PIERRE
AUGER
OBSERVATORY

# Recent measurements on ultra-high energy cosmic ray with the Pierre Auger Observatory

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**Pierre Auger Collaboration**
LPNHE, Paris

# TALK OUTLINE

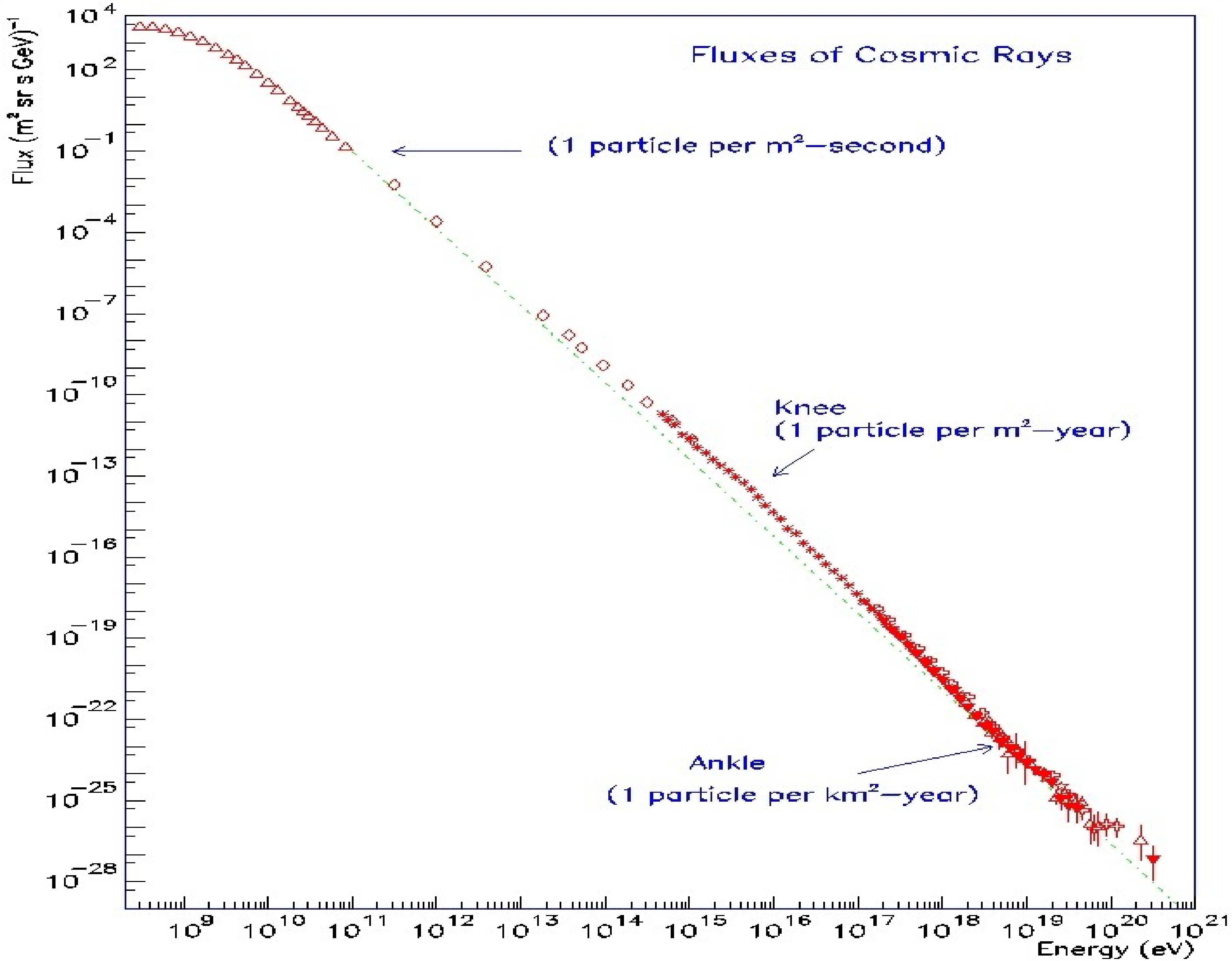
**INTRODUCTION**

**HIGHLIGHTS OF RECENT MEASUREMENTS**

**NEUTRINO LIMIT**

# INTRODUCTION

# The SPECTRUM



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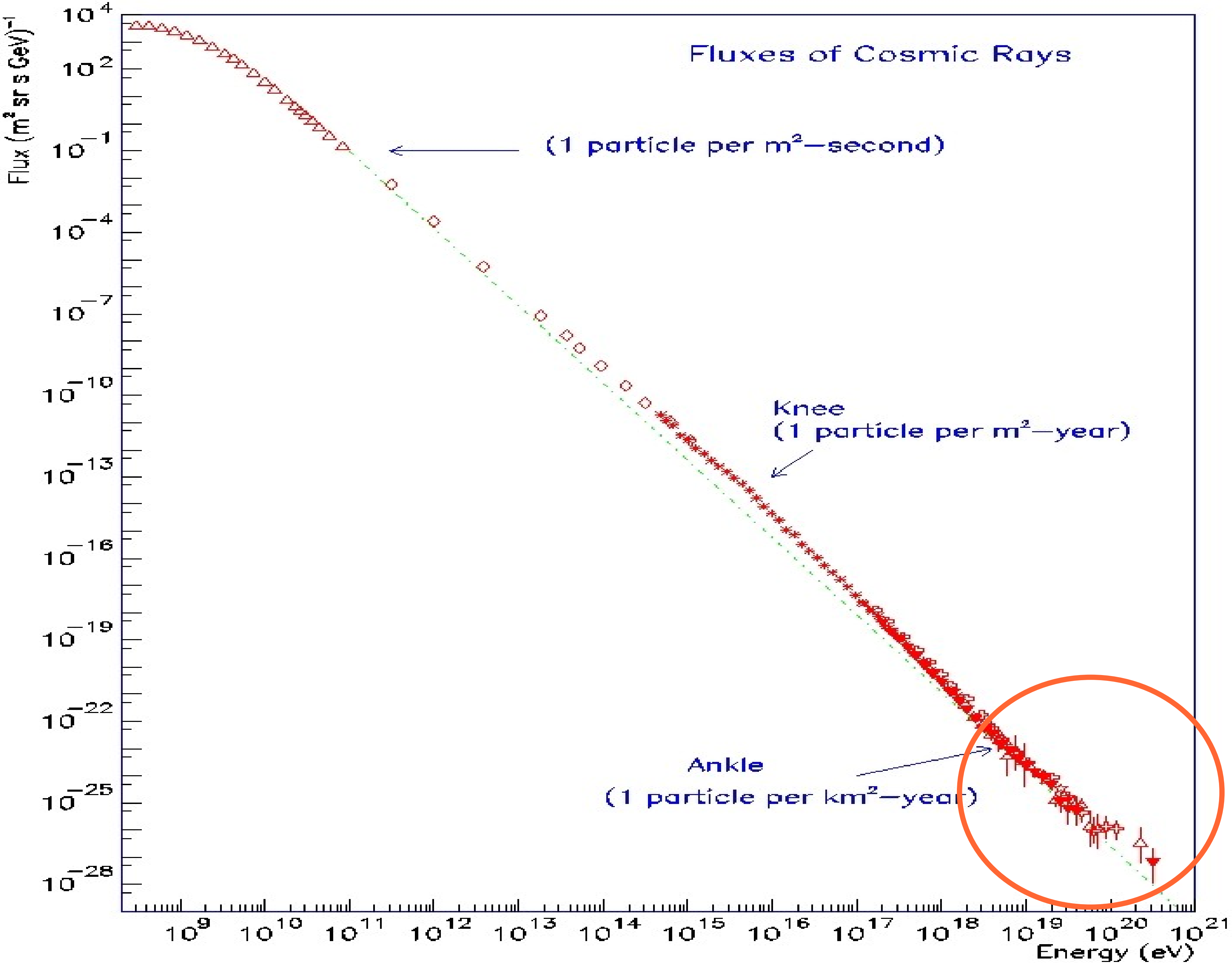

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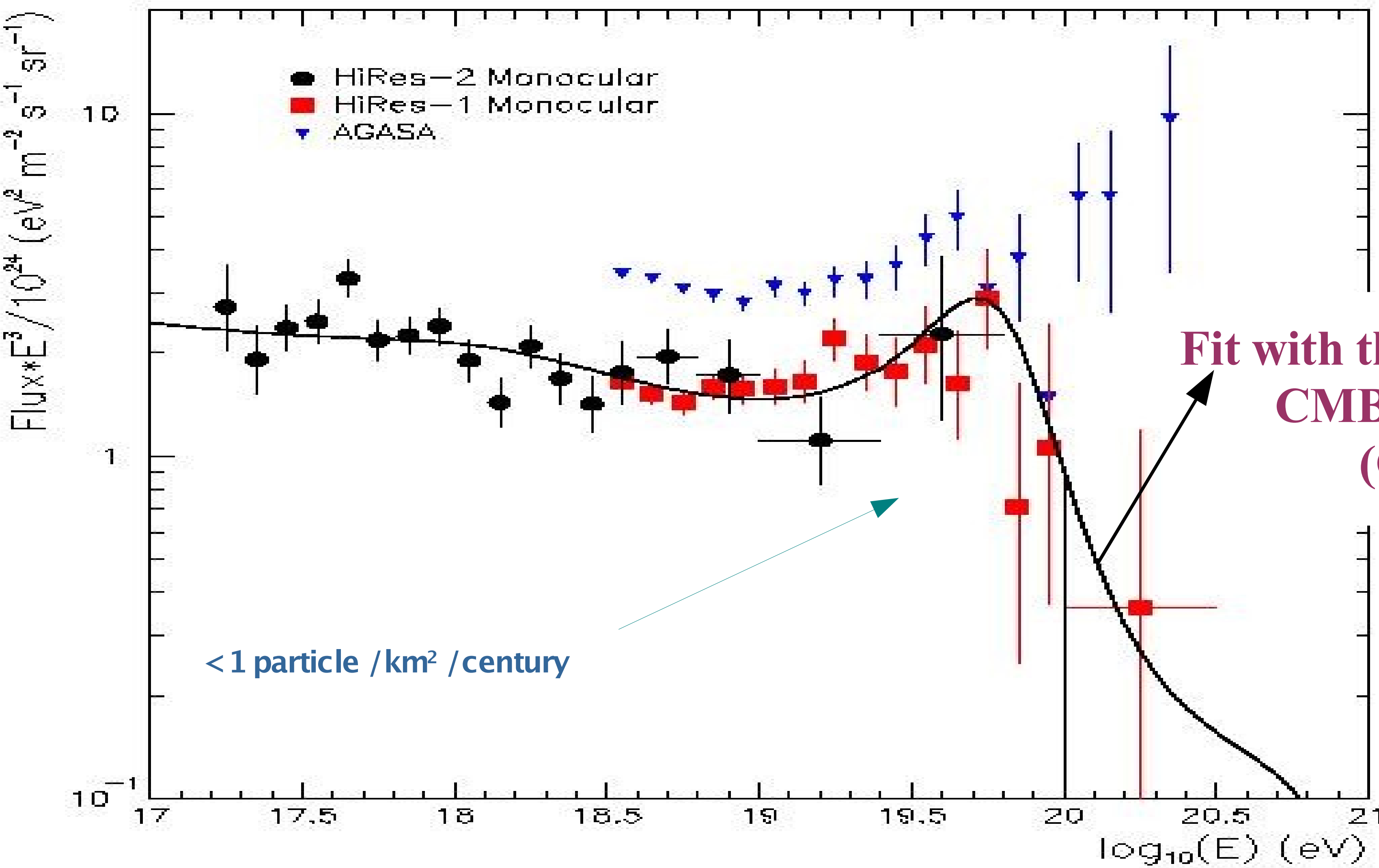



Fit with the expected CMB absorption (GZK effect)

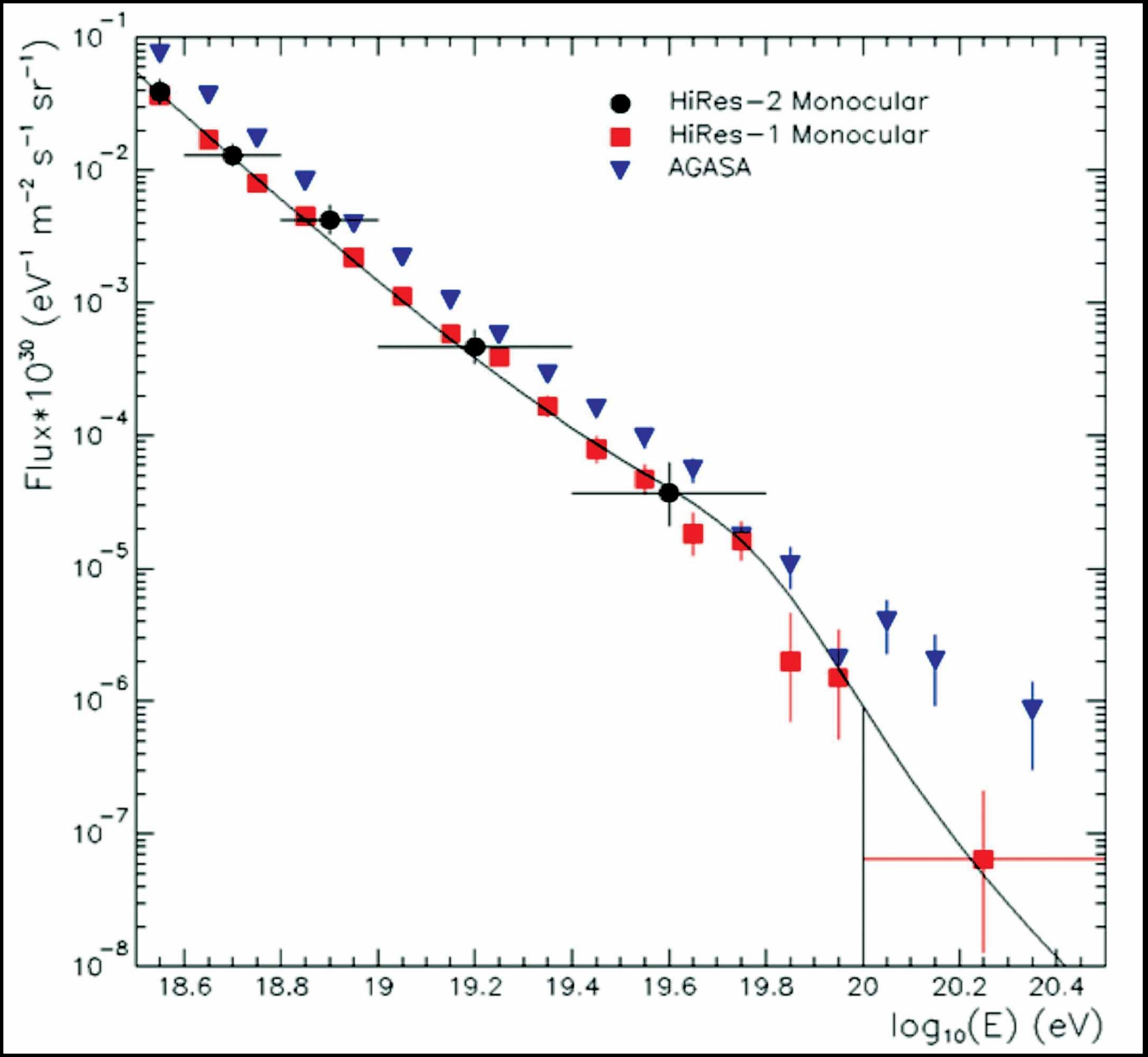
# OPEN QUESTIONS

## Open questions at the end of the spectrum

- Spectral shape
- Composition :

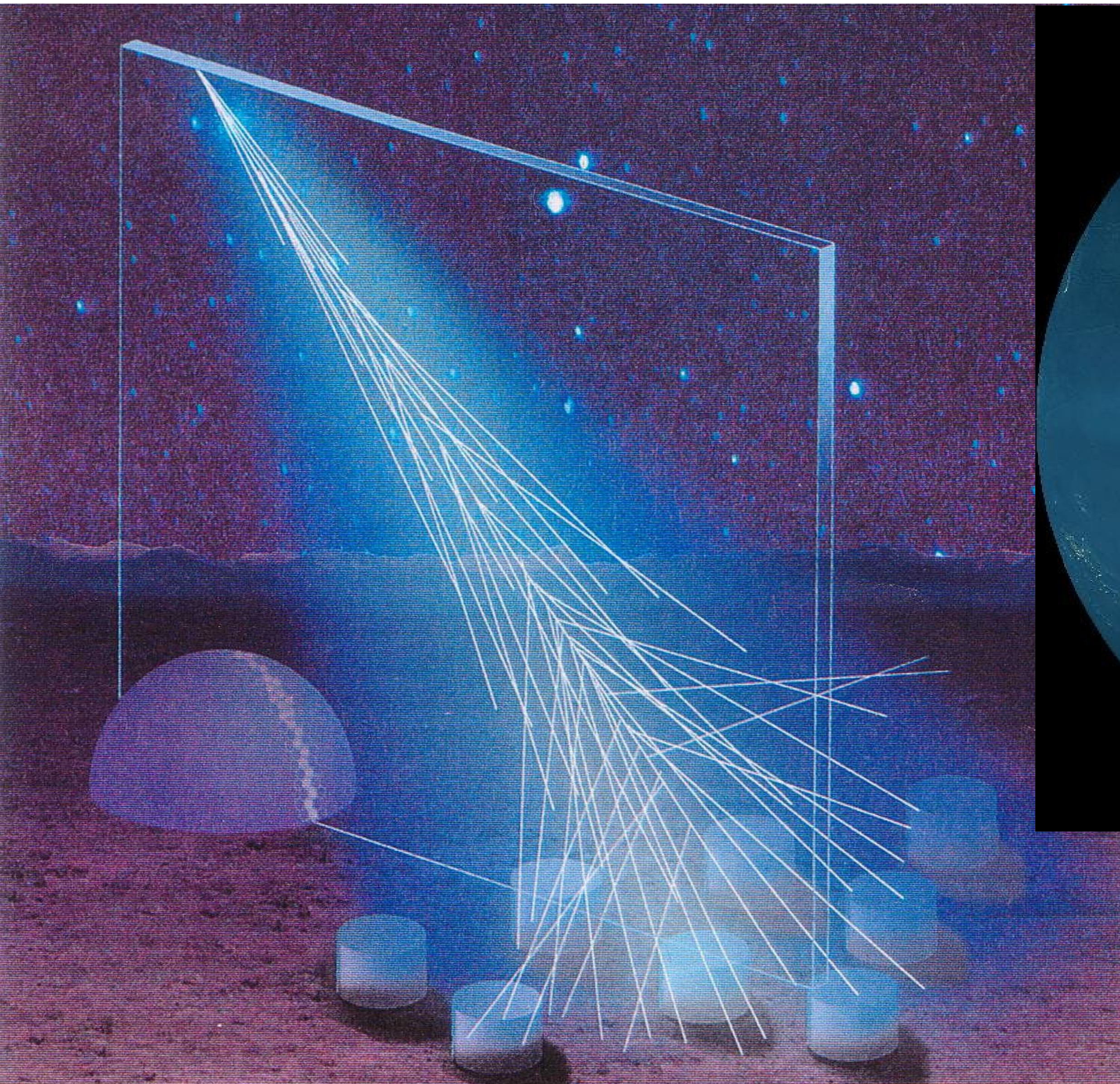
  p-Fe, γ, ν

- Sources of cosmic rays
- Production mechanisms



# The PIERRE AUGER OBSERVATORY

**A huge (3000 km²) hybrid detector of Cosmic Rays above $10^{18.5}$ eV**



Malargüe @ 1400 m a.s.l.

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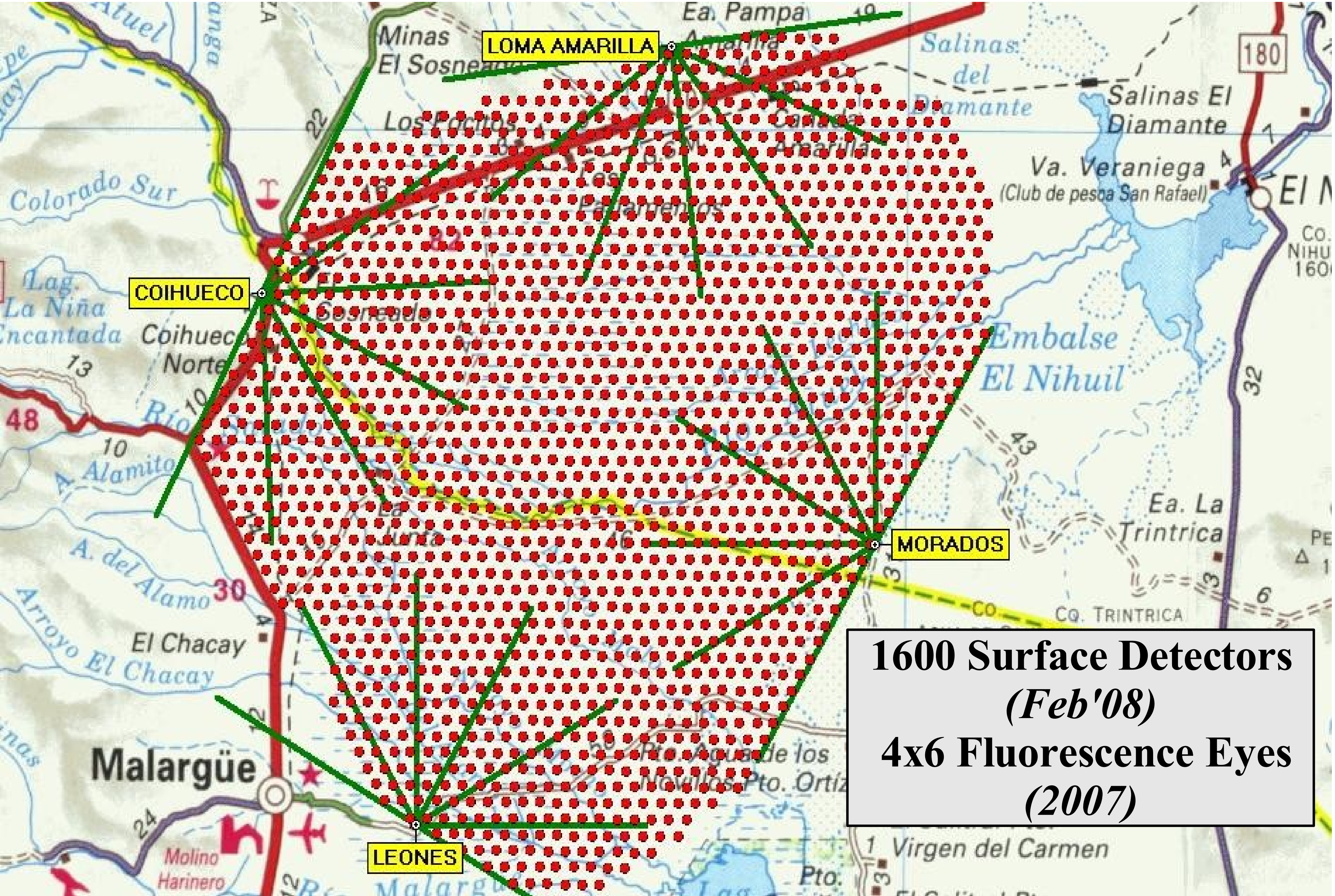

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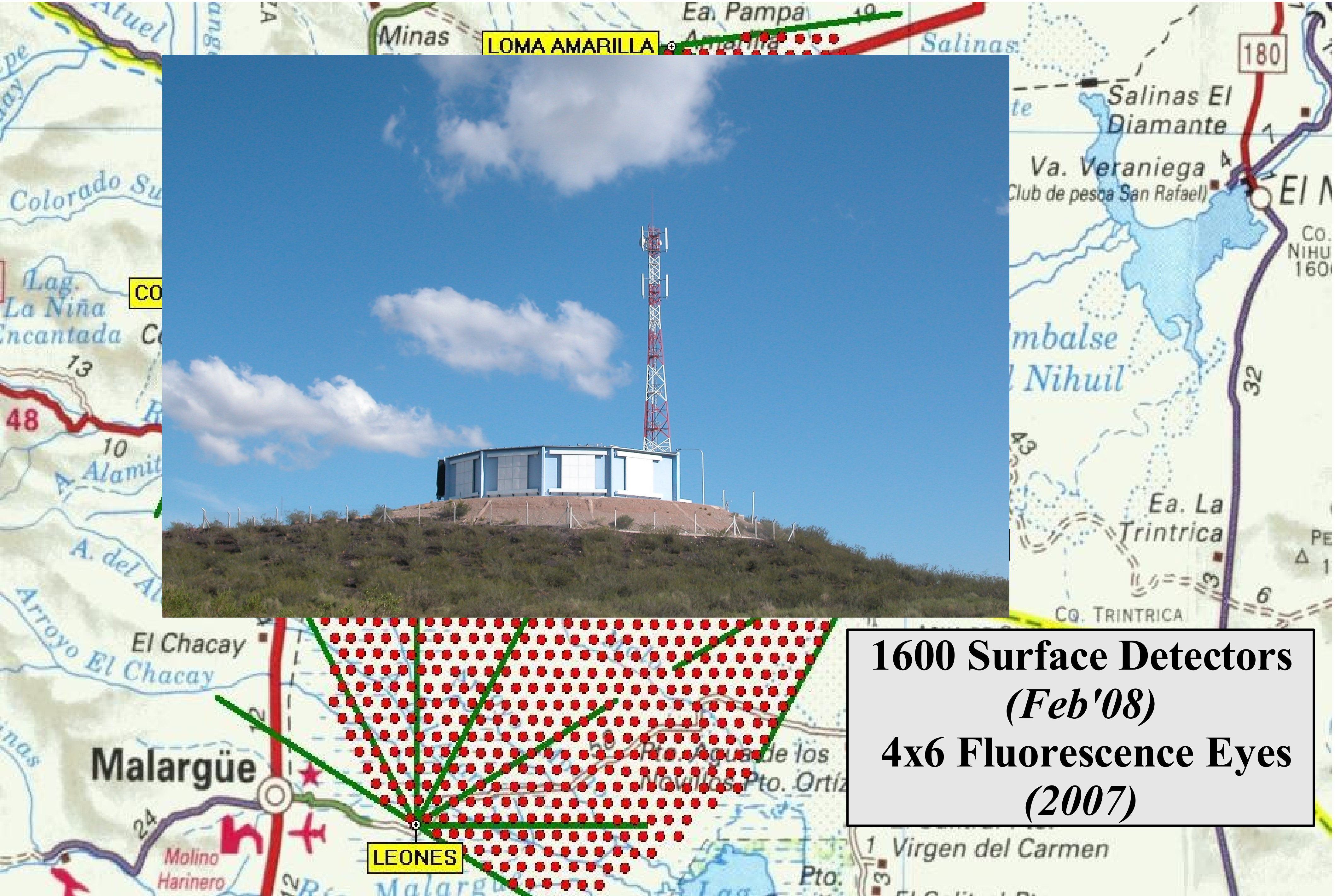
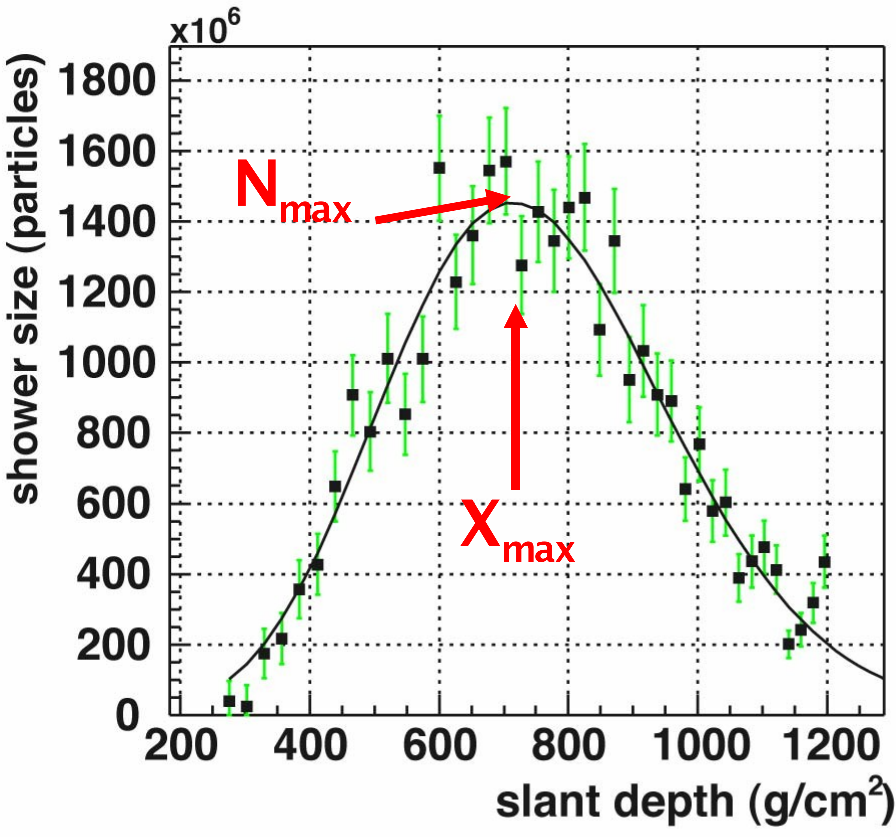


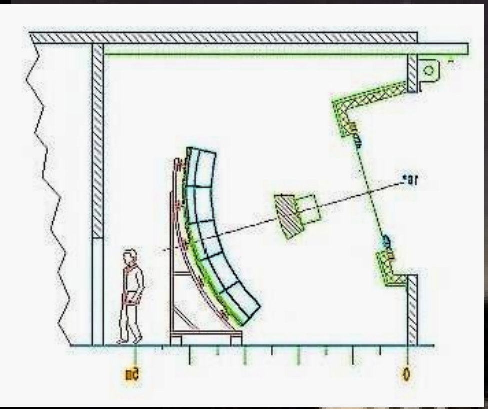

**1600 Surface Detectors**
***(Feb'08)***
**4x6 Fluorescence Eyes**
***(2007)***

# Fluorescence Detector

Longitudinal profile :

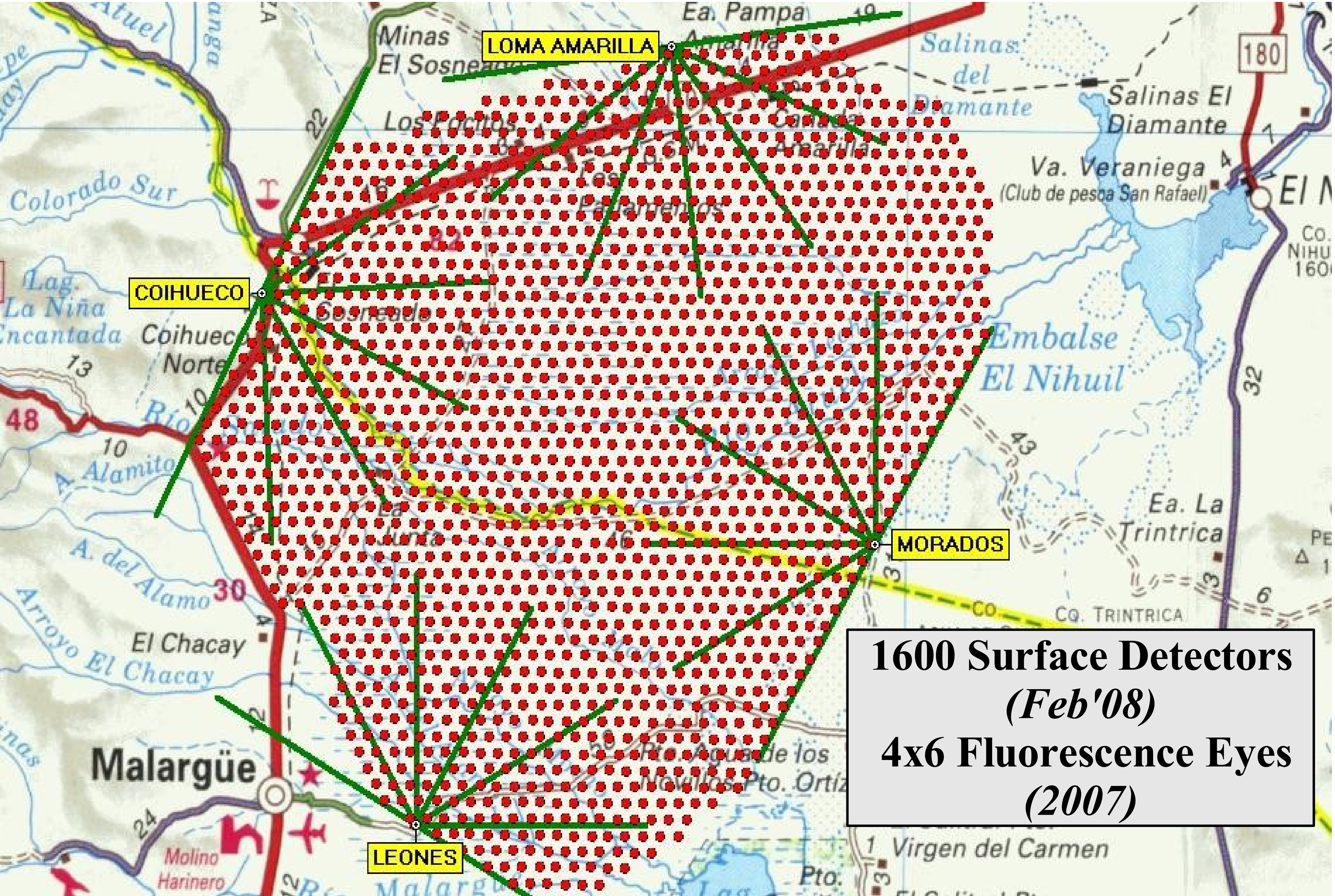



Fluorescence light



Statistically limited due to 10 % duty cycle

# The PIERRE AUGER OBSERVATORY

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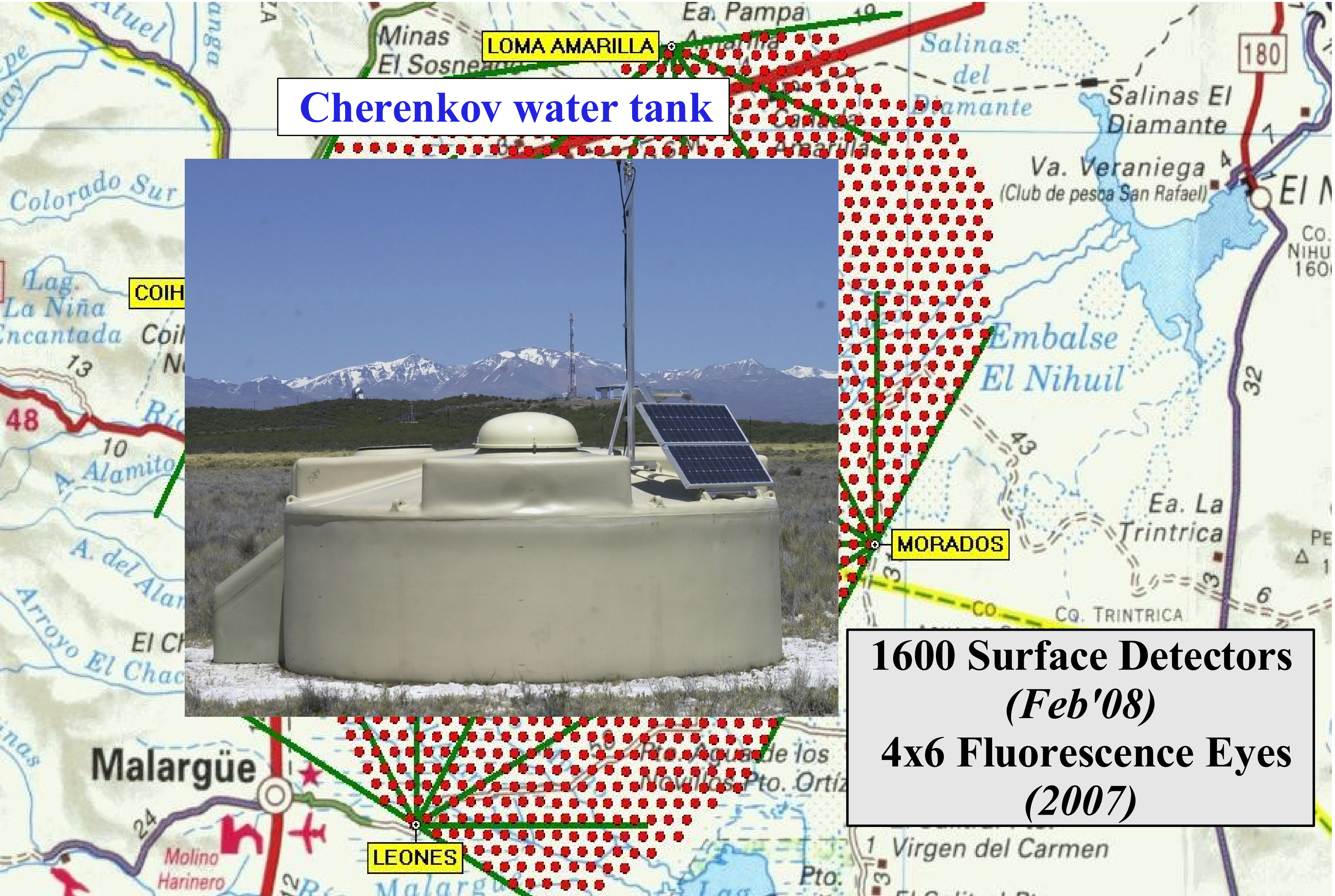
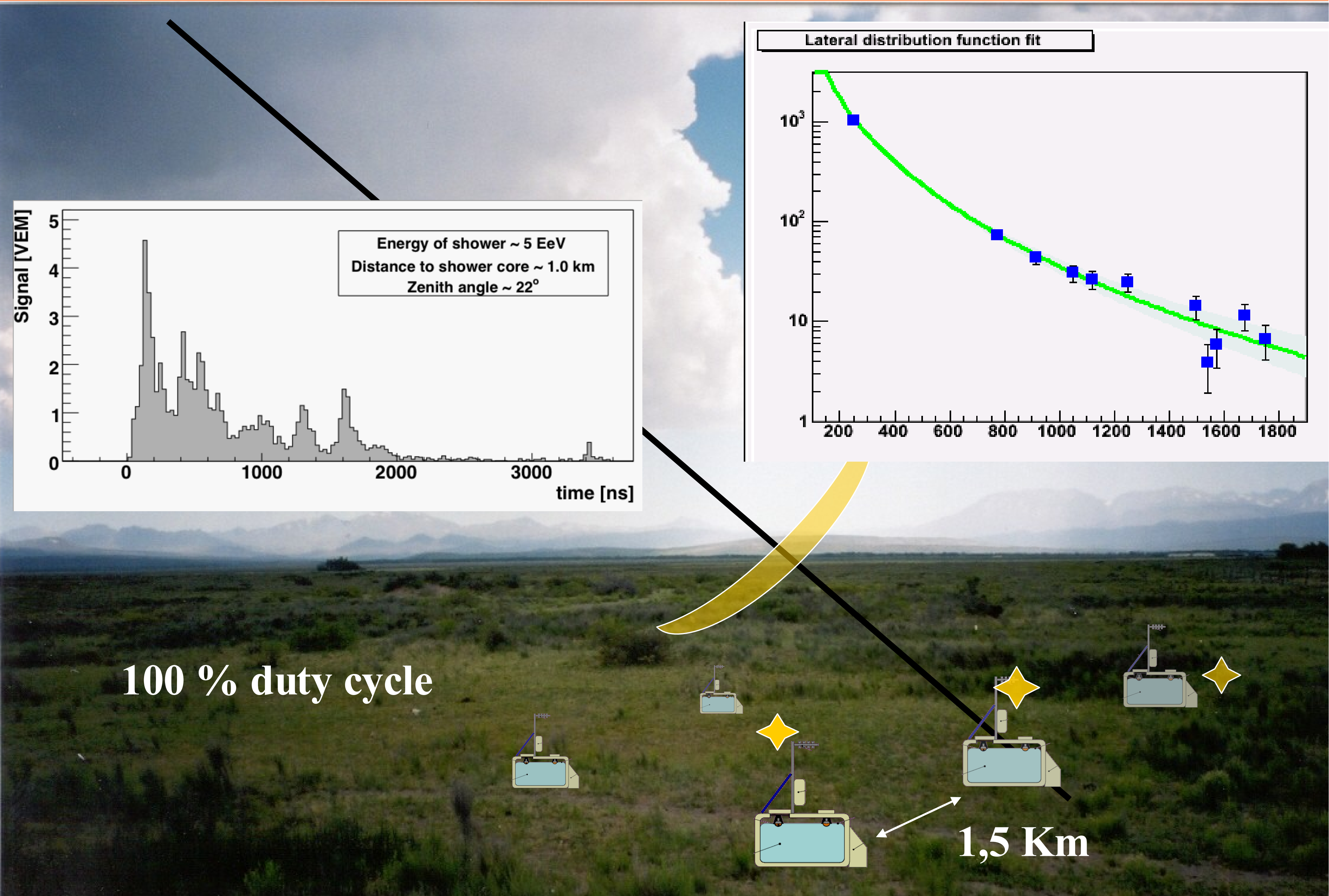
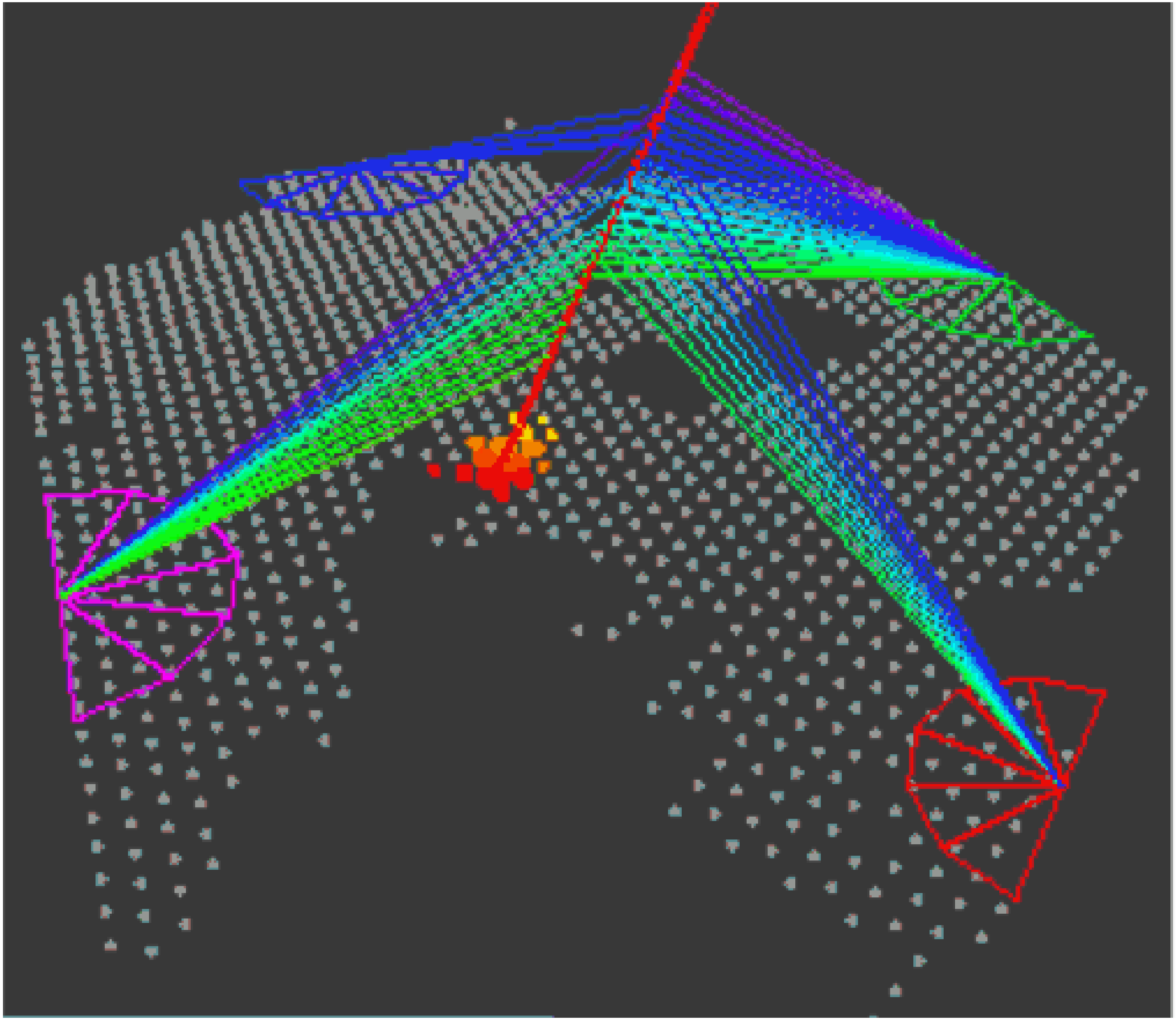


# Surface Detector



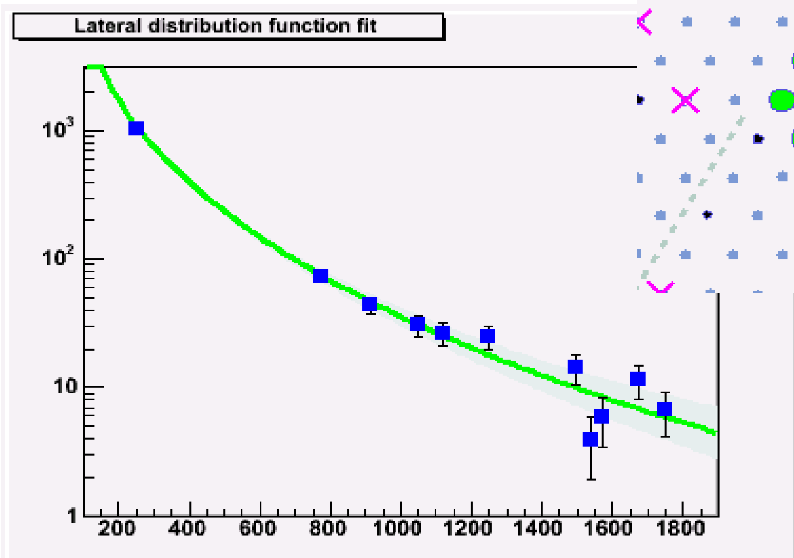
# Hybrid Detector

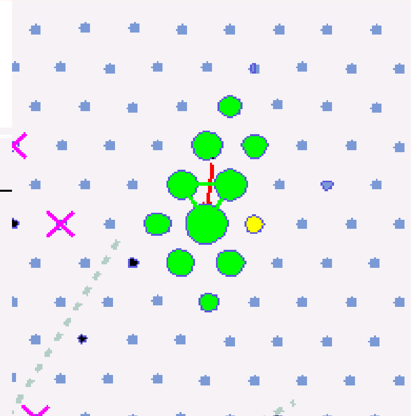


# HIGHLIGHTS OF RECENT MEASUREMENTS

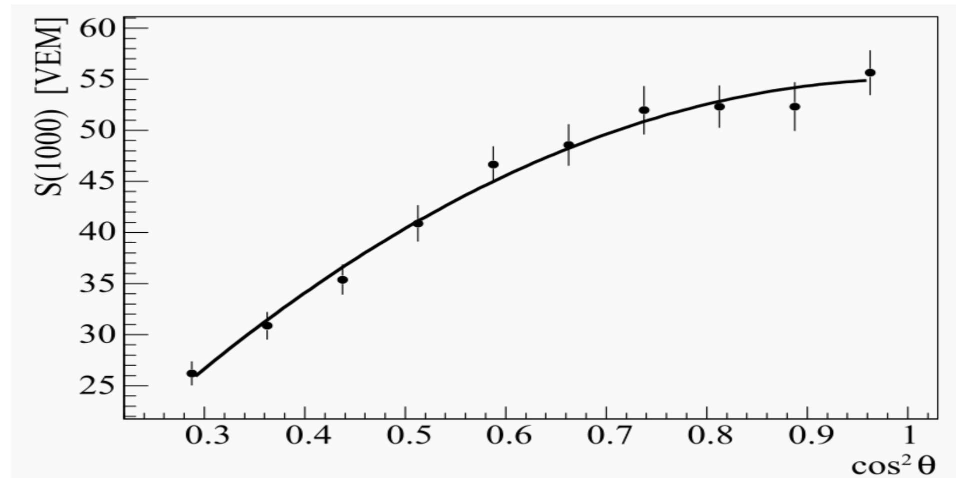
# Spectrum Method

## SD Signal



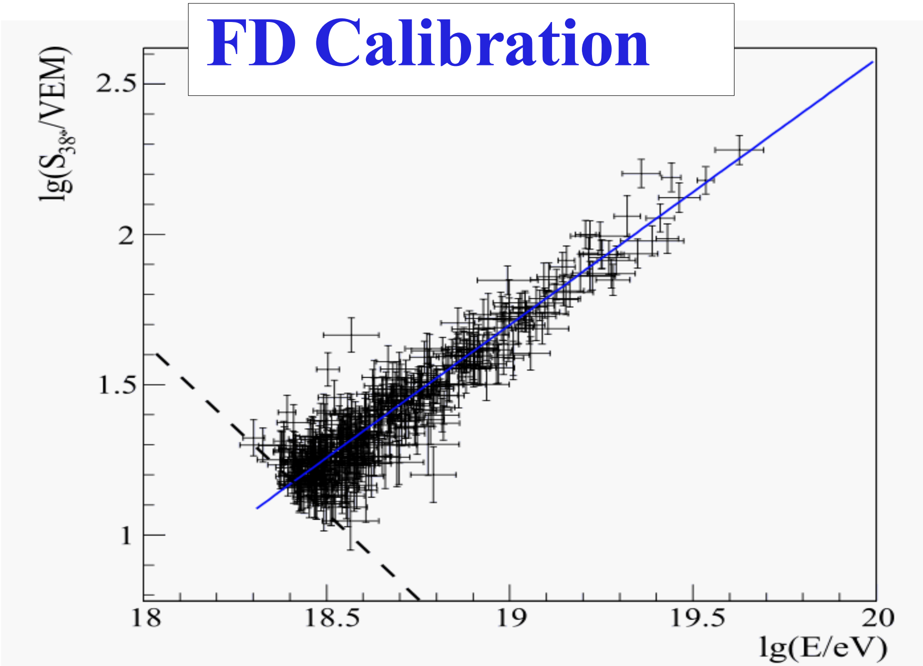



## CIC (zenith dependence)




Flux level independent of zenith.

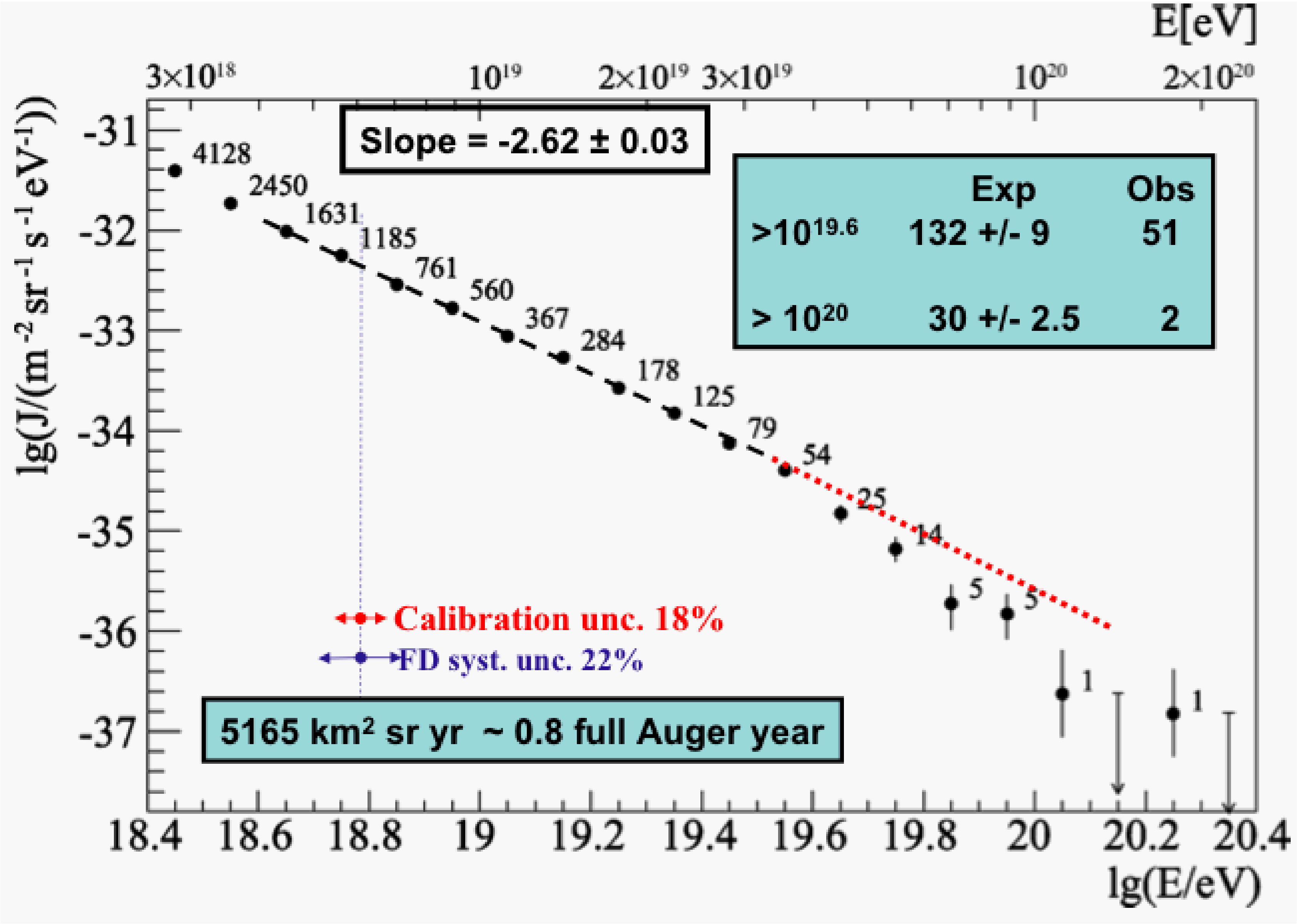
## FD Calibration




## Acceptance

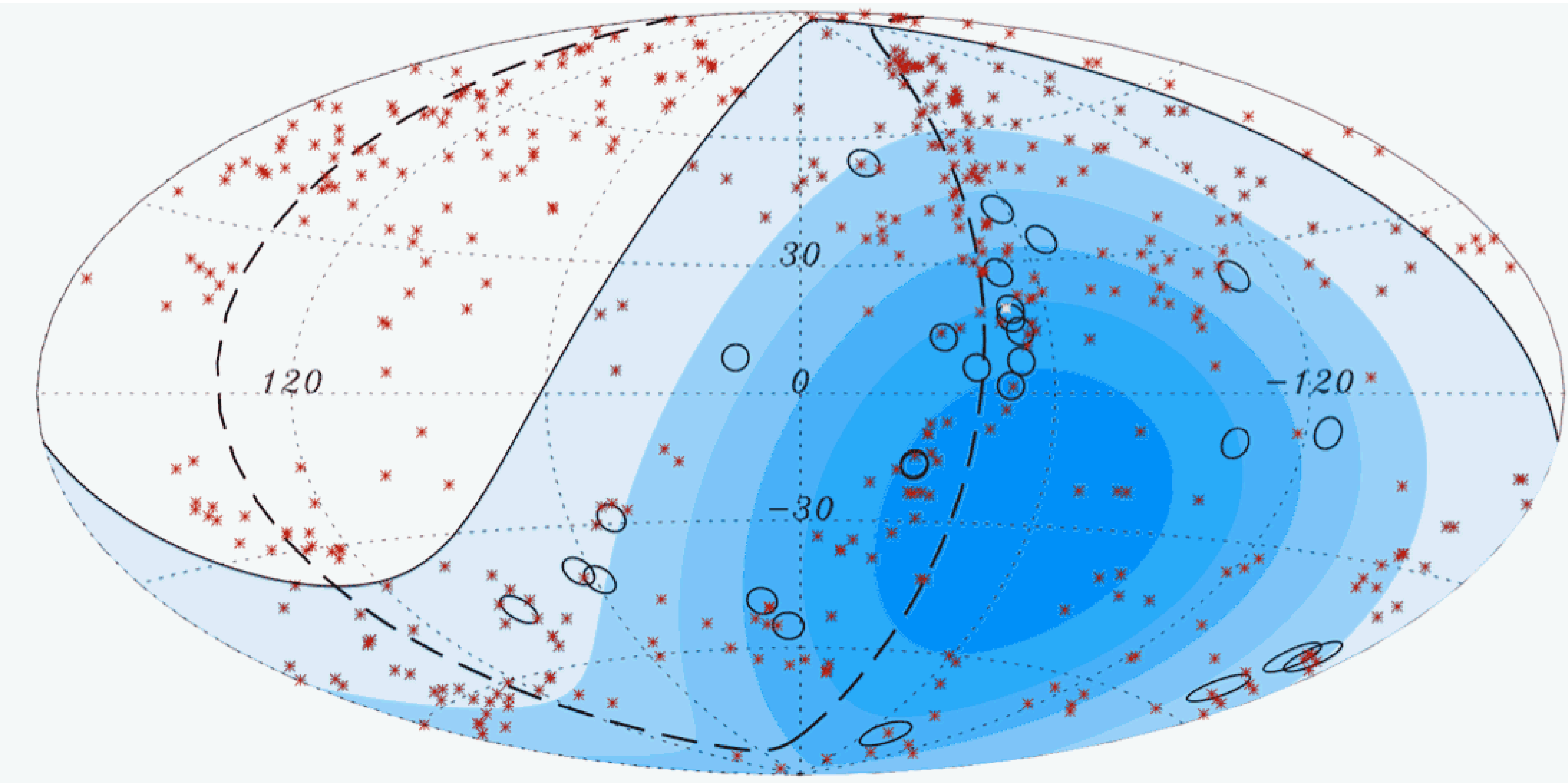
- 100 % Trigger Eff. above $10^{18.5}$ eV
- Contained events -> Aperture = Number of tanks x Effective $A_{tank}$
- Working tanks vs time, stored

# Spectrum



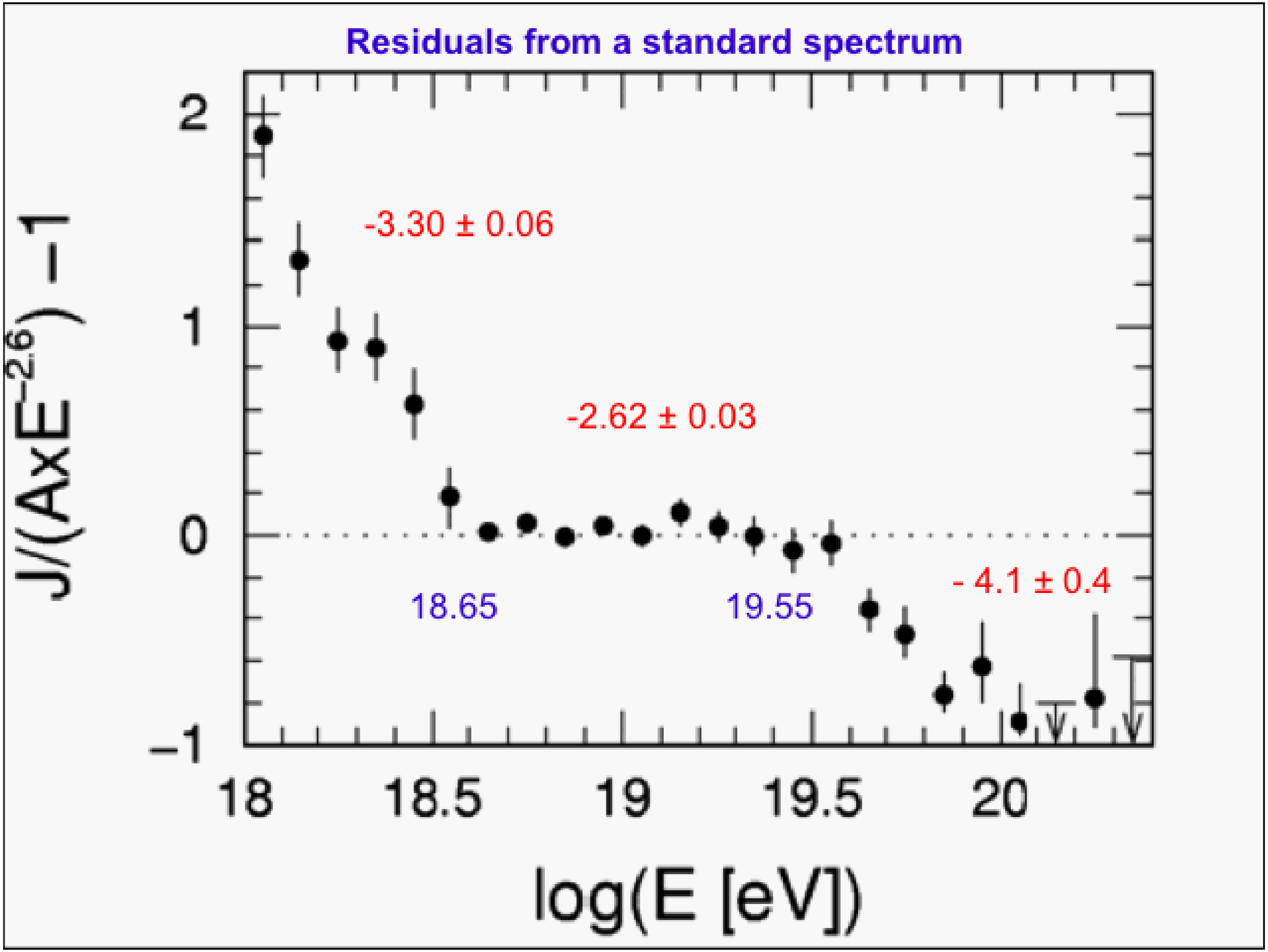

*Steepness of the Cosmic Ray flux above ~ 40 EeV (25% systematics)*

# Correlation with nearby objects



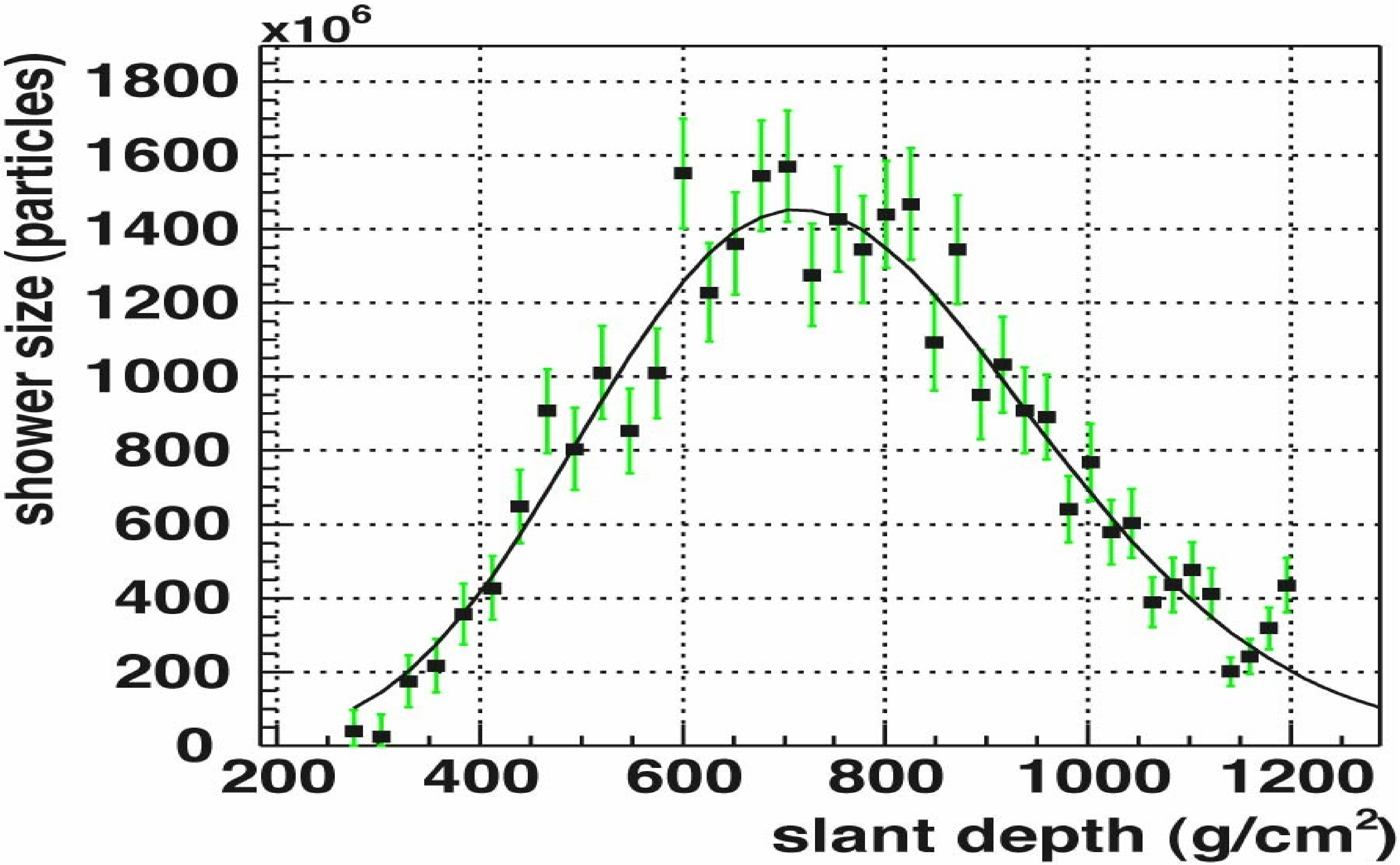

*Anisotropy at 99% CL above ~ 56 EeV (25% systematics)*

# Spectrum



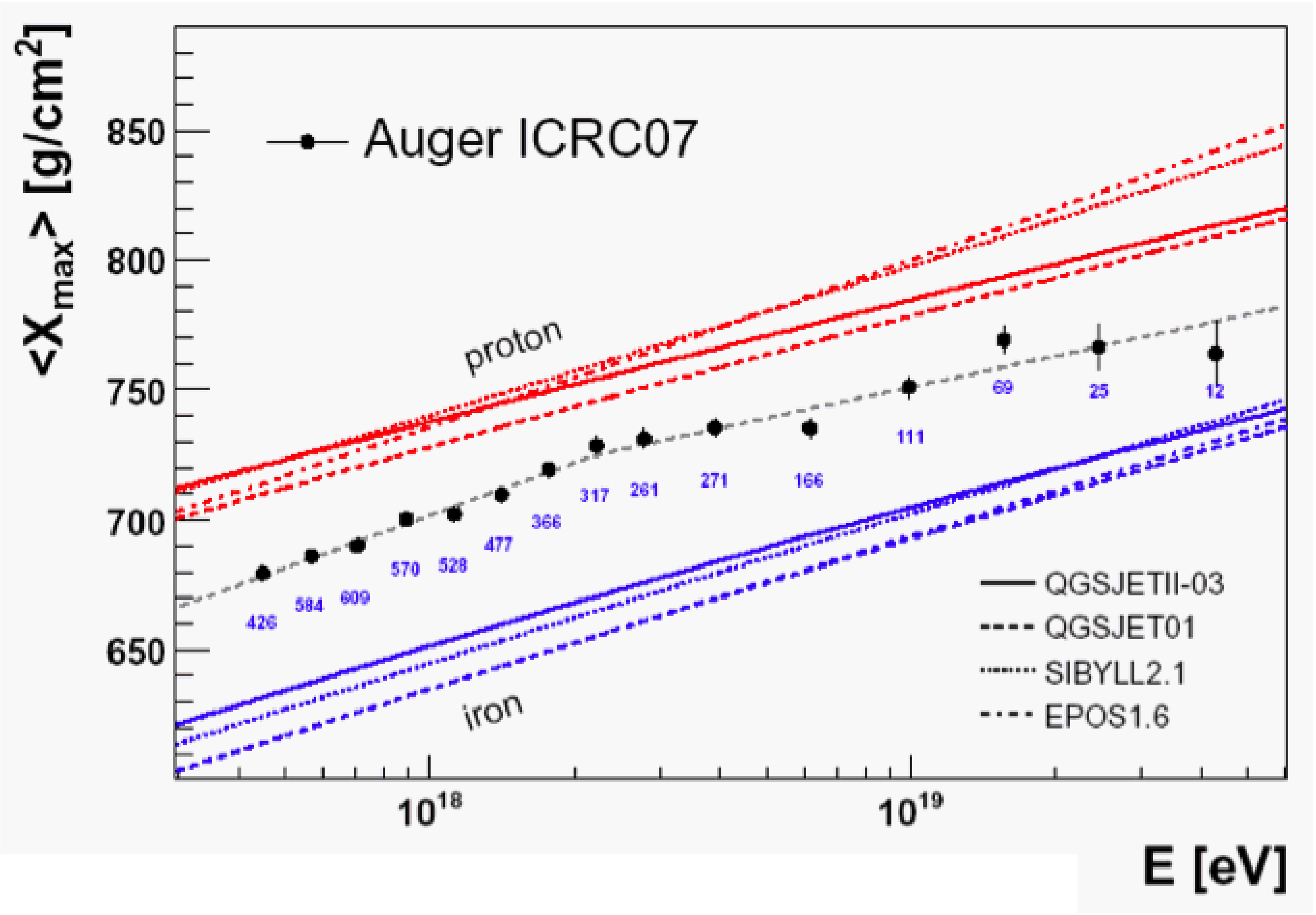

*One half of extrapolated flux at ~ 56 EeV (25% systematics)*

# Mass Composition



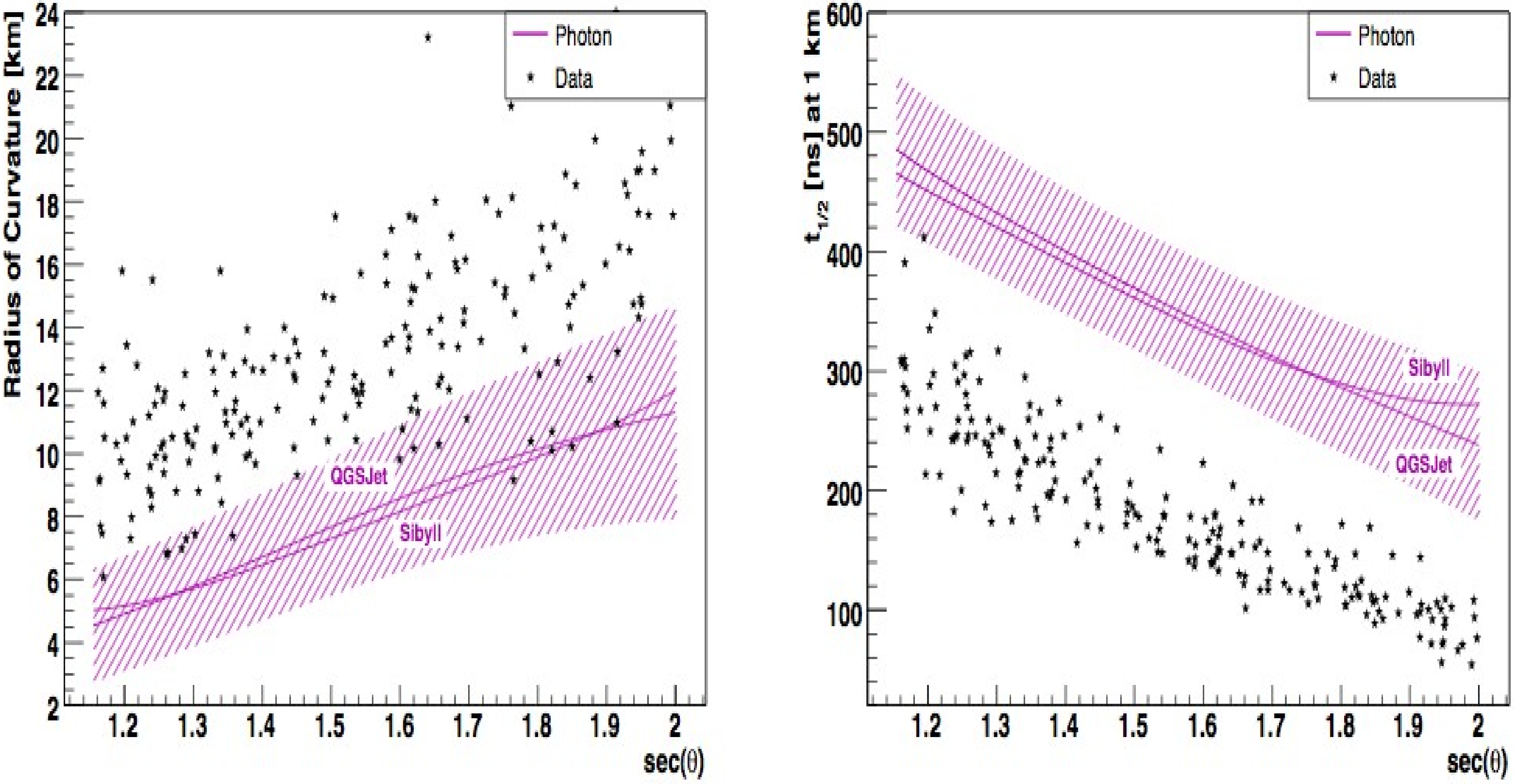

*Direct measurement of Longitudinal Profile ($X_{max}$) with FD*

# Elongation Rate



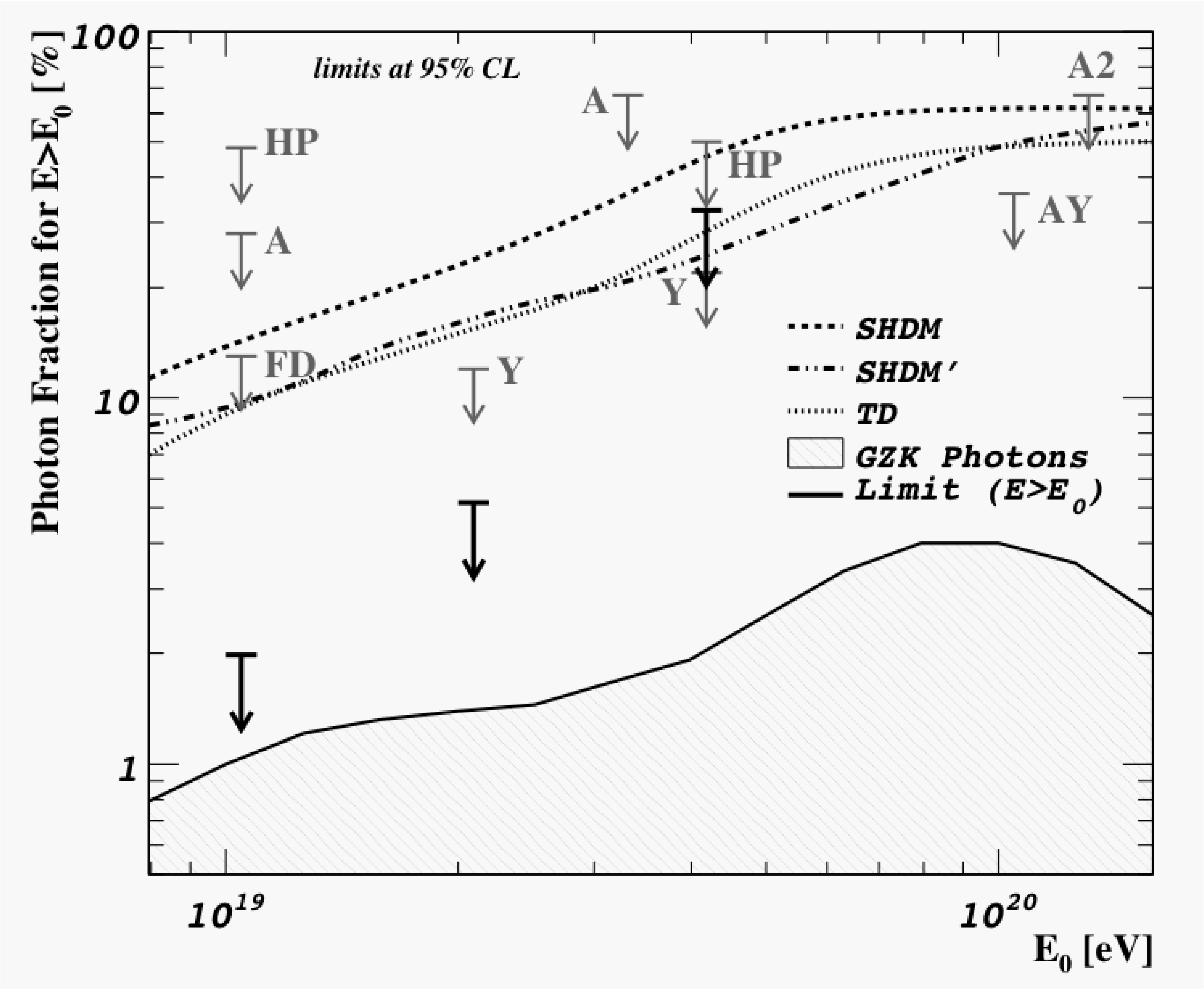

*Indication of decrease at "highest" energies: composition ?*

# PHOTON LIMIT




***SD observables sensitive to $X_{max}$ and muon component***

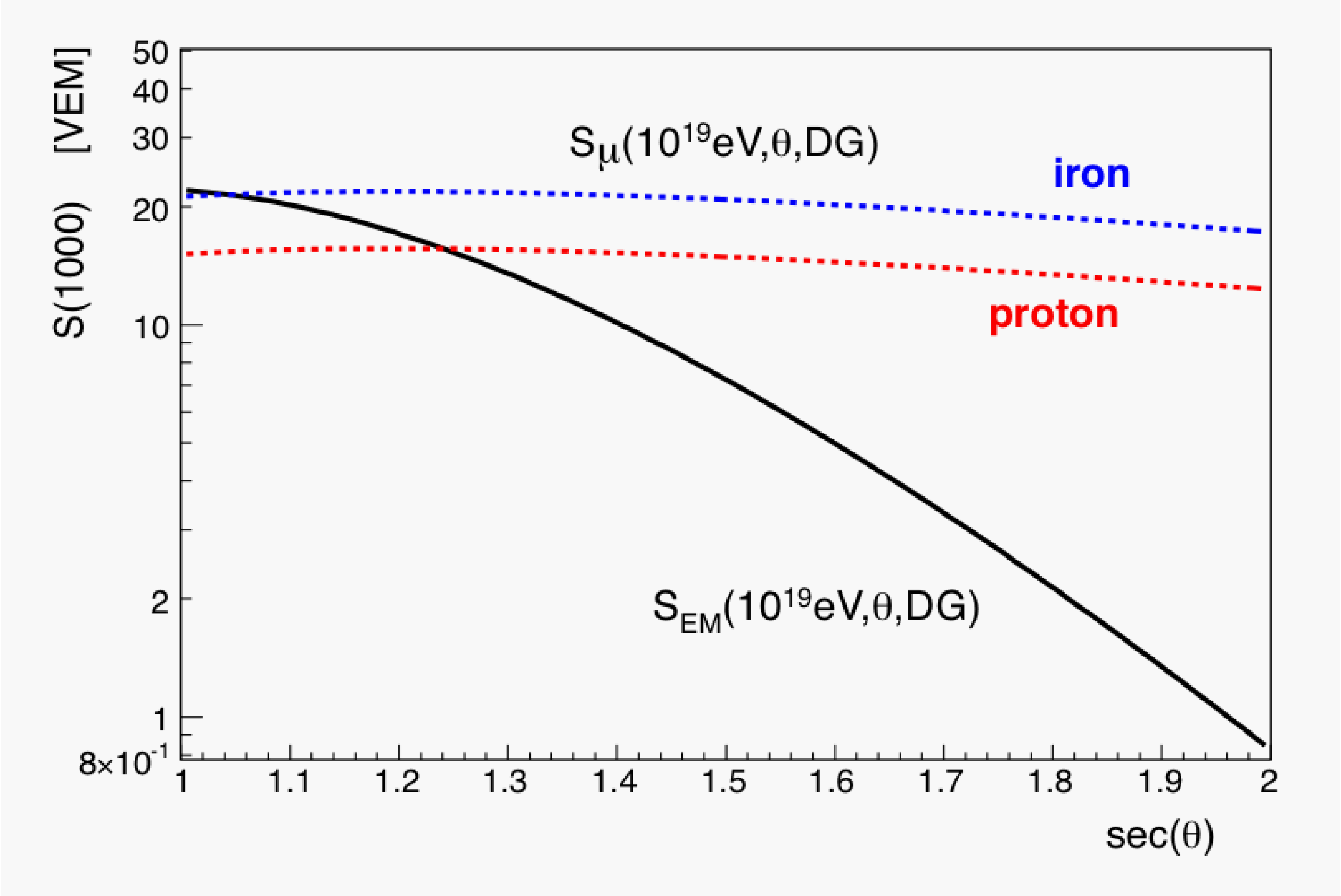
# PHOTON LIMIT




*Low photon fractions disfavour Top-down models*

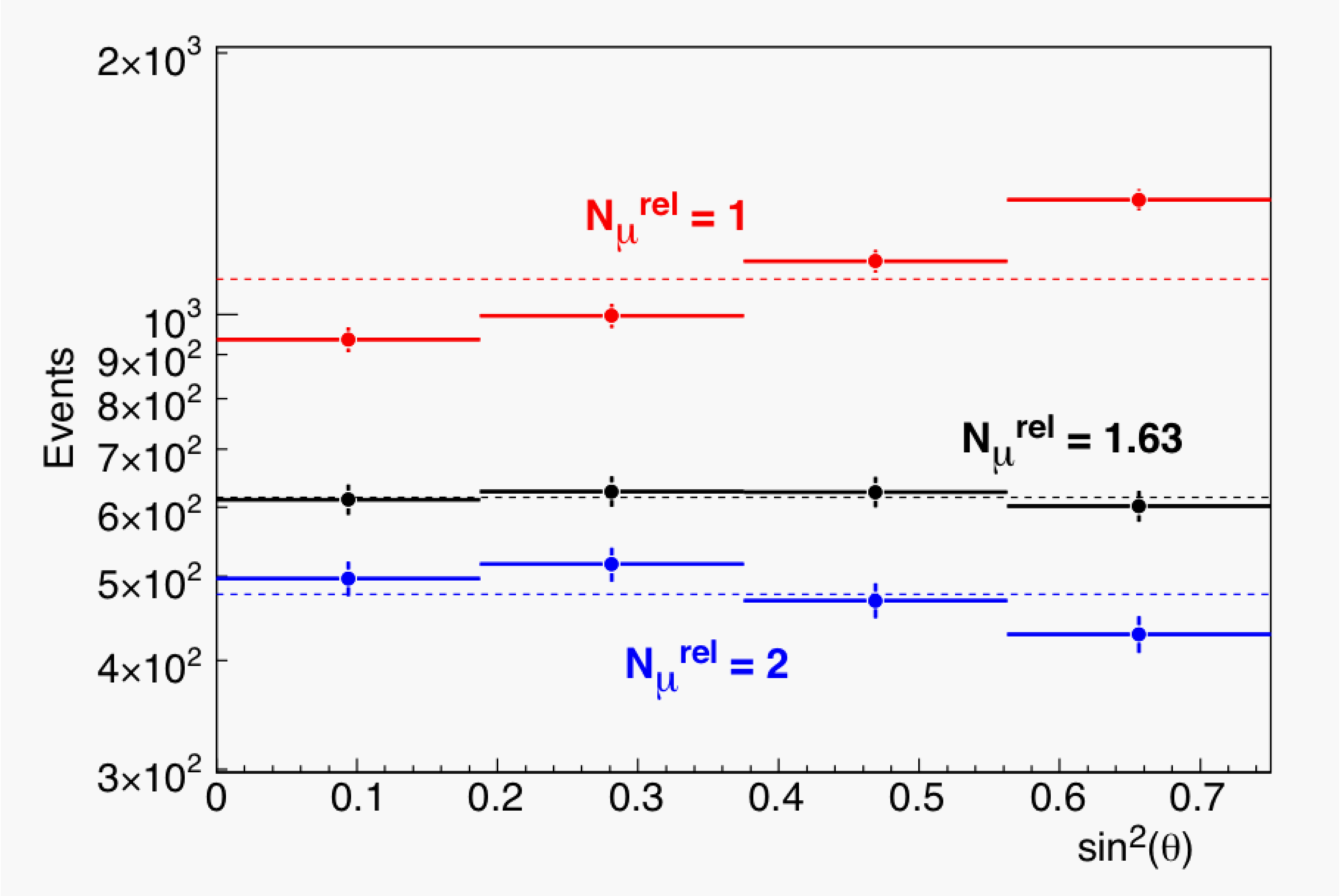
# TEST OF INTERACTION MODELS

We can get the electromagnetic contribution for the signal in the SD from the FD and hence subtract the muonic contribution.




$$S_{\rm MC}(E,\theta,X_{\rm max}) \quad = \quad S_{\rm em}(E,\theta,DG) + N_\mu^{\rm rel} S_\mu^{\rm QGSII,p}(10^{19}\,{\rm eV},\theta,DG)$$

# TEST OF INTERACTION MODELS

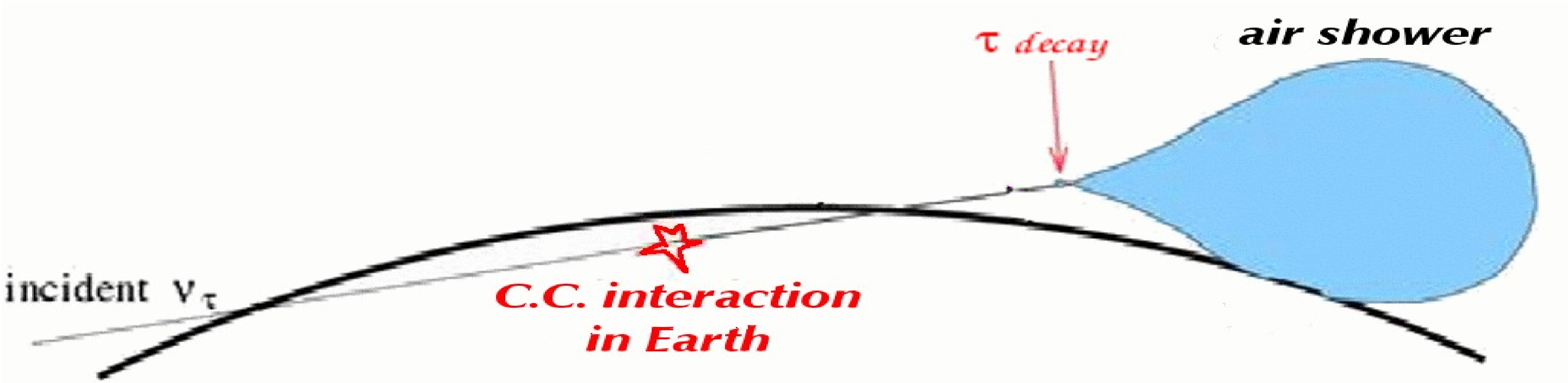



*Real Air Showers seem to be richer in muons than those simulated*

# NEUTRINO LIMIT

# SKIMMING NEUTRINOS

***All $\nu$ flavours can interact in the atmosphere and produce an EAS, but the earth-skimming mechanism can be used for $\nu_\tau$ :***




$L_{int}$ ($\nu$) ~ 500 km — $L_{decay}$ ($\tau$) ~ 50 km — $L_{Eloss}$ ~ 10 km — (at 1 EeV)

θ>95, Earth opaque — ($\mu$), much larger — (e), much smaller

Pierre Auger Observatory: 50 x 50 km$^2$

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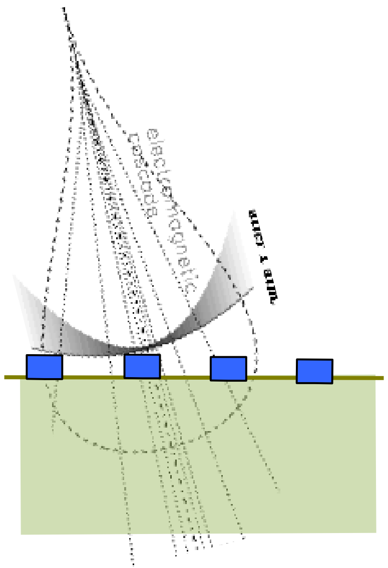
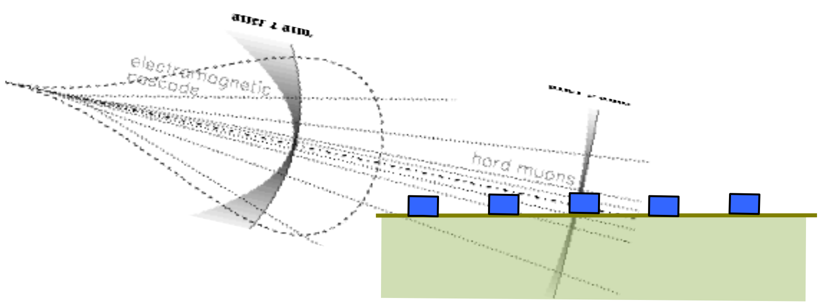
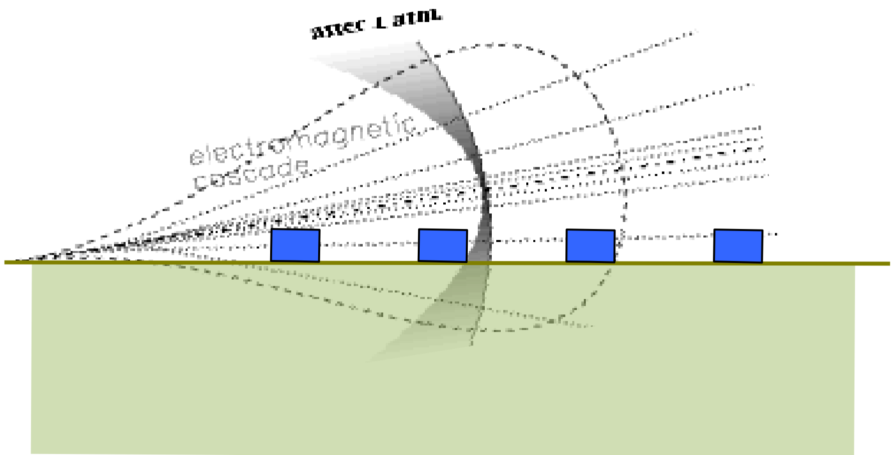
# Neutrino Characteristics

**"Standard" CR**




**Neutrino**




For a very inclined shower (above 70 deg), the presence of ***electromagnetic*** component is a clear signature of a neutrino or emerging tau shower.

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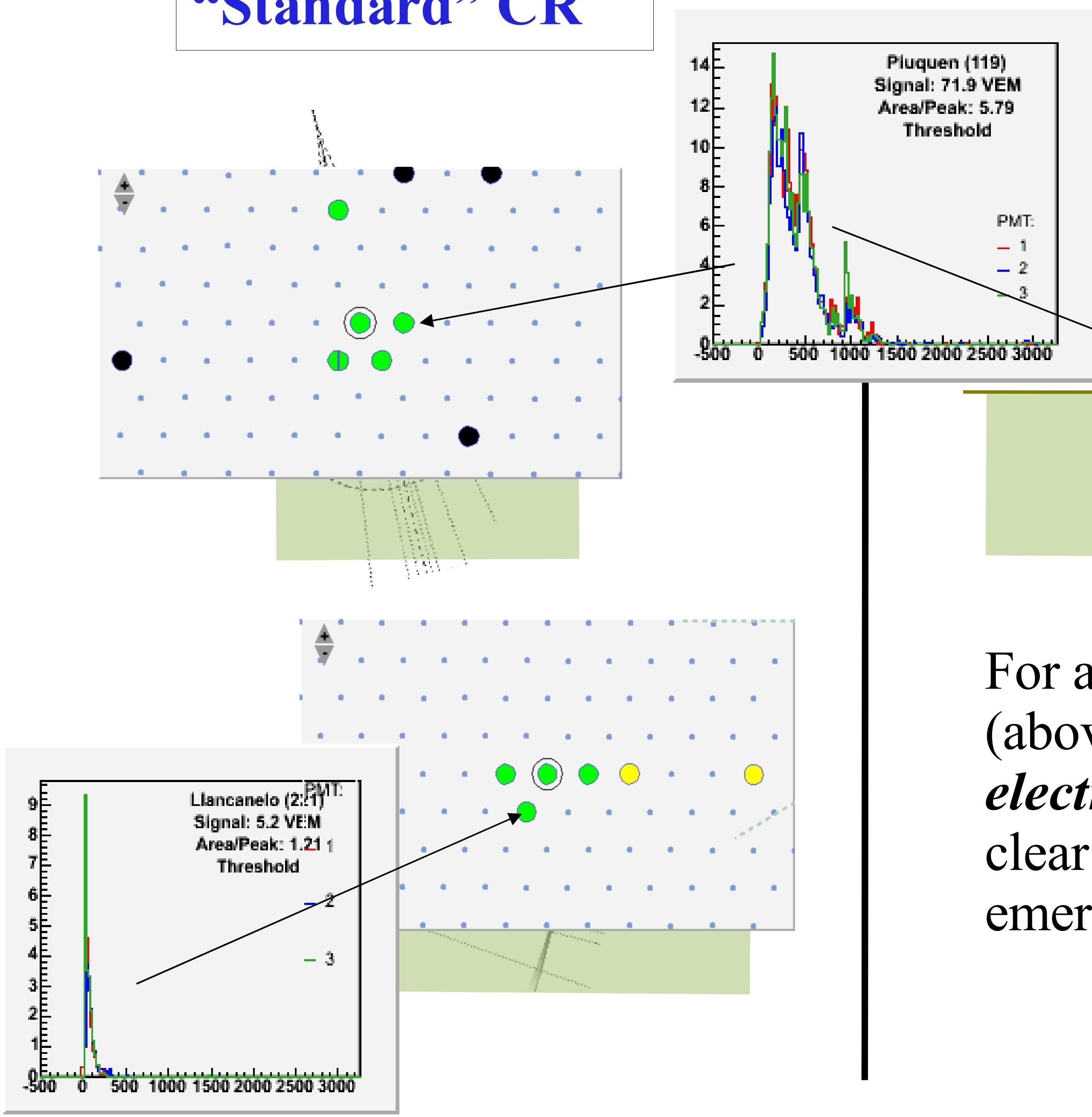


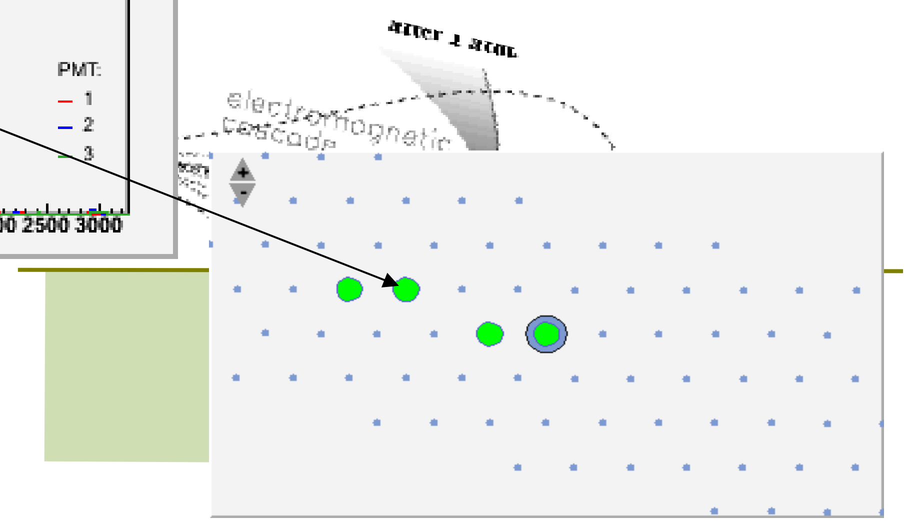


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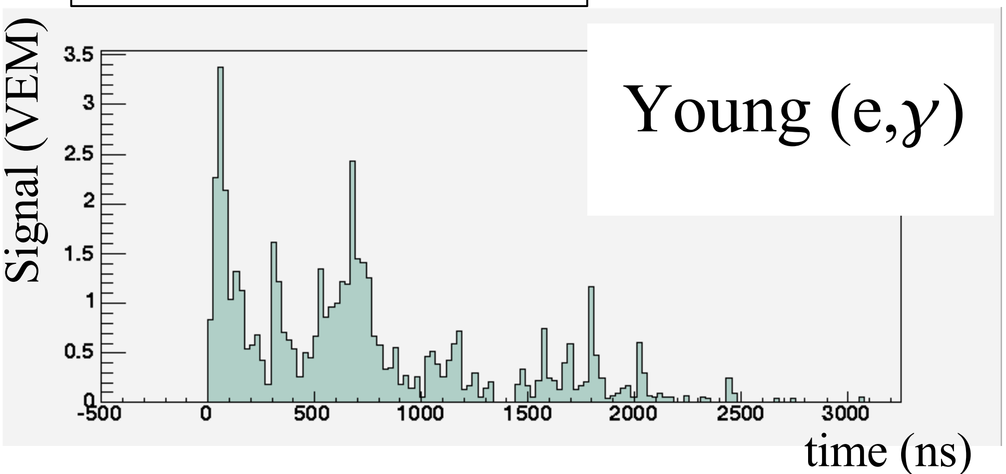
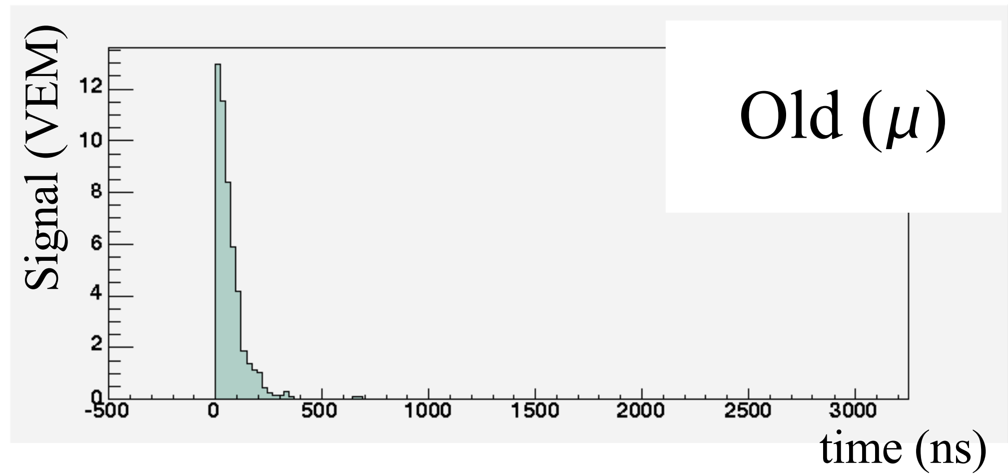
# IDENTIFICATION

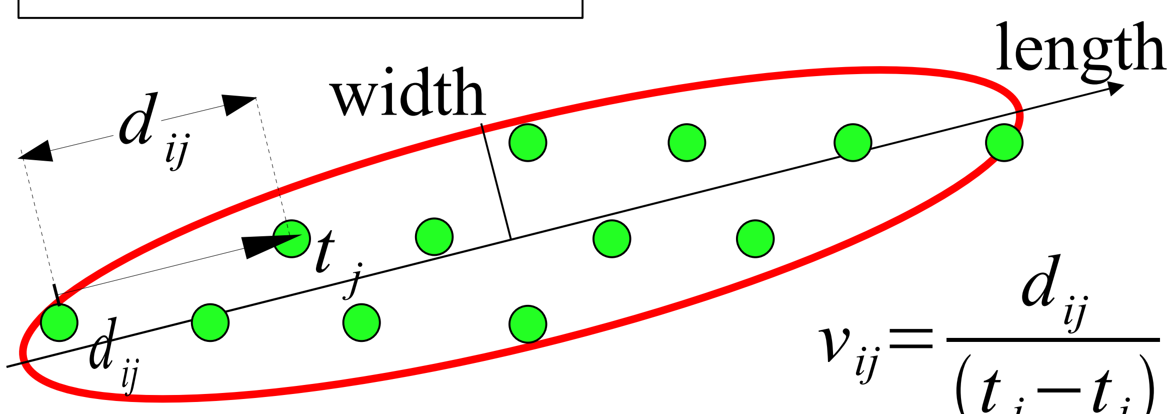
***Shower induced by emerging τ : start close to the detector (young) and is very inclined (90°< ϑ <95°)***

**Young Showers**




**Inclined Showers**




$$v_{ij} = \frac{d_{ij}}{(t_j - t_i)}$$

length/width > 5
<v> ∈ (0.29,0.31) m/ns
RMS(v) < 0.08 m/ns

***<u>No candidate</u> (Jan'04 - Aug'07), while ~80% identification efficiency***

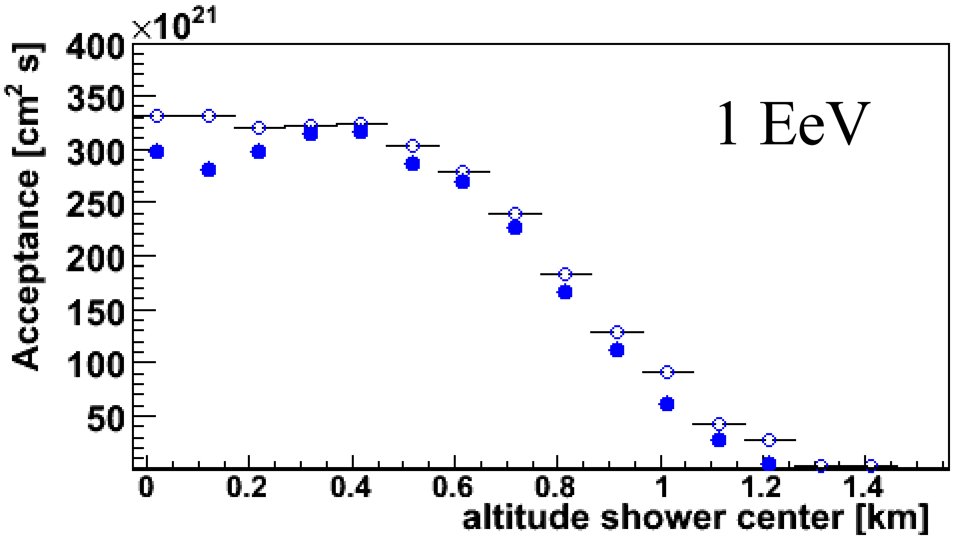
# ACCEPTANCE

## Atmosphere and detector

Acceptance for $\tau$ showers

- Depends on tau energy and altitude shower centre
- Growing detector

$$Acc_\tau(E_\tau, dh_c)$$




$$\int dh_c \frac{d^2 N}{dE_\tau dh_c} Acc_\tau(E_\tau, dh_c)$$

## Earth Monte Carlo

Conversion $\nu_\tau \rightarrow \tau$

- Neutrino cross section
- Tau energy losses
- Tau decay

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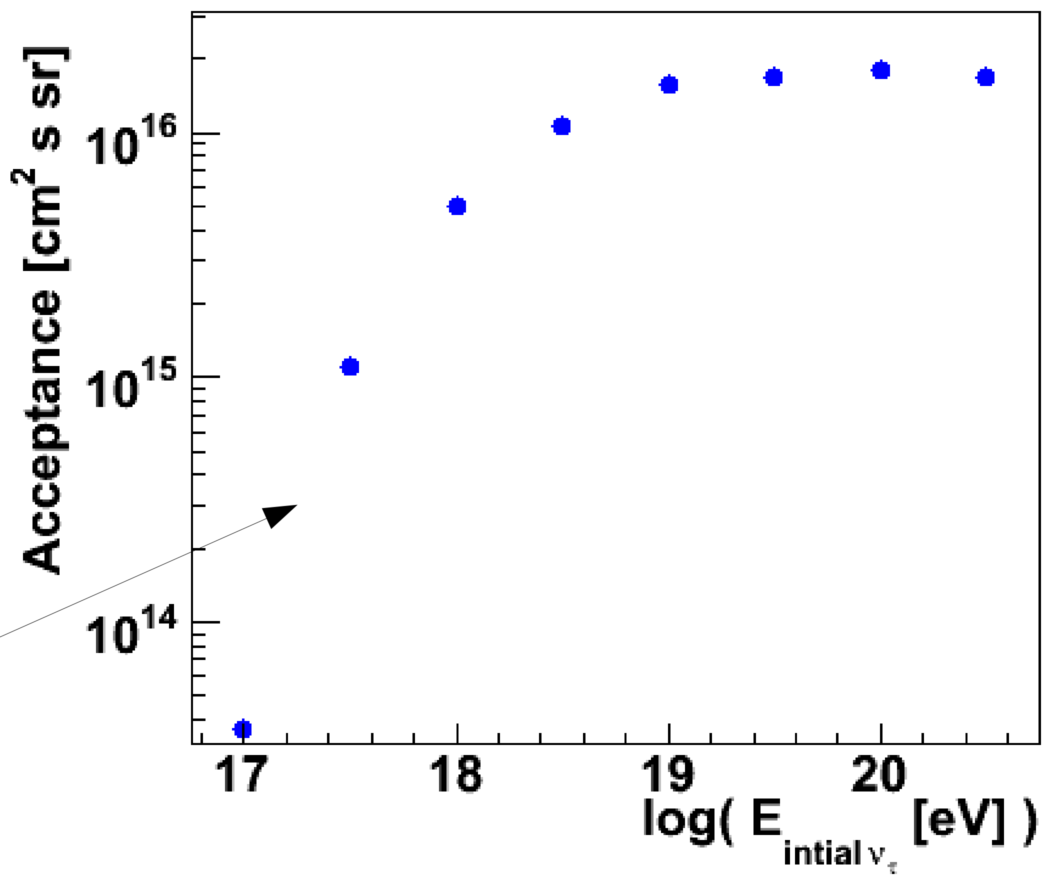

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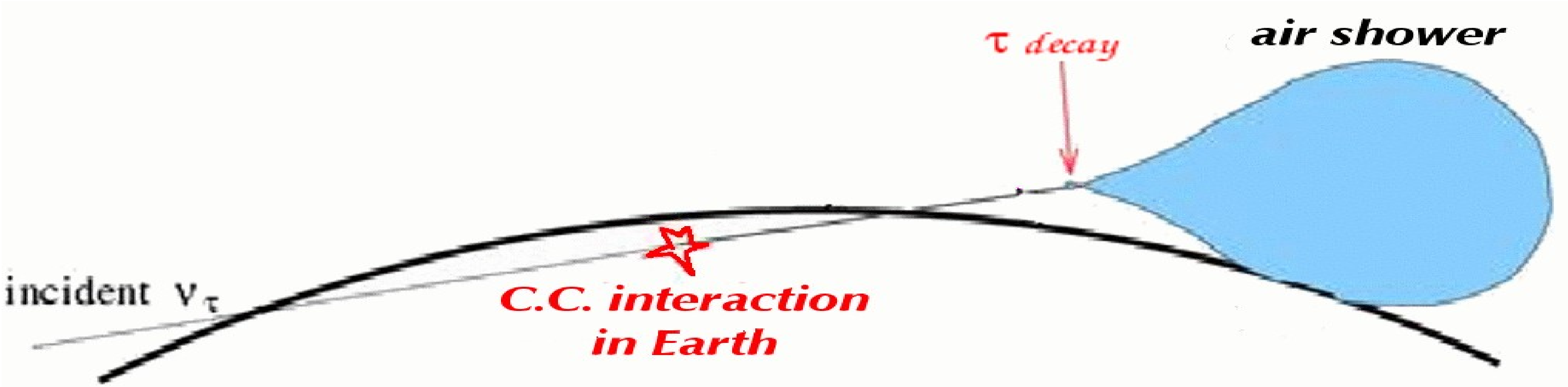


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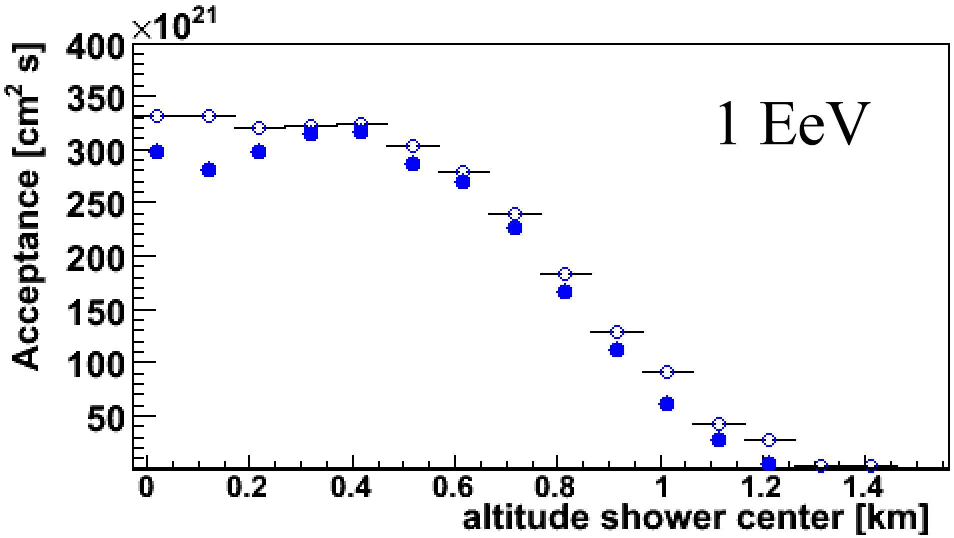


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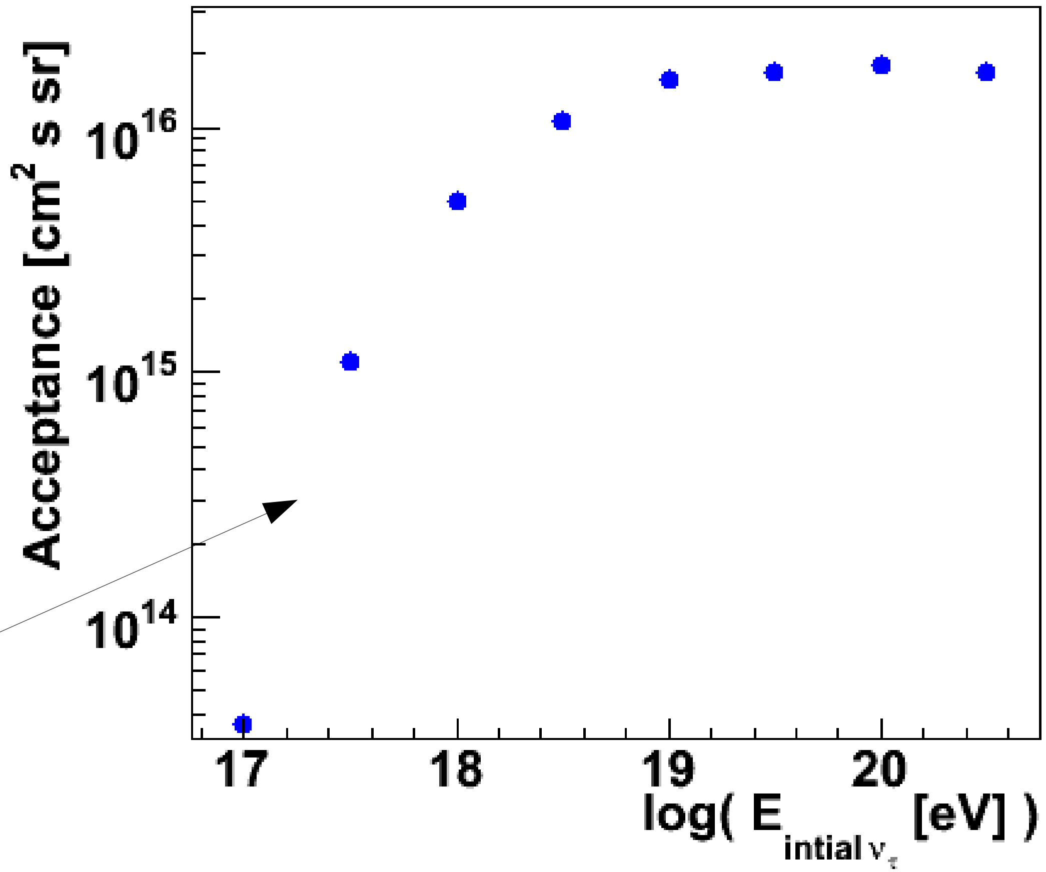

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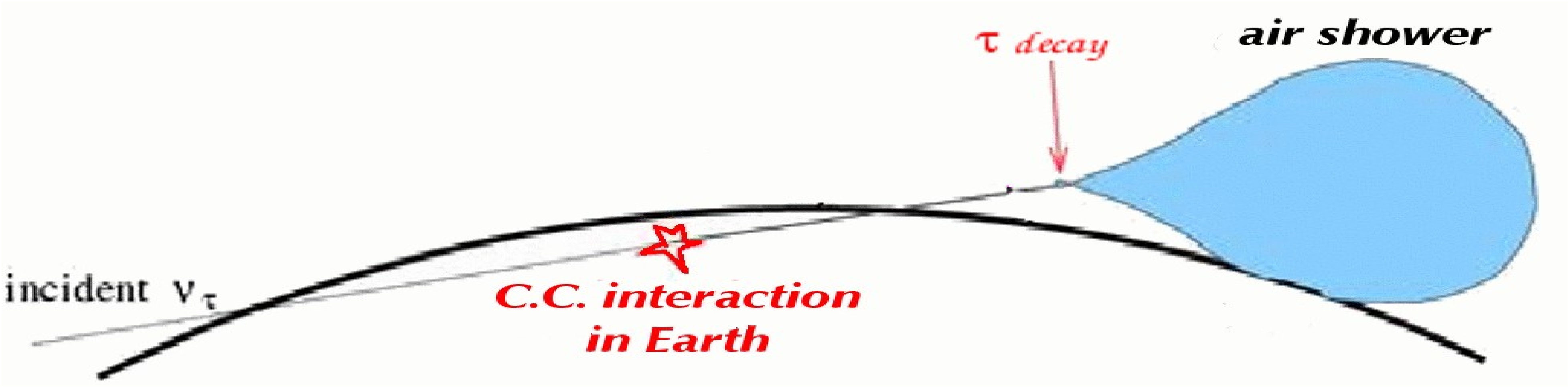


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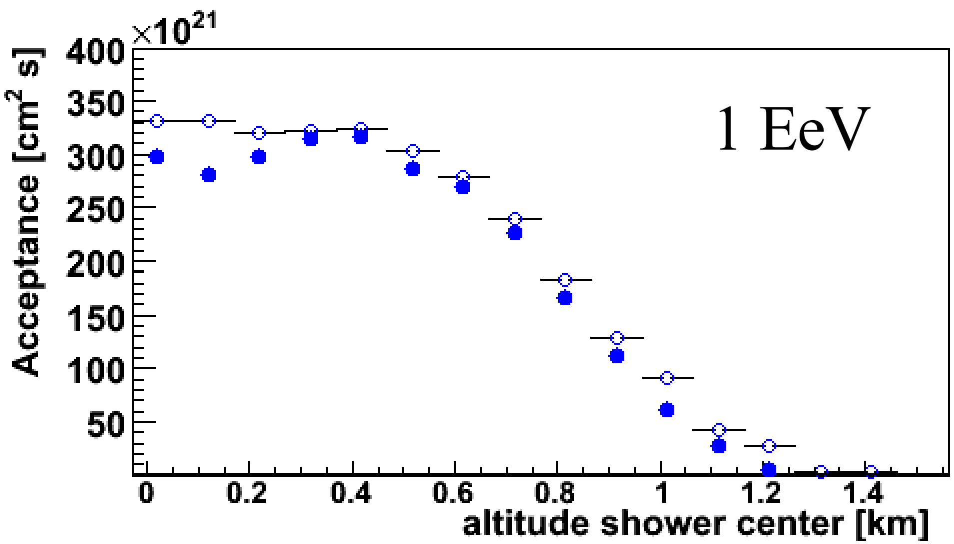


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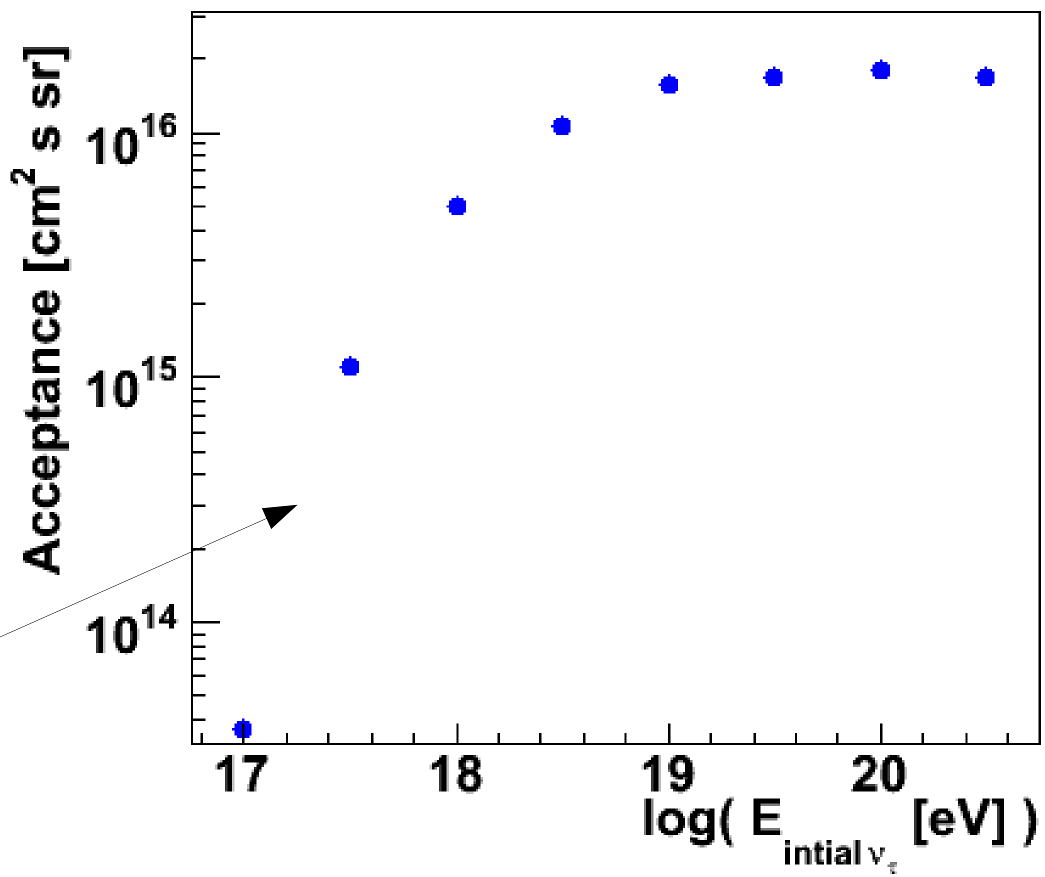
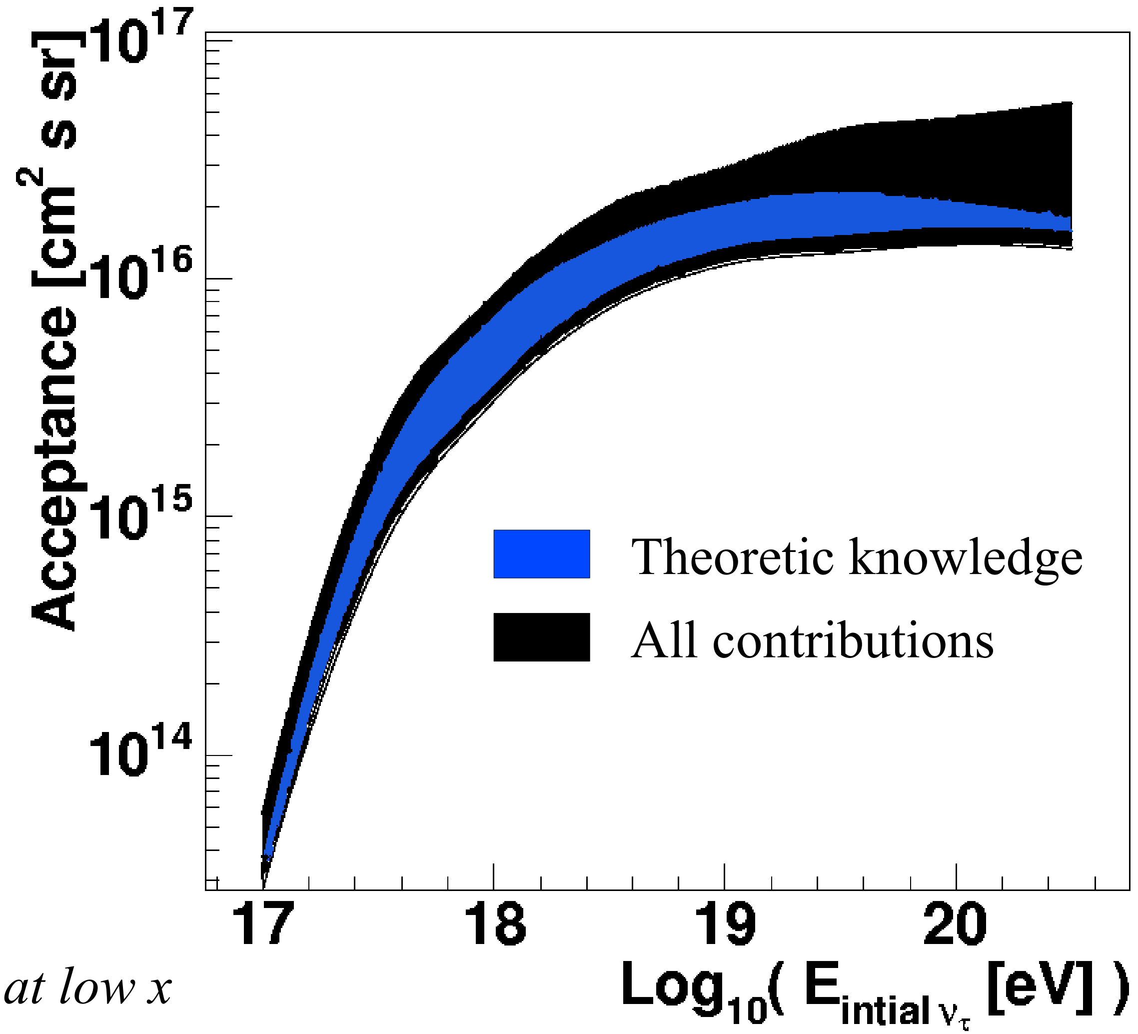


# SYSTEMATICS

| Source | Uncertainty |
|---|---|
| **MC Simulations** | |
| Interactions in Earth | ±5% |
| Extensive Air Shower | +20%, -5% |
| **Pierre Auger Observatory** | |
| Acceptance | ±2% |
| Topography | +18% |
| **Theoretic knowledge** | |
| Tau Polarisation | +17%, -10% |
| Cross Section | +5, -9% |
| Energy Losses | +25%, -10% |
| **Total** | +132%, -45% |

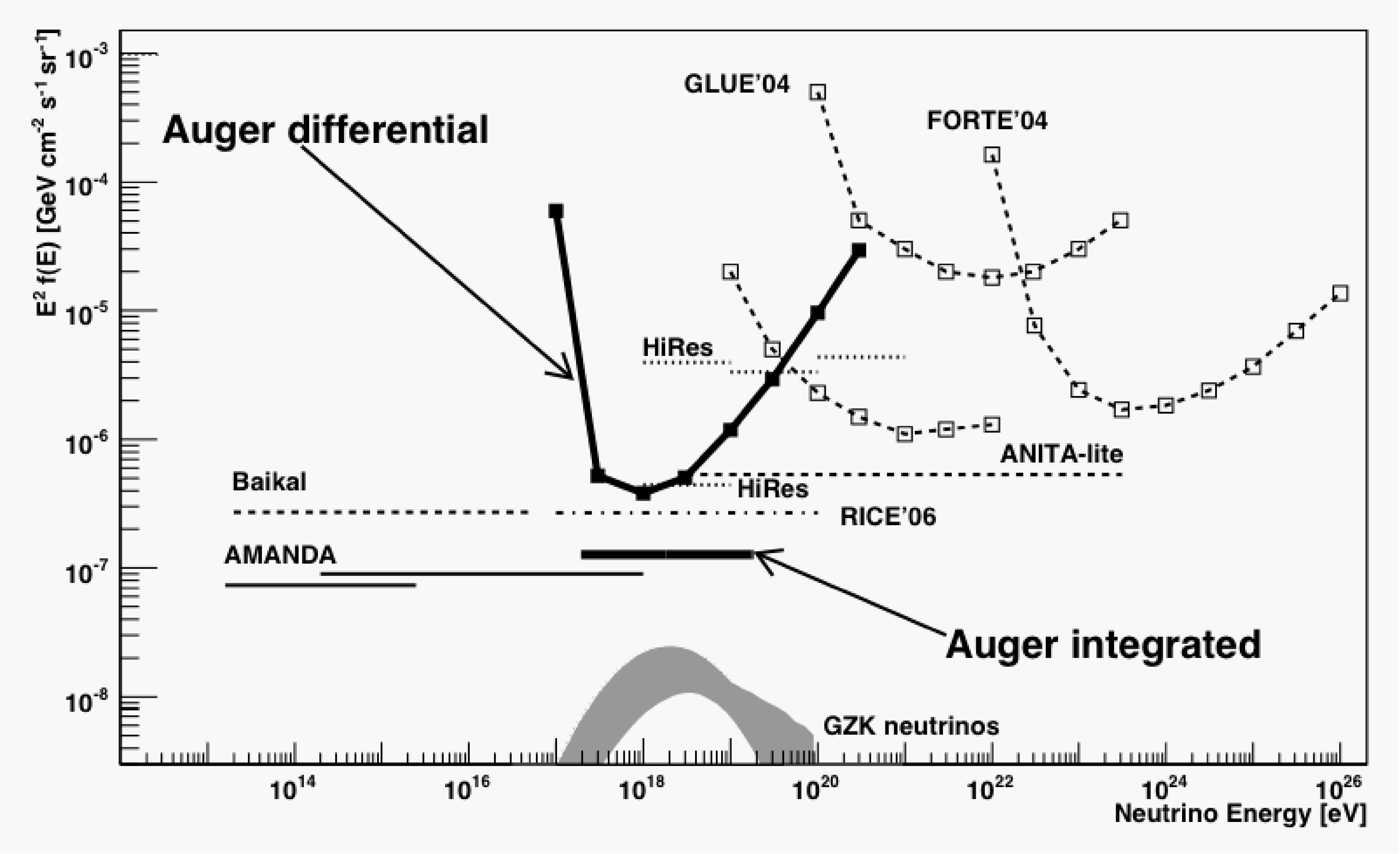



*Parton Distribution Function uncertainties at low x and high $Q^2$ are not taken into account*

***Worst/Best combination of scenarios leads to a factor ~3 difference for the flux limit***

# FLUX LIMIT

**90 % CL** <u>for each flavour</u> with the worst systematic scenario and assuming: $\frac{dN_{\nu_\tau}}{dE} = f_0 E^{-2}$



# SUMMARY AND PROSPECTS

- The Pierre Auger Observatory has collected more UHE Cosmic Rays than all previous experiments together in **1 effective year** of operation producing **outstanding physics results**.

- The observed anisotropy of the highest energy events has finally opened the door for **Cosmic Ray astronomy**.

- The fact of being correlated with nearby sources, together with the flux suppression at the same energy scale, is the first clear **experimental indication of the GZK effect**, which was predicted long time ago.

- The high quality data provided by the Pierre Auger Observatory also gives information about the **composition of the Cosmic Rays** (proton, iron, photon, neutrinos) as well as the **interactions at the highest energies**, much higher than those of the accelerators.

# THAT'S ALL FALKS

**THANKS FOR YOUR ATTENTION**