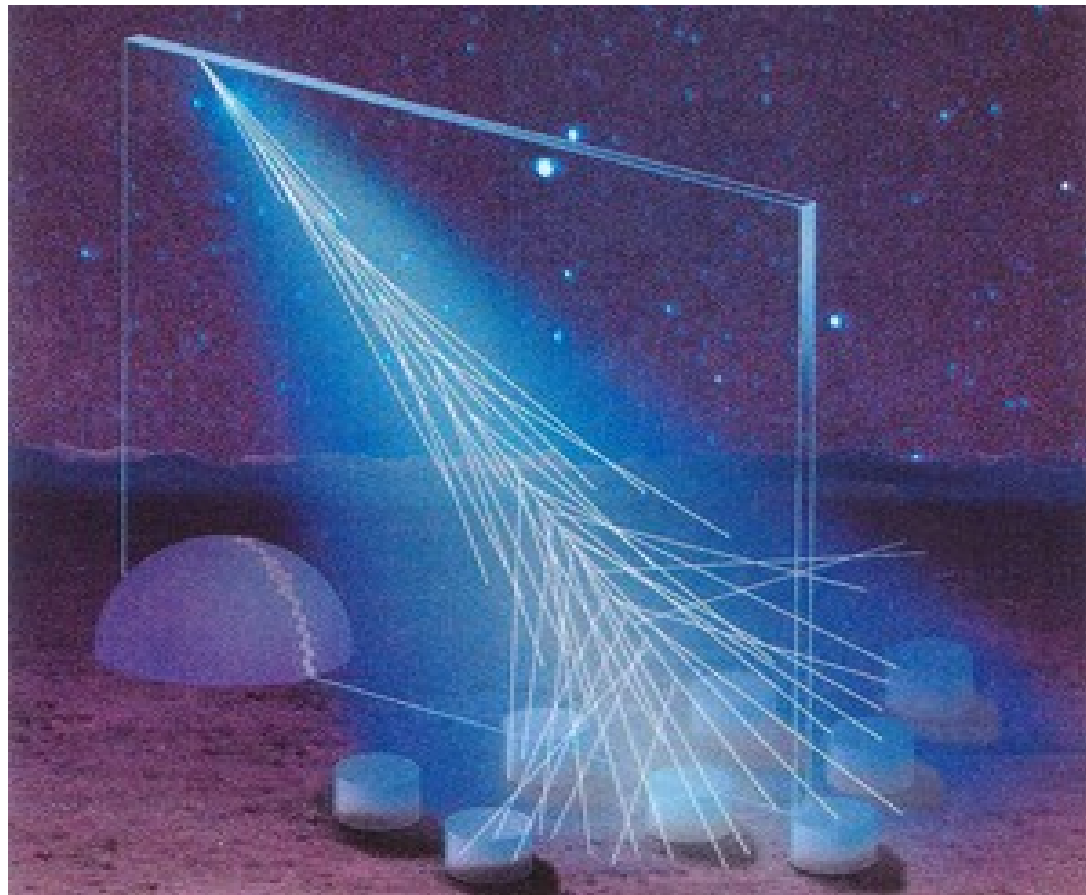


Ultra High Energy Cosmic Rays - What we have learnt from *HiRes* and *Auger*



Andreas Zech
Observatoire de Paris (Meudon) / LUTh
École de Chalonge, Paris, May 17th, 2007

Outline

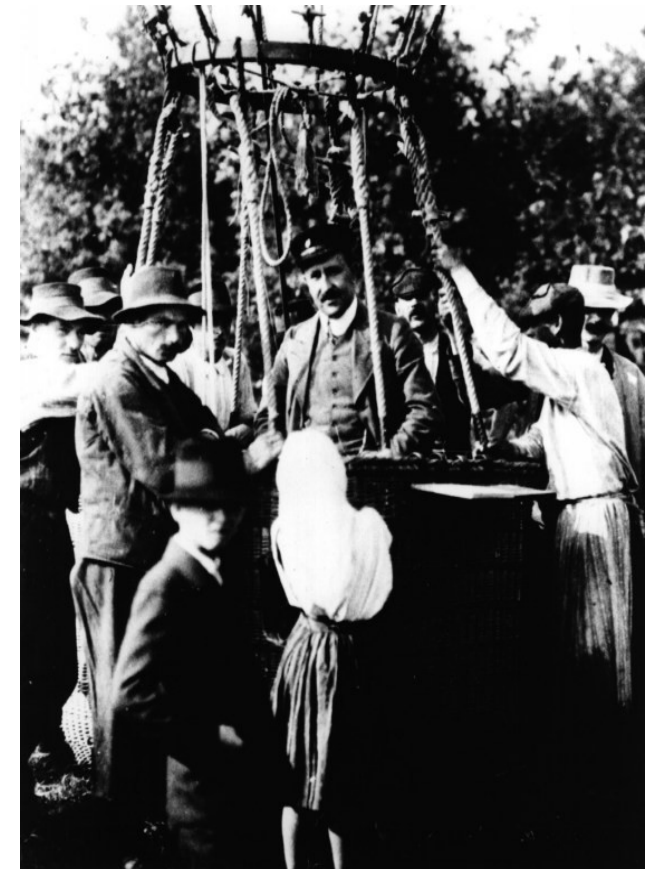
The physics of Ultra-High Energy Cosmic Rays

What we have learnt from the
High Resolution Fly's Eye (*HiRes*)

What we have learnt (so far) from the
Pierre Auger Observatory (*Auger*)

What's next ?

The physics of Ultra-High Energy Cosmic Rays



FROM FANTASTIC FOUR #1

The "Mystery" of UHECRs

What is the nature and origin of UHECRs ?

Where and how are they being accelerated ?



Energy Spectrum:

- features ?
- transition galactic / extragalactic CRs ?

Composition:

- Mixed ? Heavy ? Only protons ?
- UHE photons ?

Anisotropies:

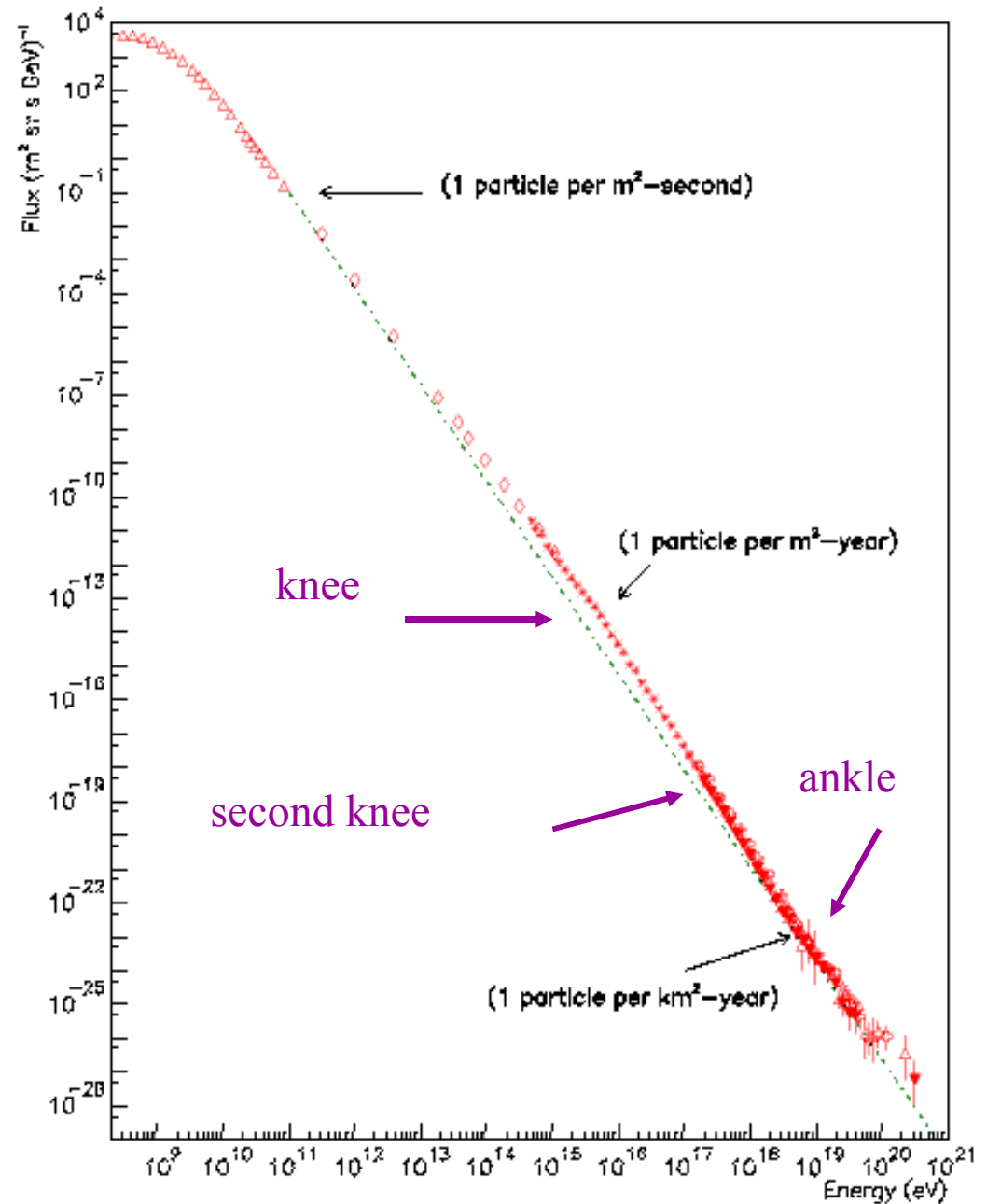
- large scale anisotropies at "low" energies ?
- see small scale anisotropies at the highest energies ?

The cosmic ray flux

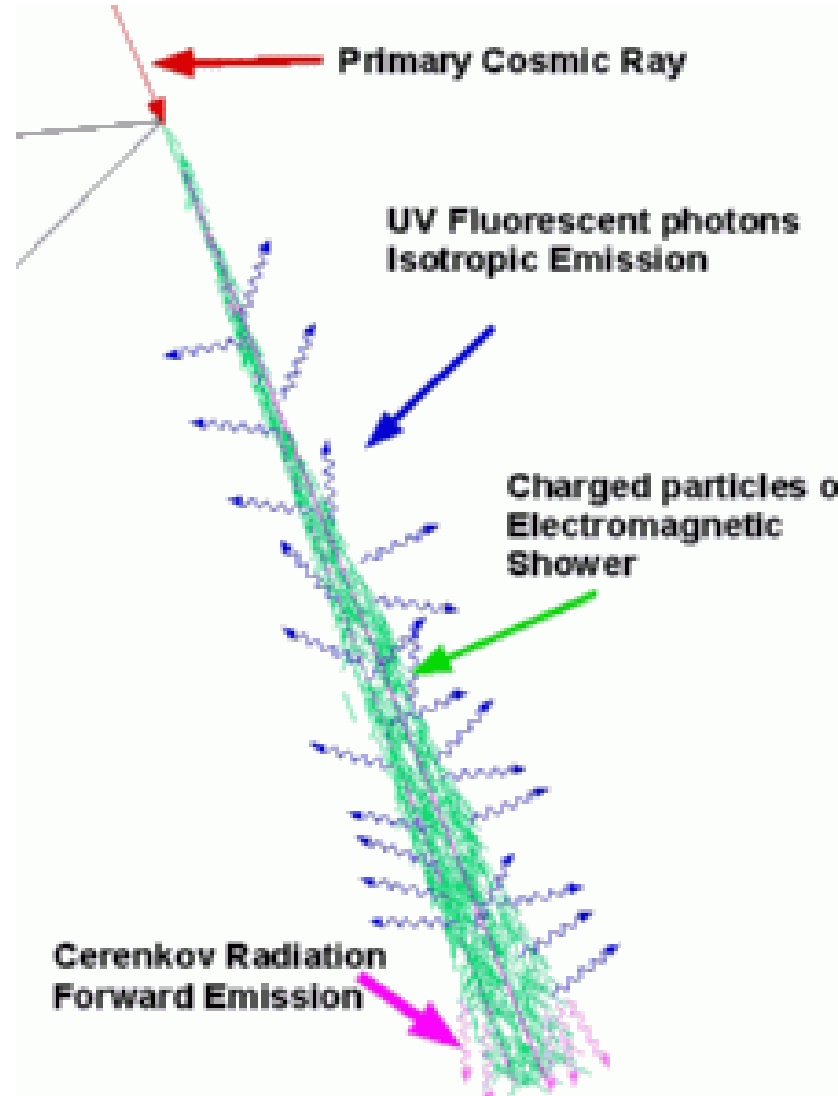
- differential flux: $dN / (dE A \Omega dt)$
- follows roughly E^{-3} power law
- direct observation not possible above ~ 1 PeV
- three established features:
 - ‘knee’ at $\sim 10^{15.5}$ eV
 - ‘second knee’ at $\sim 10^{17.5}$ eV
 - ‘ankle’ at $\sim 10^{18.5}$ eV

Major puzzle before HiRes:

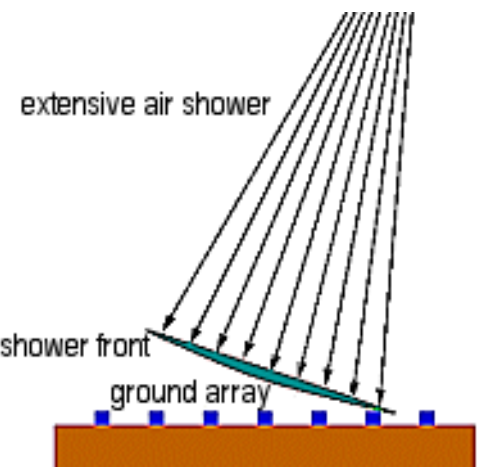
Is there a flux suppression at the highest energies ("GZK cutoff") ?



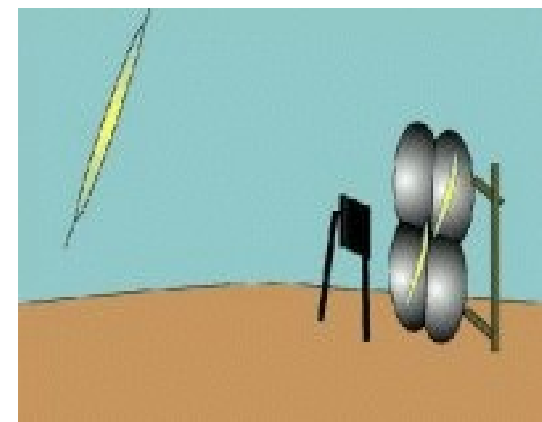
Air Showers & Detection Methods



ground arrays of surface detectors



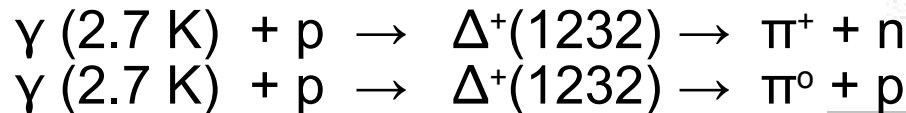
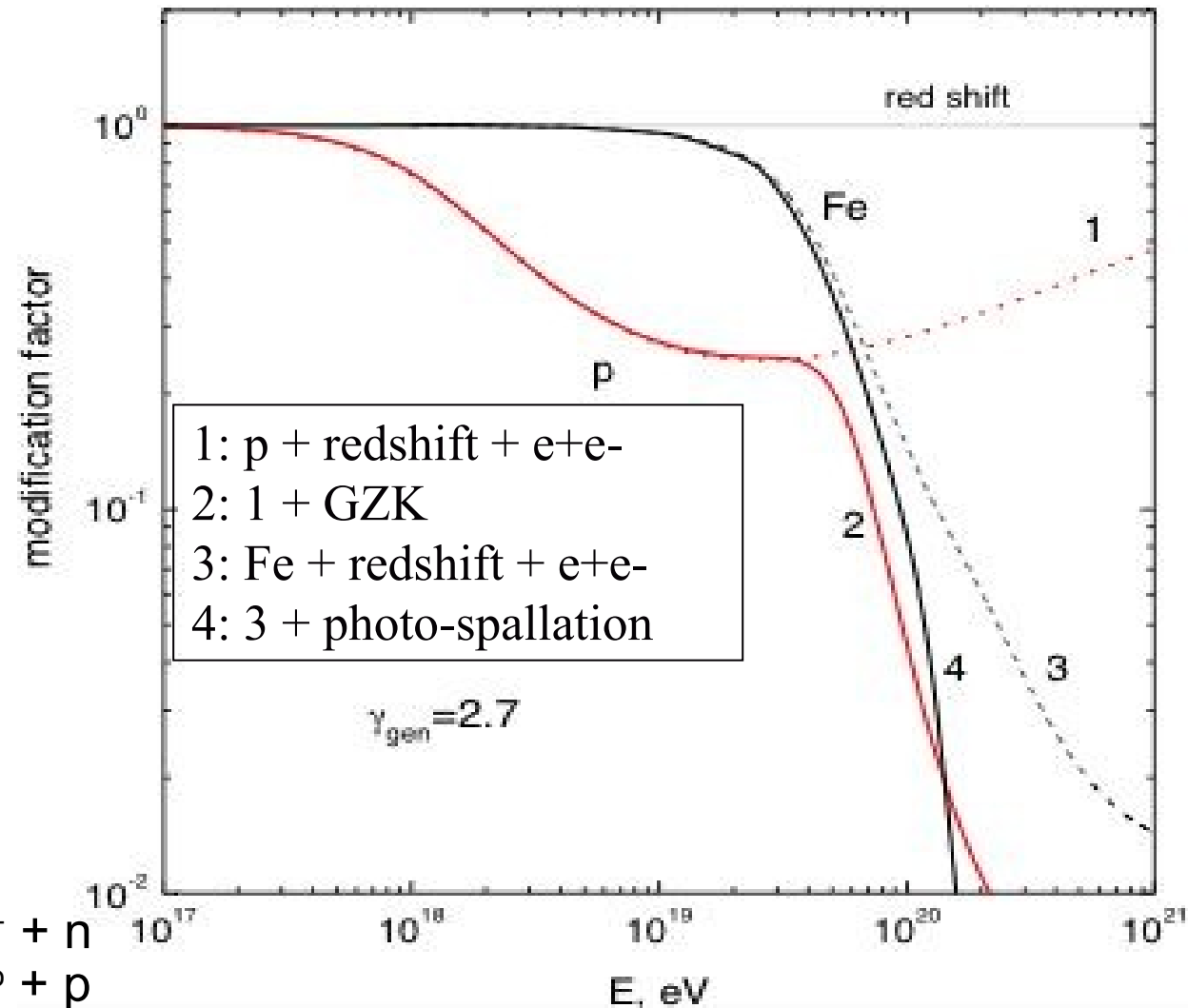
air fluorescence telescopes



- Cherenkov detectors (lower energies, TeV γ -ray detectors)
- radio detection

Propagation & the GZK Effect

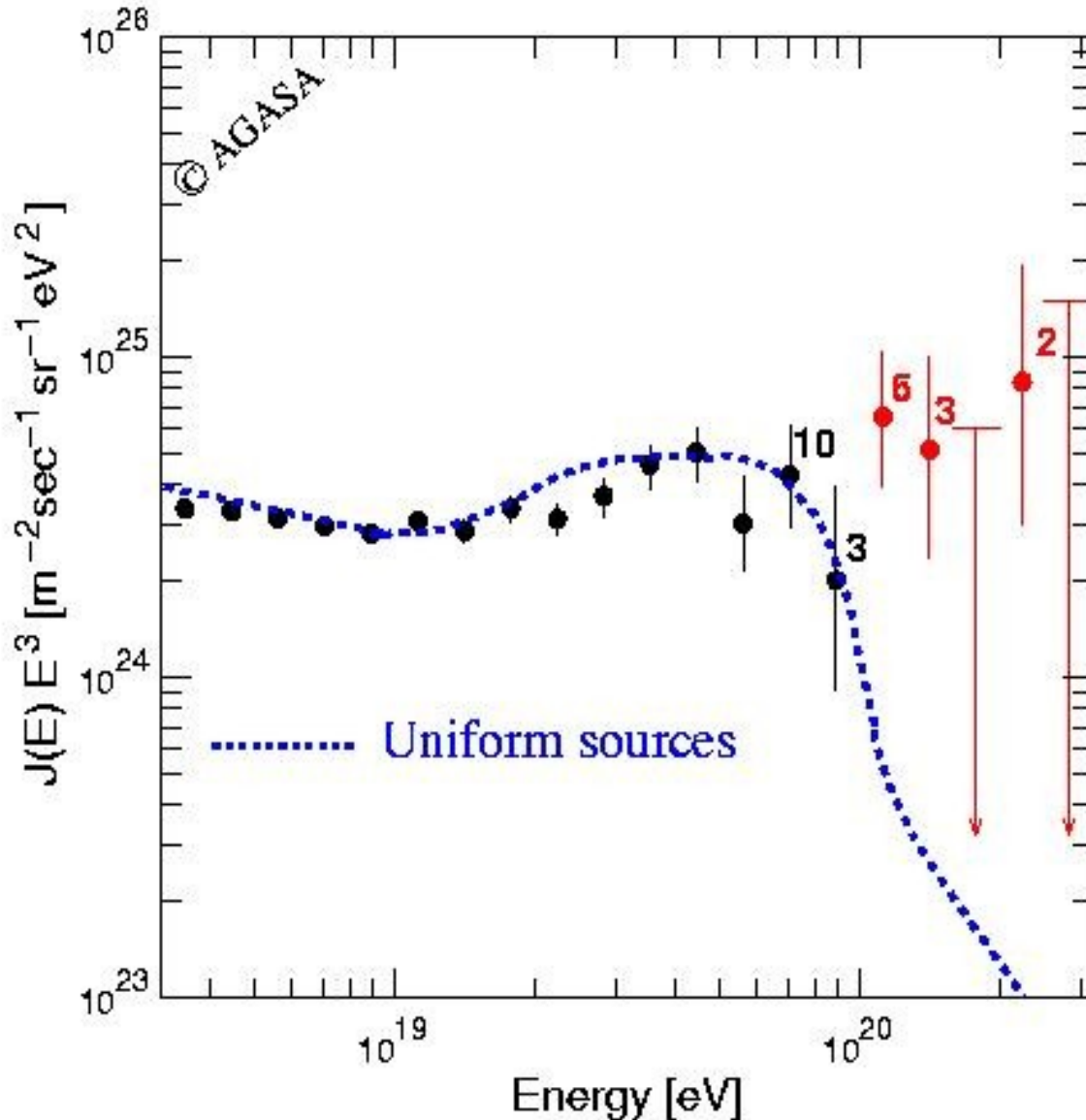
- **magnetic fields** (galactic, extragalactic)
- **adiabatic energy loss** (red-shifting)
- **e⁺e⁻ pair production** with CMBR
- **photo-spallation** of nuclei ($E_{\text{threshold}} \sim \text{atomic number}$)
- **GZK effect** with CMBR (photo pion-production)



Berezinsky et al., Phys. Lett. B 612 (2005) 147-153

=> **Strong flux suppression for extragalactic sources !**

What if there was no GZK Cutoff ?



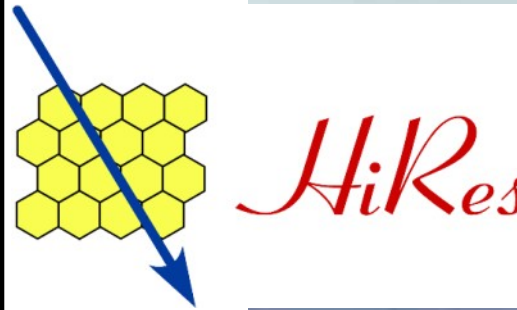
**Either sources are nearby
($< \sim 50$ Mpc) ...**

- should provide clear anisotropies / correlations with sources at the highest energies

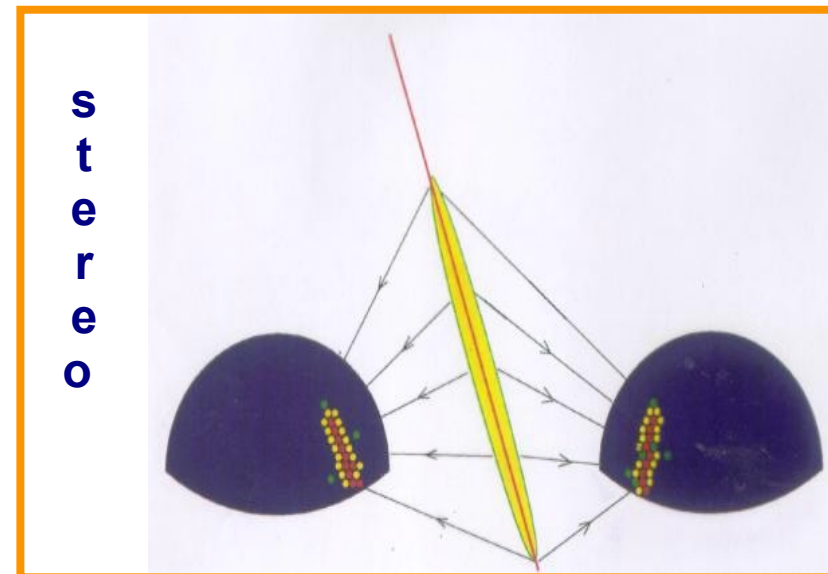
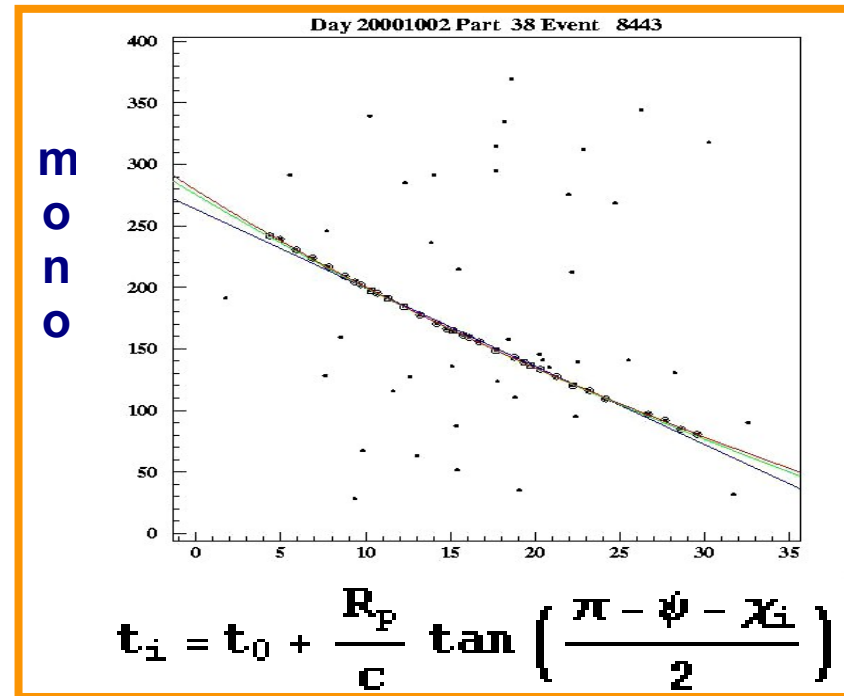
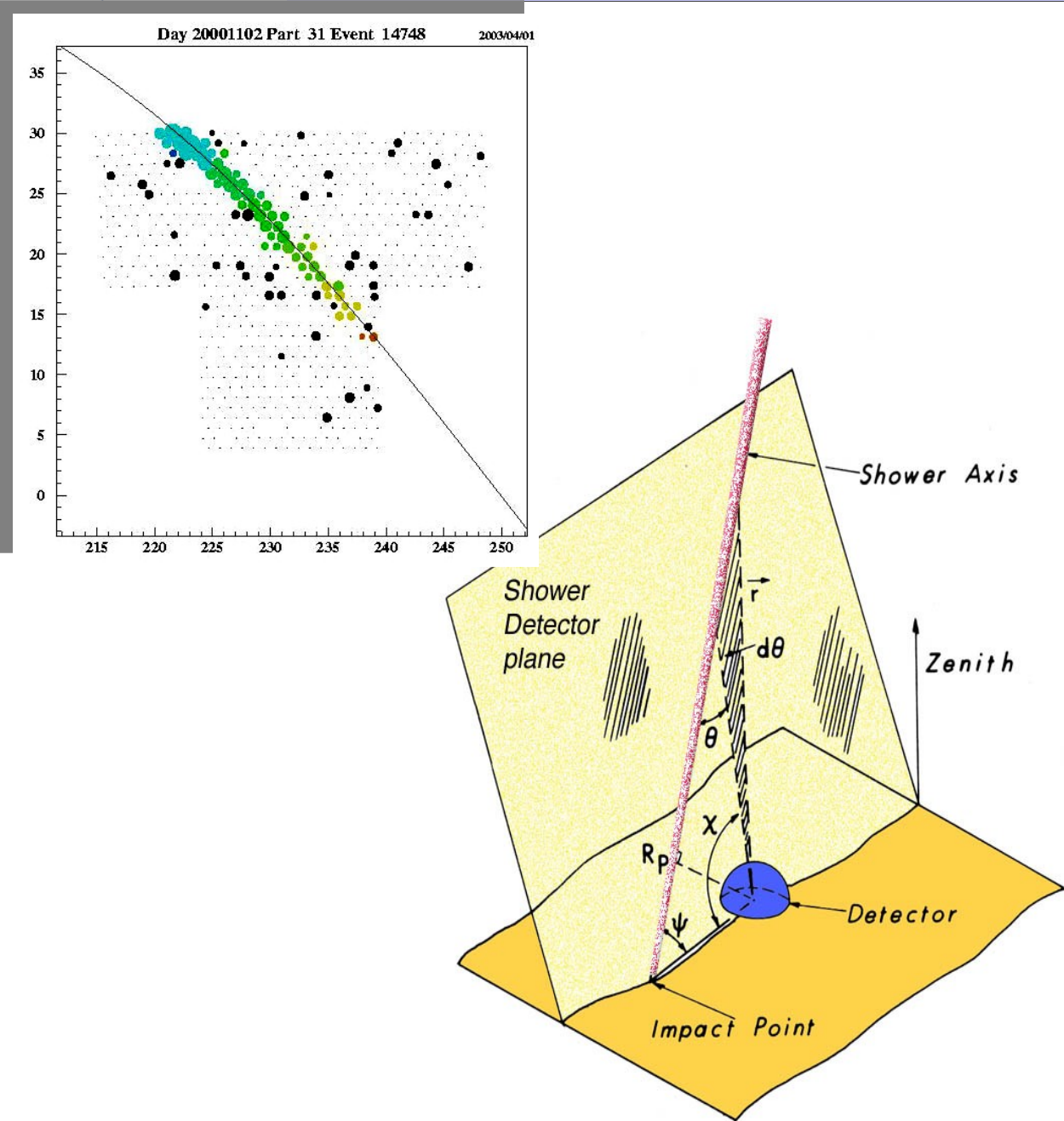
**... Or violation / extension of
standard physics required**

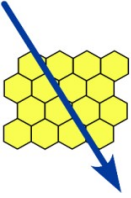
- Top-Down models: should yield a high photon & neutrino flux
- Lorentz invariance violation, etc. ...

What we have learnt from the High Resolution Fly's Eye experiment (*HiRes*)

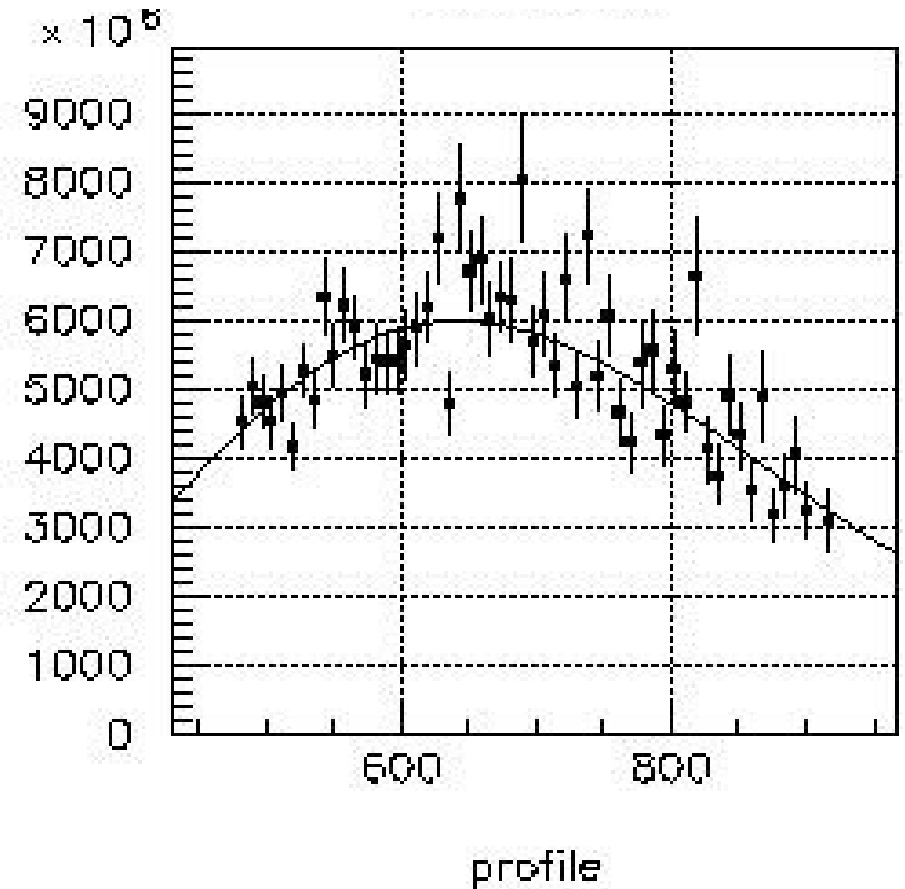
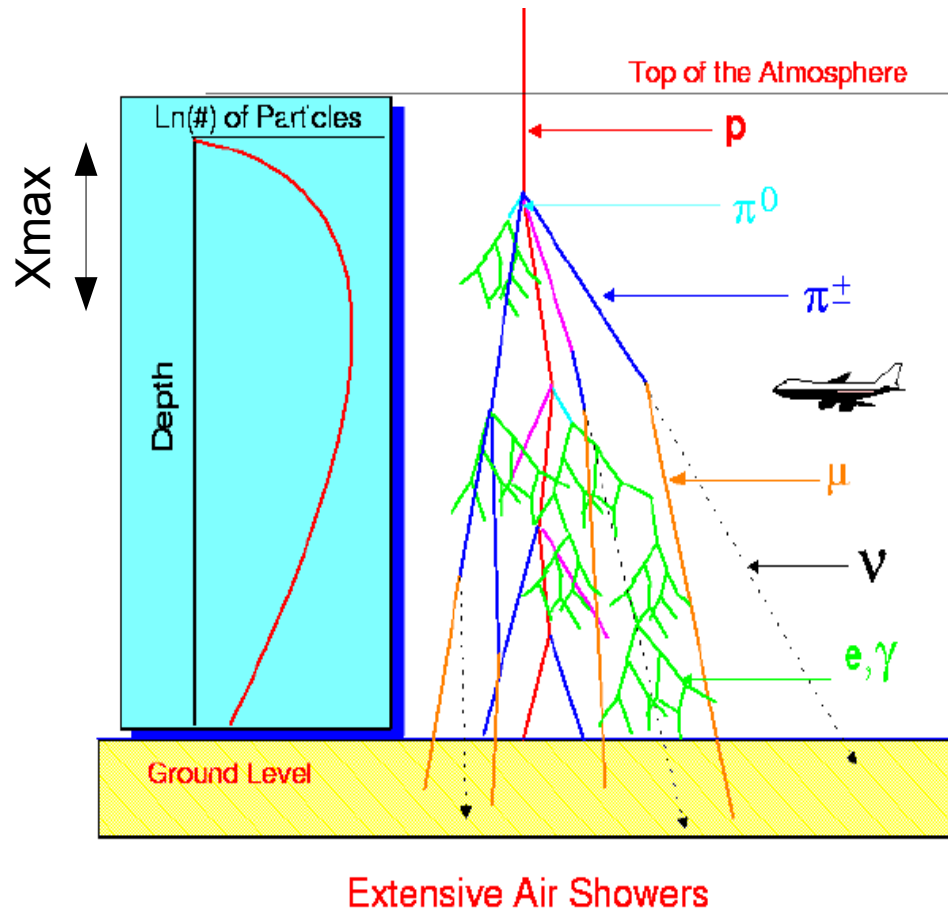


Event Reconstruction - Mono & Stereo





Energy & Xmax Reconstruction



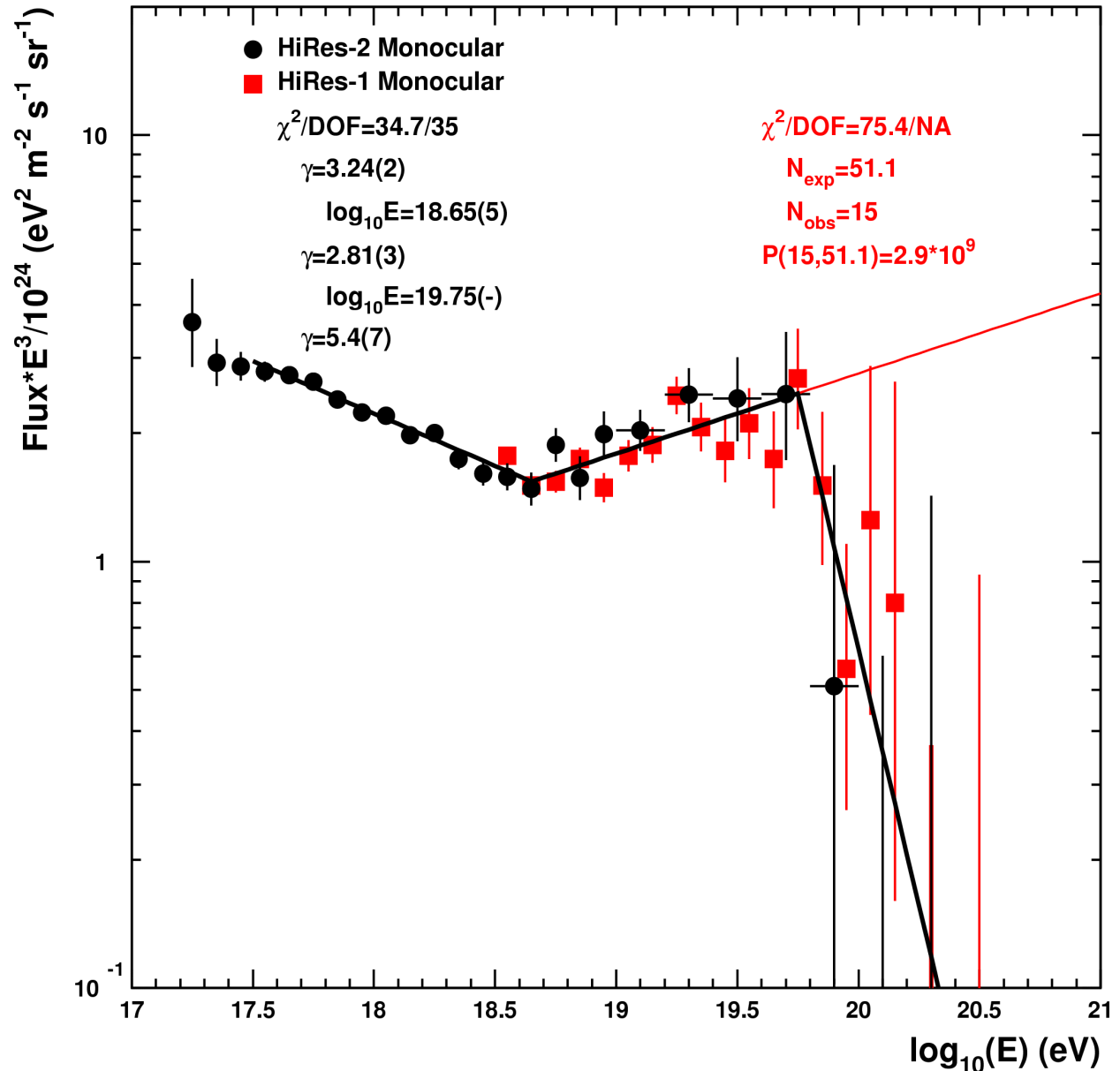
Using the atmosphere as a calorimeter...

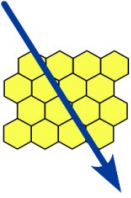
Broken Power Law Fits:

- No Break Point
 - $\chi^2/\text{DOF} = 162/39$
- One BP
 - $\chi^2/\text{DOF} = 62.9/37$
 - BP = 18.65
- Two BP's
 - $\chi^2/\text{DOF} = 39.5/35$
 - 1st BP = 18.65
 - 2nd BP = 19.75
 - χ^2 difference => **4.5 σ**

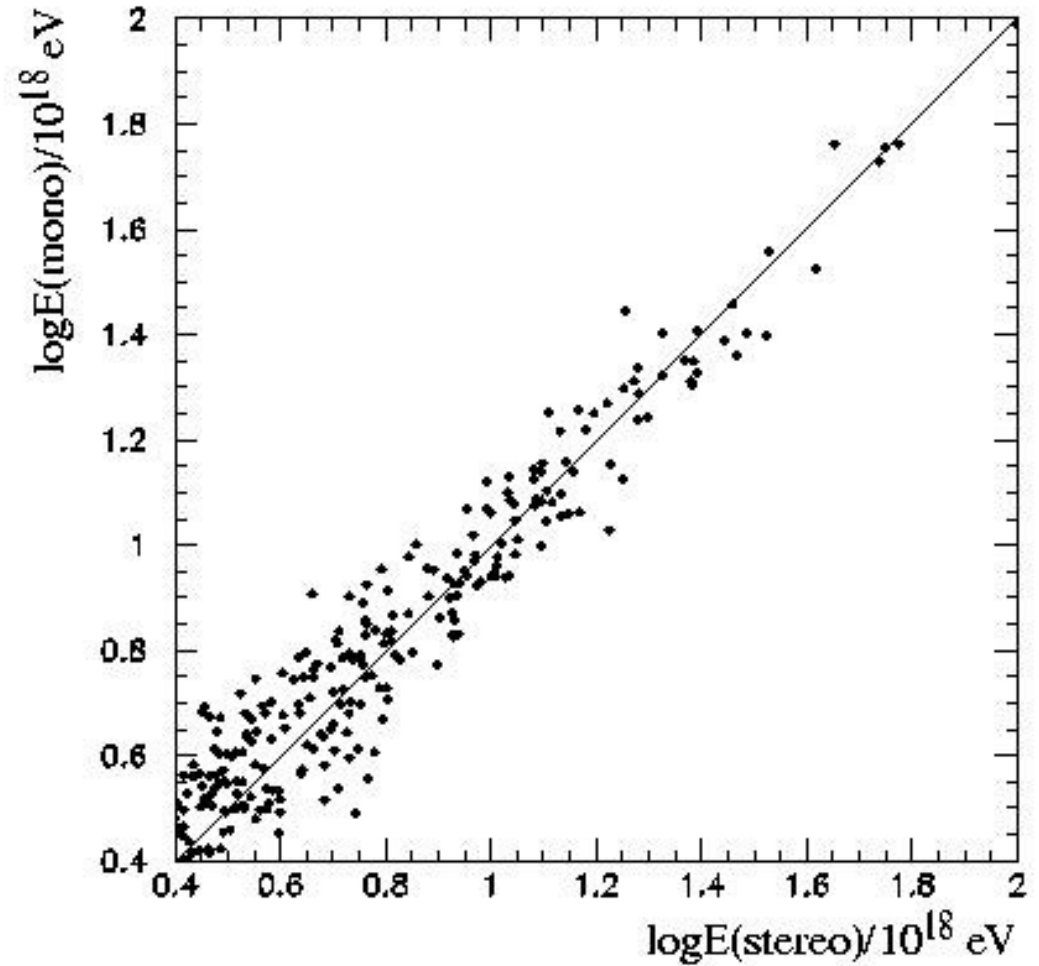
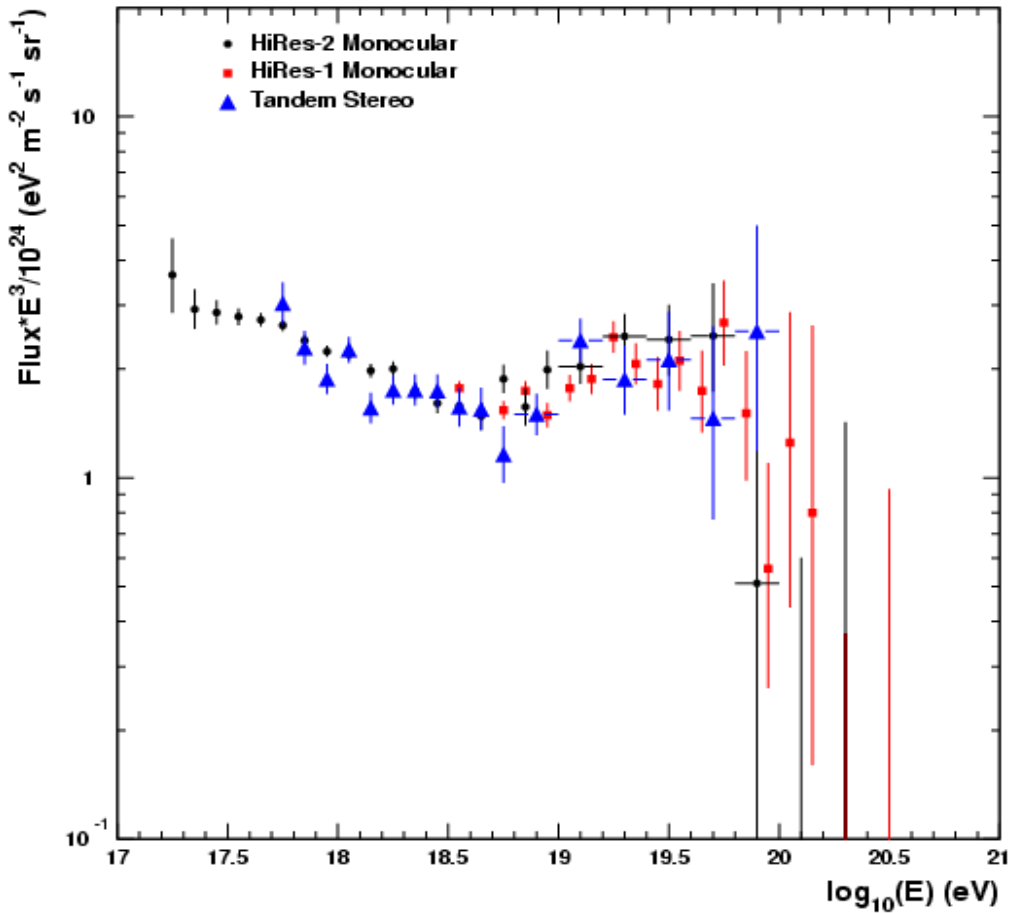
Event Statistics:

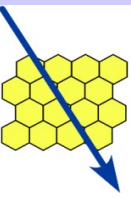
- Expect 39 events
- Observe 13 events
- Poisson probability:
 $P(13,39) = \mathbf{4.8\sigma}$



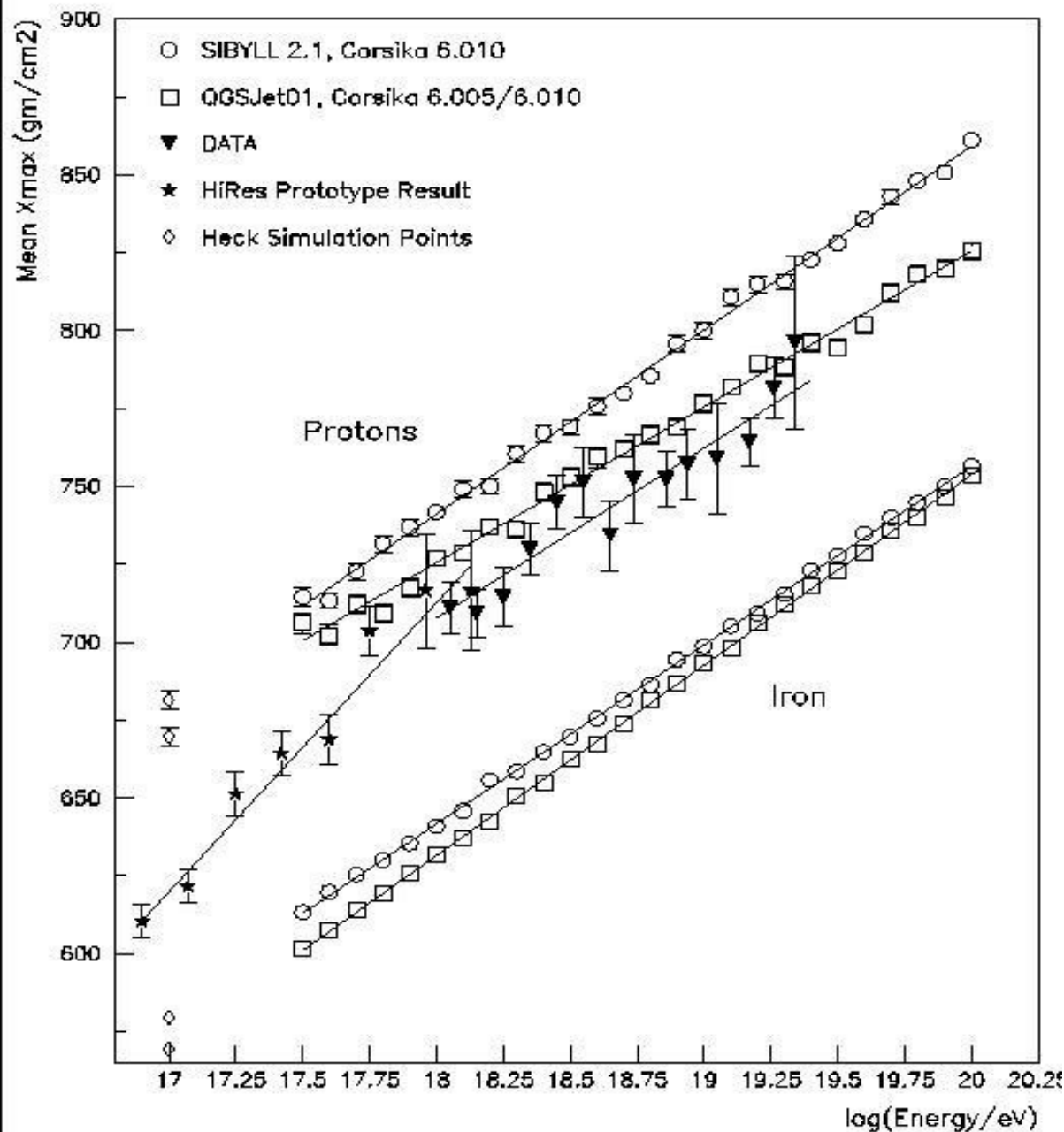


Verification against Stereo





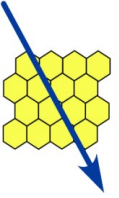
Composition



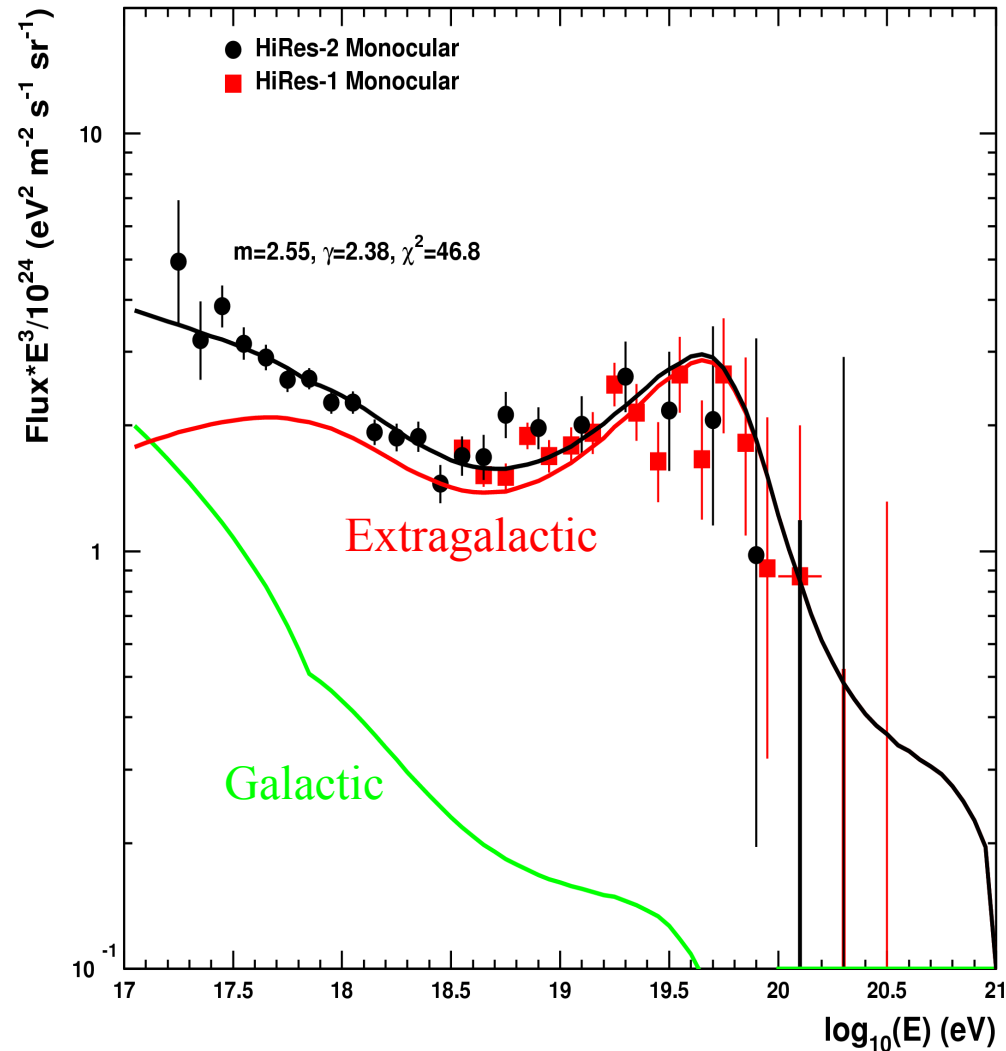
Measurements use X_{max} indicator

- HiRes/MIA (stars):
 - hybrid detector
 - $10^{17} - 10^{18}$ eV
 - resolution ~ 44 g/cm^2
 - => transition heavy \rightarrow light
- HiRes Stereo (triangles):
 - $> 10^{18}$ eV
 - resolution ~ 30 g/cm^2
 - => predominantly light

Higher precision measurements are needed !



Interpretation of the Spectrum



Fit to the HiRes spectrum:

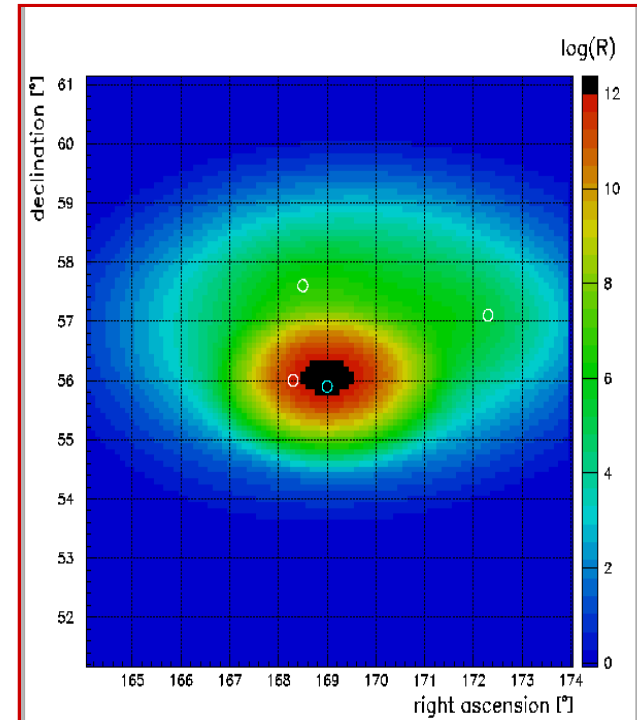
- Float normalization, input spectral slope (γ) and m
- uniform source density evolving with $(1+z)^m$
- Extragalactic component
 - 45% protons at 10^{17} eV
 - 80% protons at $10^{17.85}$ eV
 - 100% protons at 10^{20} eV
- binned maximum likelihood method

Interpretation:

- > flux suppression from "GZK cutoff"
- > "ankle" from e^+e^- pair production
- > galactic / extragalactic transition complete below the "ankle"
(motivated by composition data !)

Searches for BL Lac Correlations:

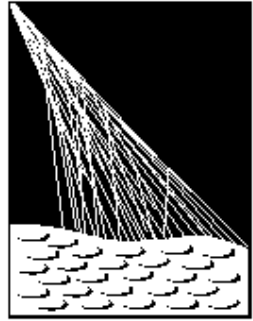
- Correlations with BL Lacs found individually in AGASA, Yakutsk, and HiRes stereo data, by *P. Tinyakov, I. Tkachev, D. Gorbunov, S. Troitsky et al.*
- HiRes stereo result ($E > 10 \text{ EeV}$):
 - BL with $m < 18$: 10^{-4} chance probability.
 - Add HP sources: 10^{-5} chance probability.
- Correlation at the scale of the $\sim 0.5^\circ$ resolution of HiRes
 - > no magnetic deflections ?
 - > neutral particles ?
- **Could not be confirmed with independent HiRes data.**



Correlation with AGASA cluster ?

- Max likelihood search in AGASA + HiRes data sets yields one possible joint source: the AGASA triplet + one HiRes event.
- **Statistical significance is not clear.**

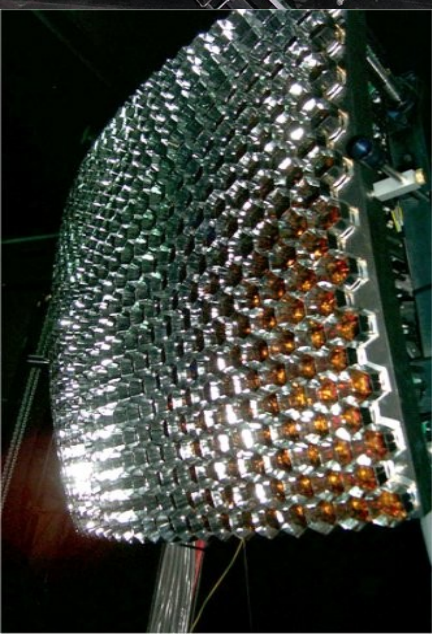
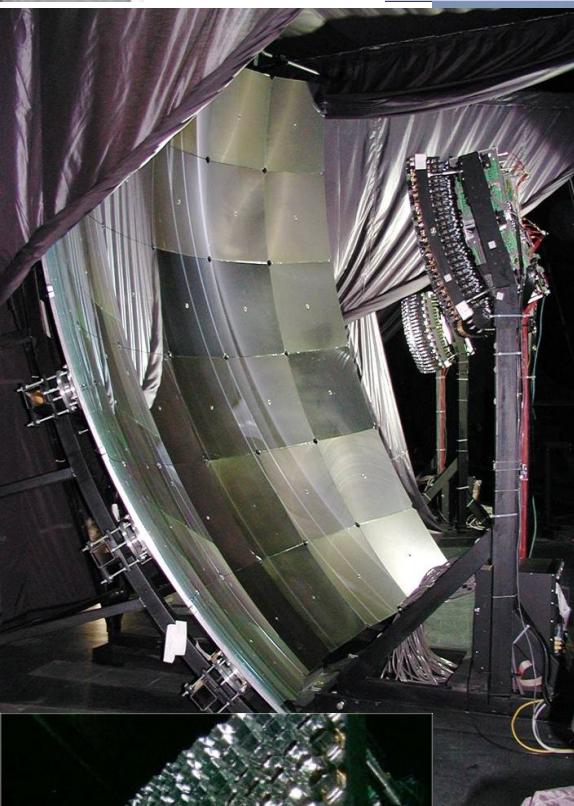
What we have learnt (so far) from the Pierre Auger Observatory (*Auger*)



**PIERRE
AUGER**
OBSERVATORY



Hybrid Detection

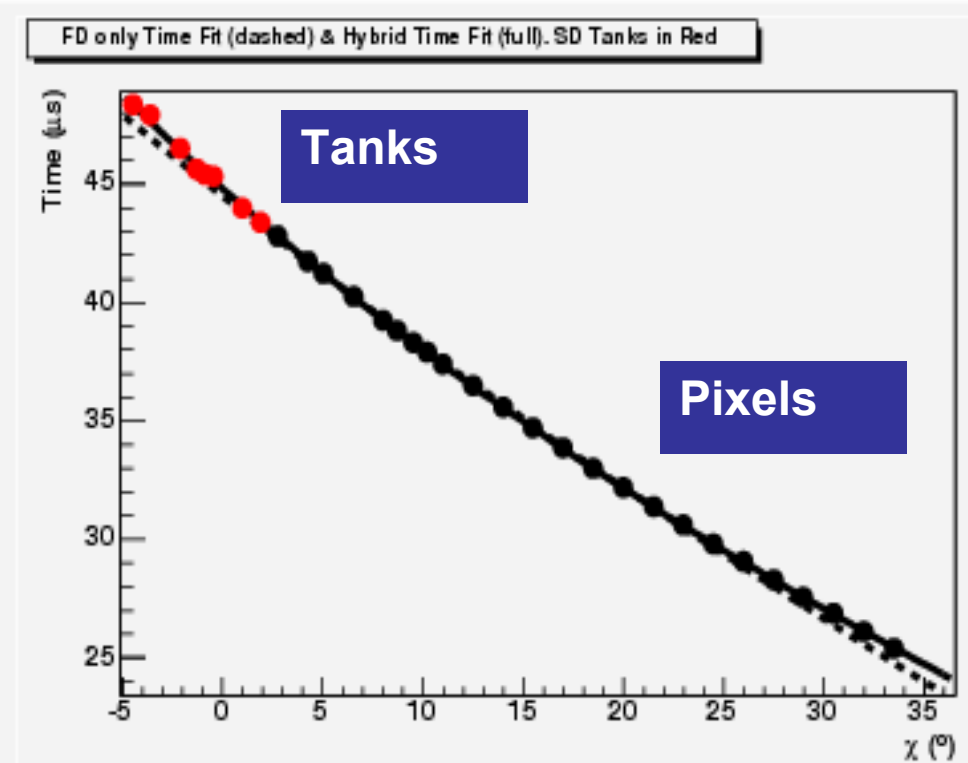
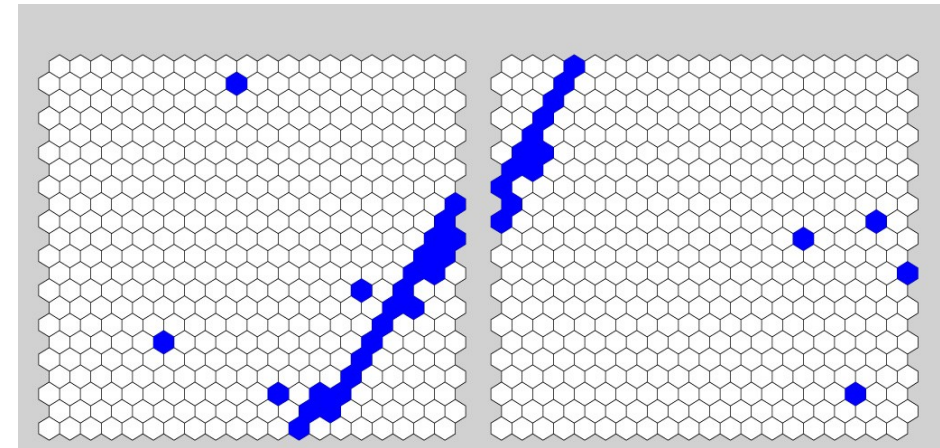
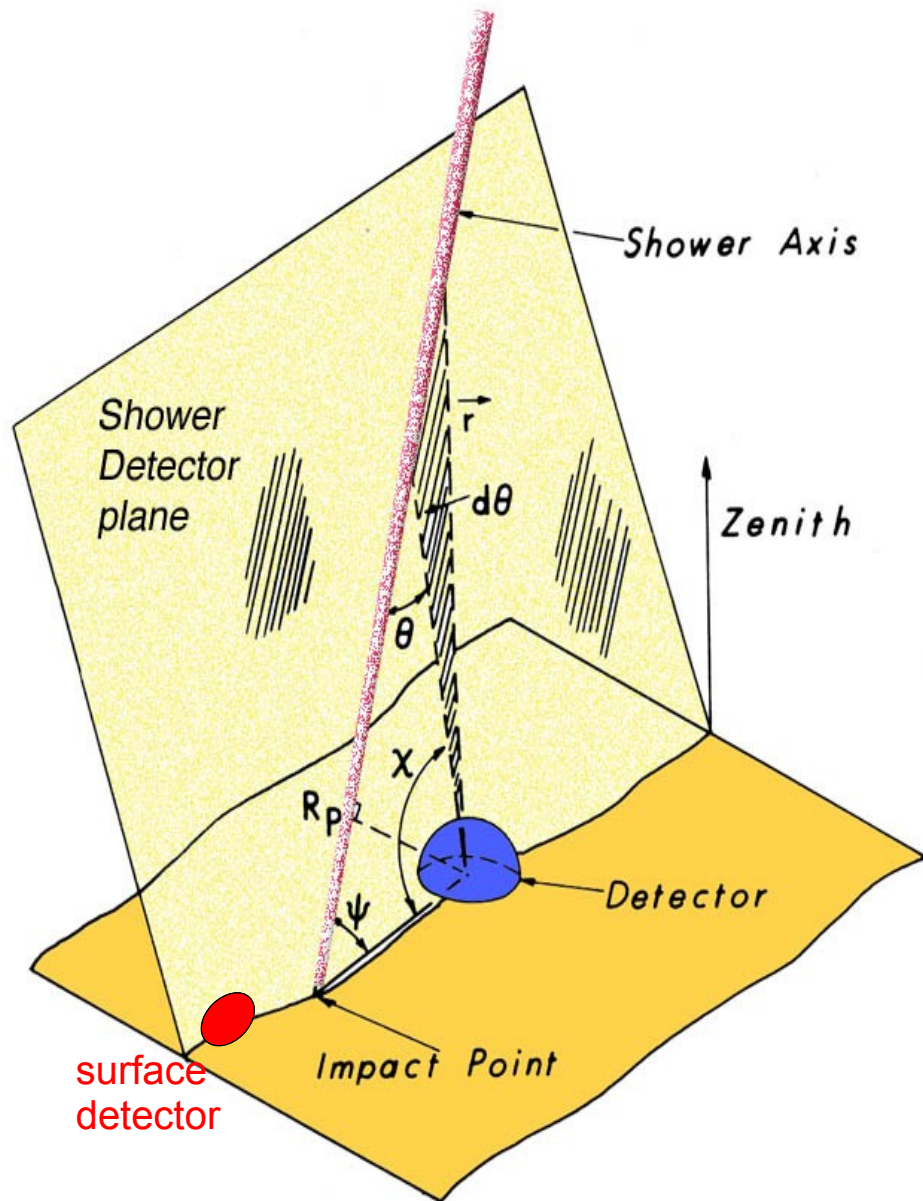




AUGER SOUTH

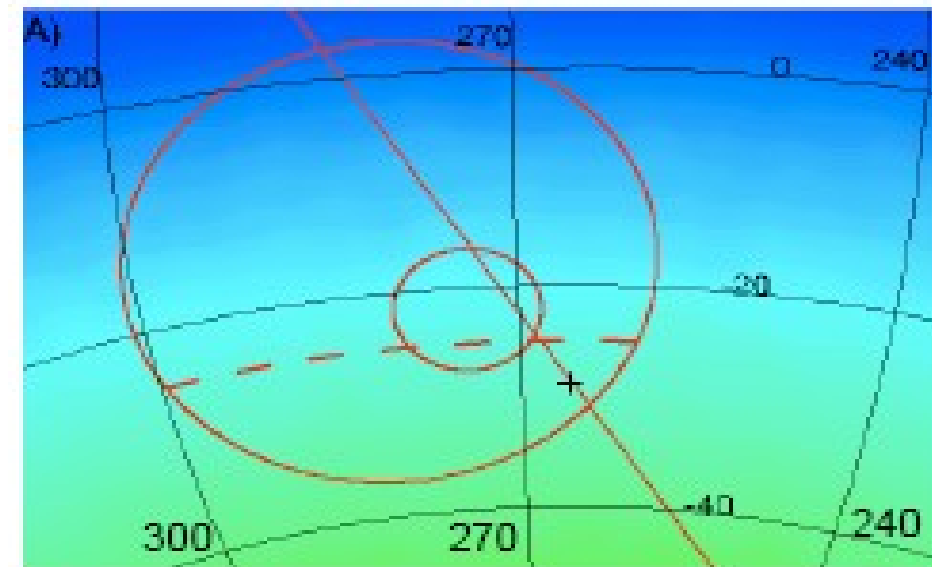
- Located in Argentina, Mendoza
- Layout: 1600 water Cherenkov tanks + 4 x 6 Air fluorescence telescopes
- Spacing of tanks: 1.5 km
=> 100% efficiency above $10^{18.5}$ eV
- 3/4 of SD stations are running, 4 FD stations up and running.
- Completion expected this year

Hybrid Geometry Reconstruction

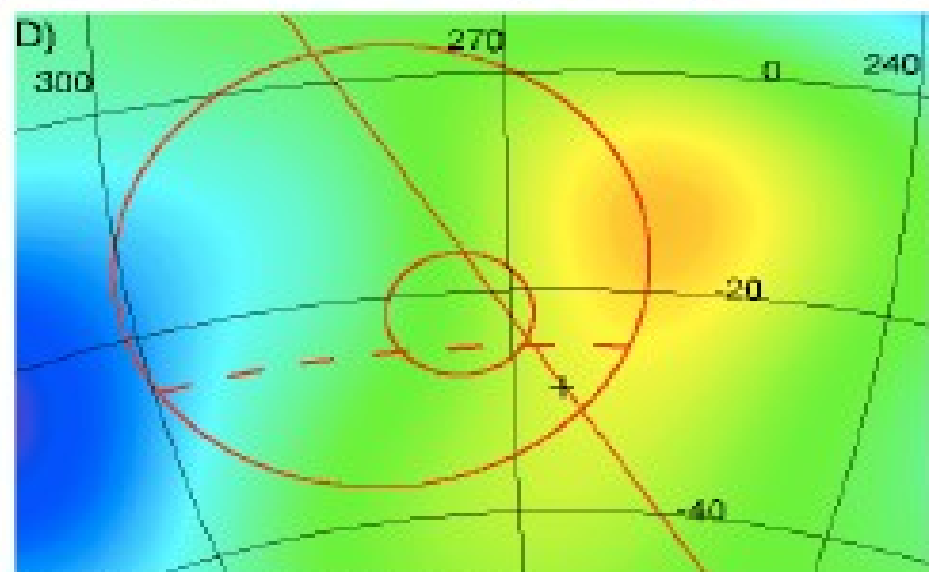
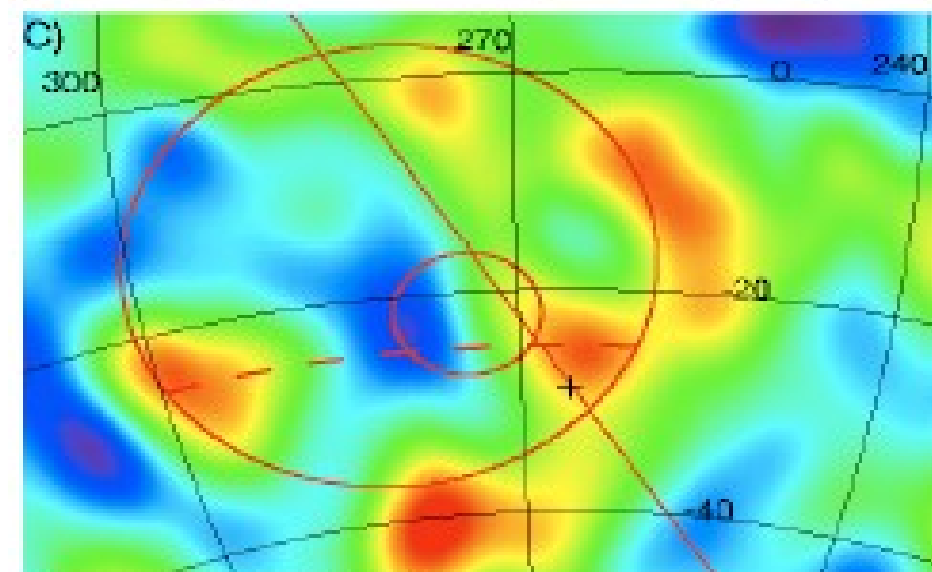
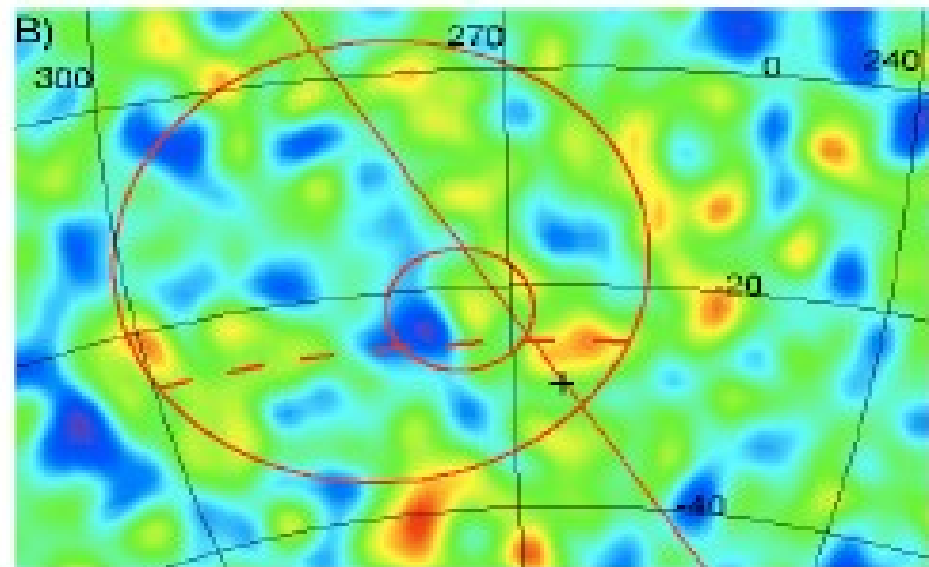


Galactic Anisotropy Searches

Coverage



Significance (1.5°)



Significance (3.7°)

Significance (13.3°)



Summary: anisotropy searches

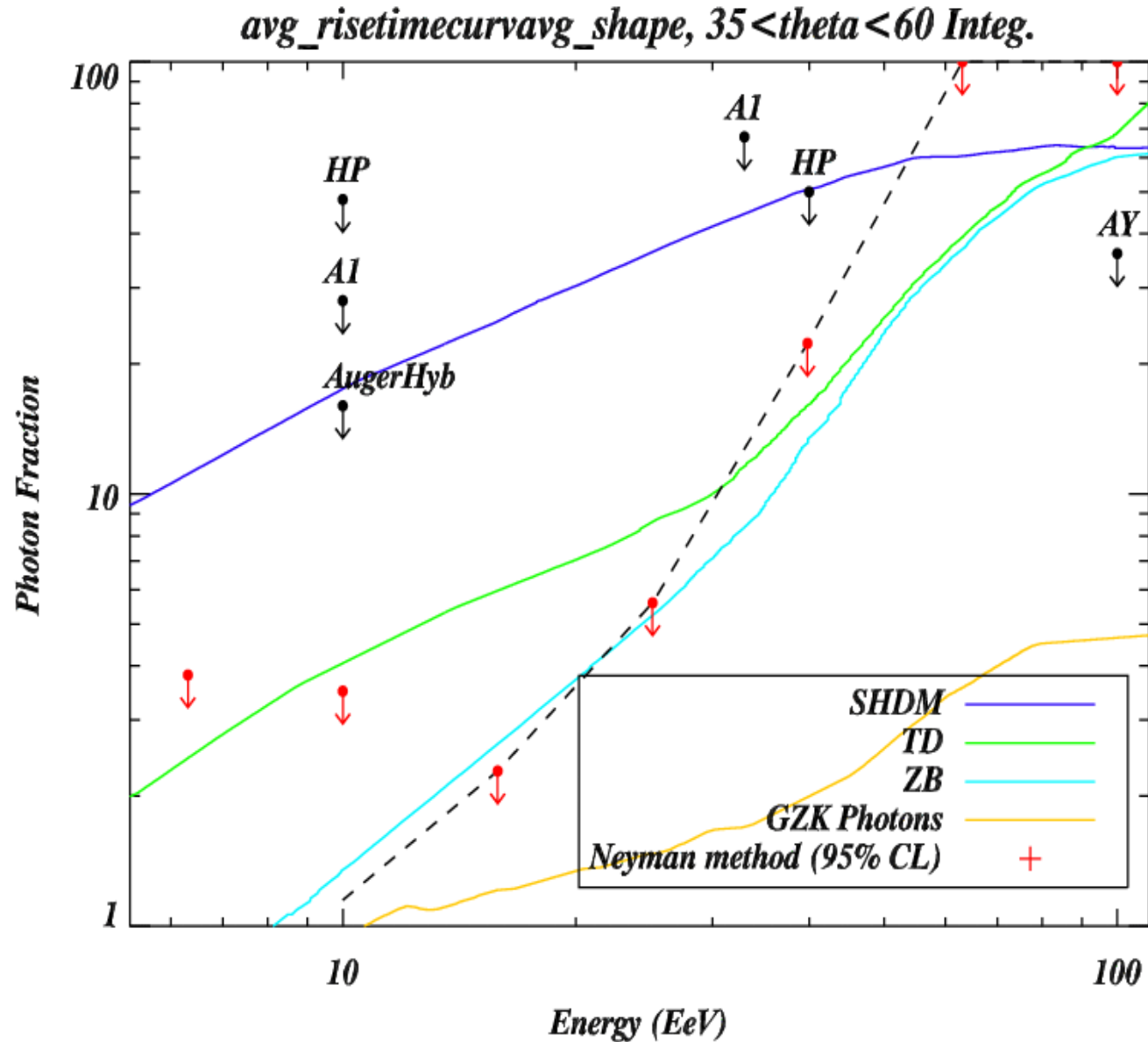
- Auger data **do not support** the claims for anisotropies towards the galactic center (AGASA, SUGAR).
Auger has already > 4 x AGASA statistics and > 10 x SUGAR statistics in this field of view.
- Point source searches towards the Galactic Center find **no excesses**. The same is true for searches towards the Galactic Plane and Supergalactic Plane.

VERY PRELIMINARY:

- Correlations with BL Lacs at energies > 10 EeV **are not supported** by the Auger data.
(**caveat:** there are significantly less BL Lacs in the southern hemisphere)



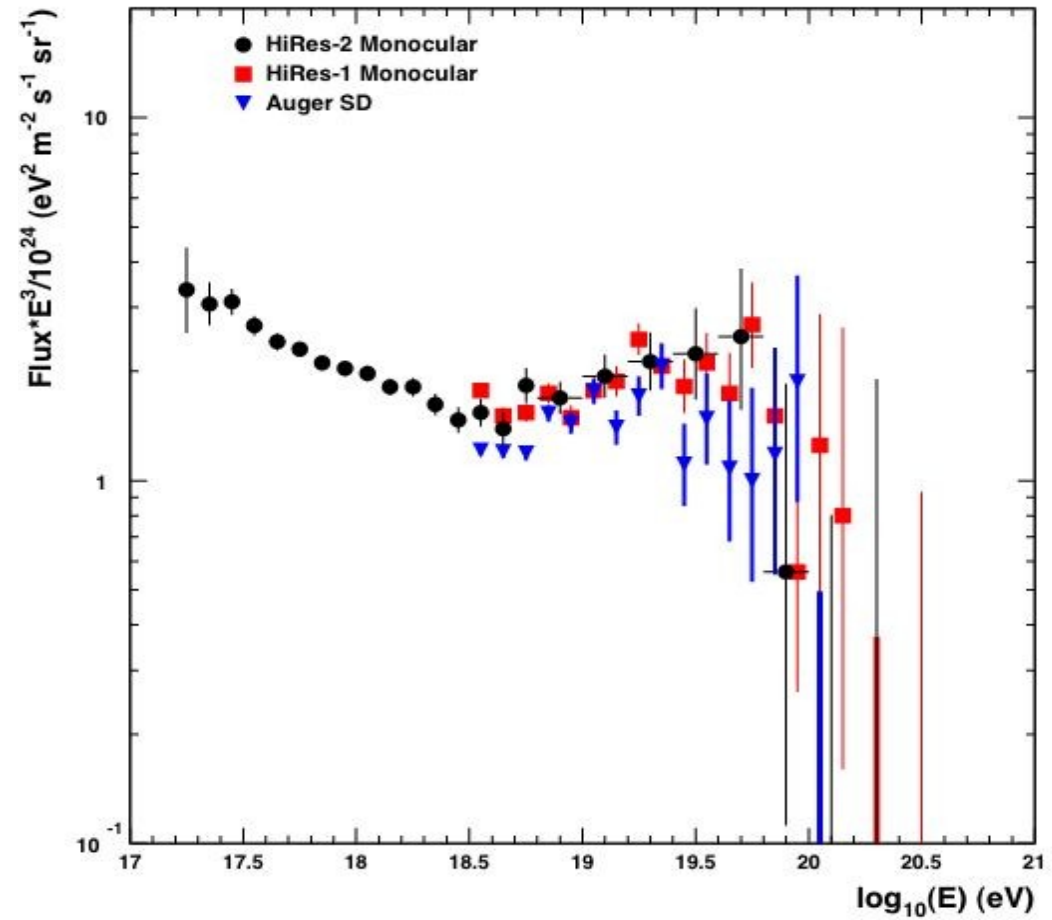
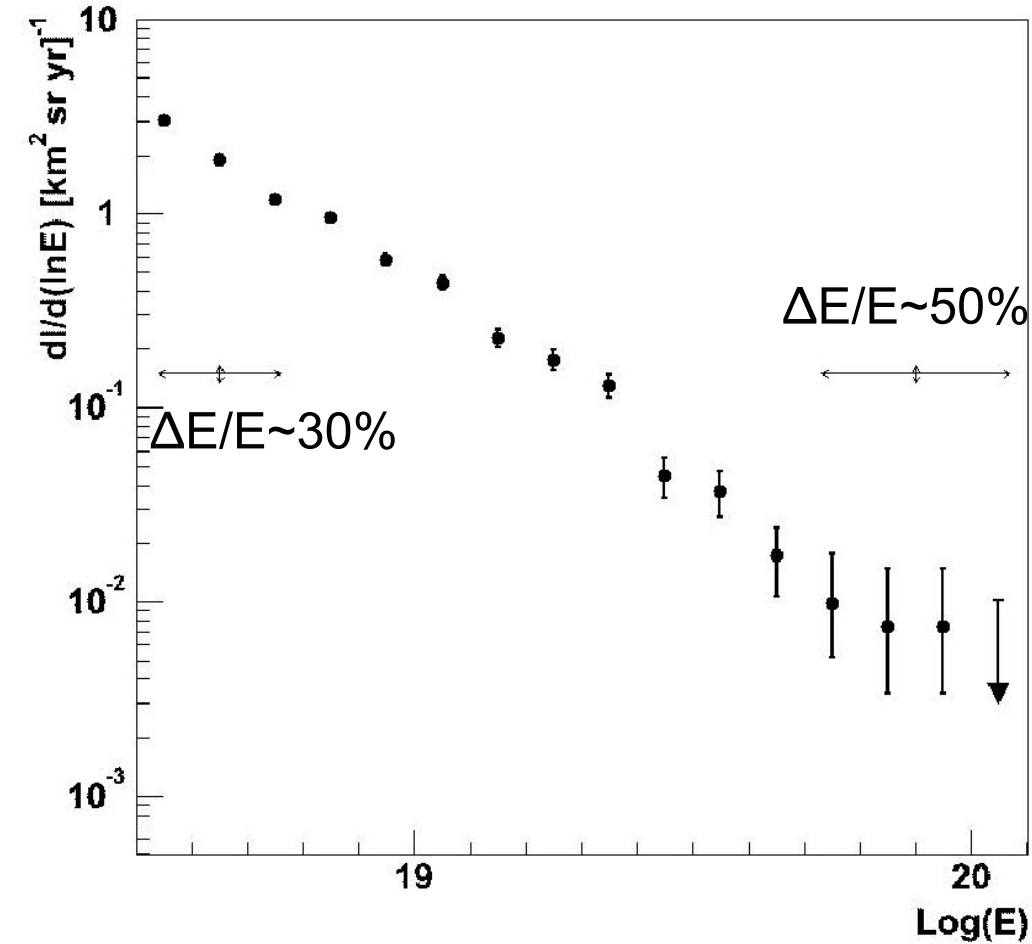
Photon Fraction Limit



Cecile Roucelle, Ph.D. thesis, 2006

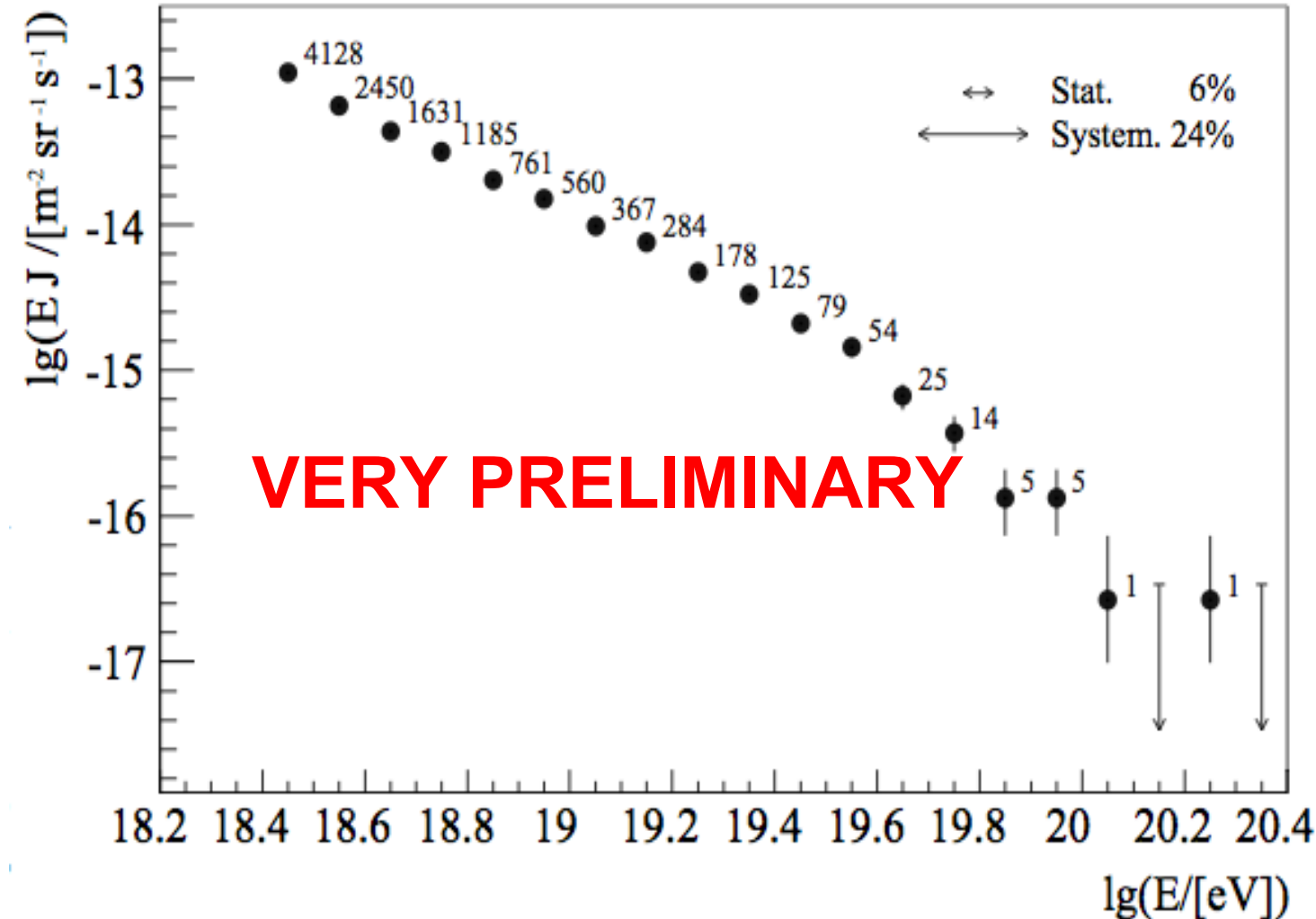


Spectrum (2005)



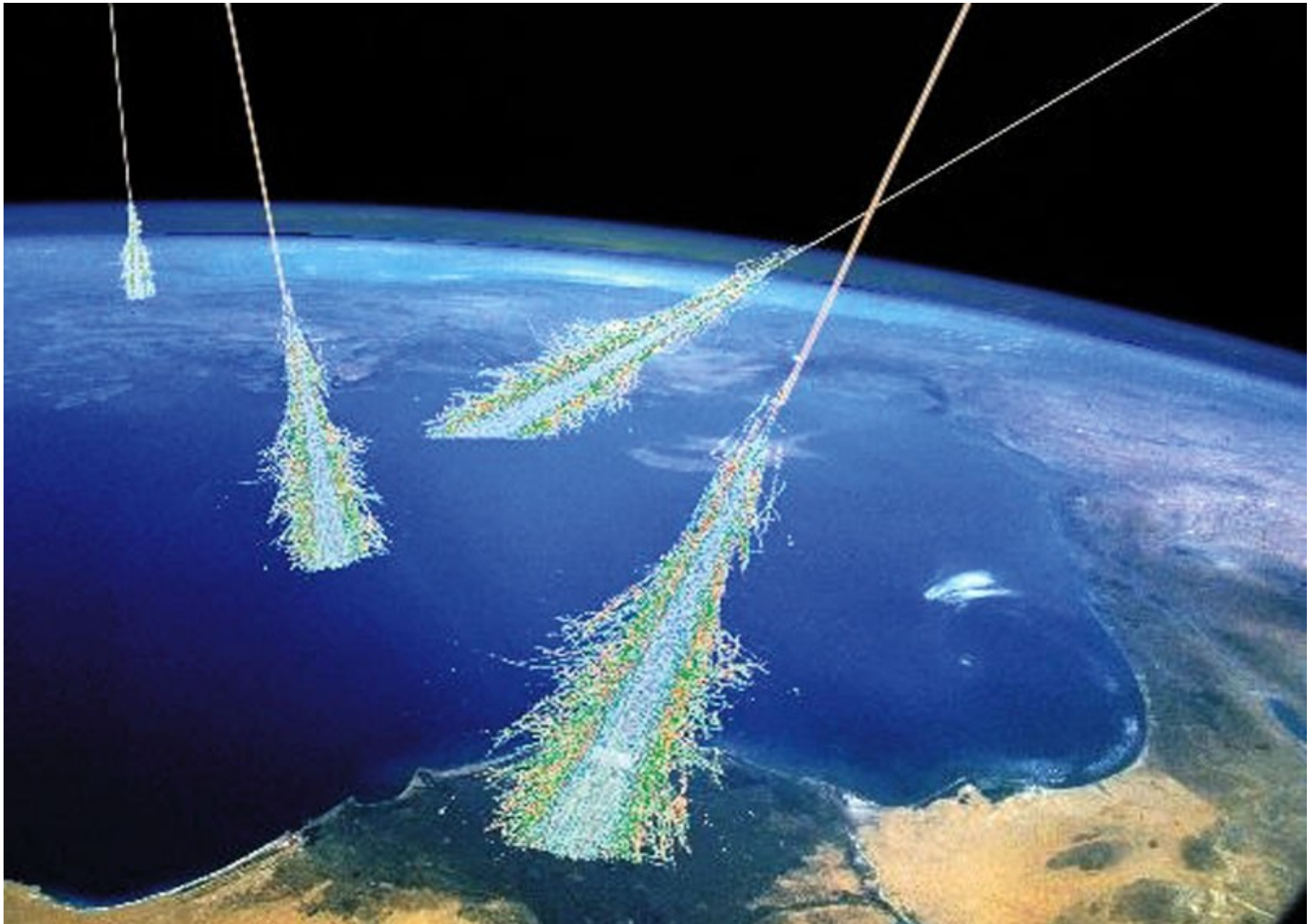


Preliminary Spectrum (2007)



- surface detector data from Jan 1 '04 - Feb 28 '07
 - > 3 x more statistics than in the 2005 spectrum
 - > 2.5 x AGASA exposure
 - ~ 12 000 events
 - systematic uncertainty in energy ~ 24%
- => seems not consistent with a simple continuation of the spectrum above the expected GZK threshold**

What's Next ?



© NASA

May 17th, 2007

A. Zech - Ecole Chalonge - Paris

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Observations on Ground

Telescope Array (TA / TALE)

first data expected soon

Auger South "Enhancements" & Radio

R & D in progress

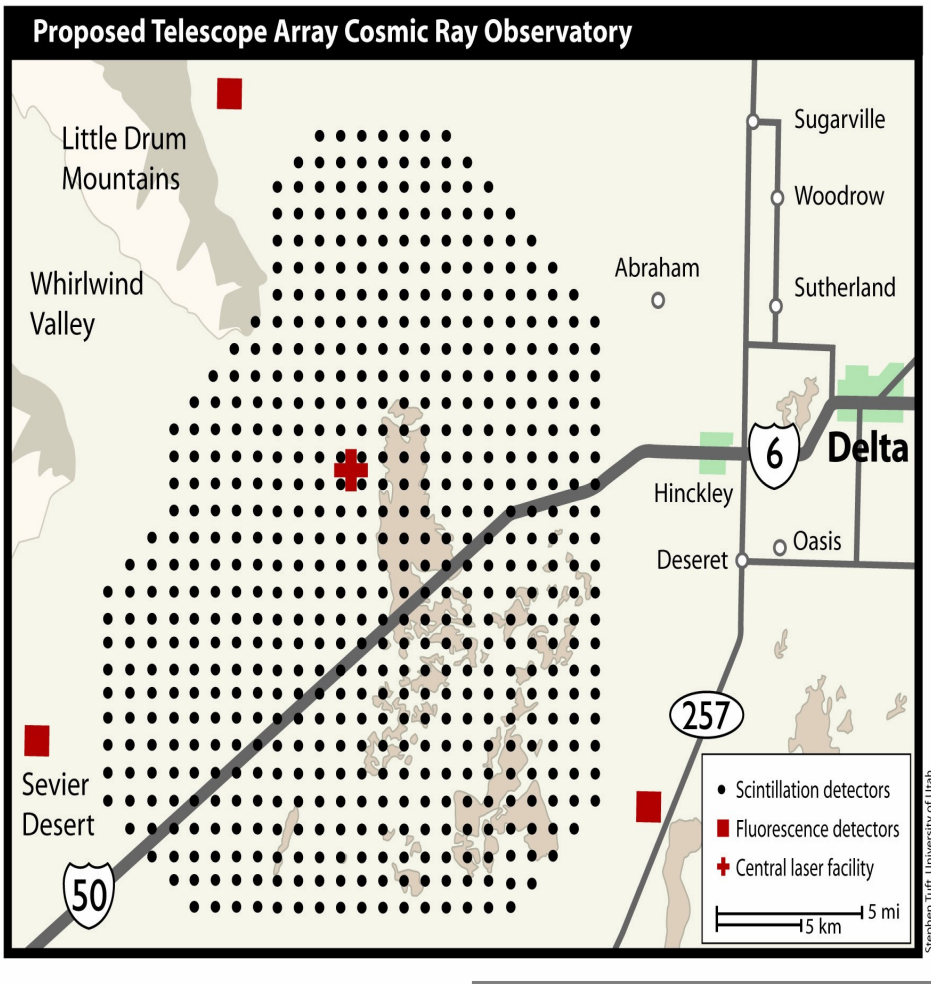
Auger North

site selected in Colorado

TeV gamma-rays:

Cherenkov Telescope Array (CTA)

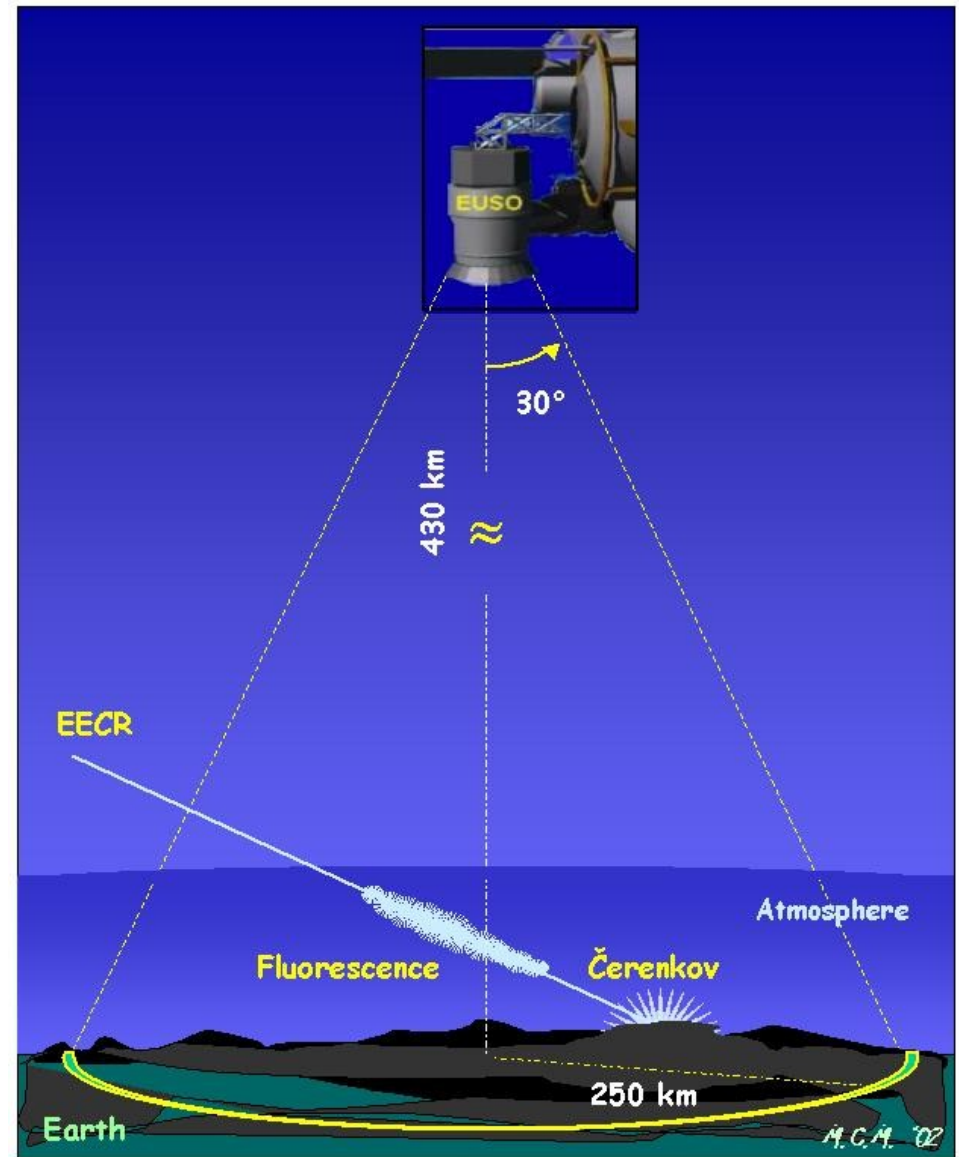
proposal submitted for desing study
in FP7 framework



Observation from Space

EUSO

- air fluorescence detector for ISS
- study of UHECR above 10^{19} eV
- observation of high energy neutrinos
- expected aperture: 6×10^5 km² sr
- successfully concluded ESA phase A study in 2004, but was then "put on ice"
- another initiative: proposal for ESA "Cosmic Vision 2015-2025"
- latest news: JEM/EUSO collaboration with Japan. Launch might be as early as 2012.



Conclusions

- HiRes has observed the GZK cutoff.
This result gets support from the latest Auger data.
- Top-Down models seem disfavored by the observation of the GZK cutoff and by the Auger photon fraction limits.
- There is no clear evidence for anisotropies at EeV energies.
- Our best assumptions on galactic sources are based on indirect evidence from TeV gamma rays (->e.g. *HESS*).
- Clear correlations with extragalactic sources have not yet been found.

More information

www.cosmic-ray.org (HiRes)

www.auger.org

www.augernorth.org

www.telescopearray.org

www.euso-mission.org

www.mpi-hd.mpg.de/hfm/CTA/CTA_home.html

