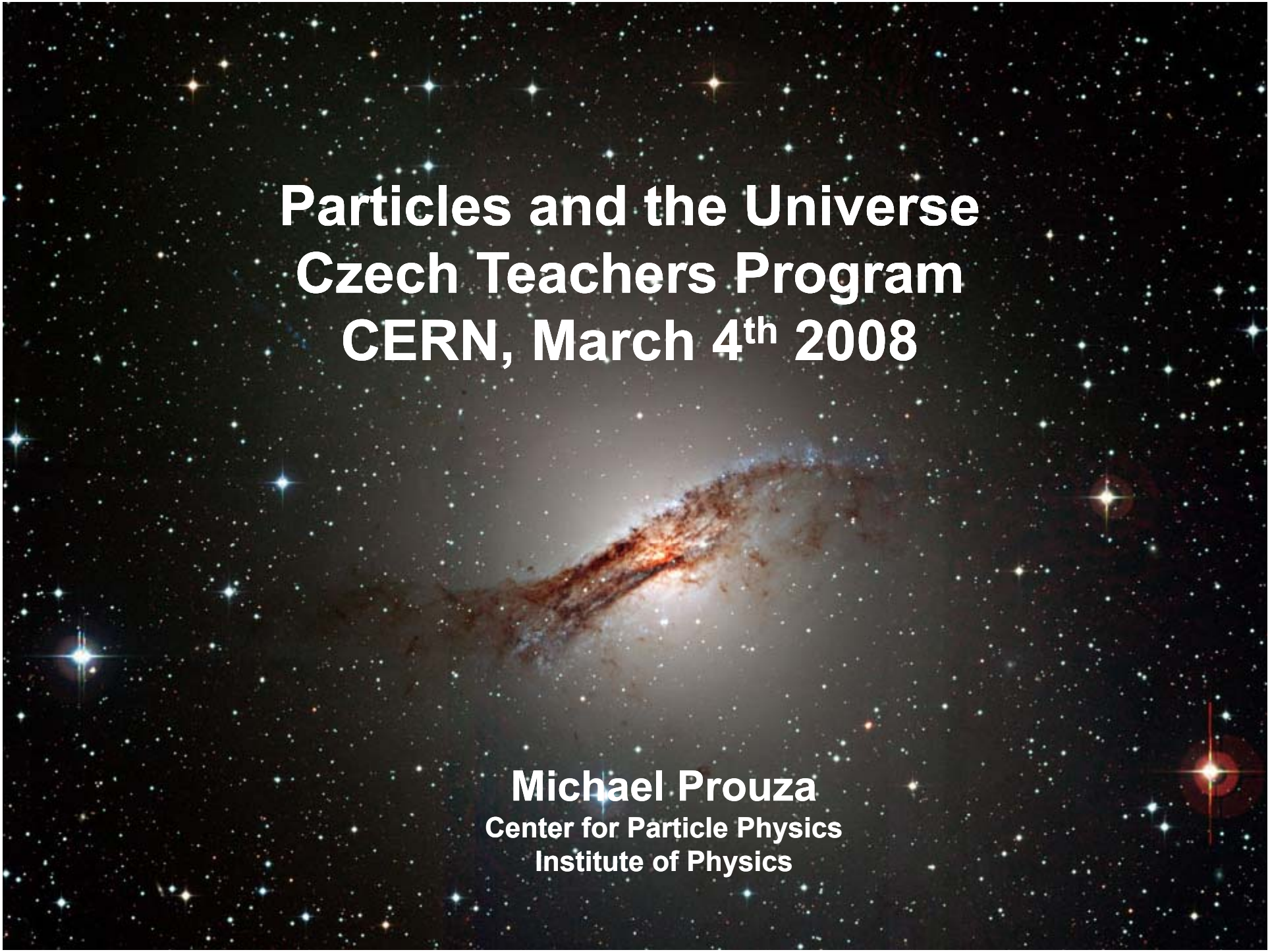


# Particles and the Universe
# Czech Teachers Program
# CERN, March 4th 2008

**Michael Prouza**
Center for Particle Physics
Institute of Physics

# Astroparticle physics

- (still) new and emerging scientific branch
- synergy between particle physics and astrophysics

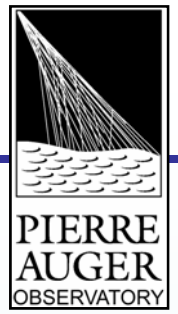
- Cosmic rays
- Gamma rays
- Neutrinos

(• Gravitational waves, Dark matter detection, Antimatter, etc.)

(• Both ground & space-borne detectors)

# Outline – talk I: Cosmic rays

- History
- Previous experiments
  - AGASA vs. HiRes contradiction
- Physics background
  - GZK cutoff
  - Magnetic fields
- Pierre Auger Observatory
- New results
  - Anisotropy
  - Spectrum
  - Composition
  - Photon limit, neutrino limit
  - Hadronic models




*"Astrophysics in the 21st century will mainly concentrate on two fundamental problems. The first problem is something we would like to see, but we don't see. This something is dark matter. And the second problem is something we don't want to see, but we unfortunately observe. In this second case I mean ultra-high energy cosmic rays."*

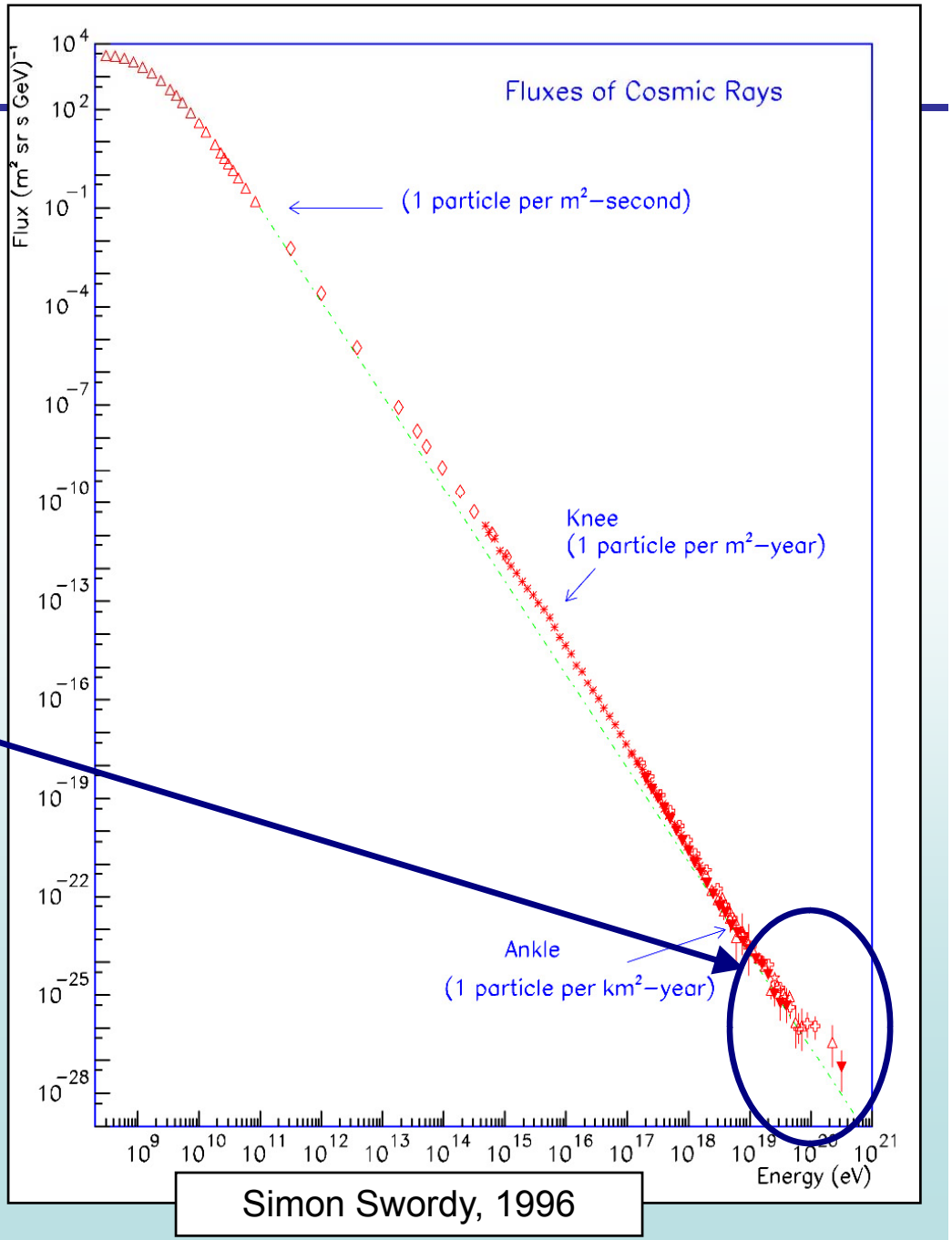
David N. Schramm

PIERRE AUGER OBSERVATORY

# What are ultra-high energy cosmic rays (UHECRs)?

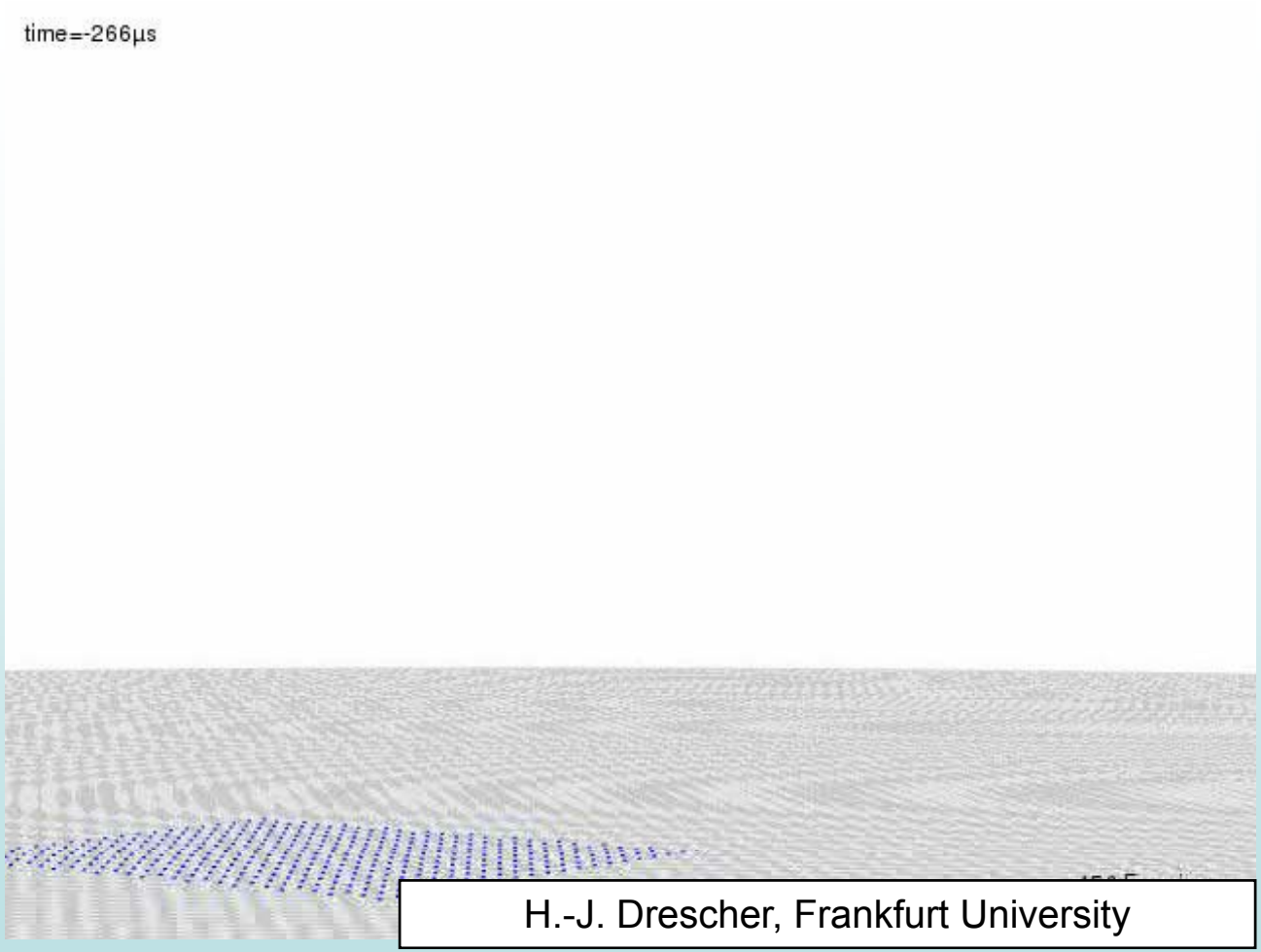
**UHECRs are particles with energy above "ankle", say, above 3 x $10^{18}$ eV.**

**The most energetic event:**
**Detector Fly's Eye, Utah, USA, October 15th 1991**
**3 x $10^{20}$ eV ≈ 50 J**




Simon Swordy, 1996

# Extensive air showers




H.-J. Drescher, Frankfurt University

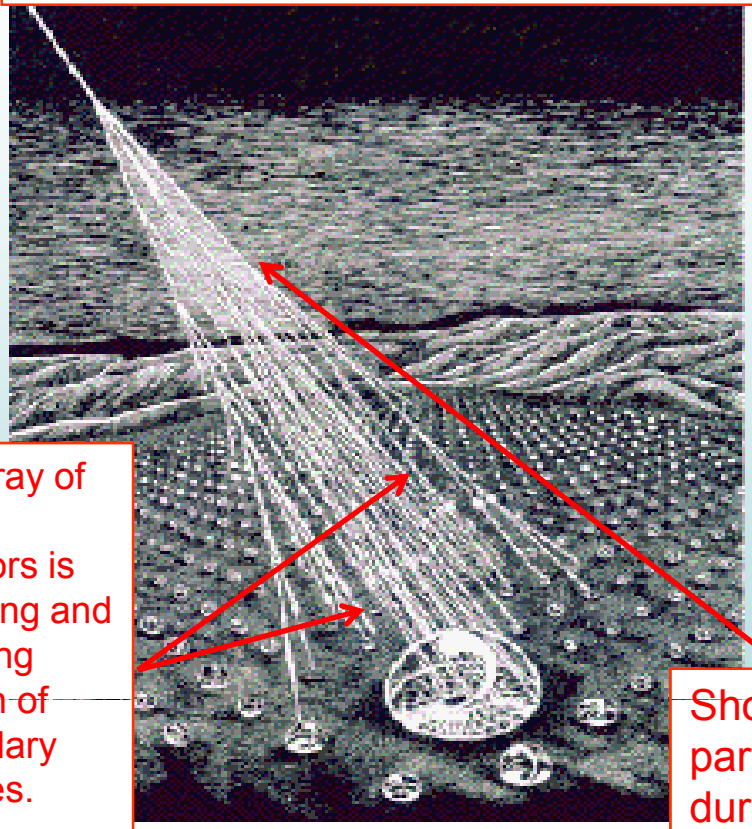
- Primary particle interacts with atmosphere
- Number of secondary particles is created
- Secondaries interact again, and again, ...
- Typical shower $10^{20}$ eV: $10^{10}$ particles at ground
- Animation color code:

blue: electrons/positrons
cyan: photons
orange: protons
red: neutrons
gray: mesons
green: muons

($10^{-6}$ thinning)

# How to detect UHECRs?

Primary particle coming from space (proton or light nucleus) hits the atmosphere of the Earth



The array of ground detectors is recording and sampling fraction of secondary particles.

Shower of secondary particles originates during collissions with molecules in the atmosphere.

- The number of secondary particles is proportional to energy of primary particle
- Relative time of detection of individual secondary particles carries information about incident direction of primary particle
- Types of detectors: ground arrays and fluorescence telescopes

# Detectors of cosmic rays with ultra-high energies

7 different detectors were in operation during 40 years of measurements and achieved detection of approximately ~ 200 particles with energies over $4.10^{19}$ eV and only ~ 20 particles with energies over $10^{20}$ eV.

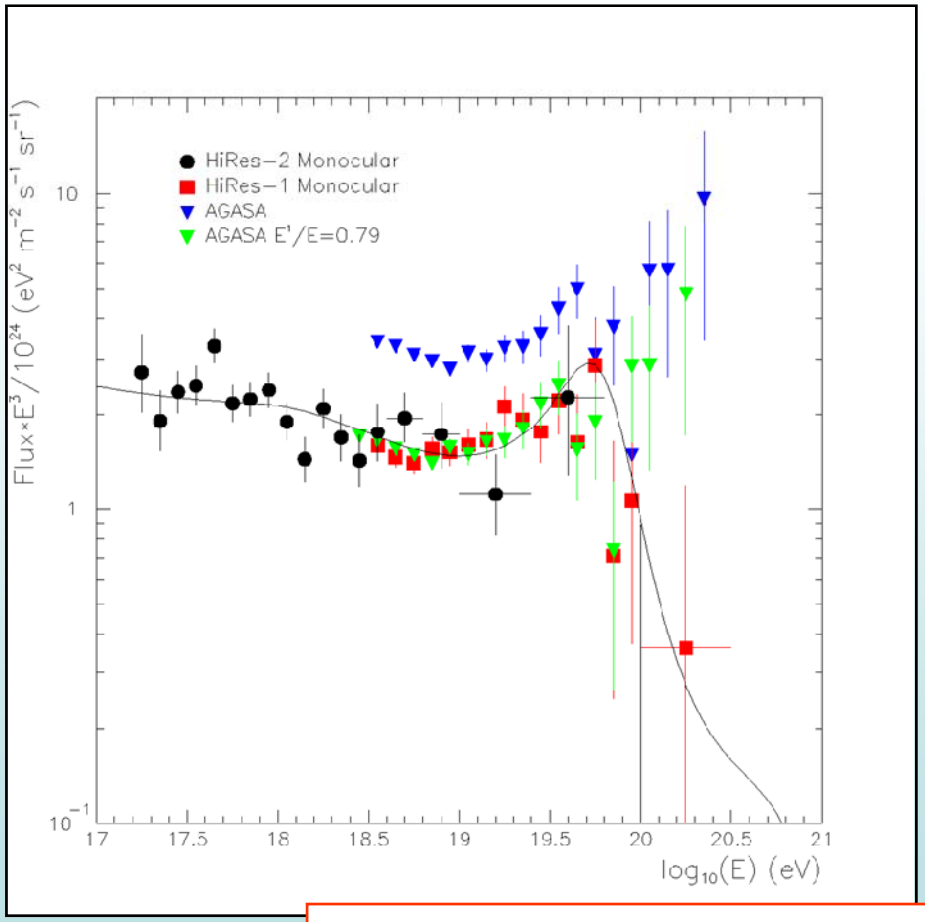
Surface detectors:

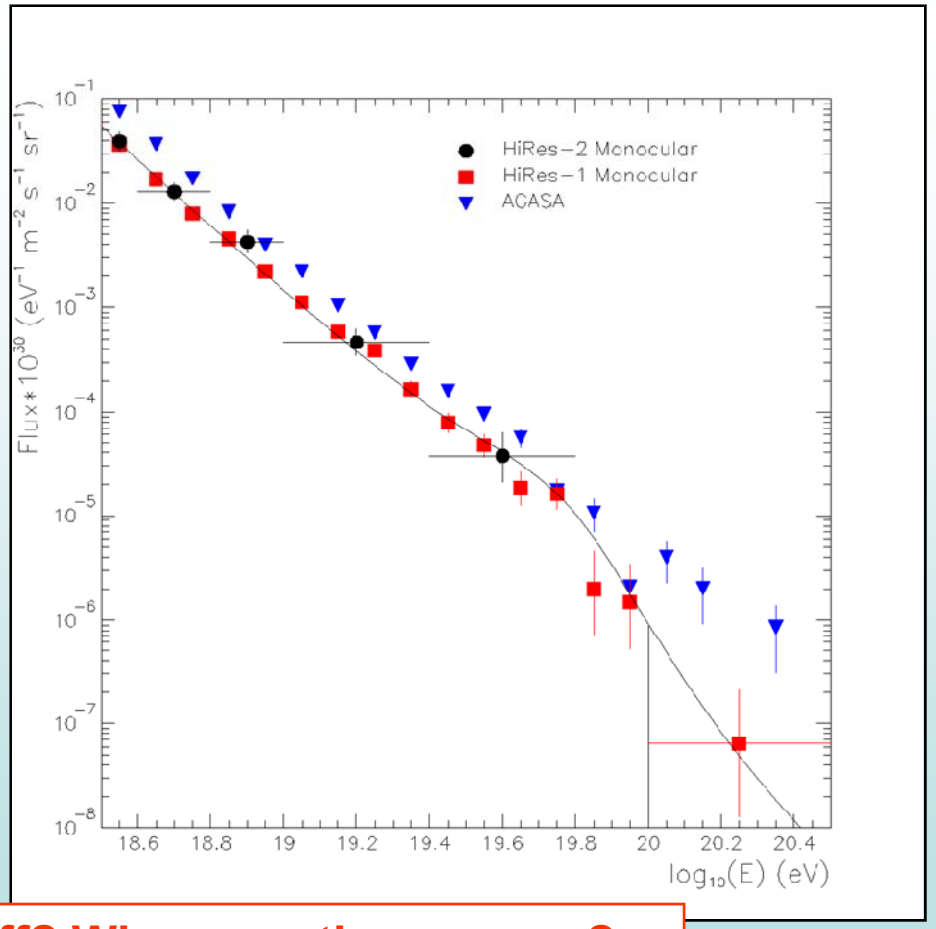
- Volcano Ranch, USA (1959 – 1963)
- SUGAR, Australia (1968 – 1979)
- Haverah Park, UK (1968 – 1987)
- Yakutsk, Russia (1970 – today)
- AGASA, Japan (1990 – 2004)

Fluorescence detectors:

- Fly's Eye, USA (1981 – 1992)
- HiRes, USA (1998 – 2006)

# GZK or not to GZK: HiRes vs. AGASA



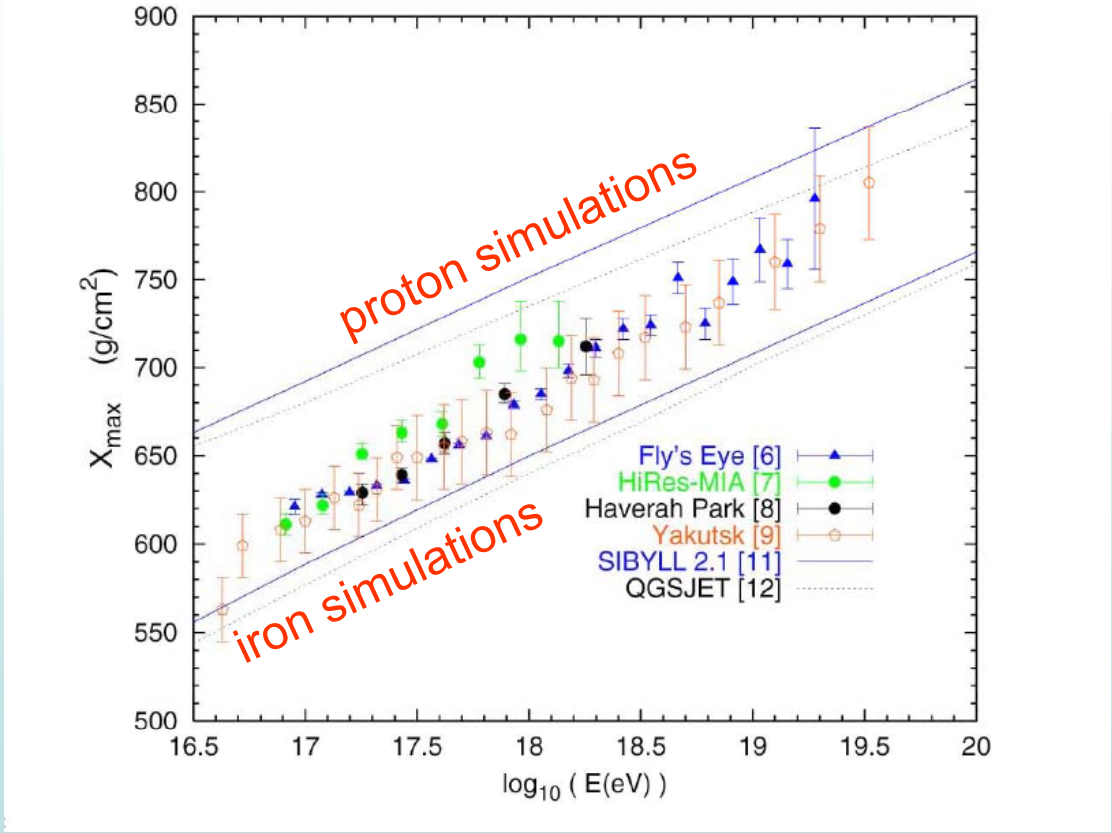




**Is there really GZK-cutoff? Where are the sources?**

# Chemical composition of UHECR

**Protons, iron nuclei or mix?**

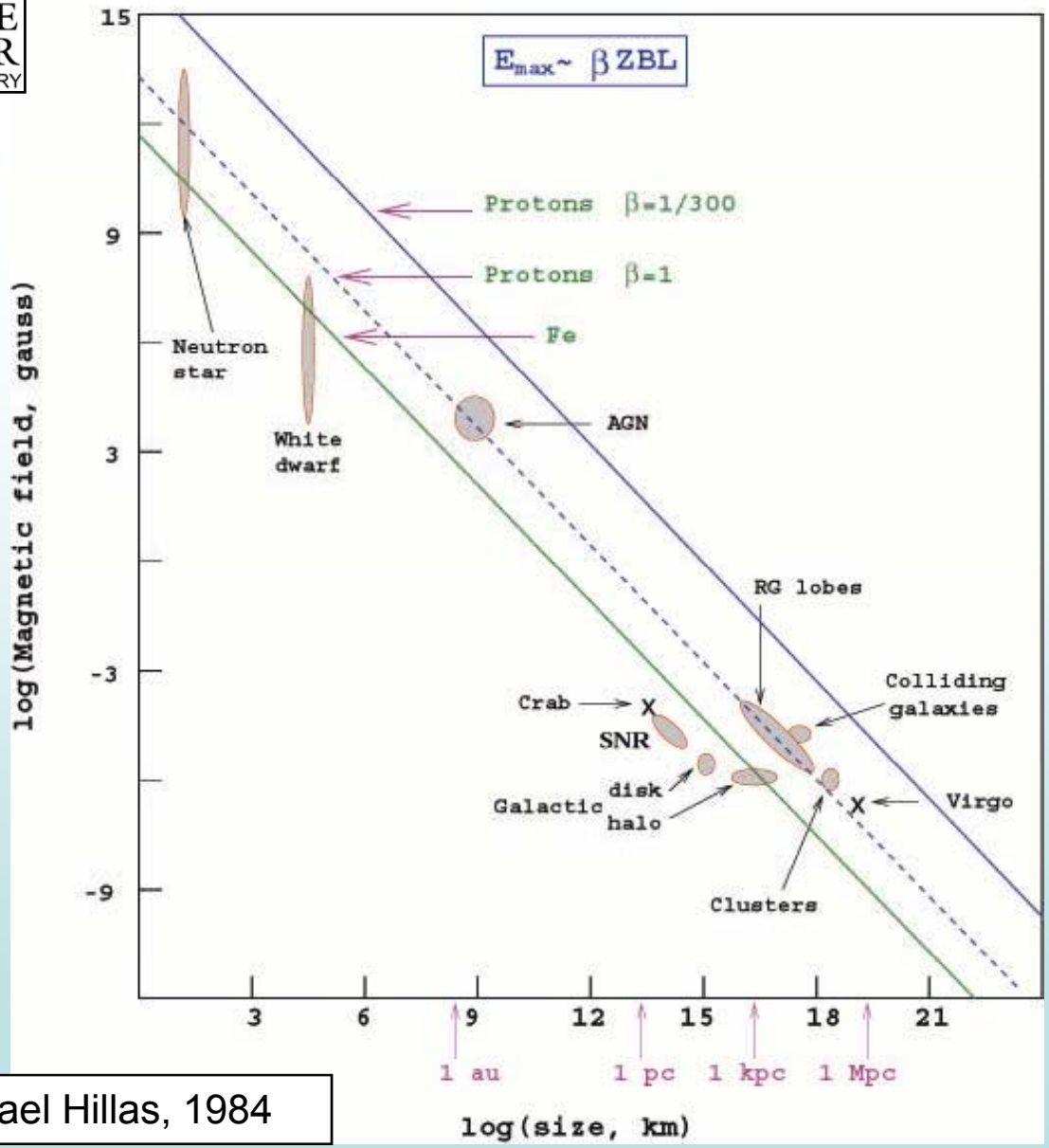
**We (once again) don‘t know.**




- **Elongation rate (mean shower maximum in the atmosphere vs. energy) indicates the dominant chemical component, but we have to compare to simulations to interpret the data (strong model dependence !)**

**T. K. Gaisser, 2000**

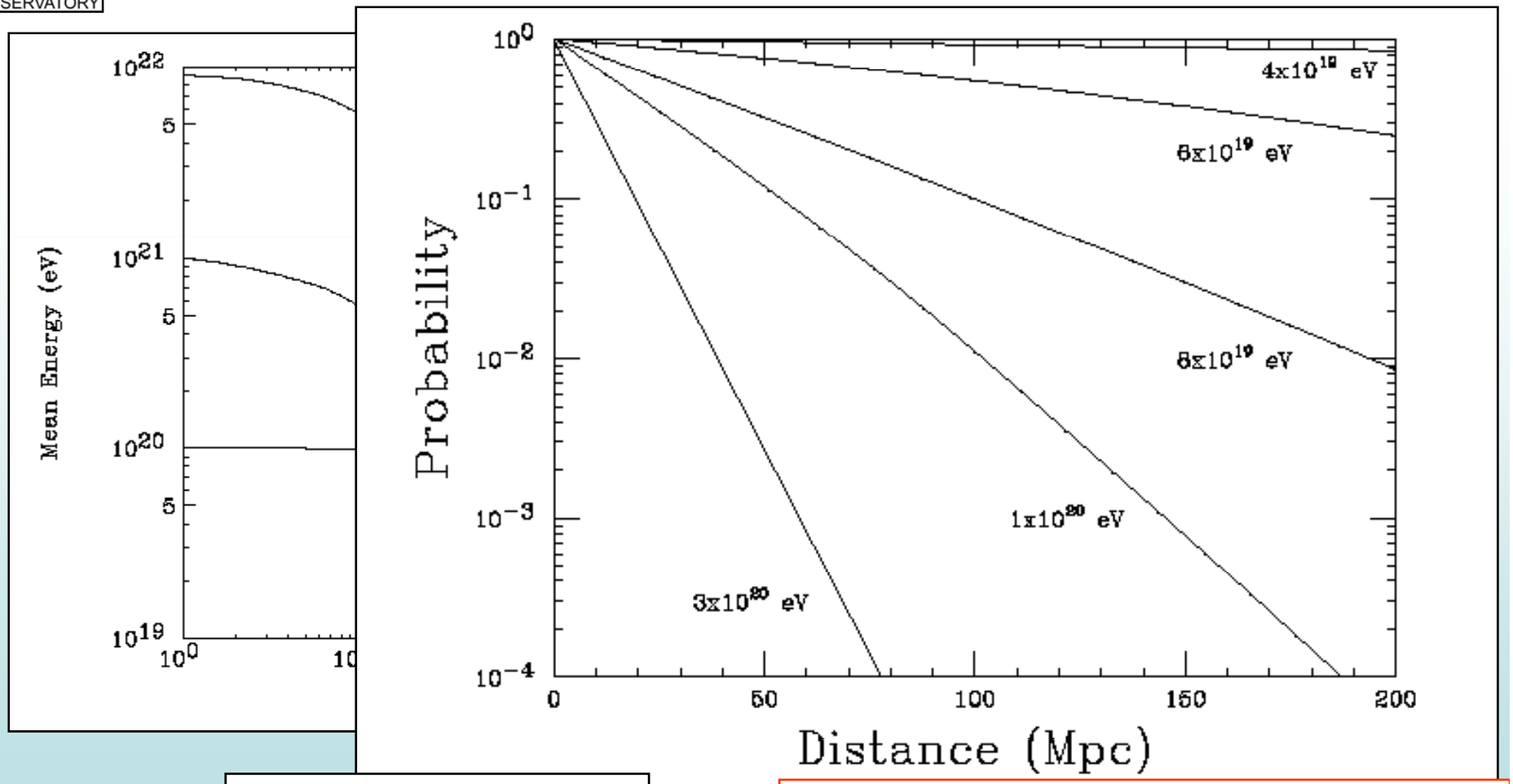
# Sites of origin of UHECRs




Michael Hillas, 1984

- Fermi acceleration in magnetic fields.
- We need magnetic fields extremely strong OR filling extremely large regions to accelerate particles above $10^{20}$ eV.
- And still, all parameters have to be finely tuned.

# GZK suppression

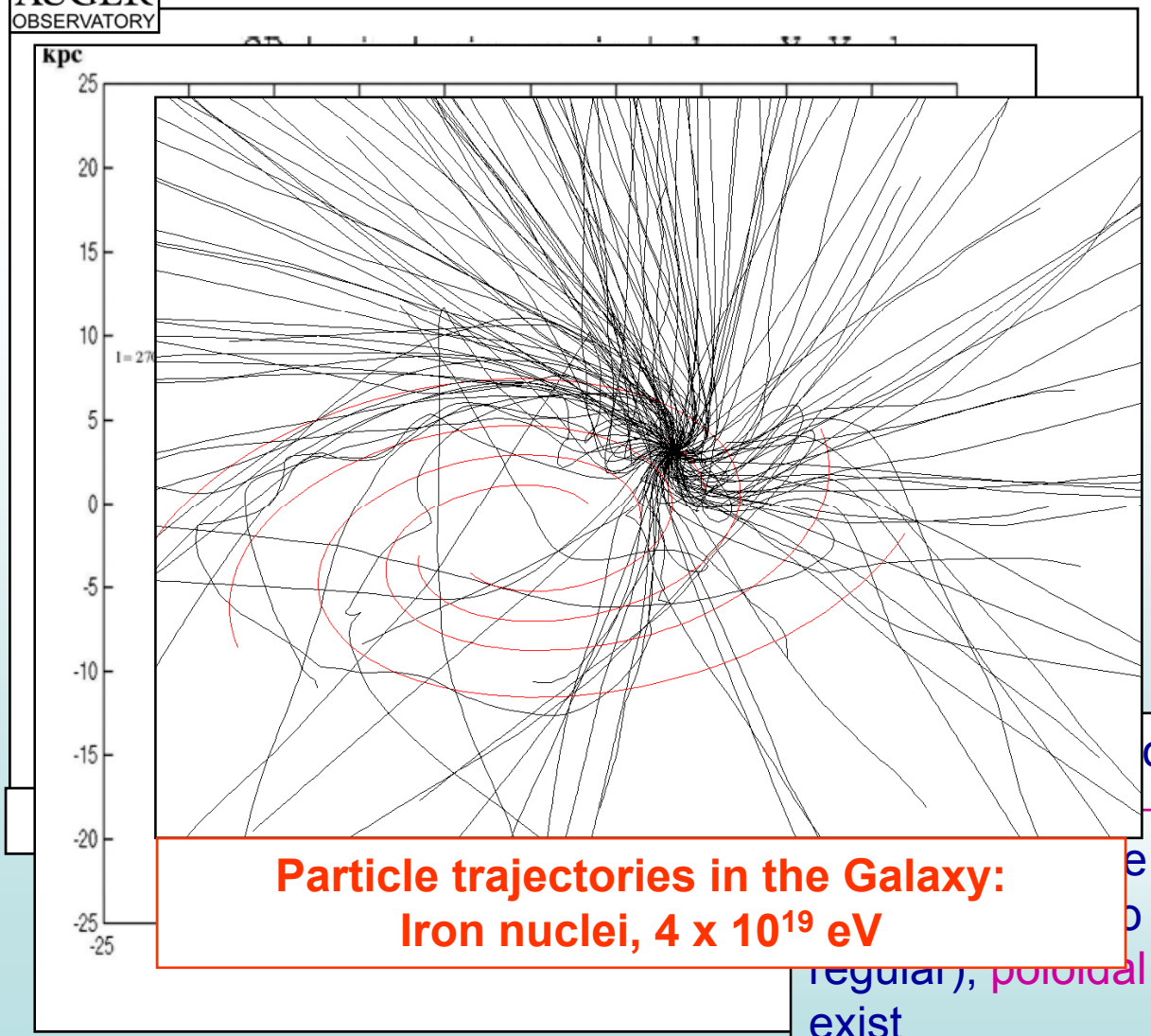



Paul Sommers, 2003

Sources of particles with $E > 10^{20}$ eV have to be within "GZK-sphere" (100 Mpc)

PIERRE AUGER OBSERVATORY

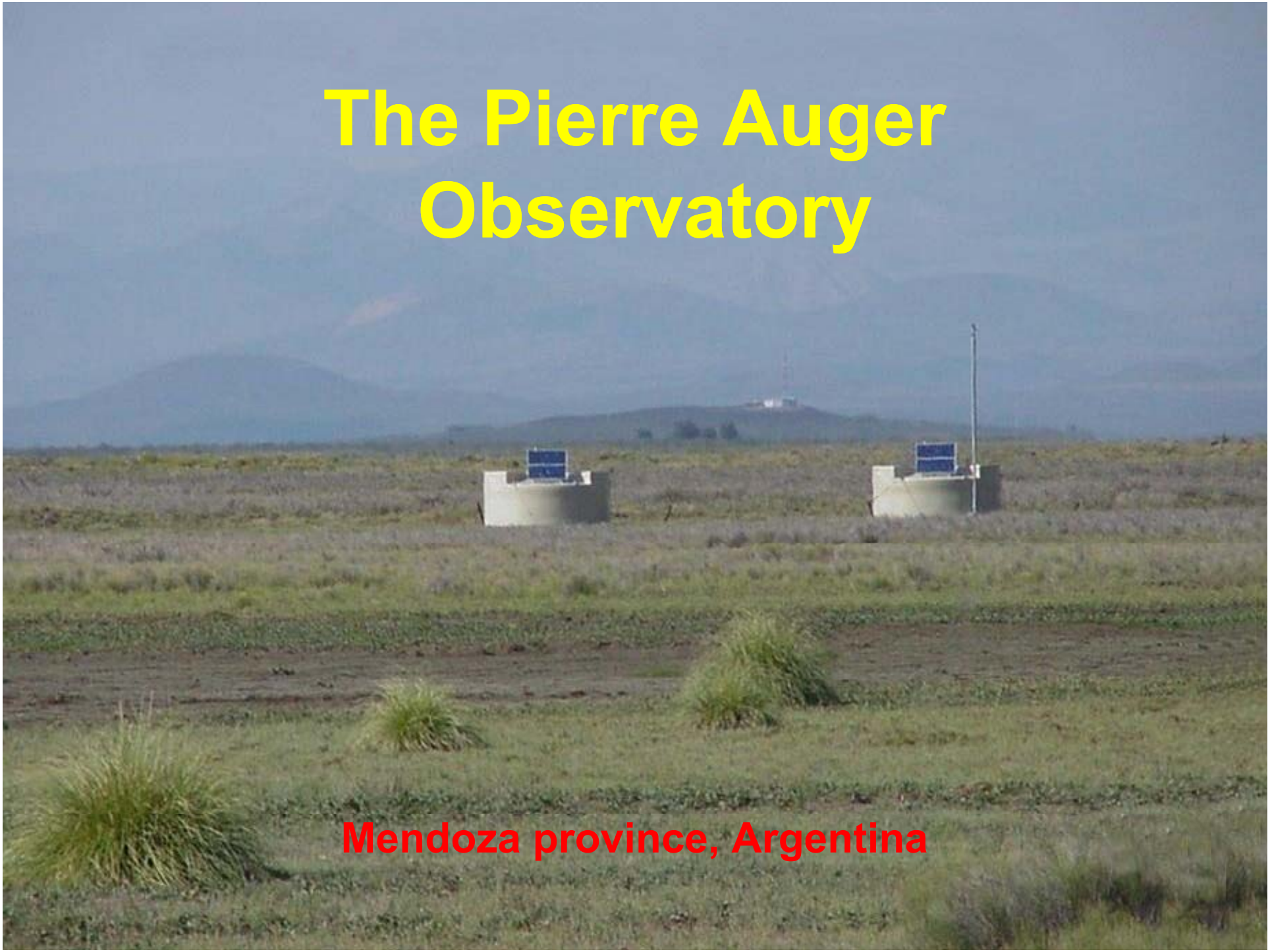
# Influence of magnetic fields




**Particle trajectories in the Galaxy: Iron nuclei, 4 x $10^{19}$ eV**

- Above $10^{19}$ eV - not curved trajectories ? - "Cosmic ray astronomy" ?
- Not so sure…
- Extragalactic magnetic fields could be very important, especially if UHECRs are mainly iron nuclei.
- And what about Galactic magnetic field?

on, …, Faraday rotation
→ field strength ~ μG
e surely spiral
o 3x higher intensity than
regular), poloidal and toroidal components exist


The Pierre Auger Observatory
Mendoza province, Argentina

# The Pierre Auger Observatory

**More than 250 PhD scientists from more than 60 institutions from 15 (+2) countries.**

**Participating countries:**
**Argentina, Australia, Bolivia*, Brazil, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, United Kingdom, USA and Vietnam***

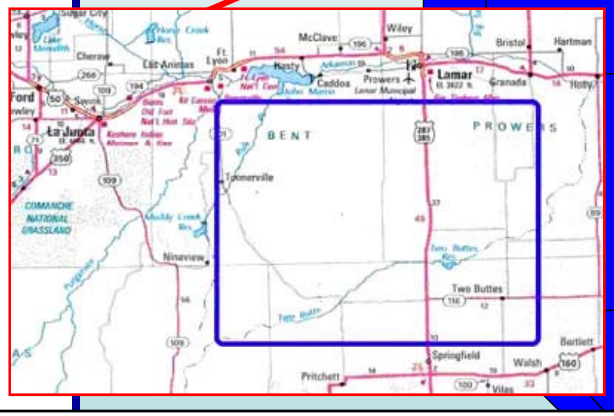
*** - associated countries**

**Participating countries are in cyan.**

# Pierre Auger Observatory

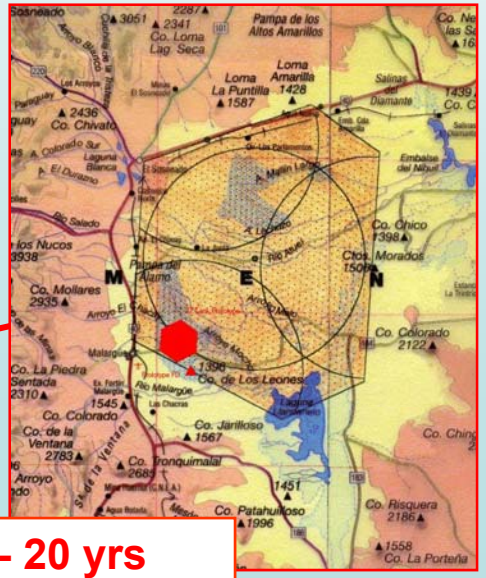
**The southern site in Argentina is currently being finished (complete by mid-2008).**

**Northern hemisphere (planned):**
**Lamar, Colorado, USA**




See www.augernorth.org for details

**Southern hemisphere:**
**Malargüe, Mendoza province, Argentina**

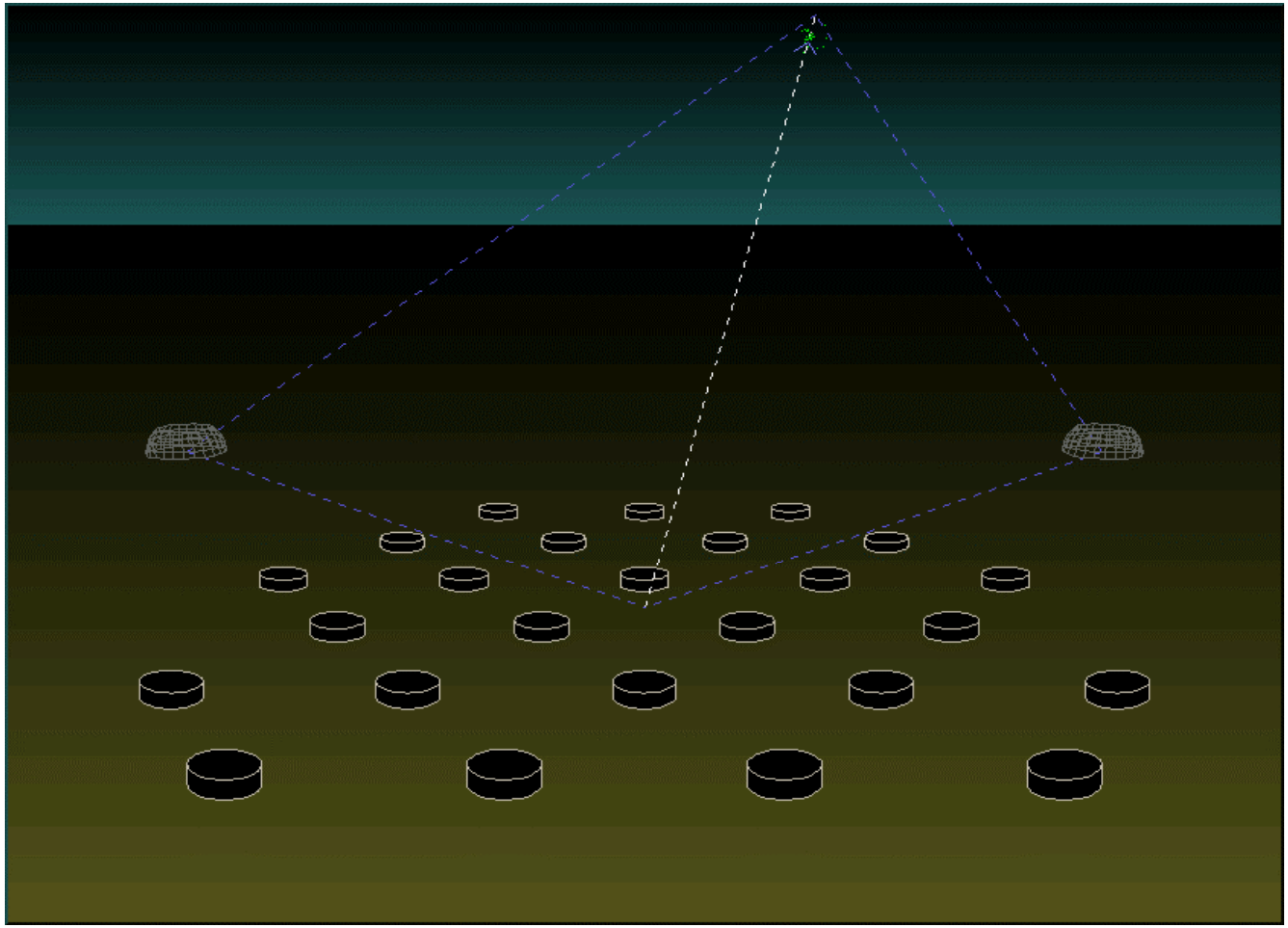



**Lifetime of the observatory: 15 - 20 yrs**

# The Pierre Auger Observatory = hybrid detector of cosmic rays

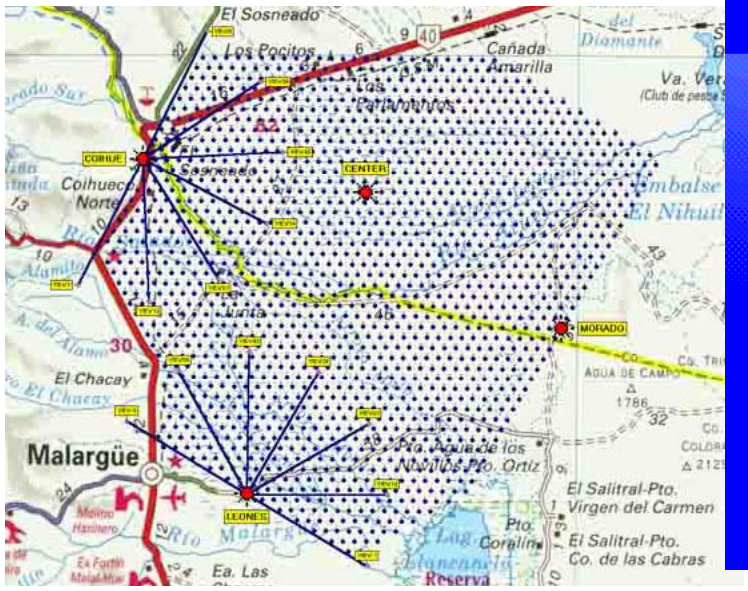
• The array of surface Cherenkovov detectors will be accompanied with system of fluorescence telescopes, which will observe faint UV/visible light during clear nights. This fluorescence light origins as by-product during the interactions of shower particles with the atmosphere.

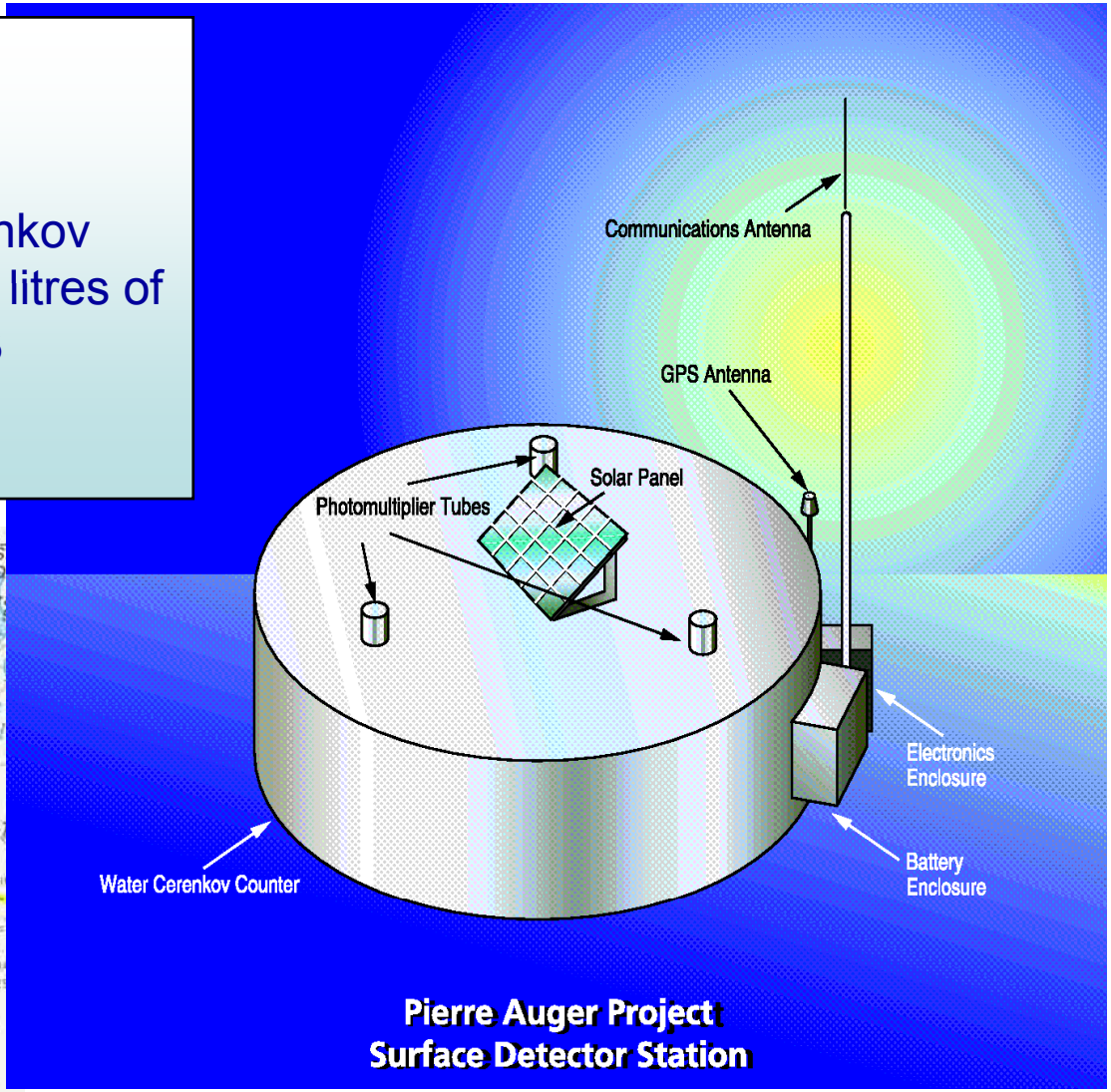
**Scheme of hybrid detector function**



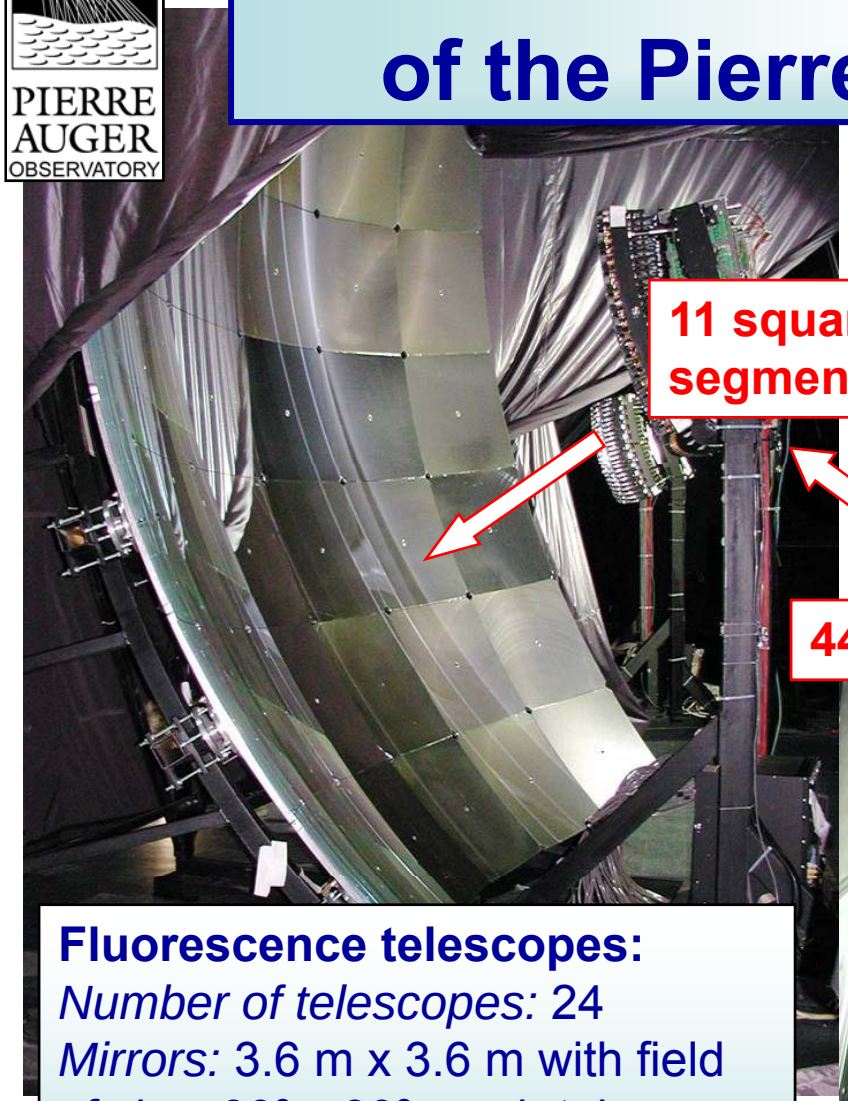
# Ground detectors of the Pierre Auger Observatory

**Ground detectors:**
*Covered surface:* 3000 km$^2$
*Number of detectors:* 1600
*Type of detector:* Detector of Cherenkov radiation, each consisting of 12 000 litres of ultrapure water and equipped with 3 photomultipliers.
*Spacing between detectors:* 1.5 km.

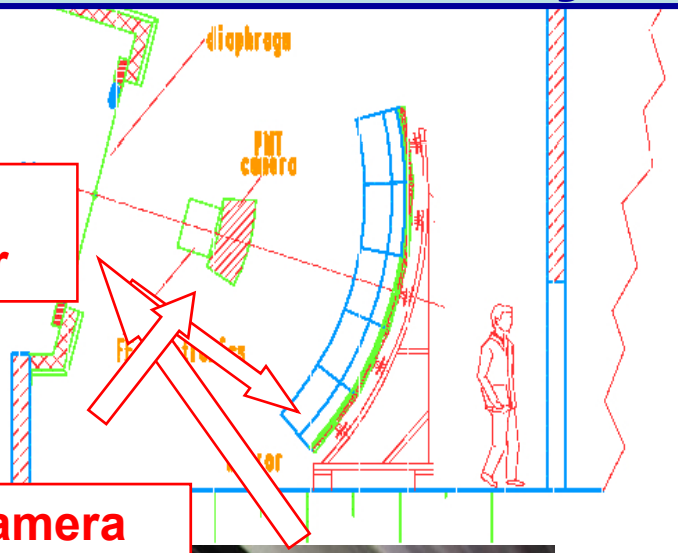


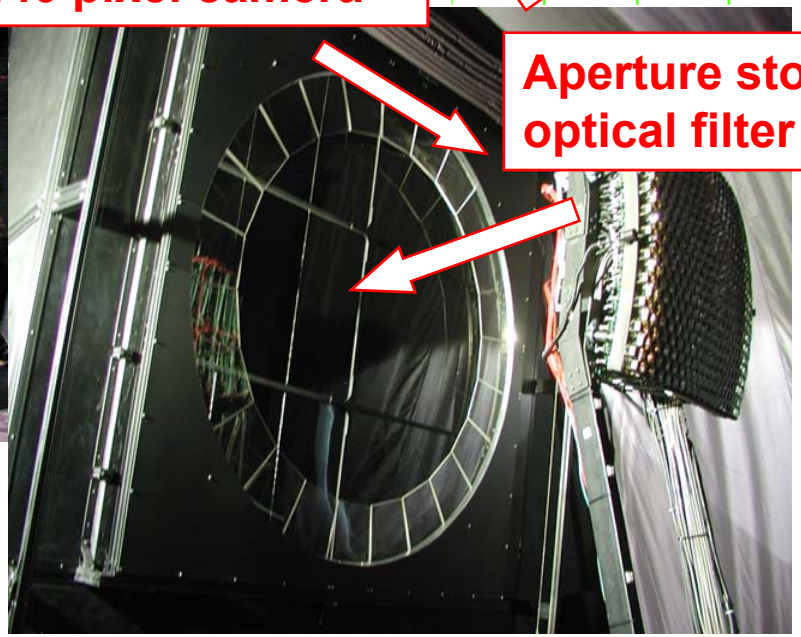
# Fluorescence detectors of the Pierre Auger Observatory



11 square meter segmented mirror



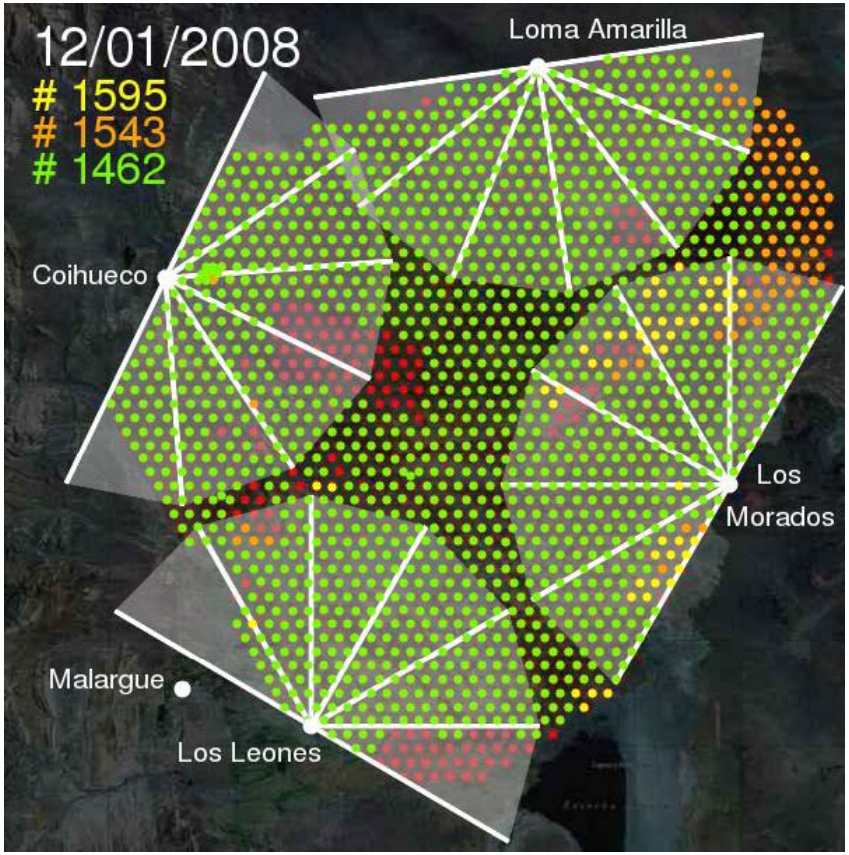

440 pixel camera

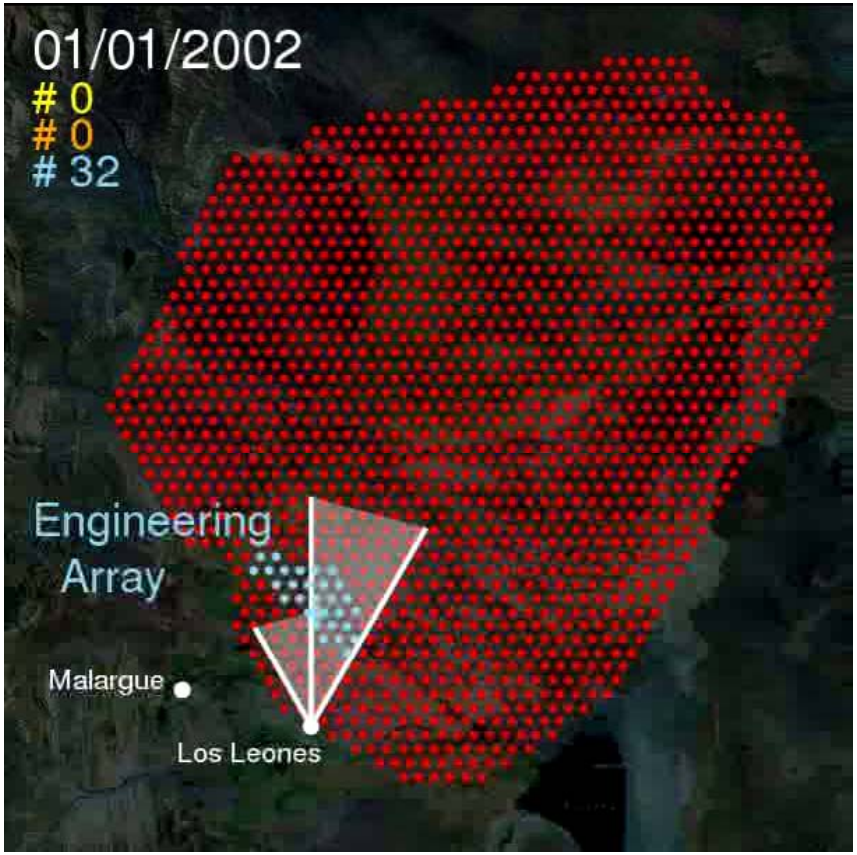


Aperture stop and optical filter

**Fluorescence telescopes:**
*Number of telescopes:* 24
*Mirrors:* 3.6 m x 3.6 m with field of view 30º x 30º, each telescope is equipped with 440 photomultipliers.

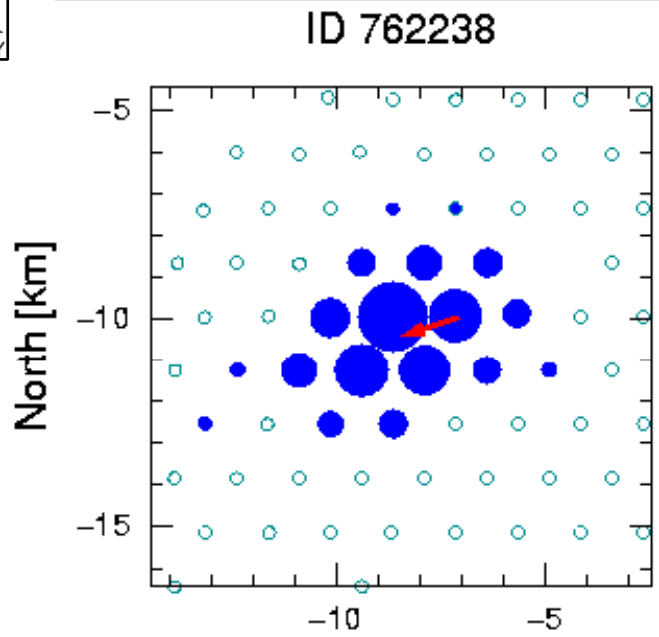
# Evolution of the *hybrid detector*

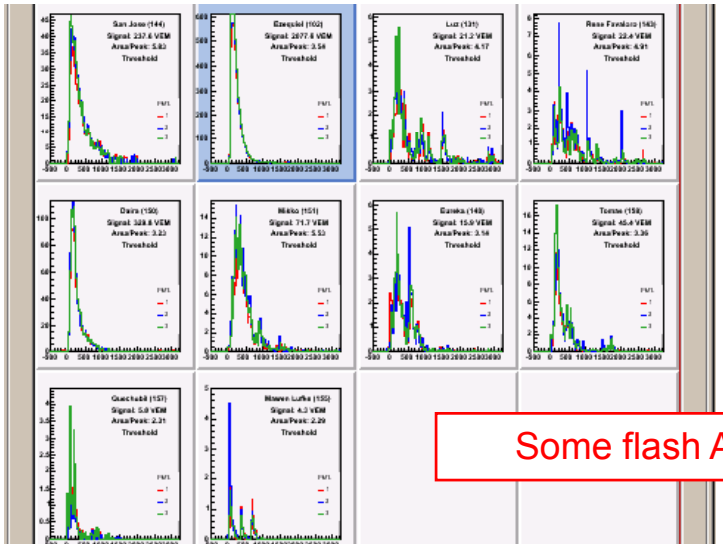


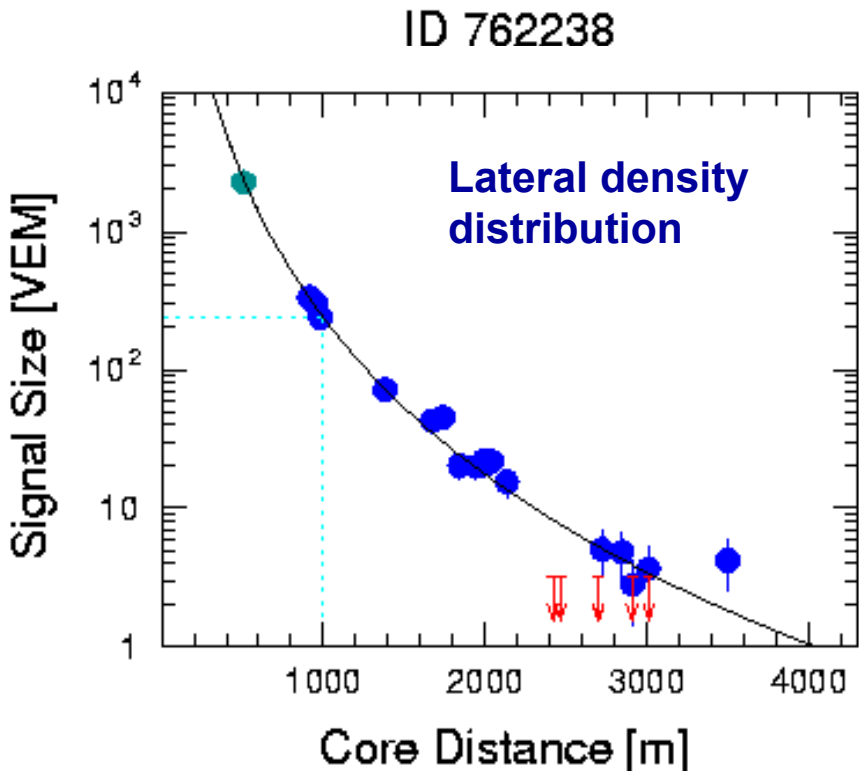

Production of scientific data since late 2003.

# Example Surface Array Event
## (Θ~ 48º, ~ 70 EeV)

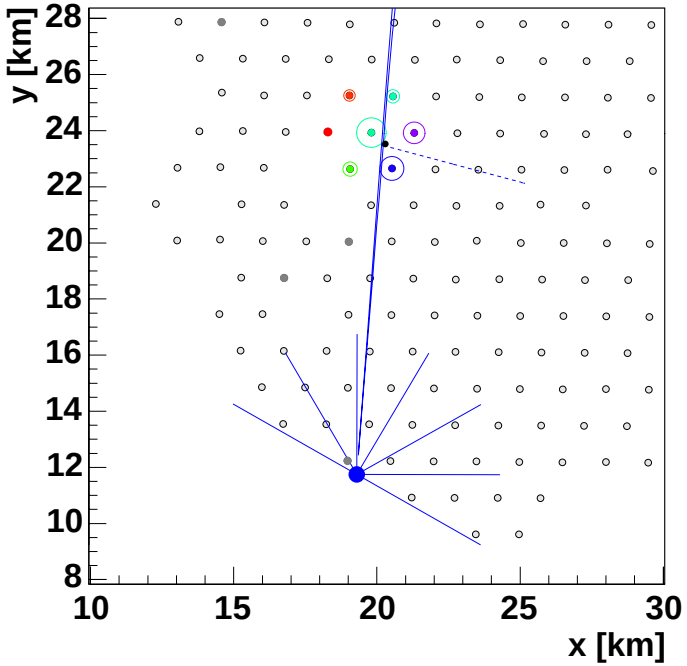


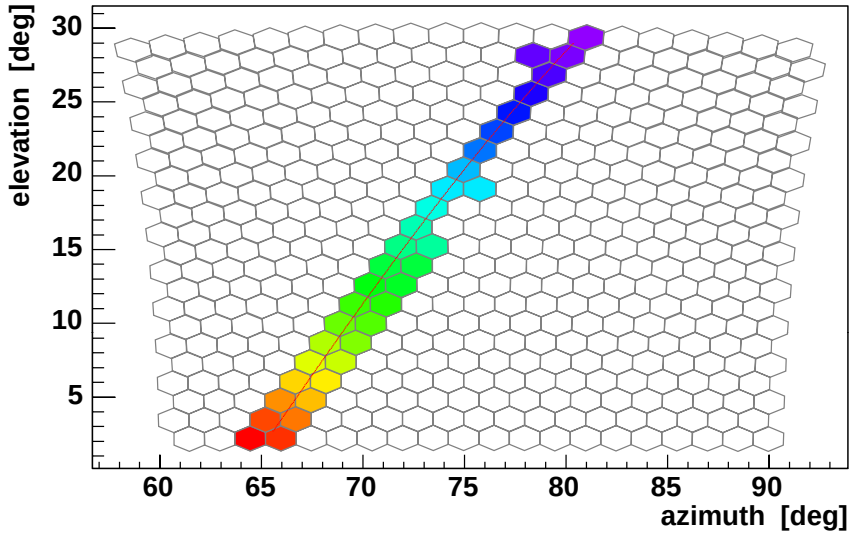



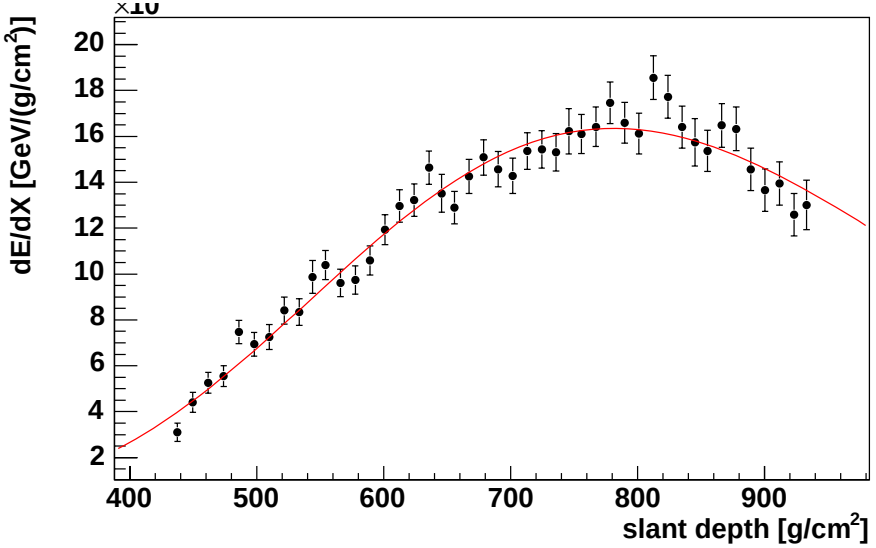
Some flash ADC traces

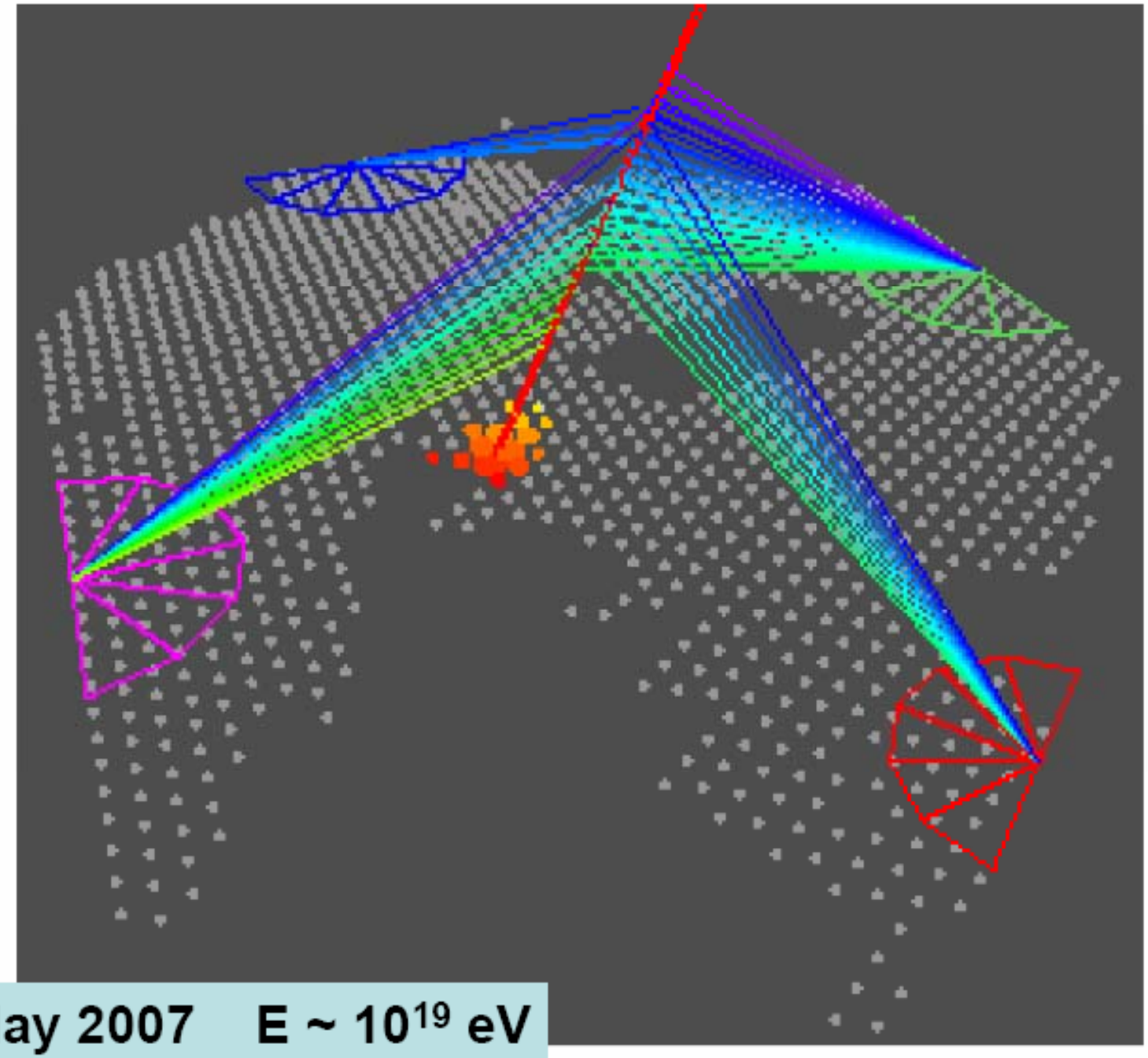


# Example Hybrid Event (Θ~ 30º, ~ 8 EeV)



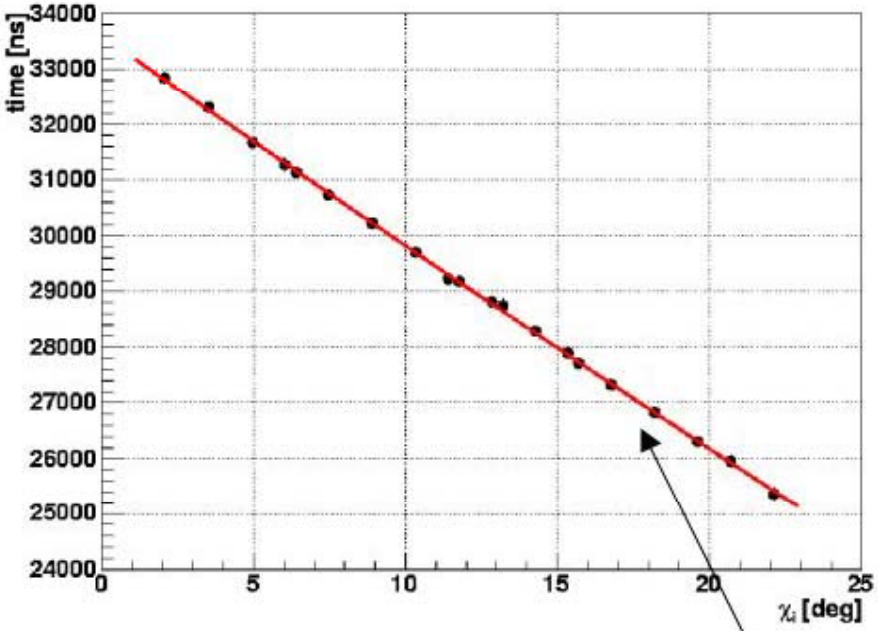





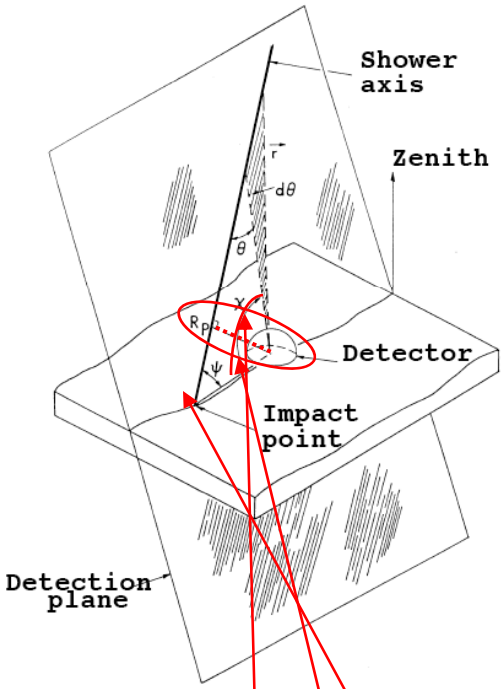
20 May 2007 E ~ $10^{19}$ eV

# (Geometrical) Hybrid advantage...




≈ line but

3 free parameters




$$t(\chi) = T_0 + \frac{R_p}{c} \tan\left[\frac{(\chi_0 - \chi)}{2}\right]$$

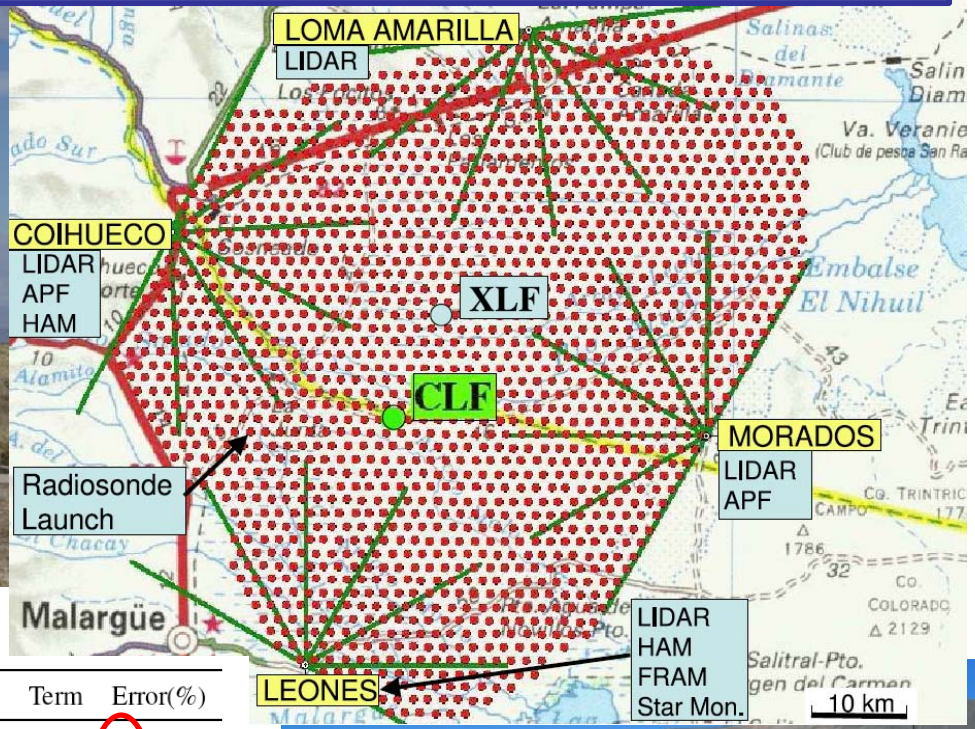
$T_0$ - time of impact

$R_p$ - perpendicular distance to the detector

$\chi_0$ – actual observation angle

# Energy estimation, atmospheric monitoring

Central Laser Facility

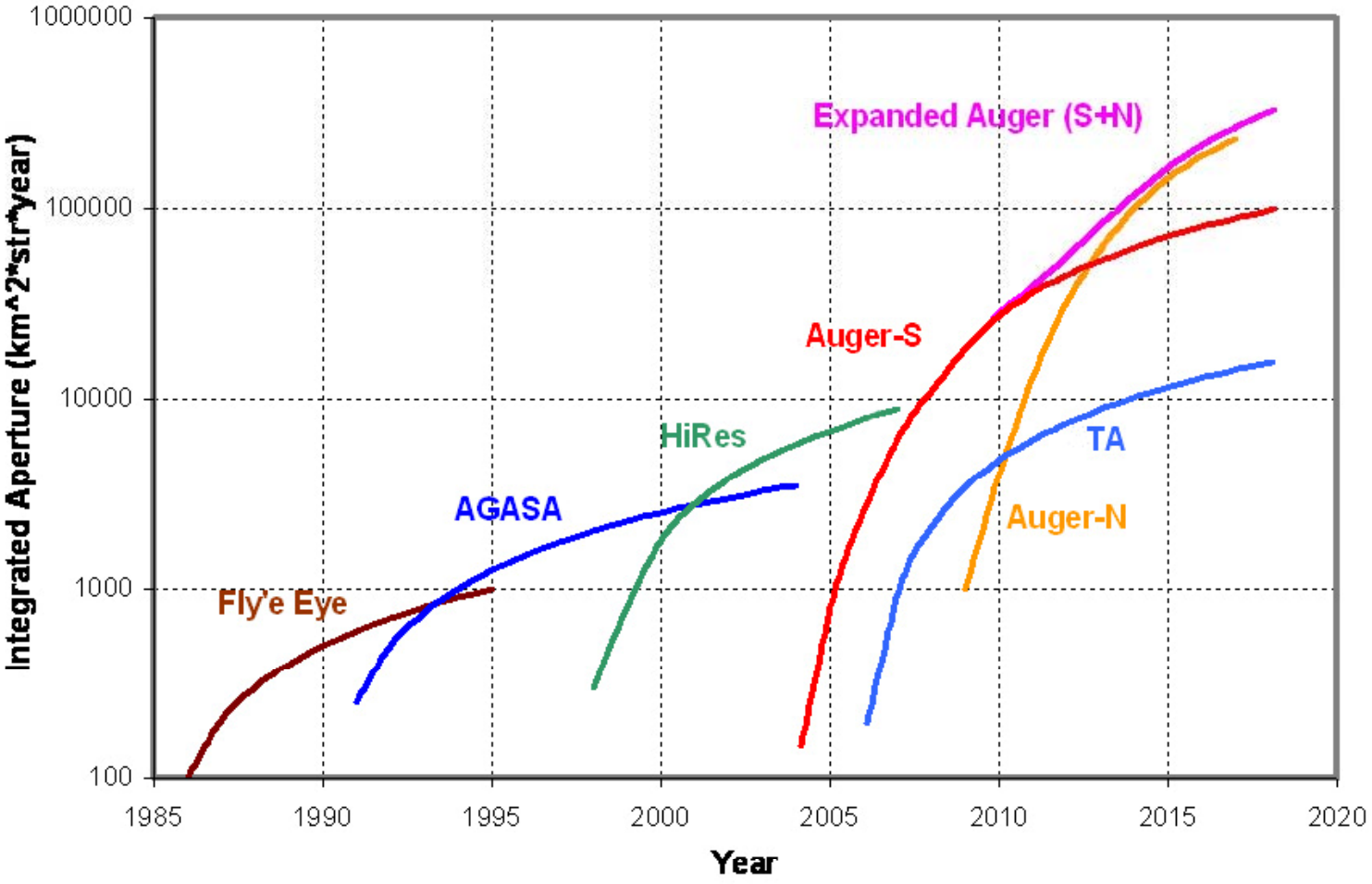



| Term | Error(%) | Term | Error(%) |
|---|---|---|---|
| Light collection | 5 | Atmosphere (aerosols) | 10 |
| Detector photometric calibration | 12 | Atmosphere (clouds) | 5 |
| Geometric reconstruction | 2 | Atmosphere (density profile) | 2 |
| Correction for Missing Energy | 3 | Fluorescence yield | 15 |
| | **Quadrature Sum = 23** | | |

**Current estimates of systematic errors of the FD energy measurement**

LIDAR

# Comparison of integrated aperture

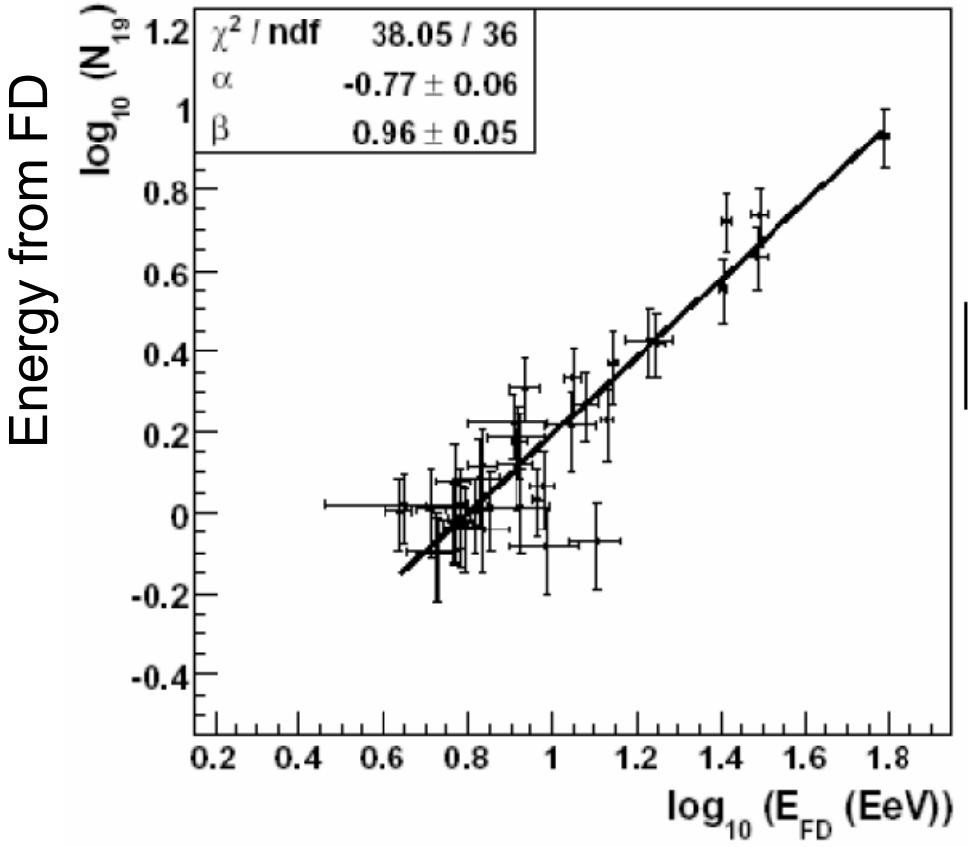


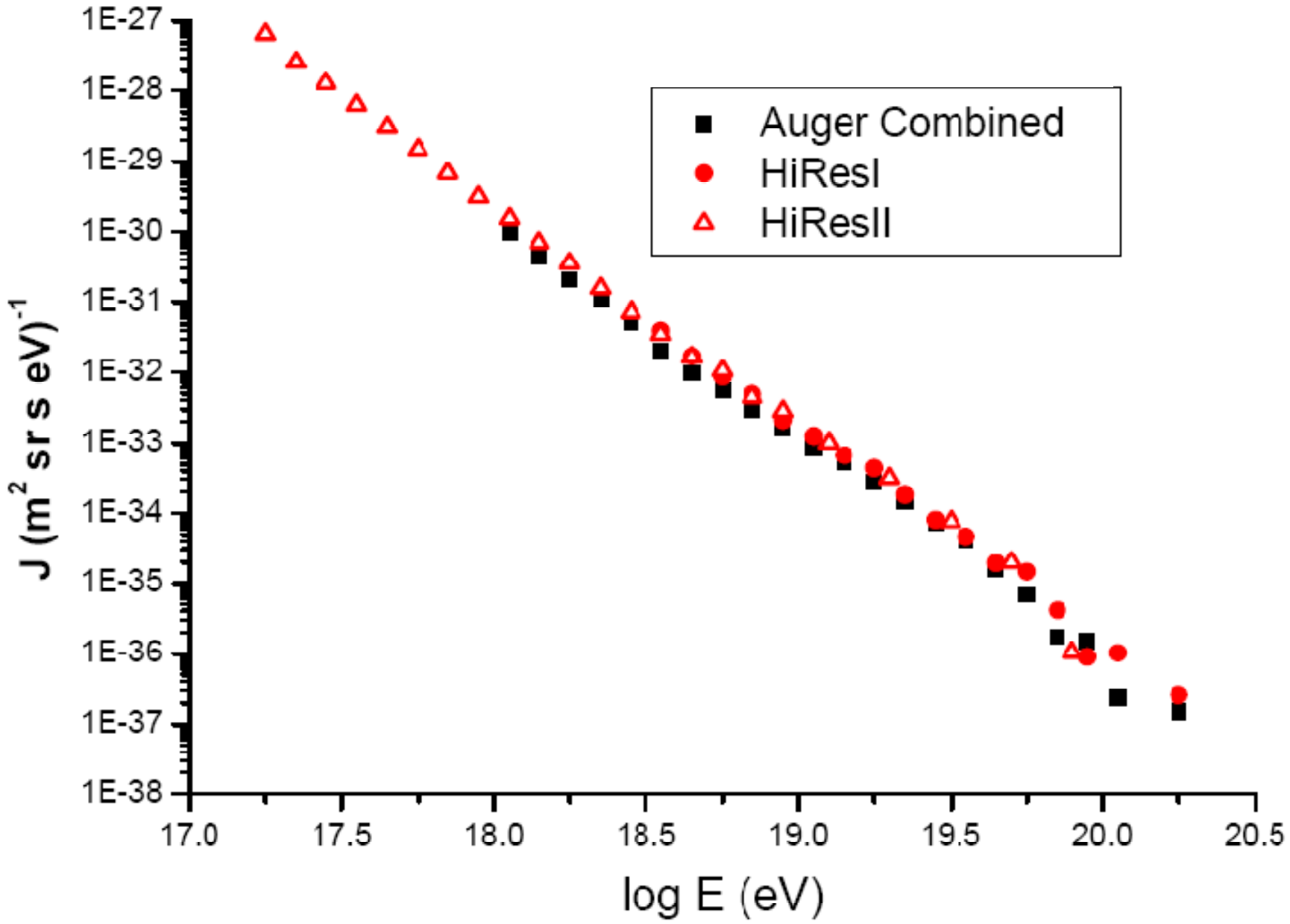

Currently (Nov 2007) ~ 4 x AGASA

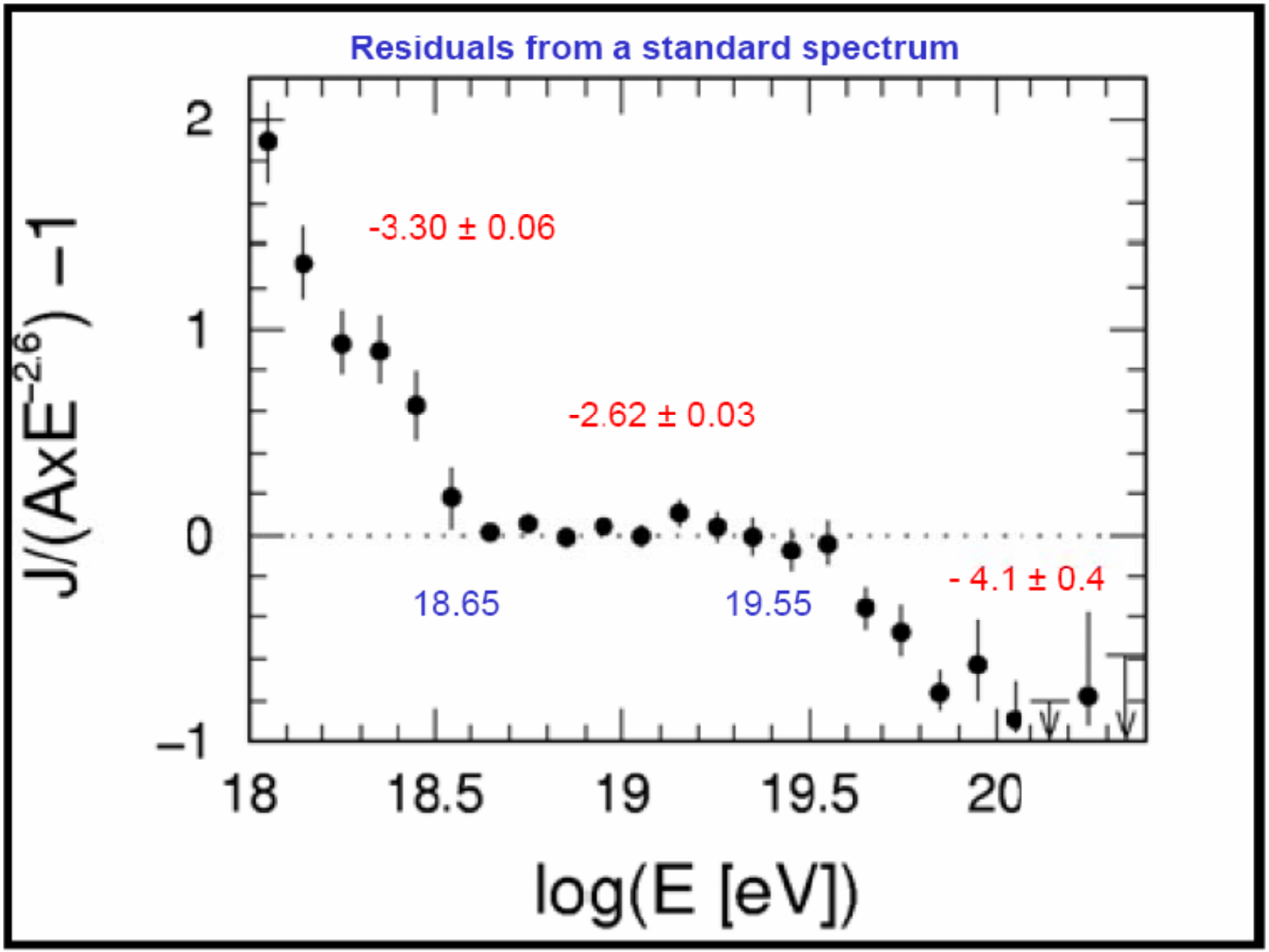
# Auger Observatory results

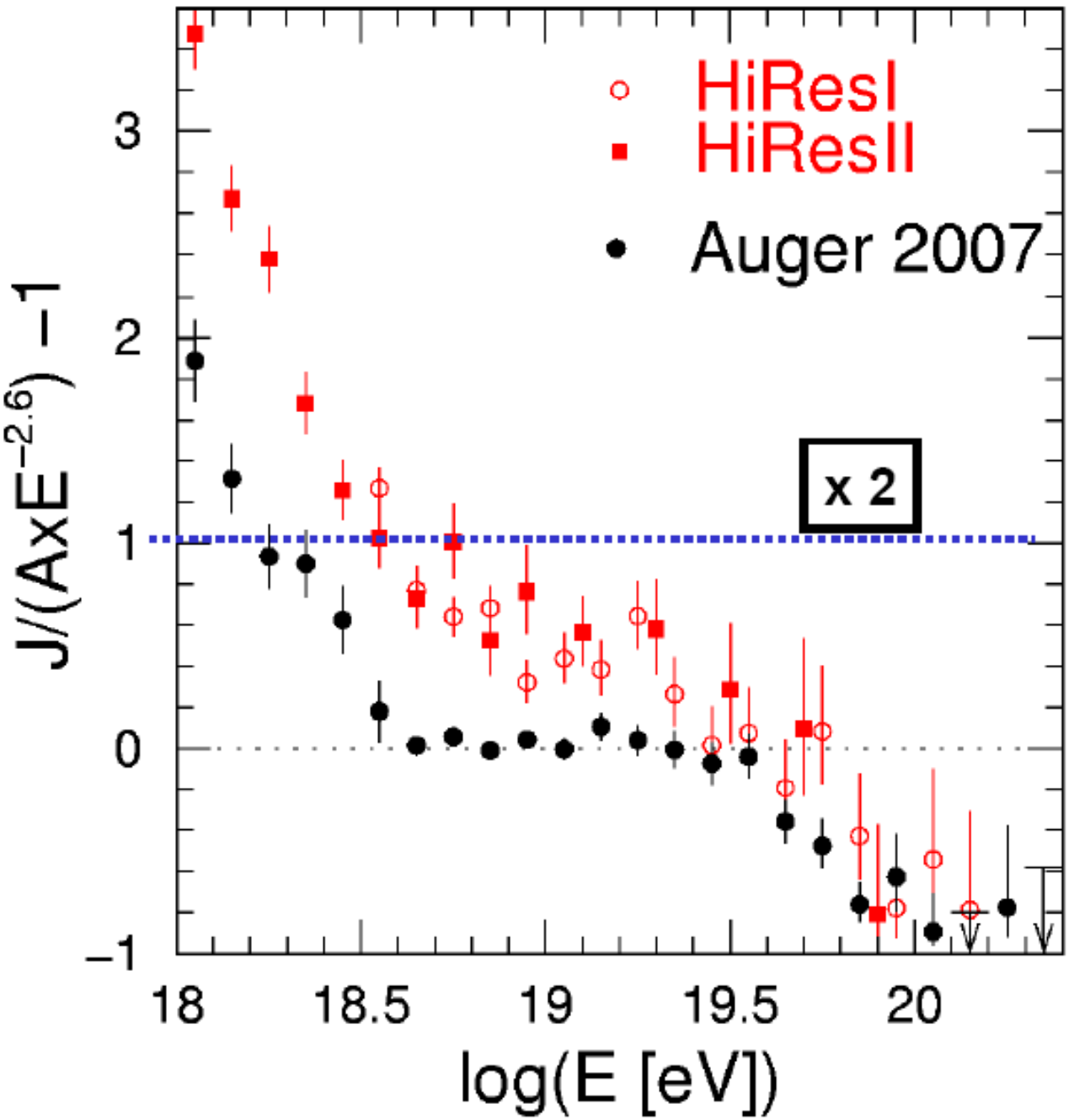
# Auger Energy Spectrum

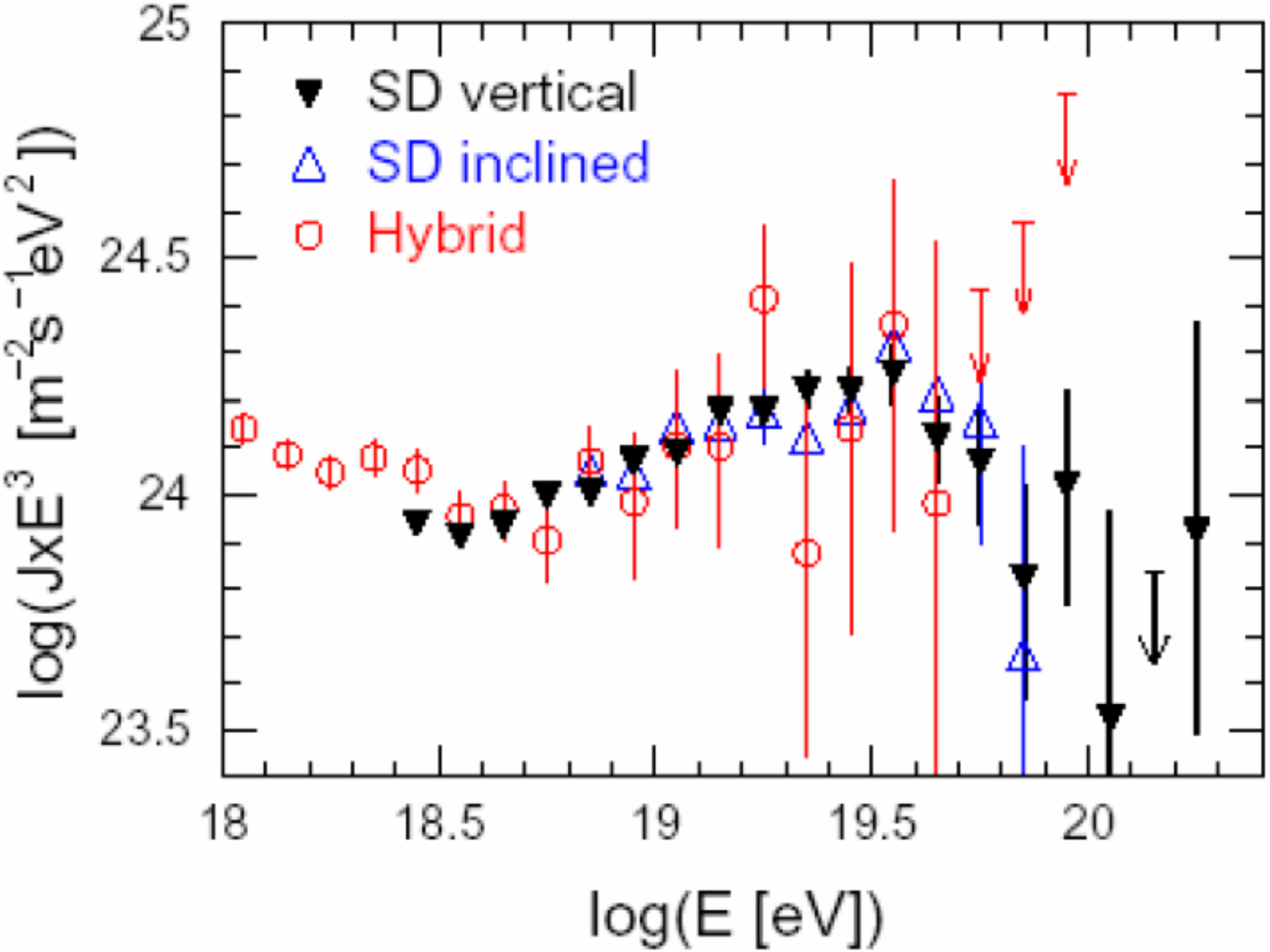
- No spectrum from SD only!
- Relation between particle density parameter S(1000) and FD energy using selected hybrid events
- Aperture from SD
- Combining advantages of FD technique (calorimetric measurement of energy) and of SD technique (well defined aperture; 100 % duty cycle)

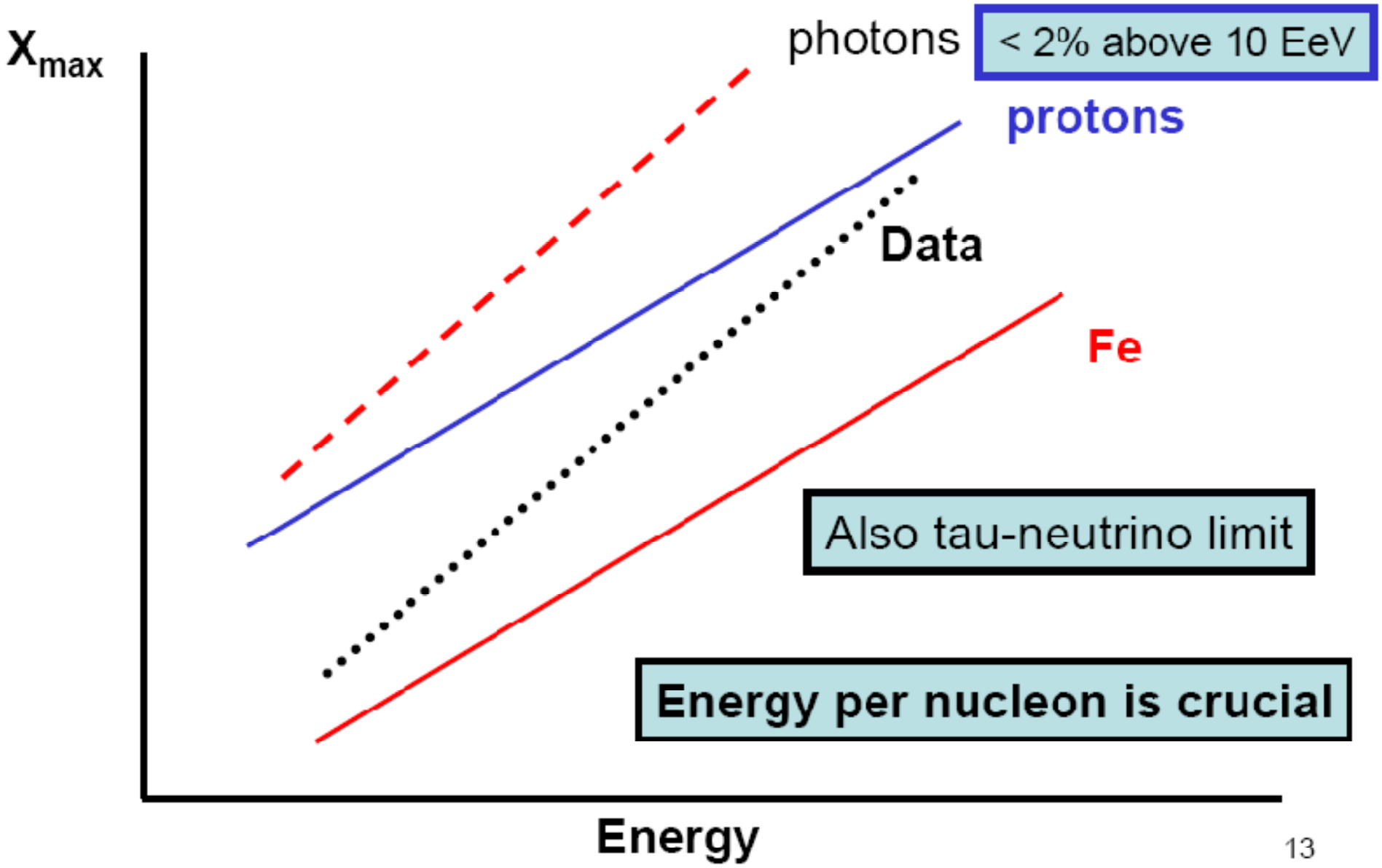


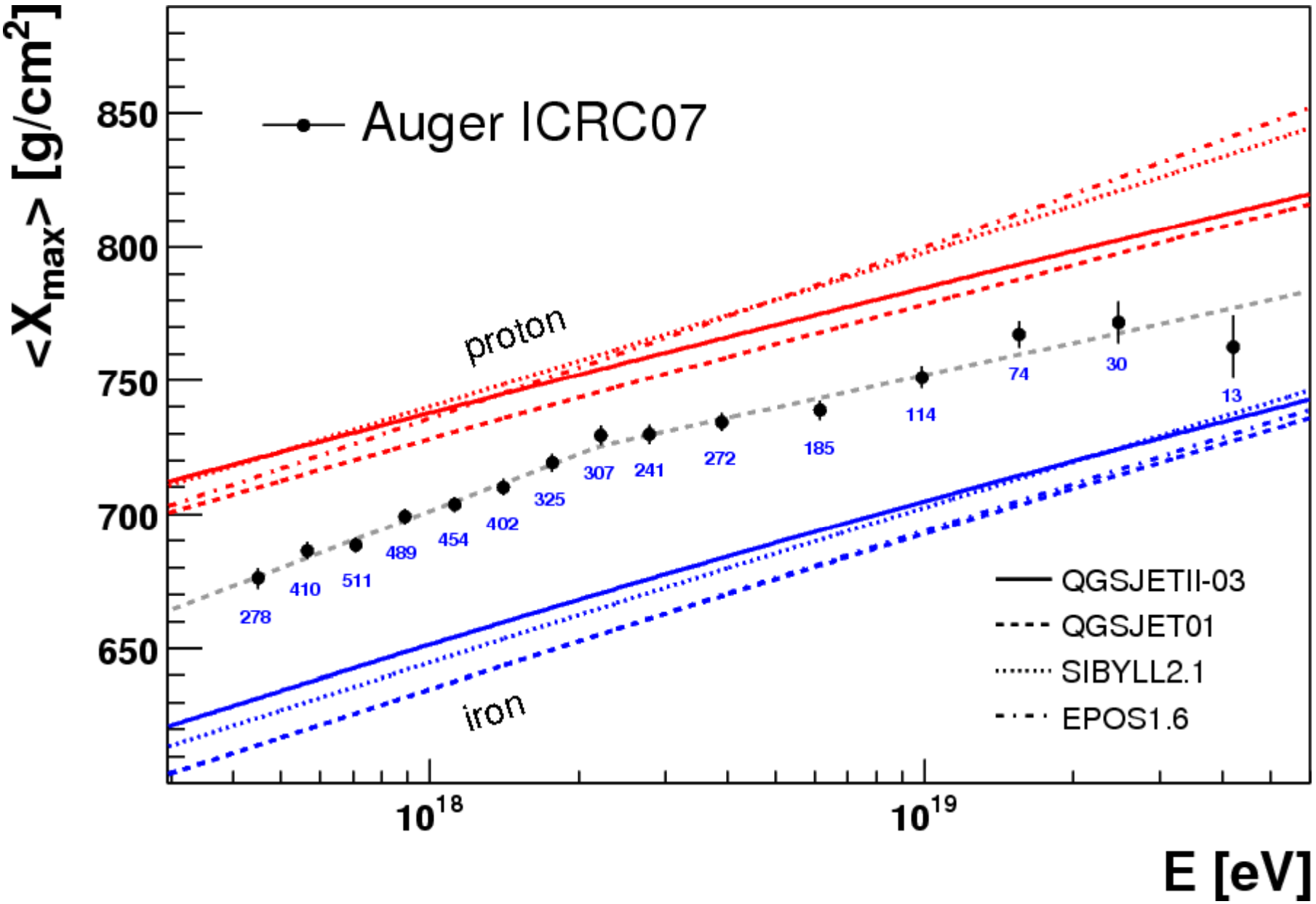

Auger Combined
HiResI
HiResII
J (m$^2$ sr s eV)$^{-1}$
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
1E-33
1E-34
1E-35
1E-36
1E-37
1E-38
17.0
17.5
18.0
18.5
19.0
19.5
20.0
20.5
log E (eV)

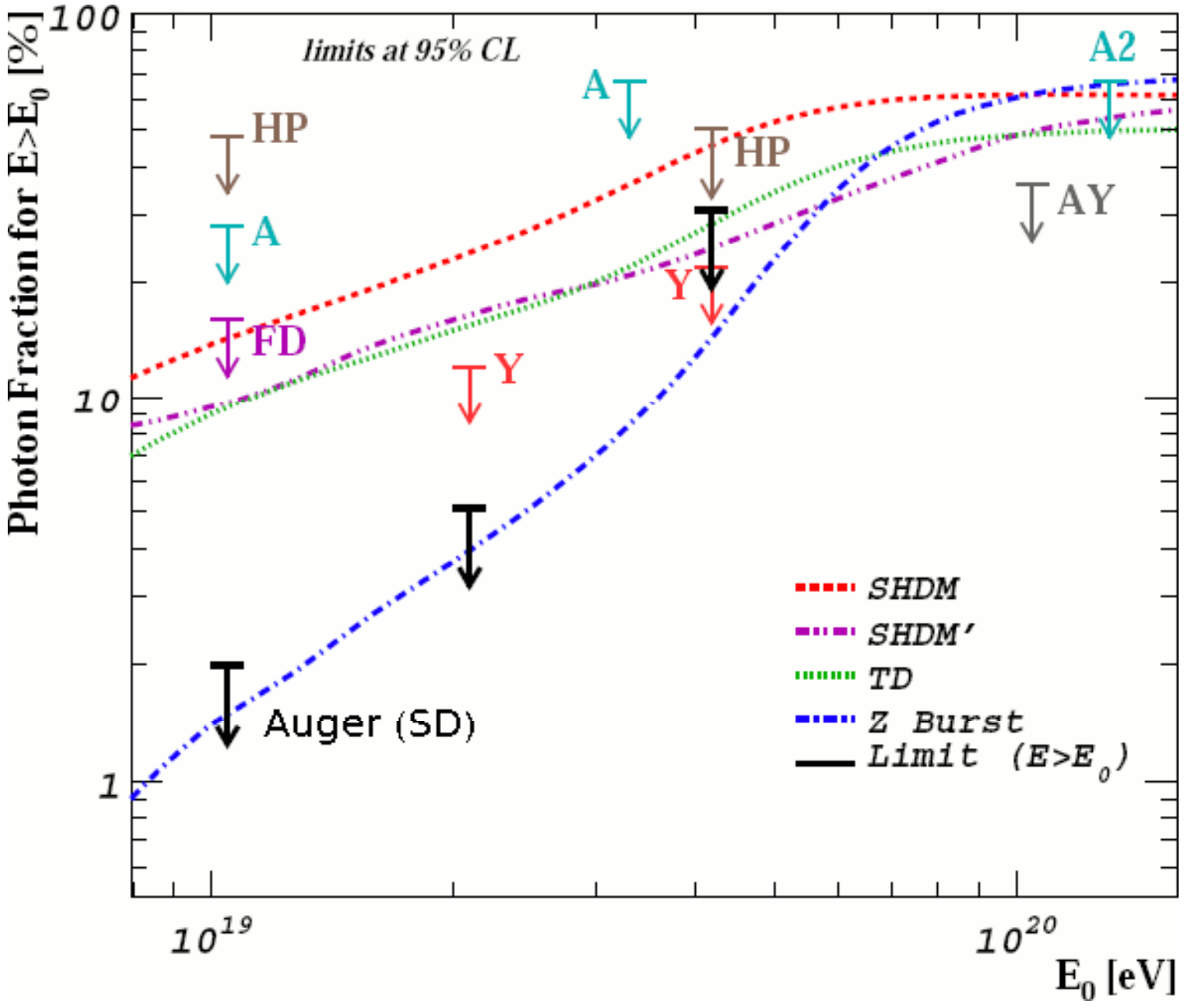

Residuals from a standard spectrum
J/(AxE^-2.6) −1
2
1
0
−1
-3.30 ± 0.06
-2.62 ± 0.03
- 4.1 ± 0.4
18.65
19.55
18
18.5
19
19.5
20
log(E [eV])

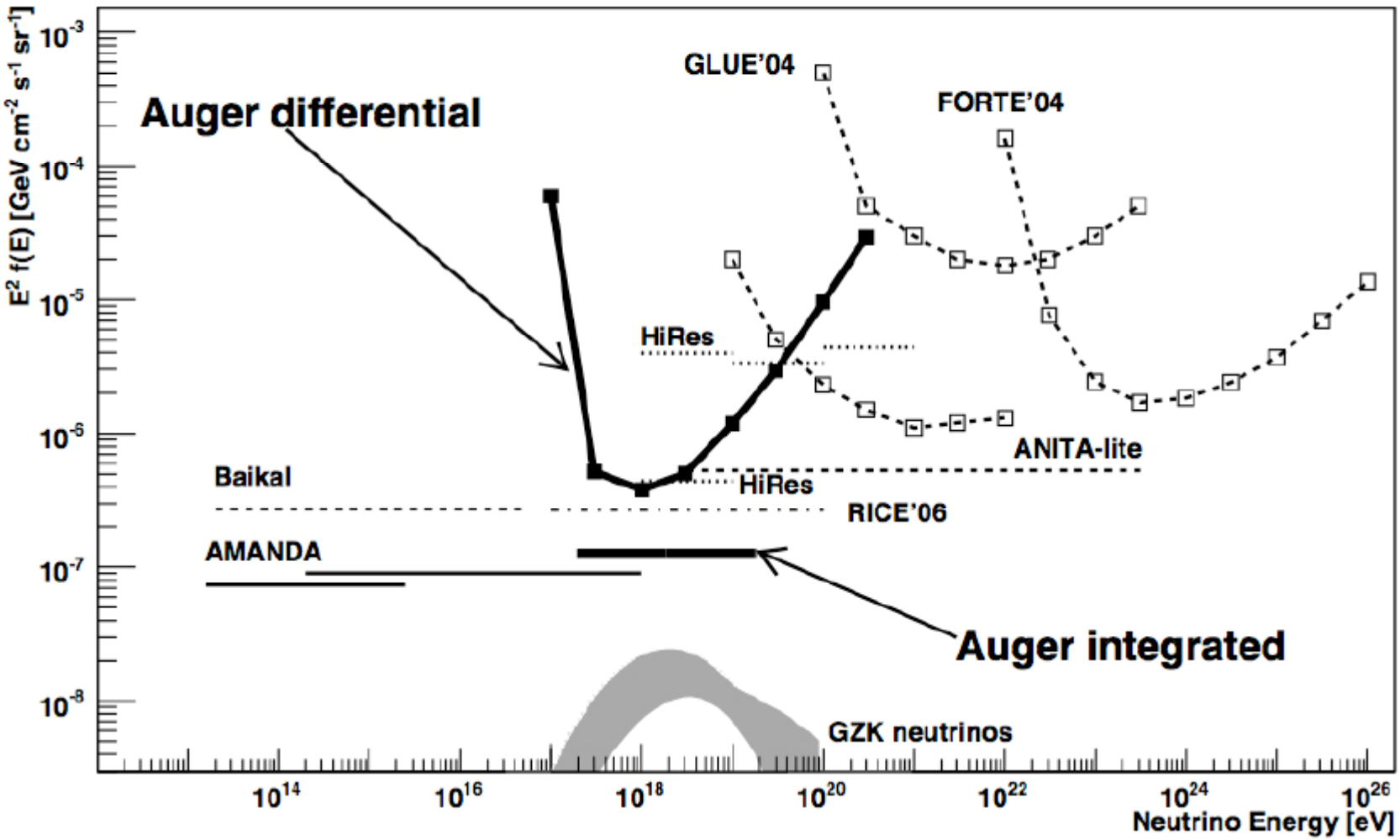

HiResI
HiResII
Auger 2007
x 2
J/(AxE^-2.6) -1
log(E [eV])
3
2
1
0
−1
18
18.5
19
19.5
20


SD vertical
SD inclined
Hybrid
log(JxE^3 [m^-2 s^-1 eV^2])
log(E [eV])
25
24.5
24
23.5
18
18.5
19
19.5
20

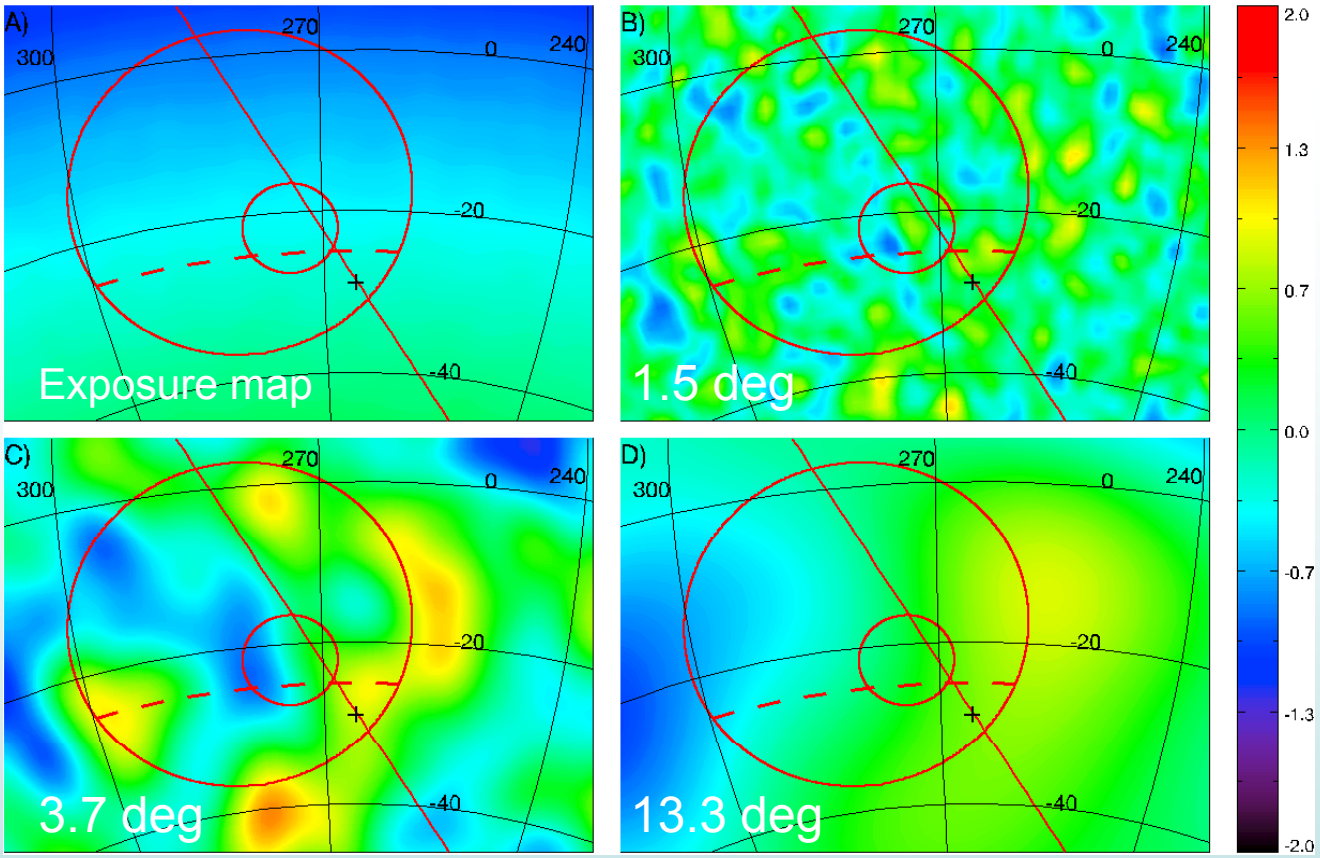

$X_{max}$
photons
< 2% above 10 EeV
protons
Data
Fe
Also tau-neutrino limit
Energy per nucleon is crucial
Energy


Auger ICRC07
proton
iron
QGSJETII-03
QGSJET01
SIBYLL2.1
EPOS1.6
278
410
511
489
454
402
325
307
241
272
185
114
74
30
13
850
800
750
700
650
$10^{18}$
$10^{19}$
$\langle X_{max} \rangle$ [g/cm$^2$]
E [eV]


limits at 95% CL
Photon Fraction for E>E0 [%]
100
10
1
HP
A
FD
Y
A
HP
Y
A2
AY
Auger (SD)
SHDM
SHDM'
TD
Z Burst
Limit (E>E0)
10^19
10^20
E0 [eV]


Auger differential
GLUE'04
FORTE'04
HiRes
ANITA-lite
HiRes
Baikal
RICE'06
AMANDA
Auger integrated
GZK neutrinos
E² f(E) [GeV cm⁻² s⁻¹ sr⁻¹]
Neutrino Energy [eV]
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10¹⁴
10¹⁶
10¹⁸
10²⁰
10²²
10²⁴
10²⁶

# Galactic center




**Anisotropy searches (around Galactic center)**

**AGASA excess is not confirmed**

**Searches considering a systematic energy shift between AGASA and Auger show no excess**

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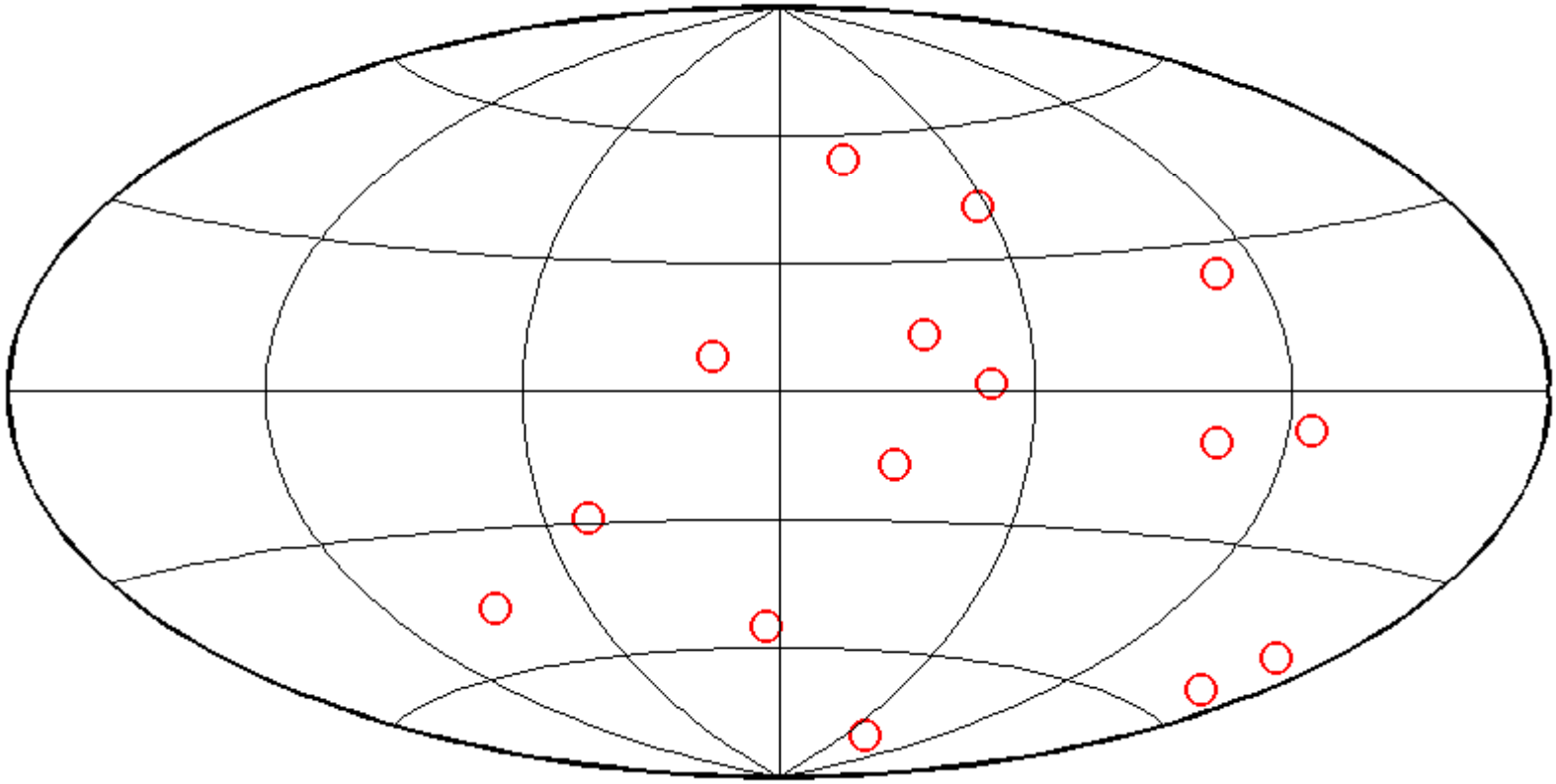
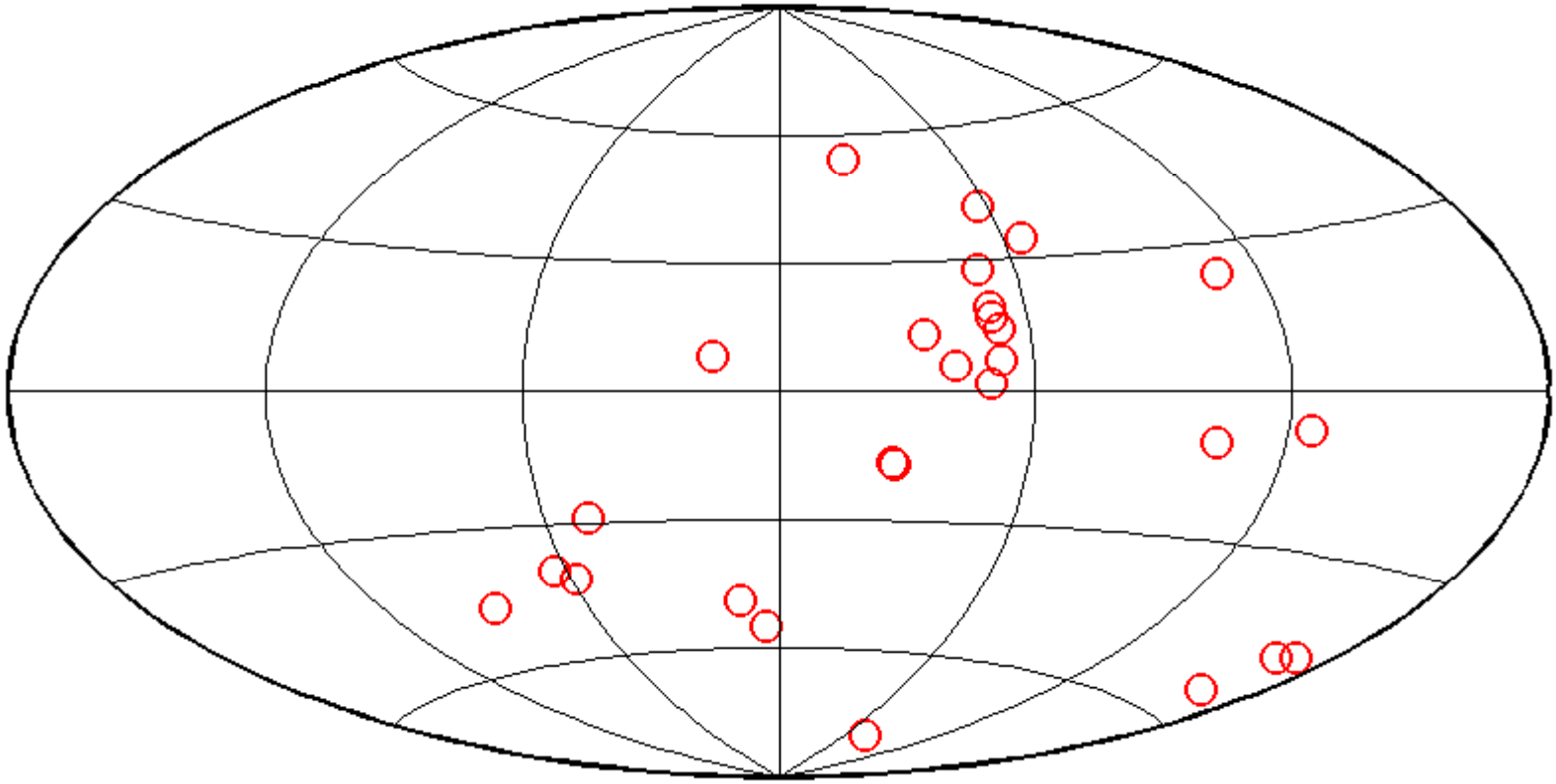
# “Discovery of the year?”



**AGASA-like situation before the start of operation of Auger**

# “Discovery of the year !”



**Particles with highest energies do not arrive isotropically.**

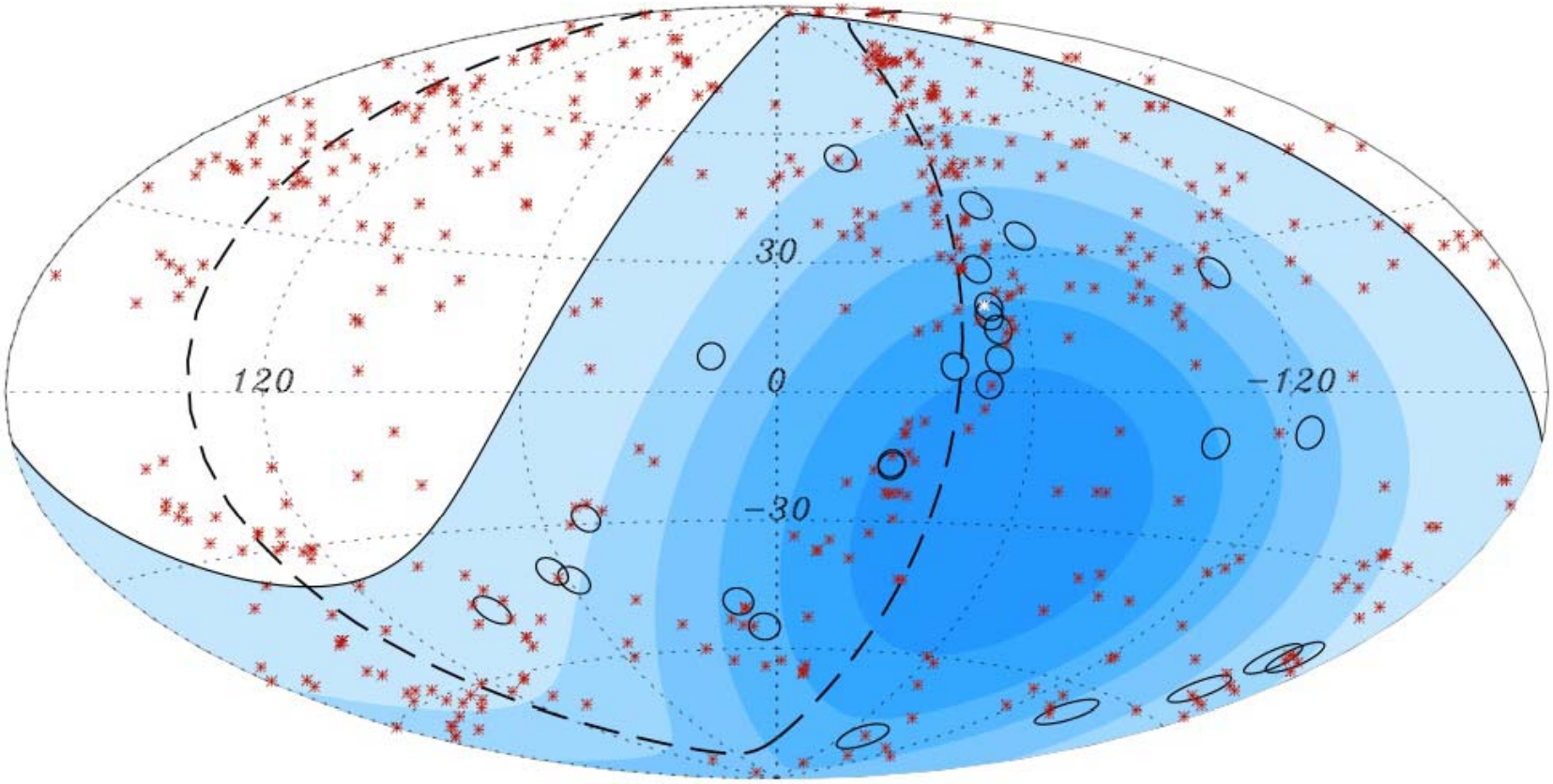
*Is observed distribution in agreement with distribution of any type of known astrophysical objects?*

9 November 2007 | $10

# Science

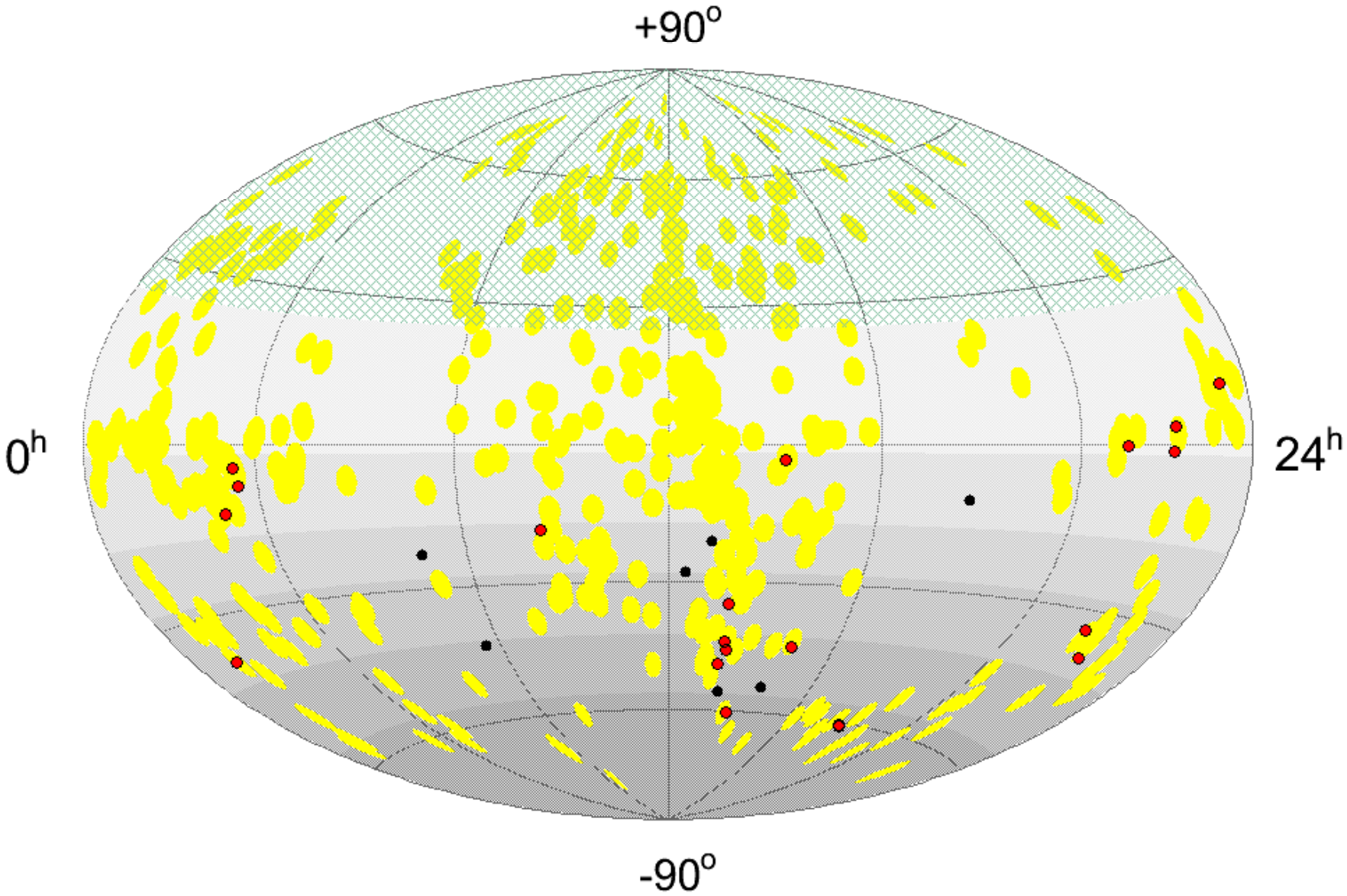
AAAS

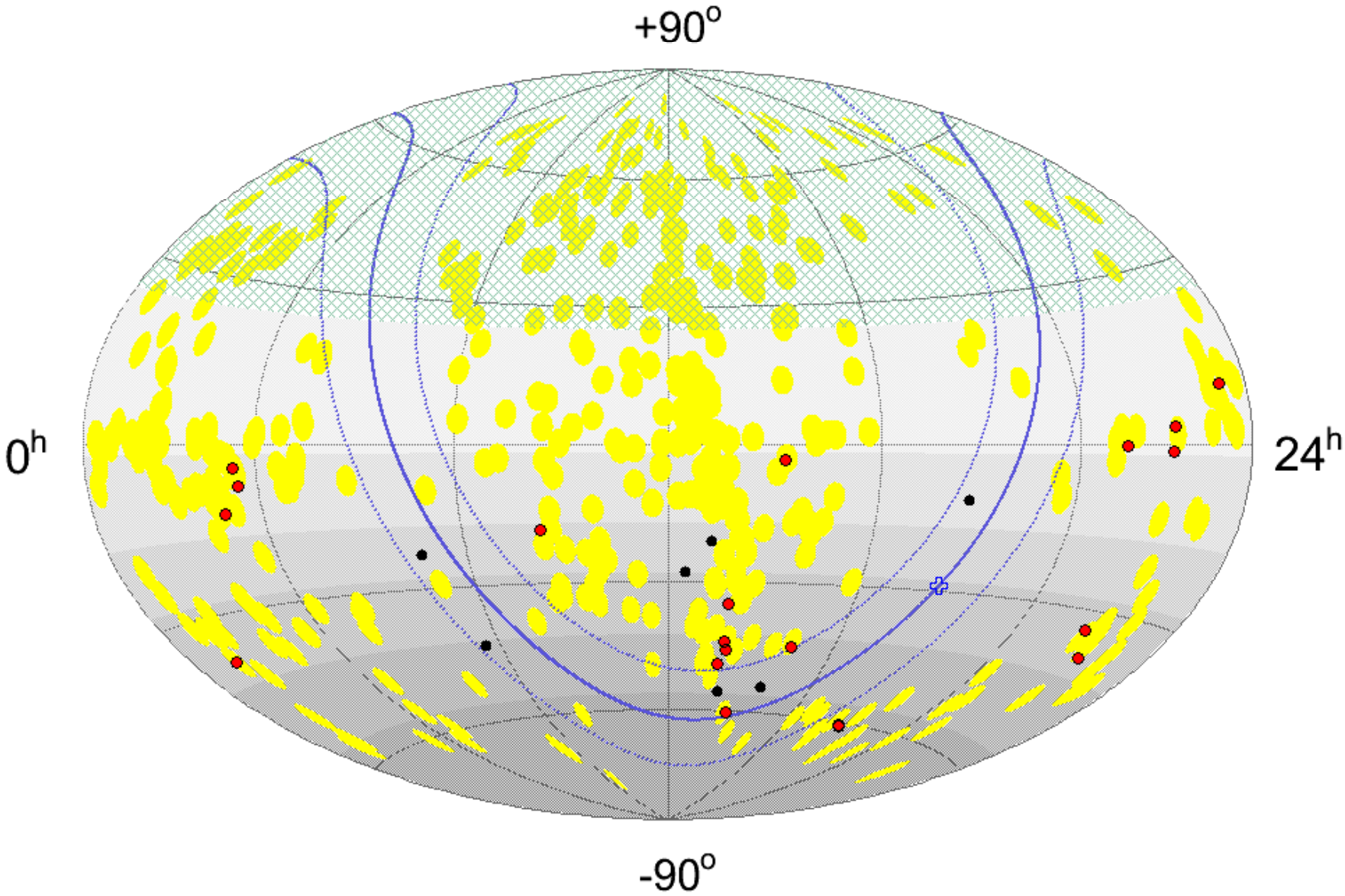
# Yes! The best agreement is with the distribution of nearby active galaxies.

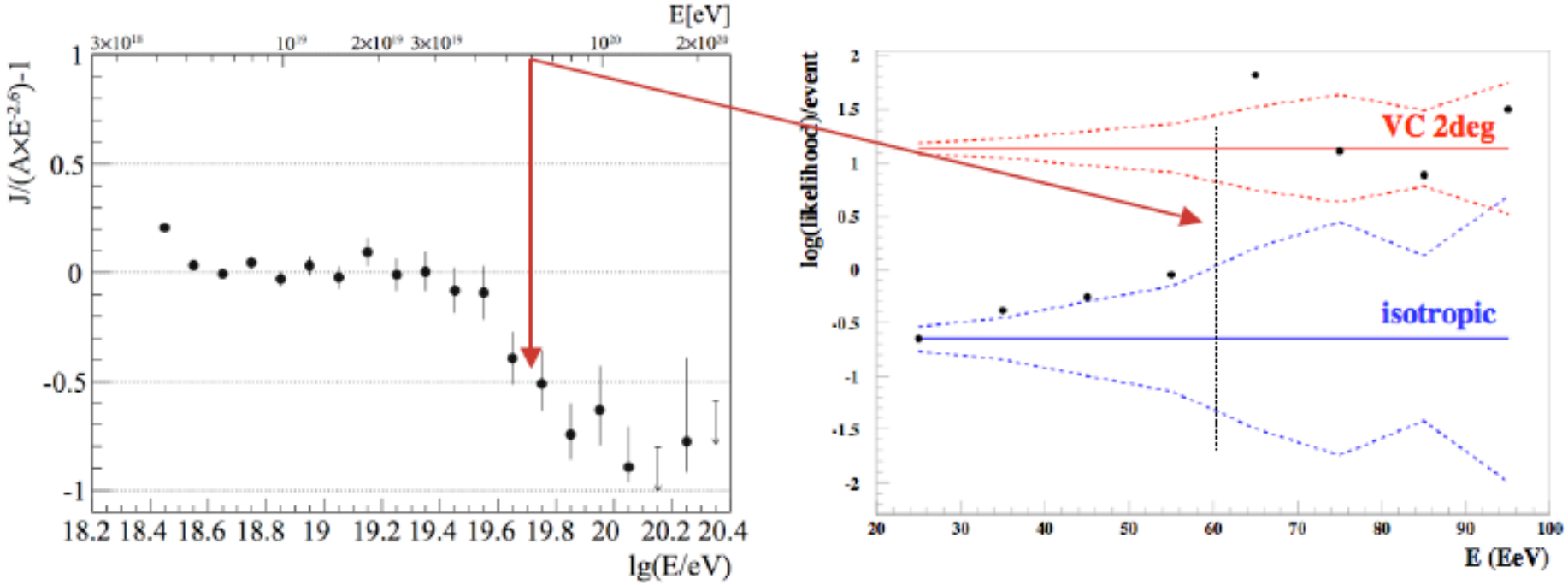



Blue – visible part of the sky
Red stars – active galactic nuclei (AGNs) with distance < 75 Mpc
– in agreement with our expectations (GZK cutoff)

Less than 1% probability to observe such correlation by chance.

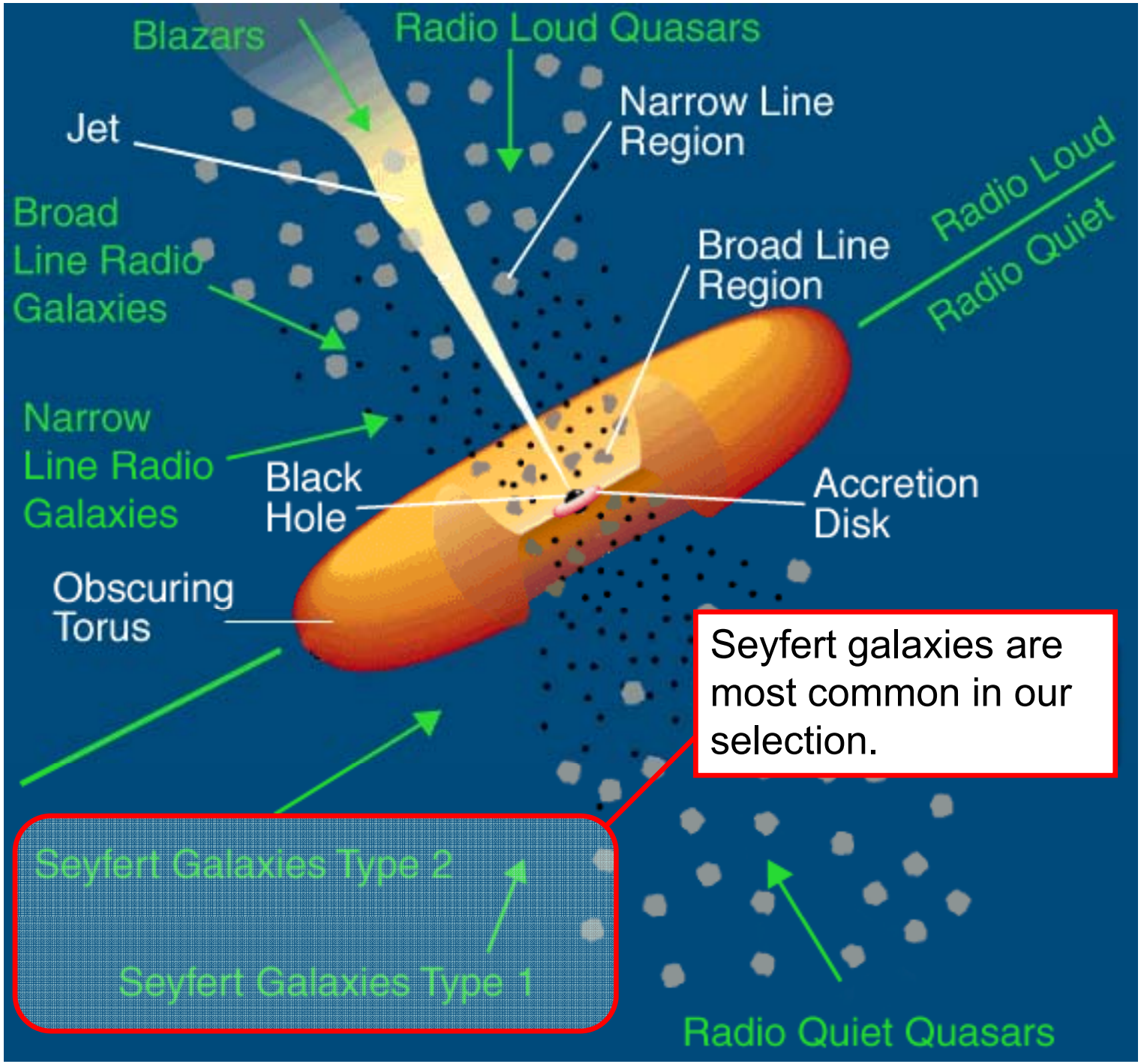



+90°
0h
24h
-90°

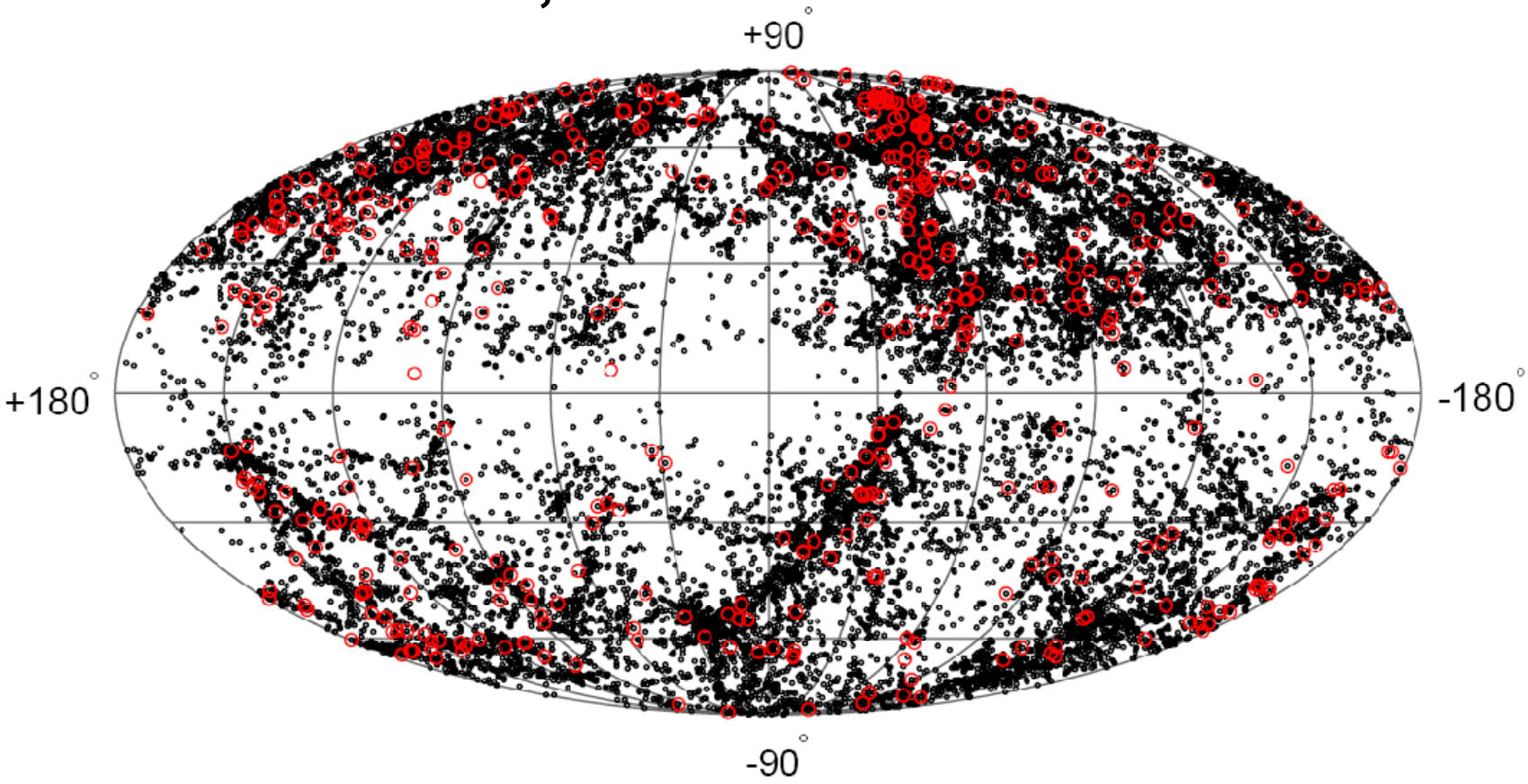

E[eV]
3×10^18
10^19
2×10^19
3×10^19
10^20
2×10^20
J/(A×E^-2.6)-1
1
0.5
0
-0.5
-1
18.2 18.4 18.6 18.8 19 19.2 19.4 19.6 19.8 20 20.2 20.4
lg(E/eV)
log(likelihood)/event
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
VC 2deg
isotropic
20 30 40 50 60 70 80 90 100
E (EeV)

# So, what are active galactic nuclei?

- galaxies with supermassive black holes in their centers; black hole mass in order of $10^7$ - $10^8$ solar masses; enough matter nearby to be swallowed


Blazars
Radio Loud Quasars
Jet
Narrow Line Region
Broad Line Radio Galaxies
Broad Line Region
Radio Loud
Radio Quiet
Narrow Line Radio Galaxies
Black Hole
Accretion Disk
Obscuring Torus
Seyfert Galaxies are most common in our selection.
Seyfert Galaxies Type 2
Seyfert Galaxies Type 1
Radio Quiet Quasars

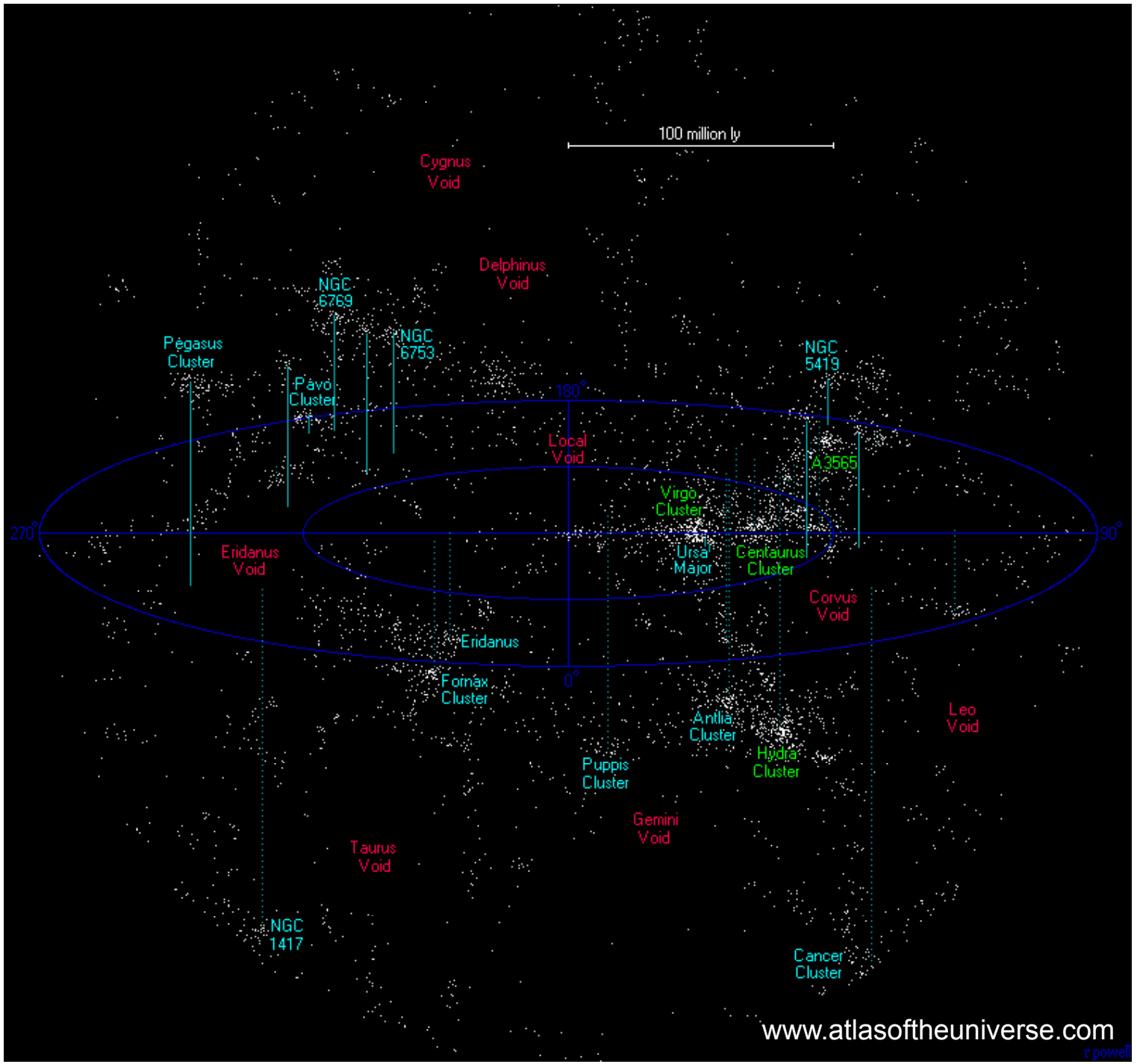
# However, we have to be careful…

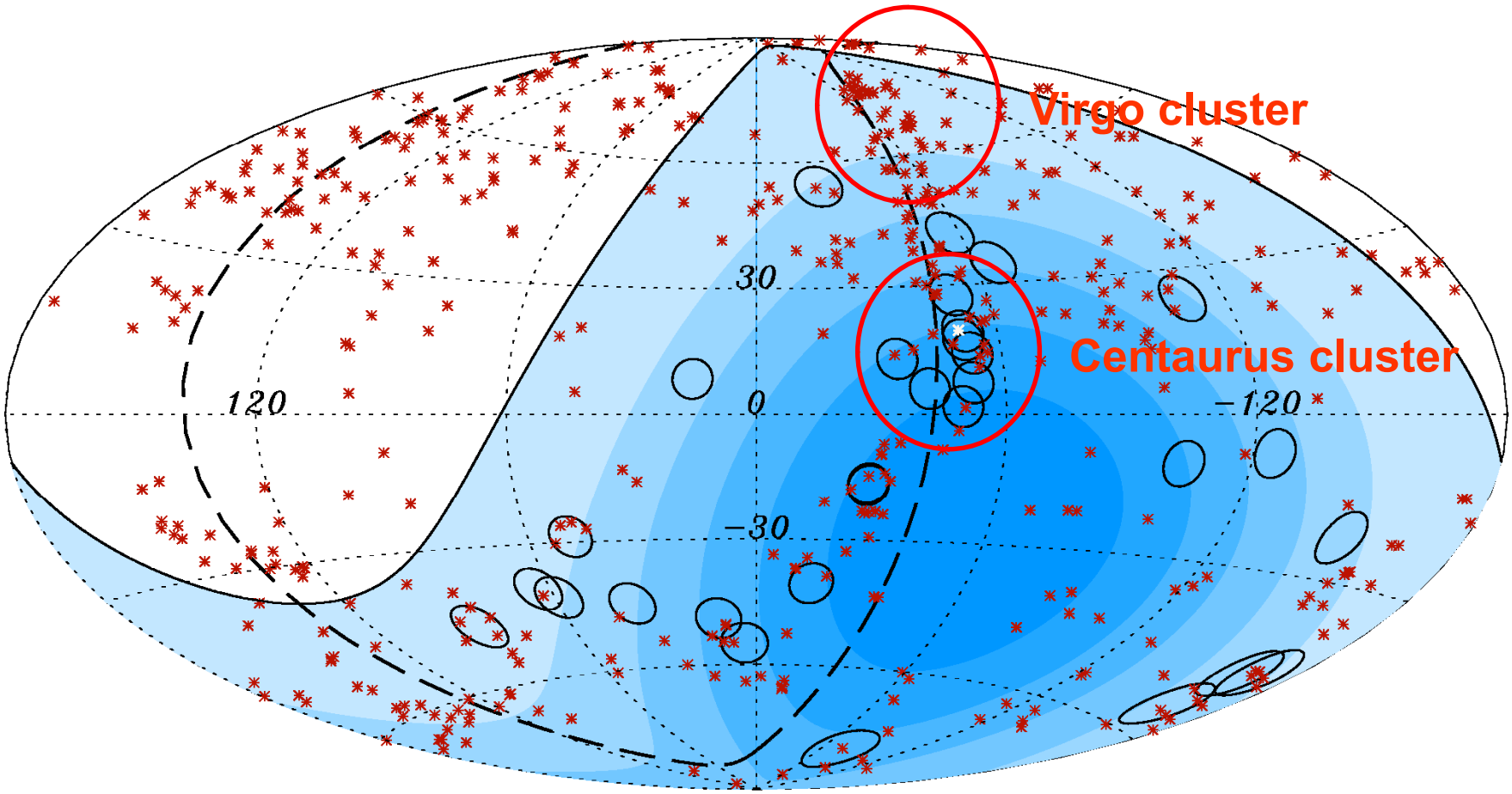



Red circles – (again) AGNs closer than 75 Mpc
Black dots – all galaxies closer than 75 Mpc (HyperLEDA catalogue)

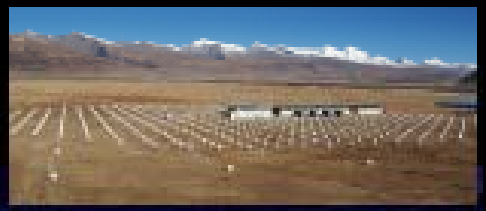
Distribution of ordinary galaxies (and matter in general) and of AGNs is very similar!

So, our first guess that the particles with the highest energies come from AGNs is not correct → we need more data from both South and North ...

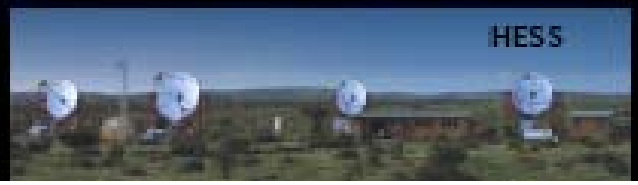

100 million ly
Cygnus Void
Delphinus Void
NGC 6769
NGC 6753
Pegasus Cluster
Pavo Cluster
NGC 5419
180°
Local Void
A3565
Virgo Cluster
270°
90°
Eridanus Void
Ursa Major
Centaurus Cluster
Corvus Void
Eridanus
Fornax Cluster
0°
Antlia Cluster
Leo Void
Hydra Cluster
Puppis Cluster
Gemini Void
Taurus Void
NGC 1417
Cancer Cluster
www.atlasoftheuniverse.com
r.powell

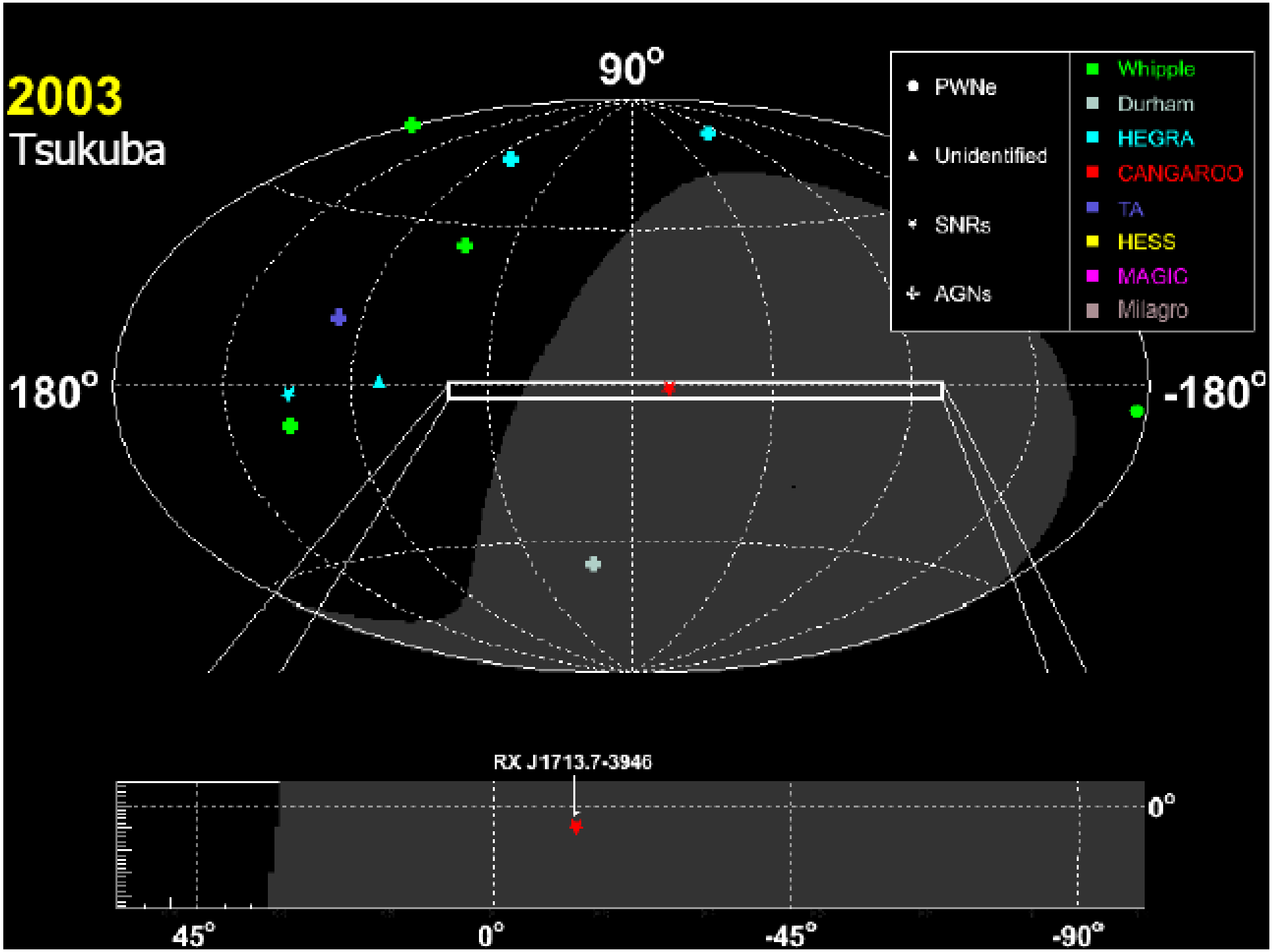

Virgo cluster
Centaurus cluster
30
0
−30
120
−120

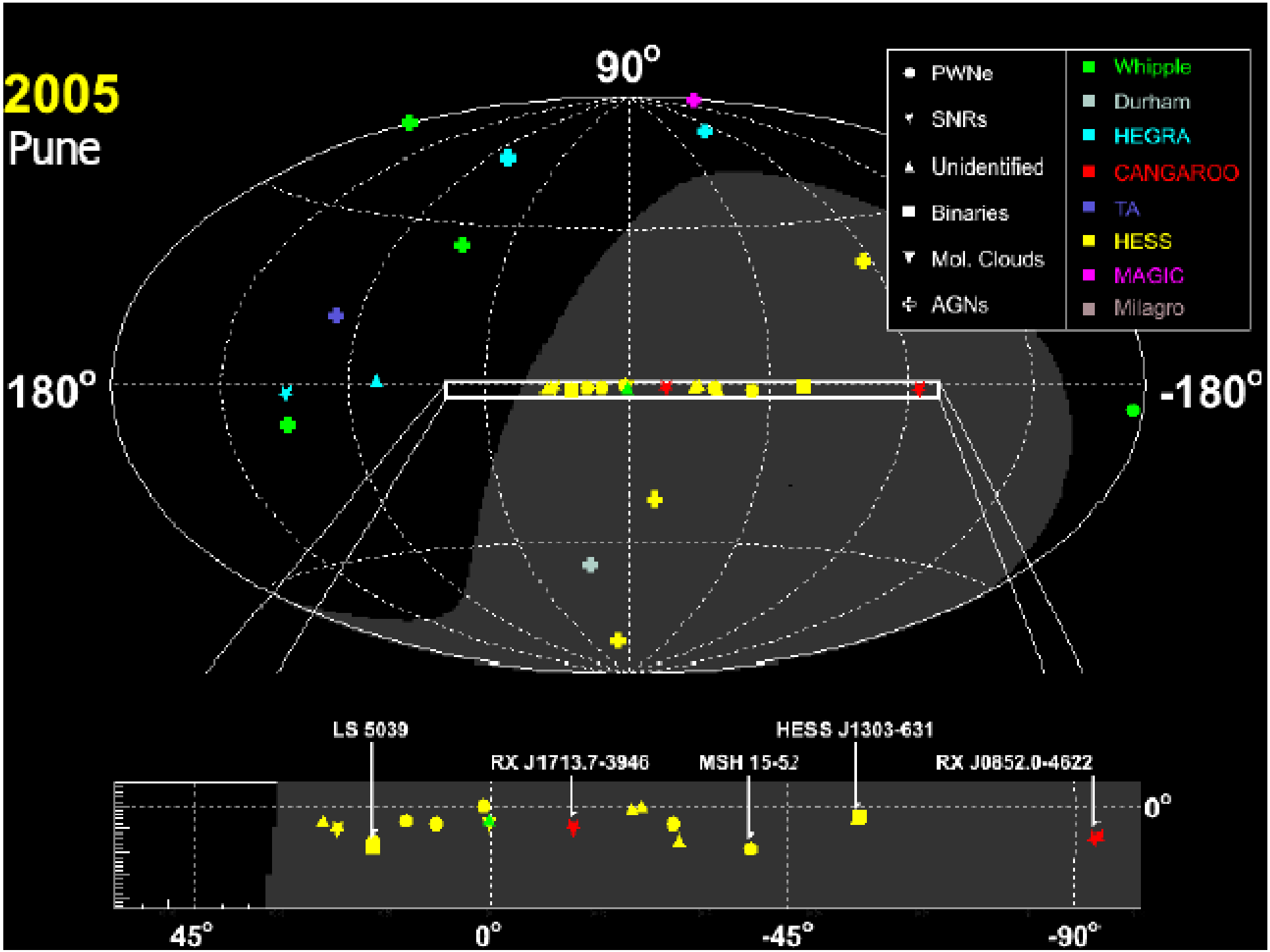
# VHE Instruments

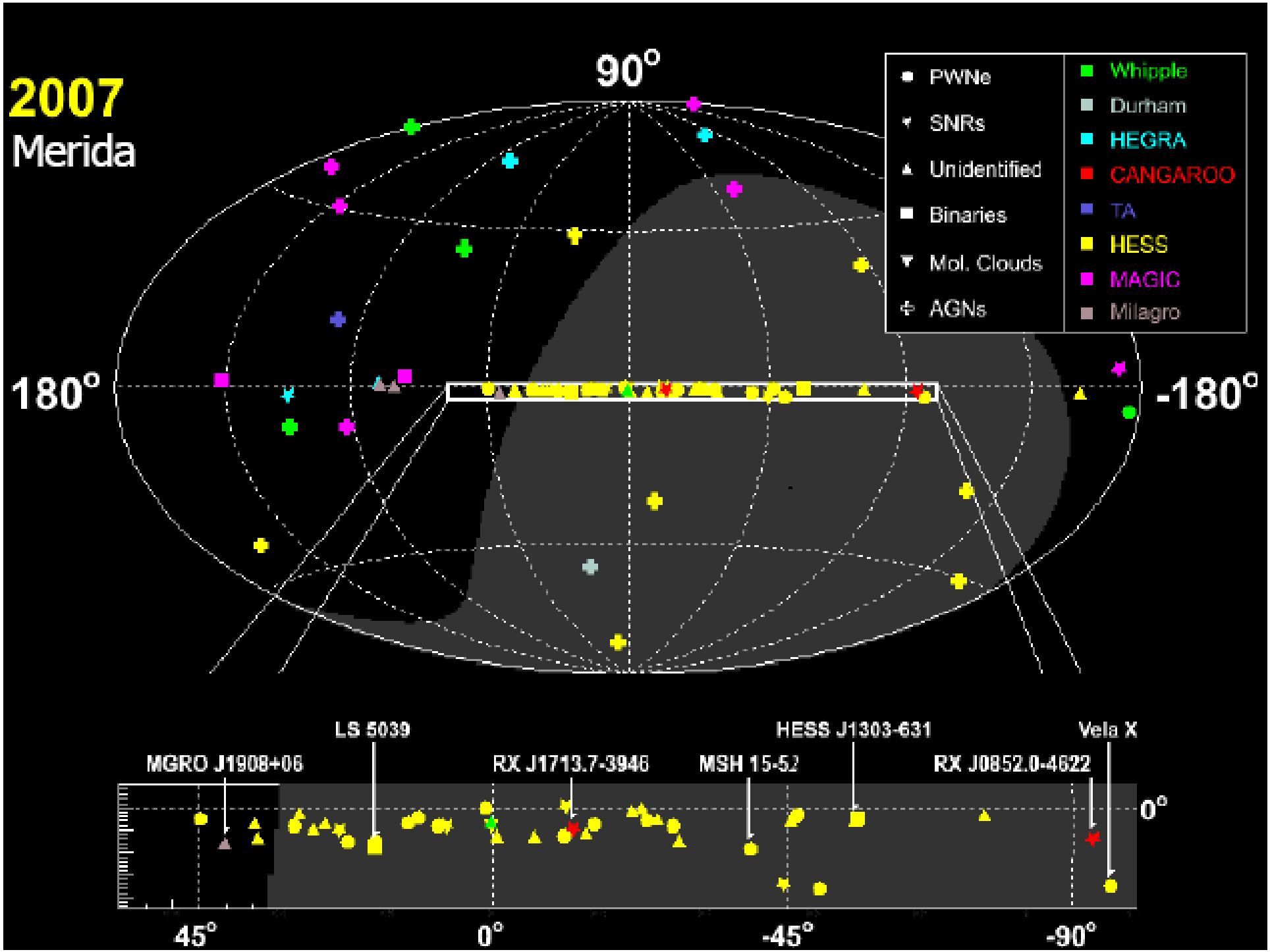


- Ong 2005

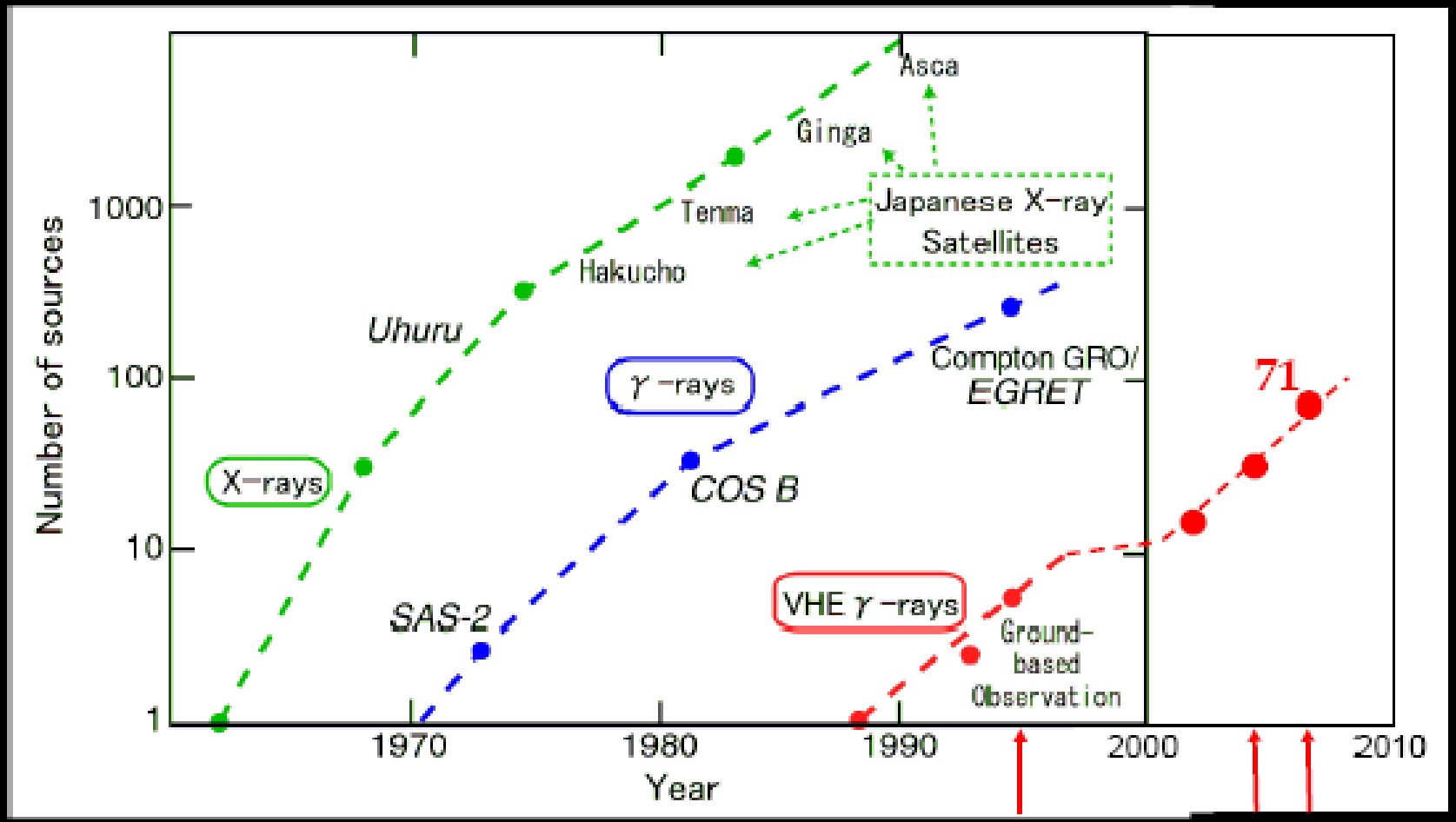



2003
Tsukuba
90°
180°
-180°
PWNe
Unidentified
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
RX J1713.7-3946
0°
45°
0°
-45°
-90°


2005
Pune
90°
180°
-180°
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
0°
45°
0°
-45°
-90°


2007
Merida
90°
180°
-180°
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
HESS J1303-631
Vela X
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
RX J0852.0-4622
0°
45°
0°
-45°
-90°

# KIFUNE PLOT




Source count versus year
[T. Kifune]