# The Pierre Auger Obervatory: Results and Open Issues

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On behalf of the Pierre Auger Collaboration

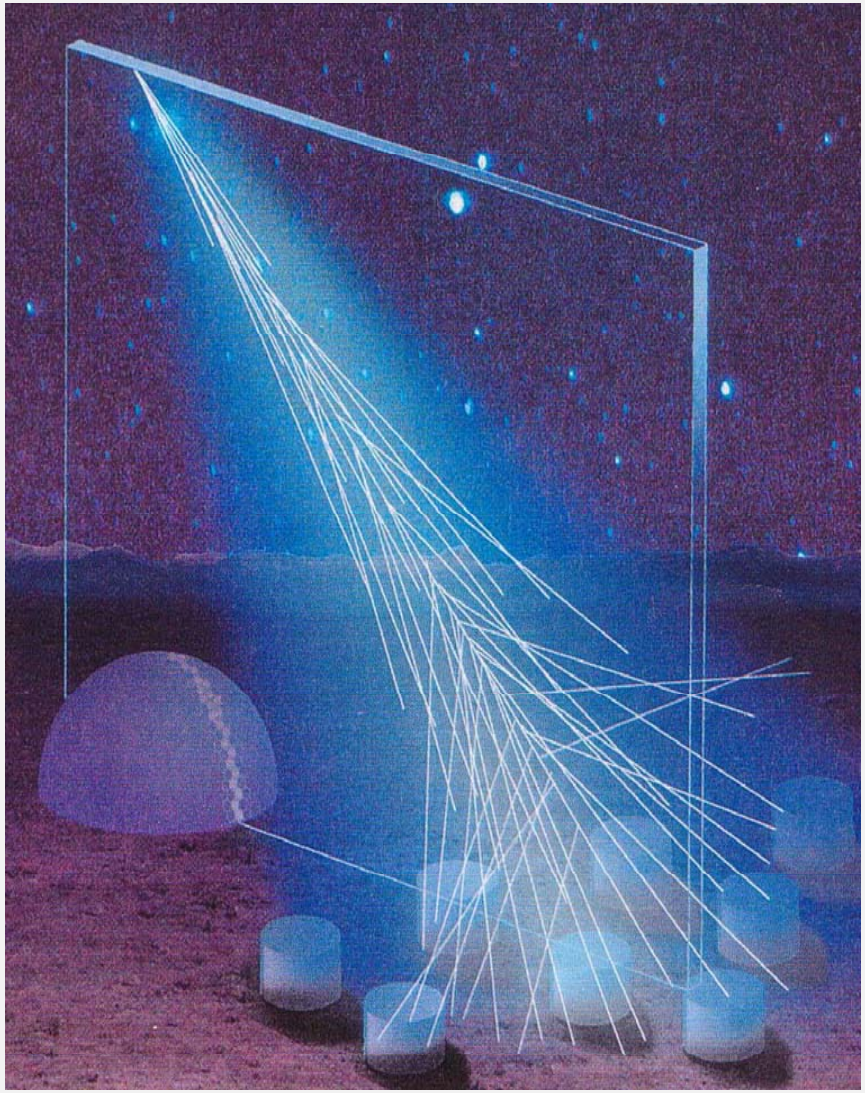
# The Hybrid Concept

**Hybrid Detector:**

**Array of 1660 water Cherenkov detectors**
- **covering 3000 km$^2$**
- **duty cycle: 100%**

**Fluorescence telescopes**
- **27 FDs (30$^o$x30$^o$ each)**
- **duty cycle: 14%**

**Better geometric reconstruction, cross-calibration, control of systematic.**



# The Pierre Auger Observatory

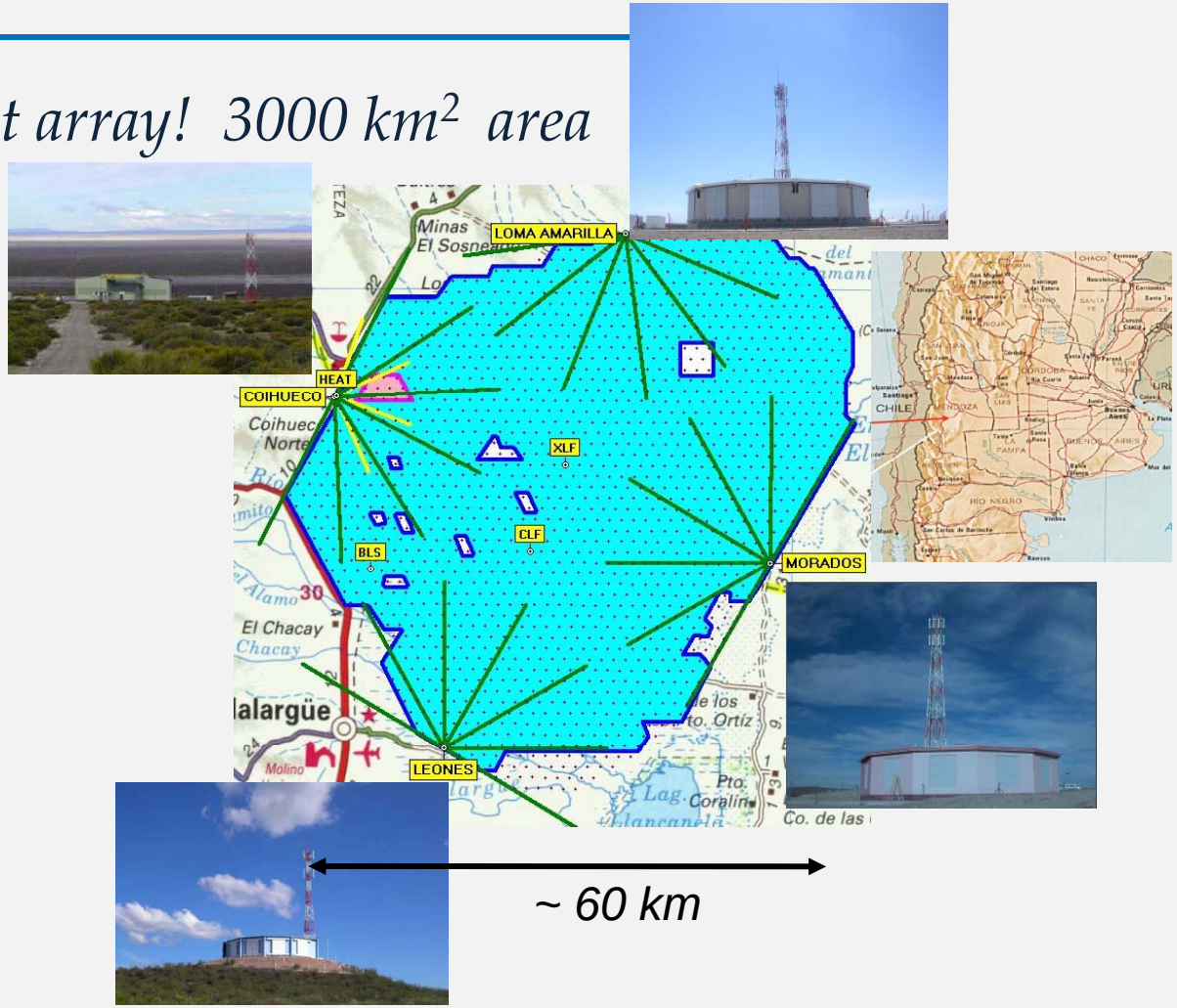
*World largest array! 3000 km² area*

1660 tanks installed!

27 FD Telescopes (4 positions)!

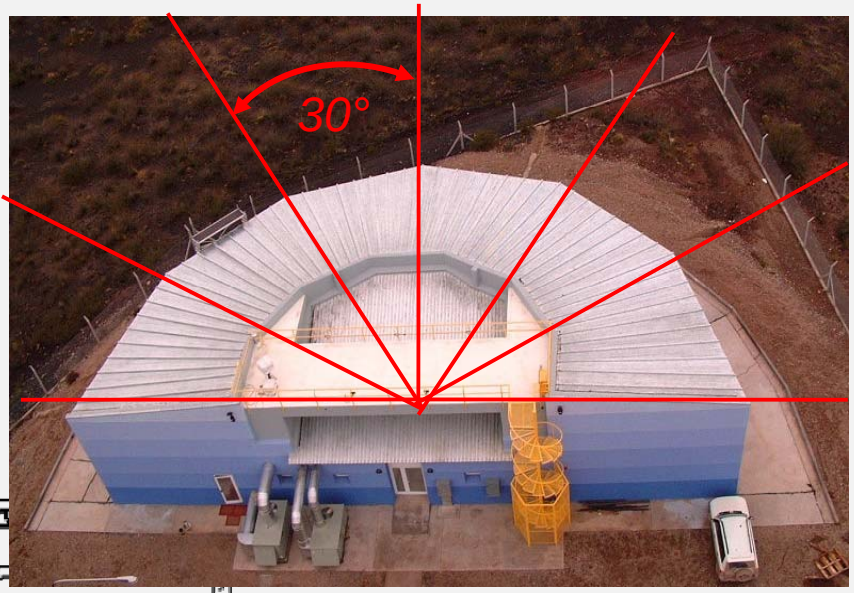
Completed in 2008 !

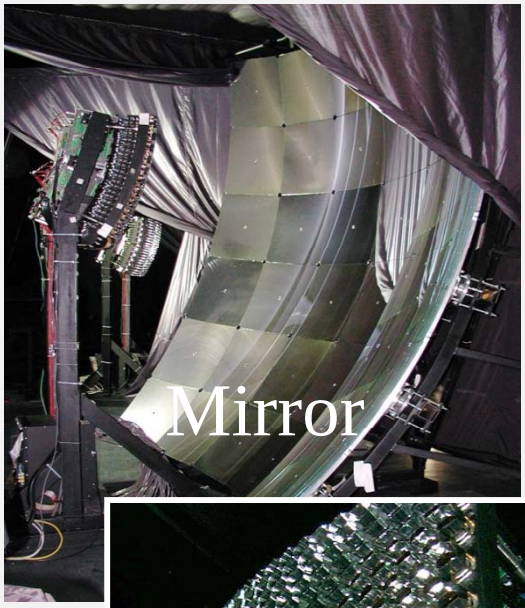
Taking data since 2004

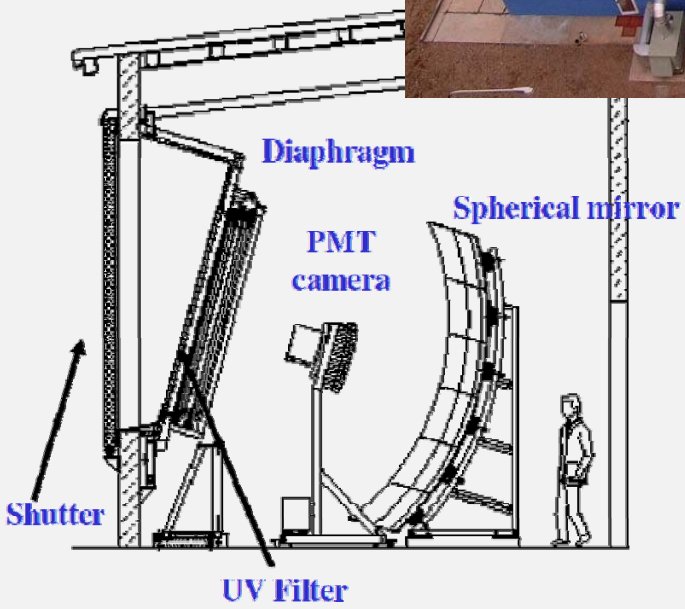



≈ 3000 evts/yr with E > $10^{19}$ eV

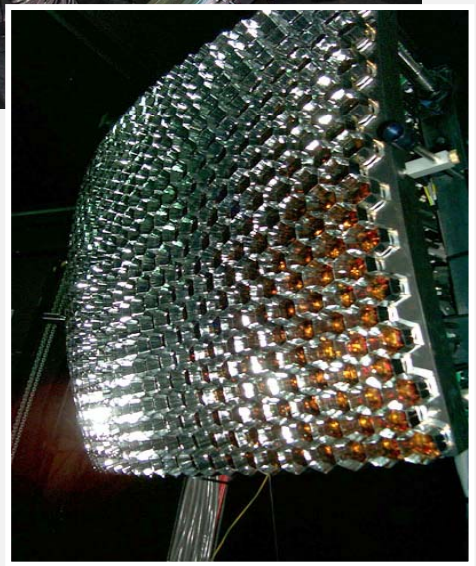
# The Fluorescence Detector (FD)



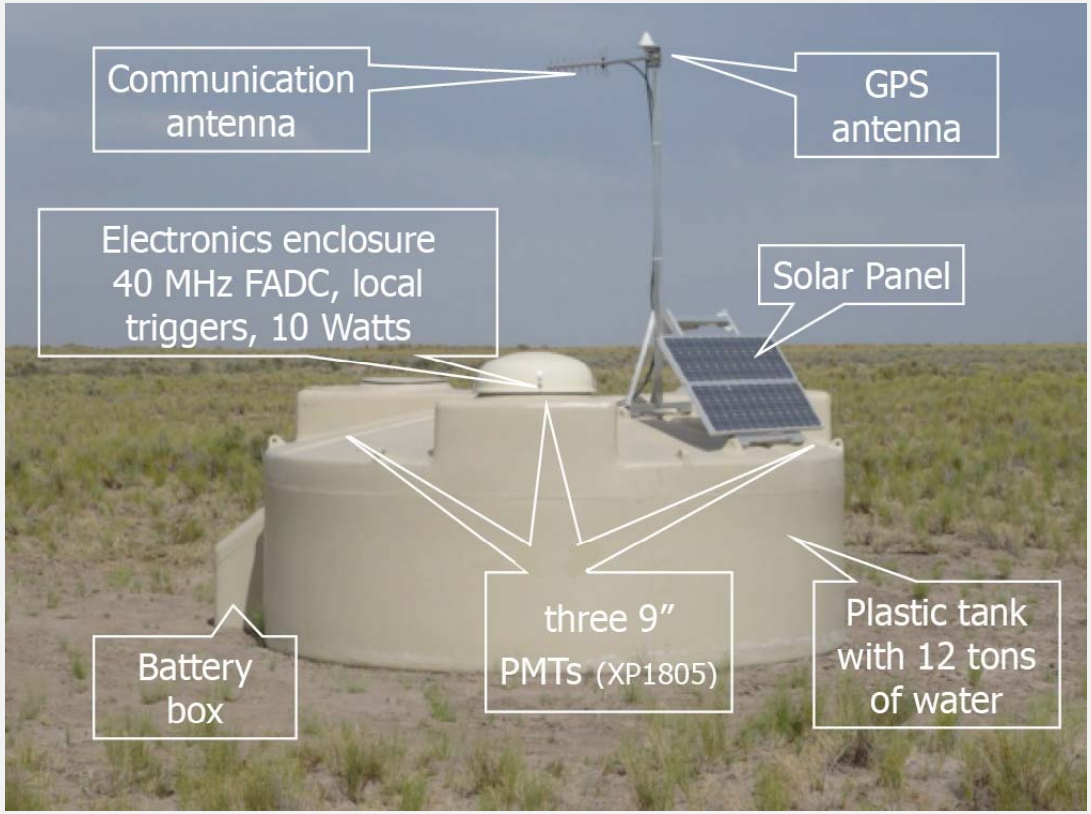




Camera with a FOV $30^o$x$30^o$

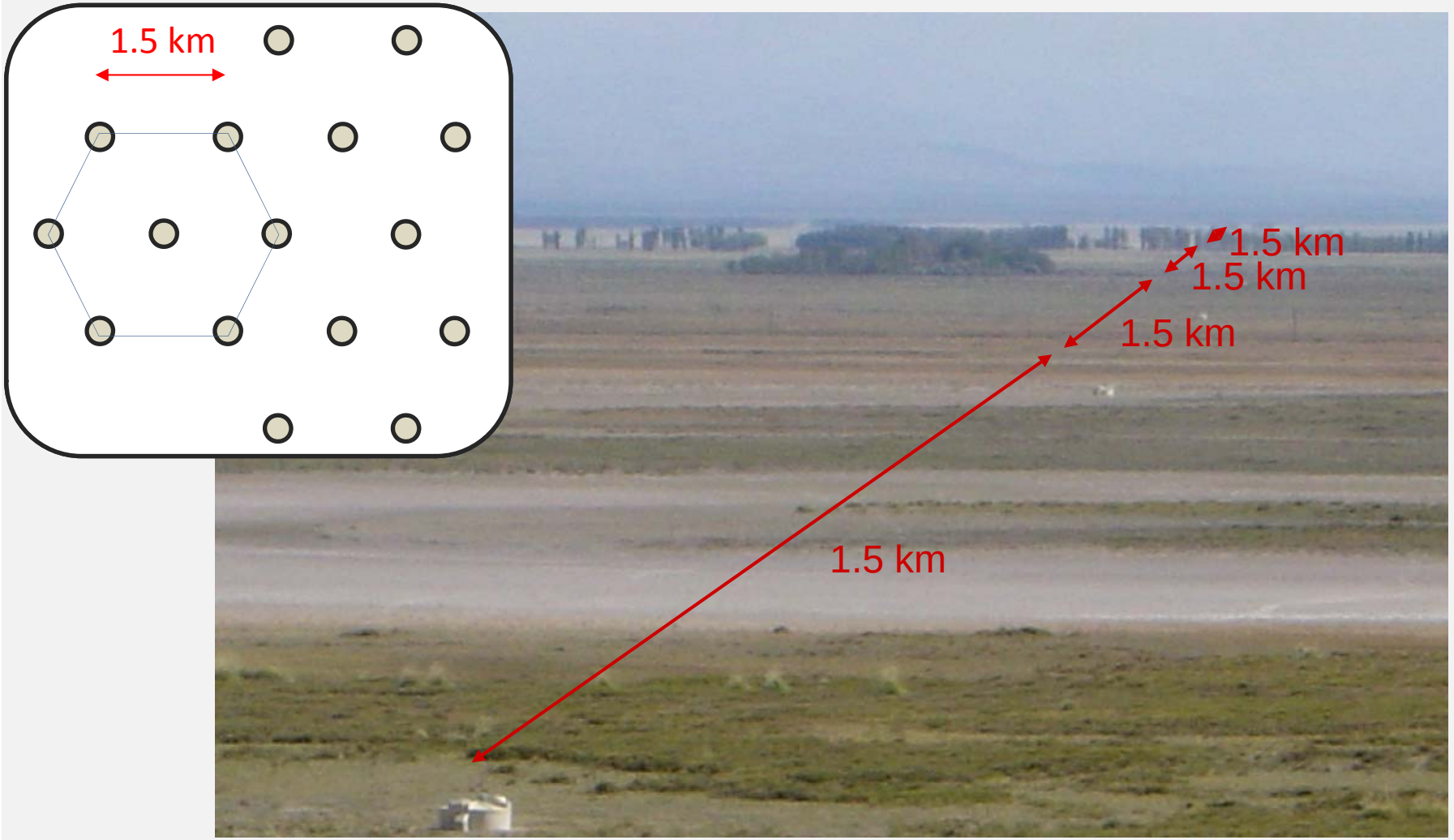


# *The Surface Detector (SD)*

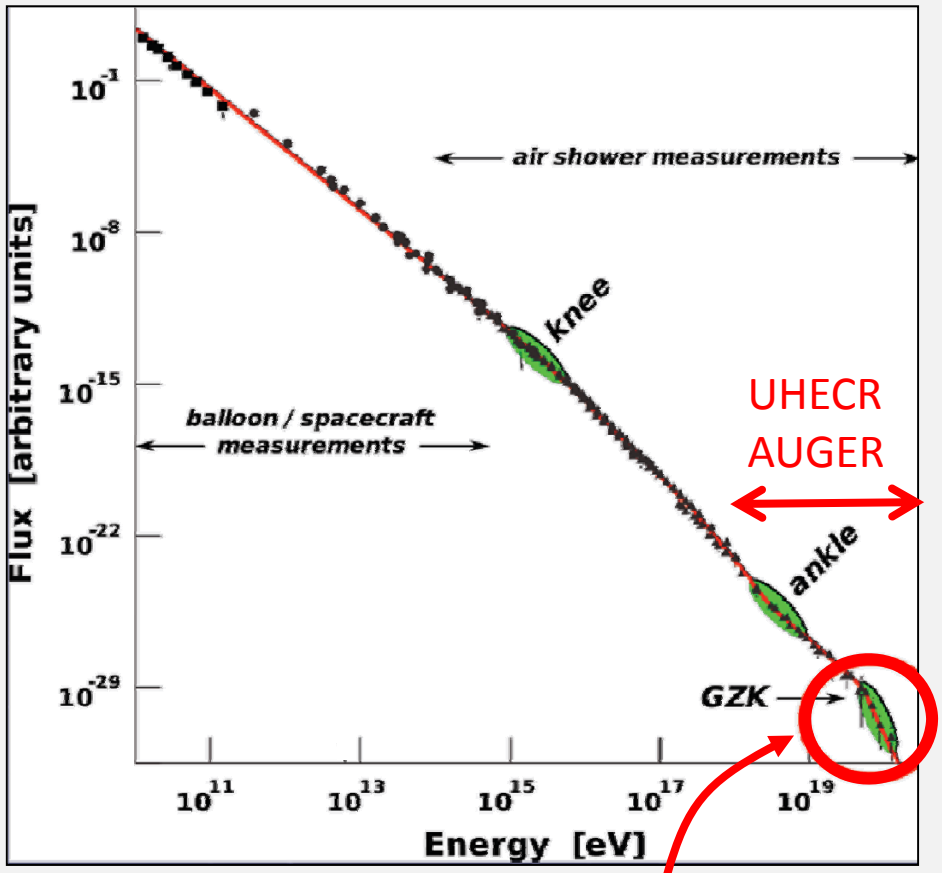
- Plastic Tank
- Ultrareflective tyvek liner
- 12 $m^3$ purified water
- 3 PMTs (9 inches)
- Independent power supply (solar panels)
- GPS antenna
- Communication antenna



# The Surface Detector (SD)



# The UHECR Physics




NEW ASTROPHYSICS

✓Measured spectrum extends to $E > 10^{20}$ eV

✓Where and how are cosmic rays accelerated to these energies

✓No known astrophysical sources seem able to produce such enormous energies

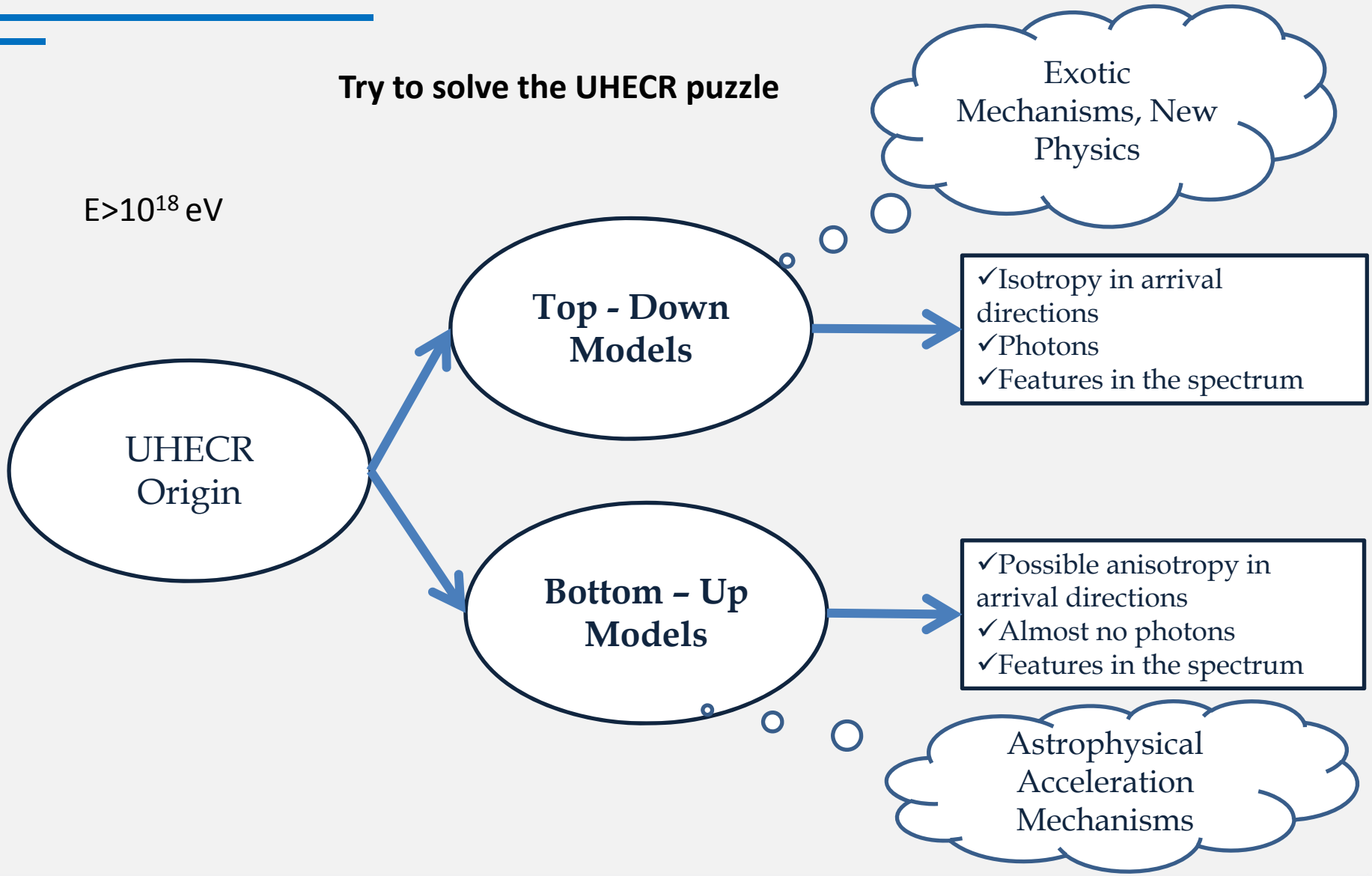
✓Chemical composition unknown

NEW PARTICLE PHYSICS

✓The high energy end of the spectrum probes physics at energies out of reach of any man made accelerator

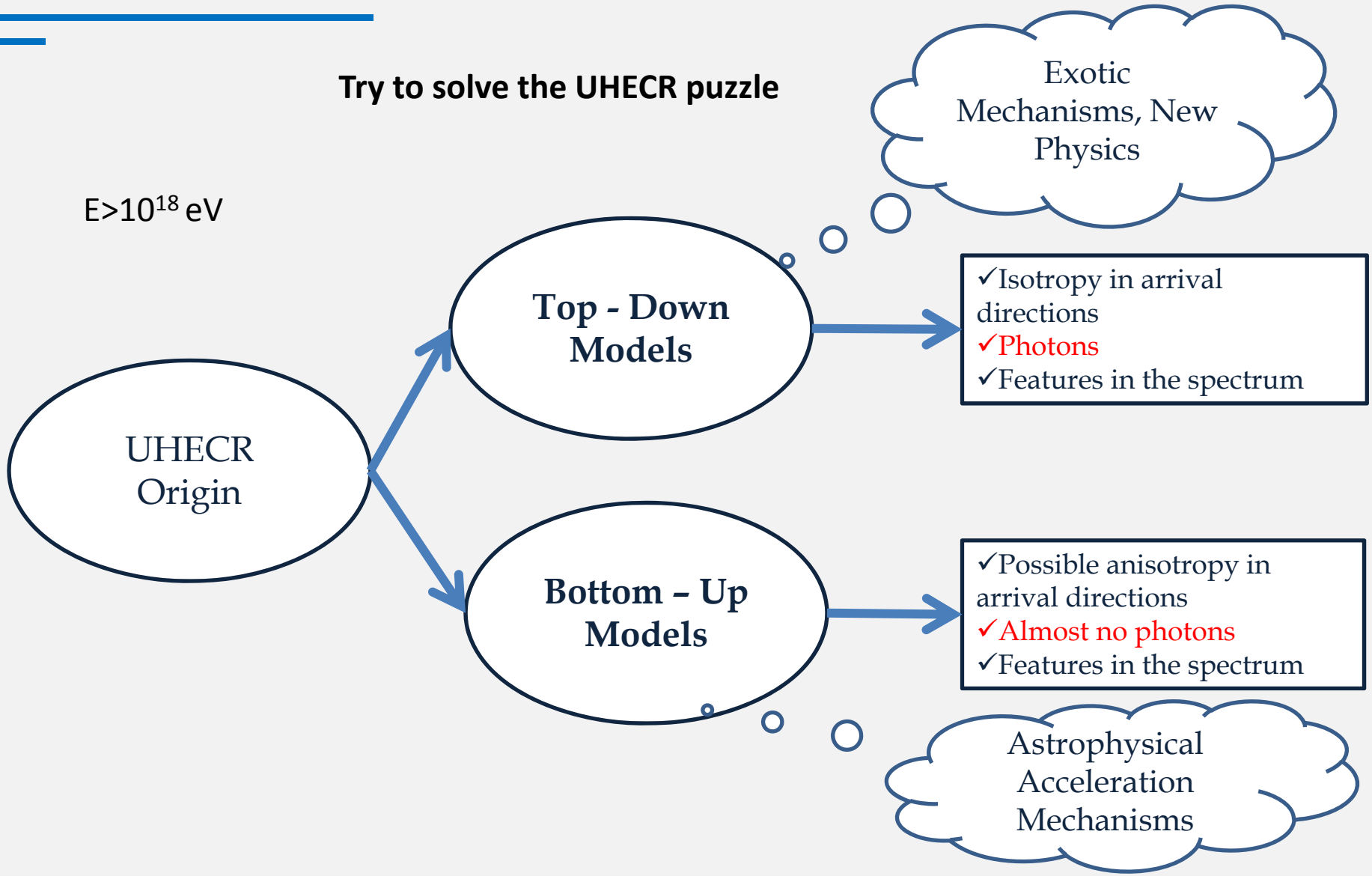
# The UHECR Physics

**Try to solve the UHECR puzzle**



# The UHECR Physics

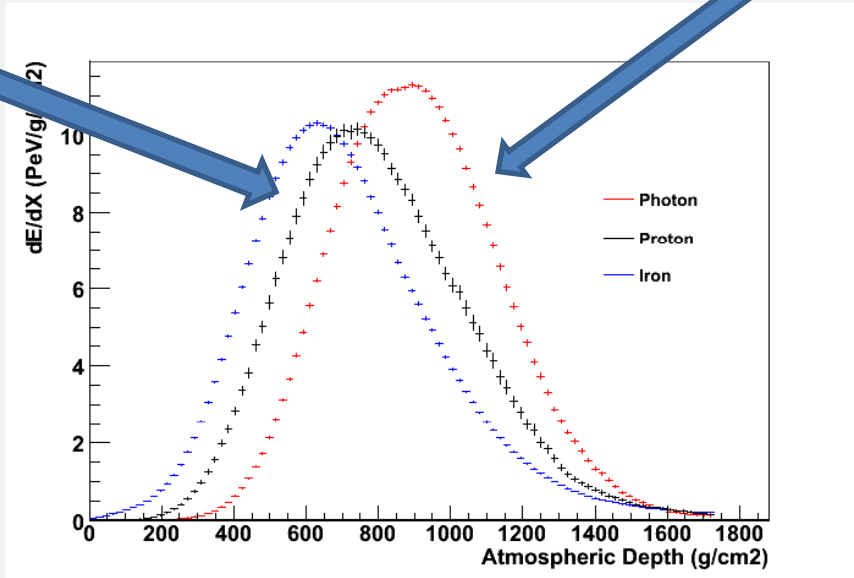
**Try to solve the UHECR puzzle**



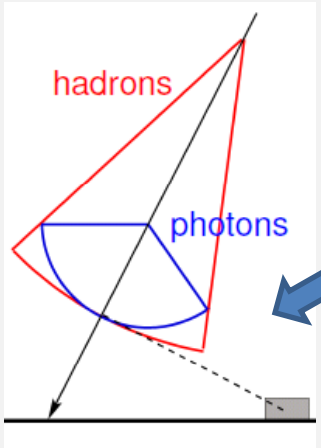
# Photons

Photons

hadrons

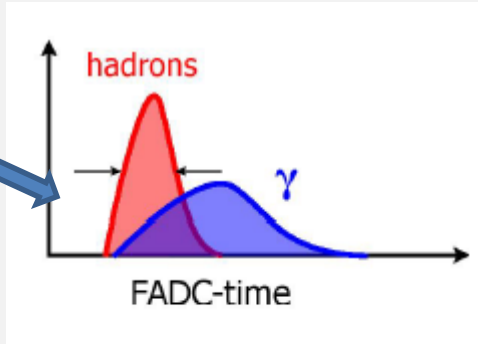



FD photons search based on $X_{max}$ distribution




Deeper showers larger curvature

Slower signal, longer risetime

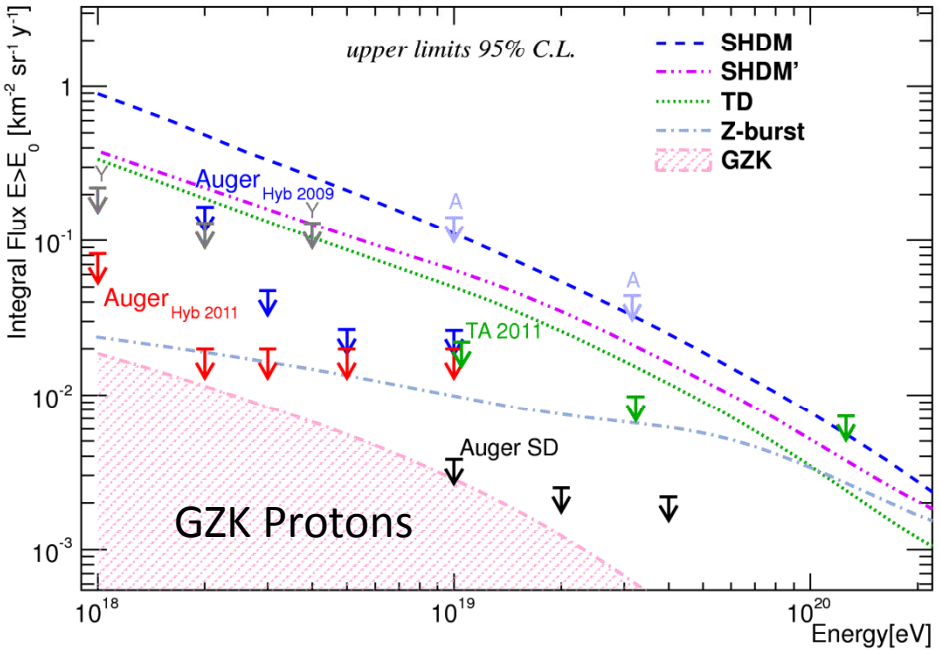



SD photons search based on signal structure

# Photons

**Exotic Mechanisms**
- ✓ Decay of topological defects
- ✓ Relic monopoles
- ✓ Etc.

**New Physics**
- ✓ Supersymmetric particles
- ✓ Strongly interacting neutrinos
- ✓ Decay of massive new long lived particles
- ✓ Etc.

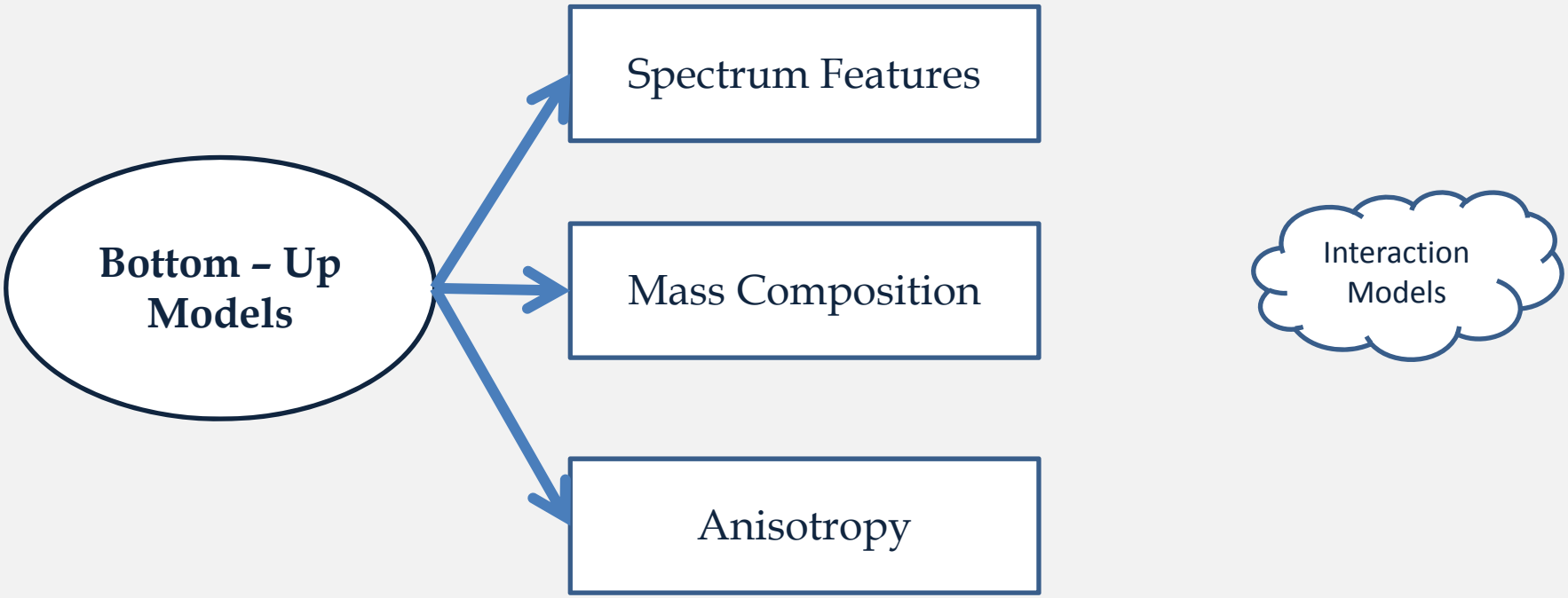



**GZK region within reach in the next years**

Top-down models severely constrained

Favour astrophysical origin of UHECR

# The UHECR physics

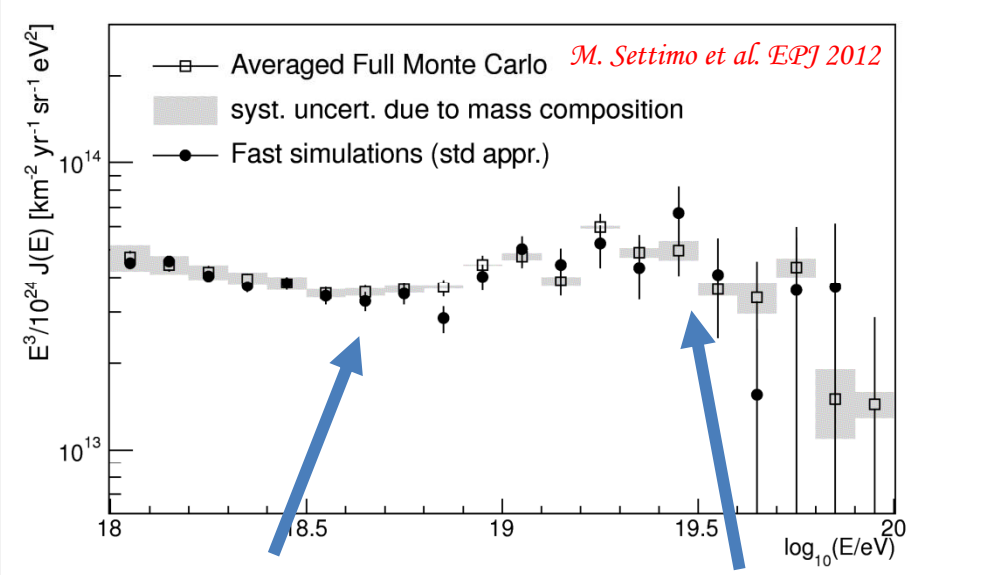


# Spectrum

Two different detectors. Three different samples of events. Many independent analysis techniques.

## Hybrid Energy Spectrum

- ✓ Mainly FD
- ✓ Calorimetric energy estimation. Energy resolution 8%
- ✓ Acceptance estimation via Monte Carlo
- ✓Full efficient at $10^{18}$ eV




Accurate identification of the ankle

Indication of a flux suppression

**Two different techniques for the estimation of the detector acceptance.**

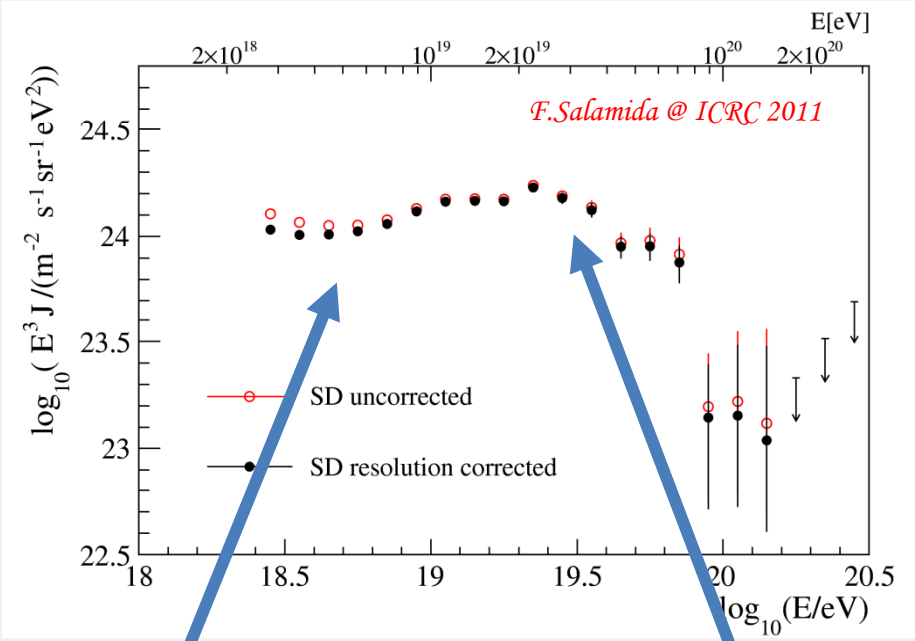
**Full Monte Carlo:**
Corsika+Geant4 ("limited" statistics, signal in the stations)

**Standard Method:**
Conex longitudinal profiles with a parametrized SD trigger response (huge statistics, allows stricter analysis cuts)

*See G. RODRIGUEZ FERNANDEZ this conf.*

# Spectrum

Two different detectors. Three different samples of events. Many independent analysis techniques.




Evidence of the ankle

Identification of the flux suppression > 20 σ

## SD Energy Spectrum: vertical events (zenith < 60º)

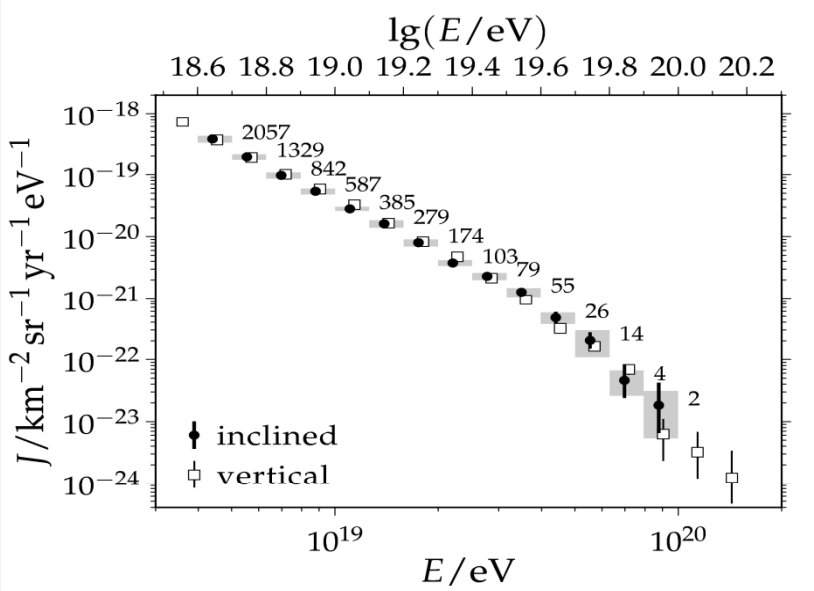
- ✓ Mainly SD
- ✓ Calibration with FD. Energy resolution 15%
- ✓ Signal in the tanks dominated by e.m. component
- ✓ Direct estimation of the acceptance (active area)
- ✓ Full efficient at $10^{18.5}$ eV
- ✓ Unfolding technique to take into account the energy resolution

*Total systematic uncertainty on flux ~ **6%***

*Systematic uncertainty **on the energy scale 22%***

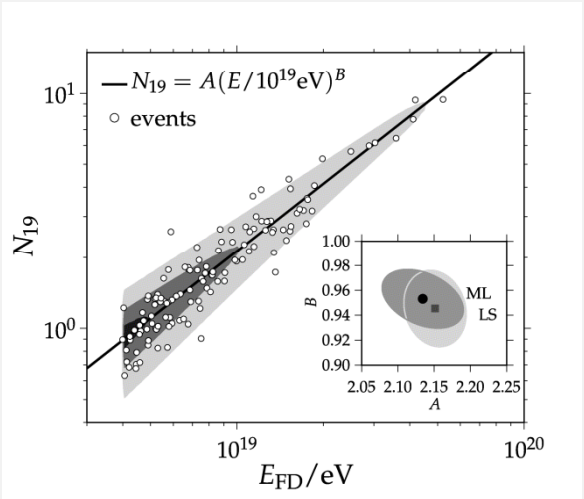
# Spectrum

Two different detectors. Three different samples of events. Many independent analysis techniques.



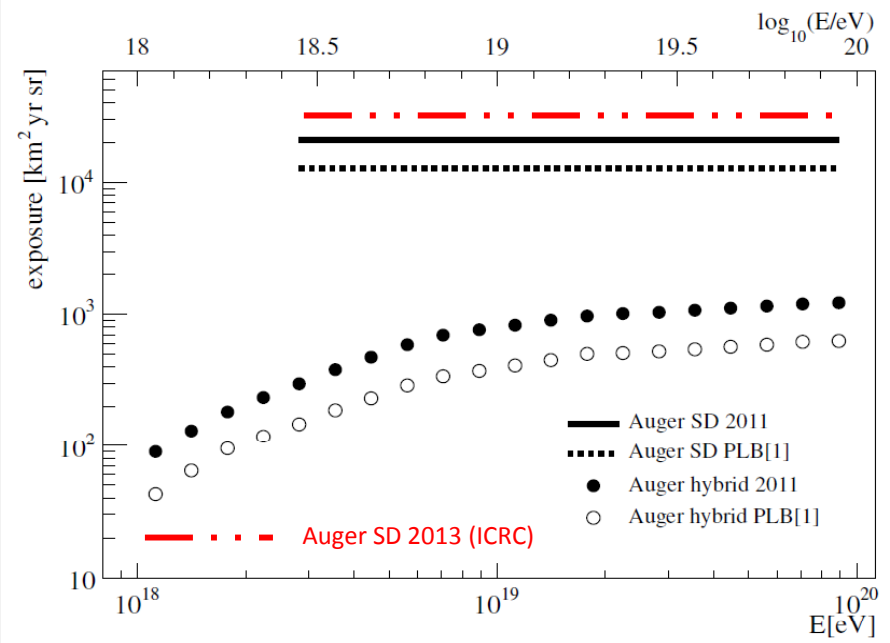

## SD Energy Spectrum: inclined events (62º <zenith < 80º)

- ✓ Mainly SD
- ✓ Calibration with FD.
- ✓ Signal in the tanks dominated by muons
- ✓ Direct estimation of the acceptance (active area)
- ✓ Full efficient at $10^{18.5}$ eV

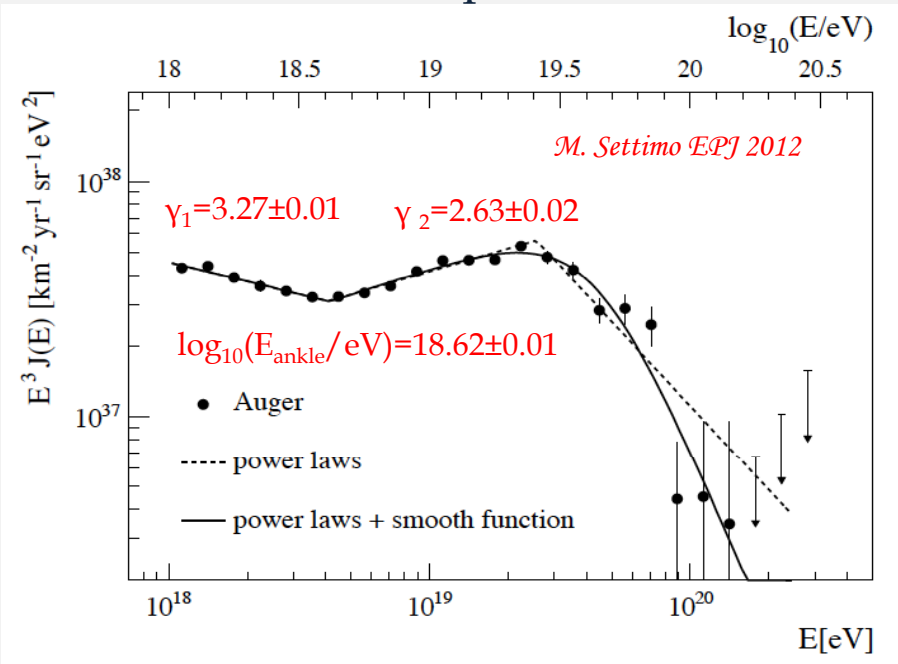



Energy estimator:
$N_{19}$ == lateral muon density

# Spectrum




## Combined Spectrum




New data release with larger exposure and updated energy scale at Rio de Janerio (ICRC 2013)

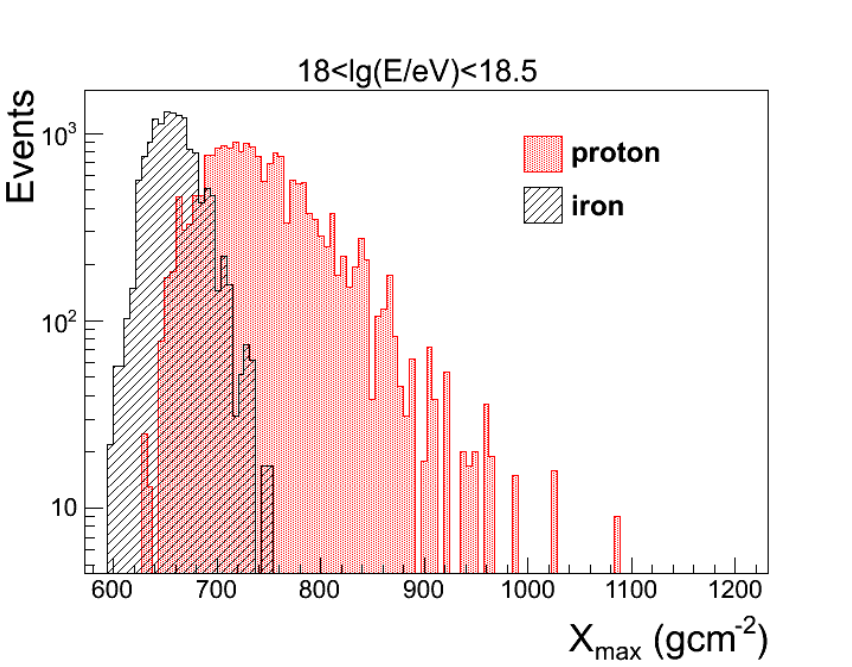
$$J(E; E > E_{\text{ankle}}) \propto E^{-\gamma_2} \frac{1}{1+\exp\left(\frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c}\right)}$$

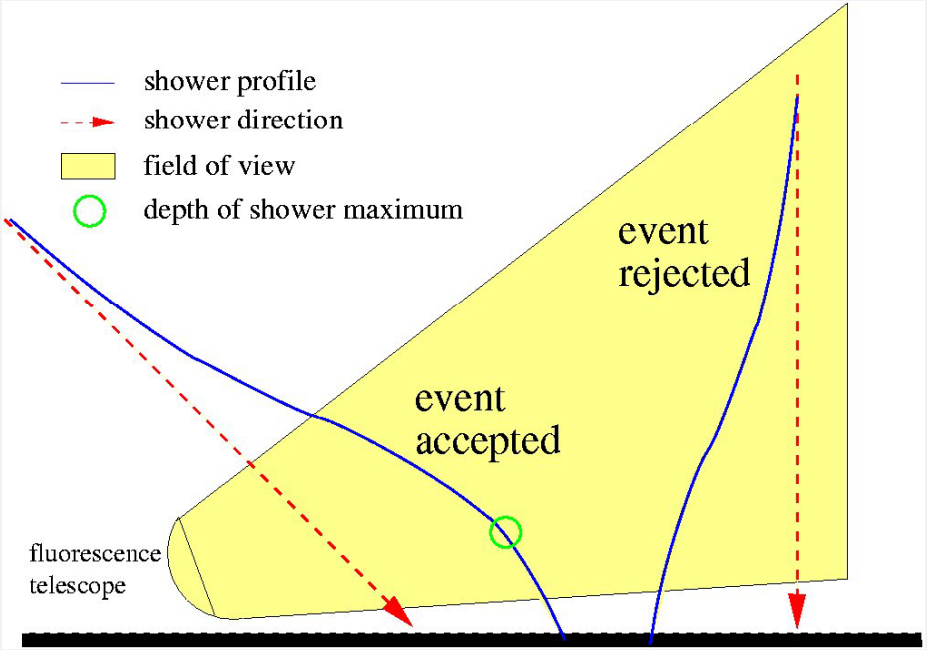
$\log_{10}(E_{1/2}/\text{eV})=19.63\pm0.02$
$\log_{10}(W_c/\text{eV})=0.15\pm0.02$

# Mass Composition

The main instrument of analysis is the Fluorescence Detector, but also the Surface Array can be used.

*See D. Boncioli next talk*

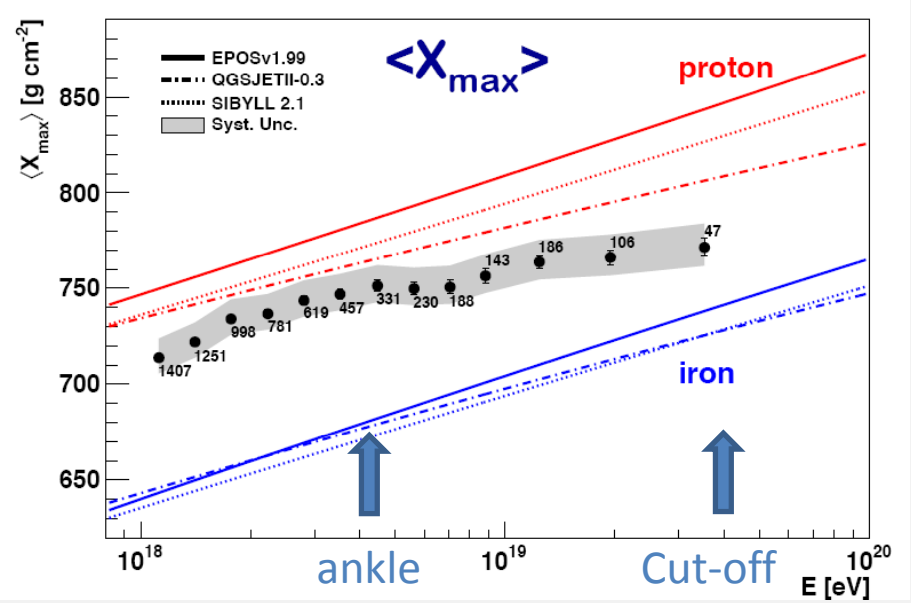


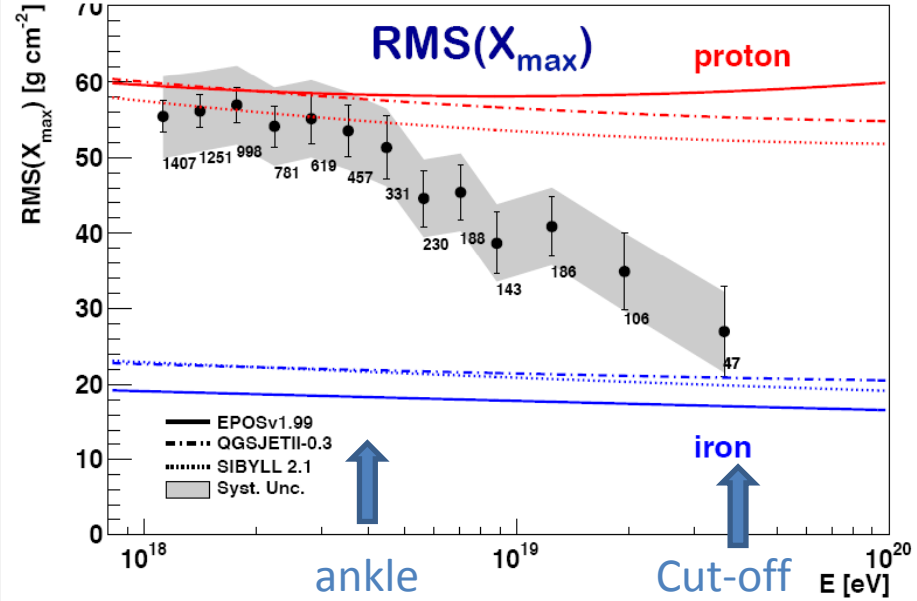




$<X_{max}>$ and its RMS sensitive to mass composition
Key observables for composition studies

Filed of View and Anti-Bias cut used to obtain detector independent results

# Mass Composition




**Syst uncertainty < 13 g cm$^{-2}$**
**$X_{max}$ resolution ~ 20 g cm$^{-2}$**

$<X_{max}>$ became lower with energy

$X_{max}$ distributions become narrower with energy

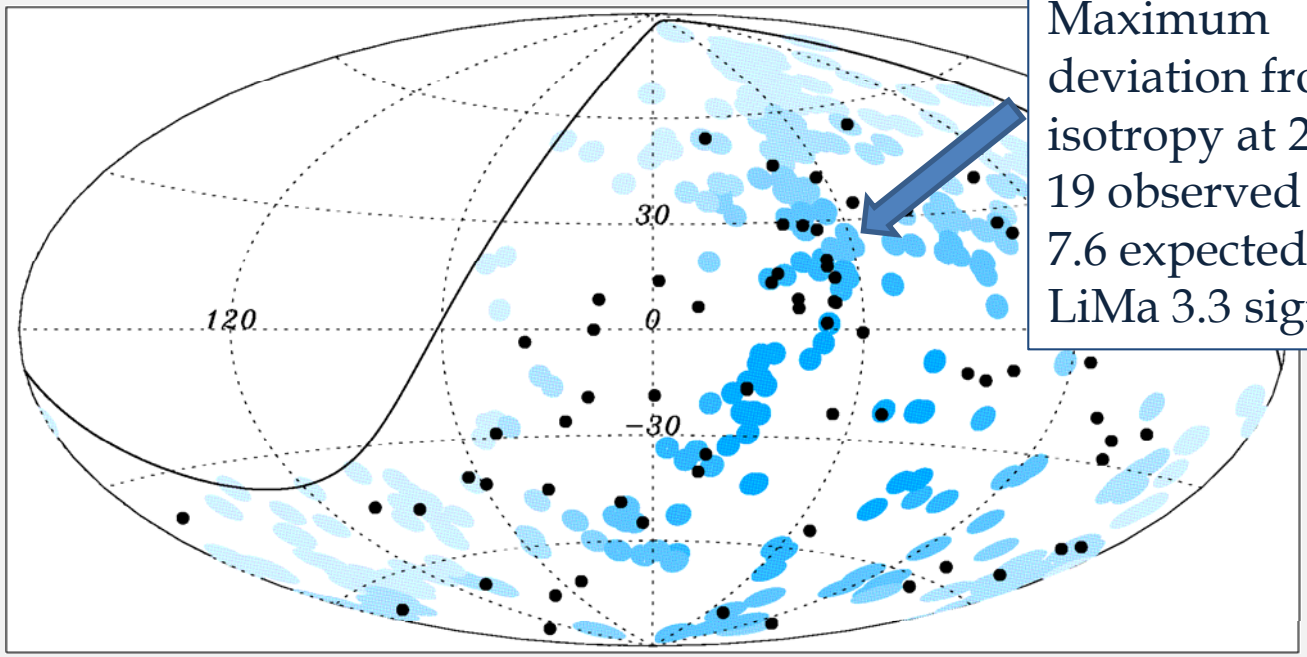
**Increase of the mean mass with the energy? Inadequate interaction models?**

# Anisotropy

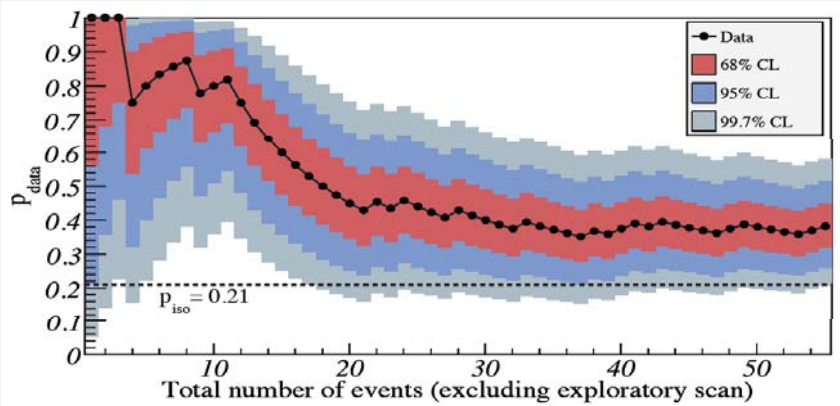
**Astropart. Phys. 34 (2010) 314**

**The 69 events with Energy > 55 EeV detected by the Pierre Auger Observatory**

Blue circles of radius 3.1° centered at the positions of the 318 AGNs < 75 Mpc in the VCV catalog.



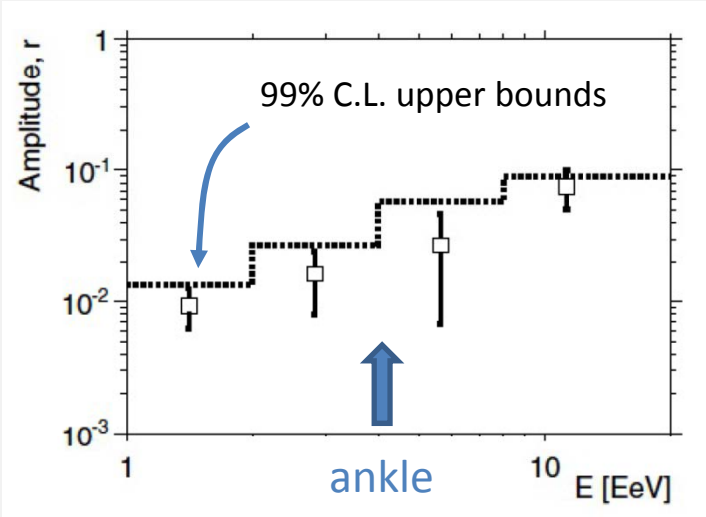

CenA: Maximum deviation from isotropy at 24° 19 observed vs 7.6 expected LiMa 3.3 sigma




The exposure weighted fraction of the sky covered by the blue circles is 21%.
**Chance probability for a isotropic source distribution < 1%**

**TA results can not exclude this conclusions**

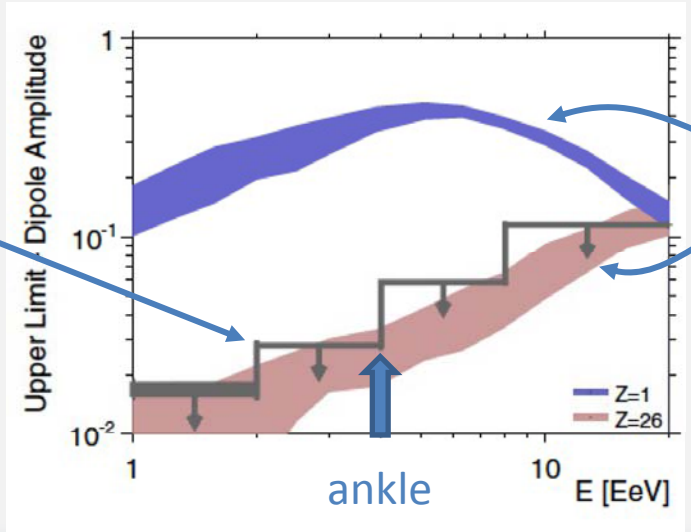
# Anisotropy




Above 1 EeV anisotropies could be imprinted in the distribution of arrival directions as the result of the escape of UHECRs from the Galaxy up to the ankle energy.

If UHECRs have already a predominant extragalactic origin their angular distribution is expected to be isotropic to a high level.

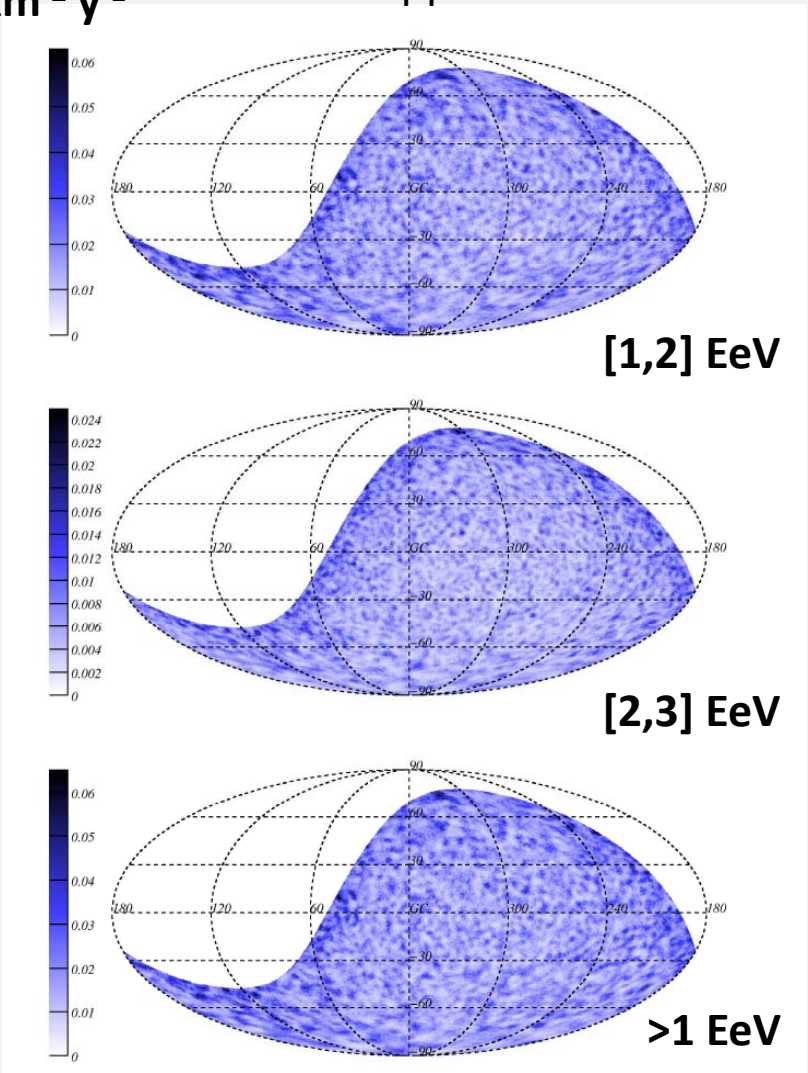
99% C.L. upper limits




Model prediction for an uniform distribution of sources in the galaxy and different compositions

# Anisotropy: Neutrons

$km^{-2}\ y^{-1}$ 95% C.L. upper limit




**AUGER has sensitivity to galactic neutron sources**

✓ Neutrons are undeflected by galactic magnetic fields!

✓ Flux of neutrons from discrete source would cause an excess of CR events in the direction of the source!

✓ 1 EeV neutron emitted by Galactic center could be seen!

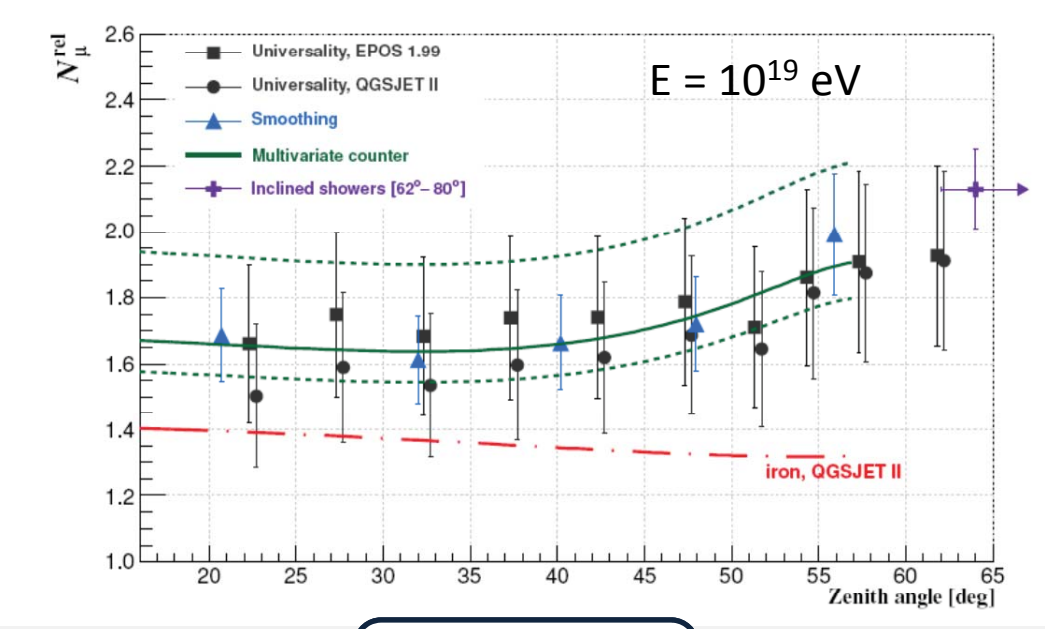
✓ Flux of gammas rays from some sources in the galaxy, could be associated to neutron fluxes detectable by Auger!

✓ Select SD events with $\theta \leq 60^0$, good event reconstruction!

✓ Exposure of 24,880 $km^2$ sr yr, with 429,138 events with energy ≥ 1 EeV!

**No excess found**

# The muons puzzle




$$N_\mu^{rel} = \frac{N_\mu^{Data}}{N_\mu^{QGSJET_{proton}}}$$

**Measure Muon shower content by four methods**

✓Smoothing

Smoothing filter over traces $S_\mu = S_{tot} - S_{em}$

✓Multivariate muon counter

Neural Network prediction of $N_\mu$ at each tank

✓Inclined showers

Shower size $N_{19}$ α $N_\mu$

✓Shower Universality

The determination of the muons signal in Auger detector is indirect. Current results show a disagreement between the data and the Monte Carlo predictions.

**Inadequate interaction models? New Physics?**

# AUGER: A summary

**Photons**

Flux photon limits above 1 EeV (top-down models disfavored)

**Spectrum flux**

Suppression established ($E > 4\ 10^{19}$ eV)
Ankle observed at about $4\ 10^{18}$ eV

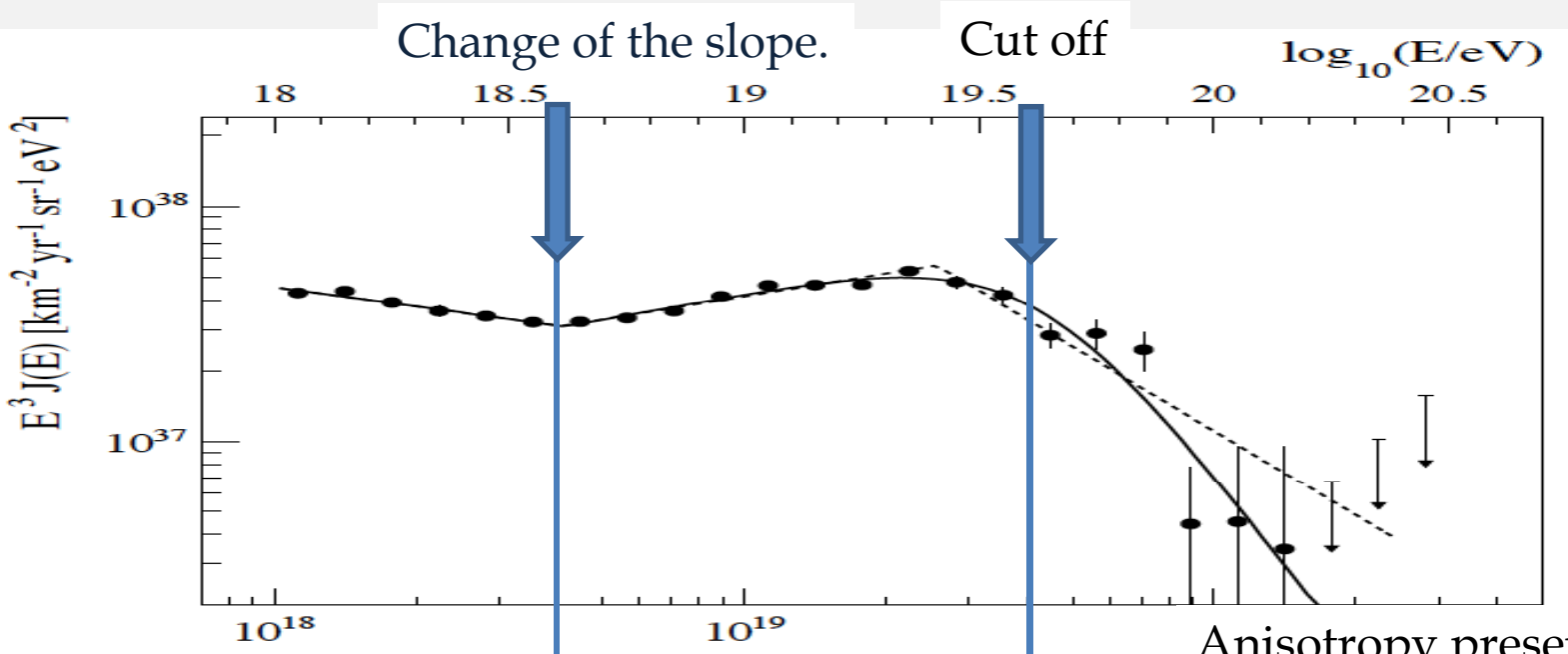
**Composition mixed**

Scenario: light dominated at low energies, heavier with increasing energy (interpretation is model dependent).

**Arrival directions**

The degree of correlation with VCV catalog is stable (about 33%)
Definitive conclusions must await additional data

# AUGER: A Summary




Light composition.
Weak or none anisotropy
(no galactic protons).

The composition
became heavy.
No galactic
neutrons.

Anisotropy present
but weak.
Not only GZK
protons.

Muons: Problems with the interaction models? New physics?

Direct measurement of muons and mass composition up to $10^{20}$ eV needed.

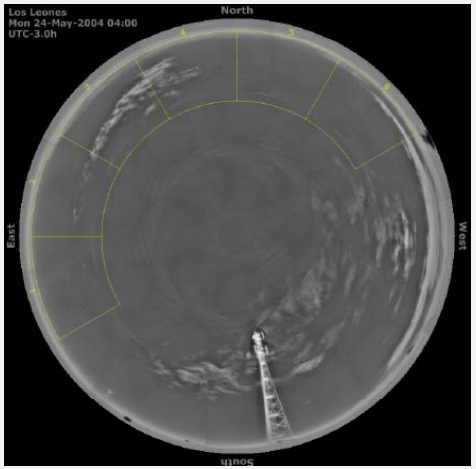
**Challenging (open) science case at the highest energy**

# The End

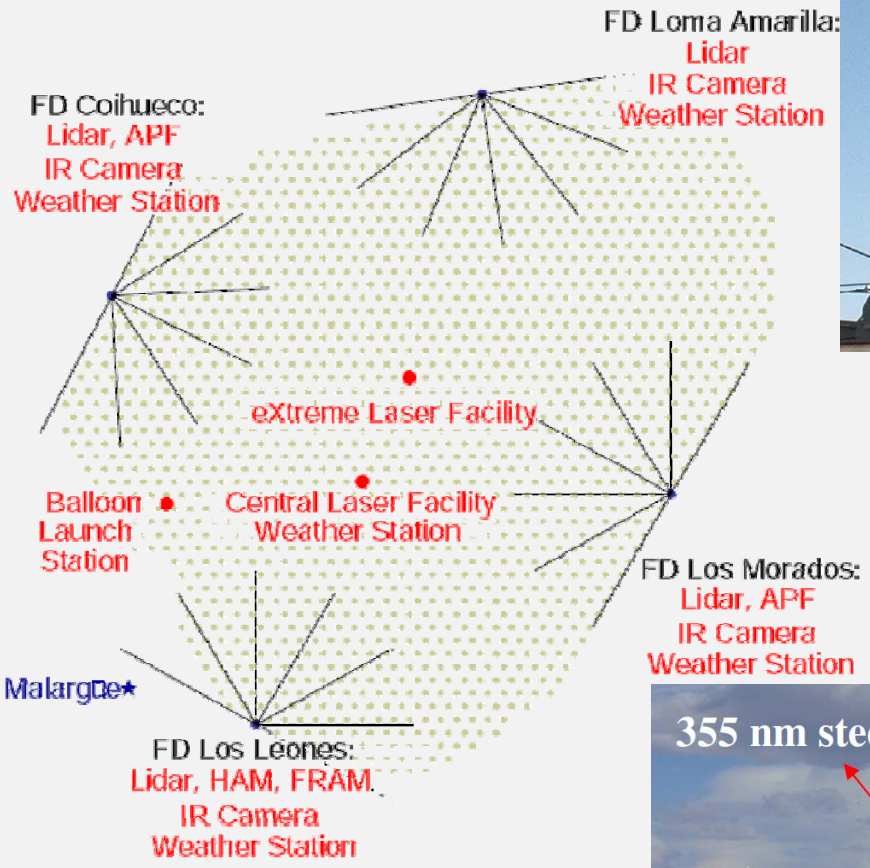
Backup

# Atmospheric monitoring

Balloon and GDAS

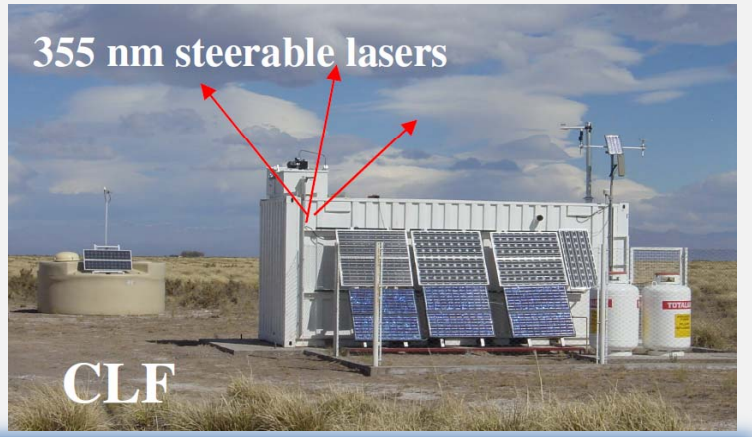



IR Camera




Lidar

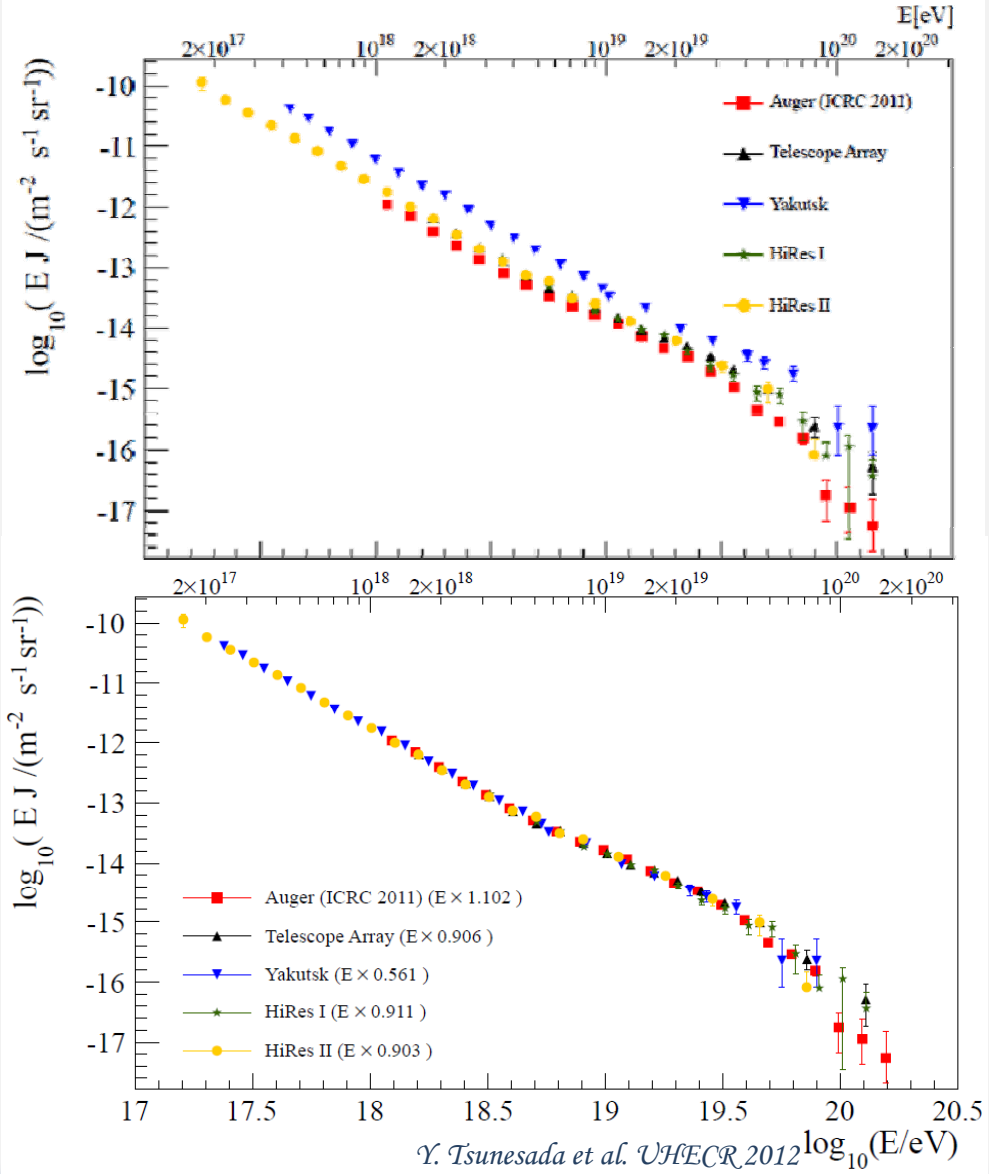
Central Laser Facility



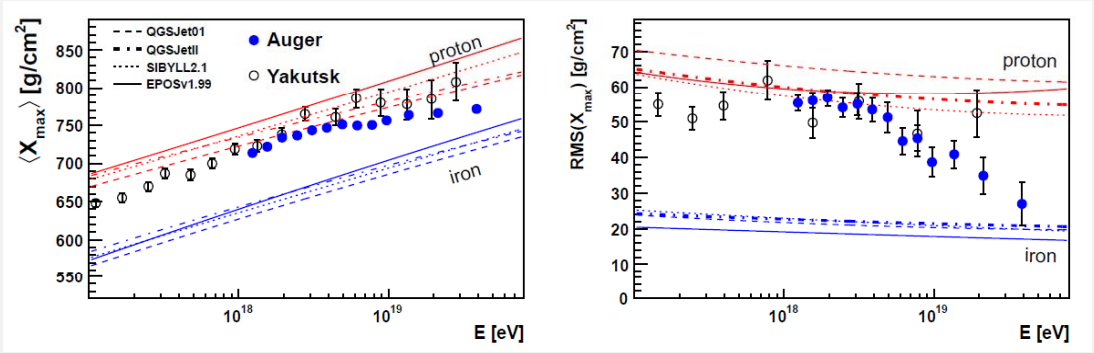
# Spectrum

Comparison between different experiments.

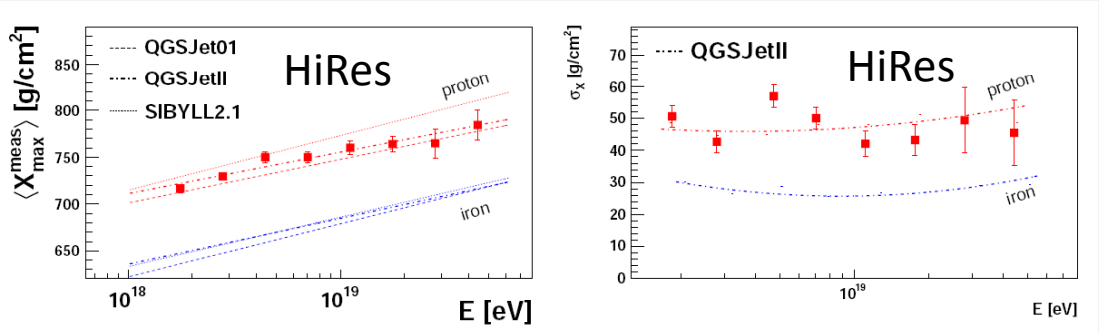
The spectrum results of the four experiments that have collect data at this energy are compatible inside the quoted systematic errors.



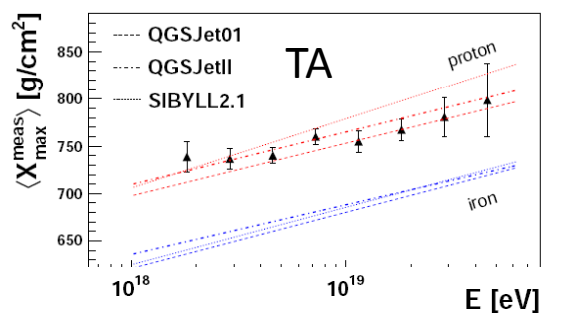
# Mass Composition




Auger and Yakutsk report the values with minimum detector bias.
Both can be compared with the model expectations.




The HiRes and TA collaborations do not apply field-of-view cuts.
They quote the $\langle X_{max} \rangle$ as measured in the detector.

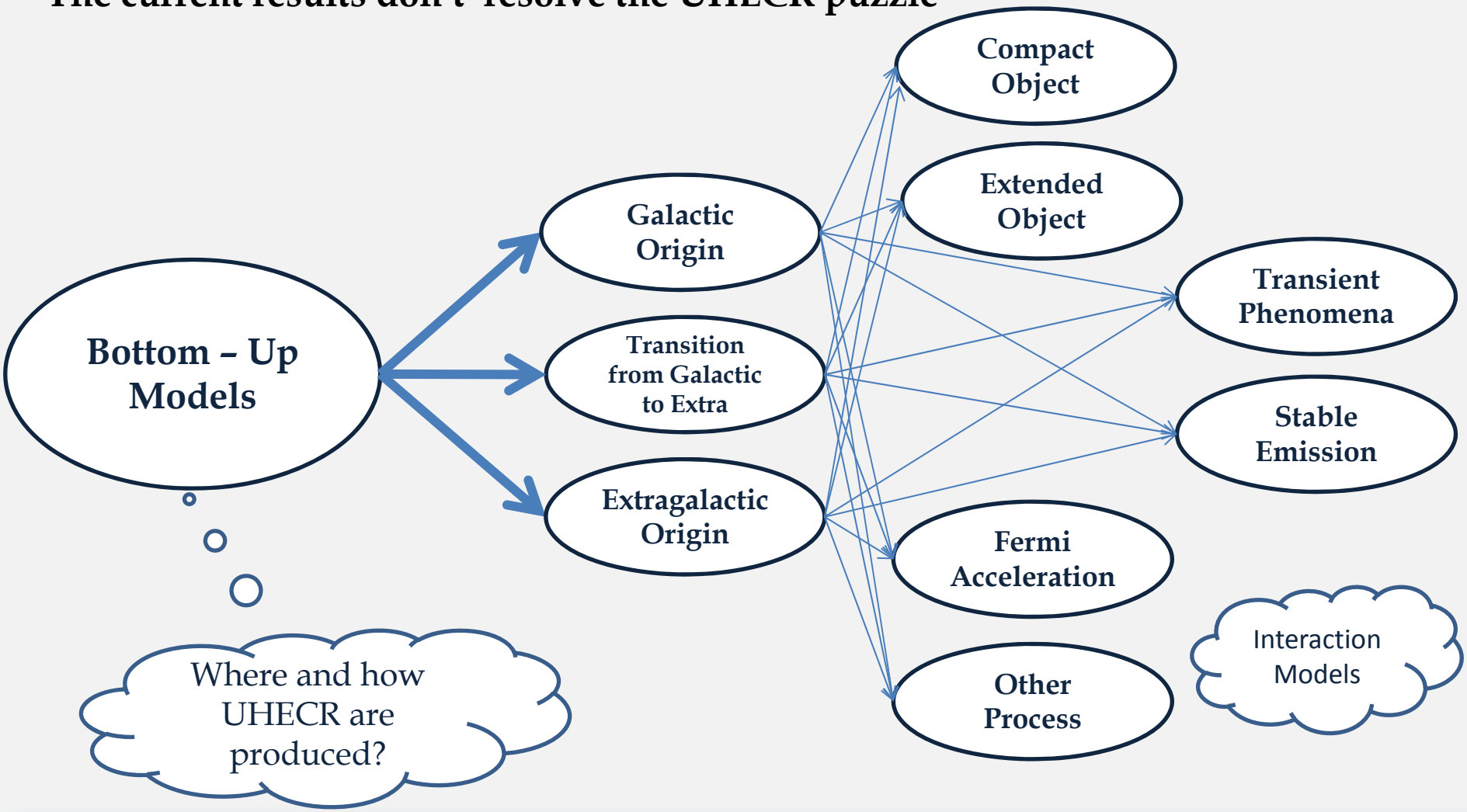



Auger and Yakutsk are compatible within the systematic uncertainty.

Auger and HiRes **not** compatible.

# UHECR: A summary

**The current results don't resolve the UHECR puzzle**

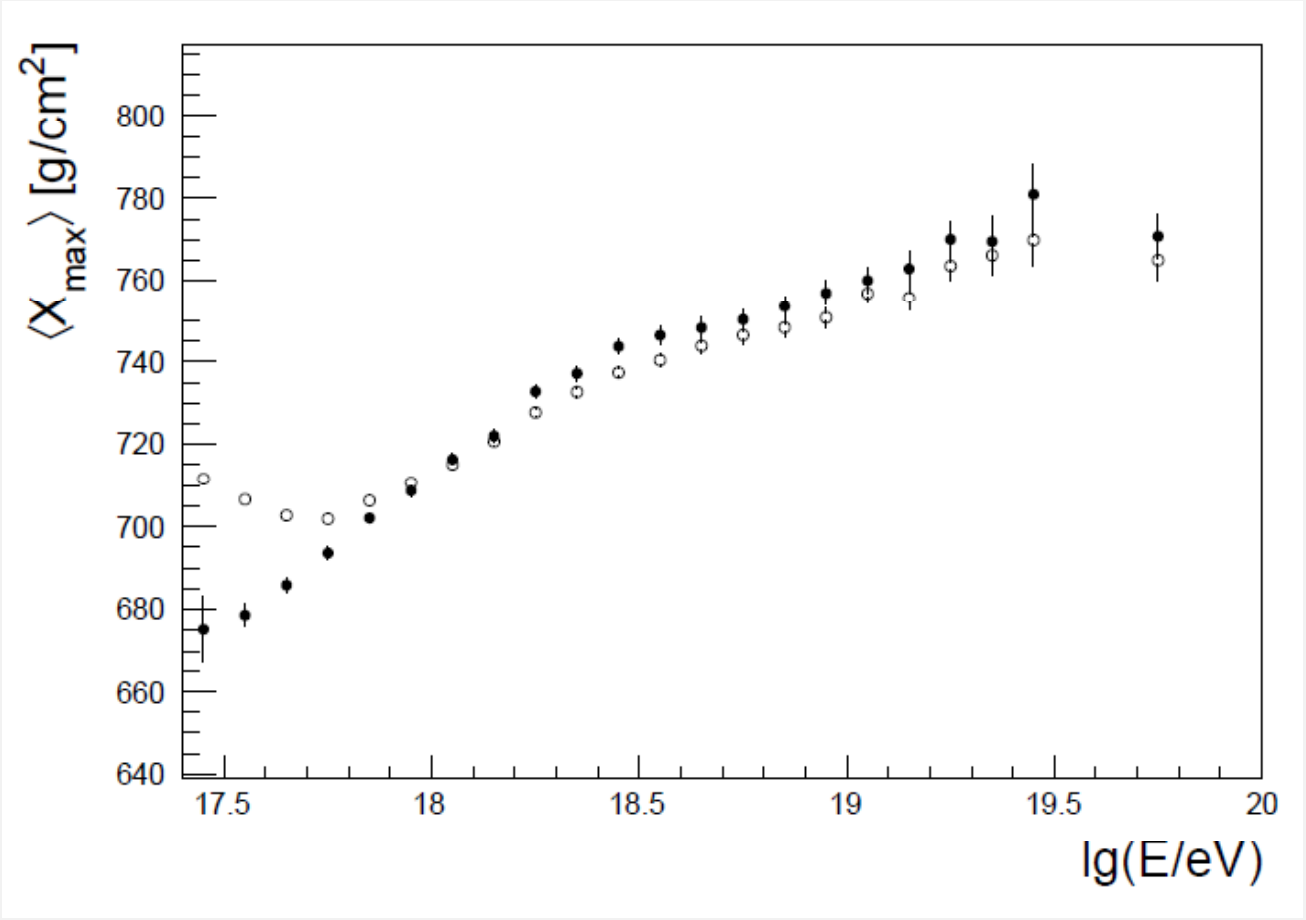


# The Hybrid Concept

| | SD-only | FD-only | Hybrid |
|---|---|---|---|
| Duty-cycle | ~100% | ~14% | ~14% |
| Angular resolution | 1-2 deg | 3-5 deg | ~ 0.6 deg |
| Energy | C & M depend | independent | independent |
| Aperture | independent | E, C, M depend | independent |
| Energy Thr. | $\sim 10^{18.5}$ eV | $\sim 10^{17,5}$ eV | $\sim 10^{18}$ eV |

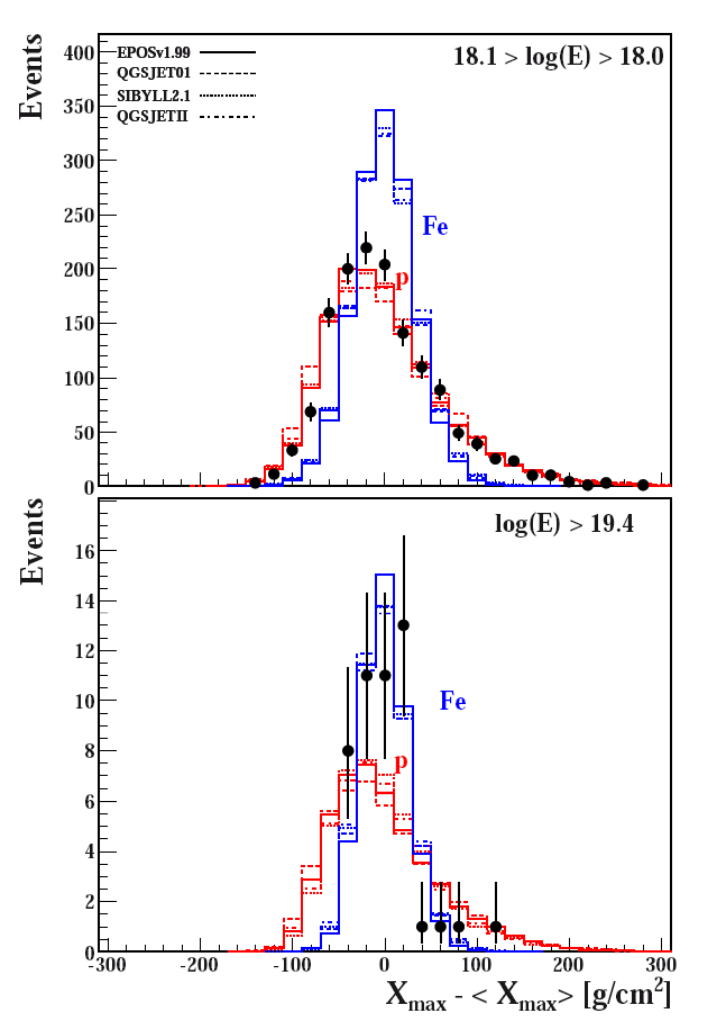
**E = Energy, M = Interaction Model, C = Composition**

# Mass Composition




<$X_{max}$> as a function of energy. Black dots show the data after quality and fiducial cuts. Open circles show the data after quality cuts only.

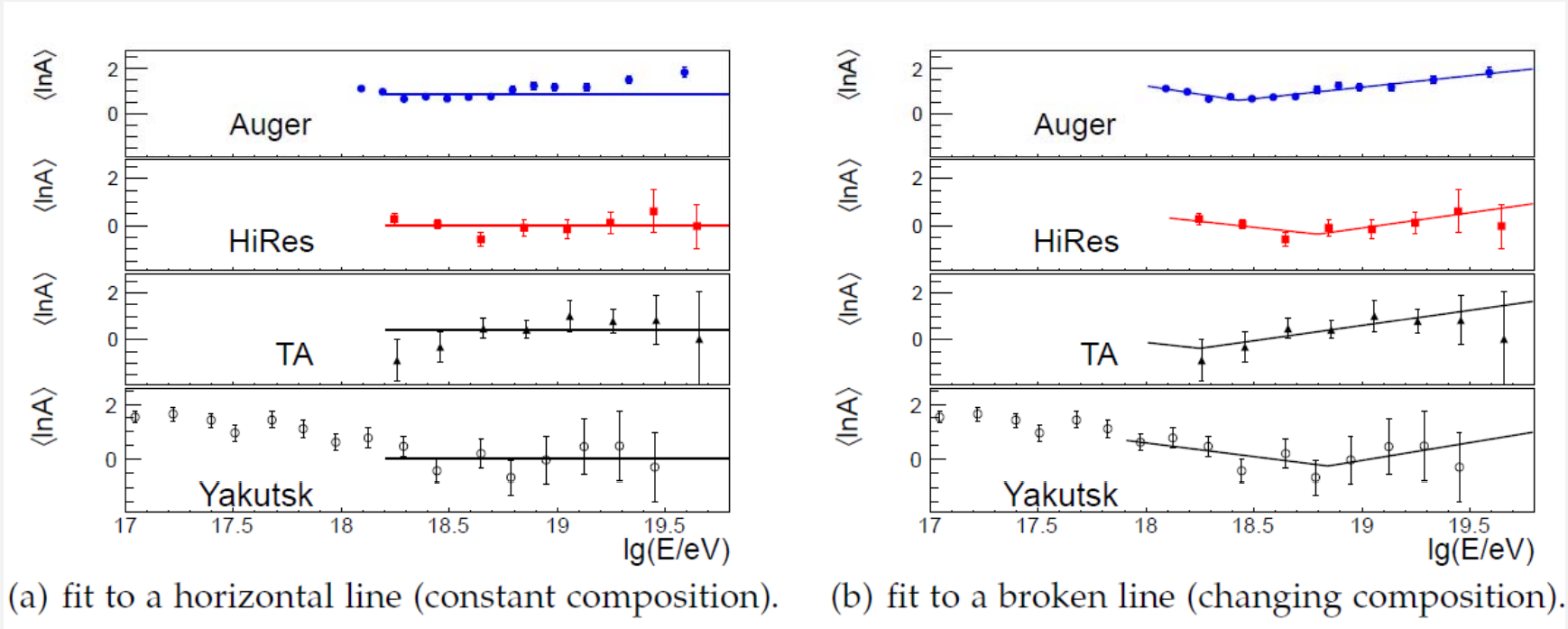
# Mass Composition




At low energy:
shape compatible with a very light or mixed composition

At high energies:
narrower shape, significant fraction of nuclei (CNO or heavier)

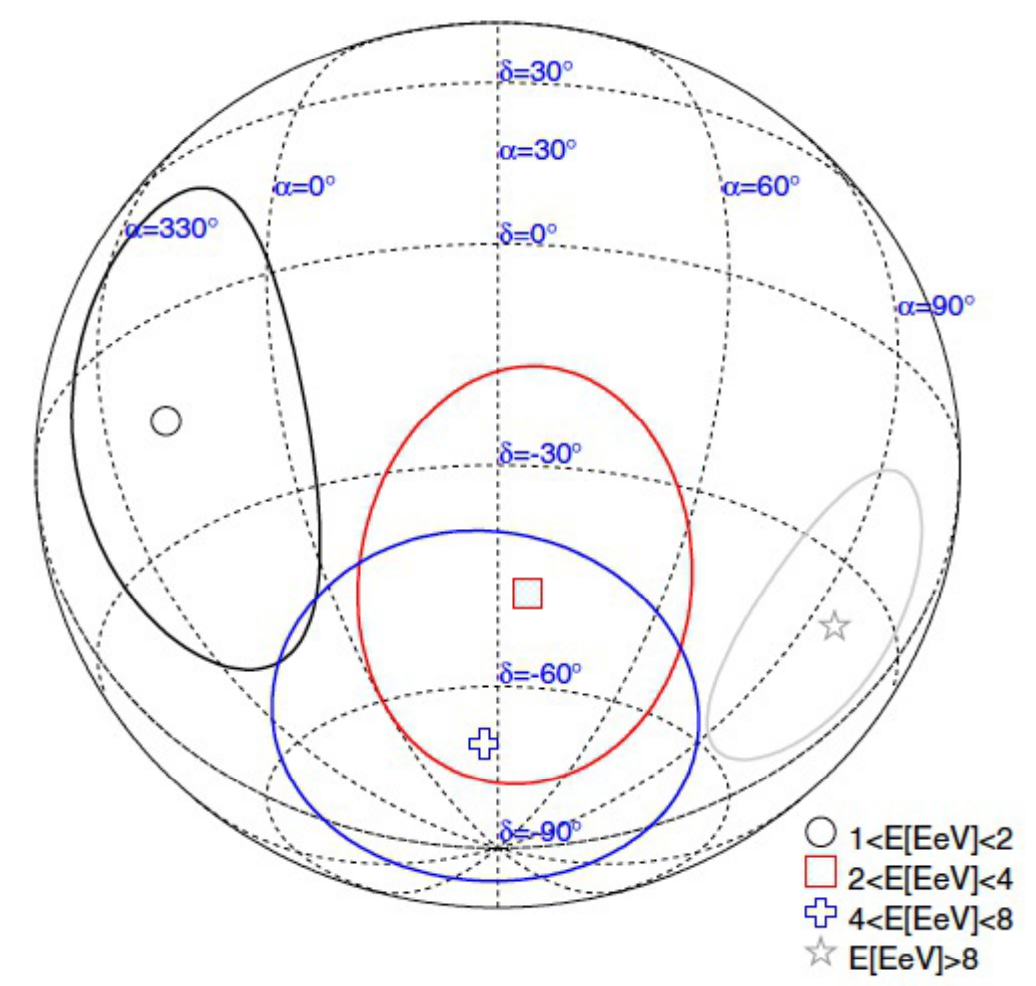
# Mass Composition

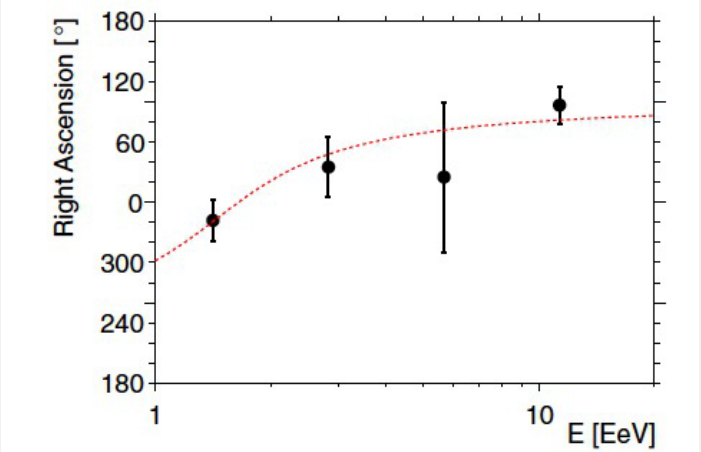



(a) fit to a horizontal line (constant composition).

(b) fit to a broken line (changing composition).

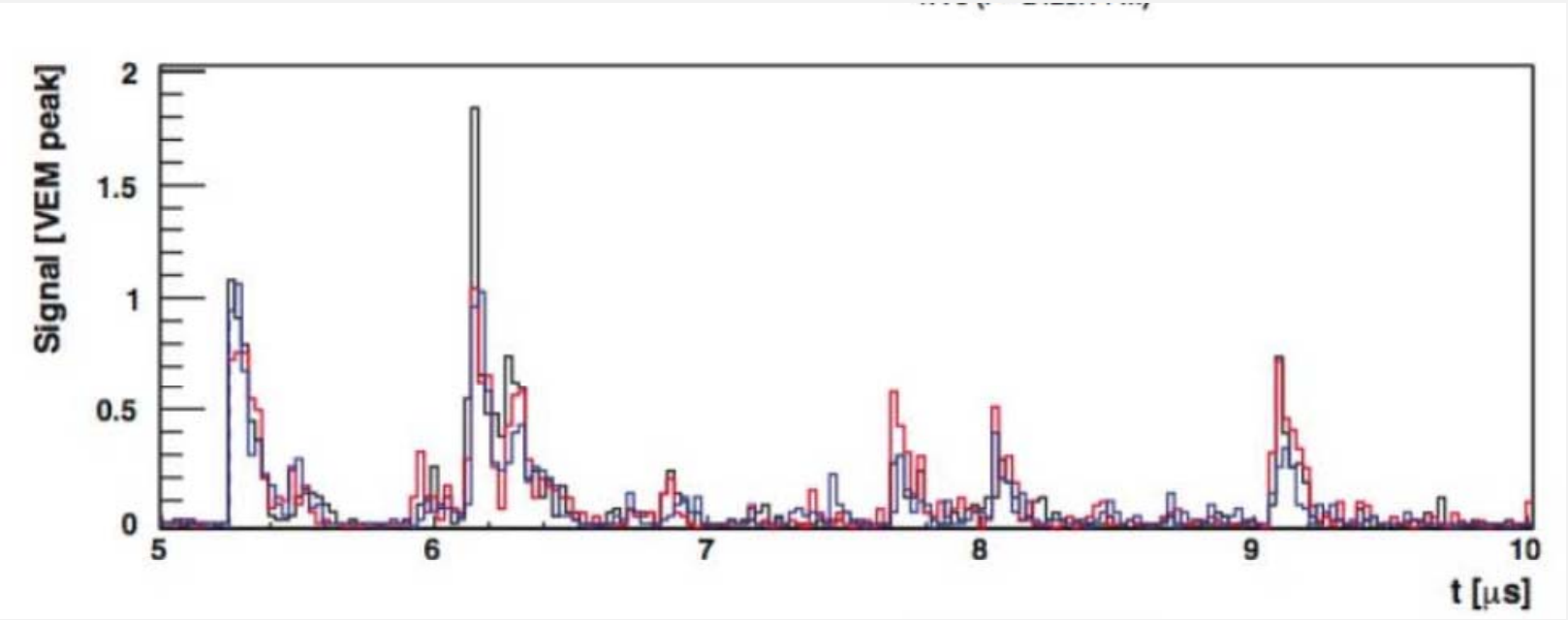
# Anisotropy




Prescription running since 2011

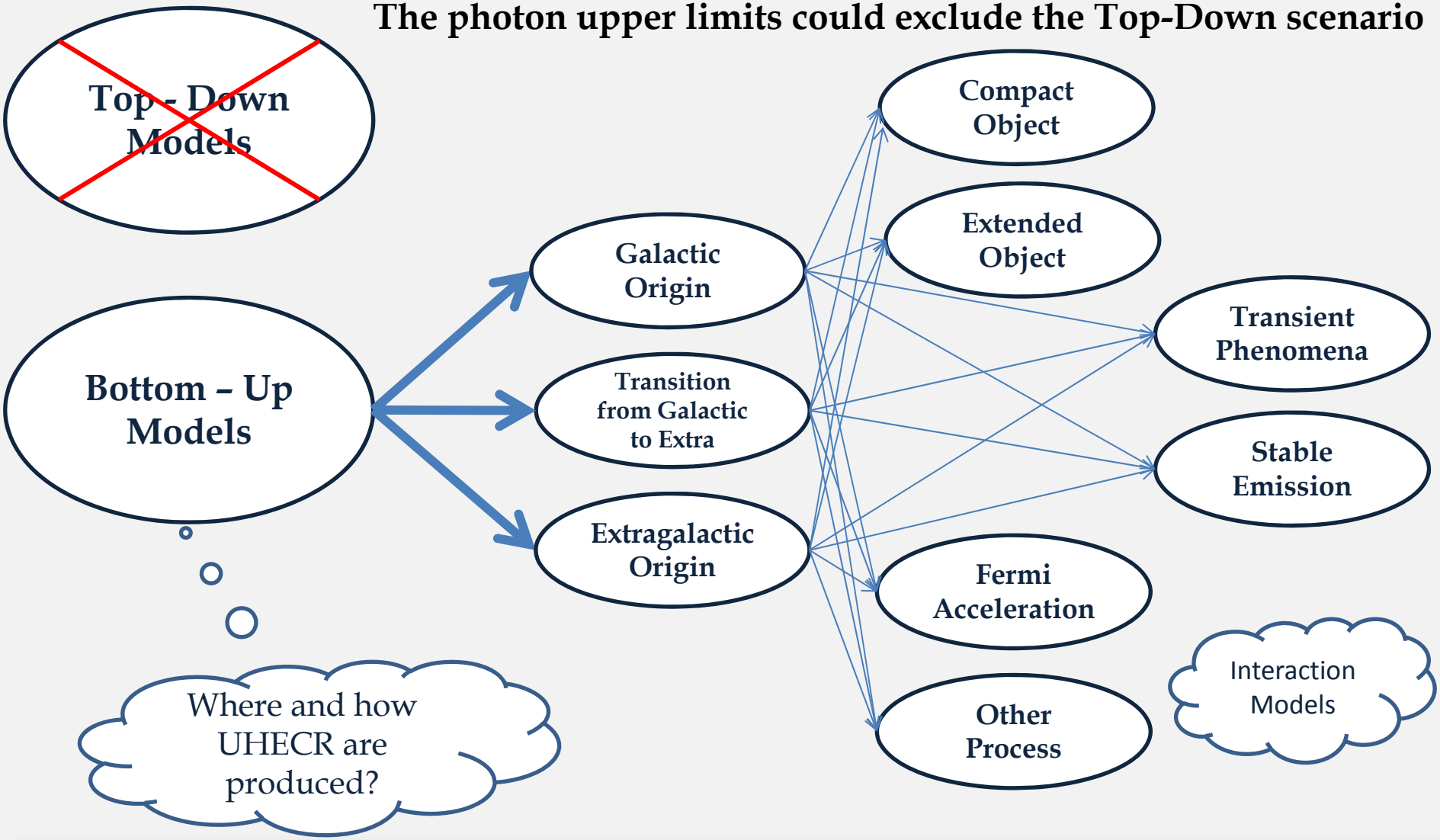
# The muons puzzle




Example of the signal in a tank

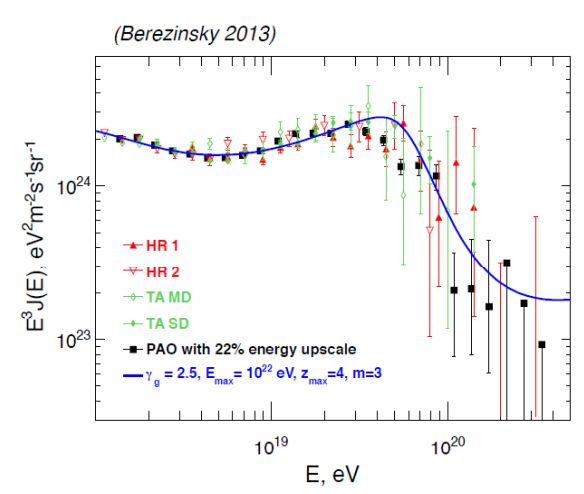
# Photons: implications

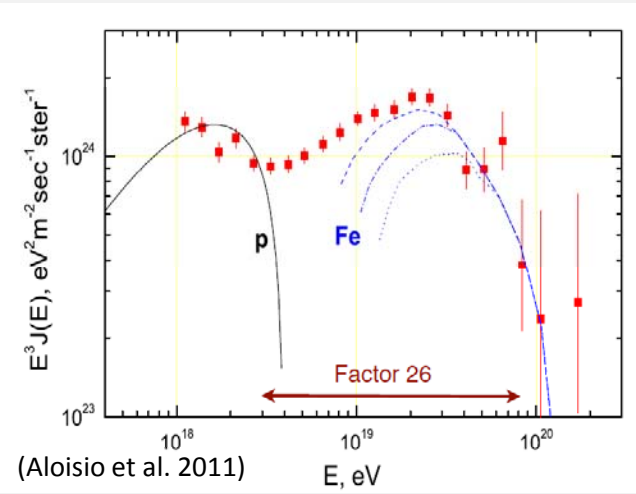
**The photon upper limits could exclude the Top-Down scenario**

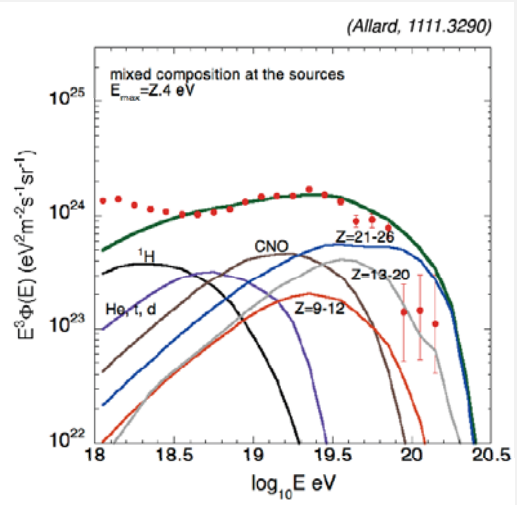


# Spectrum: implications

Suppression established ($E > 4 \cdot 10^{19}$ eV)
Ankle observed at about $4 \cdot 10^{18}$ eV




✓UHECR are Protons
✓GZK effect produce the cut off
✓Natural explanation for the ankle

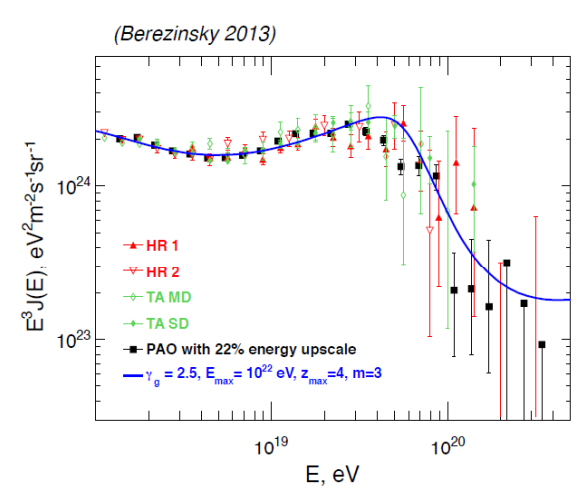
✓UHECR Rigidity dependent composition of Extragalactic origin
✓GZK effect not needed
✓ Transition from galactic to extragalactic at lower energy (2nd knee)

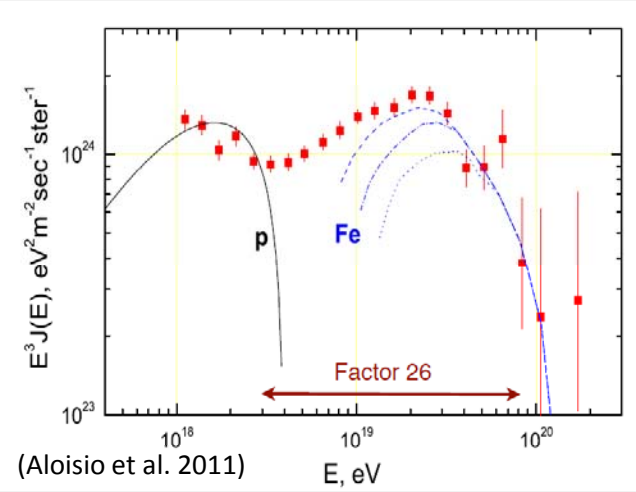
✓UHECR Mixed composition at the sources (Extragalactic origin)
✓GZK effect but for Heavy Elements
✓ Ankle due to transition between Galactic and Extragalactic spectrum.

Do not resolve between different scenario.
Also the galactic origin is not excluded.

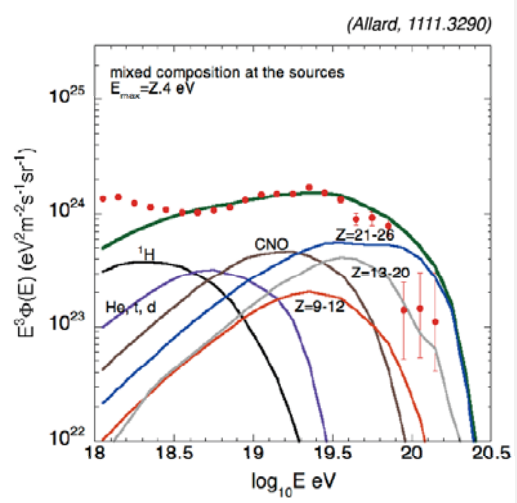
# Mass Composition: implications

AUGER results:
Light dominated at low energies, heavier with increasing energy



(Aloisio et al. 2011)




✓ AUGER Excluded? Still possible if new physics is responsible of the change in the $<X_{max}>$ and RMS($X_{max}$) distributions.

✓ Not in contradiction with Auger Mass Composition Data.

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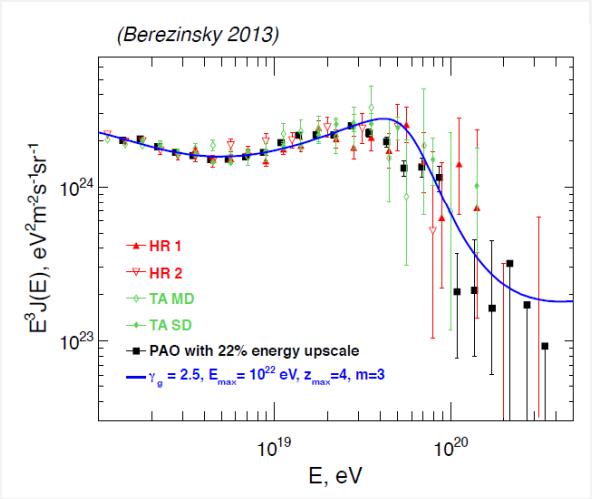
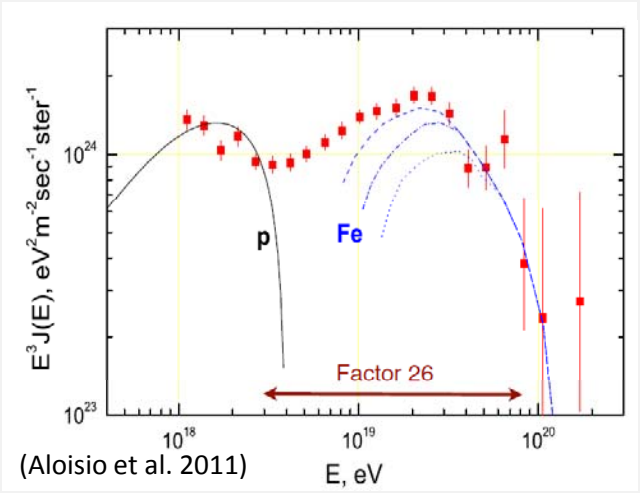
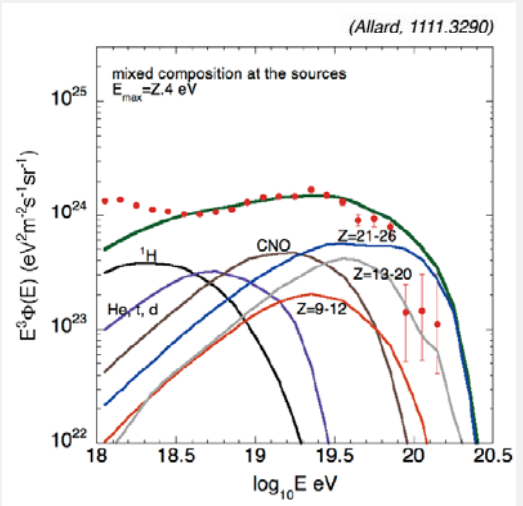
# Anisotropy: implications

The degree of correlation with VCV catalog is stable (about 33%)
Definitive conclusions must await additional data
No neutron sources (constrain on galactic origin)
Lower energy events, if protons, has to be extragalactic



(Aloisio et al. 2011)




✓ Explain the missing anisotropy below the ankle.
✓ Require a stronger correlation with the extragalactic mass distribution.

✓ Not totally explain the still present correlation with the distribution of the mass near our galaxy.
✓ Not in contradiction with the results of the other detectors.

✓ Better explanation of the anisotropy at higher energy.
✓ Require a heavy galactic component at the ankle.

# UHECR: What next?

AUGER and ground based detectors

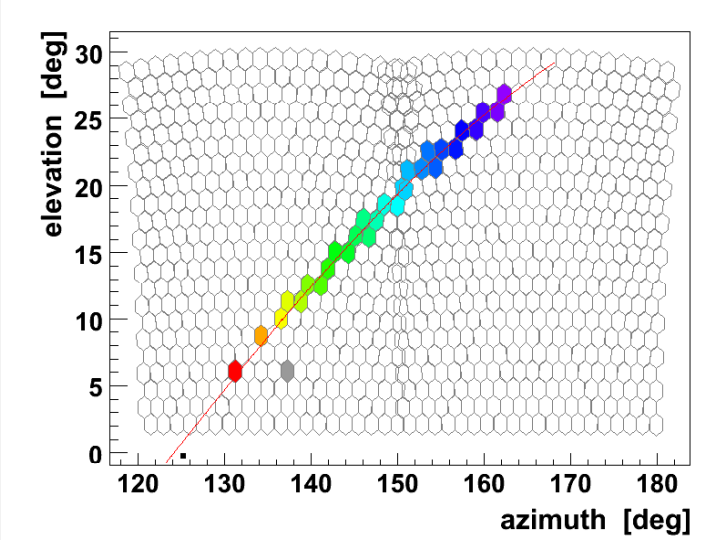
**Goal: identify the primary cosmic ray nature at the highest energy**
**→ investigate the interaction properties more deeply**

Upgrade: Muons identification with SD detectors

JEM-EUSO

**Goal: identify sources and/or help in anisotropy analysis**

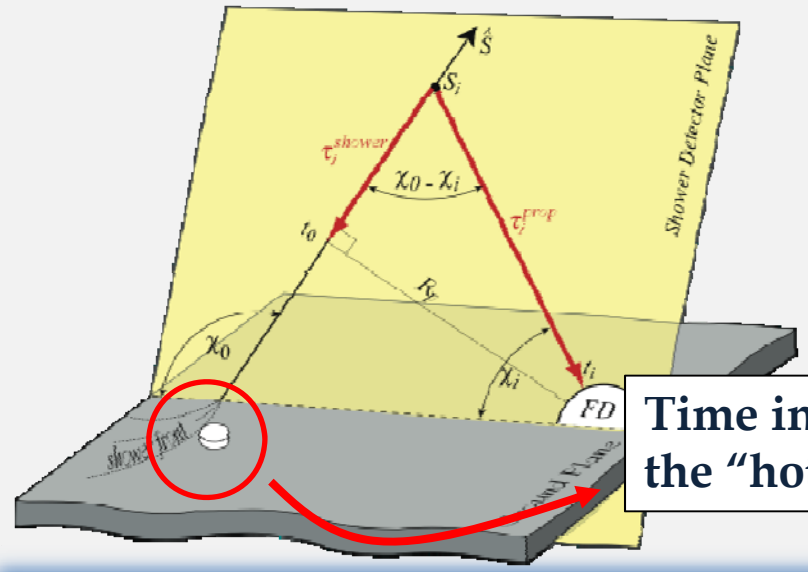
# The Hybrid Concept



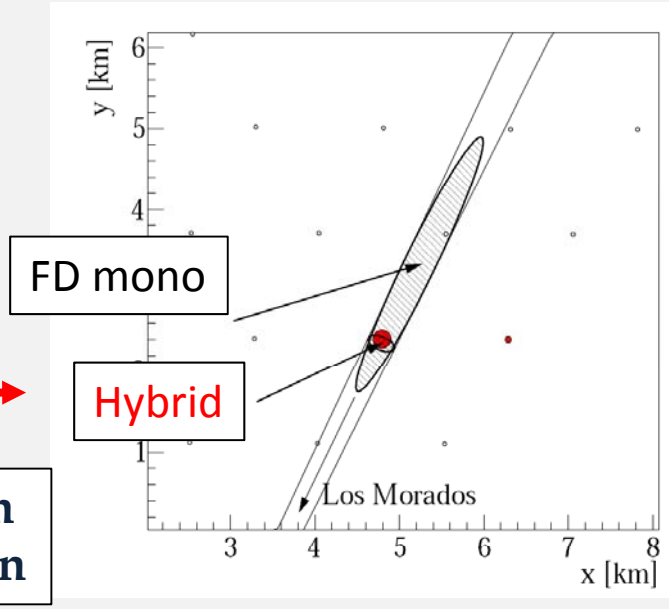

## FD monocular reconstruction

✓ShowerDetector Plane (SDP) using the directions of the triggered pixels

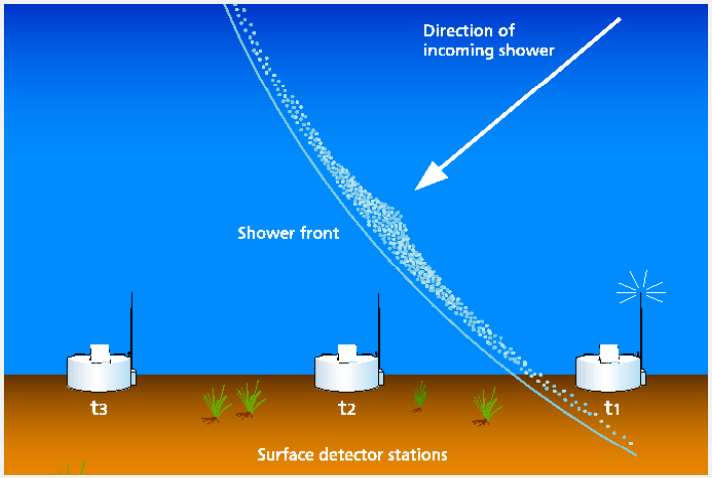
✓Shower axis from the time sequence of triggered FD pixels




**Time information from the "hottest" SD station**



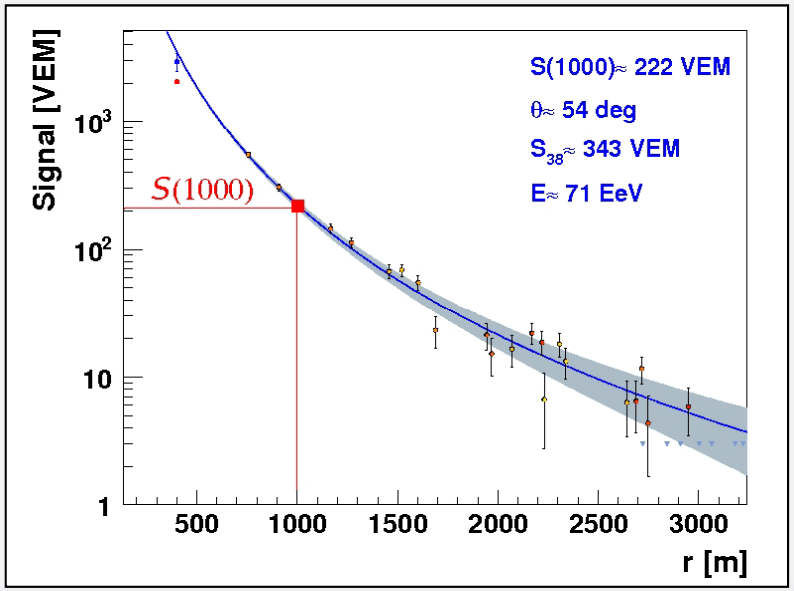
# The Hybrid Concept

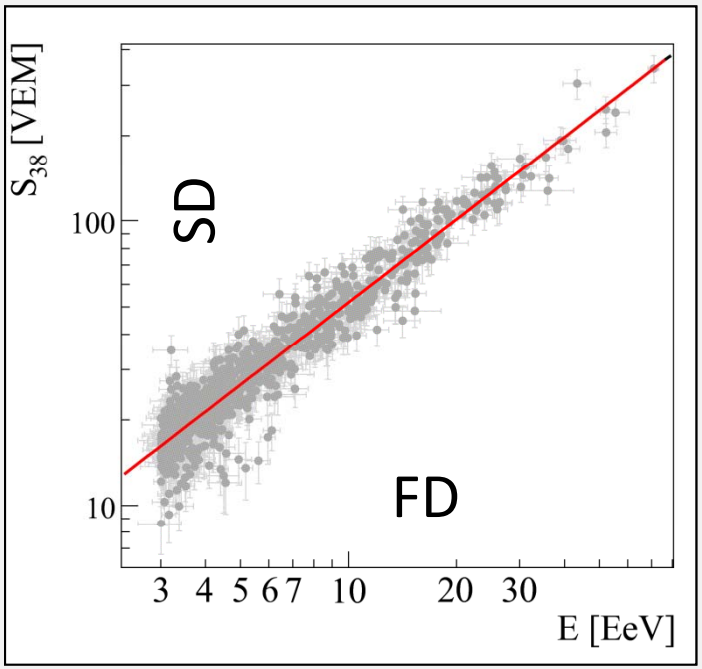



## SD reconstruction

✓Energy estimator: S(1000) particle density at 1000 m from shower axis

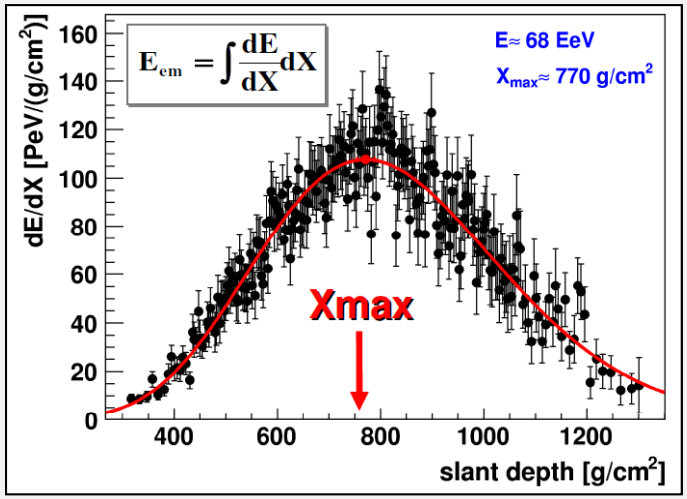
✓Systematic uncertainties on energy determination 30% (Monte Carlo)



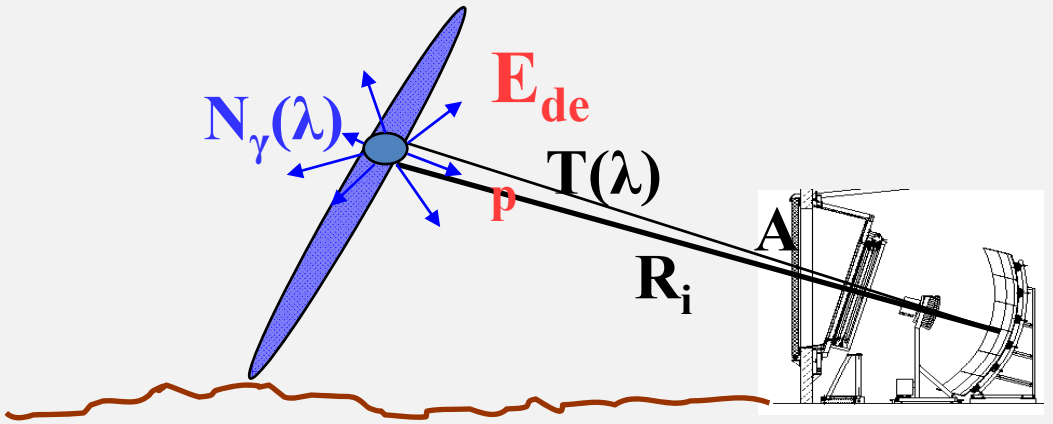




**Using hybrid events, the SD energy estimator is calibrated without relying on Monte Carlo**

# The Hybrid Concept




Energy "Calorimetric measurement"




$E_{dep}$ → $N_\gamma(\lambda)$ → **Photons in FD FOV** → **Photons at diaphragm** → **ADC counts**

**Fluorescence yield** (from laboratory measurements)

**Geometry** $\frac{A}{R_i^2}$

**Atmosphere** T(λ)

**Detector calibration**