be established with independent data

Some further searches

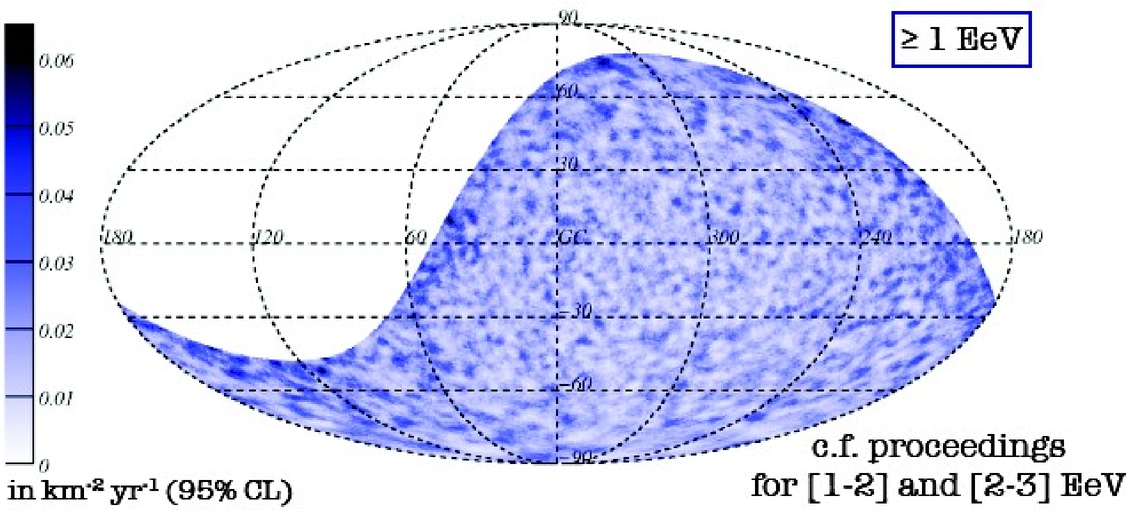
Multiplete search



- Search for energy-position correlated multiplets for E > 20 EeV
- Chance probability from an isotropic distribution to obtain at least 12-plet is 6%
- Density of sources ~ 10^{-4}

Neutron point sources search

- Search for EeV neutrons possible as the mean decay length is λ_n = (9.2 x E) kpc
- Production of neutrons from interactions of CR with hadronic/radiations background
- Neutron emission rate > γ rate with hadronic origin.



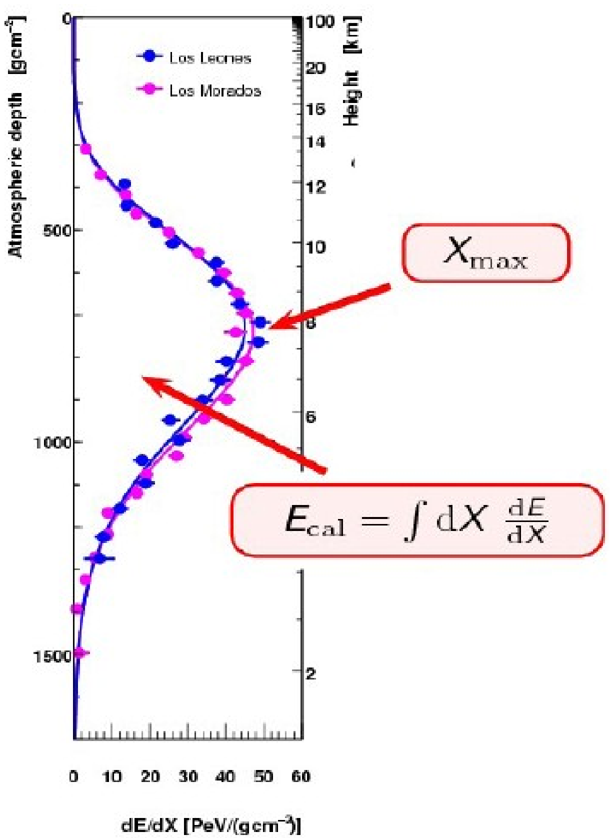
No excess found for E>1EeV in blind search nor search for γ-ray emitters (HESS, Fermi-LAT sources)

Mass composition measurements

Many different observables are sensitive to the primary mass composition:

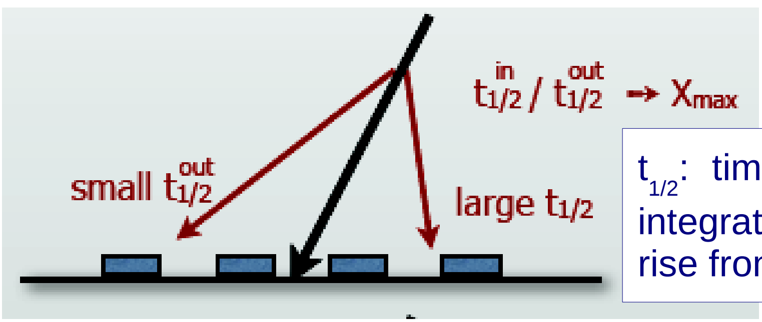
From FD detector:

- Full longitudinal profile
- Depth of the shower maximum Xmax
- Fluctuations on Xmax

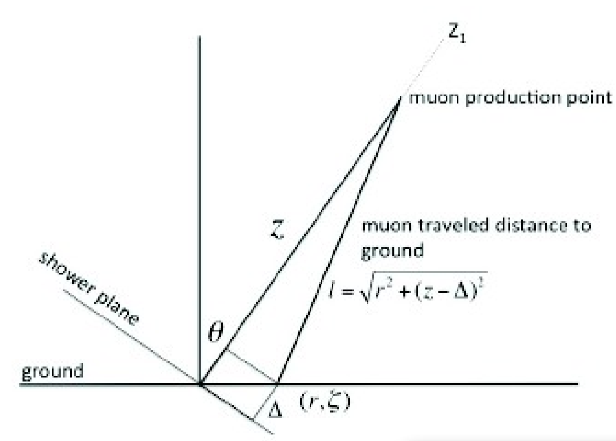


From SD detector:

- Azimuthal asymmetry of the signal risetime
- Depth profile of muon production points



$t_{1/2}$: time taken for the integrated tank signal to rise from 10% to 50%.

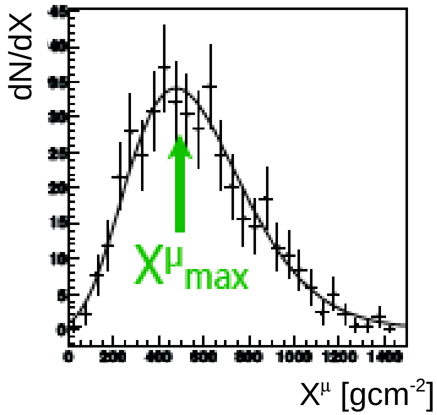


Muon production distance z:

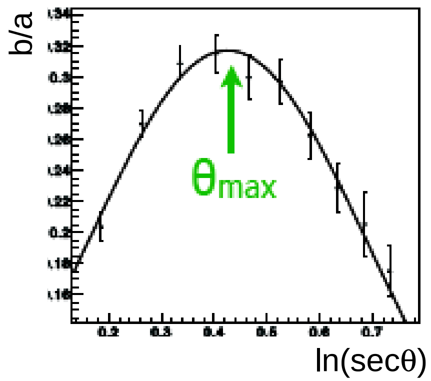
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

Muon production depth Xμ:

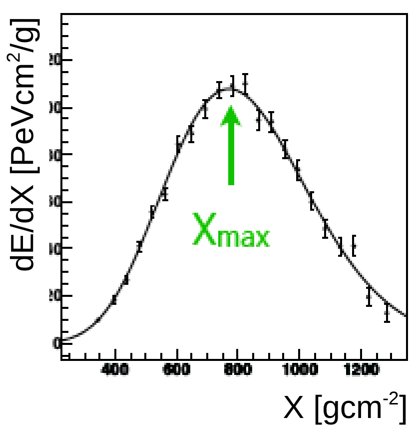
$$x^{\mu} = \int_z^{\infty} \rho(z')dz'$$



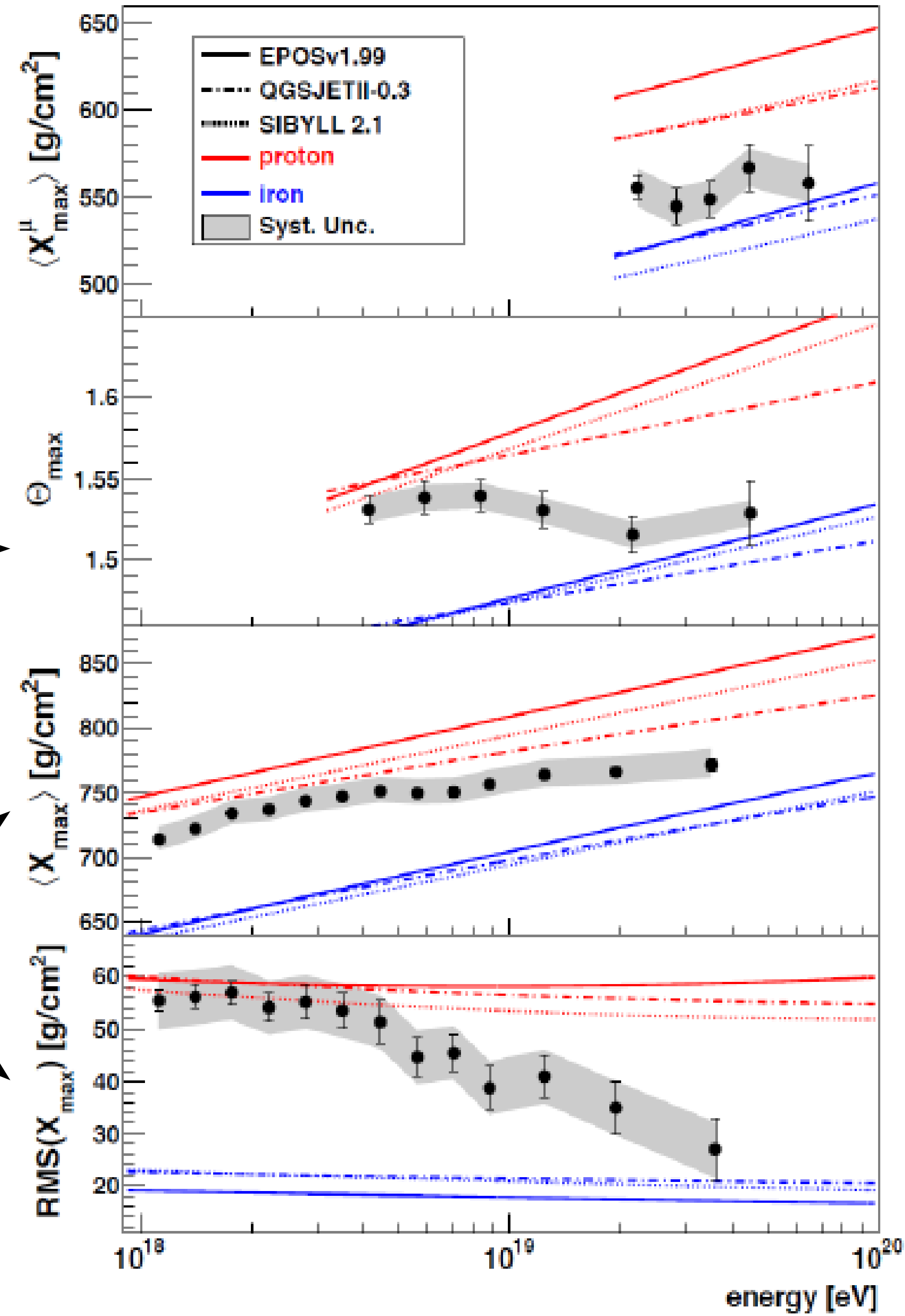
Muon production depth from timing differences



Shower depth from asymmetries of risetime



X_{max} observation



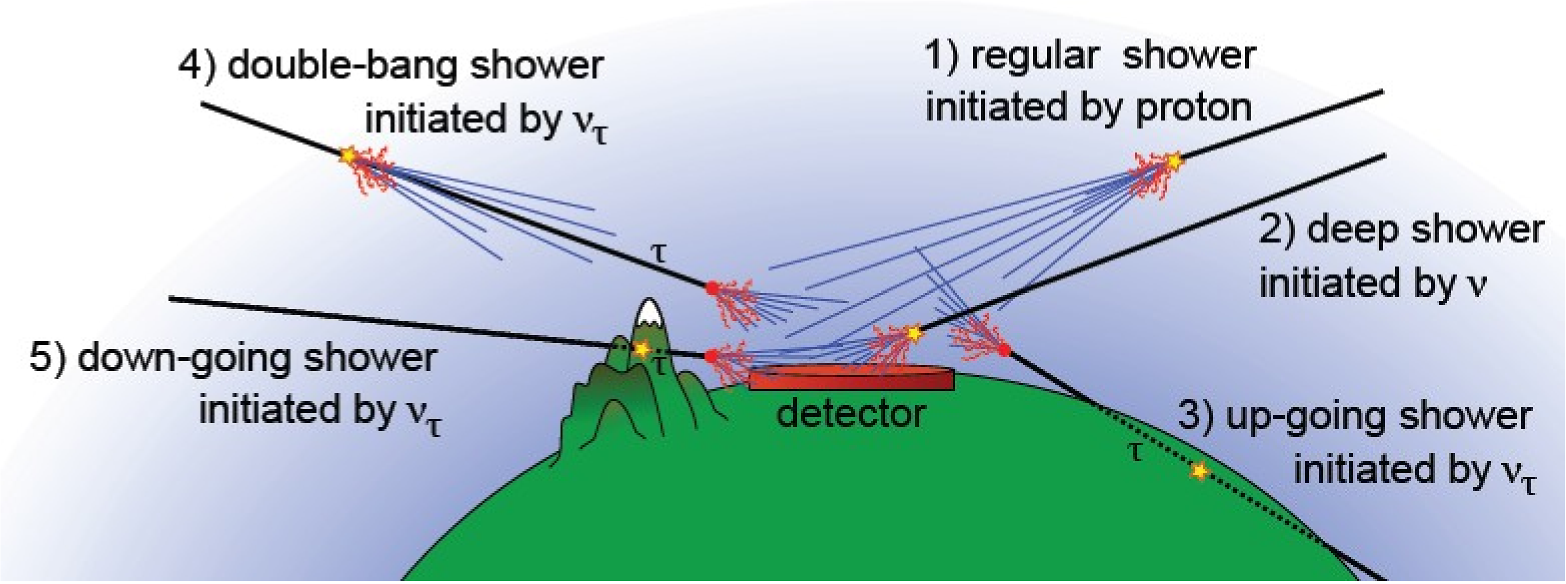
Assuming hadronic models are correct:

mean mass rises as the energy increases.

Neutrinos

Searching for:

- Upgoing Earth-skimming showers
- Downgoing neutrinos (all the flavours)

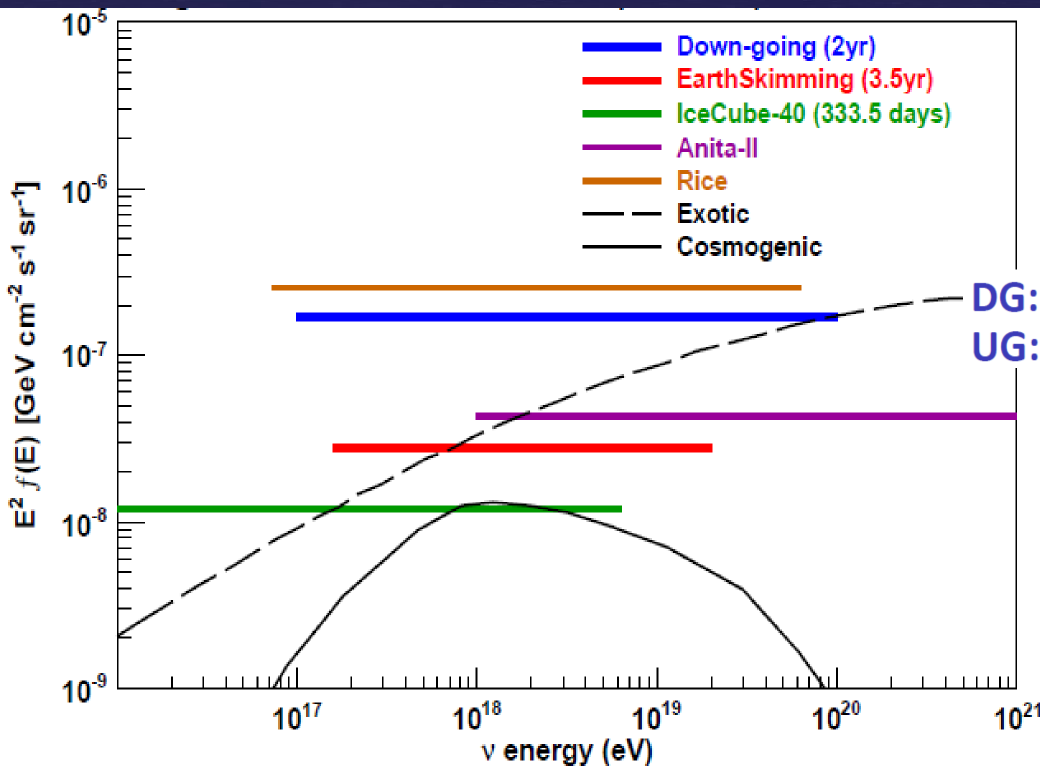


Identification criteria:

- Inclined showers: elongated footprint and propagation speed of the shower front ~ c
- Deep (young) showers: broad time distributions in **surface detectors**

Blind search: 0 candidates

Results from search for neutrinos

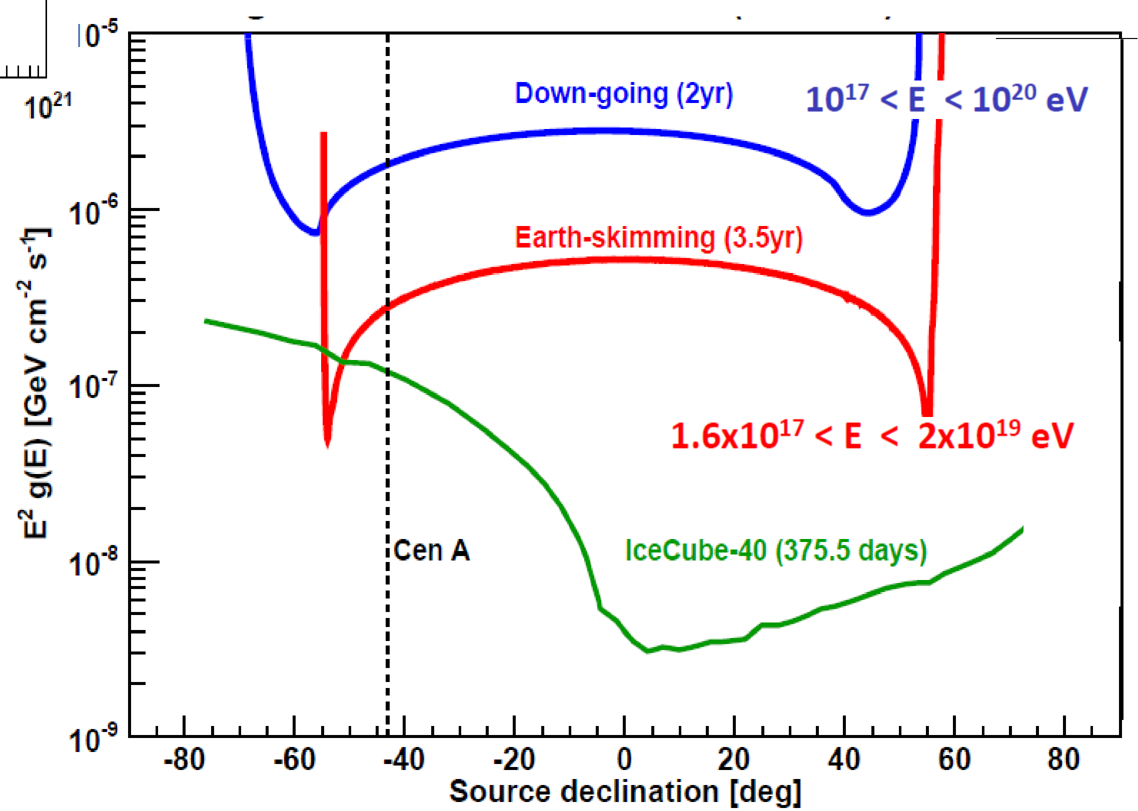


Diffuse neutrino limits
(90% CL single flavour limits)

DG: $k < 1.7 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} in $10^{17} < E < 10^{20}$ eV
UG: $k < 2.8 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} in $1.6 \times 10^{17} < E < 2 \times 10^{19}$ eV

Point source limits
(90% CL single flavour limits)

SD sensitive to potencial sources of UHE neutrinos in a broad range of declinations



Photon search

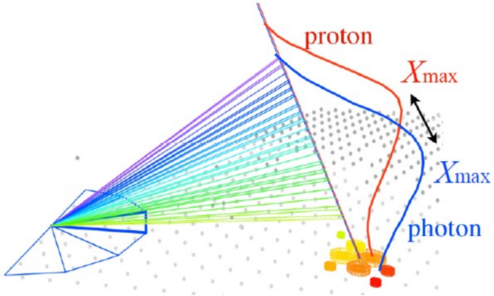
Identification criteria

Search in SD data

- Small reconstructed curvature radius
- Large risetime
- Small number of muons at ground

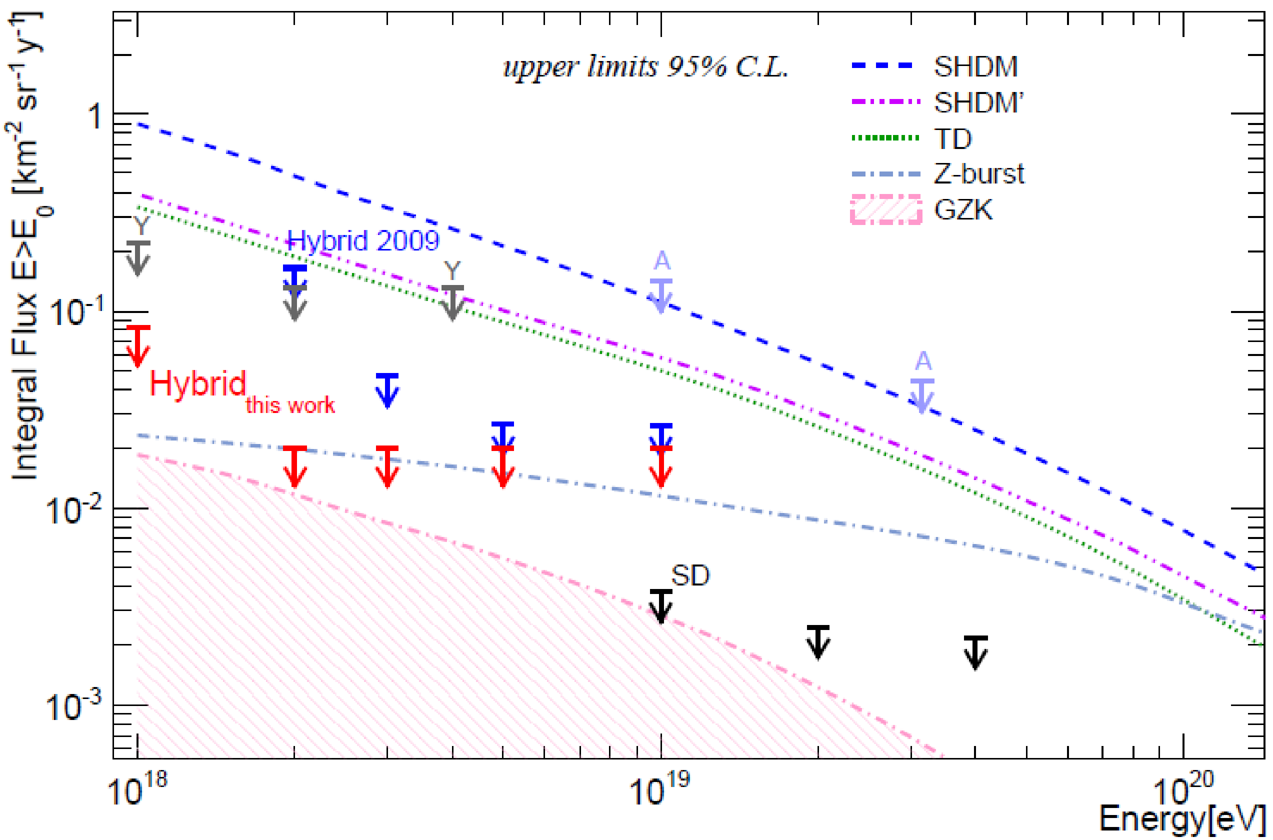
Search in Hybrid data

- Deep Xmax in FD
- Small signal at a given distance
- Few triggered detectors in SD



Photon upper limit

- Exotic models disfavoured down to 1 EeV.
- GZK in reach



PARTICLE PHYSICS RESULTS:

muon content in air showers, p-air cross section

Arxiv: 1107.4804

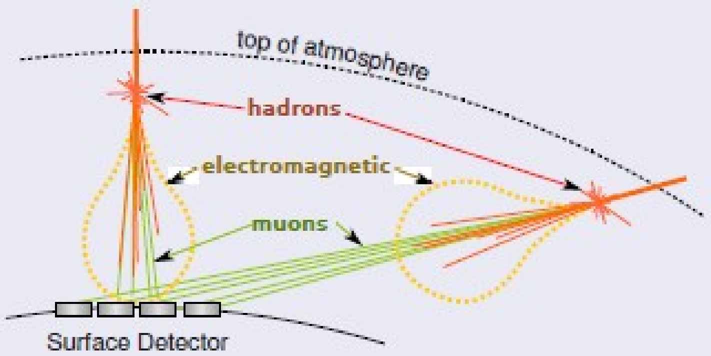
Muon production in EAS

The missing muon problem: none of the existing models can consistently describe the data on muon number: data show more muon production than simulations

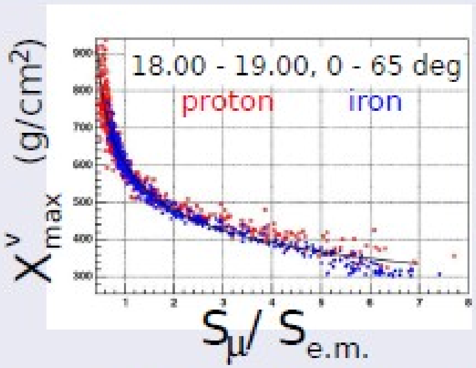
Techniques of muon number measurements

Time Structure of Tank Signals

Very Inclined Events



Electromagnetic Universality

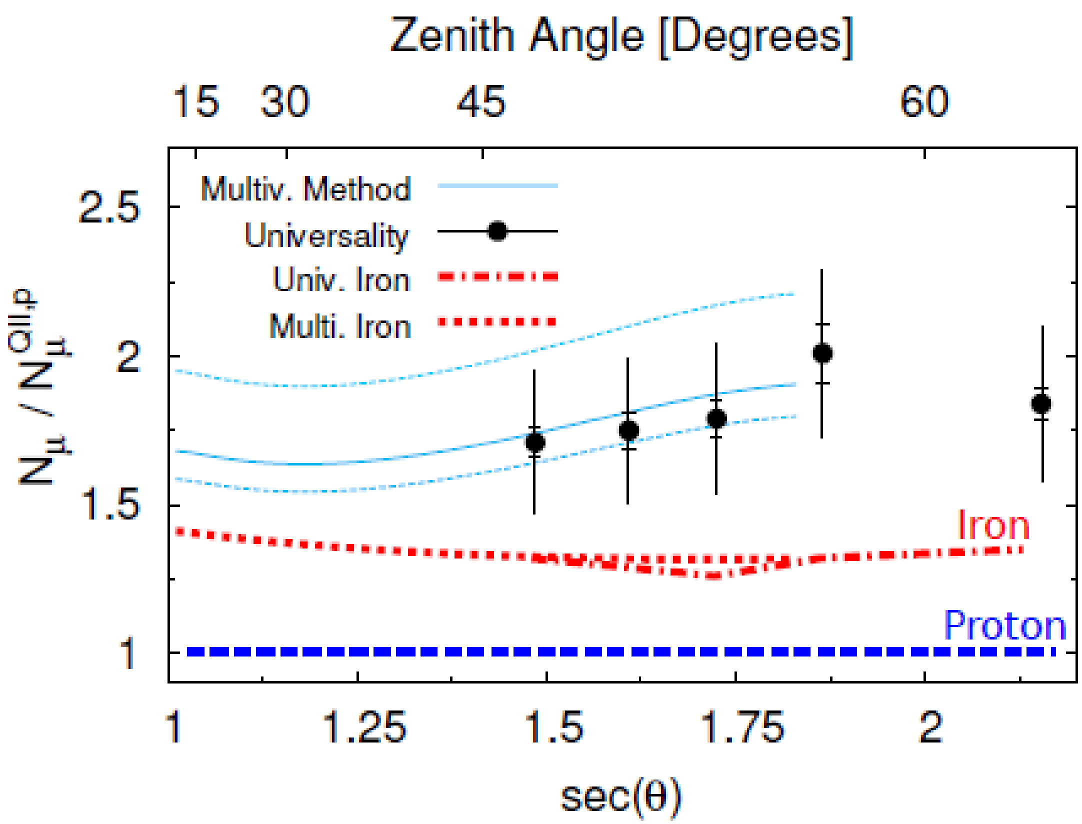


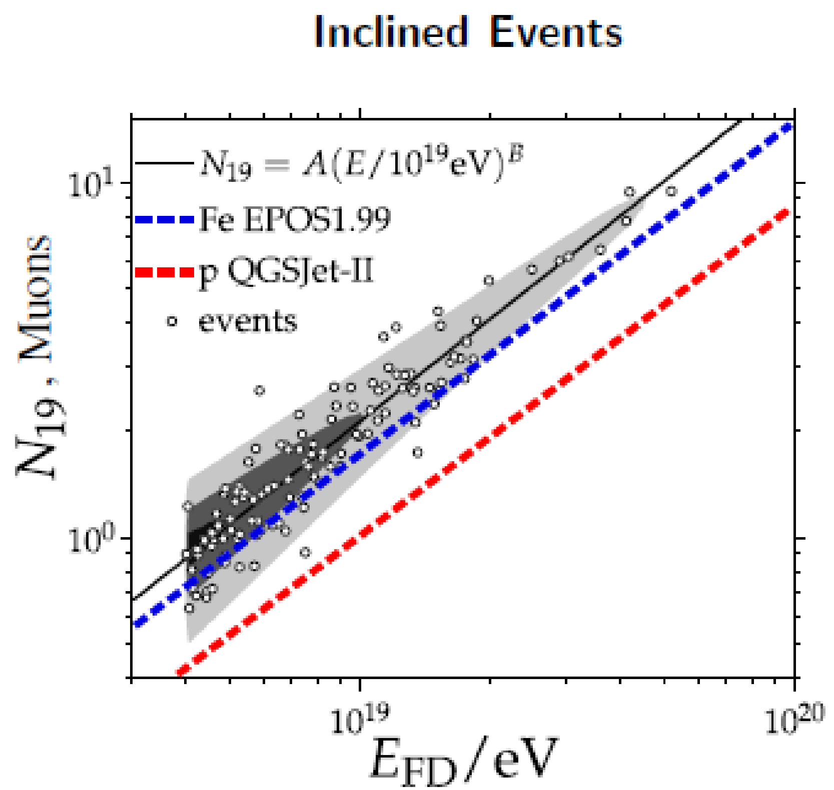
$$S_\mu = f(S_{1000}, \theta, \langle X_{max} \rangle)$$

Golden Hybrid Events

S(muons) = S_2 - S_1

Muon production in EAS





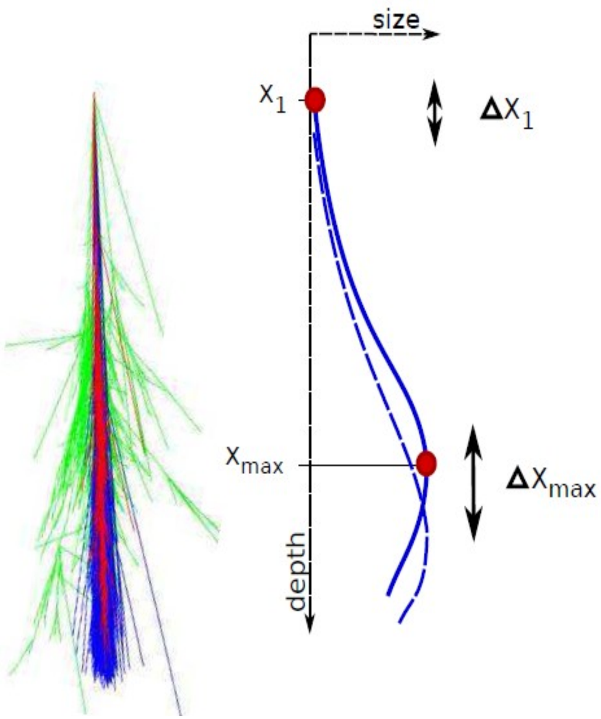
- Models significantly under-predict muons in air showers

- Muon deficit largest at high zenith angles: $N_\mu/N_\mu^{QII,p} = 2.1$, $N_\mu/N_\mu^{Epos,Fe} = 1.2$

- Discrepance could be caused for energy scale and/or shortcomings in the simulation of hadronic and muonic showers components

Proton-air Cross Section

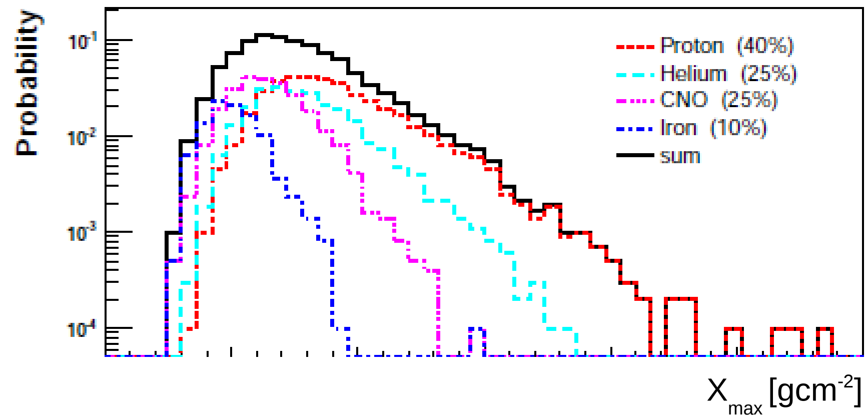
Measurement technique



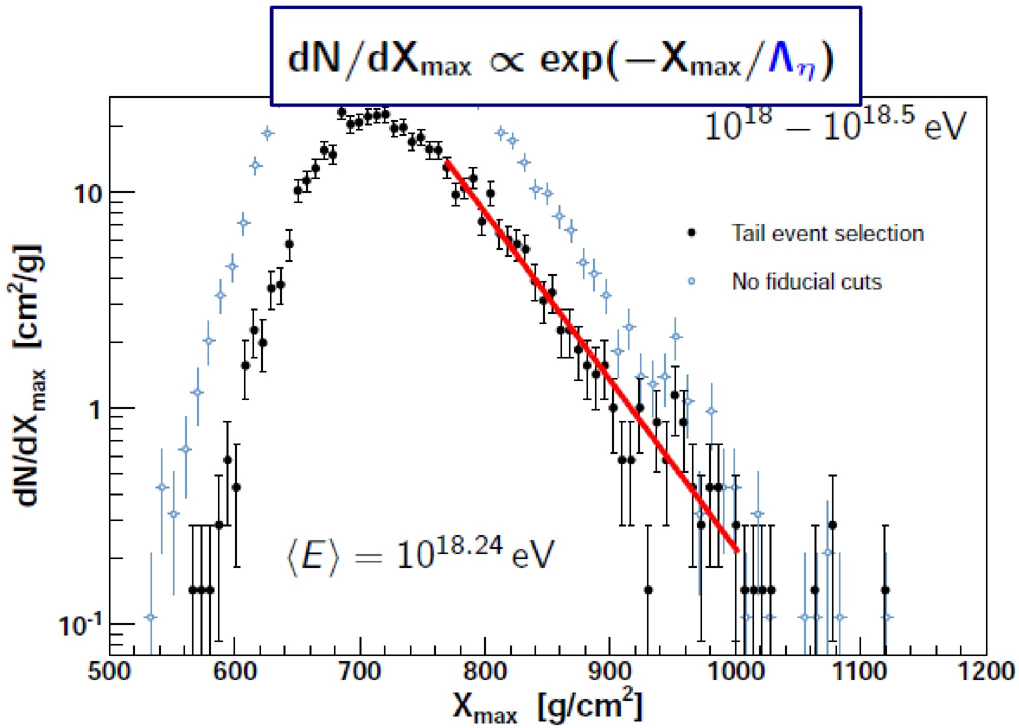
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\mathrm{RMS}(X_1) = \lambda_{int}$$

$$\sigma_{int} = \frac{<m_{air}>}{\lambda_{int}}$$



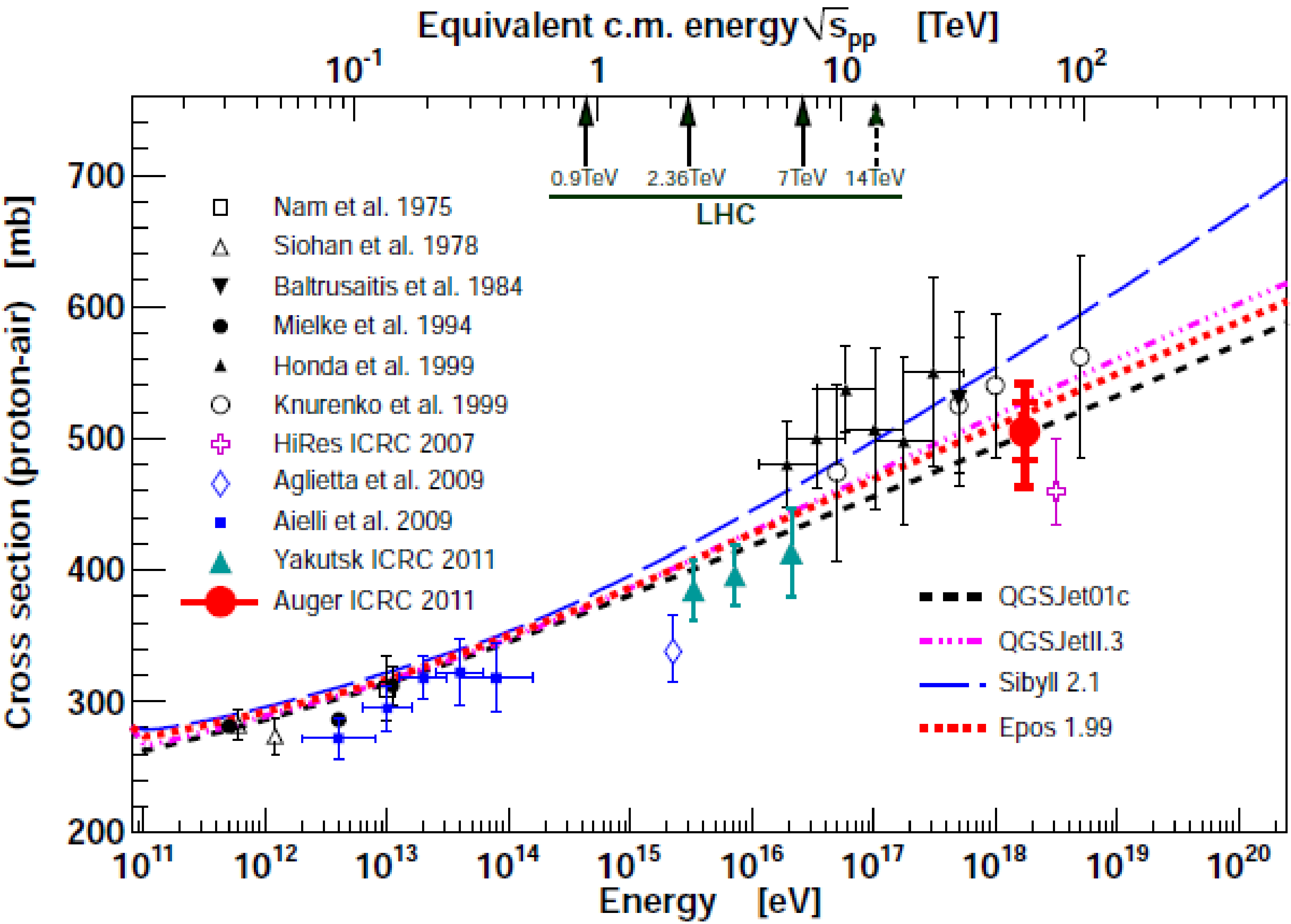
To selec the tail of the Xmax distribution to enhance proton fraction



→ Λ_η converted to $\sigma_{p\text{-}air}$ by tunning models to described tail in data ($\Lambda_\eta = k_\eta \lambda_{p\text{-}air}$)

$$\Lambda_\eta = [55.8 \pm 2.3_{stat} \pm 1.6_{sys}]\ \mathrm{g/cm^2}$$

Proton-air Cross Section



Proton-air cross-section at $\sqrt{s_{pp}}$ = 57 TeV

$$\sigma_{p\text{-}air} = [505 \pm 22_{stat} \, (^{+28}_{-36})_{sys}] \text{ mb}$$

Summary

- The cut-off in the spectrum in clearly seen and compatible with GZK prediction.
- Extragalactic cosmic rays are anisotropic (signal stabilizing).
- Primary cosmic rays detected are hadronic.
- Neutrino and photon limits nearing the GZK regime.

Exciting results related to particle physics at 10 EeV:

- First p-air (and pp) cross section much beyond LHC energies.
- Hadronic interaction models underestimate muon number in extensive air showers.