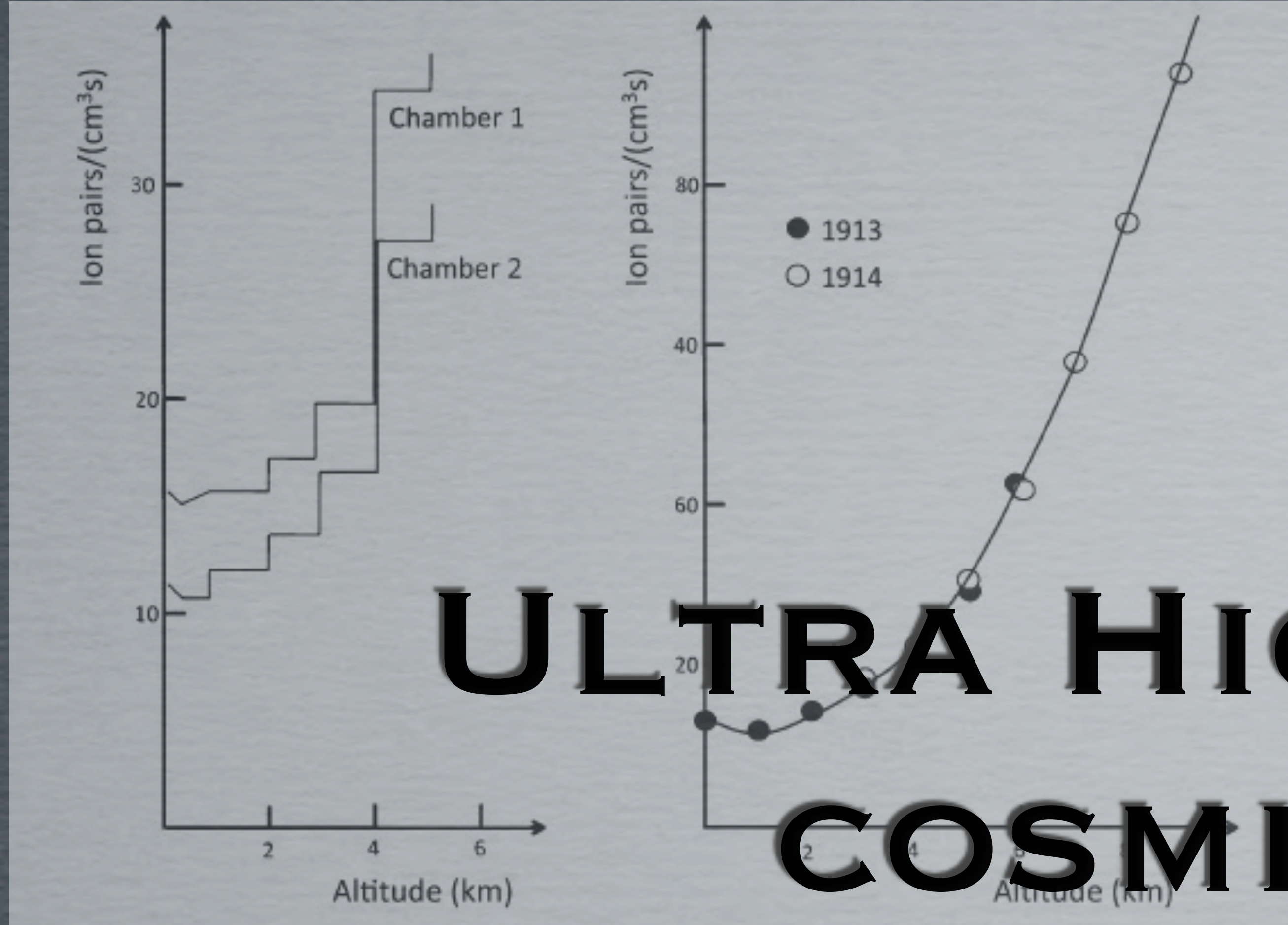
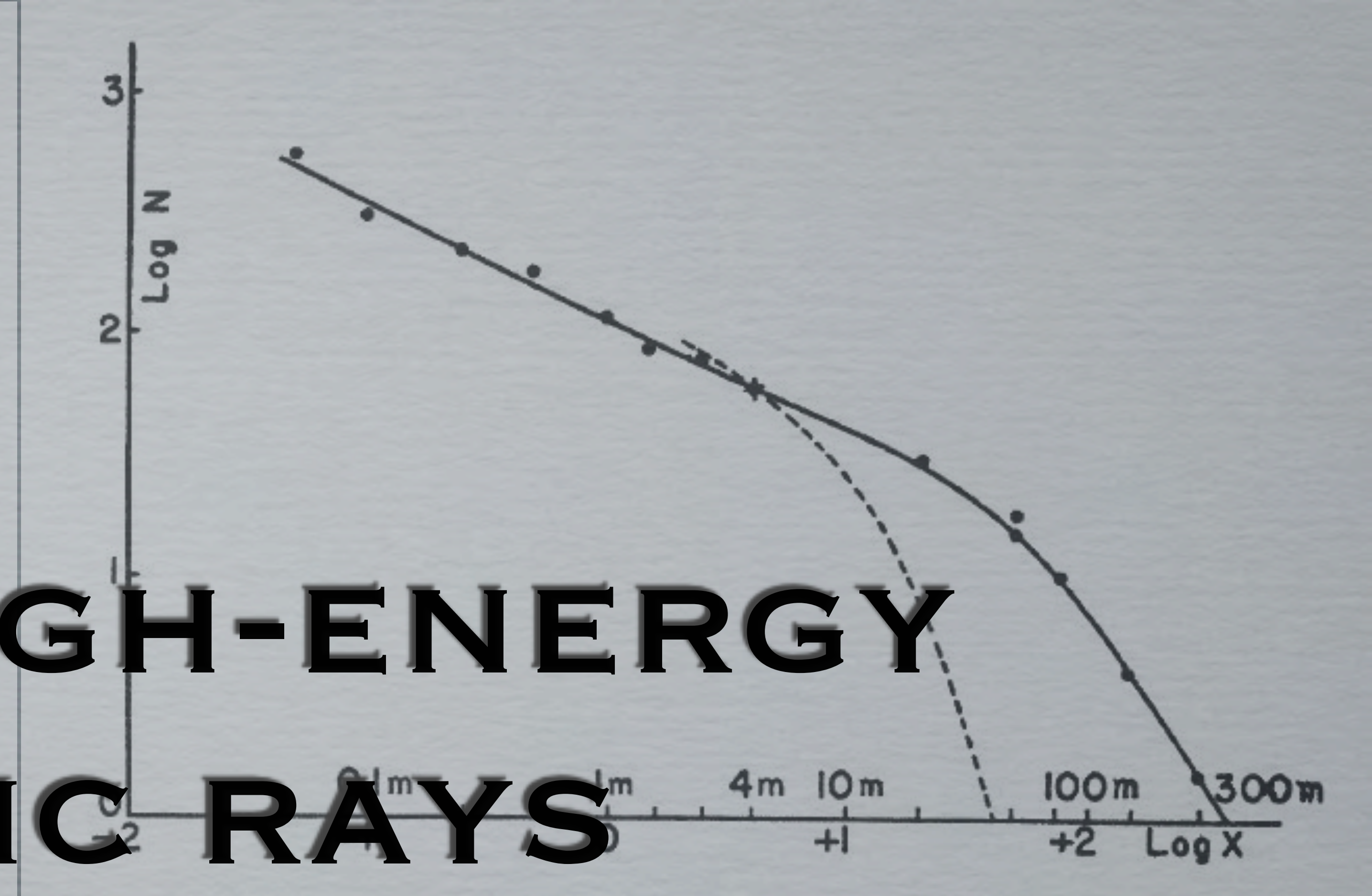
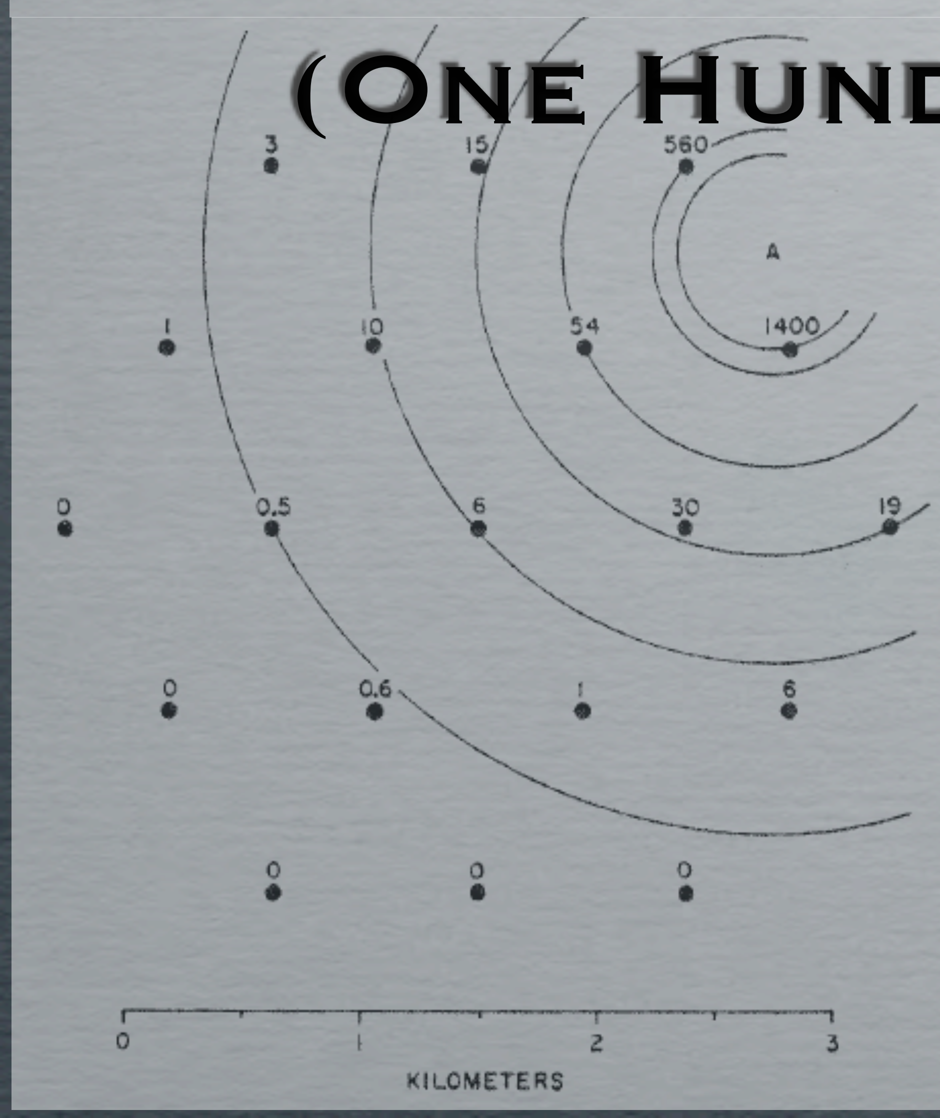
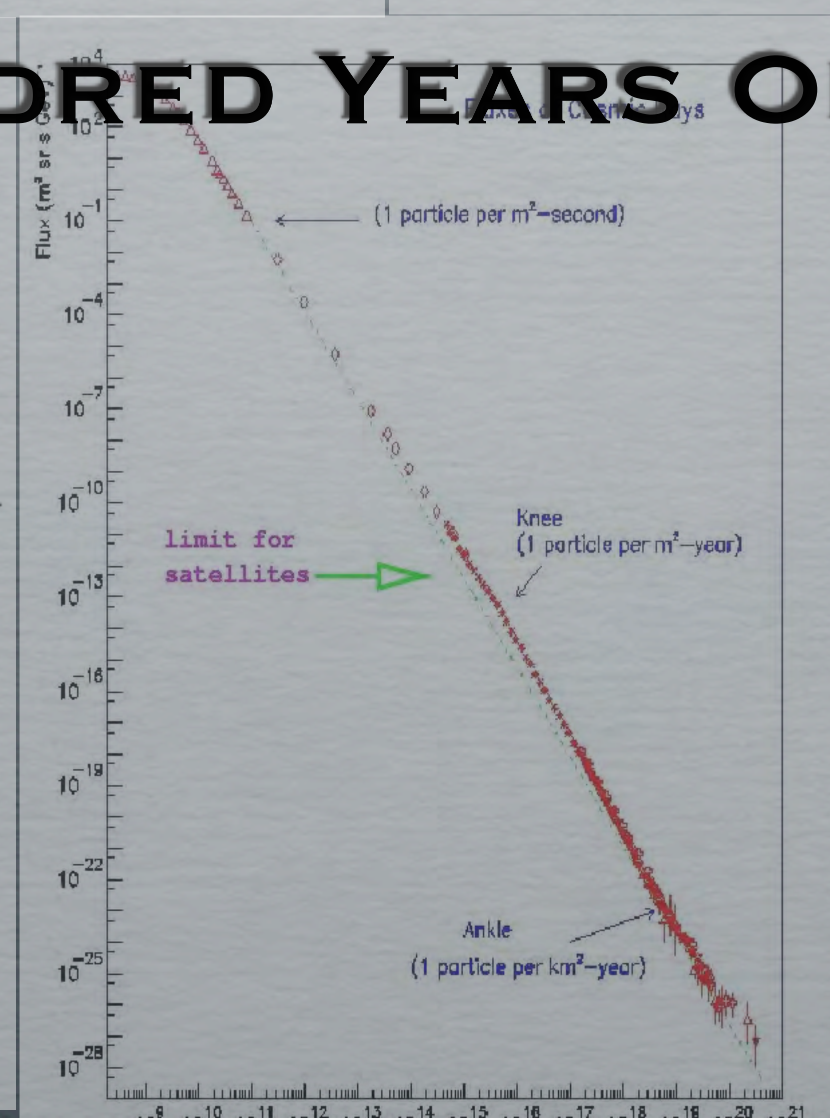
# ULTRA HIGH-ENERGY COSMIC RAYS

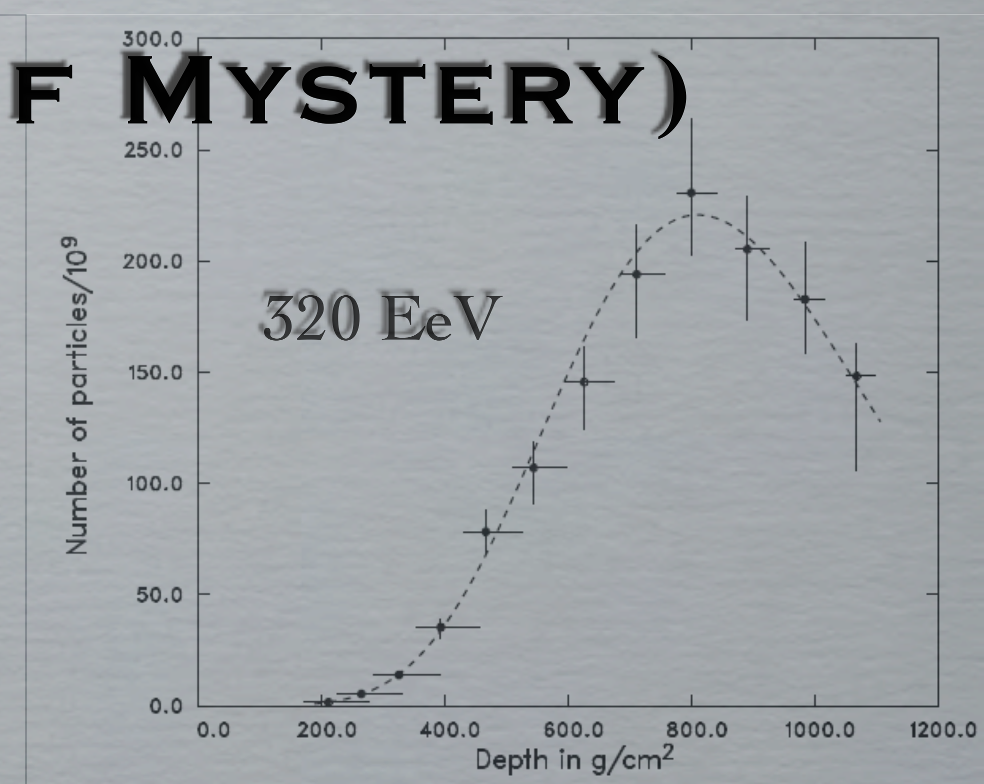
## (ONE HUNDRED YEARS OF MYSTERY)





ANTONIO BUENO
U. GRANADA


NOV, 2012

# Fundamental Physics: Experimental aspects

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- You need particles and detectors ➪ Two approaches:

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  - "King Midas" model:
    - Pay for particle source
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# Fundamental Physics: Experimental aspects

- You need particles and detectors ➪ Two approaches:
  - “King Midas” model:
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  - “Merkelian” model:
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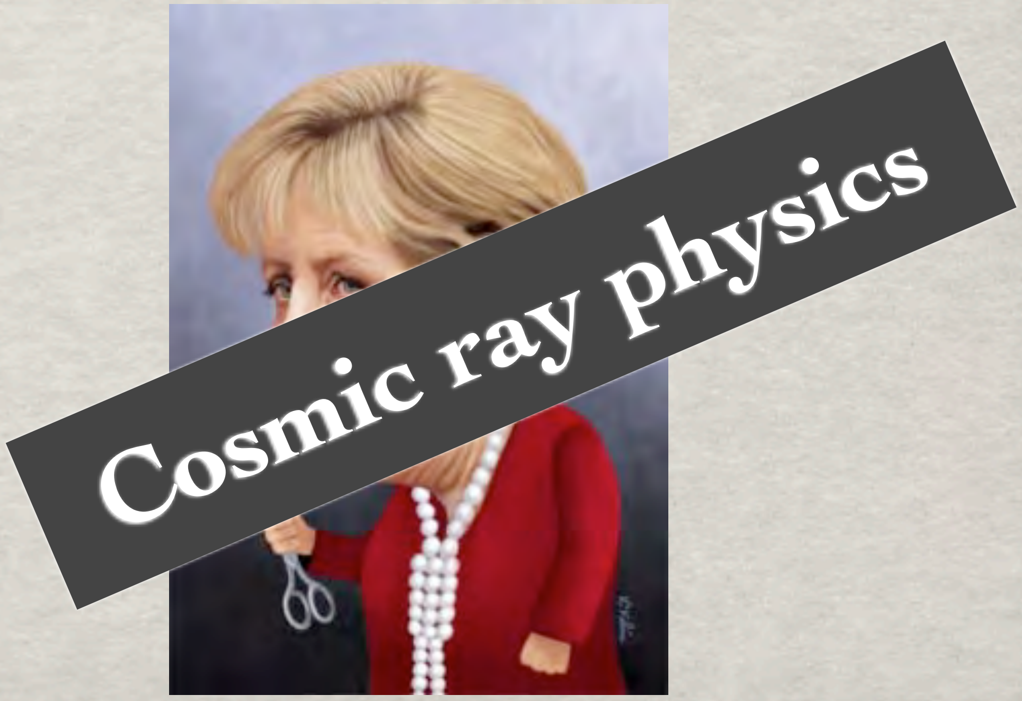
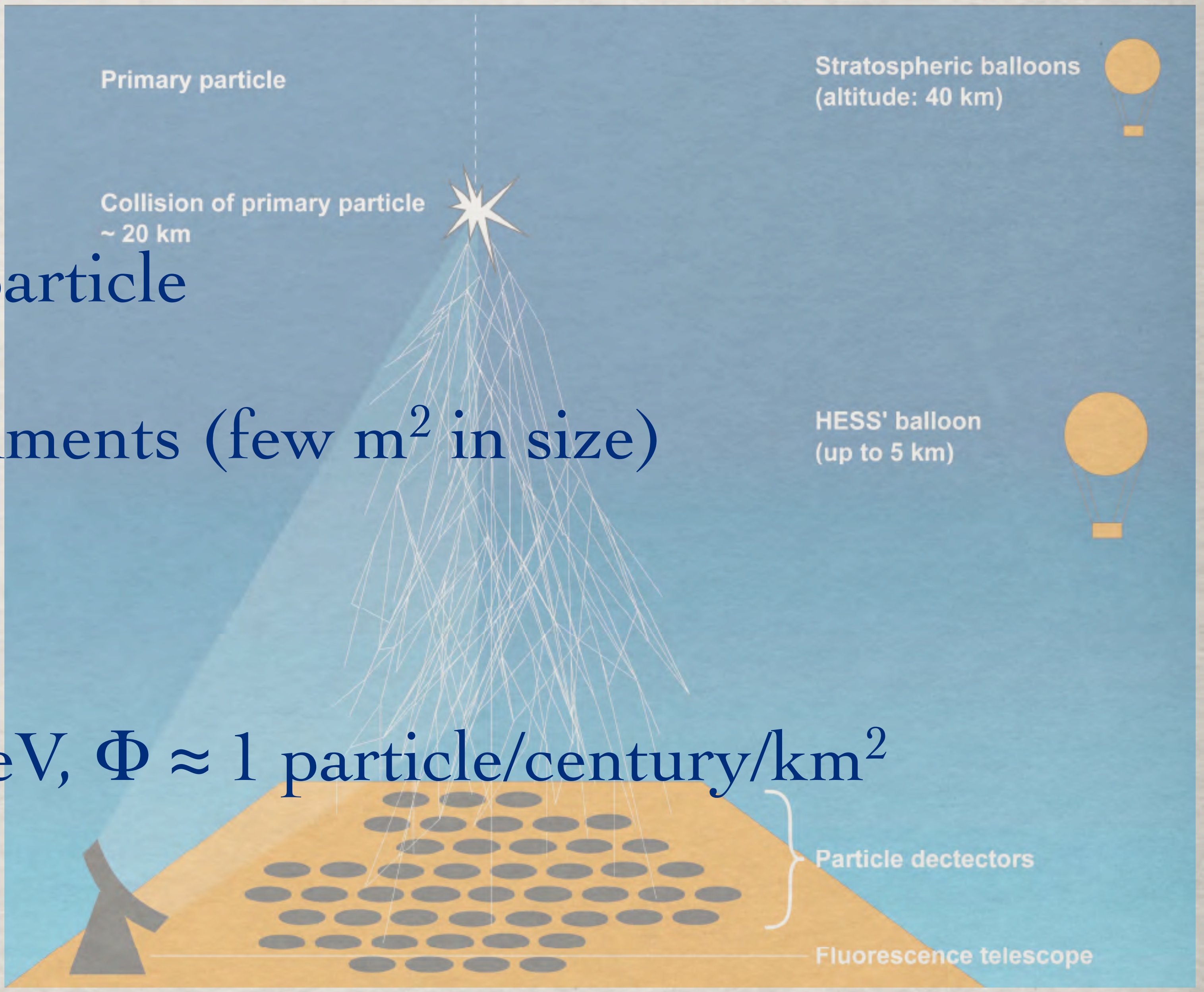


# Detection Methods
## (over many orders of magnitude in E)

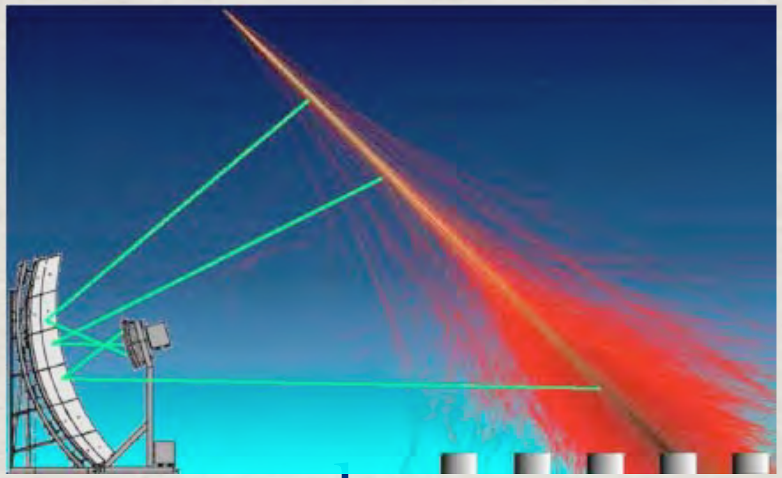



- E< $10^{15}$ eV
  - Detect directly incident particle
  - Balloon or satellite experiments (few $m^2$ in size)
- E> $10^{15}$ eV
  - Small flux ➠For E≈$10^{20}$ eV, $\Phi \approx 1$ particle/century/$km^2$
  - Two techniques:
    - AIR-SHOWER GROUND ARRAYS
    - FLUORESCENCE TELESCOPES

A vertical proton with $10^{19}$ eV generates at sea level approx. $3 \times 10^{10}$ particles

# GROUND BASED DETECTORS

**Particle detector arrays**



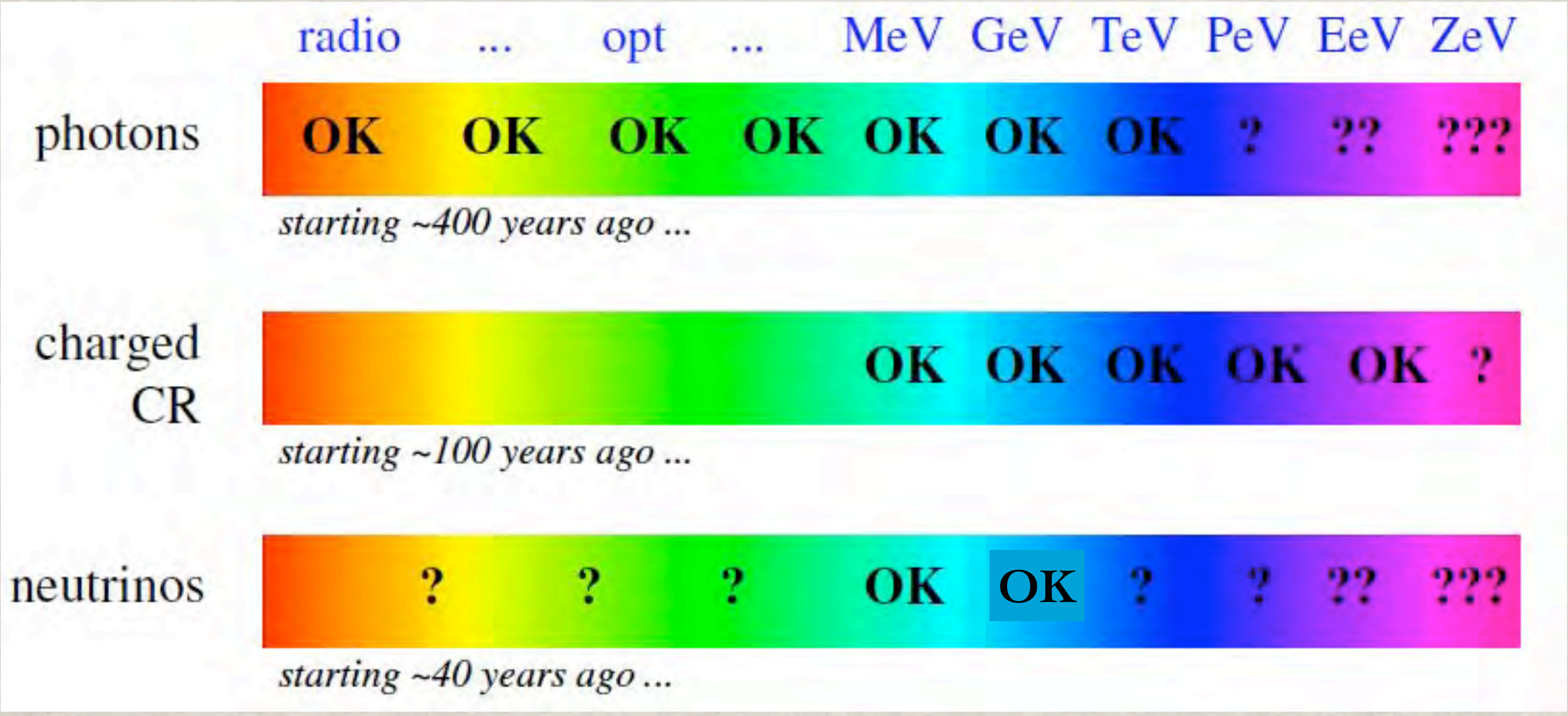
**Fluorescence telescopes**

- Extensive Air Showers spread out over considerable areas
- Area covered by sensors function of probed energies: O(1000 $km^2$) for E~$10^{19}$ eV
- Sensor spacing *d* also a function of energy: *d* ~O(1km) for E~$10^{18}$ eV
- Scintillators, water Cherenkov tanks, muon counters, ...
- **≈100% duty cycle**

- UV light emitted by excited nitrogen molecules
  - Light yield ≈ 5.5 γ/MeV
- Isotropic
  - Shower observation from large distances (~ 20 km)
- Calorimetric estimate of the initial energy
- **Less than 15% duty cycle**

# Exploring a new realm

M. Risse et al., UEHCR 2012



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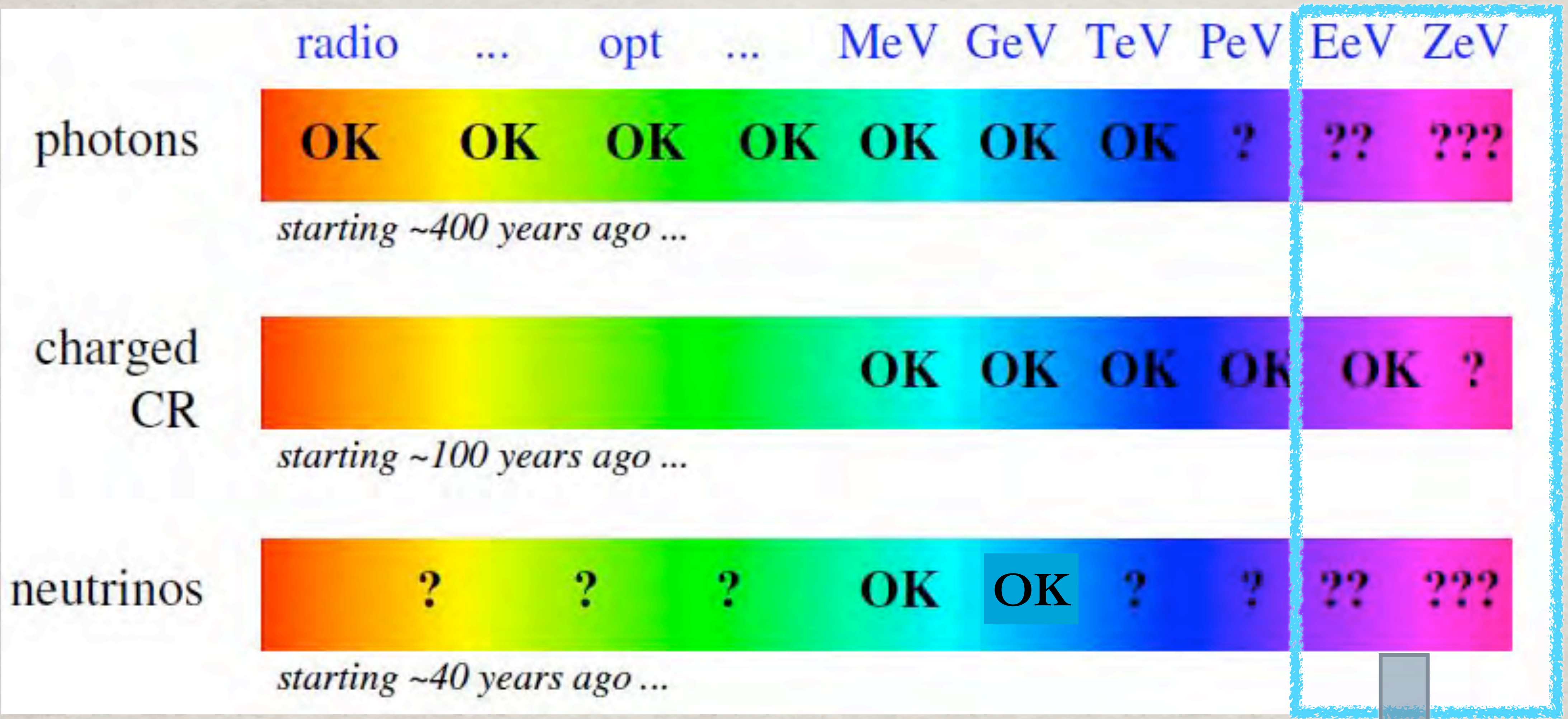
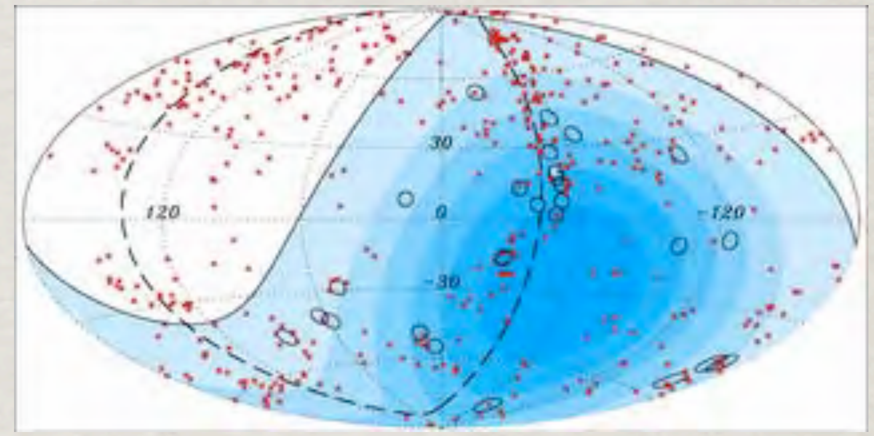


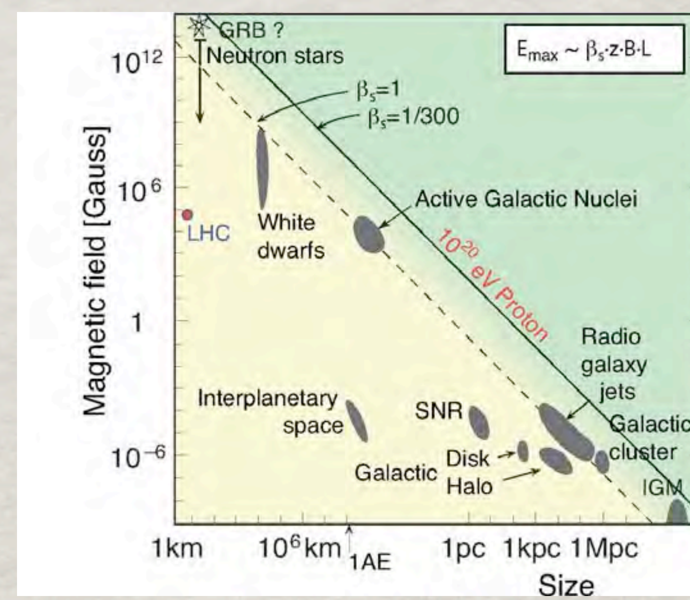

**History of physics:**
**open new windows... uncover the secrets of Nature**

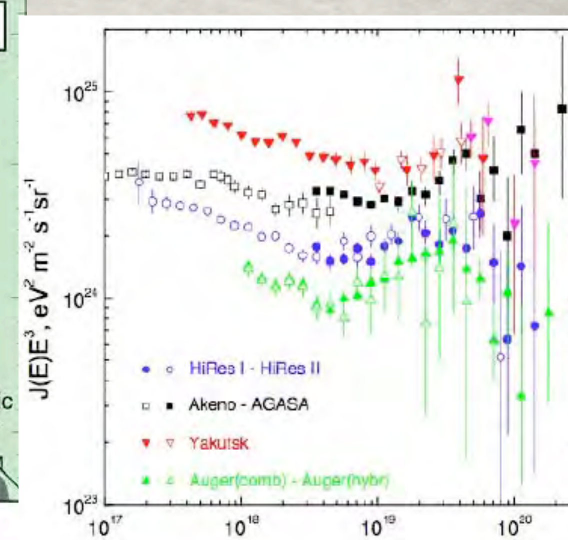
# Unanswered questions: Astrophysics

- Production sources

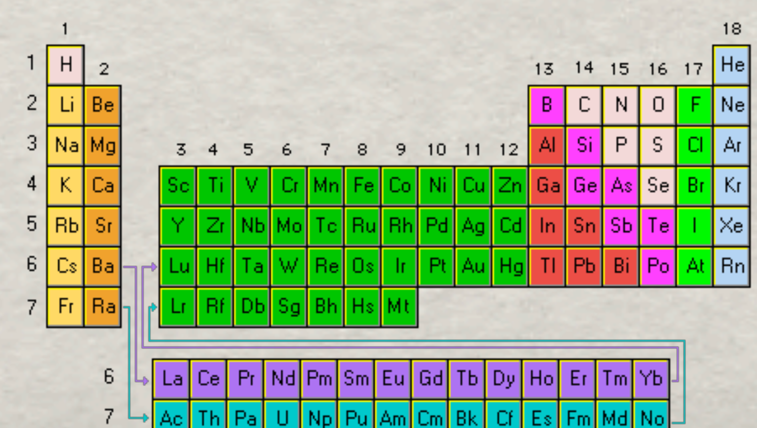



- Acceleration mechanisms



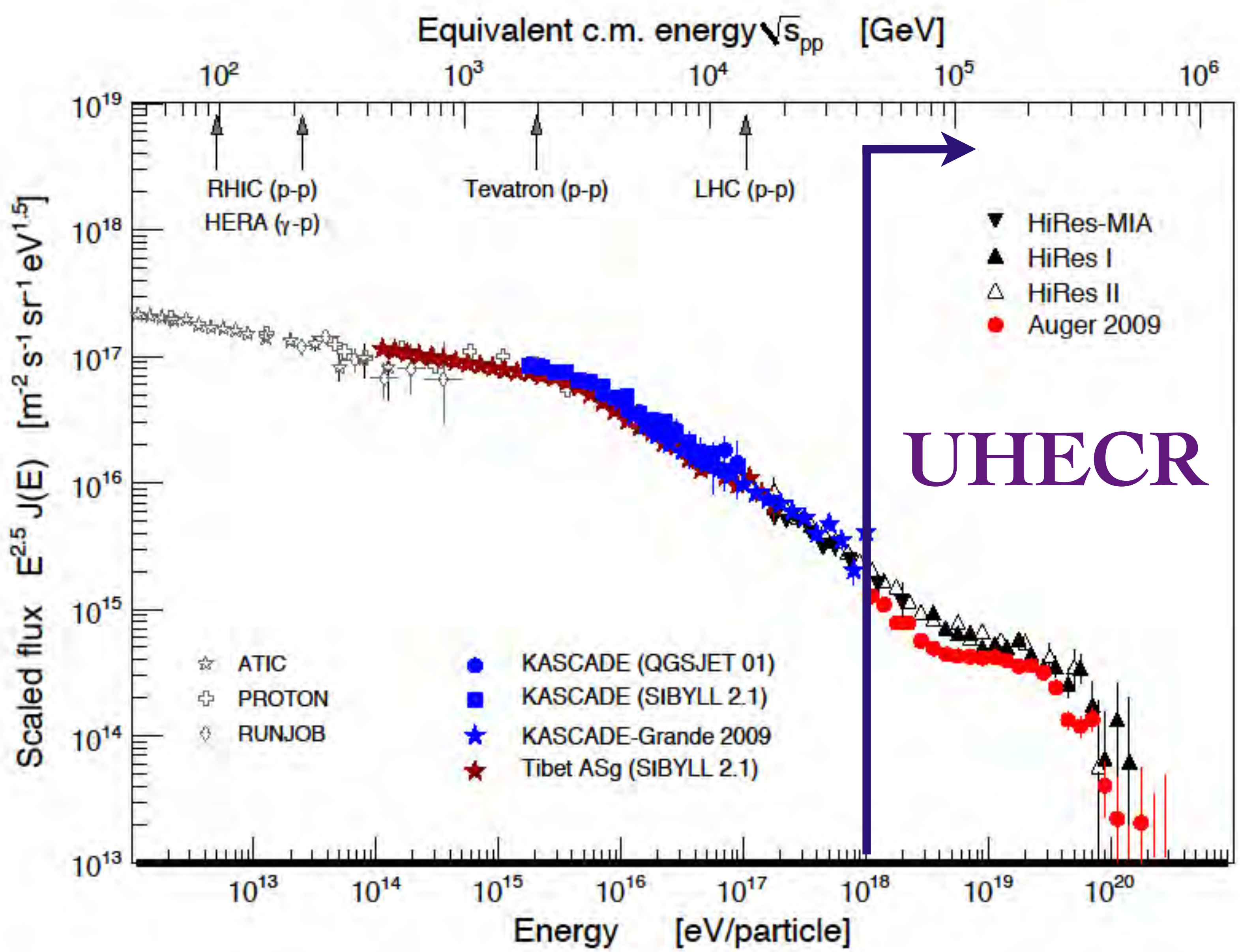




- Mass composition

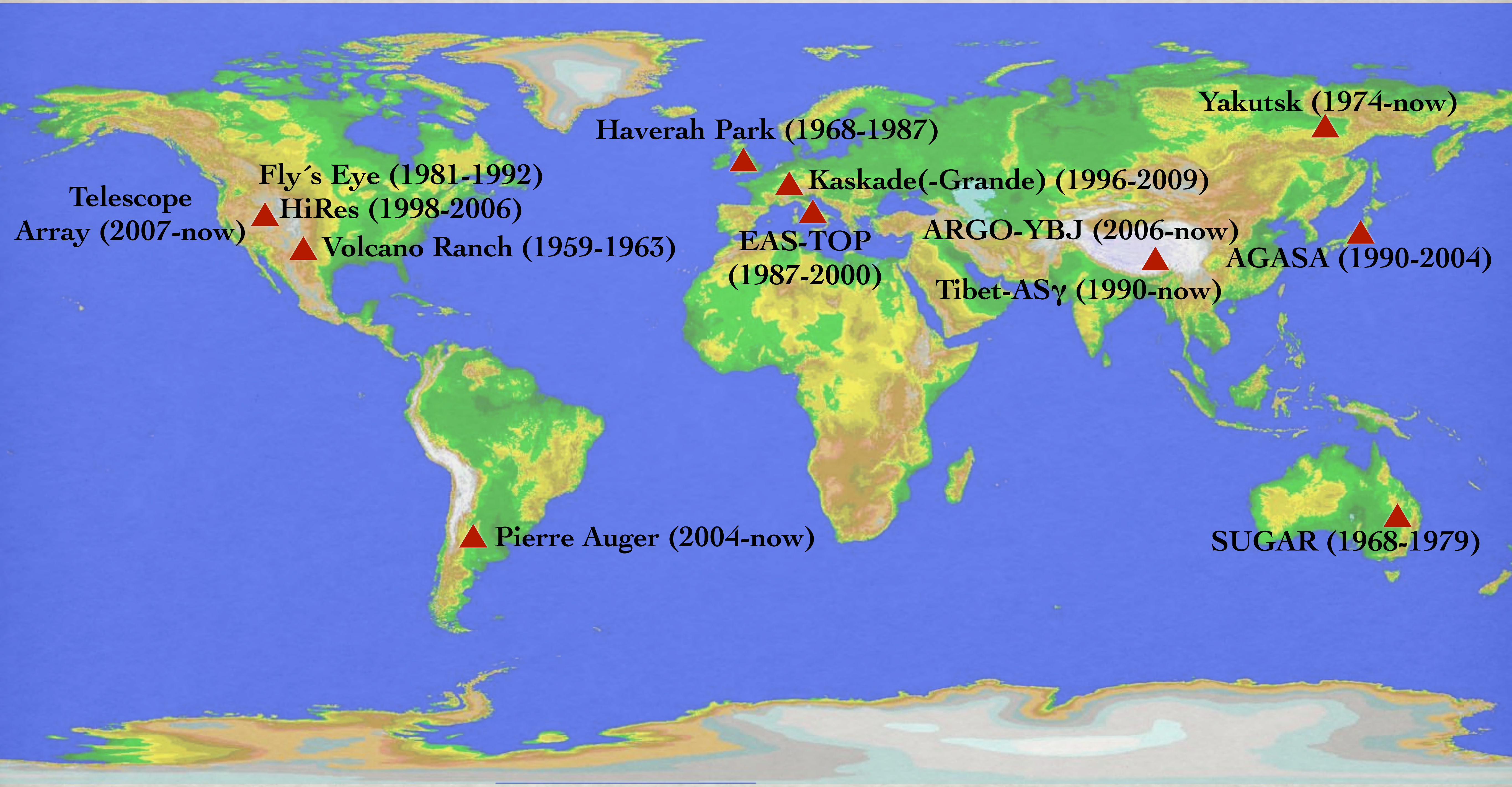


# Unanswered questions: Particle Physics

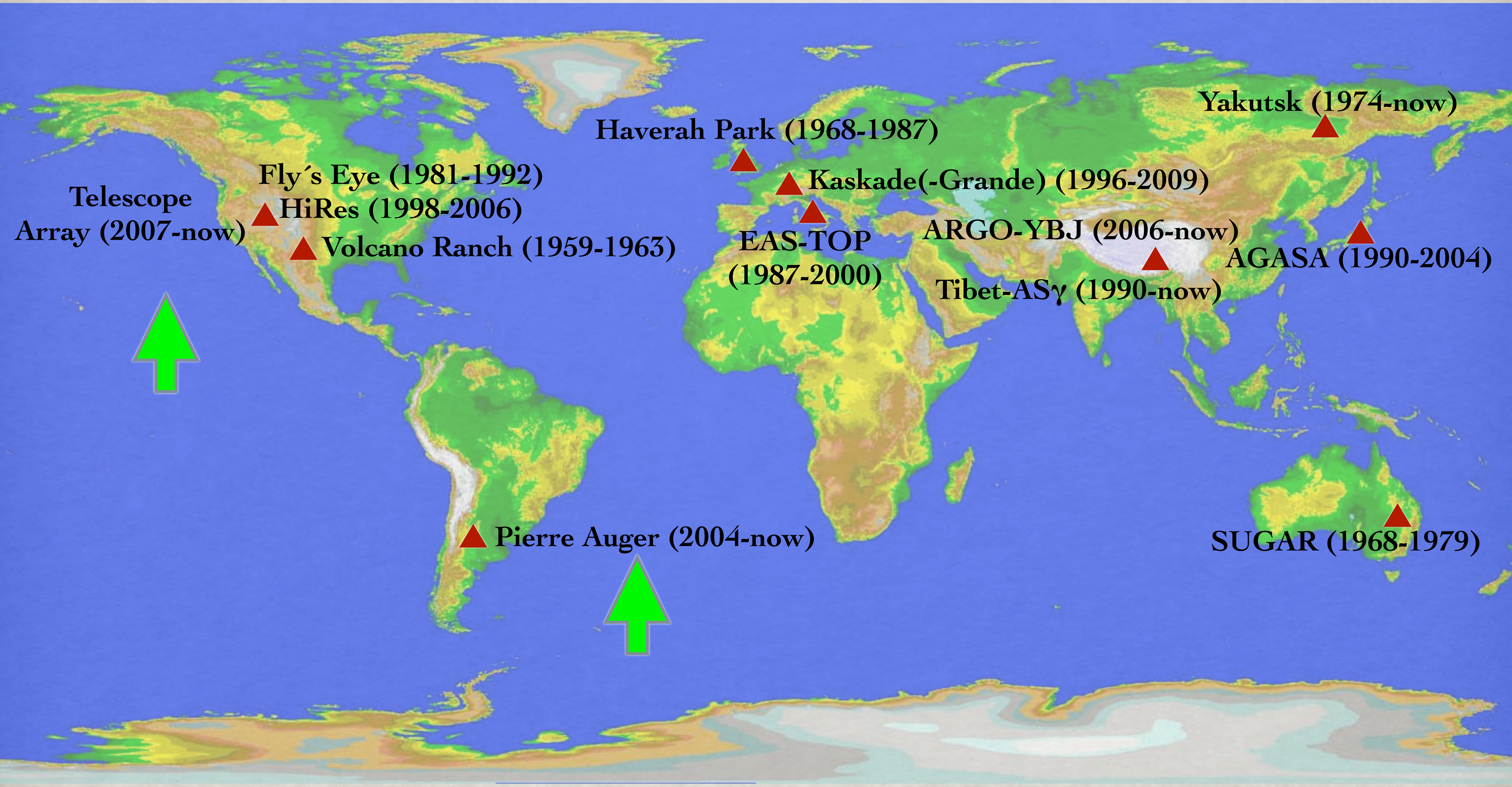
Test particle interactions at the highest energies!



# Experiments



# Experiments



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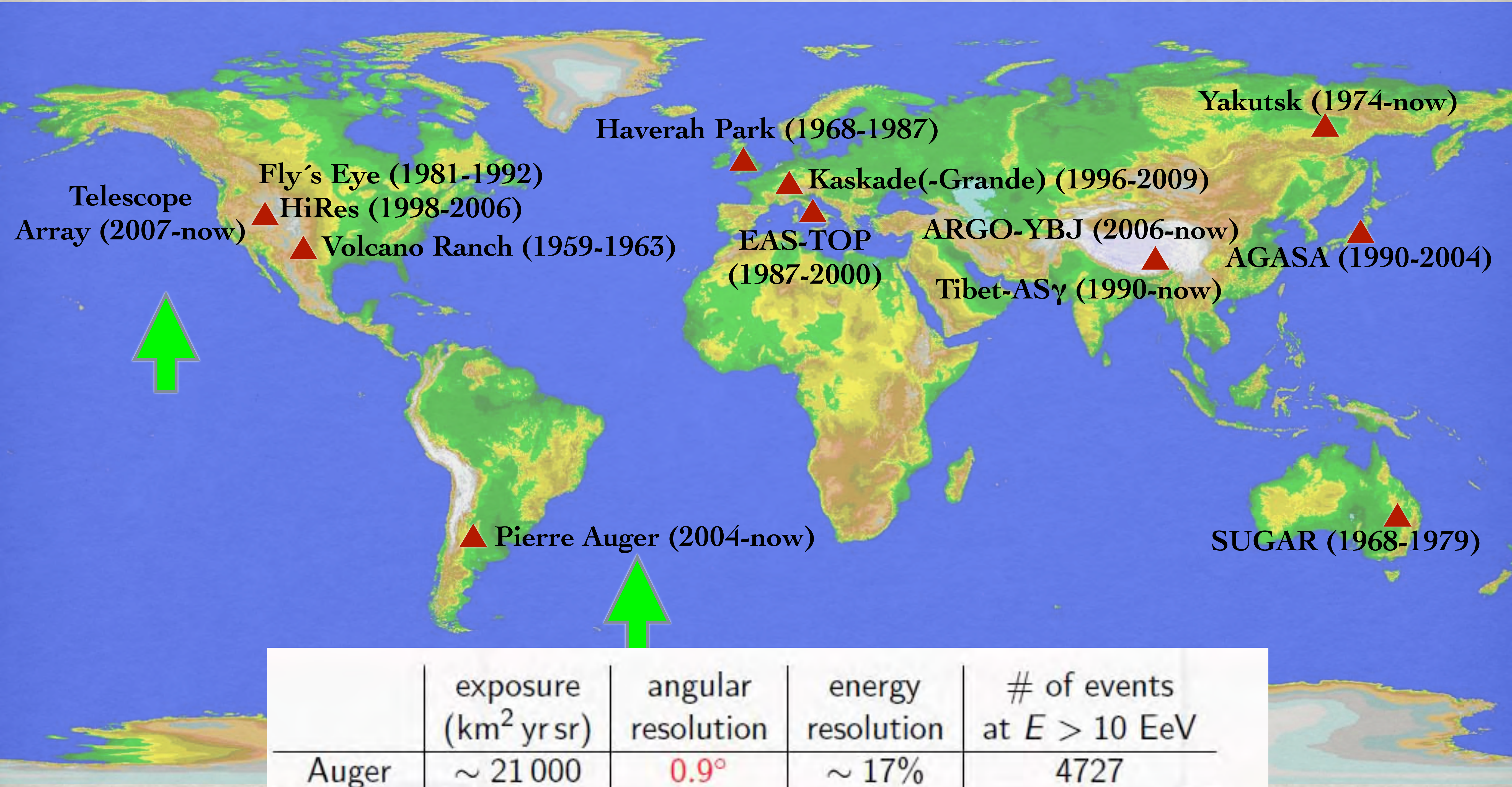



| | exposure ($km^2$ yr sr) | angular resolution | energy resolution | # of events at $E > 10$ EeV |
|---|---|---|---|---|
| Auger | $\sim 21\,000$ | 0.9° | $\sim 17\%$ | 4727 |
| HiRes | $\sim 2\,500$* | 0.6° | $\sim 14\%$ | 378 |
| TA | $\sim 2\,900$ | 1.5° | $\sim 20\%$ | 854 |
| Yakutsk | 824 | 2.5° | $\sim 30\%$ | 364 |

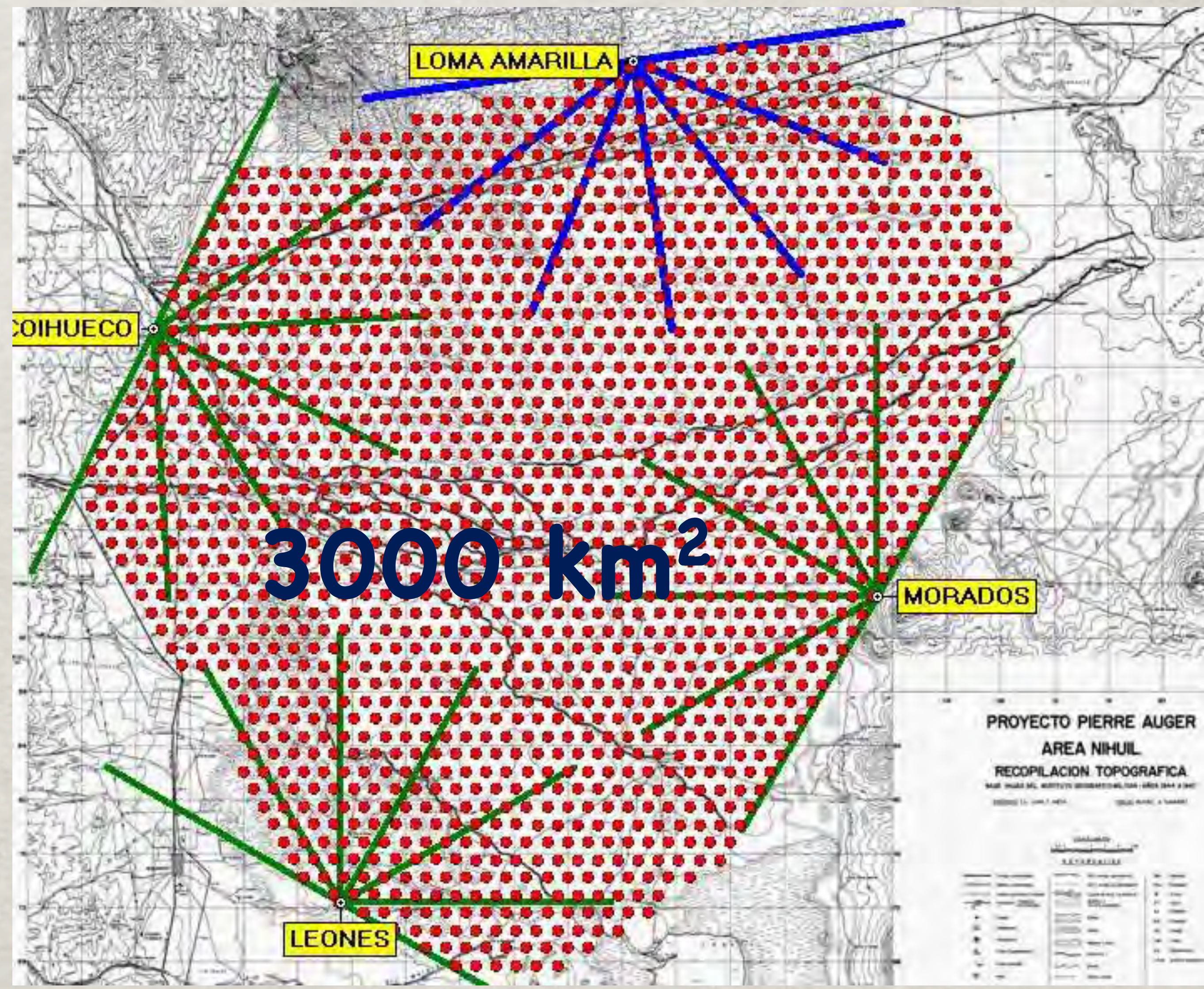
* at $E = 10^{20}$ eV

# Pierre Auger Observatory

**Malargüe $35^0$ S latitude**
**≈ 1400 m height ≈ 875 g/cm$^2$**

(completed in June, 2008)

## <u>Hybrid detector</u>

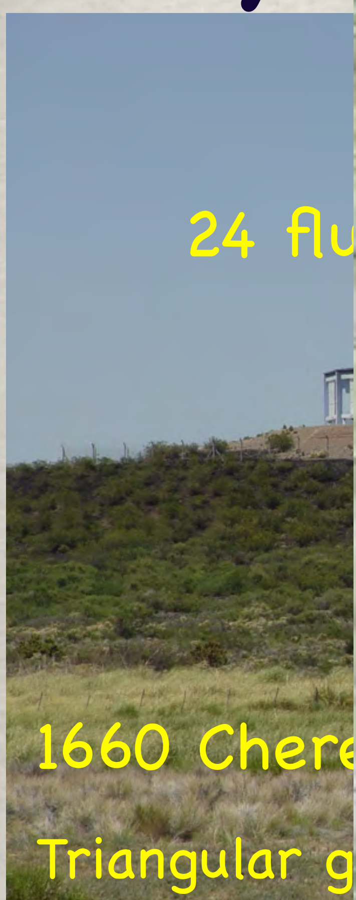

◄ **50 km** ►

# Pierre Auger Observatory

Malargüe
≈ 1400 m

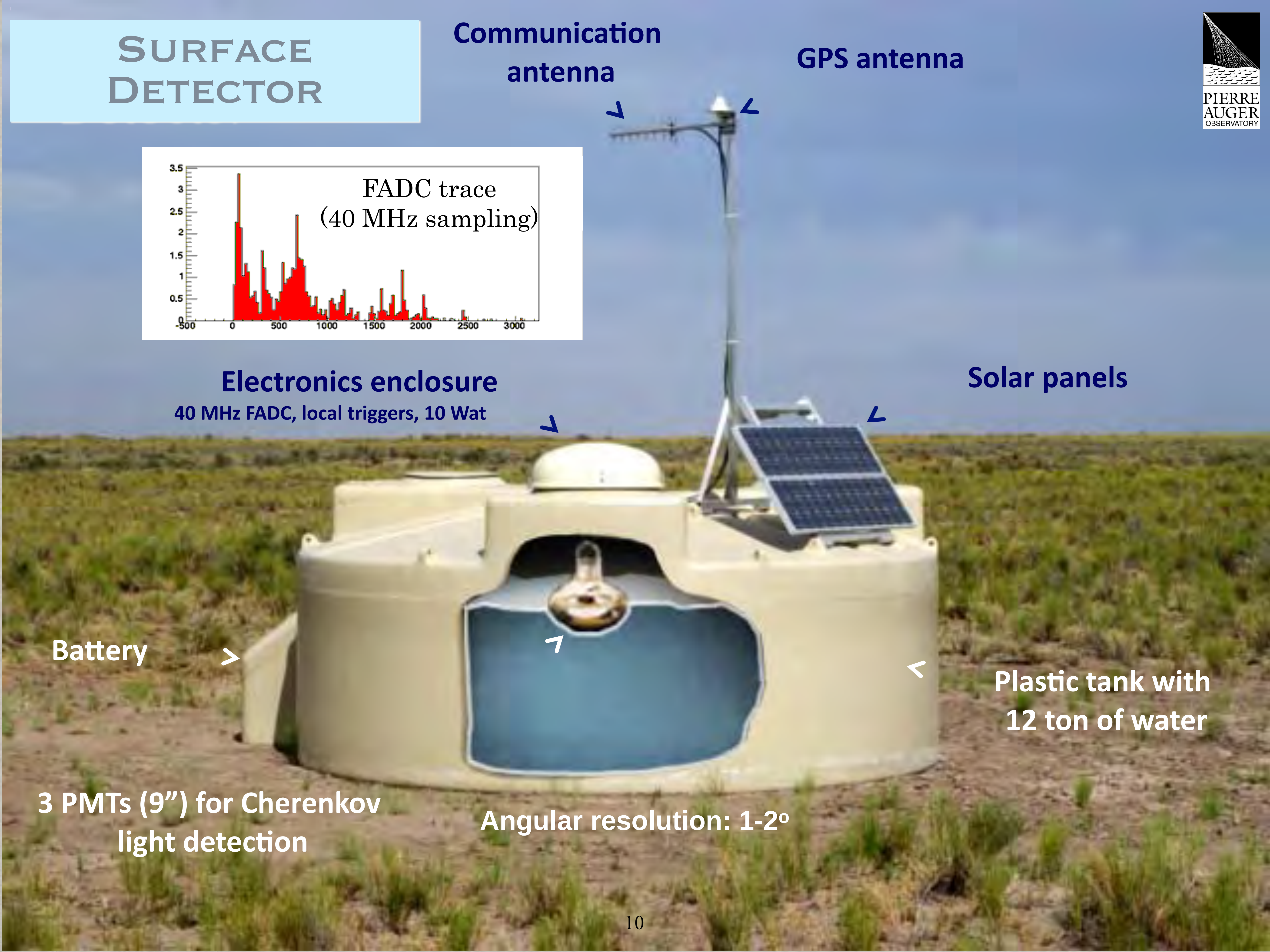
2008)

## Hyb

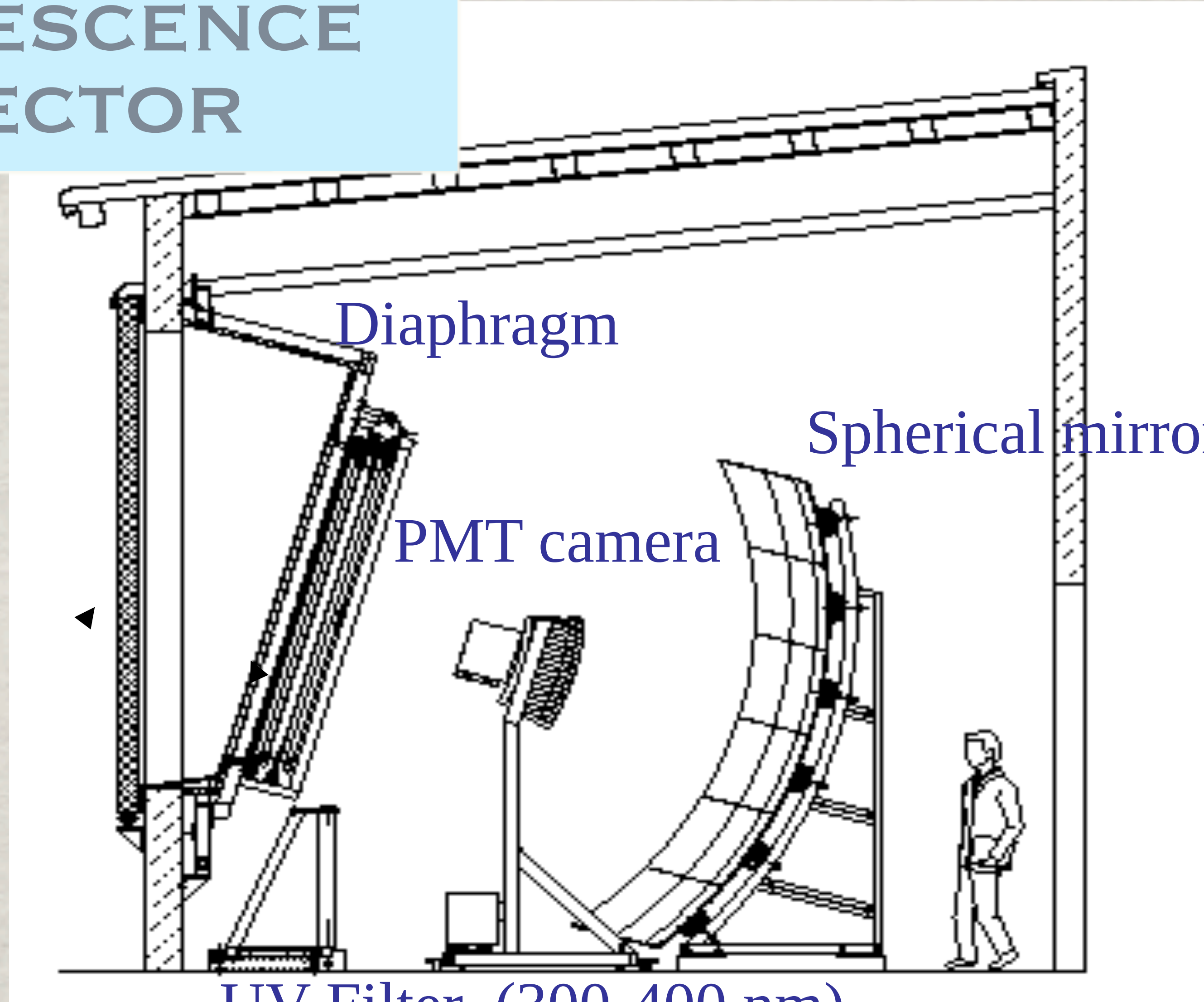


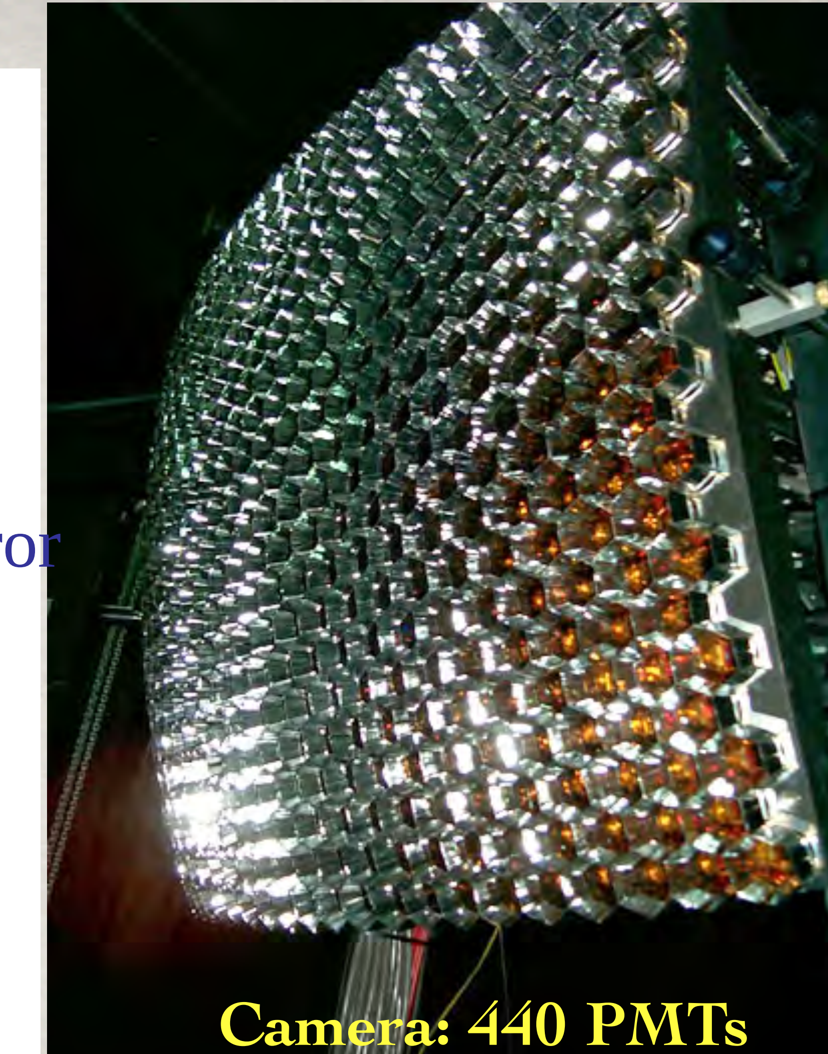


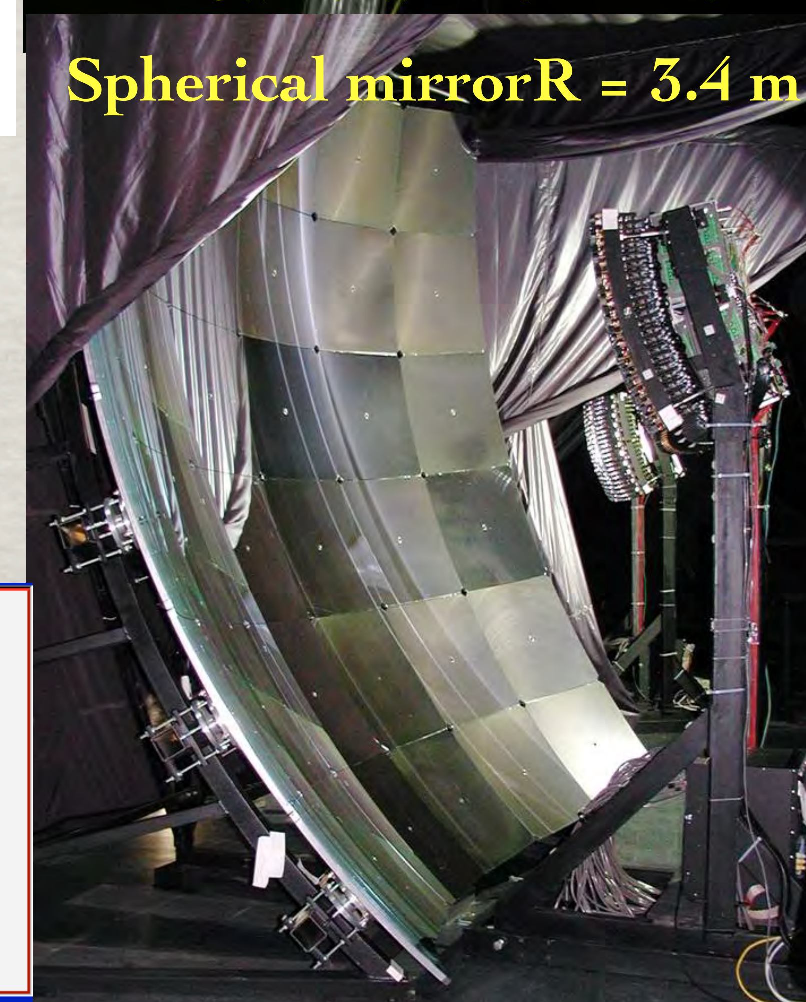
# Surface Detector



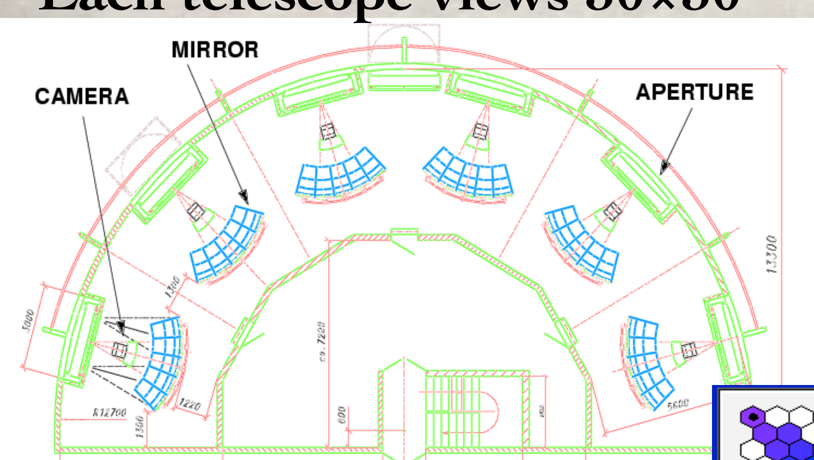
# Fluorescence Detector



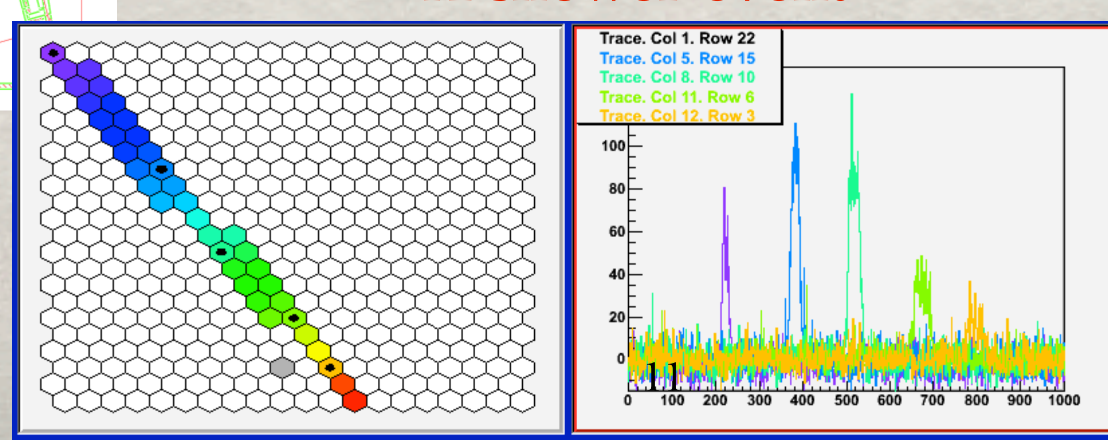



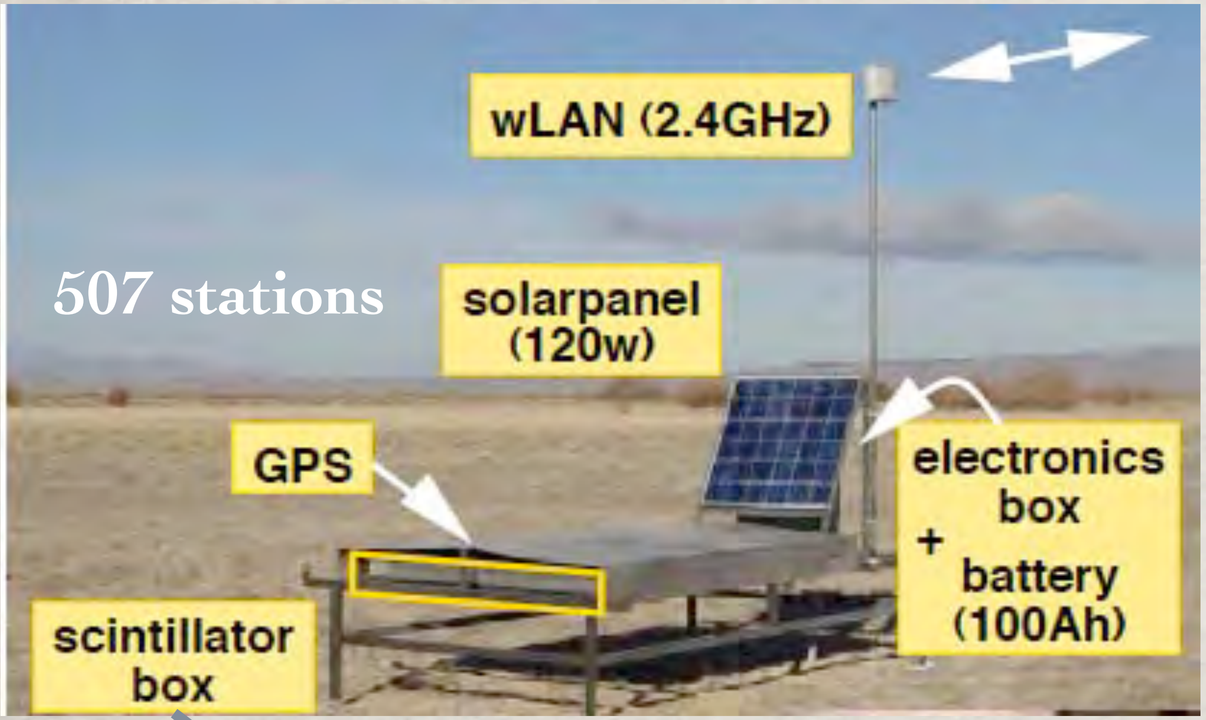

Each telescope views 30×30°



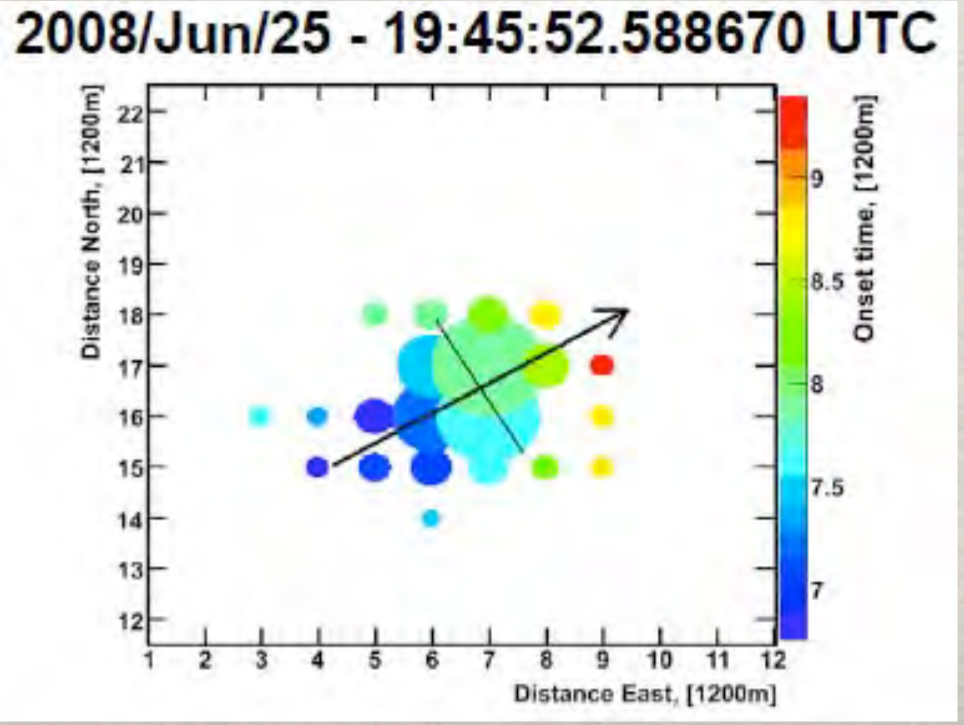

A shower event



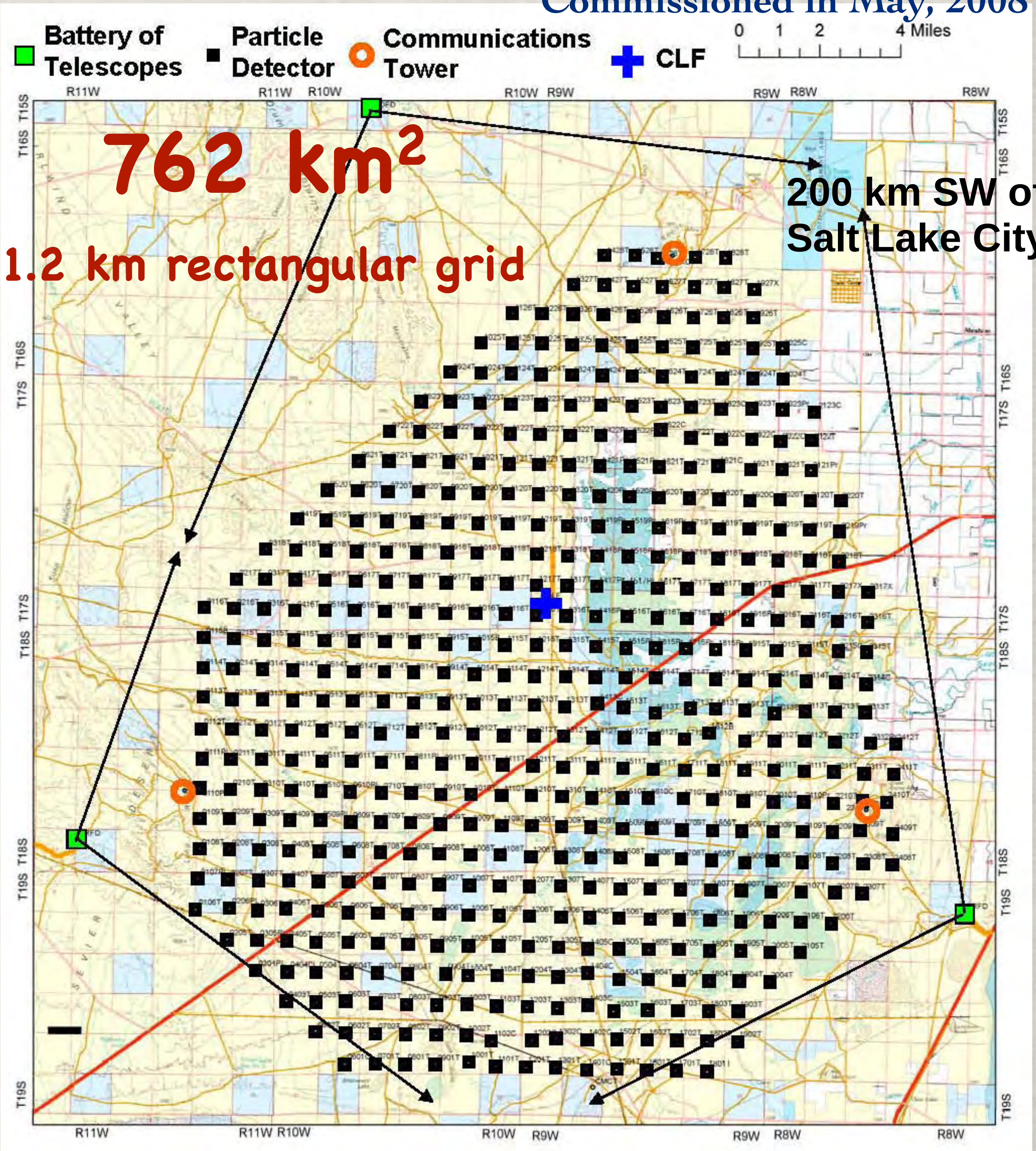
# Telescope Array: Surface Detector



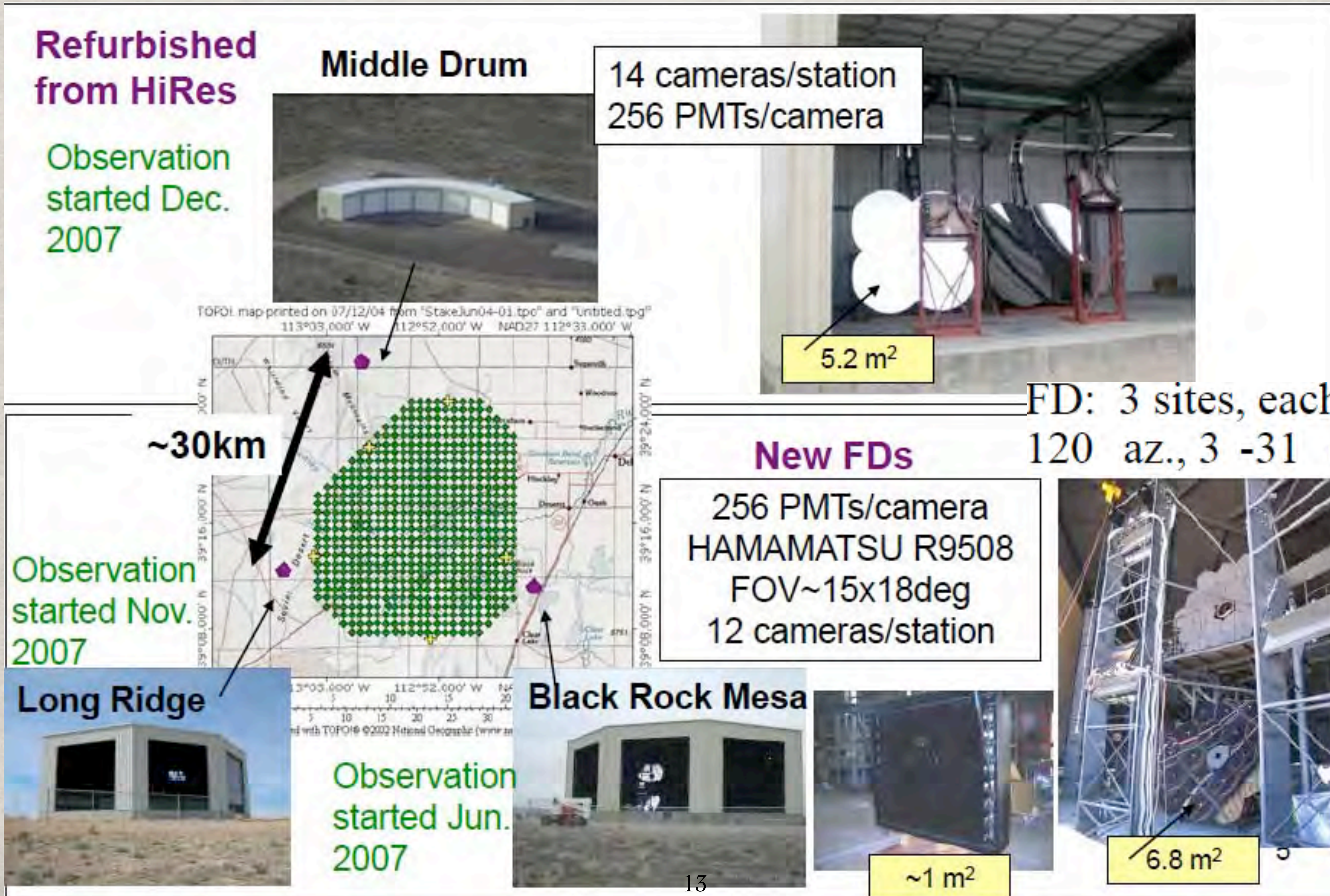

PMTs: ET 9123SA × 2
$3m^2$ (12mm × 2 layers)




Commissioned in May, 2008



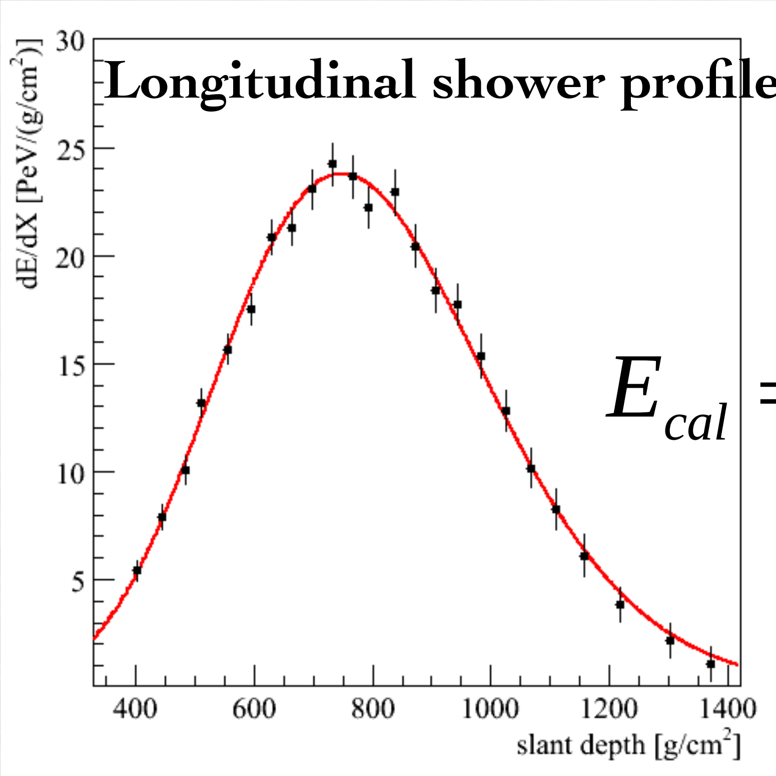
# Telescope Array: Fluorescence Detector



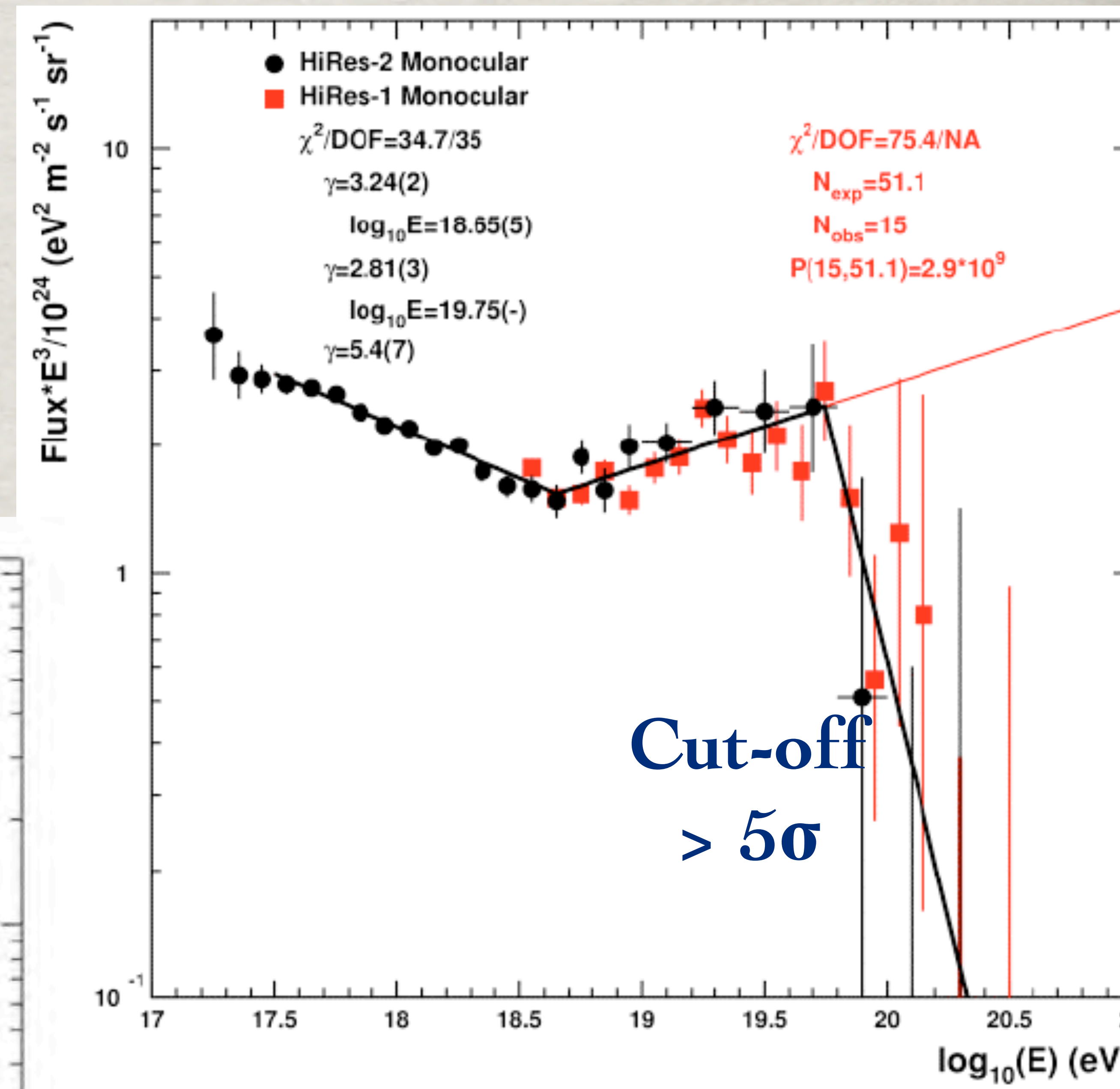

FD: 3 sites, each covers 120 az., 3 -31 elev.

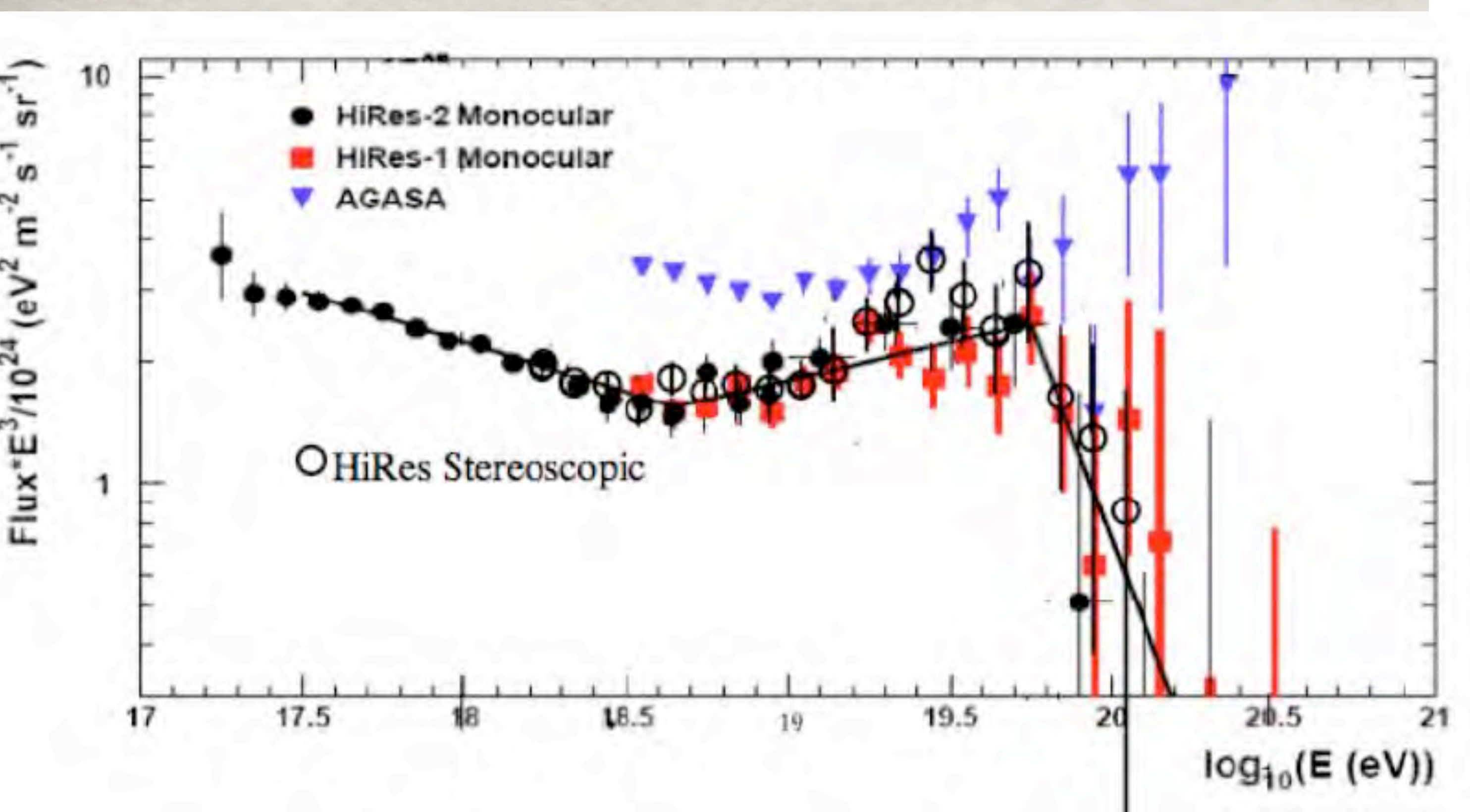
# ENERGY SPECTRUM

# Fluorescence Detector

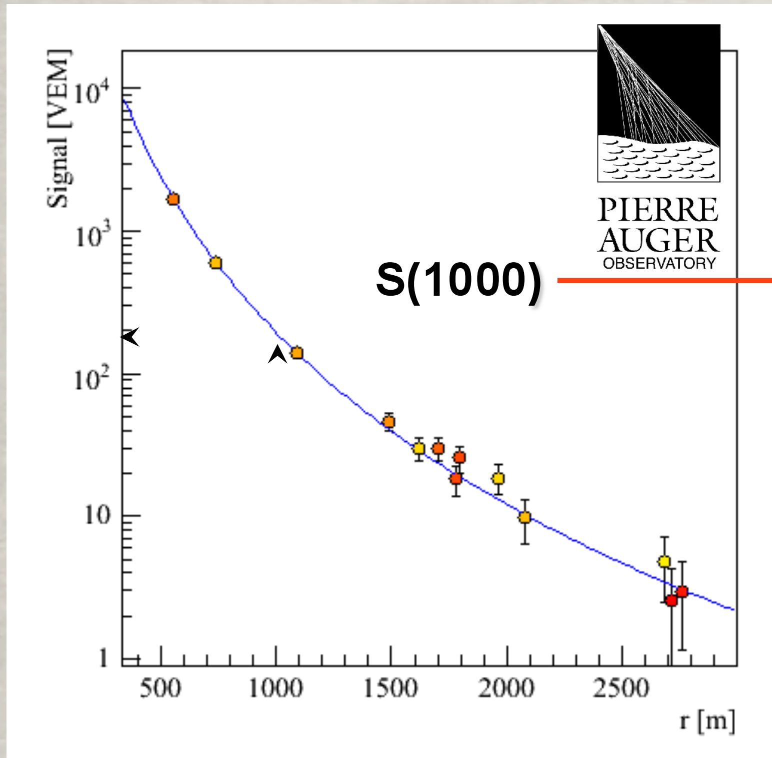


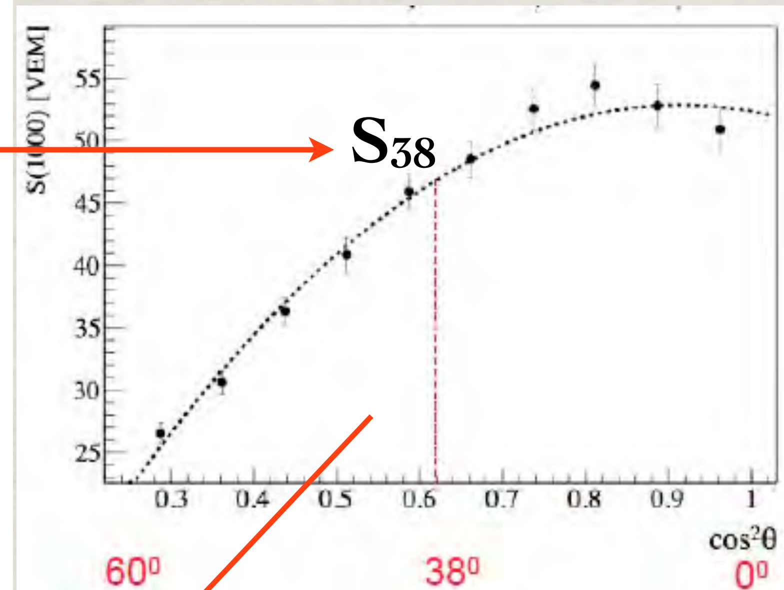

$$E_{cal} = \int dX \frac{dE}{dX}$$

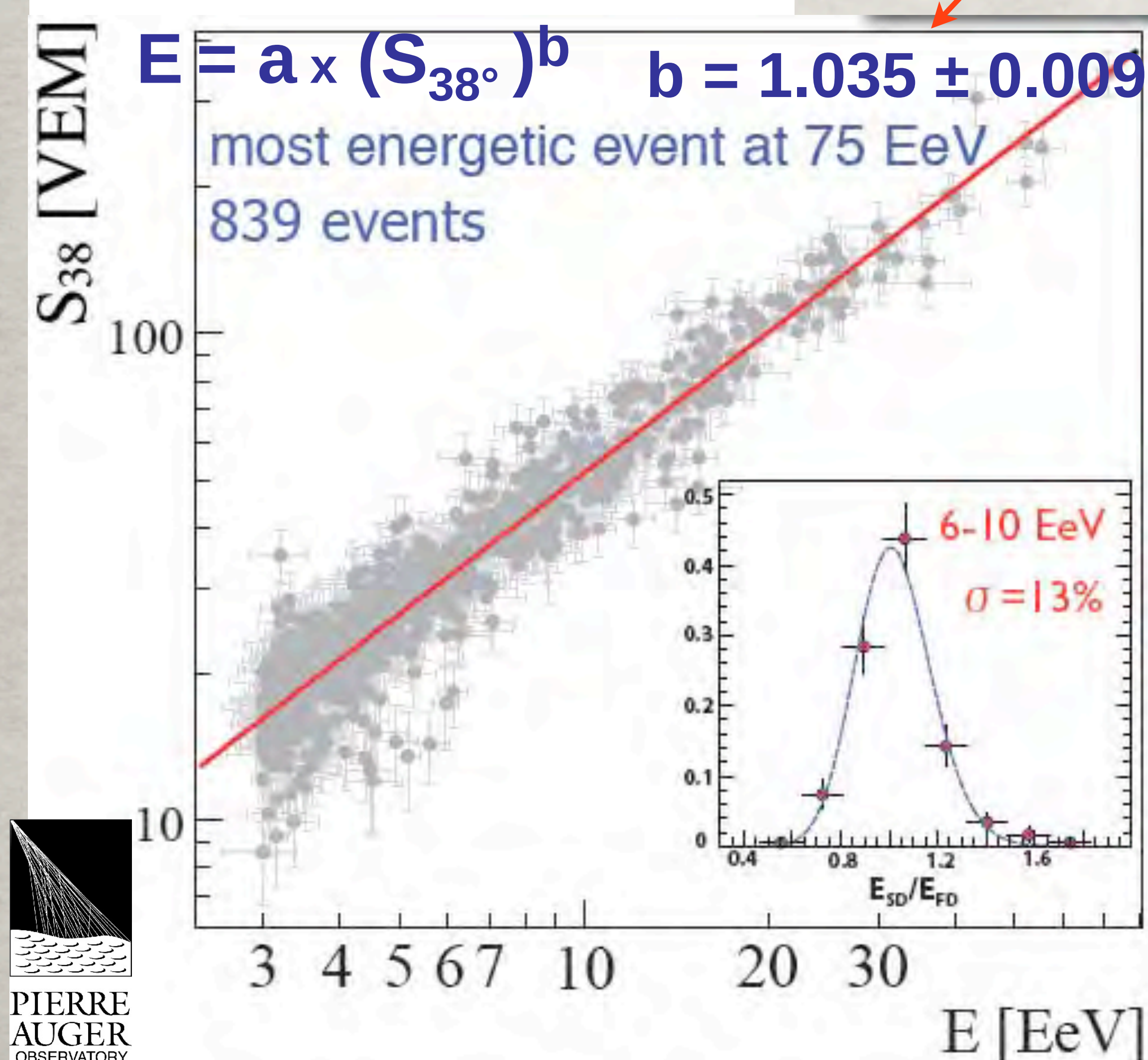


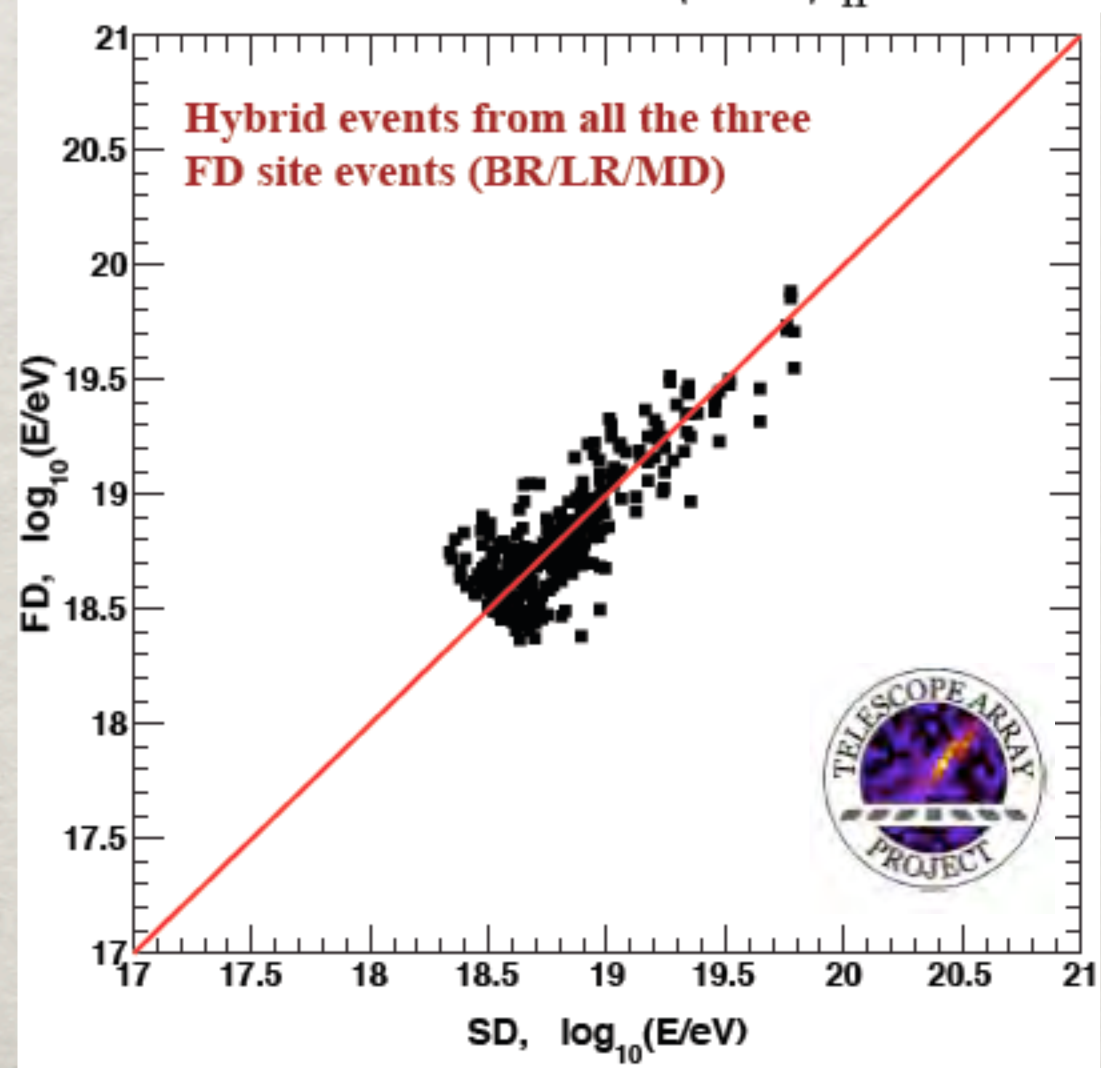
# Surface Detector



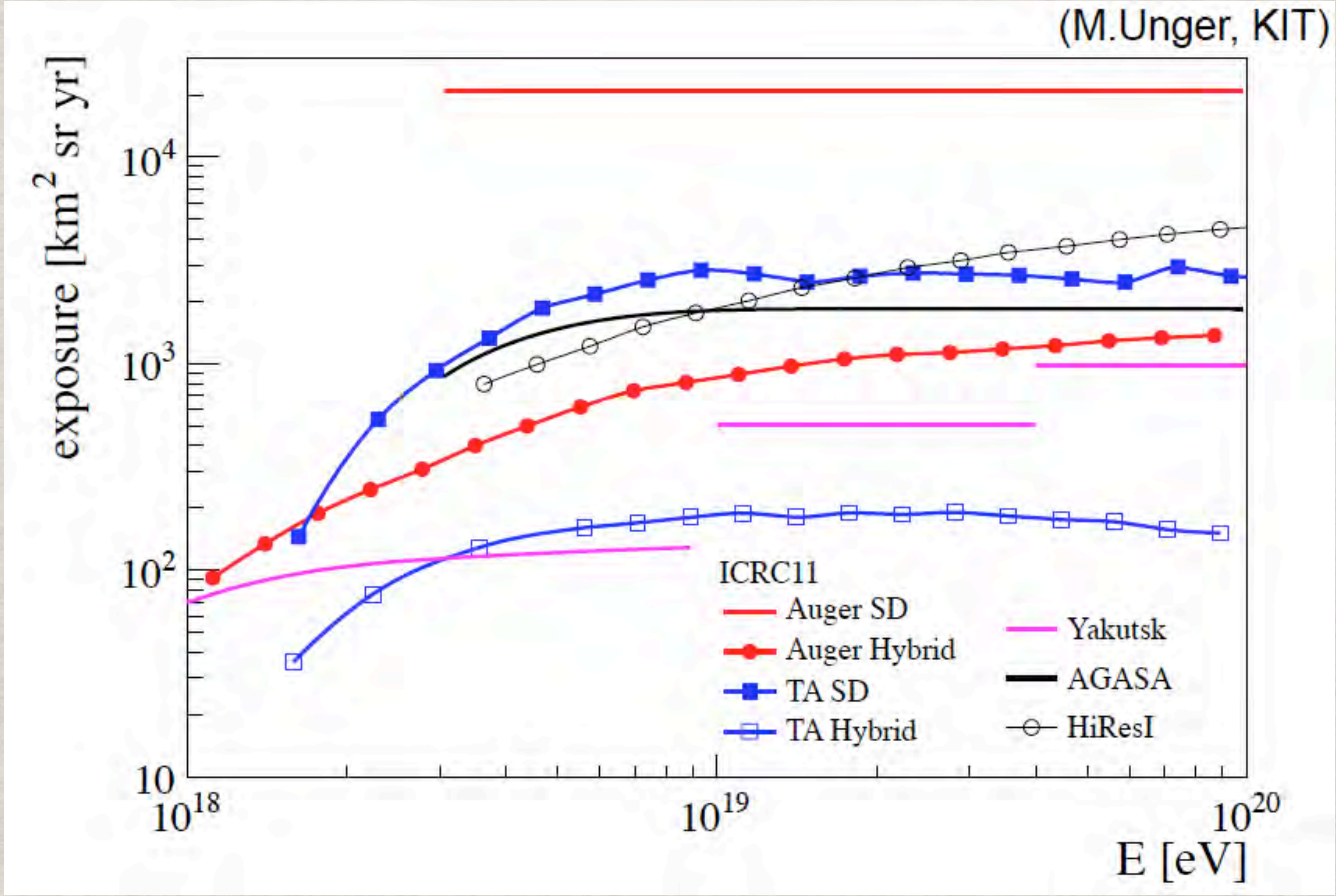

$$E = E_{\mathrm{FD}}(E_{\mathrm{MC}}(S_\theta)) = \frac{1}{\left\langle \frac{E_{\mathrm{SD}}}{E_{\mathrm{FD}}} \right\rangle_{\mathrm{h}}} E_{\mathrm{MC}}(S_\theta)$$



# Energy Uncertainty

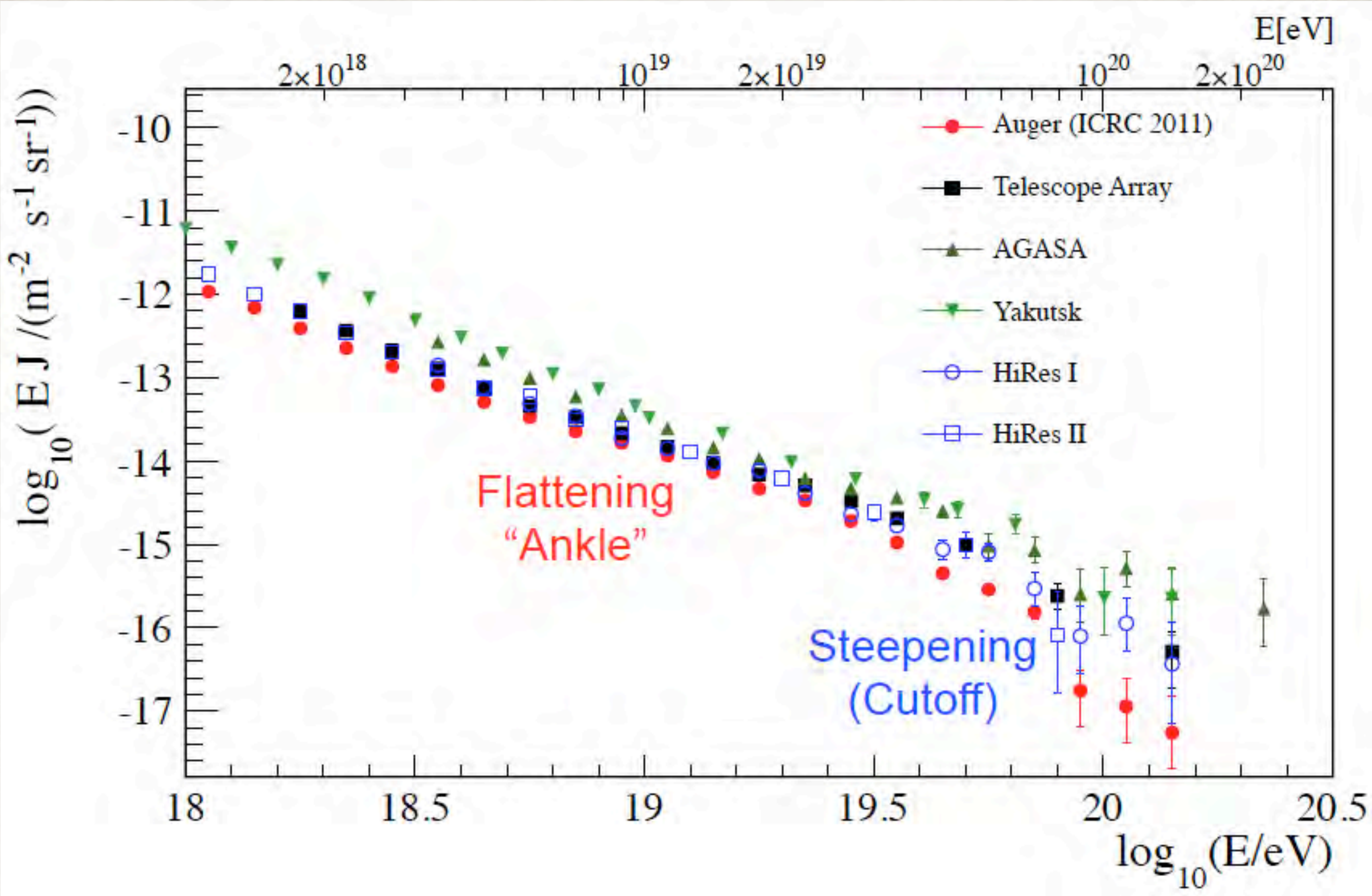
| | HiRes | Auger | TA |
|---|---|---|---|
| Calibration | 10% | 9.5% | 10% |
| Fluorescence yield | 6% | 14% | 11% |
| Atmosphere | 5% | 8% | 11% |
| Reconstruction | 15% | 10% | 10% |
| Invisible energy | 5% | 4% | (included above) |
| **Total** | **17%** | **22%** | **21%** |

# Exposures

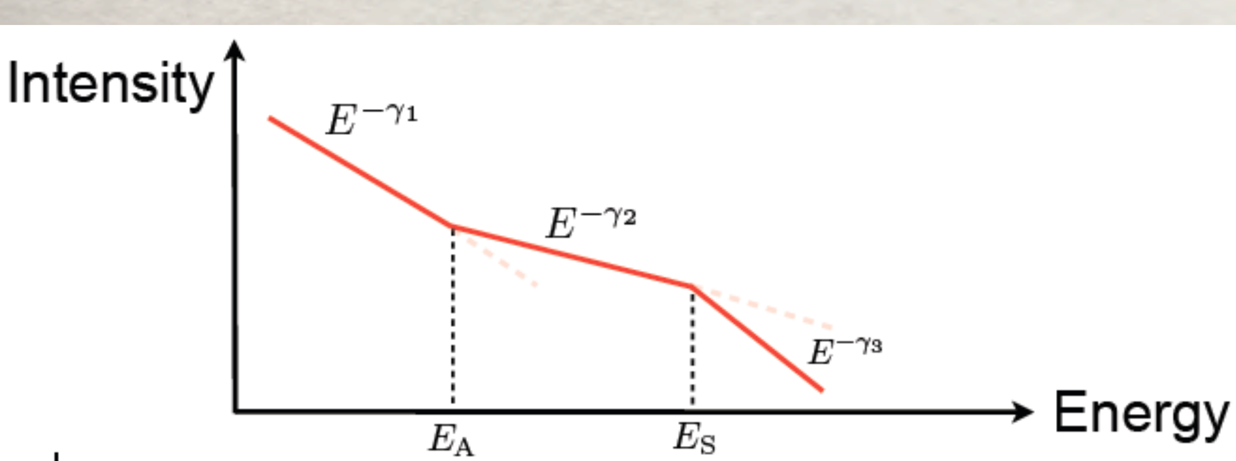


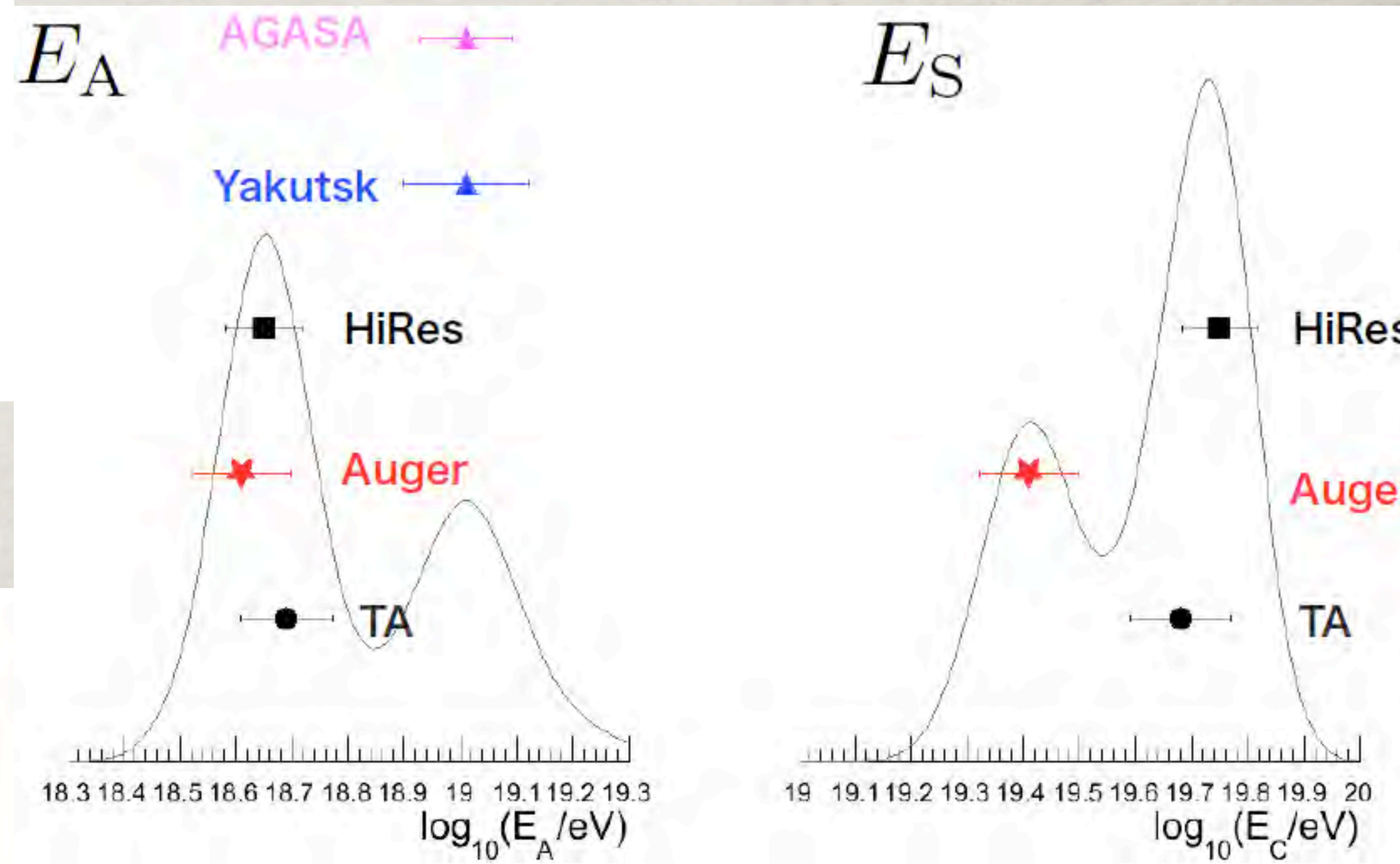
(M.Unger, KIT)
exposure [km$^2$ sr yr]
$10^4$
$10^3$
$10^2$
10
$10^{18}$
$10^{19}$
$10^{20}$
E [eV]
ICRC11
Auger SD
Auger Hybrid
TA SD
TA Hybrid
Yakutsk
AGASA
HiResI

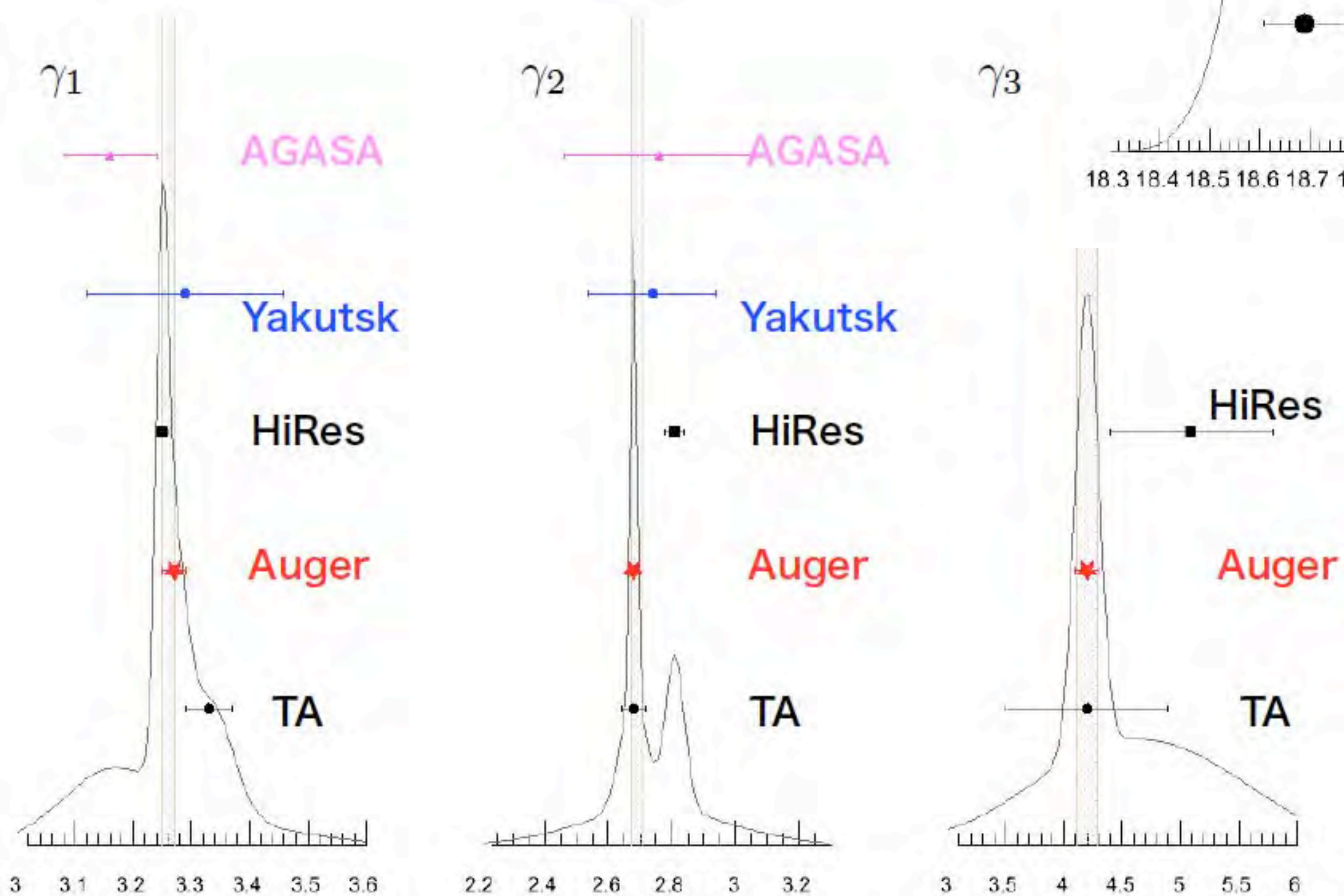
# UHECR SPECTRUM



# Power Law Fits

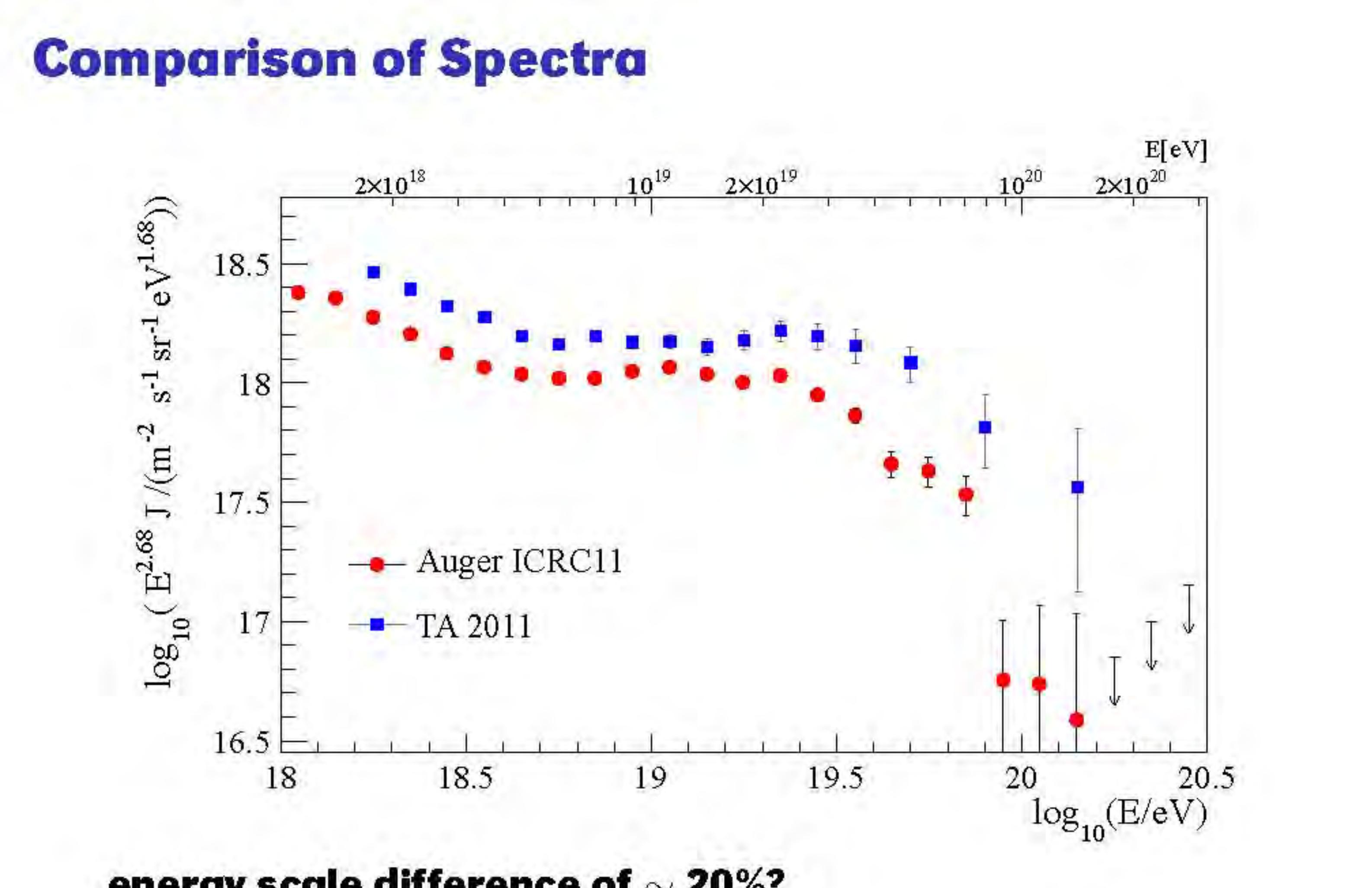


# International Working Group

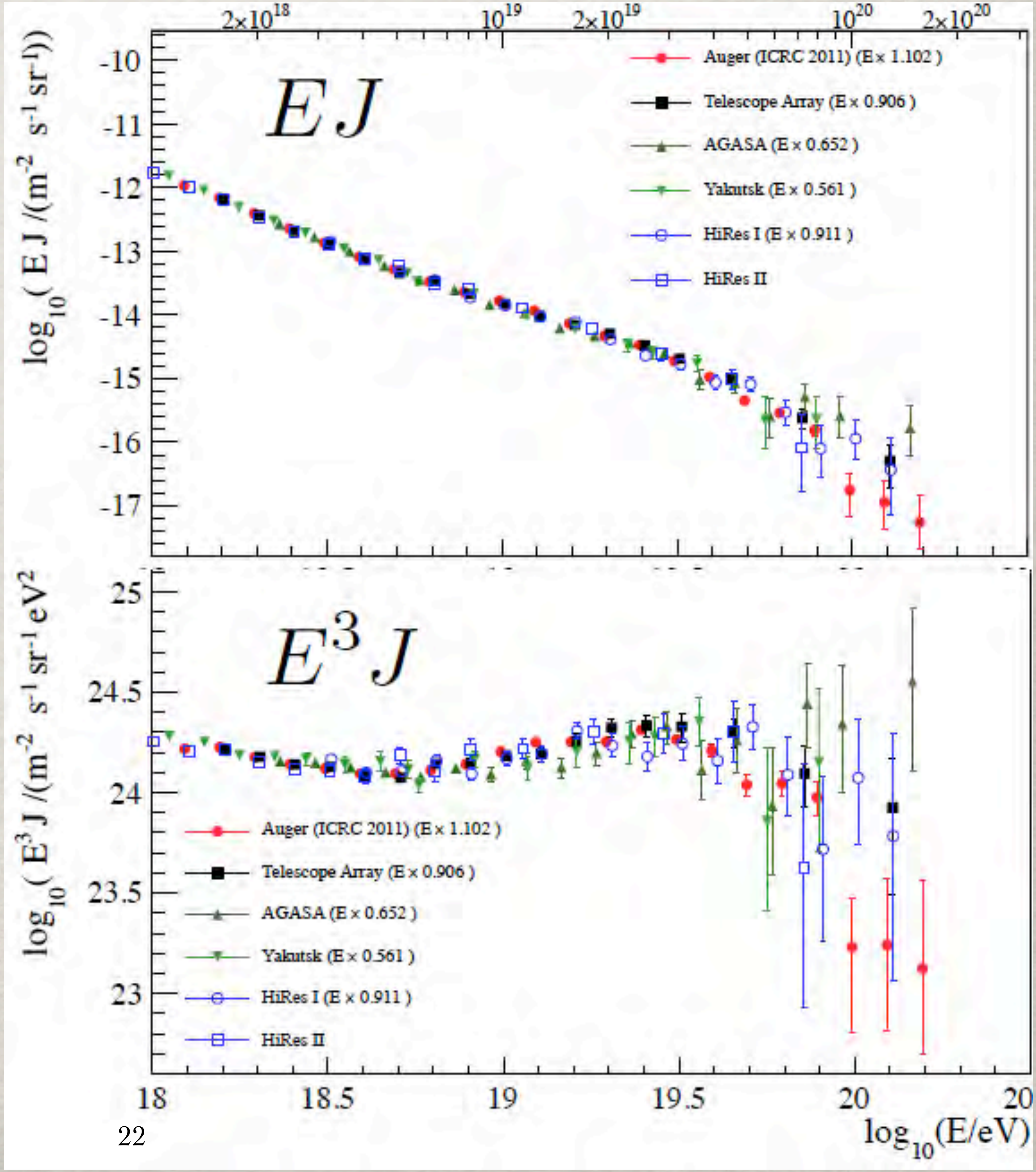
- Common effort from HiRes, TA, Yakutsk and Pierre Auger collaborations
  - Set up for UHECR 2012 Symposium




Energy scale difference not fully explained

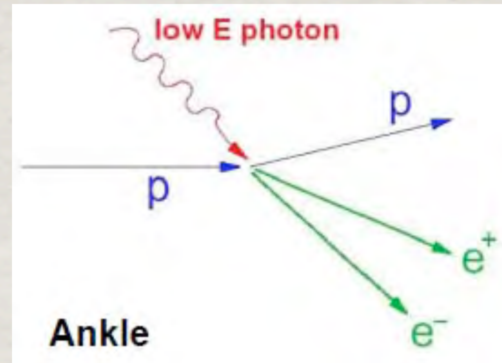
# Scaling the Spectrum

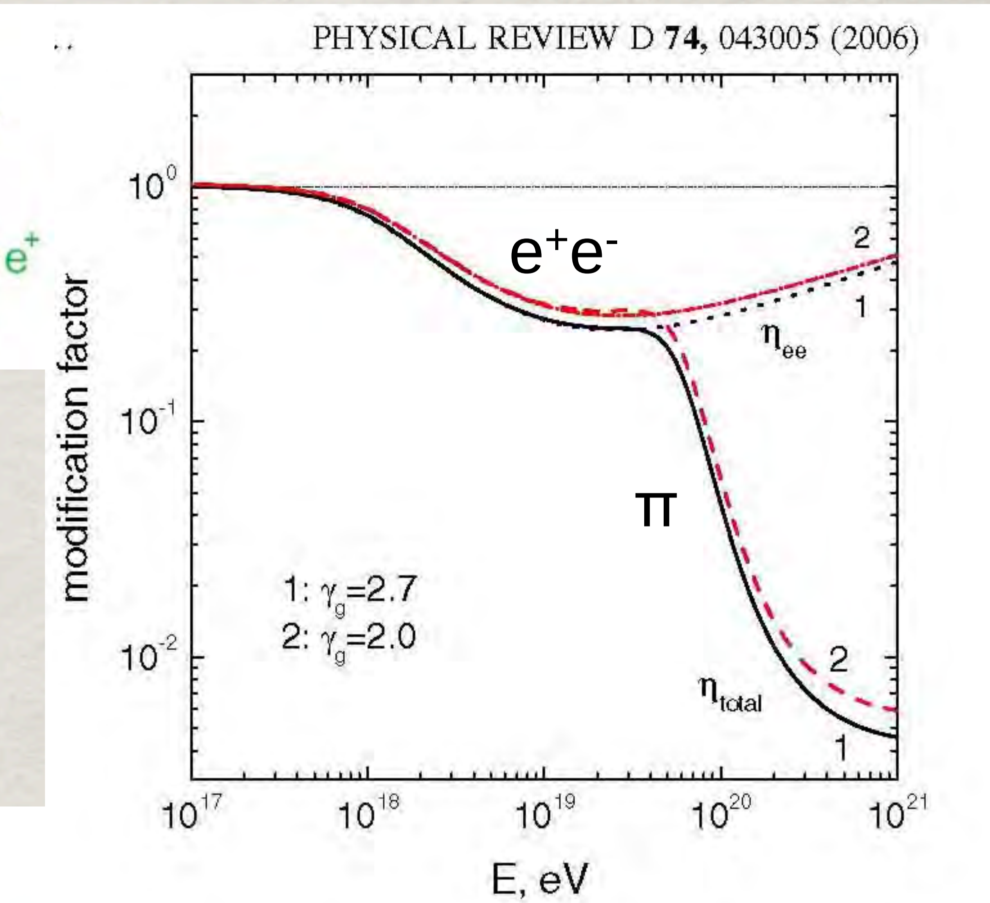
- Good agreement between HiRes/TA/ Pierre Auger within systematics

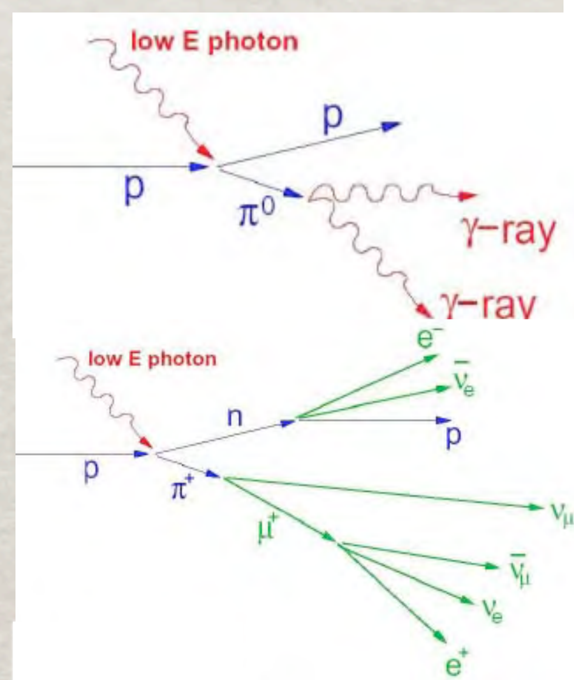


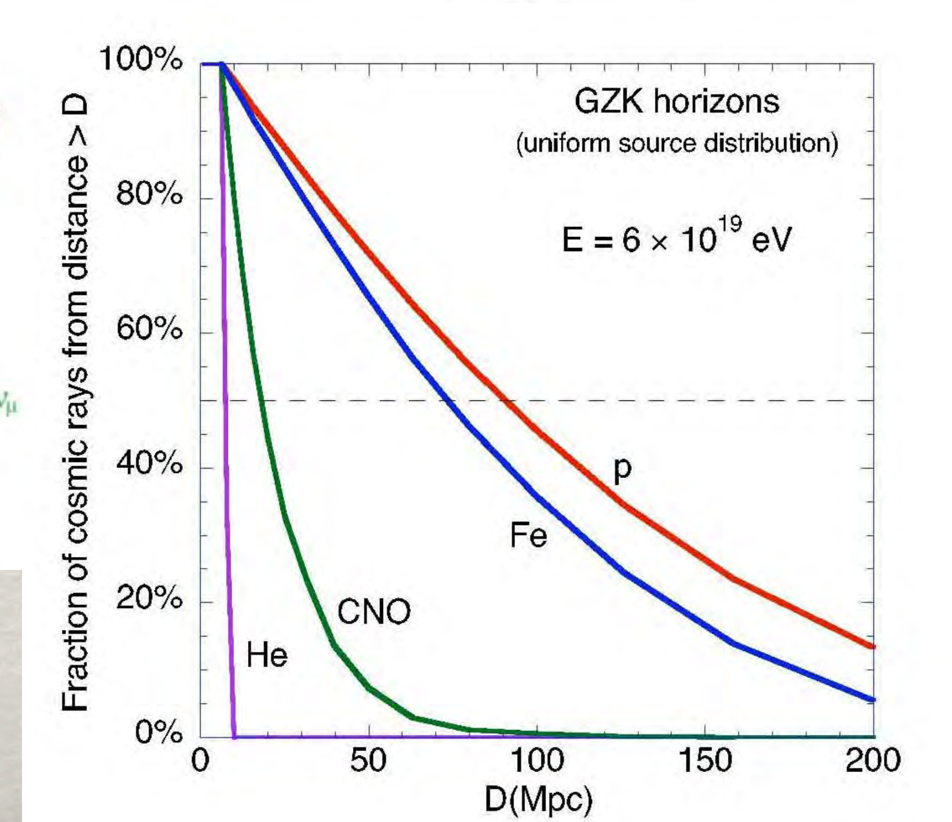
# Features in the spectrum

- Ankle
  - Pure proton: Pair production
  - Mixed composition: Galactic-Extragalatic transition
- Cut-off
  - GZK mechanism
    - (pion production)
  - Energy limit at which sources can accelerate particles



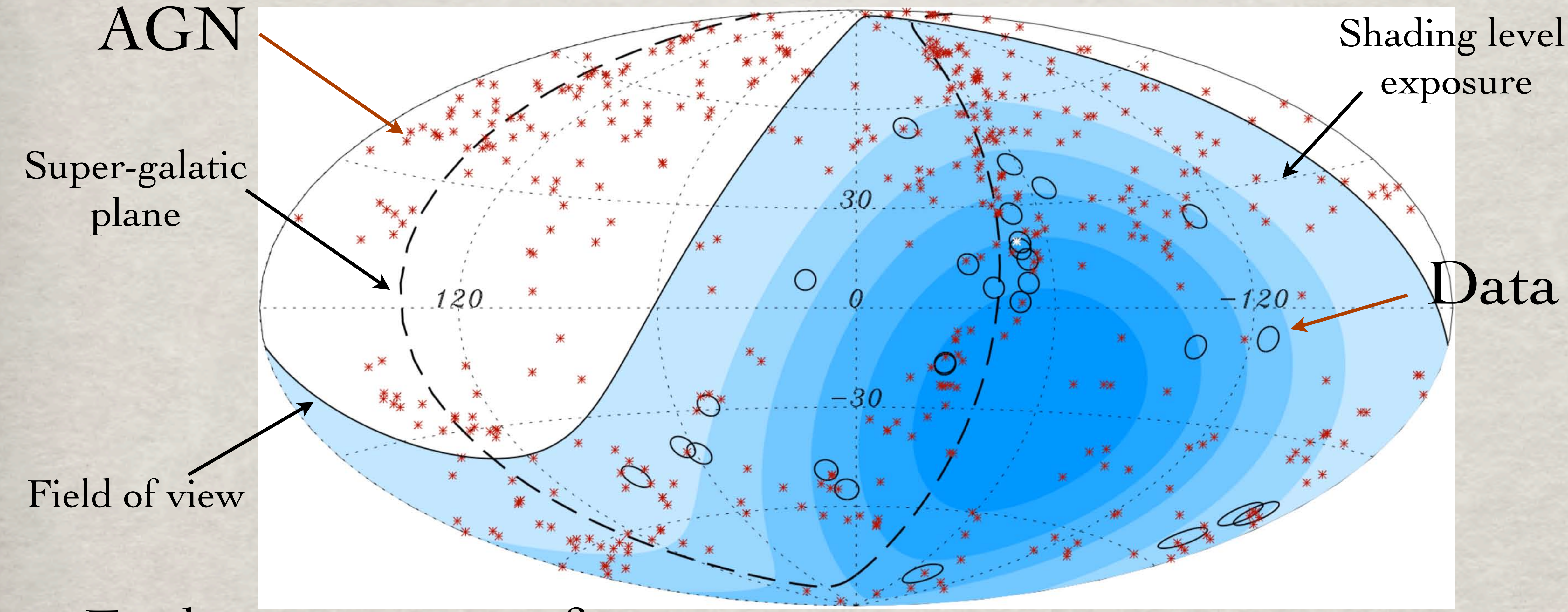



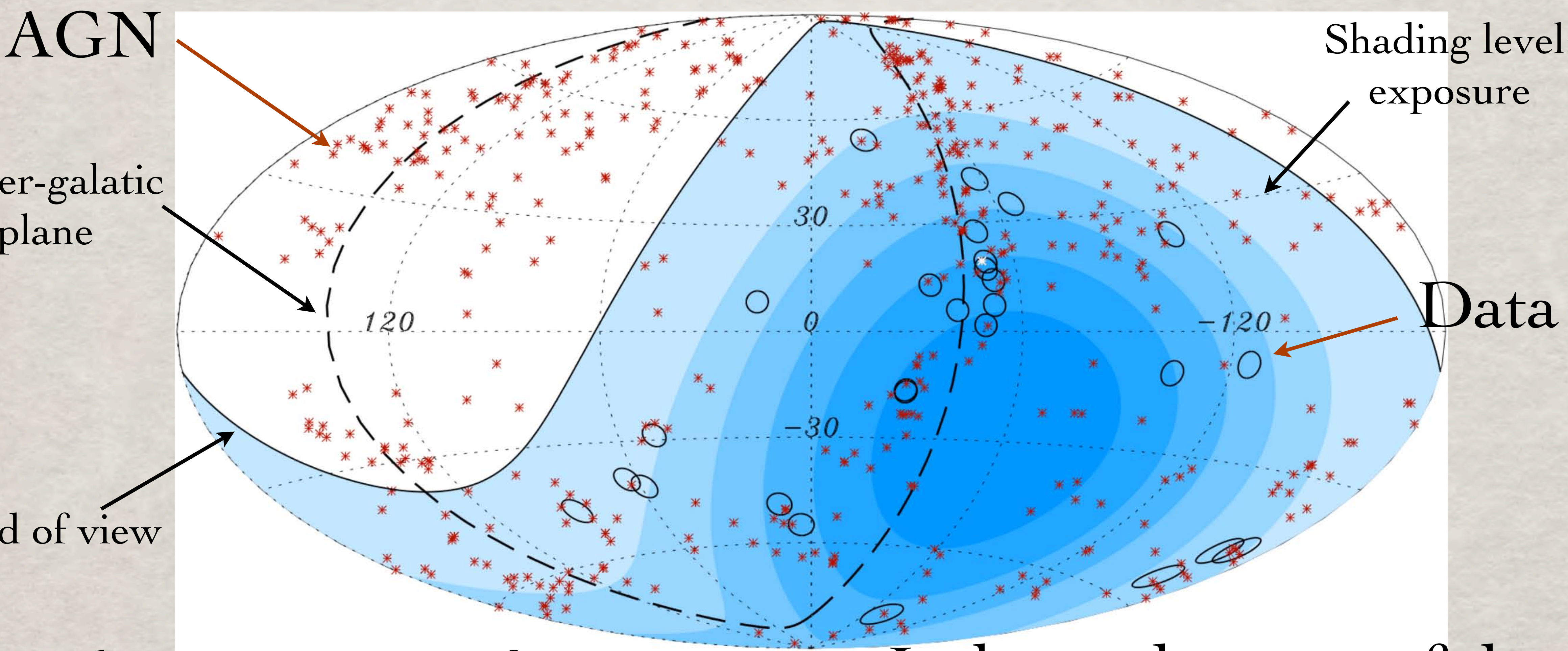
# Arrival Directions

# Correlation with AGNs in VCV Catalogue



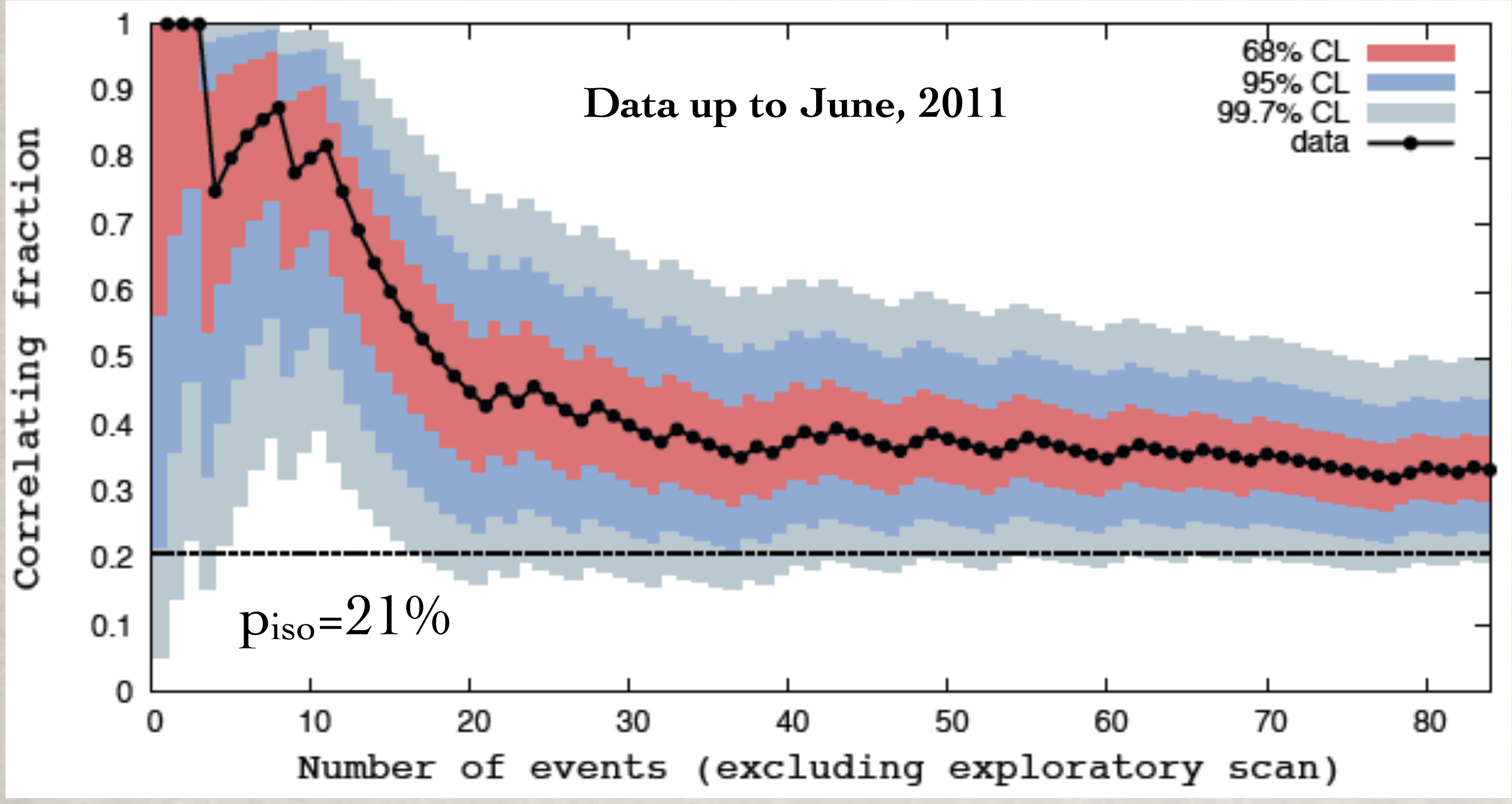

- Exploratory scan to fix parameters
  - E>56 EeV, D < 75 Mpc, angular distance < 3.1°
  - 12 out of 15 correlate, 3.2 expected in case of isotropy

# Correlation with AGNs in VCV Catalogue



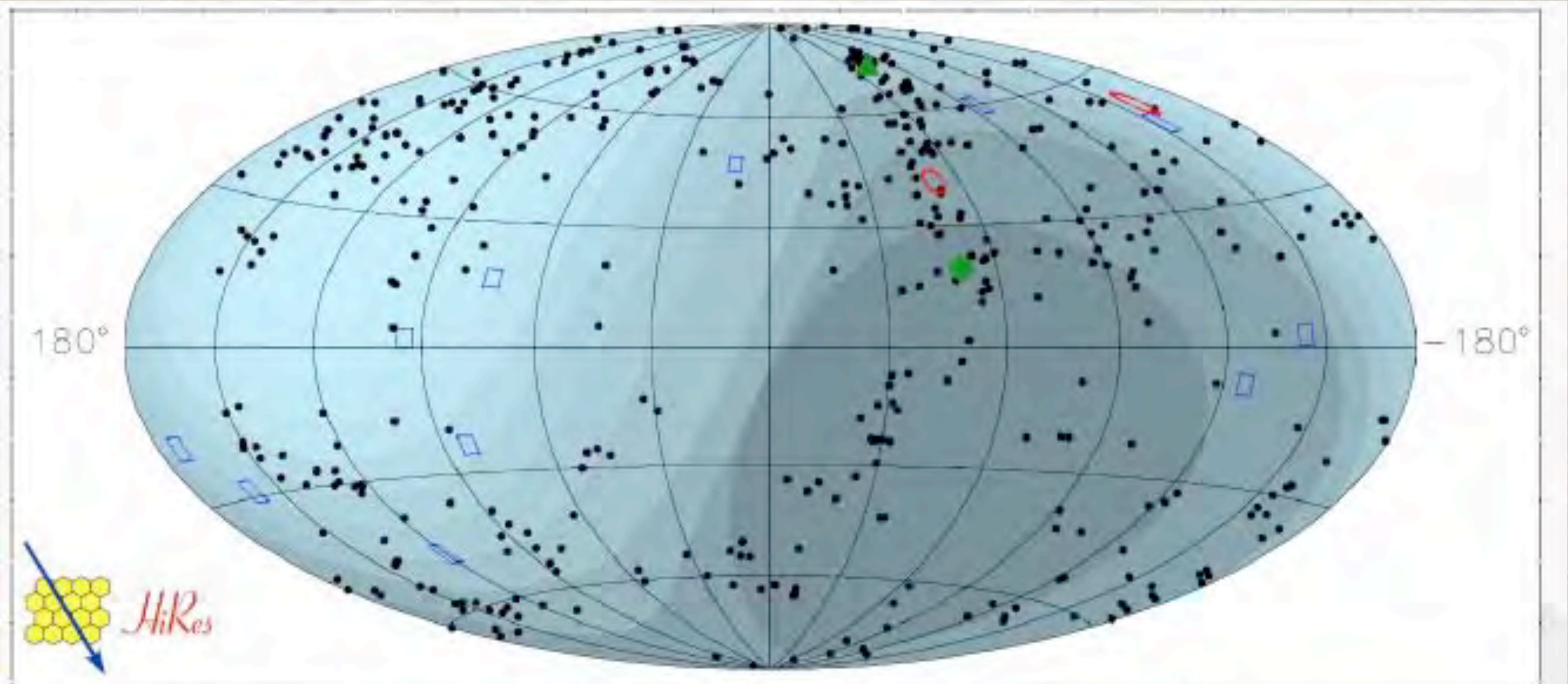

- Exploratory scan to fix parameters
  - E>56 EeV, D < 75 Mpc, angular distance < 3.1°
  - 12 out of 15 correlate, 3.2 expected in case of isotropy
- Independent set of data:
  - 8 out of 13 correlate, 2.7 expected in case of isotropy
  - Probability for this configuration to occur by chance in case of isotropy: $1.7 \times 10^{-3}$

# Update on Correlation



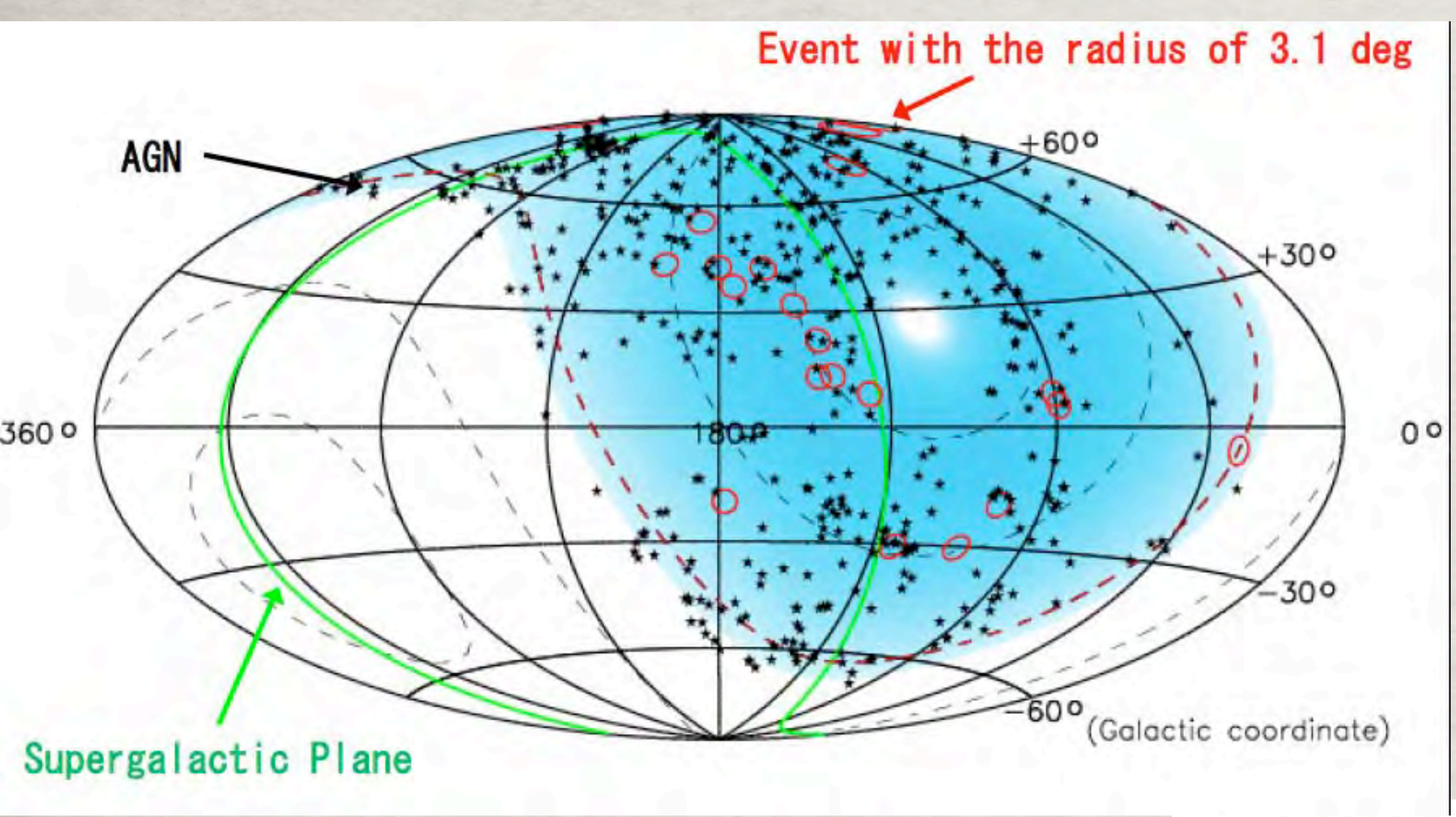

- 28 out of 84 correlate
- The amount of correlation is 33 ±5%
  - Assume isotropy, the probability of finding such correlation P=0.006

# AGN Correlation with HiRes

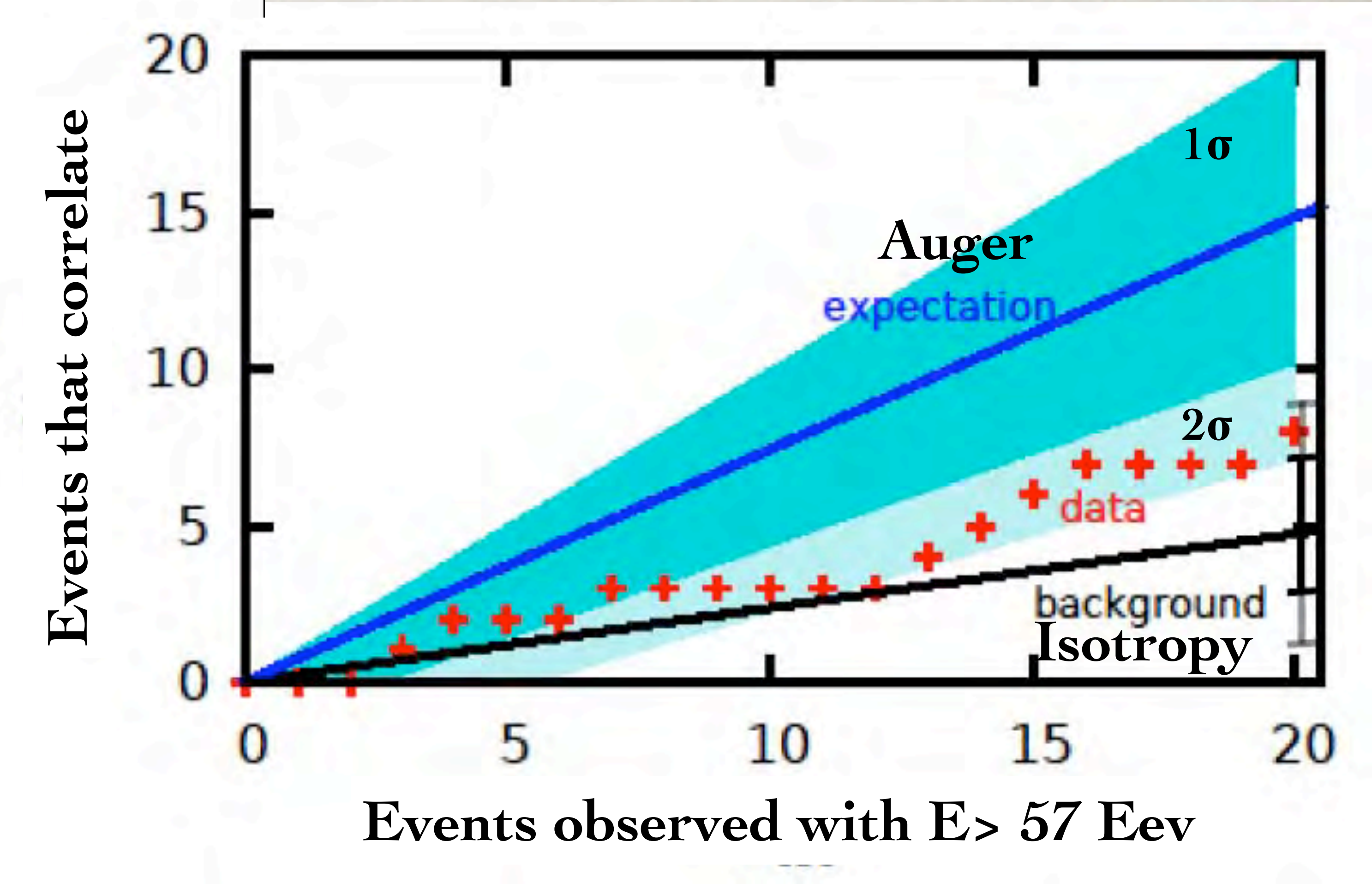



2 events out of 13 correlate, 3.2 expected from random coincidences

# AGN Correlation with TA



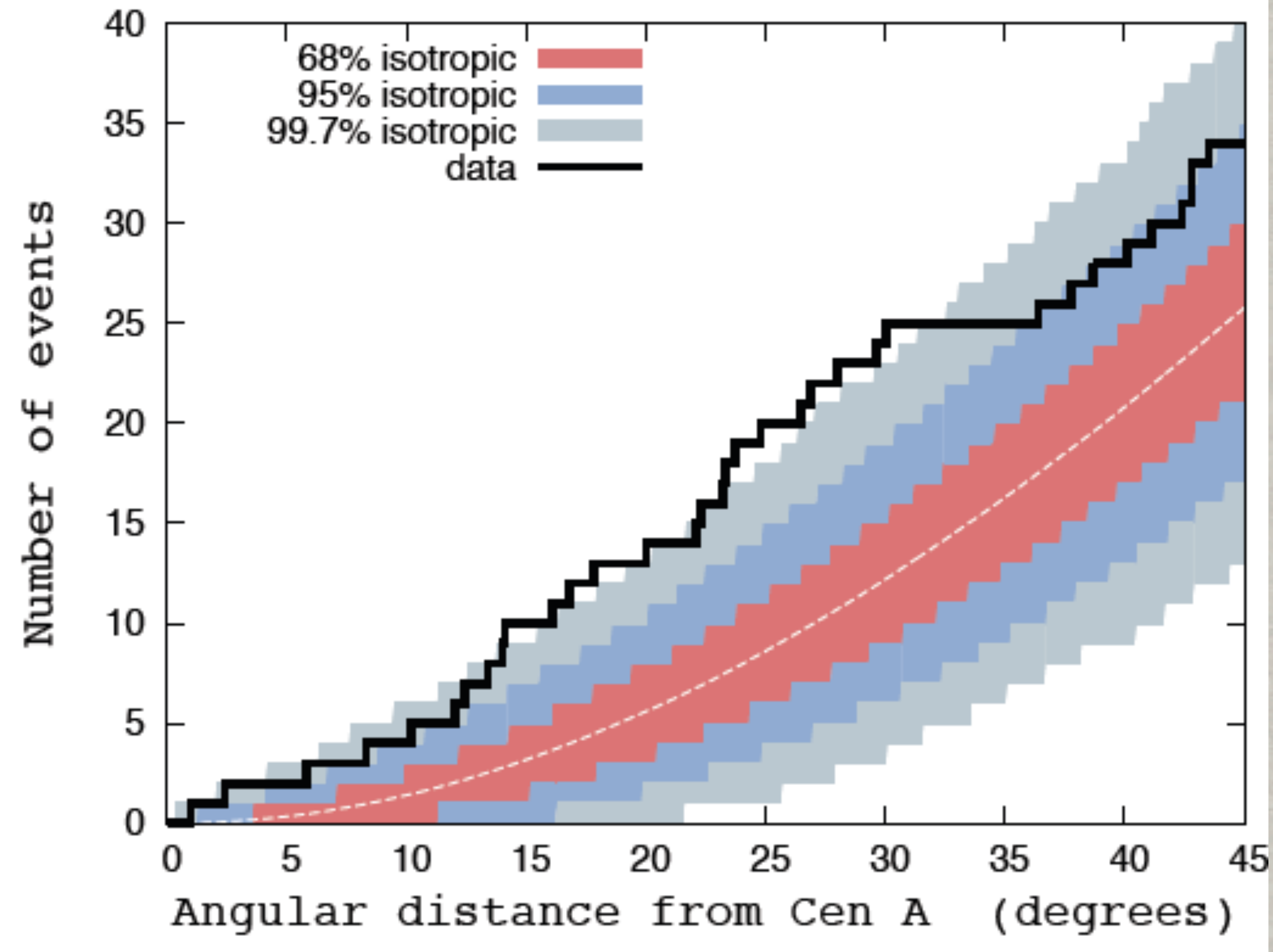

- 8 out of 20 correlate
- Consistent with no correlation
- ~3 times present statistics for a conclusive test!



# Is Centaurus A a Source of UHECR?

PIERRE
AUGER
OBSERVATORY

- Closest radio-galaxy in sourthern hemisphere (3.8 Mpc)
- Largest departure at 24°
  - 19 observed
  - 7.6 expected
- Outside of HiRes and TA field of view



# Mass Composition

# Experimental data


The BIG question: infer how does the grandmother look like?

# Experimental data

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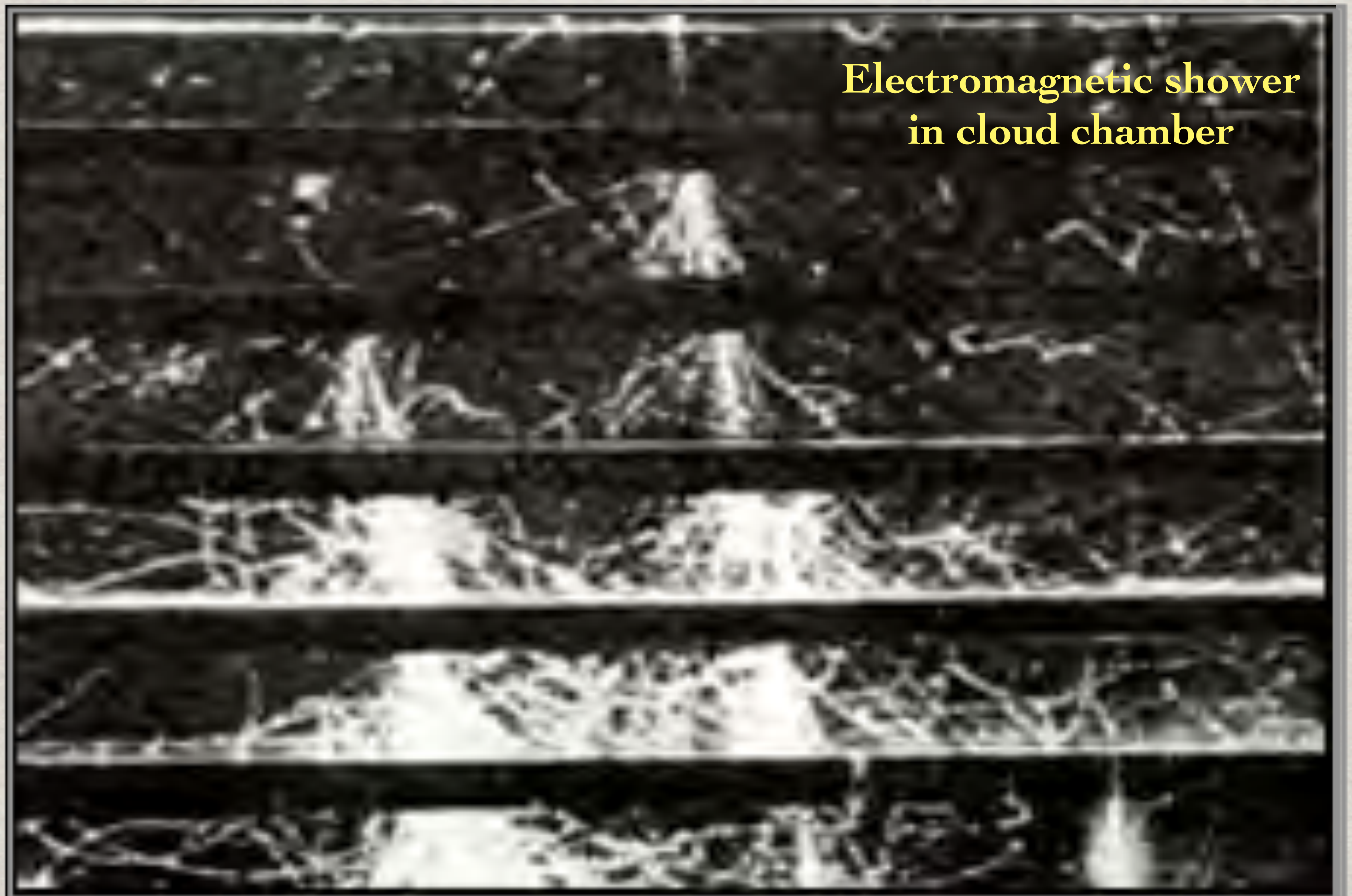
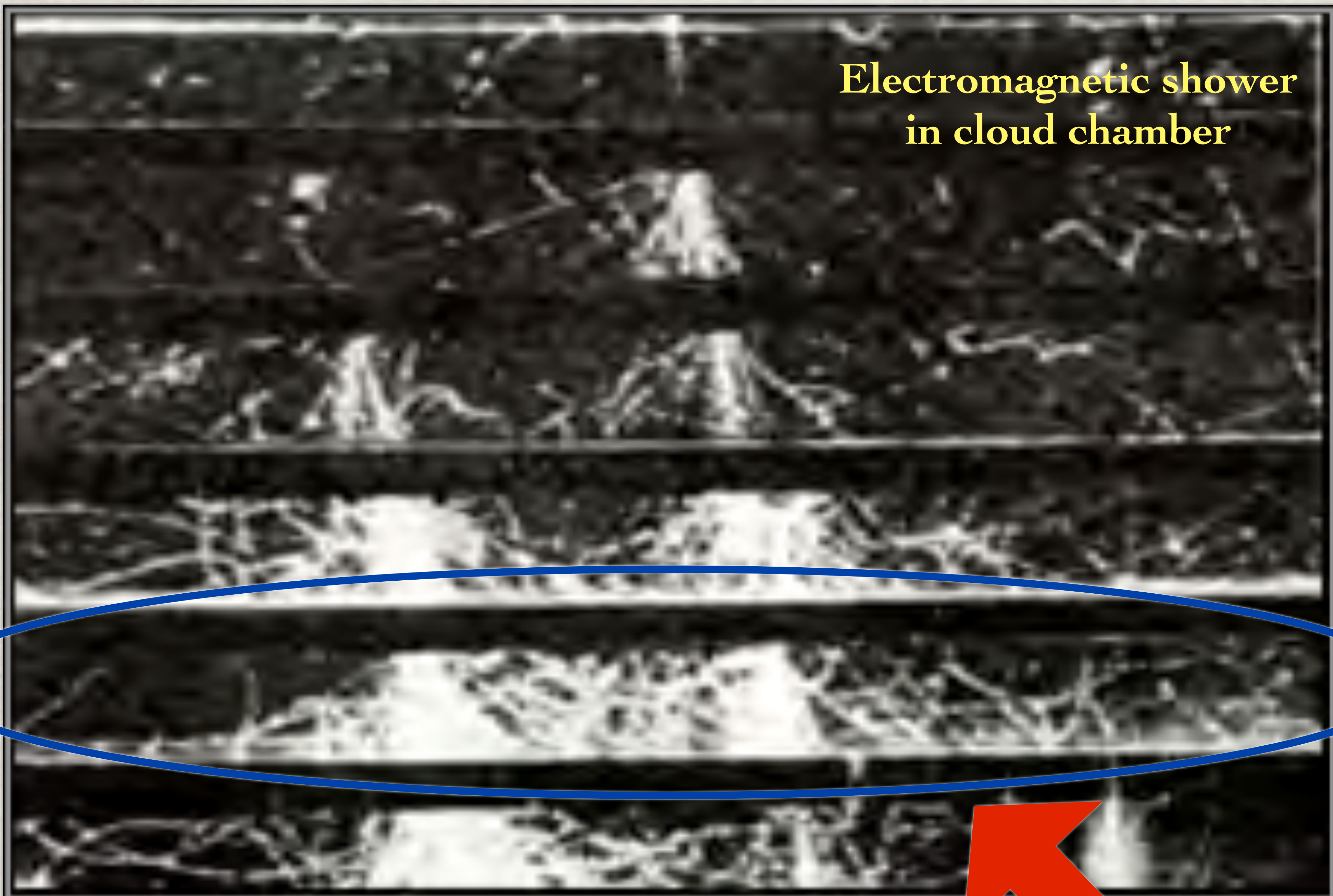
# Experimental data

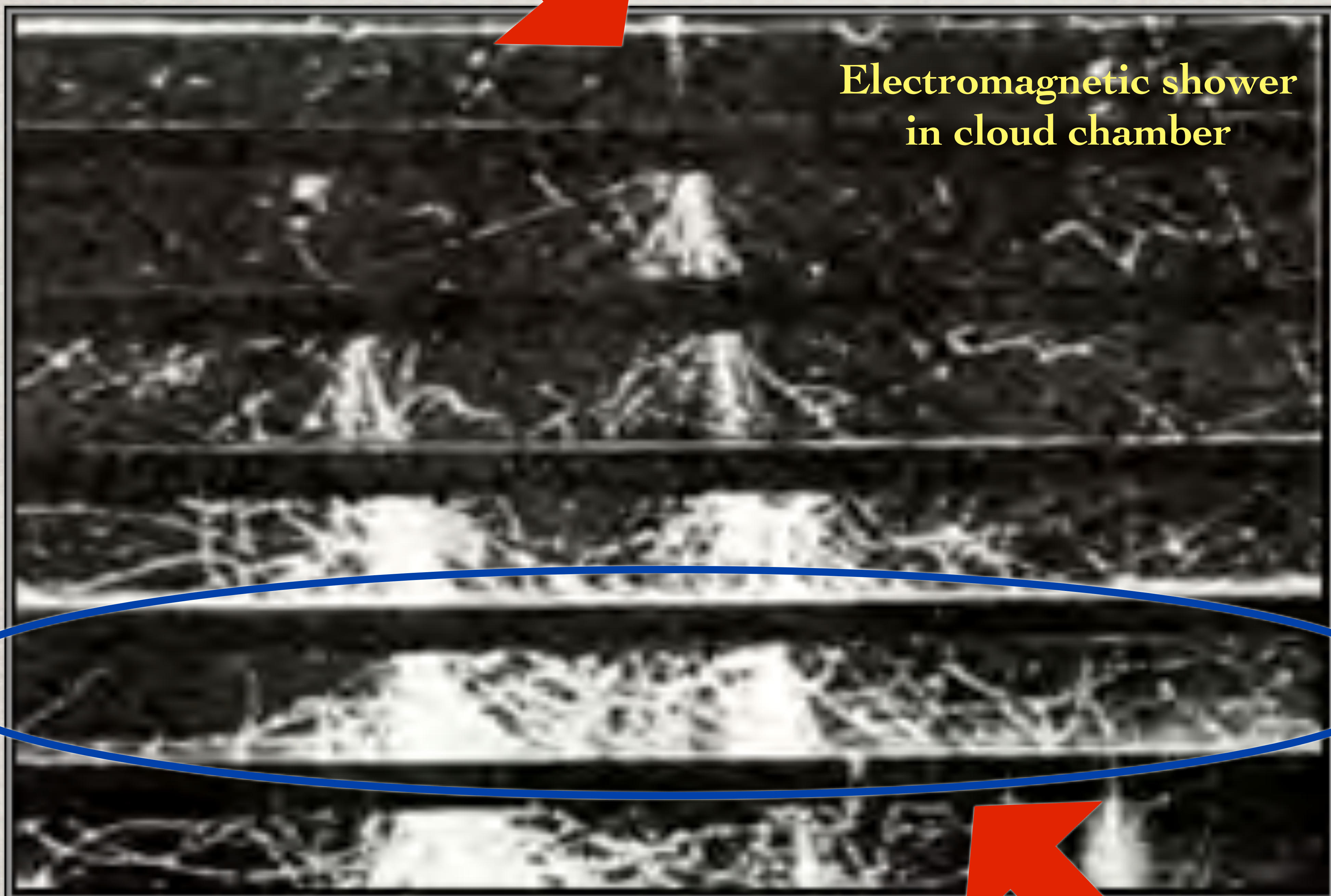
The BIG question: infer how does th e?


Electromagnetic shower
in cloud chamber



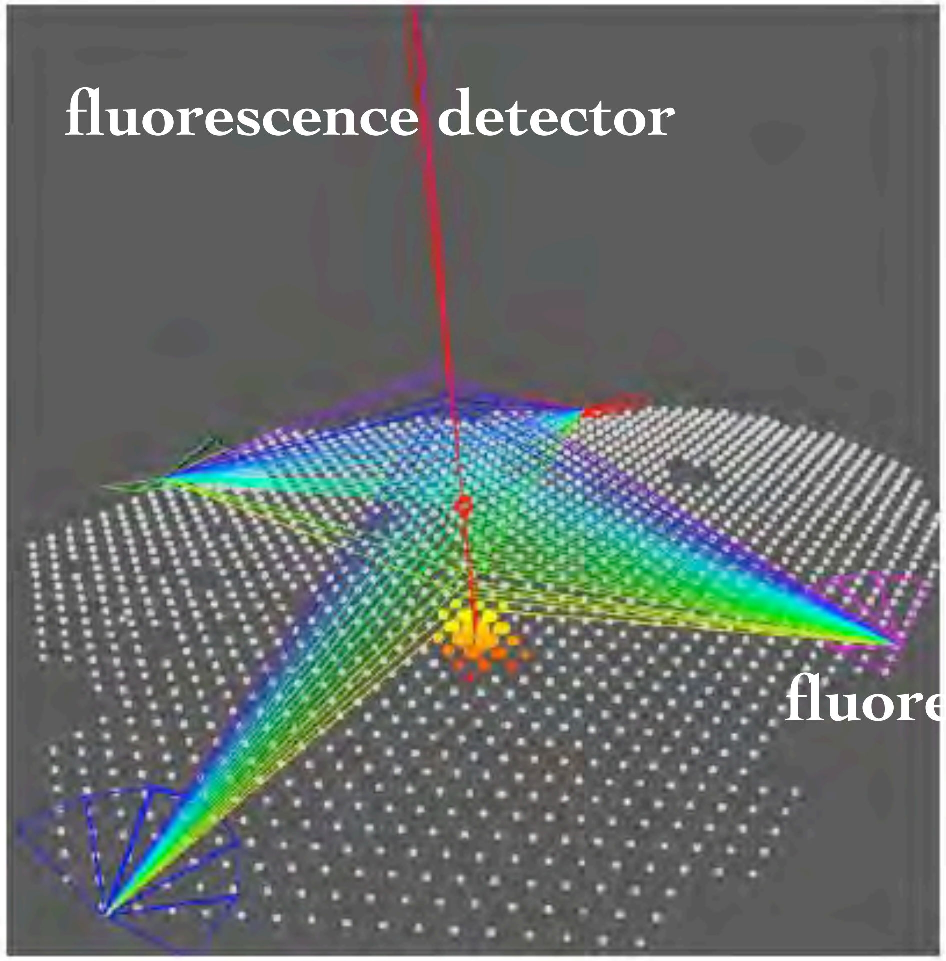

The grandchildren we observe

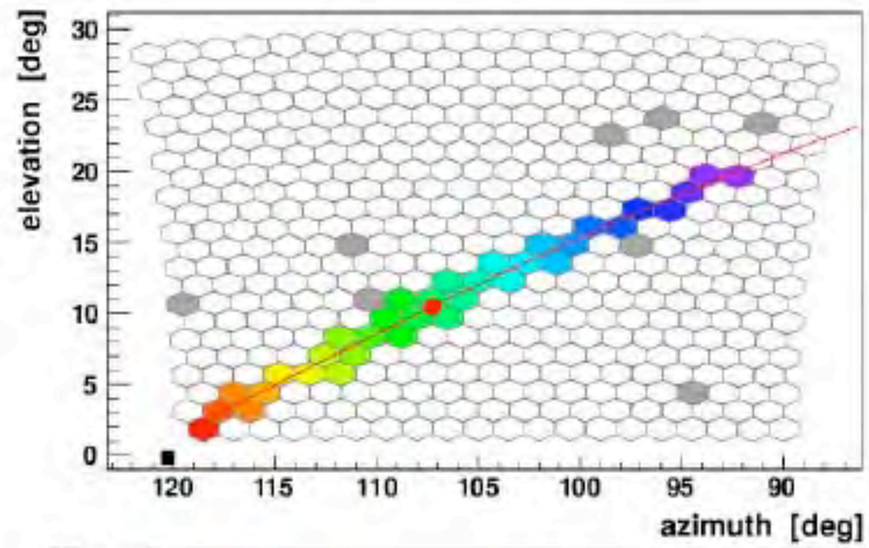
# The grandmother we infer

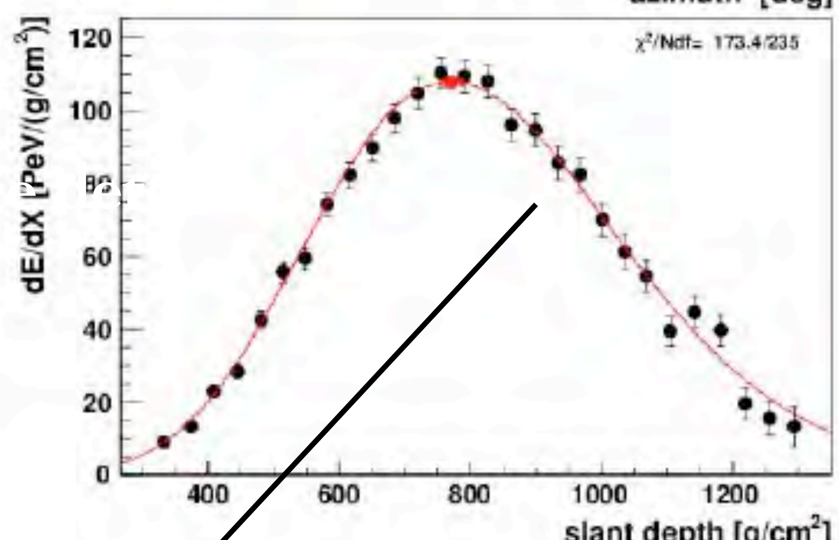


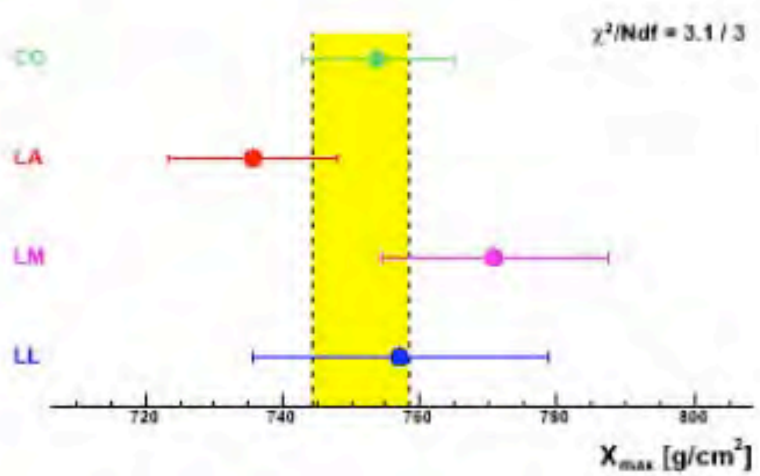

The grandchildren we observe

# Depth of Shower Maximum: Xmax Reconstruction




PIERRE AUGER OBSERVATORY

**Energy**

E = (7.1± 0.2) $10^{19}$ eV

**Depth of the maximum**

$X_{max}$ = (752 ± 7) g/cm²

Total number of events used in composition analyses for log(E/eV)> $10^{18}$

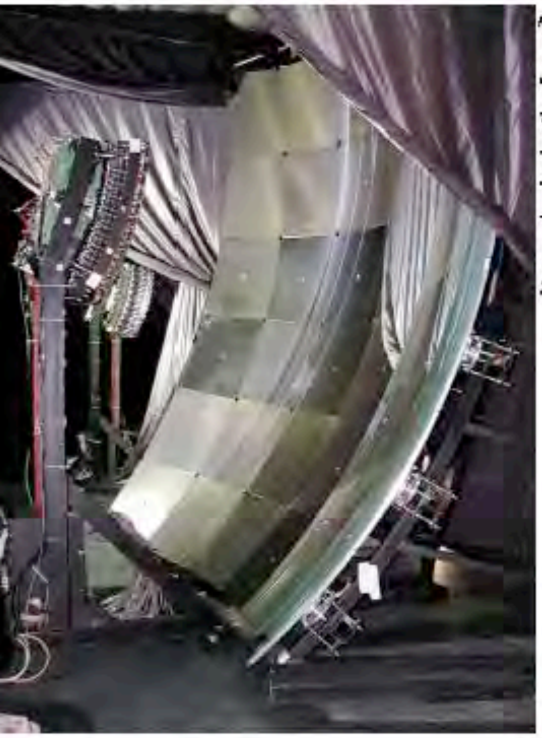
6744 Auger
2301 Yakutsk
815 HiRes
279 TA

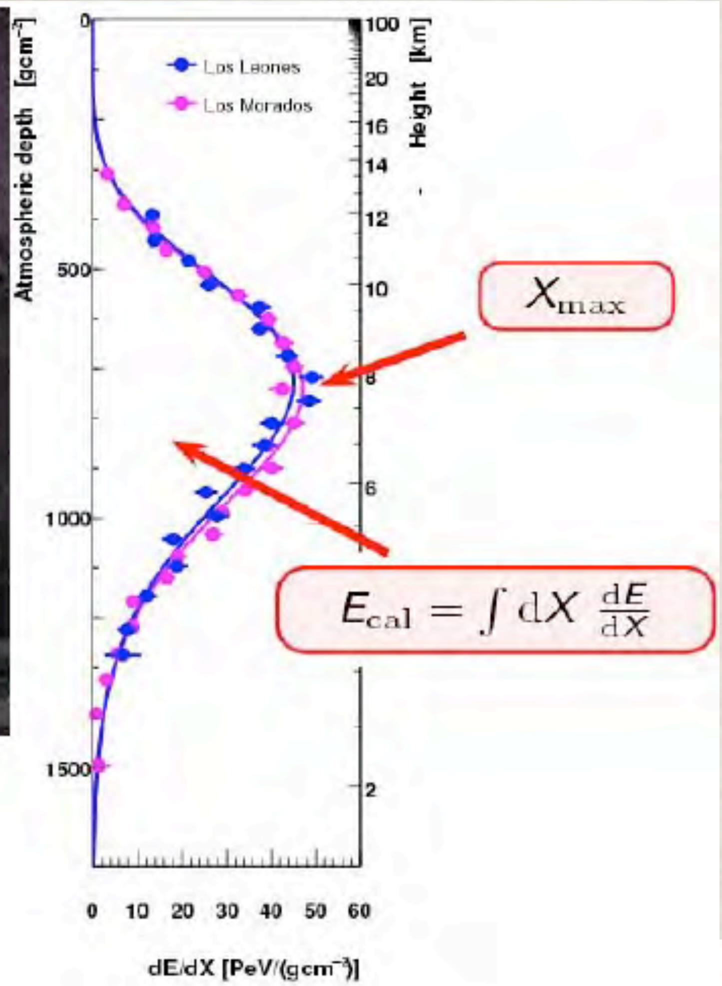
Fit with empirical Gaisser-Hillas formula

$$N(X) = N_{max}\left(\frac{X-X_0}{X_{max}-X_0}\right)^{\frac{X_{max}-X_0}{\Lambda}}\exp\left(\frac{X_{max}-X}{\Lambda}\right)$$

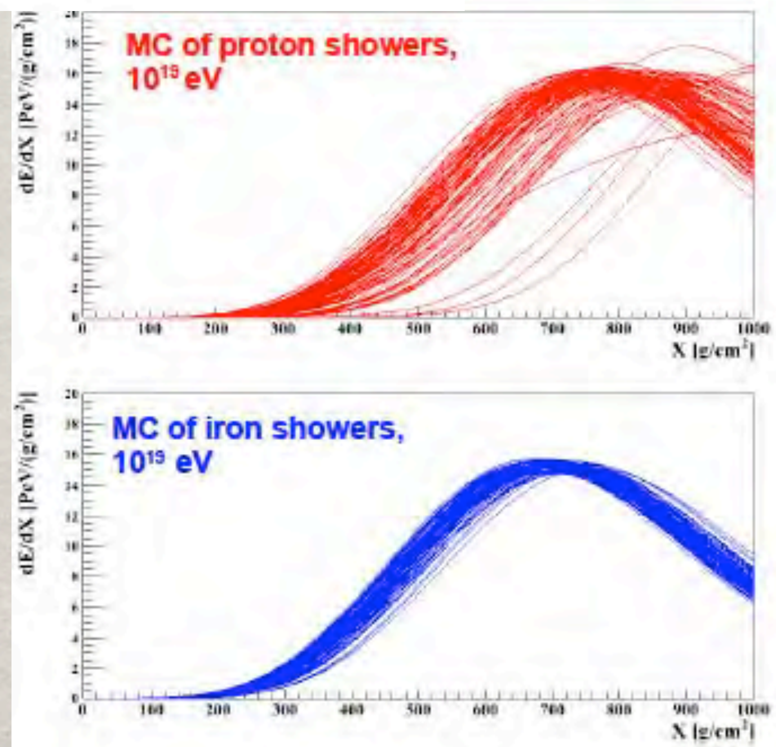
33

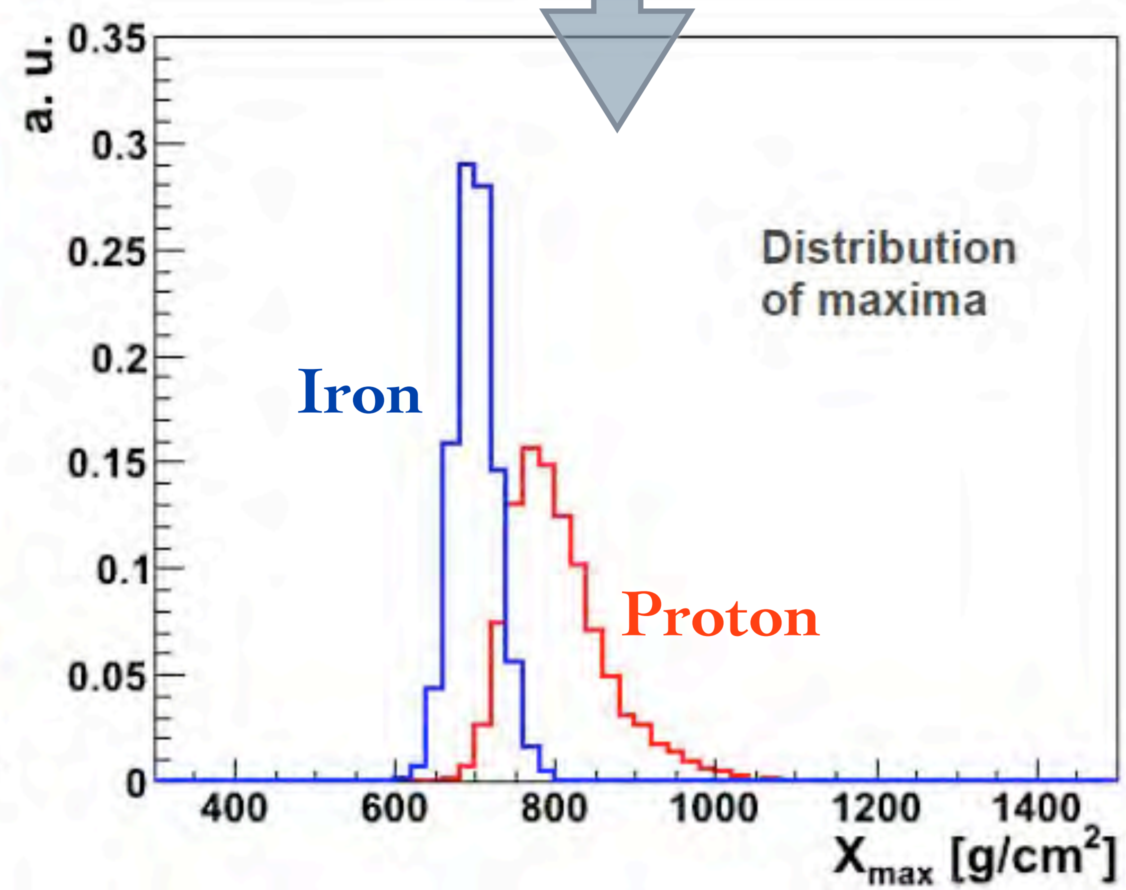
# Xmax & Mass Composition



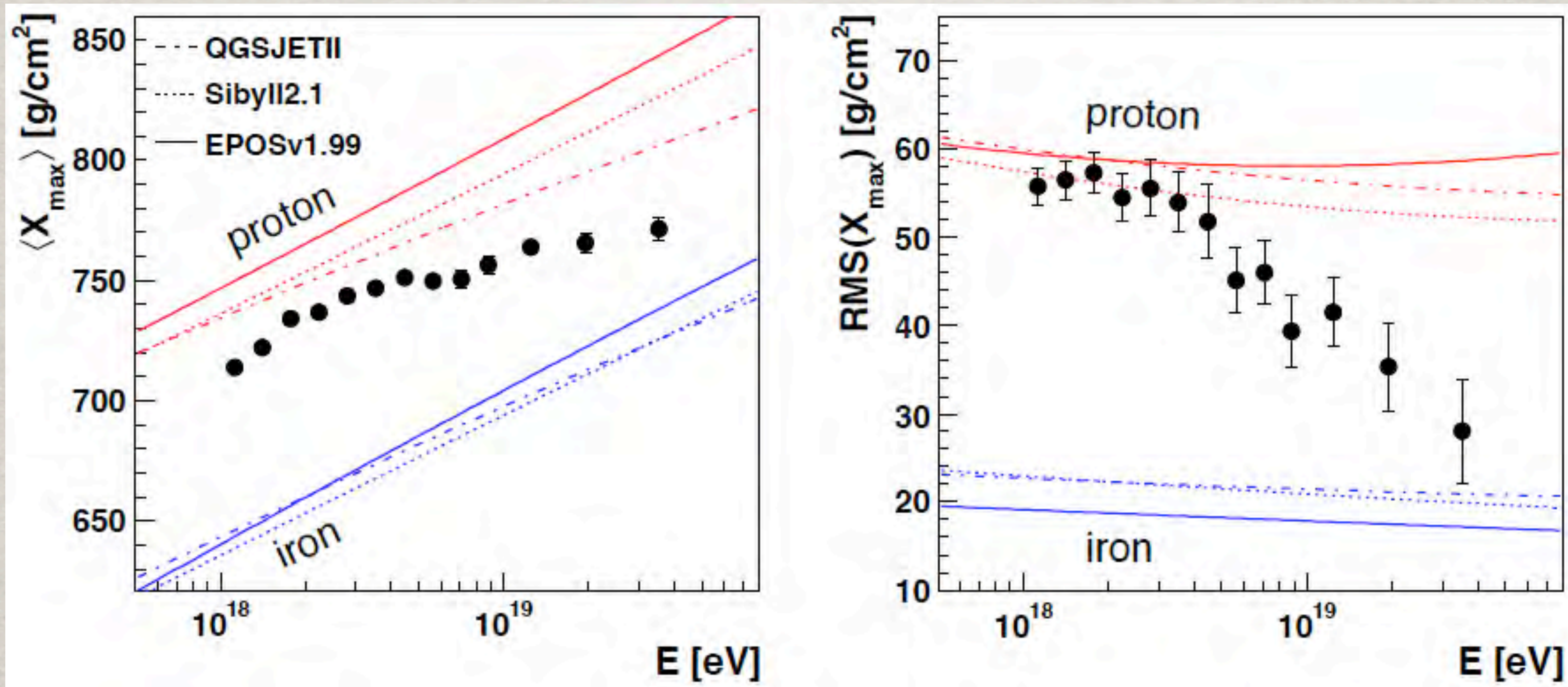



- Measured by fluorescence detector event by event
- The observable **Xmax** contains information about the mass of the primary
  - Heavy primaries are shallower and fluctuate less (RMS(Xmax) is sensitive to composition as well)

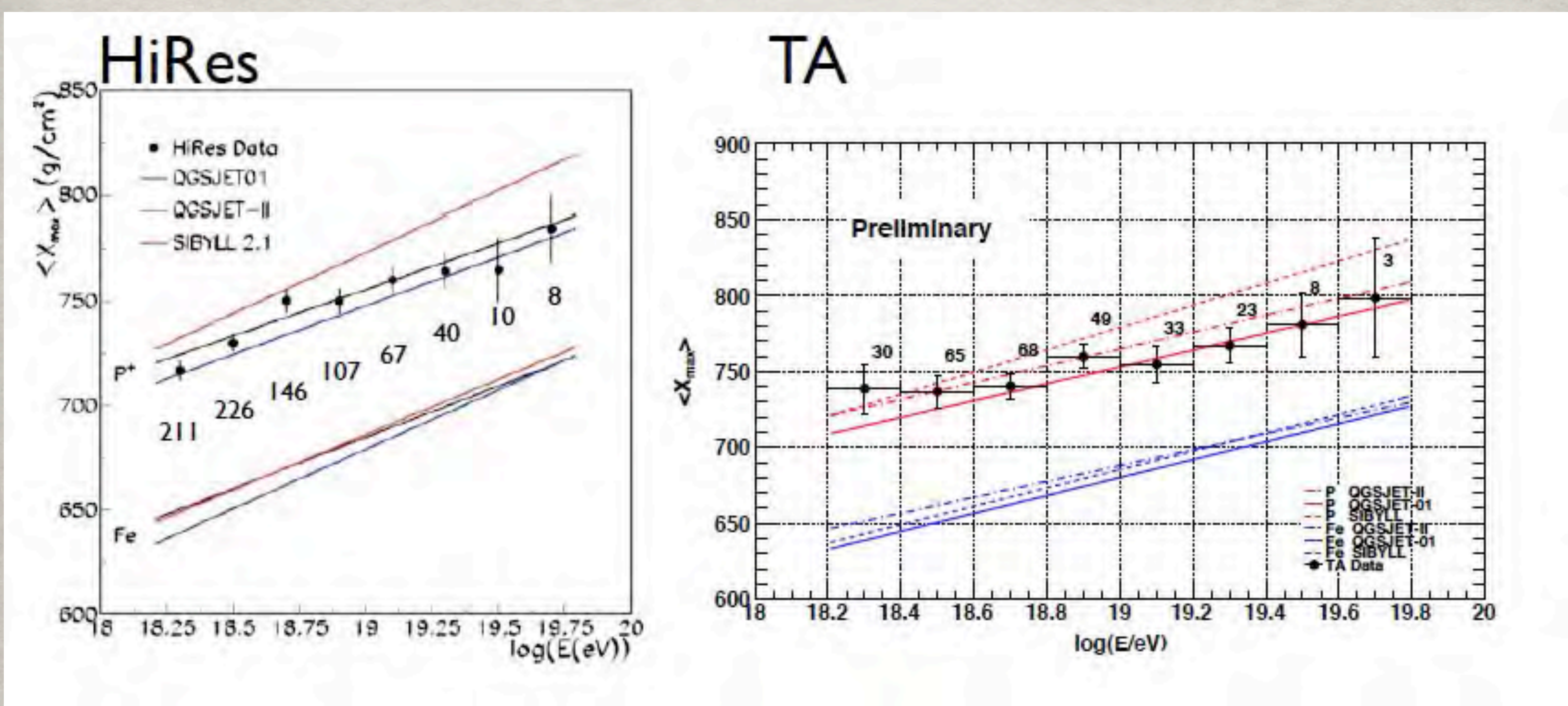


# Pierre Auger Results

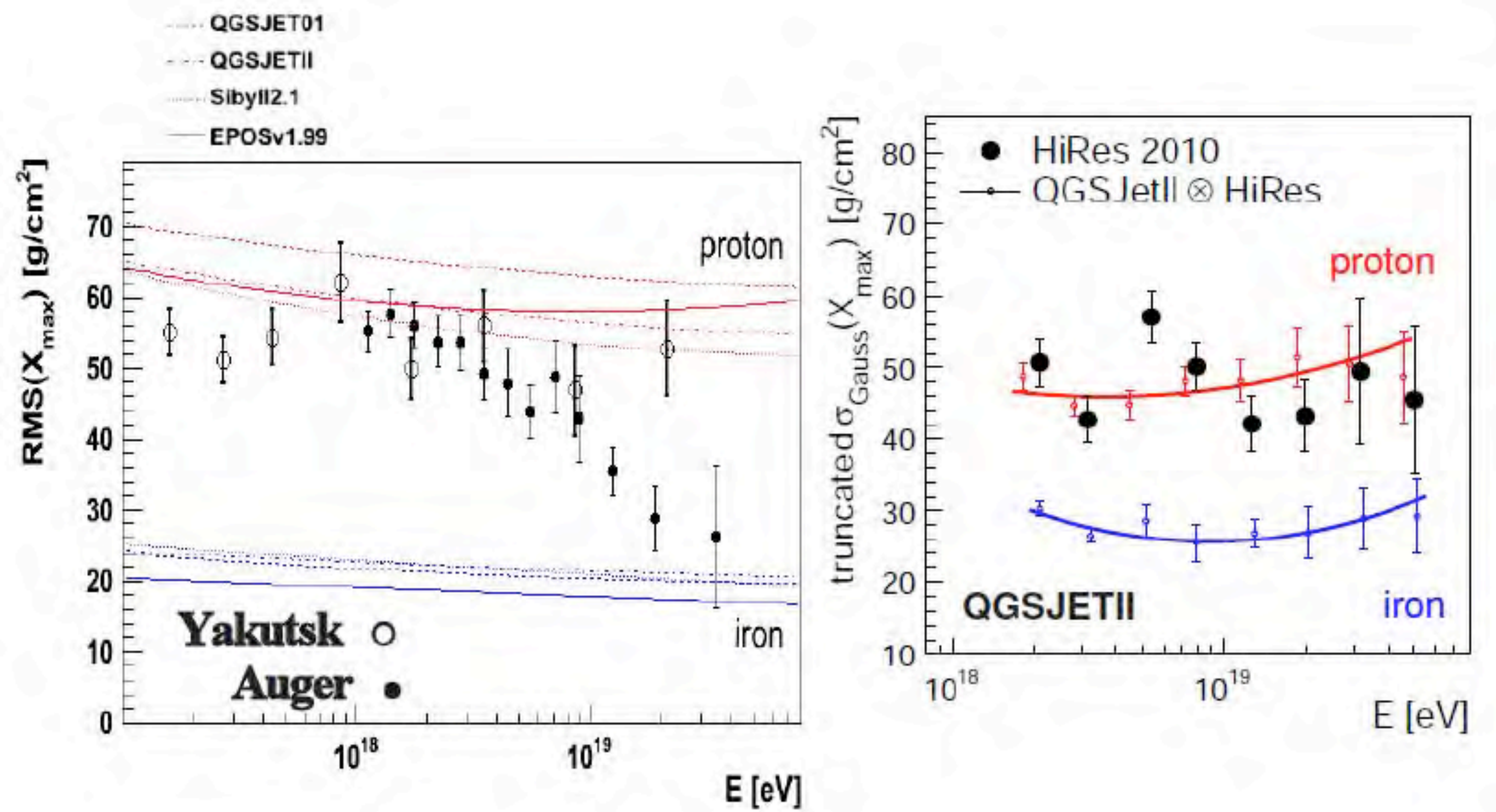


# HiRes & TA: Evolution of Xmax with Energy



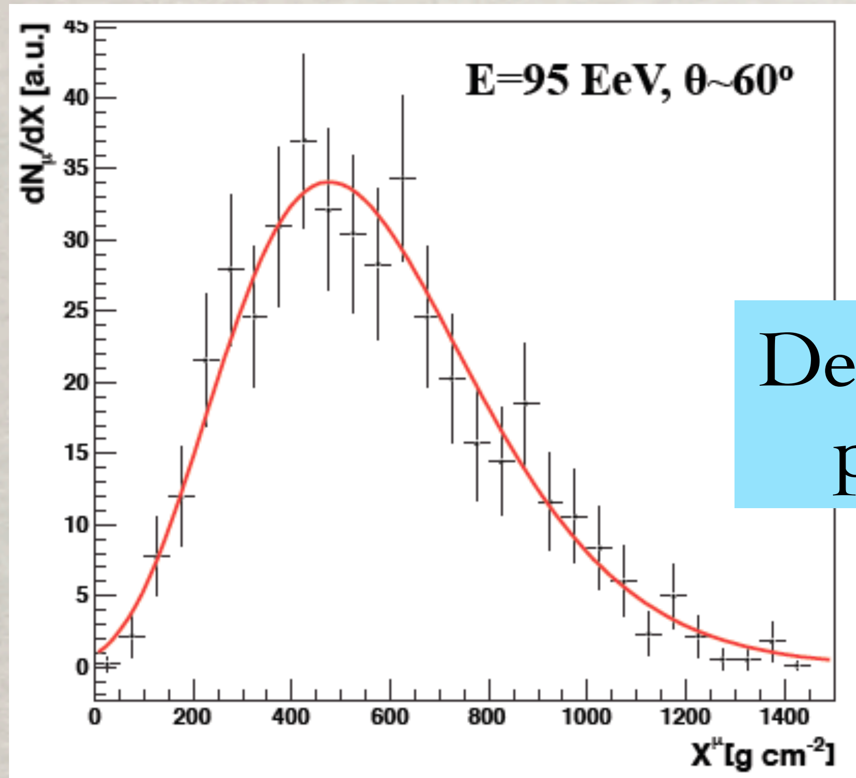

Consistent with QGSJET proton model

# RMS(Xmax) vs E

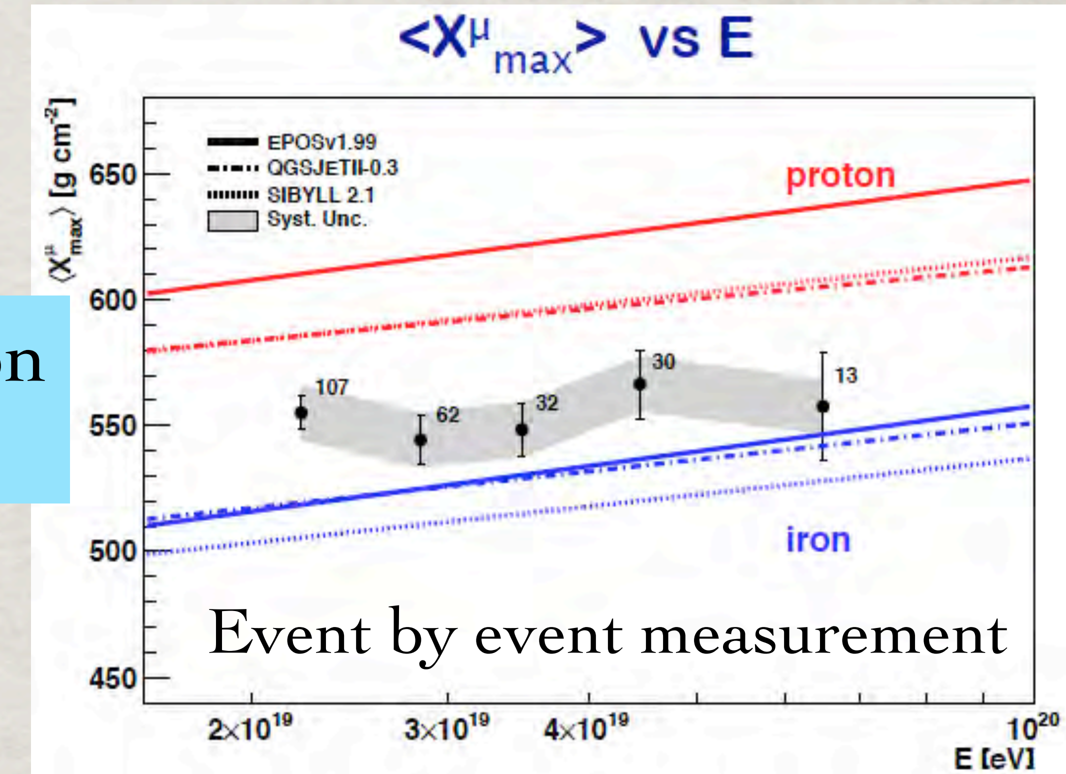


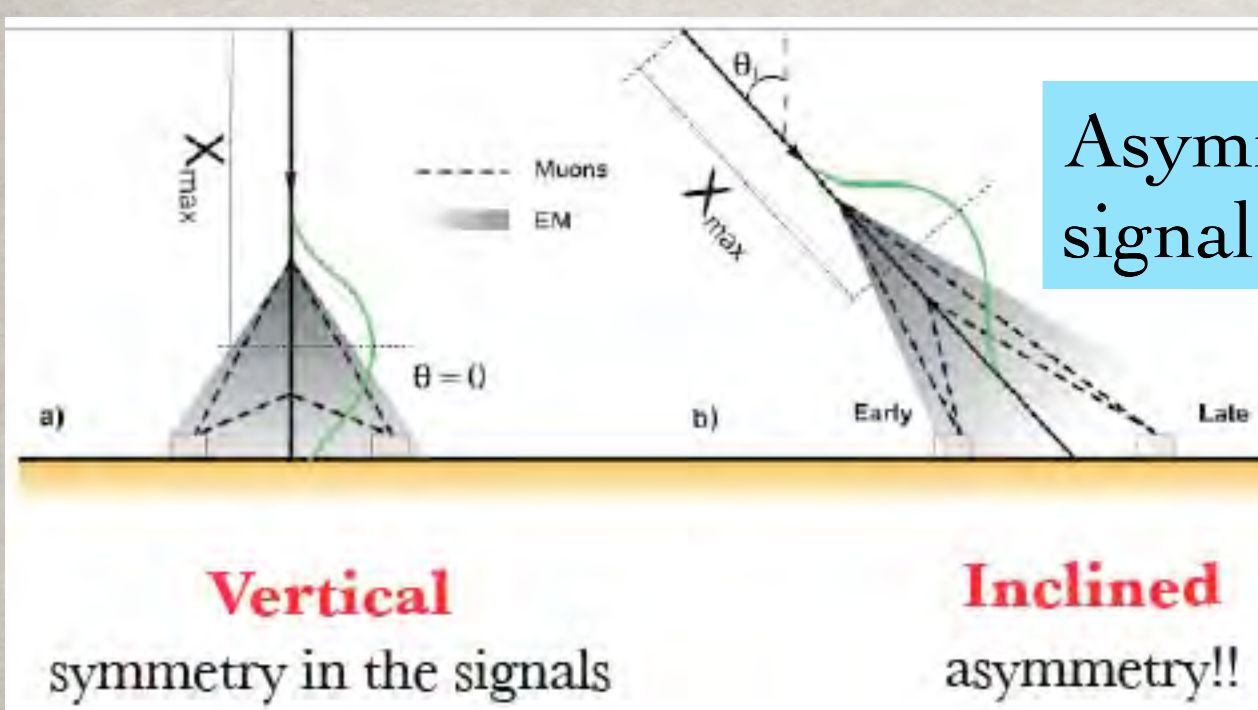

Yakutsk energy scale normalized to the Auger energy scale.

# Mass Composition with Surface Detector Data

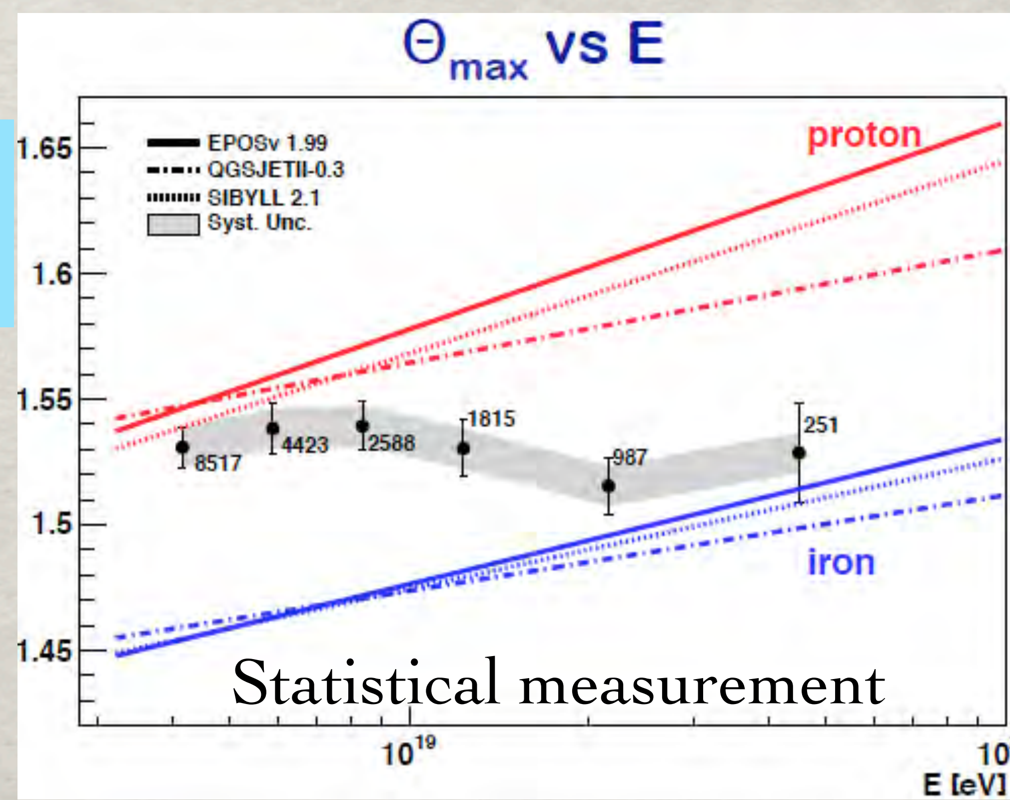



Depth profile of muon production points



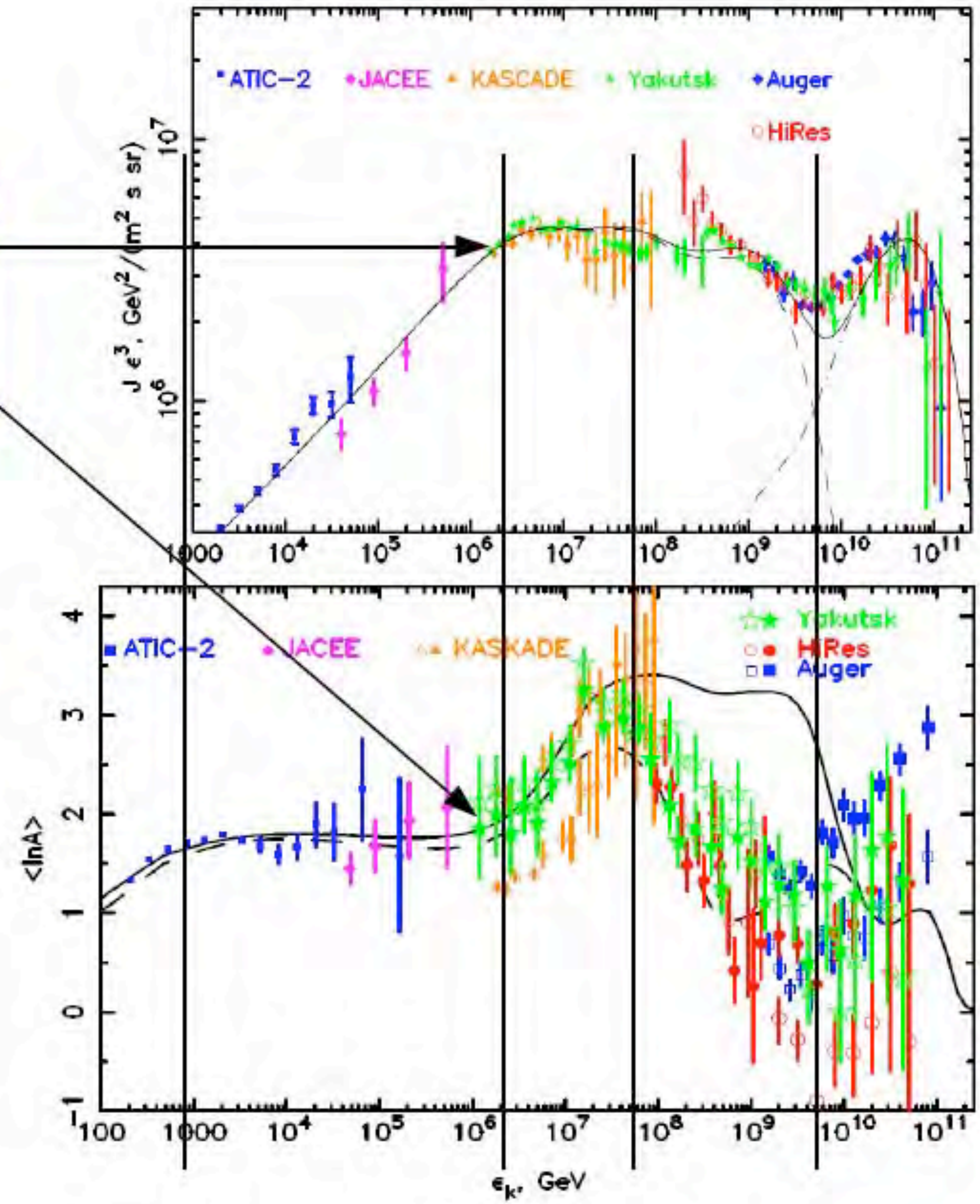




Asymmetry of signal risetime



# The Big Picture

Features in the evolution of <lnA> with energy seem to correlate with features in the energy spectrum.




**Model dependent conversion**

$$\langle \ln A \rangle = \frac{\langle X_{max} \rangle_p - \langle X_{max} \rangle_{data}}{\langle X_{max} \rangle_p - \langle X_{max} \rangle_{Fe}} \ln 56$$

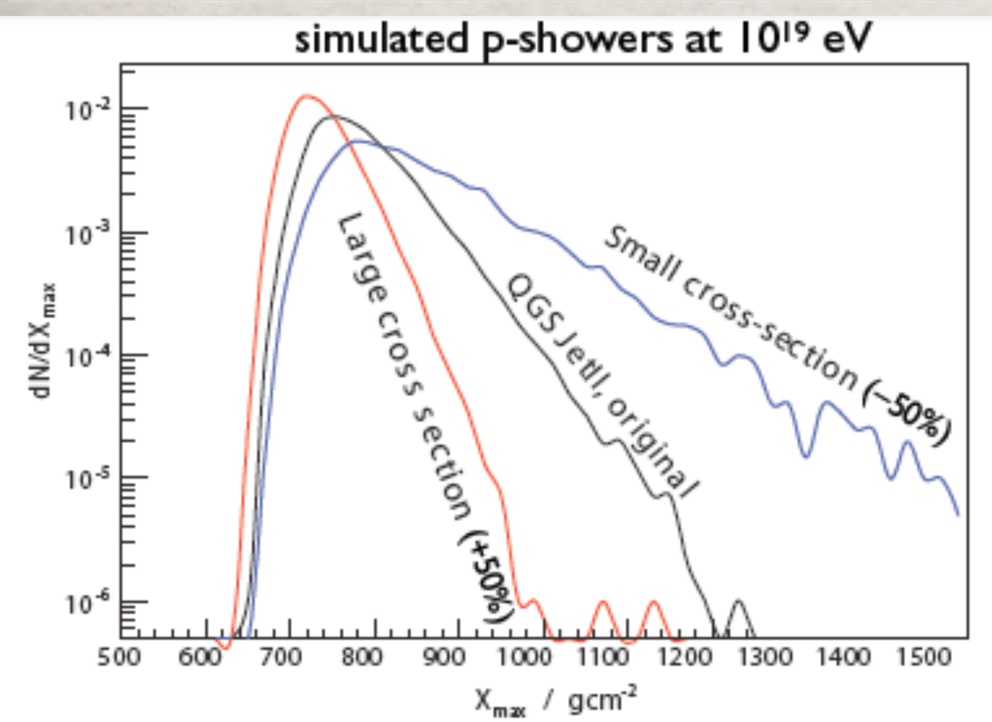
Plots provided by our Yakutsk colleagues (to be published this year).

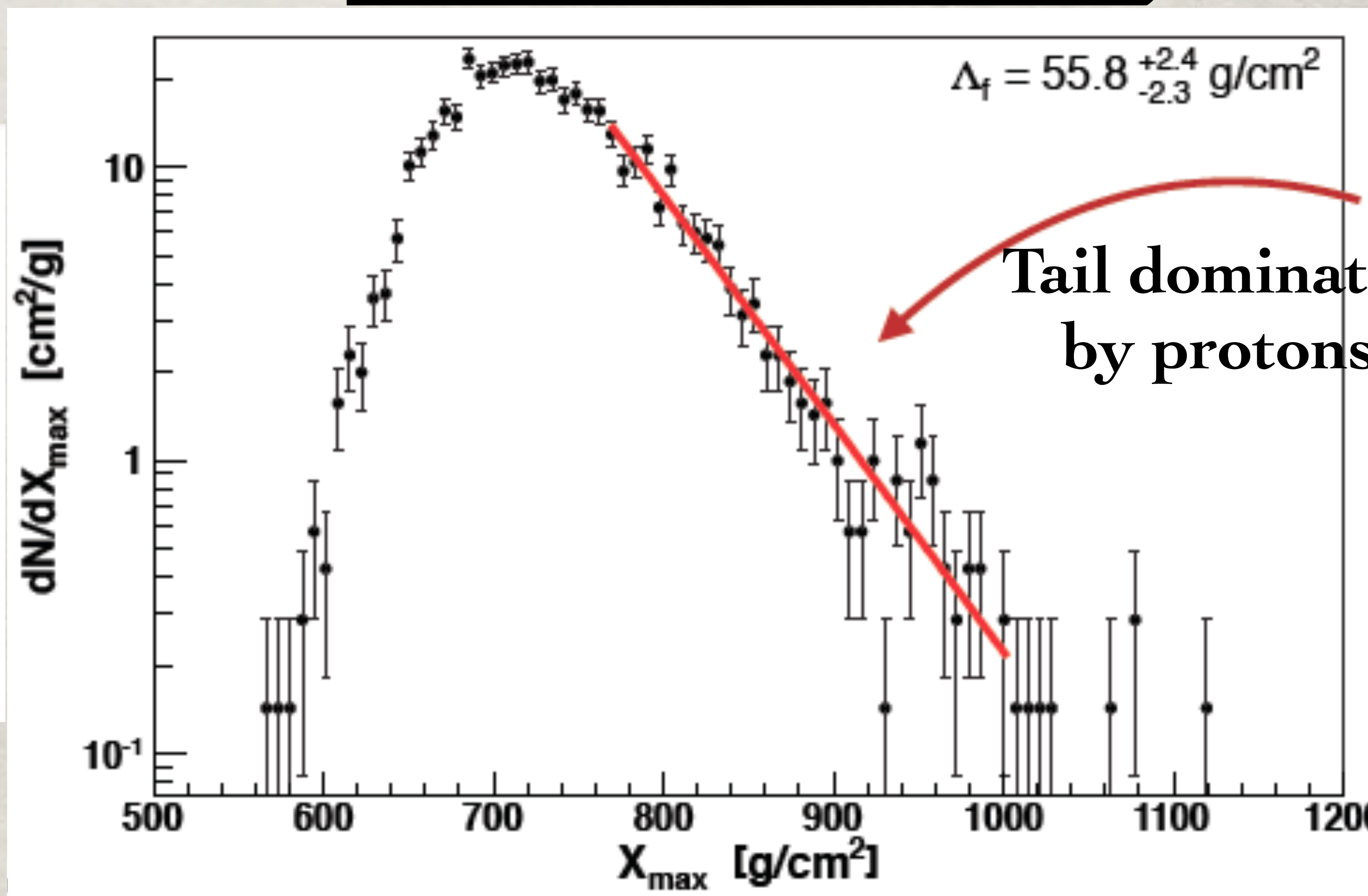
# Tests of Fundamental Interactions

# P-Air Cross Section

**Tail of Xmax distribution sensitive to cross section**

$10^{18}$ eV< E < $10^{18.5}$ eV

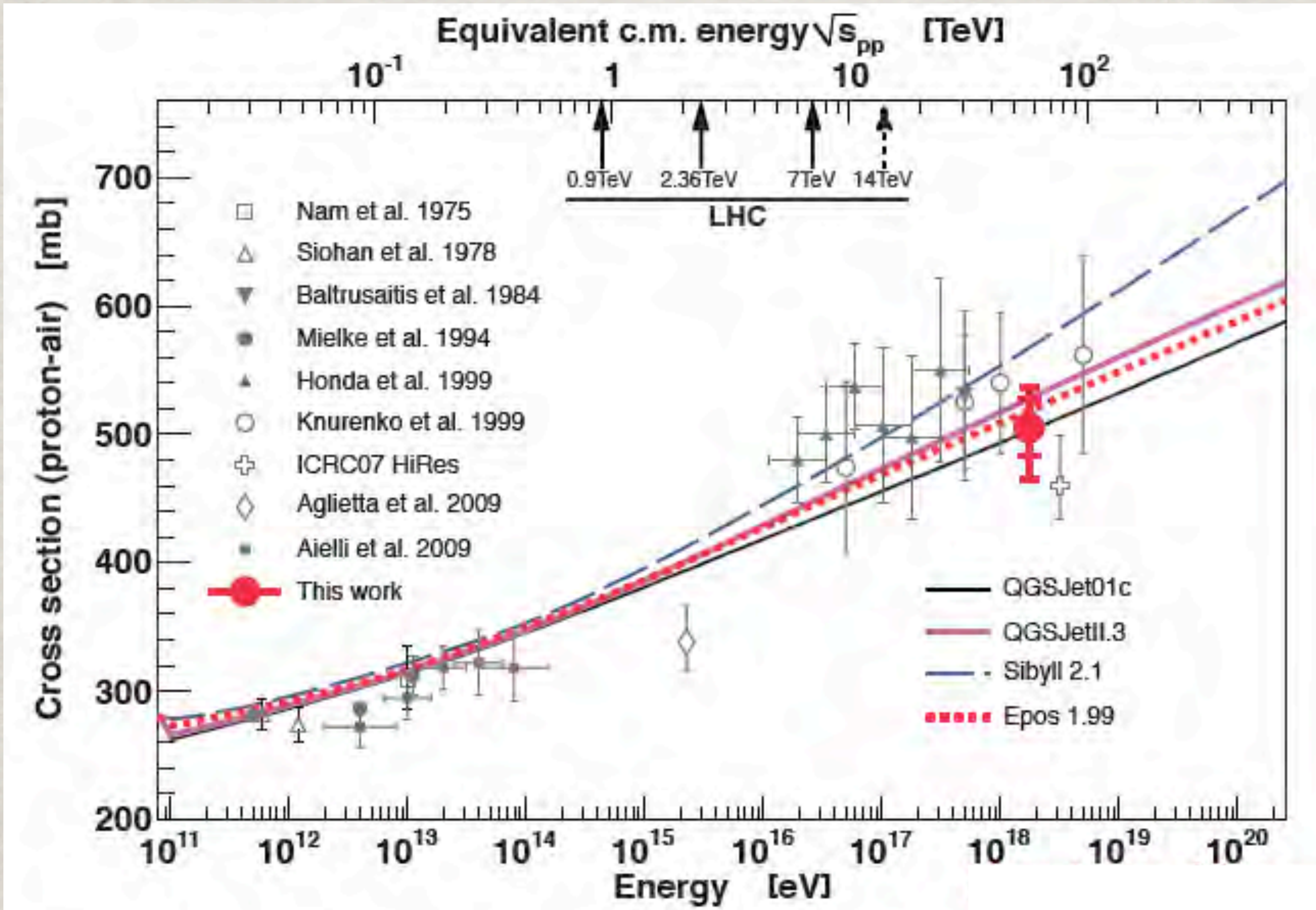



$$dN / dX_{max} \propto e^{-X_{\max}/\Lambda_f}$$

$$\Lambda_f = 1/(\rho \boxed{\sigma_{p-air}})$$

# $\sigma_{\text{PROTON-AIR}}$



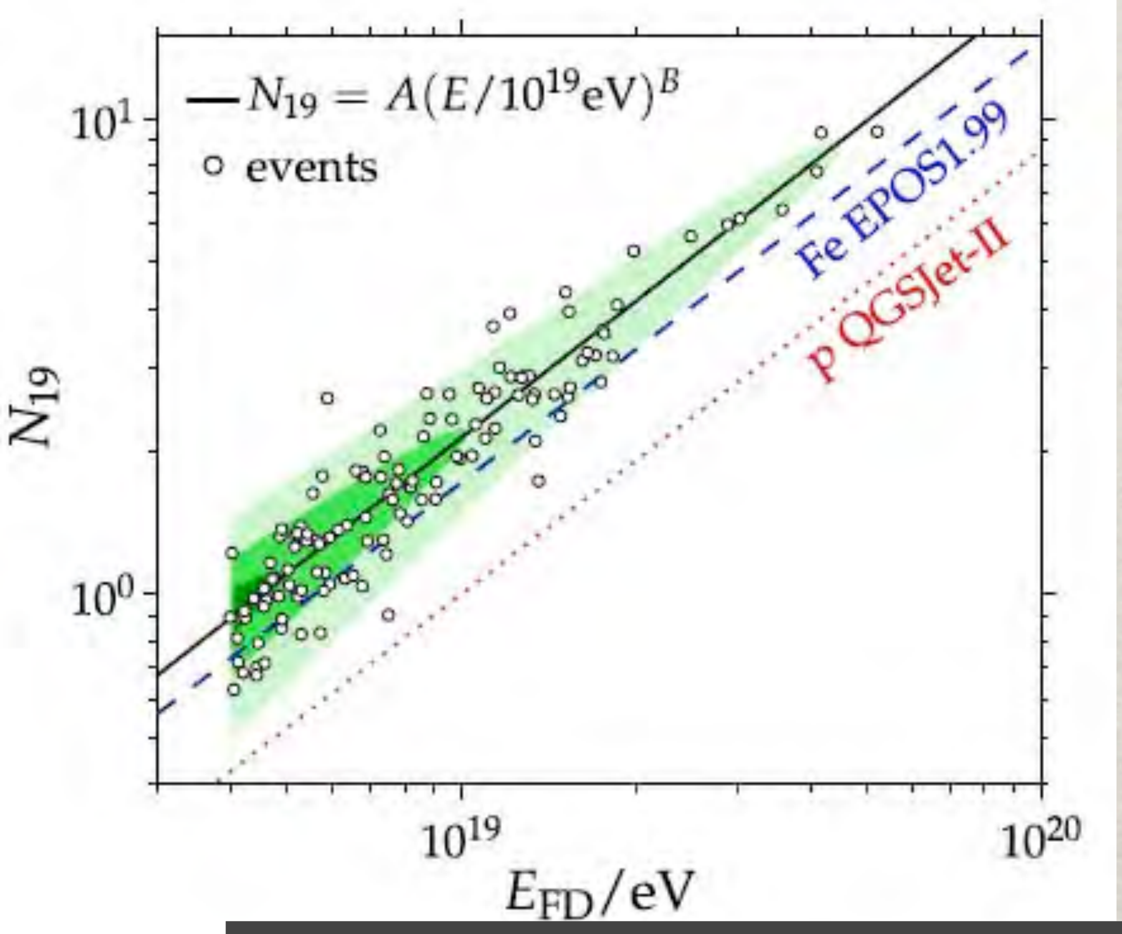

$$\sigma_{\text{p-Air}} = (505 \pm 22_{\text{stat}} \left({}^{+26}_{-34}\right)_{\text{sys}}) \text{ mb}$$

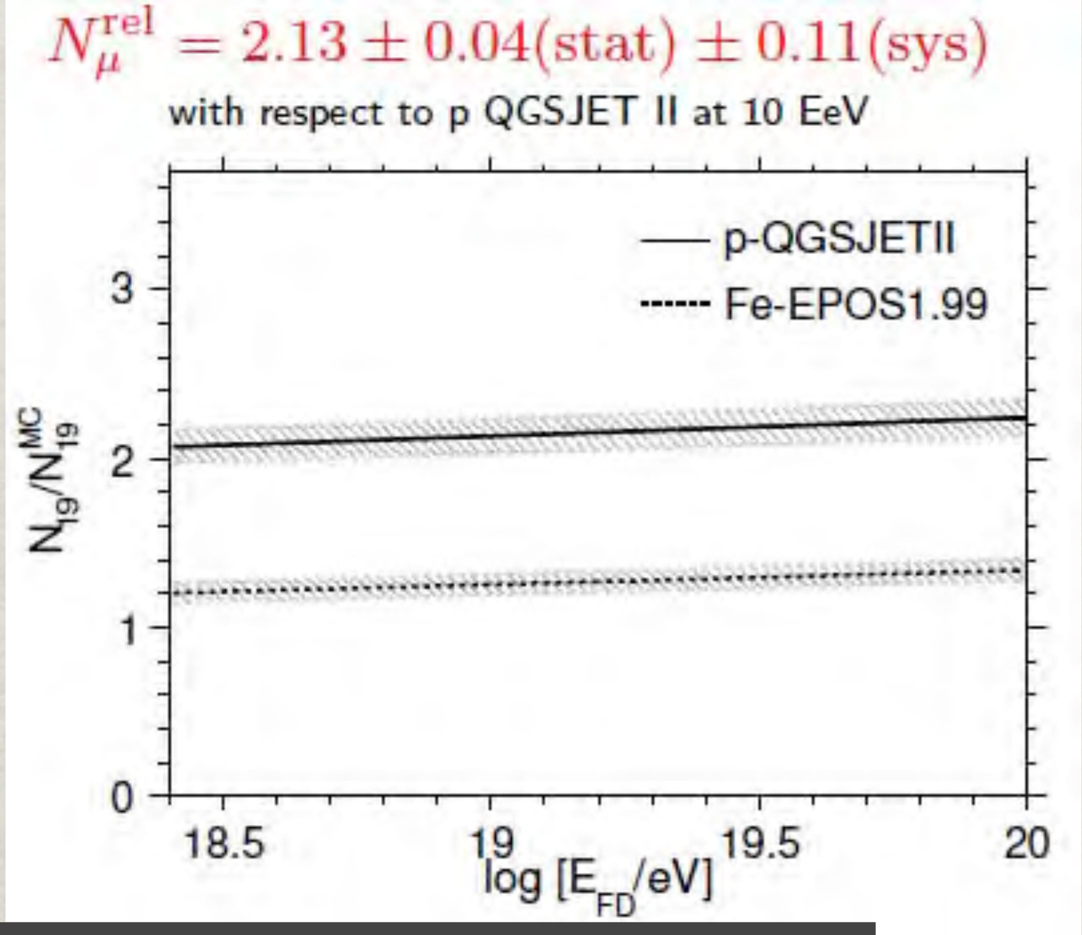
Contaminations assumed for systematics:

**< 25% He    < 0.5% $\gamma$**

# Tests of Hadronic interactions

- Use inclined showers (θ>60°, large atmospheric depths)
- Signal dominated by muons
  - Small EM contamination subtracted




**Deficit of muons in simulations**

(similar results with independent methods and data samples)

# A Cosmic Ray Odyssey

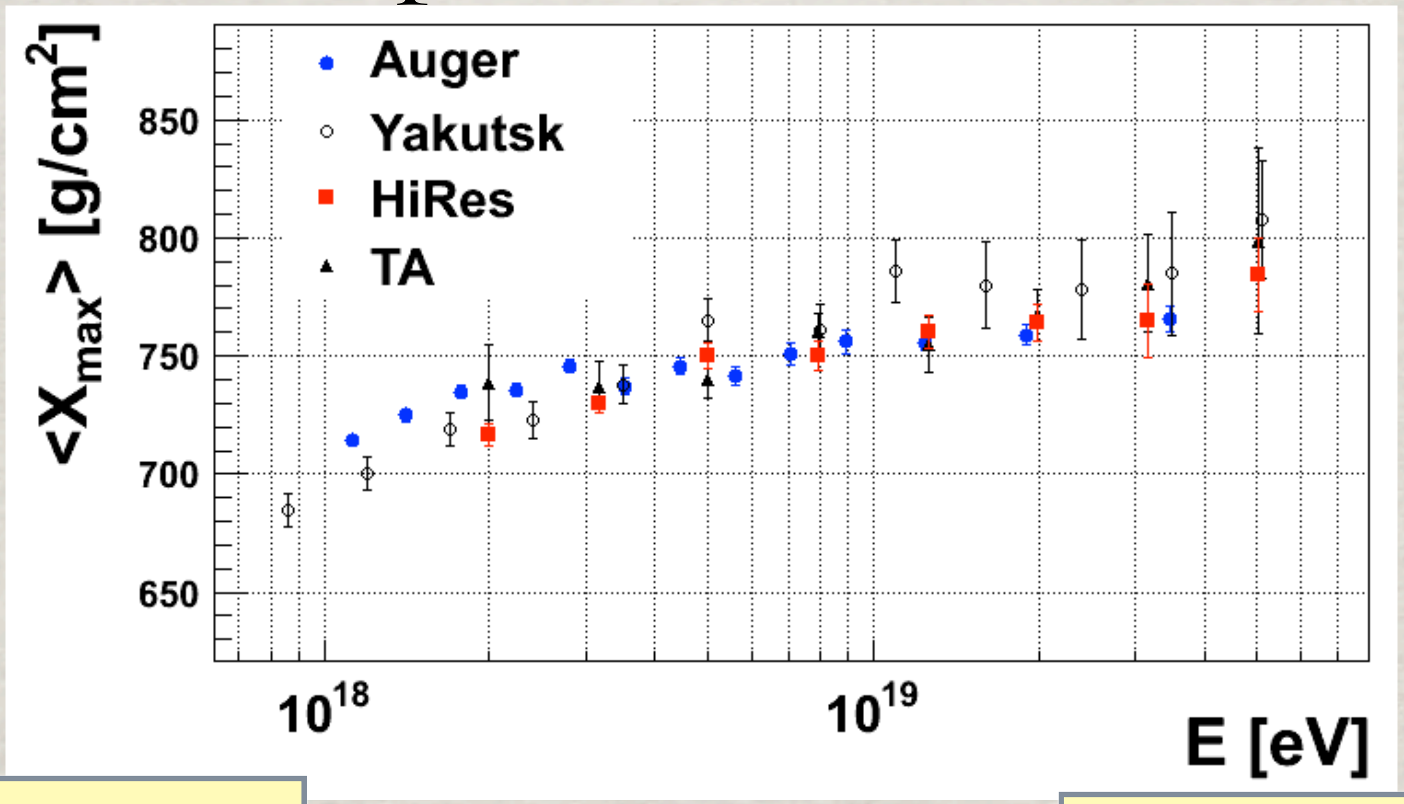
- After hundred years of wanderings, Odysseus (a cosmic ray physicist) did not come back to Troy yet (i.e. the truth is still far from us)...


**Odysseus' wanderings**

- ...but the voyage is so filled of notable experiences that we will keep on striving to meet Penelope (the true origin of ultra-high energy cosmic rays) at last!

# A Word of Warning!

- Different analyses between different experiments prevent a direct comparison of measurements!




Pierre Auger uses MC to estimate:
A) Average Xmax reconstruction bias as a function of energy
B) Average Xmax resolution as a function of energy

HiRes/TA uses MC to estimate:
the expected Xmax distributions afer all detector effects. Expected and observed distributions are used to infer composition

# Summary from Mass Composition Working Group

- Common effort from HiRes, TA, Yakutsk and Pierre Auger collaborations
  - Set up for UHECR 2012 Symposium

•<u>Are the differences due to issues in any of the analysis?</u>

Apparently no.

• <u>Are the differences within systematic uncertainties?</u>

Auger and HiRes are not consistent within the **quoted** systematic uncertainties.

• <u>Are the Southern and Northern sky different in terms of composition?</u>

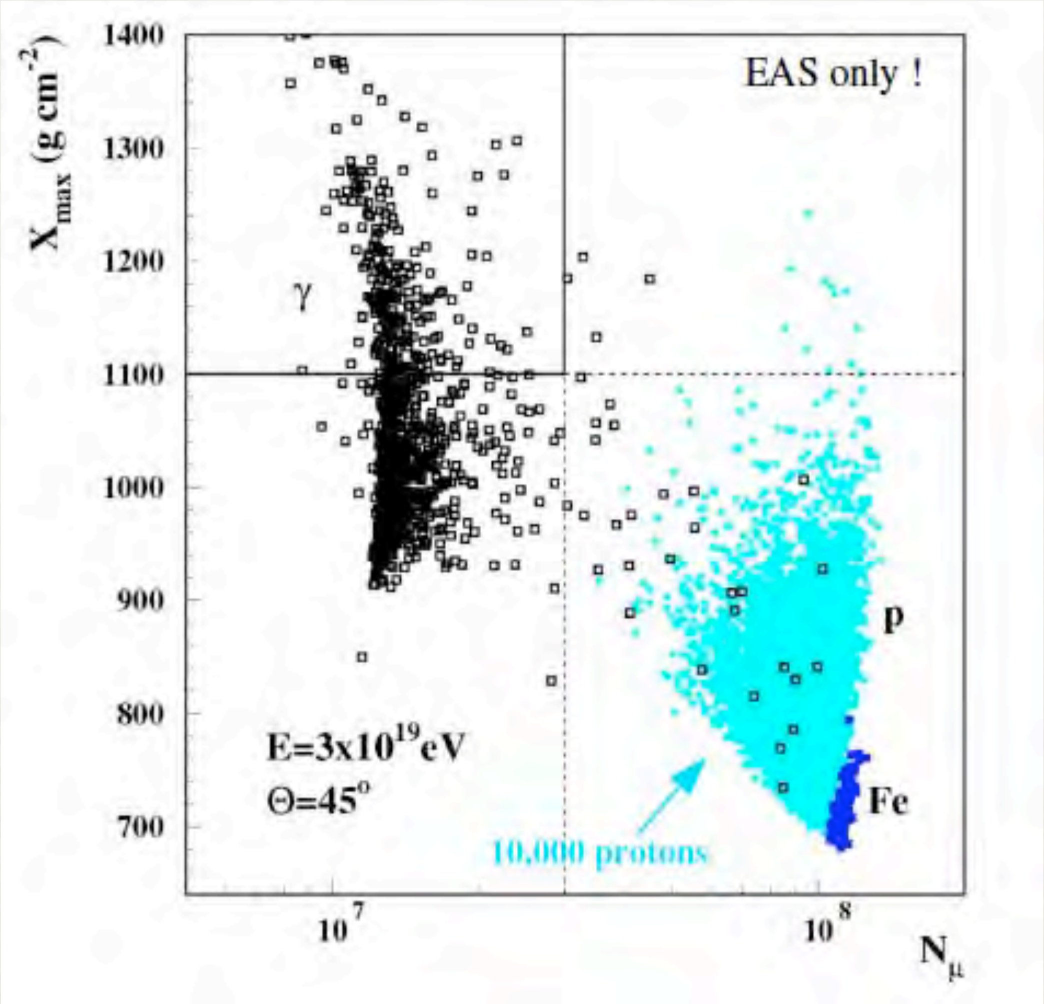
We need more statistics in the Northern hemisphere (about 4 times the current statistics) to give a conclusive answer. The current statistics in the northern hemisphere do not allow to discriminate between a constant composition or a changing composition as suggested by Auger. More statistics is also necessary to establish whether there is a systematic difference in the RMS(Xmax) at higher energies.

• It is interesting to point out that all three experiments (Yakutsk, HiRes and TA) are consistent (within ~5g/cm^2). But, there is a large systematic difference in <lnA> equivalent to about 30 g/cm^2 between Auger and the other experiments.

# Multi-messenger Physics

# Photons

- What is a photon?



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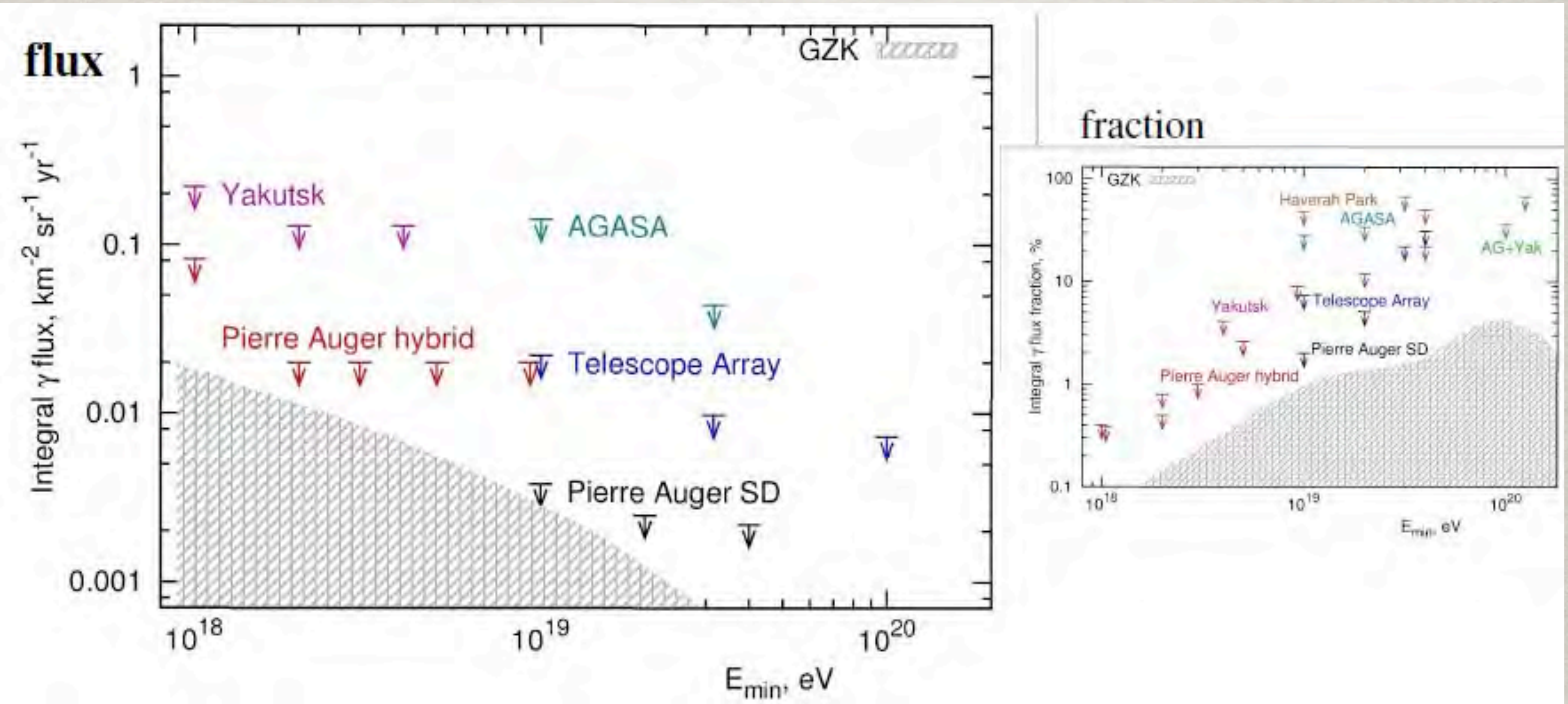
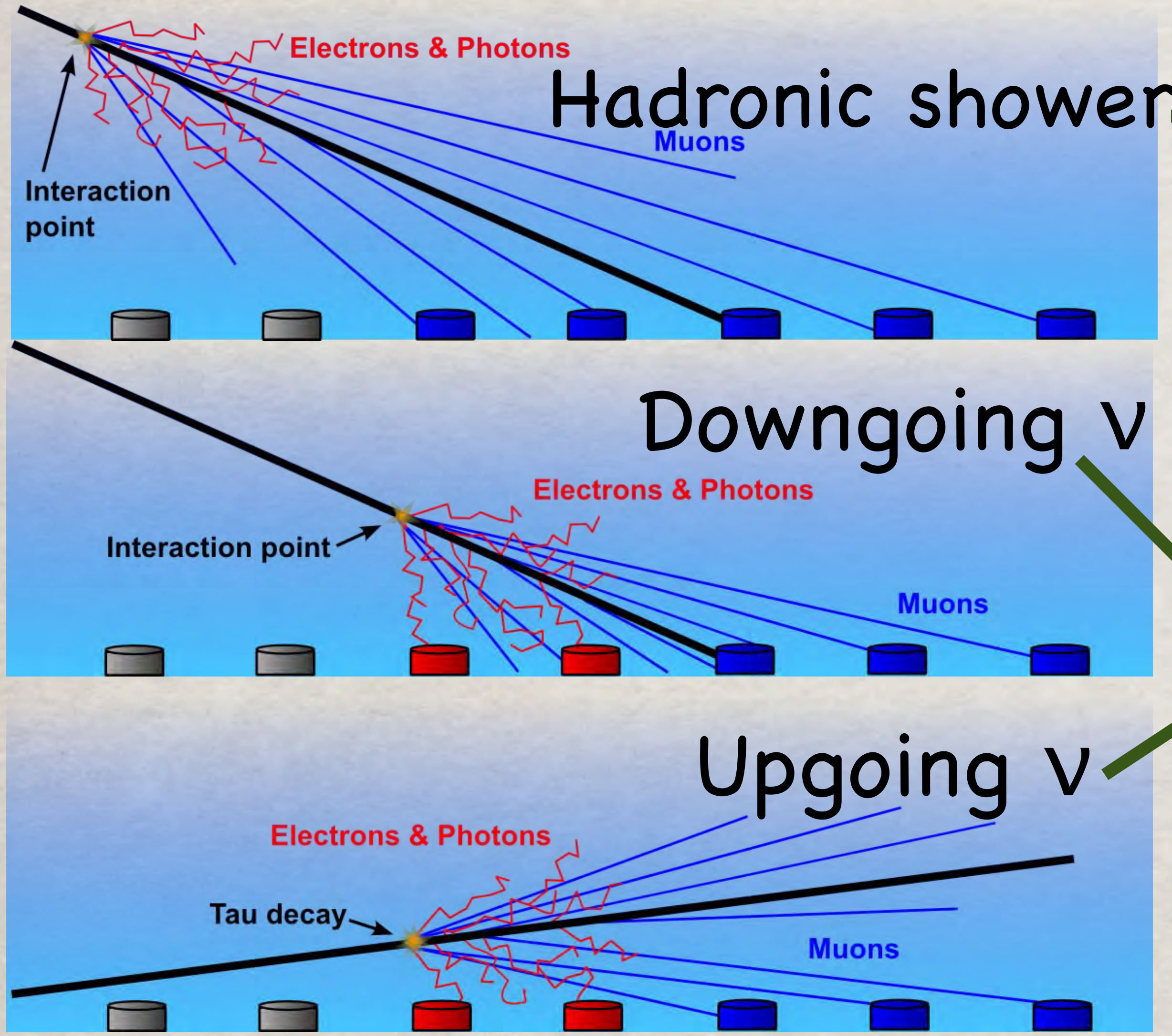


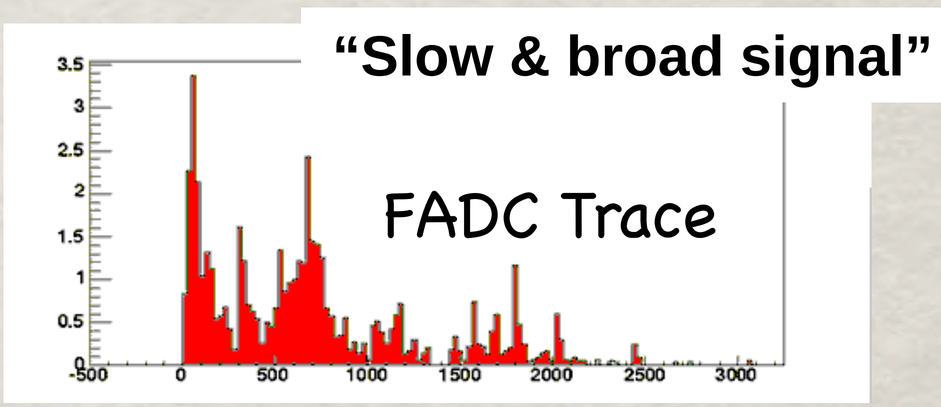

Different techniques but NO CANDIDATES found so far

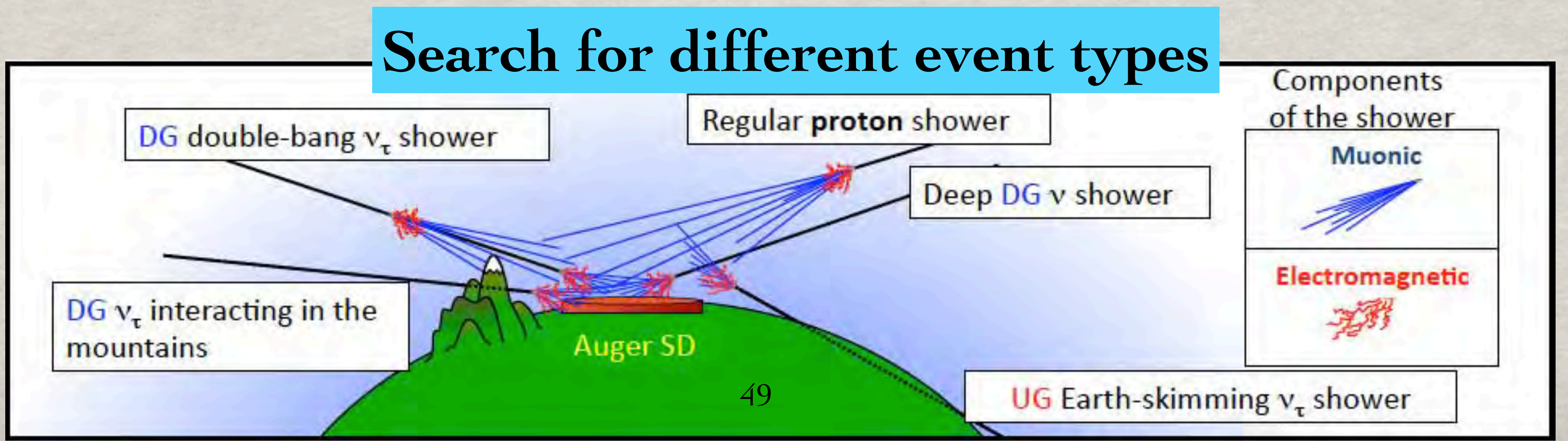
# Neutrinos

- What is a neutrino?



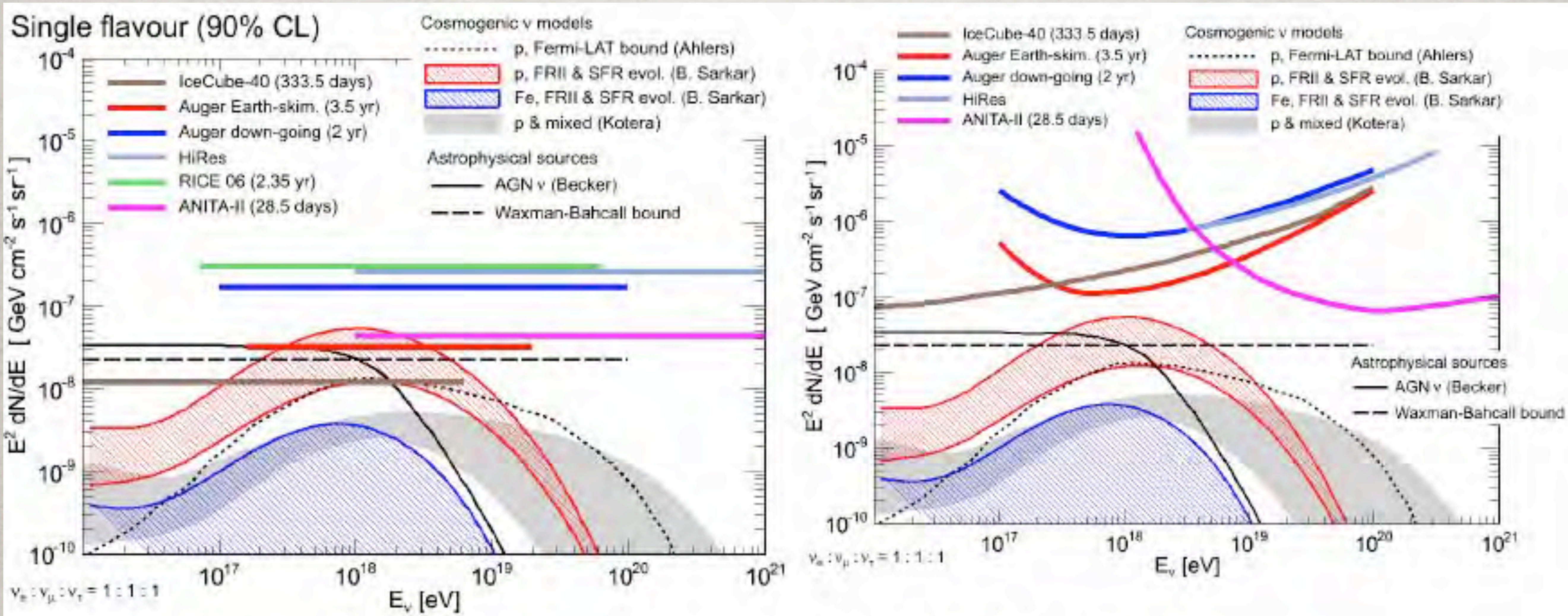




# Neutrino Limits

**NO CANDIDATES found so far**



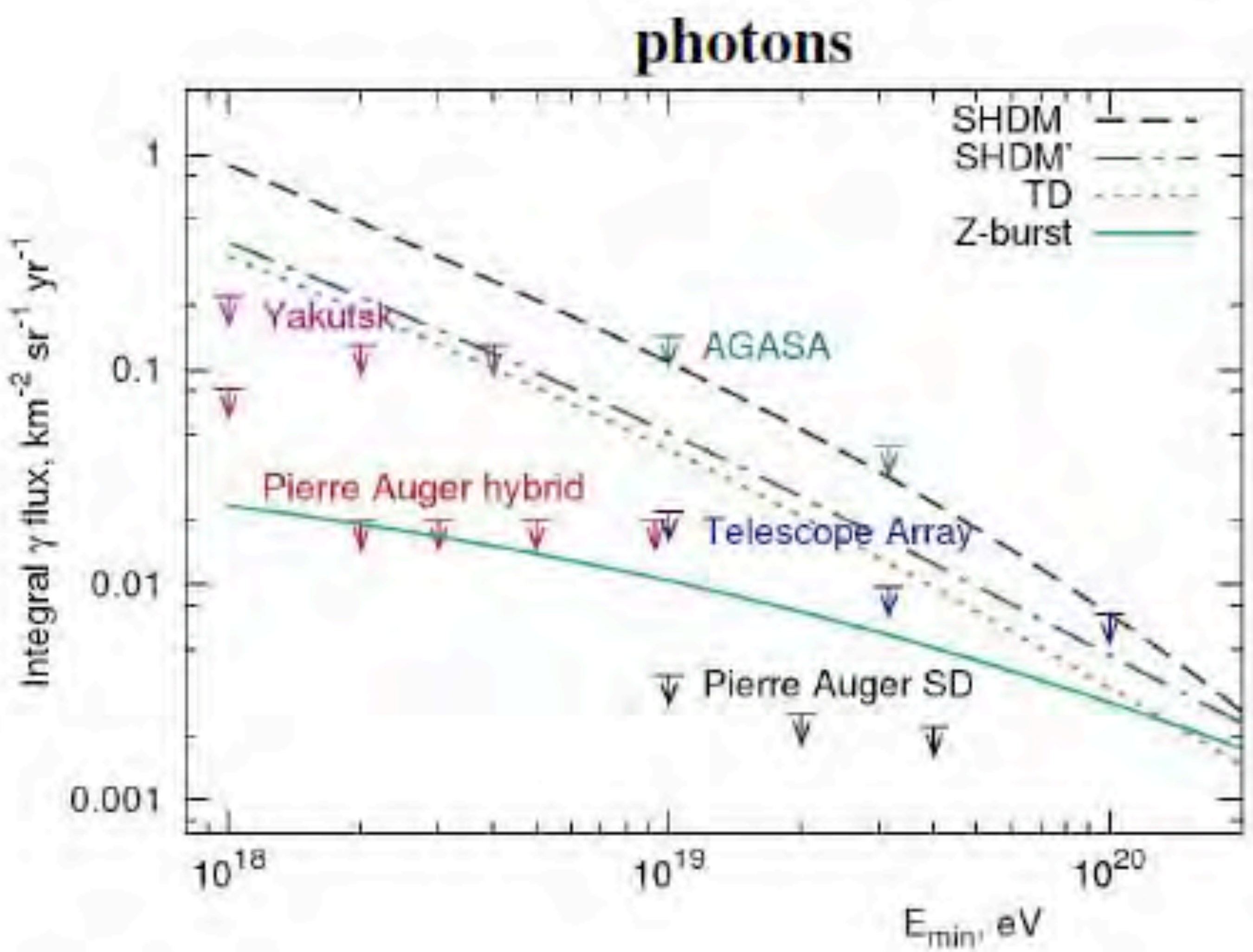

**integral limits**: assume $E^{-2}$ $\nu$ flux & find normalization needed to detect ~ 2.4 events

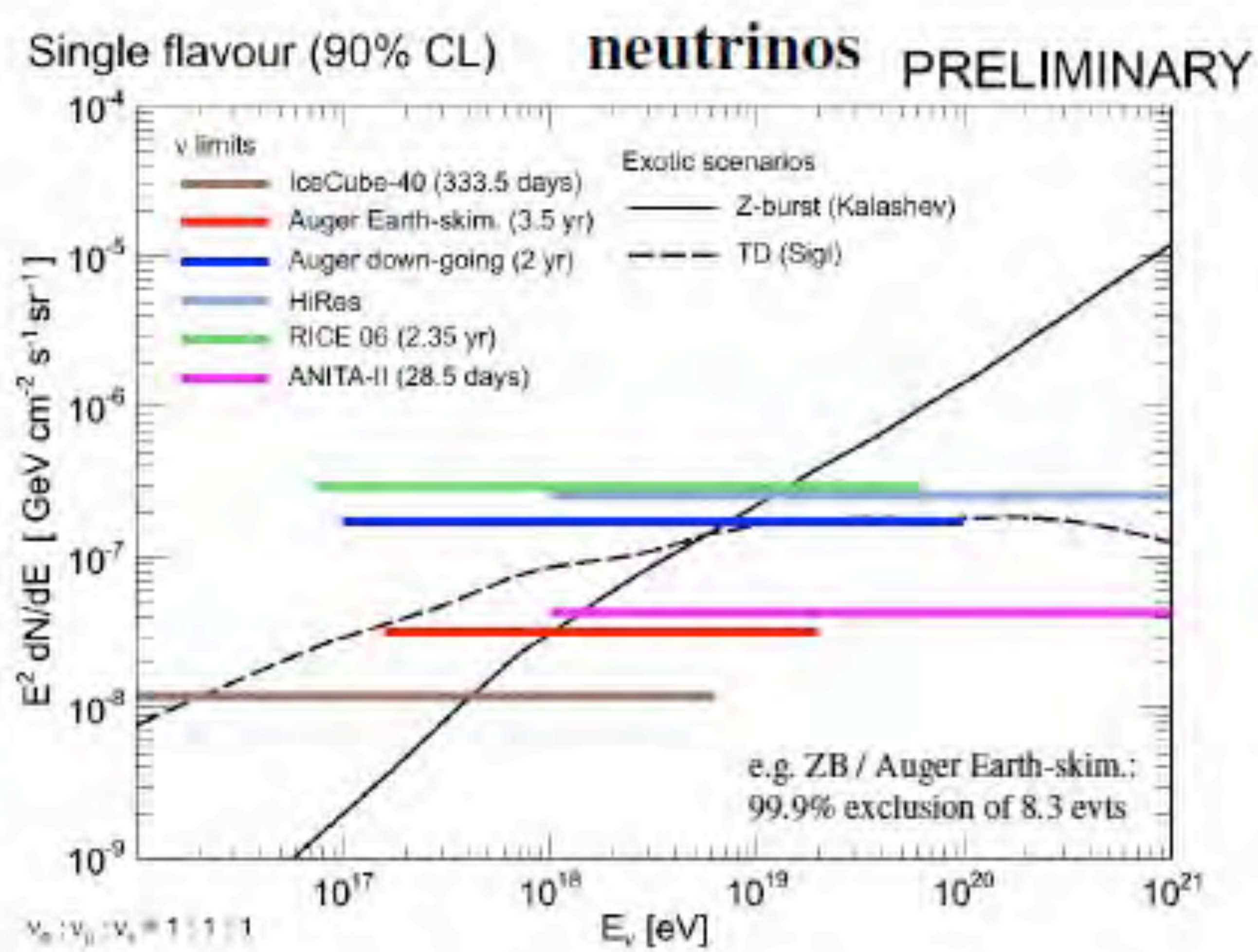
**differential limits:** assume $E^{-2}$ $\nu$ flux in energy bins & find normalization to have 2.4 events in each bin

# Multi-Messengers: Constraints on models

- Very strong constraints on Top-Down Models*

*UHECRs come from decays of super-heavy particles



# The Future is coming...

# Microwave radiation

**P. Gorham et al., Phys. Rev. D 78, 032007 (2008)**

- Soft electron plasma (T=$10^5$ K)
  - Acceleration in collisions with $N_2$
- Emission in the GHz band
  - Coherent, $P \bullet N_e^2$
  - Incoherent, $P \bullet N_e$
- Advantages
  - Duty cycle: 100%
  - Non-polarized isotropic emission
  - Cover areas O(10 000 $km^2$) in a cost-effective way

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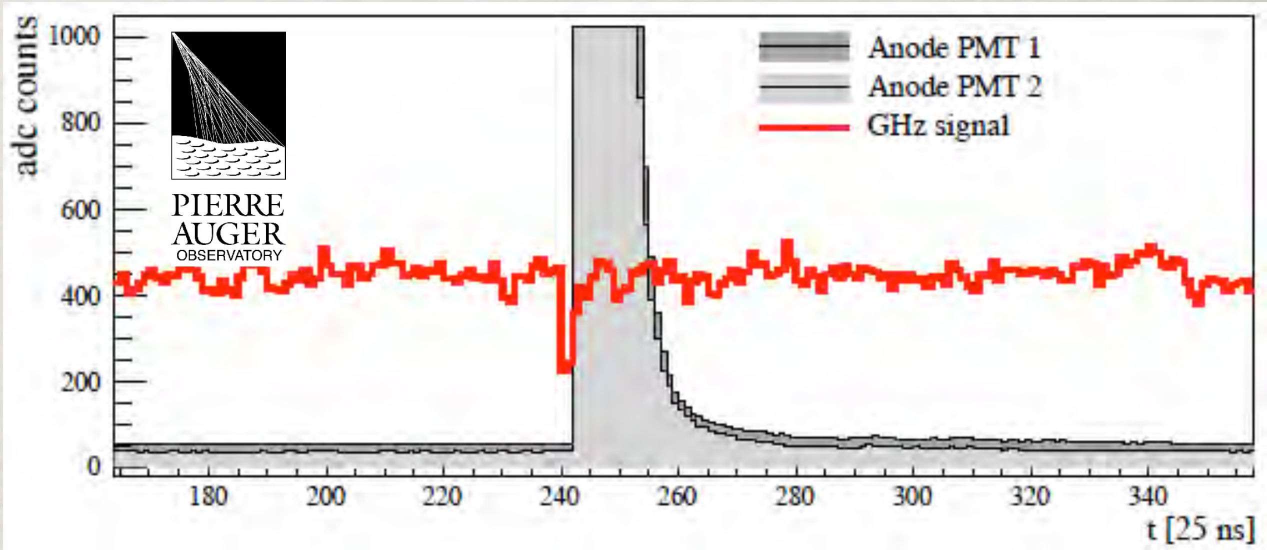


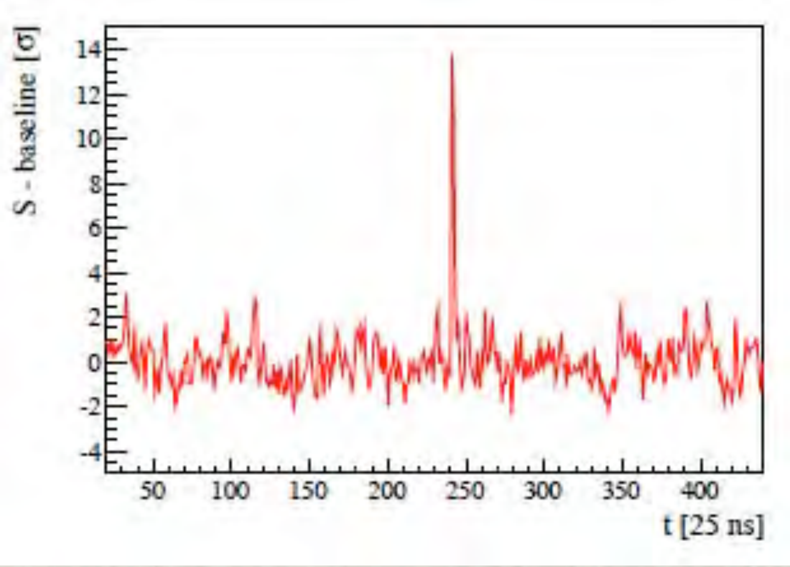


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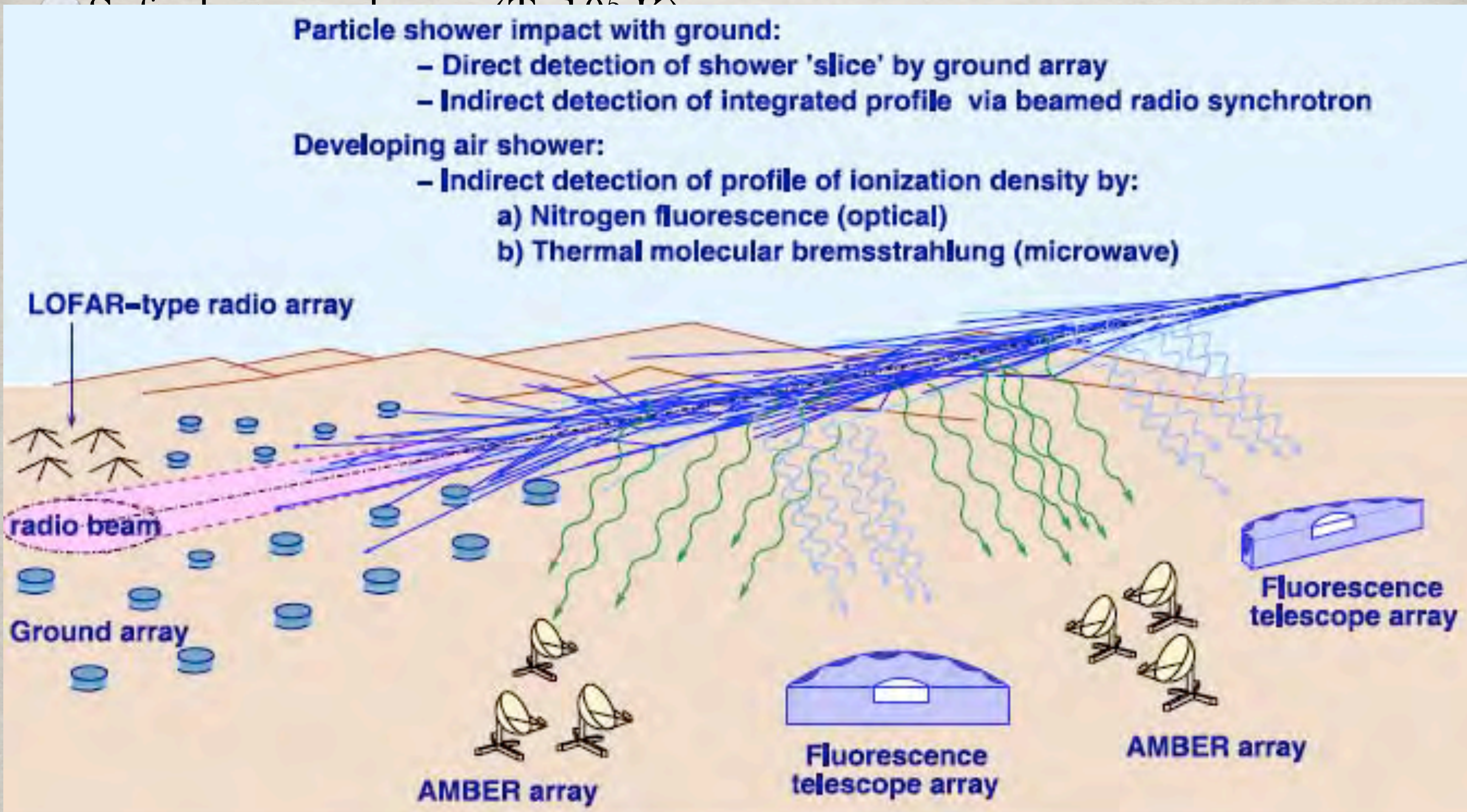
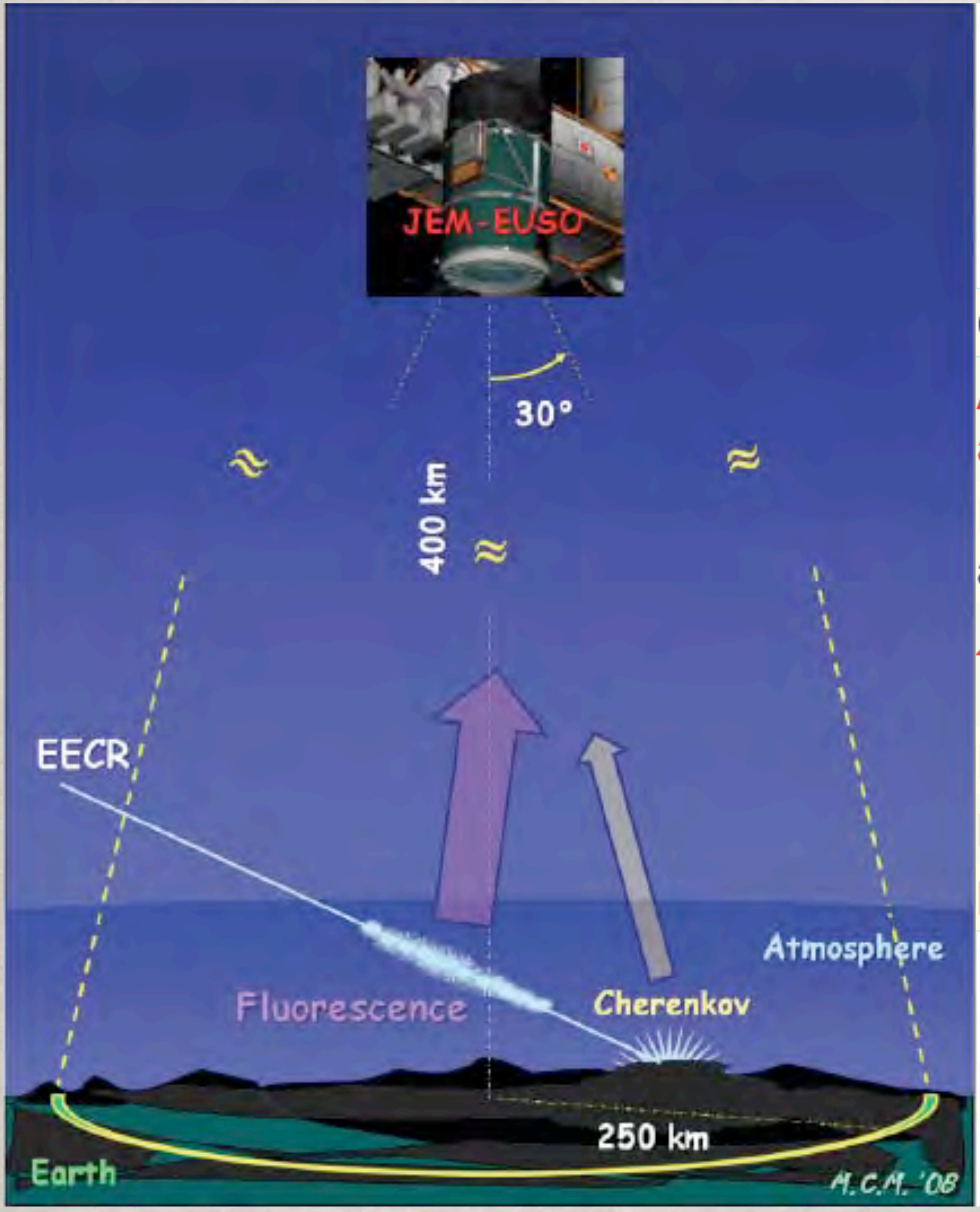



cost-effective way

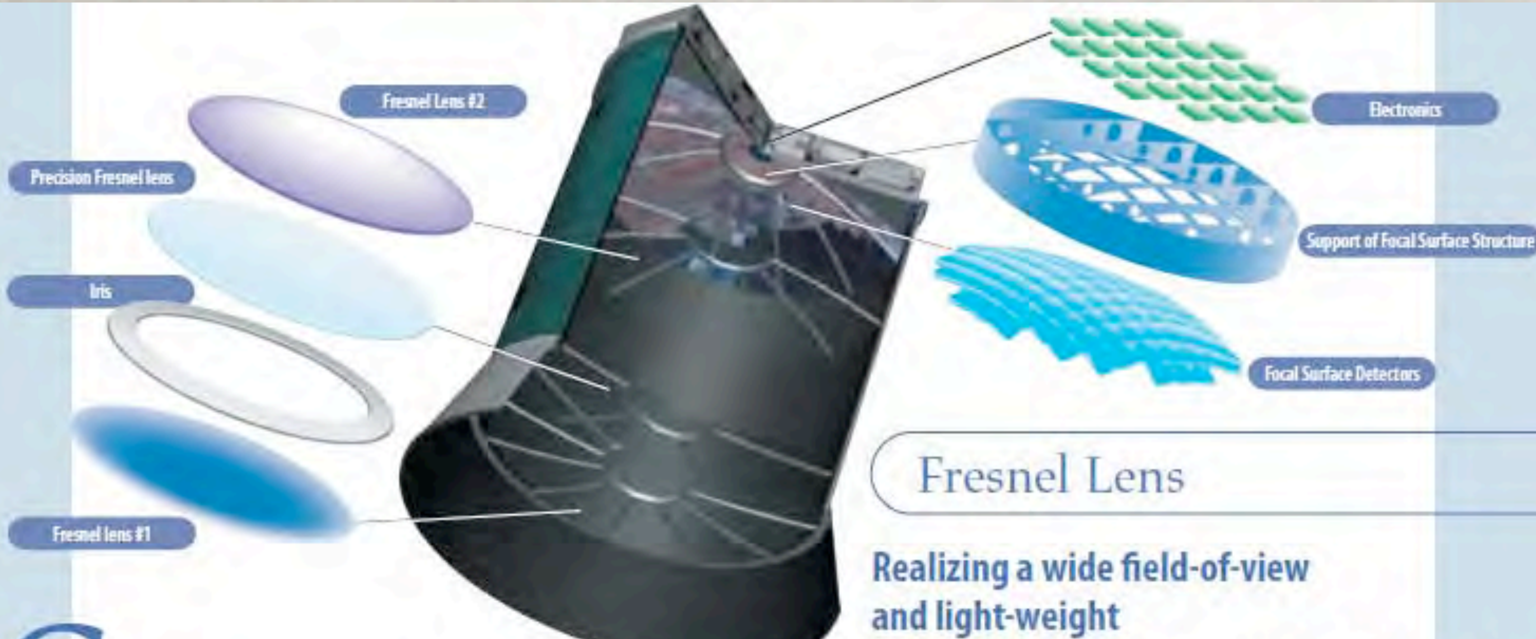
# JEM-EUSO




Fluorescence from space

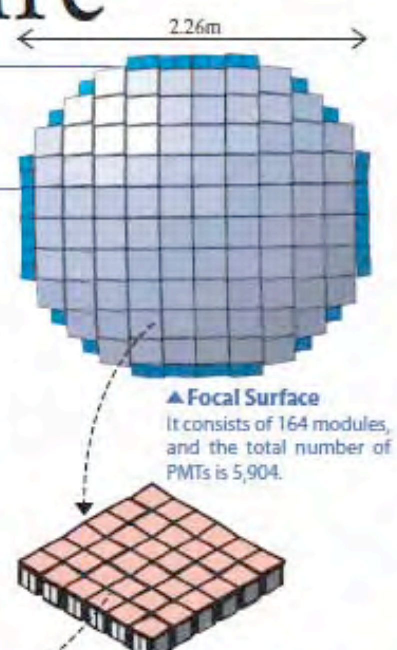
(orbits the Earth every 90 min.)

| | |
|---|---|
| Observation area (Nadir) | $\geq 1.3\times10^5\,(H_{orbit}/400[km])^2\ km^2$ |
| Arrival direction determination accuracy | ≤ 2.5° (at $E$=$10^{20}$ [eV] and 60° zenith angle) |
| Energy determination accuracy | ≤ 30% (E=$10^{20}$ [eV] and 60° zenith angle) |
| $X_{max}$ determination accuracy | ≤ 120 [g/cm$^2$] (E=$10^{20}$ [eV] and 60°zenith angle) |
| Energy threshold | ≤ $5.5\times10^{19}$ [eV] |
| Duty cycle | ≥ 17% |
| Lifetime | > 3 years (goal: > 5 years) |




# Structure

## Focal Surface Detectors




### 6,000 photomultipliers

The focal surface is curved with a diameter of 2.26m. About 6,000 1-inch square multianode photomultiplier tubes (PMTs) detect the light from the different locations in the earth's atmosphere. Earlier PMTs had a limited photo-sensitive area of only 45%. JEM-EUSO and Hamamatsu Photonics jointly developed PMTs to have a higher effective area of 85%.

▲**Focal Surface**
It consists of 164 modules, and the total number of PMTs is 5,904.

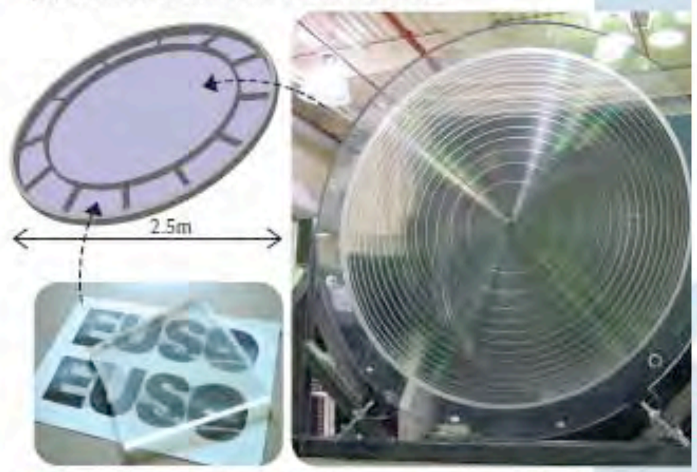
▲**Light-sensing module**
Covering a focal surface of 2.26m diameter with 5,904 PMTs, each PMT having 6 × 6 =36 photo-sensitive units.

▲**Photomultipliers**
The PMT surface has 85% active area, having 6 × 6 pixels with a total area of 26.2 mm square.

## Fresnel Lens

### Realizing a wide field-of-view and light-weight

The JEM-EUSO telescope uses Fresnel lenses. A Fresnel lens is a semi-flat lens having circular grooves that eliminate the large mass of a standard convective or concave lens. A thin and light Fresnel lens is necessary for use in space, performing the optical functions in the same way as a thick and heavy lens. JEM-EUSO uses two curved double-sided Fresnel lenses of UV-transmitting plastic and one micro-grating Fresnel lens. This design allows the best efficiency for the widest field-of-view. The size of the triple-lens is 2.5-m diameter, composed of the central 1.5-m part and the circular outer annular lenses.




▲Central lens and annular lenses configuration enable a lens size larger than can be manufactured on a single machine.

# Launch

### JAXA's Space Station Transfer Vehicle (HTV) carries JEM-EUSO

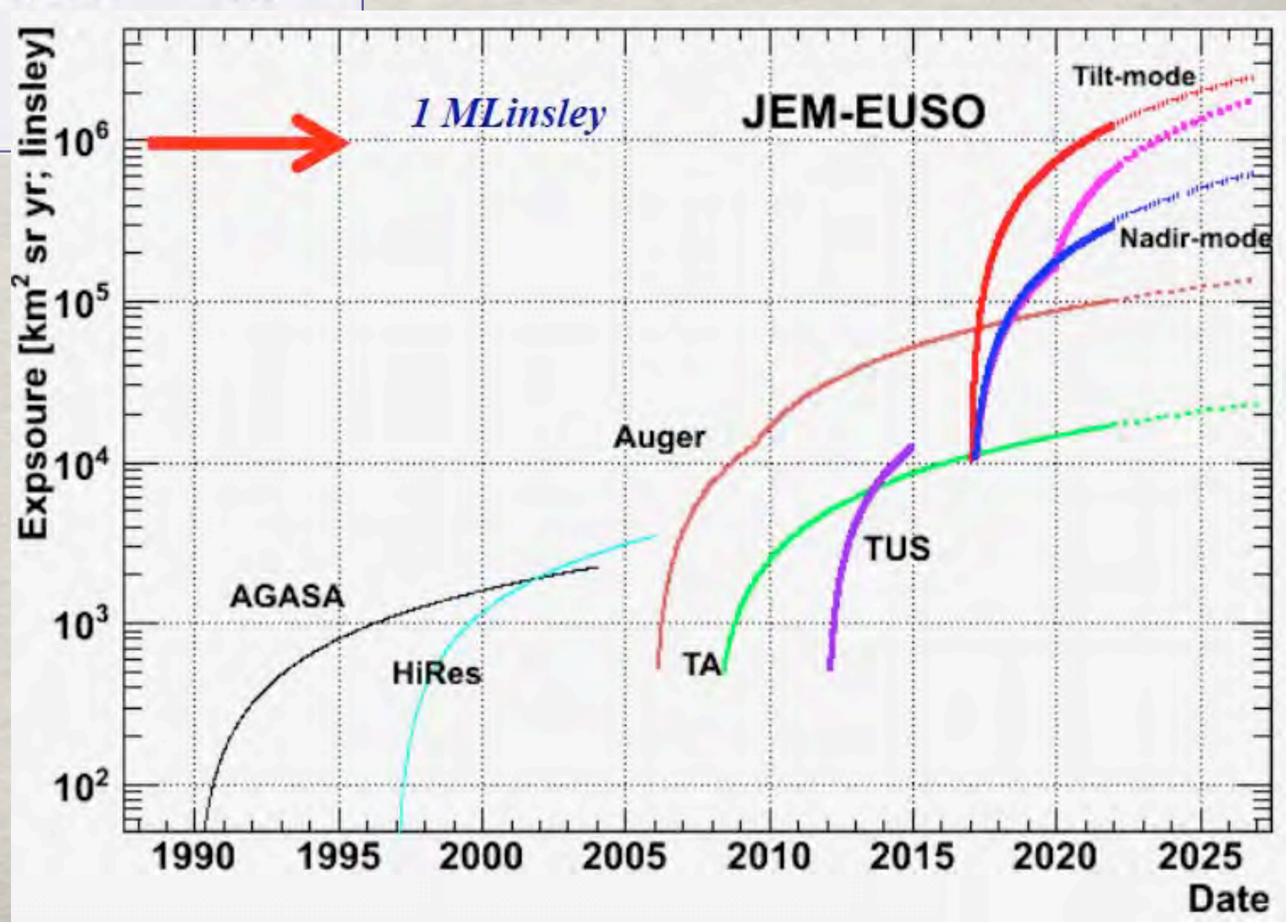
HTV will be launched by a H-IIB rocket (JAXA) and autonomously carry JEM-EUSO to ISS. Robotic arms of ISS will deploy JEM-EUSO at JEM module of "Kibo."

▲Space Station Transfer Vehicle (HTV) approaching ISS ©JAXA

| | |
|---|---|
| Japan | RIKEN Konan Univ. Fukui Tech. Univ. Aoyama Gakuin Univ. Saitama Univ. NIRS Univ. Tokyo Tohoku Univ. ICRR, Univ. Tokyo KEK Chiba Univ. NAOJ ISAS/JAXA Kanazawa Univ. Nagoya Univ STE Lab., Nagoya Univ. Yukawa Inst., Kyoto Univ. Kyoto Univ. Kobe Univ. Kinki Univ. Hiroshima Univ. Hokkaido Univ Tokyo Inst. Tech. |
| USA | NASA/MSFC UAH LBL, UCB UCLA Vanderbilt Univ. Univ. Arizona. |
| France | APC-Paris 7 LAL, IN2P3-CNRS |
| Germany | MPI Munich Univ. Tuebingen MPI Bonn Univ. Erlangen LMU&MPQ |
| Italy | Univ. Florence Univ. Naples Univ. Palermo Univ. Rome "Tor Vergata" Univ. Turin INOA/CNR IASF-PA/INAF IFSI-TO/INAF INFN |
| Mexico | ICN-UNAM BUAP UMSNH |
| Republic of Korea | Ehwa W. Univ. Yonsei Univ. |
| Russia | SINP MSU Dubna JINR |
| Switzerland | Neuchatel, CSEM IACETH |
| Spain | Univ. Alcalá |
| Poland | IPJ Podlasie Univ. Kielce Univ. Jagiellonian Univ. |
| Slovakia | Inst. Experimental Physics, KOSICE |

# Comparative exposures

| Observatory | Aperture km$^2$ sr | Status | Start | Lifetime | Duty cycle | Annual Exposure km$^2$ sr yr | Relative to Auger |
|---|---|---|---|---|---|---|---|
| Auger | 7,000 | Operations | 2006 | 4 (16) | 1 | 7000 | 1 |
| TA | 1,200 | Operations | 2008 | 2 (14) | 1 | 1,200 | 0.2 |
| TUS | 30,000 | Developed | 2012 | 5 | 0.14 | 4,200 | 0.6 |
| JEM-EUSO (E≈$10^{20}$ eV) | 430,000 | Design | 2017 | 5 | 0.14 | 60,000 | 9 |
| JEM-EUSO (highest energies) Tilted mode 35° | 1,500,000 | Design | 2017 | 5 | 0.14 | 200,000 | 28 |



# CONCLUSIONS

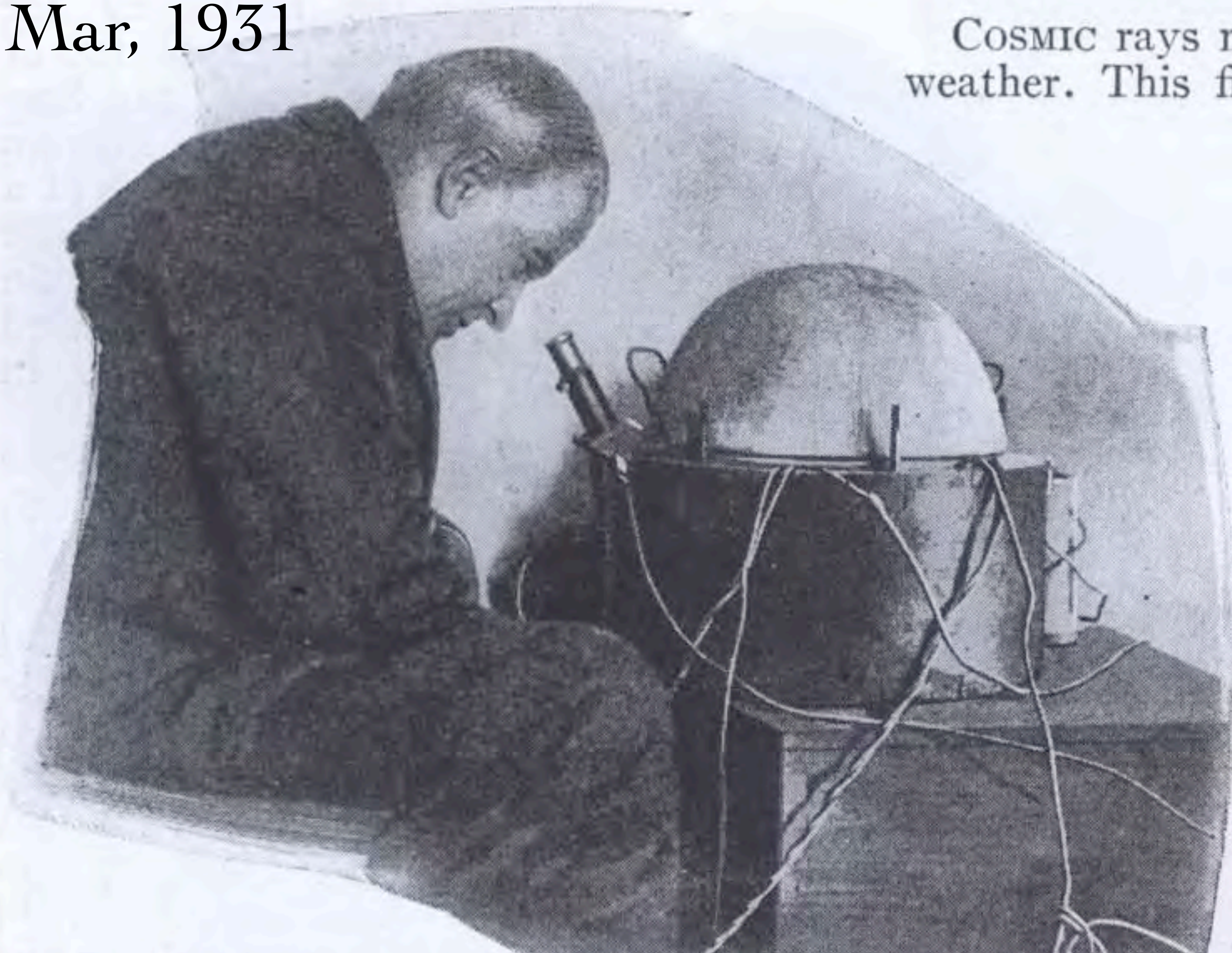
- The eventful journey to solve the UHECR puzzle is far from completion
- Enticing physics that demands larger statistics and multiparametric observations
  - larger detectors? new techniques?
  - ...but hard times for getting fresh funding!

# CONCLUSIONS

Not all is lost! There´s hope for cosmic ray physicists: become a TV star with daily appearances at prime time TV-News

## COSMIC RAYS MAY FORECAST WEATHER

Mar, 1931



Dr. R. A. Millikan at work with his latest electroscope, with which he is studying the cosmic rays. He believes these mysterious rays may be used in making reliable forecasts of the weather.

COSMIC rays may help to prophesy the weather. This first practical use for the mysterious radiations from outer space was recently announced by Dr. R. A. Millikan, Calif. Institute of Technology physicist.

The "cosmic rays" are more penetrating than radium or X-rays, but it is not known whether they affect human beings.

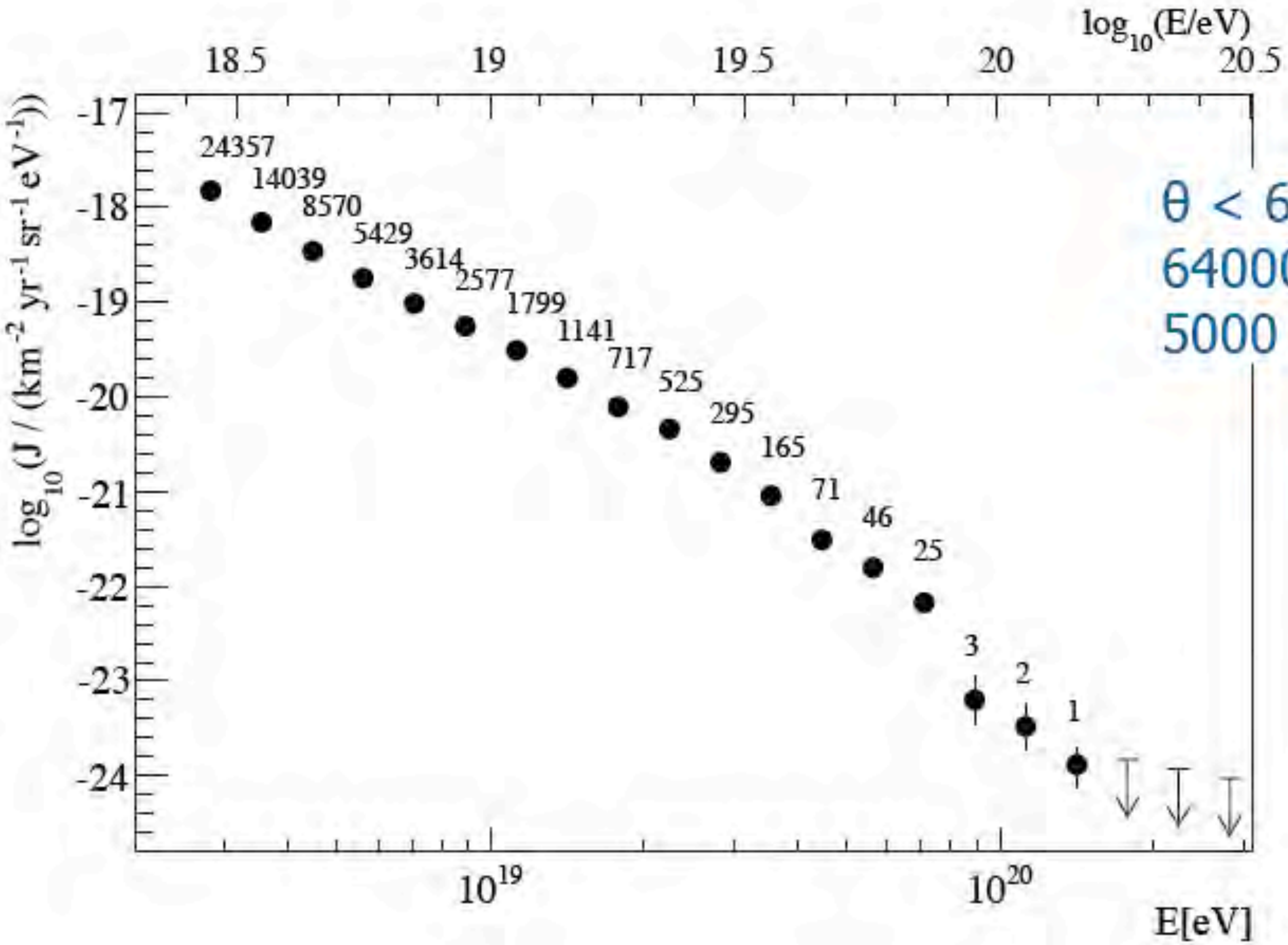
Dr. Millikan, who discovered the source of the rays (P. S. M., July, '28, p. 13), has measured their strength with his new electroscope, and is able to determine high-altitude atmospheric conditions.

# Back-Up

# "GZK-Cut-offs" do happen in every day's life, as well!

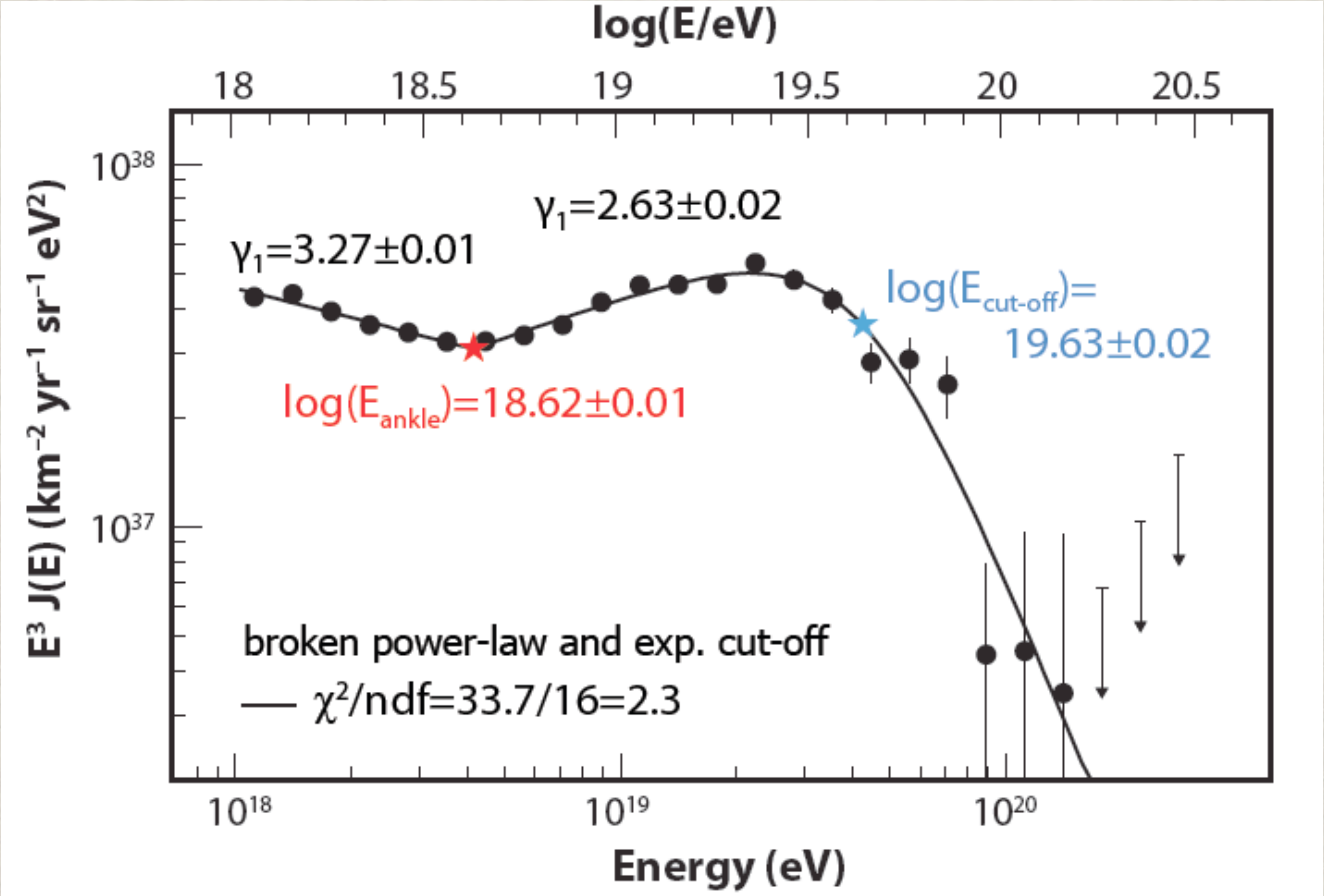

Former Bankia CEOs:
**candidates for 2012 Nobel Prize in Physics?**
or in Economic Sciences?

# Pierre Auger SD Spectrum

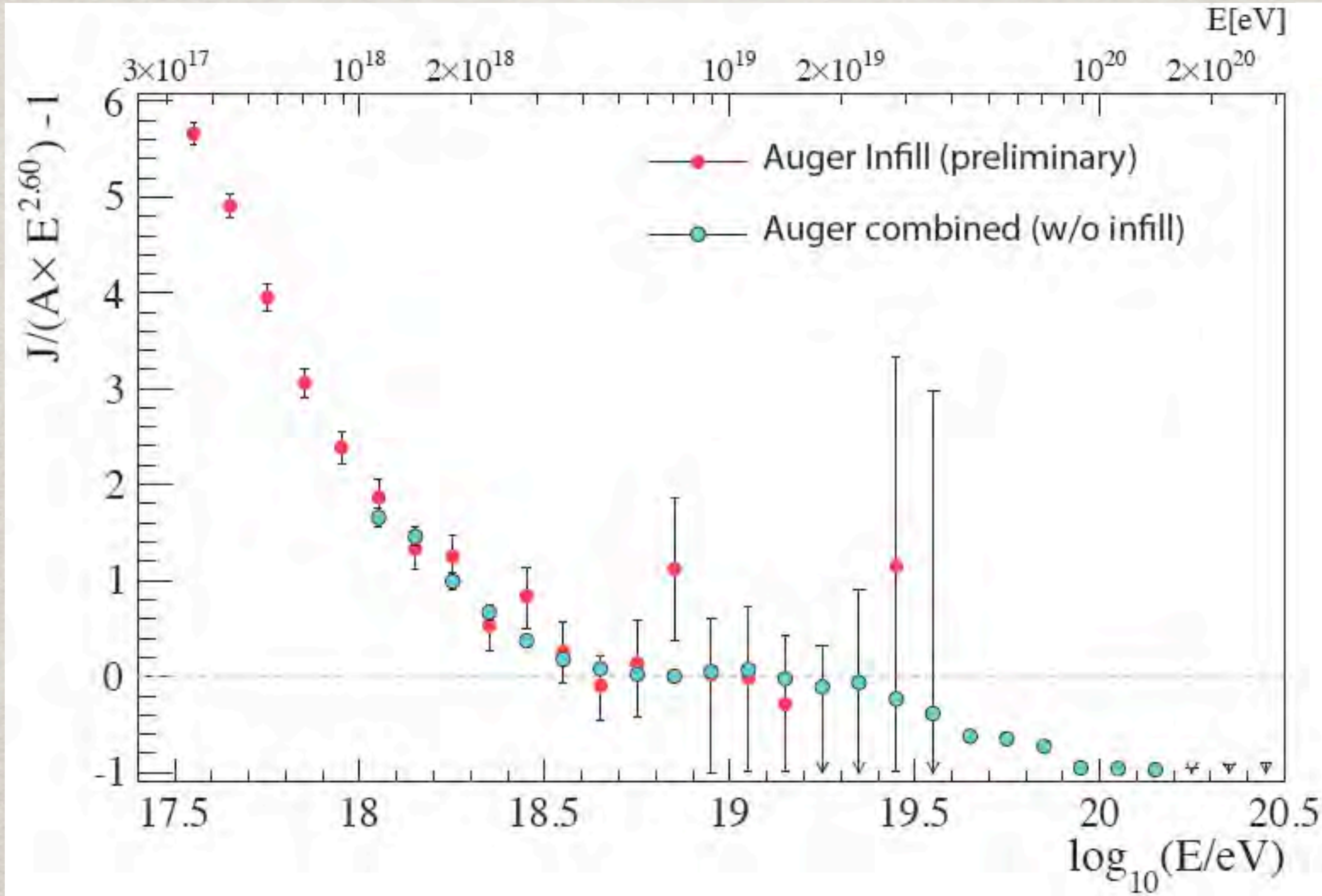


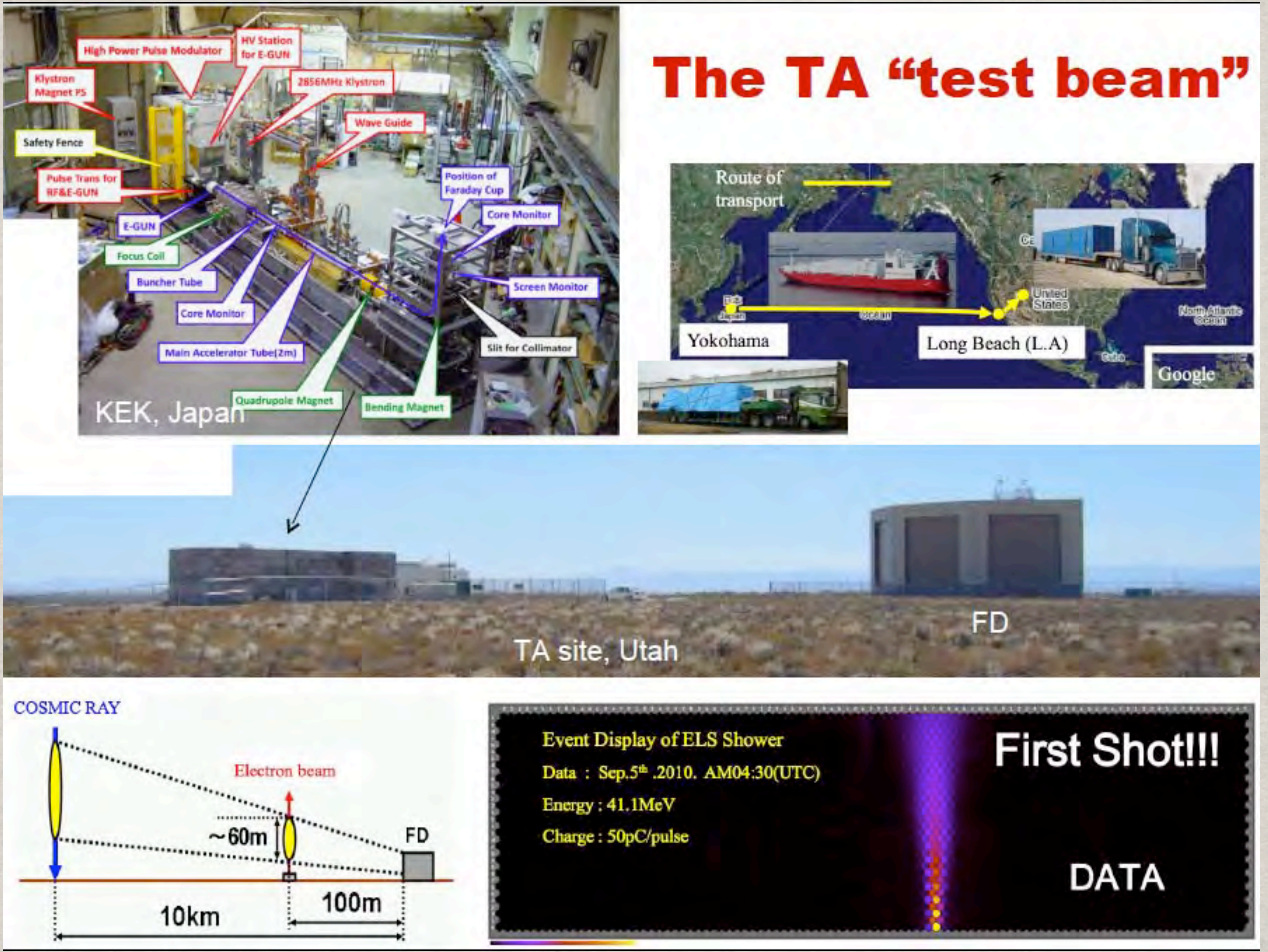

θ < 60°
64000 events > 3 EeV
5000 events > 10 EeV

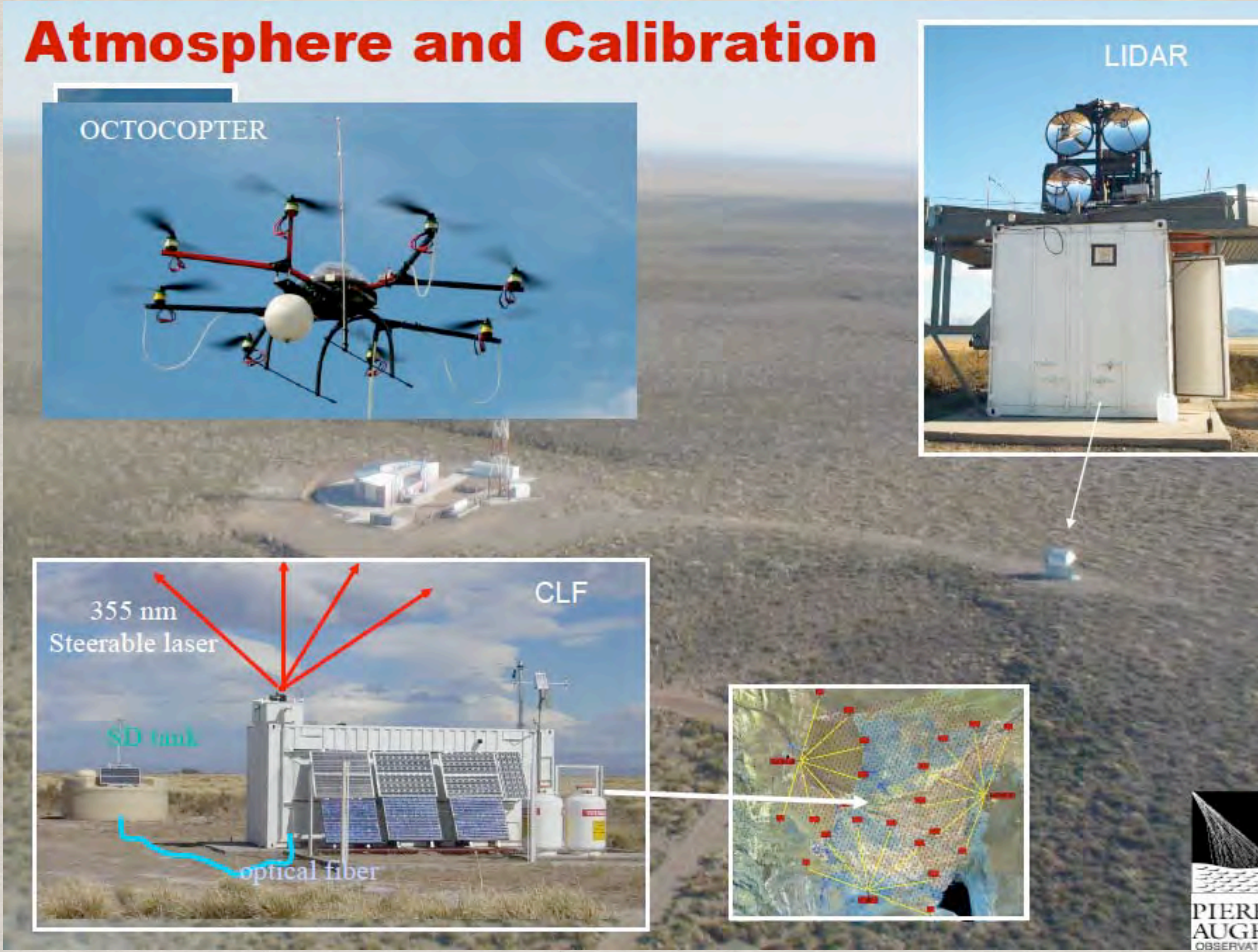
# SD + Hybrid Spectrum



# Infill Spectrum



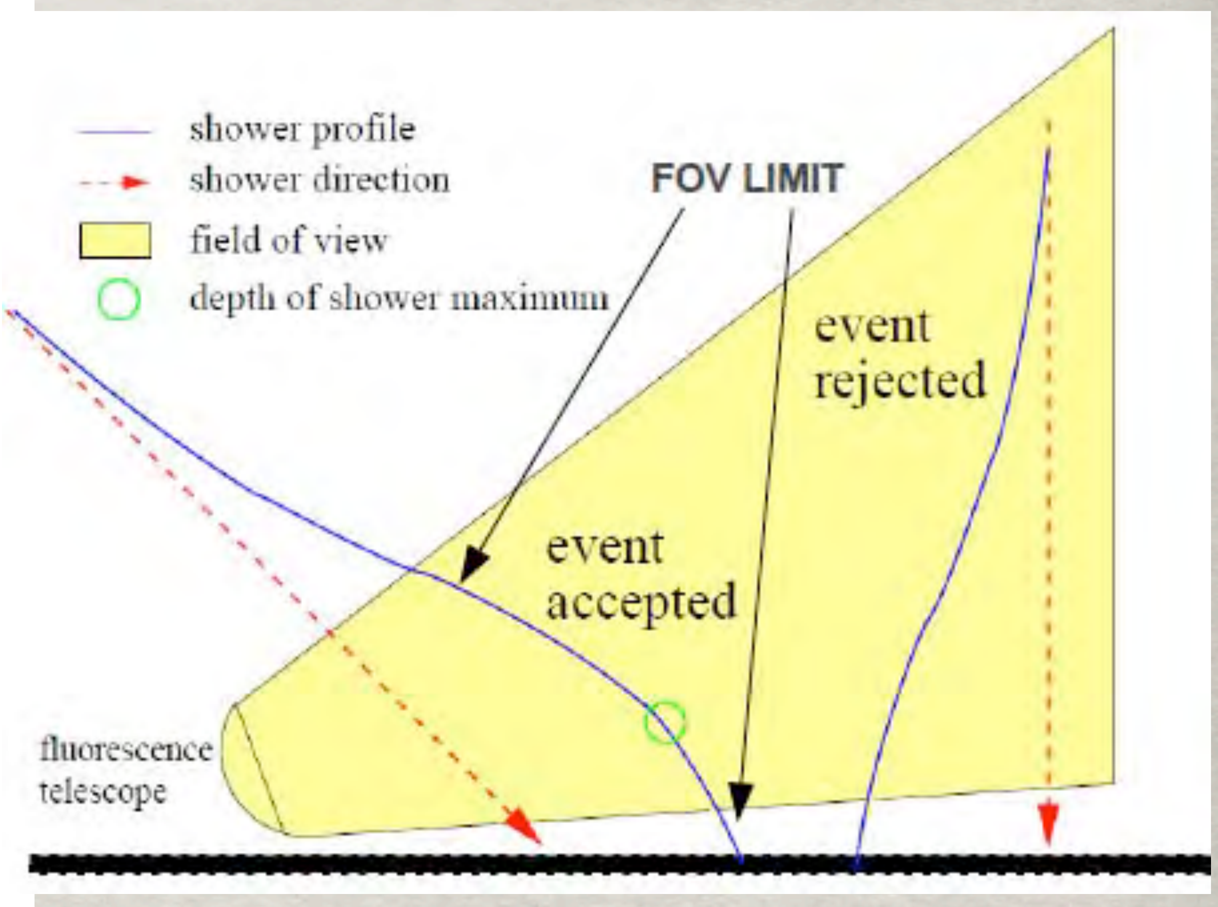

The TA "test beam"
High Power Pulse Modulator
HV Station for E-GUN
Klystron Magnet PS
2856MHz Klystron
Wave Guide
Safety Fence
Pulse Trans for RF&E-GUN
Position of Faraday Cup
Core Monitor
E-GUN
Focus Coil
Buncher Tube
Screen Monitor
Core Monitor
Main Accelerator Tube(2m)
Slit for Collimator
Quadrupole Magnet
Bending Magnet
KEK, Japan
Route of transport
Yokohama
Long Beach (L.A)
Google
TA site, Utah
FD
COSMIC RAY
Electron beam
~60m
FD
10km
100m
Event Display of ELS Shower
Data : Sep.5th .2010. AM04:30(UTC)
Energy : 41.1MeV
Charge : 50pC/pulse
First Shot!!!
DATA


Atmosphere and Calibration
OCTOCOPTER
LIDAR
355 nm
Steerable laser
CLF
SD tank
optical fiber

# Xmax Analysis

**Goal:** determine properties of $X_{\max}$ distribution in the atmosphere (not in detector)

- **data base cuts**
  - clear atmosphere
  - good calibration
  - no clouds
- **quality cuts**
  - $X_{\max}$ observed
  - $\sigma(X_{\max}) \leq 40\ g/cm$
  - minimum viewing angle
- **fiducial cuts**
  - distance to hybrid station
    $\rightarrow$ hybrid trigger 100%
  - large field of view
    $\rightarrow$ unbiased sampling of $X_{\max}$ distr.

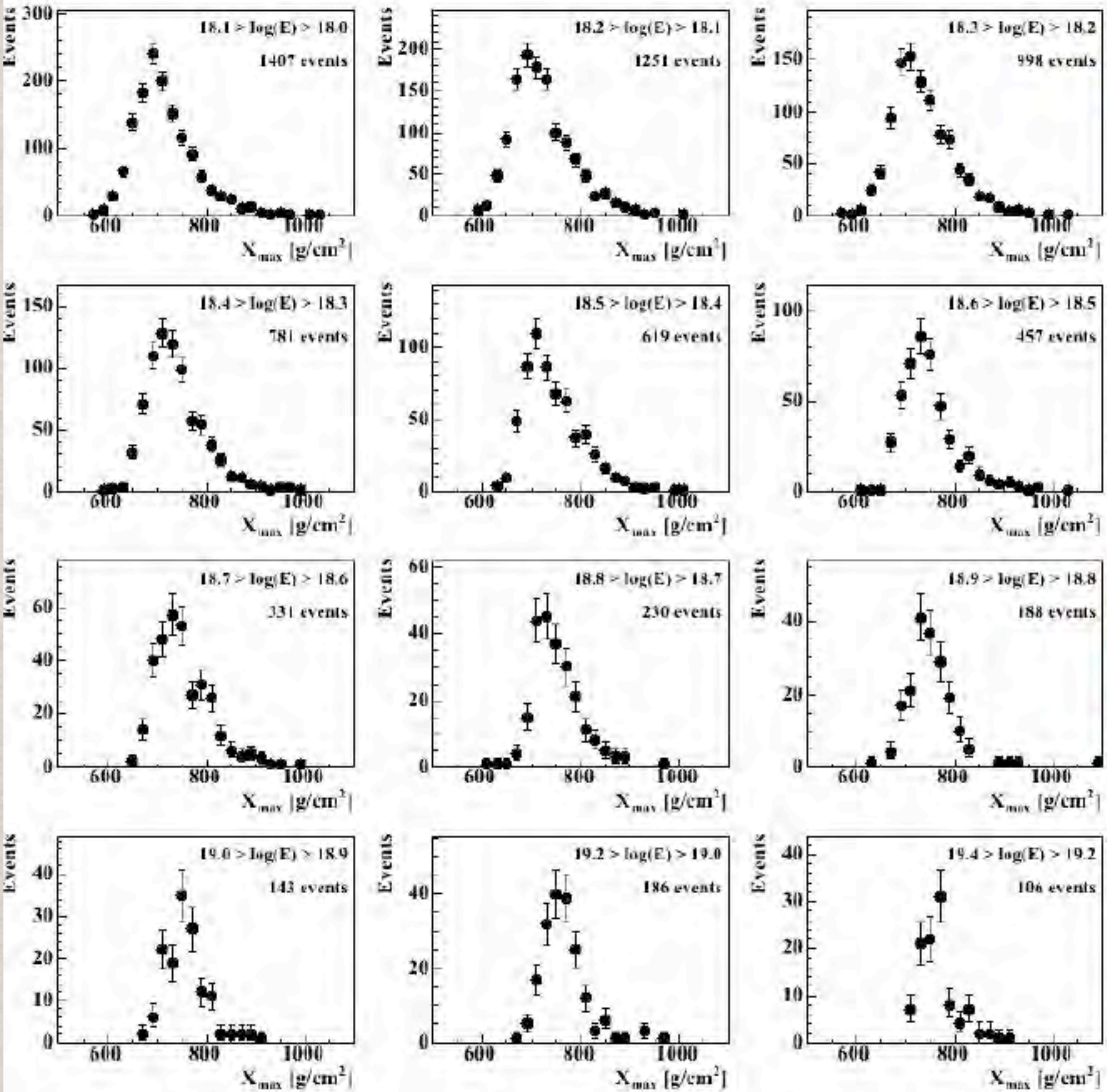


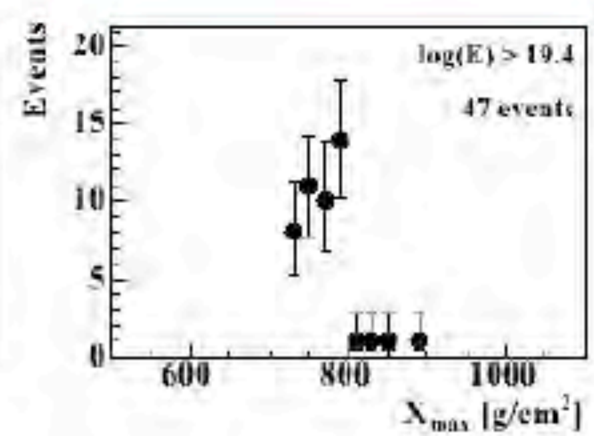
# $X_{max}$ distributions

As the energy increases:

- distributions become narrower, and

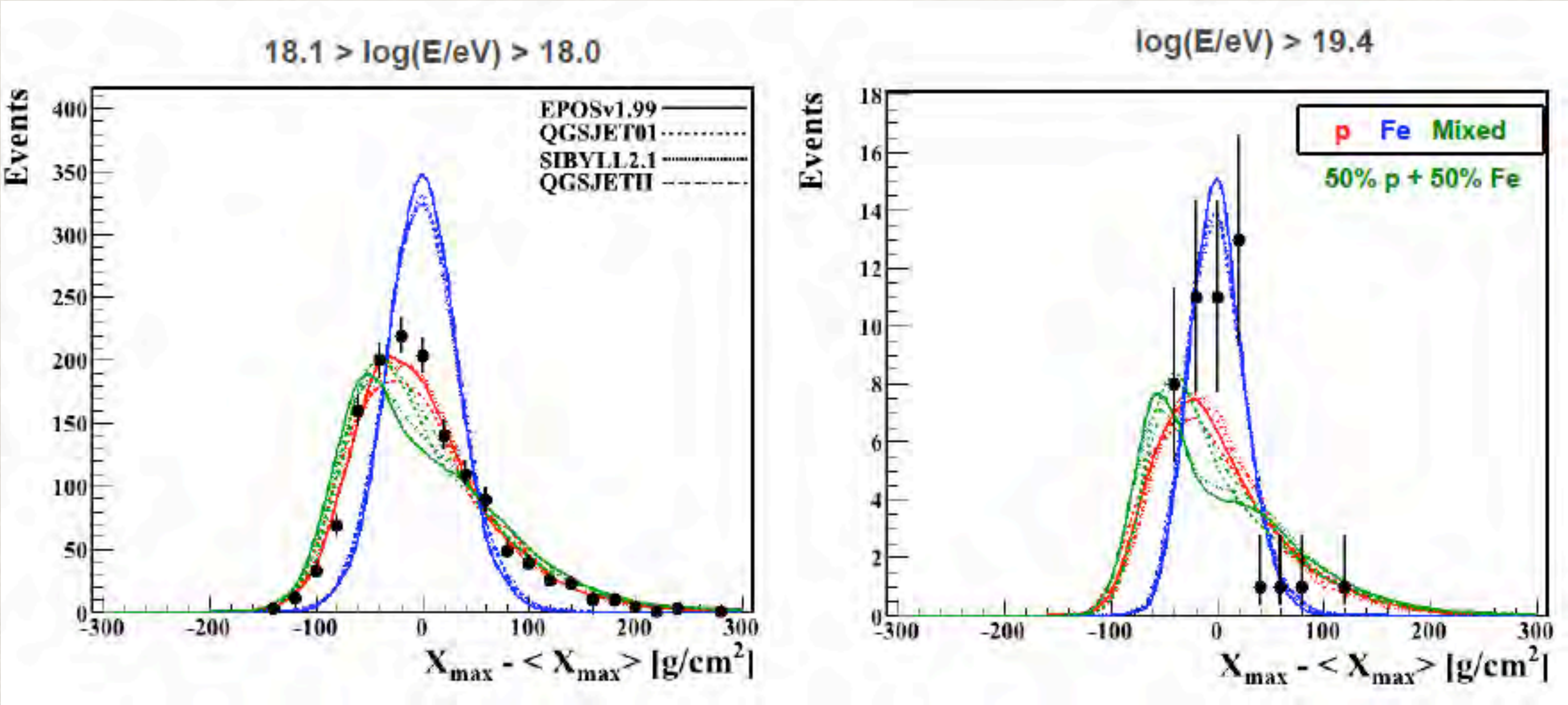
- deep $X_{max}$ tail becomes less evident



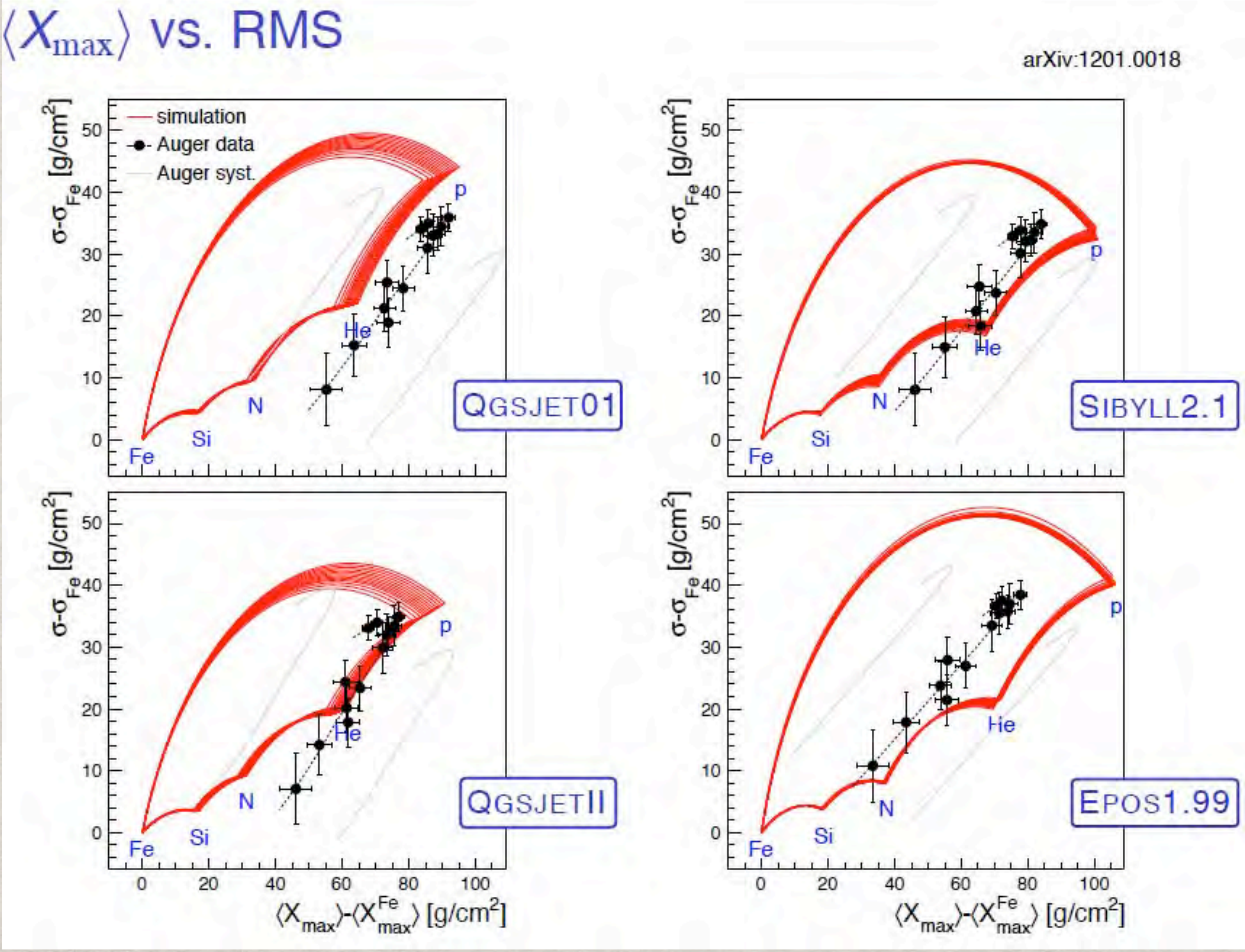




Interpretation, especially at high energy, is difficult since we have to rely on the extrapolation provided by the different models

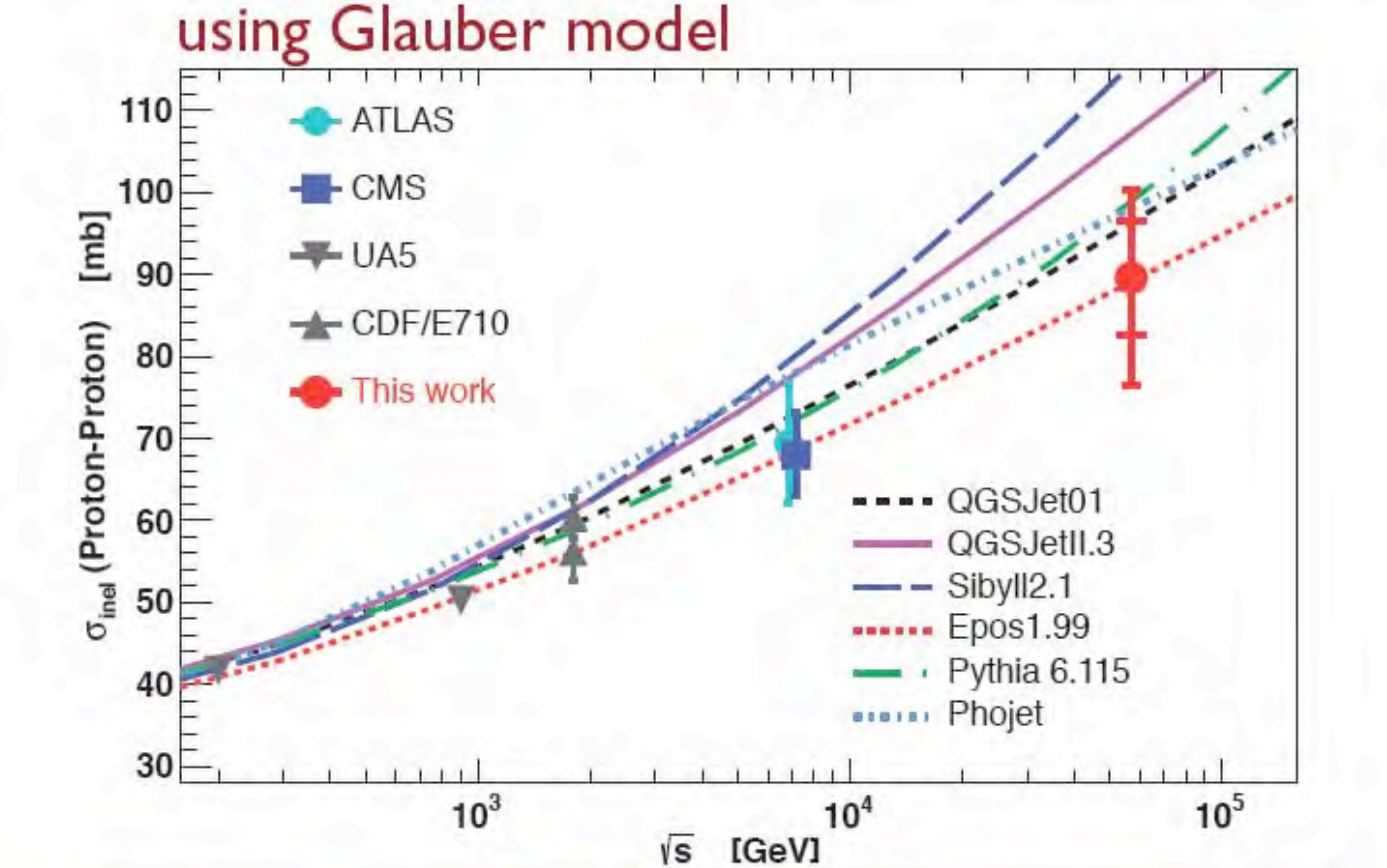
# Shape of Distributions



# Comparison with Monte Carlo



# p-p Cross section at $\sqrt{s}$=57 TeV




$$\sigma_{pp} = (90 \pm 7_{stat} \left({}^{+8}_{-11}\right)_{sys} \pm 1.5_{Glauber})\ \text{mb}$$

# The Knee(s)

→ steepening close to $10^{17}$eV (2.1σ) in all-particle spectrum

→ steepening due to heavy primaries (3.5σ)

→ light+medium primaries show steeper spectrum,