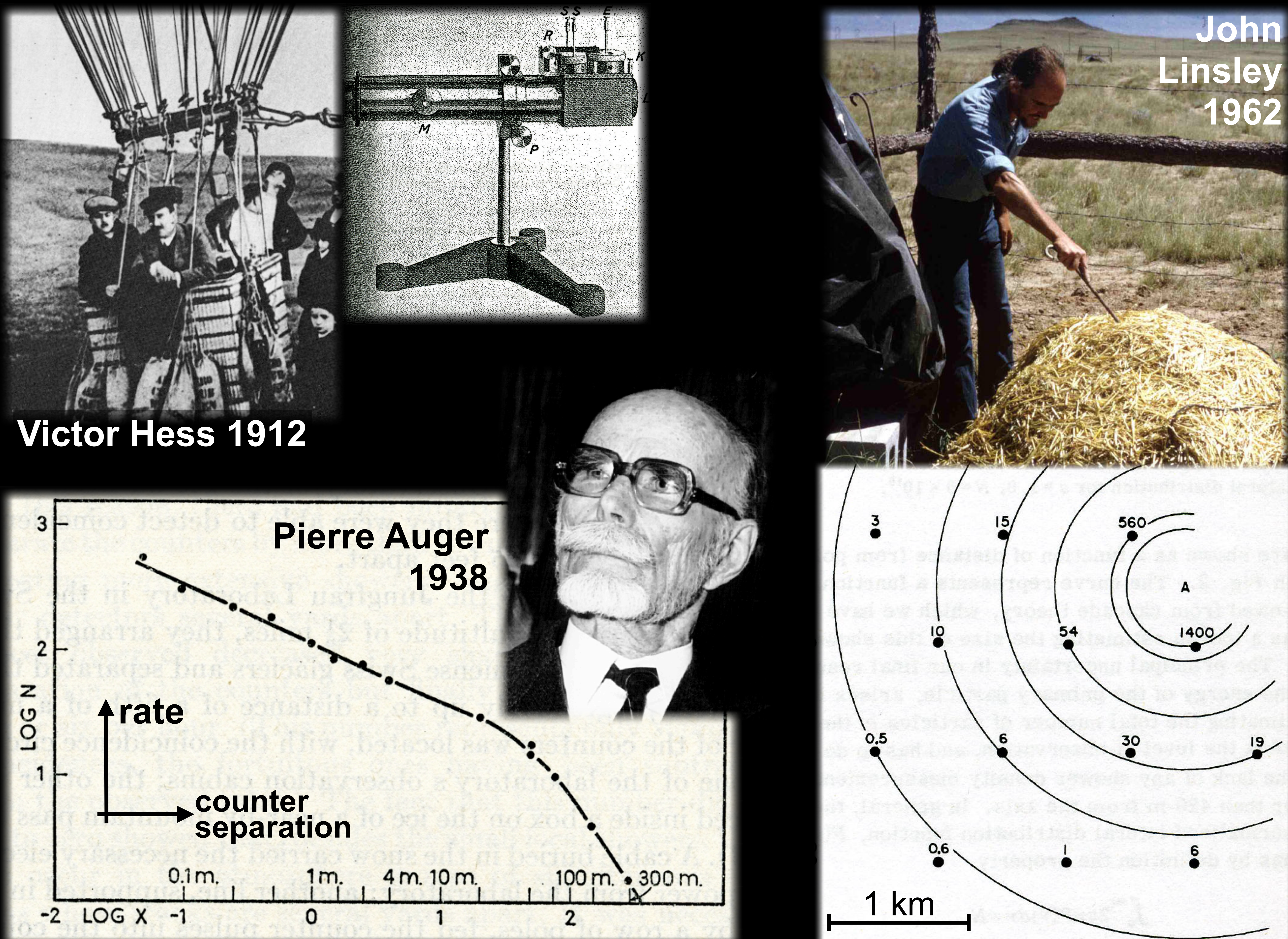
Karlsruhe Institute of Technology

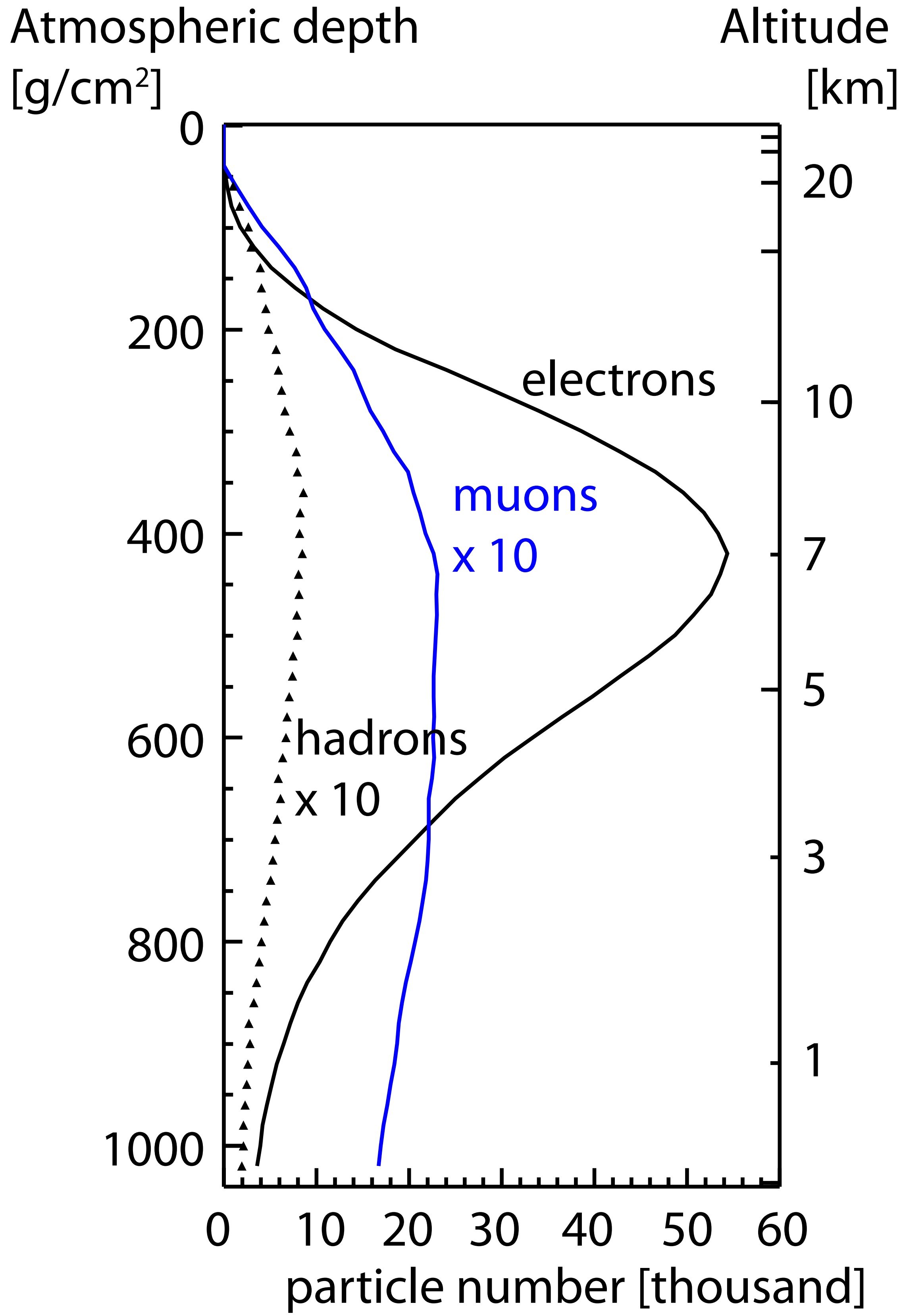
KYOTO 23-28 MAY 2010 IPAC'10

THE PIERRE AUGER OBSERVATORY: COSMIC ACCELERATORS AND THE MOST ENERGETIC PARTICLES IN THE UNIVERSE

Johannes Blümer

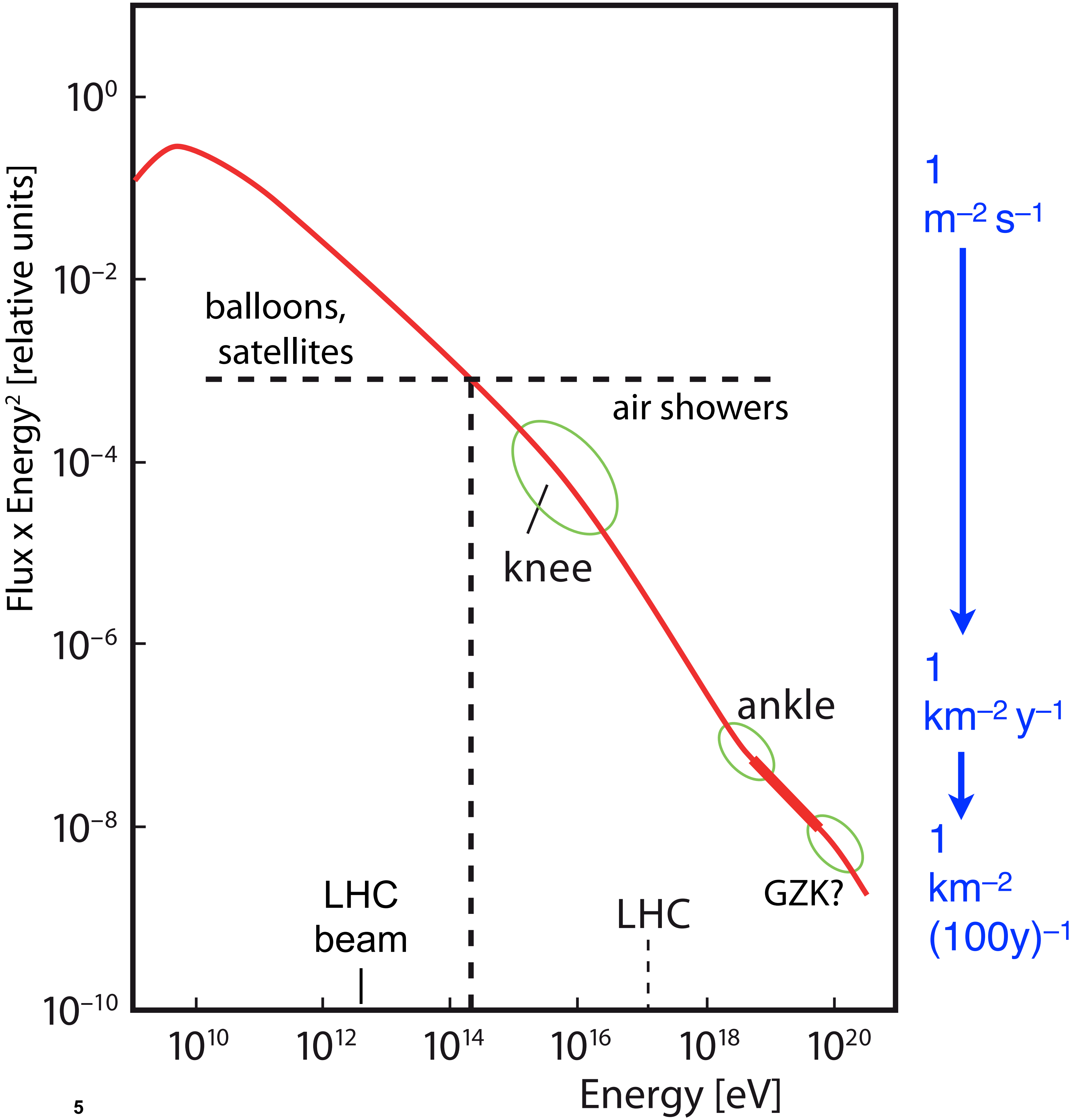
KIT-Center Elementary Particle and Astroparticle Physics KCETA


Victor Hess 1912
John Linsley 1962
Pierre Auger 1938
LOG N
3
2
1
rate
counter separation
0.1 m.
1 m.
4 m. 10 m.
100 m.
300 m.
-2
LOG X
-1
0
1
2
3
15
560
A
10
54
1400
0.5
6
30
19
0.6
1
6
1 km



π^0 decay feeds electromagnetic part

$\pi^\pm$ decay feeds muonic part



element abundances: 15 My in galaxy & halo

energy density ~like light, magnetic field, CMB; equiv. to 3 SN/ century at 10% eff.

powerlaw spectrum
$dN/dE \sim E^{-3}$
10 decades in energy; flux range very large

stochastic acceleration in shocked plasma, confined by mag. fields

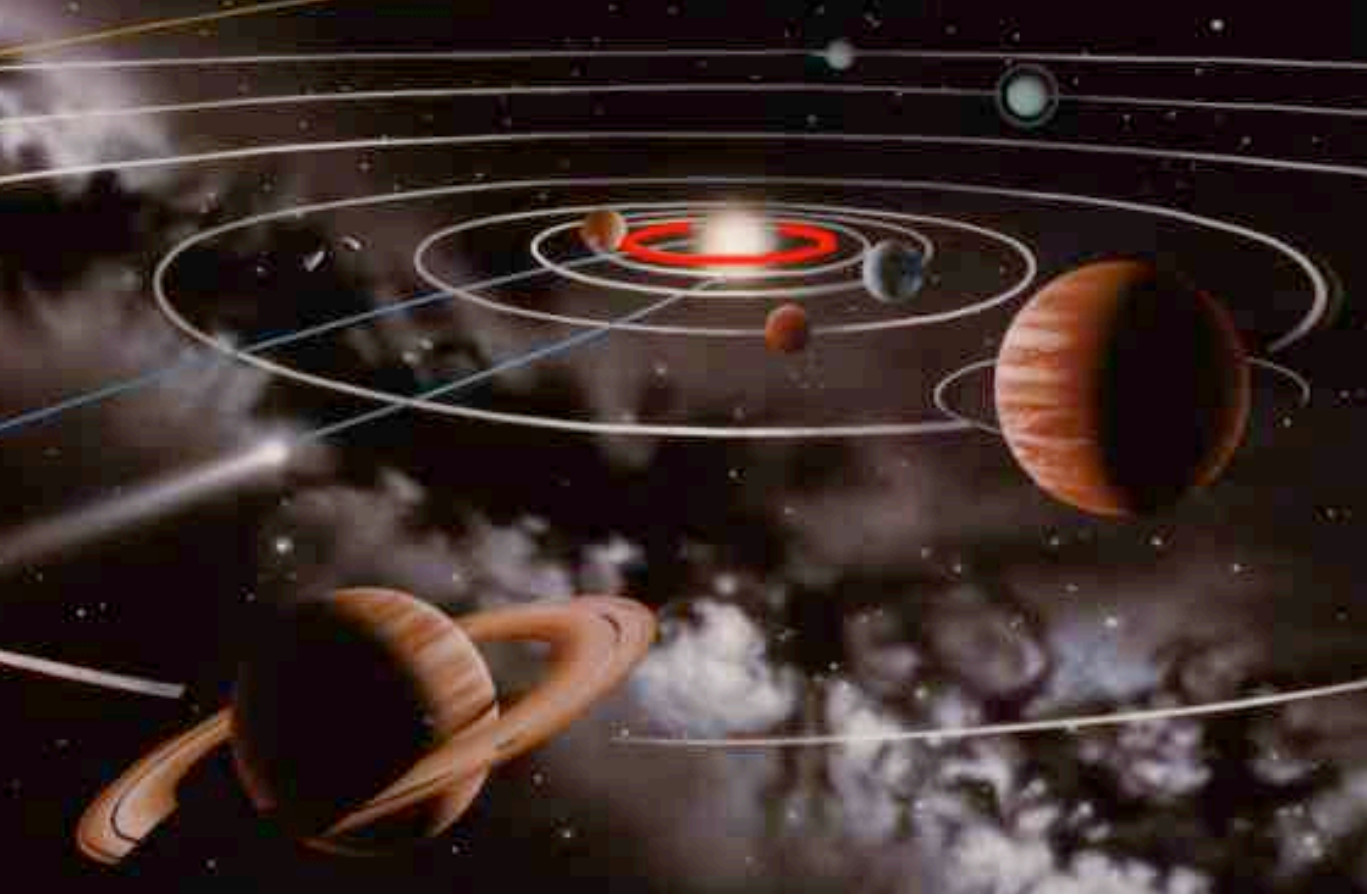
knee: p drop out first; end of SN acceleration?

isotropic directions

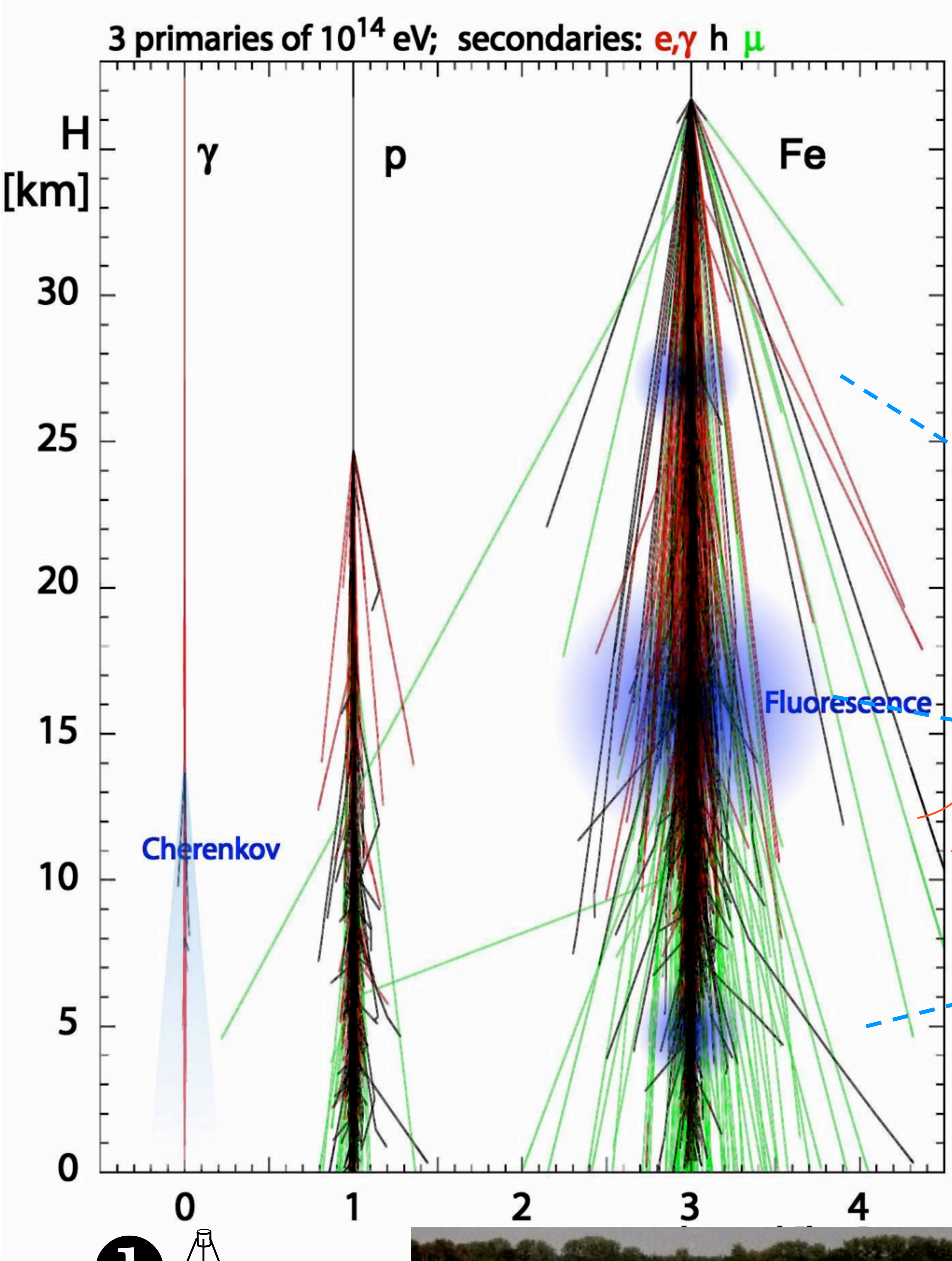
ankle: harder component, extraglactic

GZK: flux suppression above 60 EeV

composition?
sources?
propagation?
particle physics?

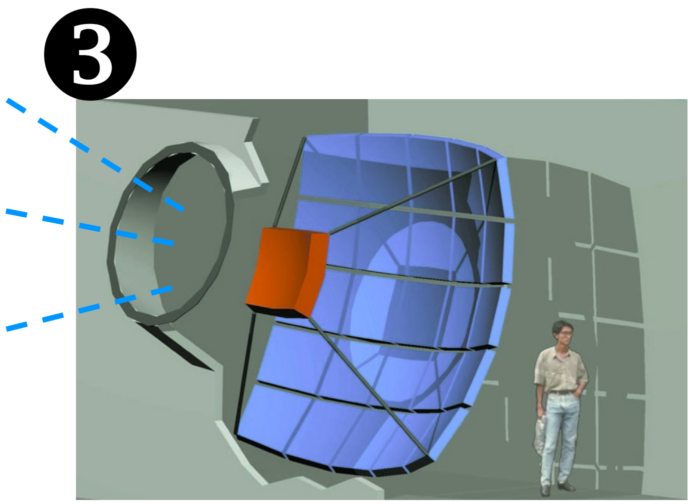


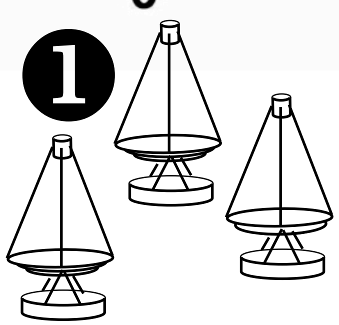
acceleration to 100 EeV using LHC technology would require Mercury's orbit;
acceleration time:>800 years...



❶ Cherenkov telescopes
❷ particle detector arrays
❸ Fluorescence telescopes
❹ Radio antenna

HYBRID detection: more than one method!



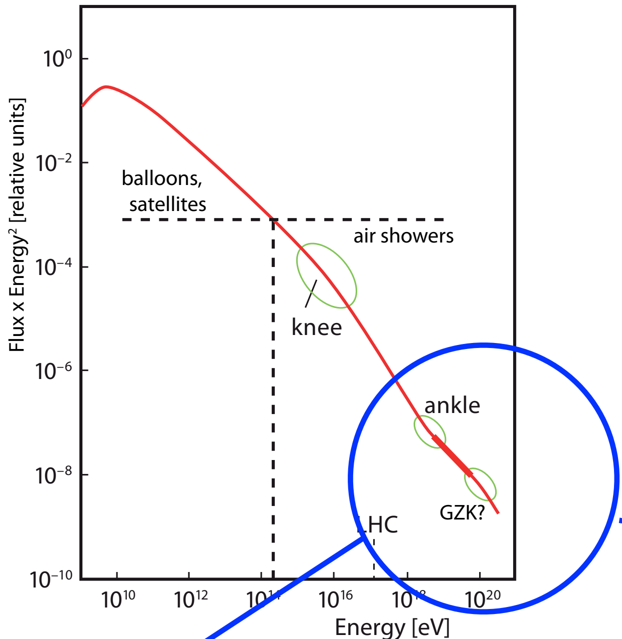


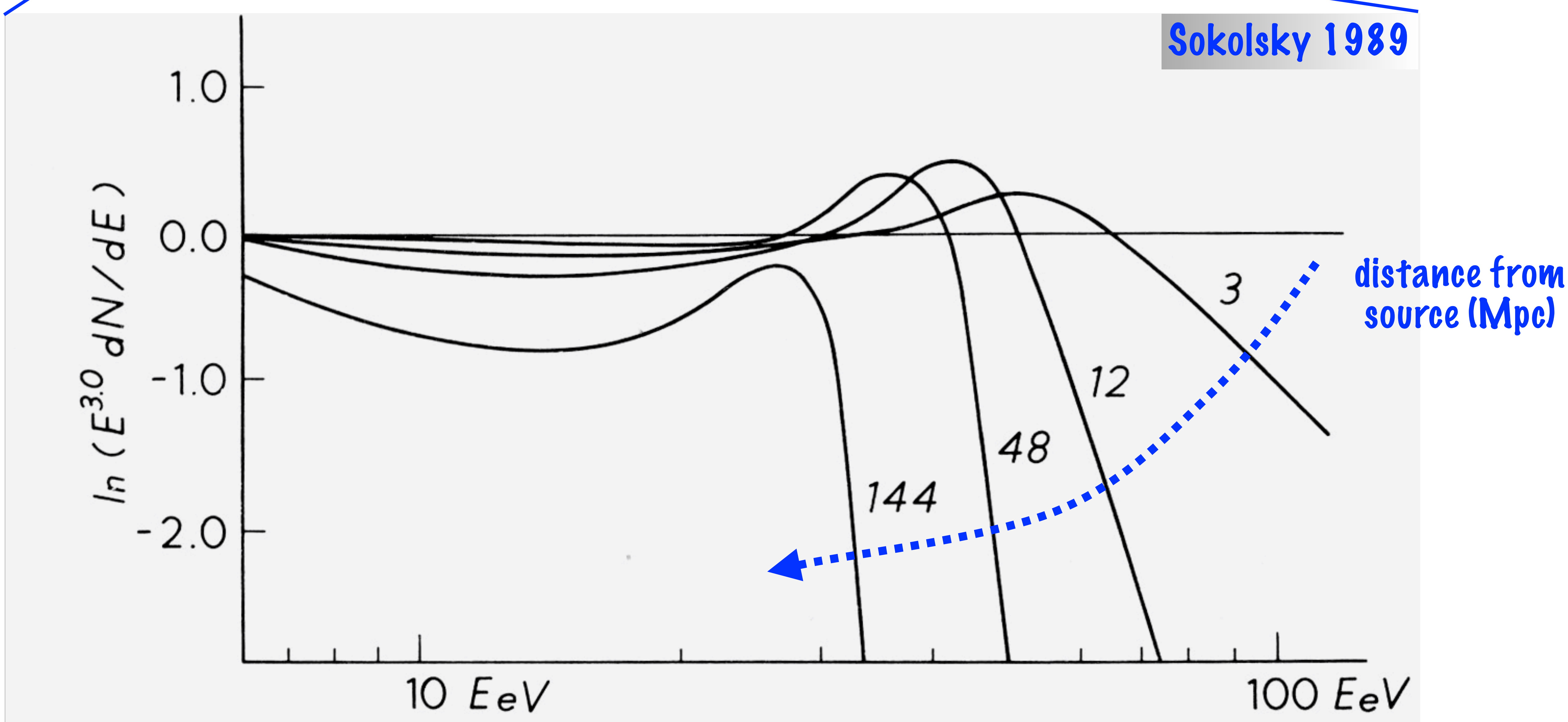
Greisen Zatsepin-Kuzmin (GZK) effect:
protons scatter with the CMB:
threshold effect above 6×10^{19} eV:

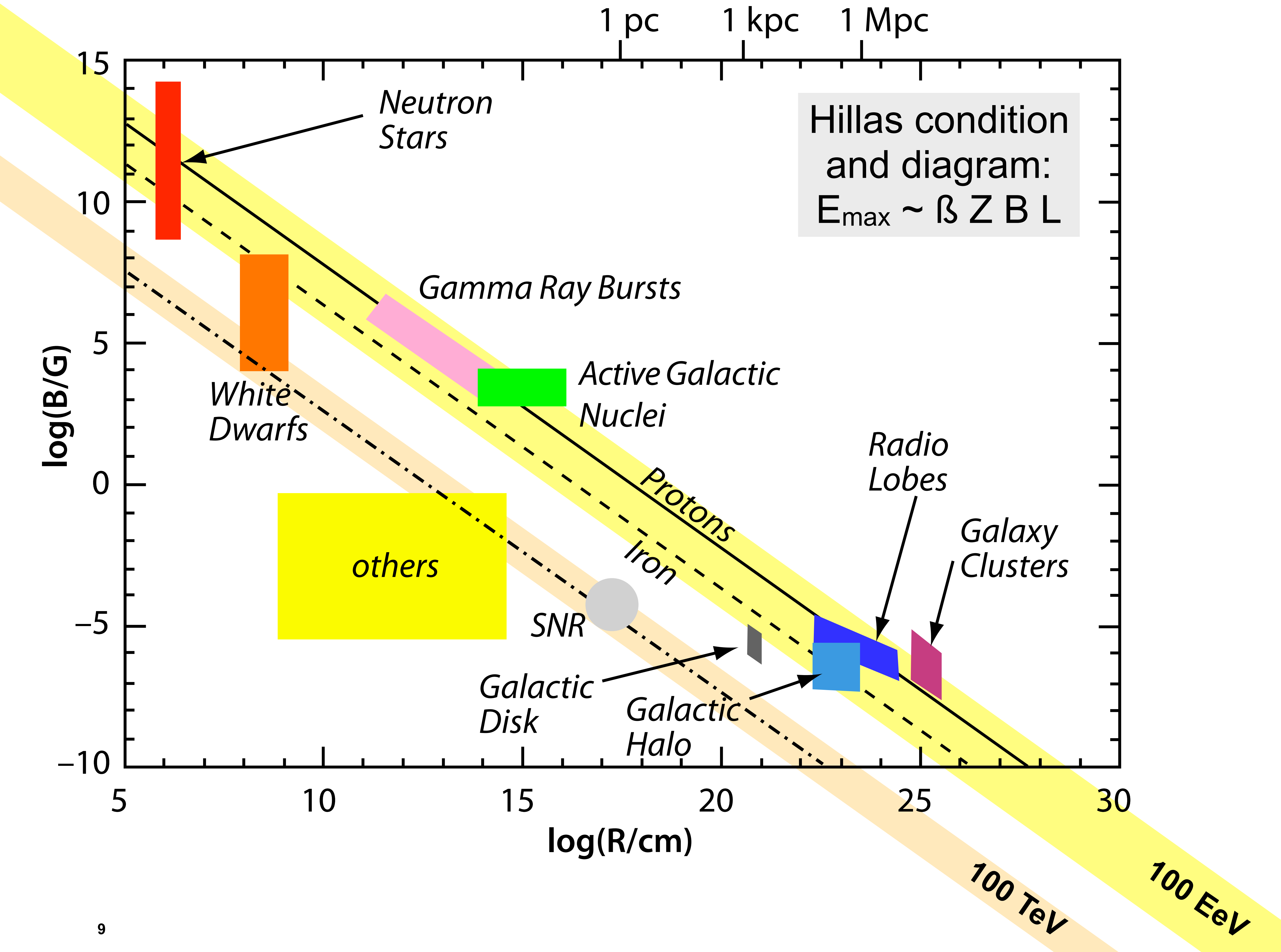
$p+\gamma_{3K} \rightarrow \Delta(1232) \rightarrow p\pi^0 \rightarrow p\,\gamma\gamma$ or $n\pi^+ \rightarrow pe^+\nu$

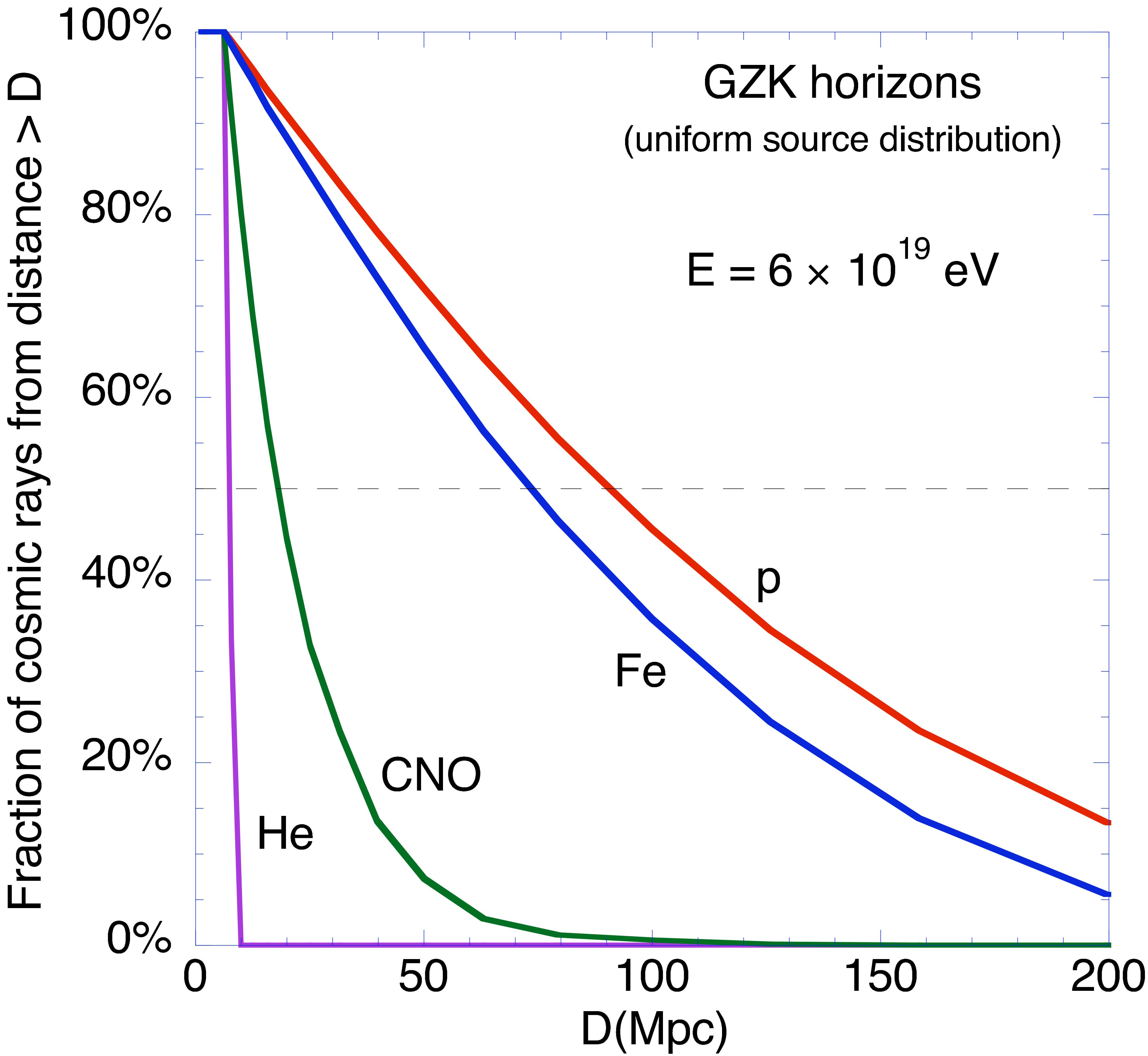
$$2E_p\epsilon > (m_\Delta^2 - m_p^2)$$

ε=meV, 400 cm^{-3}

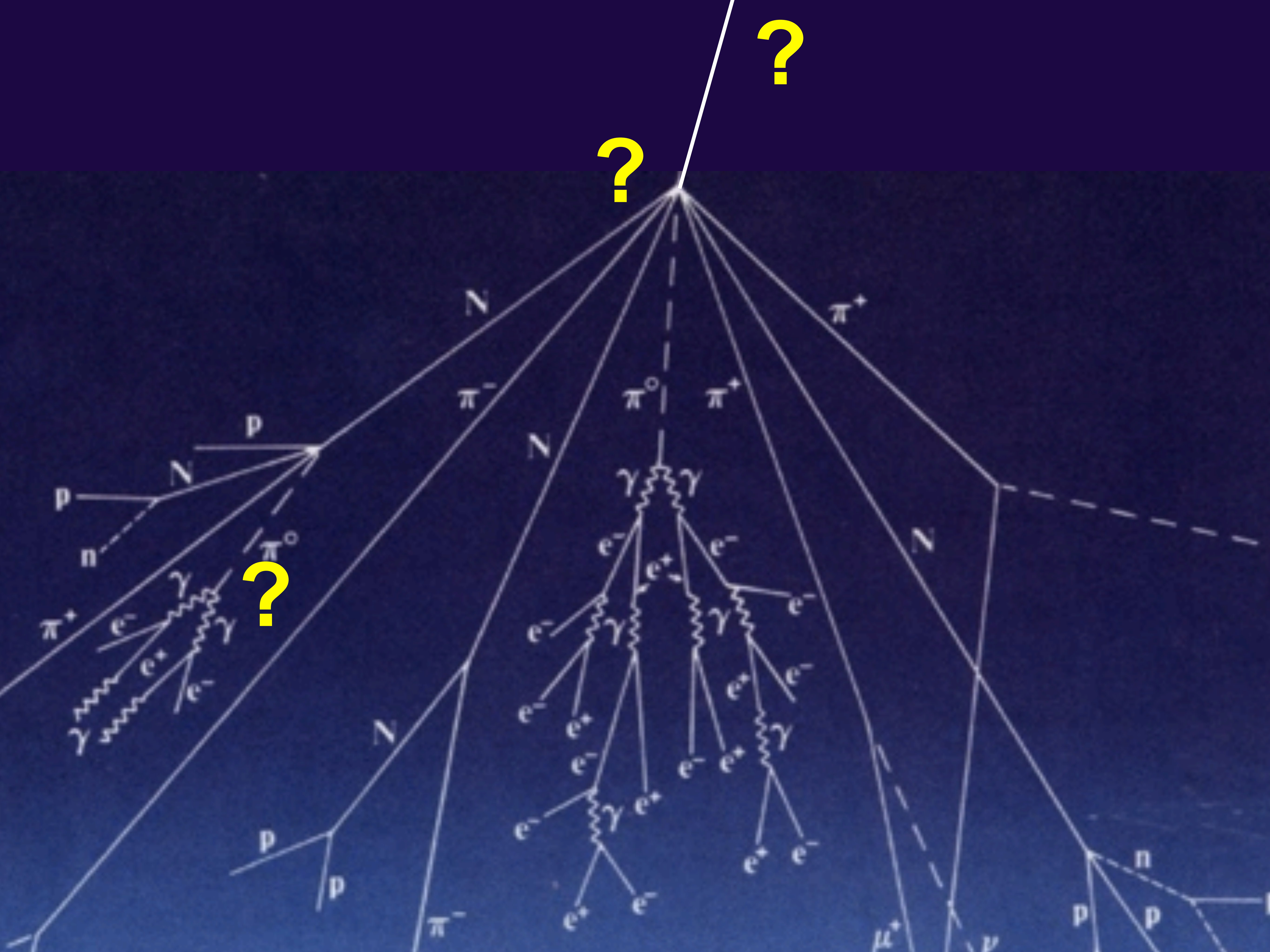


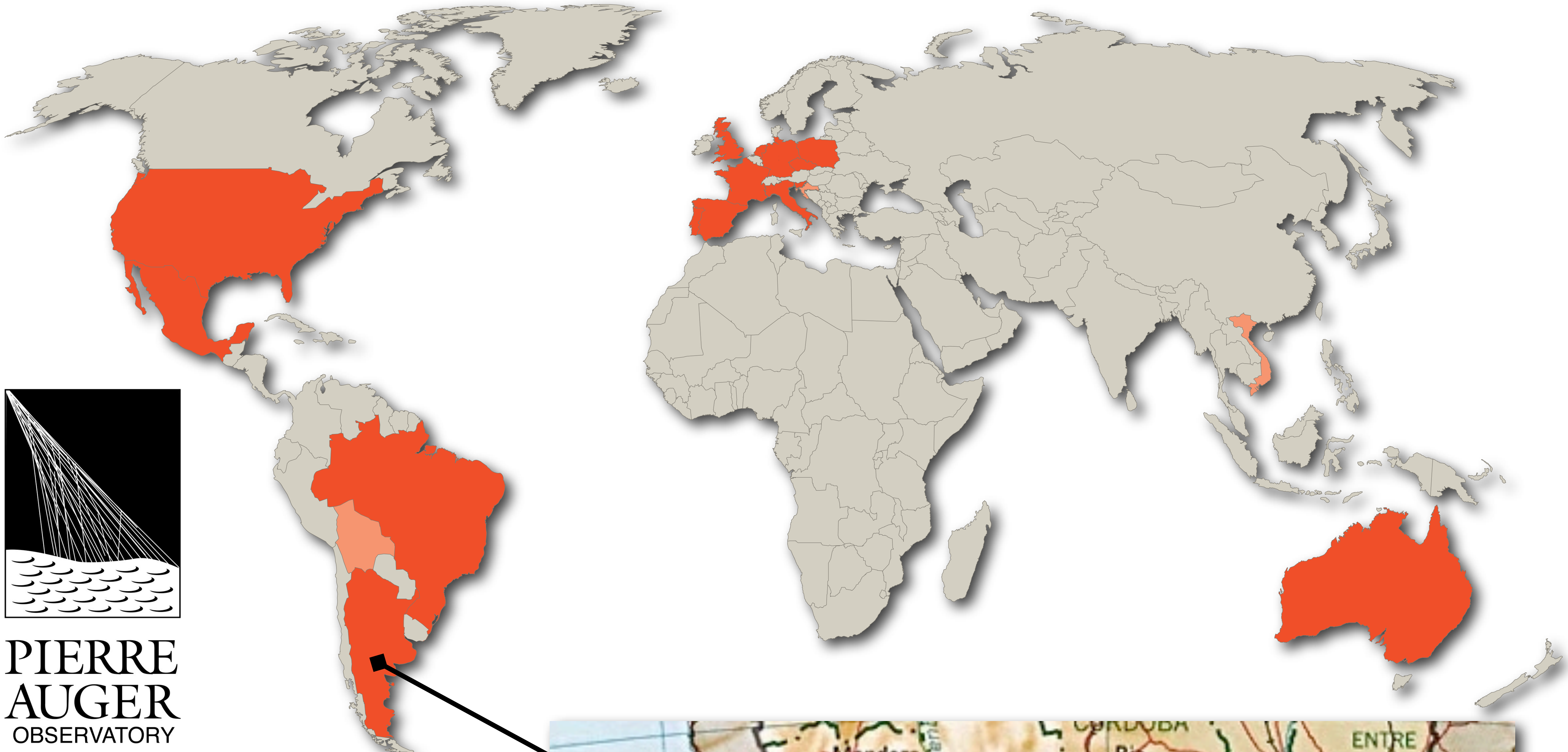



Hillas condition
and diagram:
Emax ~ ß Z B L
1 pc
1 kpc
1 Mpc
15
10
5
0
−5
−10
log(B/G)
5
10
15
20
25
30
log(R/cm)
Neutron
Stars
Gamma Ray Bursts
Active Galactic
Nuclei
White
Dwarfs
others
SNR
Protons
Iron
Radio
Lobes
Galaxy
Clusters
Galactic
Disk
Galactic
Halo
100 TeV
100 EeV



GZK horizons
(uniform source distribution)
E = 6 × 10^19 eV
p
Fe
CNO
He
Fraction of cosmic rays from distance > D
D(Mpc)
100%
80%
60%
40%
20%
0%
0
50
100
150
200

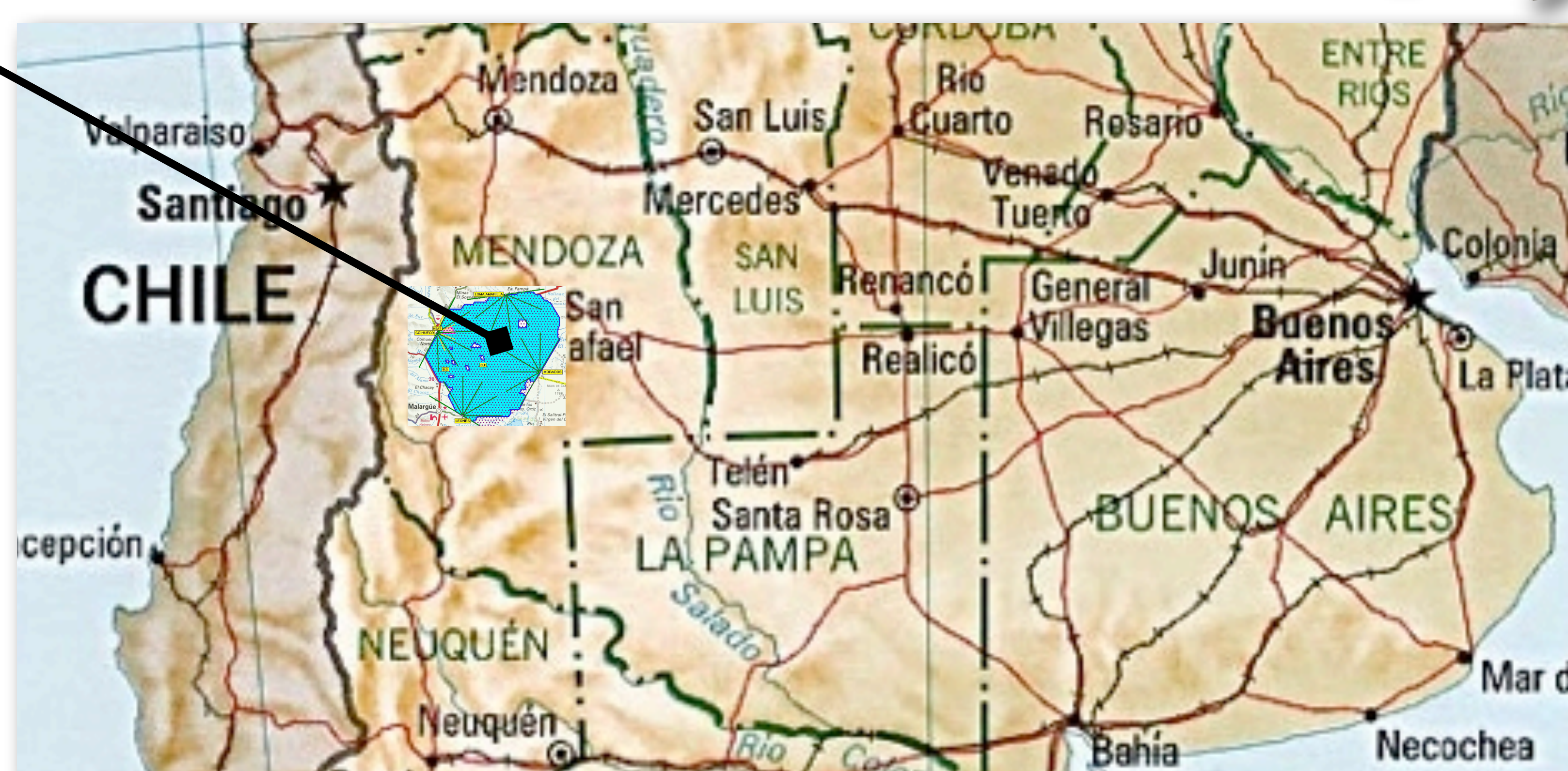

?
?
N
π⁺
π⁻
π°
π⁺
N
p
N
p
n
π°
?
π⁺
γ γ
e⁻
e⁺
e⁻
γ
e⁻
e⁺
e⁻
γ
γ
e⁻
e⁺
e⁻
N
e⁻
e⁺
e⁻
e⁺
e⁻
γ
e⁺
e⁻
e⁺
γ
e⁺
e⁻
p
p
π⁻
μ⁺
ν
n
p
p

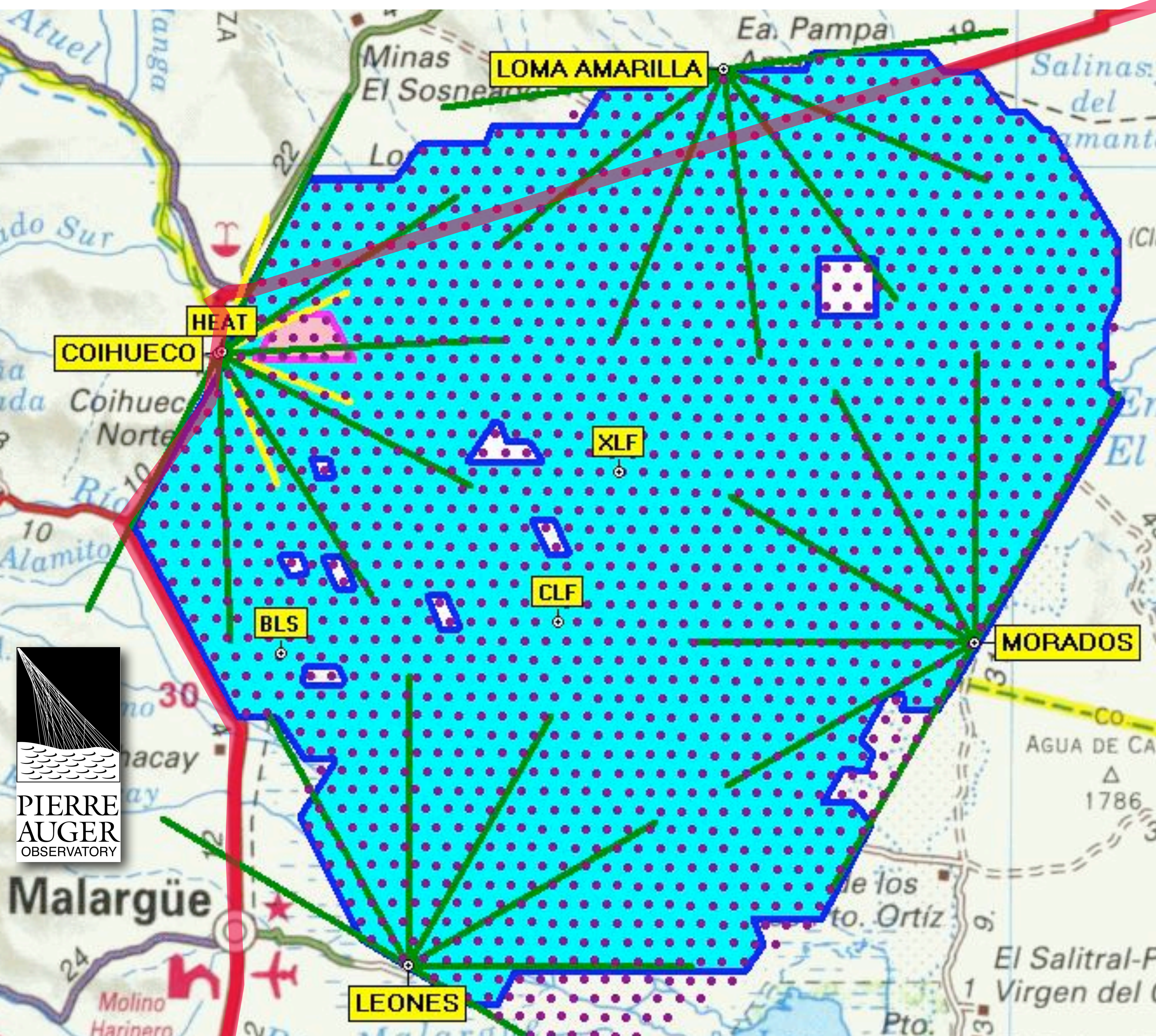


PIERRE AUGER
OBSERVATORY

1. Argentina
2. Australia
3. Bolivia*
4. Brazil
5. Croatia*
6. Czech Republic
7. France
8. Germany
9. Italy
10. Mexico
11. Netherlands
12. Poland
13. Portugal
14. Slovenia
15. Spain
16. UK
17. USA
18. Vietnam*

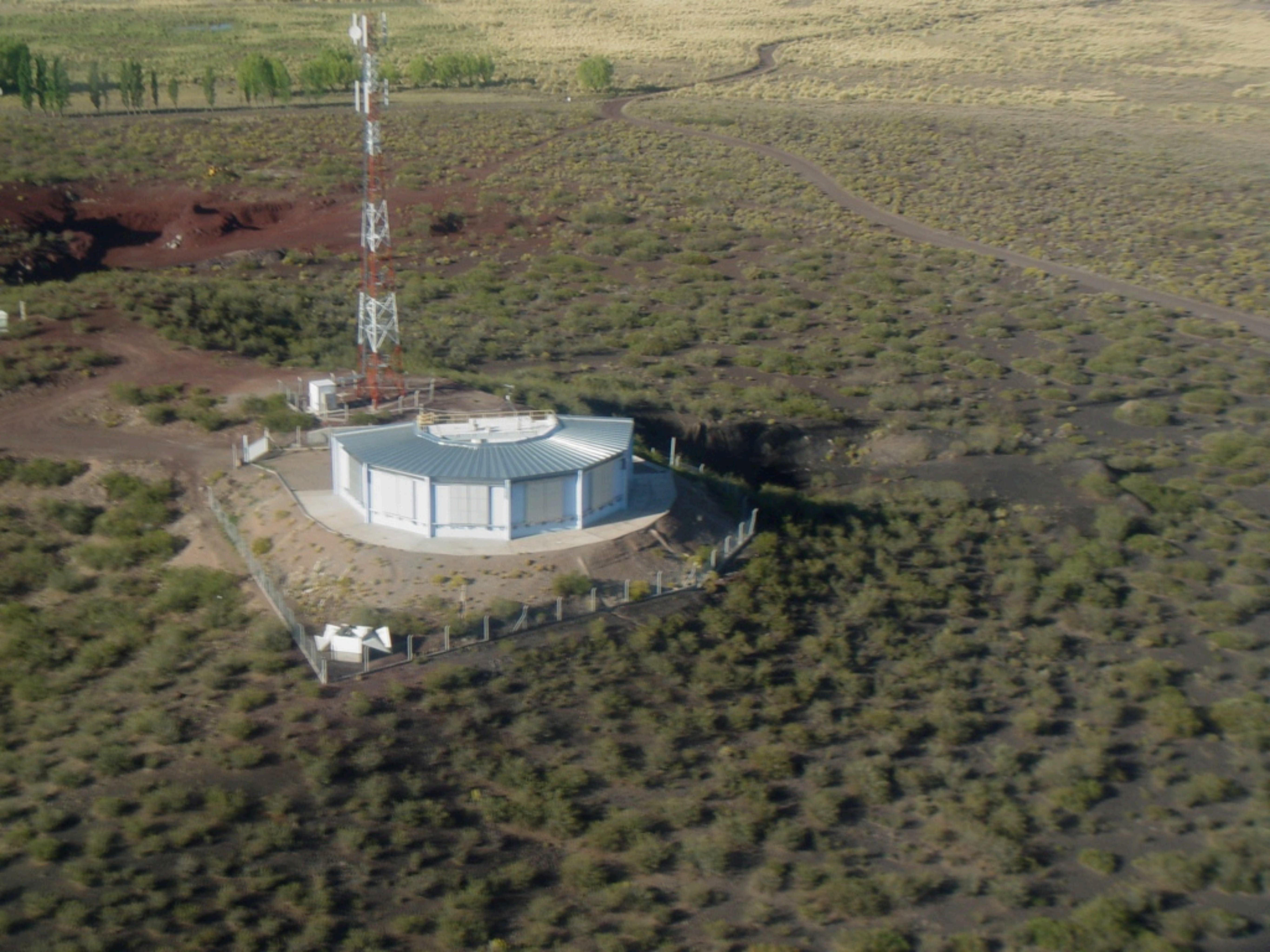
* associated countries



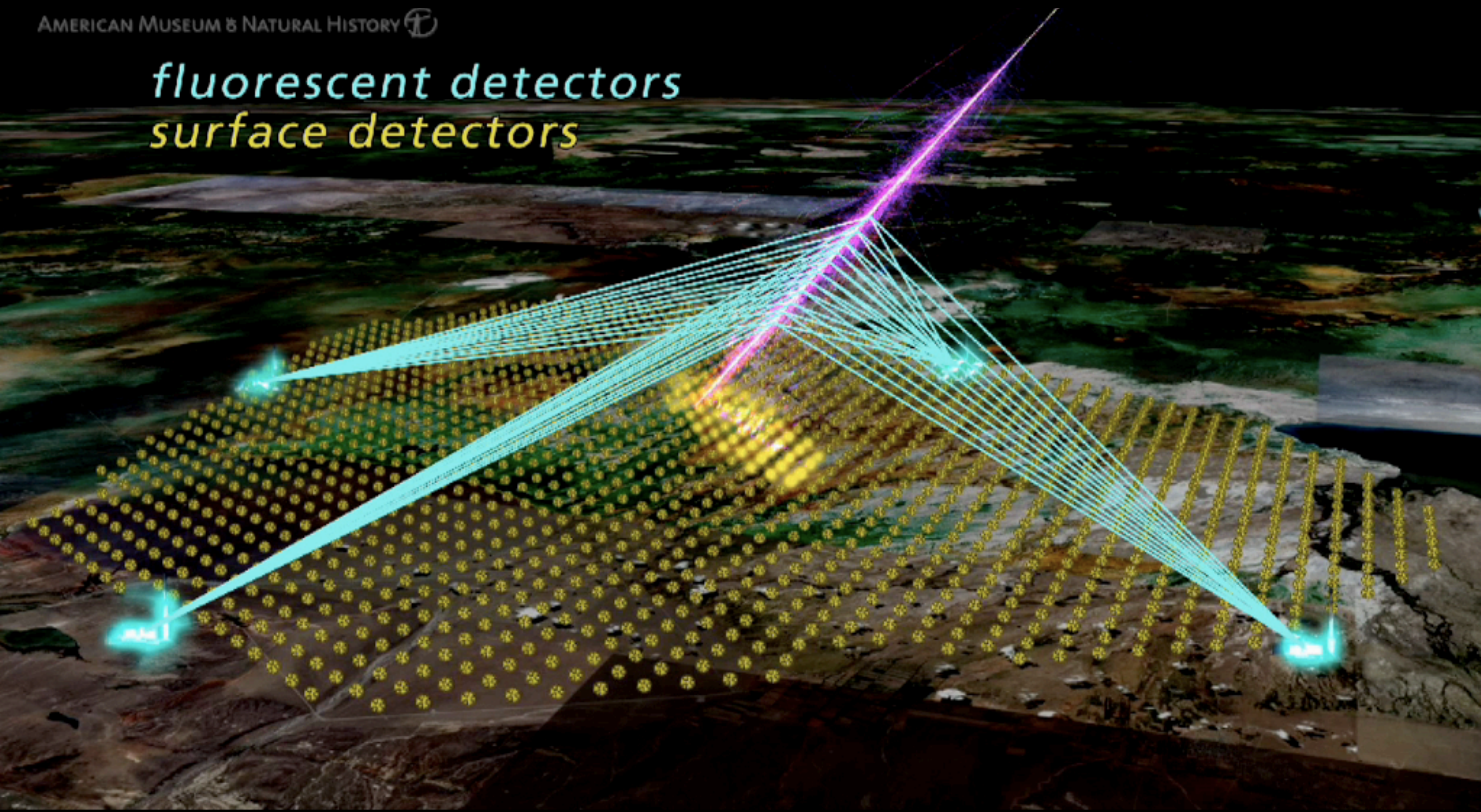


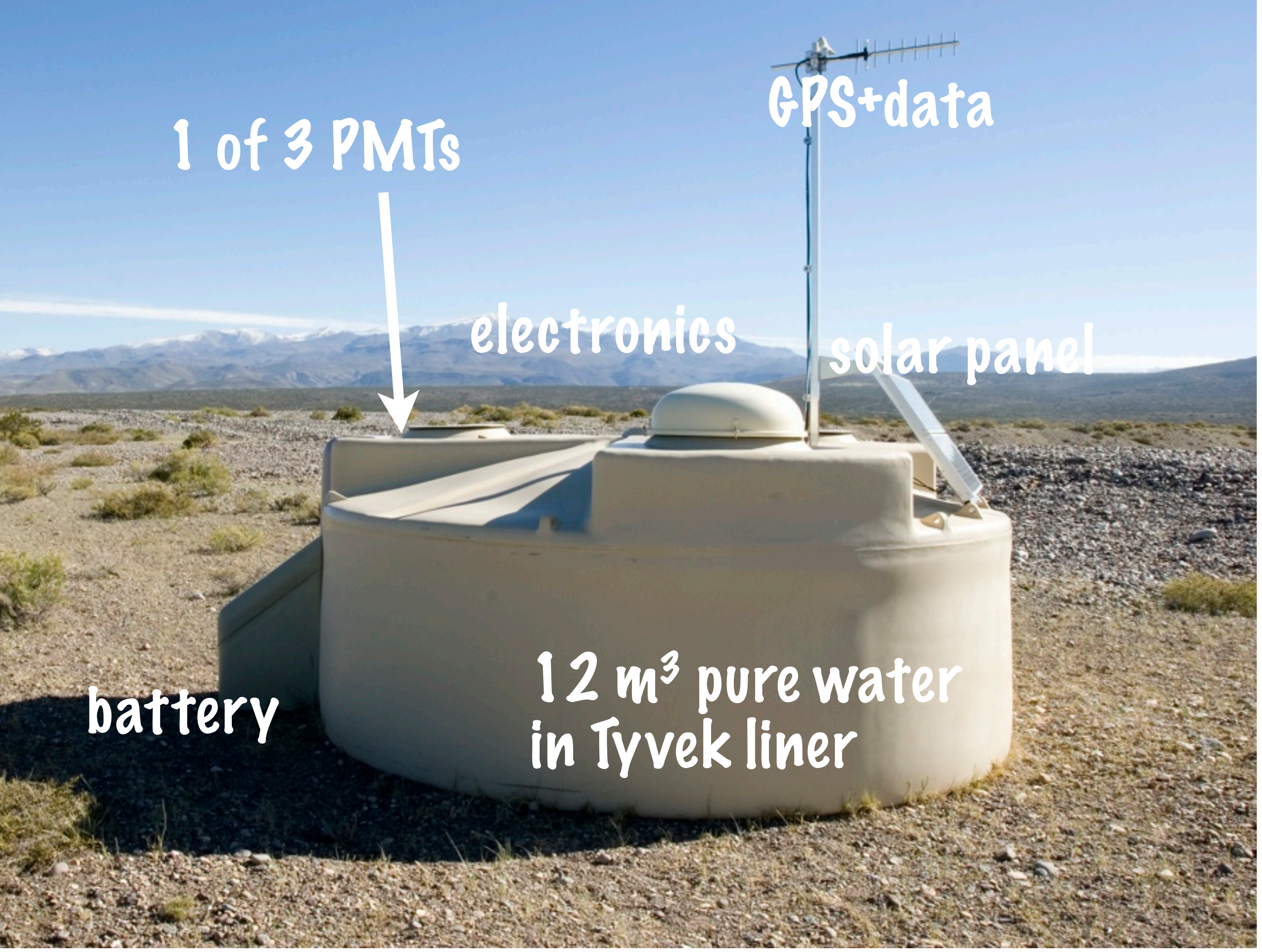
1660 water Cherenkov detectors covering 3000 km^2

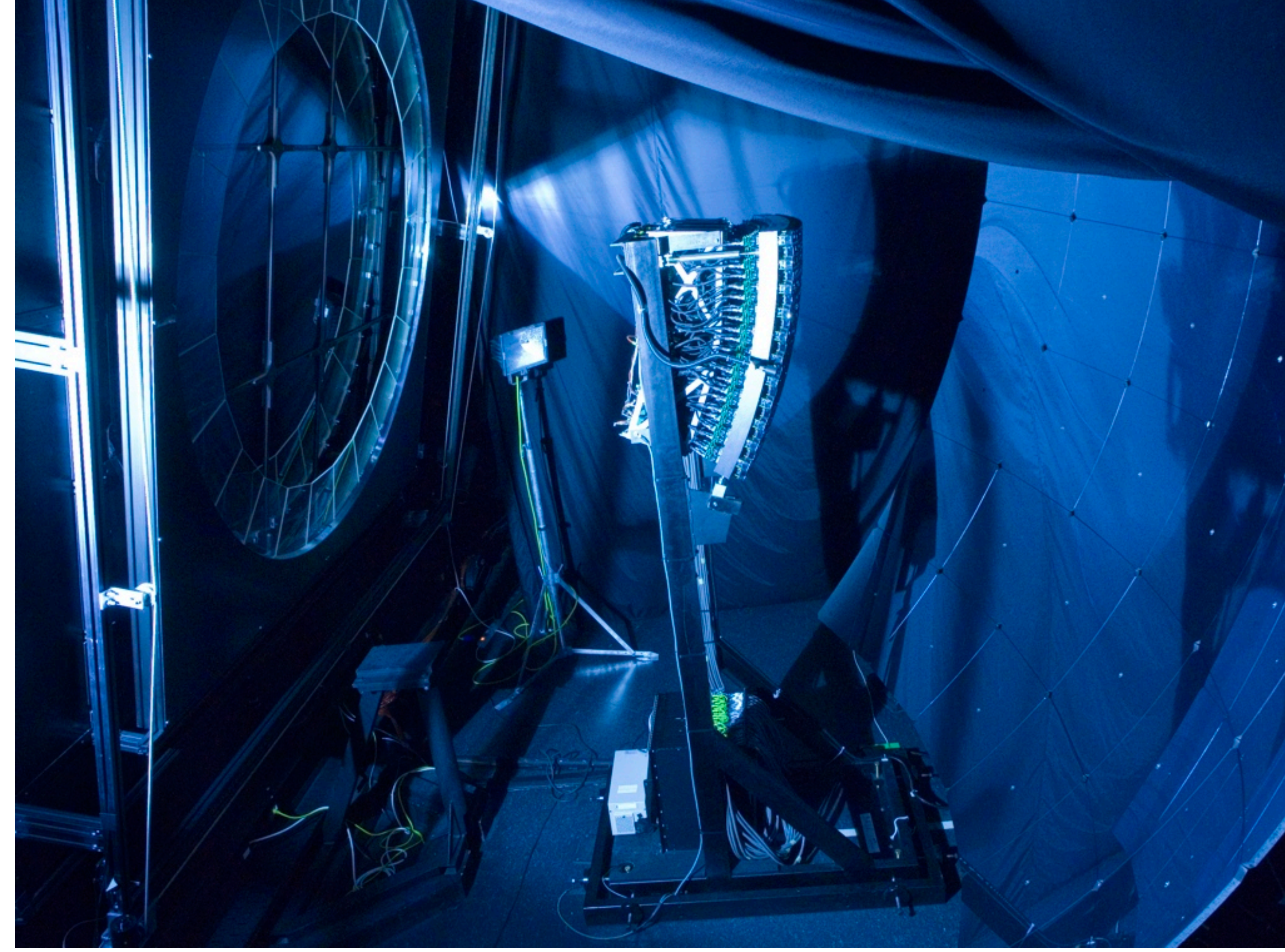
4 x 6 fluorescence telescopes

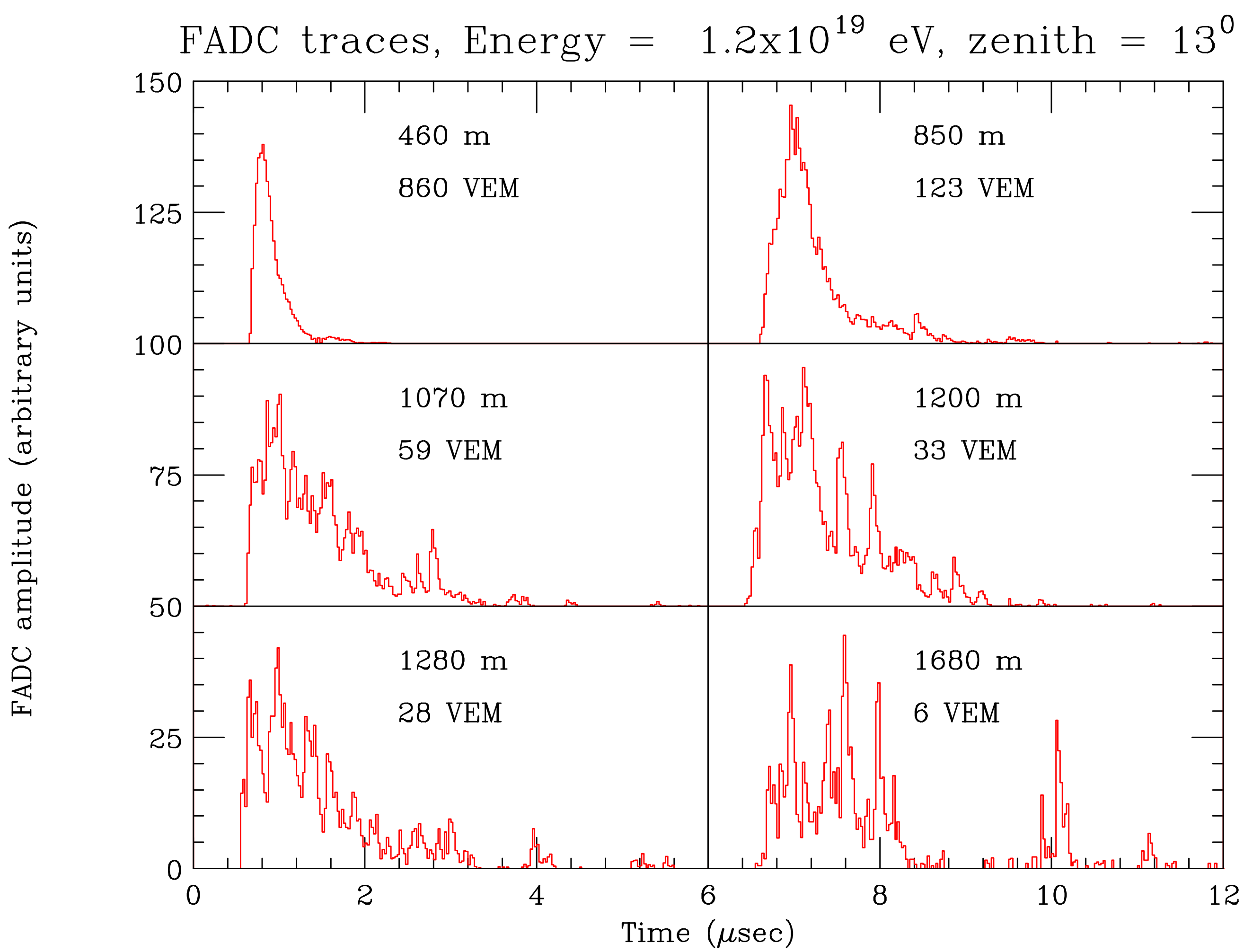


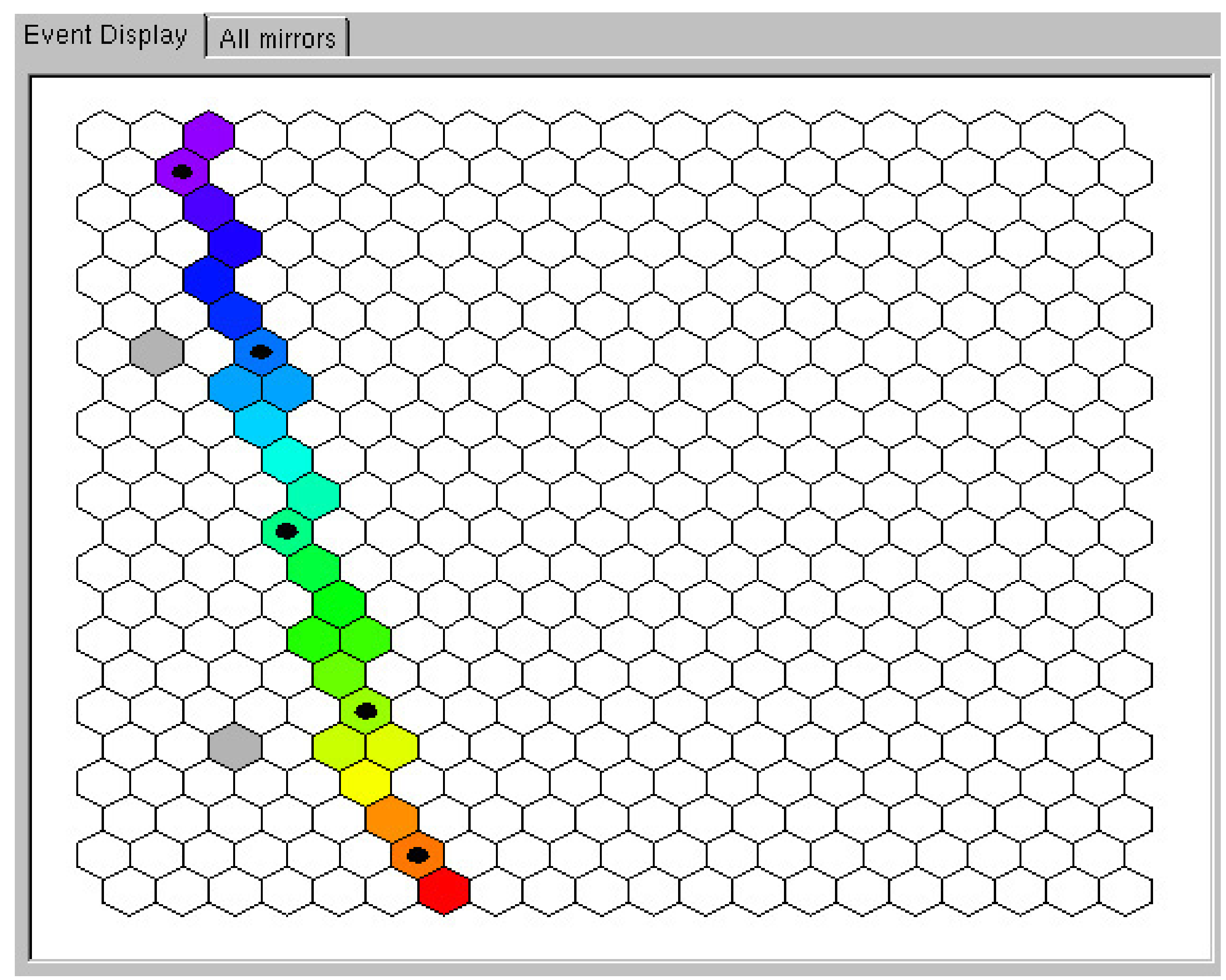

E


AMERICAN MUSEUM & NATURAL HISTORY
fluorescent detectors
surface detectors


GPS+data
1 of 3 PMTs
electronics
solar panel
battery
12 m³ pure water
in Tyvek liner

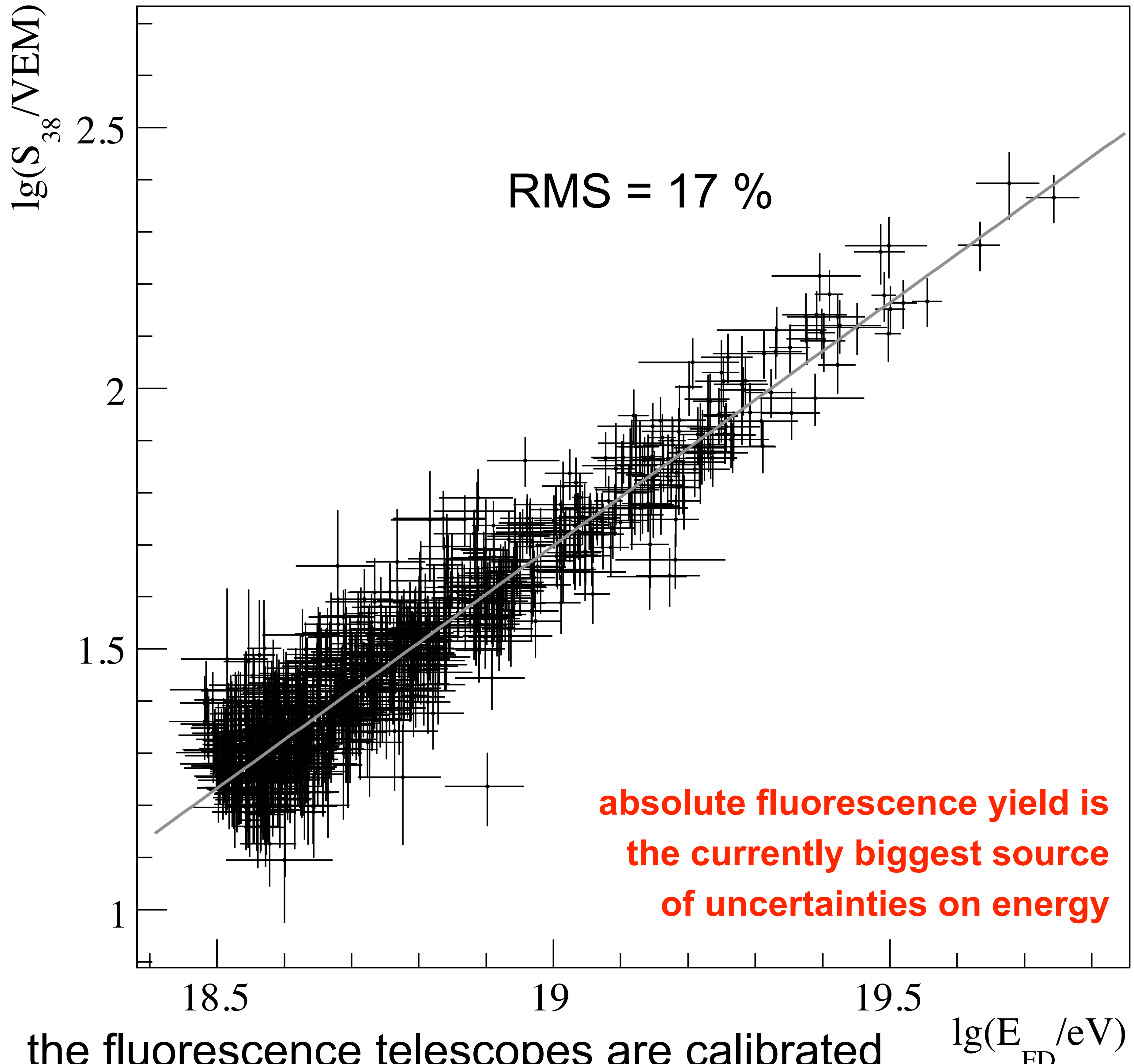



FADC traces, Energy = 1.2x10^19 eV, zenith = 13^0
460 m
860 VEM
850 m
123 VEM
1070 m
59 VEM
1200 m
33 VEM
1280 m
28 VEM
1680 m
6 VEM
FADC amplitude (arbitrary units)
Time (μsec)
0
25
50
75
100
125
150
0
2
4
6
8
10
12


Event Display
All mirrors

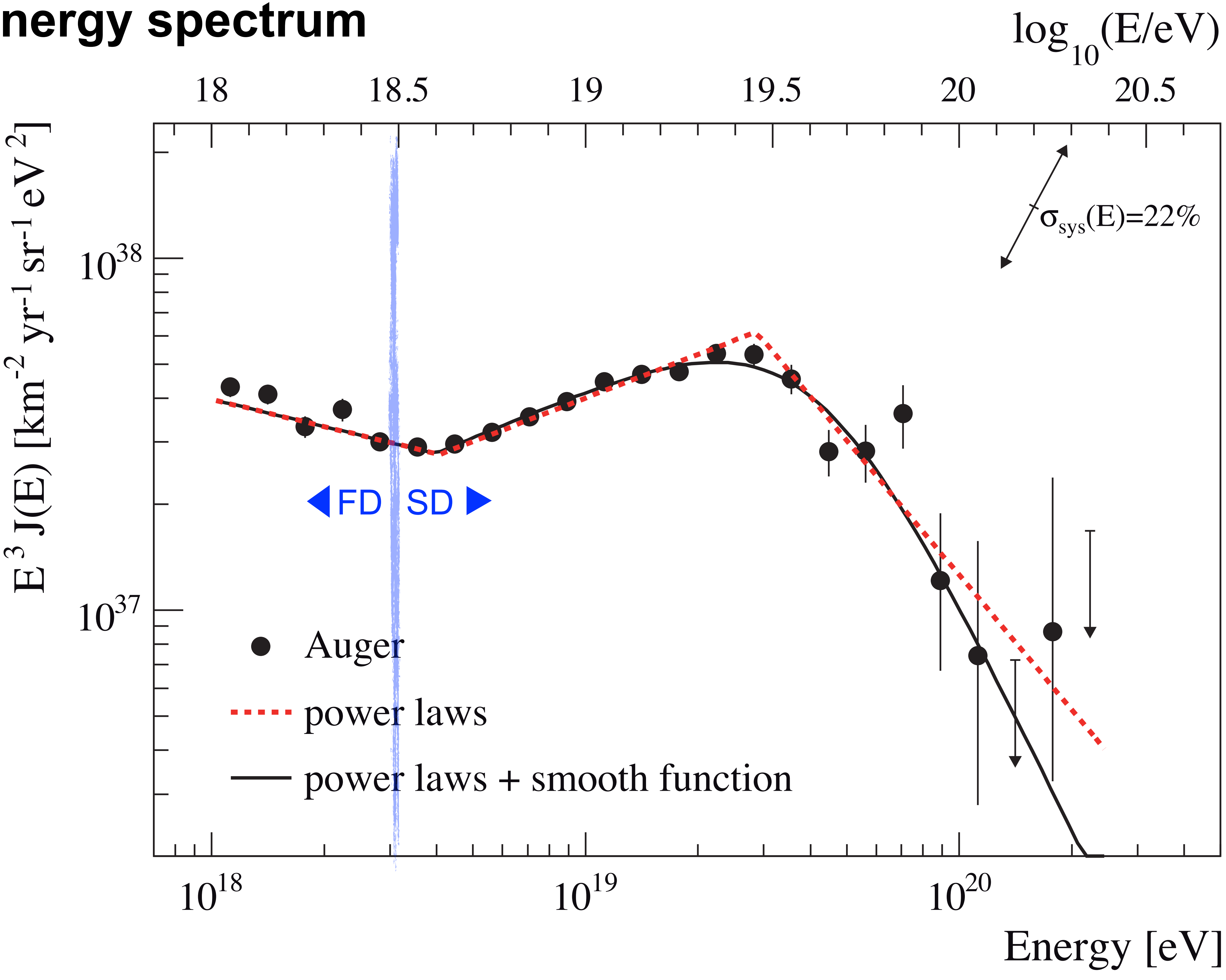
The surface detectors are self-calibrating by single muons
VEM = Vertical Equivalent Muon

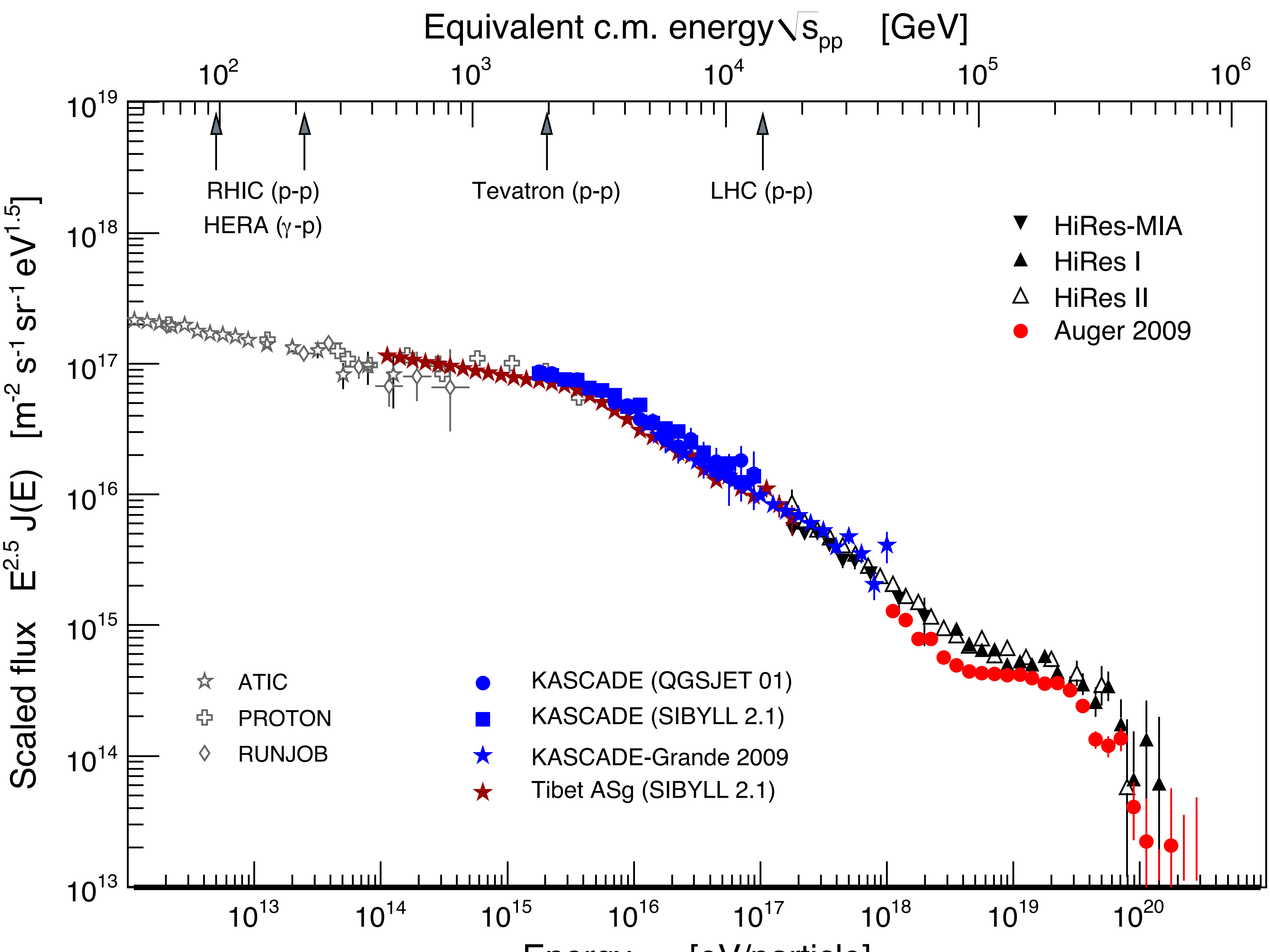
correct for attenuation of the shower as function of zenith angle!



the fluorescence telescopes are calibrated piece by piece on an absolute scale
it is an optical calorimeter!

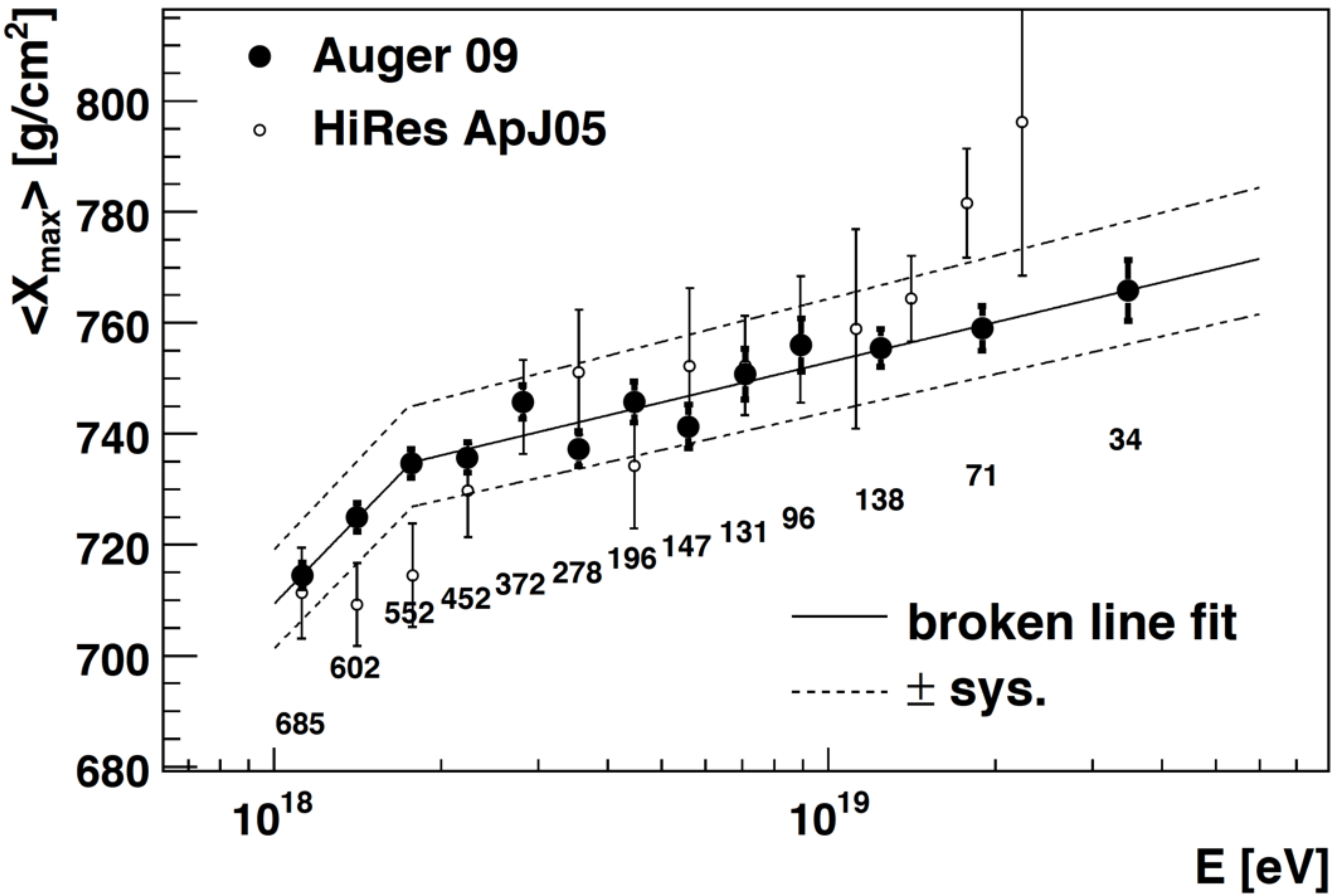
Energy spectrum





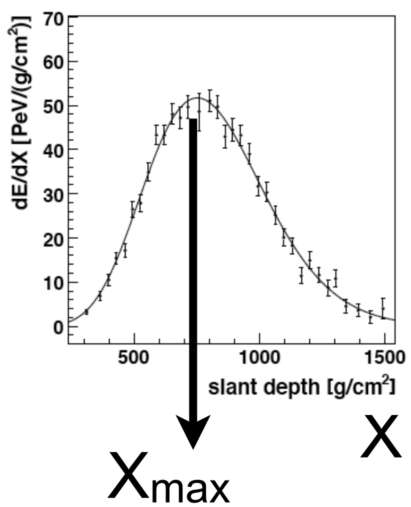
Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger 2009
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Scaled flux $E^{2.5}$ J(E) [m^{-2} s^{-1} sr^{-1} $eV^{1.5}$]
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy [eV/particle]

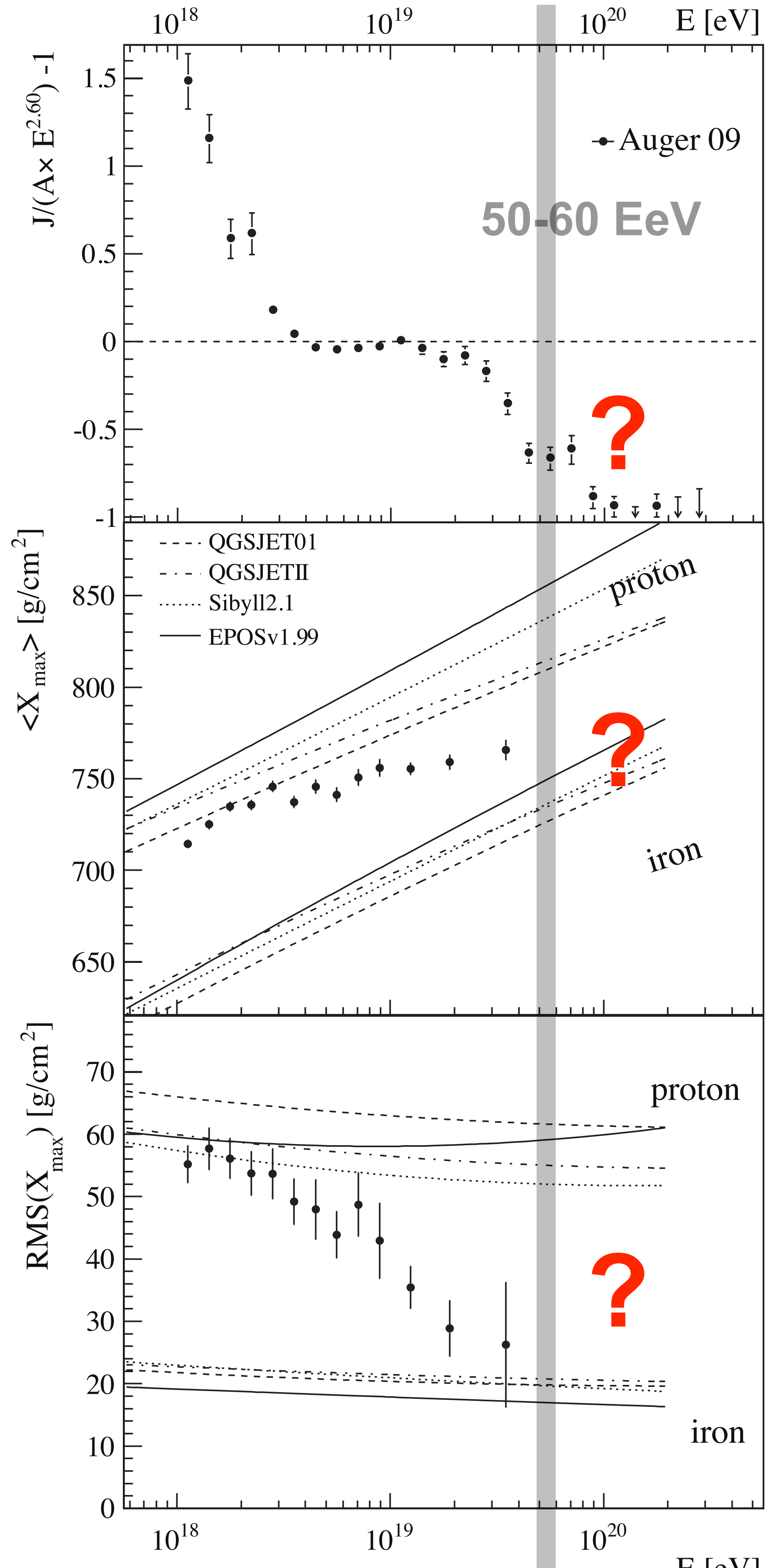
the depth of the shower maximum, X_{max}, is the best estimator for the primary mass



relative intensity

de/dX





fluctuations of X_{max}

models assume no change in particle physics...

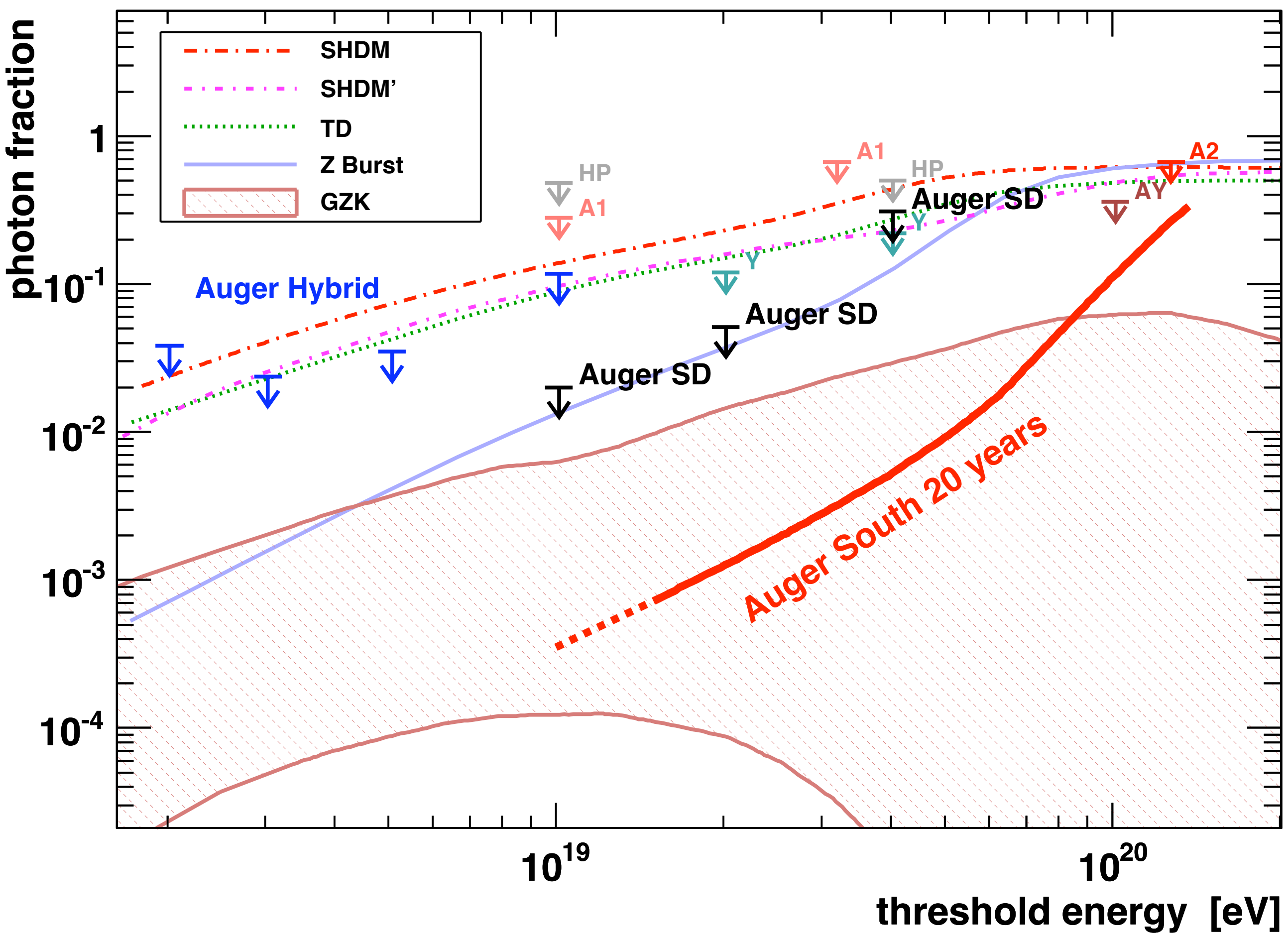
energy spectrum: convoluted information about sources, propagation, particle id

shower profiles: best estimator for the mass of the primary particle

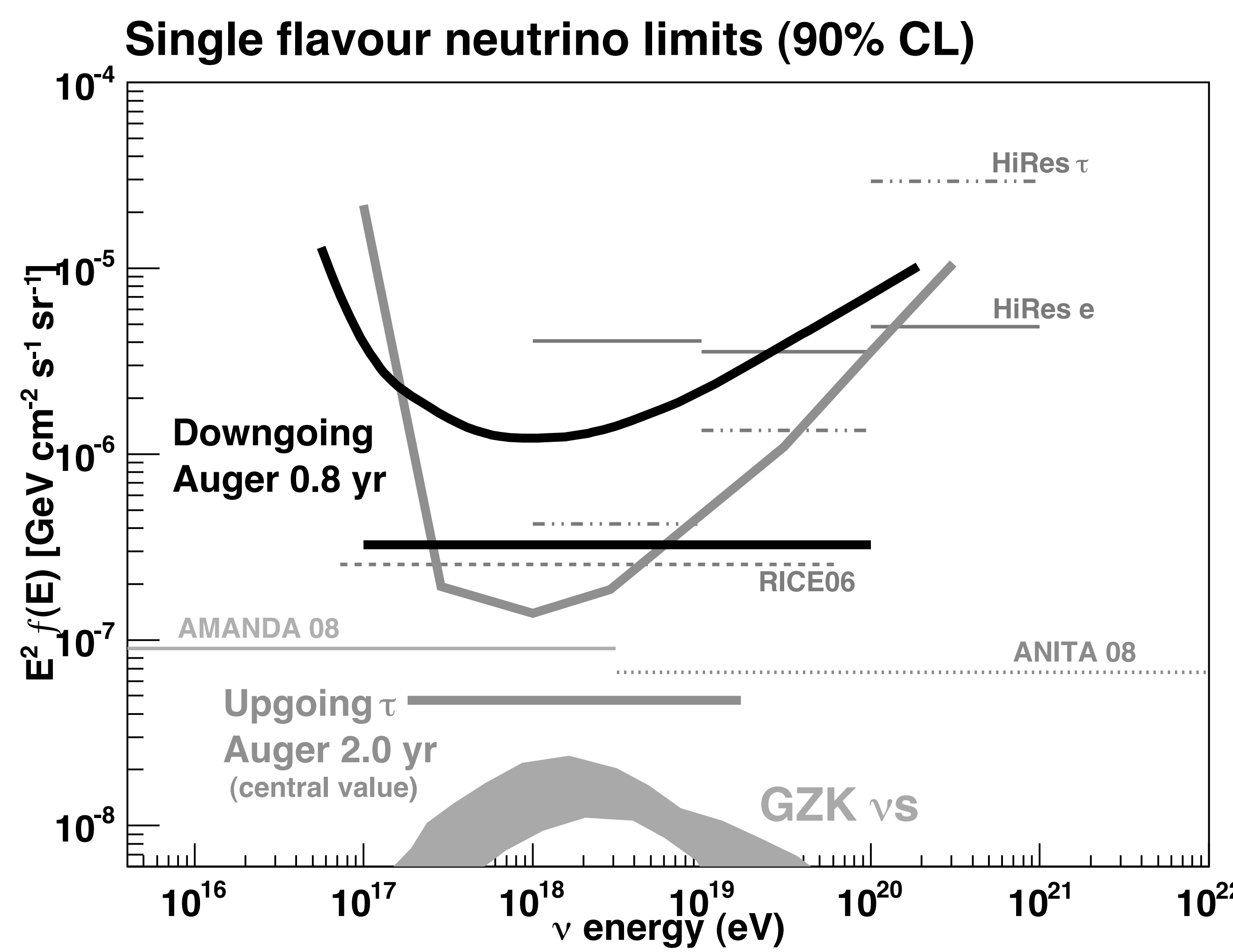
very small fluctuations... all showers develop alike???

photon and neutrino limits

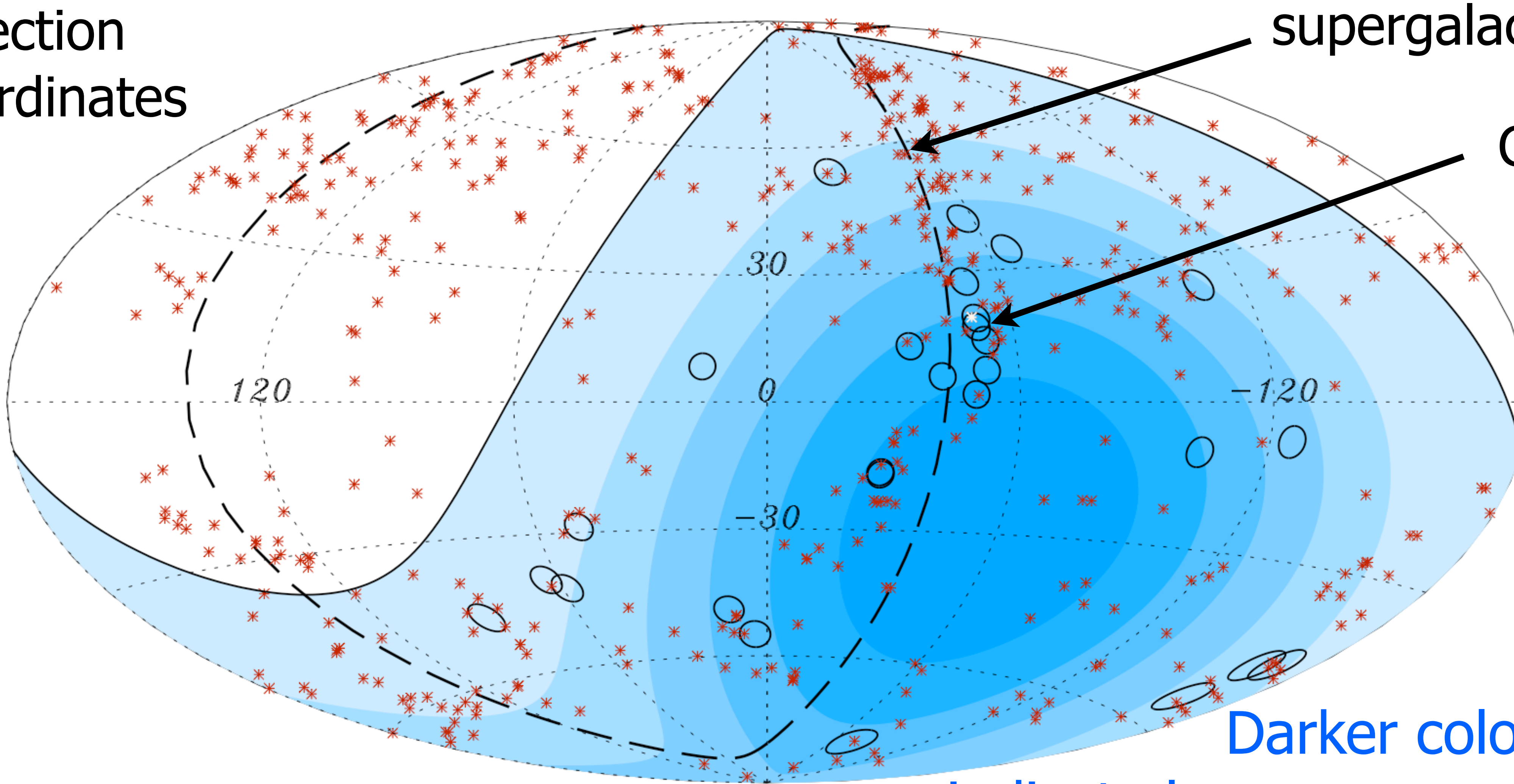
photon showers have a distinct shape and can be ‘readily’ identified



only neutrino induced showers can have large zenith angles (~ 90°) and still interact close to the detector



this limits the ‘exotic models’...



In total **27 events** measured at E > 57 EeV

out of which 20 correlate

5.6 expected (p=0.21)

Net chance for isotropic distr. **$P < 10^{-5}$**

Auger Coll.; Science 318 (2007) 938

Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects

Journalists:
"cosmic rays come from black holes".

Auger:
... We have demonstrated the **anisotropy** of the arrival directions of the highest-energy cosmic rays and their **extragalactic origin**. Our observations are **consistent** with the hypothesis that the rapid decrease of flux measured by the Pierre Auger Observatory above 60 EeV is due to the **GZK effect** and that most of the cosmic rays reaching Earth in that energy range are **protons** from **nearby astrophysical sources**, either AGN or other objects with a similar spatial distribution....

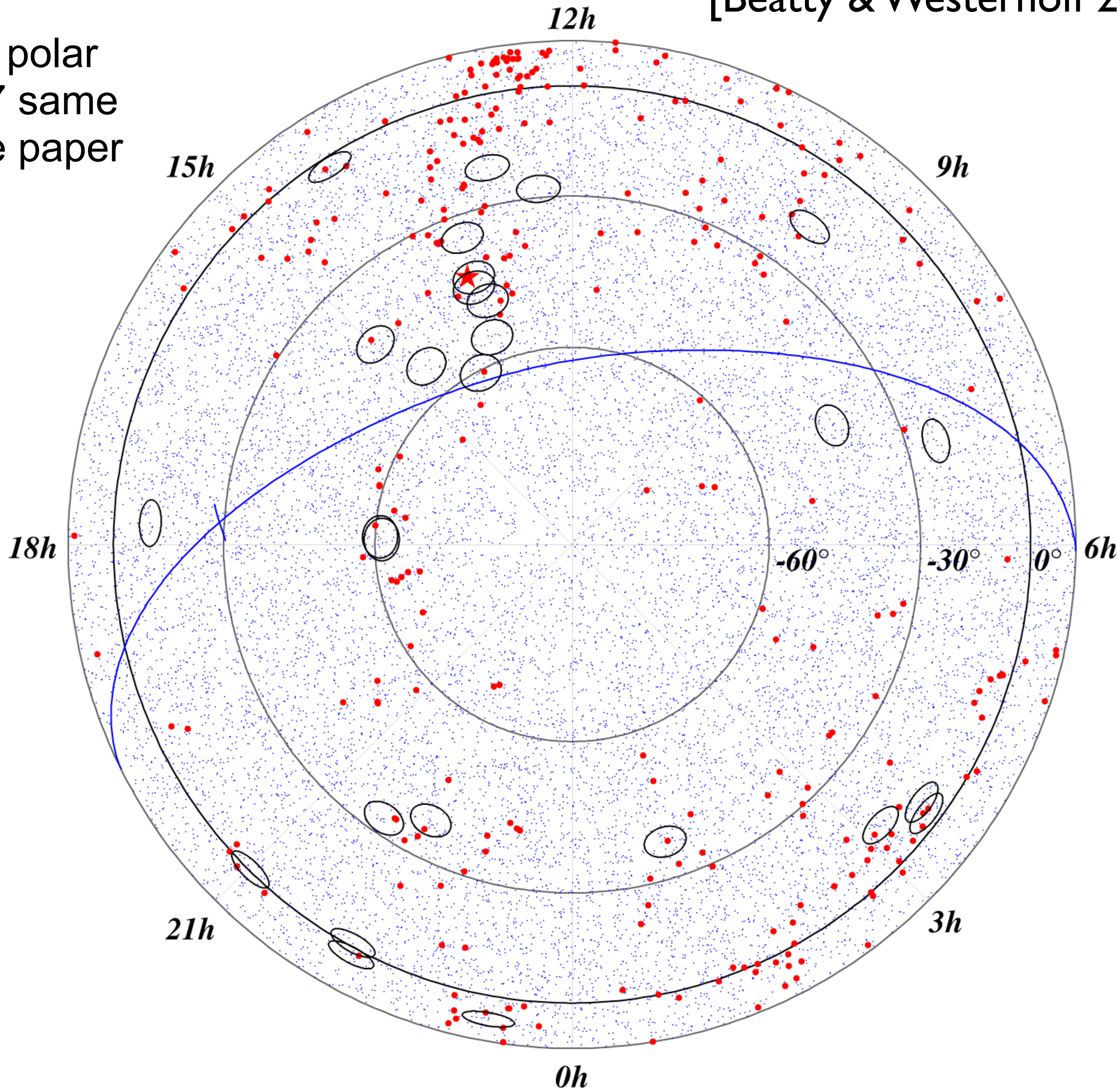
[Beatty & Westerhoff 2008]

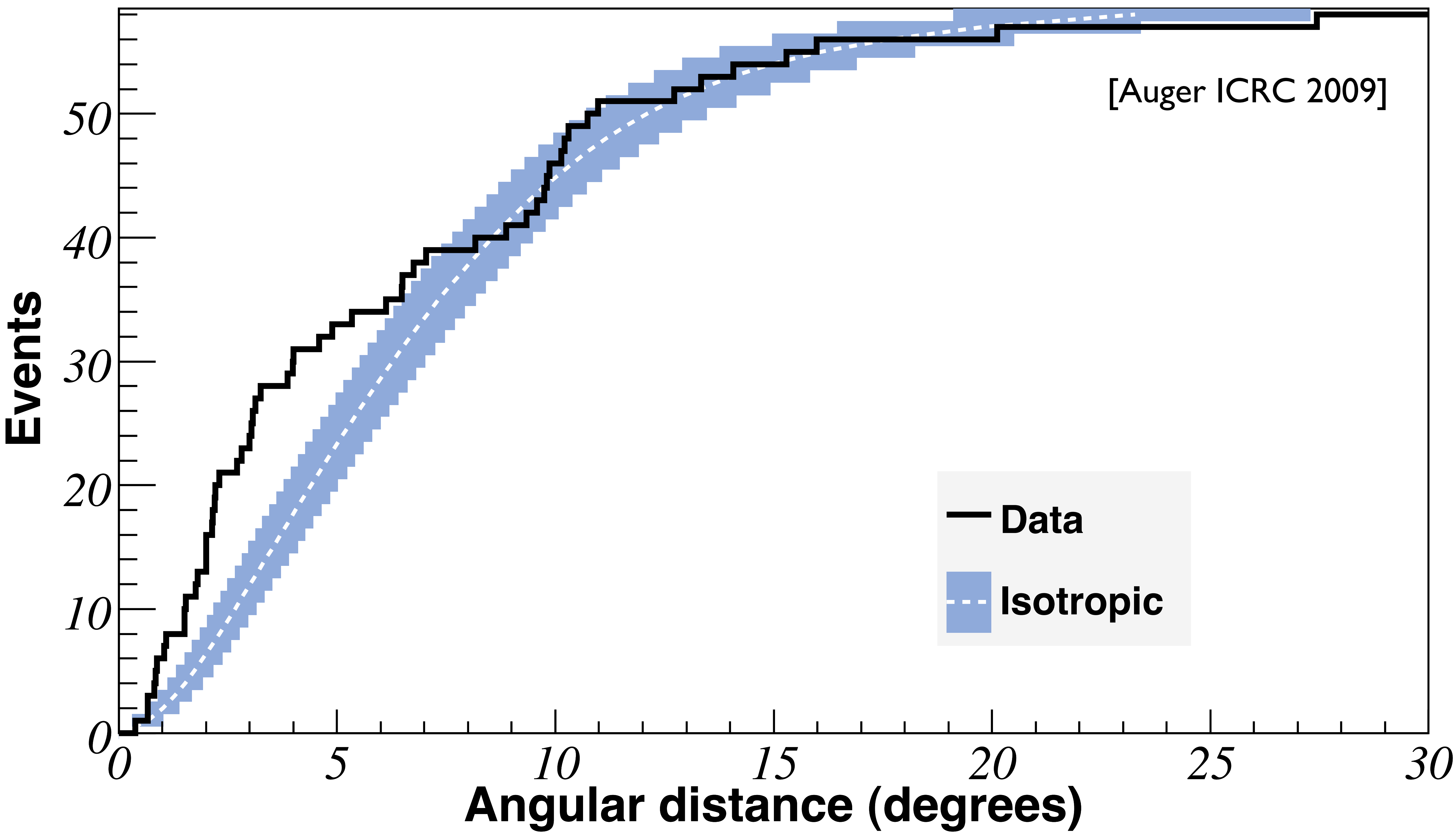
equal exposure polar projection: 2007 same data as Science paper

AGN

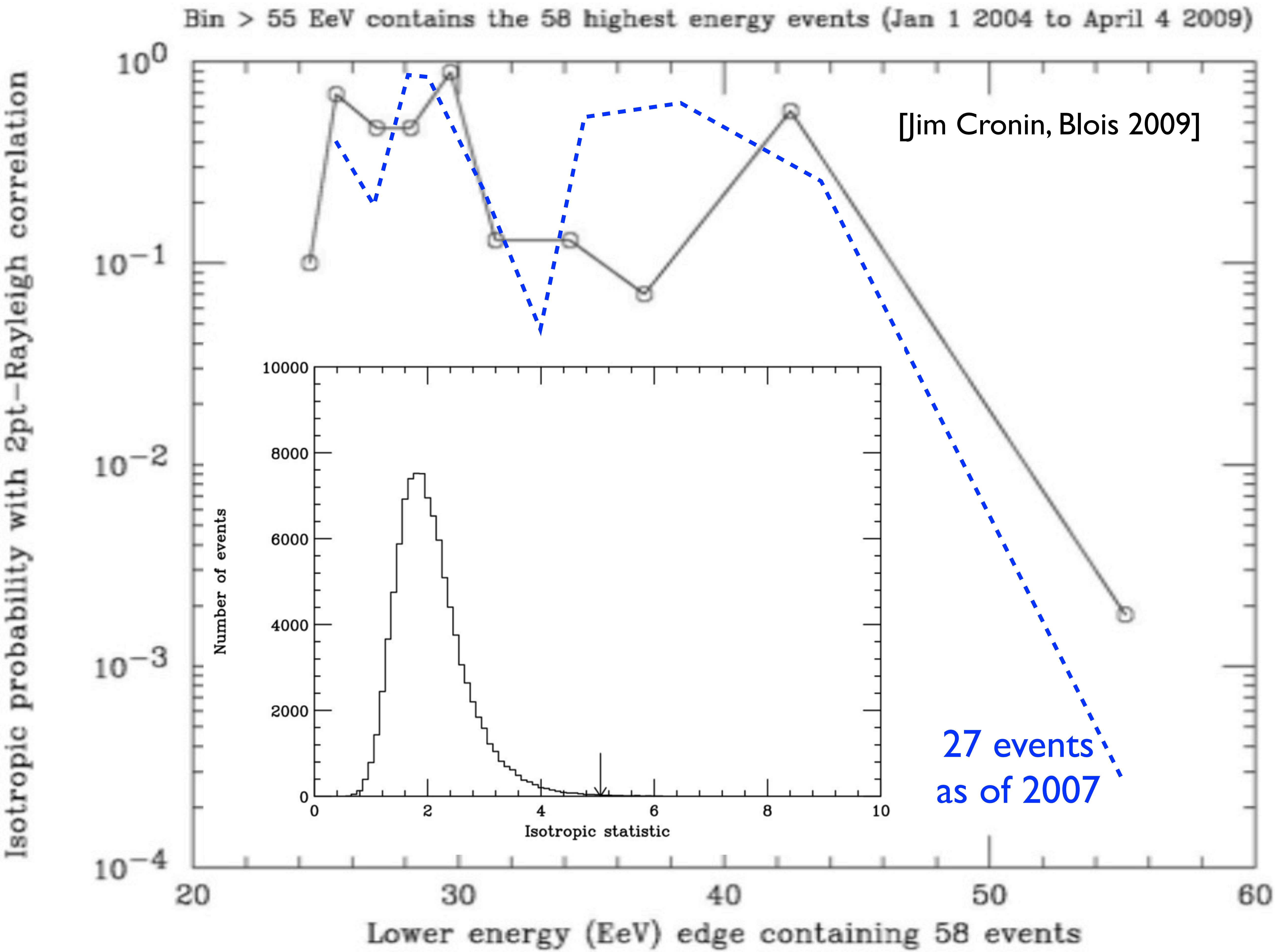
Auger events
E > 3 EeV

Auger events
E > 55 EeV

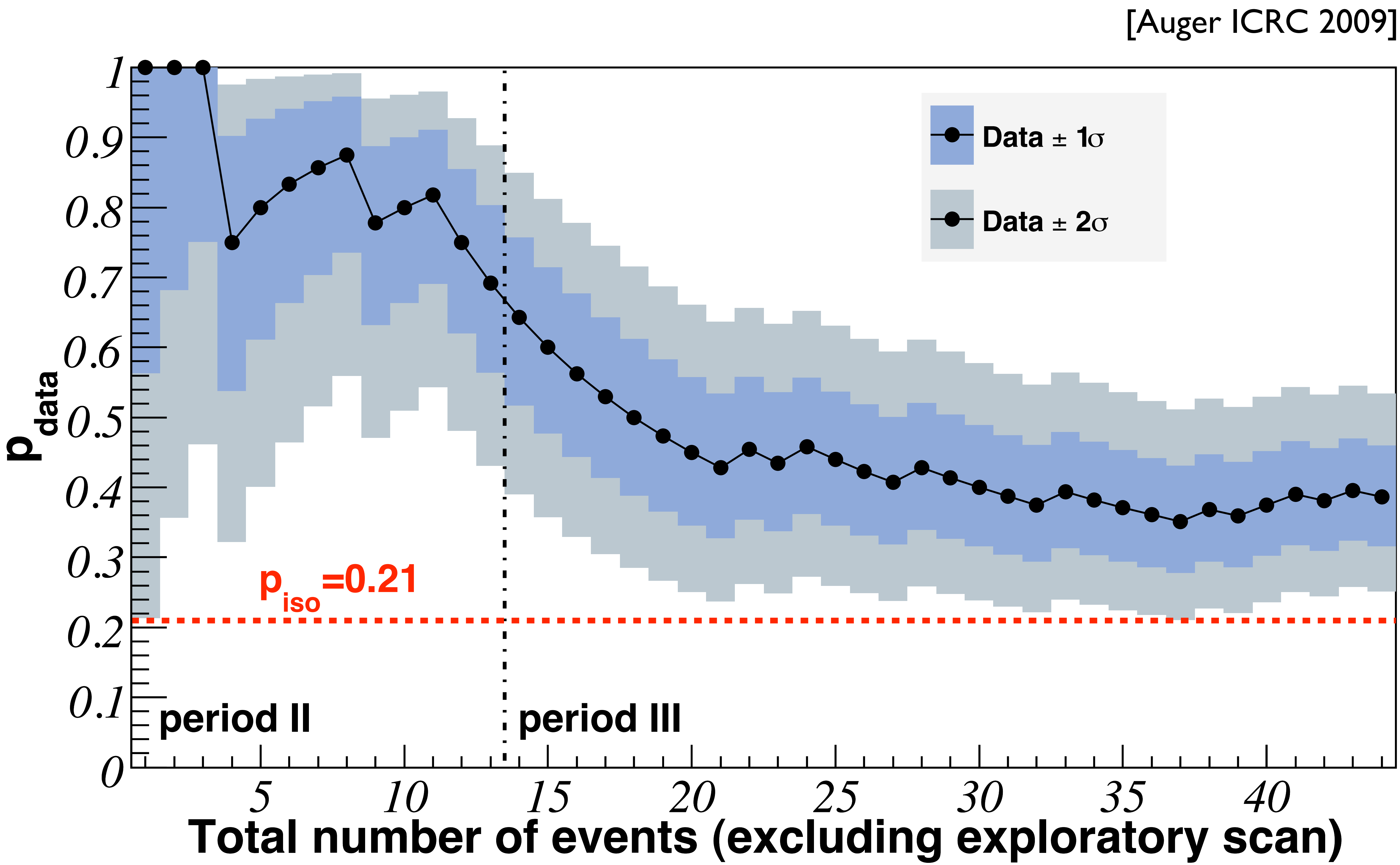




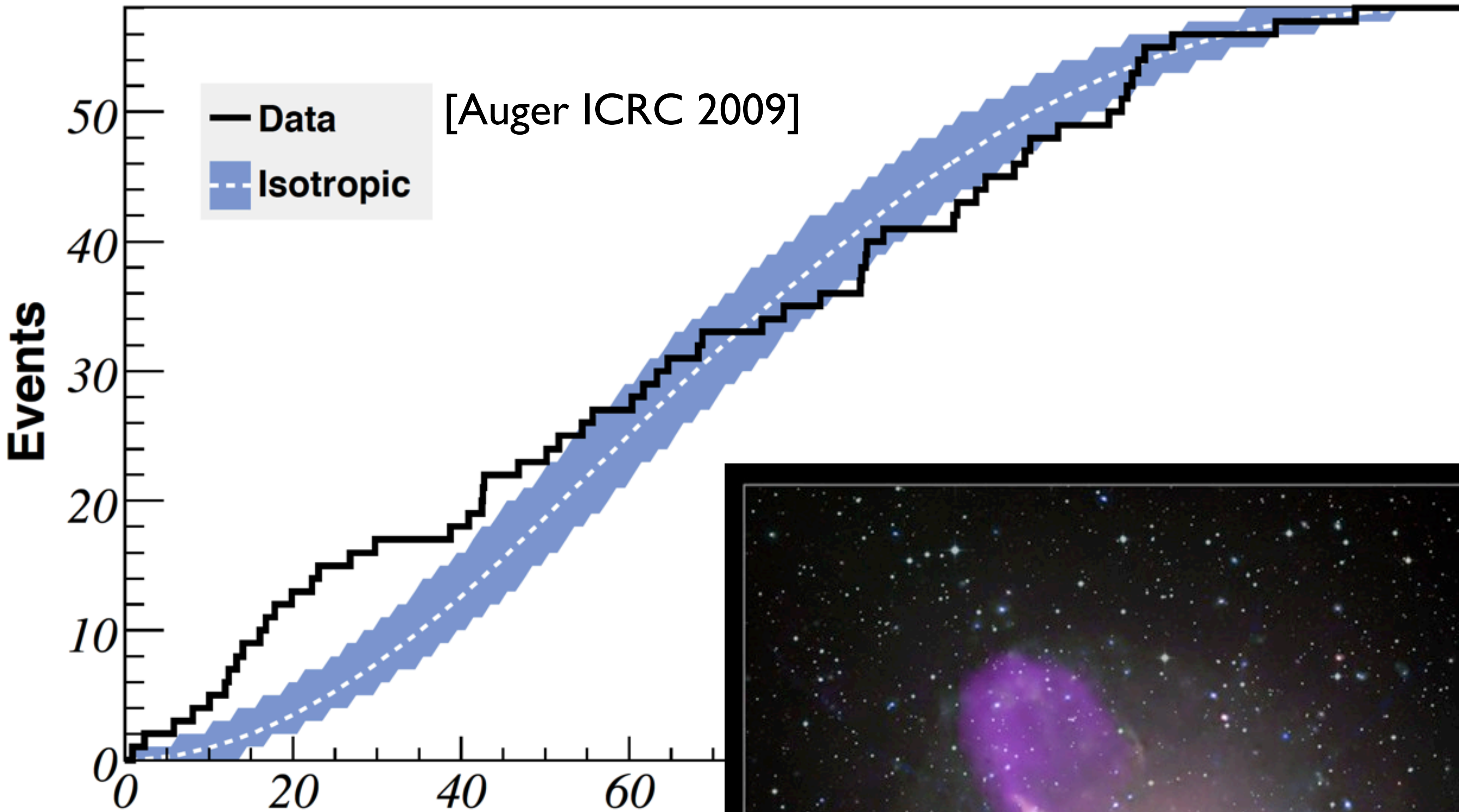
Distribution of angular separations between the 58 events with $E > 55$ EeV and the closest AGN in the VCV catalog within 75 Mpc



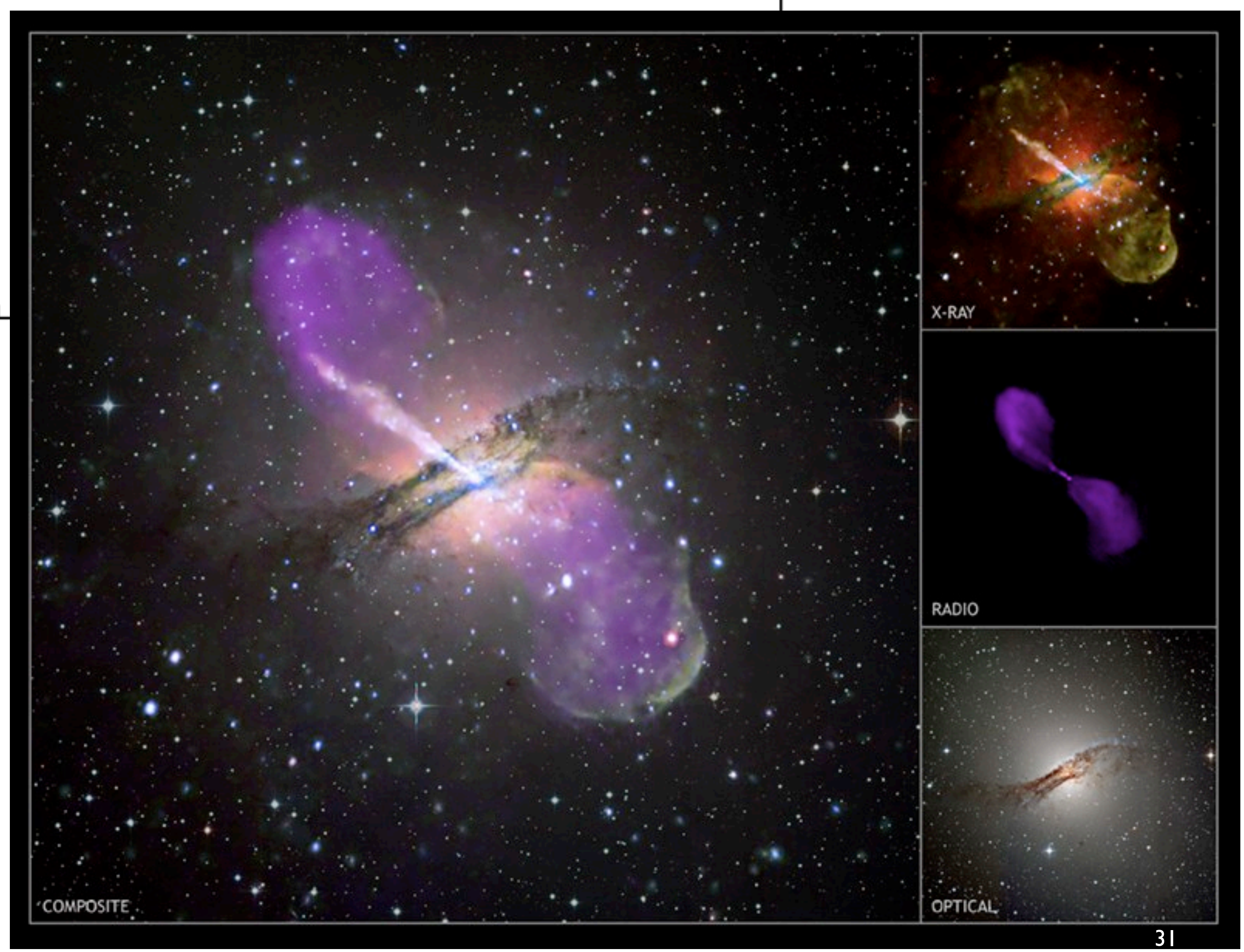
Bin > 55 EeV contains the 58 highest energy events (Jan 1 2004 to April 4 2009)
Isotropic probability with 2pt−Rayleigh correlation
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
20
30
40
50
60
Lower energy (EeV) edge containing 58 events
[Jim Cronin, Blois 2009]
27 events
as of 2007
10000
8000
6000
4000
2000
0
Number of events
0
2
4
6
8
10
Isotropic statistic



[Auger ICRC 2009]
Data ± 1σ
Data ± 2σ
p_iso=0.21
period II
period III
p_data
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
5
10
15
20
25
30
35
40
Total number of events (excluding exploratory scan)

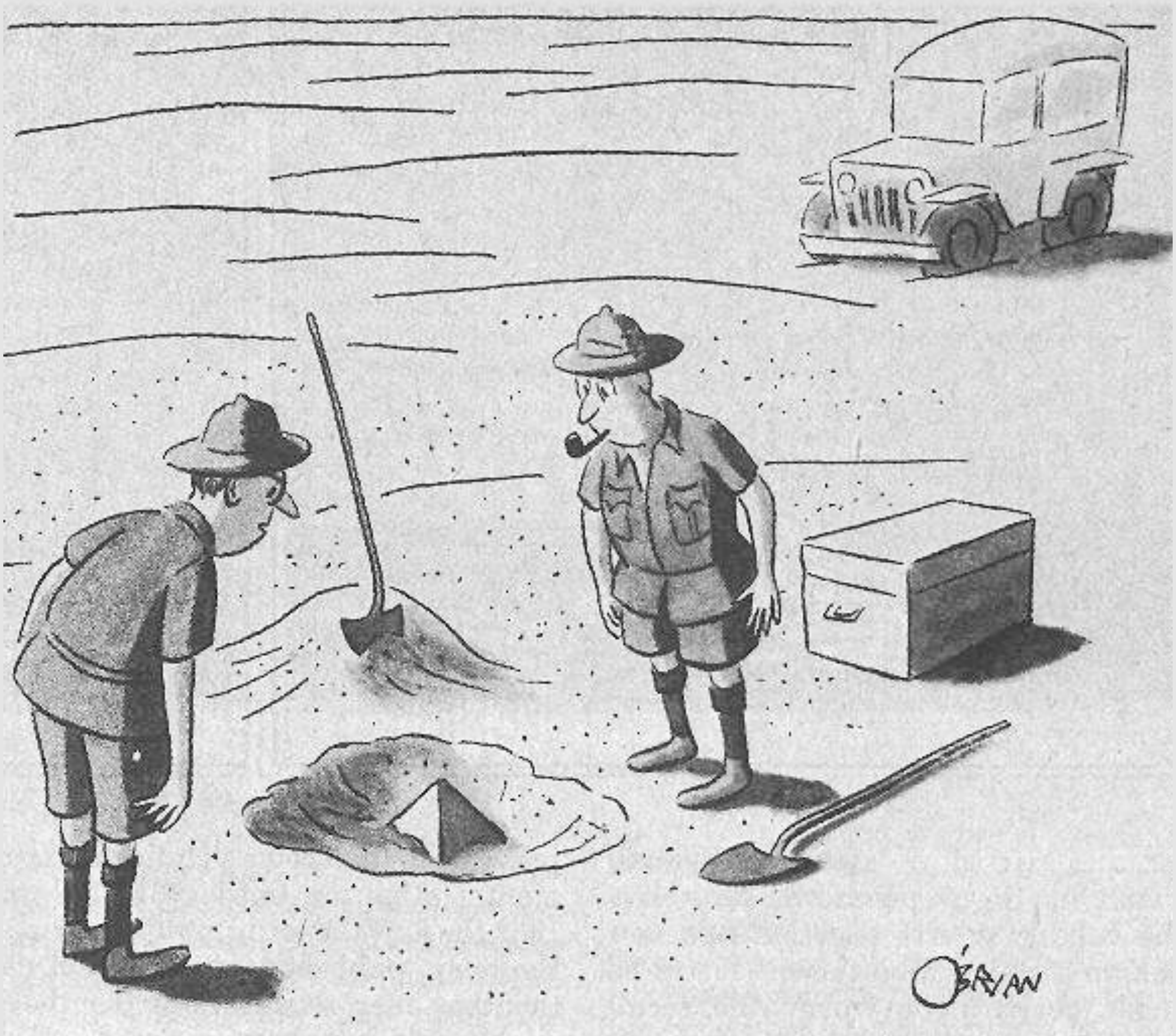


cumulative number of events with $E \geq$ 55 EeV as a function of angular distance [°] from Cen A



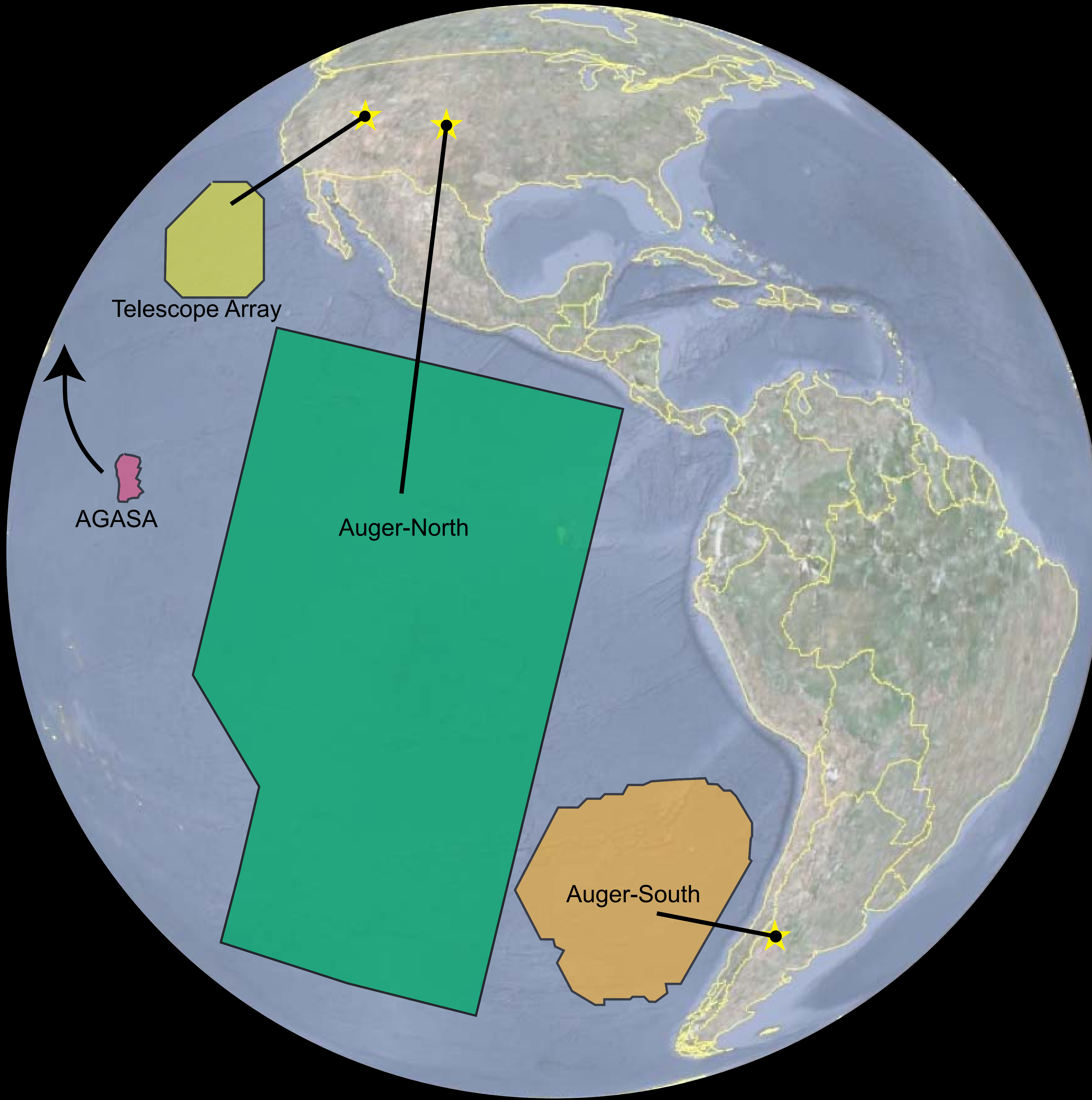
Preliminary conclusions

- First precise energy spectrum from 1 EeV to above 100 EeV
- Fluorescence detection of showers sets the energy scale to ± 22%,
  - biggest contribution from absolute fl. yield
- Ankle at 2-3 EeV: transition from galactic to extragalactic cosmic particles
- Flux suppression at 50-60 EeV: GZK effect or maximum accelerator energy?
- With increasing energy air showers develop higher up in the atmosphere and show less fluctuations – astrophysics and/or particle physics? E.g. heavier particles or higher cross section?
- arrival directions of cosmic rays become abruptly anisotropic above 50-60 EeV, in coincidence with the flux suppression.
- cosmic ray arrival directions correlate with the distribution of nearby (<75 Mpc) extragalactic objects; several reference maps are being tested. The correlating fraction is (38 ± 6)% [was (69^{+11}_{-13})% initially].
- The reference-free anisotropy is a robust feature.

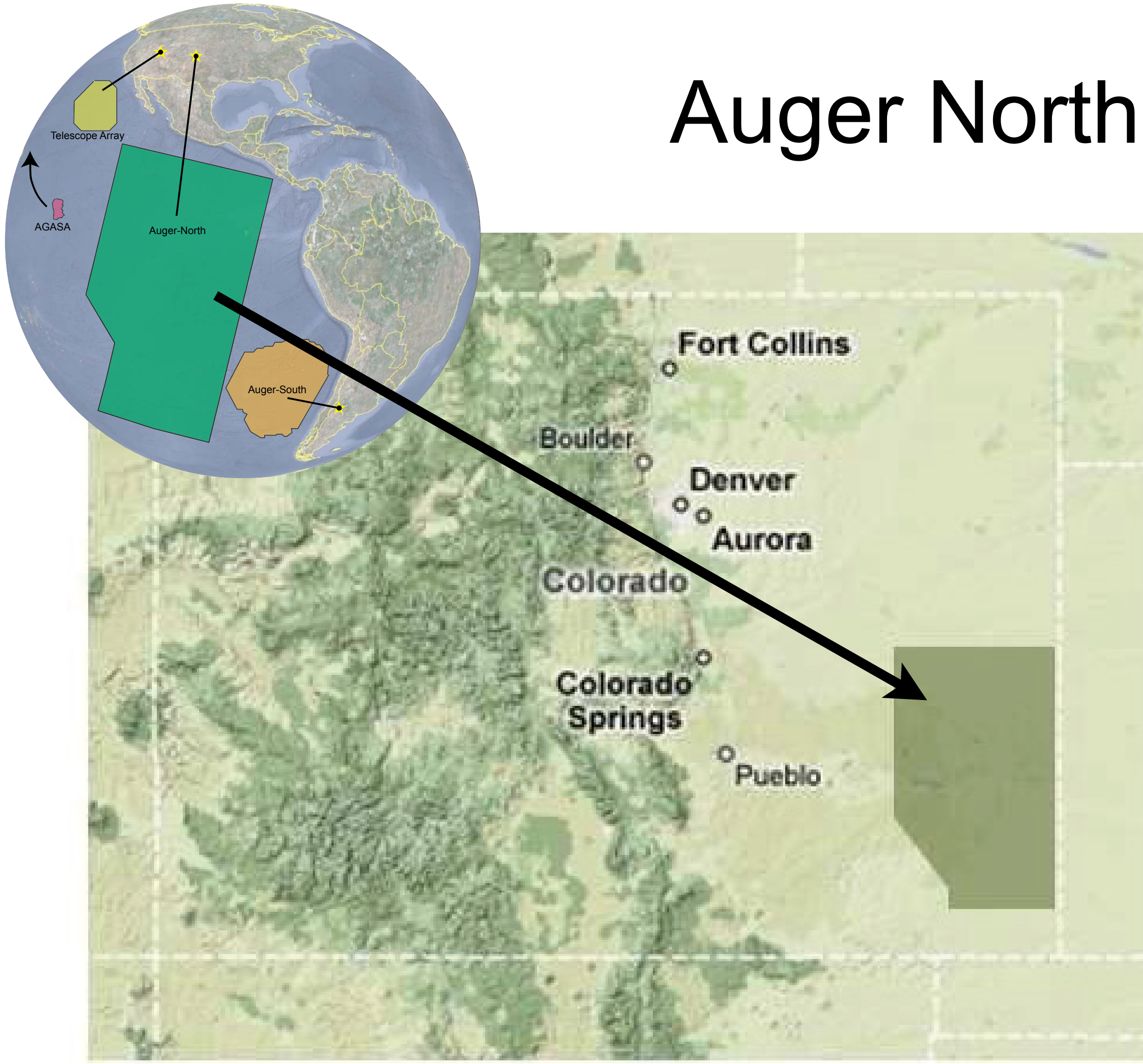


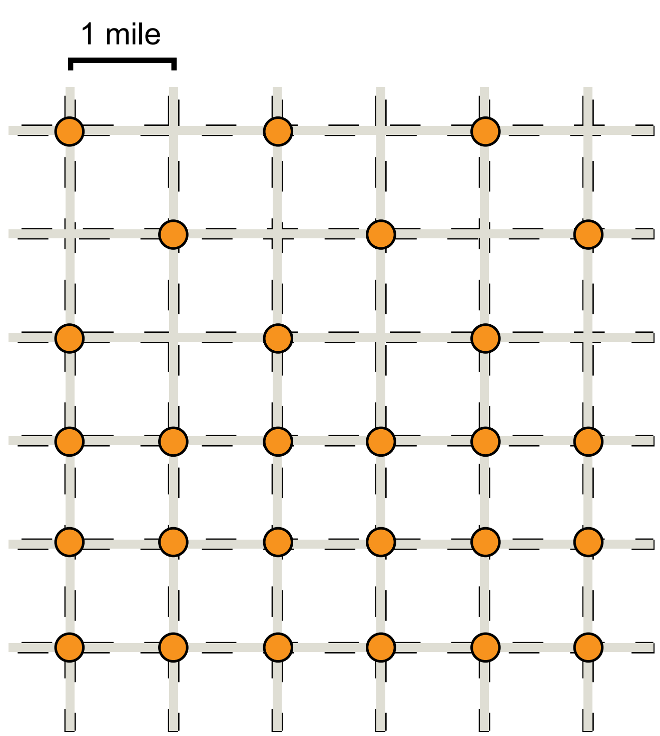
"This could be the discovery of the century. Depending, of course, on far down it goes."

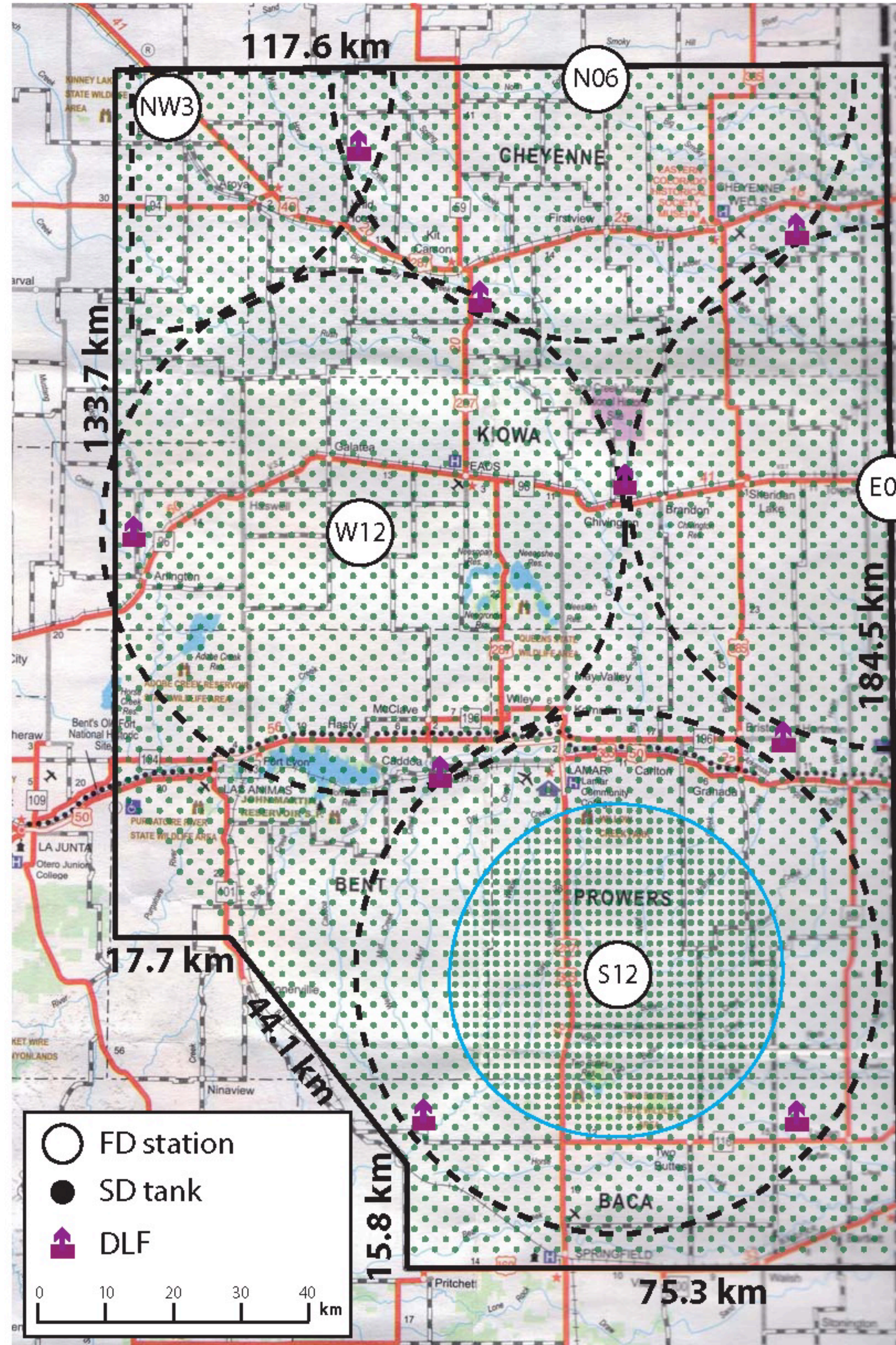
Auger had always been designed as a two-instrument, full-sky coverage cosmic ray observatory


Telescope Array
AGASA
Auger-North
Auger-South

Auger North

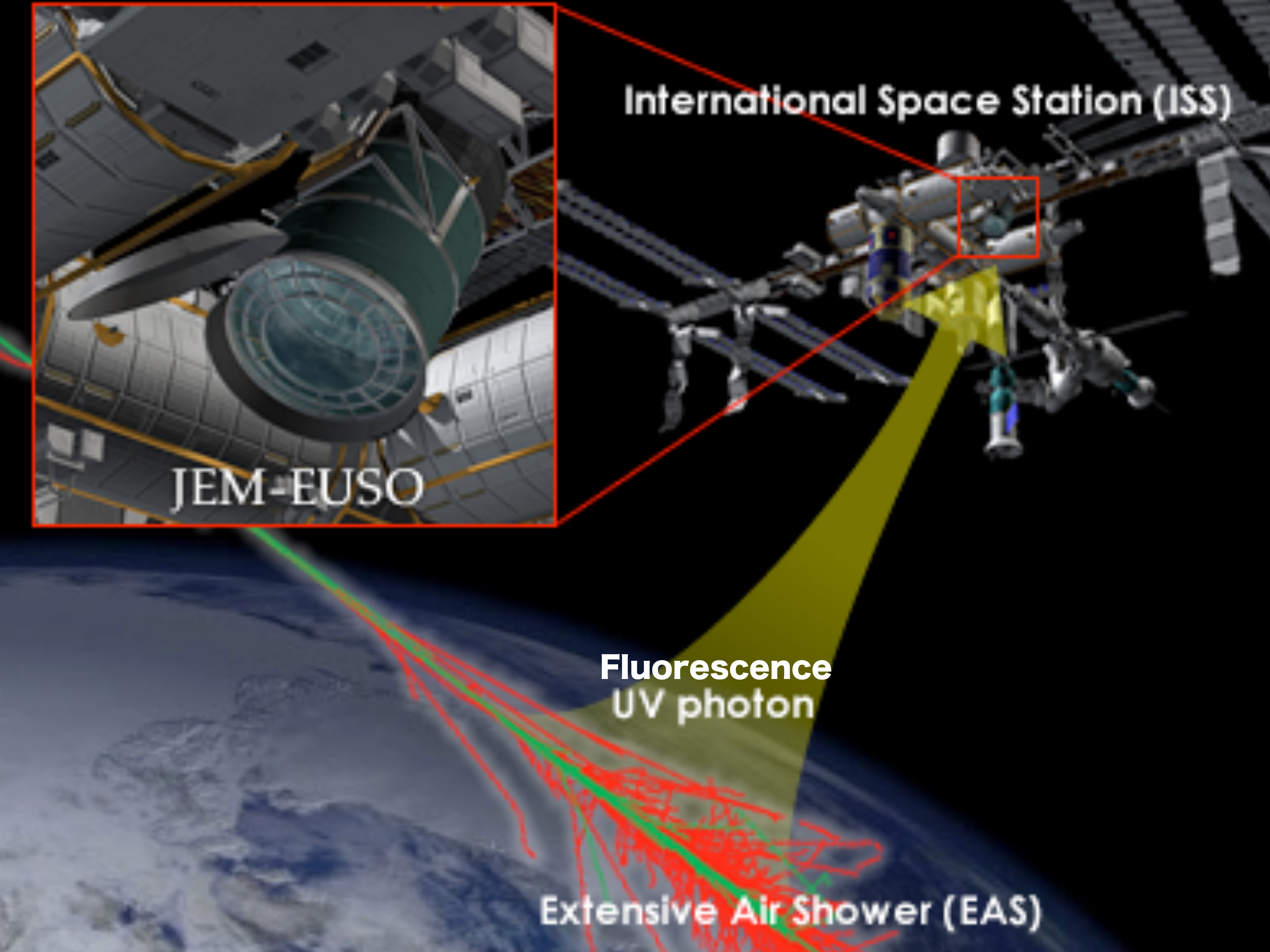


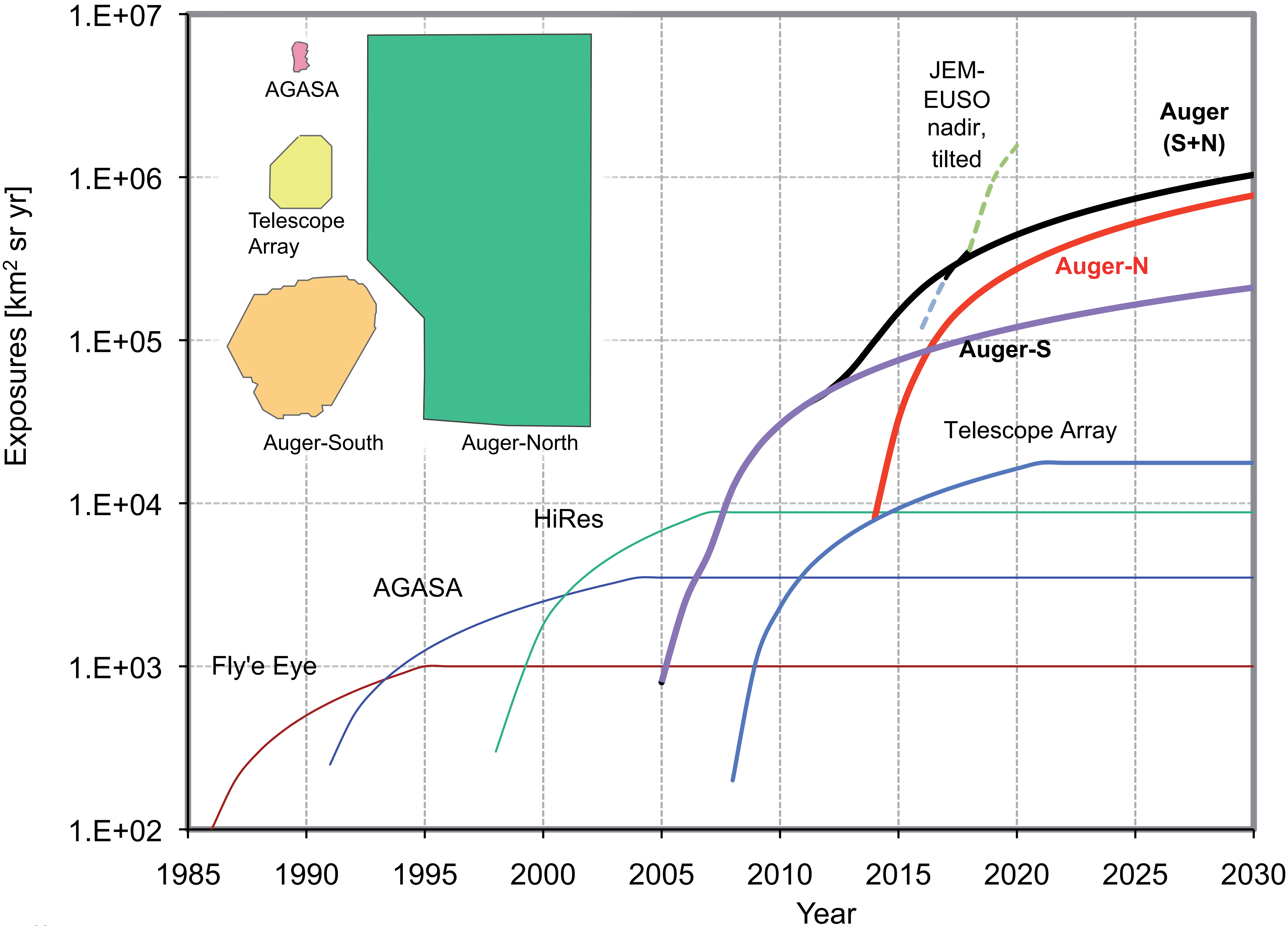




4400 tanks on
20.000 km^2
39 telescopes

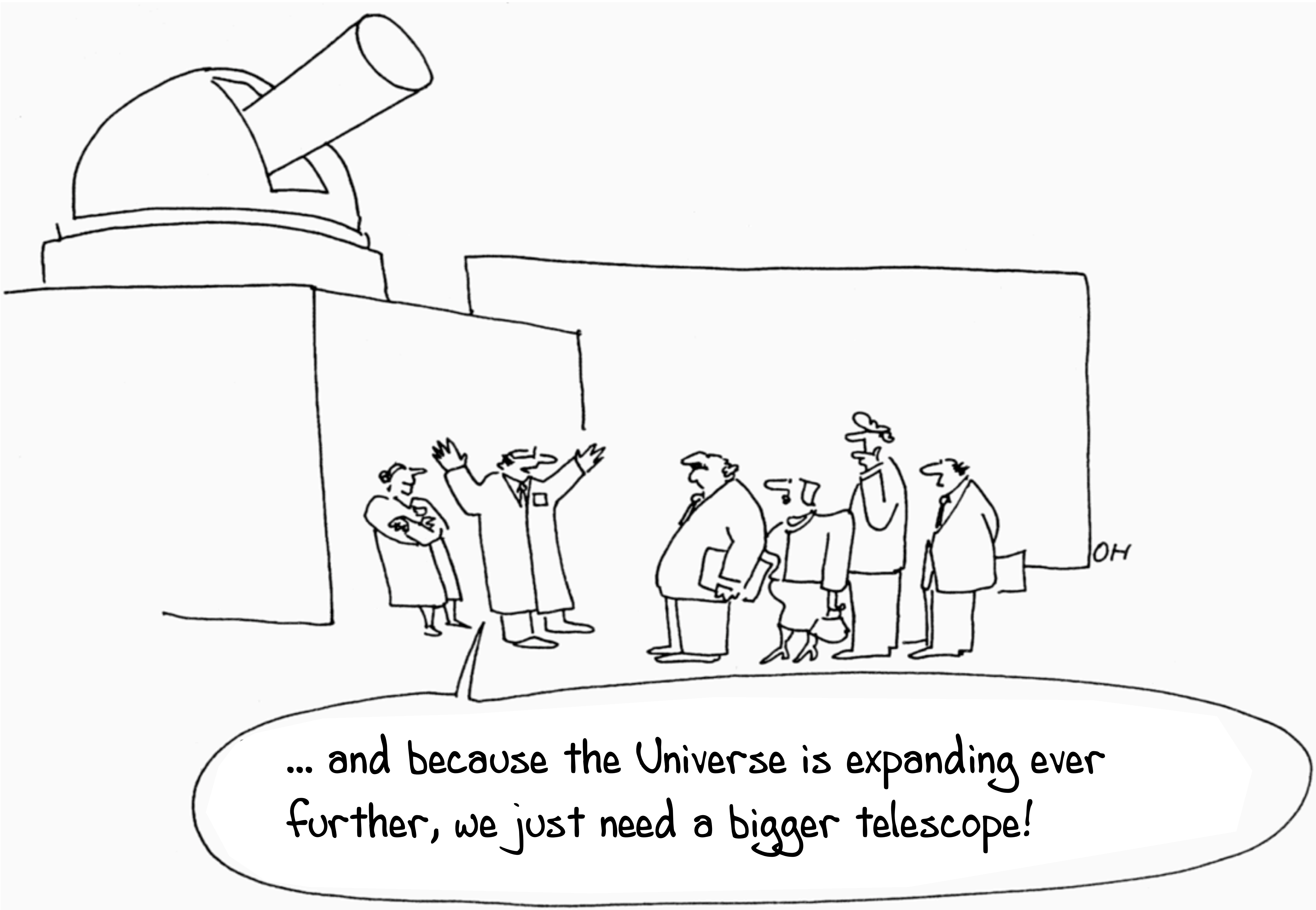
	Auger South	Auger North
Location	35° S, 69° W	38° N, 102° W
Altitude	1,300 - 1,500 [m a.s.l.	1,300 [m a.s.l.]
Area	3,000 km^2	20,000 km^2
Number of SD stations	1,600	4,000
(infill)		(400)
SD spacing	1,500 m	2,300 m
(infill)		(1,600 m)
PMT sensors / SD station	3	1
Communications network	SD-tower radio	peer-to-peer
SD array 50% efficient at	0.7-1 EeV	8-10 EeV
SD array 100% efficient at	3 EeV	80 EeV
FD stations	4	5
FD telescopes	24 (4×6)	39 $(2 \times 12 + 2 \times 6 + 1 \times 3)$
Begin construction	1999	2012
End construction	2008	2016


International Space Station (ISS)
JEM-EUSO
Fluorescence
UV photon
Extensive Air Shower (EAS)


1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
Exposures [km² sr yr]
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
Year
AGASA
Telescope
Array
Auger-South
Auger-North
JEM-
EUSO
nadir,
tilted
Auger
(S+N)
Auger-N
Auger-S
Telescope Array
HiRes
AGASA
Fly'e Eye

Final conclusions

- First precise energy **spectrum** from 1 EeV to above 100 EeV
- Optical fluorescence detection of showers set the **energy scale** to ± 22%,
  - biggest contribution from absolute fl. yield
- **Ankle** at 2-3 EeV: transition from galactic to extragalactic cosmic particles
- Flux suppression at 50-60 EeV: **GZK effect or maximum accelerator energy?**
- With increasing energy **air showers develop** higher up in the atmosphere and show less fluctuations – **astrophysics and/or particle physics? E.g. heavier particles or higher cross section?**
- arrival directions of cosmic rays become abruptly **anisotropic** above 50-60 EeV, in coincidence with the flux suppression
- **cosmic ray arrival directions correlate with the distribution of nearby (<75 Mpc) extragalactic objects**; several reference maps are being tested. **The correlating fraction is (38 ± 6)% [was (69+11-13)% initially] -- need more data**
- Many open important questions remain to be answered – **Auger North** is needed with a much larger (x7) aperture. A complementary approach (detection from space, ~less precise, even larger statistics) is **JEM-EUSO**.


OH
... and because the Universe is expanding ever further, we just need a bigger telescope!