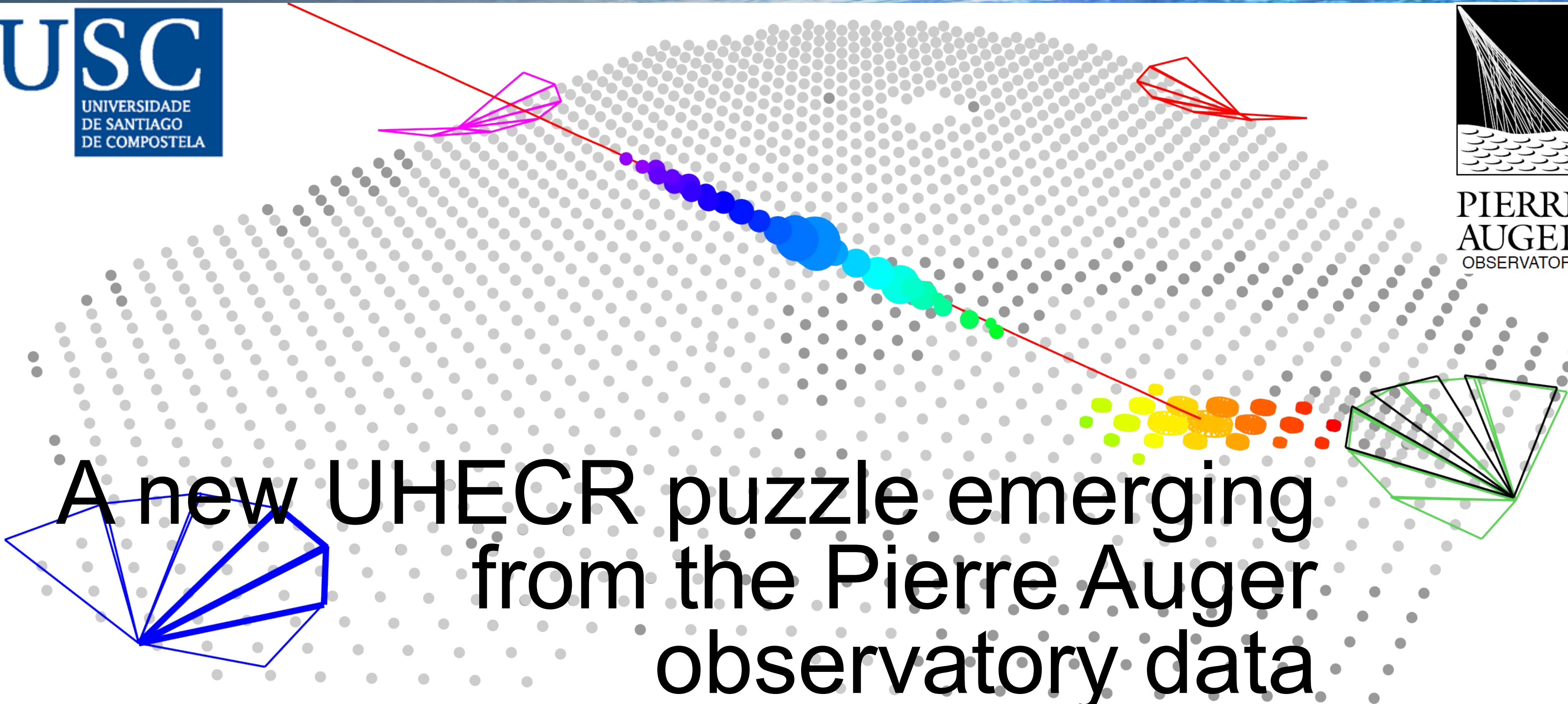
University of Santiago de Compostela
PACT IFT Madrid October 25th 2013

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

PIERRE AUGER OBSERVATORY

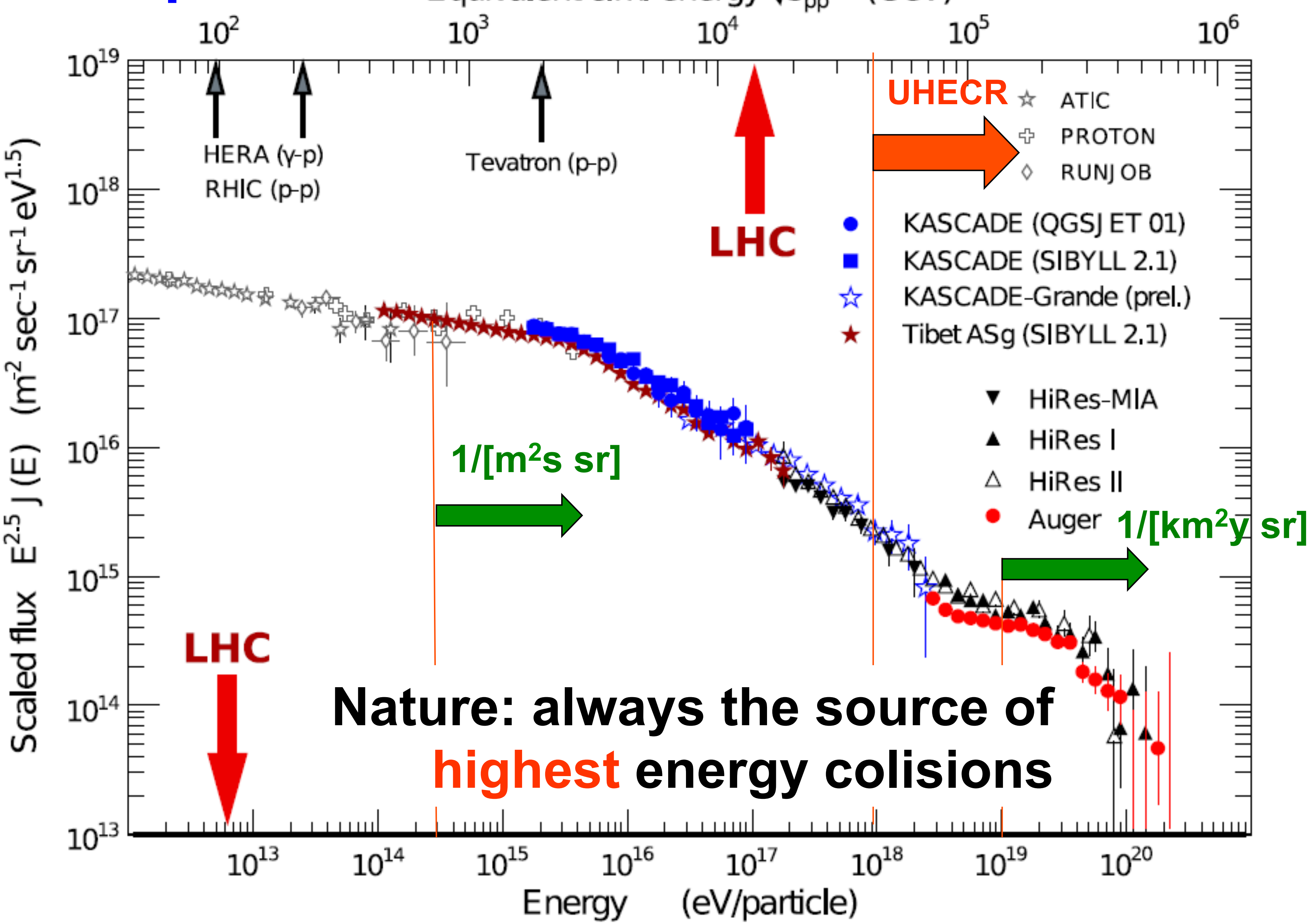


A new UHECR puzzle emerging from the Pierre Auger observatory data

Outline:

- UHECR, the picture before s XXI
- The Pierre Auger observatory
  - *The complex*
  - *Spectrum*
- Digression on showers
- Auger observatory results
  - *Anisotropies*
  - *Bounds Neutrinos and Photons*
  - *Composition*
  - *Particle Physics*
    - *Cross section measurements*
    - *Muon deficit in simulations*
- Summary and outlook

The spectrum



Nature: always the source of highest energy colisions

Scientific motivation

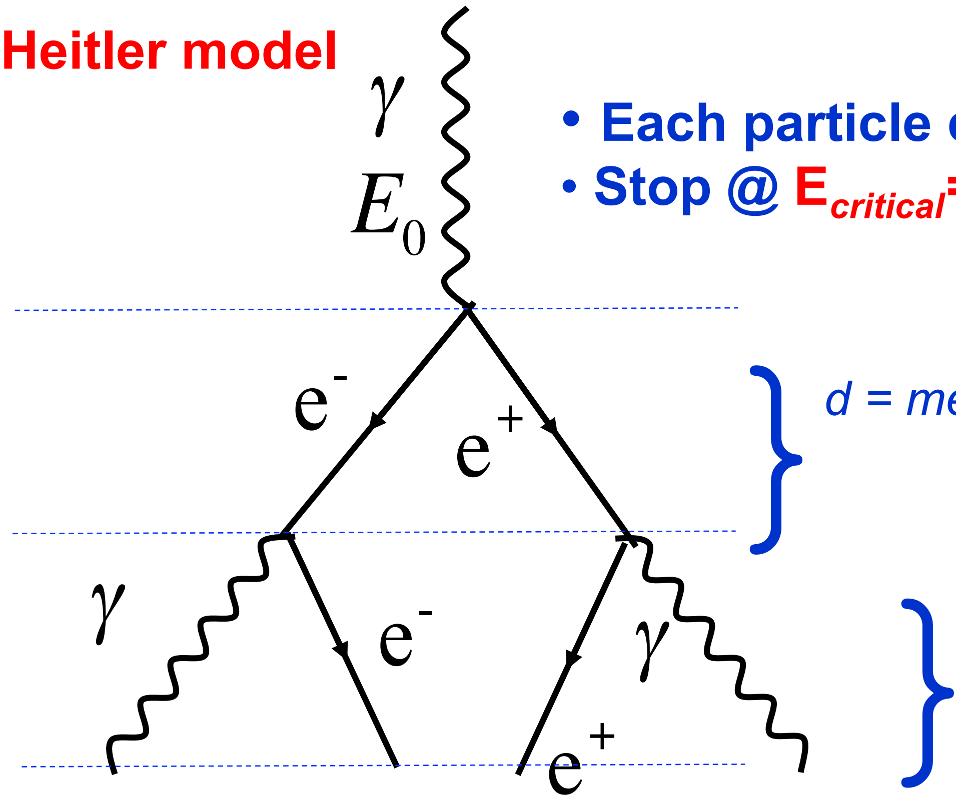
- Particle Physics
  - Test interactions at (always) highest energies
  - Test forward region
- Astrophysics
  - Unknown origin (particle nature, where, how)
  - Relation to cosmology (Extragalactic sources) i.e.=> CMB interactions
  - Large E => Sufficiently small angular deviations?
    - Astronomy
    - Learn about B fields

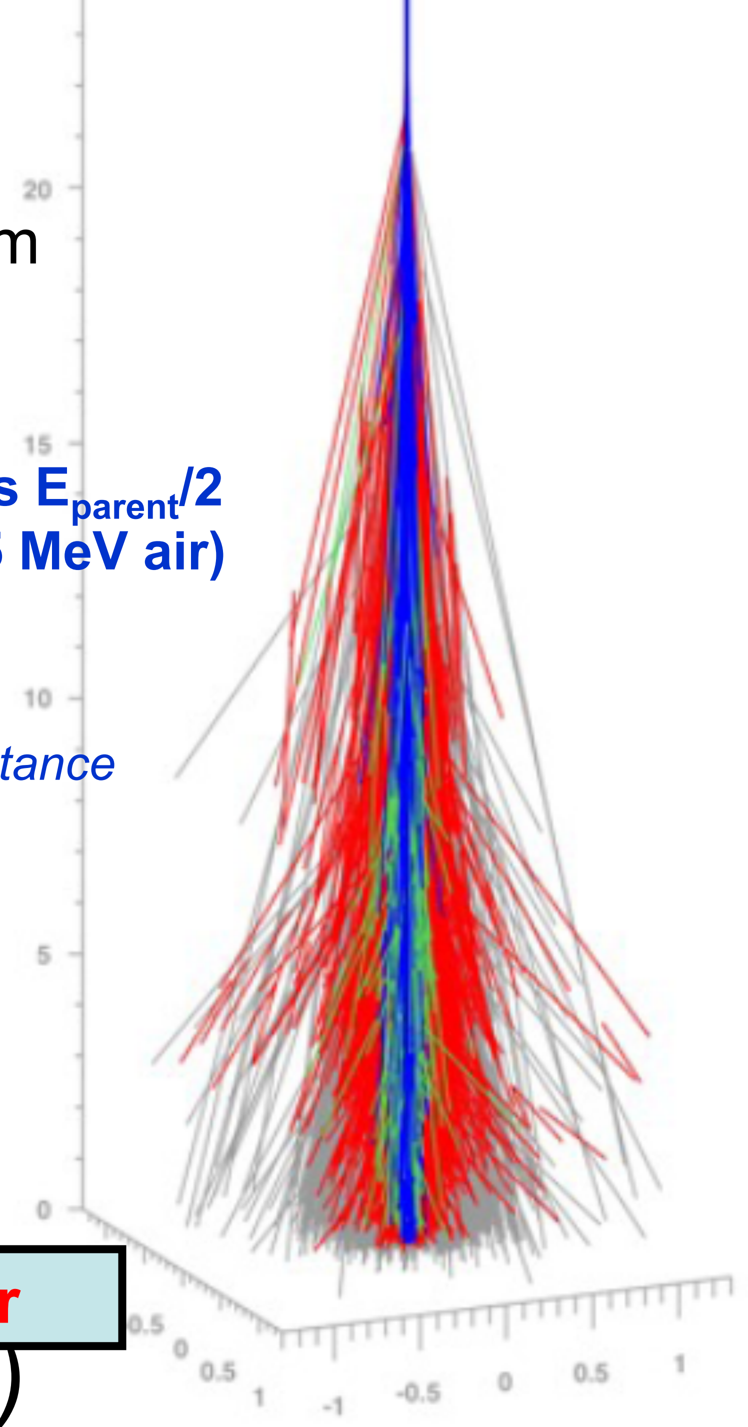
Detection Challenge

Low rate. Use atmosphere as detector.
Detect **air showers:** they are **large** ~km

Heitler model

- **Each particle carries $E_{parent}/2$**
- **Stop @ $E_{critical}=\xi_c$ (85 MeV air)**

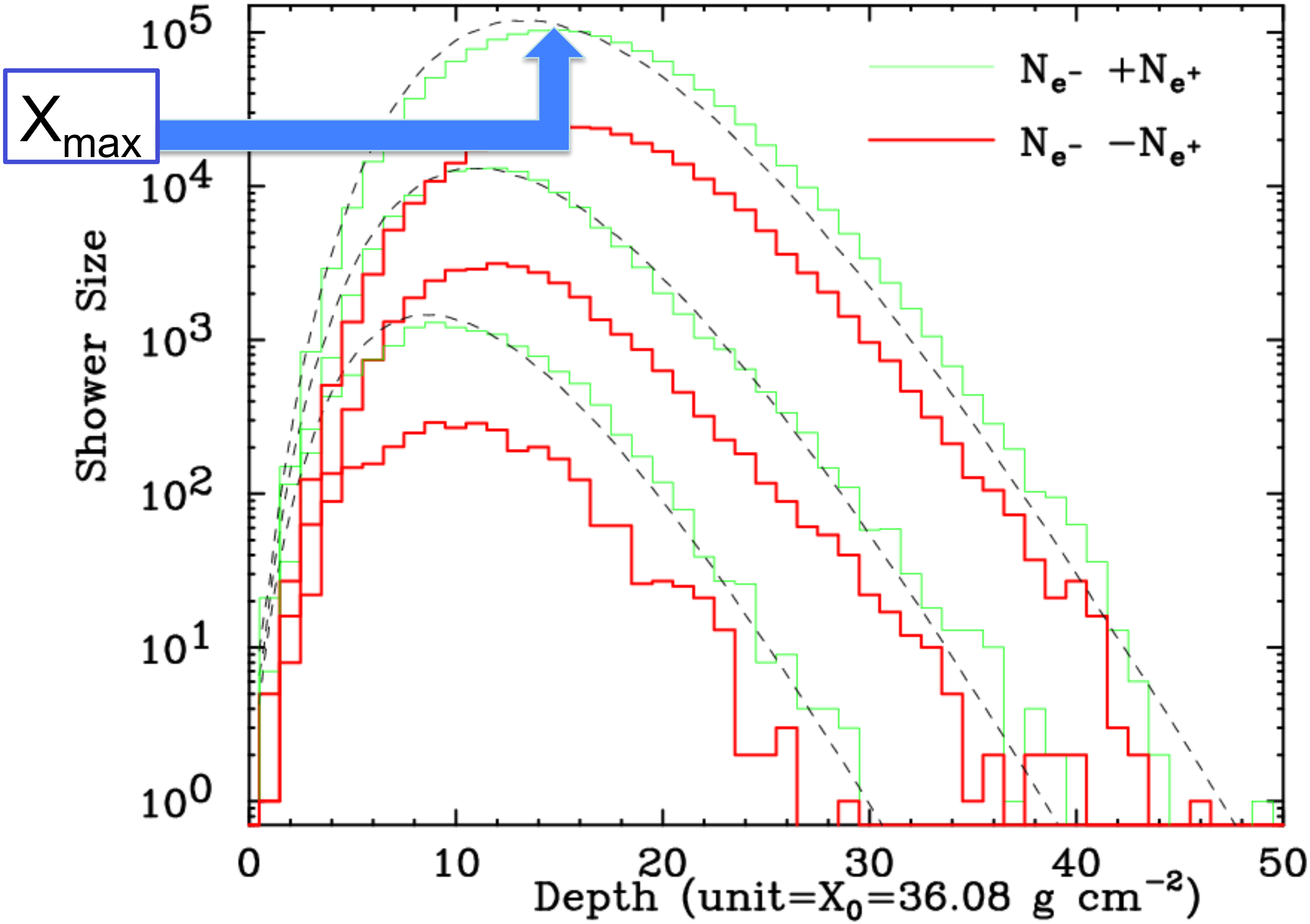




$$d = X_0 \ln 2$$

X_0 = 37 g cm^{-2} in air

(radiation length)



X$_{max}$
$N_{e^-} + N_{e^+}$
$N_{e^-} - N_{e^+}$
Shower Size
10^5
10^4
10^3
10^2
10^1
10^0
0
10
20
30
40
50
Depth (unit=X_0=36.08 g cm^{-2})

After "n" steps (depth *x*) Energy split in N=2^n particles (e^+,e^-,γ) of energy E/N

$$N = 2^n = 2^{x/d} = 2^{x/[X_0 \ln 2]} = e^{x/X_0}$$

Number of particles at maximum (E drops to critical energy):

$$n_c = \ln\left[E_0/\varepsilon_c\right]/\ln 2$$

$$N_{\max} = 2^{n_c}$$

Complex simulations:

Energy related to N_{max} & N_{max} :

$$X_{\max} = n_c X_0 \ln 2 = X_0 \ln\left[E/\varepsilon_c\right]$$

$$E_0 = \varepsilon_c N_{\max}$$

- ***X_{max} ~ ln E_o***
- ***E_o ~ N_{max}***

"Elongation rate":

$$\Lambda = \frac{dX_{\max}}{d\log E_0} = 2.3X_0$$

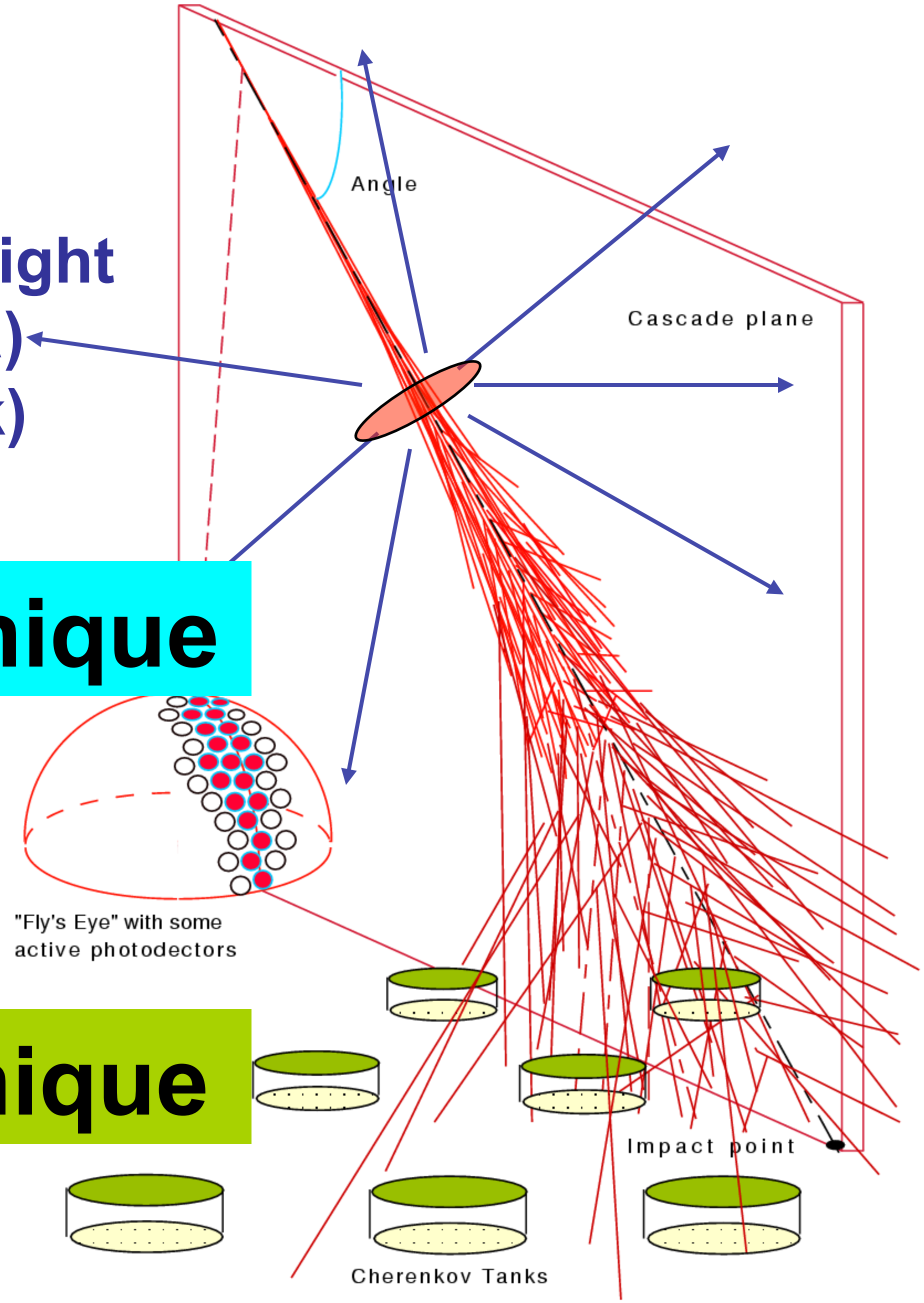
- **Λ= 85 (gcm^{-2})/decade**

Only two succesful techniques

Isotropic Fluorescence light from nitrogen (aurora) (4 γ per meter of track)

Fluorescence Technique

Particle array Technique

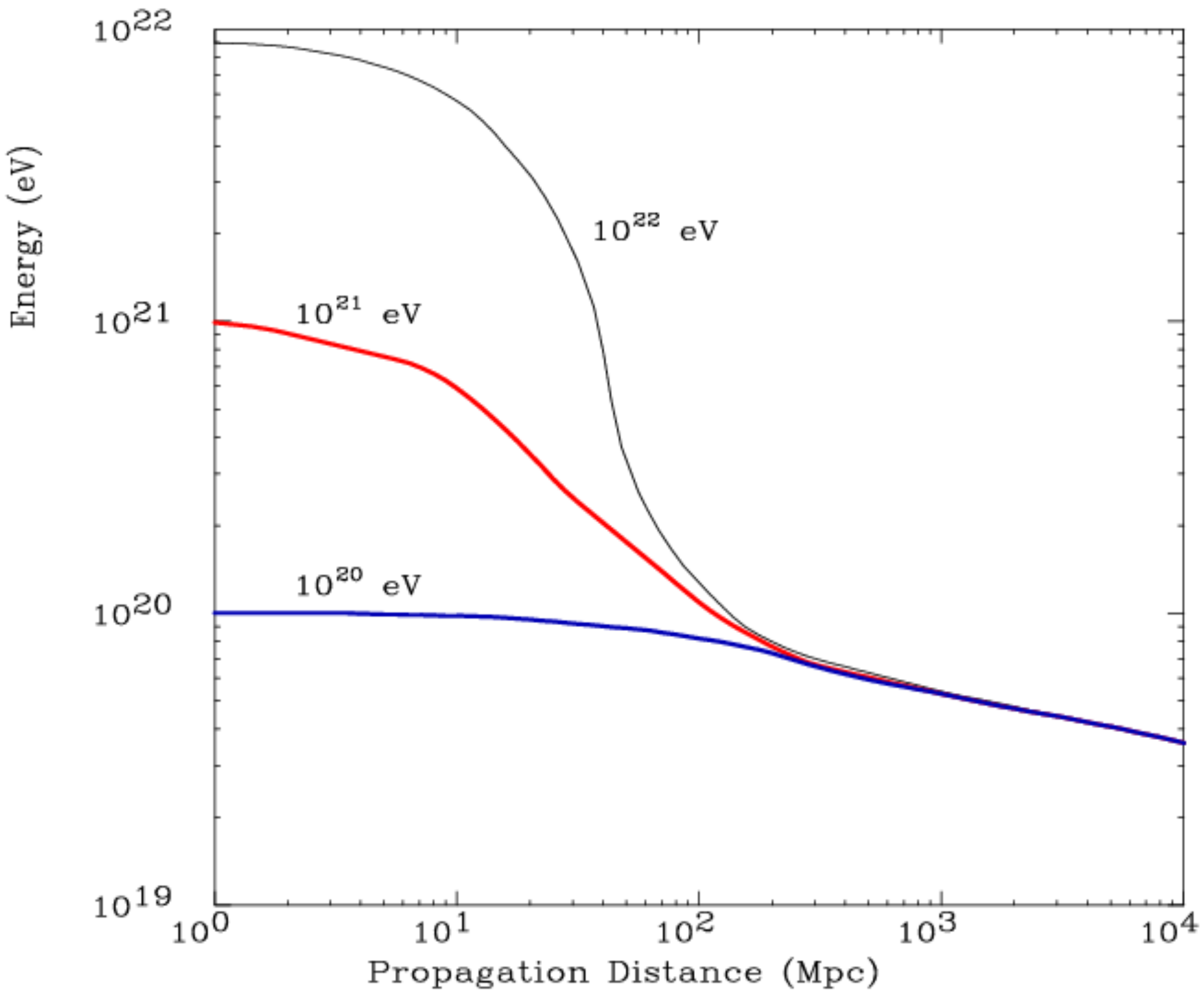


The UHECR prejudice/paradigm in the 1990s:

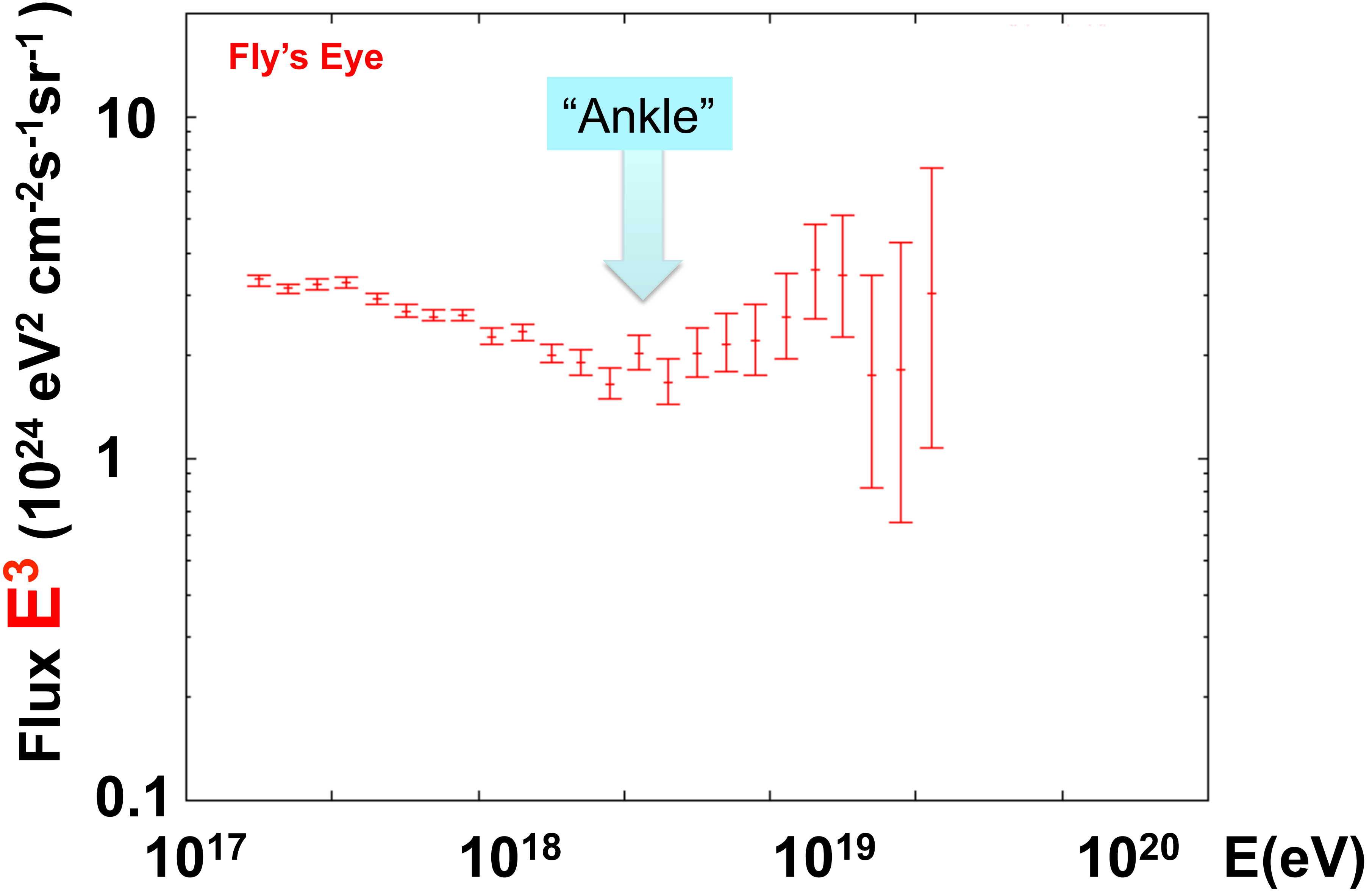
- UHECR believed to be:
    - Protons (ankle feature)
    - Extragalactic (few feasible galactic sources)
- But observations suggested:
    - No interactions with CMB
- Large discovery potential:
    - >10 events per year per 1000 km^2 above 10^{20} eV
    - Nearby sources? (Fermi acceleration or TD sources?)
    - Other incoming particles? New Physics?
    - Proton astronomy?

The Greisen-Zatsepin-Kuz'min (GZK) cut-off

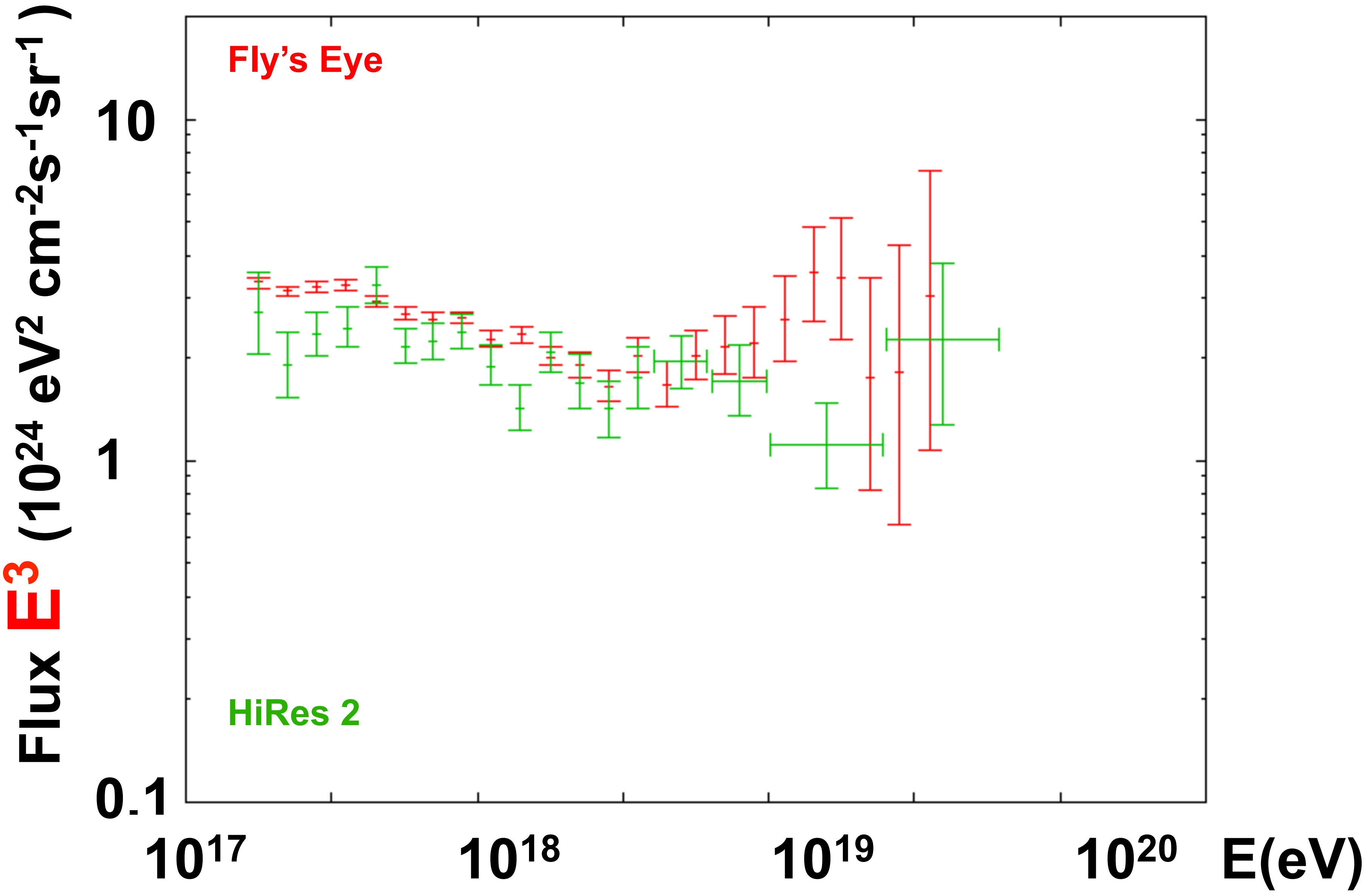
$p+\gamma_{CMB}$



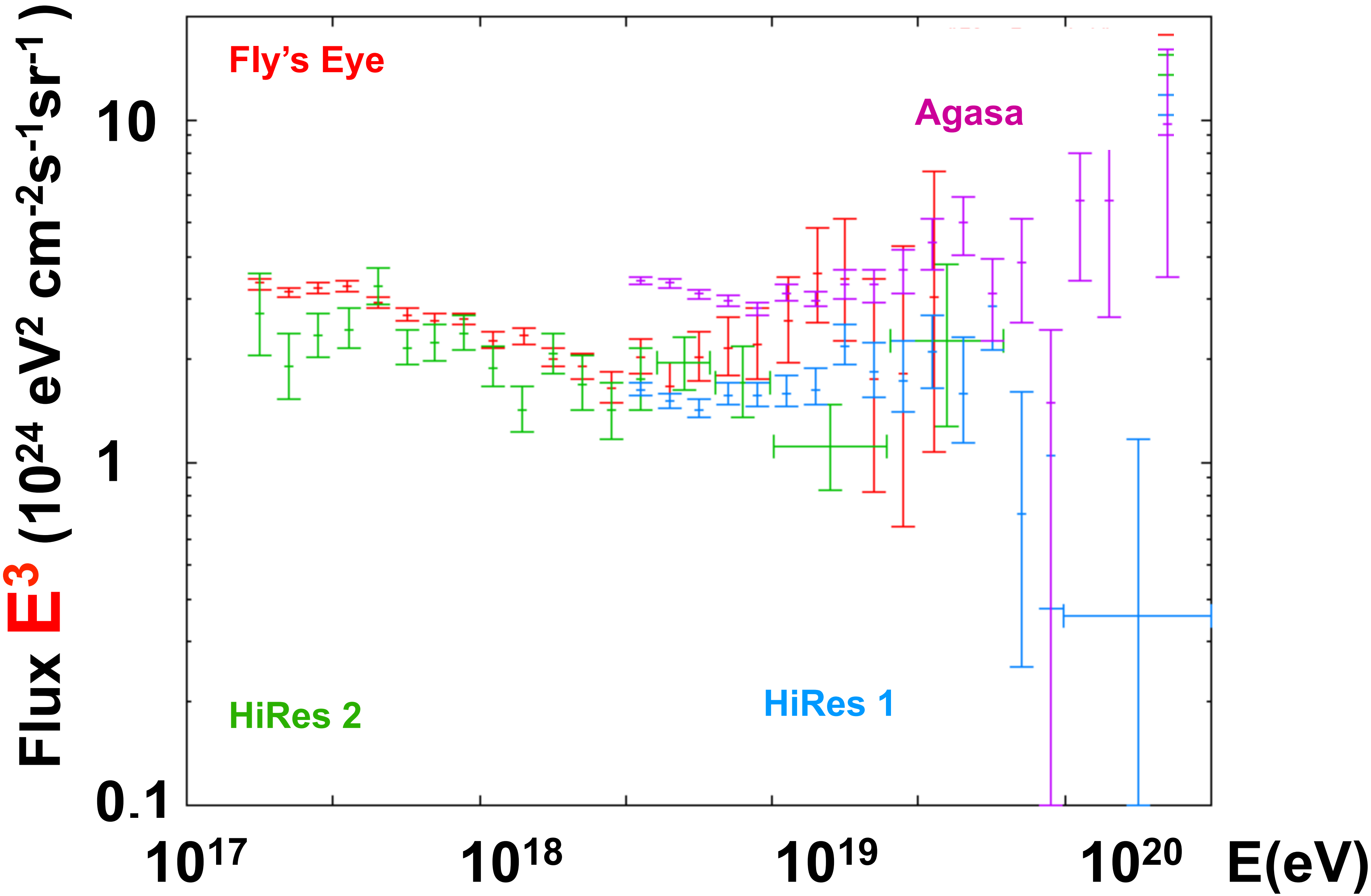
The UHECR data in the 1990s:



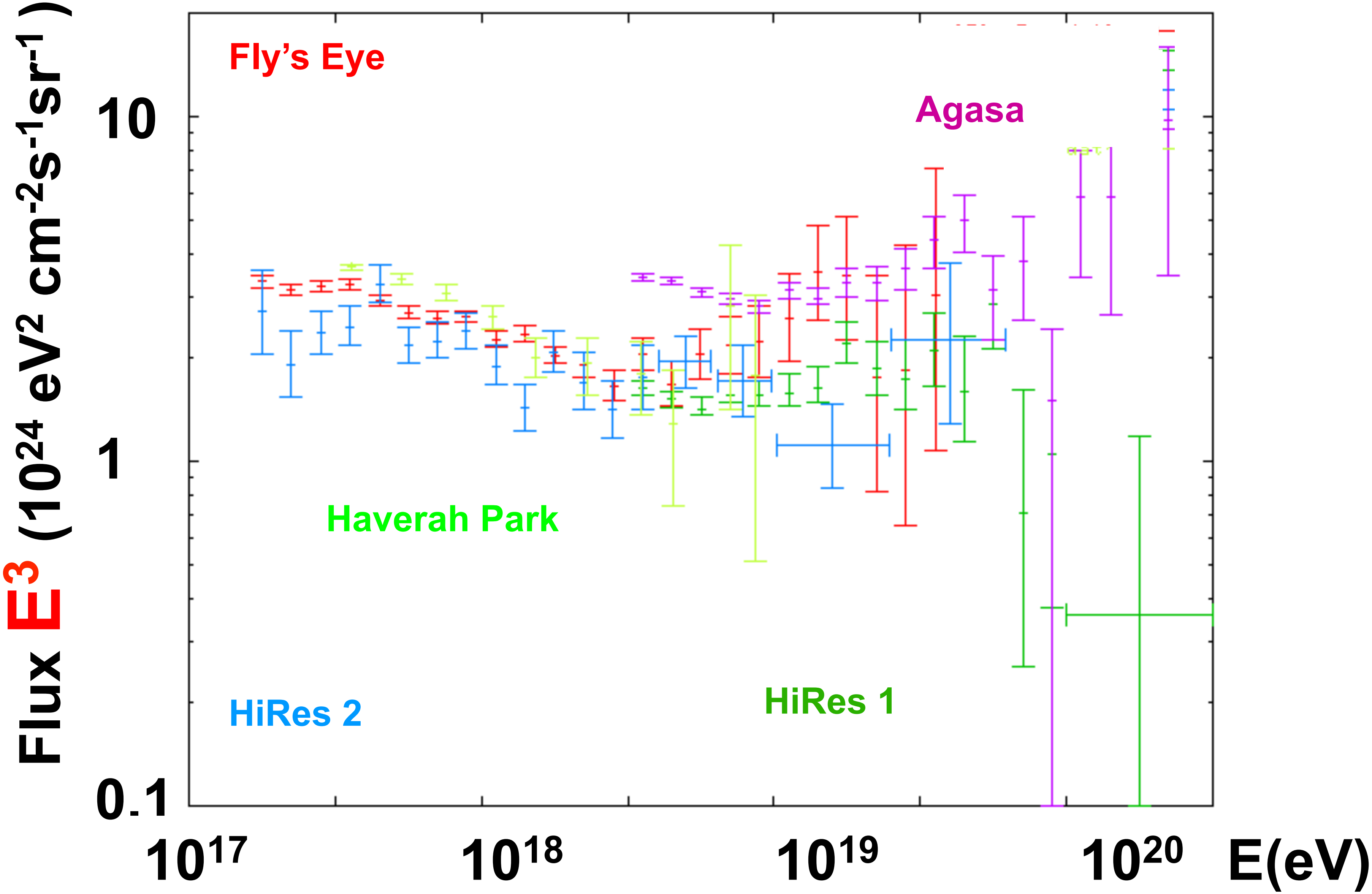
The UHECR data in the 1990s:



The UHECR data in the 1990s:



The UHECR data in the 1990s:



Precision CR Physics is not easy:

- There is no control of the beam:
  - No energy, direction or particle type
- Interaction models at these energies are extrapolated
  - Results inevitably have some model dependence
- Measurements are indirect through air showers
  - Must deduce properties after stochastic processes
- Showers fluctuate in size and development
  - Depending on composition and interaction properties

How can this be overcome?:

- **Redundancy** in detection methods
- **New ideas** to exploit data in complementary ways


The Pierre Auger Observatory

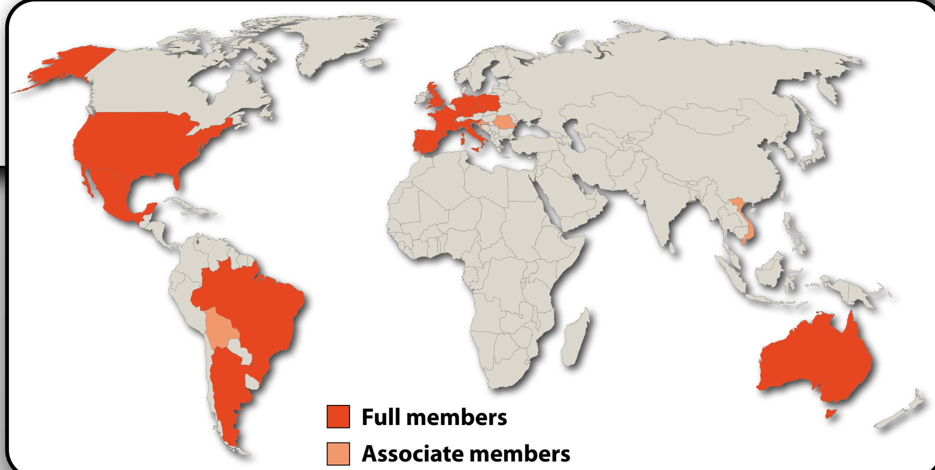
Pierre Auger Collaboration

19 Countries 500+ Scientists 100+ Institutions

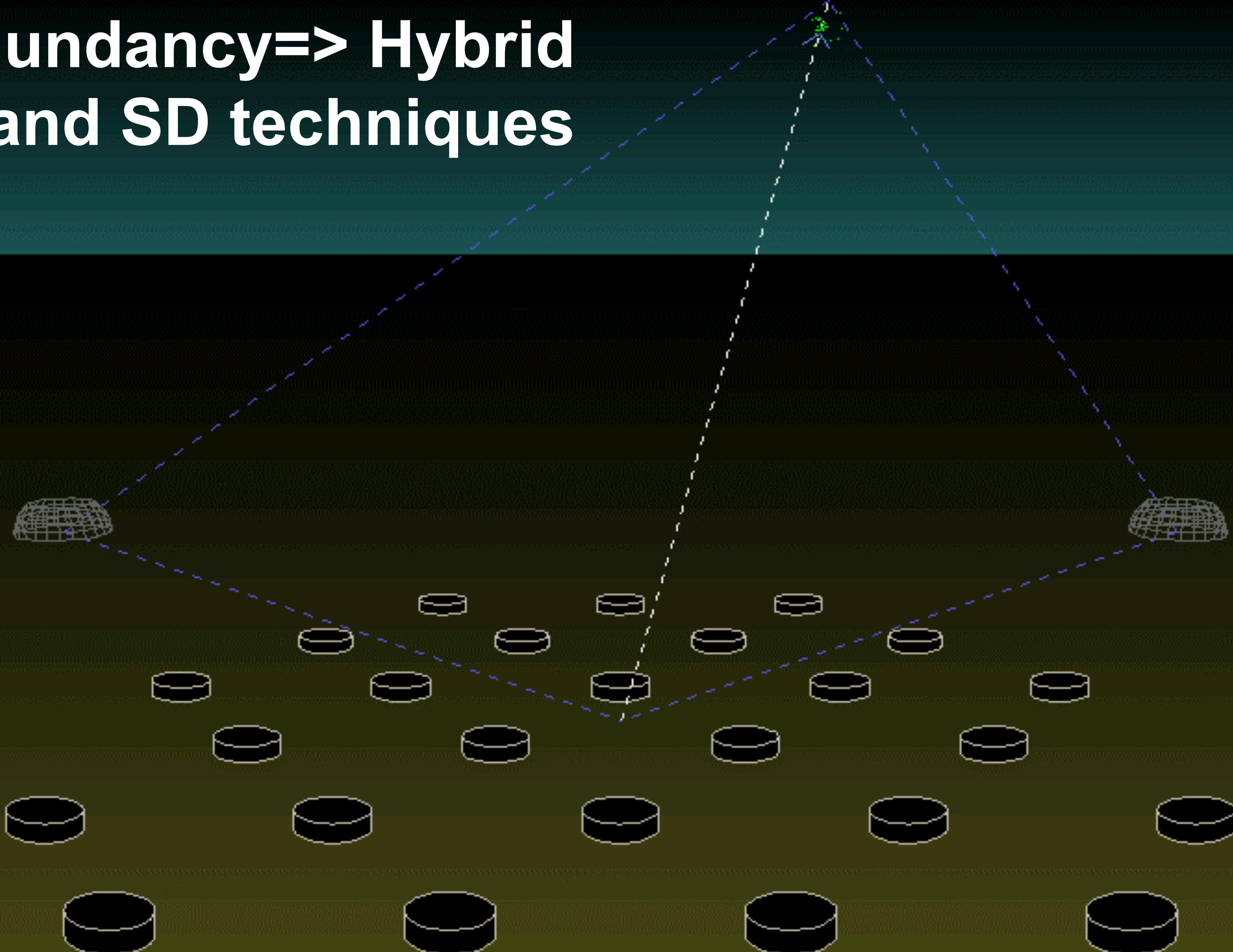
Argentina
Australia
Brasil
Croatia
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
UK
USA
Bolivia*
Romania*
Vietnam*

*Associated

PIERRE AUGER OBSERVATORY



Redundancy=> Hybrid FD and SD techniques



A complex project: Brief Historical Background:

- **1991: Project is conceived and discussed**
- **1994-95 : Design Studies Work in Spain for Auger North**
- **2001-02 : Engineering Array Spain formally joins**
- **2004: Data taking phase starts**
- **2006: Anisotropy prescription**
- **2007: Innauguration**
- **2008 : Completion**
- **2010 : HEAT operational**
- **2011 : AMIGA infill completed, first AERA self trigger and molecular bremsstrahlung tested (GHz): MIDAS, AMBER**
- **2012 : 61 EASIER Microwave antennas deployed**
- **2013 : 124 AERA (+100) Stations running MHz radio array**

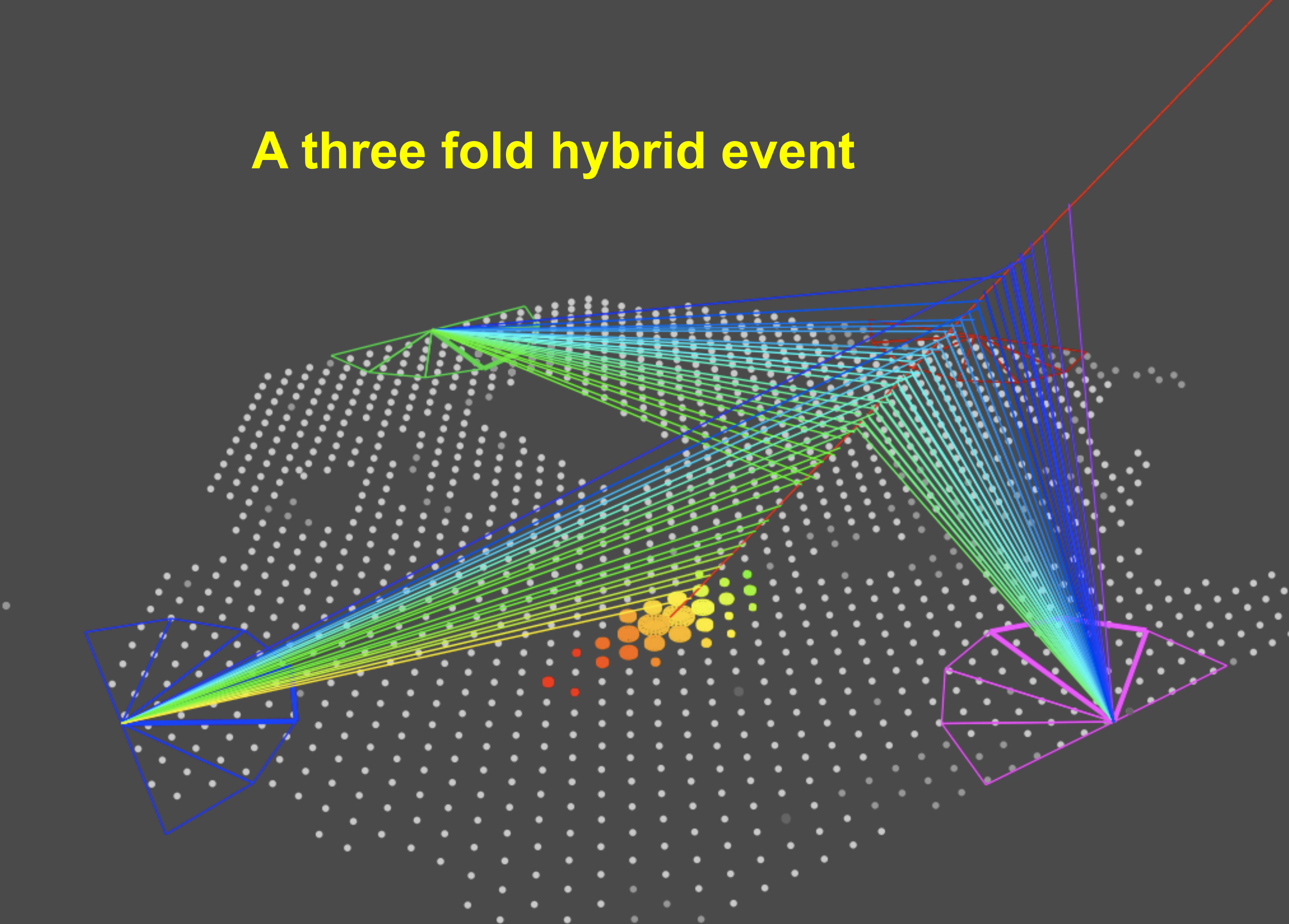
Multiple techniques => Broad range of physics results (incomplete):

- **2007**: Anisotropy of events above 56 EeV
  - Galactic center anisotropy search
  - Photon limits (hybrid data)
- **2008**: Spectrum: suppression compatible with GZK effect
  - Upper limit with earth skimming tau neutrinos
  - **Photon limit (SD data)**
- **2009**: EeV depth of maximum (elongation rate)
  - Hybrid spectrum: feature:ankle
  - Inclined shower spectrum
  - Down going neutrino bound
- **2010**: Depth of maximum (First composition measurements)
- **2011**: Scaler mode: connection with solar physics
  - **Muon content measurements**
  - Muon production depth
  - Infill low energy spectrum
  - AERA: Self trigger radio measurements
  - **Large Scale Anisotropy prescription**
- **2012**: **Proton-air cross section at equivalent pp sqrt(s)=57 TeV**
  - Search for point like neutrino sources
  - Search for neutron sources
  - Blind searches for directional CR sources
- **2013**: **Combined neutrino bound**
  - **Combined spectrum**
  - Directional photon searches

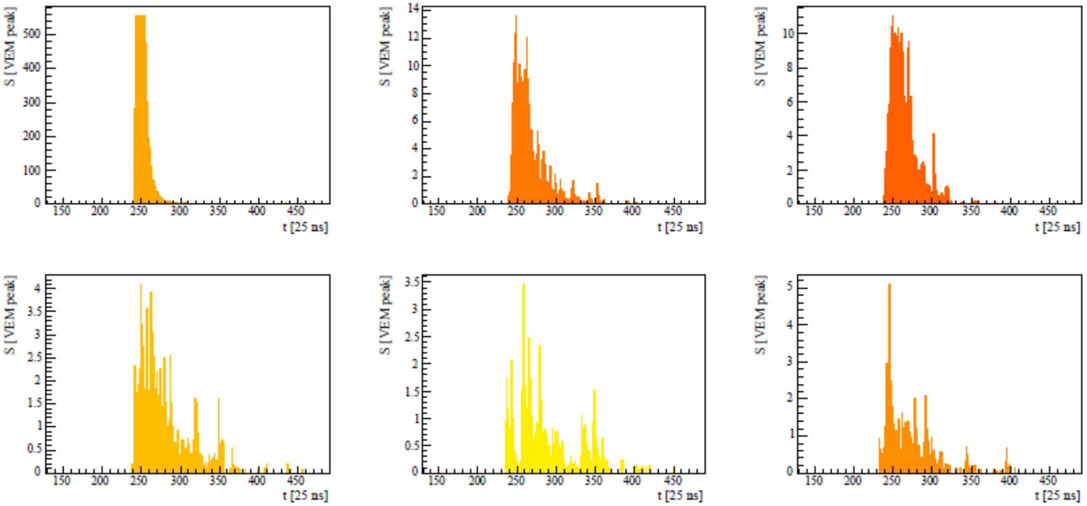
SPECTRUM

- Two ideas (avoid composition and interaction models):
  - Constant Intensty Cut (isotropy to get θ dependence)
  - Hybrid calibration (FD to measure energy)
- Important findings:
  - Suppression consistent with GZK cutoff
  - UUHECR flux/**30!!** Only 1 per 3000 km^2 above 10^{20} eV

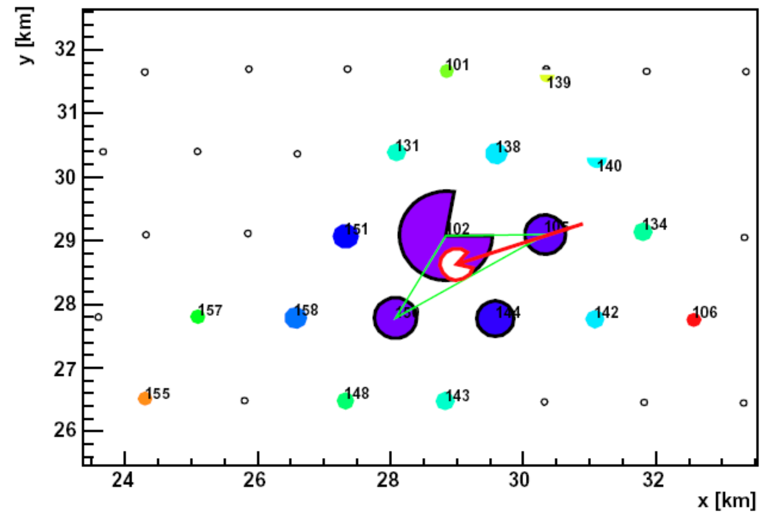
A three fold hybrid event



SD reconstruction: S(1000)



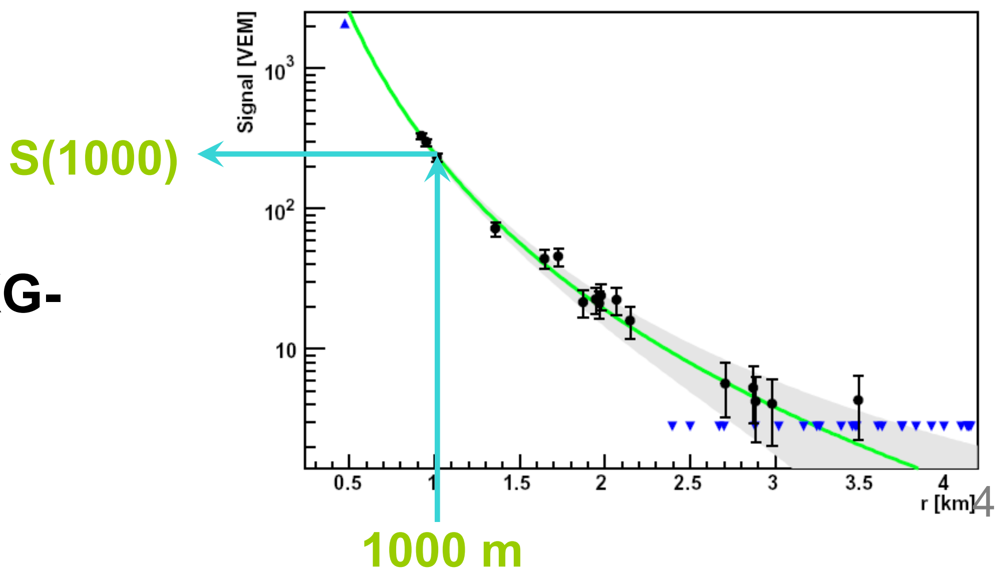
Example Event (48°, E~70 EeV)

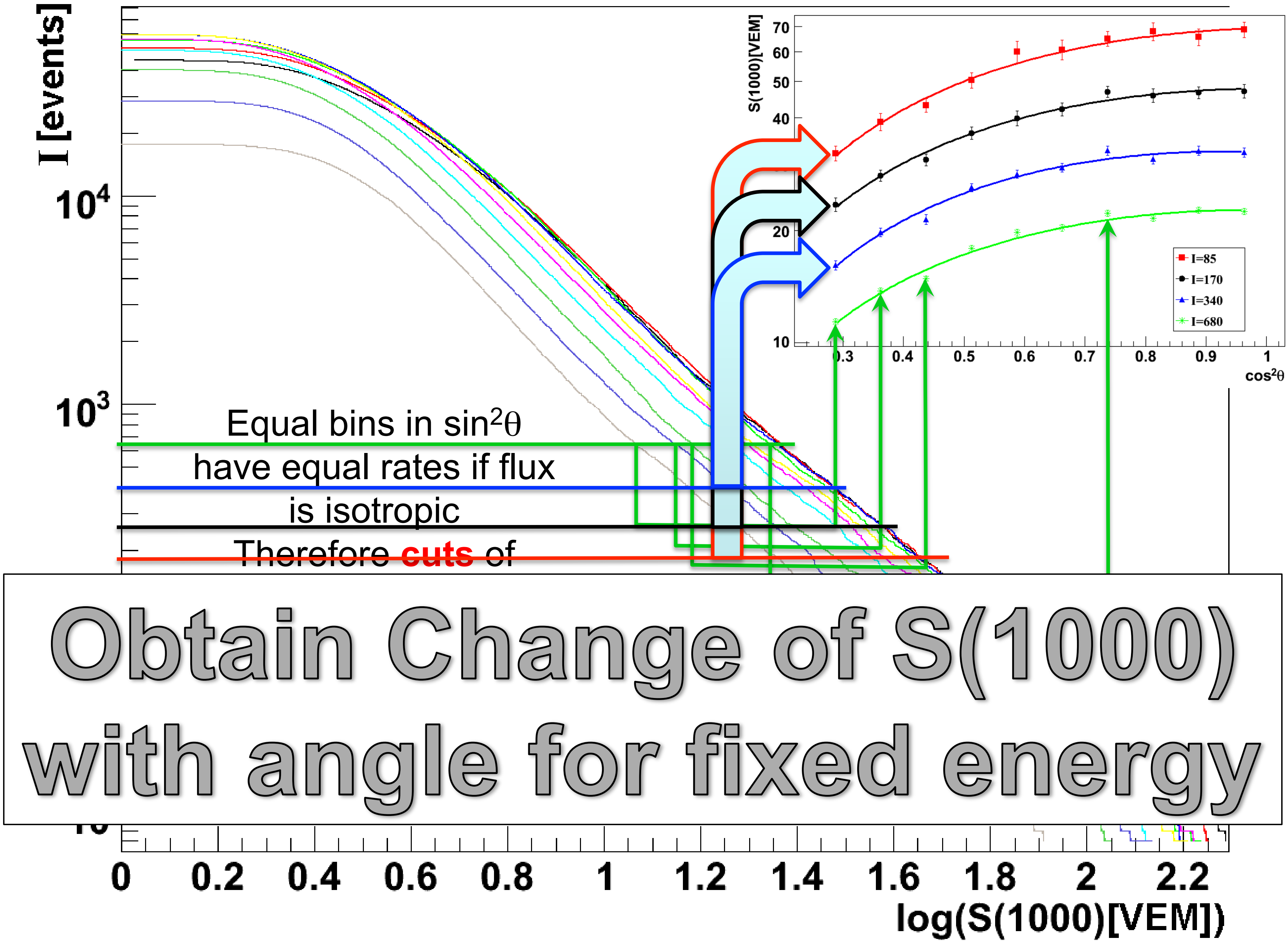


Reconstruction procedure:

- **χ^2-method to fit angles (θ,ϕ)**

- **Likelihood method to fit a NKG-type function, parameters:**
    - **Core position**
    - **S(1000)**

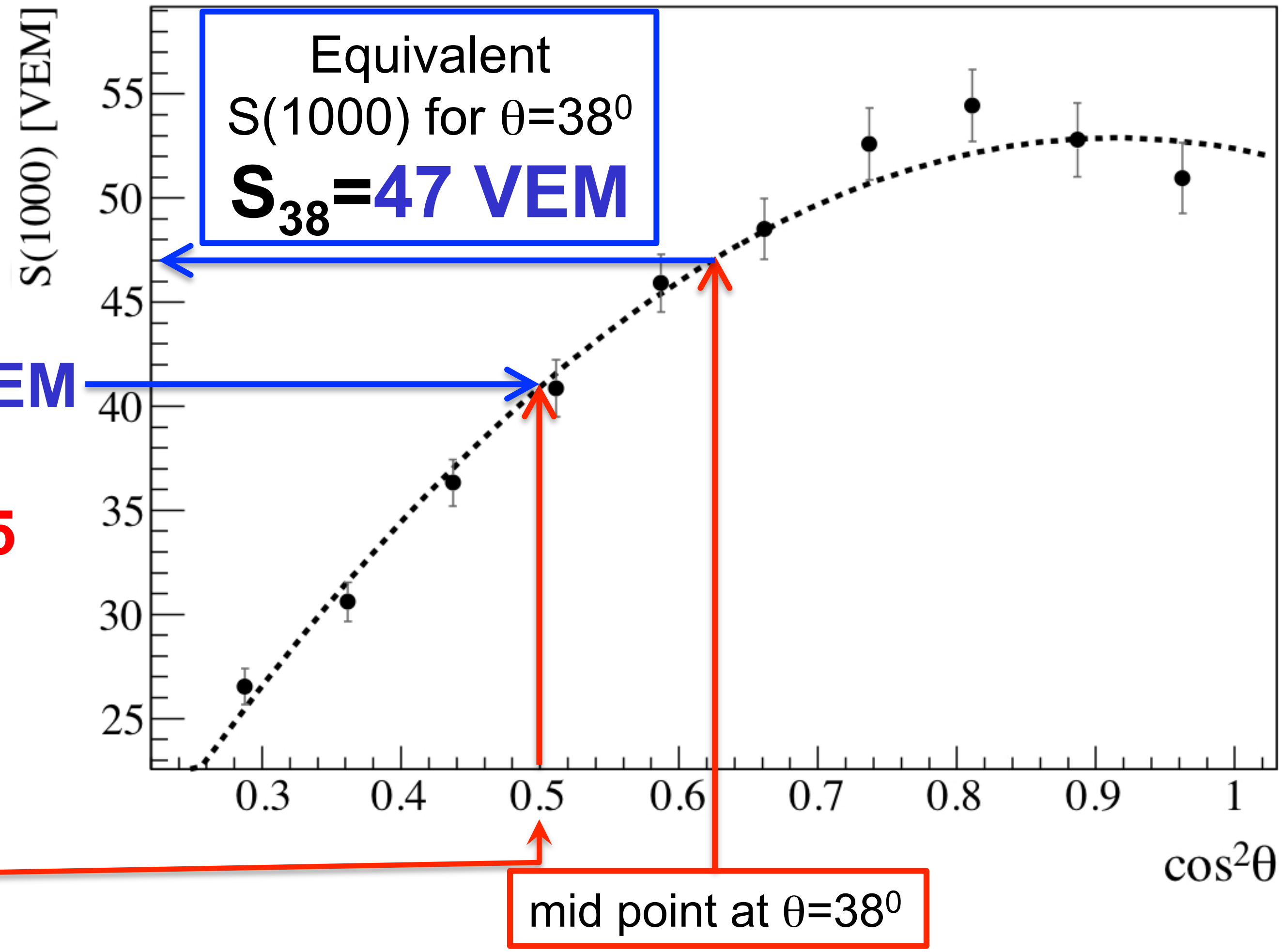




Obtain Change of S(1000) with angle for fixed energy

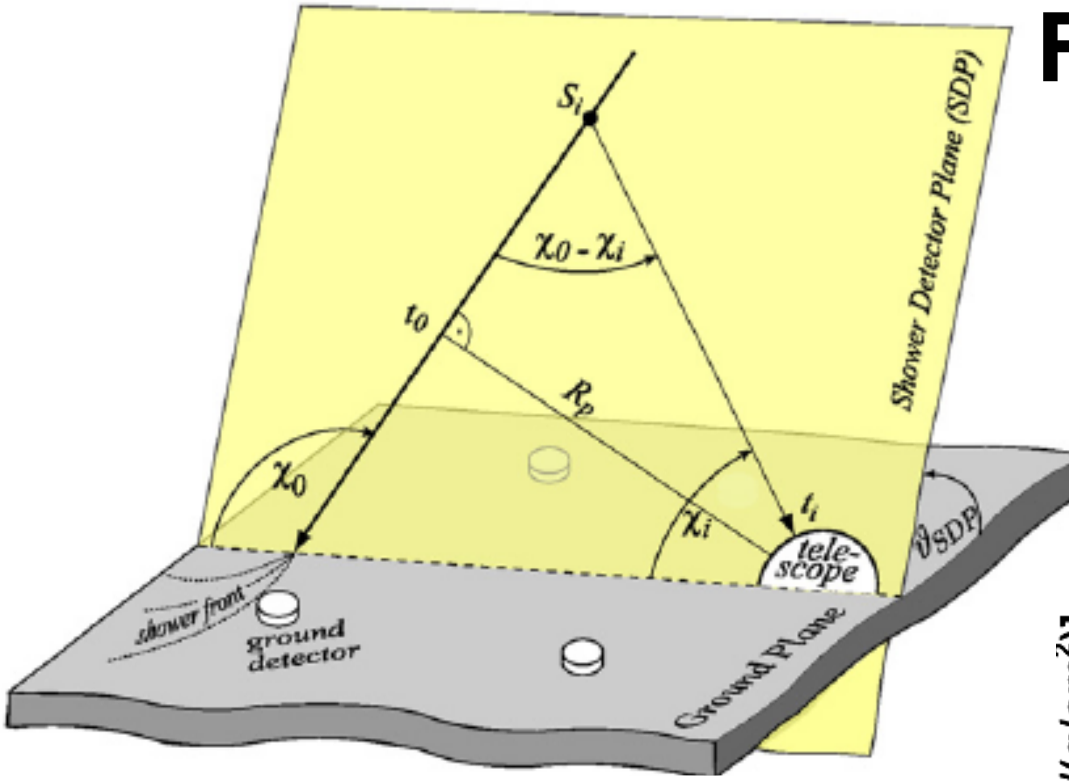
S_{38} as energy estimator

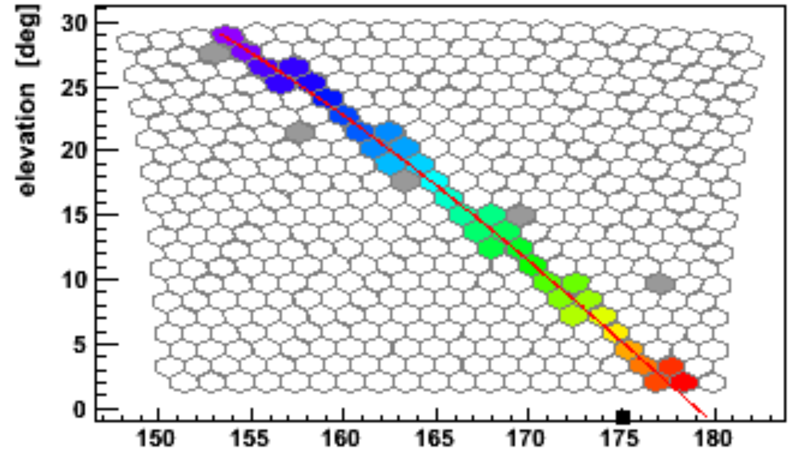
S(1000) = 41 VEM
at θ=45⁰
i.e. cos²θ=0.5

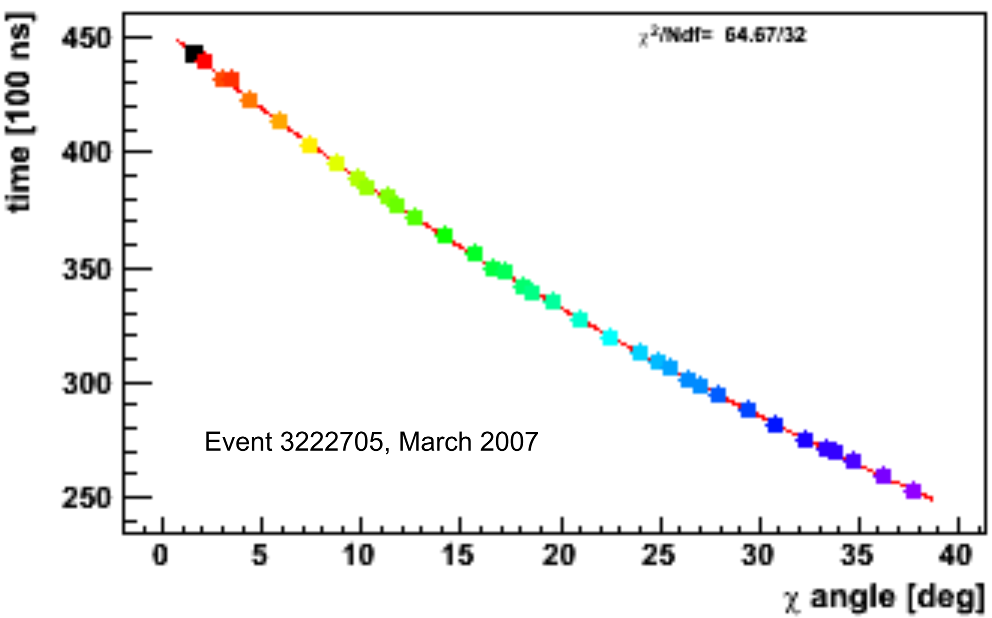


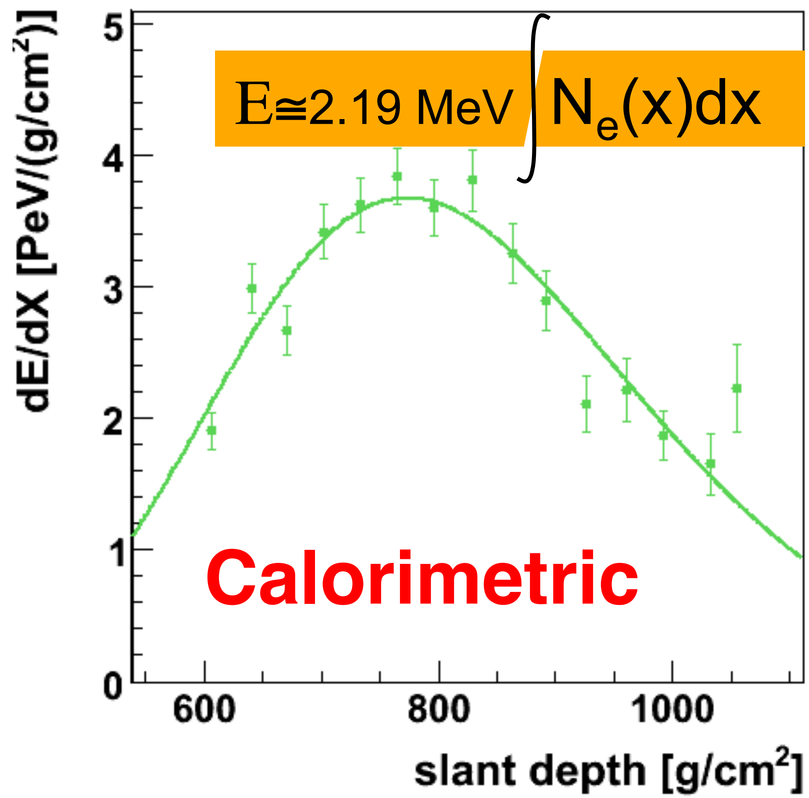
Get corresponding attenuation curve

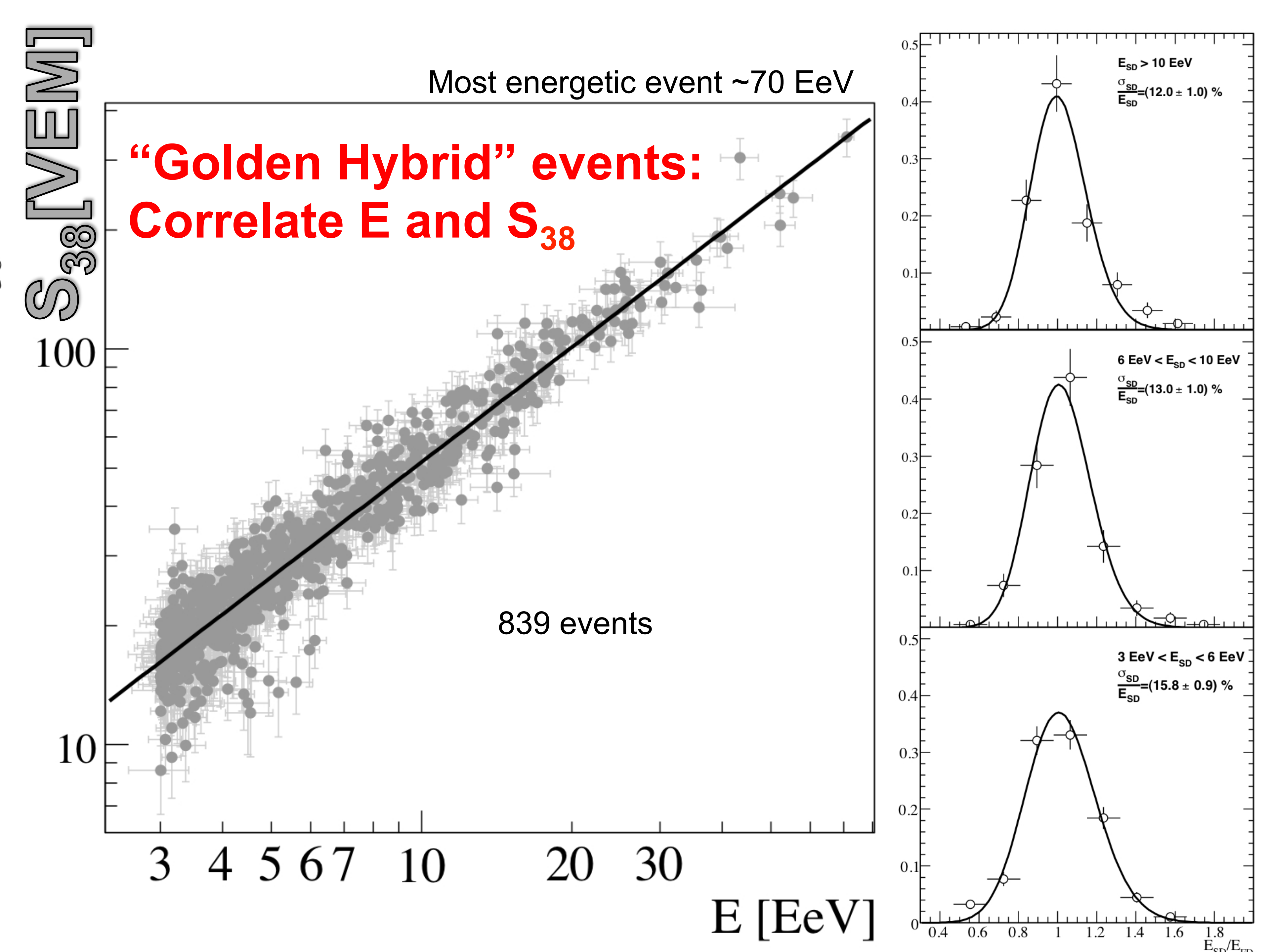
FD reconstruction





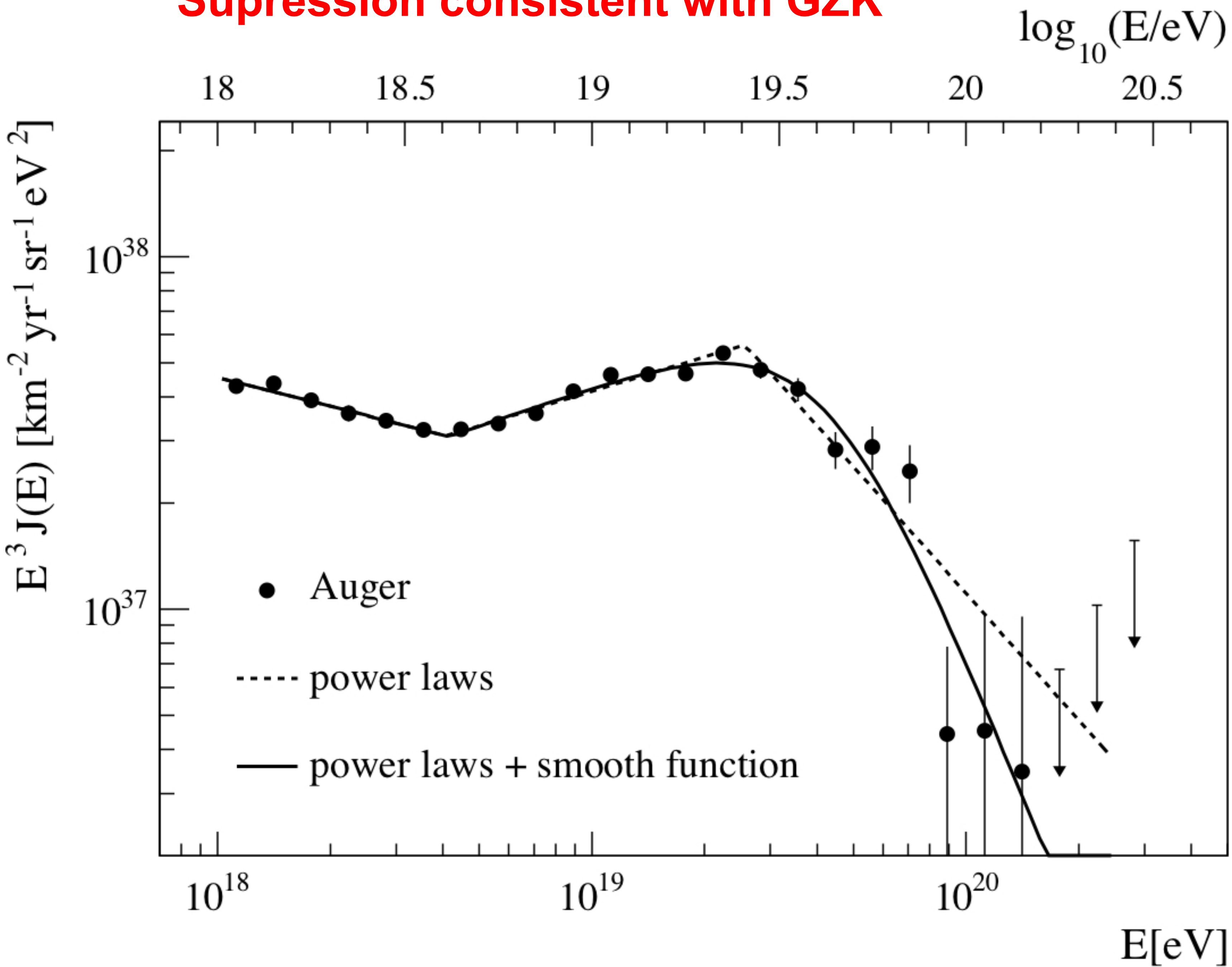






"Golden Hybrid" events:
Correlate E and S_{38}
Most energetic event ~70 EeV
839 events
S_{38} [VEM]
E [EeV]
100
10
3 4 5 6 7 10 20 30
E_{SD} > 10 EeV
$\frac{\sigma_{SD}}{E_{SD}}$=(12.0 ± 1.0) %
6 EeV < E_{SD} < 10 EeV
$\frac{\sigma_{SD}}{E_{SD}}$=(13.0 ± 1.0) %
3 EeV < E_{SD} < 6 EeV
$\frac{\sigma_{SD}}{E_{SD}}$=(15.8 ± 0.9) %
0 0.1 0.2 0.3 0.4 0.5
0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
E_{SD}/E_{FD}

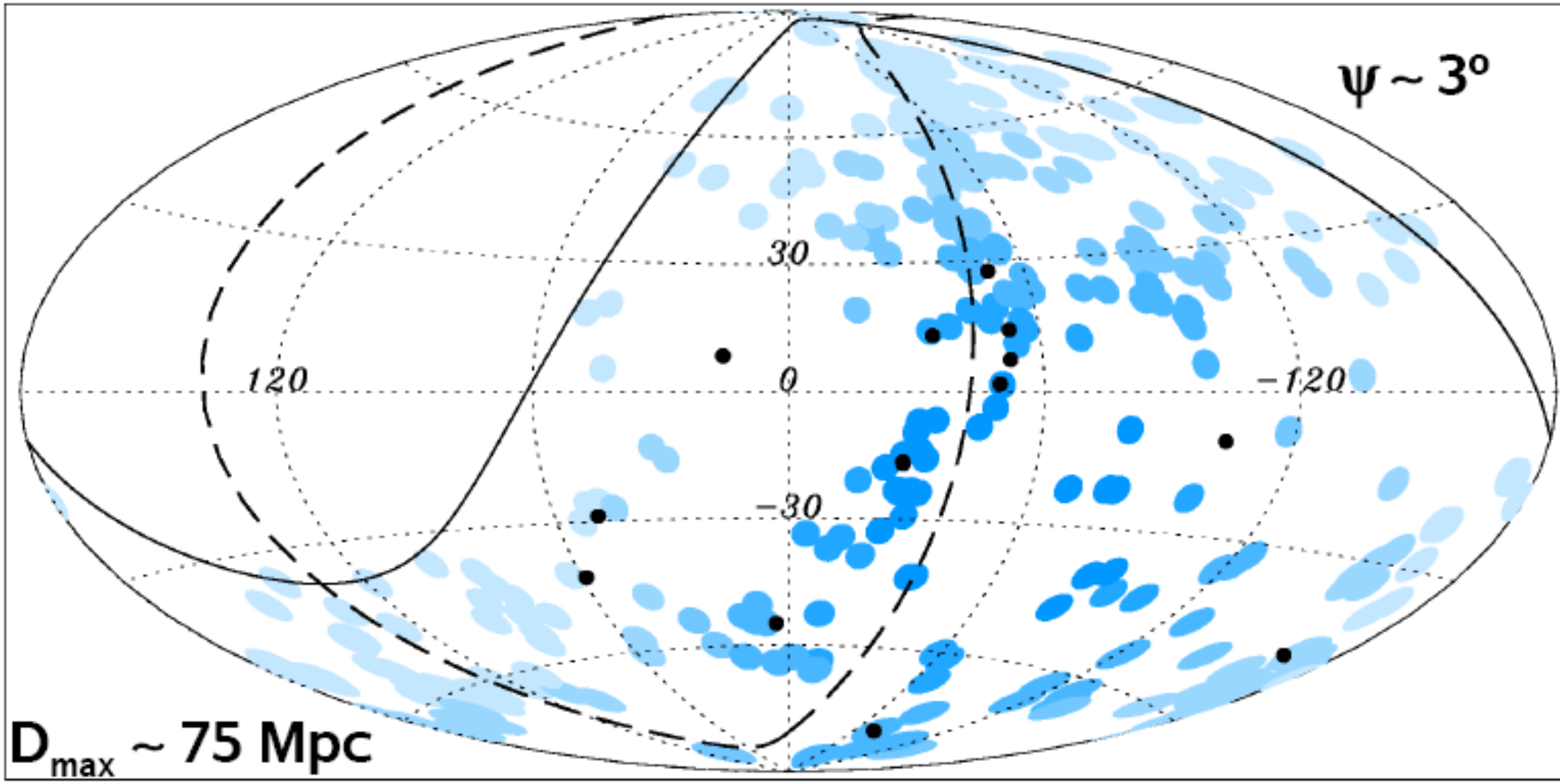
Supression consistent with GZK



Anisotropies

- Aproaches:
  - Correlations with catalogs
  - Autocorrelations
  - Harmonic analysis
- Findings:
  - Weak anisotropy signal at E>56 EeV
  - Bounds on large scale anisotropy
  - Hints of large scale anisotropy (small effect)

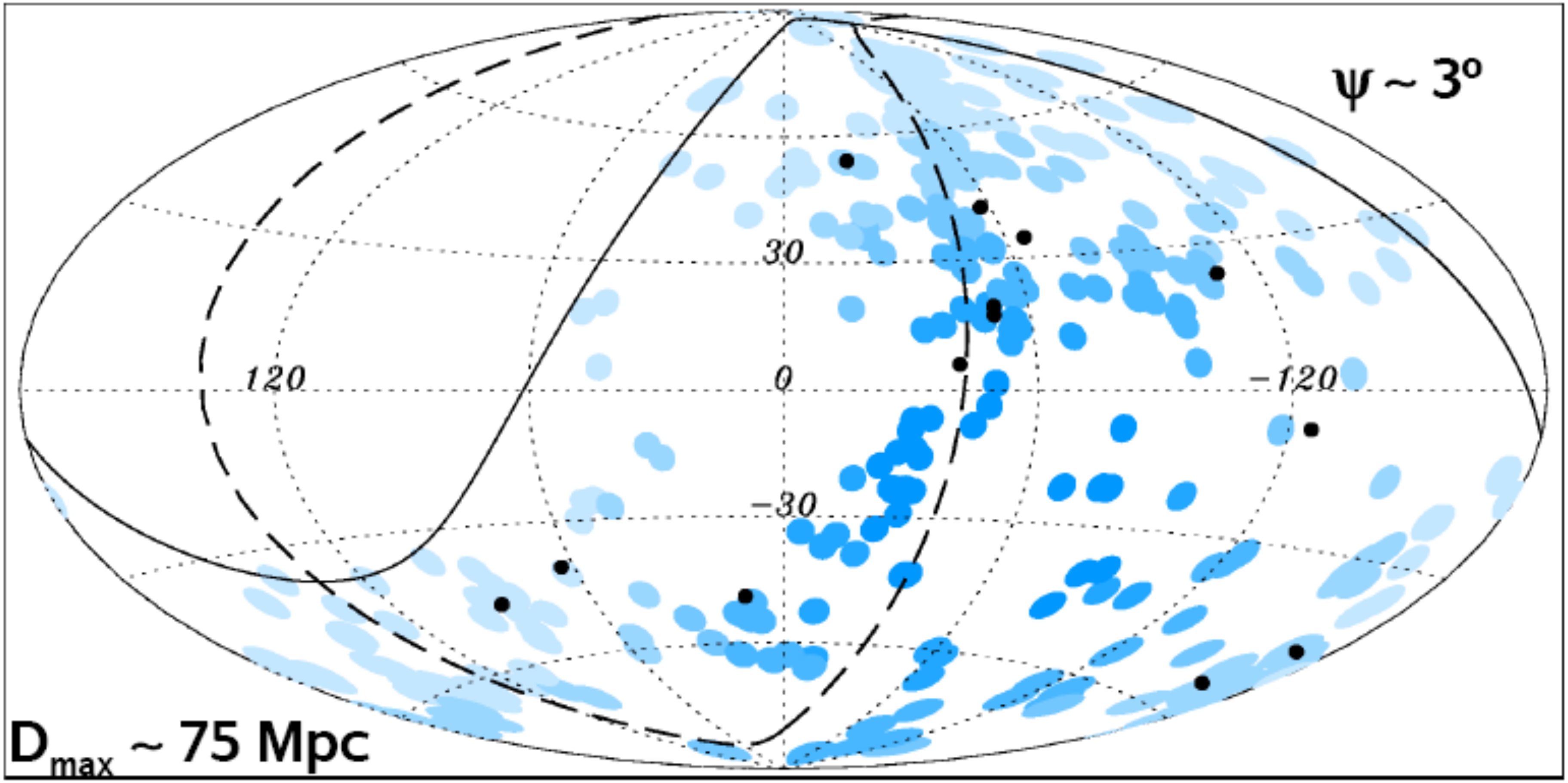
Exploratory scan: data until 27 May 2006



Largest significance for $E_{th} \sim 6\times10^{19}$ eV $\psi \sim 3^o$ $D_{max} \sim 75$ Mpc

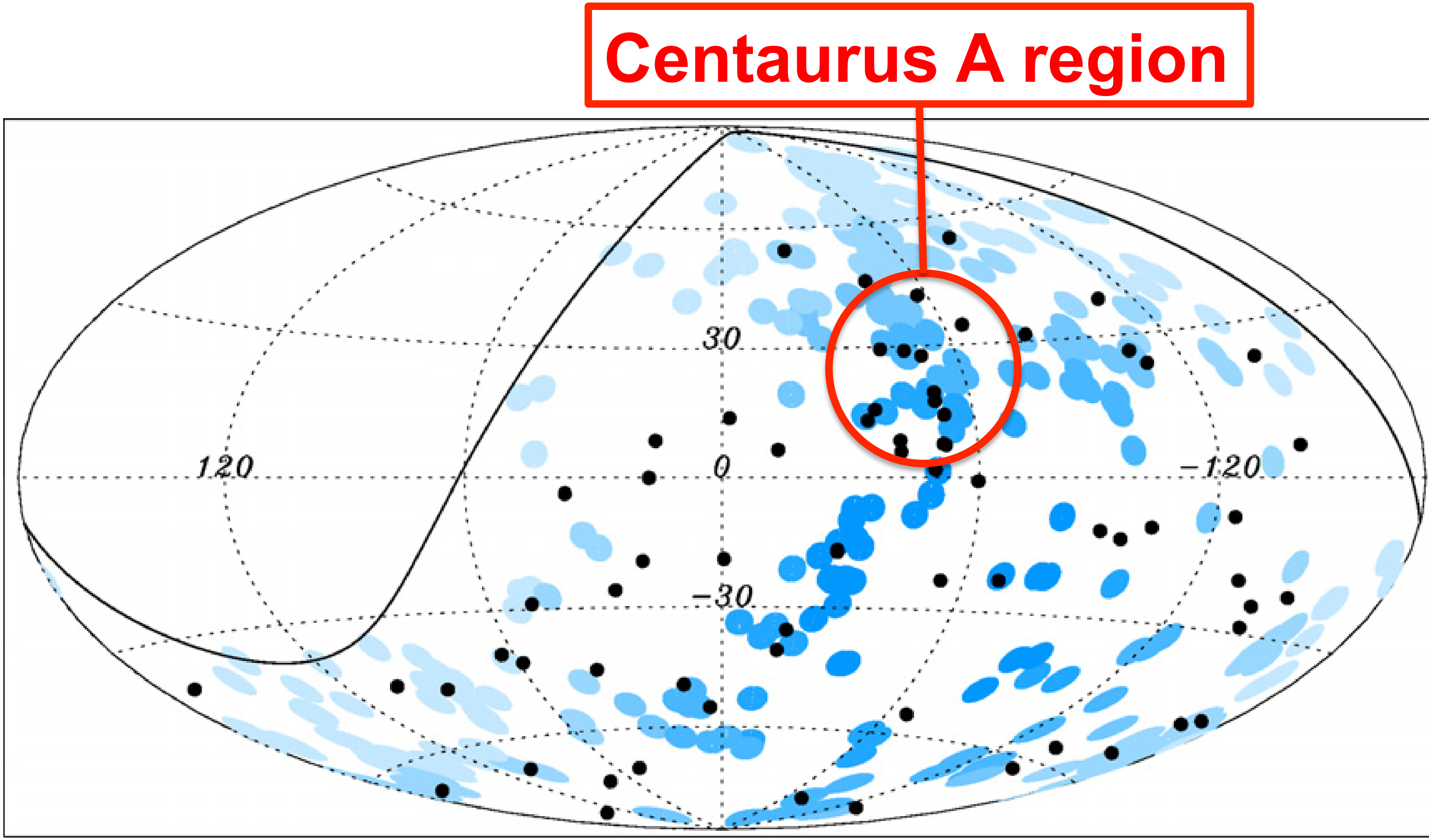
12/15 events close to AGNs in Veron-Cetty Catalogue

Test Using Independent Data Set



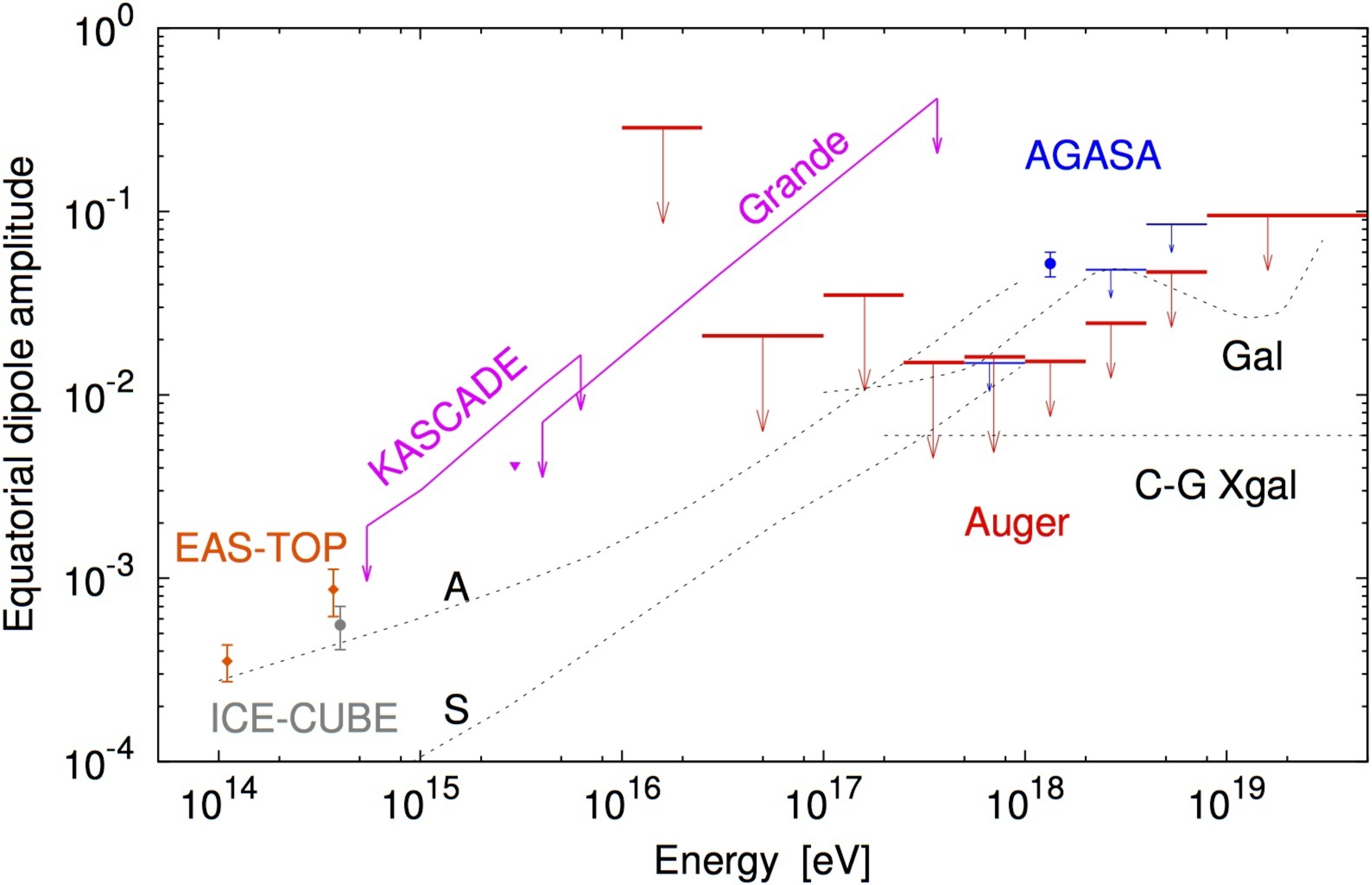
Data from 27 May 2006 until 31 August 2007

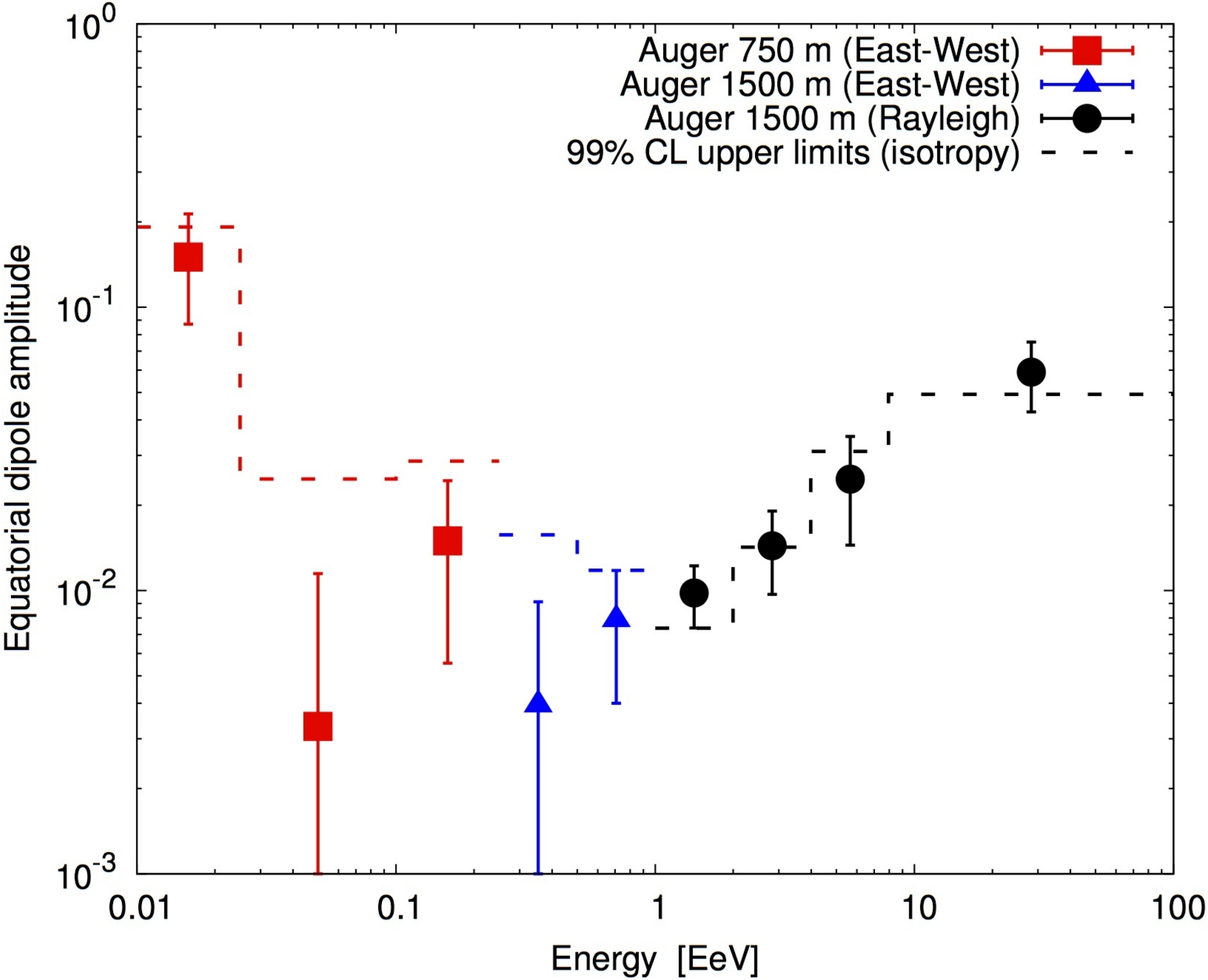
8/13 events lined up as before: chance 1/600

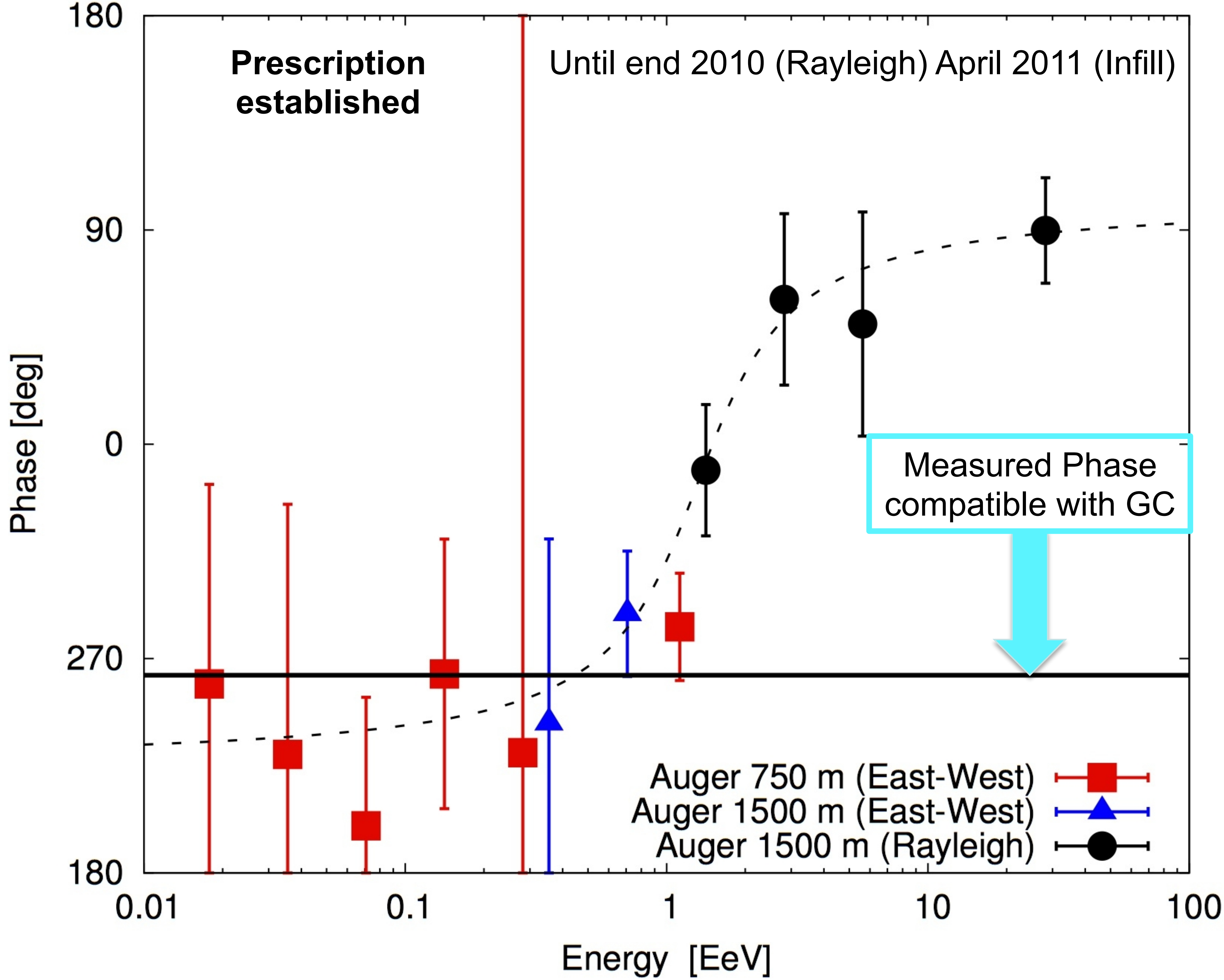


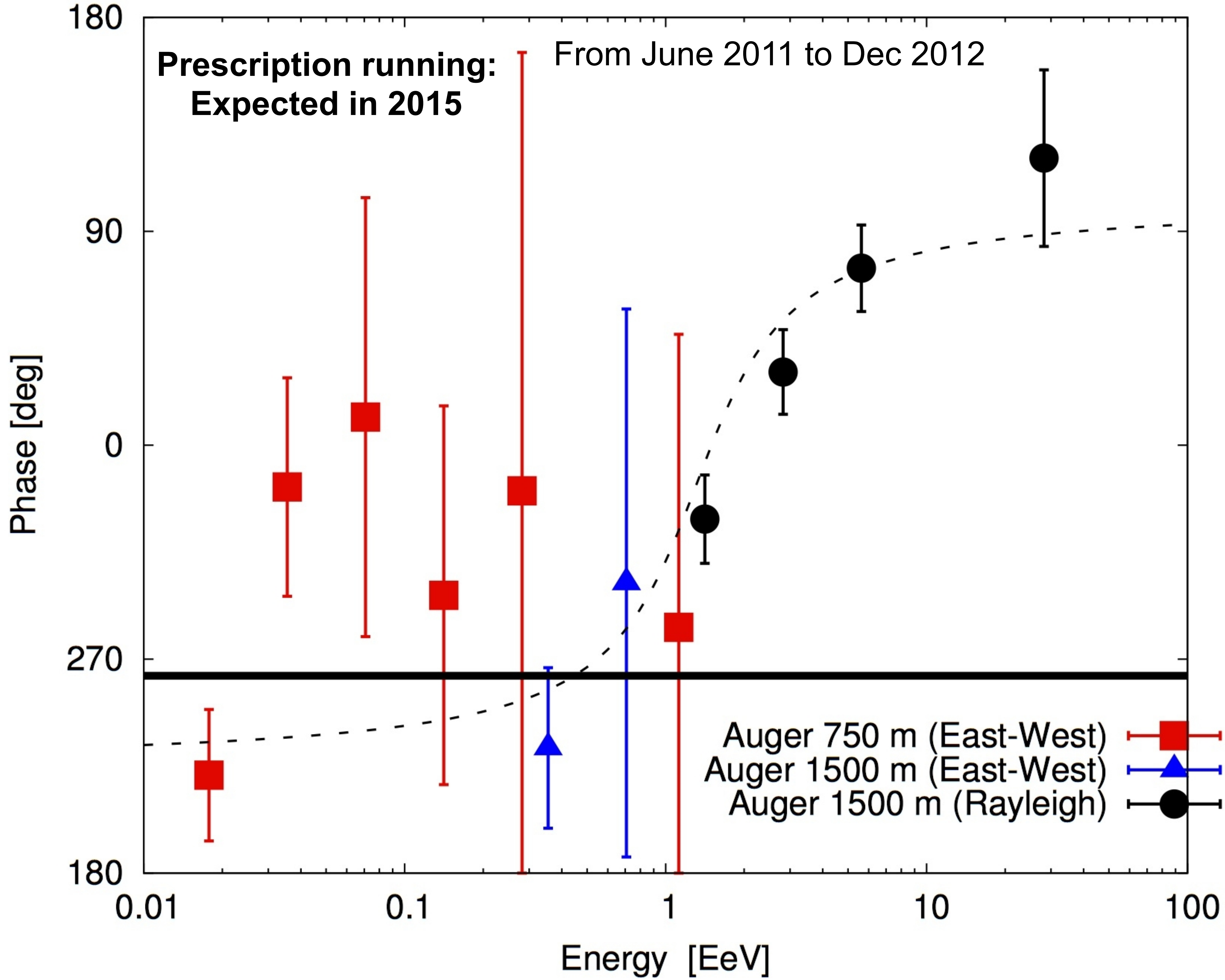
Data until 31 December 2009

Upper limits on the dipole amplitude 99% C.L.



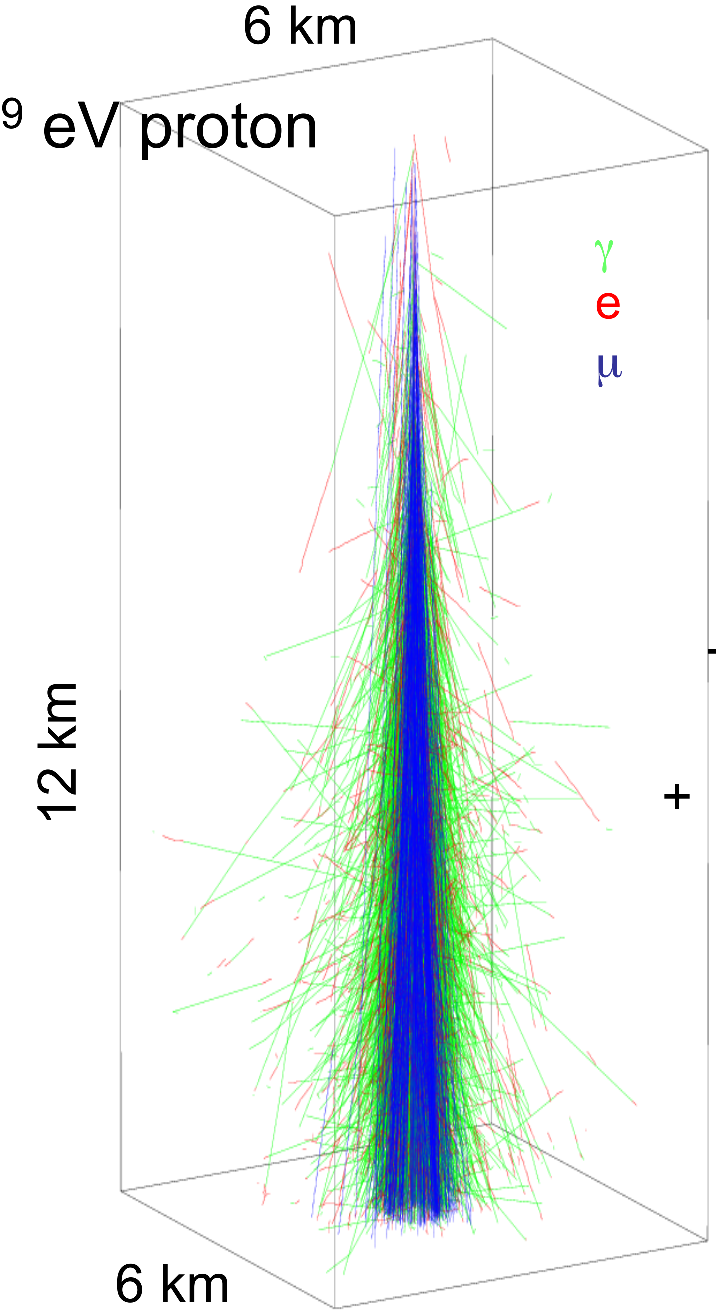

Auger 750 m (East-West)
Auger 1500 m (East-West)
Auger 1500 m (Rayleigh)
99% CL upper limits (isotropy)
Equatorial dipole amplitude
Energy [EeV]
10^{0}
10^{-1}
10^{-2}
10^{-3}
0.01
0.1
1
10
100


Prescription established
Until end 2010 (Rayleigh) April 2011 (Infill)
Measured Phase compatible with GC
Phase [deg]
Energy [EeV]
180
90
0
270
180
0.01
0.1
1
10
100
Auger 750 m (East-West)
Auger 1500 m (East-West)
Auger 1500 m (Rayleigh)


Prescription running:
Expected in 2015
From June 2011 to Dec 2012
180
90
0
270
180
Phase [deg]
0.01
0.1
1
10
100
Energy [EeV]
Auger 750 m (East-West)
Auger 1500 m (East-West)
Auger 1500 m (Rayleigh)

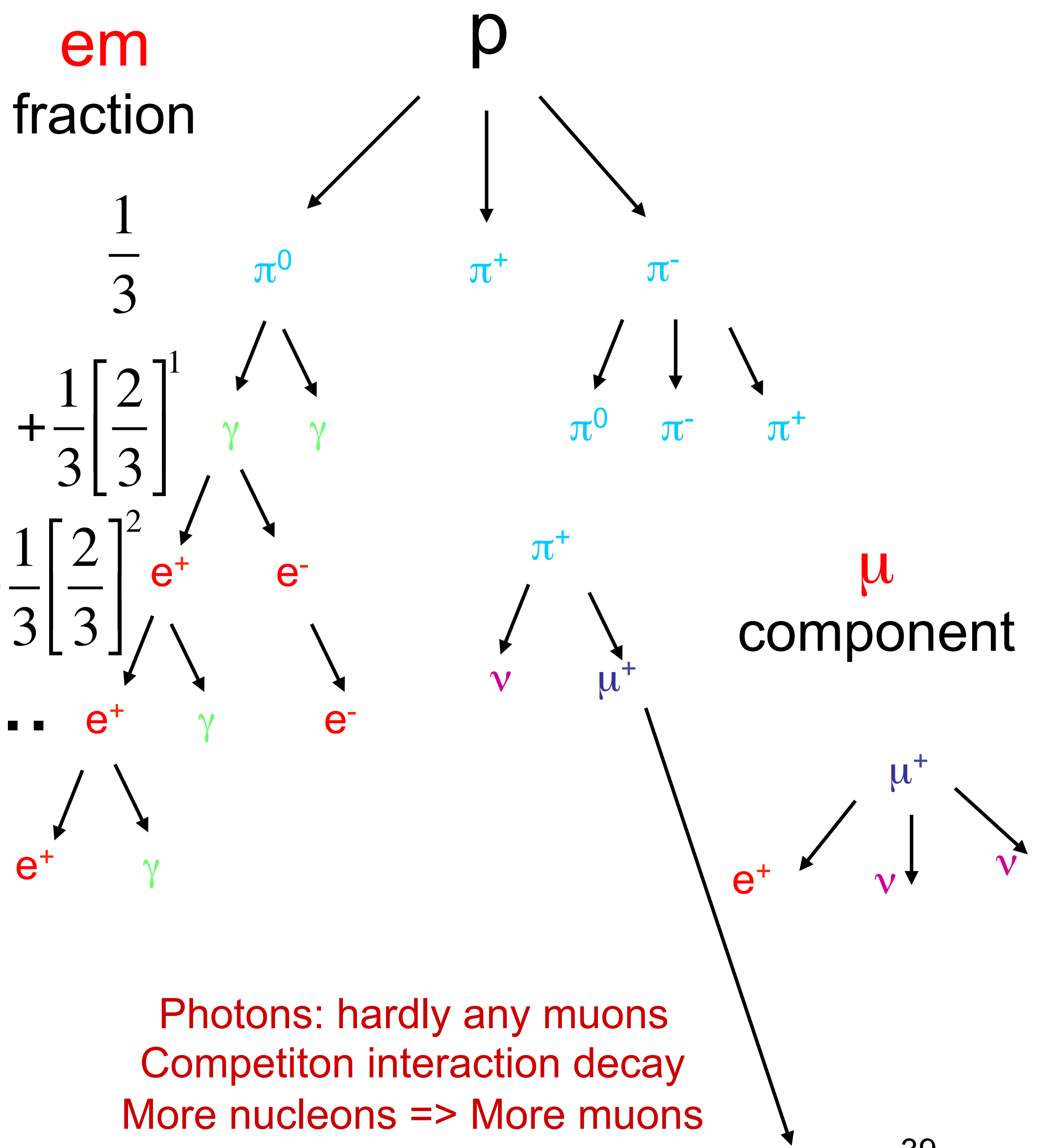
Digression : More on showers

- Depth of Maximum, X_{max}
  - Photons
  - Nuclear masses
  - Neutrinos (not directly used)
- Muons
  - Composition sensitivity
  - Inclined showers: more redundancy (&neutrino search)
  - New ideas



em fraction

$$\frac{1}{3} + \frac{1}{3}\left[\frac{2}{3}\right]^1 + \frac{1}{3}\left[\frac{2}{3}\right]^2 + \dots$$



μ component

Photons: hardly any muons
Competiton interaction decay
More nucleons => More muons

Measurements of X_{max}

Extend Heitler analysis for a proton shower:

$$\boxed{X_{\max} \approx \lambda_p + X_0 \ln\left[\frac{k_{in}E}{2N\varepsilon_c}\right]}$$

N=multiplicity; k_{in}=*inelasticity*; 2 photons per π^0

For a shower induced by a nucleus of mass *A* (superposition):

$$\boxed{X_{\max} \approx \lambda_p + X_0 \ln\left[\frac{k_{in}E}{2AN\varepsilon_c}\right]}$$

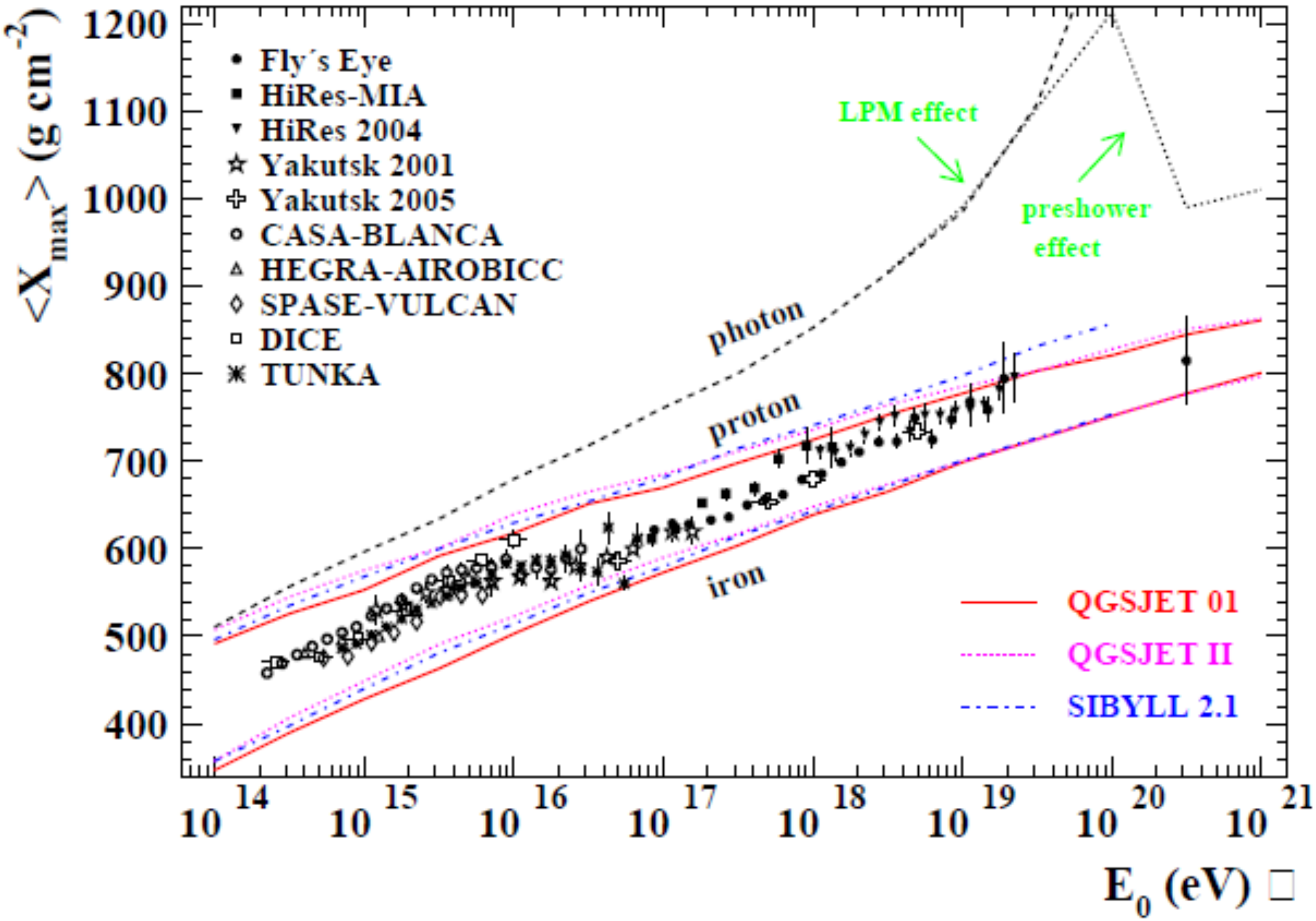
RMS(X_{max})also decreases with A

Detailed simulations confirm this

A given model gives ln(A) from X_{max} & σ^2[ln(A)] from RMS(X_{max})

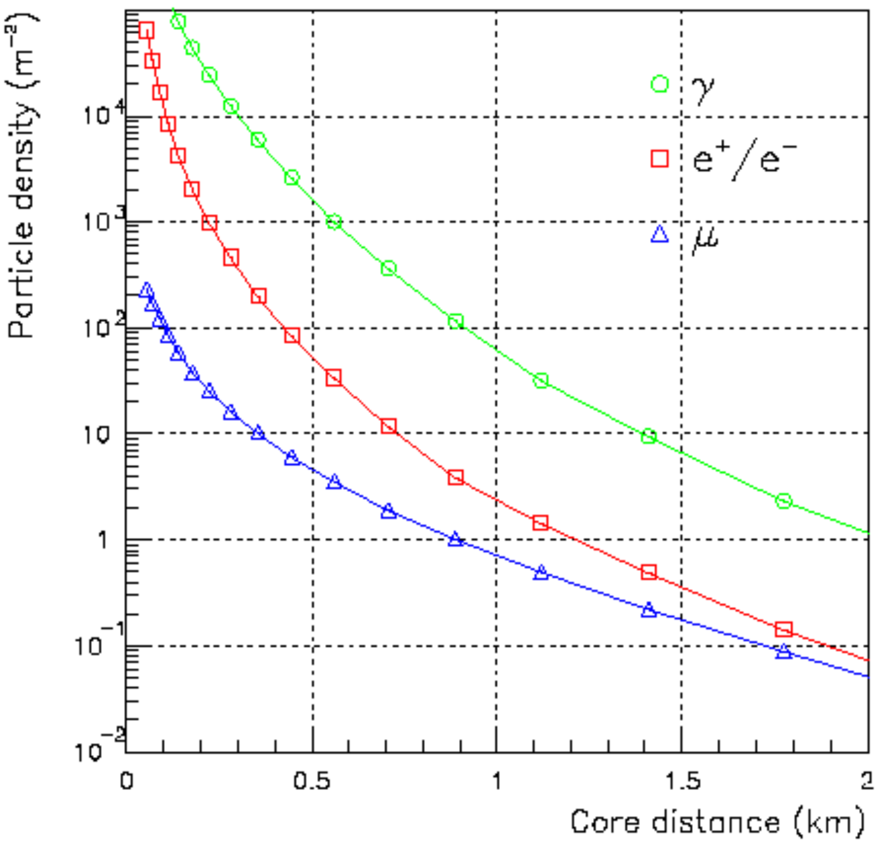
X_{max}: compare to models

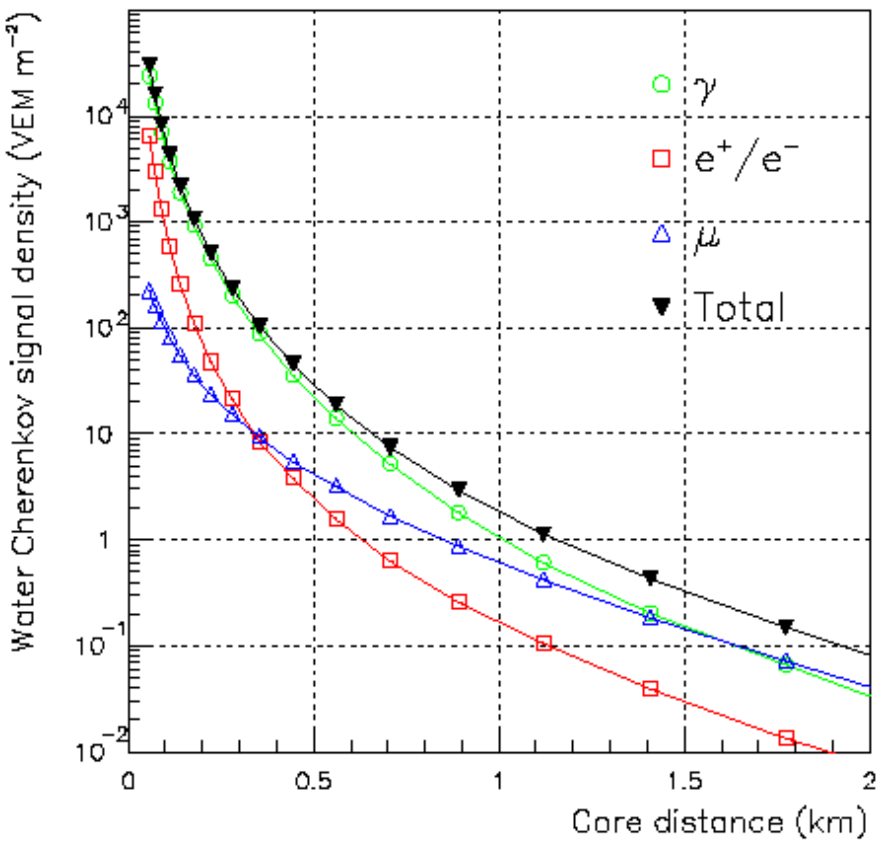
P. Homola for the Auger Collab., ICRC 2009



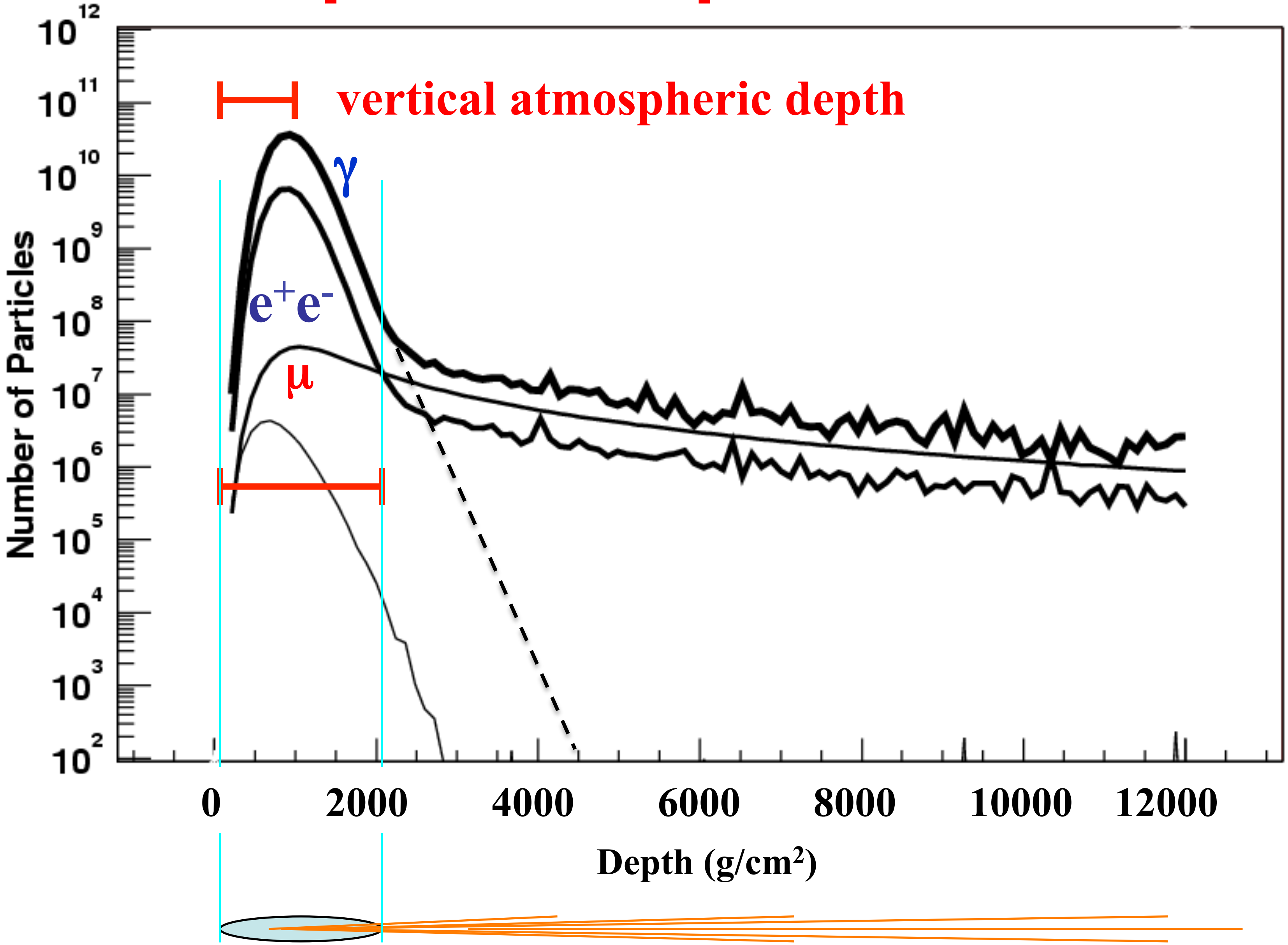
γ-induced showers reach maximum deeper in the atmosphere than nucleonic ones

Particle distribution (vertical)

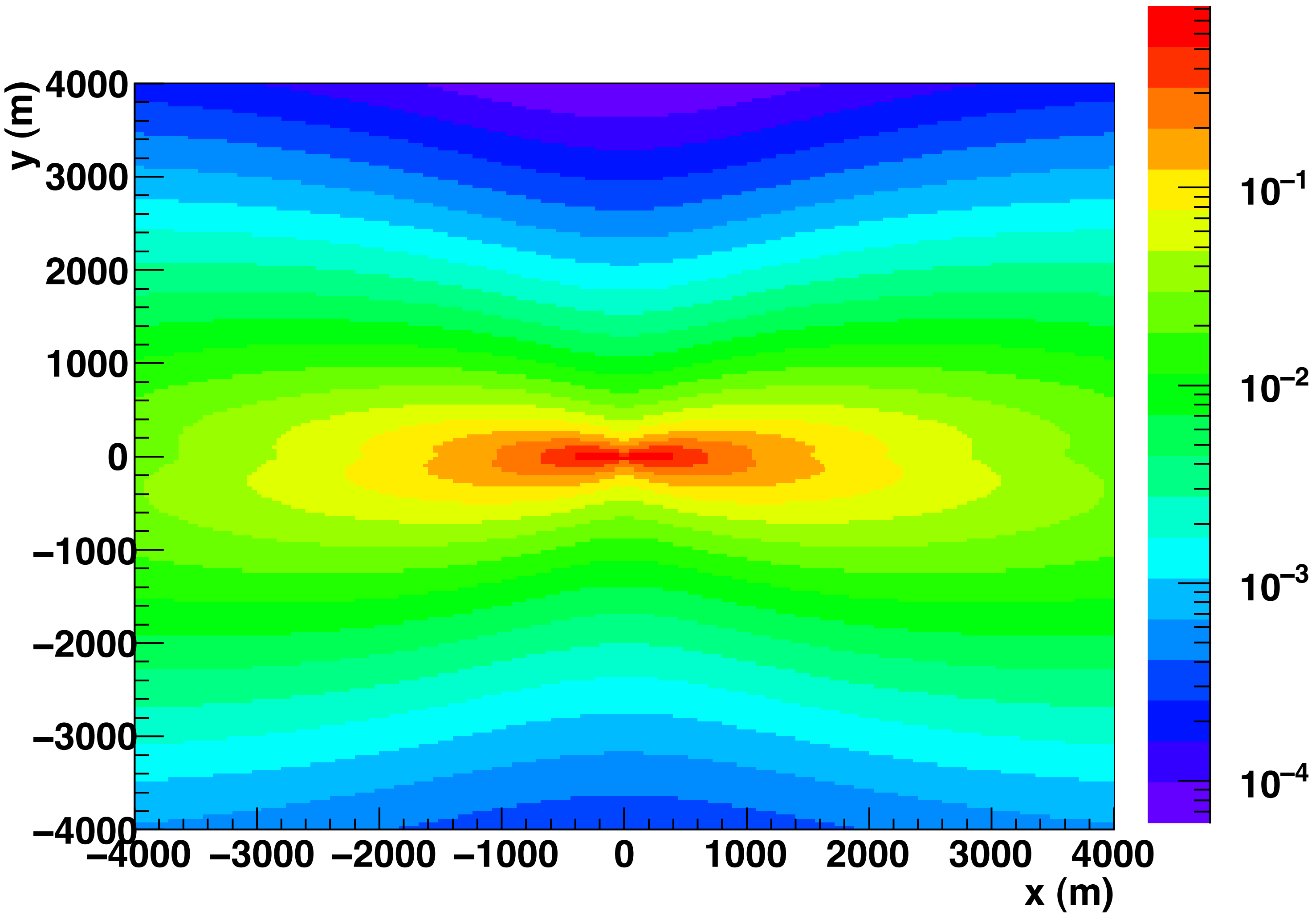


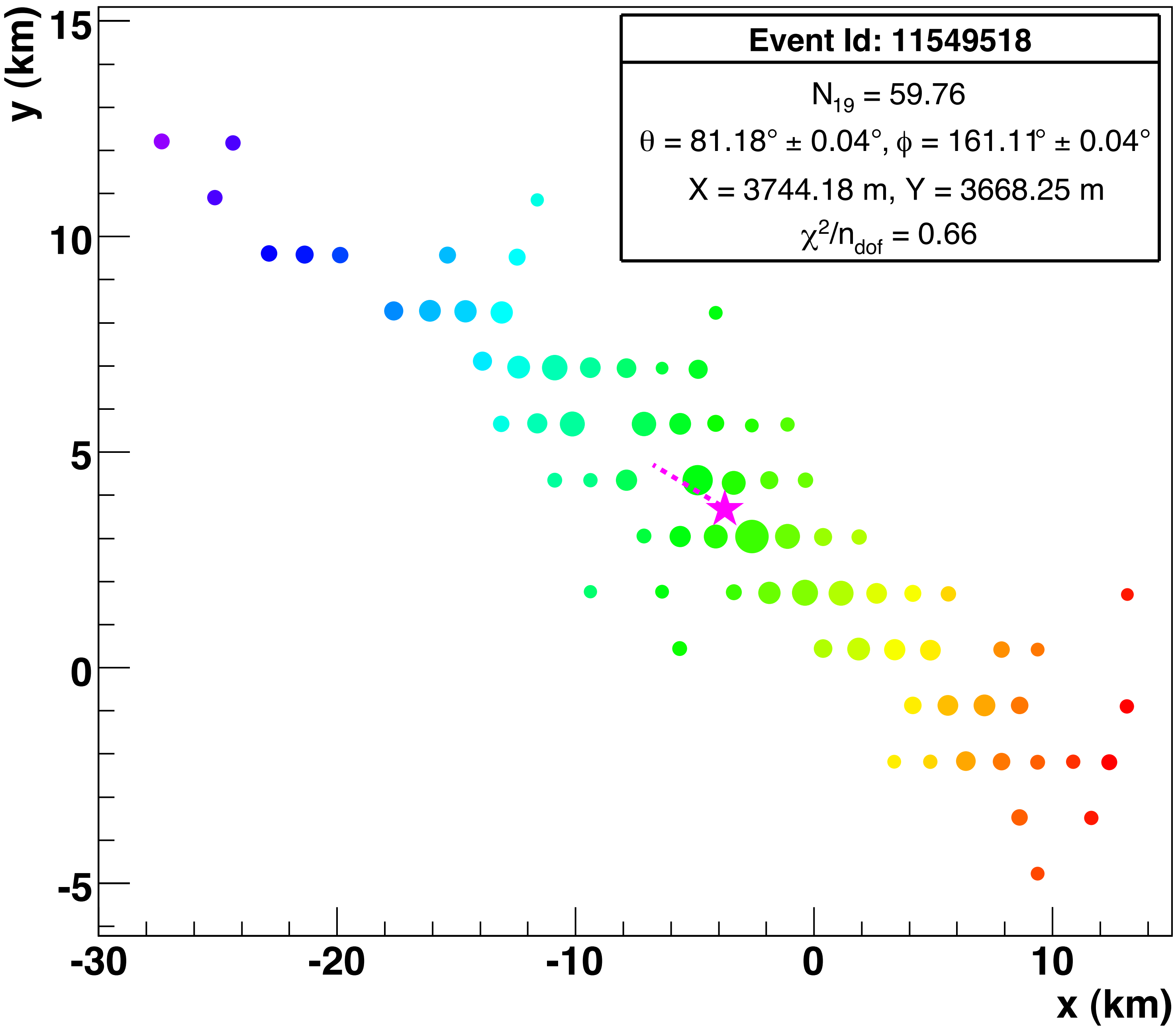


Development of proton showers



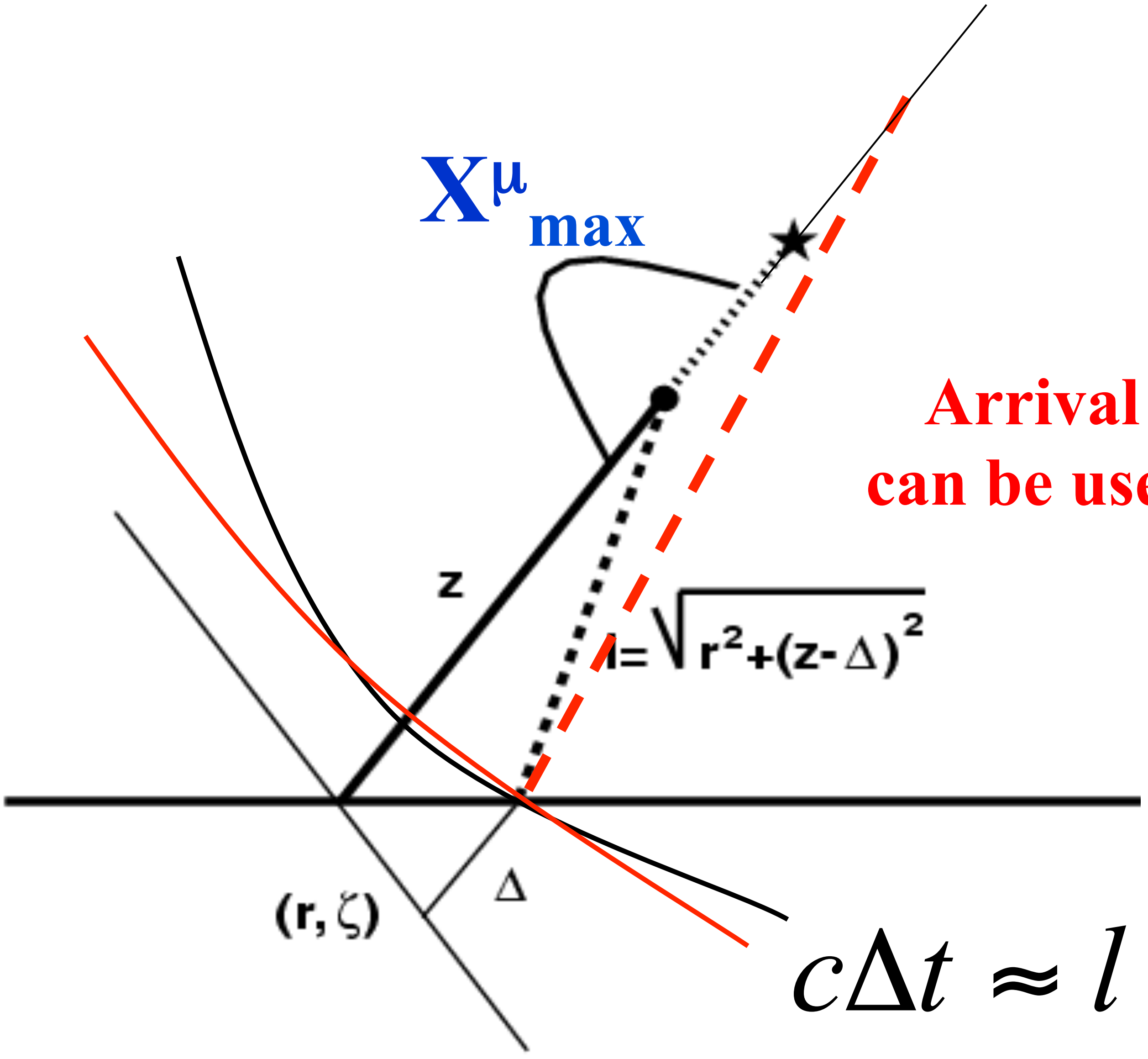
Muon distribution (inclined)





Event Id: 11549518
N19 = 59.76
θ = 81.18° ± 0.04°, φ = 161.11° ± 0.04°
X = 3744.18 m, Y = 3668.25 m
χ2/ndof = 0.66
y (km)
x (km)
15
10
5
0
-5
-30
-20
-10
0
10

New observable X^{μ}_{max} related to time



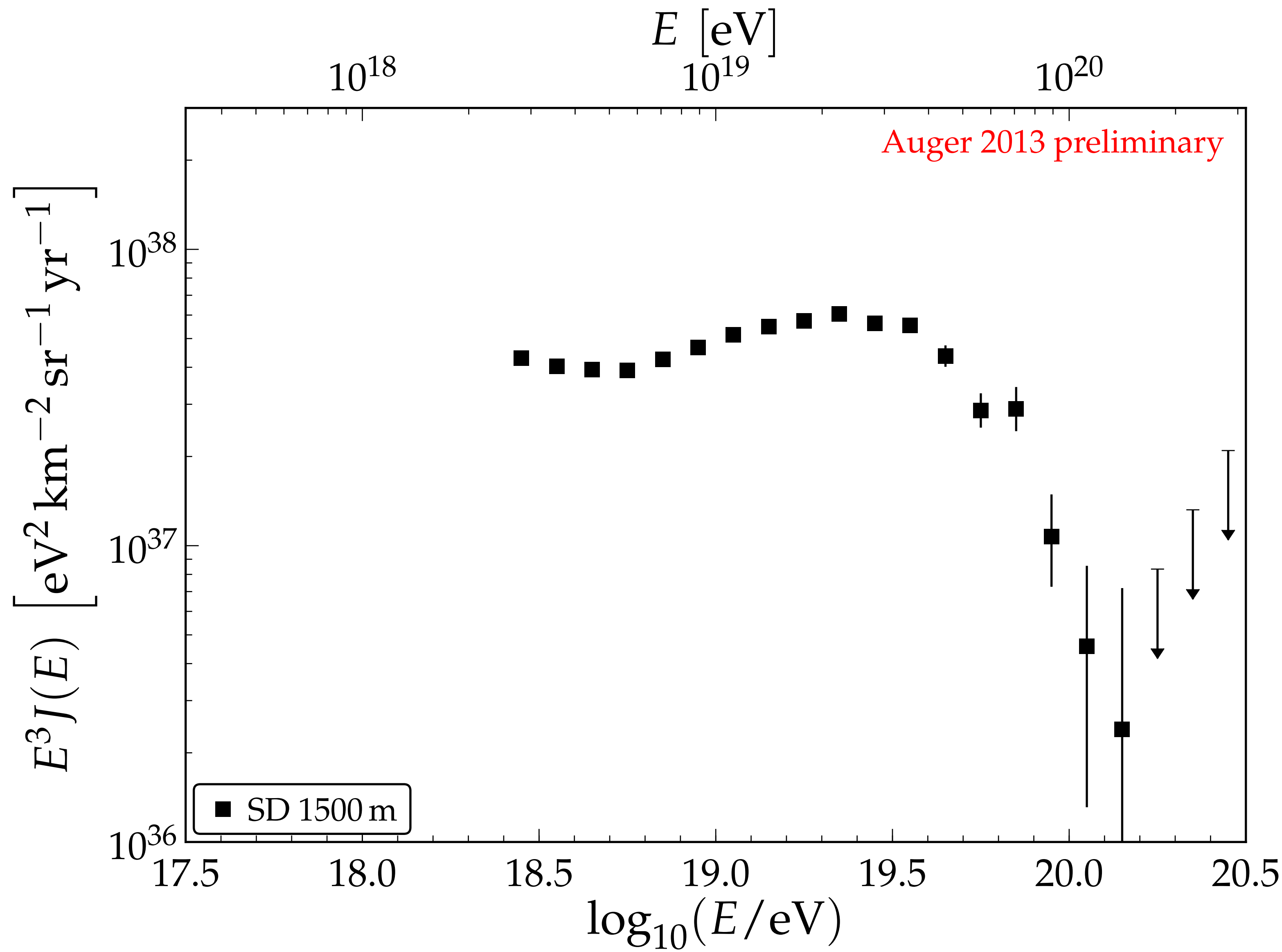
Arrival times of muons can be used to obtain X^{μ}_{max}

$$c\Delta t \approx l - z \approx \frac{1}{2}\frac{r^2}{z^2}$$

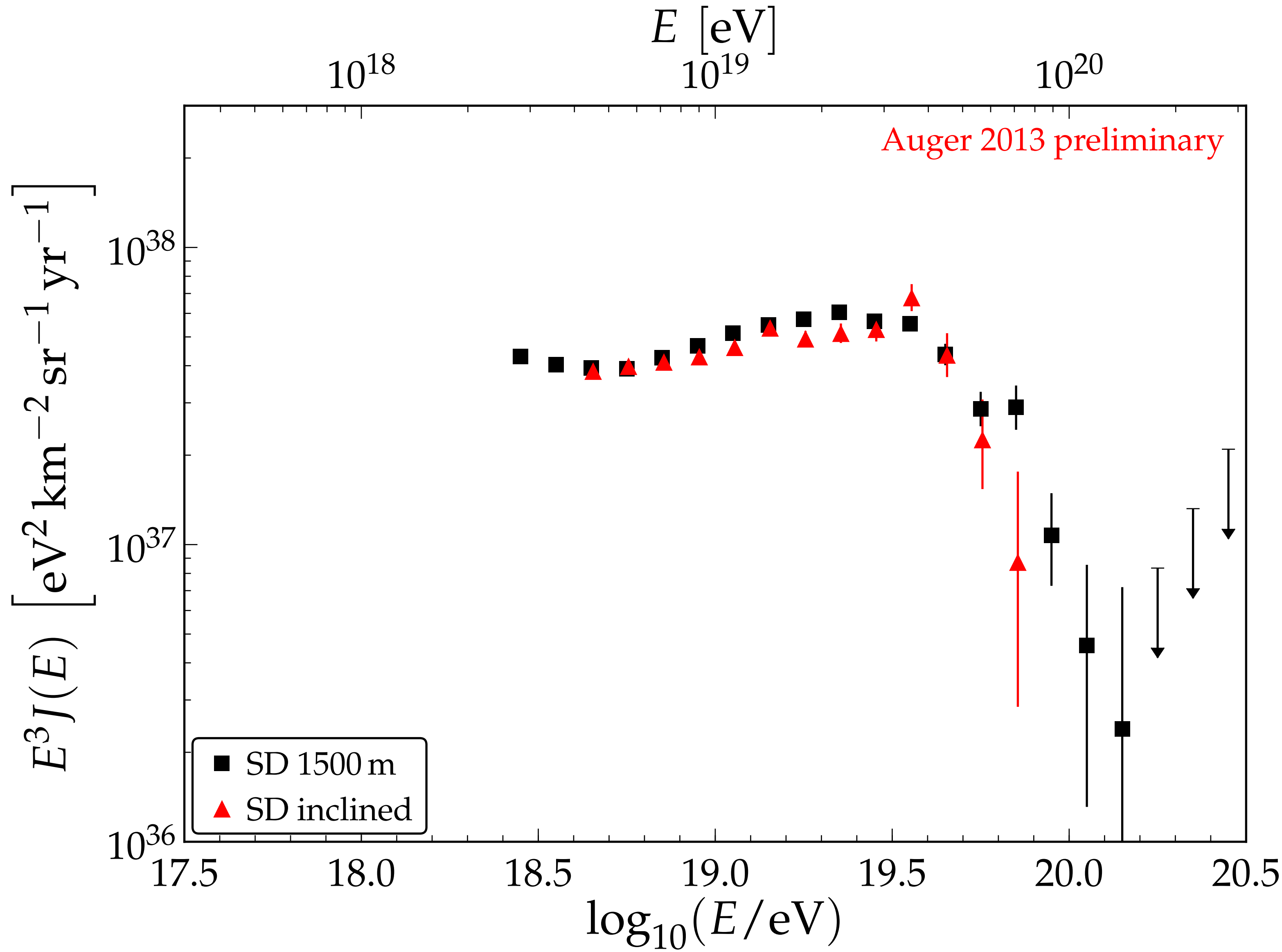
L C, RAV, AAW, EZ (Ap Phys 2004, 2005)

Combined Spectrum

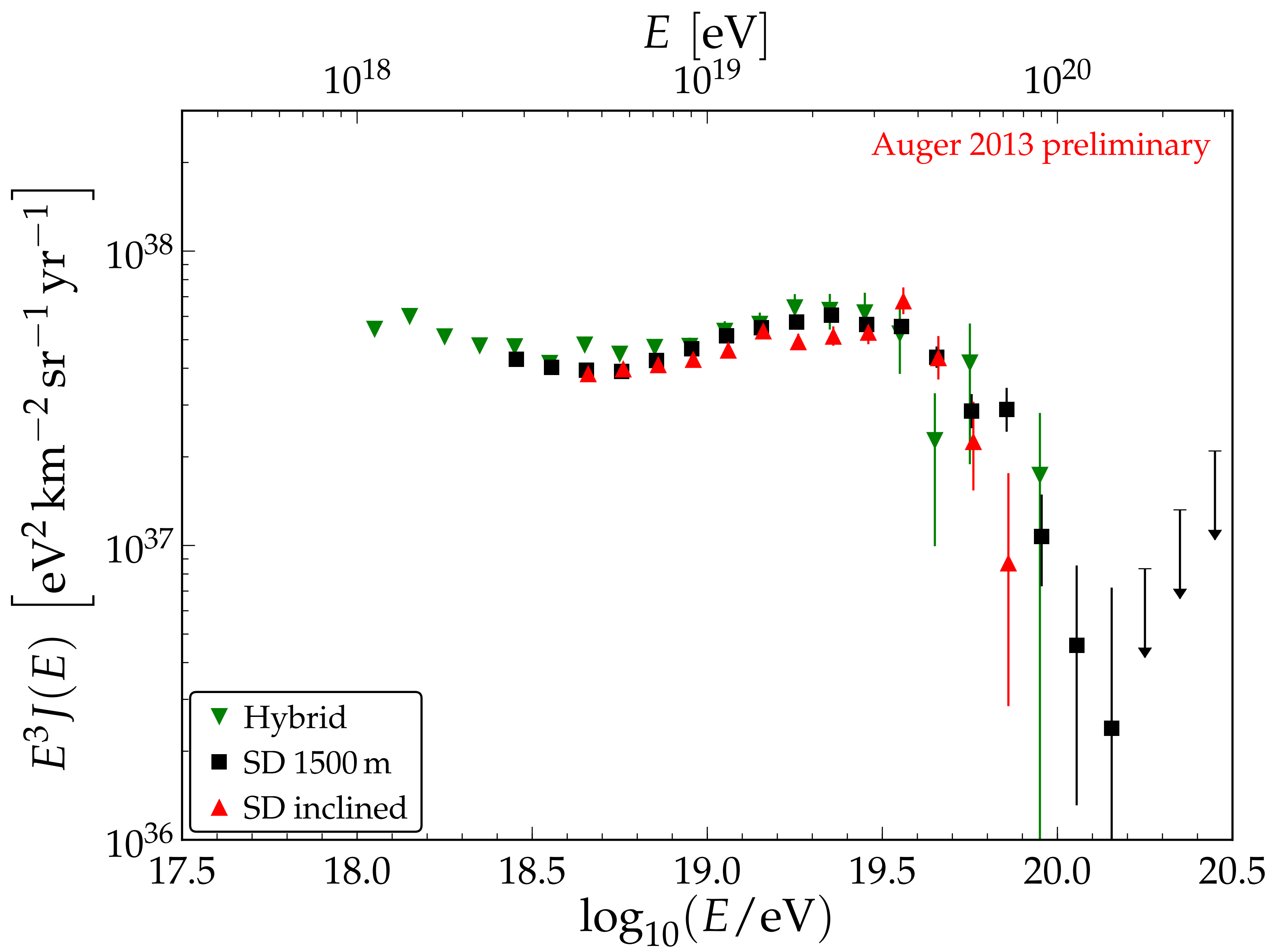
- Several independent measurements
  - SD < 60^0
  - Inclined SD > 60^0
  - Hybrid
  - Infill

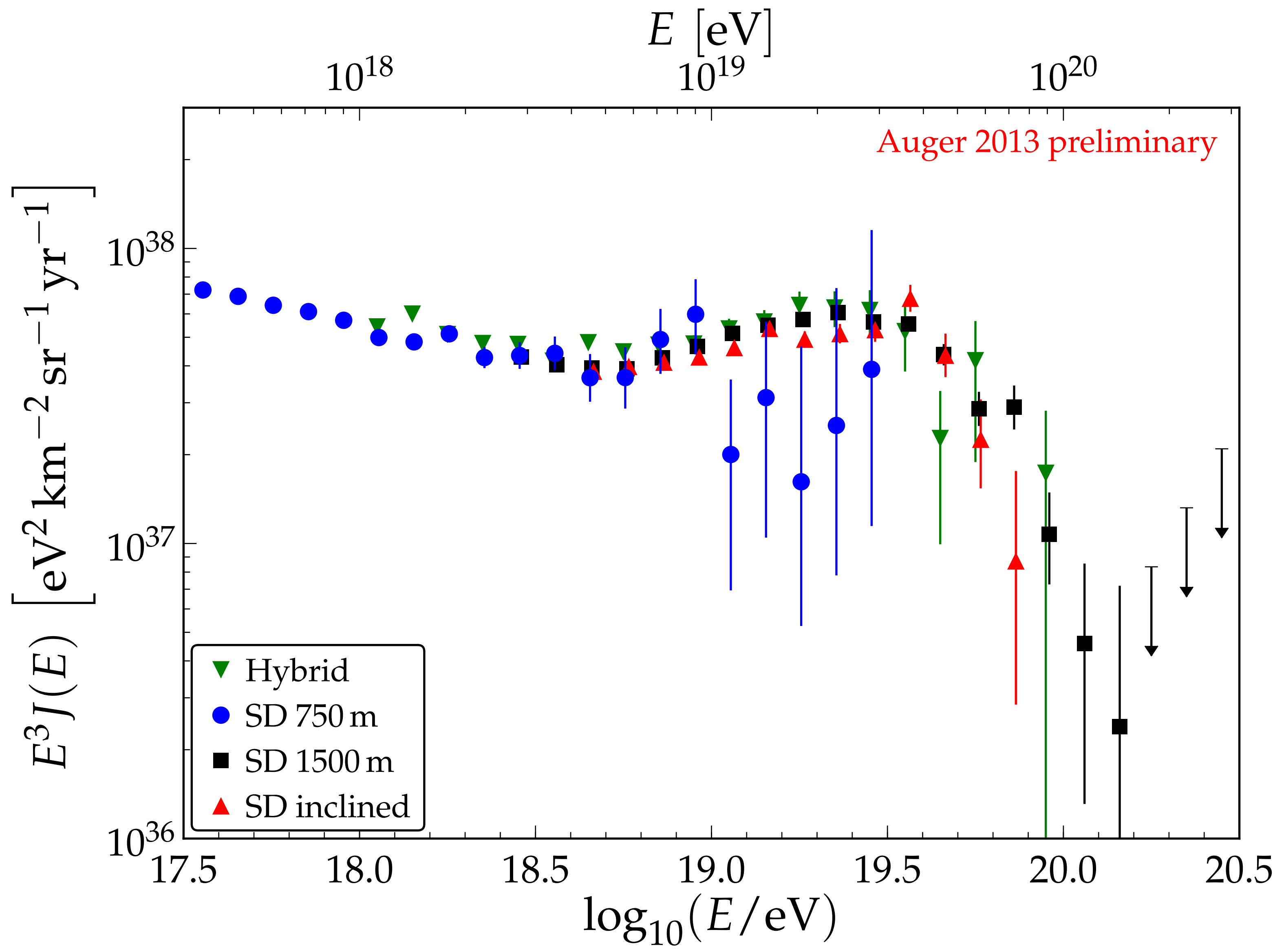


E [eV]
10^{18}
10^{19}
10^{20}
Auger 2013 preliminary
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$
10^{38}
10^{37}
10^{36}
SD 1500 m
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$

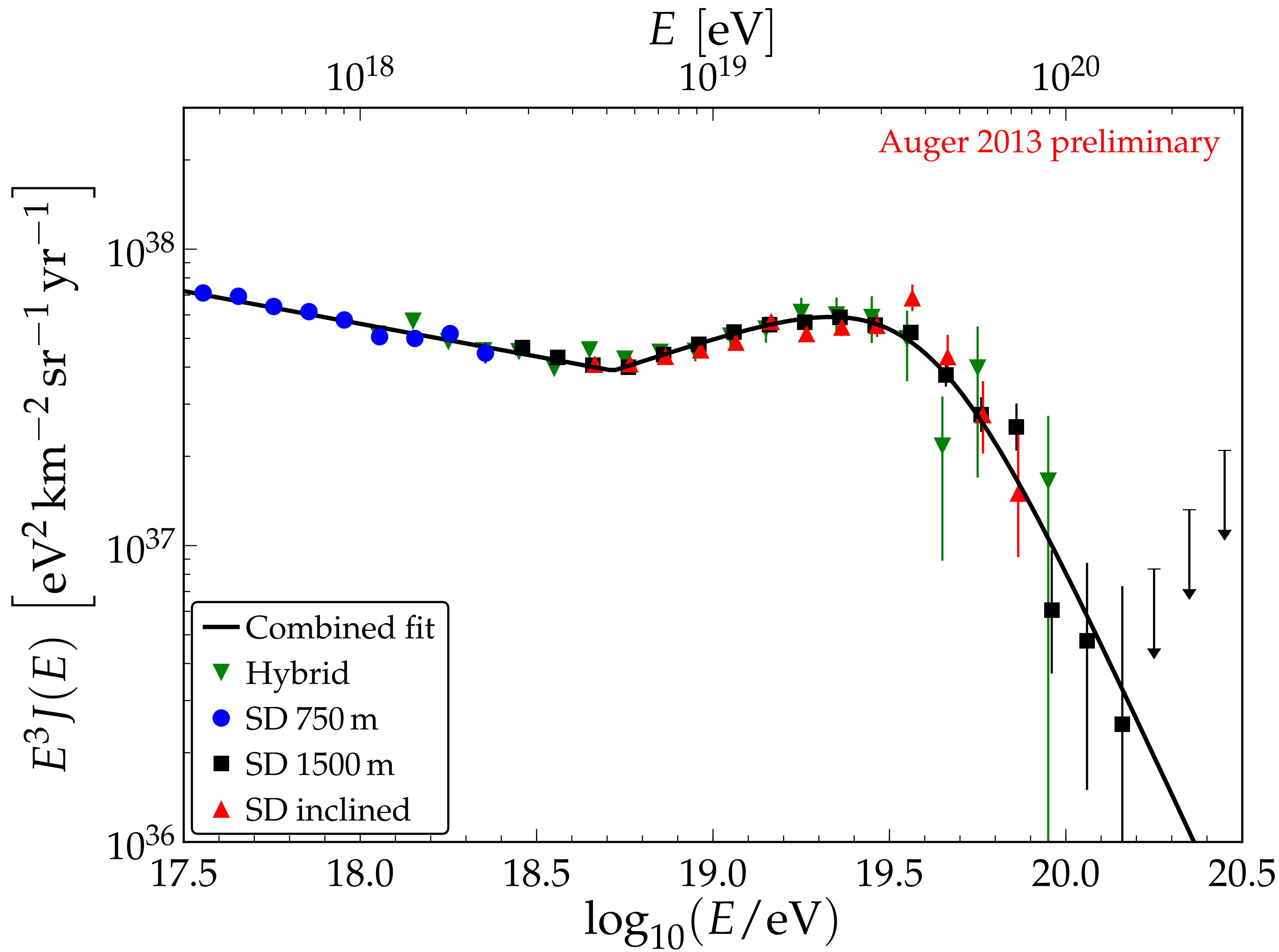


E [eV]
10^{18}
10^{19}
10^{20}
Auger 2013 preliminary
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$
10^{38}
10^{37}
10^{36}
SD 1500 m
SD inclined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$


E [eV]
10^{18}
10^{19}
10^{20}
Auger 2013 preliminary
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$
10^{38}
10^{37}
10^{36}
Hybrid
SD 1500 m
SD inclined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$



E [eV]
10^{18}
10^{19}
10^{20}
Auger 2013 preliminary
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$
10^{38}
10^{37}
10^{36}
Hybrid
SD 750 m
SD 1500 m
SD inclined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$

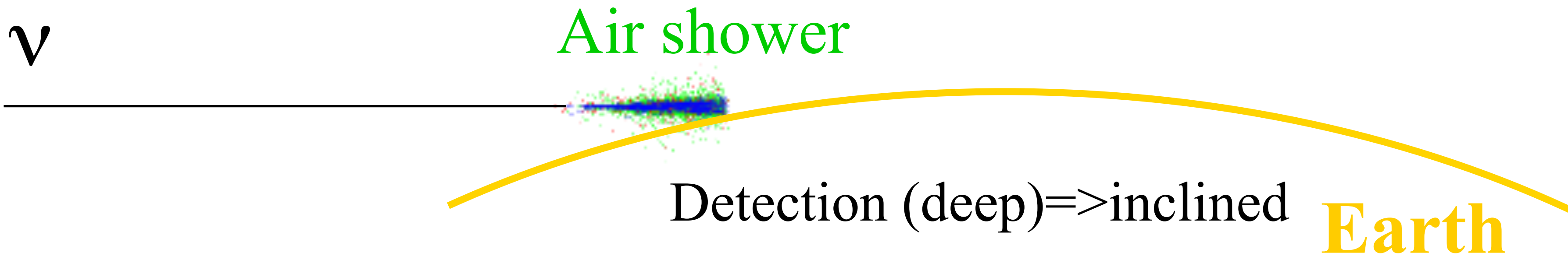


E [eV]
10^{18}
10^{19}
10^{20}
Auger 2013 preliminary
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$
10^{38}
10^{37}
10^{36}
Combined fit
Hybrid
SD 750 m
SD 1500 m
SD inclined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$

Neutrino Bounds

- Two main channels:
  - Earth skimming tau neutrinos
  - Down going neutrinos (All flavors):
- Important findings:
  - Enhanced Earth skiming sensitivity in the EeV region
  - Competitive bounds obtained
  - Total sensitivity below Waxman-Bahcall flux

Case 1: DG down-going ν



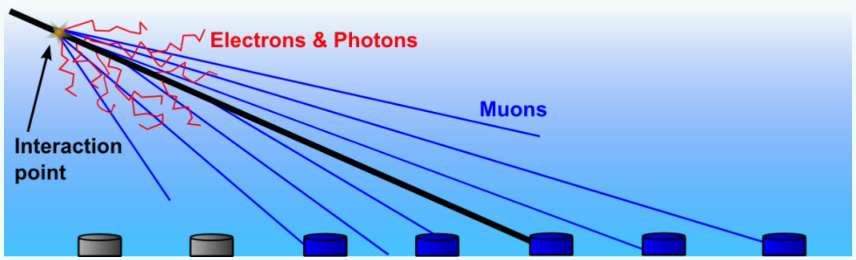
Case 2: ES Earth-skimming ν_τ

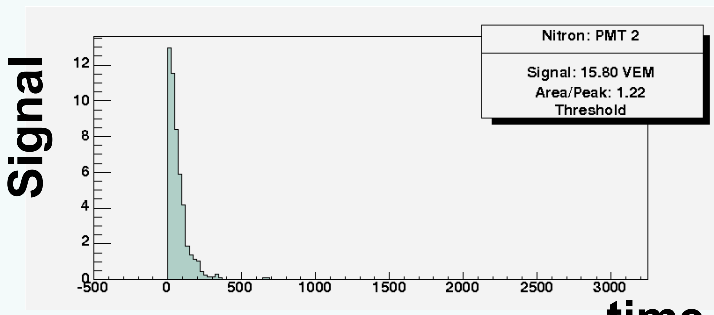
Complex three stage process

- Attenuation through Earth and regeneration: NC
  CC & τ CC
  CC & τ decay
- CC interaction, τ energy loss and no decay
- Exit and τ decay in the atmosphere

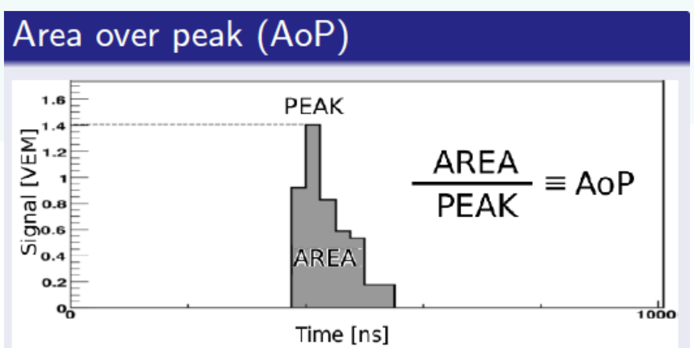
Search for ν-induced showers in data: deep showers

p/nuclei-induced showers

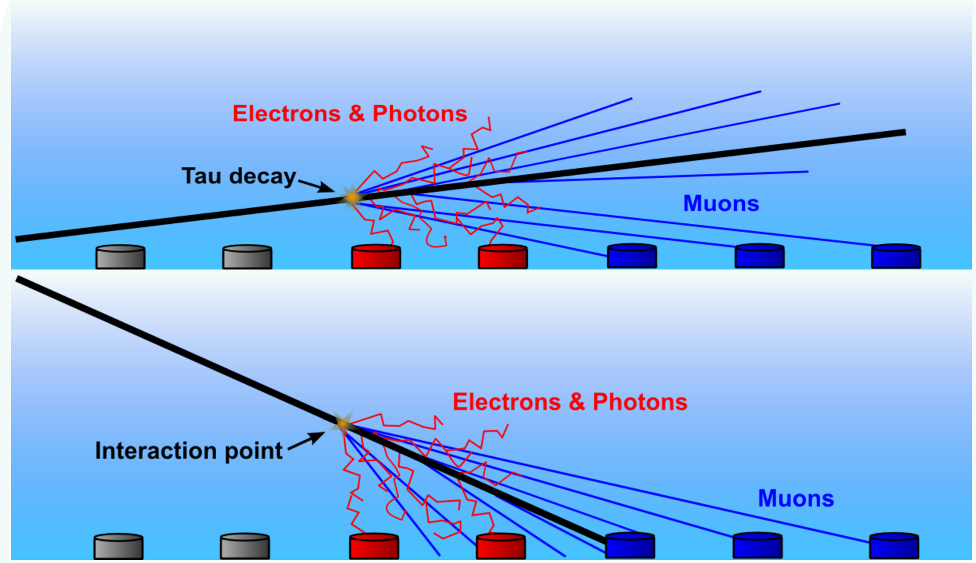


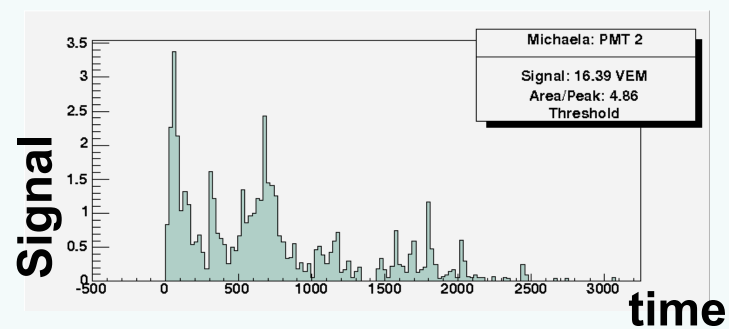


Fast & narrow signal produced by μ
All detectors equivalent



ν-induced showers

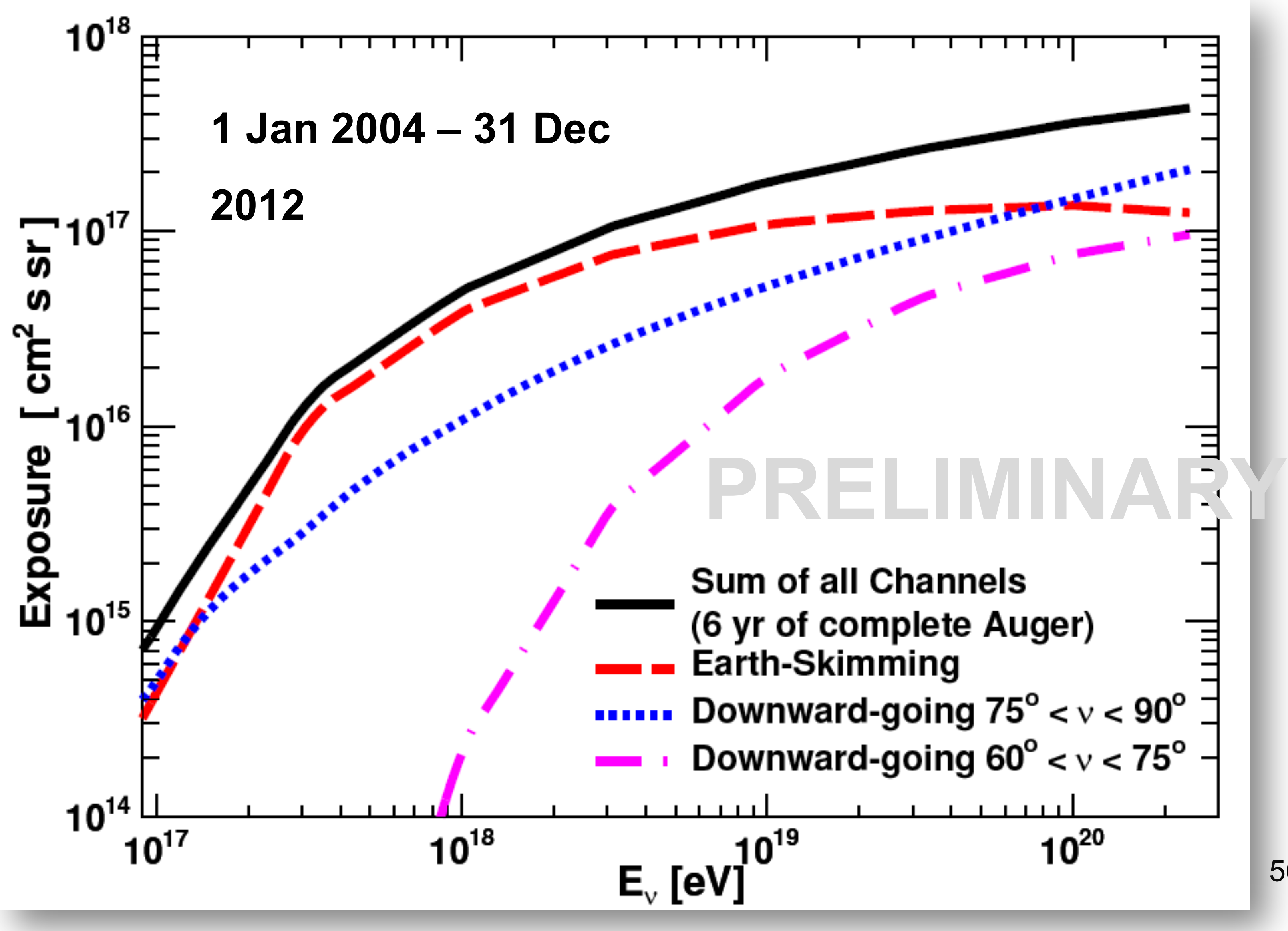


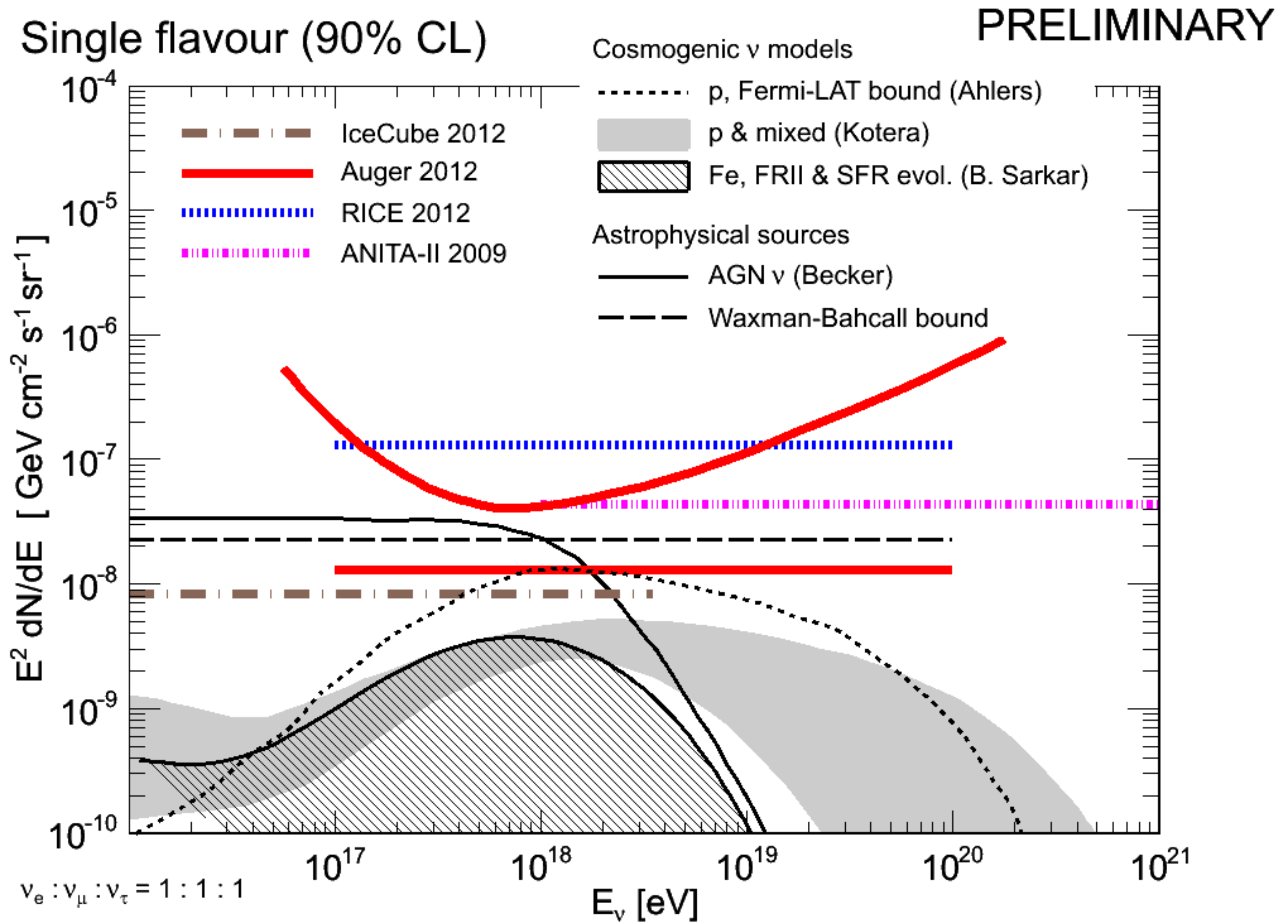


Broad signal produced by e±,γ in early tanks
Narrow signal in late tanks

Combined exposure

Each simulated ν-event that passes either ES or DGH or DGL criteria contributes corresponding to θ.
(i.e. simulated DGH shower passing ES criterio contributes to ε_{DGH})

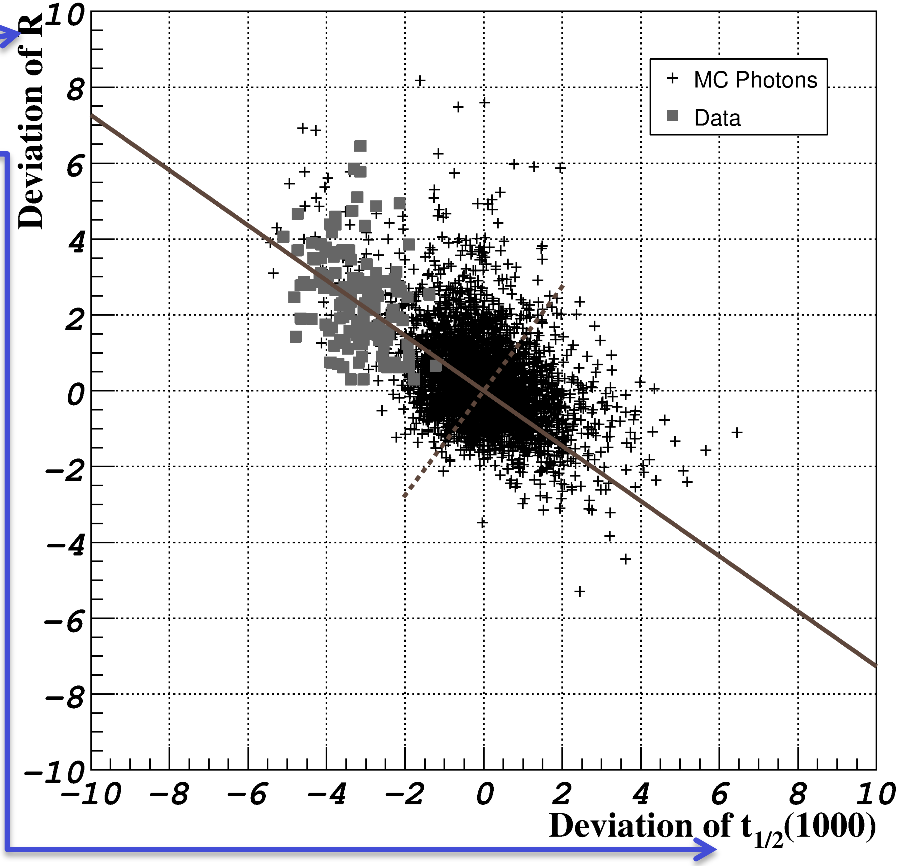


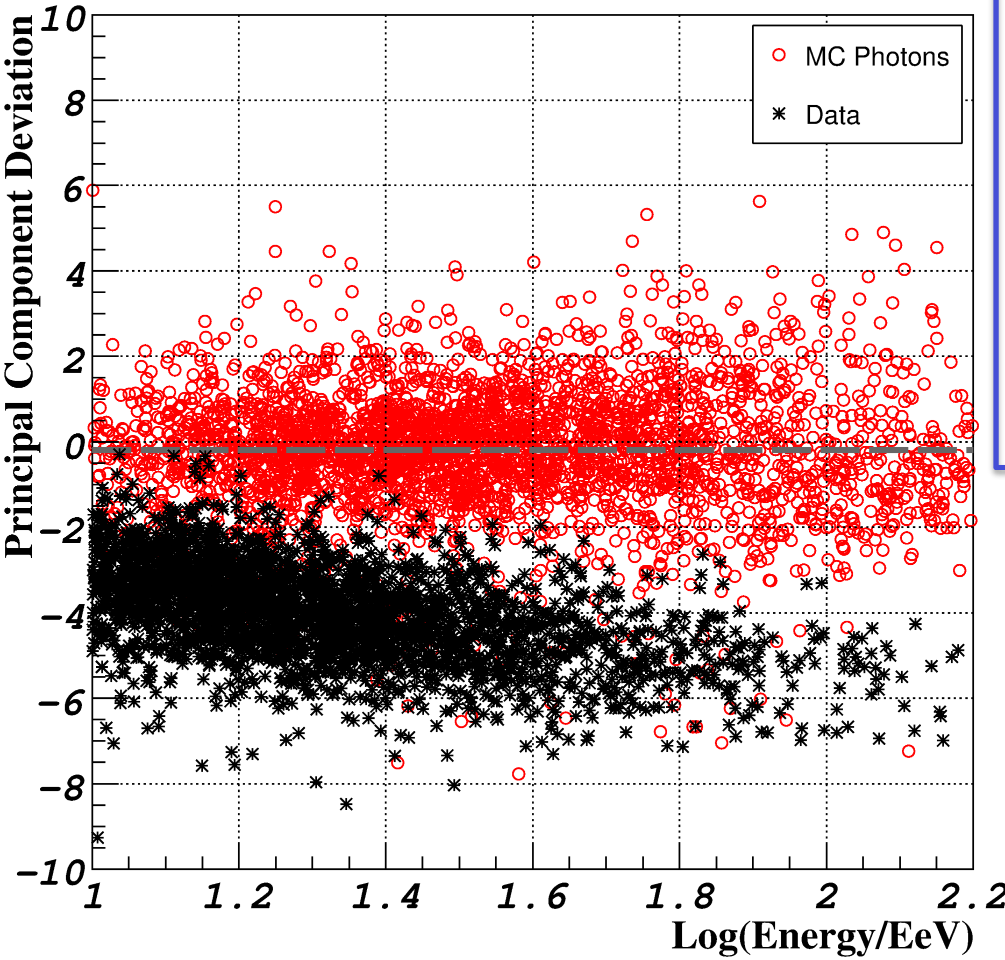

Single flavour (90% CL)
PRELIMINARY
Cosmogenic ν models
p, Fermi-LAT bound (Ahlers)
p & mixed (Kotera)
Fe, FRII & SFR evol. (B. Sarkar)
Astrophysical sources
AGN ν (Becker)
Waxman-Bahcall bound
IceCube 2012
Auger 2012
RICE 2012
ANITA-II 2009
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
E_ν [eV]
$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

Photon Bounds

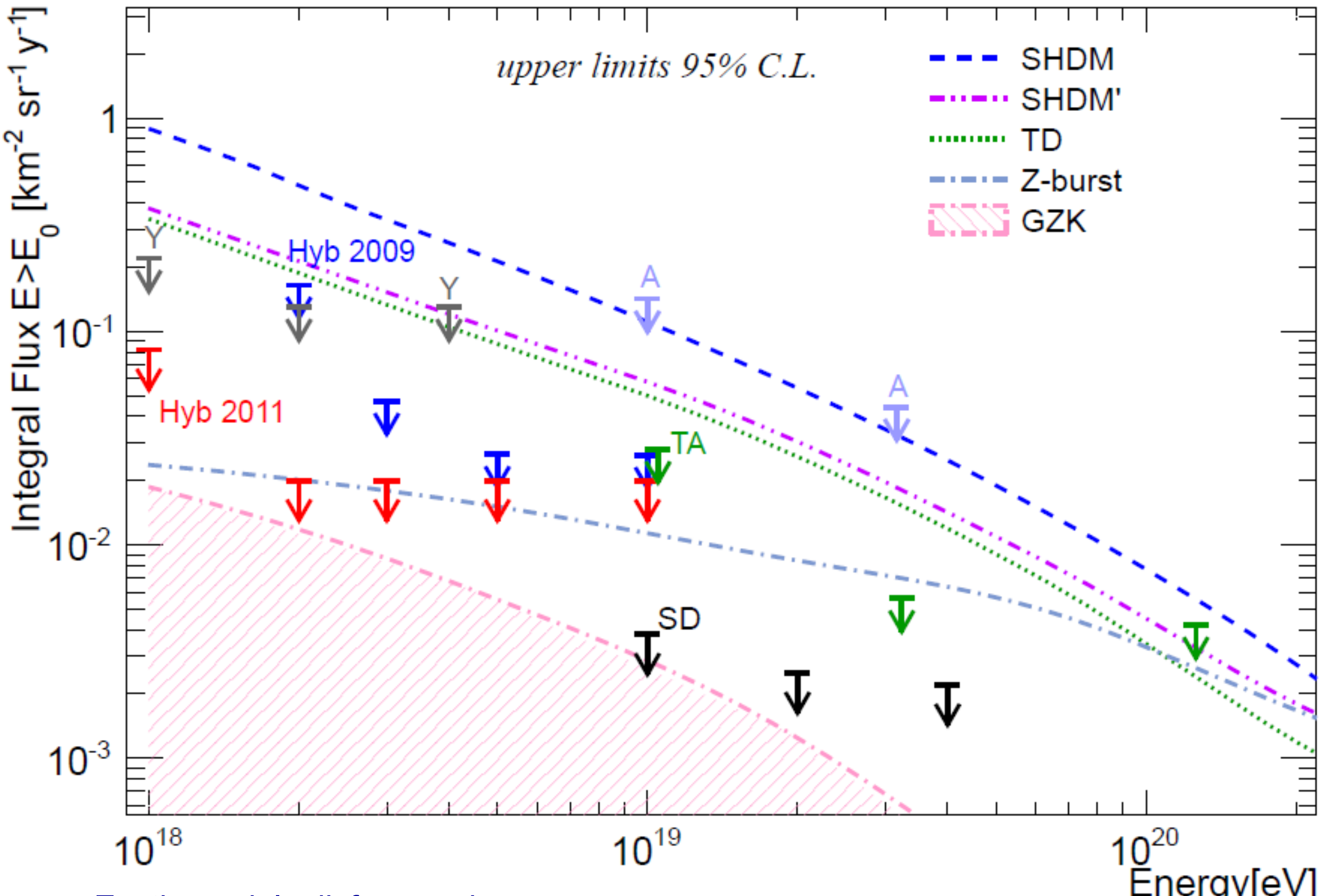
- Approaches based on deeper X_{max} lower N_μ
  - Diffuse bounds: SD observables
  - Diffuse bounds: SD and FD
  - Point sources: Multiviariate (SD and FD)
- Important findings:
  - Competitive bounds obtained: TD models disfavoured
  - GZK photons within reach in a few years

SD: use curvature
and risetime
they are related to Xmax





Upper limits to the diffuse photon flux

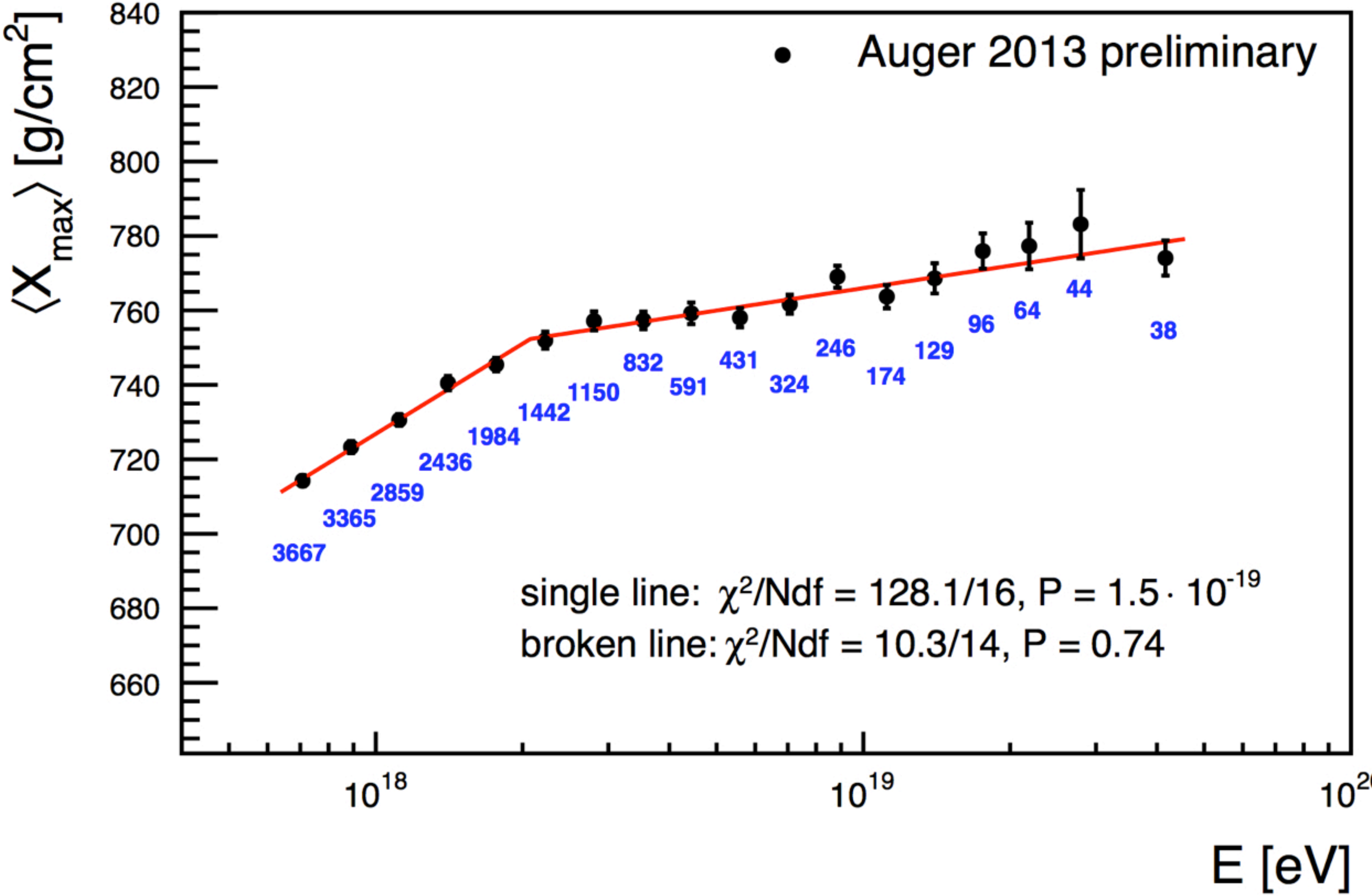


- Exotic models disfavoured
- GZK region within reach in the next few years

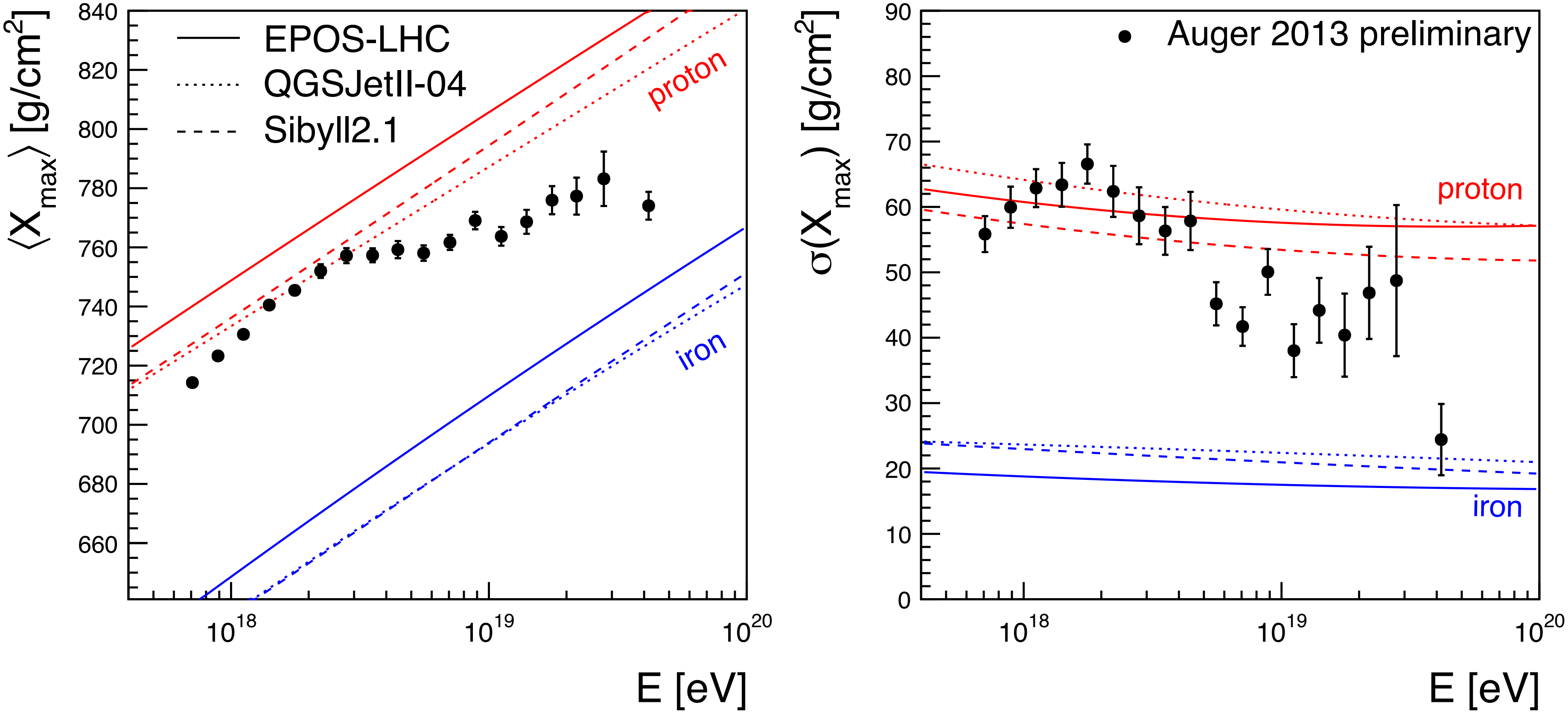
Auger ICRC 2011(0393)
TA ICRC 2013 (0149)

Composition

- Aproaches (hybrid data):
  - Average of X_{max} distribution
  - Variance of X_{max} distribution
- Findings:
  - Change of behavior at ~2 EeV
  - $<X_{max}>$ becomes smaller (hevaier compostion)
  - σ_{Xmax} also reduces (not much dispersion in A)



$\langle X_{max} \rangle$ [g/cm^2]
840
820
800
780
760
740
720
700
680
660
Auger 2013 preliminary
3667
3365
2859
2436
1984
1442
1150
832
591
431
324
246
174
129
96
64
44
38
single line: χ^2/Ndf = 128.1/16, P = $1.5 \cdot 10^{-19}$
broken line: χ^2/Ndf = 10.3/14, P = 0.74
10^{18}
10^{19}
10^{20}
E [eV]



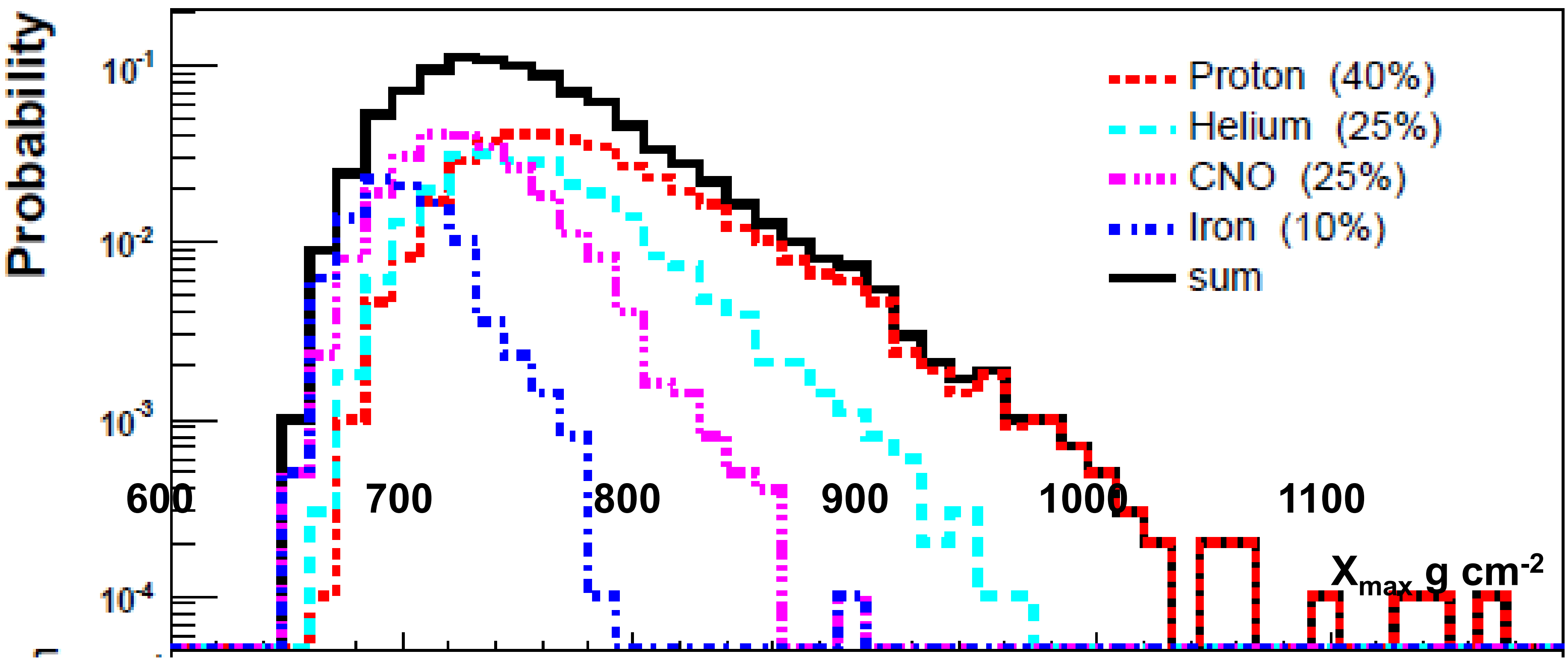
EPOS-LHC
QGSJetII-04
Sibyll2.1
proton
iron
$\langle X_{max} \rangle$ [g/cm^2]
840
820
800
780
760
740
720
700
680
660
10^{18}
10^{19}
10^{20}
E [eV]
Auger 2013 preliminary
$\sigma(X_{max})$ [g/cm^2]
90
80
70
60
50
40
30
20
10
0
proton
iron
10^{18}
10^{19}
10^{20}
E [eV]

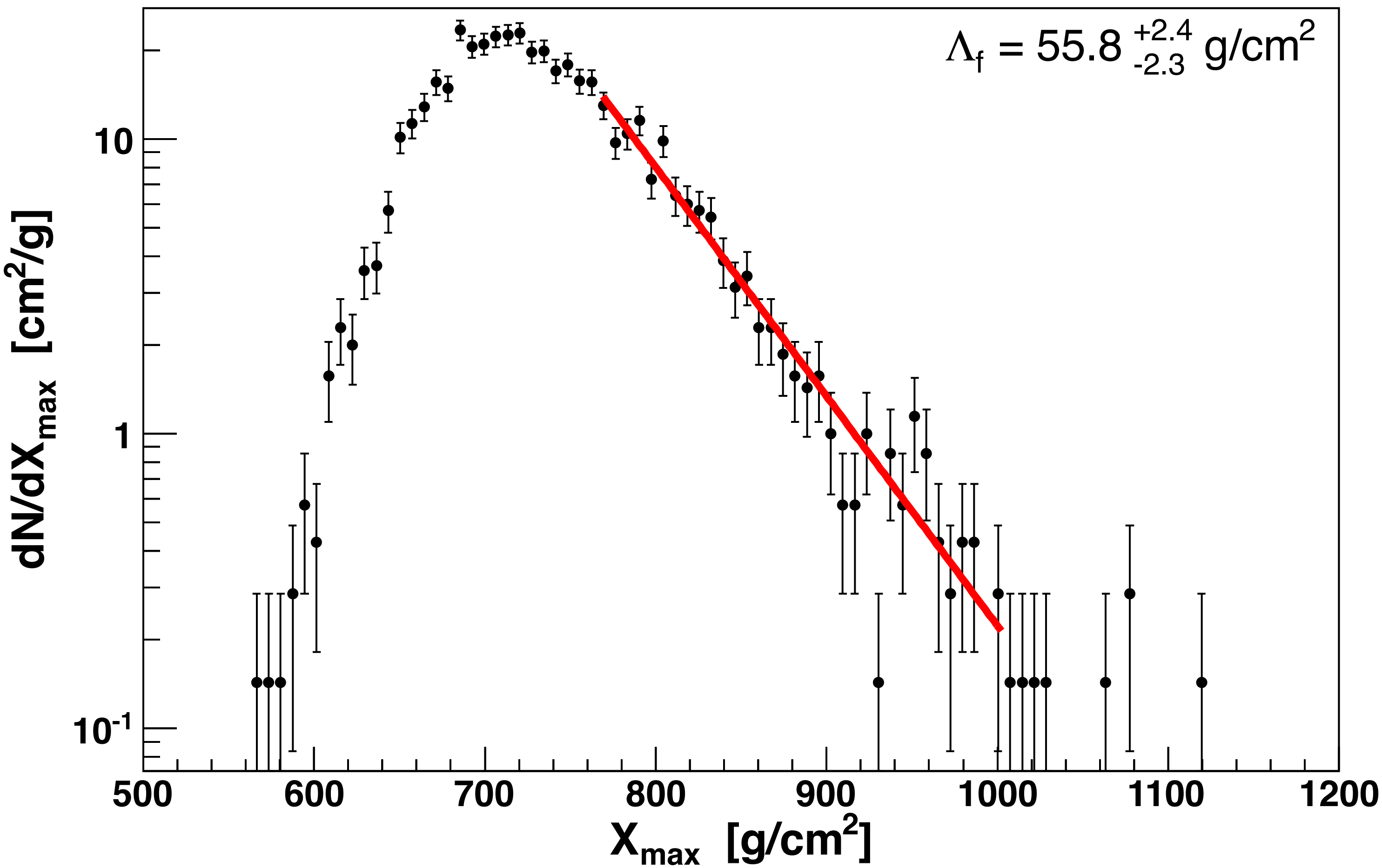
Particle Physics

- Cross sections
  - Proton air cross section at sqrt(s)=56 TeV (pp eq.)
- Test interaction models
  - Simulations give deficit of muons

Remember

$$X_{\max} \approx \lambda_p + X_0 \ln\left[\frac{k_{ela}E}{2AN\varepsilon_c}\right]$$

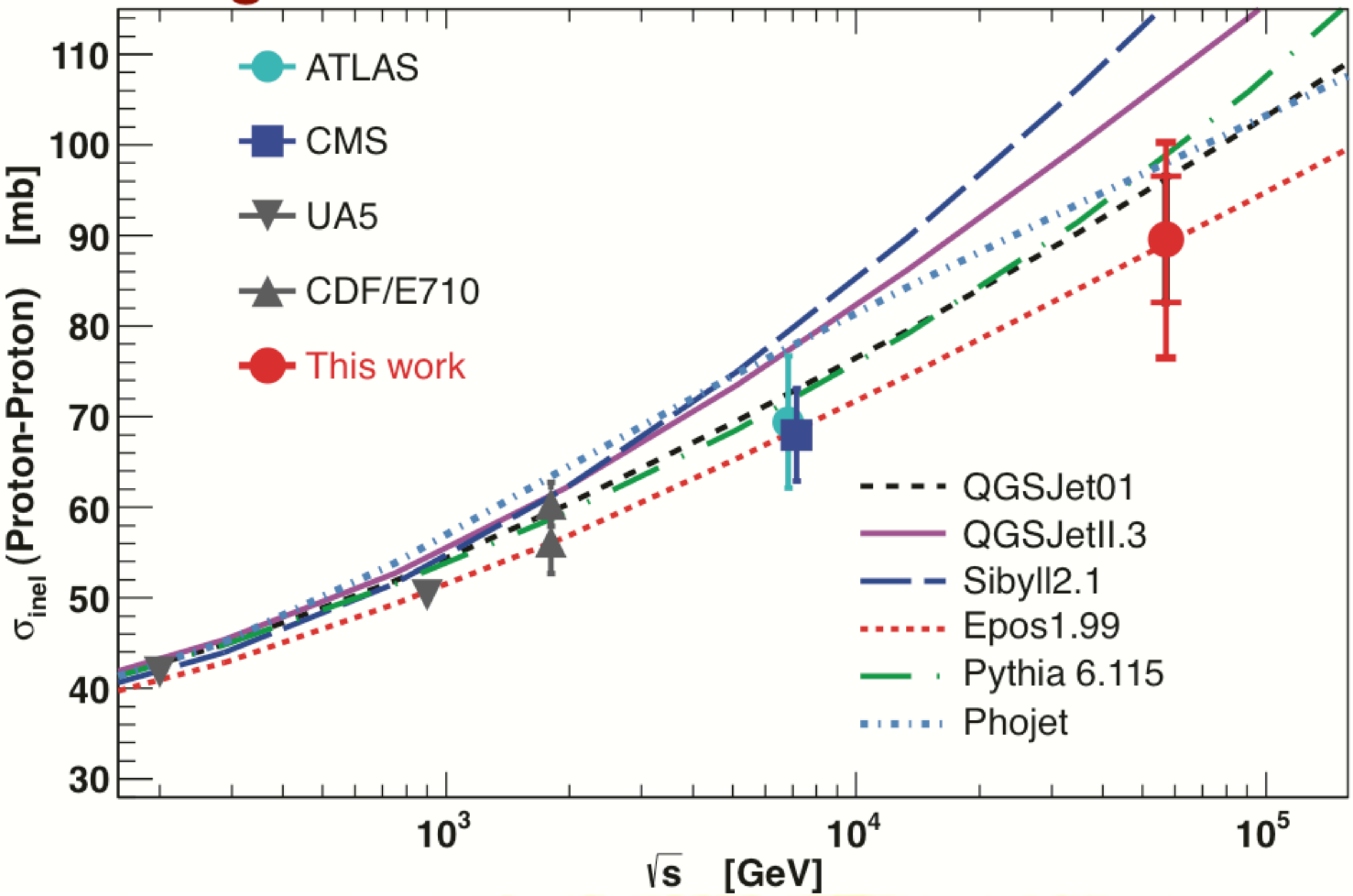




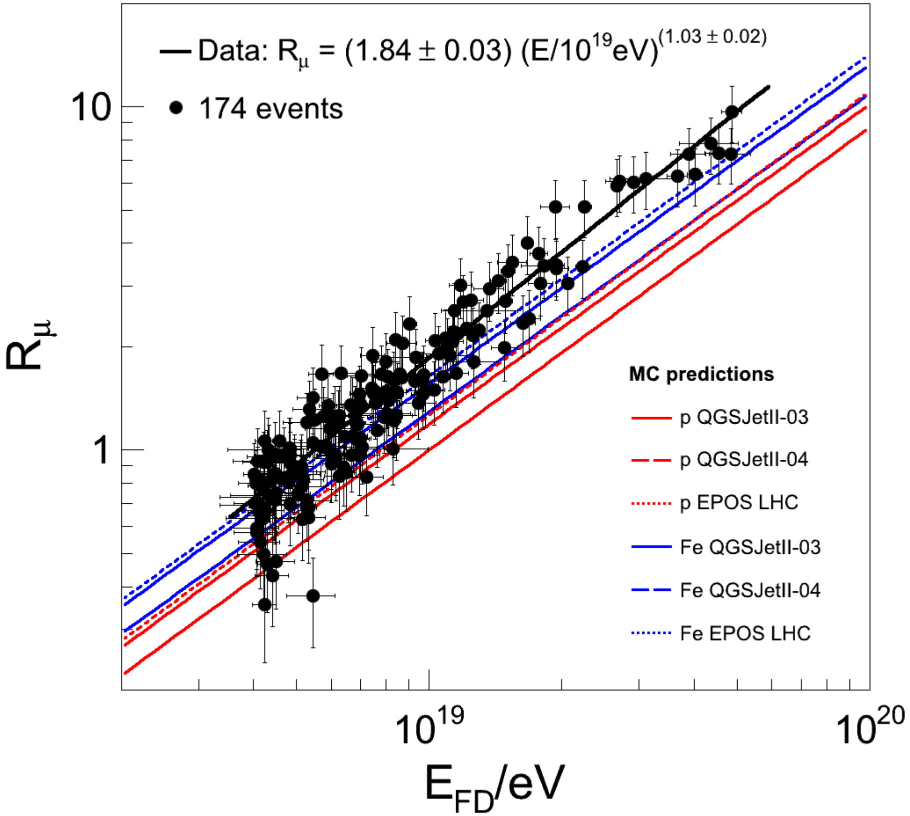
$\Lambda_f = 55.8\,^{+2.4}_{-2.3}$ g/cm^2
dN/dX$_{max}$ [cm^2/g]
10
1
10^{-1}
500
600
700
800
900
1000
1100
1200
X$_{max}$ [g/cm^2]

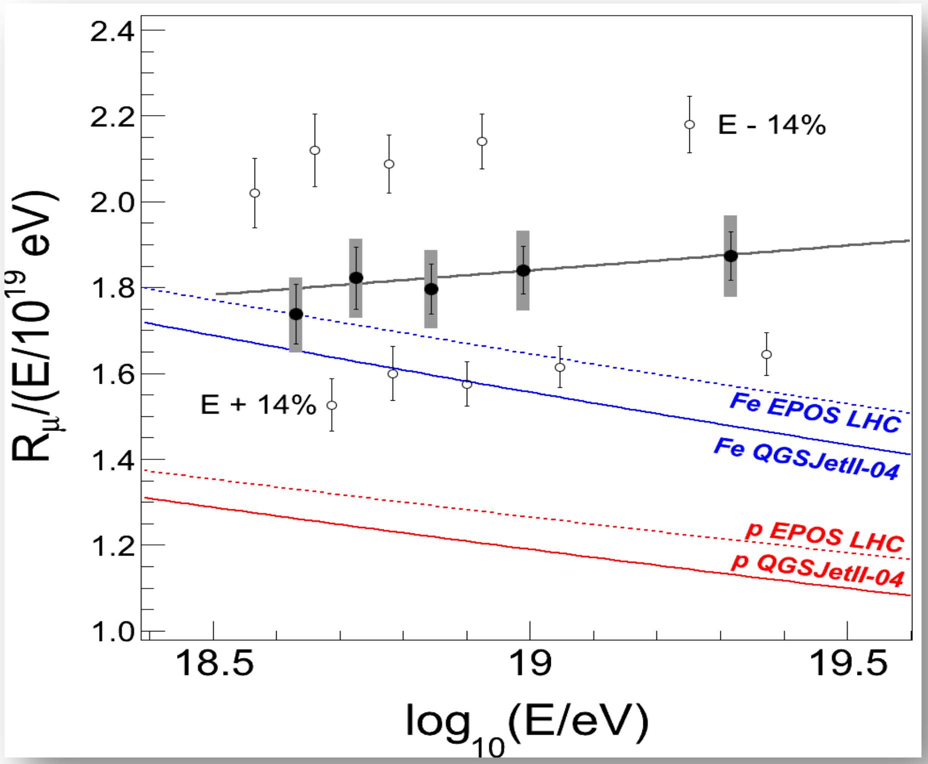
$\sigma_{p\text{-}p}=90\pm7_{stat}(+8-11)_{sys}\ \pm1.5_{Glauber}$ mb

using Glauber model

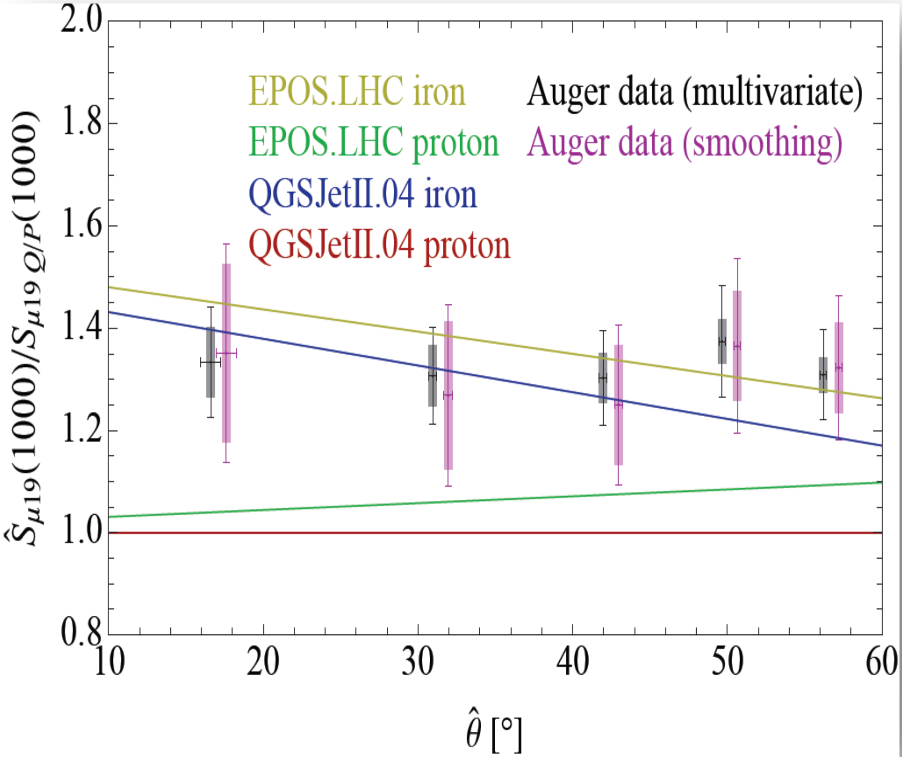


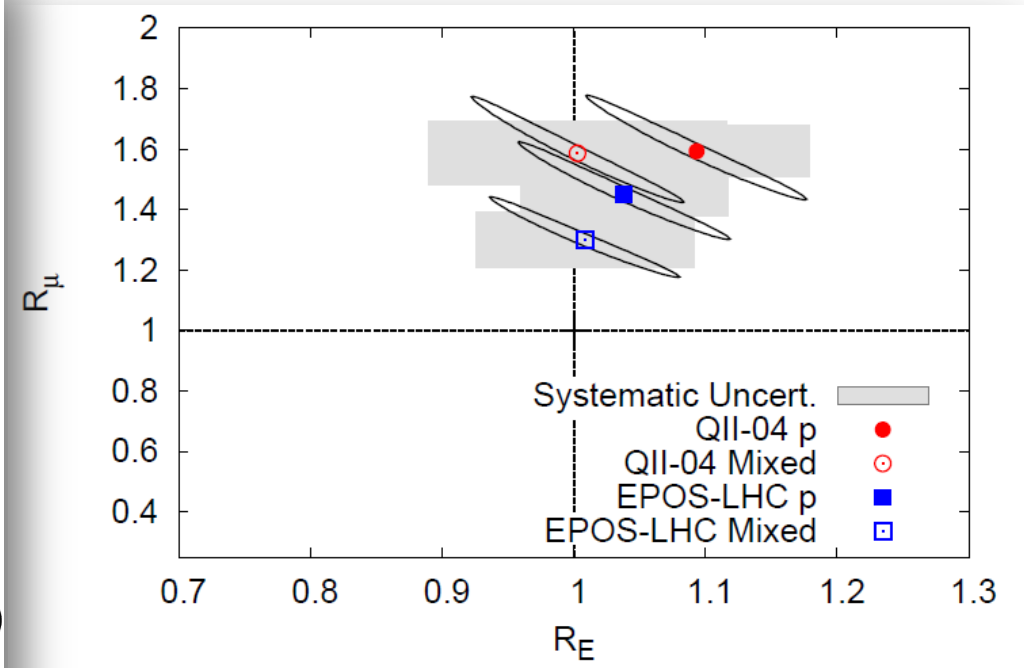
Redundancy: Inclined events measure muons relative to a reference (p-QGSJETII)





Confirmed with standard events!
(more sophisticated ideas)



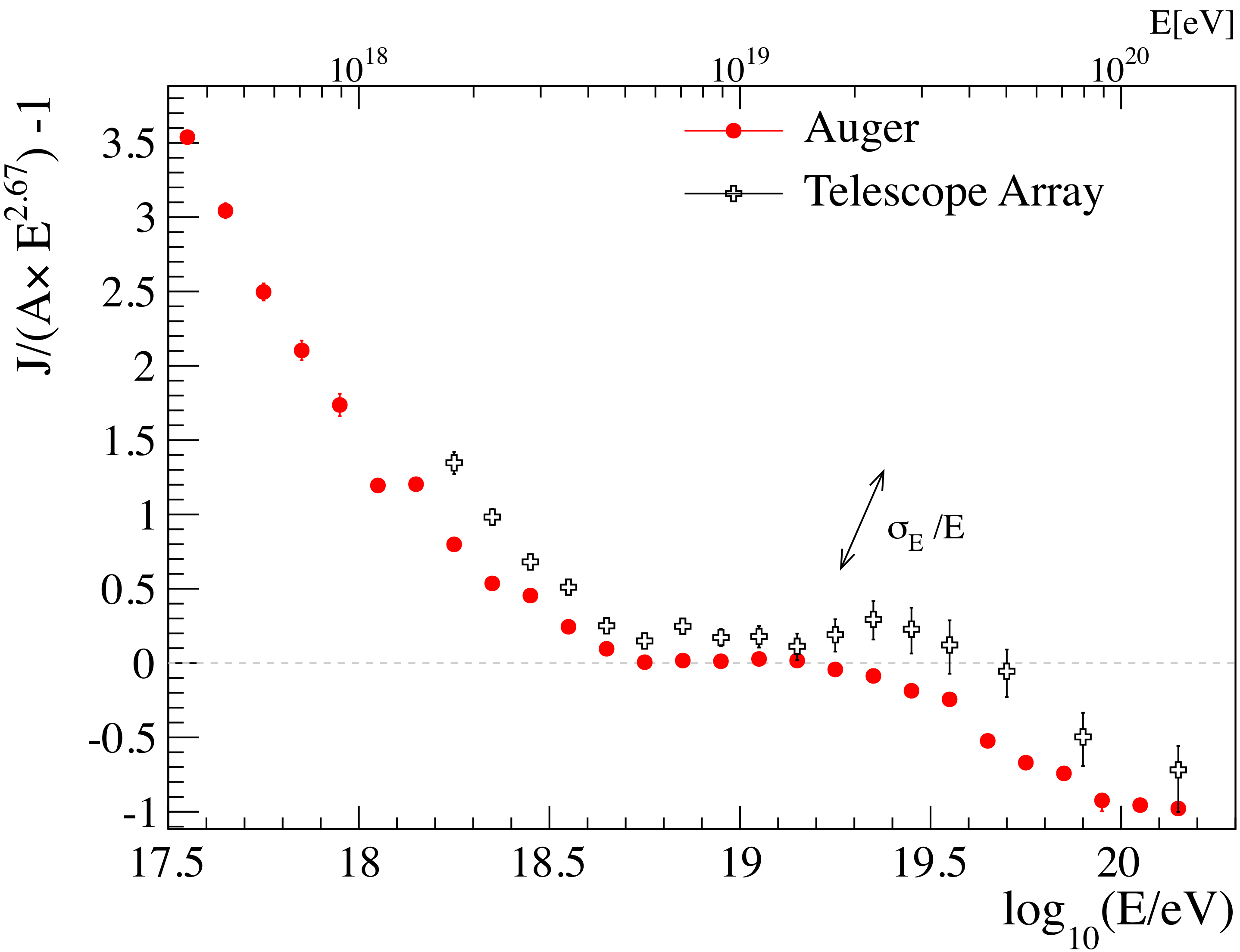


Model	R_E	R_μ
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.59 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.01 \pm 0.07 \pm 0.08$	$1.30 \pm 0.13 \pm 0.09$

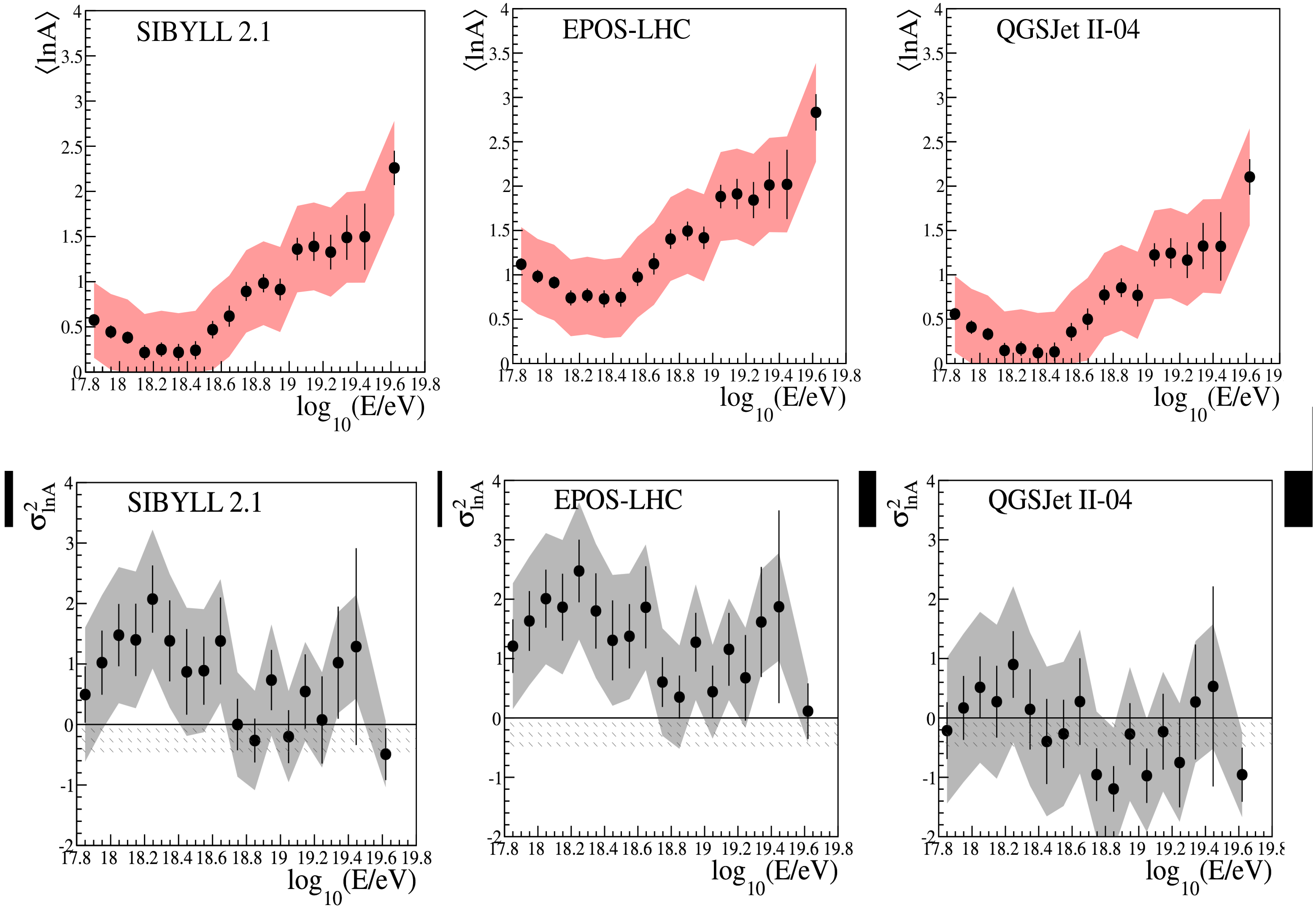
Tension

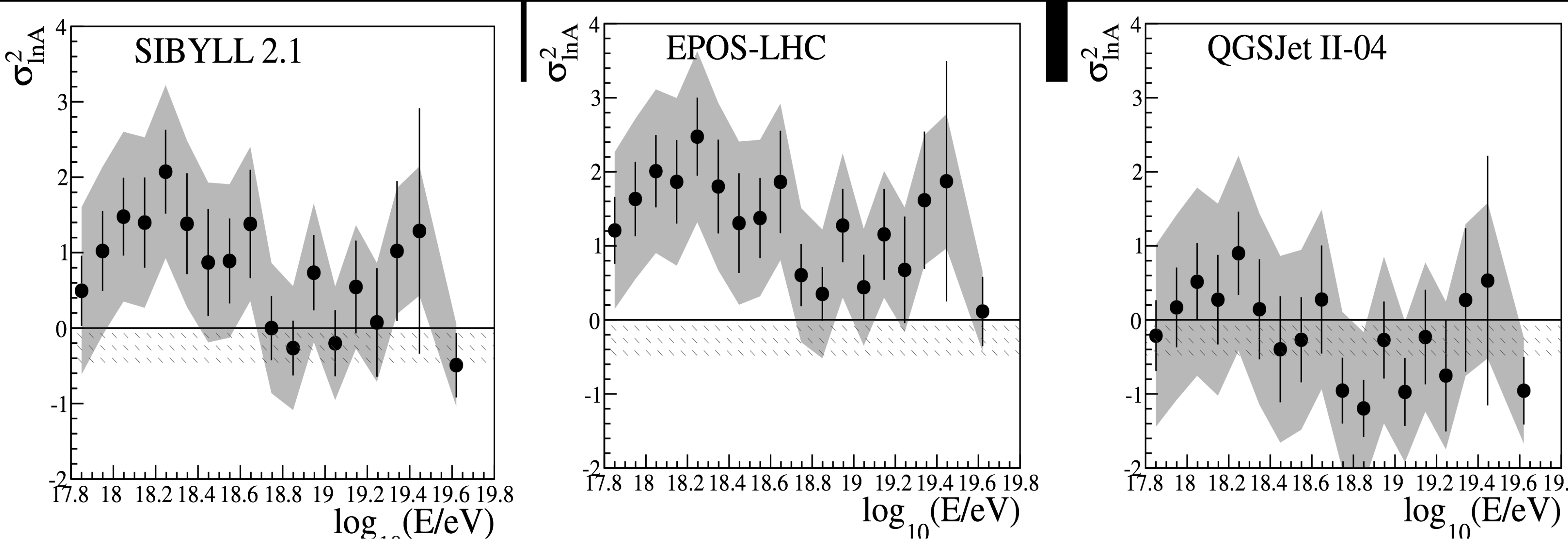
- Telescope Array in NH: claims consistency with protons
  - Joint effort in progress
- More muons than predicted by models
- Composition and results from X_{max} & X^{μ}_{max}

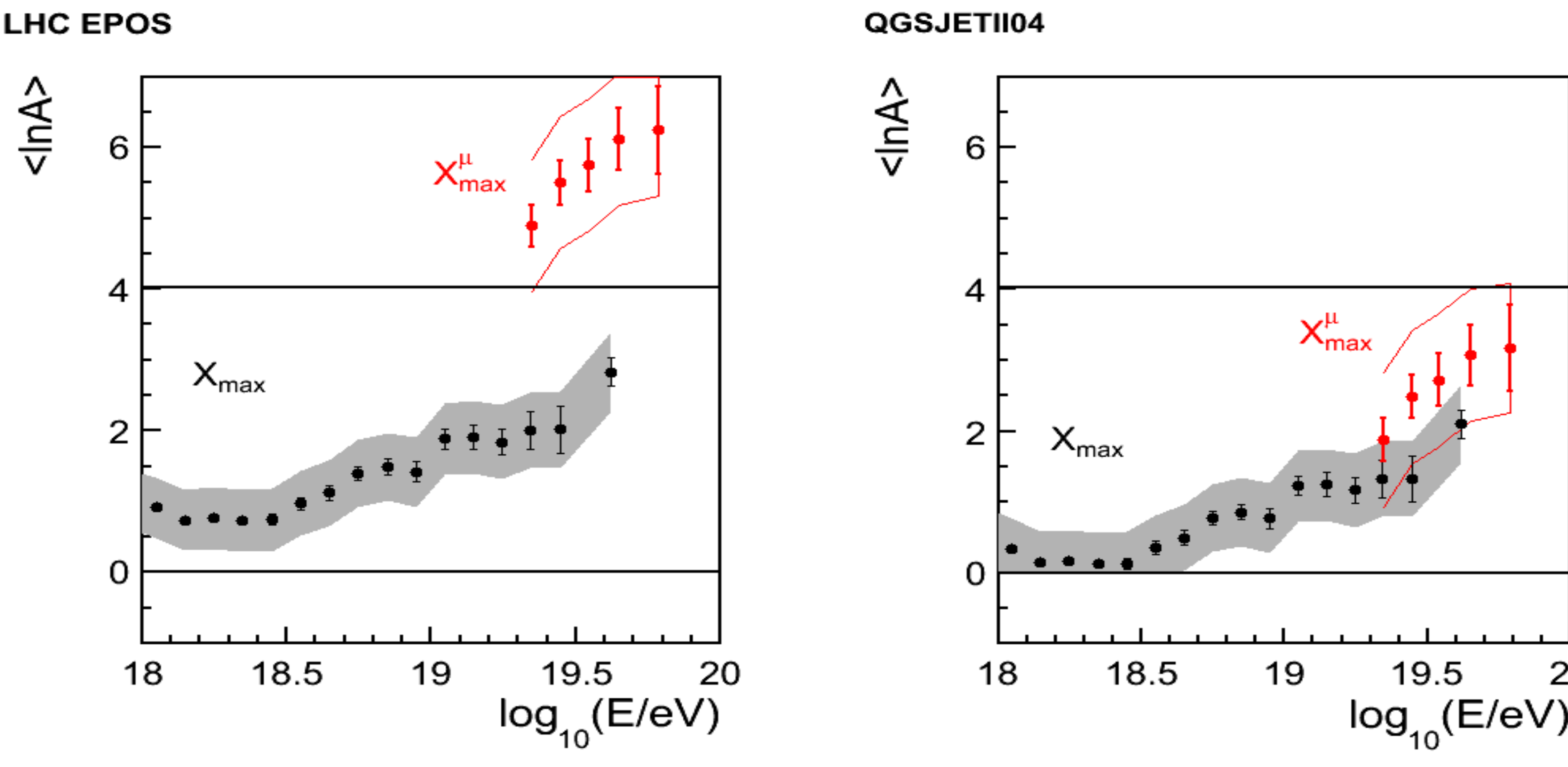
Generally consistent results between experiments



X_{max} measurements conversion to ln(A)




SIBYLL 2.1
EPOS-LHC
QGSJet II-04
$\sigma^2_{\ln A}$
$\log_{10}(E/eV)$


LHC EPOS
QGSJETII04
<lnA>
X^{μ}_{max}
X_{max}
$\log_{10}(E/eV)$

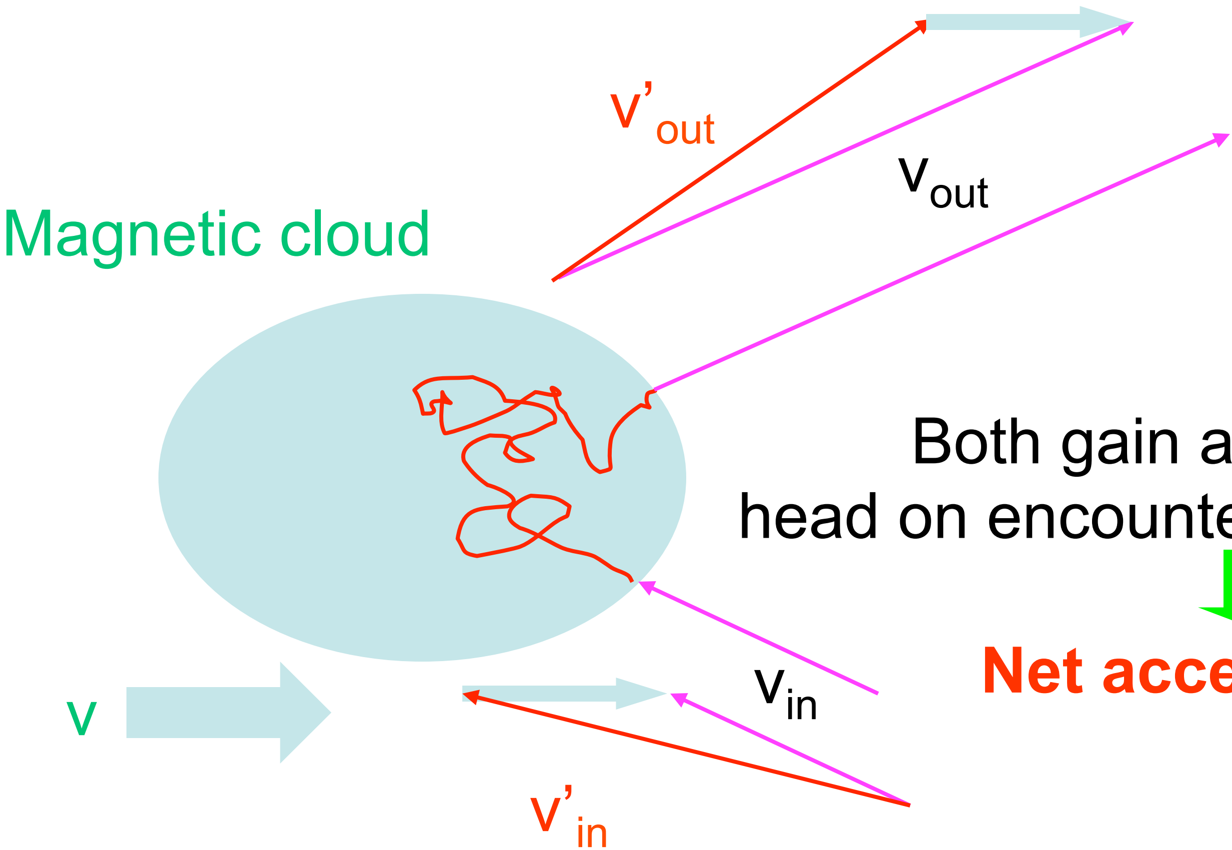
Summary

- Auger contributed to solving long standing issues, flux, GZK cutoff, ankle
- Auger is producing a broad range of relevant results, bounds, muon content, cross section, anisotropies
- Auger points out to tension with models and needs more data taking and more redundancy to further constrain composition

The Future: A new proposal

- To extend Int. Agreement till 1023
- To enhance the performance
    - **Improved electronics**
- To enlarge the area with redundancy
    - Radio technique? Seems out without small spacings
    - Enhanced FD coverage? Not now
    - **Provide muon detectors**
- New detectors from space

Acceleration (2nd order Fermi 1949):



Both gain and loss but
head on encounters more frequent

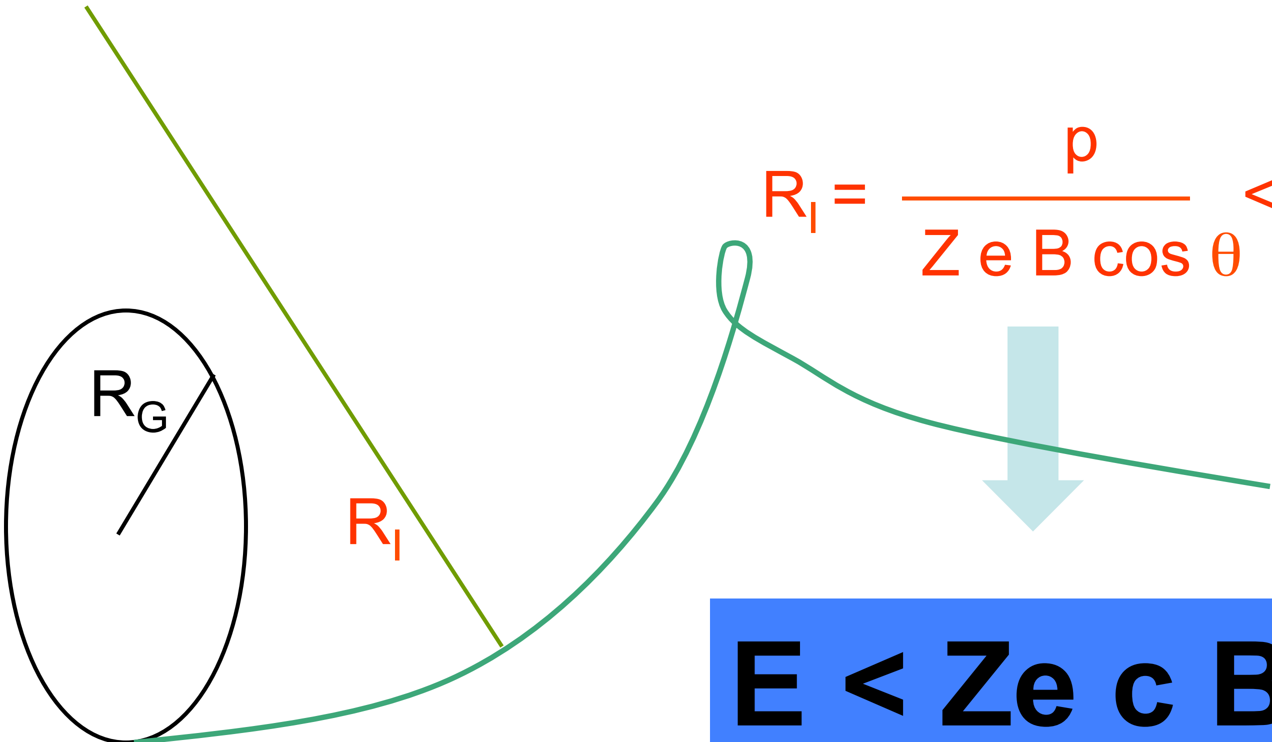
Net acceleration

$$\frac{\Delta E}{E} = \frac{4\,v^2}{3\,c^2}$$

Spectrum $\alpha\ E^{-\gamma}$ $(\gamma = 2.2\text{-}2.7)$

1st order acceleration at shocks (more efficient)

Acceleration size (L) **MUST EXCEED** radius (R_l)

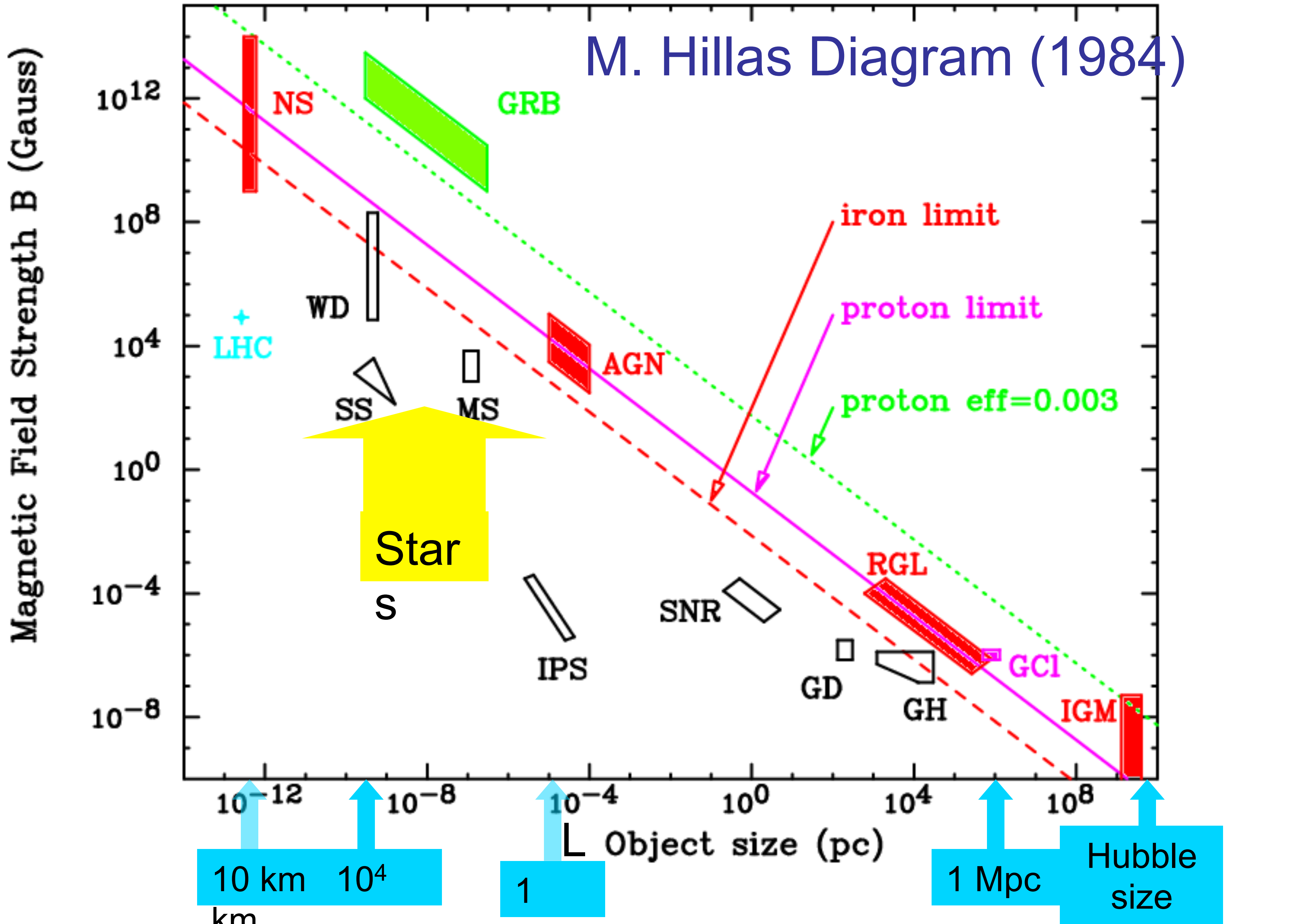


$$R_l = \frac{p}{Z\, e\, B \cos\theta} < L$$

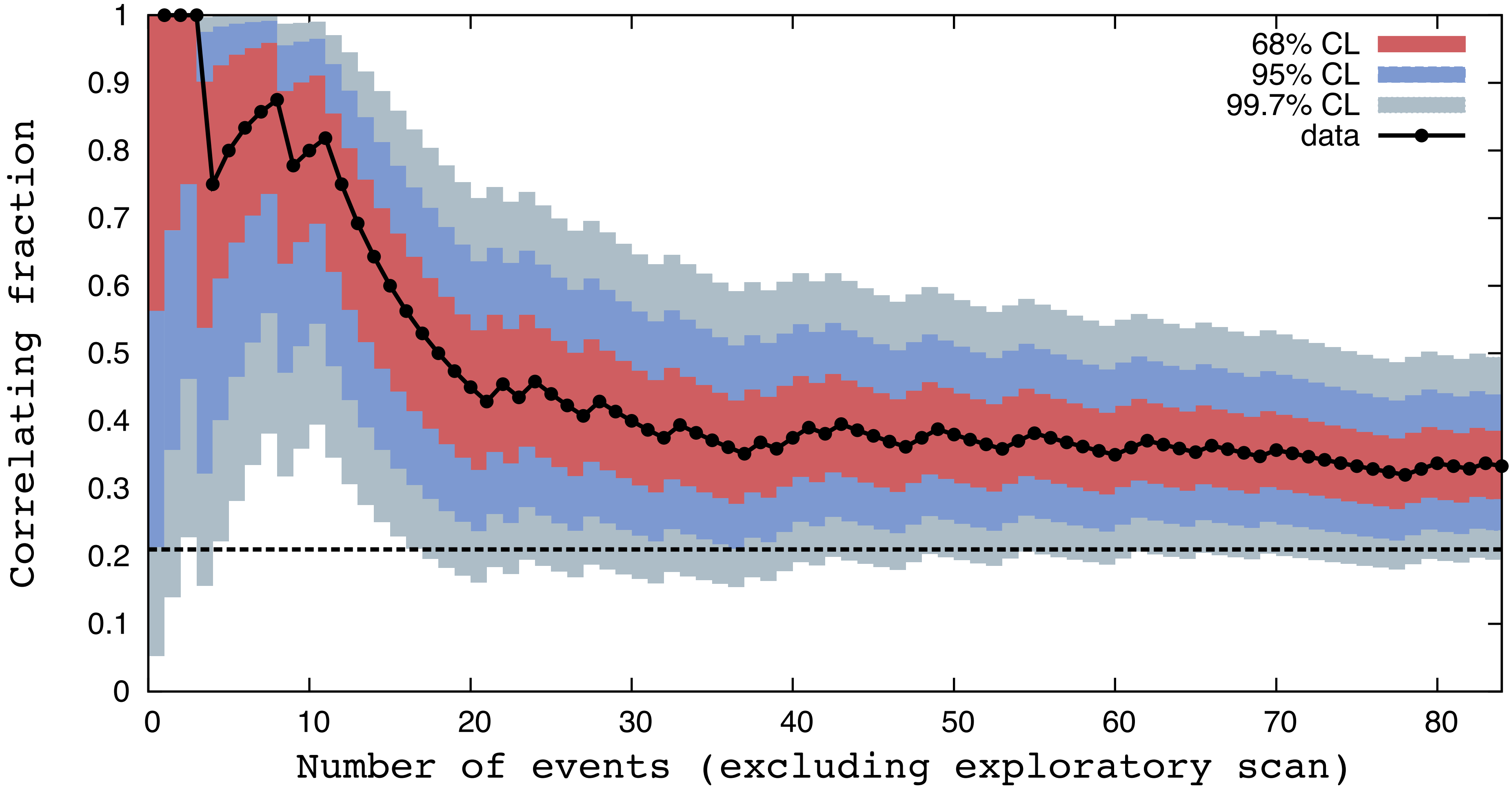
$$\mathbf{E < Ze\; c\; BL}$$

Diffusive propagation in accelerating region

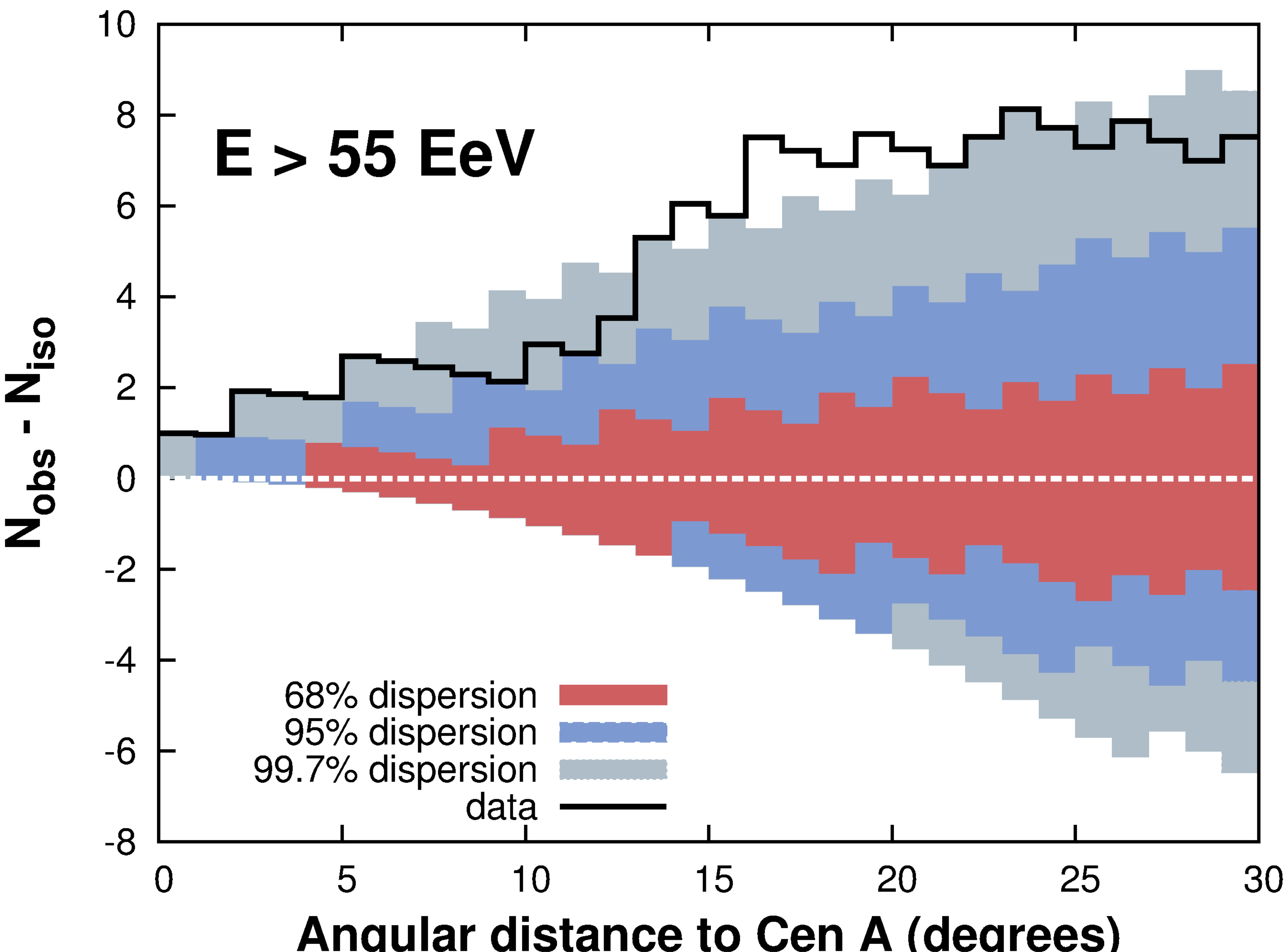
The difficulty to accelerate partic

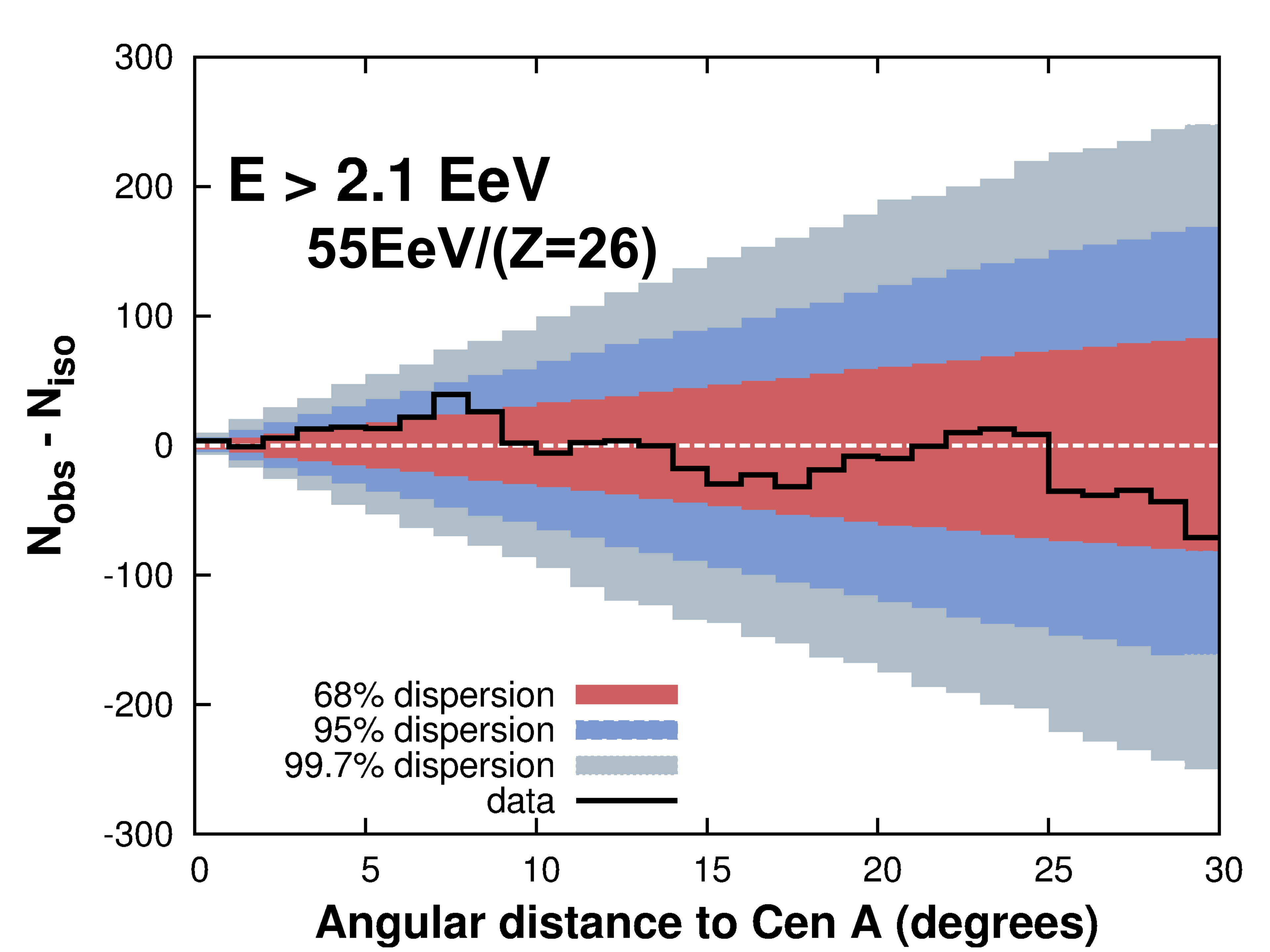


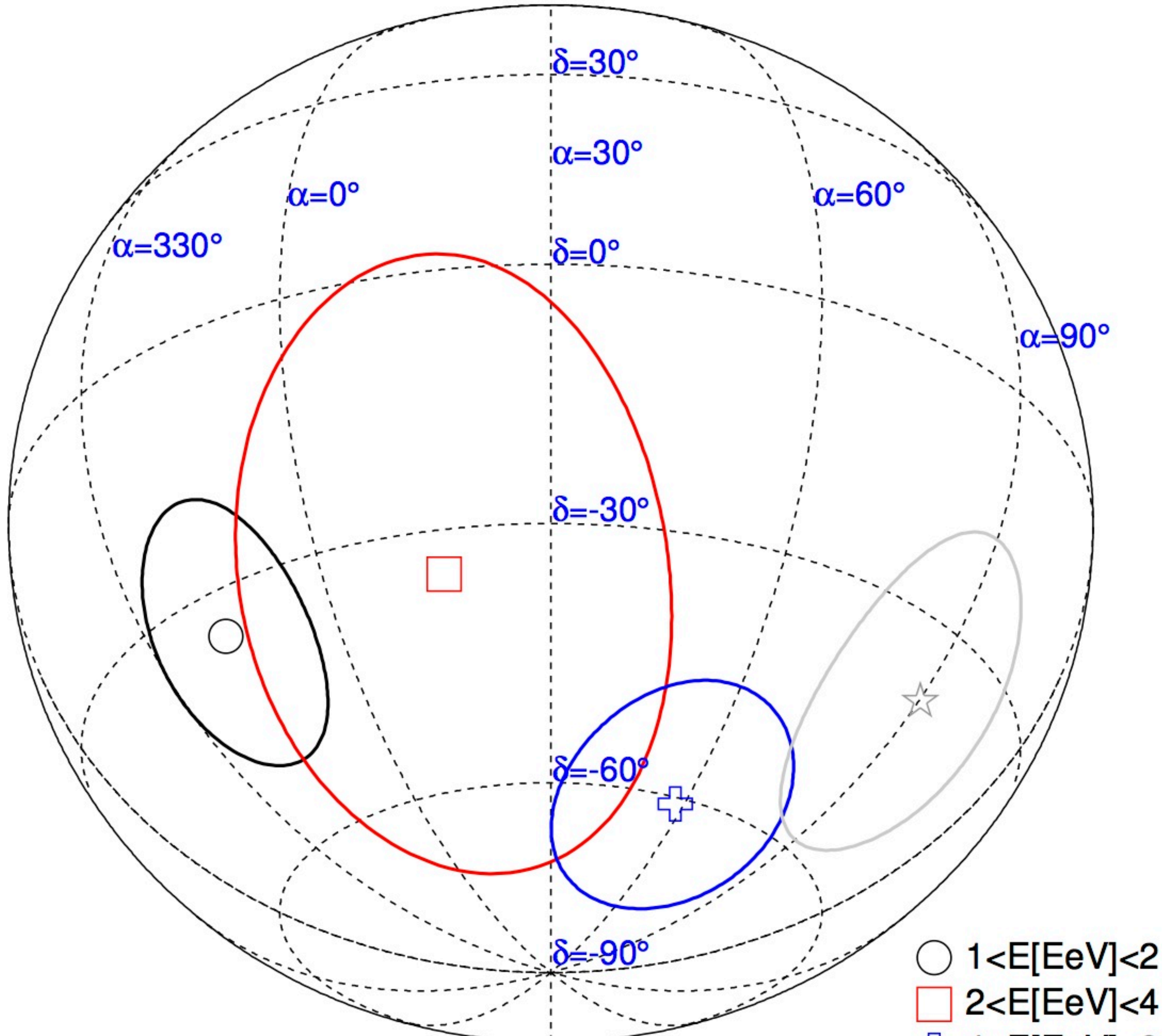
Signal has weakened since



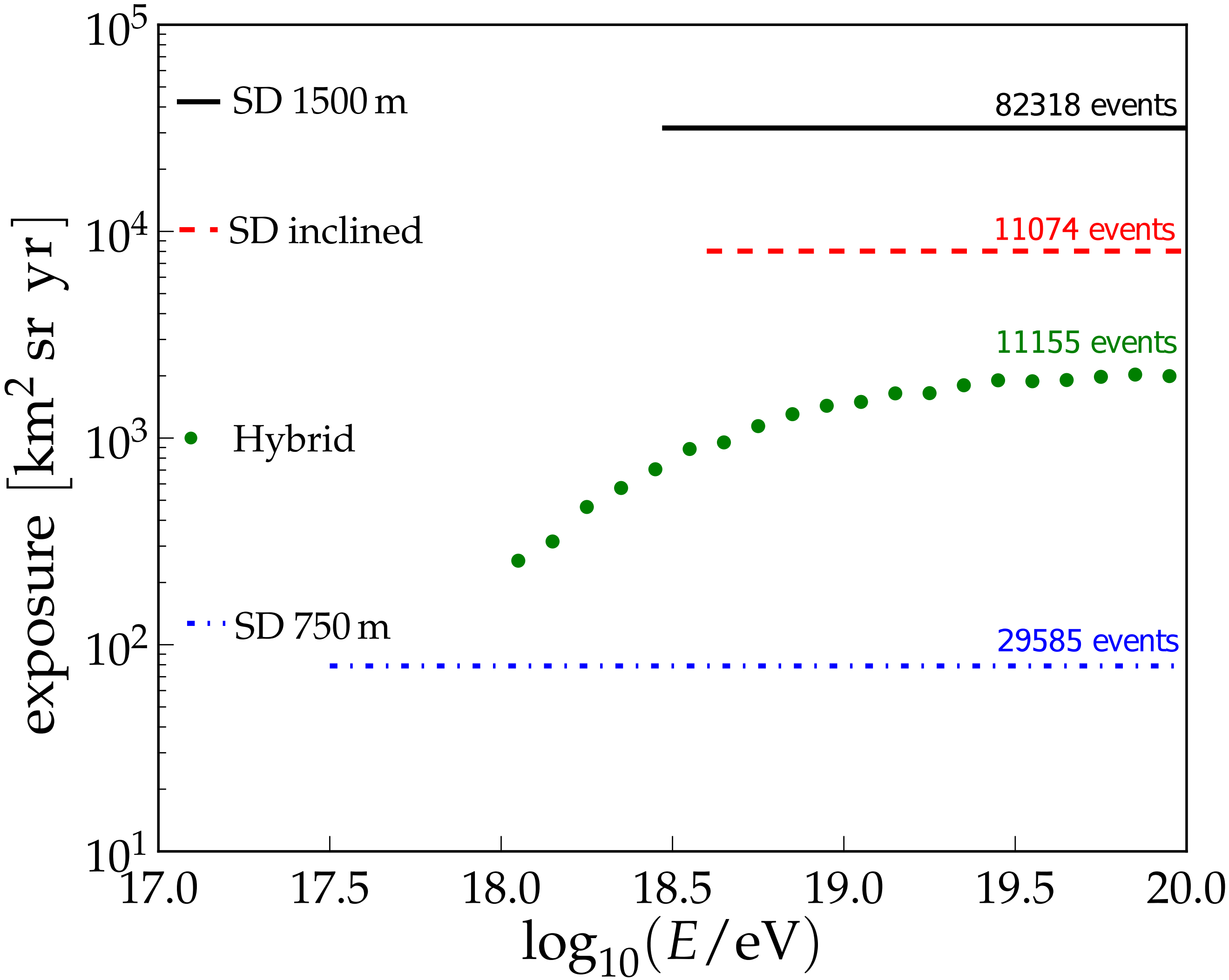
33+-5% 28/84 P=0.006 TA 40% 8/20 ISO 24%


E > 55 EeV
68% dispersion
95% dispersion
99.7% dispersion
data
Angular distance to Cen A (degrees)
N_obs - N_iso
10
8
6
4
2
0
-2
-4
-6
-8
0
5
10
15
20
25
30


E > 2.1 EeV
55EeV/(Z=26)
N_obs - N_iso
Angular distance to Cen A (degrees)
68% dispersion
95% dispersion
99.7% dispersion
data
300
200
100
0
-100
-200
-300
0
5
10
15
20
25
30



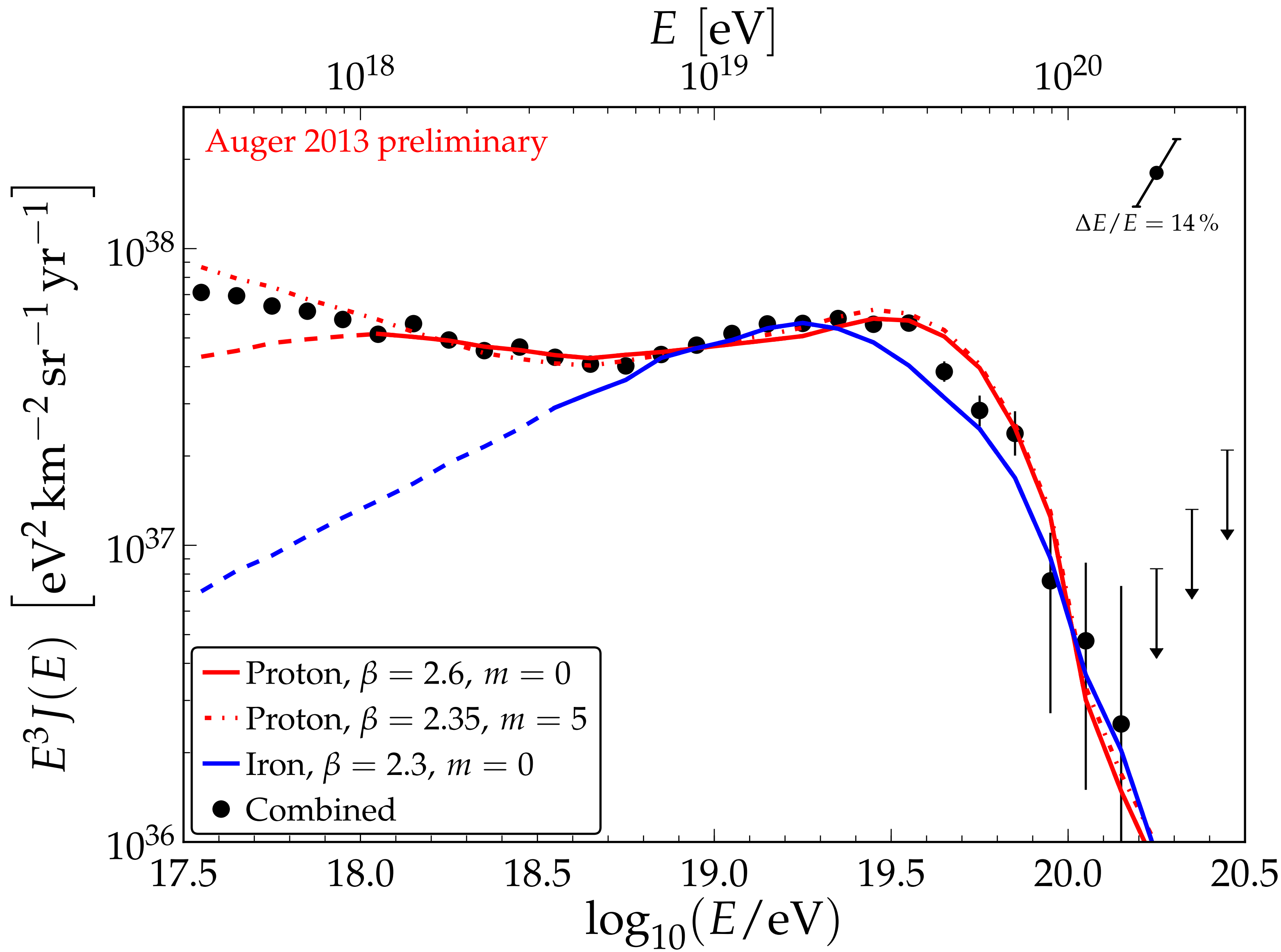
δ=30°
α=30°
α=0°
α=60°
α=330°
δ=0°
α=90°
δ=-30°
δ=-60°
δ=-90°
1<E[EeV]<2
2<E[EeV]<4
4<E[EeV]<8
E[EeV]>8



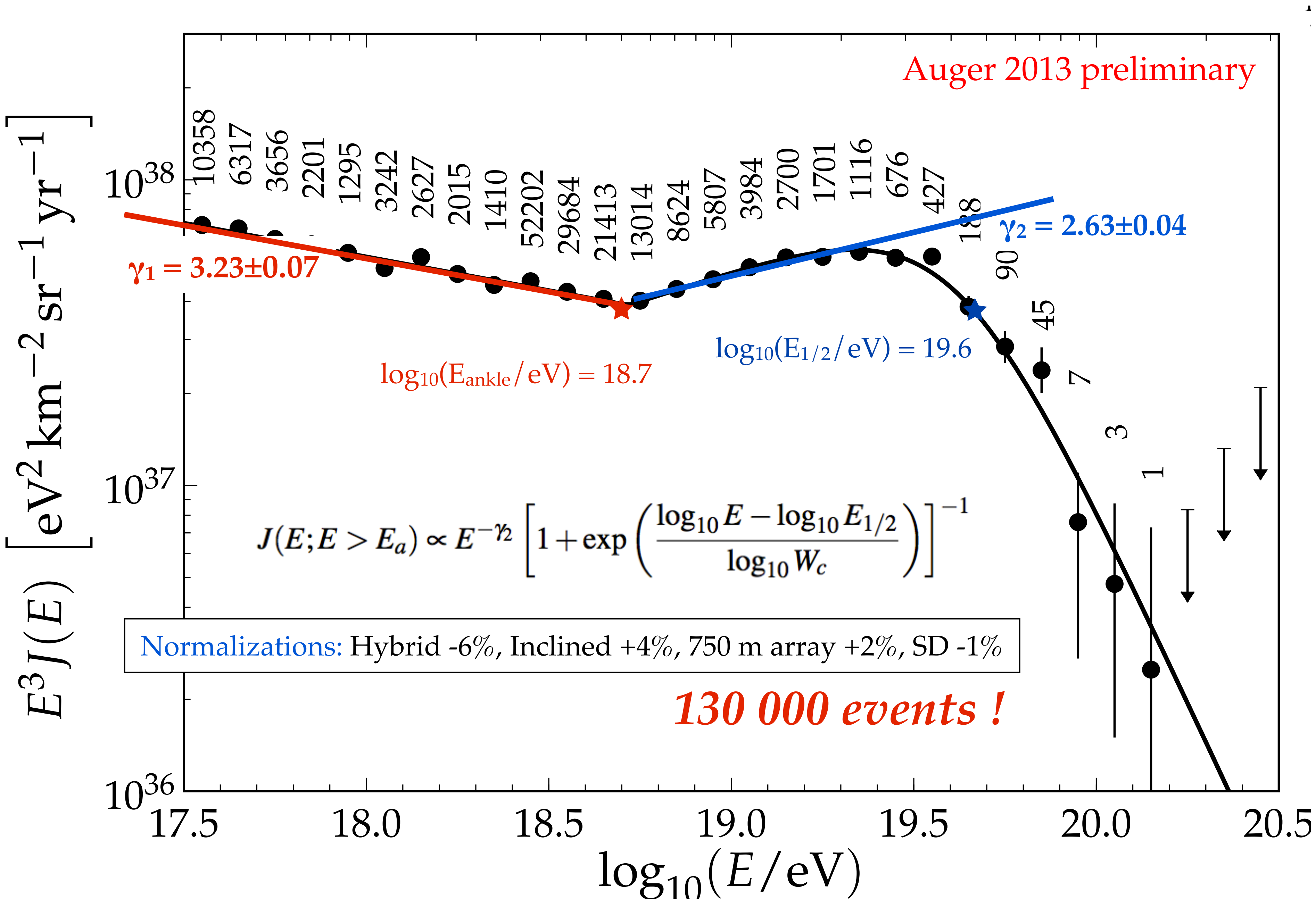
Exposures at 10 EeV:

[km^2 sr yr]

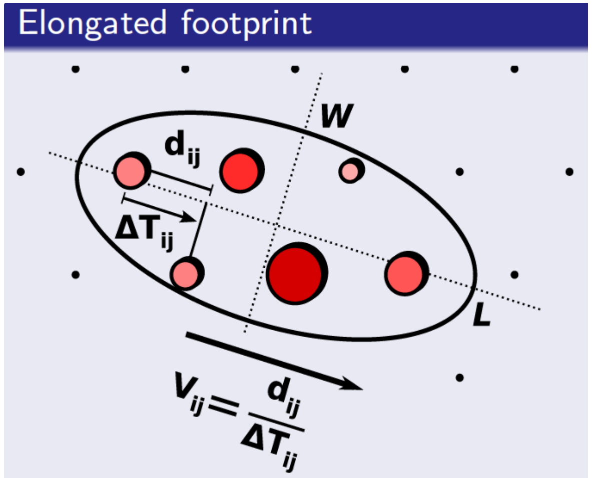
- SD vertical: 31645 ± 950
- SD inclined: 8027 ± 240
- Hybrid: 1496 ± 25
- SD 750 m: 79 ± 4



E [eV]
10^{18}
10^{19}
10^{20}
Auger 2013 preliminary
$\Delta E/E = 14\,\%$
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$
10^{38}
10^{37}
10^{36}
Proton, $\beta = 2.6$, $m = 0$
Proton, $\beta = 2.35$, $m = 5$
Iron, $\beta = 2.3$, $m = 0$
Combined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$



Auger 2013 preliminary
10358
6317
3656
2201
1295
3242
2627
2015
1410
52202
29684
21413
13014
8624
5807
3984
2700
1701
1116
676
427
188
90
45
7
3
1
$\gamma_1 = 3.23 \pm 0.07$
$\gamma_2 = 2.63 \pm 0.04$
$\log_{10}(E_{ankle}/eV) = 18.7$
$\log_{10}(E_{1/2}/eV) = 19.6$
$J(E; E > E_a) \propto E^{-\gamma_2} \left[1 + \exp\left(\frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1}$
Normalizations: Hybrid -6%, Inclined +4%, 750 m array +2%, SD -1%
130 000 events !
$E^3 J(E)$ $[\mathrm{eV}^2 \mathrm{km}^{-2} \mathrm{sr}^{-1} \mathrm{yr}^{-1}]$
10^{38}
10^{37}
10^{36}
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$



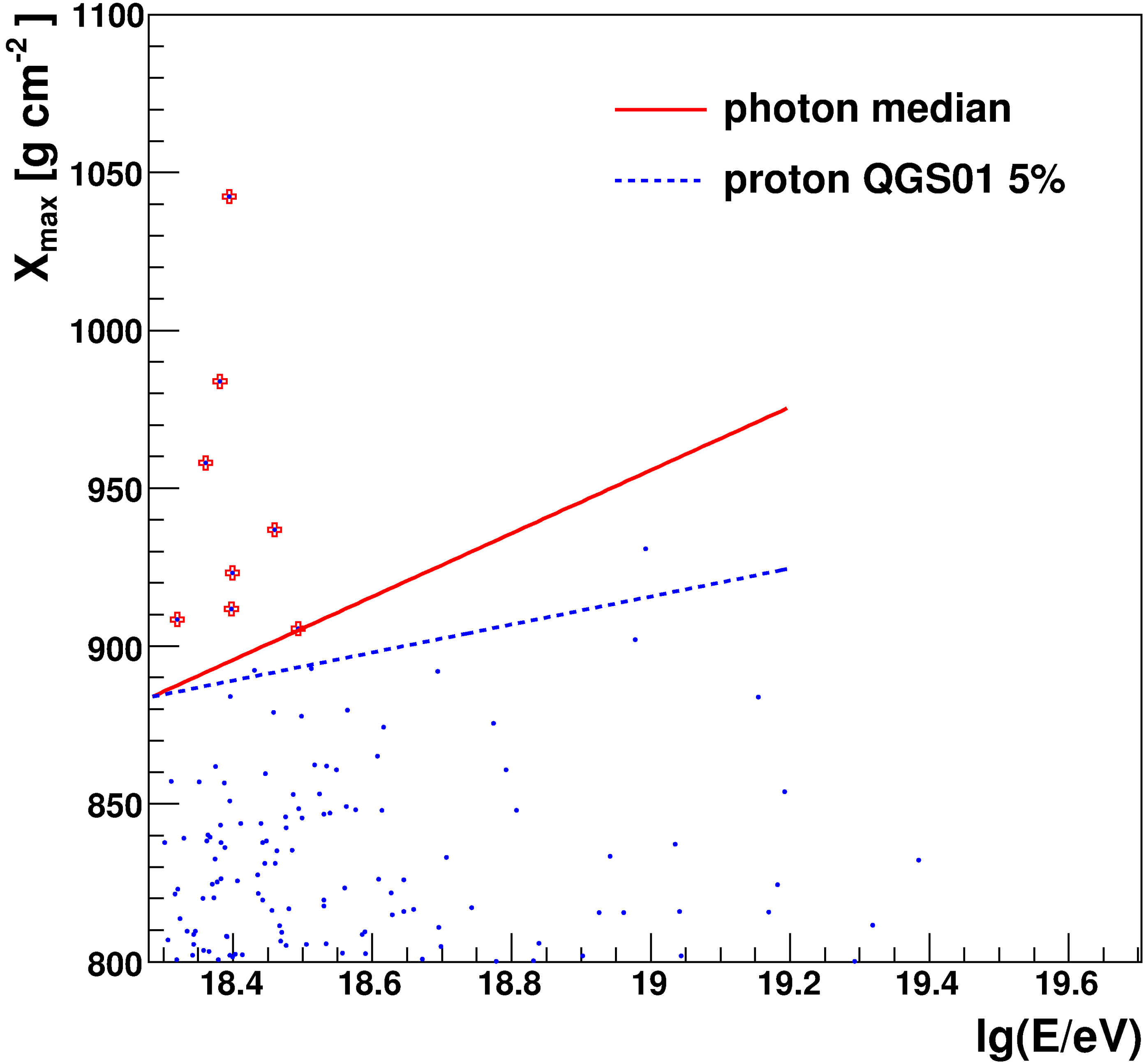
Inclined shower selection:

- shape (elongated footprint) : large L/W
- apparent speed of ground signal ~c & low RMS
- zenith angle θ_{rec} (only for downgoing)

ES	DGH (75°,90°)	DGL (60°,75°)
L/W > 5	L/W > 3	-
$\langle V \rangle \in (0.29, 0.31)$ m ns^{-1}	$\langle V \rangle < 0.313$ m ns^{-1}	-
RMS(V) < 0.08 m ns^{-1}	RMS(V)/V < 0.08	-
-	$\theta_{rec} > 75°$	$\theta_{rec} \in (58.5°, 76.5°)$

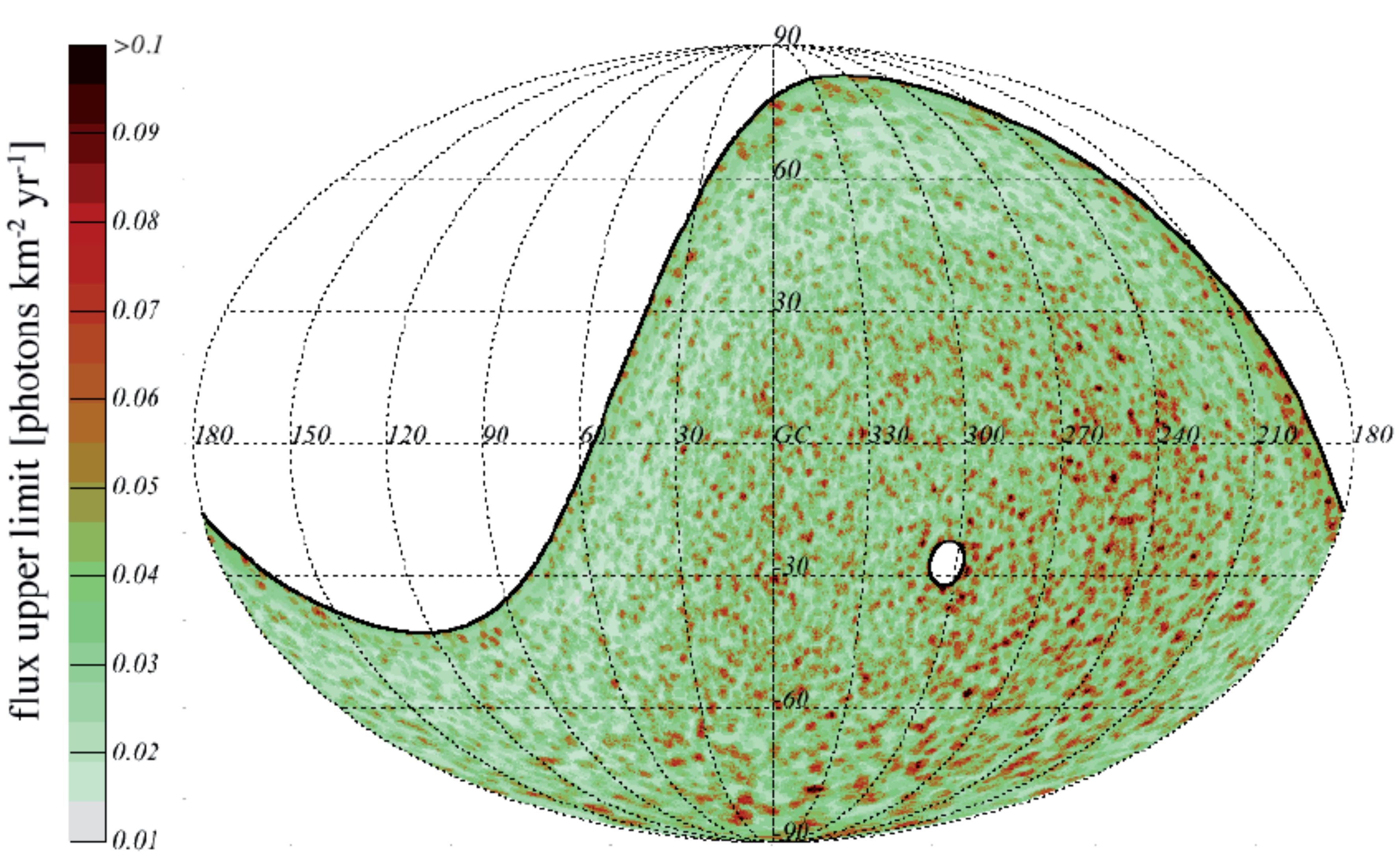
ν identification

ES	DGH (75°,90°)	DGL (60°,75°)
Data 1 Jan 2004 - 31 May 2010: ≥ 60% stations with ToT & AoP_{min} > 1.4	Fisher discriminant based on AoP of early stations	≥75% of stations close to shower core with ToT & Fisher discriminant based on AoP of early stations close to shower core
Data 1 Jun 2010 - 31 Dec 2012: <AoP> > 1.83 or AoP_{min} > 1.4 if 3 stations		



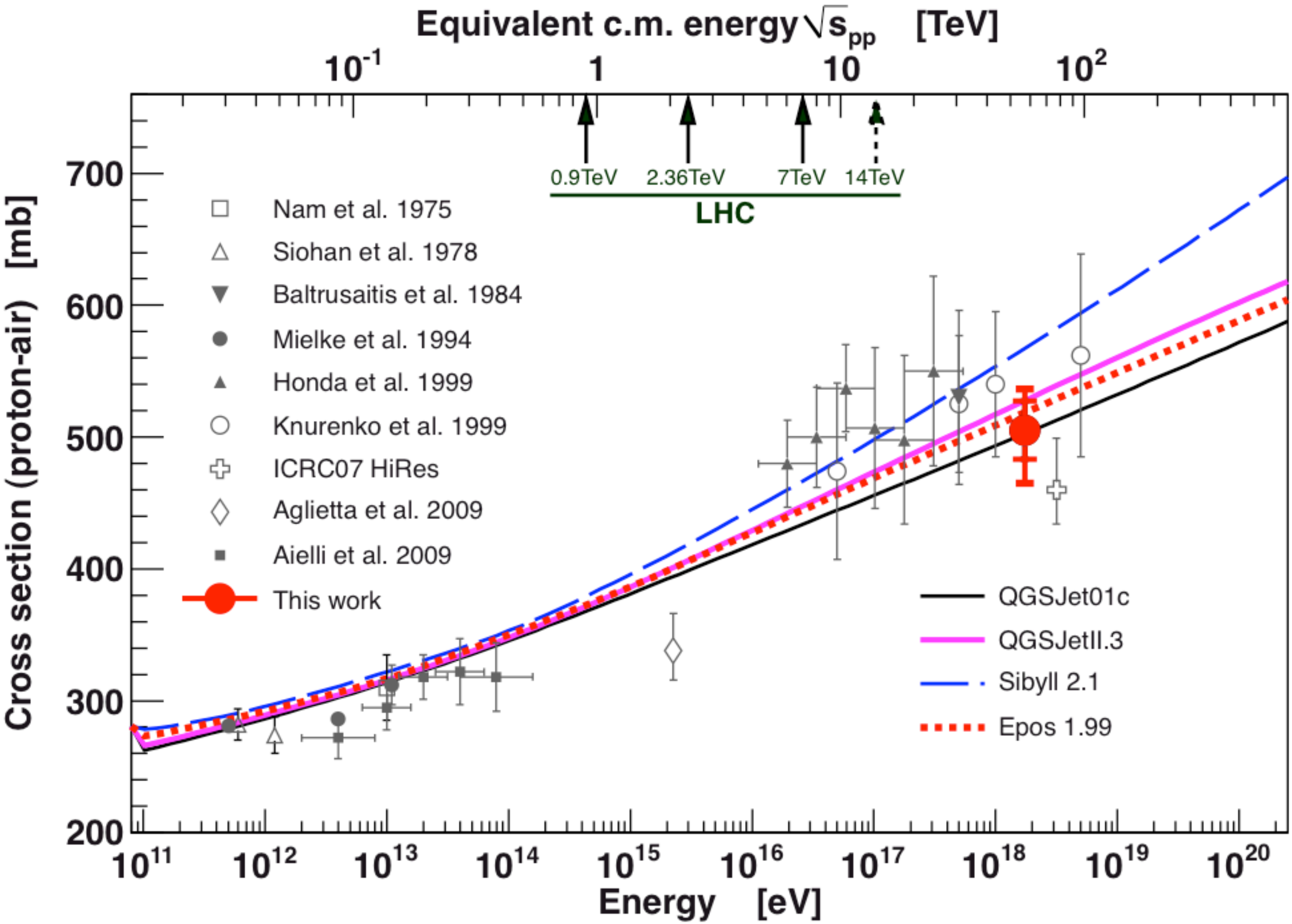
photon median
proton QGS01 5%
X_{max} [g cm^{-2}]
1100
1050
1000
950
900
850
800
18.4
18.6
18.8
19
19.2
19.4
19.6
lg(E/eV)

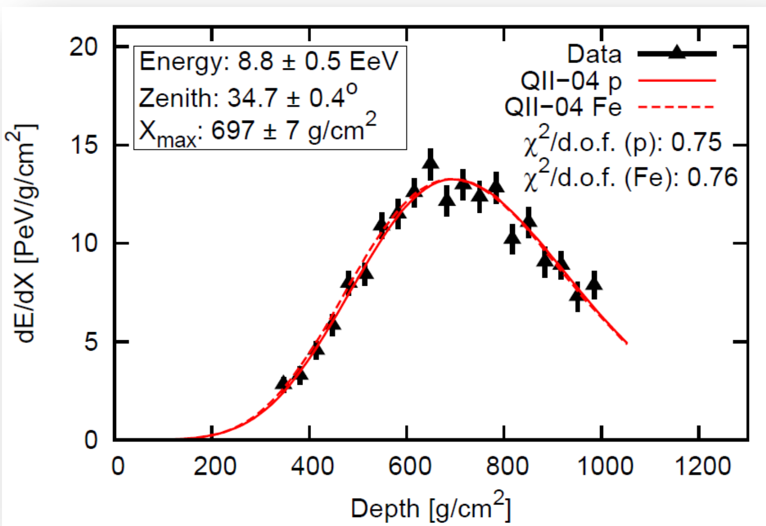
Upper limits to directional photon fluxes

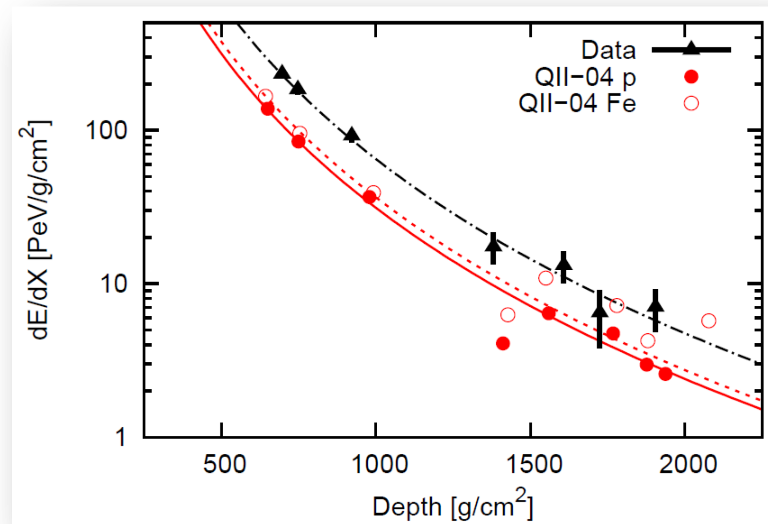


- No significan photon point source excess observed

$\sigma_{p\text{-}air}=505+\text{-}22_{stat}(+26\text{-}34)_{sys}$ mb




Energy: 8.8 ± 0.5 EeV
Zenith: 34.7 ± 0.4°
X_{max}: 697 ± 7 g/cm^2
Data
QII−04 p
QII−04 Fe
χ^2/d.o.f. (p): 0.75
χ^2/d.o.f. (Fe): 0.76
dE/dX [PeV/g/cm^2]
Depth [g/cm^2]


Data
QII−04 p
QII−04 Fe
dE/dX [PeV/g/cm^2]
Depth [g/cm^2]