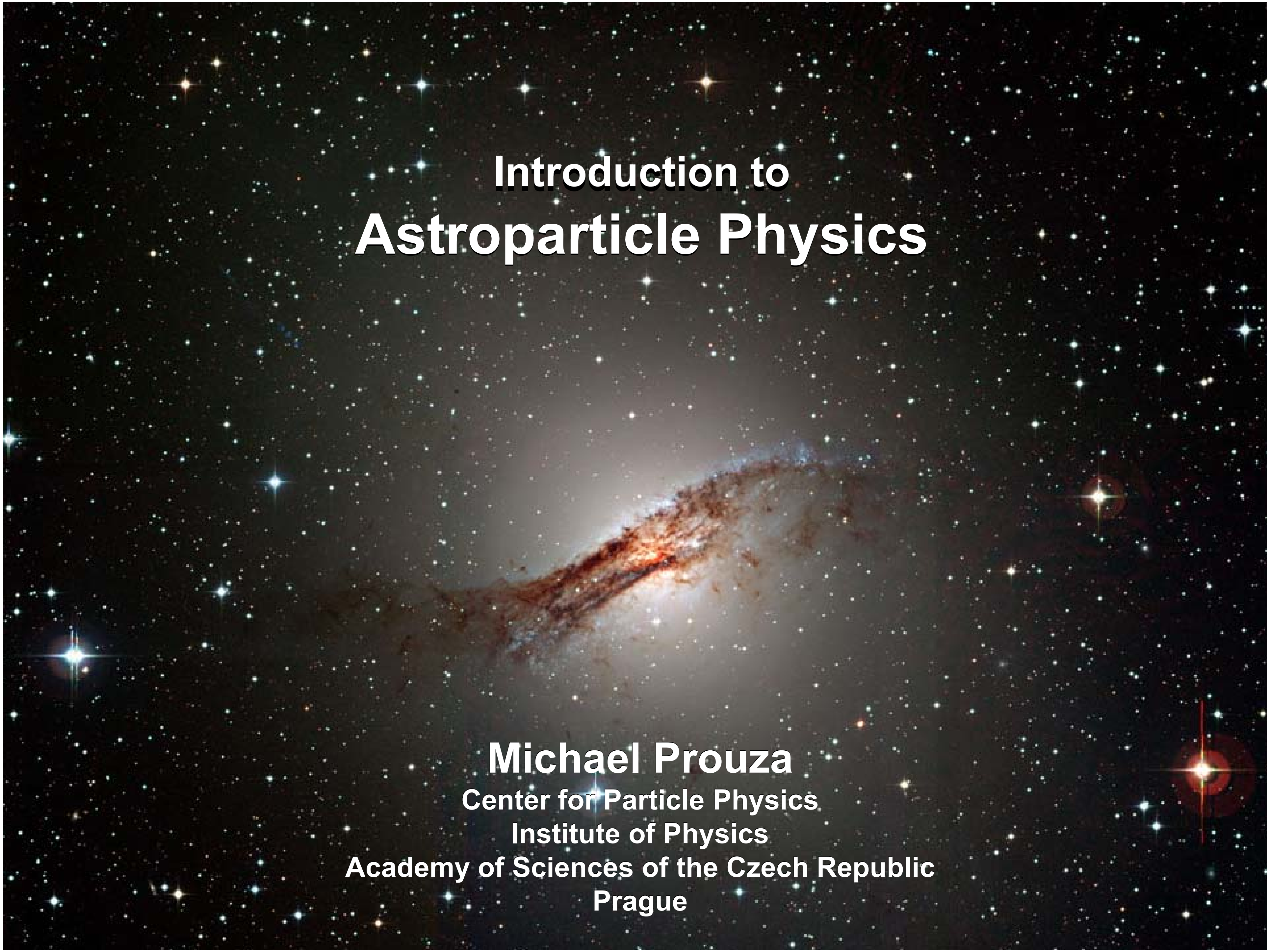
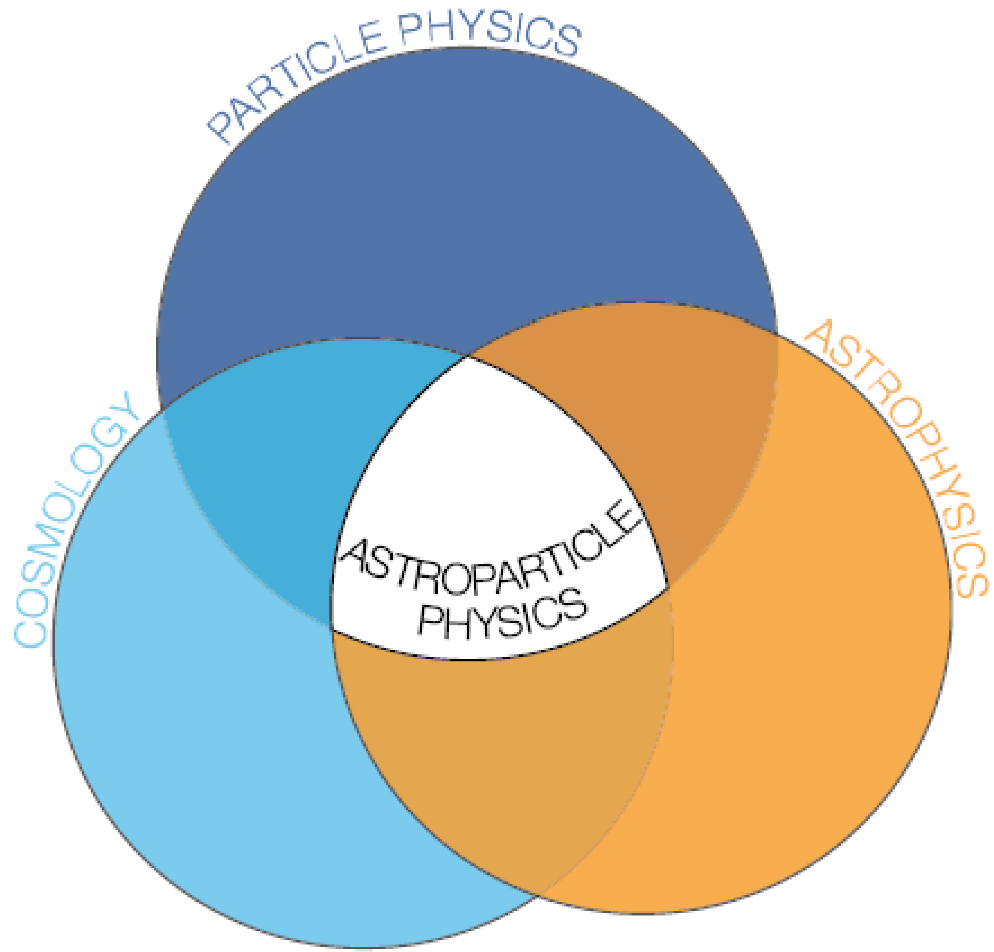


Introduction to Astroparticle Physics

Michael Prouza
Center for Particle Physics
Institute of Physics
Academy of Sciences of the Czech Republic
Prague



ASPERA Roadmap: http://www.aspera-eu.org

Outline

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

What else is part of the astroparticle physics?

- similar technique (as for CR) – different energy range:
  imaging atmospheric Cherenkov telescopes
  (most energetic gamma-rays)

- detectors in ice, water, salt, etc.:
  high energy neutrinos

- dark matter detection

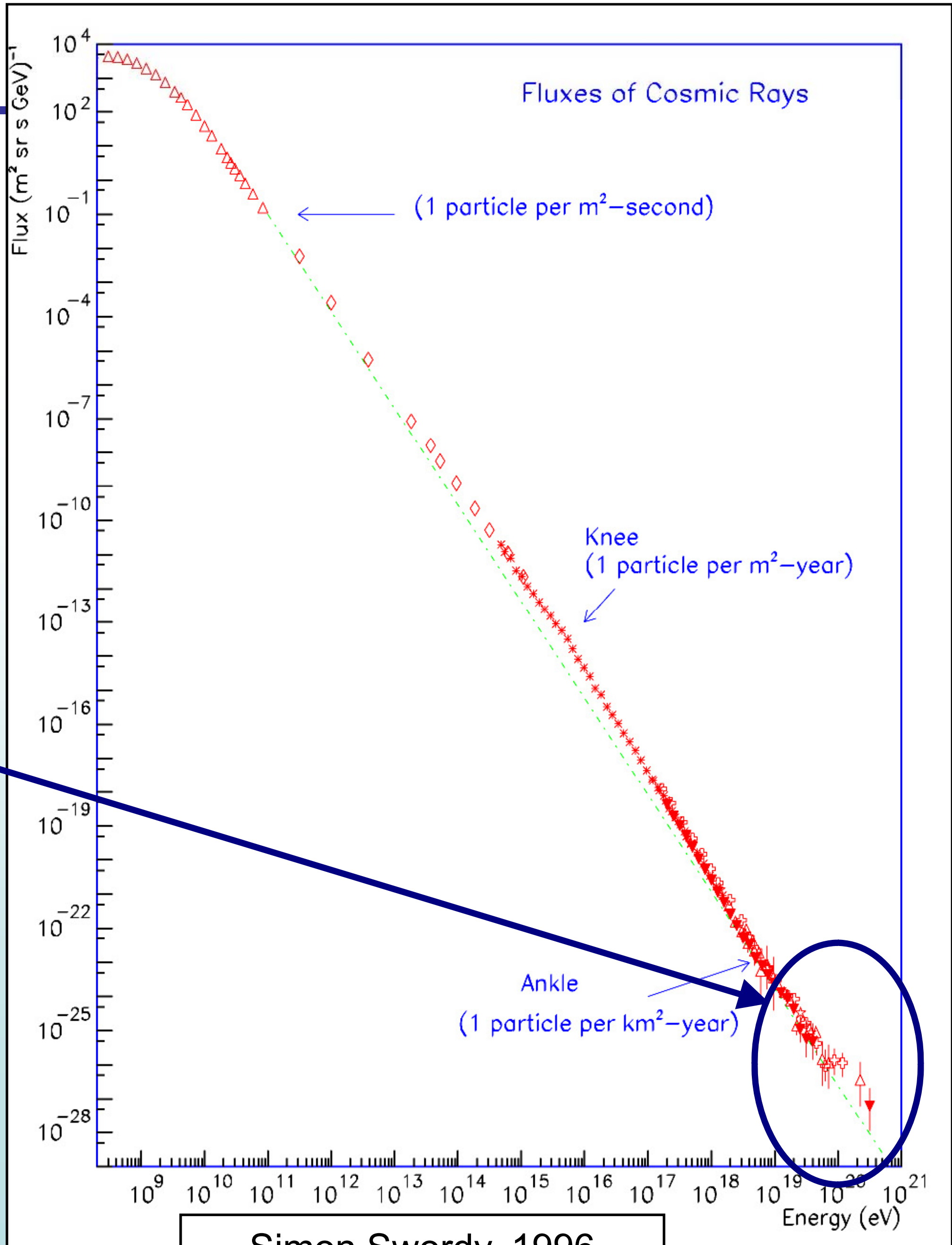
- detectors of gravitational waves

“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

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

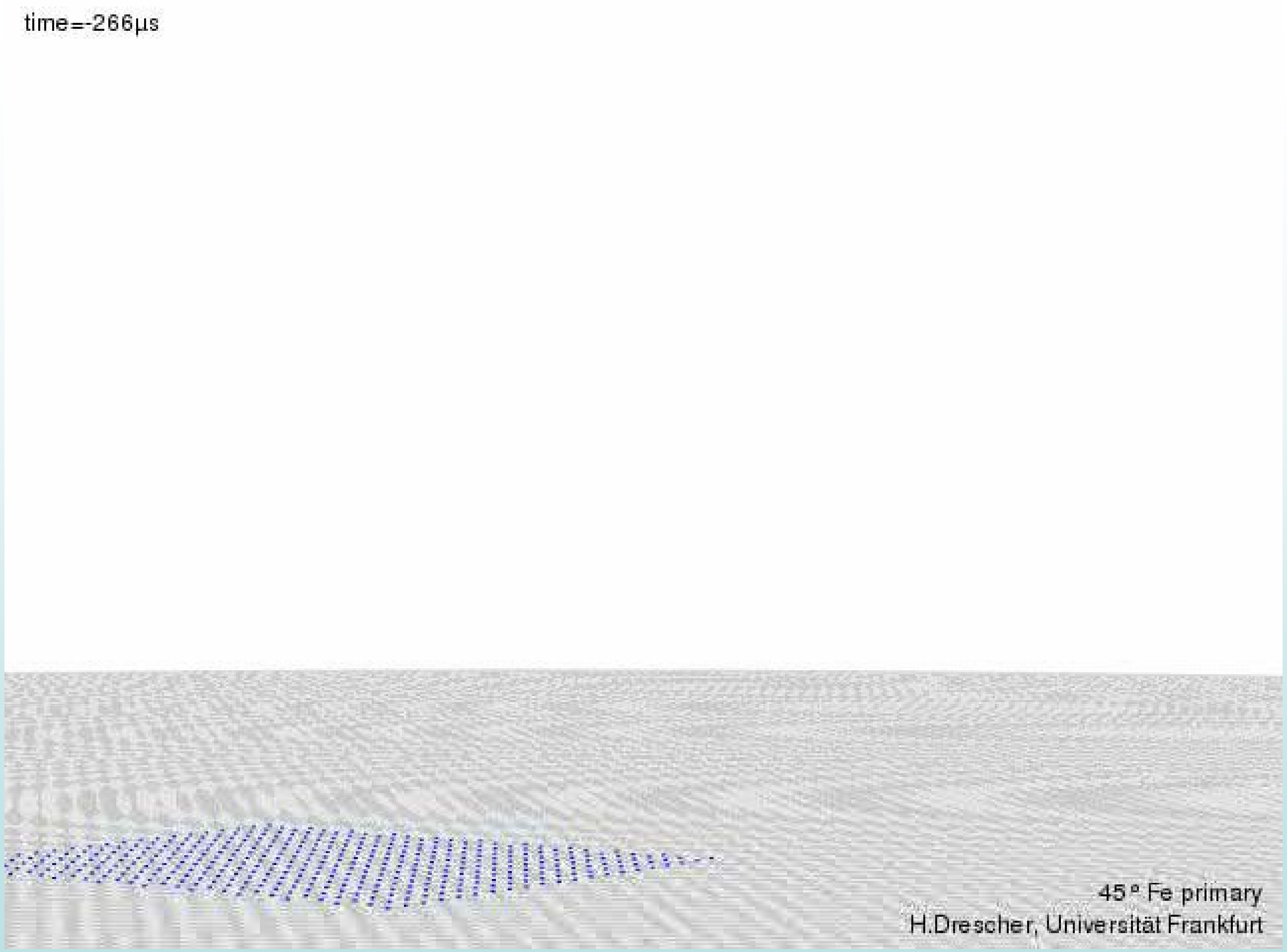
UHECRs are particles with energy above "ankle", say, above 3 x 10^{18} eV.



Simon Swordy, 1996

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

Extensive air showers



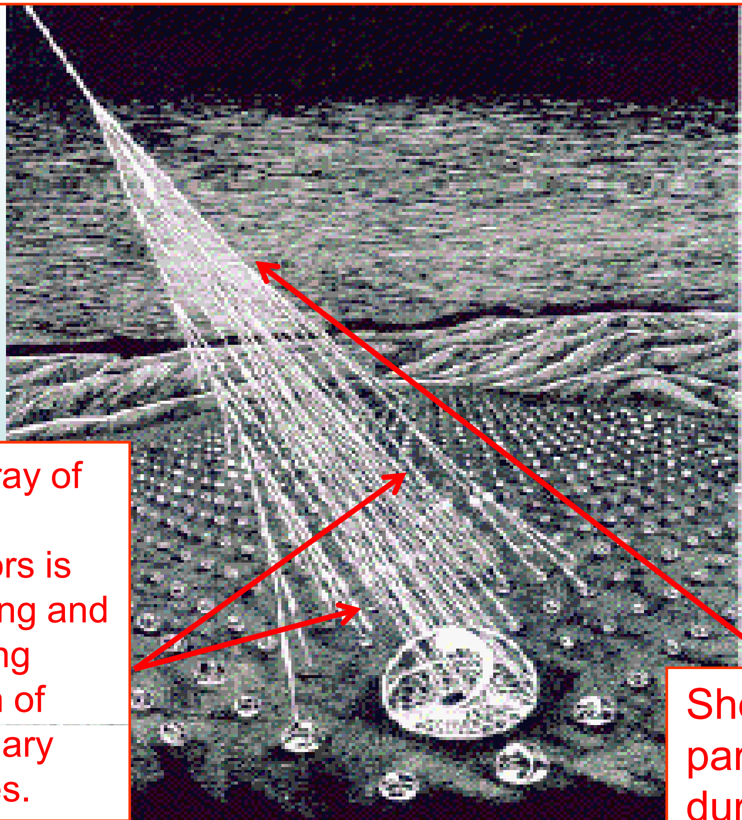
H.-J. Drescher, Frankfurt University

- 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?



- 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.

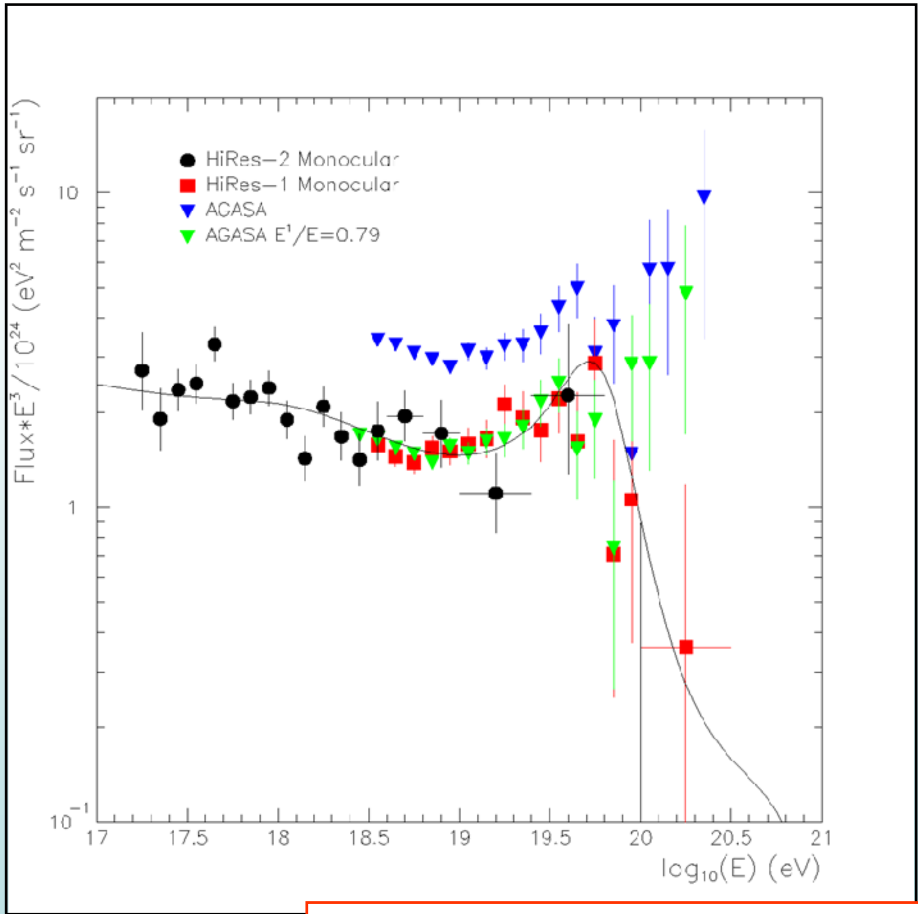
Surface detectors:

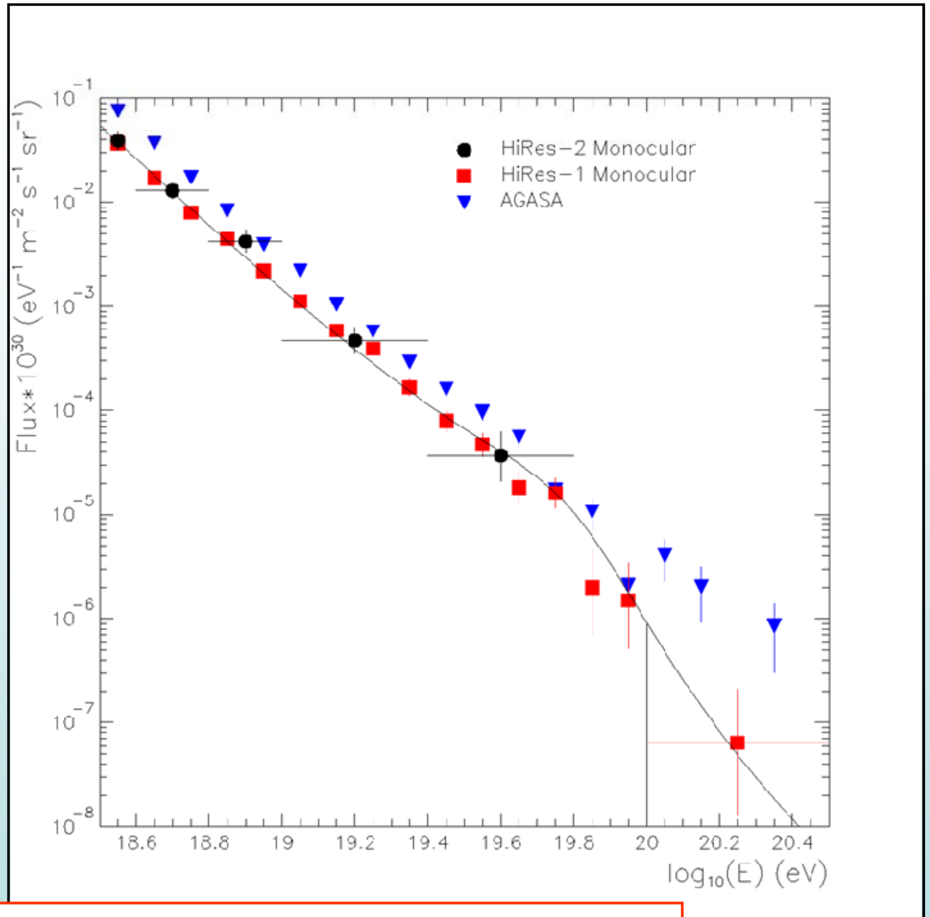
- Volcano Ranch, USA (1959 – 1963)
- SUGAR, Australia (1968 – 1979)
- Haverah Park, UK (1968 – 1987)
- Yakutsk, Russia (1970 – today)
- AGASA, Japan (1990 – 2004)

Fluorescence detectors:

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

GZK or not to GZK: HiRes vs. AGASA

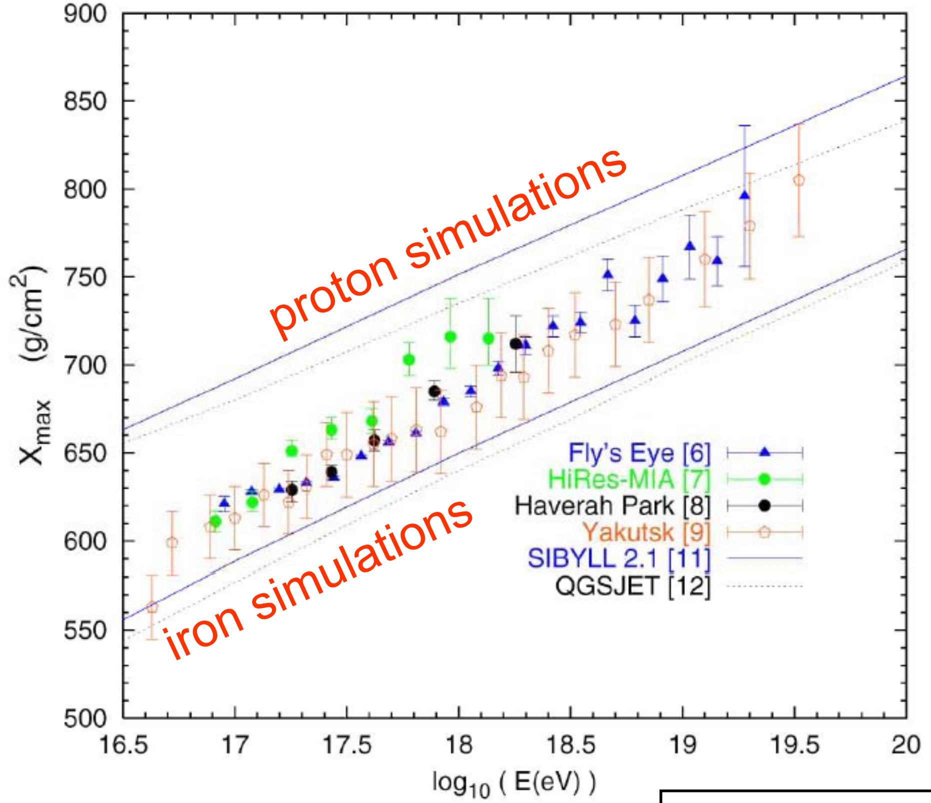




Is there really GZK-cutoff? Where are the sources?

Chemical composition of UHECR

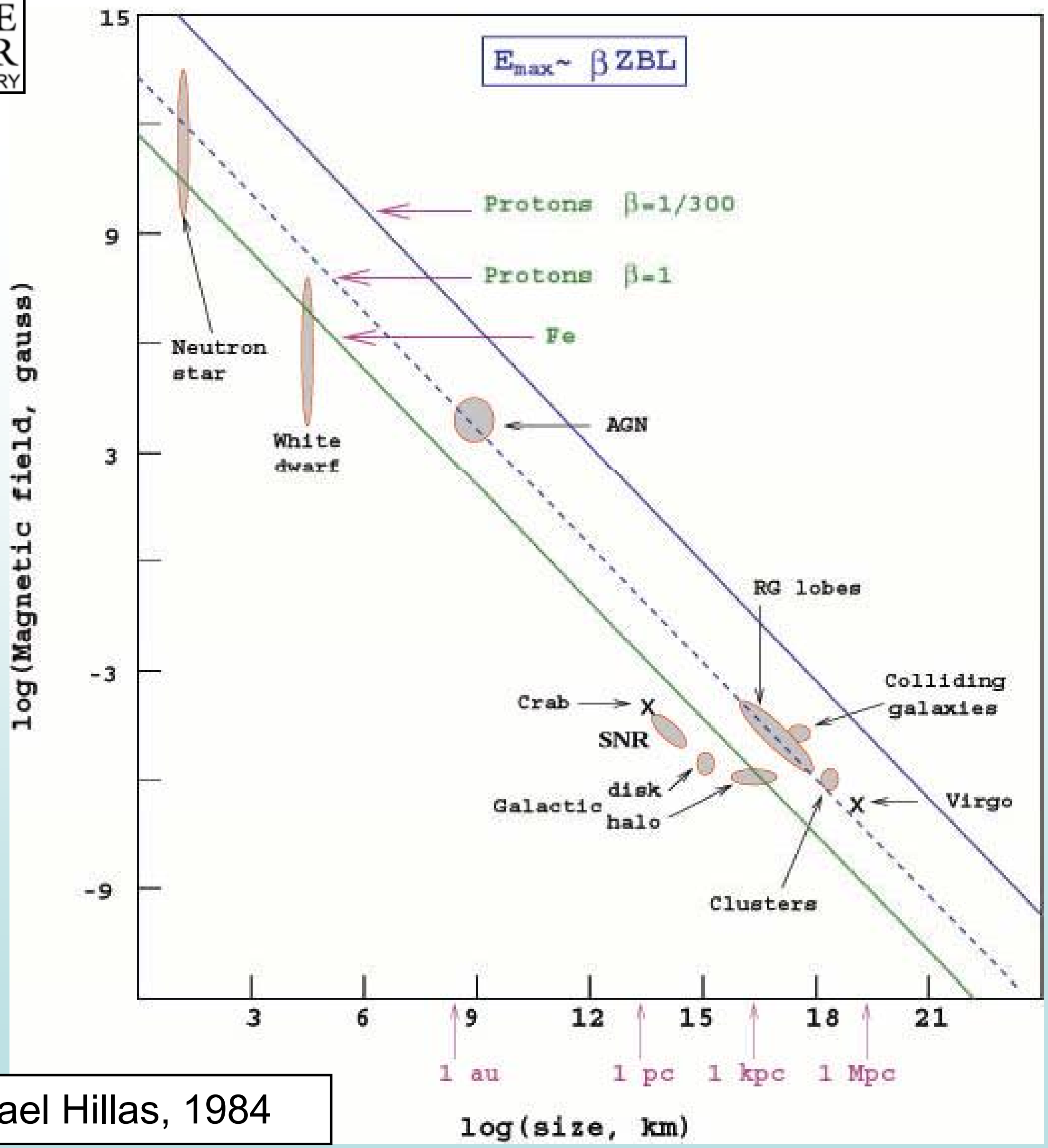
Protons, iron nuclei or mix?
We (once again) don‘t know.



Tom Gaisser, 2000

- **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 !)**

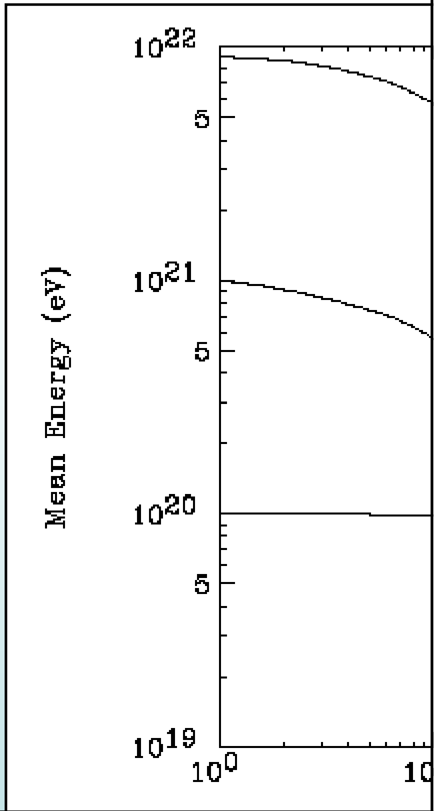
Sites of origin of UHECRs



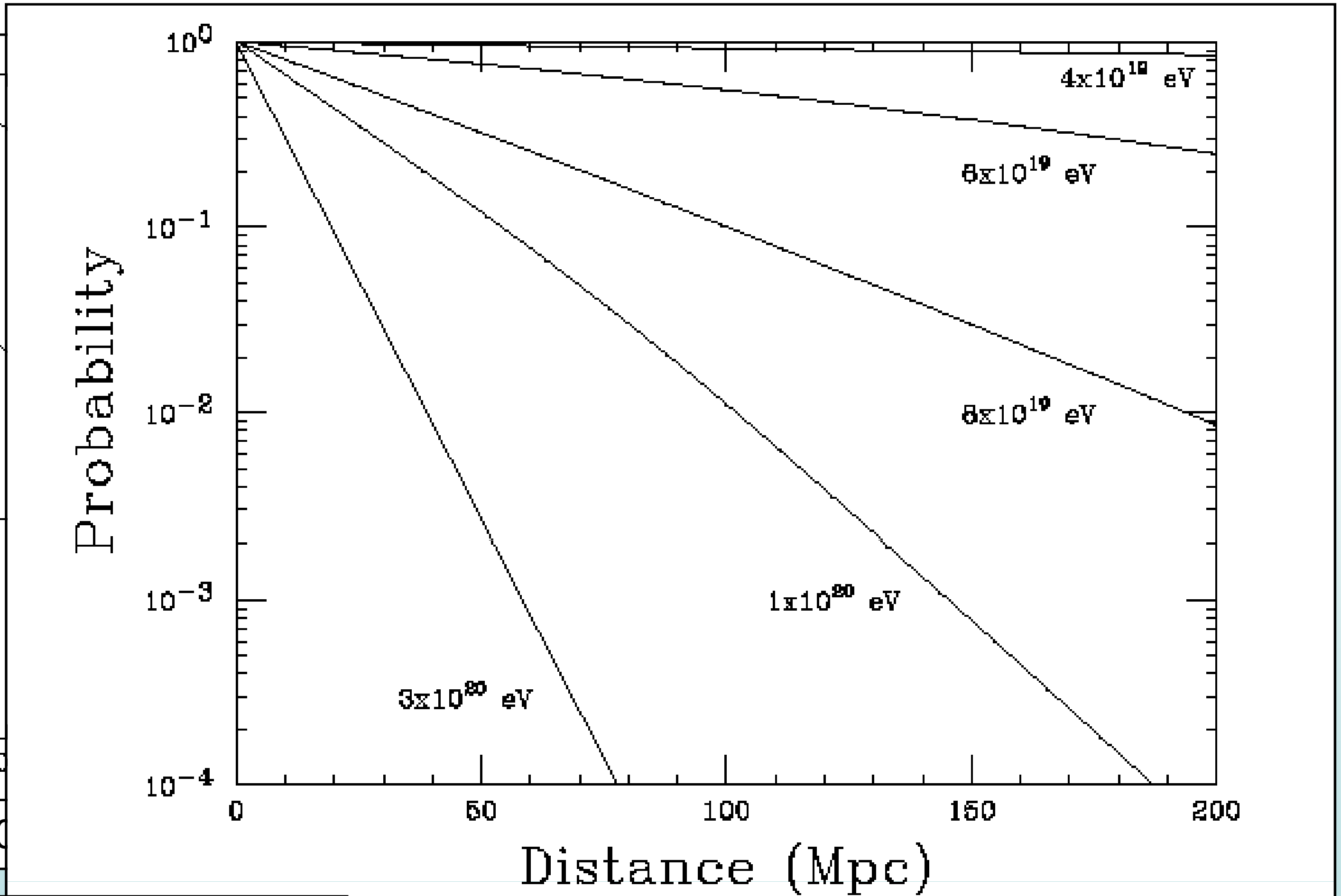
Michael Hillas, 1984

- 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



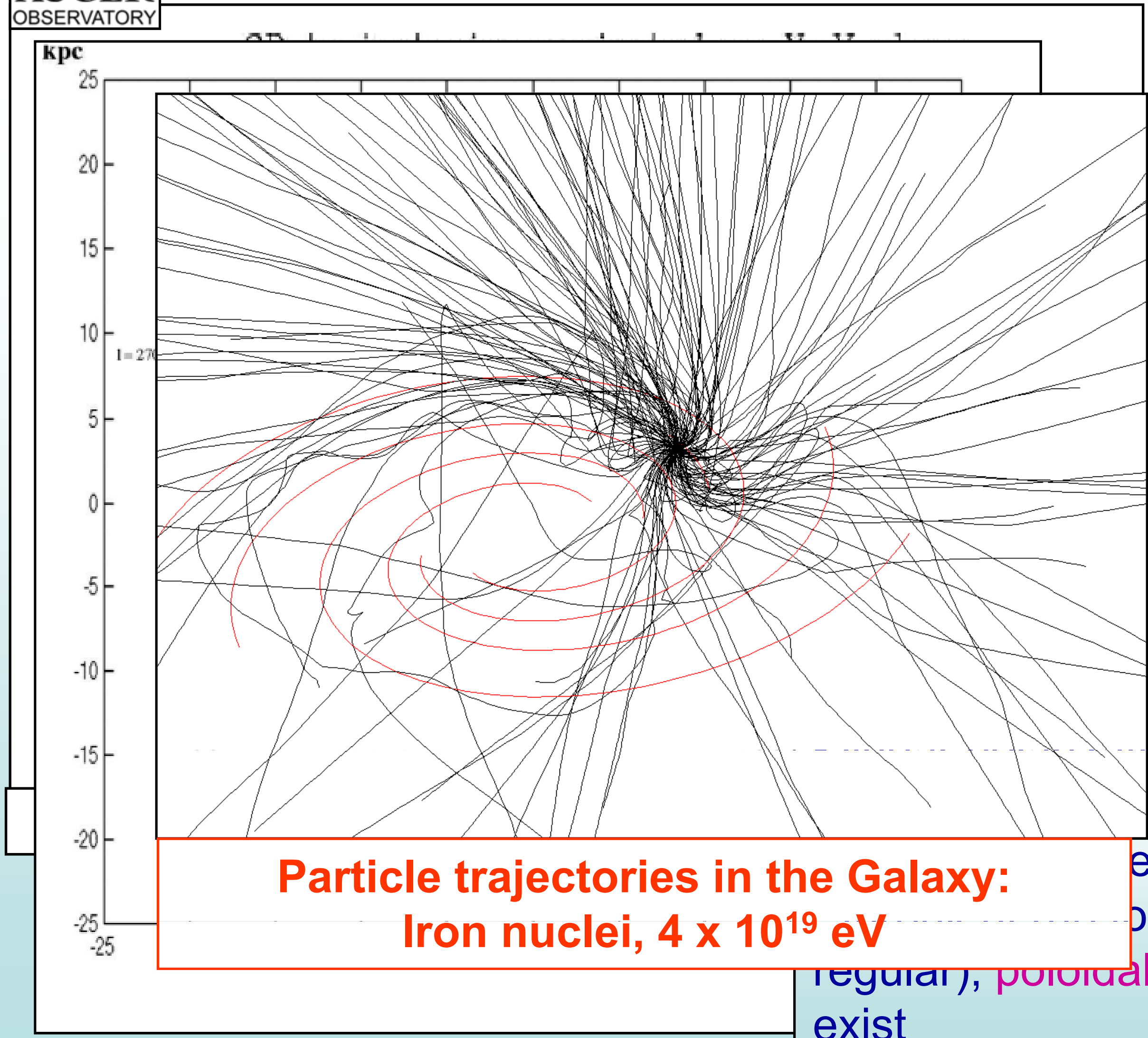
James W. Cronin, 200



Paul Sommers, 2003

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

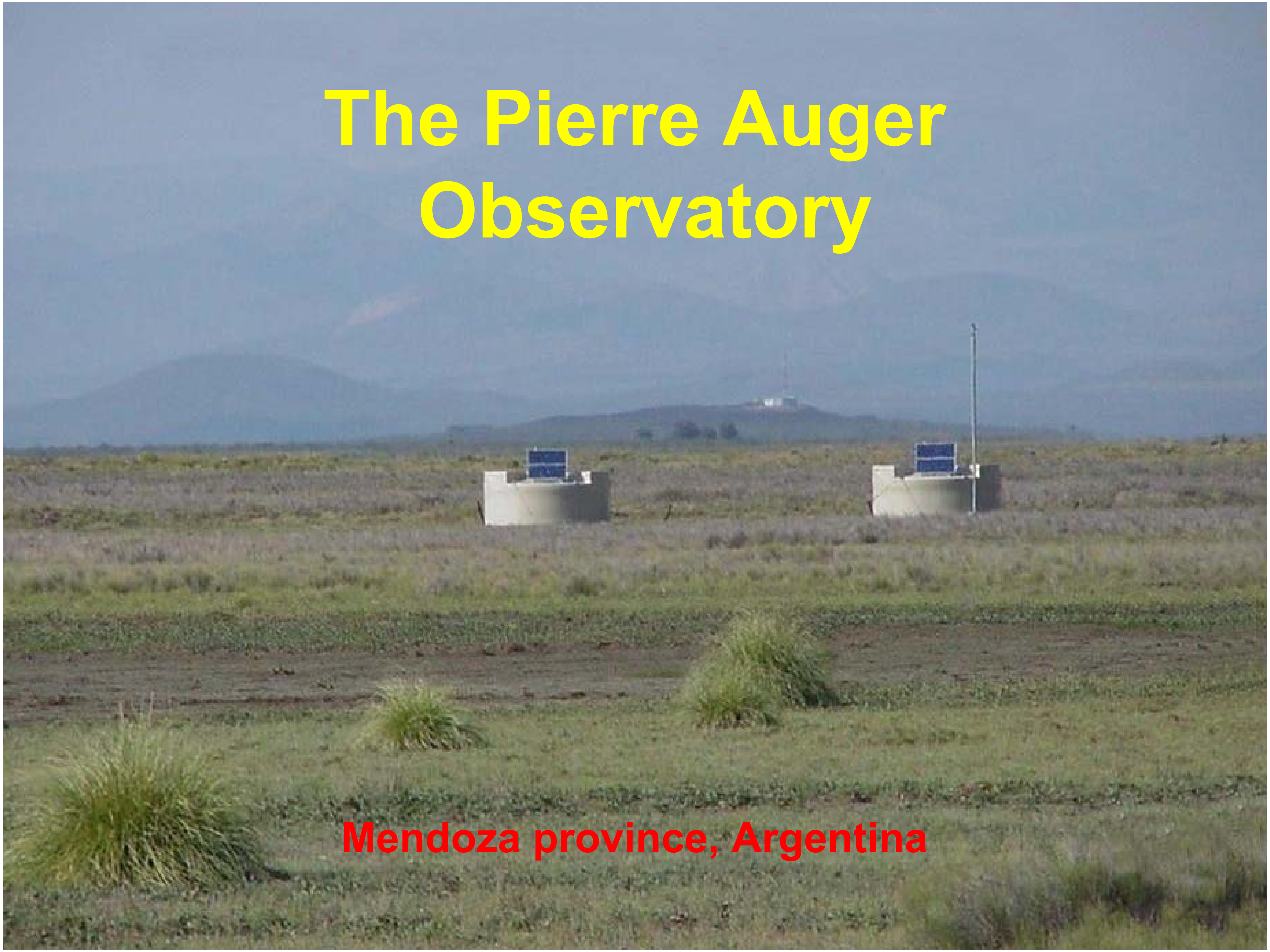
Influence of magnetic fields



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
ɔ 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*

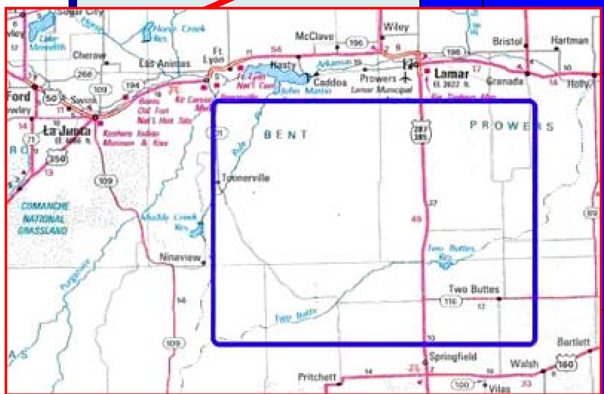
* - associated countries

Participating countries are in cyan.

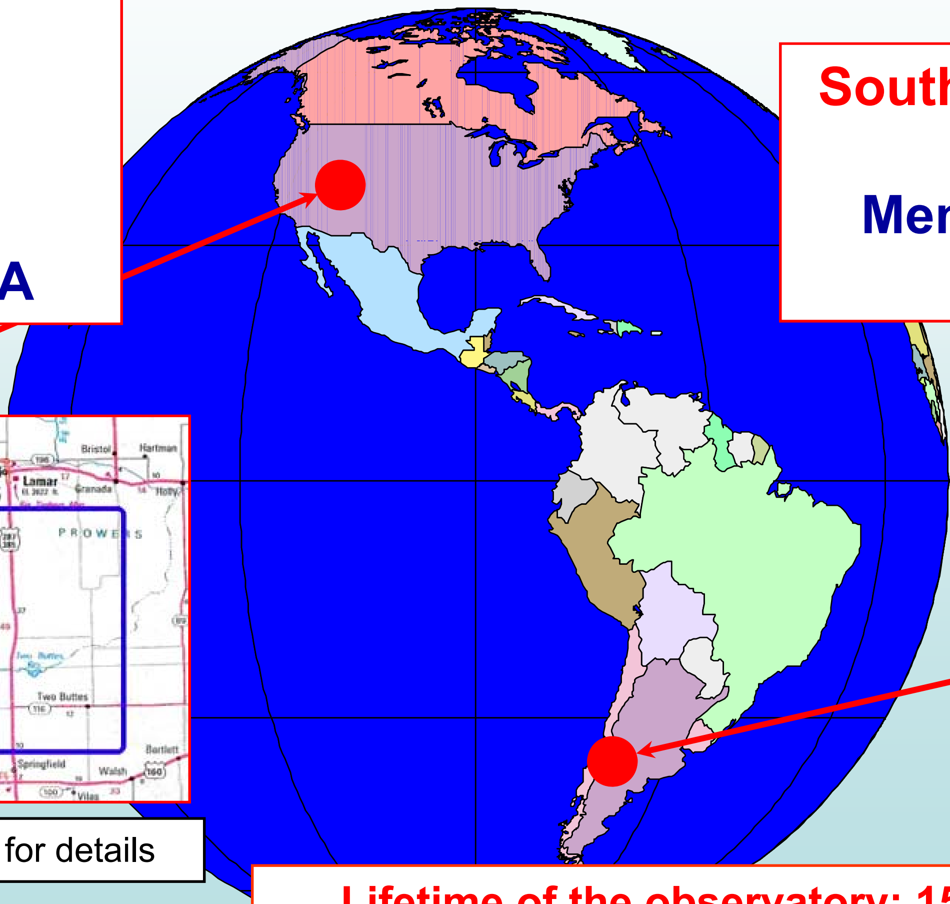
Pierre Auger Observatory

The construction of the southern site in Argentina is (almost) completed.

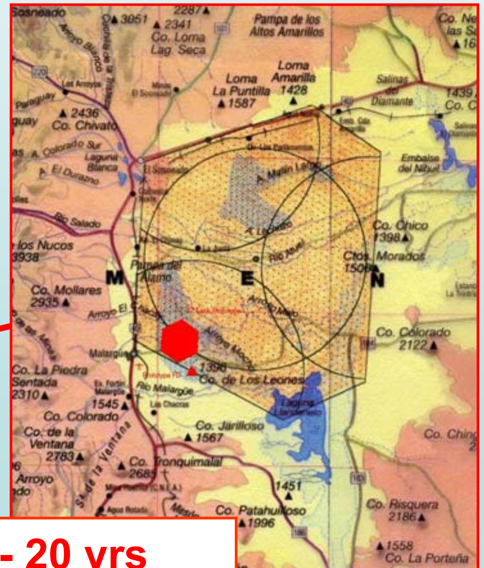
Northern hemisphere (planned):
Lamar, Colorado, USA



See www.augernorth.org for details



Southern hemisphere:
Malargüe, Mendoza province, Argentina

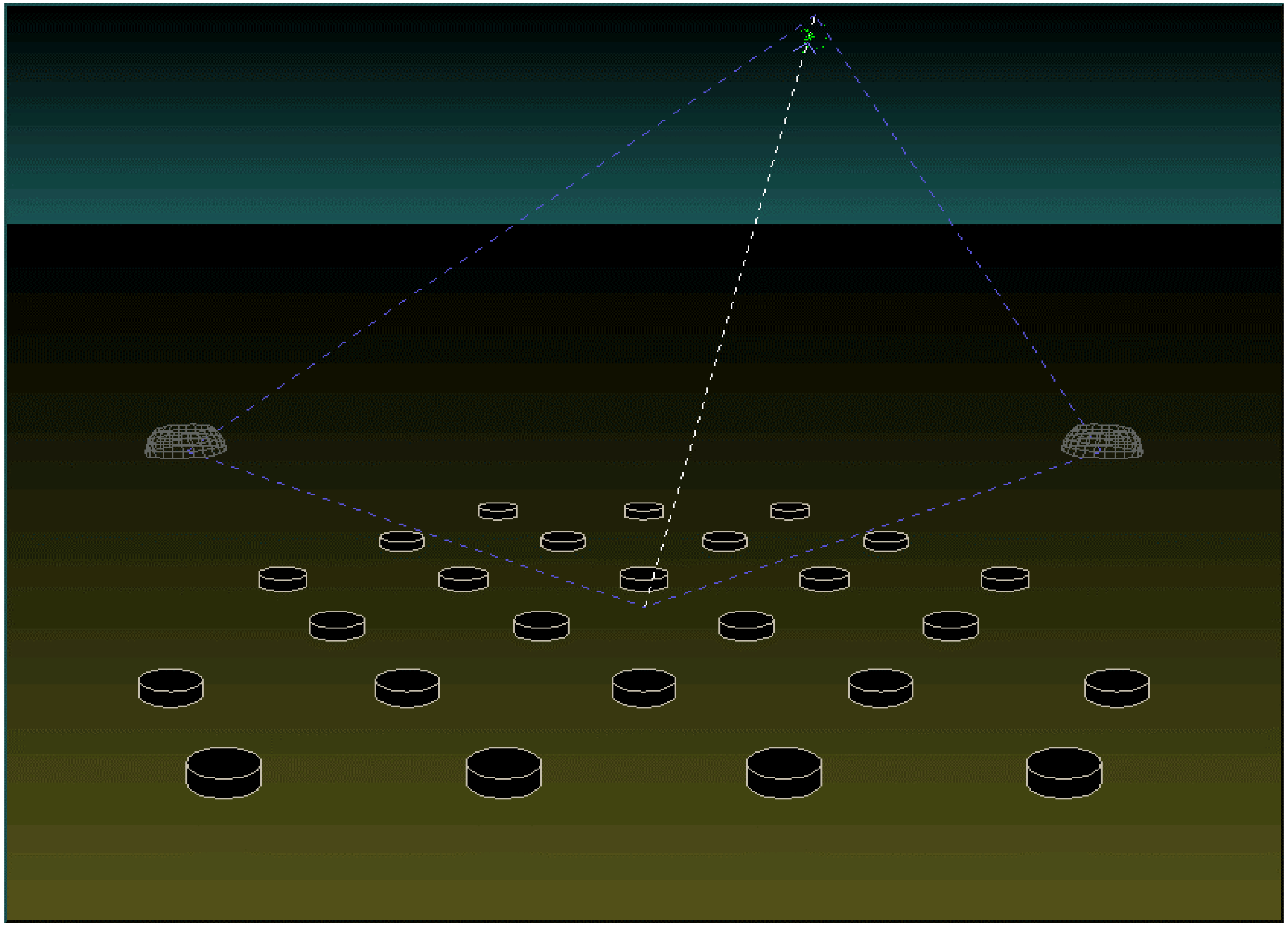


Lifetime of the observatory: 15 - 20 yrs

The Pierre Auger Observatory = hybrid detector of cosmic rays

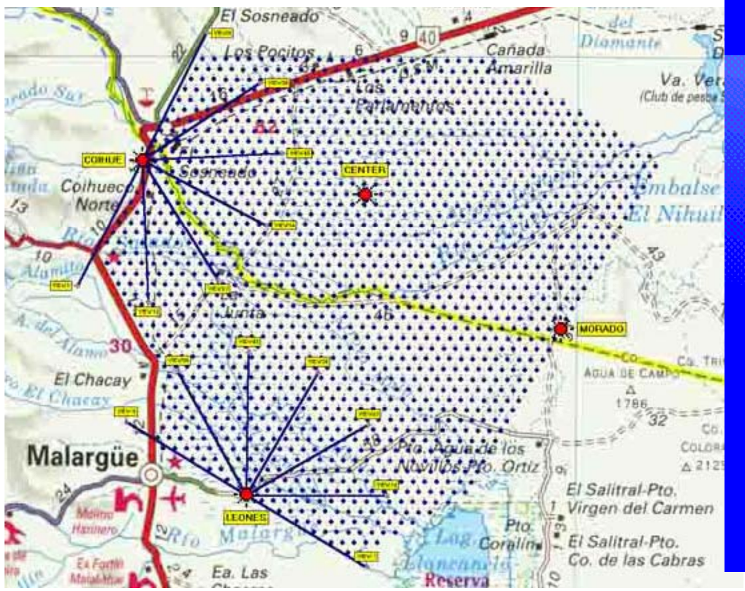
• The array of surface Cherenkovov detectors will be accompanied with system of fluorescence telescopes, which will observe faint UV/visible light during clear nights. This fluorescence light origins as by-product during the interactions of shower particles with the atmosphere.

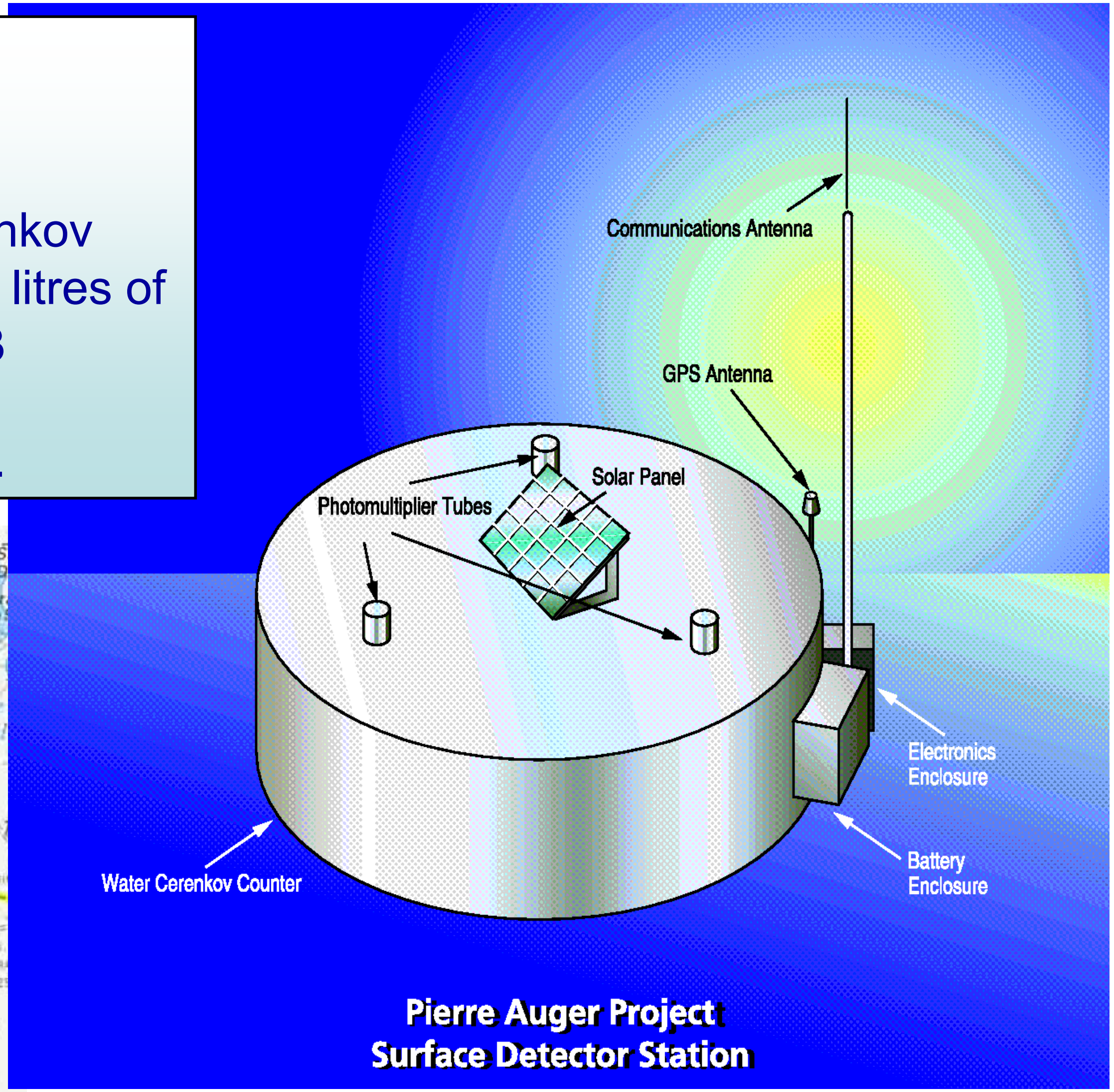
Scheme of hybrid detector function



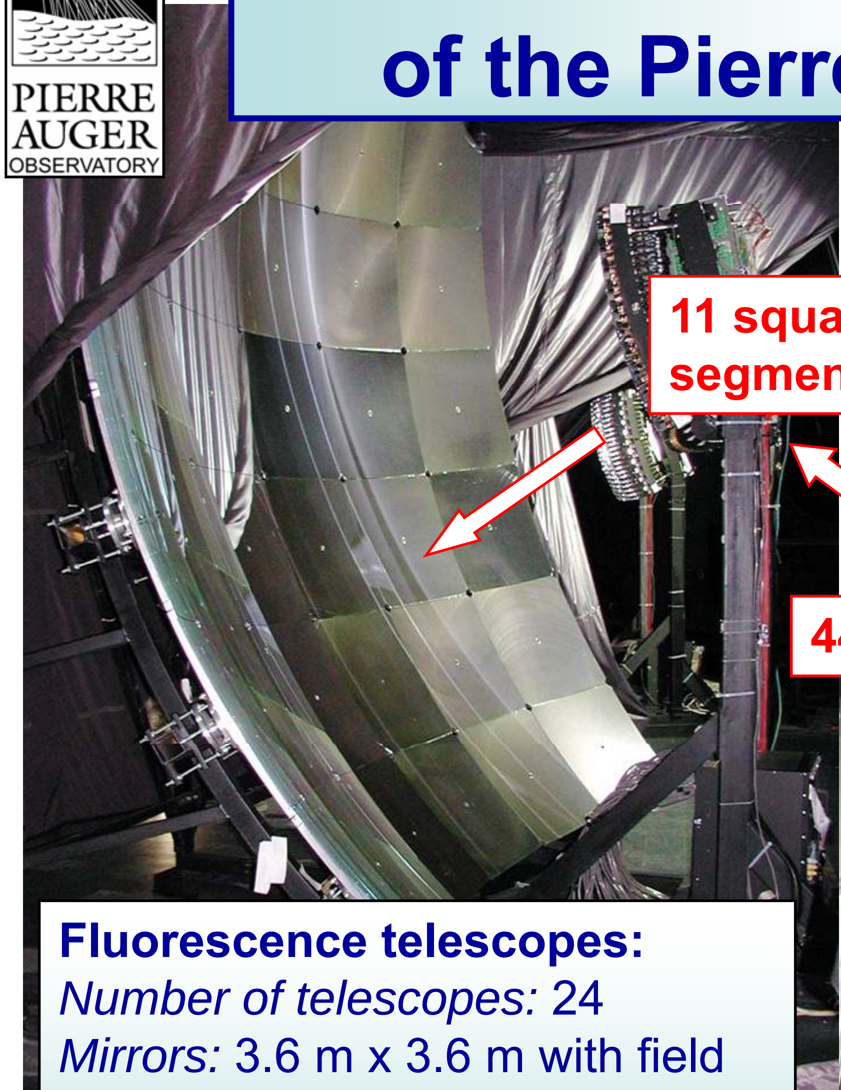
Ground detectors
of the Pierre Auger Observatory

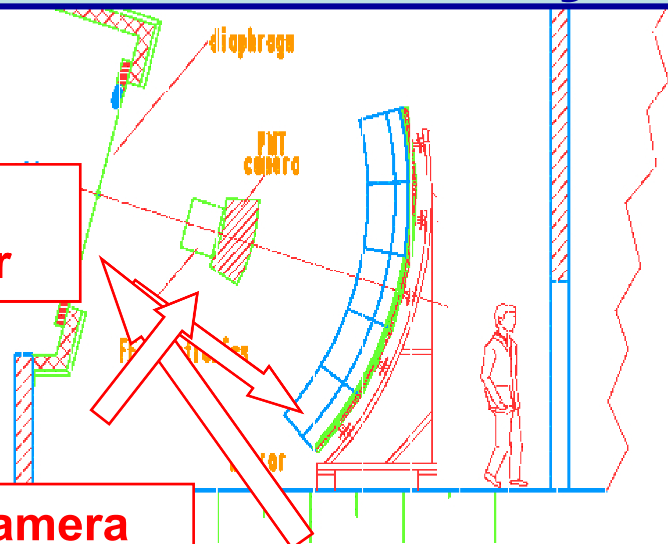
Ground detectors:
Covered surface: 3000 km^2
Number of detectors: 1600
Type of detector: Detector of Cherenkov radiation, each consisting of 12 000 litres of ultrapure water and equipped with 3 photomultipliers.
Spacing between detectors: 1.5 km.





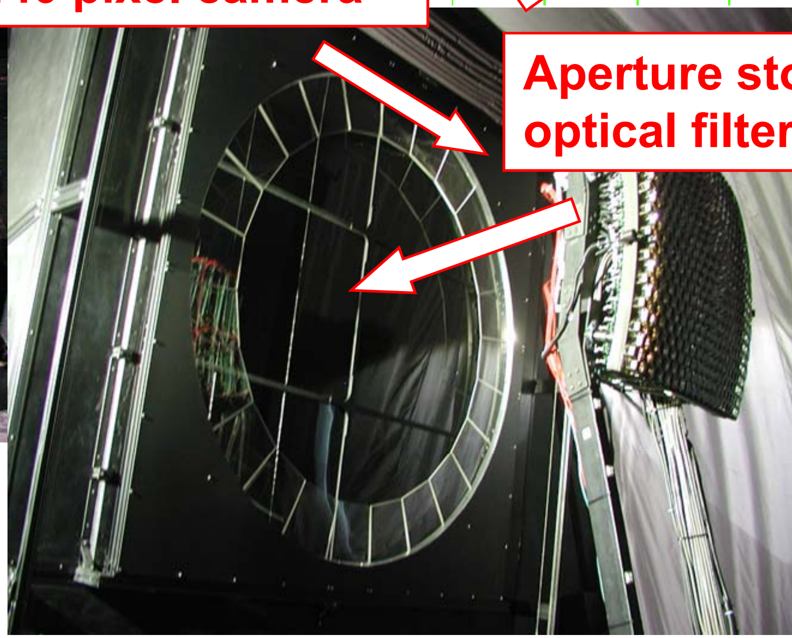
Fluorescence detectors of the Pierre Auger Observatory





11 square meter segmented mirror

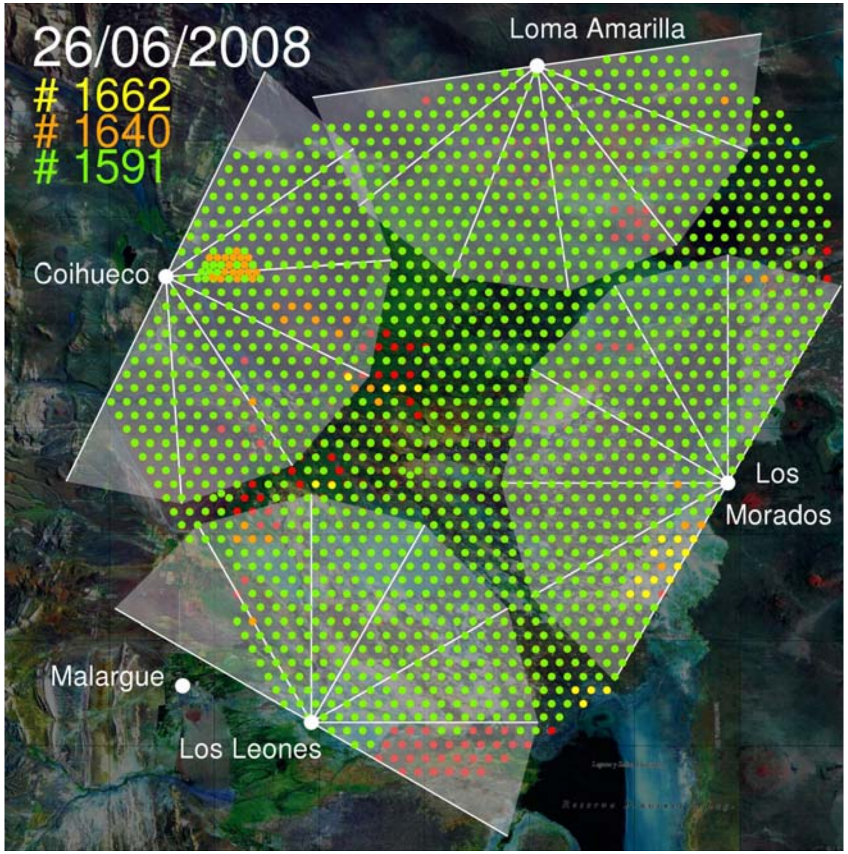
440 pixel camera

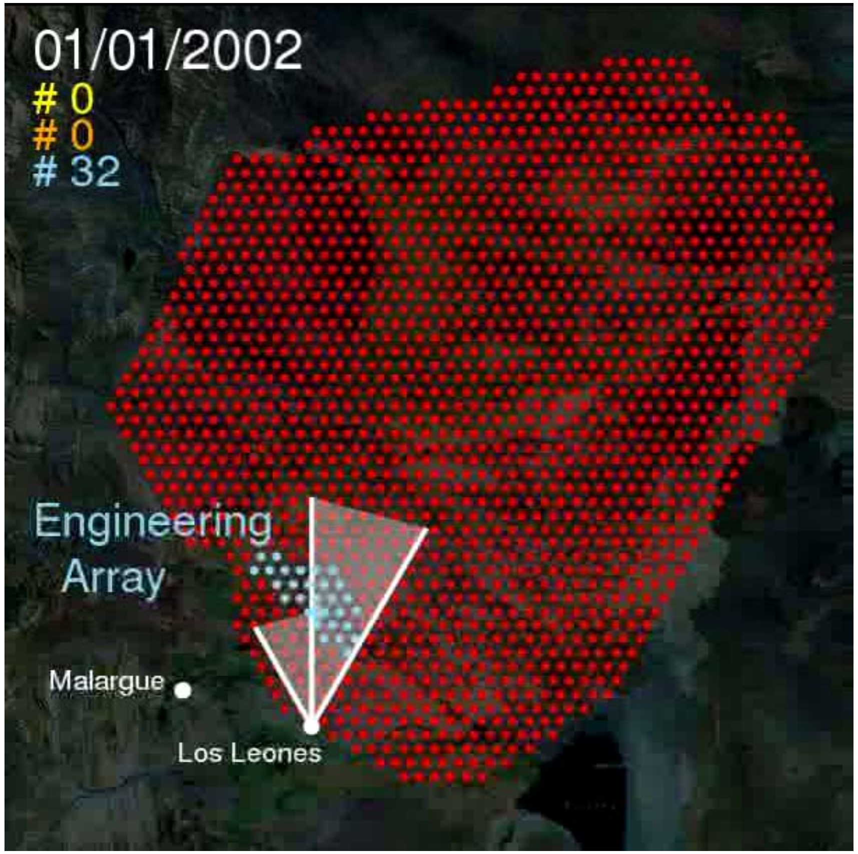


Aperture stop and optical filter

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*

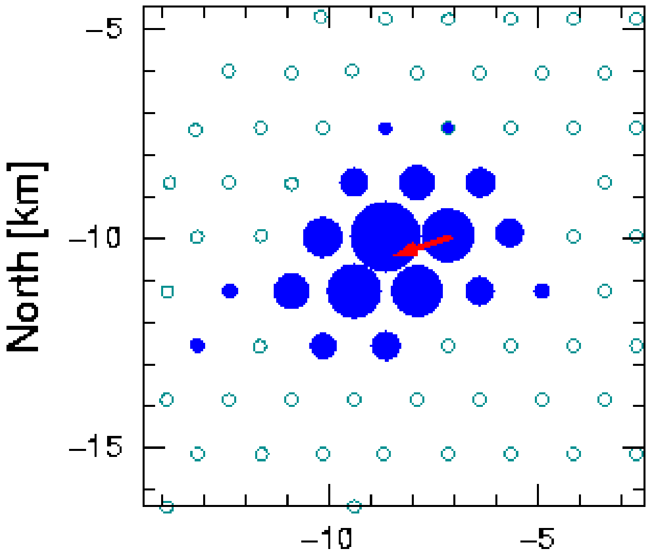


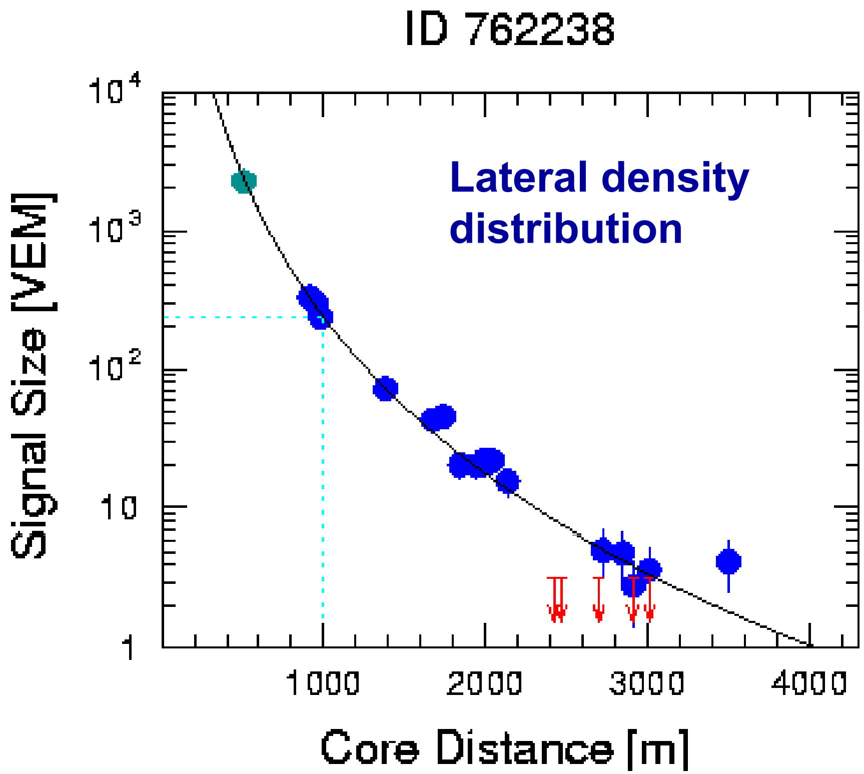


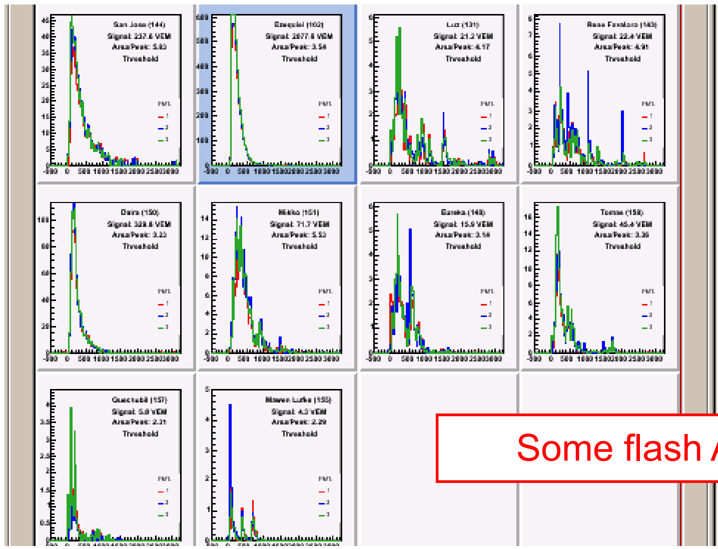
Production of scientific data since late 2003.

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

ID 762238

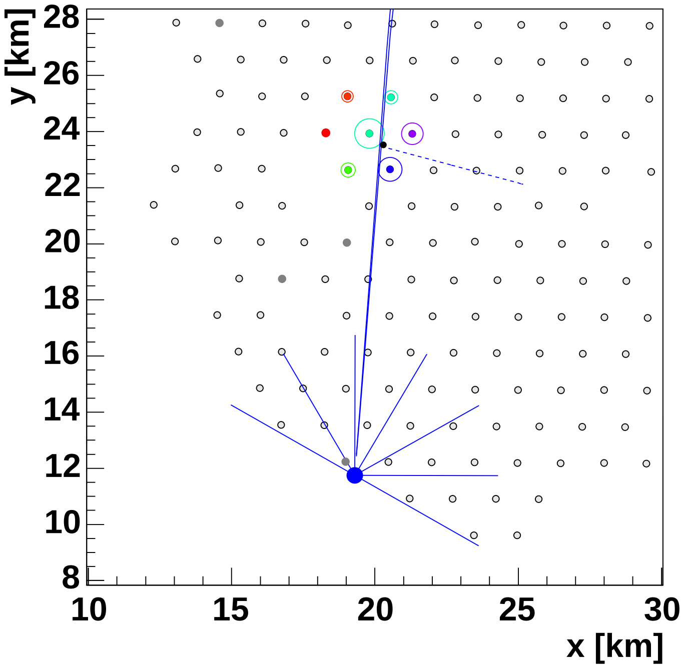


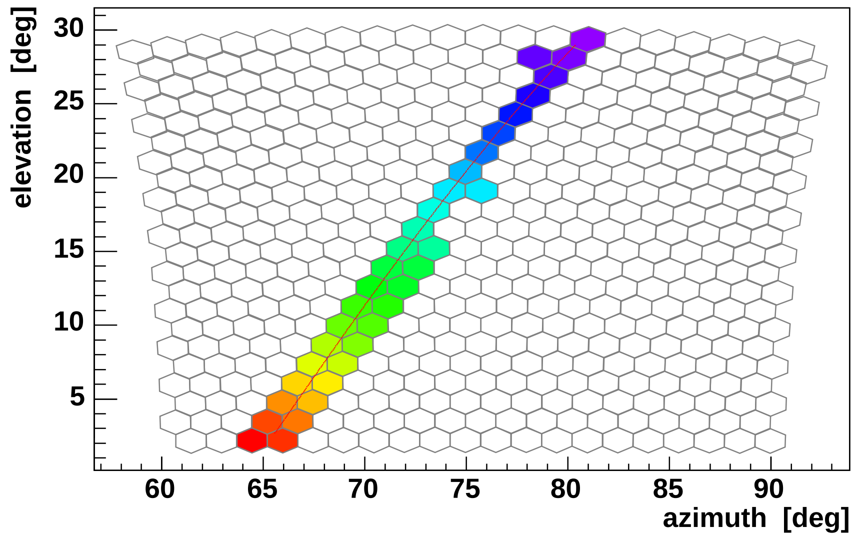


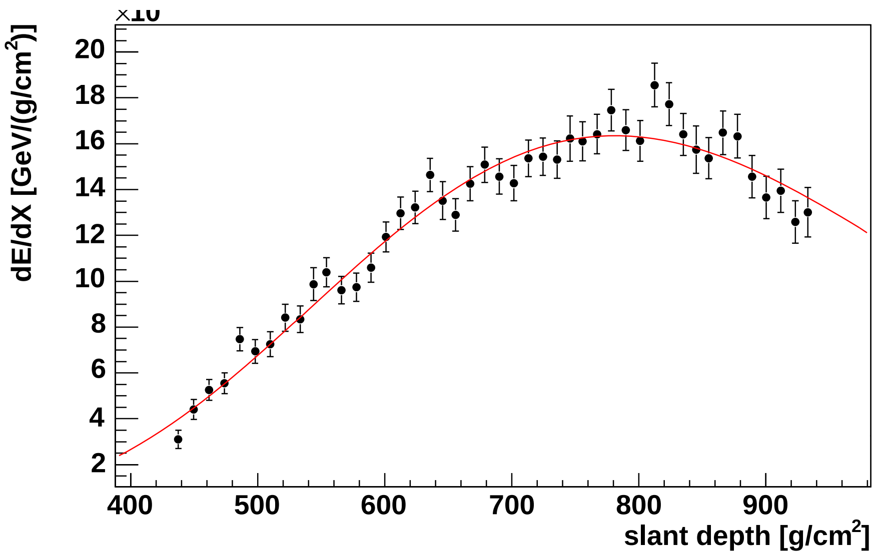


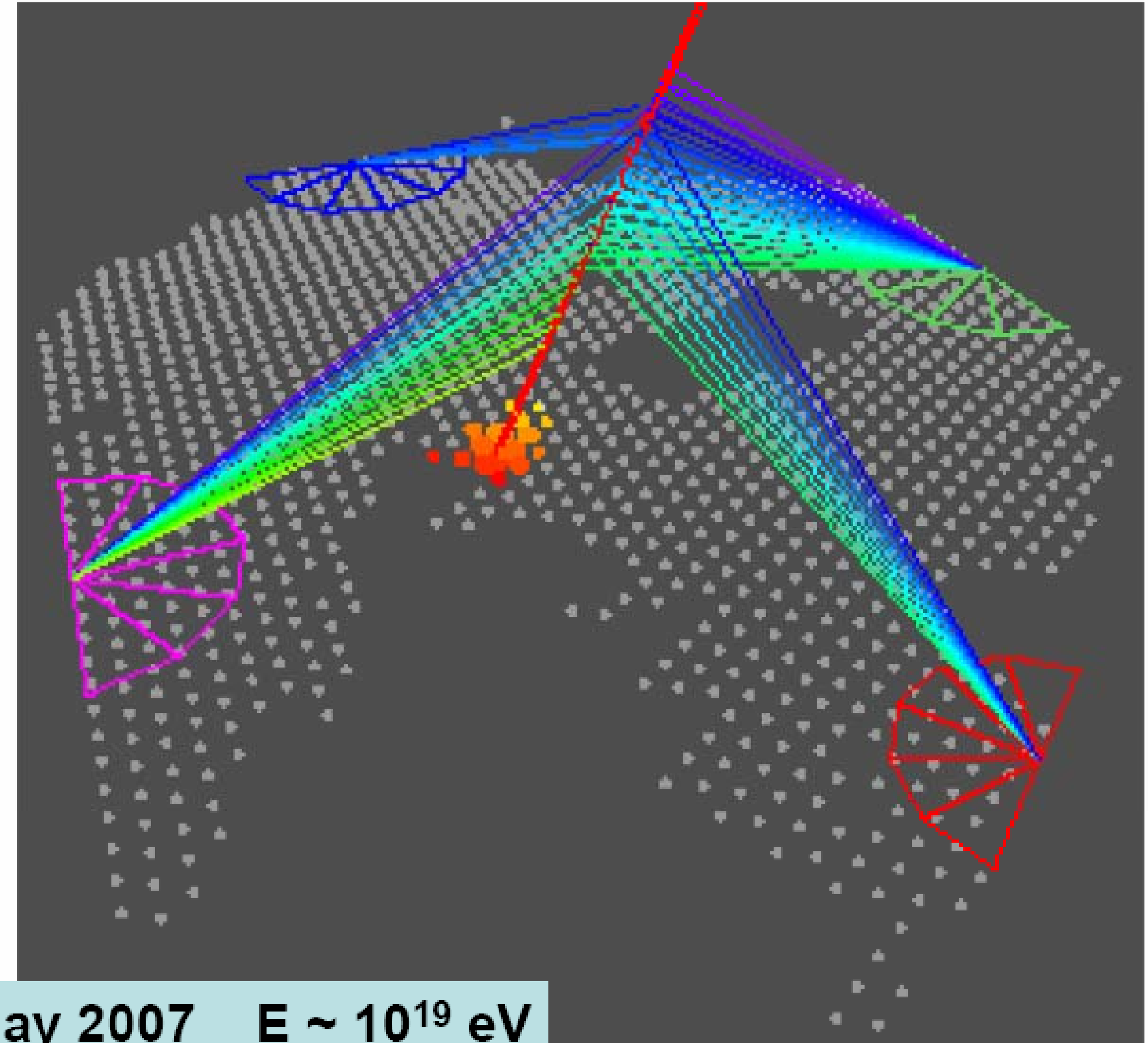
Some flash ADC traces

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



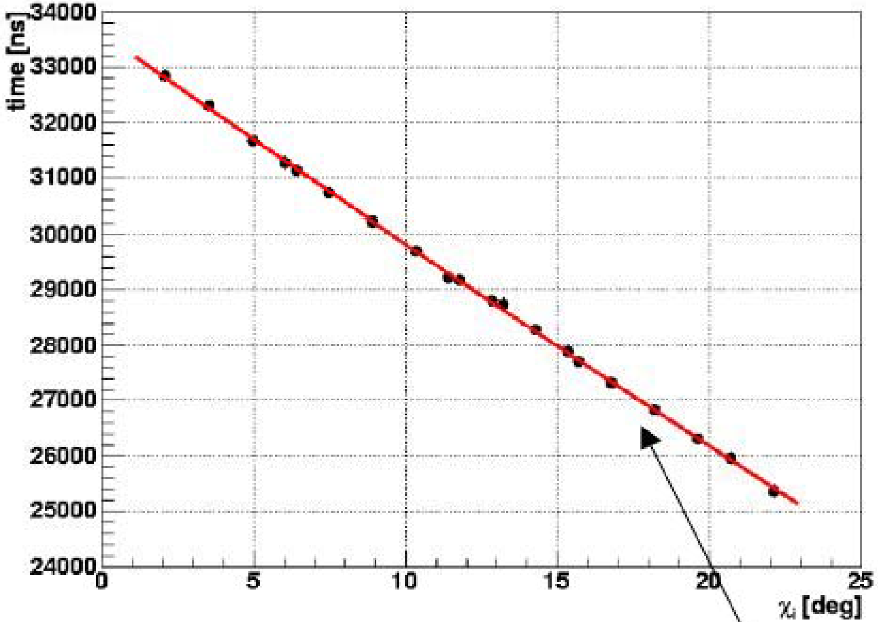






20 May 2007   E ~ 10^{19} eV

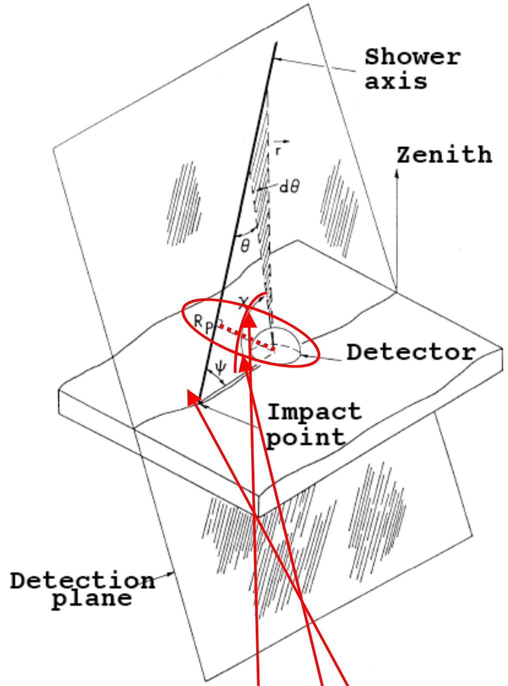
(Geometrical) Hybrid advantage...



≈ line but

3 free parameters

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



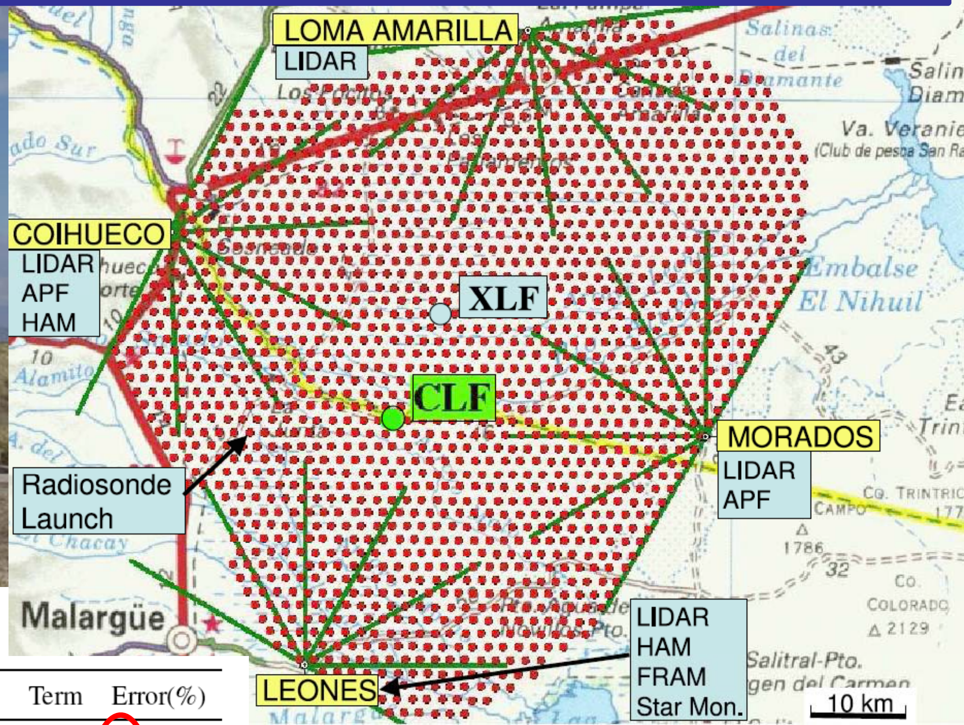
T_0 - time of impact

R_p - perpendicular distance to the detector

χ_0 – actual observation angle

Energy estimation, atmospheric monitoring

Central Laser Facility

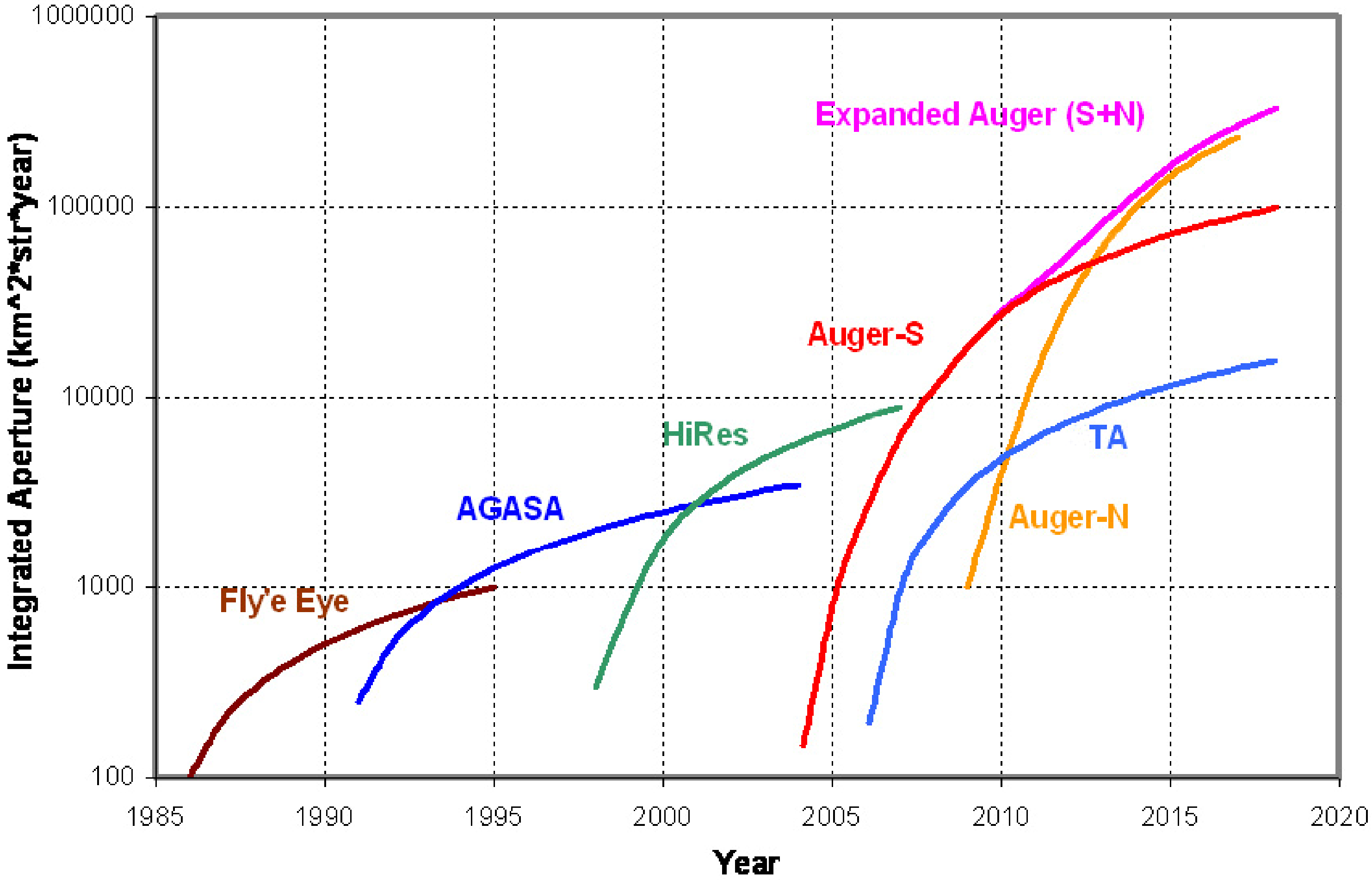


Term	Error(%)	Term	Error(%)
Light collection	5	Atmosphere (aerosols)	10
Detector photometric calibration	12	Atmosphere (clouds)	5
Geometric reconstruction	2	Atmosphere (density profile)	2
Correction for Missing Energy	3	Fluorescence yield	15
	Quadrature Sum = 23		

Current estimates of systematic errors of the FD energy measurement

LIDAR

Comparison of integrated aperture



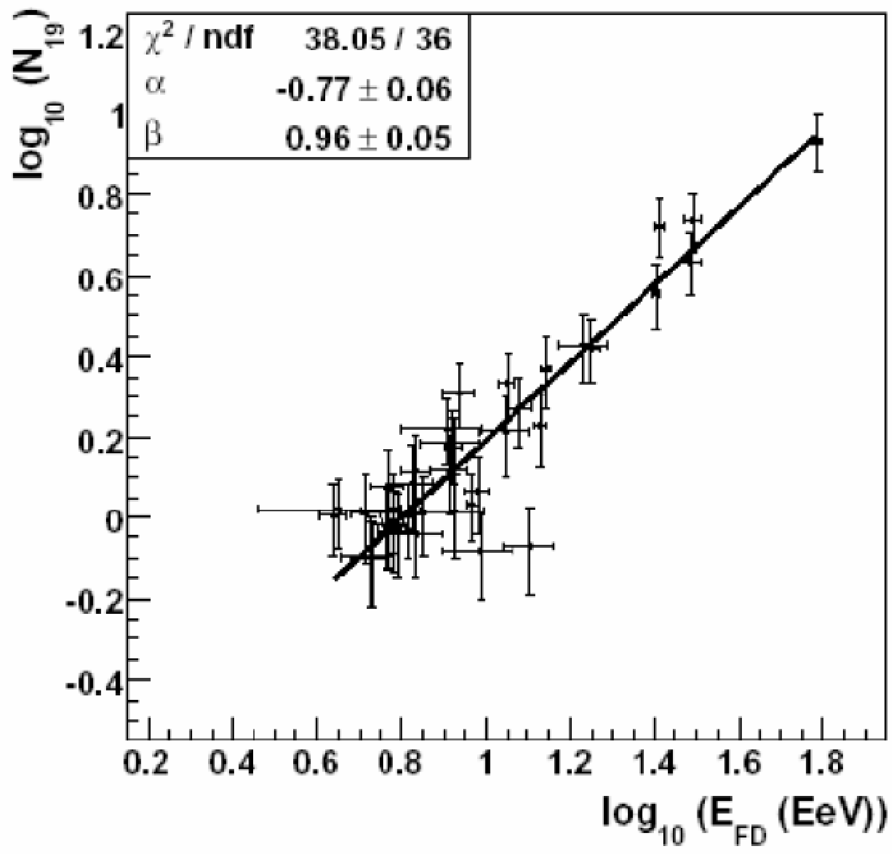
Currently (Mar 2009) ~ 10 x AGASA

Auger Observatory results

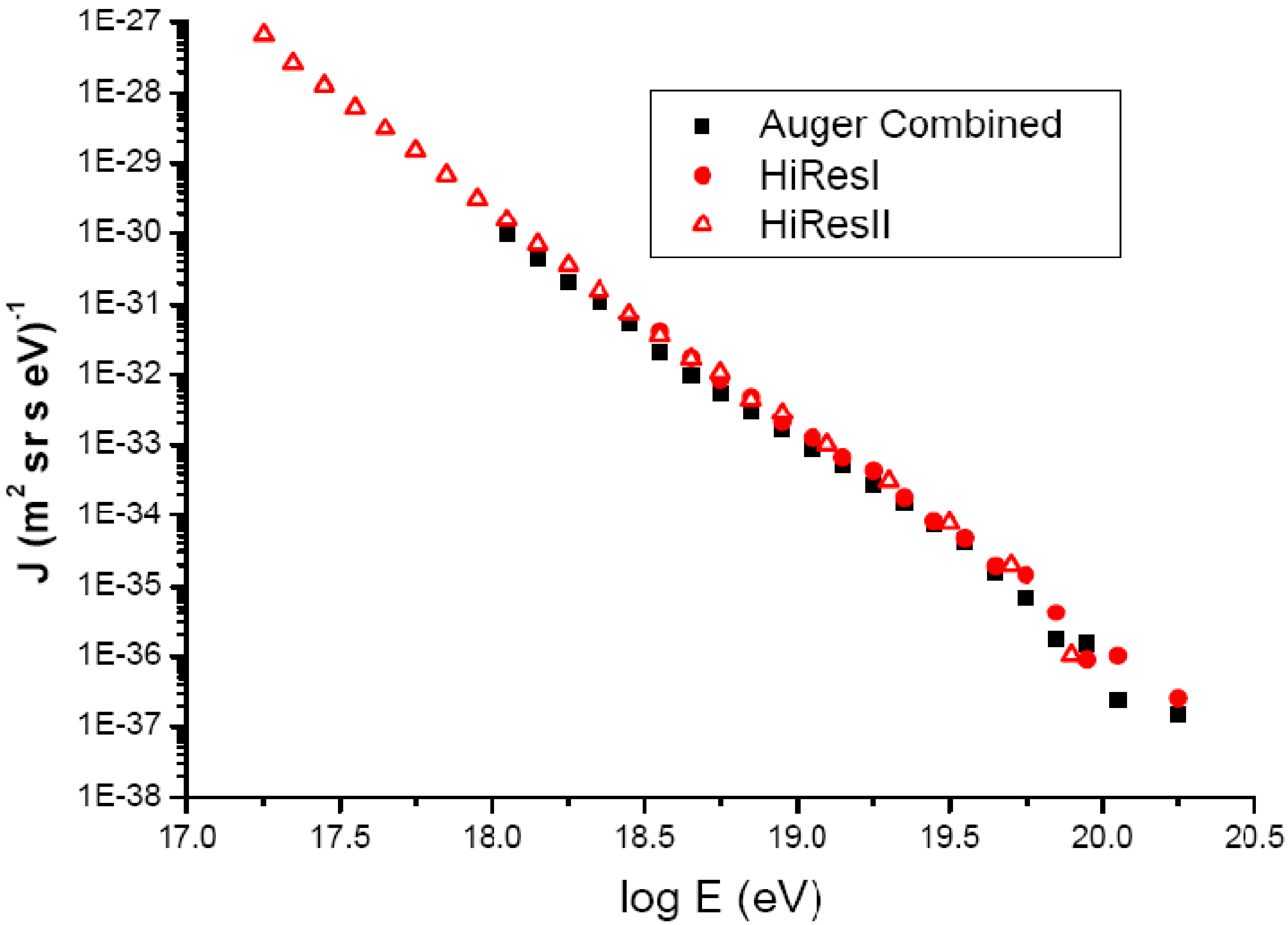
Auger Energy Spectrum

- 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)

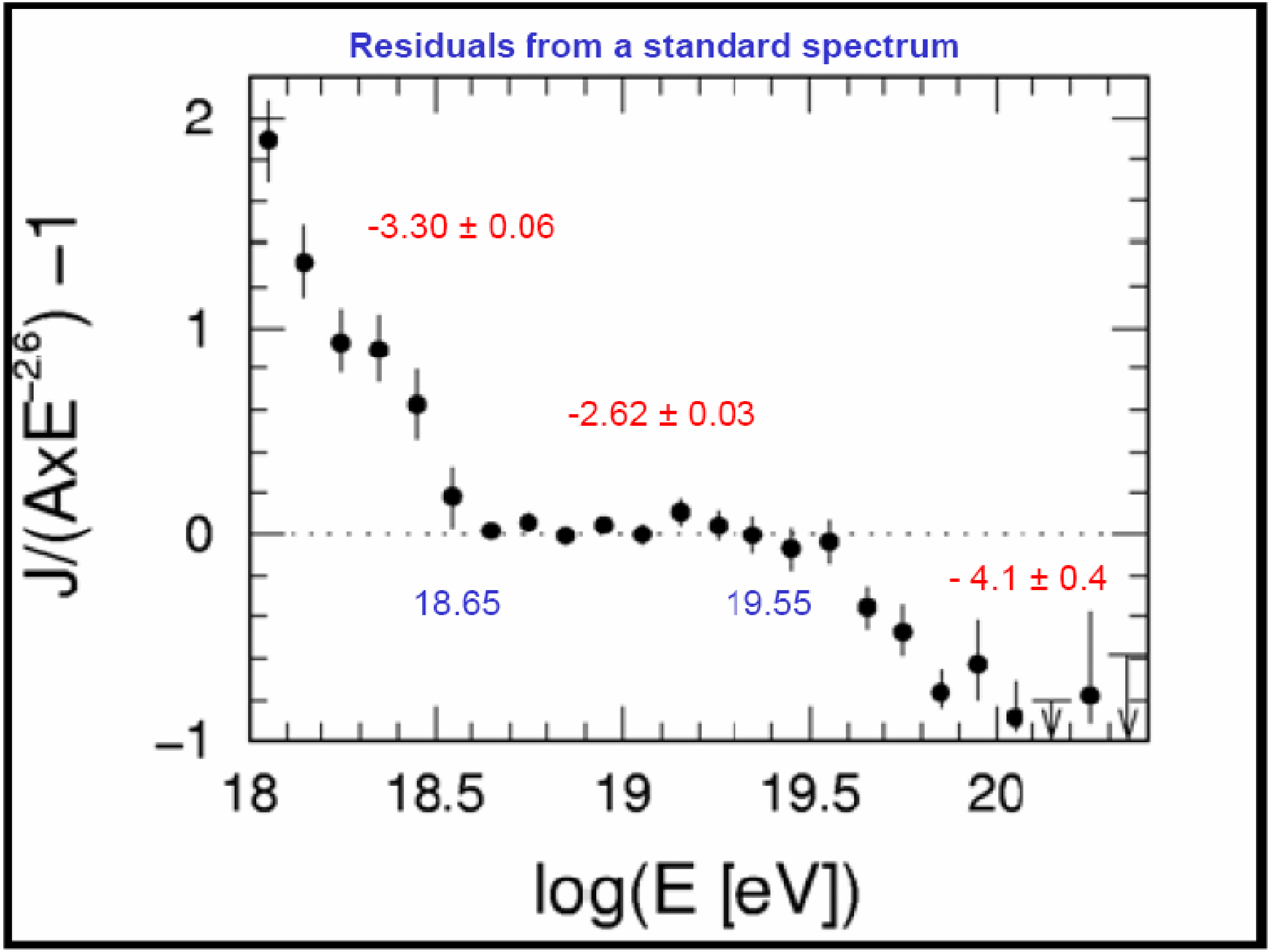
Energy from FD



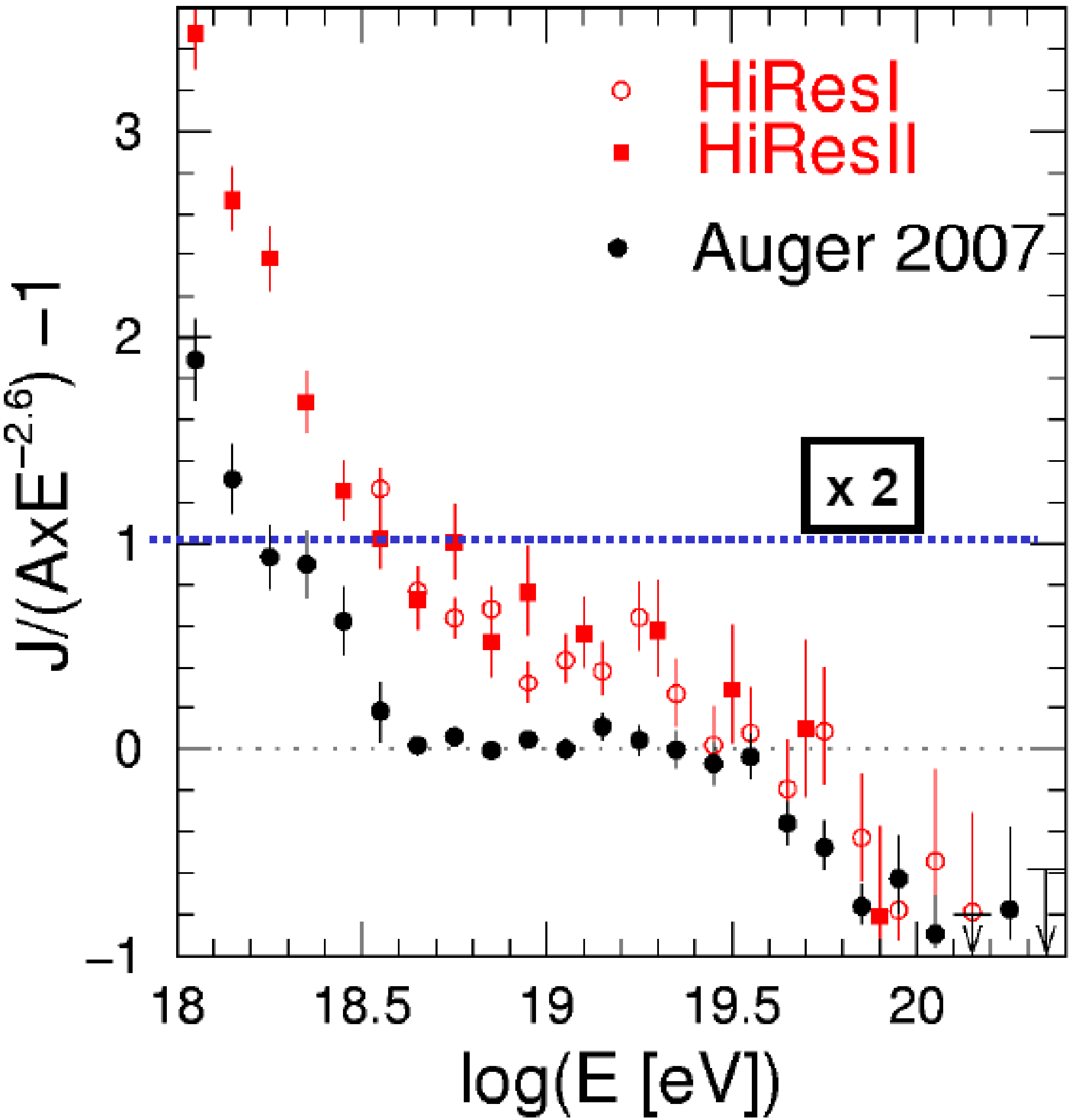
Ground parameter

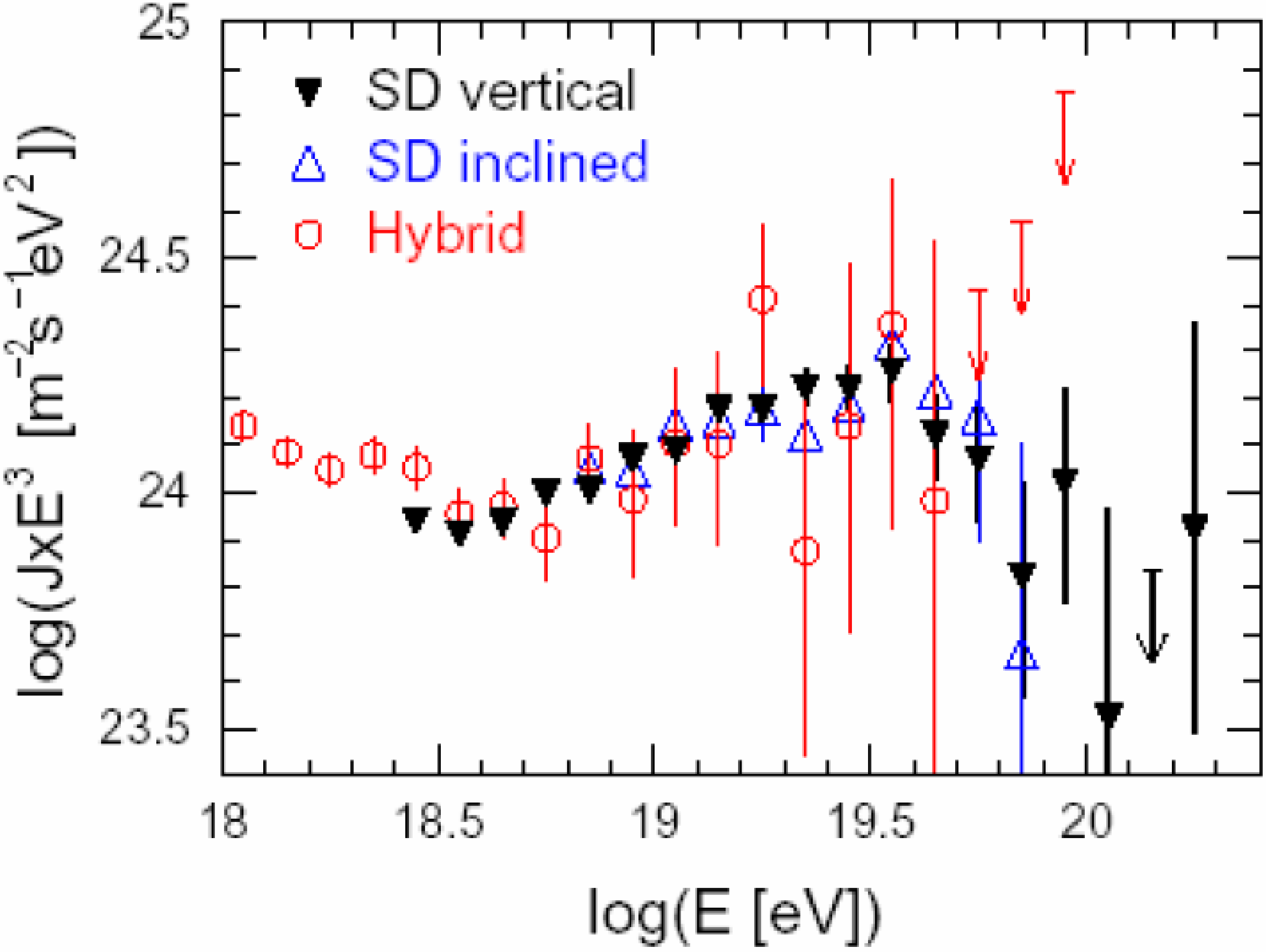


Auger Combined
HiResI
HiResII
J (m^2 sr s eV)$^{-1}$
log E (eV)
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
1E-33
1E-34
1E-35
1E-36
1E-37
1E-38
17.0
17.5
18.0
18.5
19.0
19.5
20.0
20.5

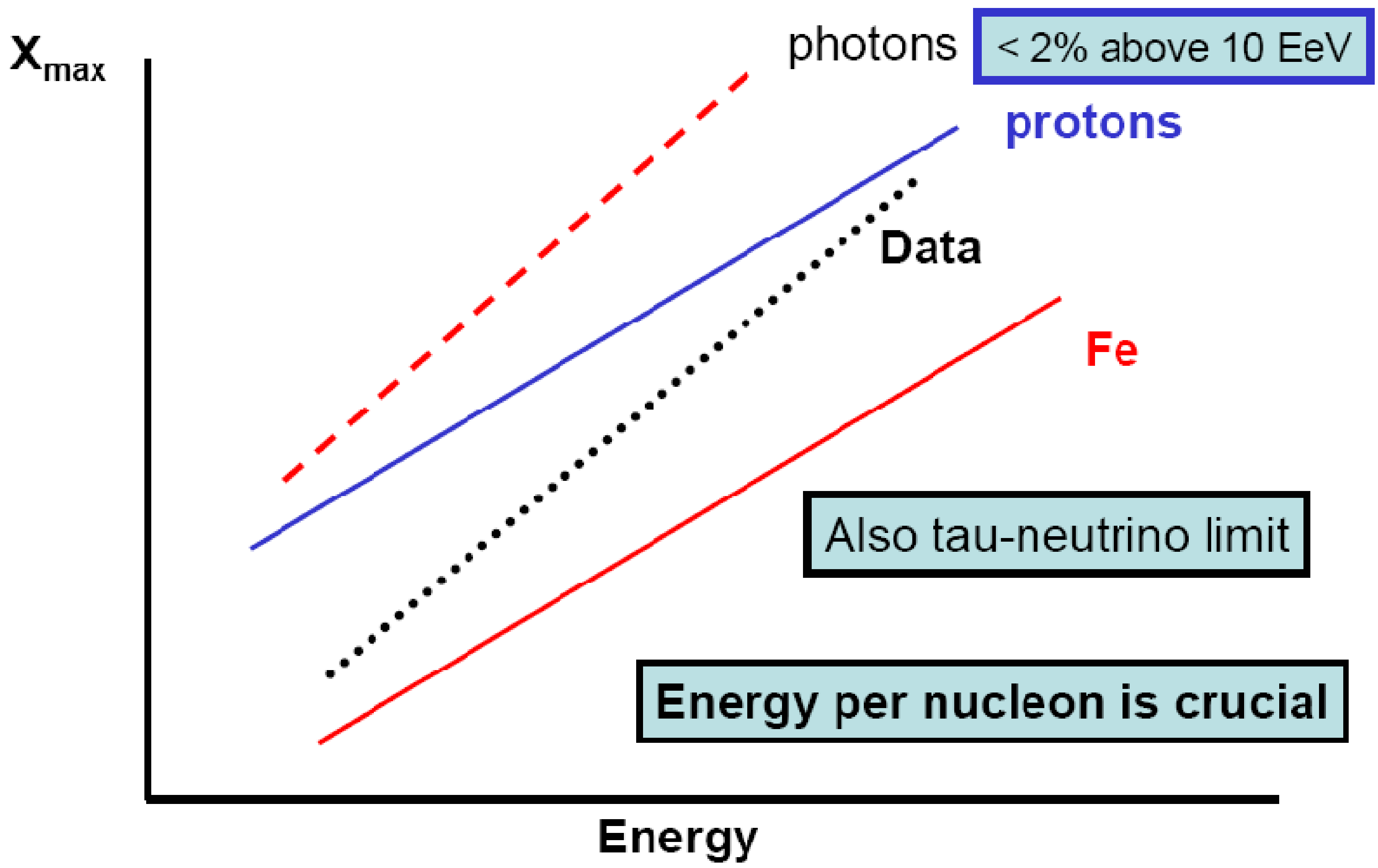


Residuals from a standard spectrum
-3.30 ± 0.06
-2.62 ± 0.03
- 4.1 ± 0.4
18.65
19.55
J/(AxE^-2.6) −1
log(E [eV])

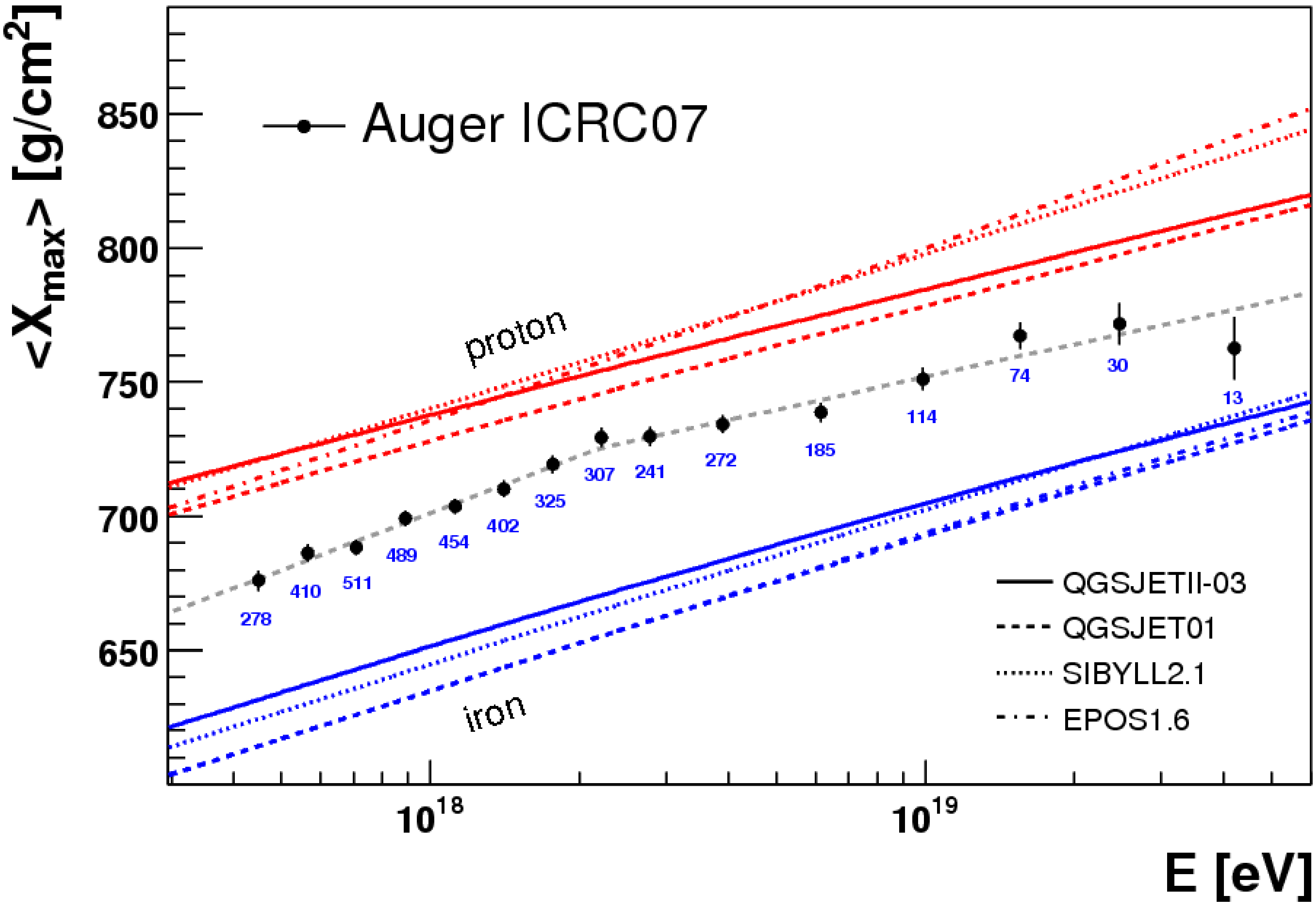

HiResI
HiResII
Auger 2007
x 2
J/(AxE$^{-2.6}$) −1
log(E [eV])
18
18.5
19
19.5
20
−1
0
1
2
3



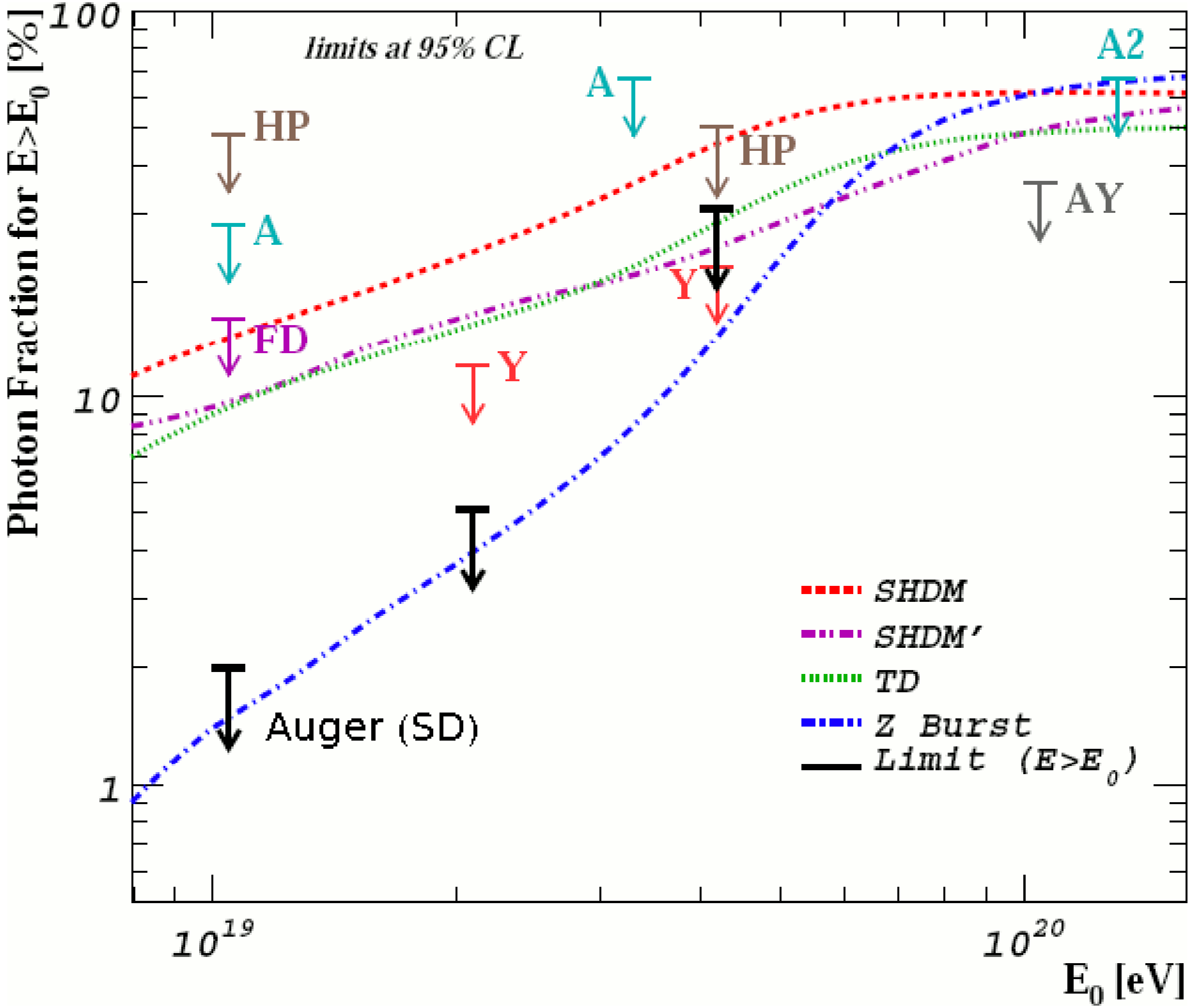
SD vertical
SD inclined
Hybrid
log(JxE^3 [m^{-2}s^{-1}eV^2])
25
24.5
24
23.5
18
18.5
19
19.5
20
log(E [eV])



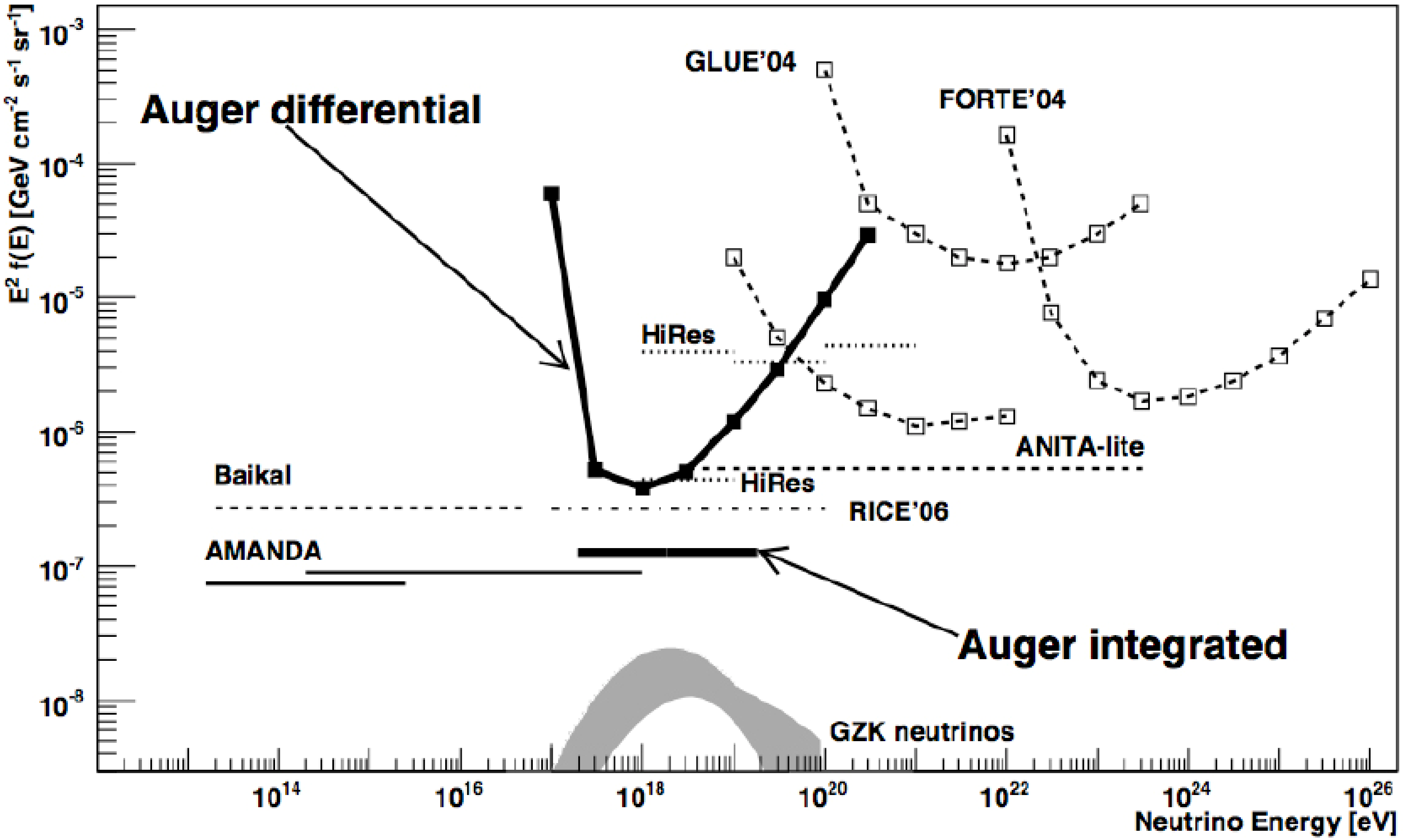
X_{max}
photons
< 2% above 10 EeV
protons
Data
Fe
Also tau-neutrino limit
Energy per nucleon is crucial
Energy



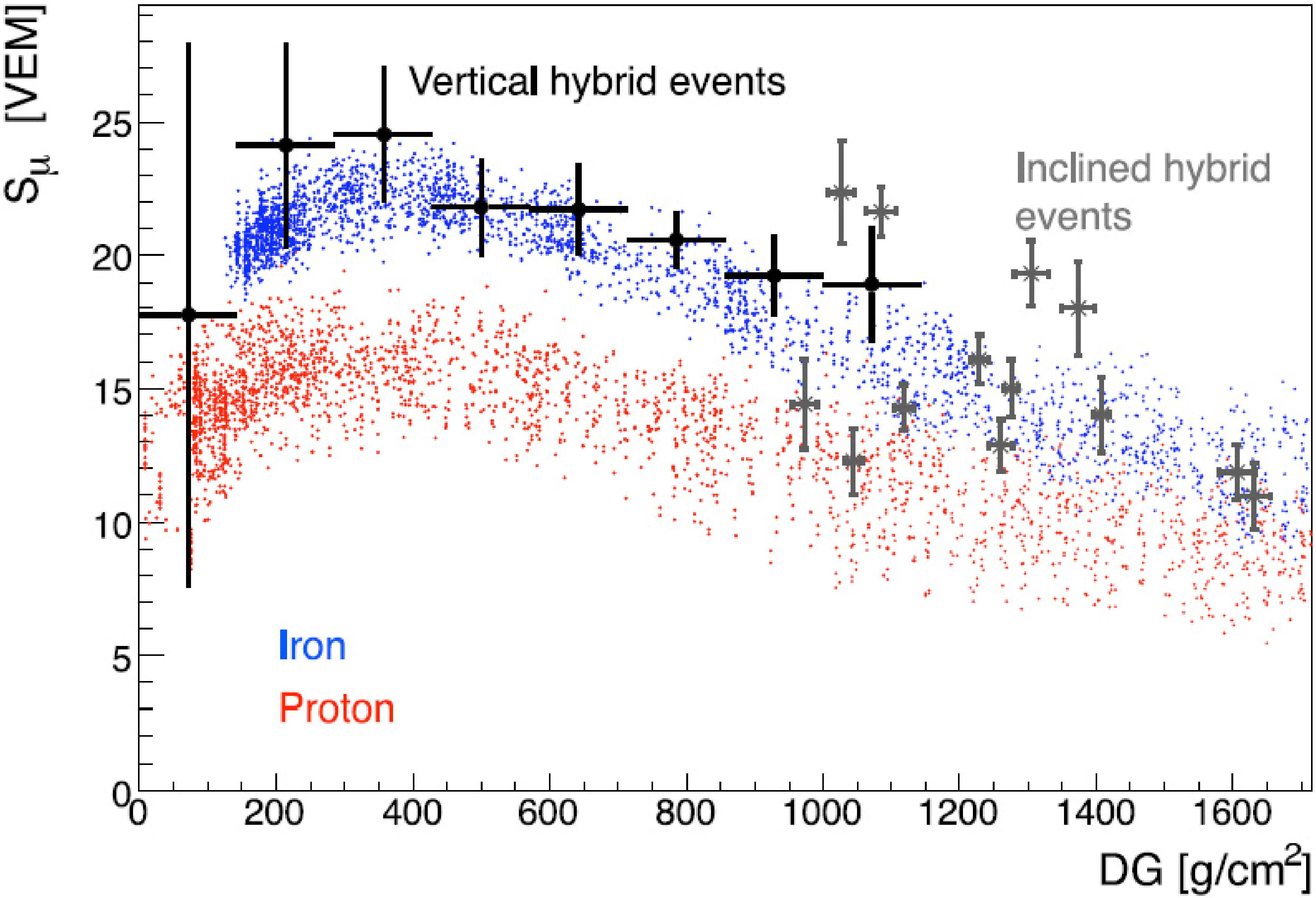
Auger ICRC07
proton
iron
QGSJETII-03
QGSJET01
SIBYLL2.1
EPOS1.6
278
410
511
489
454
402
325
307
241
272
185
114
74
30
13
850
800
750
700
650
10^{18}
10^{19}
$<X_{max}>$ [g/cm^2]
E [eV]



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

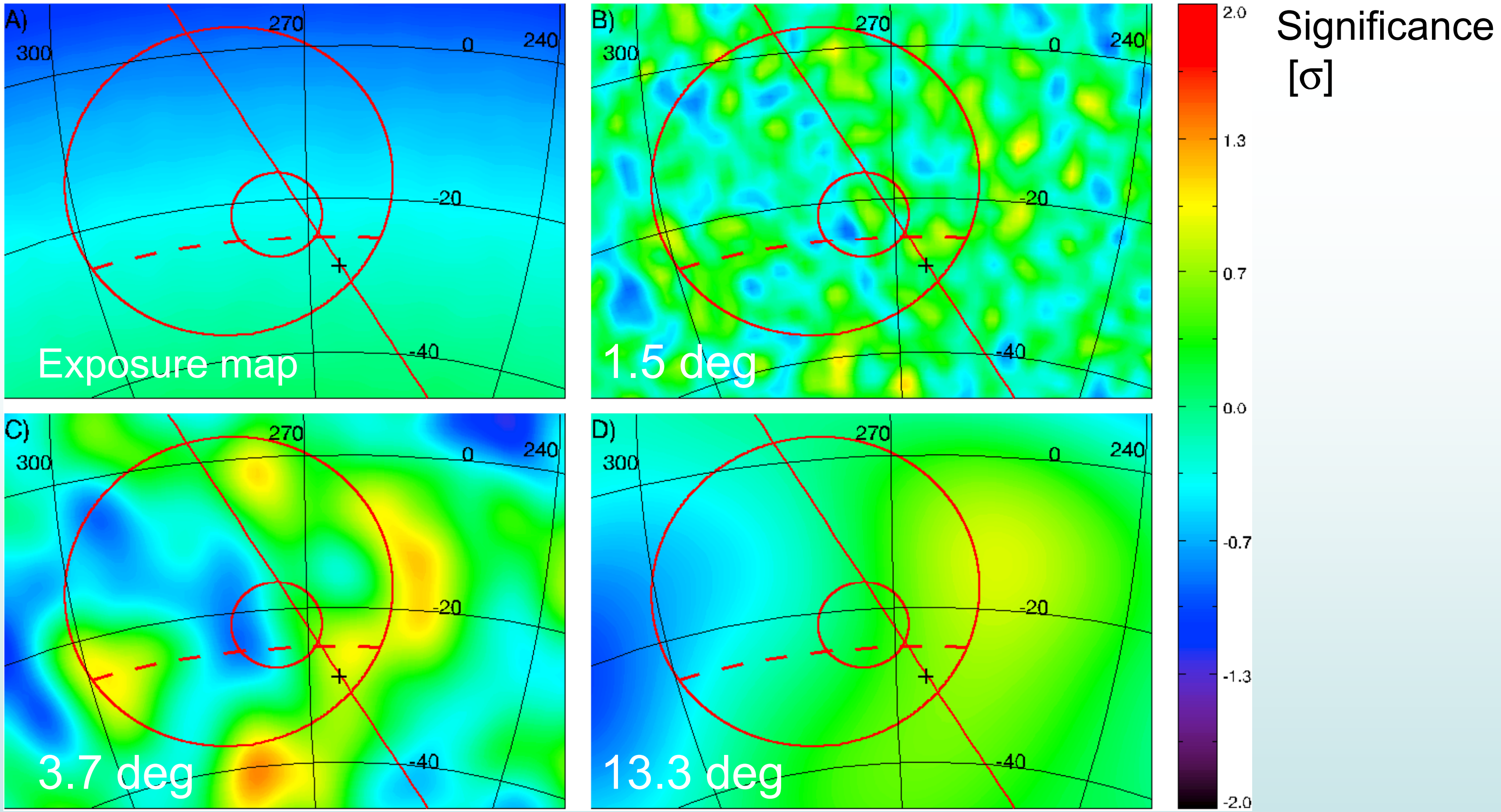


E2 f(E) [GeV cm-2 s-1 sr-1]
10-3
10-4
10-5
10-6
10-7
10-8
GLUE'04
FORTE'04
Auger differential
HiRes
ANITA-lite
Baikal
HiRes
RICE'06
AMANDA
Auger integrated
GZK neutrinos
10^14
10^16
10^18
10^20
10^22
10^24
10^26
Neutrino Energy [eV]



S_μ [VEM]
Vertical hybrid events
Inclined hybrid events
Iron
Proton
DG [g/cm^2]
0
5
10
15
20
25
0
200
400
600
800
1000
1200
1400
1600

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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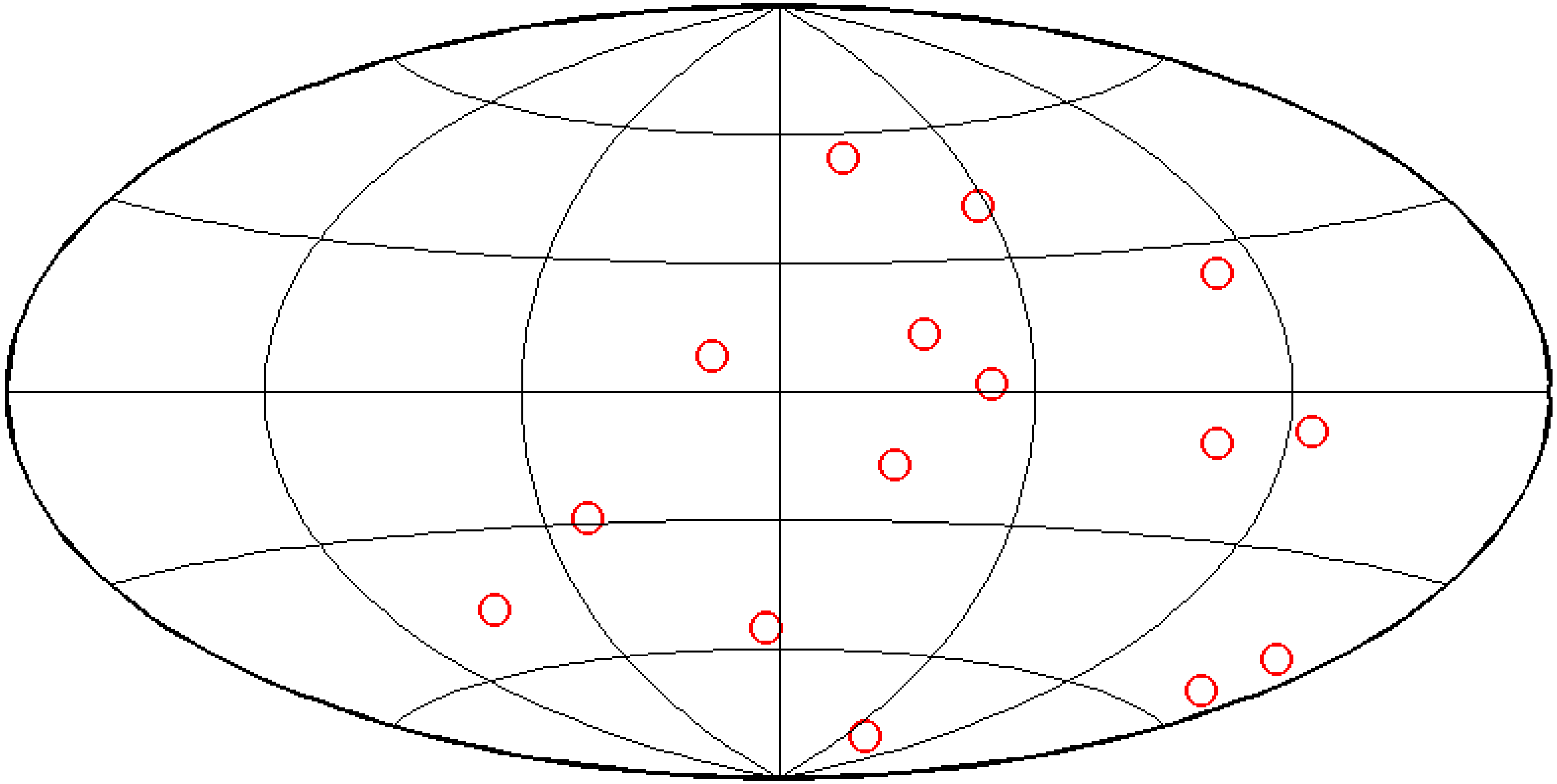
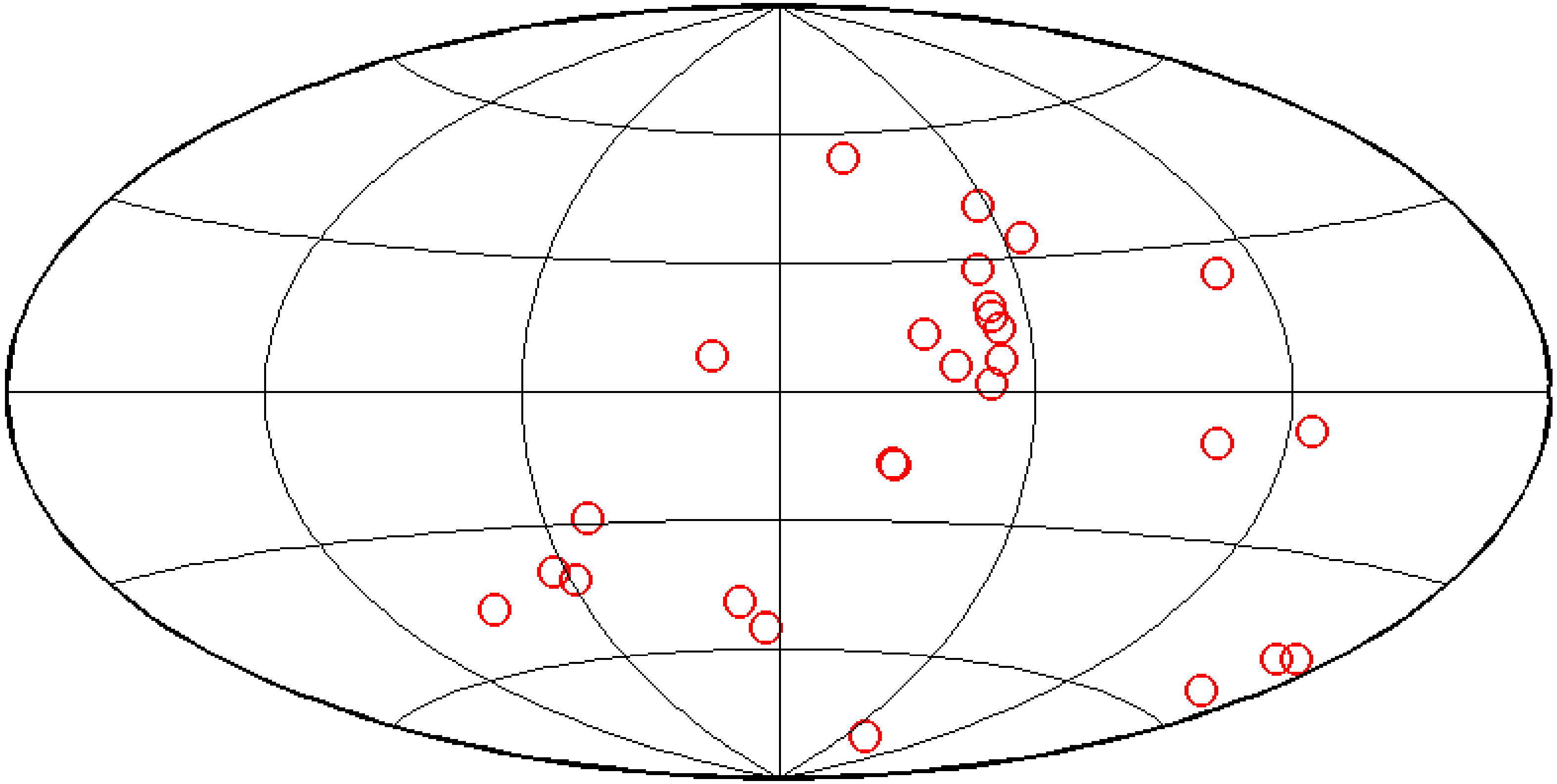
“Discovery of the year?”



AGASA-like situation before the start of operation of the Pierre Auger Observatory

“Discovery of the year !”



Particles with highest energies do not arrive isotropically.

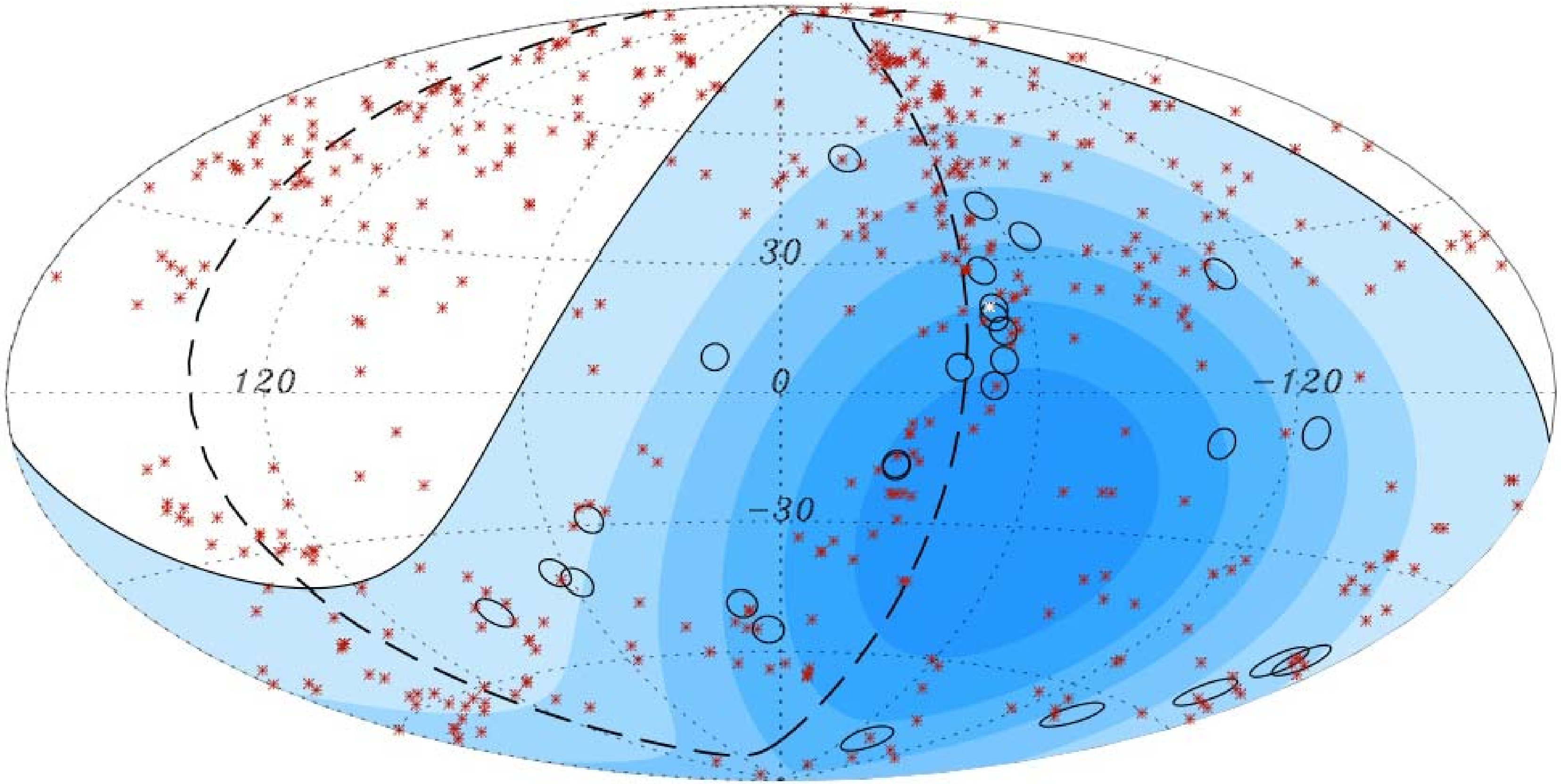
Is observed distribution in agreement with distribution of any type of known astrophysical objects?

Science

9 November 2007 | $10

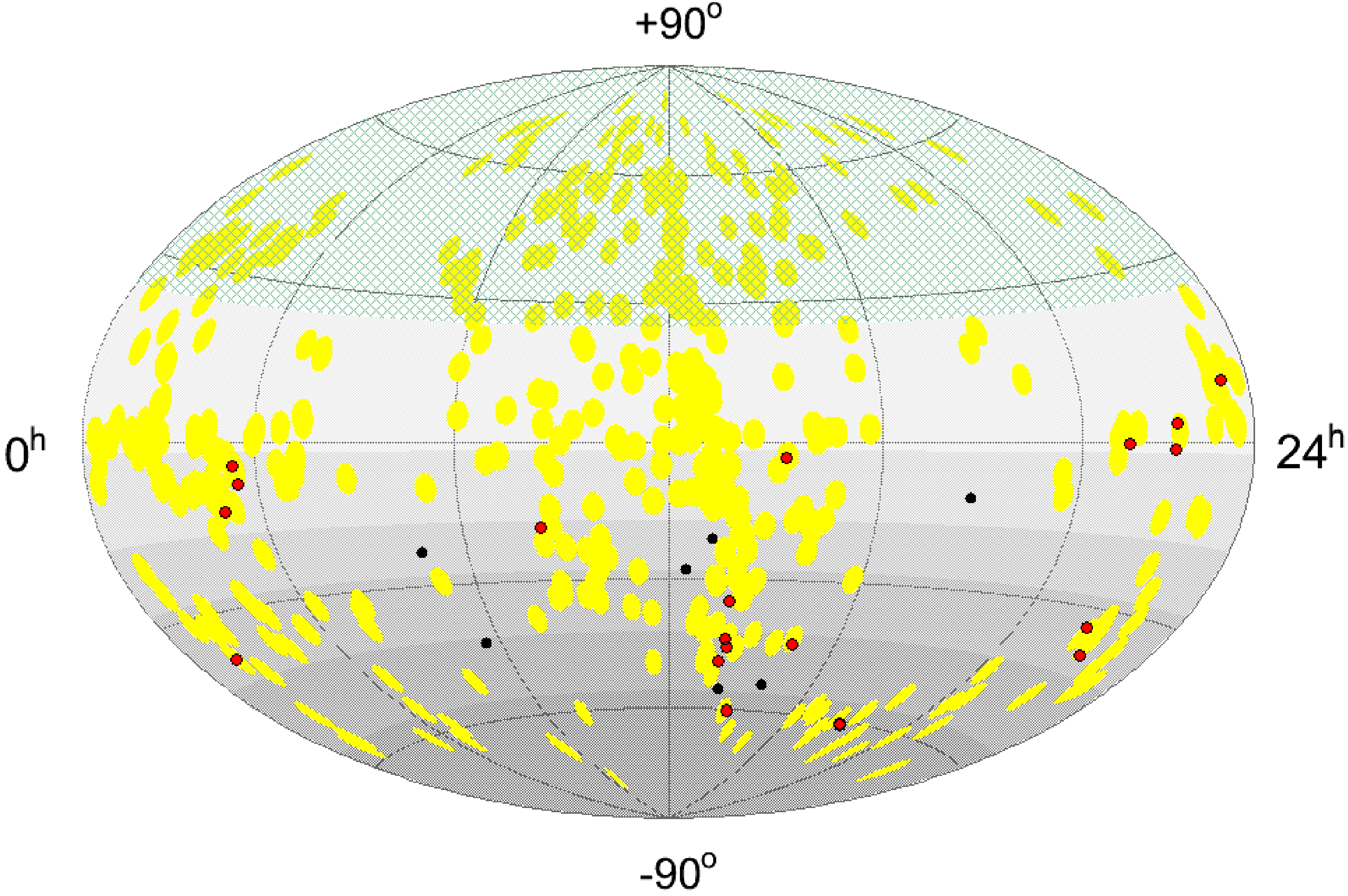
AAAS

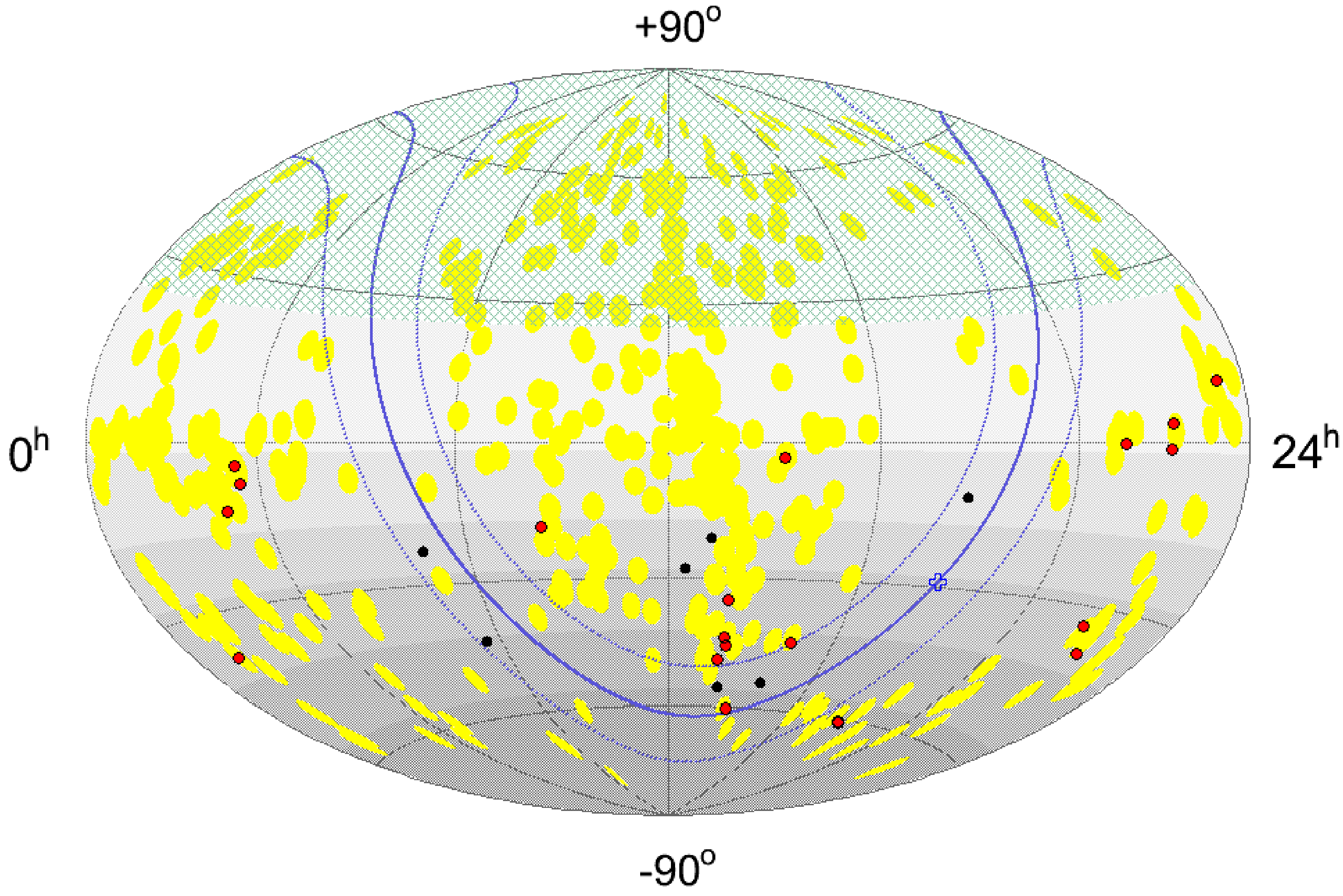
Yes! The best agreement is with the distribution of nearby active galaxies.



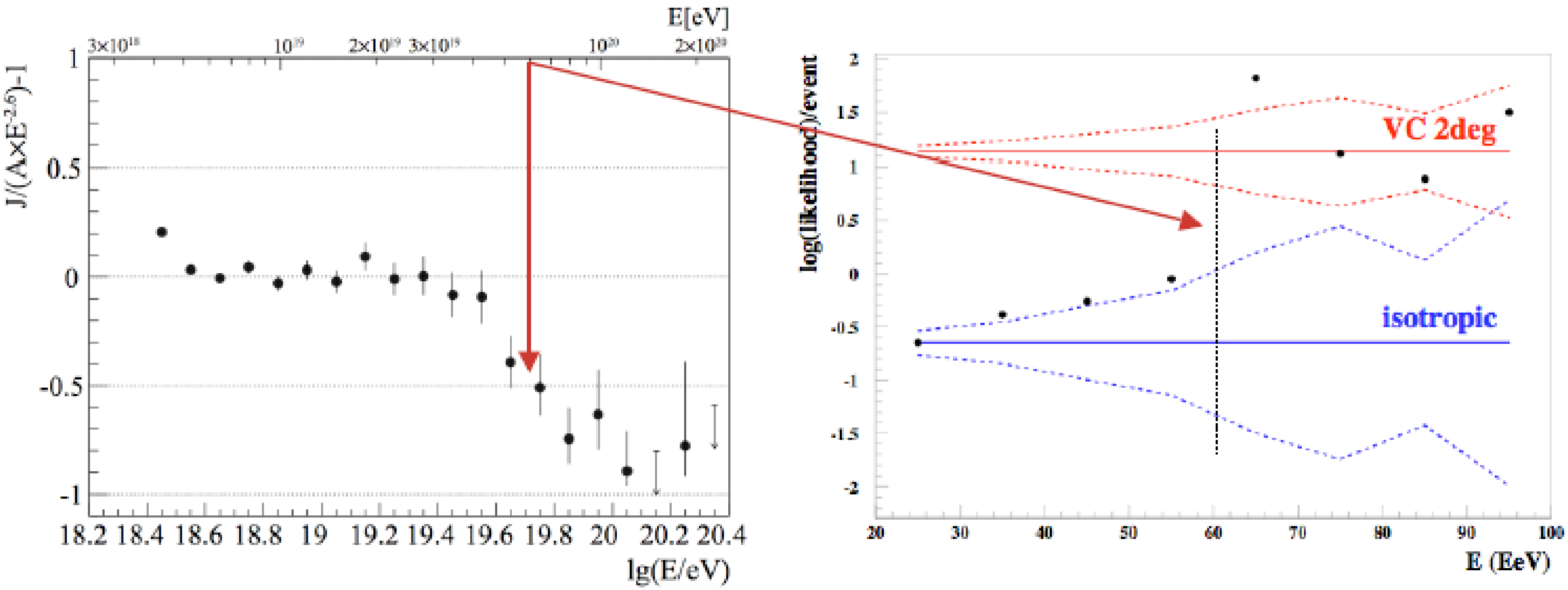
Blue – visible part of the sky
Red stars – active galactic nuclei (AGNs) with distance < 75 Mpc
– in agreement with our expectations (GZK cutoff)

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





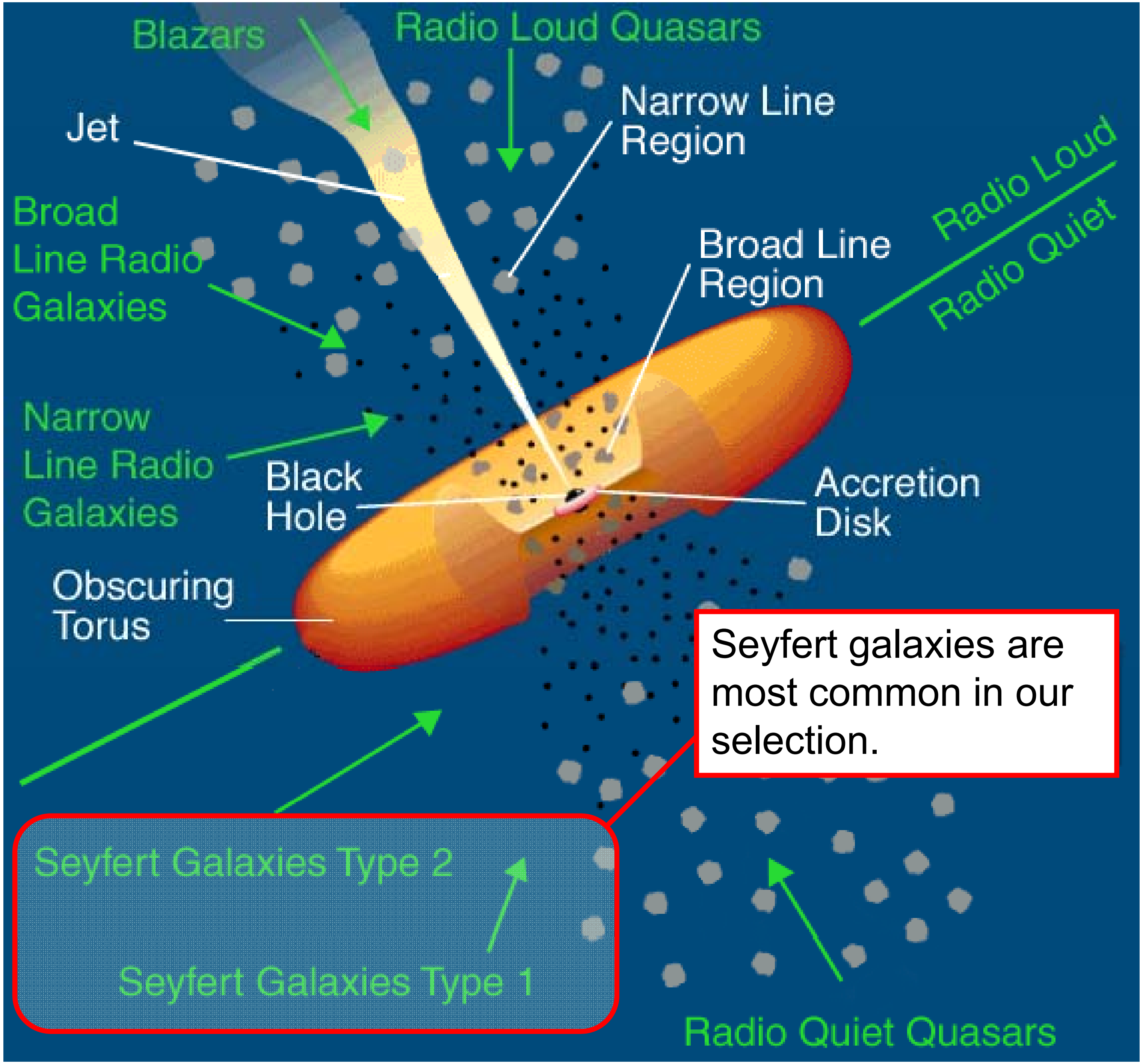
+90°
0h
24h
-90°



E[eV]
3×10^18
10^19
2×10^19
3×10^19
10^20
2×10^20
J/(A×E^-2.6)-1
lg(E/eV)
log(likelihood)/event
VC 2deg
isotropic
E (EeV)

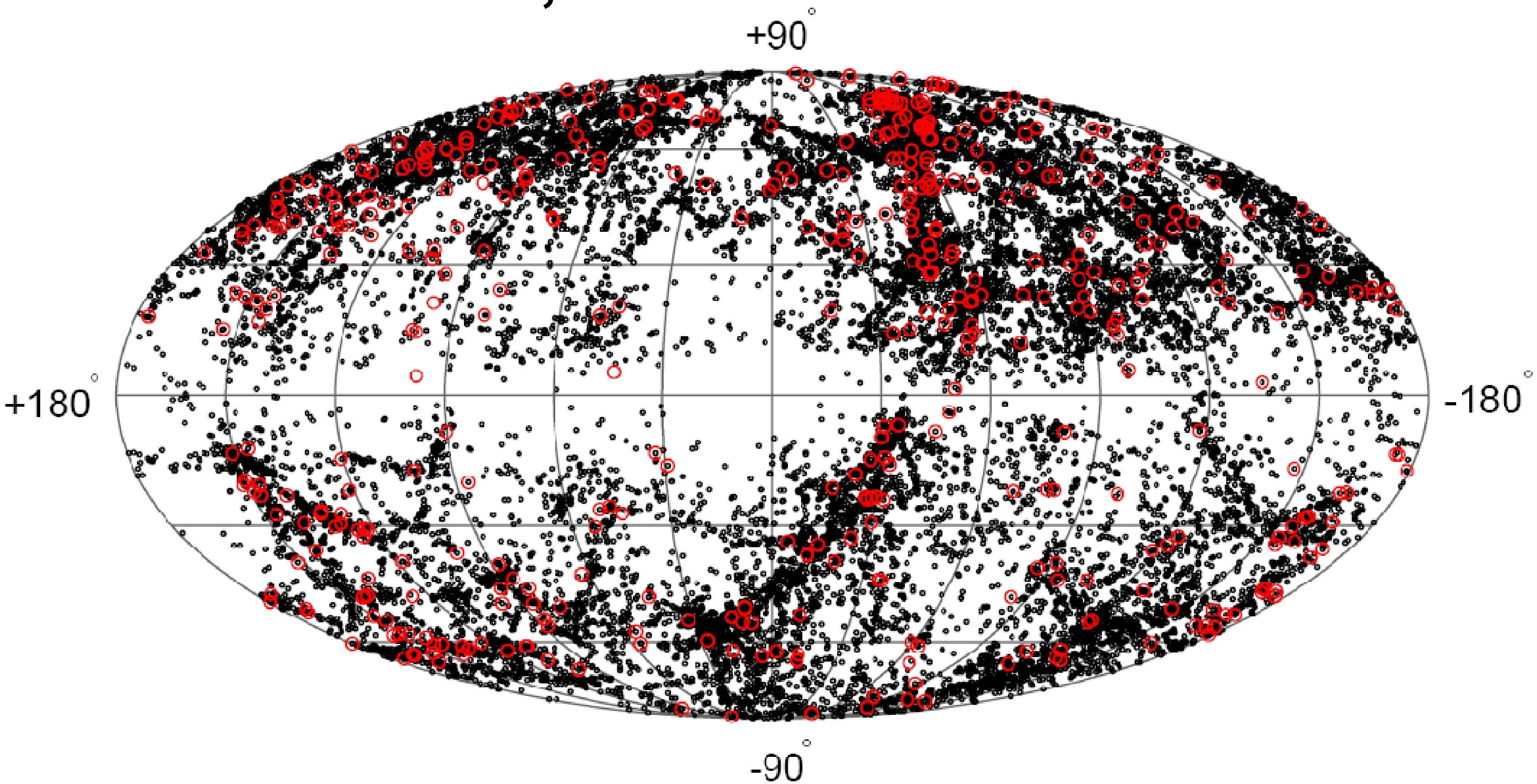
So, what are active galactic nuclei?

- 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



Seyfert galaxies are most common in our selection.

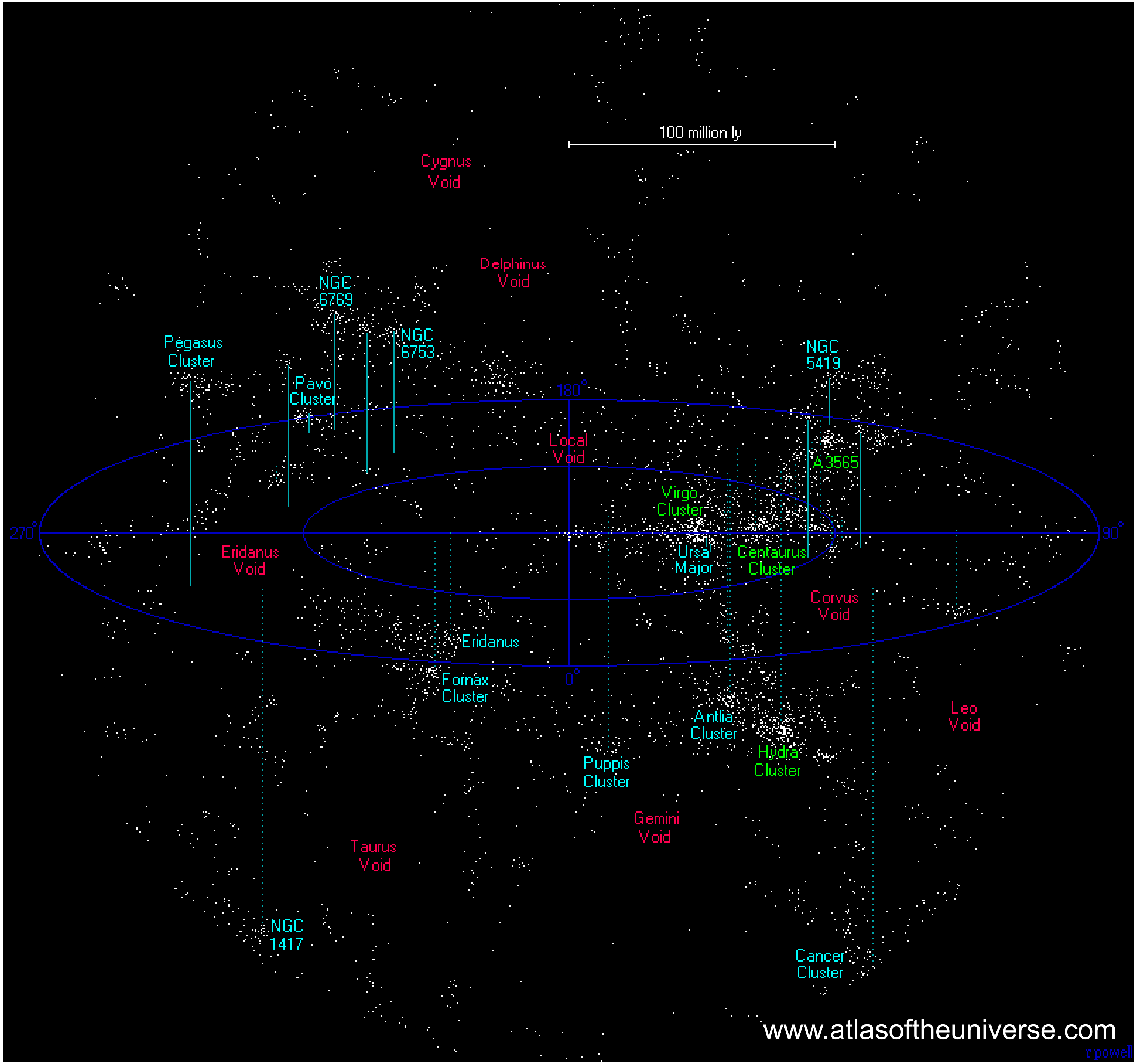
However, we have to be careful…

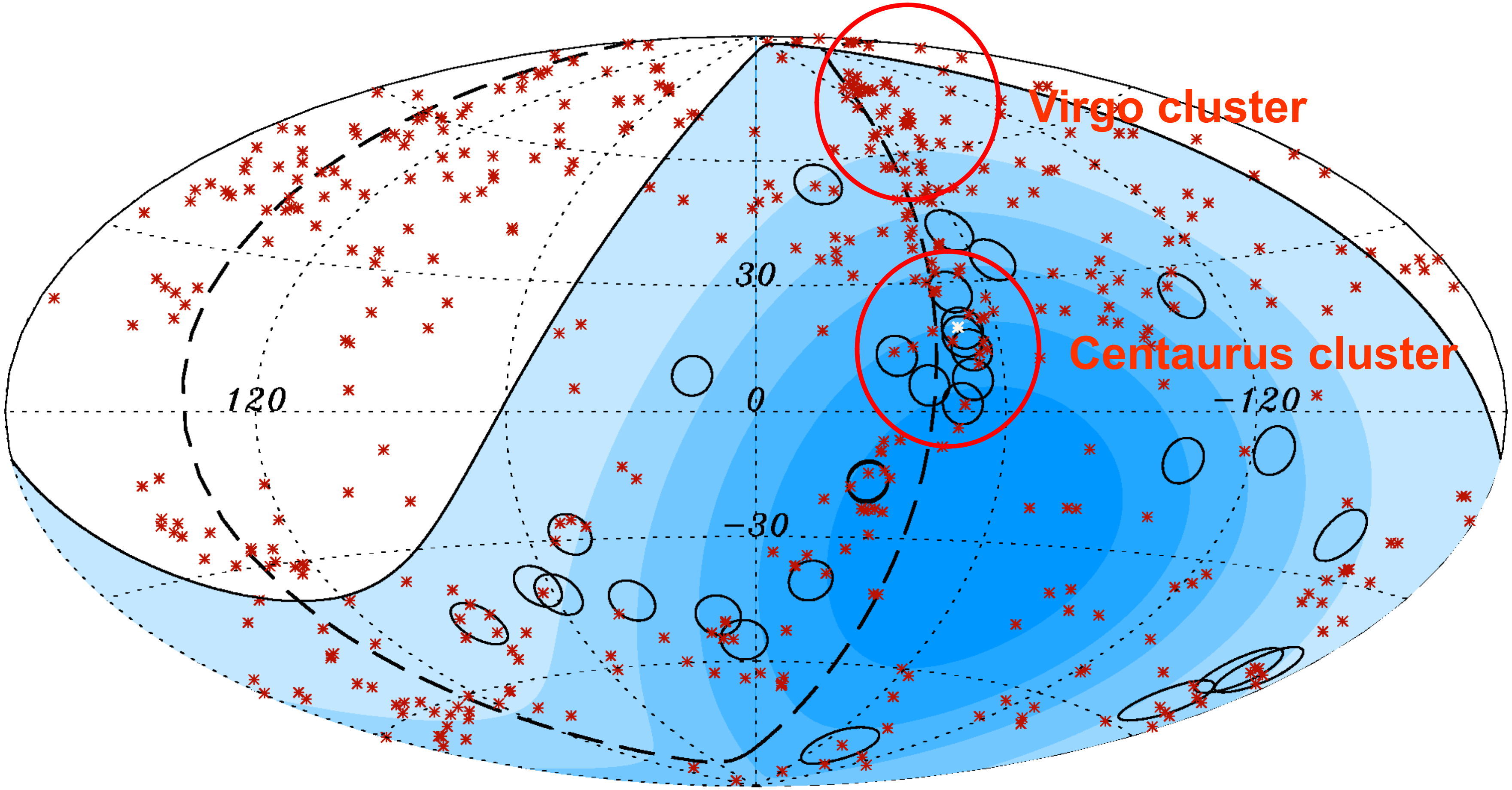


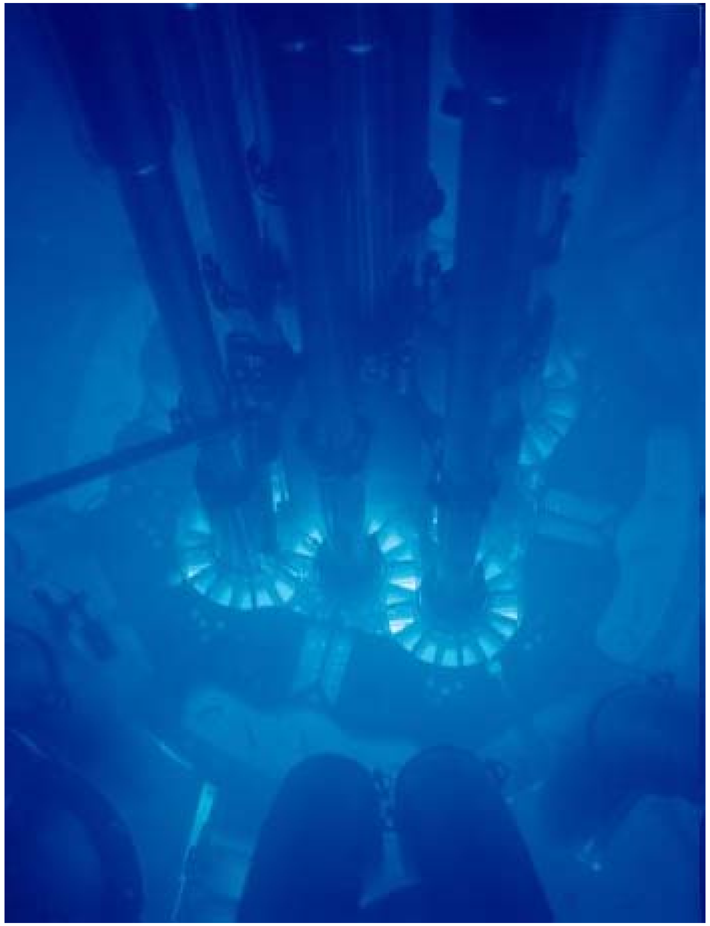
Red circles – (again) AGNs closer than 75 Mpc
Black dots – all galaxies closer than 75 Mpc (HyperLEDA catalogue)

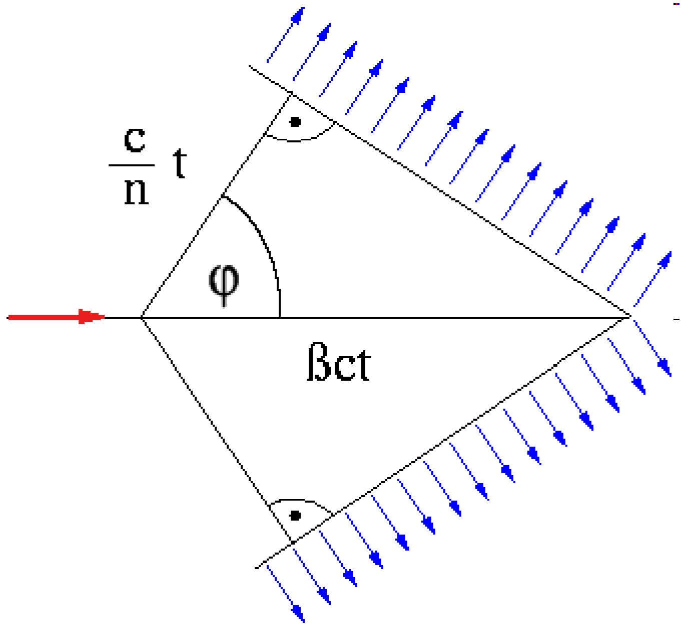
Distribution of ordinary galaxies (and matter in general) and of AGNs is very similar!

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 ...

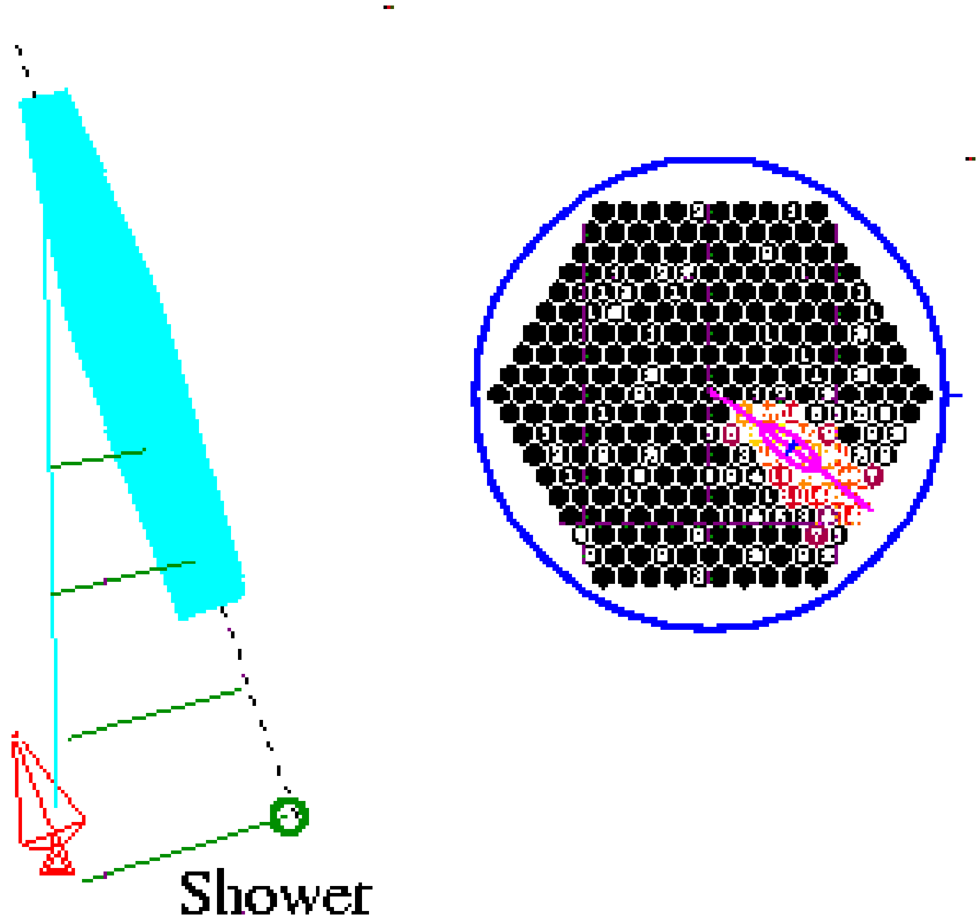

100 million ly
Cygnus Void
Delphinus Void
NGC 6769
NGC 6753
Pegasus Cluster
Pavo Cluster
NGC 5419
180°
Local Void
A3565
Virgo Cluster
270°
90°
Eridanus Void
Ursa Major
Centaurus Cluster
Corvus Void
Eridanus
Fornax Cluster
0°
Antlia Cluster
Leo Void
Puppis Cluster
Hydra Cluster
Gemini Void
Taurus Void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

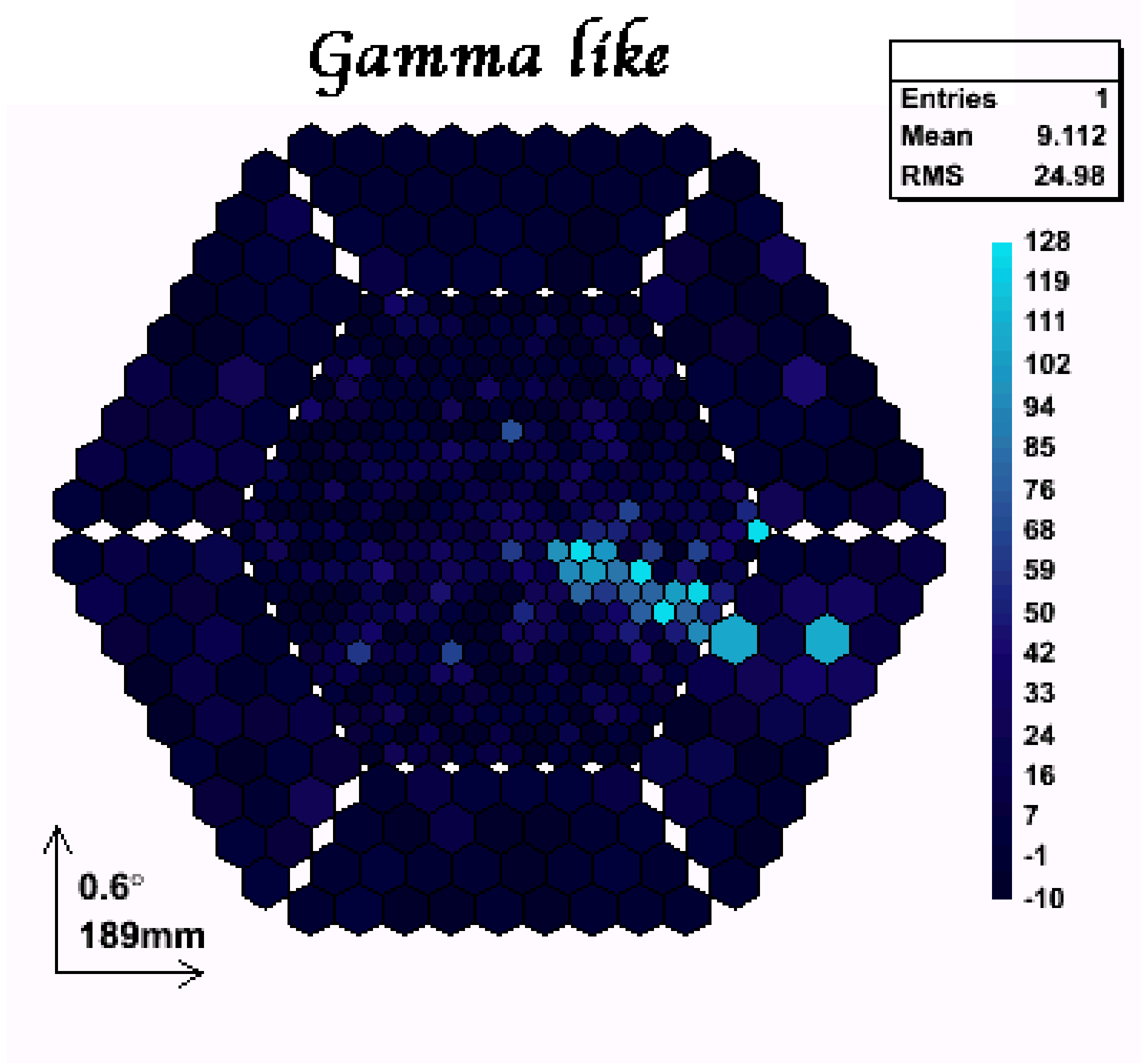

Virgo cluster
Centaurus cluster
30
120
0
−120
−30

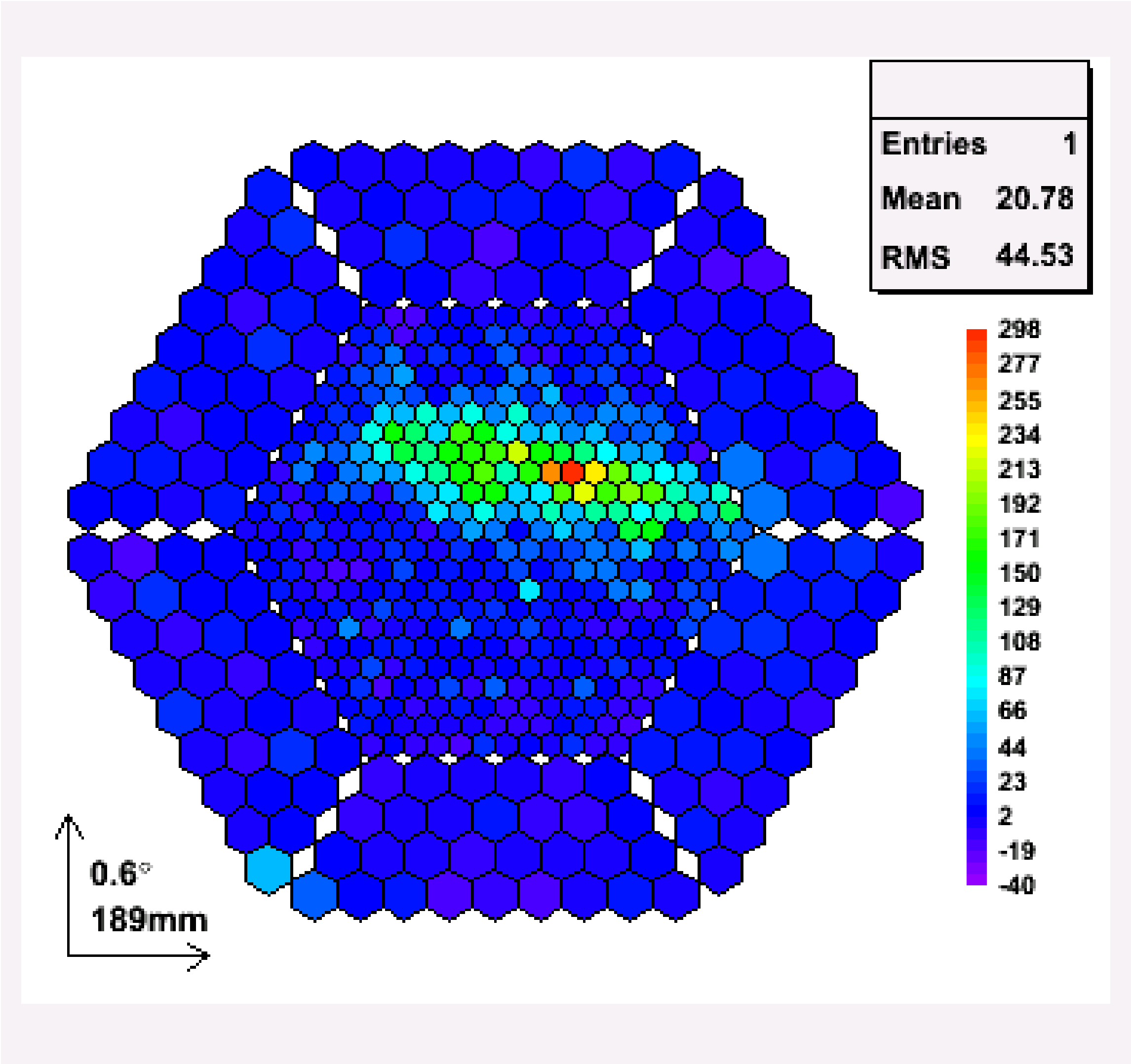




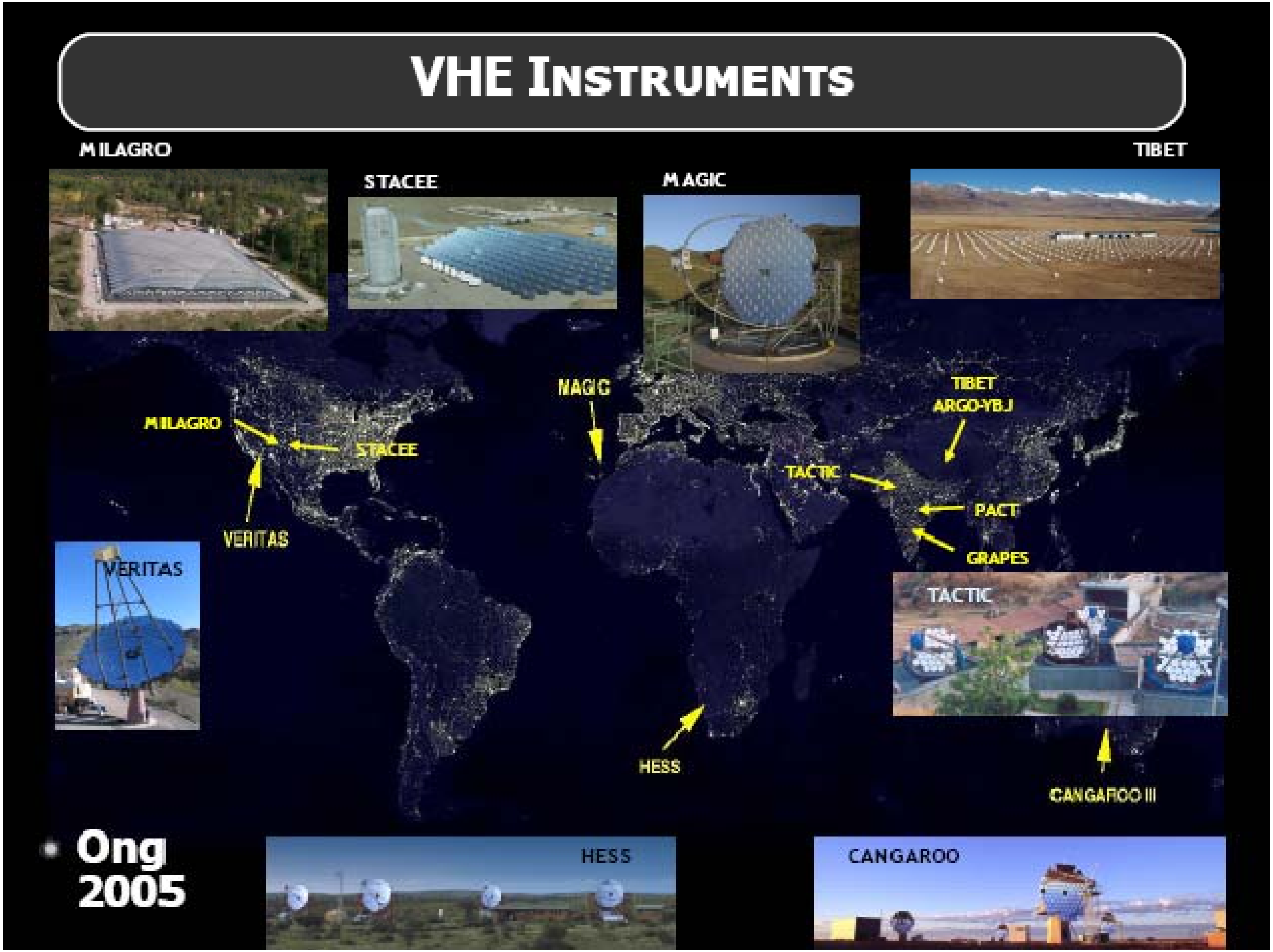
c/n t
φ
ßct

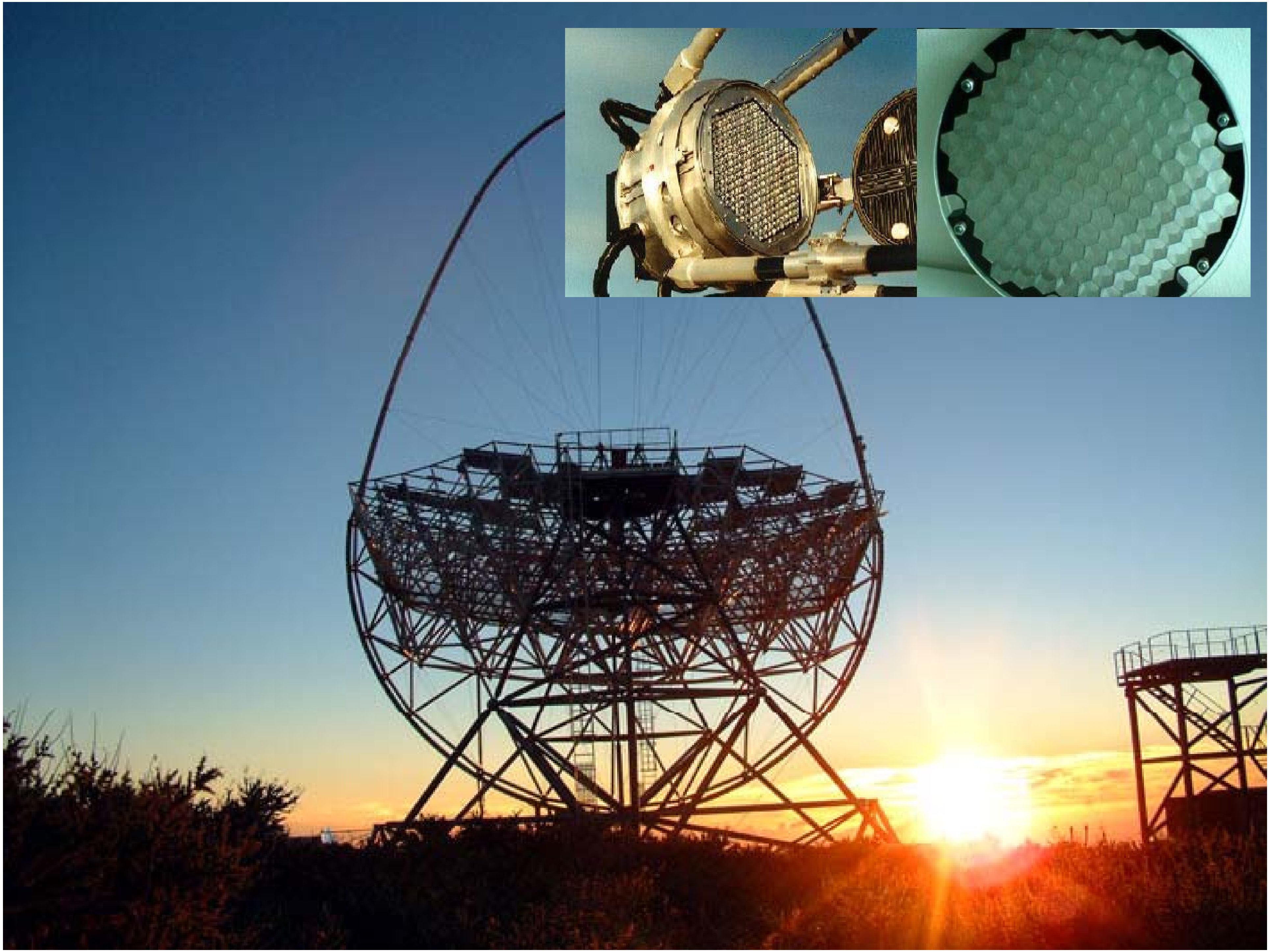

Shower

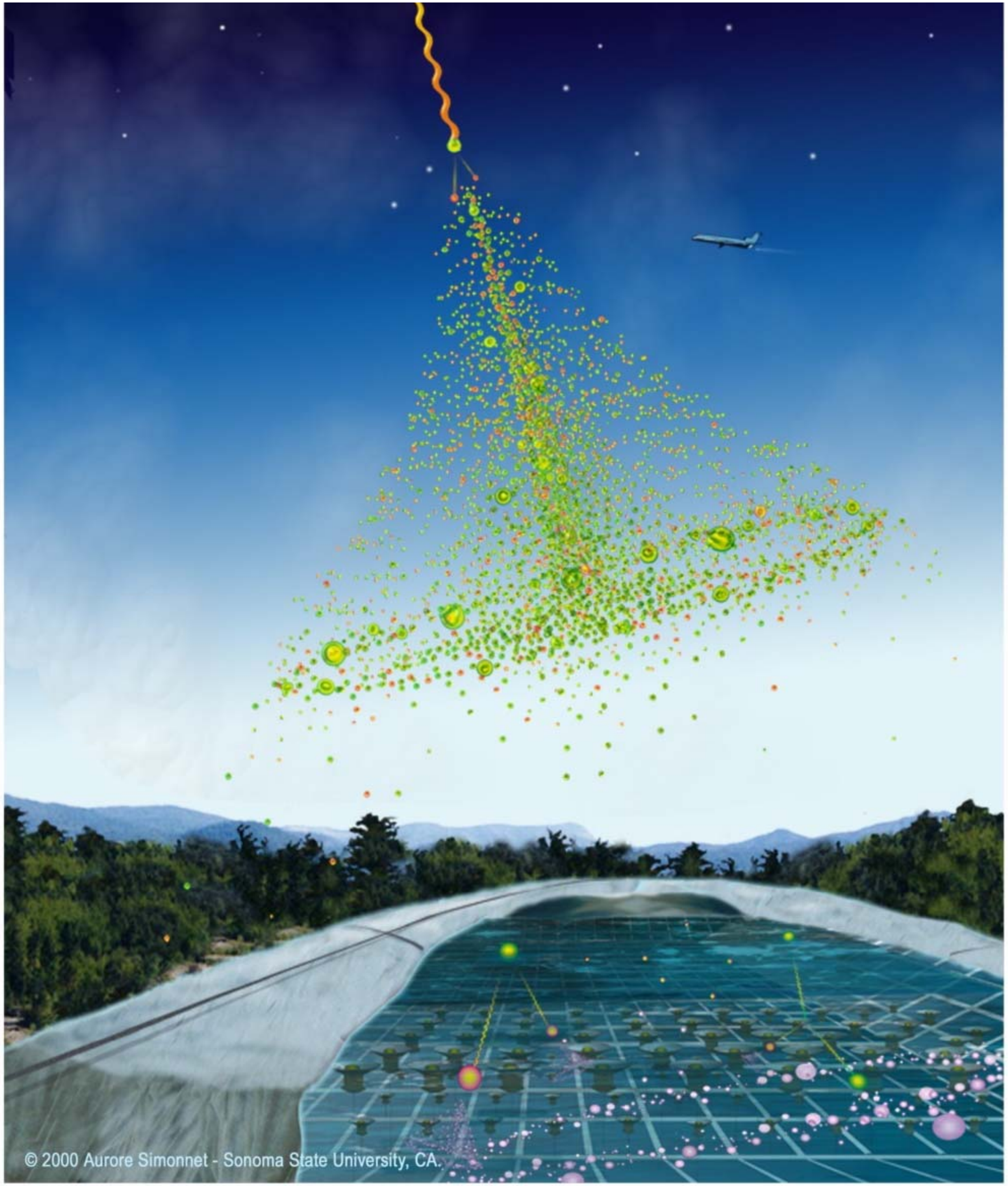

Gamma like
Entries 1
Mean 9.112
RMS 24.98
128
119
111
102
94
85
76
68
59
50
42
33
24
16
7
-1
-10
0.6°
189mm

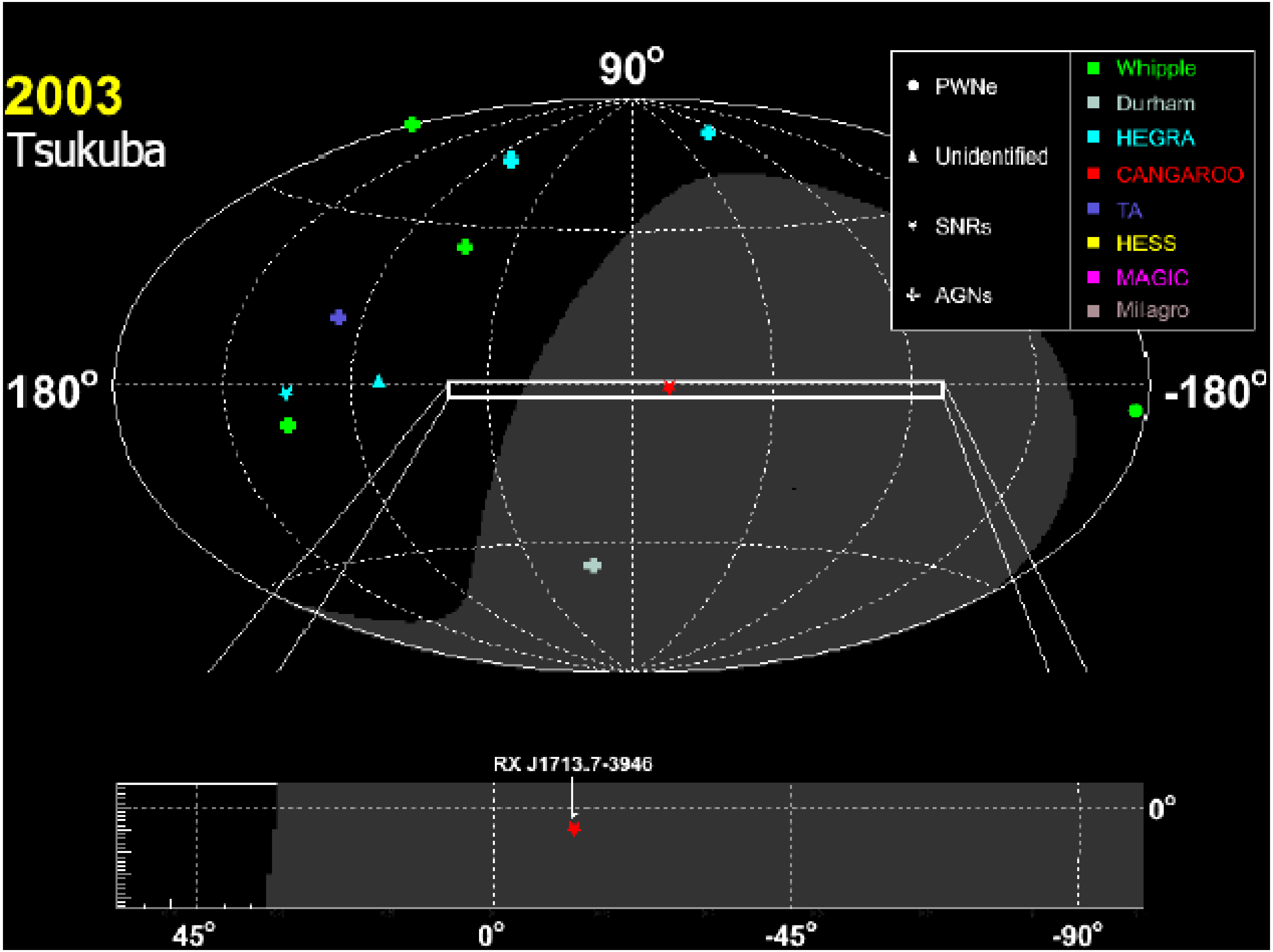


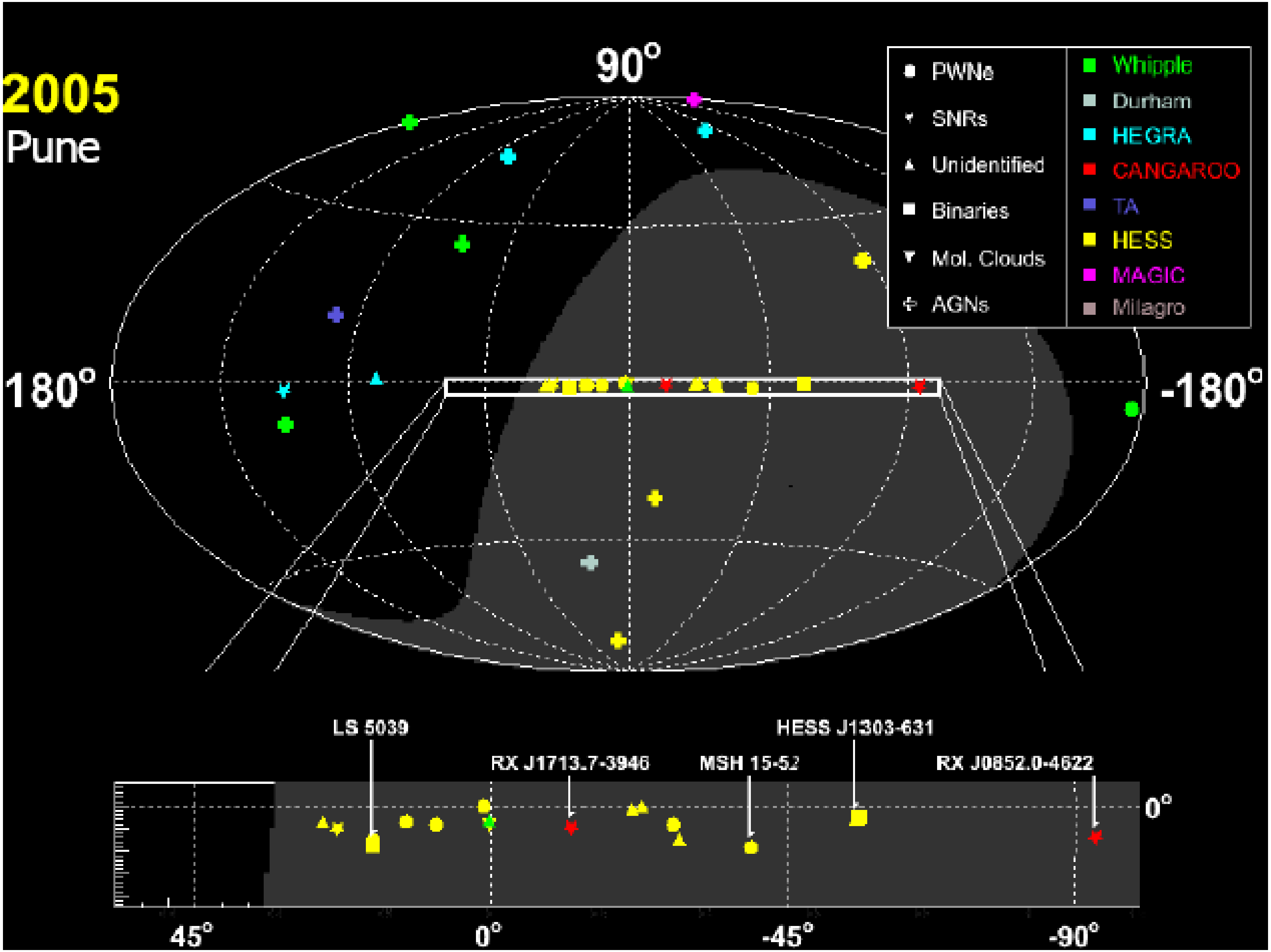
Entries 1
Mean 20.78
RMS 44.53
298
277
255
234
213
192
171
150
129
108
87
66
44
23
2
-19
-40
0.6°
189mm

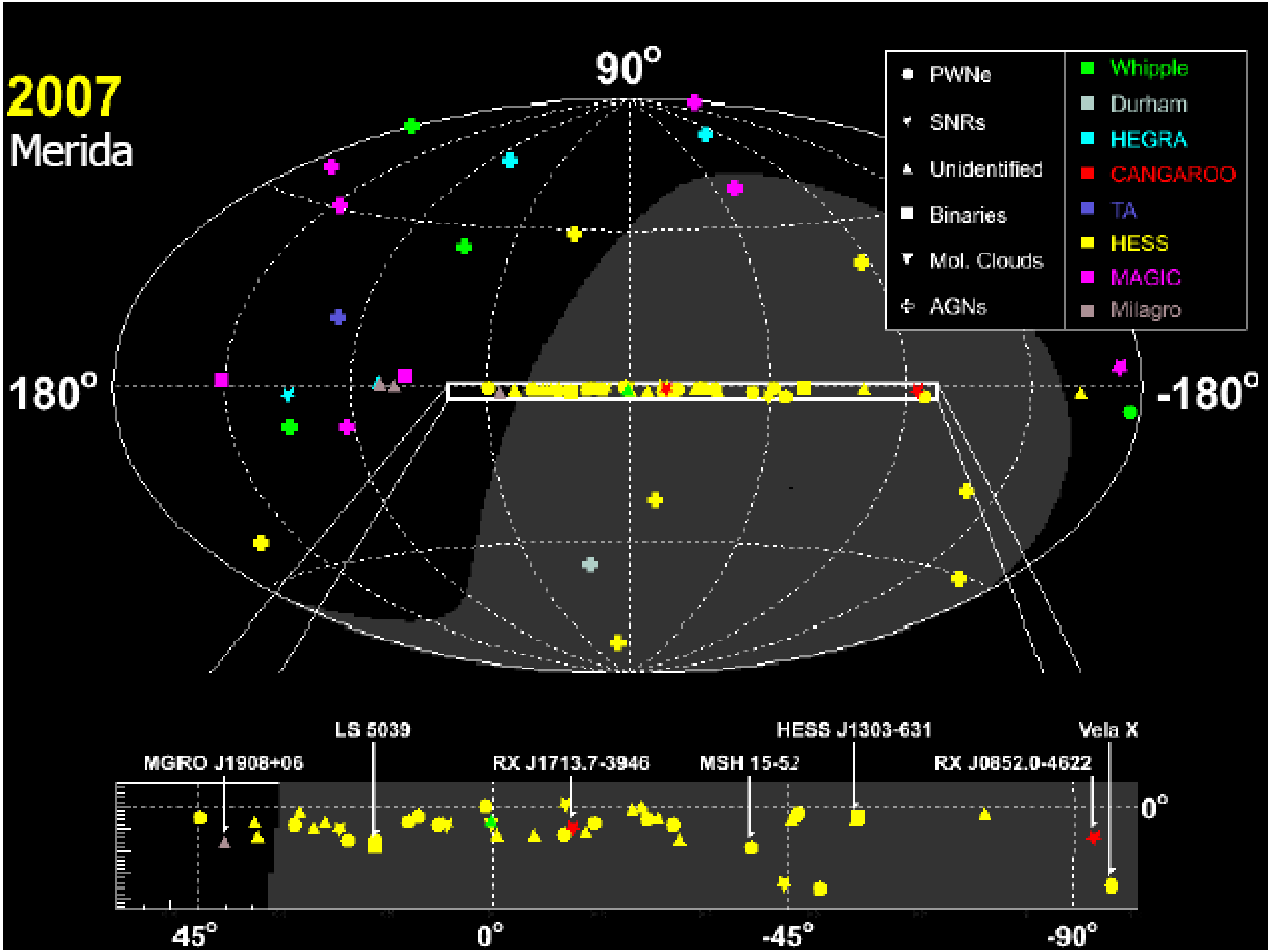

VHE INSTRUMENTS
MILAGRO
TIBET
STACEE
MAGIC
MAGIC
TIBET
ARGO-YBJ
MILAGRO
STACEE
TACTIC
PACT
VERITAS
GRAPES
VERITAS
TACTIC
HESS
CANGAROO III
Ong
2005
HESS
CANGAROO




© 2000 Aurore Simonnet - Sonoma State University, CA.

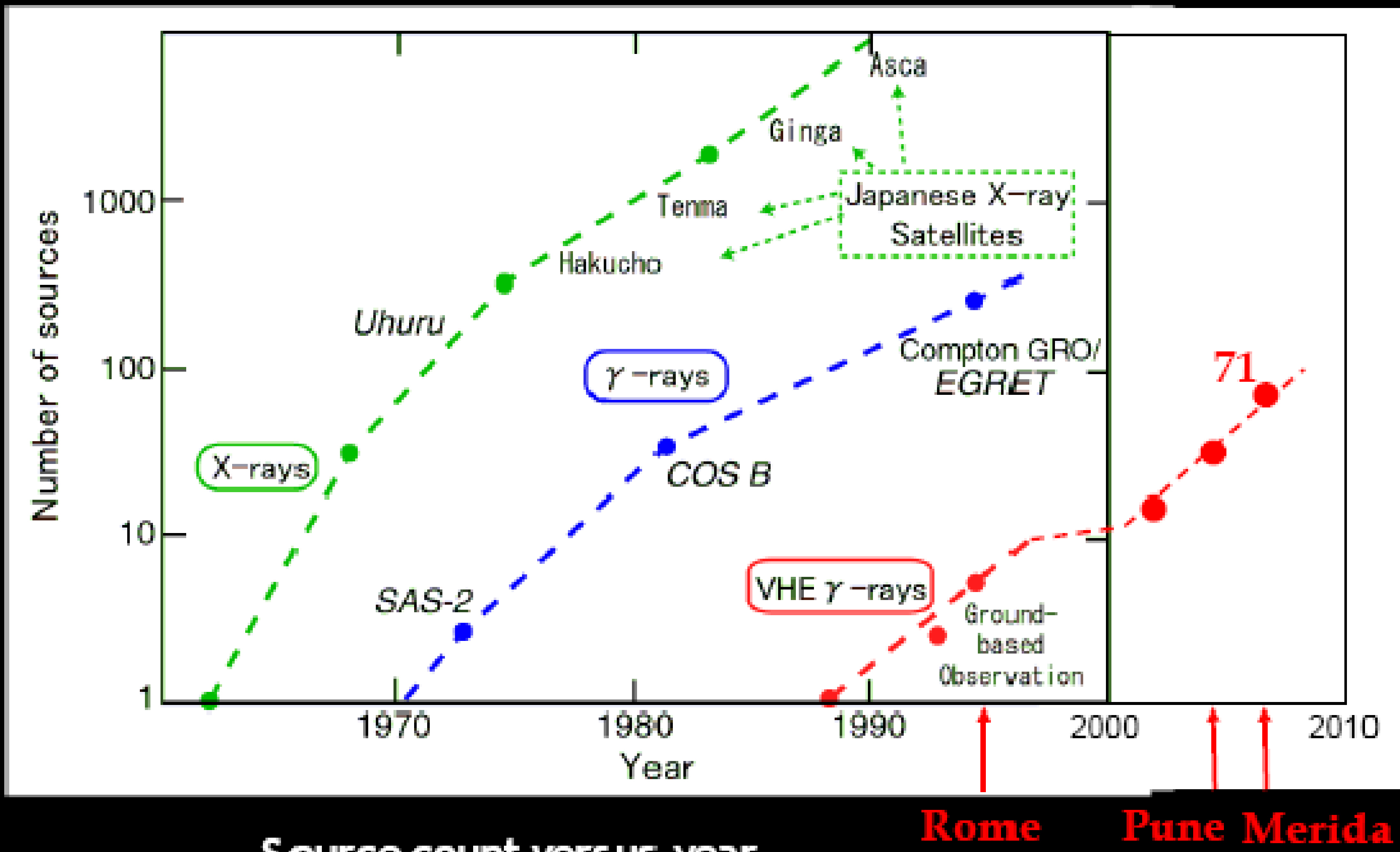

2003
Tsukuba
90°
180°
-180°
PWNe
Unidentified
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
RX J1713.7-3946
0°
45°
0°
-45°
-90°


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°

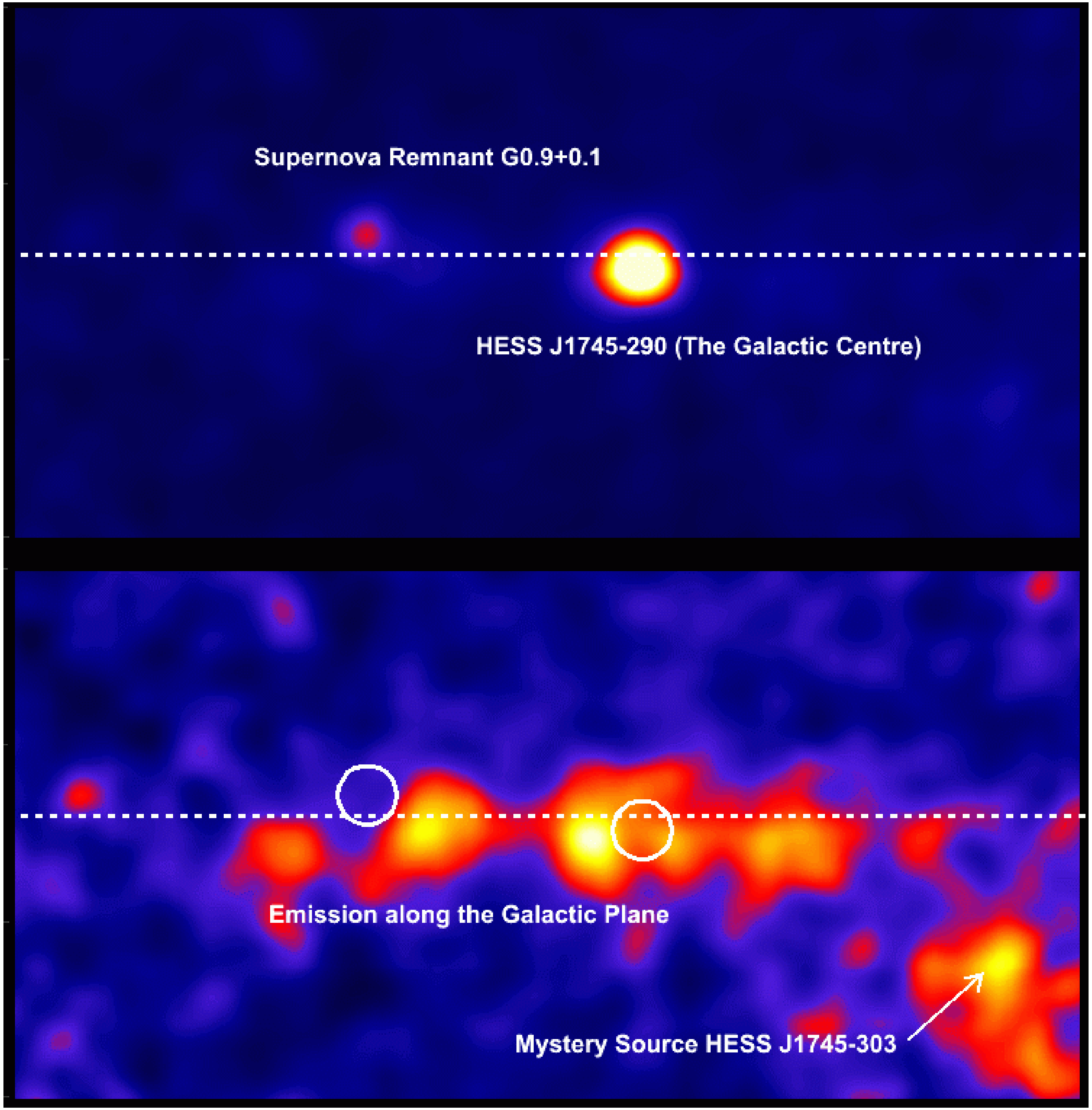


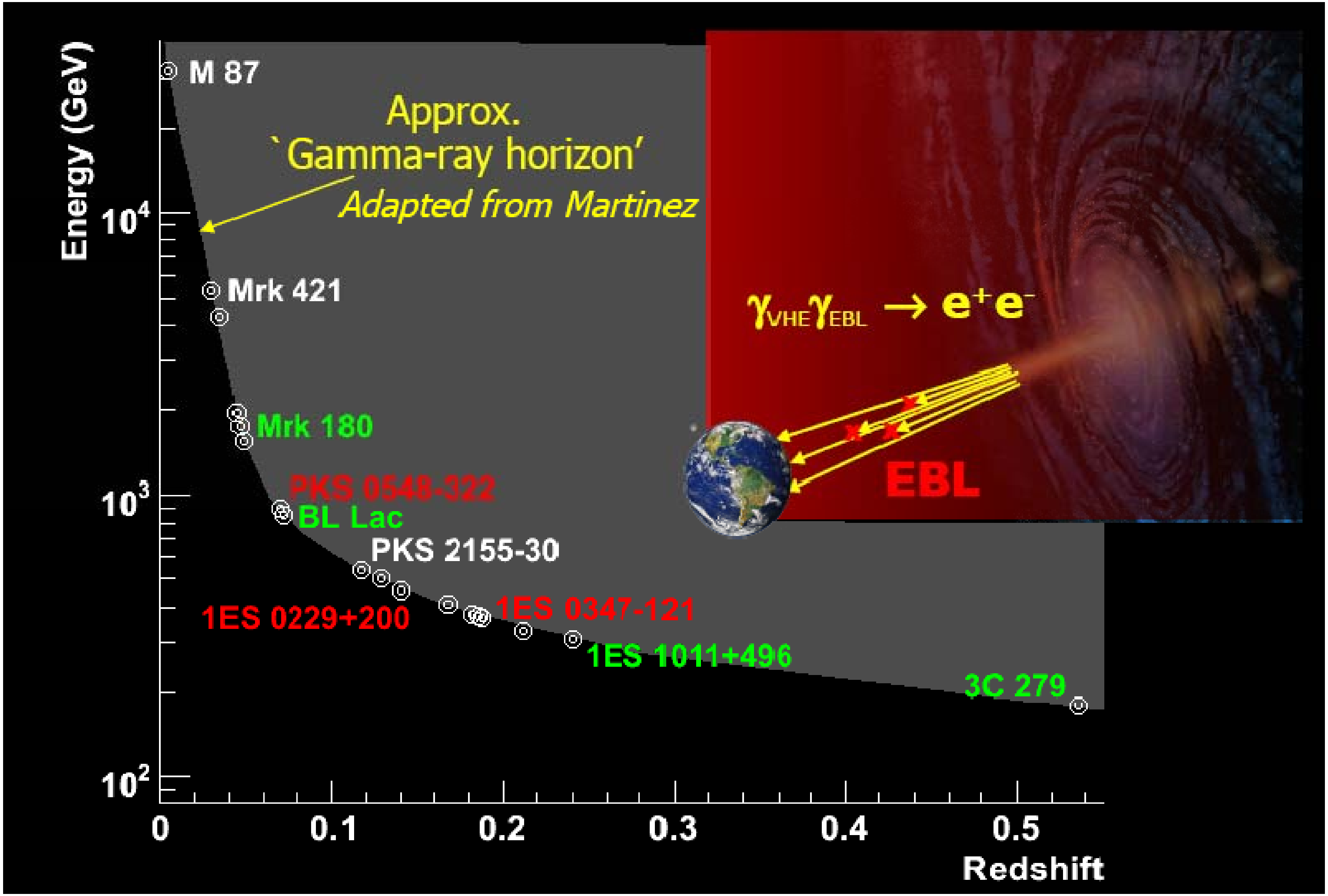
2007
Merida
90°
180°
-180°
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
HESS J1303-631
Vela X
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
RX J0852.0-4622
0°
45°
0°
-45°
-90°

Kifune Plot

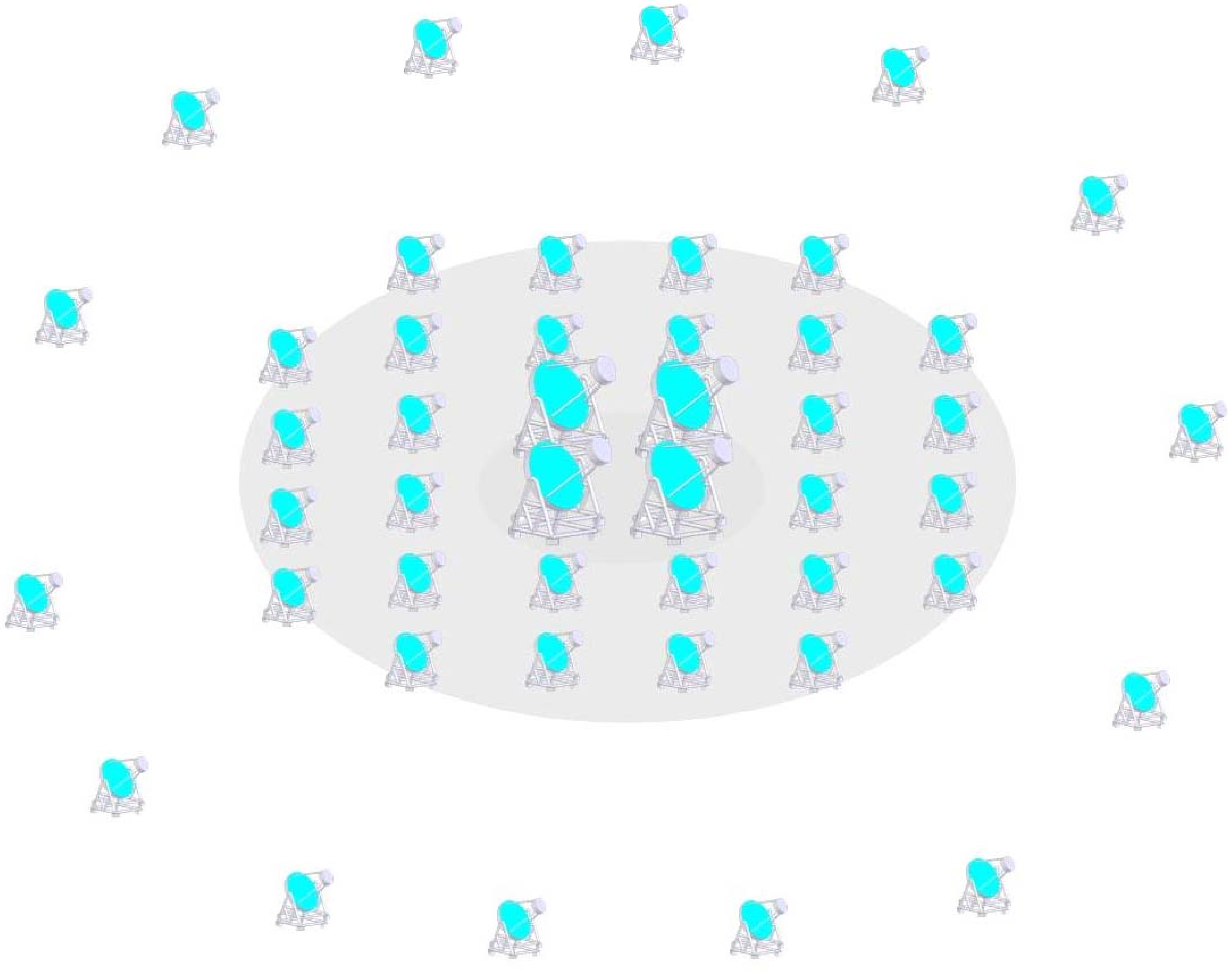


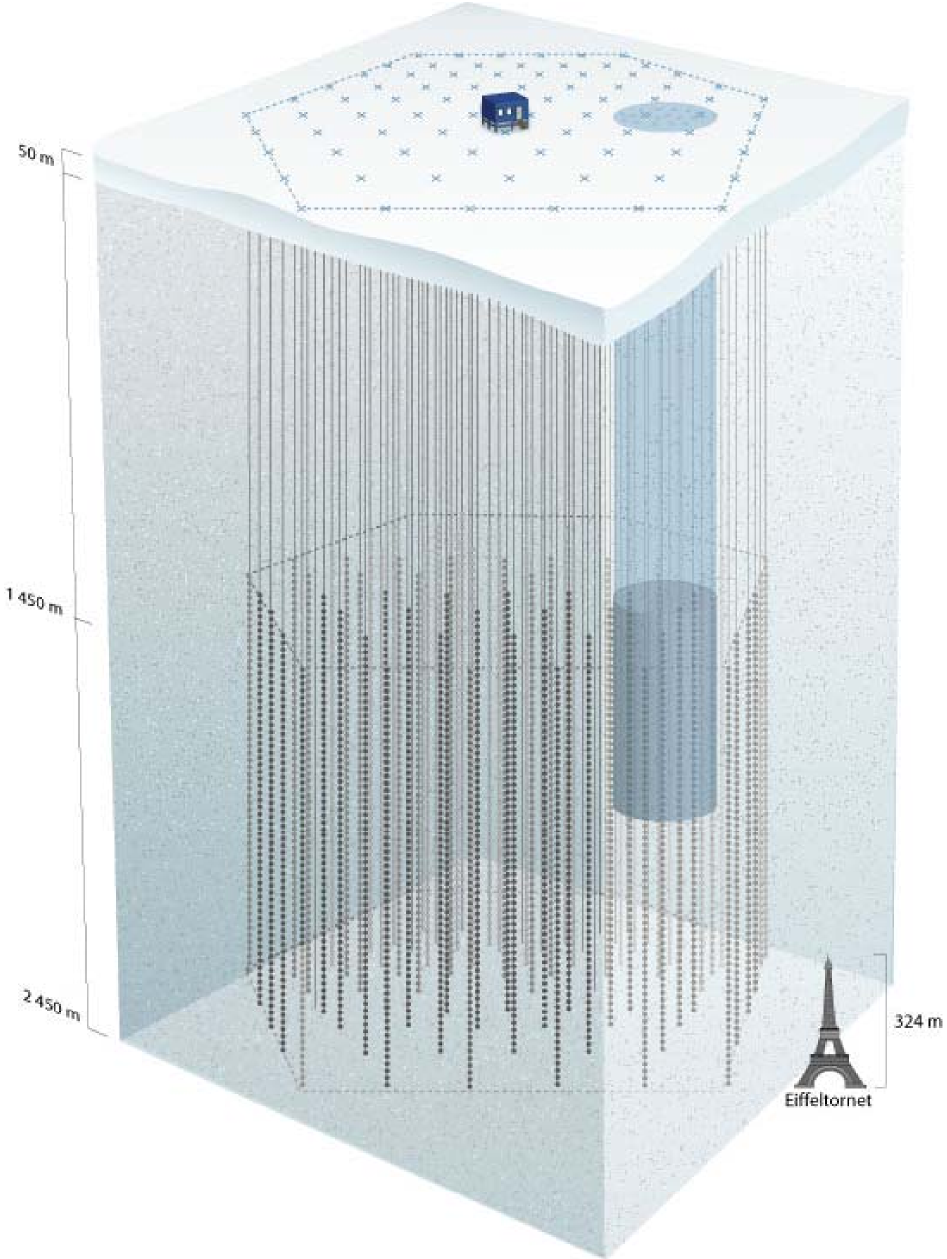
Source count versus year
[T. Kifune]


Supernova Remnant G0.9+0.1
HESS J1745-290 (The Galactic Centre)
Emission along the Galactic Plane
Mystery Source HESS J1745-303

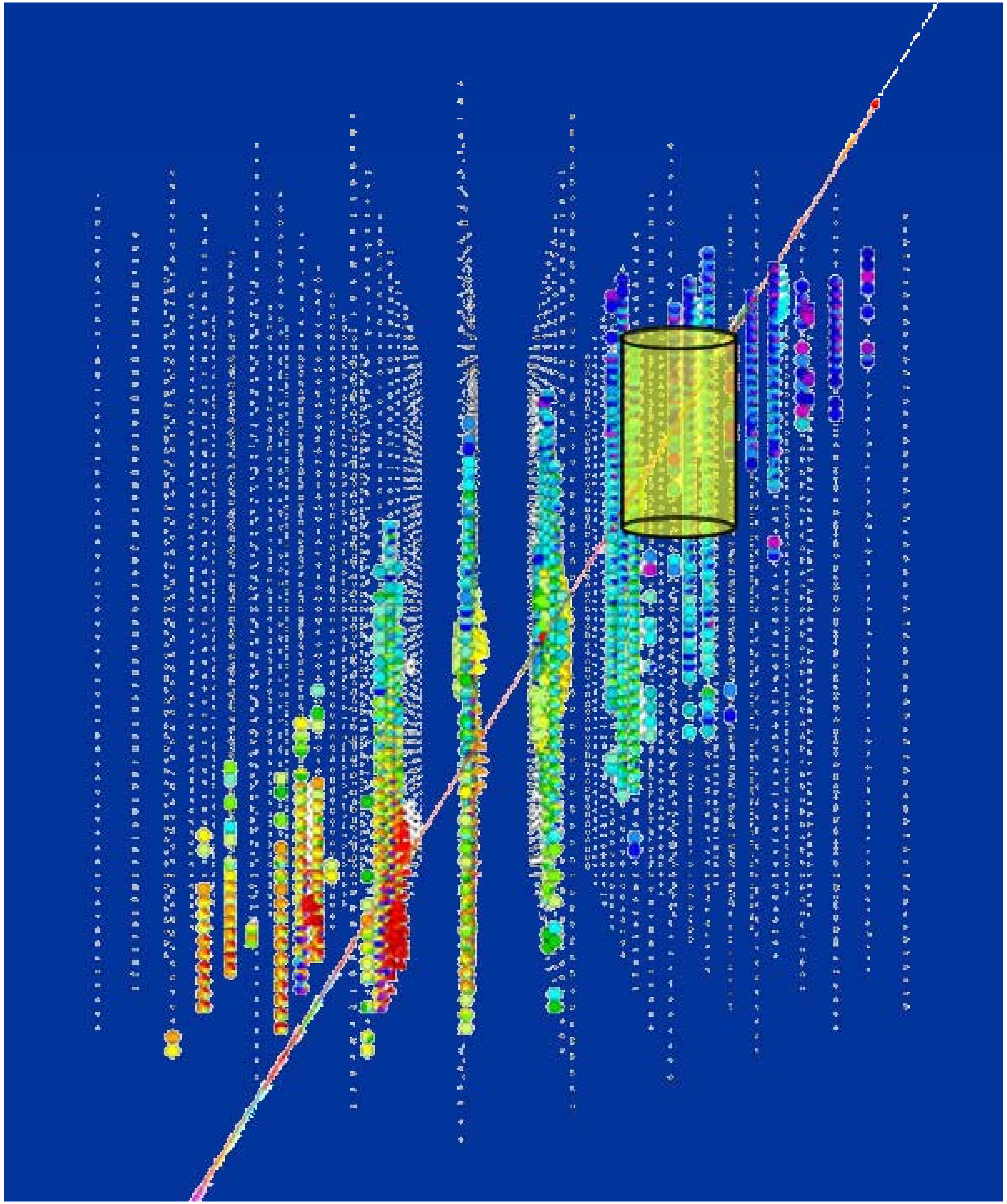


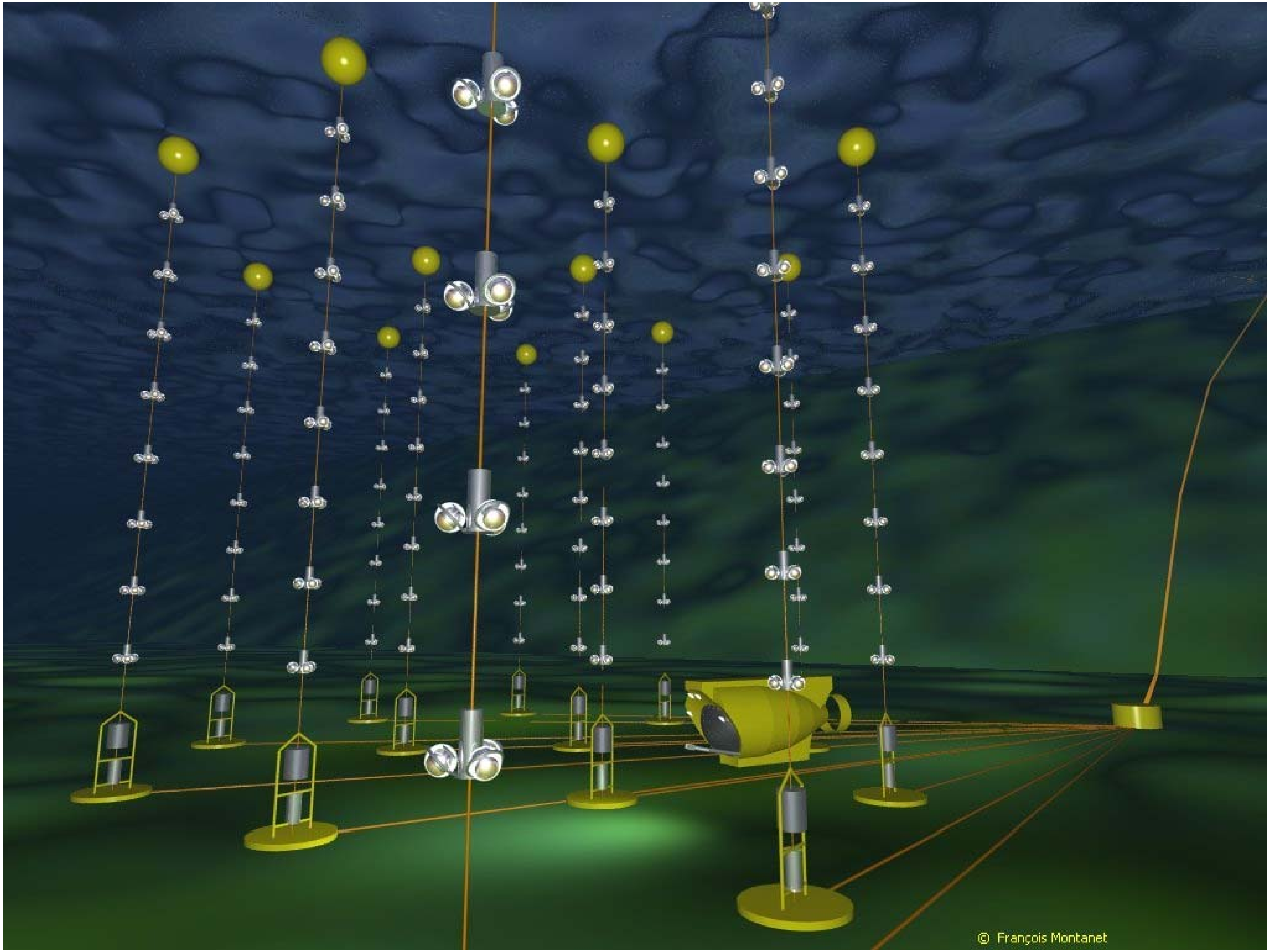
Energy (GeV)
M 87
Approx.
`Gamma-ray horizon'
Adapted from Martinez
Mrk 421
Mrk 180
PKS 0548-322
BL Lac
PKS 2155-30
1ES 0229+200
1ES 0347-121
1ES 1011+496
3C 279
$\gamma_{VHE}\gamma_{EBL} \rightarrow e^+e^-$
EBL
10^4
10^3
10^2
0
0.1
0.2
0.3
0.4
0.5
Redshift

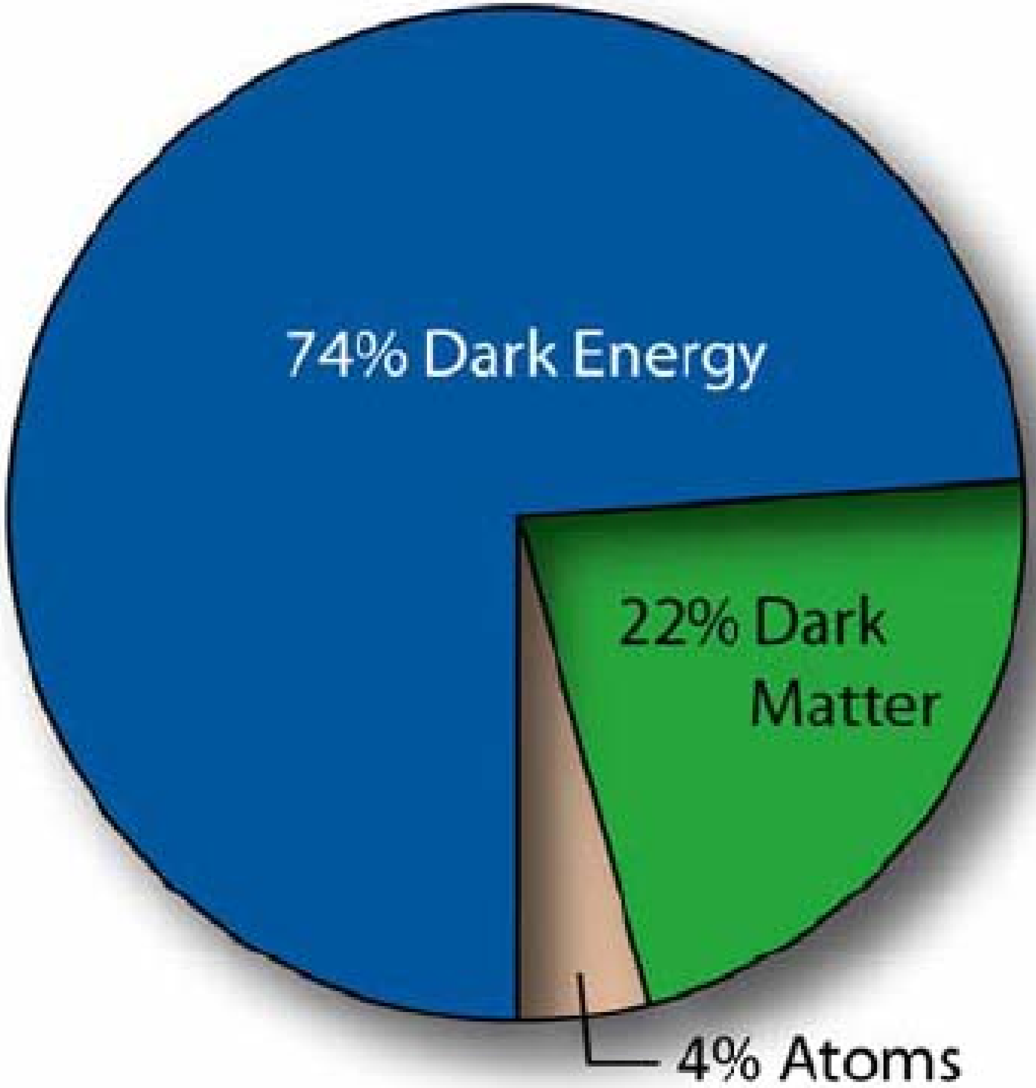


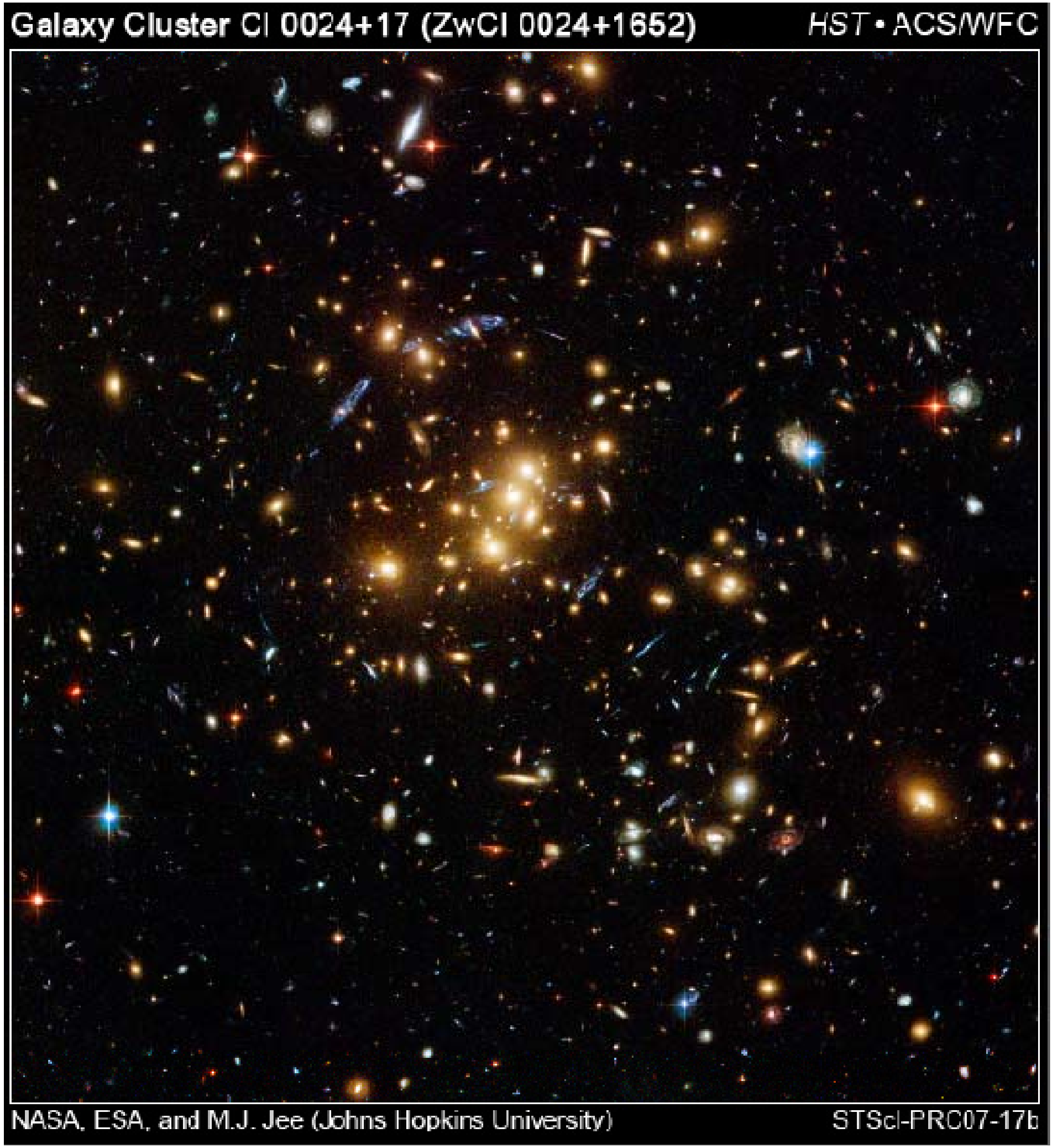


50 m
1 450 m
2 450 m
324 m
Eiffeltornet

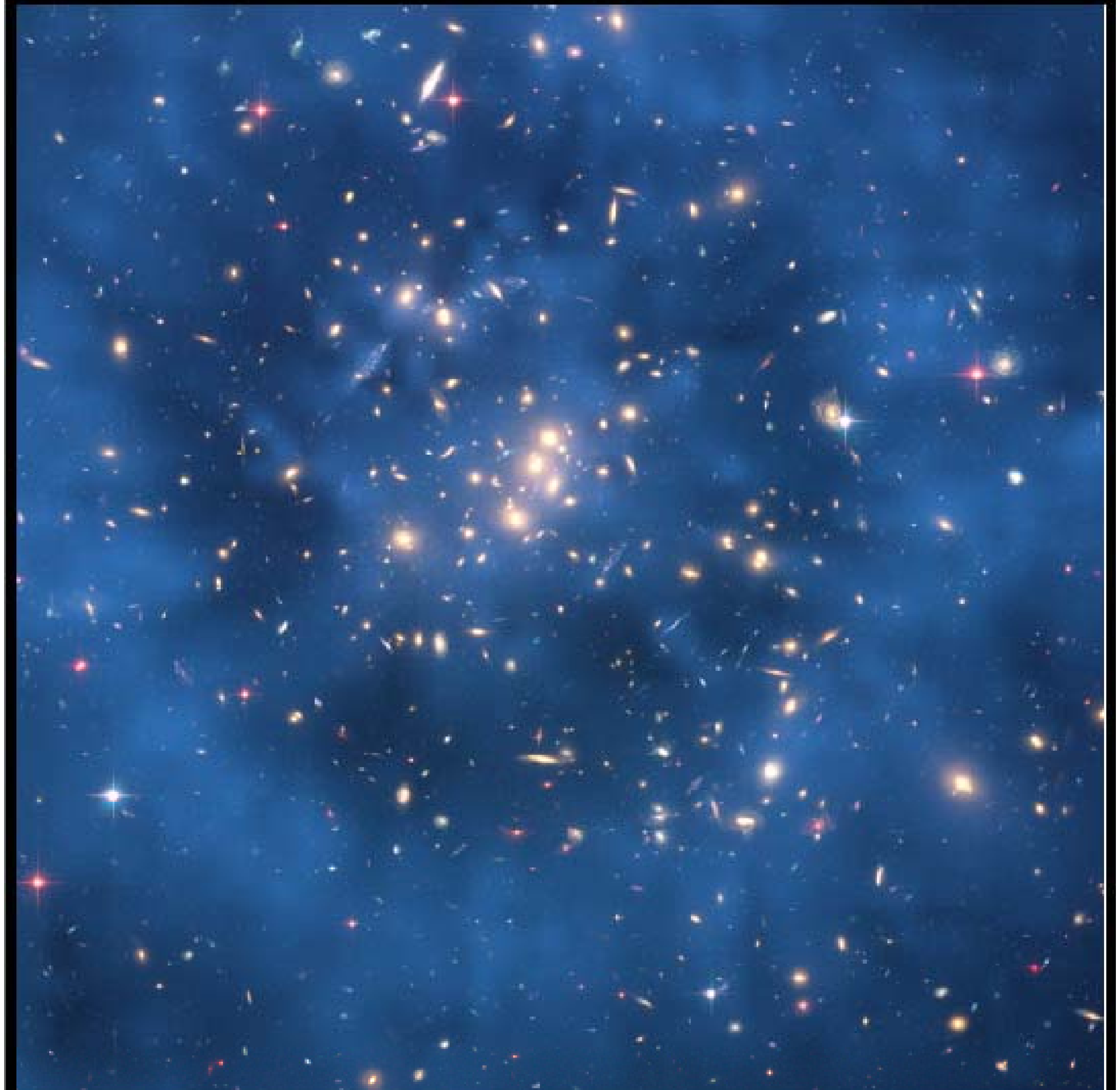



© François Montanet


74% Dark Energy
22% Dark Matter
4% Atoms

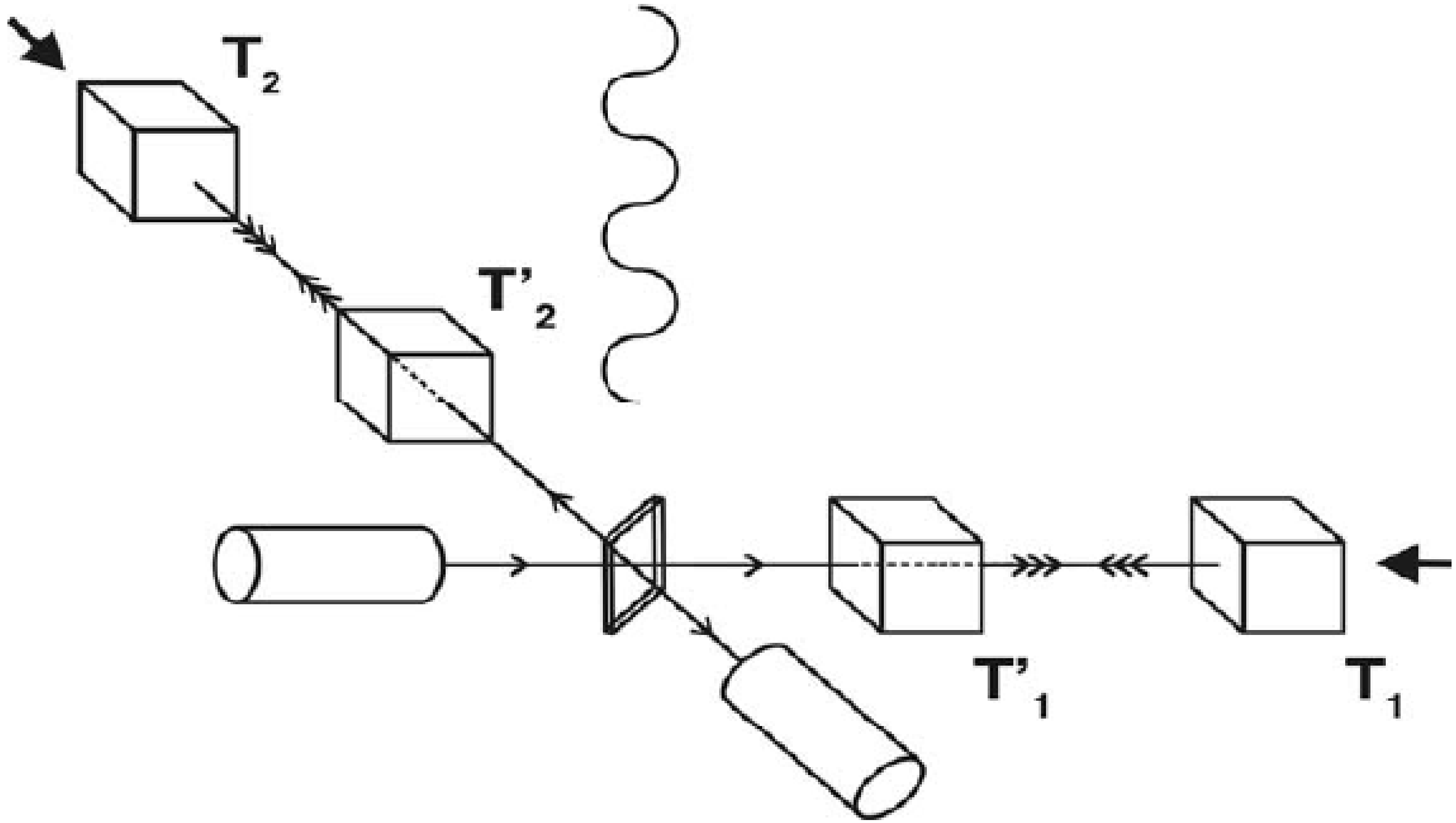

Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
HST • ACS/WFC
NASA, ESA, and M.J. Jee (Johns Hopkins University)
STScI-PRC07-17b

Dark Matter Ring in Cl 0024+17 (ZwCl 0024+1652) *HST* • ACS/WFC



NASA, ESA, and M.J. Jee (Johns Hopkins University) STScI-PRC07-17b


Dark matter search strategies
WIMP
1. Direct detection >
Milky way
2. Indirect detection >
WIMP
WIMP
γ
ν
Sun
Earth
< 3. Production at the Large Hadron Collider



Obrázek 2 – Interferometry projektu LIGO budou dosahovat vyšší citlivosti zásluhou Fabryho-Perotových rezonančních dutin. Paprsky se budou v obou ramenech mnohonásobně odrážet mezi volně zavěšenými tělesy T_1 a T'_1 resp. T_2 a T'_2. Teprve poté se složí a dopadnou na fotodetektor.