Ultra High Energy Cosmic Rays & Recent Results from the Pierre Auger Observatory

WAPP 2011, Darjeeling J Knapp, U of Leeds, UK

- UHECRs
- Auger
- Spectrum
- Anisotropy
- Composition
- Hadronic Physics
- Exotics

Ultra-High Energy Cosmic Rays:

Astroparticles: particles from astrophysical sources

... The highest energy particles in the universe !!!!!

Energies:	keV ...	MeV ...	GeV ...	TeV ...	PeV ...	EeV ...	ZeV
	10^3 ...	10^6 ...	10^9 ...	10^{12} ...	10^{15} ...	10^{18} ...	10^{21} eV

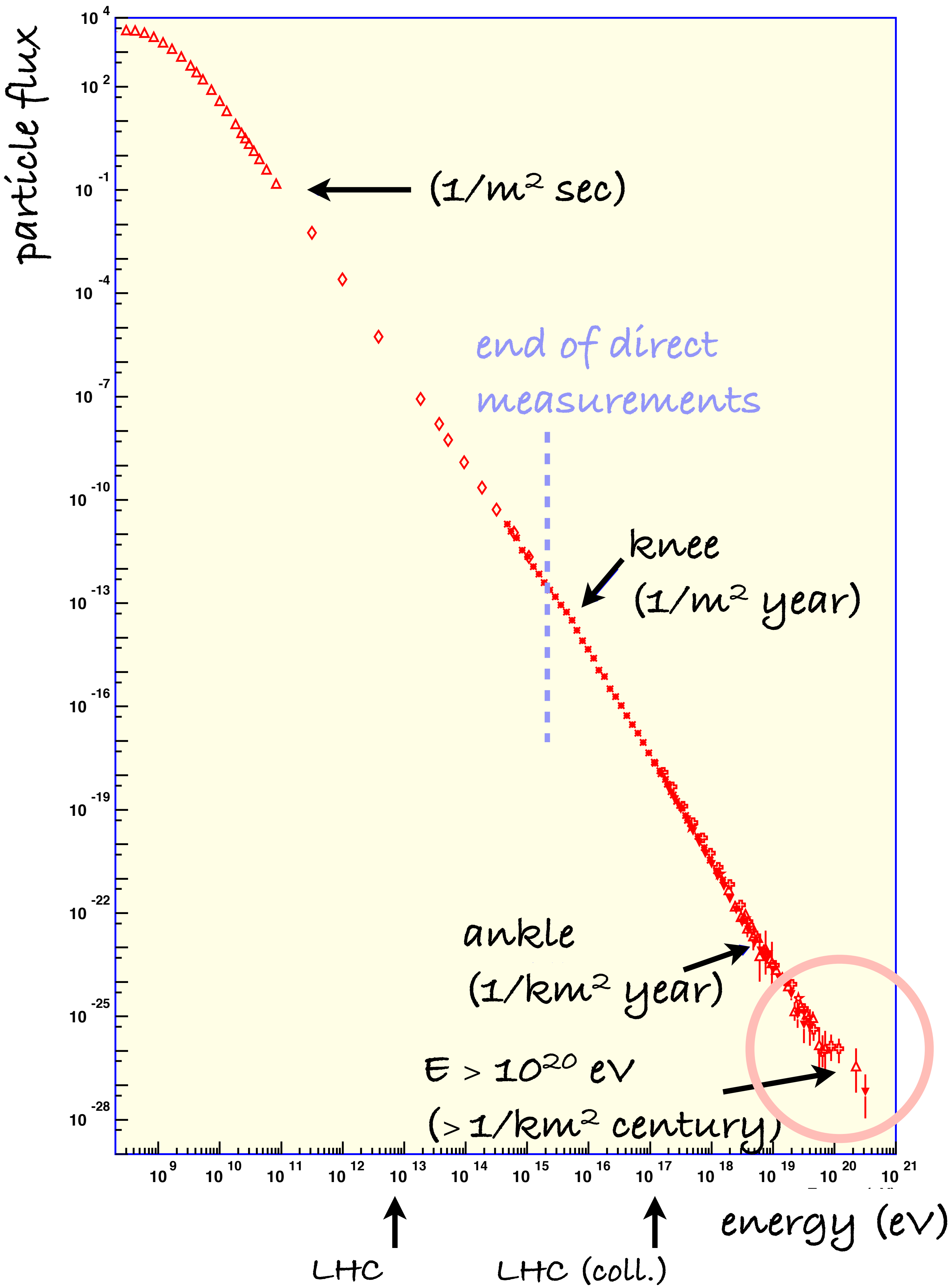
Cosmic Rays: p, He, ... Fe, ... fully ionised nuclei,

electrons

Photons: classical astronomy + high-energy γ-rays

Neutrinos: astrophysical ν (solar, SN, AGN, ...)

Flux of Cosmic Rays



12 orders of magnitude in energy,
33 " in flux !

10x up in energy, 500x down in flux

Highest energy events:
$\approx 3 \times 10^{20}$ eV

Not much structure in the spectrum:
A single mechanism at work ?

10^{20} eV particles do exist

There are Cosmic Particle Accelerators out there, going up to > 10^{20} eV !!

Where are they? How do they work?

Cosmic Rays: the real high-energy physics

Cosmic Rays, Gamma Rays and Neutrinos are linked

$$p, He, \ldots Fe \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_e + \nu_{\mu}$$

$$\pi^0 \rightarrow \gamma\gamma$$

CRs can be accelerated
in electromagnetic fields,
but are deflected in mag. fields.

νs travel straight,
but are very
difficult to detect

γs travel in straight lines,
but can't travel far
at high energies

point back at sources
"astronomy"

As Cosmic Rays exist,
also γ and ν must exist
at somewhat lower energies.

Direct measurements impossible for $E > 10^{15}$ eV.

Measure reaction products of primaries in large, natural absorber : Air showers

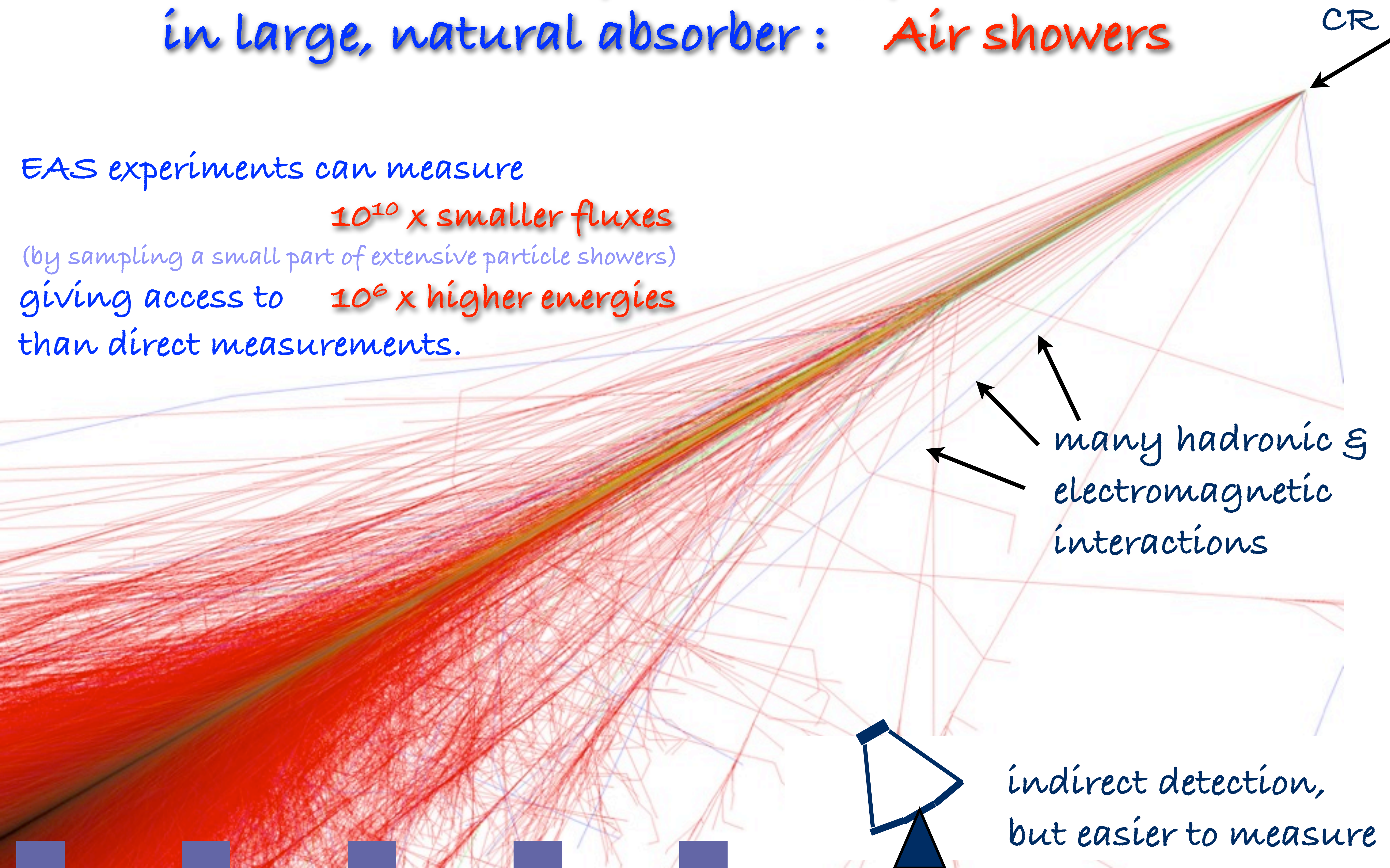
EAS experiments can measure

10^{10} x smaller fluxes

(by sampling a small part of extensive particle showers)

giving access to 10^{6} x higher energies

than direct measurements.



Unknown at high energies :

- elemental composition (p, He, O, ... Fe, γ , ν)
- energy spectrum
- details of nuclear and hadronic interactions

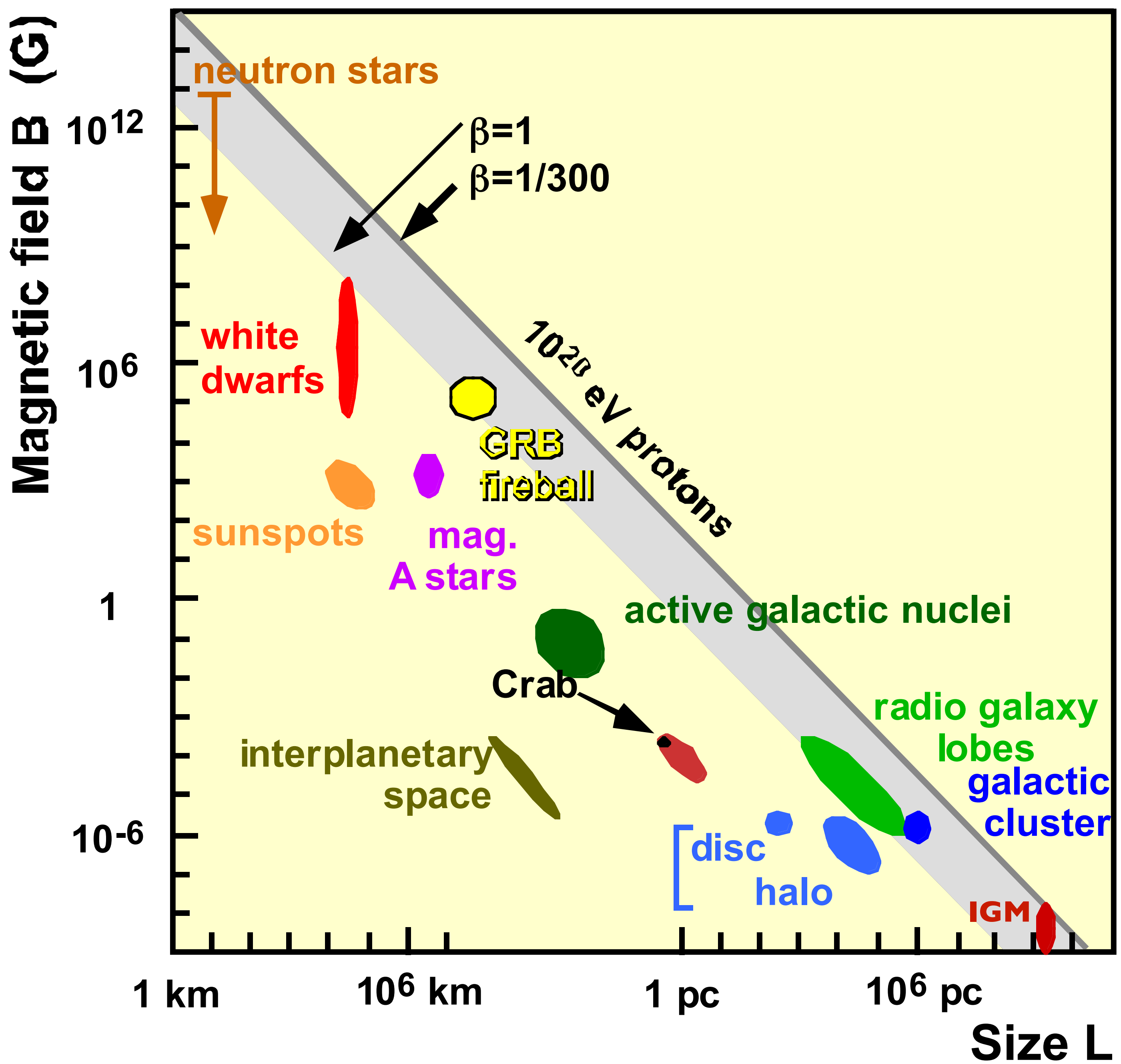
  Construct an air shower model based on reliable particle physics data and theories at lower energies. Extrapolate it to the UHECR region.

Find consistent description of all points (■) simultaneously.

Requires some iteration ...

A difficult problem ...

Possible Acceleration Sites (>10^{20} eV)



Michael Hillas

$B_{\mu G} \times L_{kpc} > 2\ (c/V)\ E_{EeV} / Z$

to fit gyroradius within L and to allow particles to diffuse during acceleration

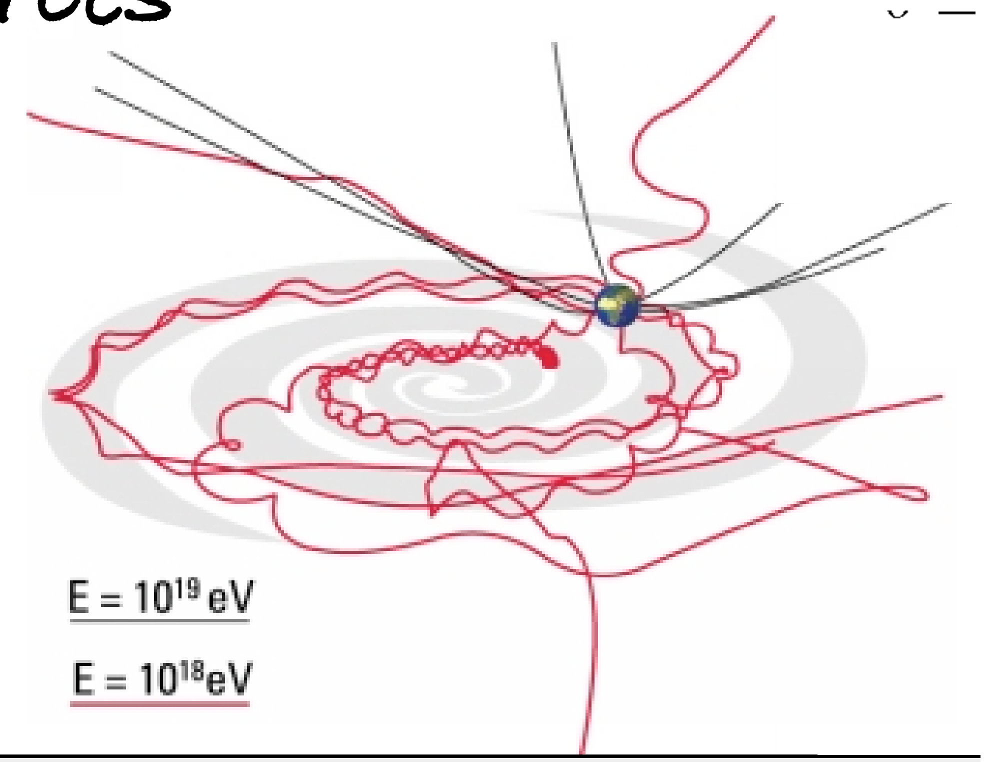
But also:
energy gain should be larger than losses

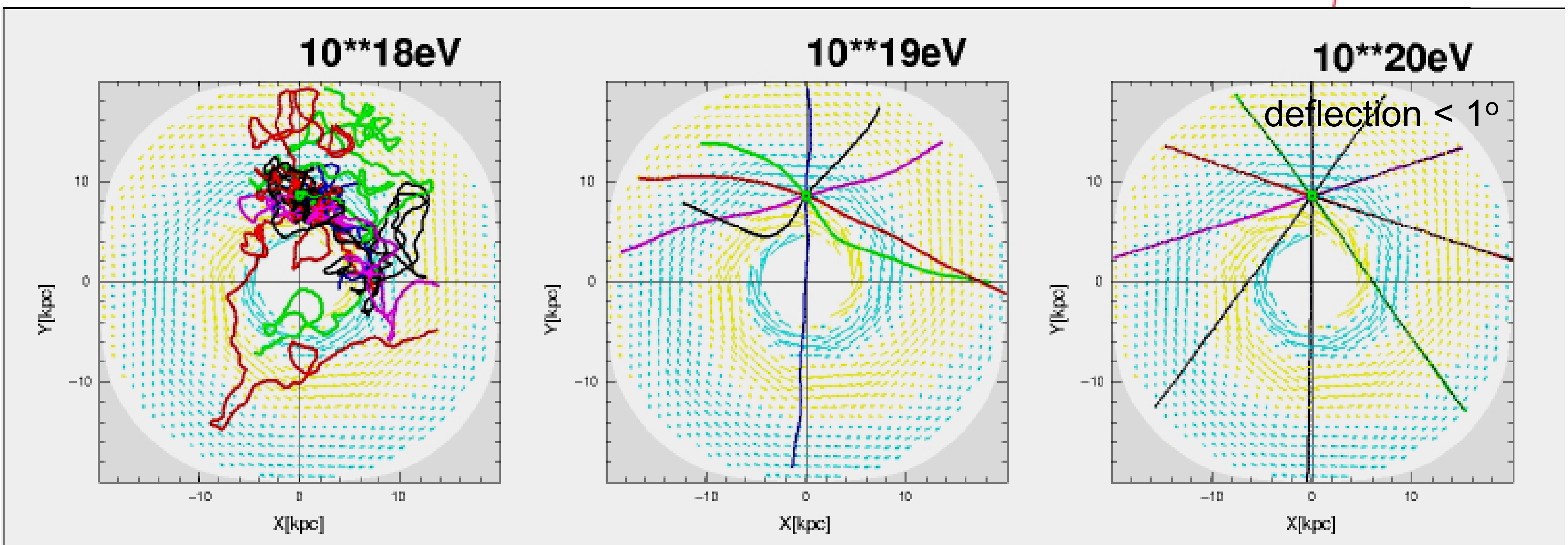
No obvious candidates.

Highest Energy Particles are not deflected much !

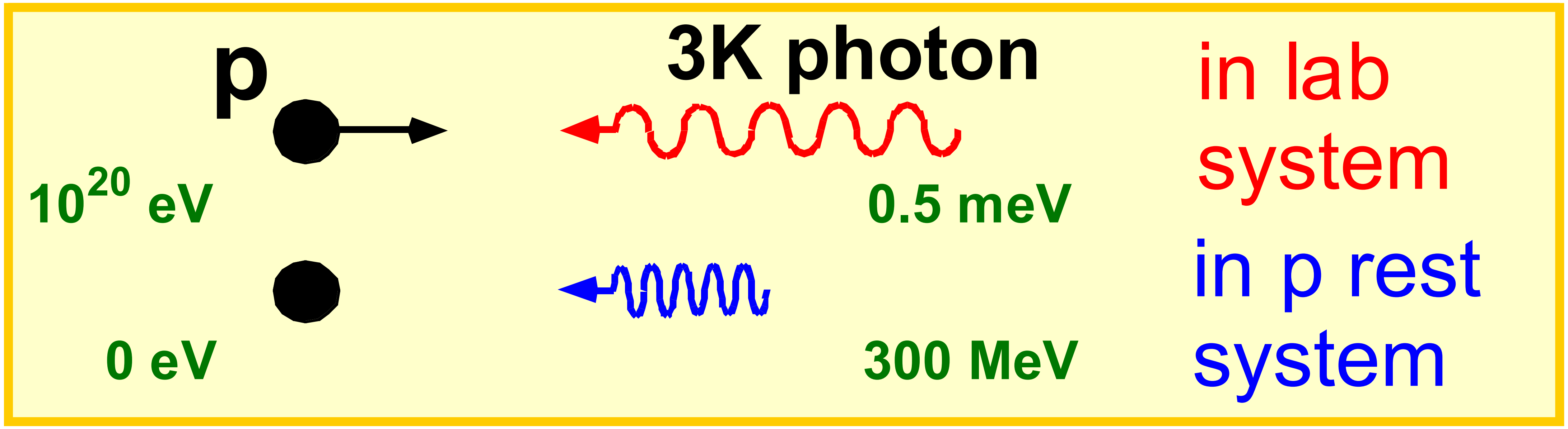
i.e. CR start pointing back at sources

"Charged particle astronomy"





… and sources must be close for $E > \text{few} \times 10^{19}$ eV.



$$p + \gamma_{3K} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \quad (\rightarrow \gamma)$$

$$\rightarrow n + \pi^{+} \quad (\rightarrow \nu)$$

photo - pion production

$$^{56}Fe + \gamma_{3K} \rightarrow {}^{55}Fe + n$$

photo dissociation

Greisen (1966)

Zatsepin & Kuzmin (1966)

universe becomes opaque for $E > \text{few} \times 10^{19}$ eV.

The Pierre Auger Observatory

"What is the origin of the Ultra High Energy Cosmic Rays ?"

(UHECRs: > 10^{19} eV)

Measure them with unprecedented statistics and quality.

Where do UHECRs come from?
What are they?
How are they accelerated?
Does their spectrum end?

Extensive Air Shower:

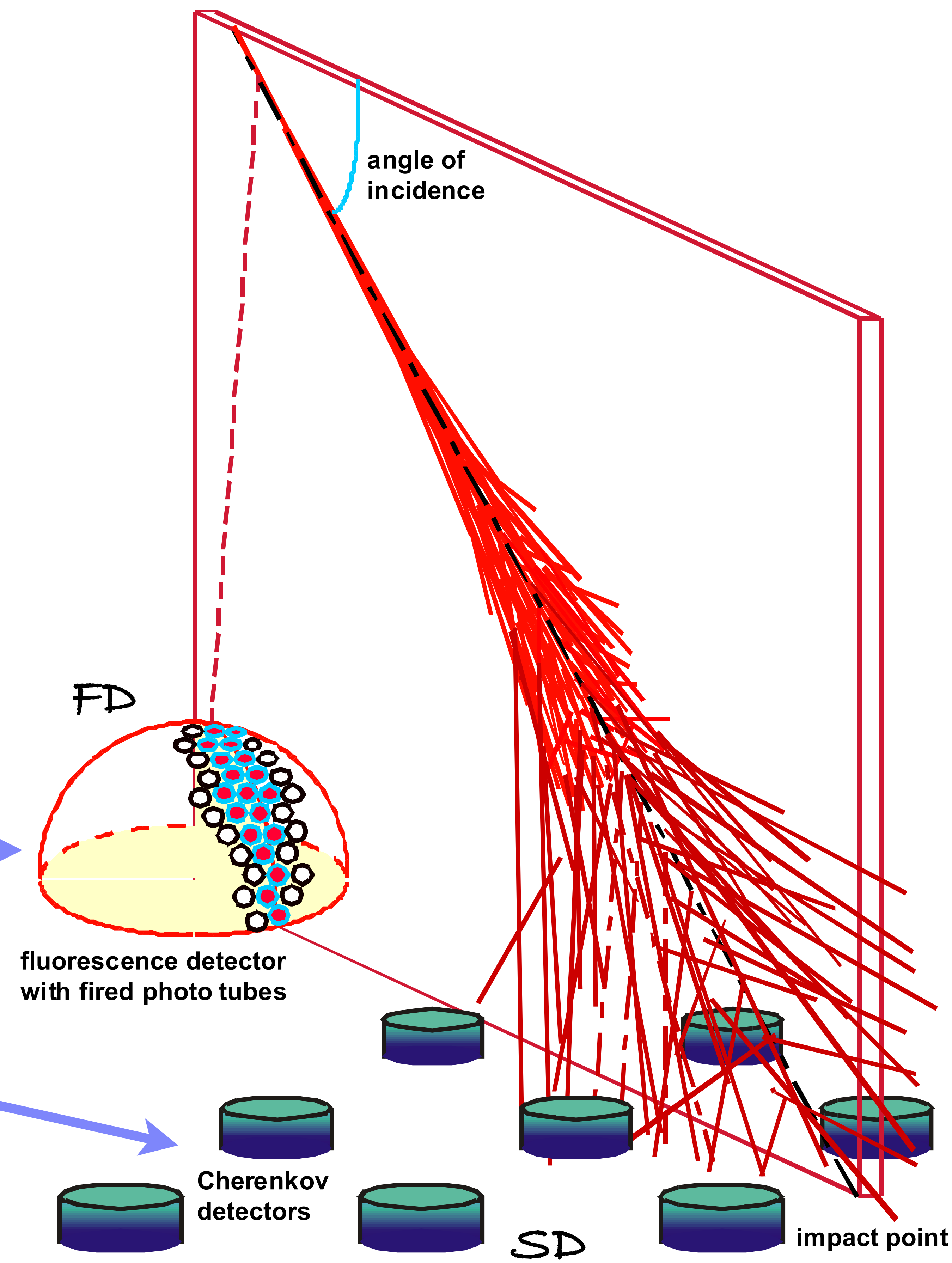
indirect measurement,
shape and particle content

Auger: Hybrid Detector

measure extensive air shower with:

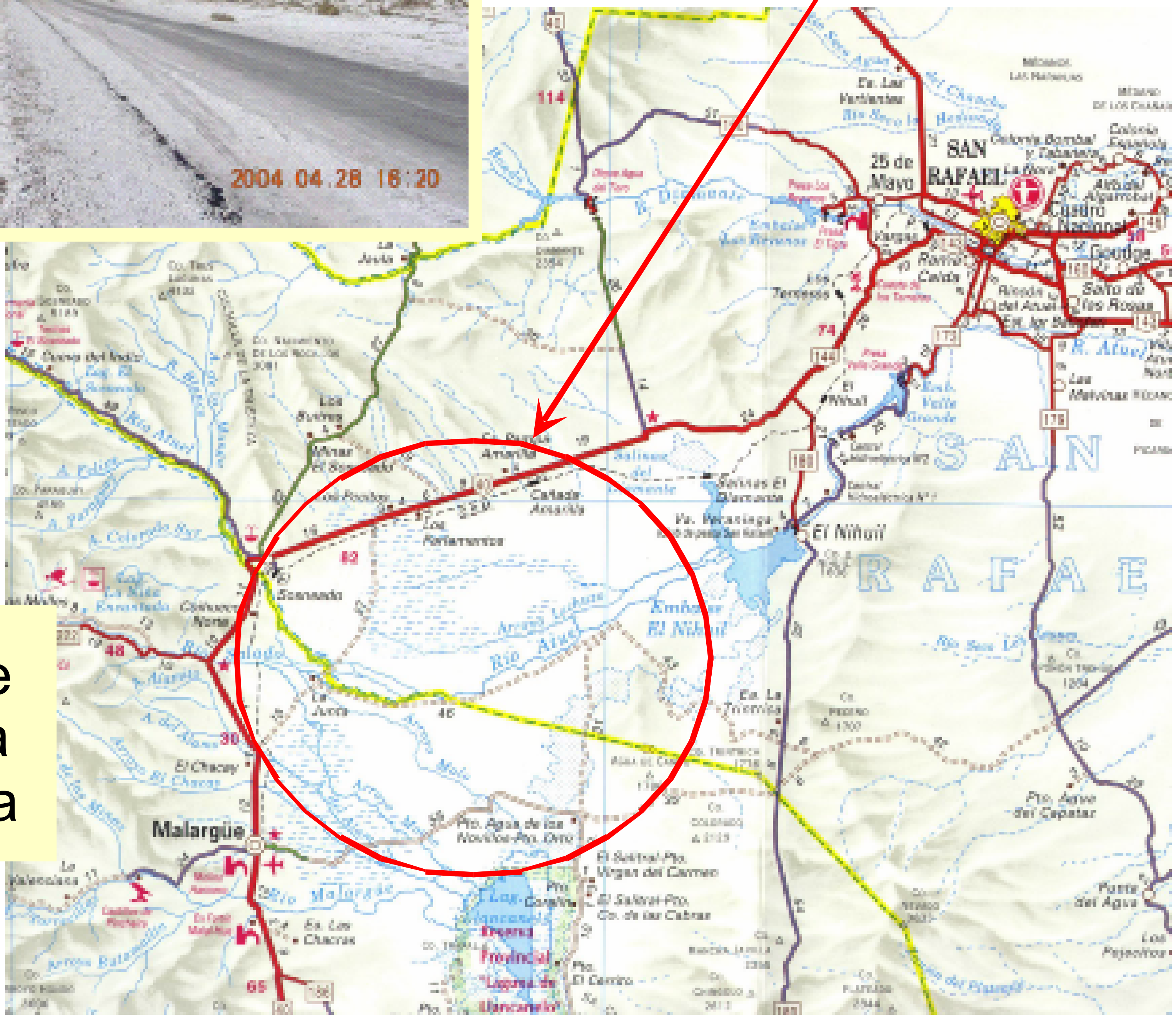
24 Fluorescence telescopes
$30^o \times 30^o$ FoV, 10% duty cycle,
good energy resolution

array of 1600 water Cherenkov tanks
on 3000 km^2, 100% duty cycle,
well-known aperture



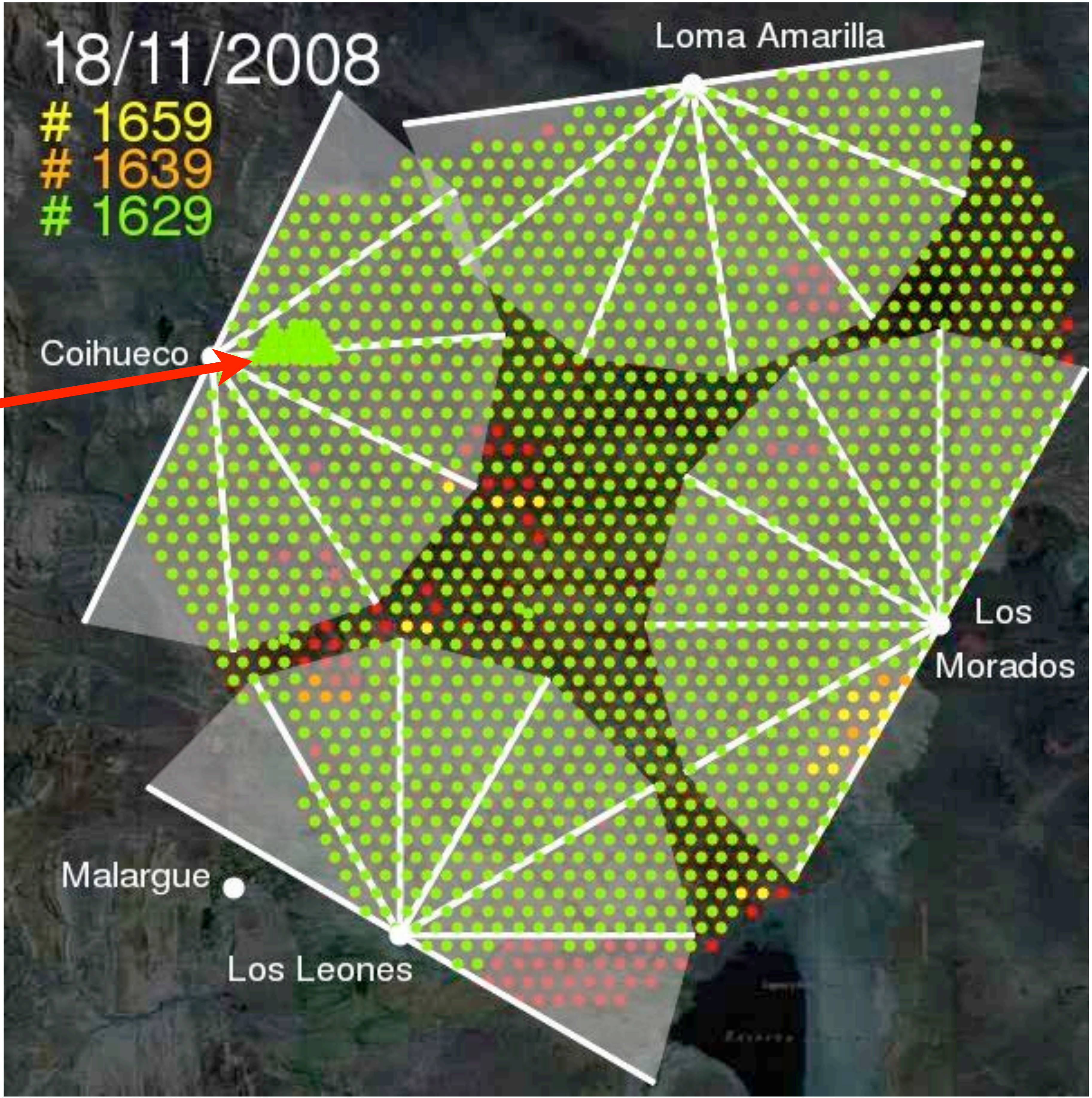
Auger South

(1400 m a.s.l.,
35.2° S, 69.2° W)



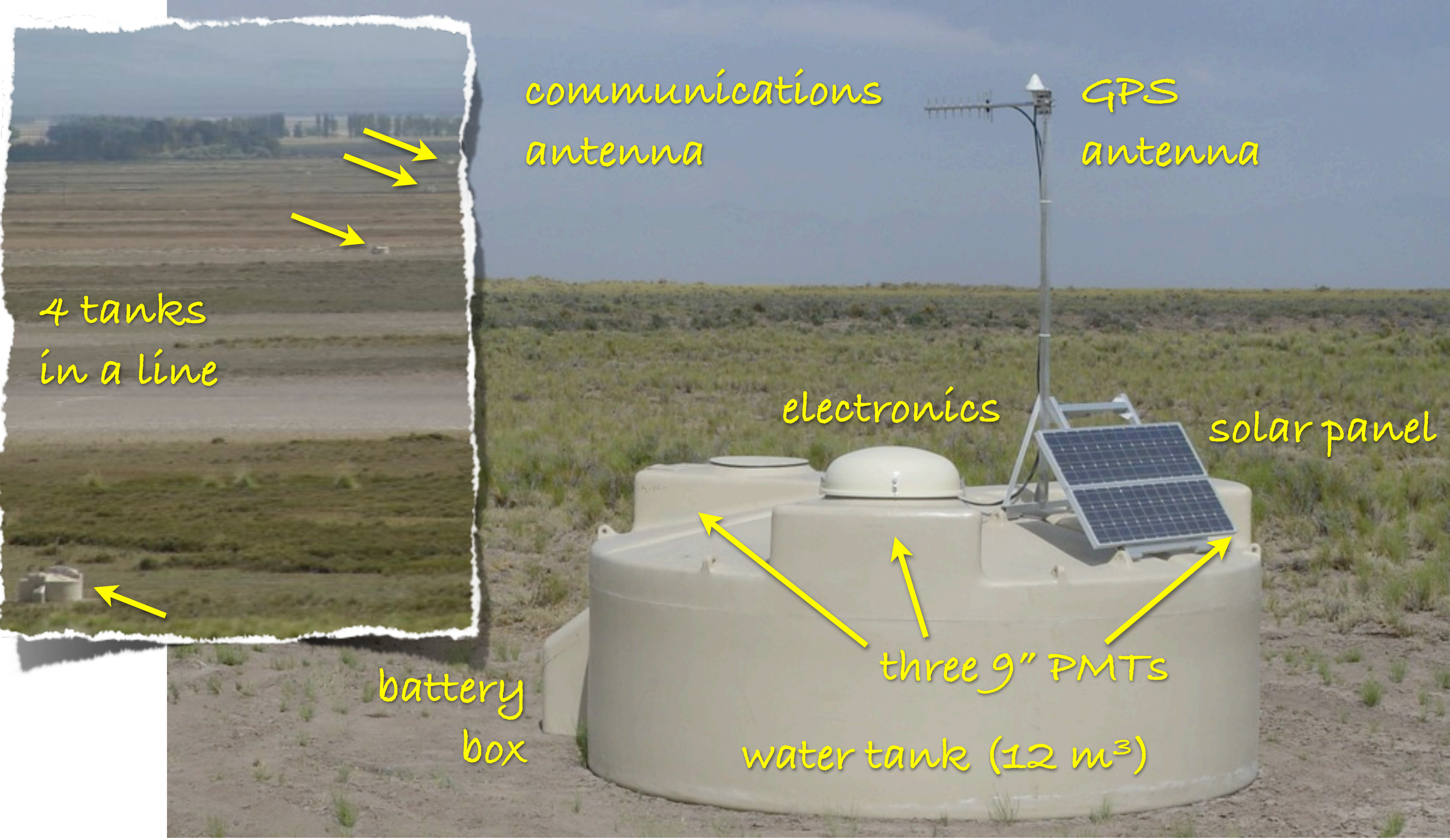
Malargüe
Mendoza
Argentina

"Completion" Nov 2008

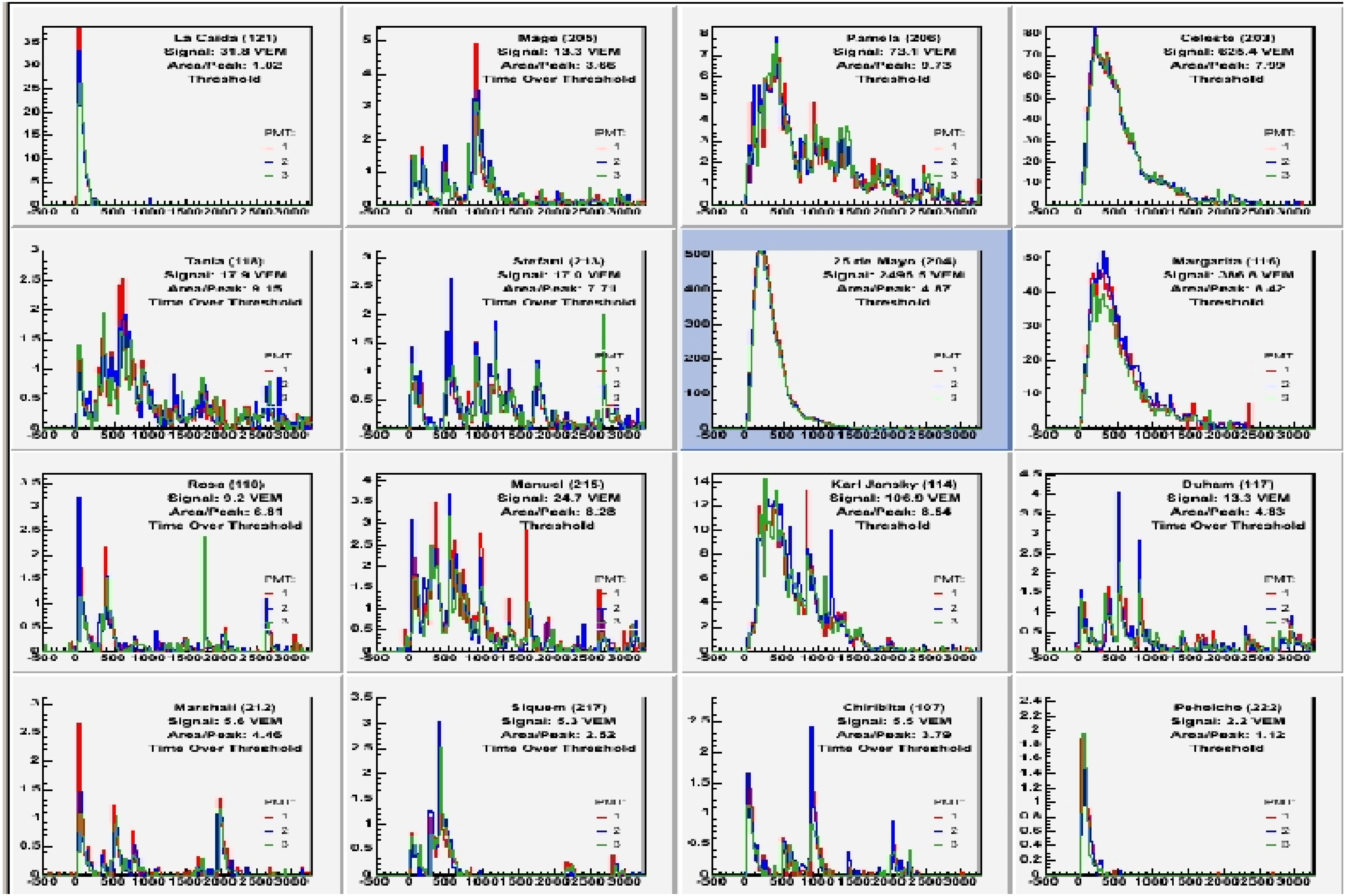


infill array

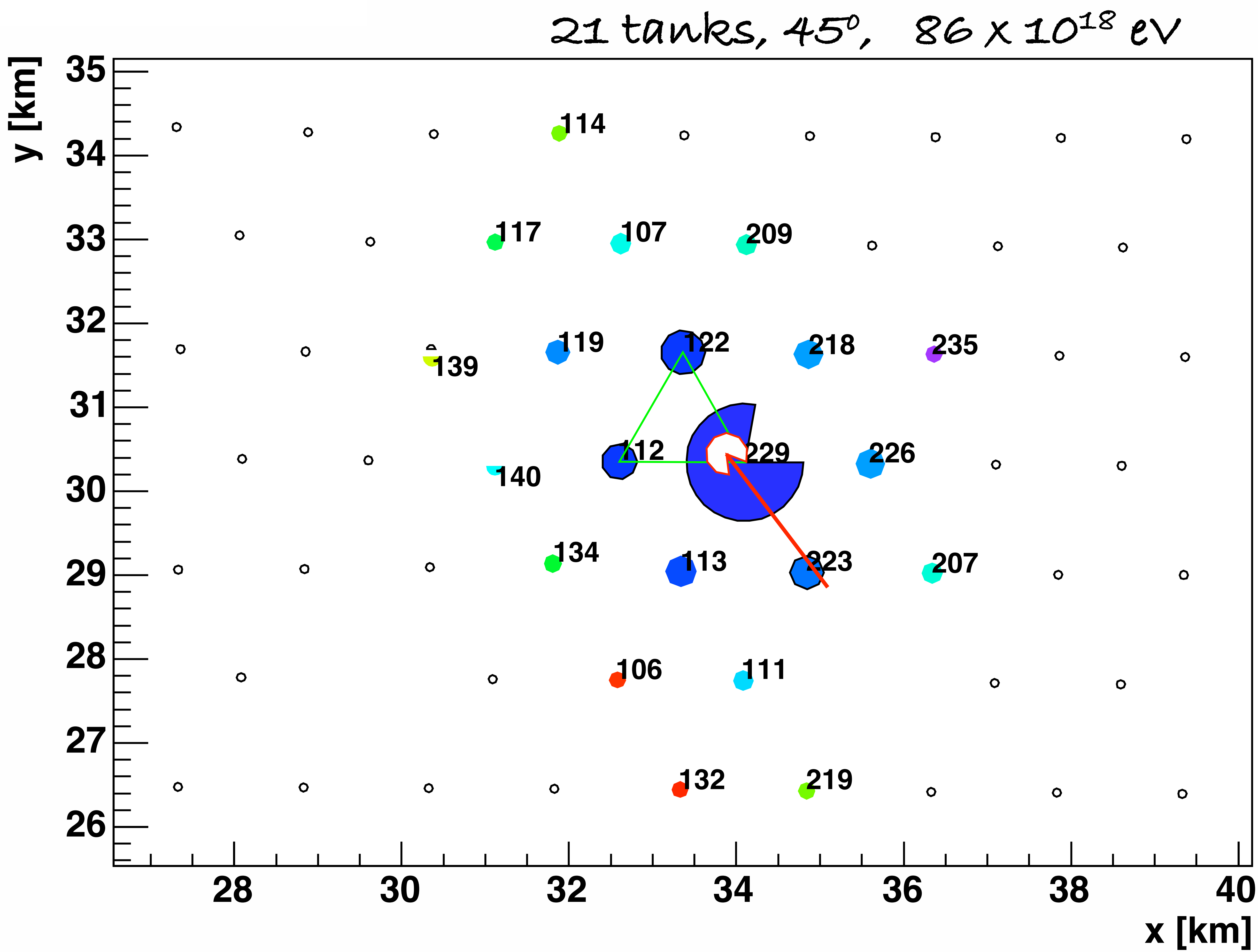
Inauguration
Nov 2009



>1600 tanks deployed over 3000 km²
triangular grid, 1.5 km distance

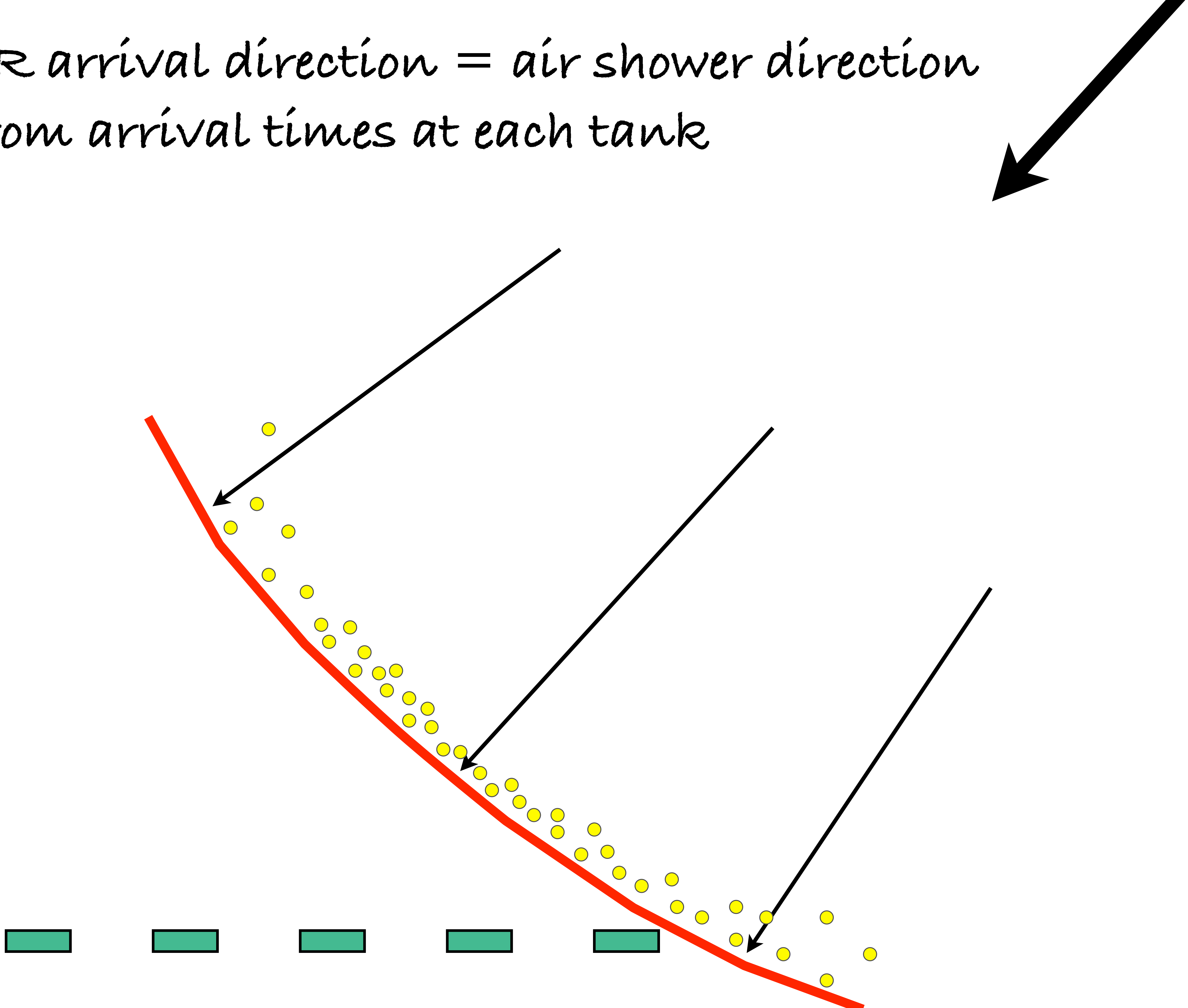


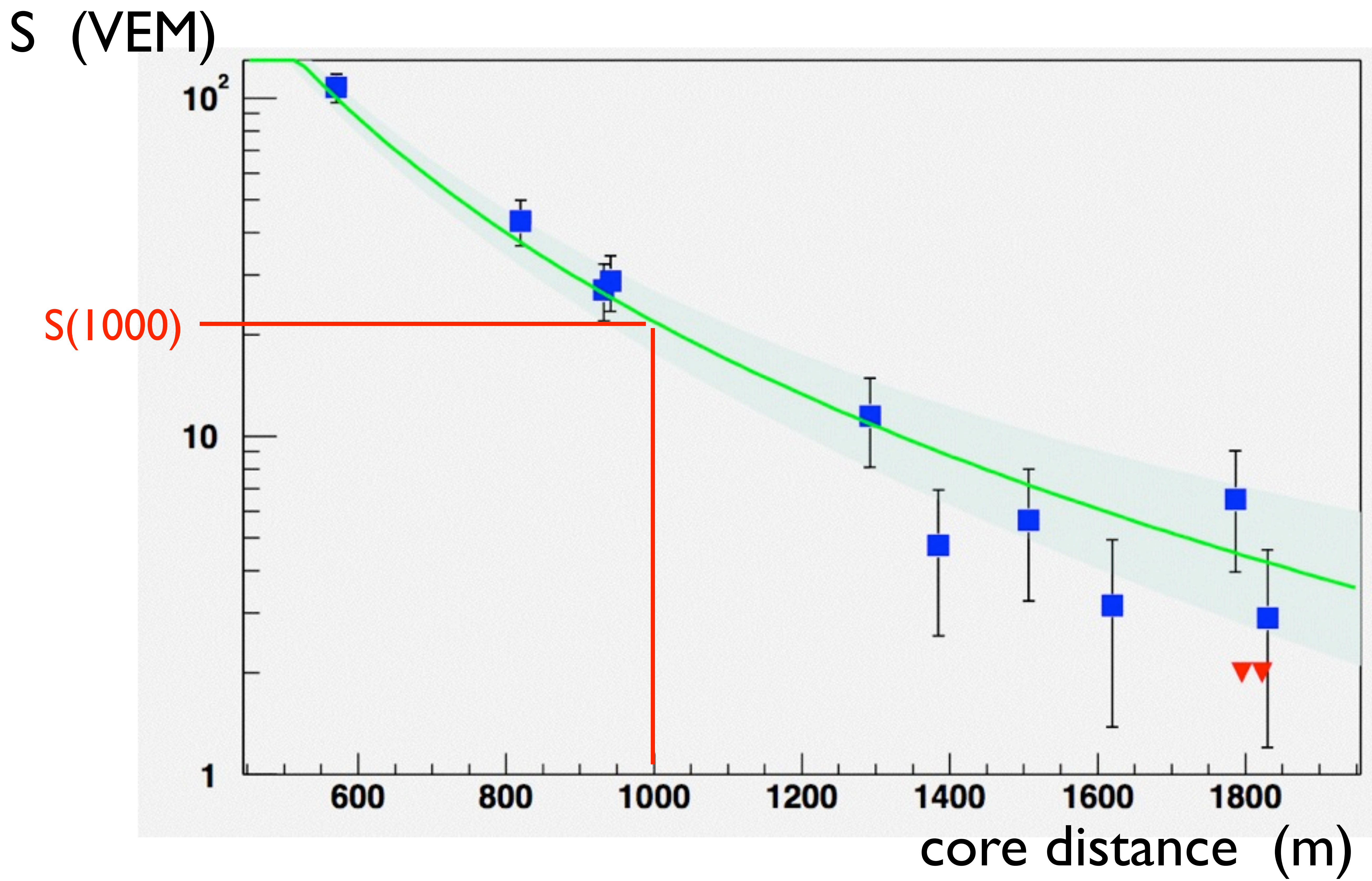
High & smooth pulses close to shower core, low & spiky pulses far away.



21 tanks, 45°, 86 x 10^18 eV
y [km]
x [km]
35
34
33
32
31
30
29
28
27
26
28
30
32
34
36
38
40
114
117
107
209
119
122
218
235
139
112
229
226
140
134
113
223
207
106
111
132
219

CR arrival direction = air shower direction
from arrival times at each tank





S(1000) is a good SD-only parameter to estimate the energy.

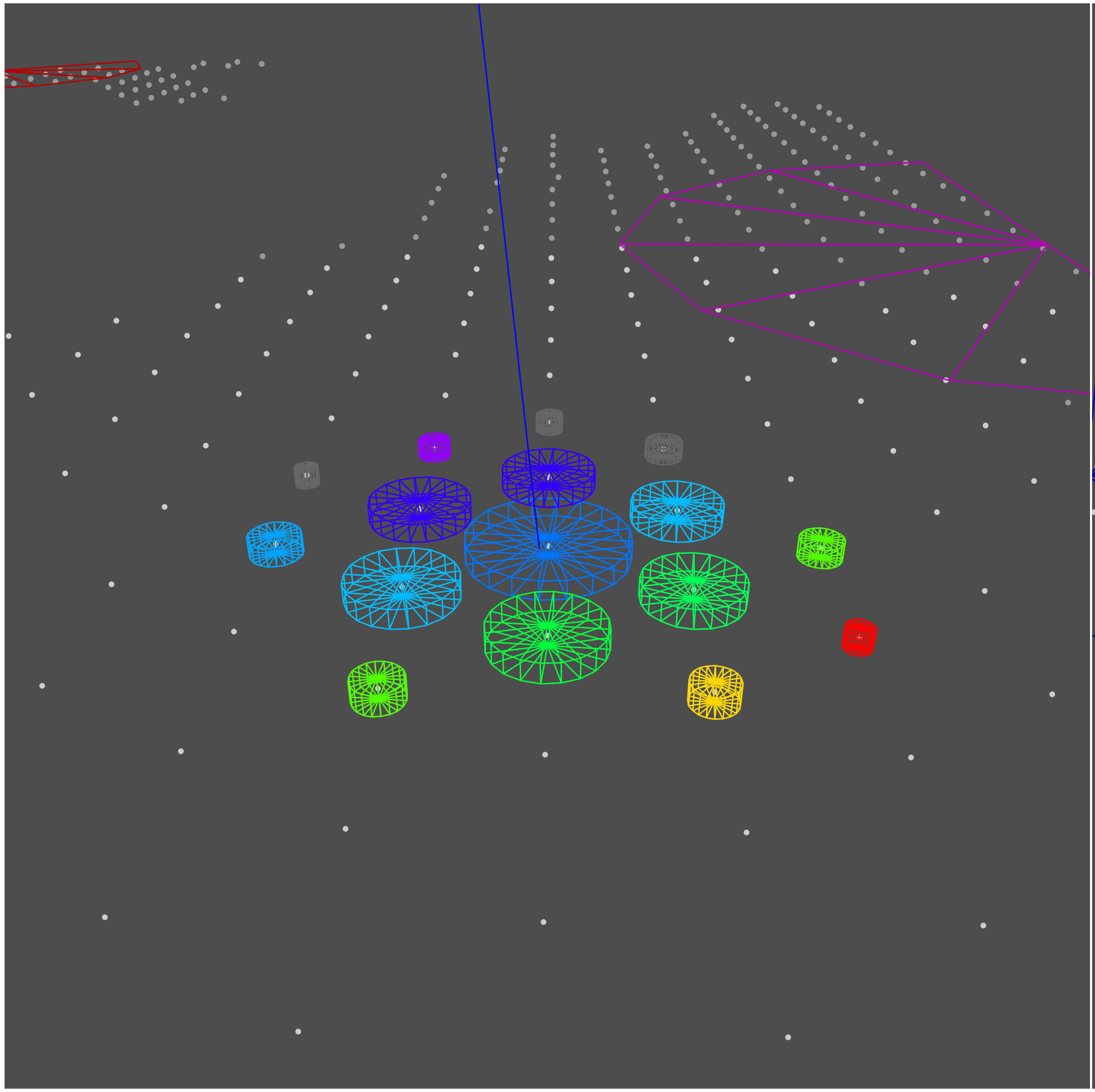
E as function of S(1000): either from MC

or from cross-calibration with FD.

some of the highest energy SD events:

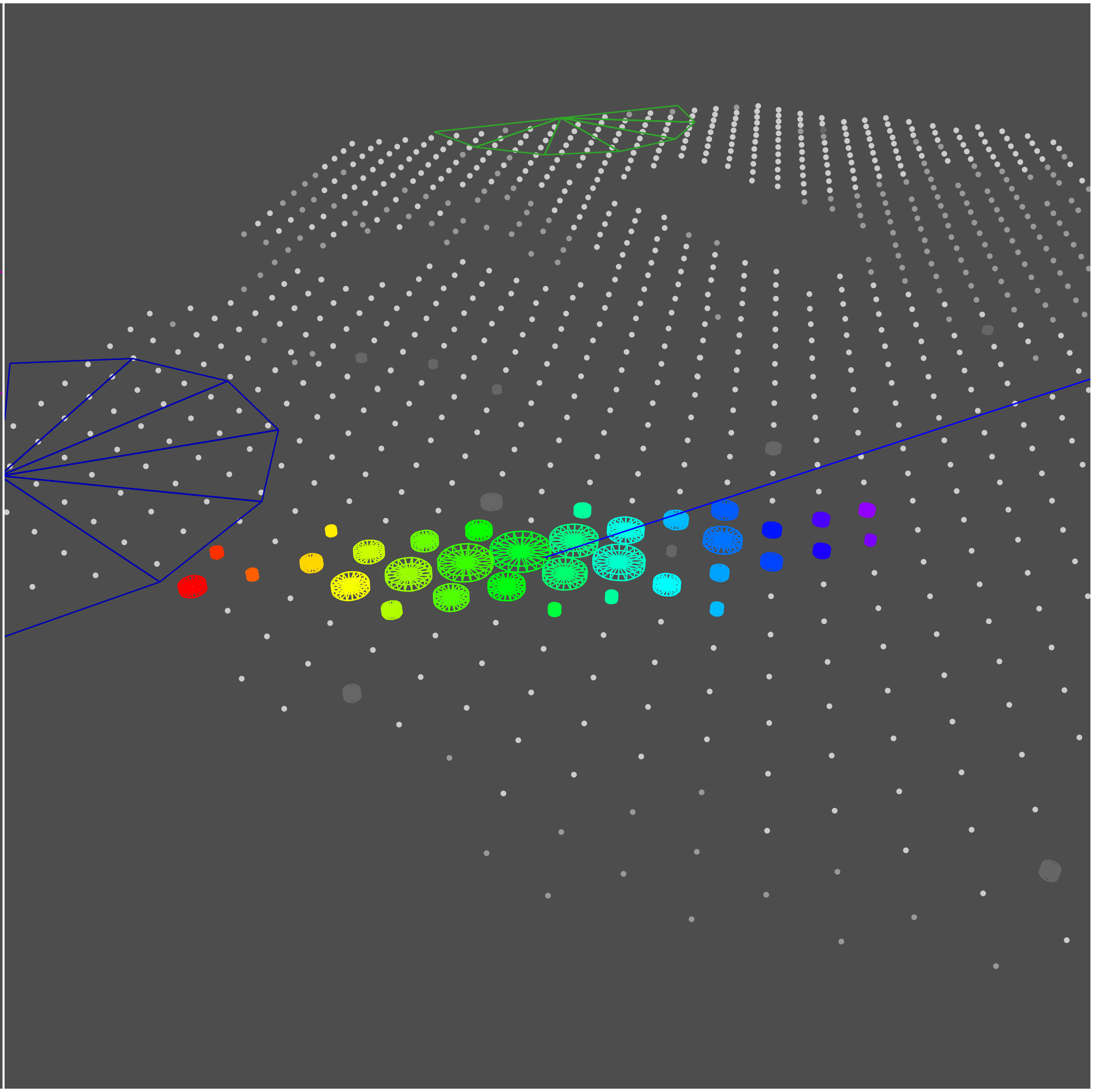
near vertical

E = 1.67 x 10^{20} eV θ = 14°

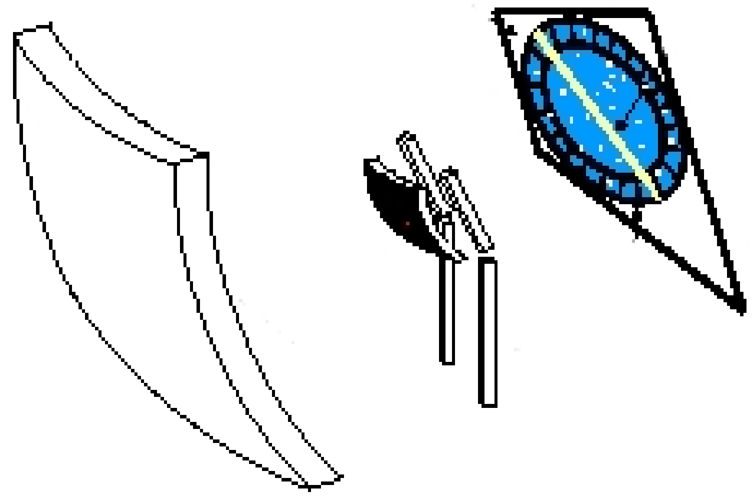


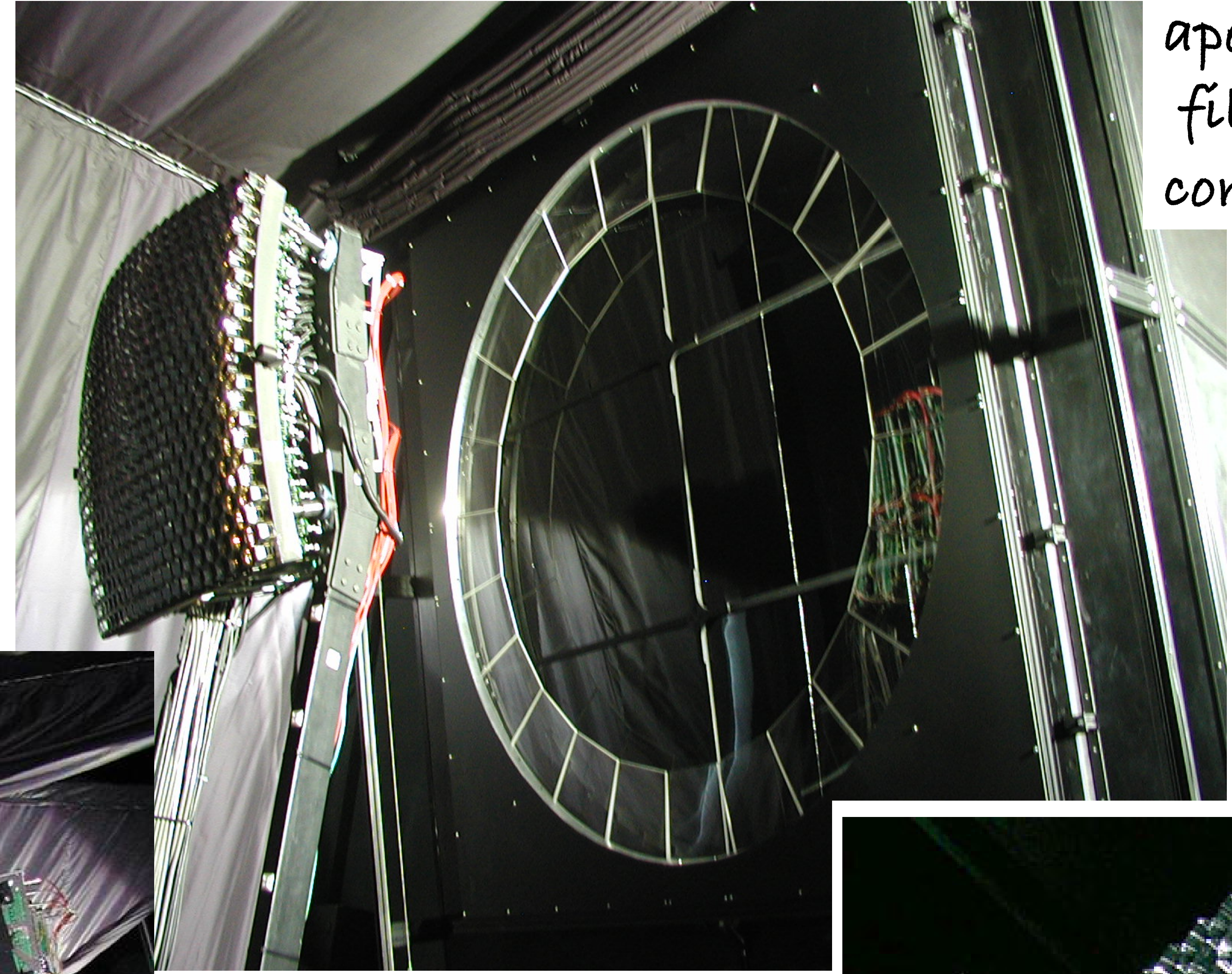
inclined

E = 0.37 x 10^{20} eV θ = 74°

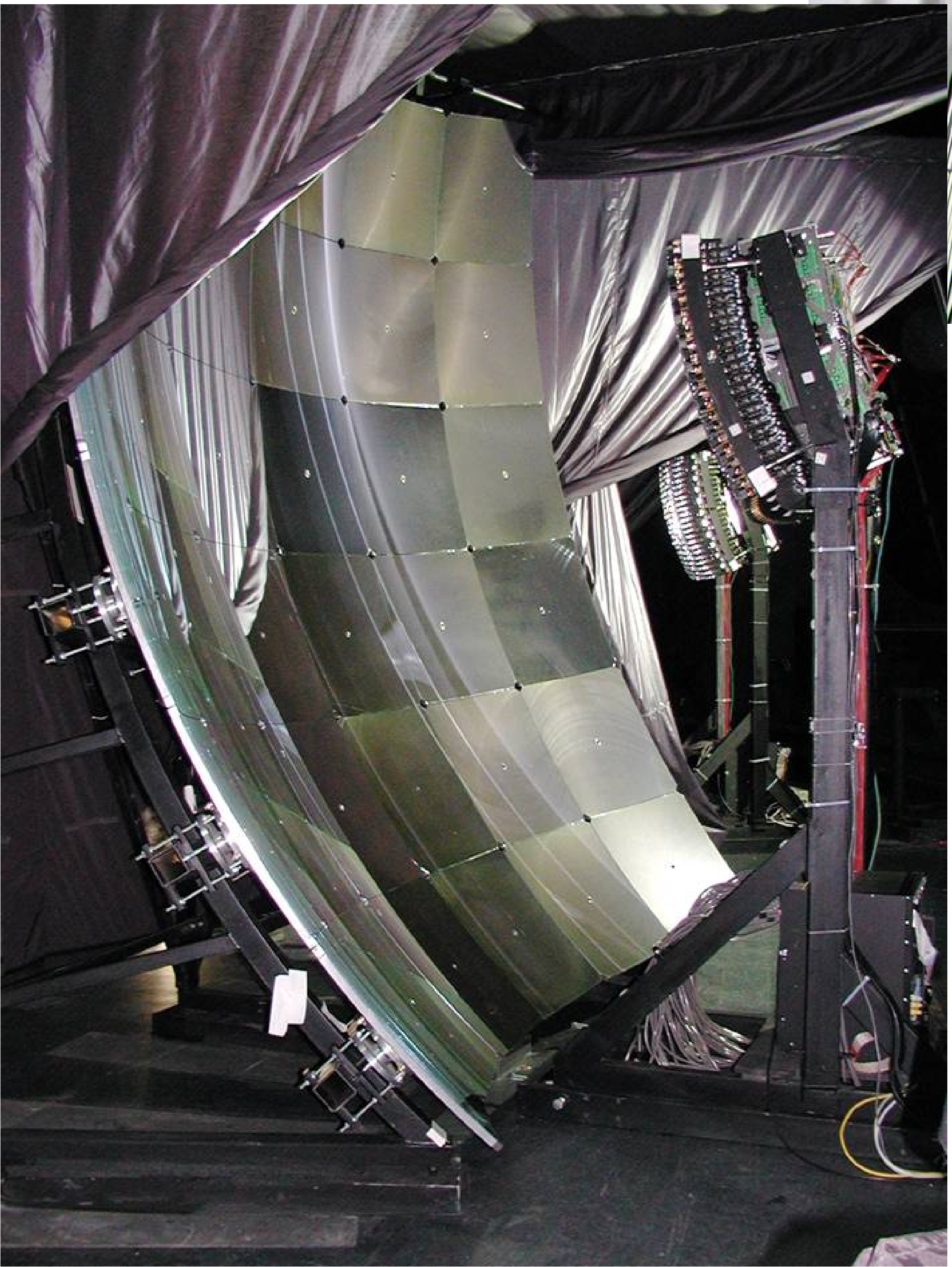


FD telescope:



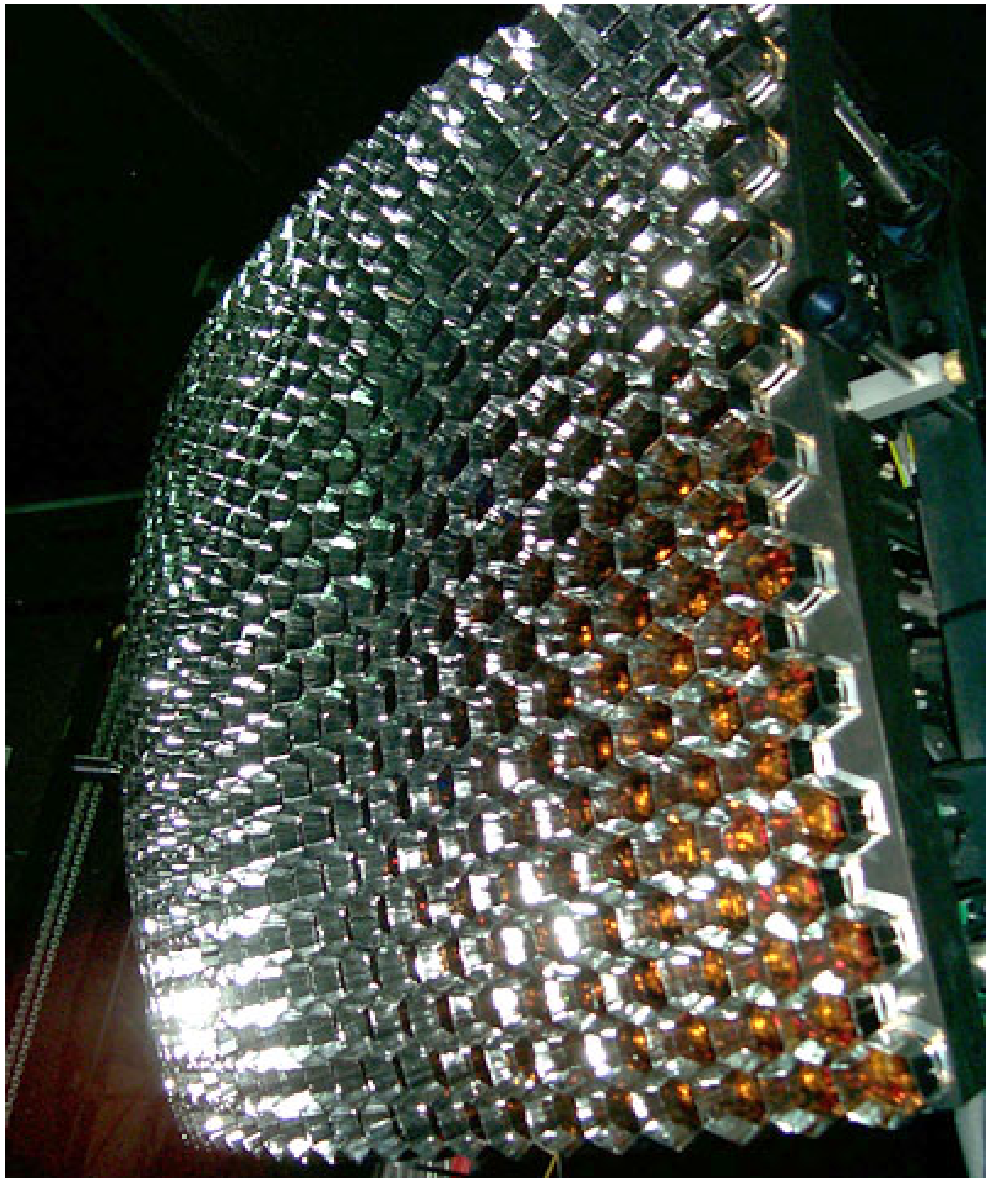


aperture with shutter, filter and Schmidt corrector lenses

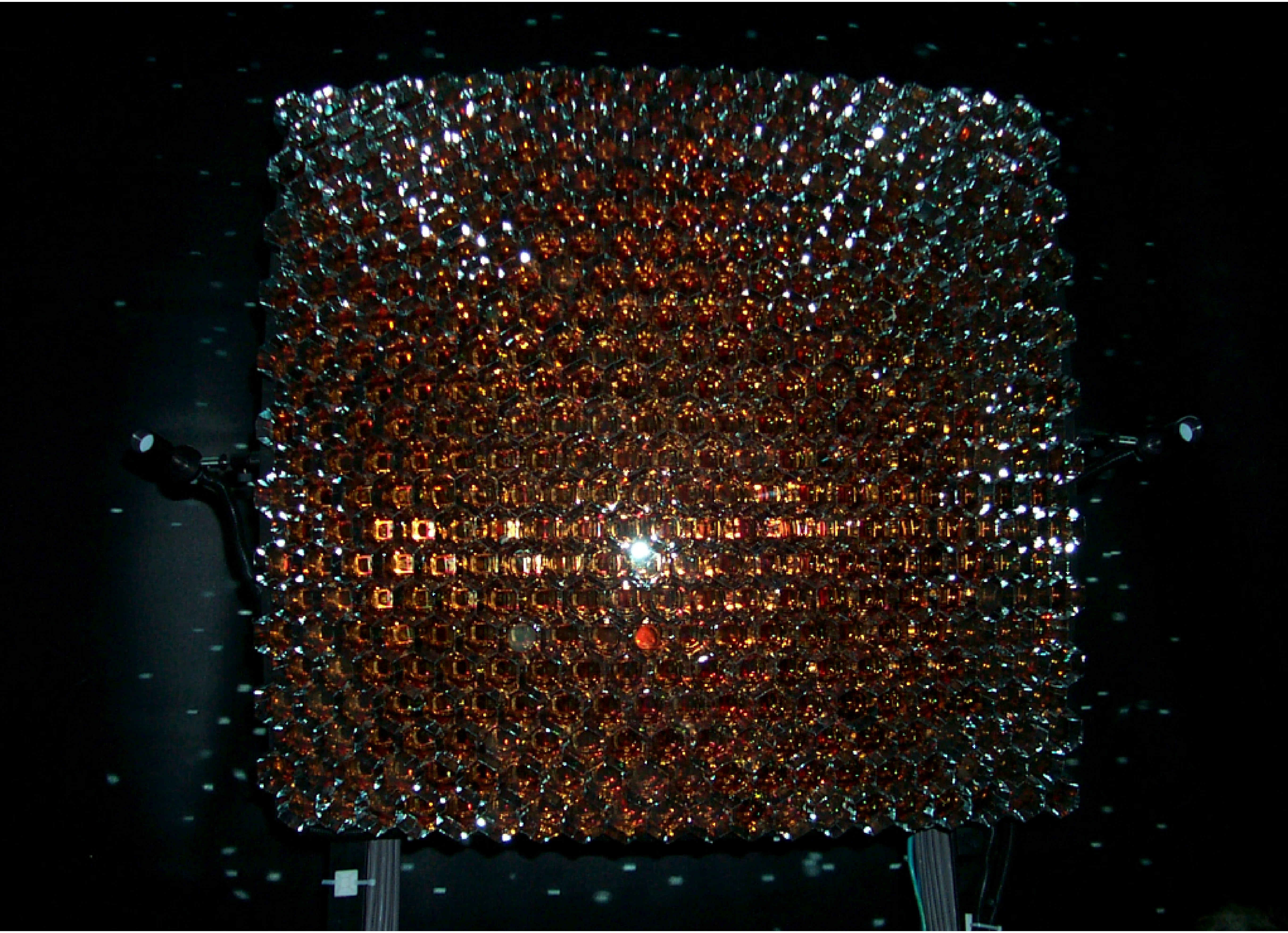


$11\ m^2$ mirror (Aluminium)

440 PMT camera



24 telescopes at 4 sites
30°x30° FOV, each

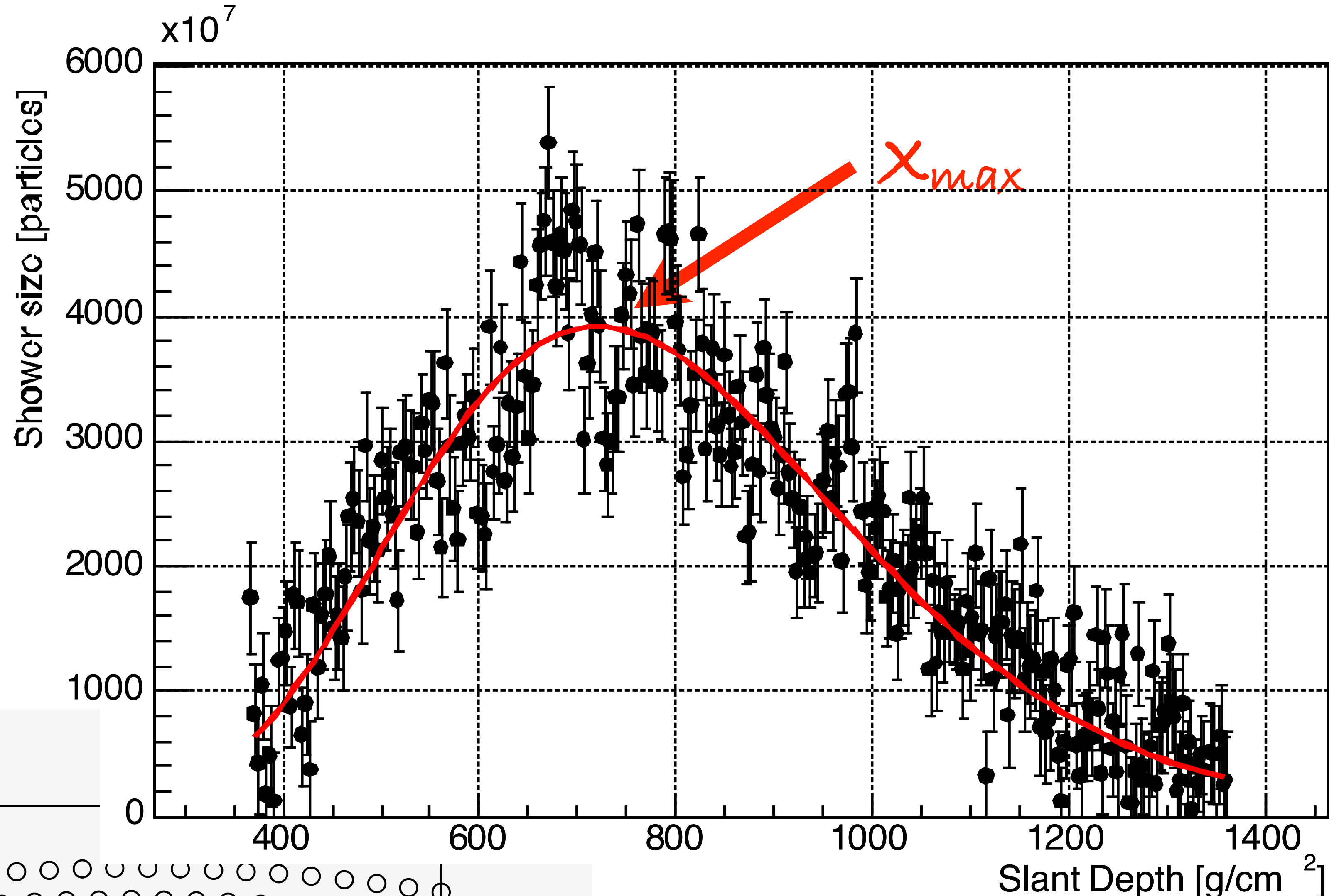


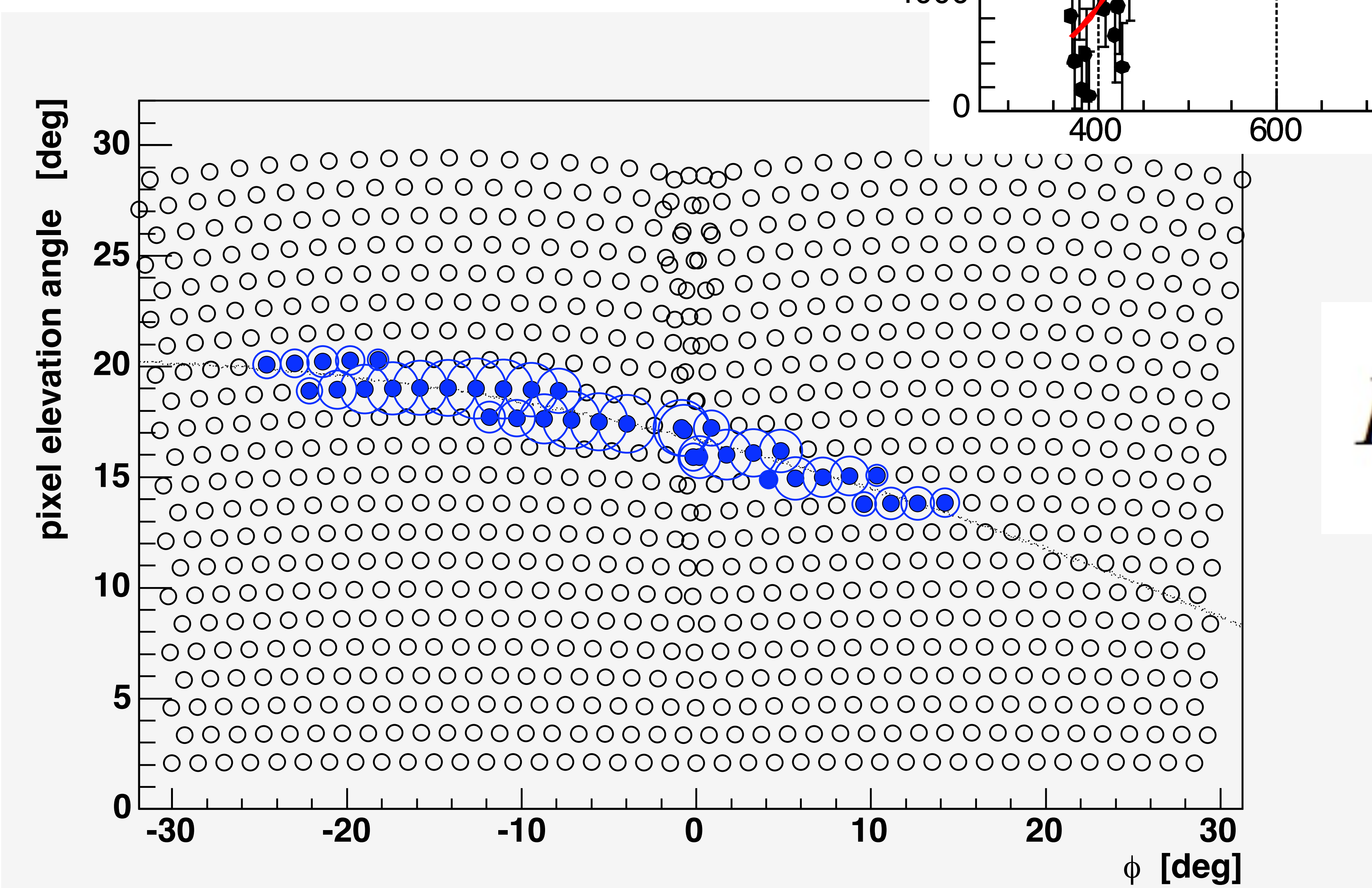
FD:

longitudinal profile,

calorimetric energy,

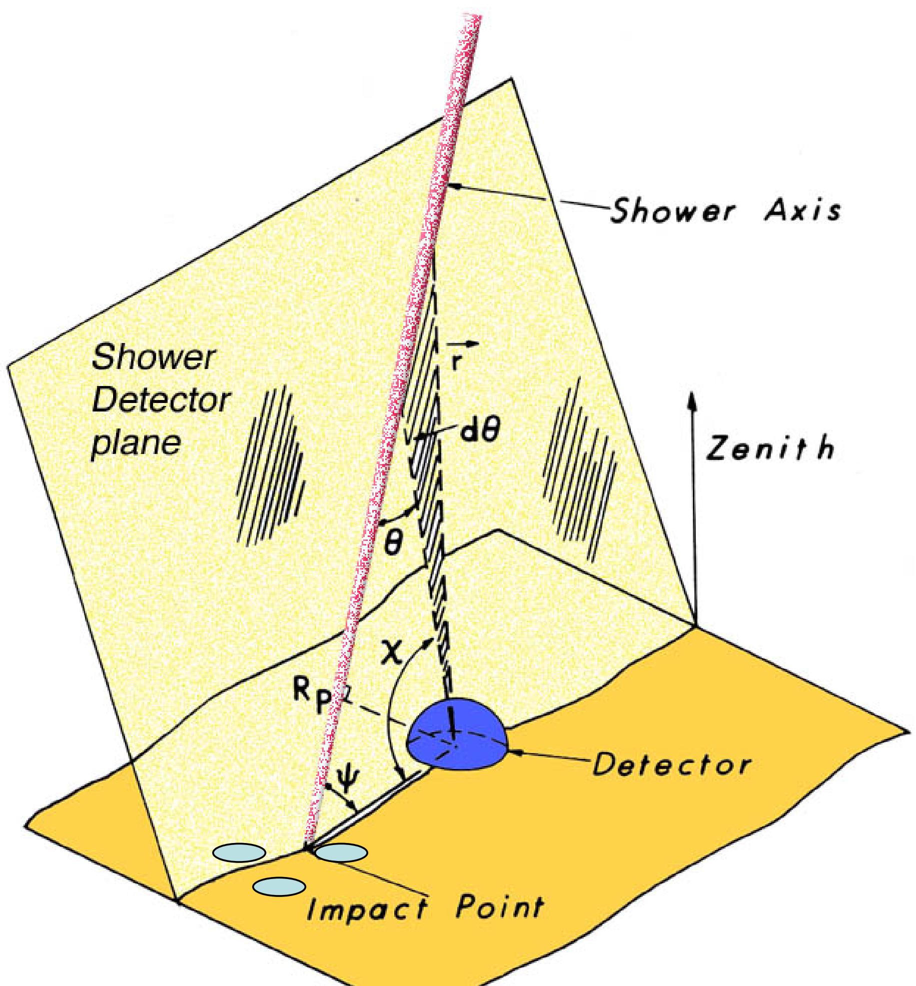
X_{max} for mass comp.

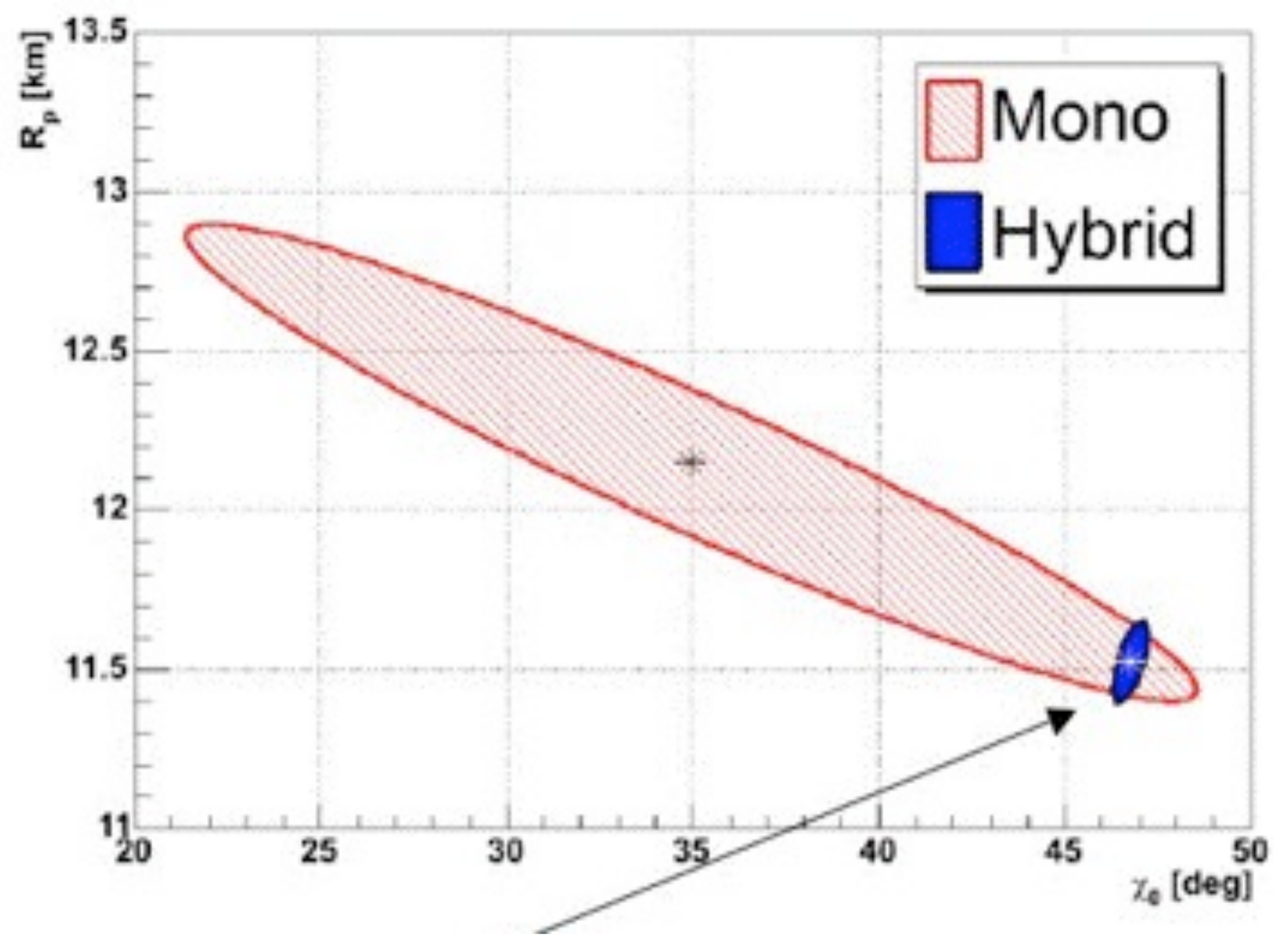




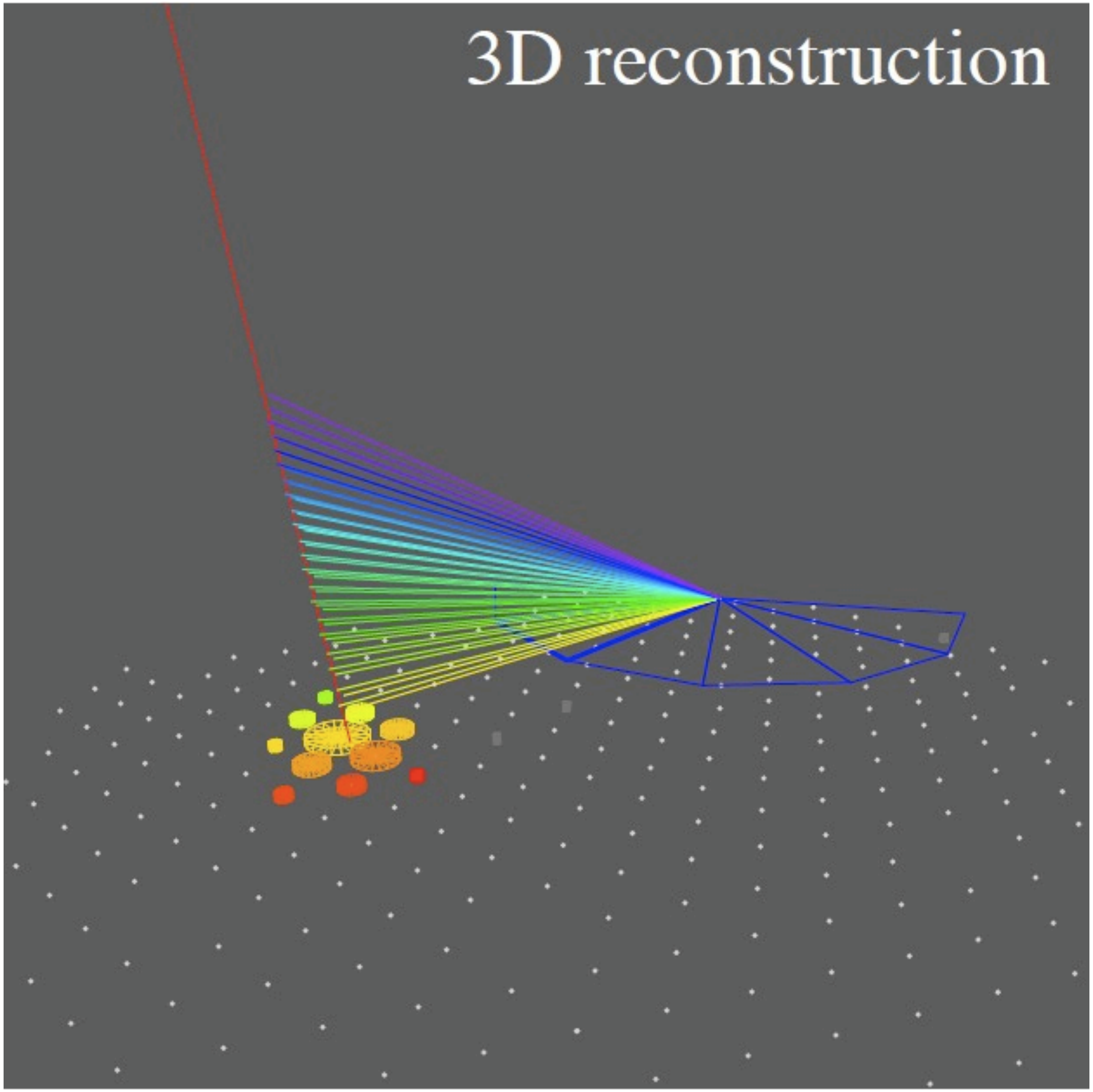
$$E \propto \int_0^\infty N(t)dt$$

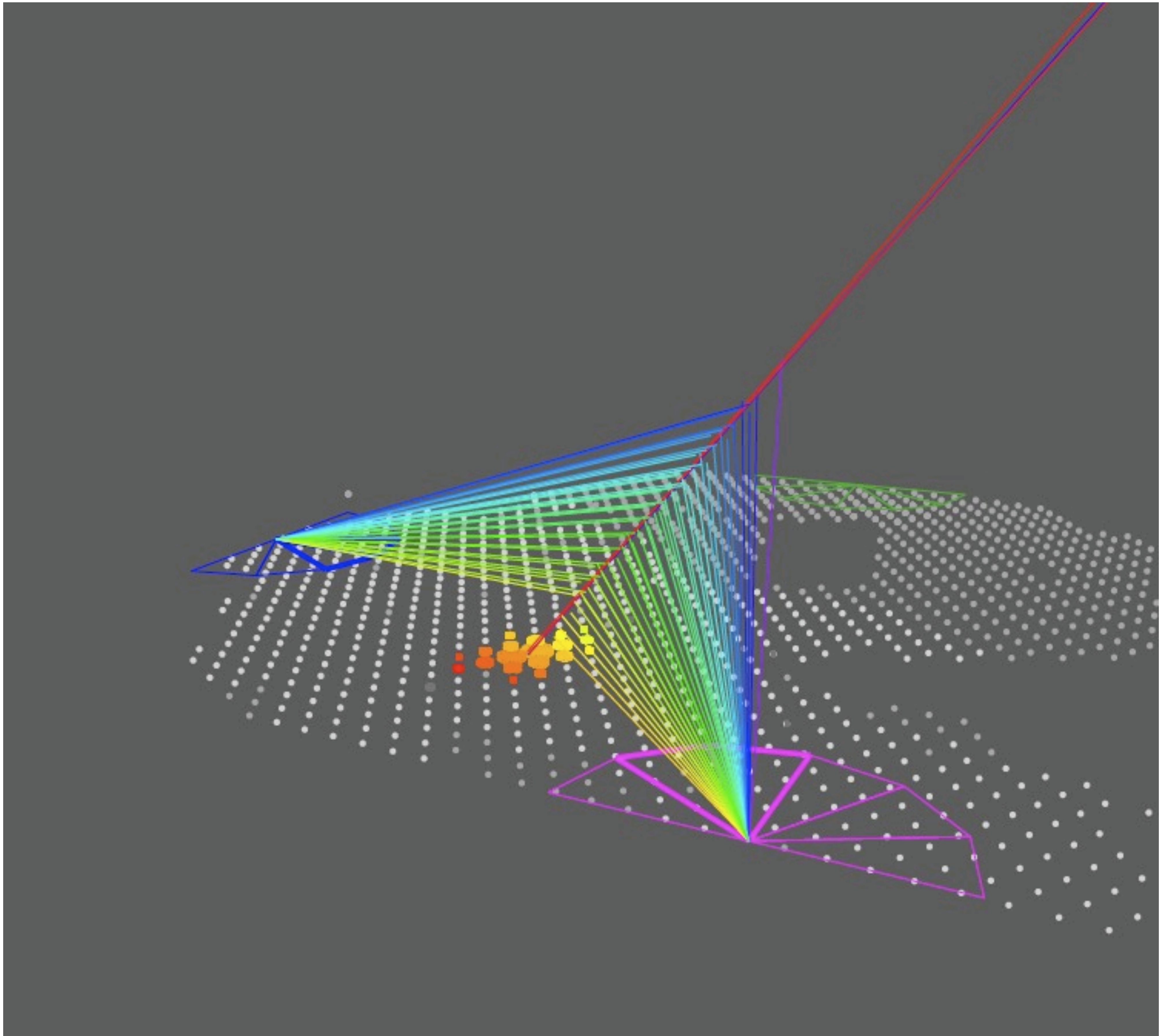
	hybrid	SD only	FD only
angular resolution	0.2°	1-2°	3-5°
aperture	independent of E, mass, models	independent of E, mass, models	dependent of E, mass, models and spectral slope
energy	independent of mass, models	dependent of mass, models	independent of mass, models





golden hybrid event



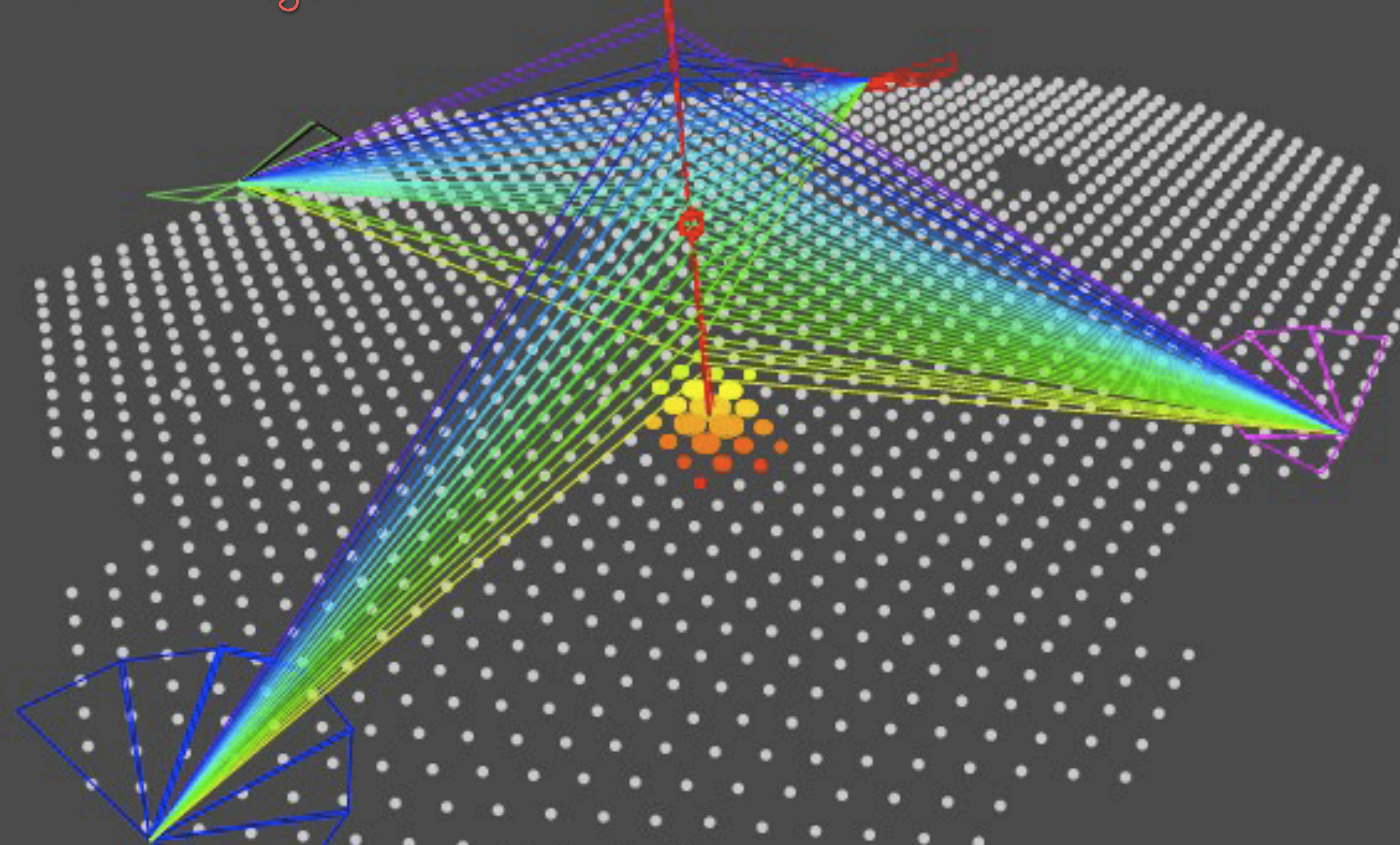


Shower seen by the

array and all 4 FDs

$E \approx 7 \times 10^{19}$ eV

a "Platinum Hybrid"



Results

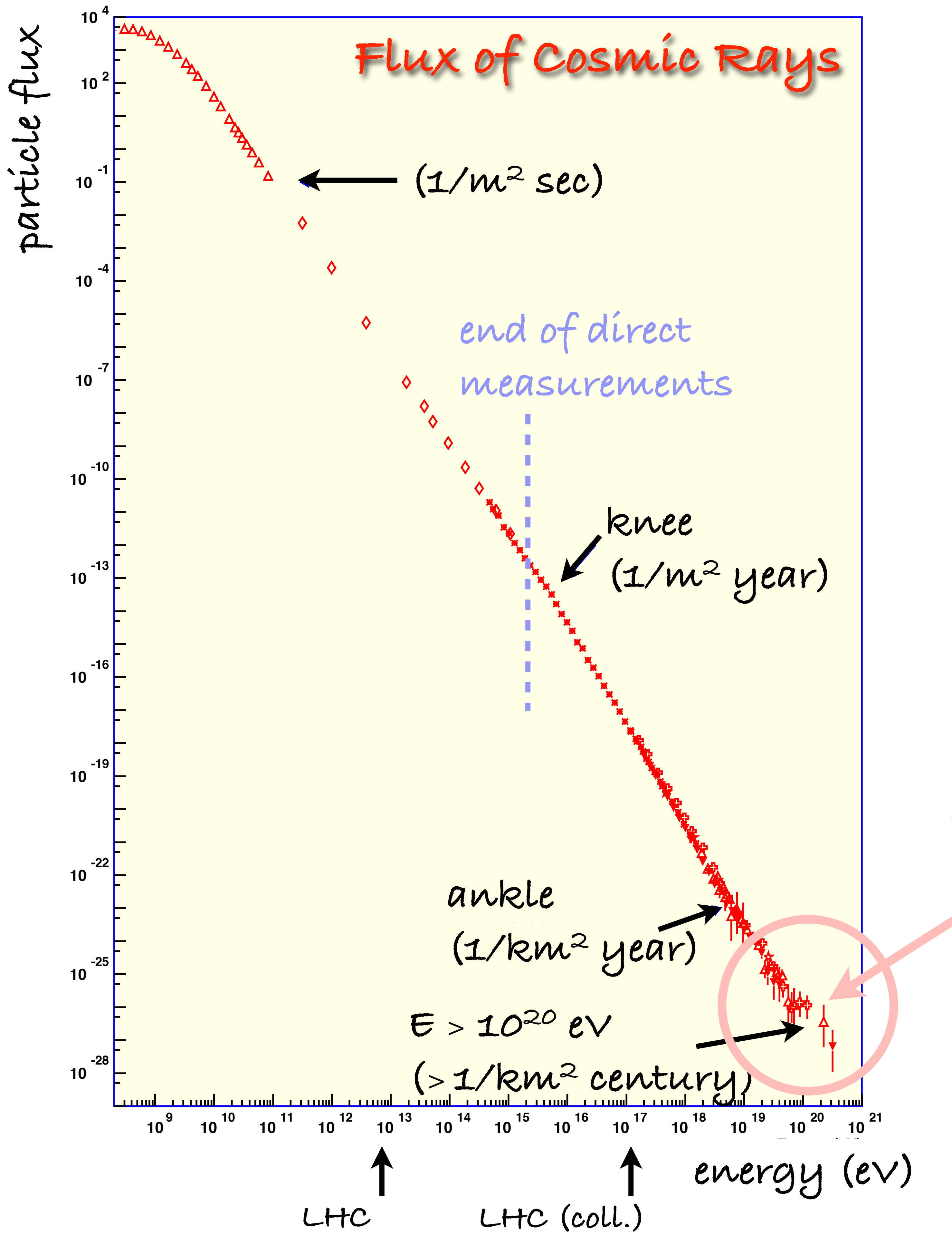
- Spectrum
- Anisotropy
- Composition
- Particle Physics at 10^{19} eV ?
- Exotics

Data until Dec. 2010

≈ 21000 km^2 yr sr

≈ 3.2 full-Auger yrs

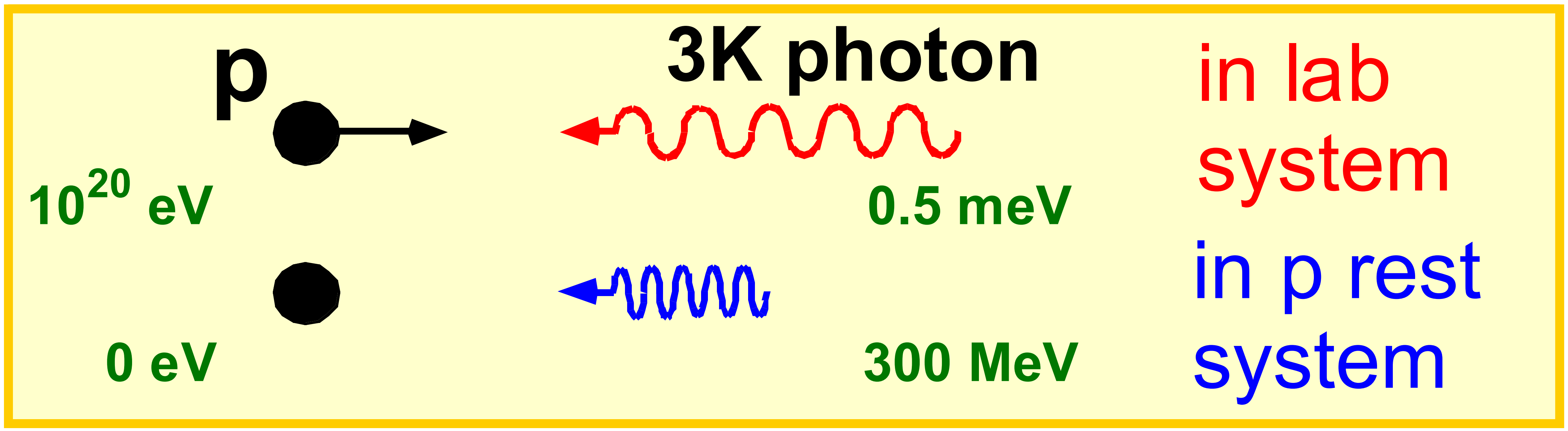
Spectrum



The Auger range ...
with the prediction of a spectral feature:
the GZK cut-off
due to interaction of CR protons with the CMBR

GZK Cut-Off

Greisen Zatsepin Kuzmin



$$p + \gamma_{3K} \rightarrow \Delta^+ \rightarrow p + \pi^0 \;(\rightarrow \gamma)$$
$$\rightarrow n + \pi^+ \;(\rightarrow \nu)$$

photo - pion production

$$^{56}Fe + \gamma_{3K} \rightarrow {}^{55}Fe + n$$

photo dissociation

Universe becomes opaque for $E >$ few $\times 10^{19}$ eV.

beyond this: **Sources must be close !**

If sources are universal: **cut-off in CR spectrum.**

Test of Lorentz Invariance for $\gamma \approx 10^{11}$!

$$\text{Flux} = \frac{N_{evts(>E)}}{t \cdot A \cdot \Omega}$$

E: straight forward from FD

(but FD only active for 10% of time)

model dependent from SD

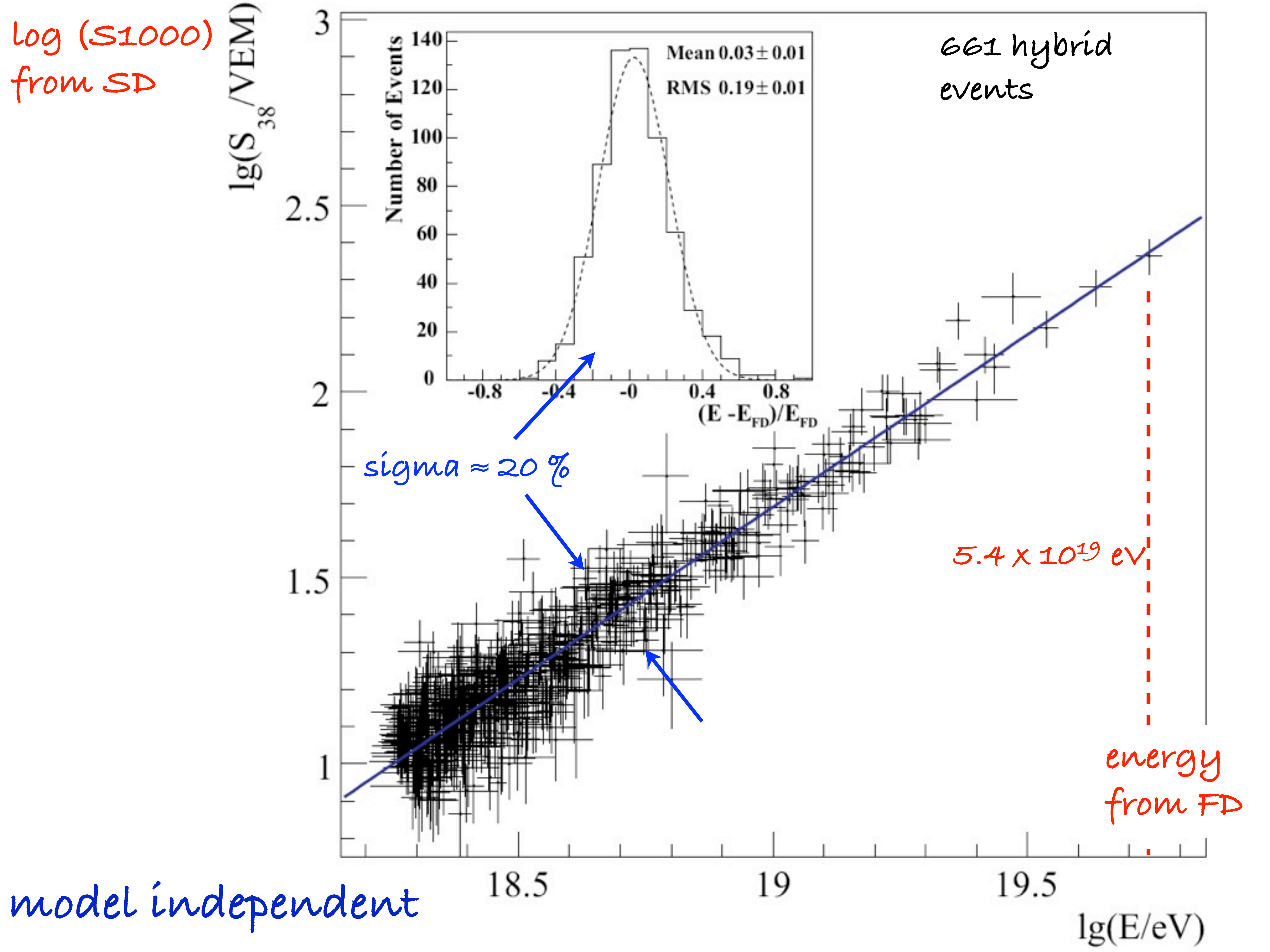
(SD active for 100% of time)

get energy calibration from FD

for high statistics from SD

A: directly from size of SD

(above 3×10^{18} eV)

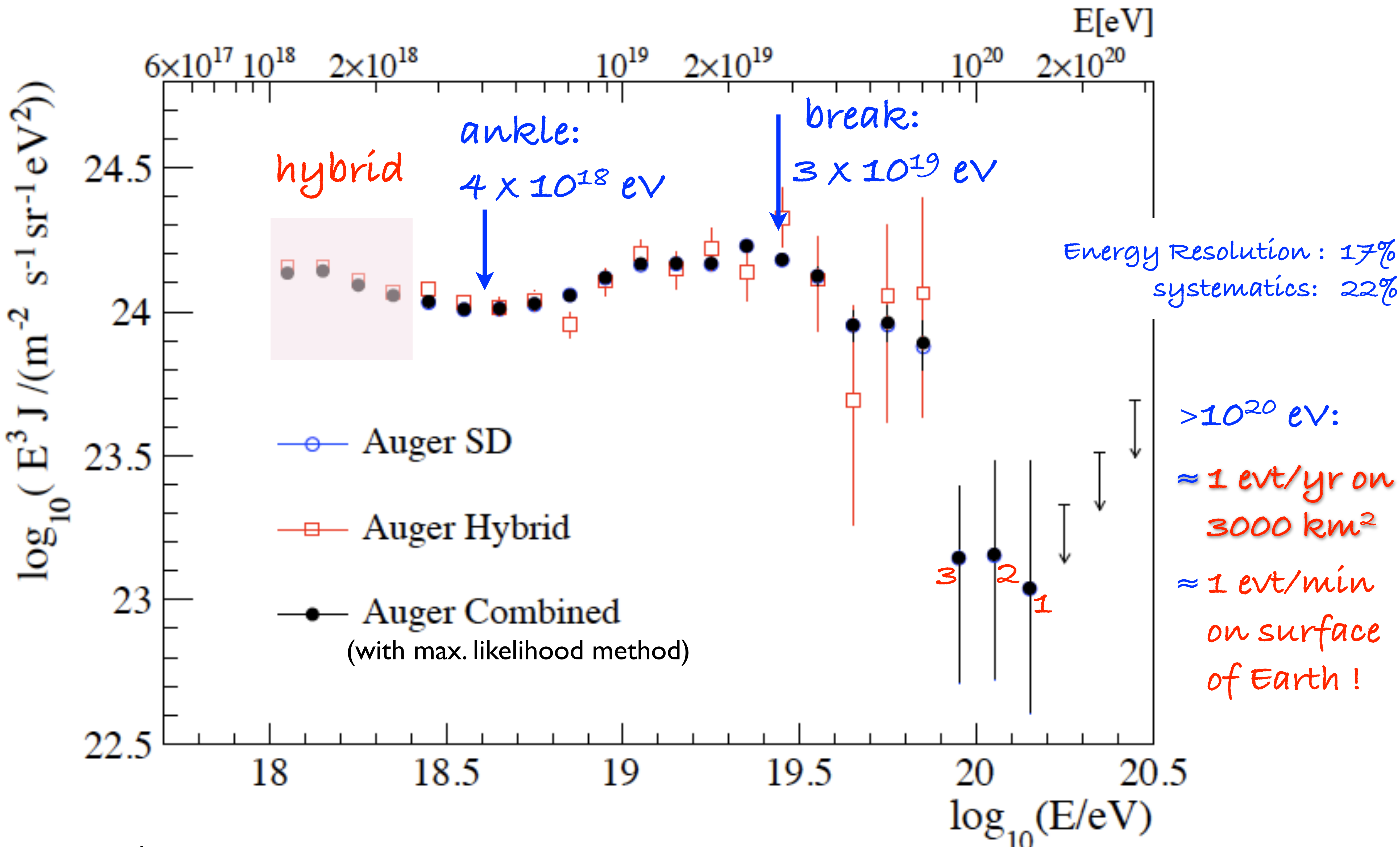

log (S1000)
from SD
lg(S38/VEM)
3
2.5
2
1.5
1
Number of Events
140
120
100
80
60
40
20
0
-0.8
-0.4
-0
0.4
0.8
(E -EFD)/EFD
Mean 0.03±0.01
RMS 0.19±0.01
661 hybrid
events
sigma ≈ 20 %
5.4 x 10^19 eV
energy
from FD
18.5
19
19.5
lg(E/eV)
model independent

Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

model dependent

Efforts to decrease these uncertainties under way.

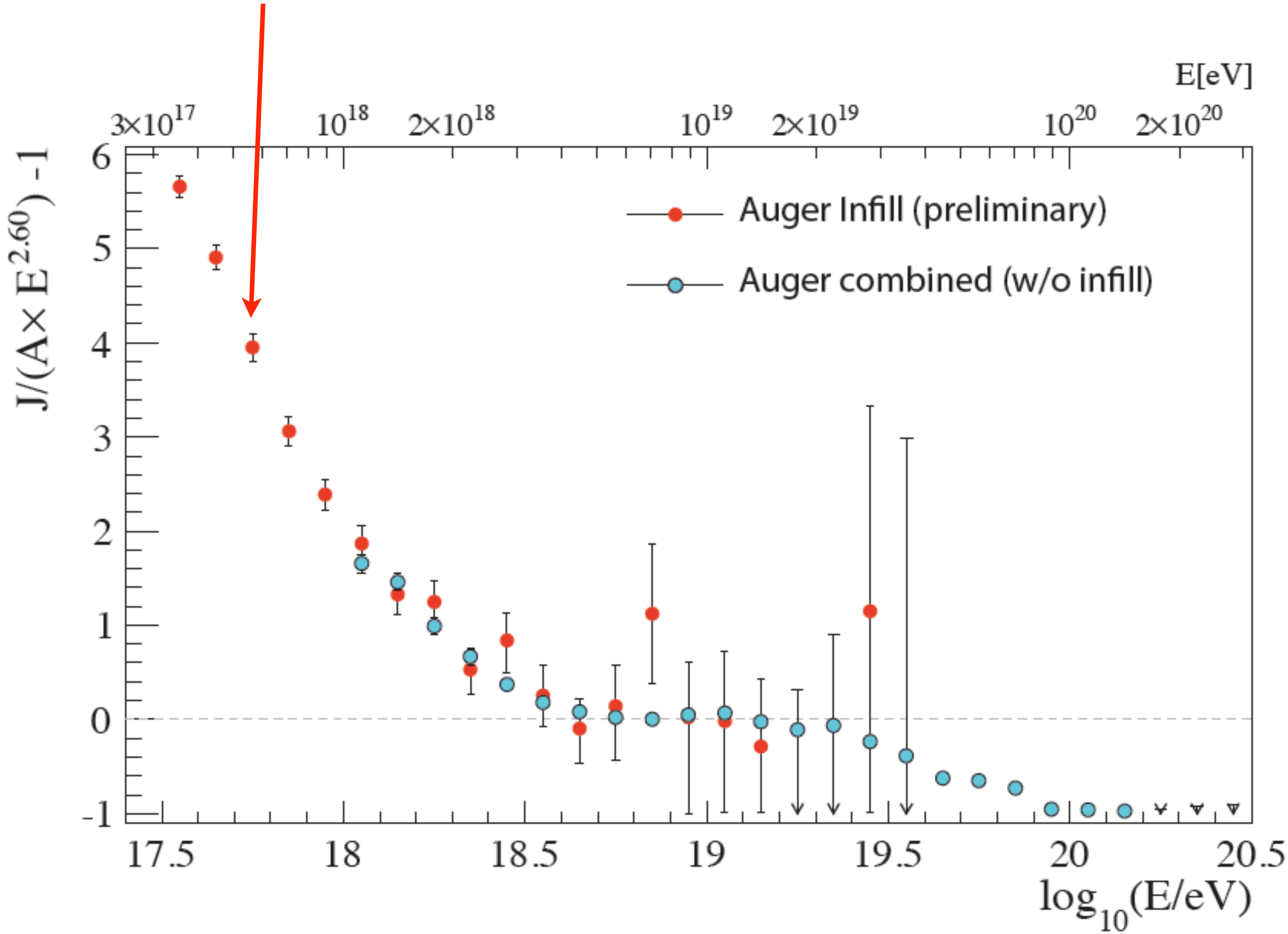
Energy spectrum



Auger finds "ankle" and a clear (>20 σ) spectral steepening at $E \approx 3 \times 10^{19}$ eV.

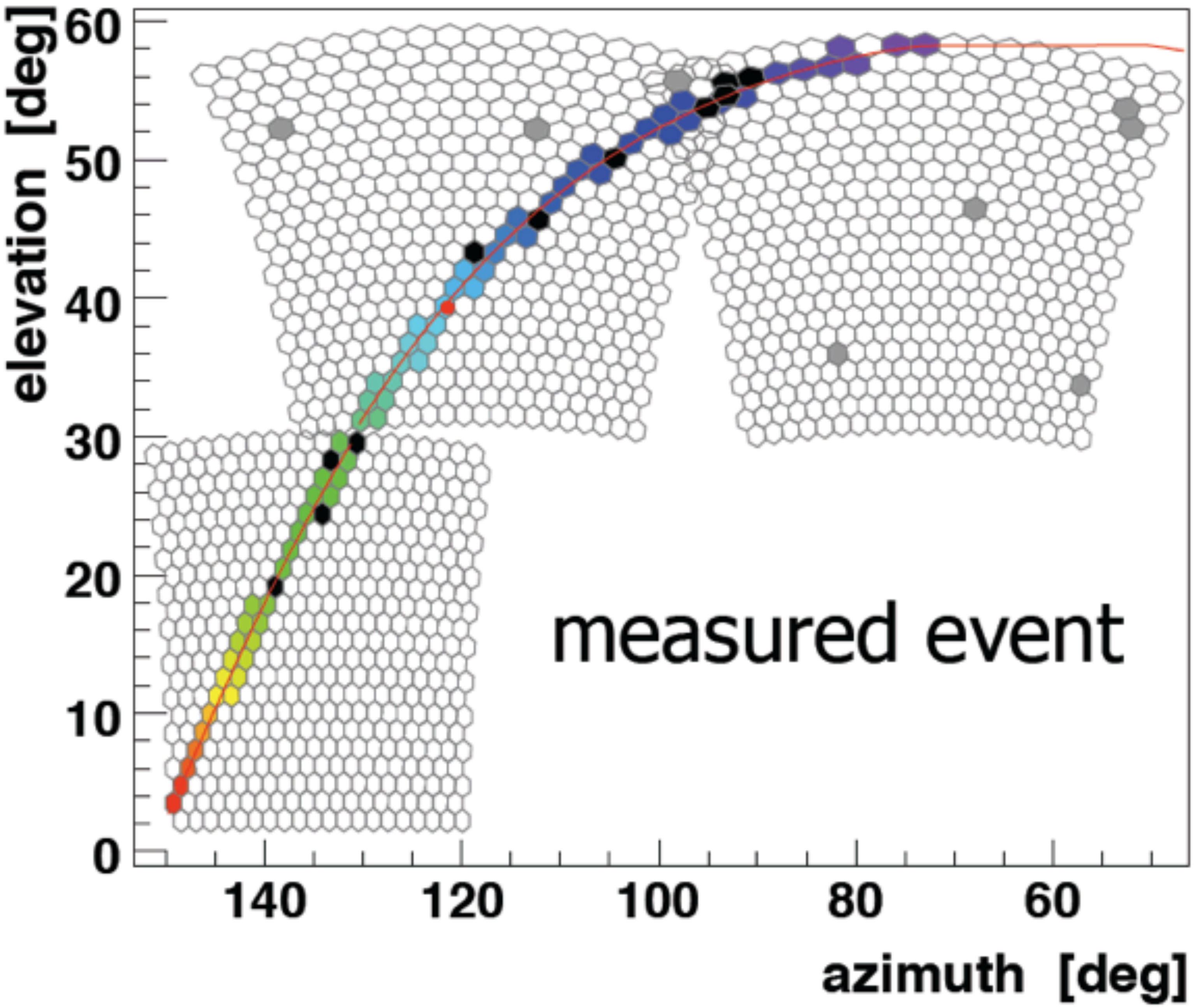
$\theta = 0 - 60^o$

Extension to lower energies: Infill array



Exposure of infill array: ≈26 km² sr yr

Heat: High Elevation Auger Telescopes



Does Auger see the GZK cut-off ?

GZK cut-off: if CRs are protons

power-law spectrum at source $> 10^{20}$ eV

sources are universally distributed

then depression of flux at $\approx$ few x 10^{19} eV

(Also nuclear primaries would be absorbed, but not quite in the same way....)

... so probably: yes i.e. CRs are likely protons

Alternatives:

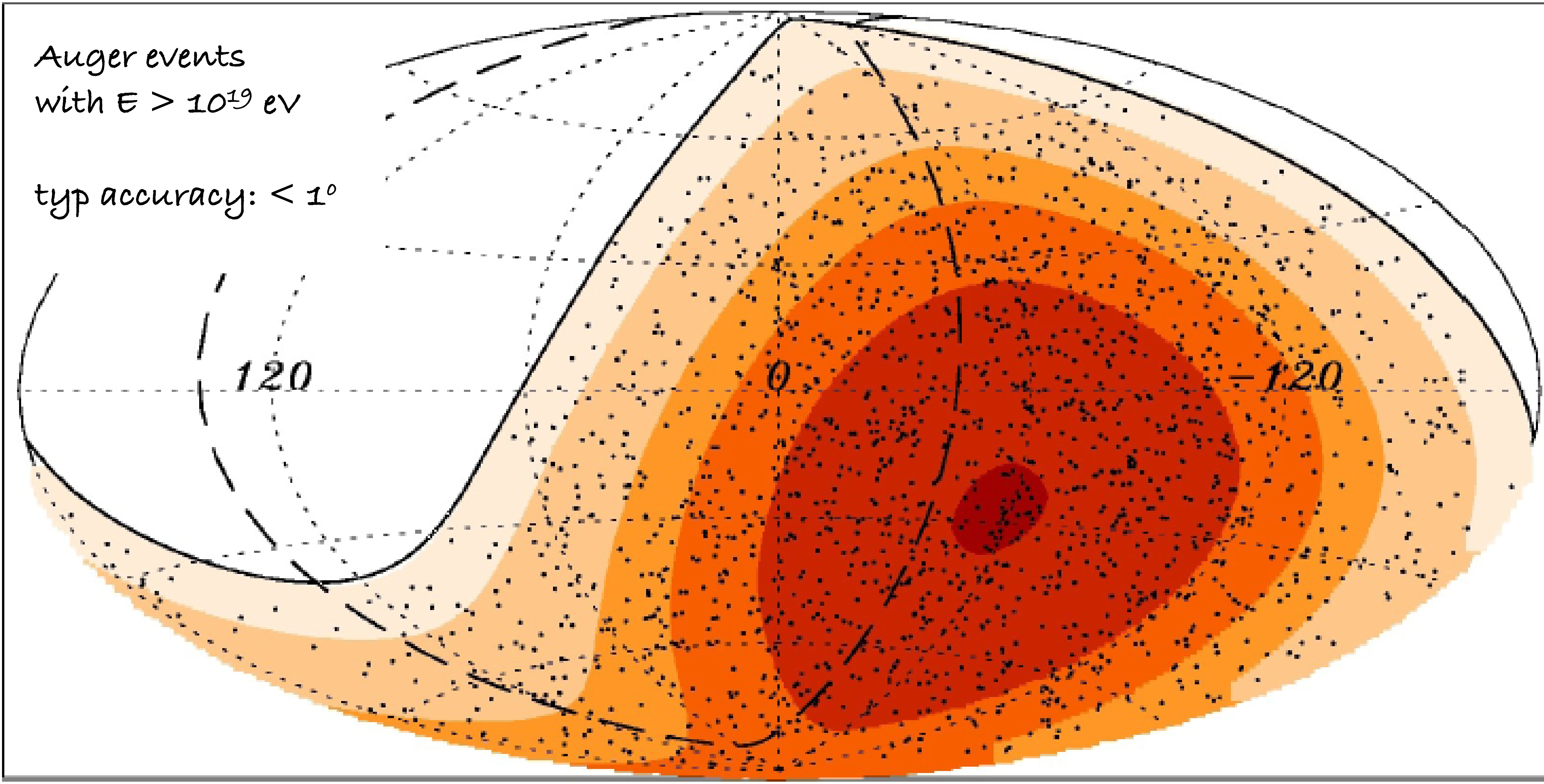
maximum energy of accelerator ?

effect of a local source ?

Is ankle the transition point between galactic and extragalactic CRs ?

... need more info on composition ...

Anisotropy



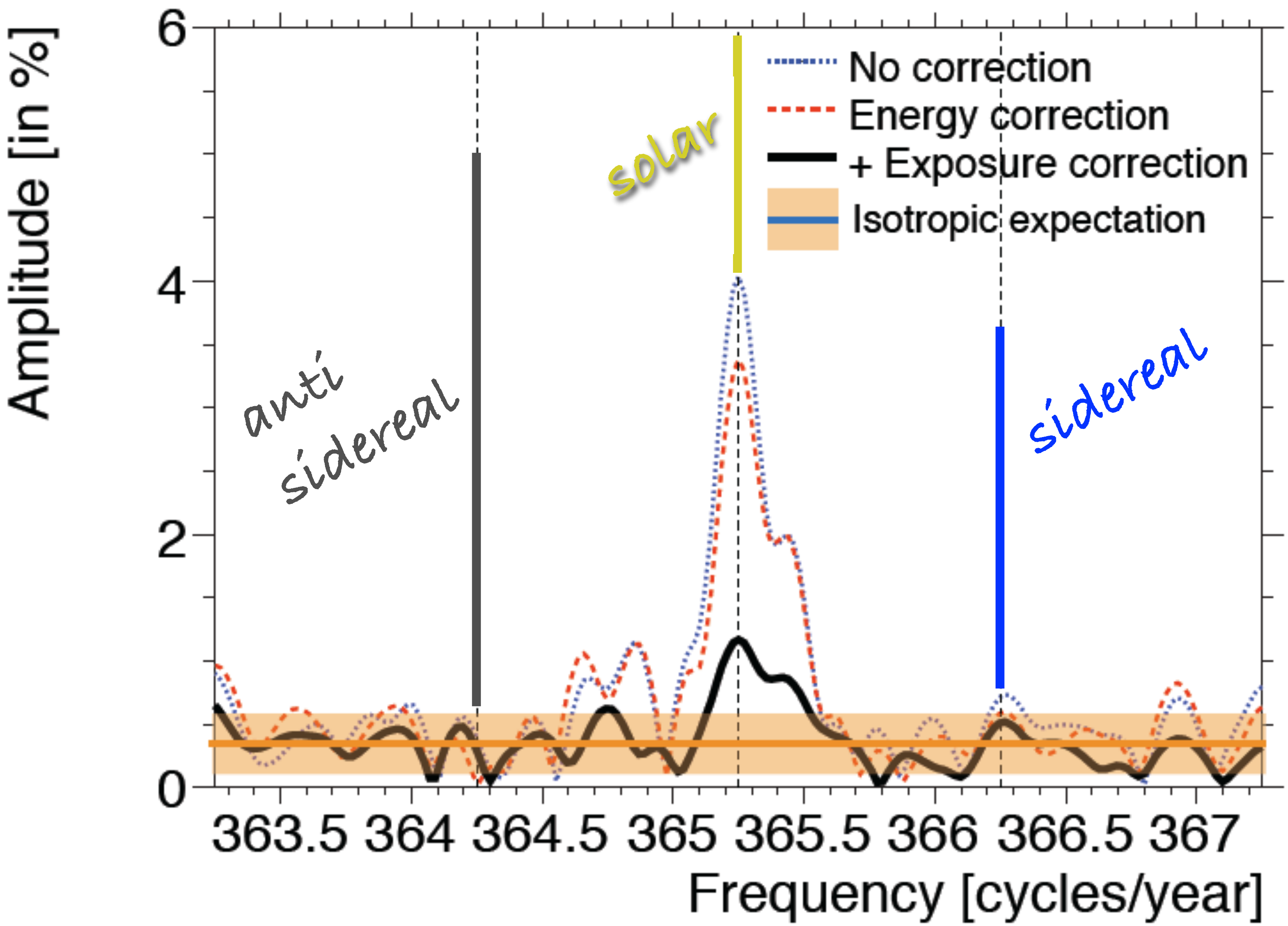
No enhancement along galactic disk: UHE particles are extragalactic.

Clusters? Point sources? Large-scale anisotropies? Correlations with source populations?

Large-Scale anisotropy:

Transition galactic - extra galactic should induce change in large-scale angular distribution of CRs.

Fourier Analysis of event arrival times



$E > 5 \times 10^{17}$ eV

2 complementary analyses: Generalised Rayleigh Method
East-West method

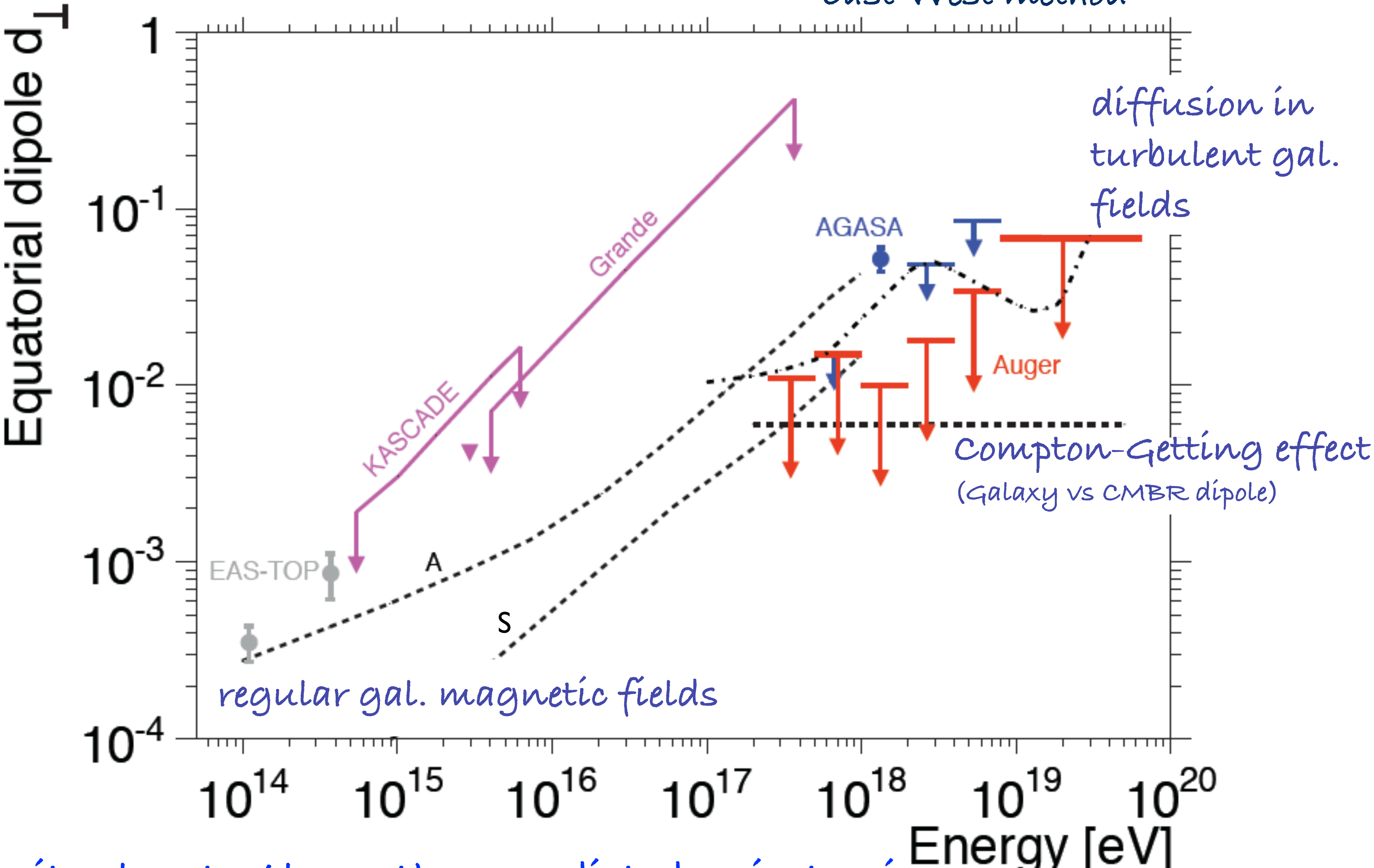
both erase - non-uniformity in acceptance and
- weather effects

amplitudes

Energy range [EeV]	Rayleigh analysis				E-W method				upp.limit [%] (95%c.l.)
	r_{sid}[%]	Prob [%]	r_{sol}[%]	r_{asid}[%]	r_{sid}[%]	Prob [%]	r_{sol}[%]	r_{asid}[%]	
all enegies					0.49	19.3	0.29	0.25	0.86
0.2 - 0.5					0.25	84.2	0.52	0.46	0.91
0.5 - 1					1.08	4.8	0.75	0.42	1.72
1 – 2	0.92	1.5	0.81	0.8	0.78	49.5	1.1	0.65	1.39
2 – 4	0.83	42.7	1.01	0.73	1.66	45.9	1.57	1.6	1.71
4 – 8	0.77	84.7	2.48	1.84	5.04	18.2	2.49	5.61	2.82
> 8	5.42	3.1	3.95	5.13	2.76	79.5	4.52	3.81	8.42

Large-Scale Anisotropy

- Fourier analysis of arrival times
- Generalised Rayleigh Method
- East-West method



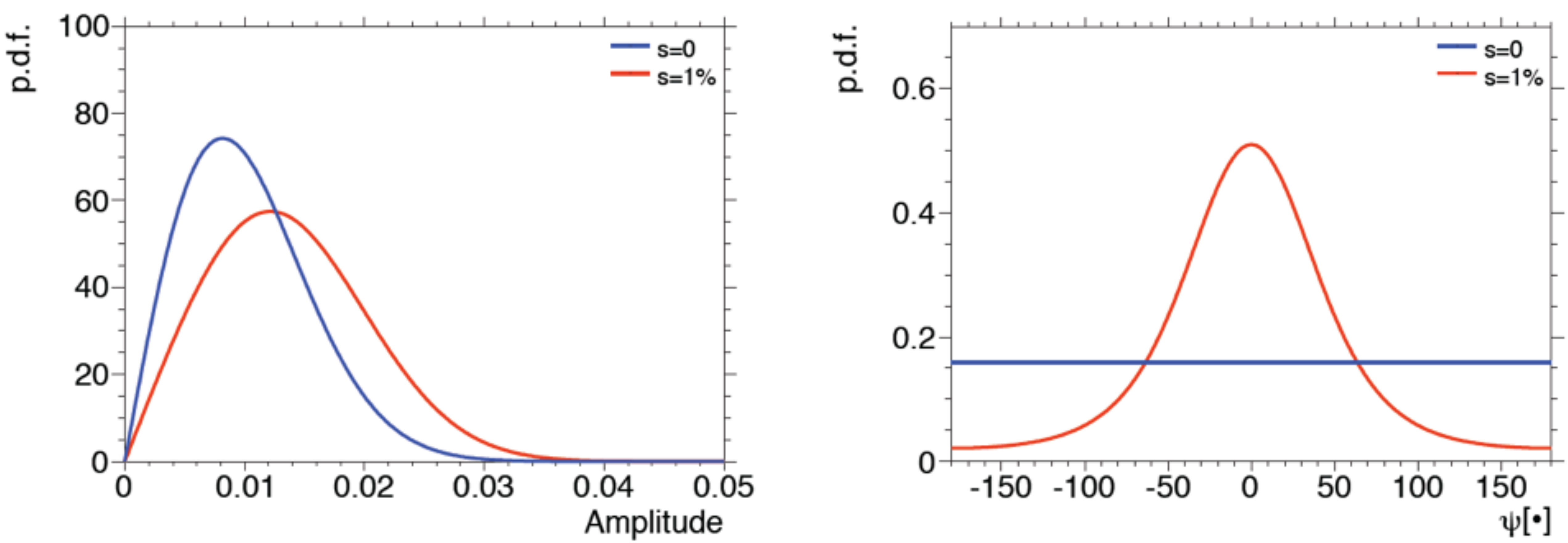
Limits close to / lower than predicted anisotropies.

More data will give an anisotropy signal or model constraints.

Amplitude vs Phase ?

For a real anisotropy:

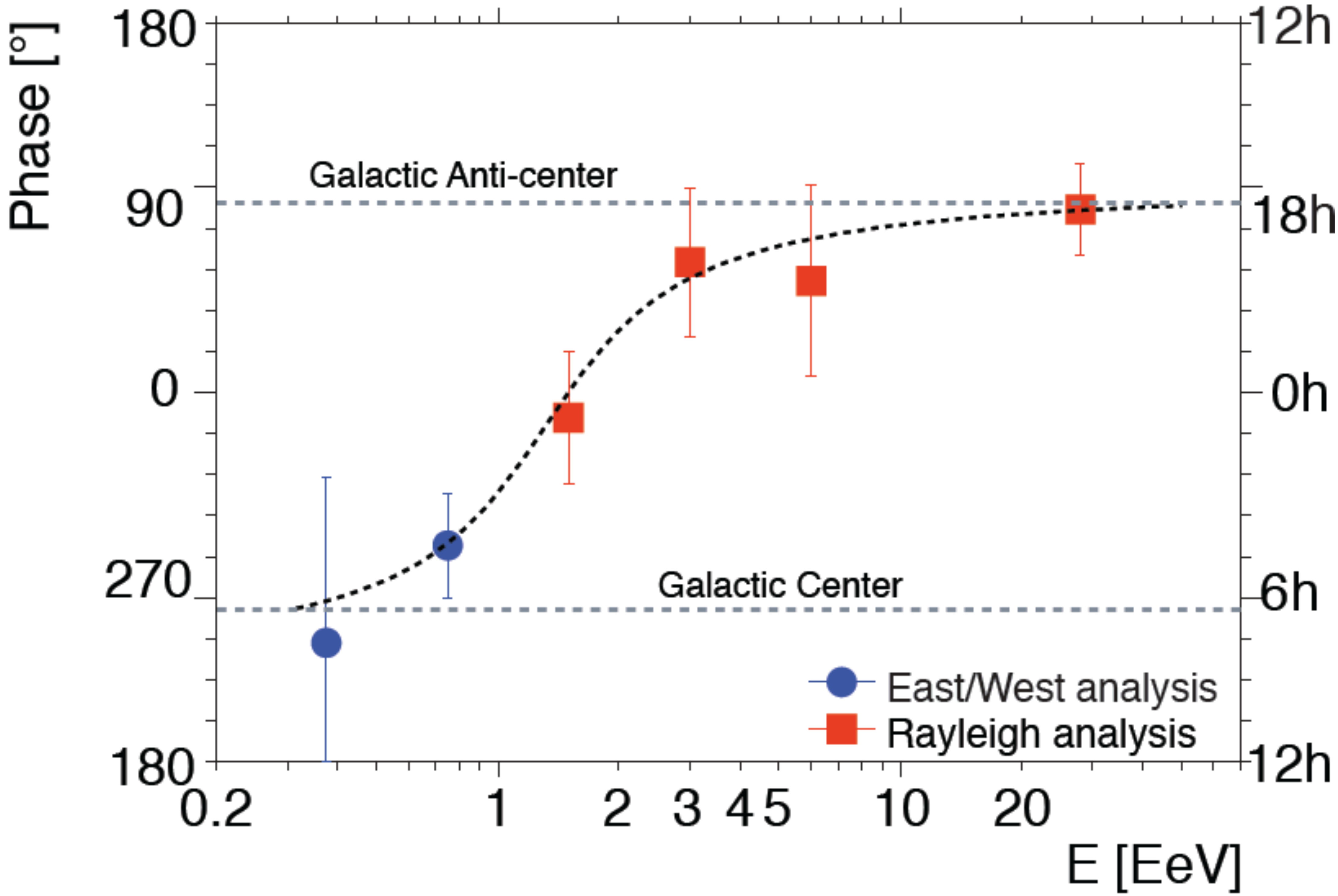
Consistency of the phase measurement is expected with lower statistics than the amplitude to significantly stand out of the background. (J Linsley, 1975)



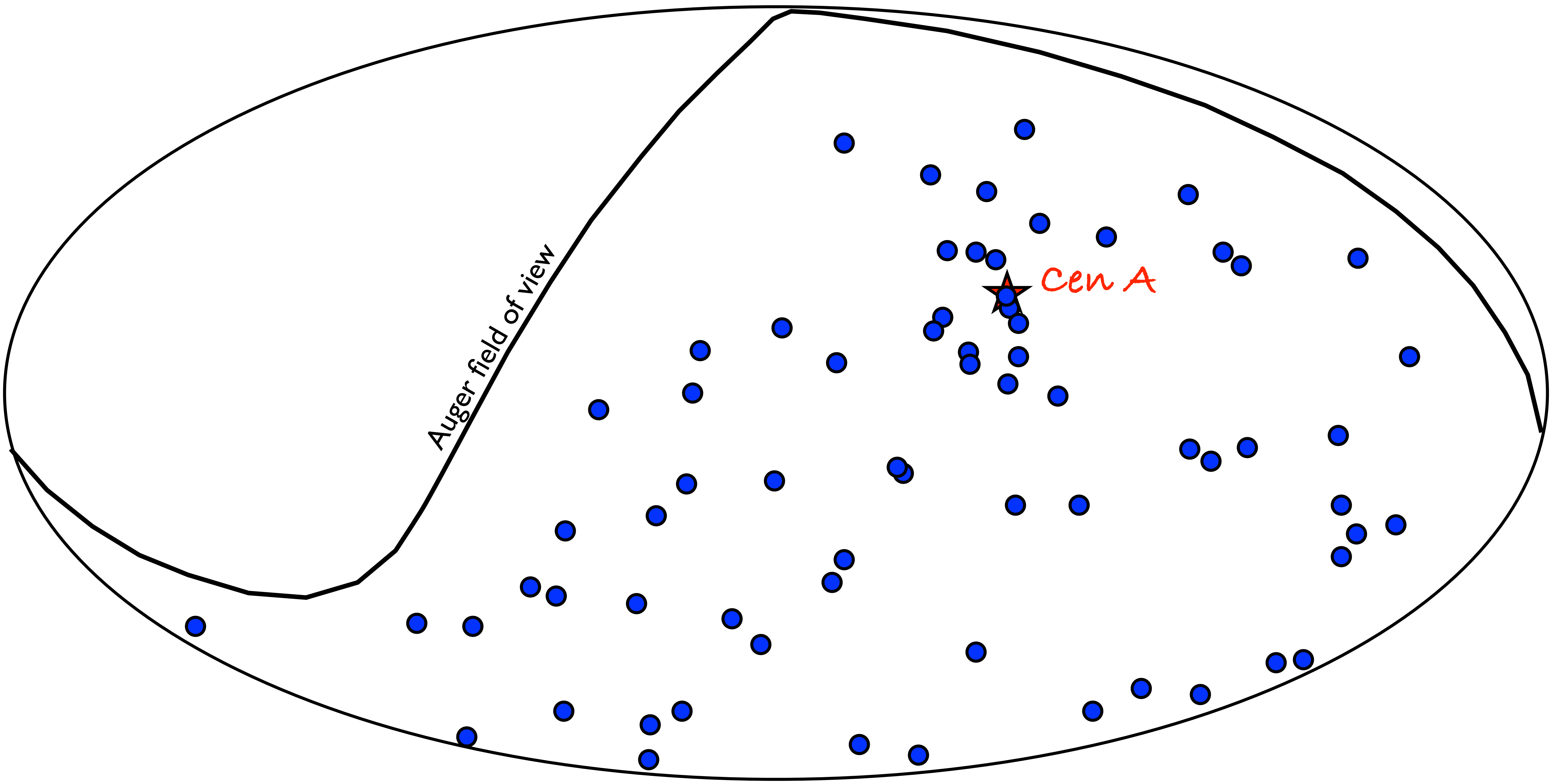
Phase is ≈2.5 x more sensitive than amplitude.

Smooth transition in RA from 270° to 90°

chance probability: 10^{-3} (a posteriori)



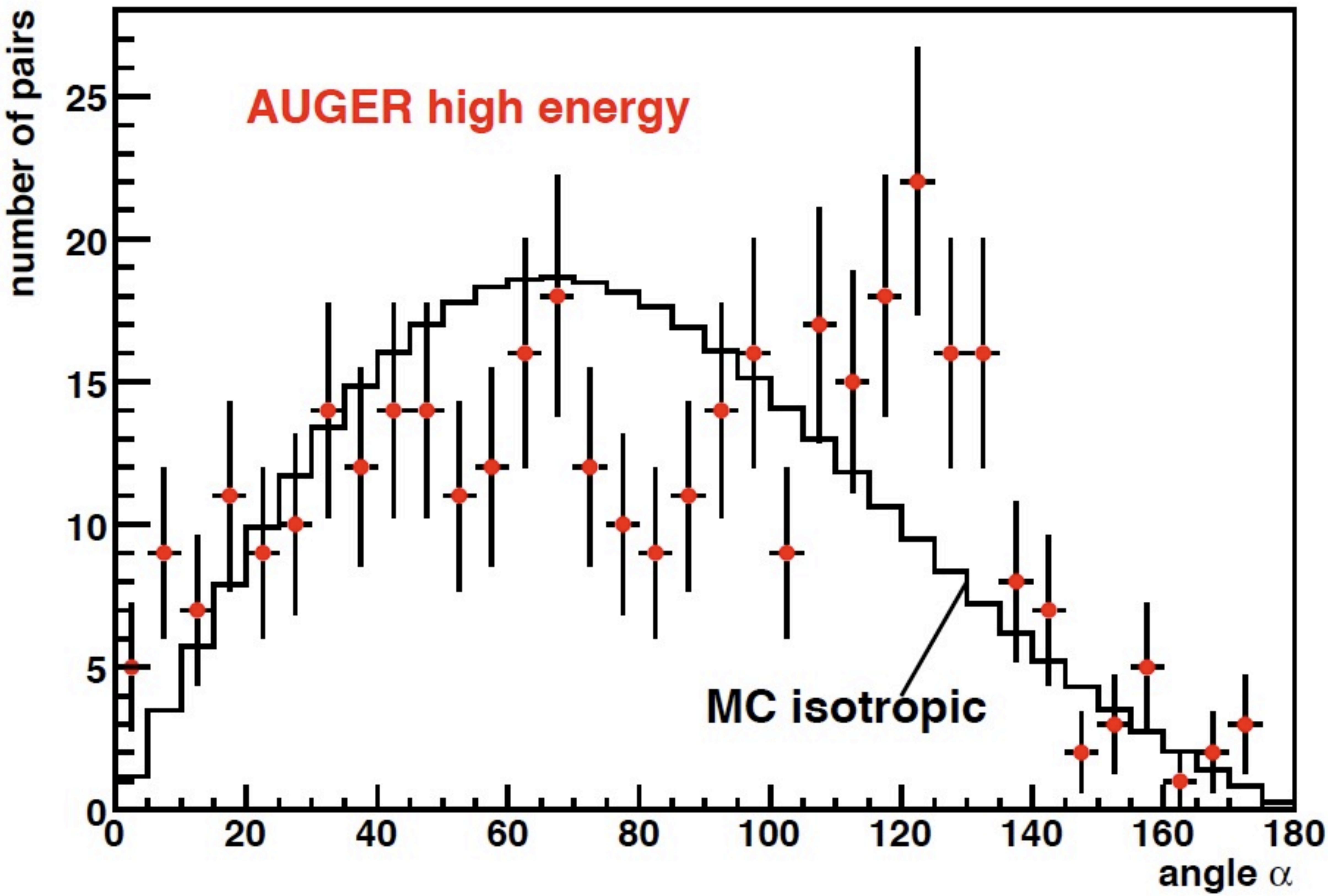
69 Highest Energy Events >55 EeV (Dec 2009)



Isotropic ? Clustering ? Is Cen A a source of UHECRs ? ...

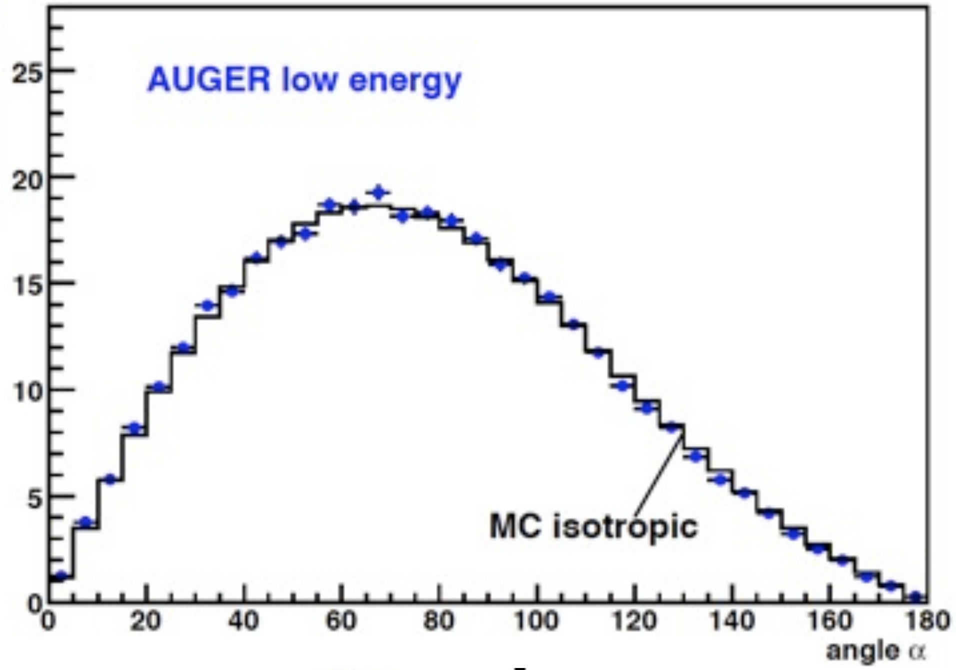
No evidence for enhancement from galactic disk. How to quantify ?

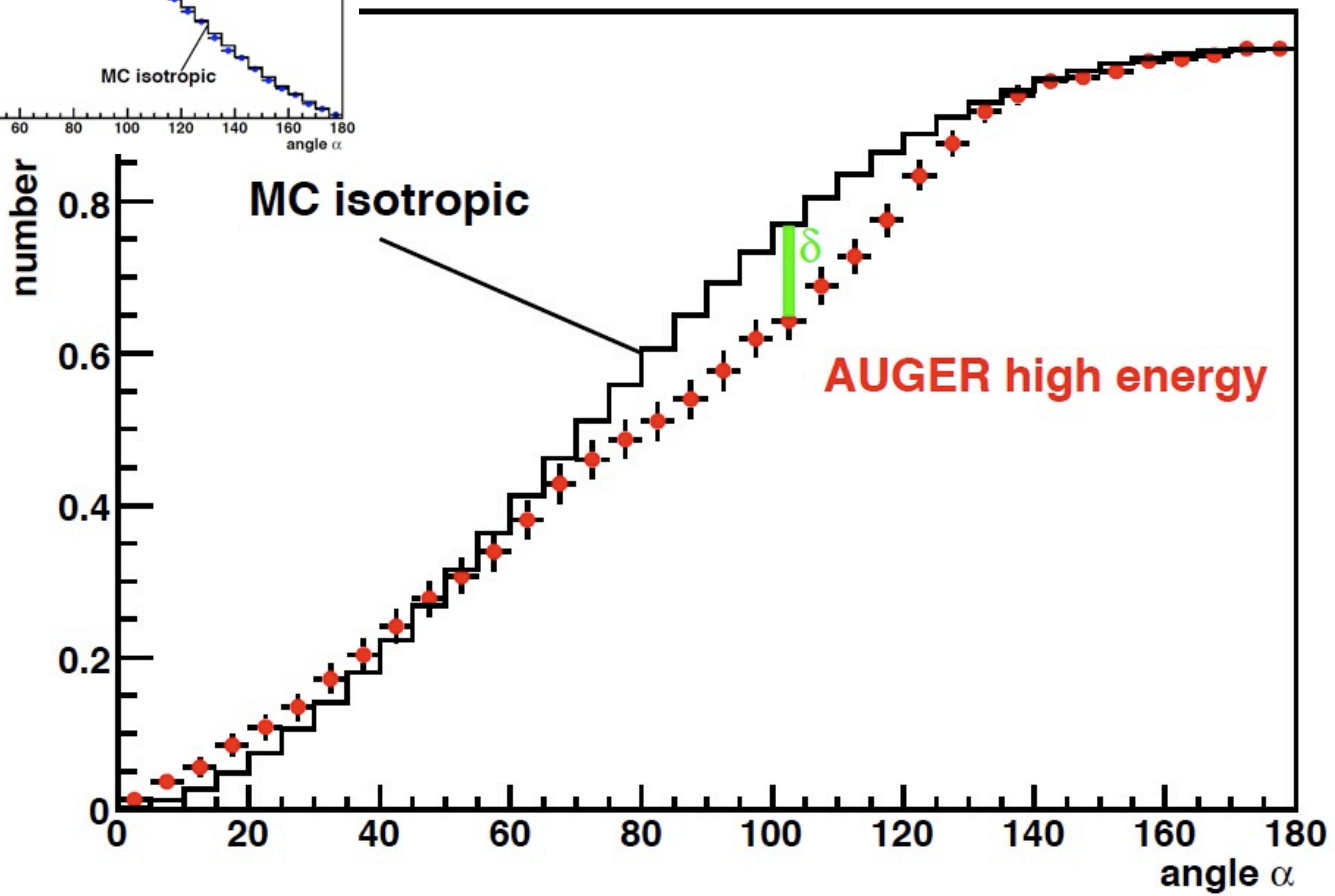
2-point correlation function



Kolmogorov-Smirnov Test

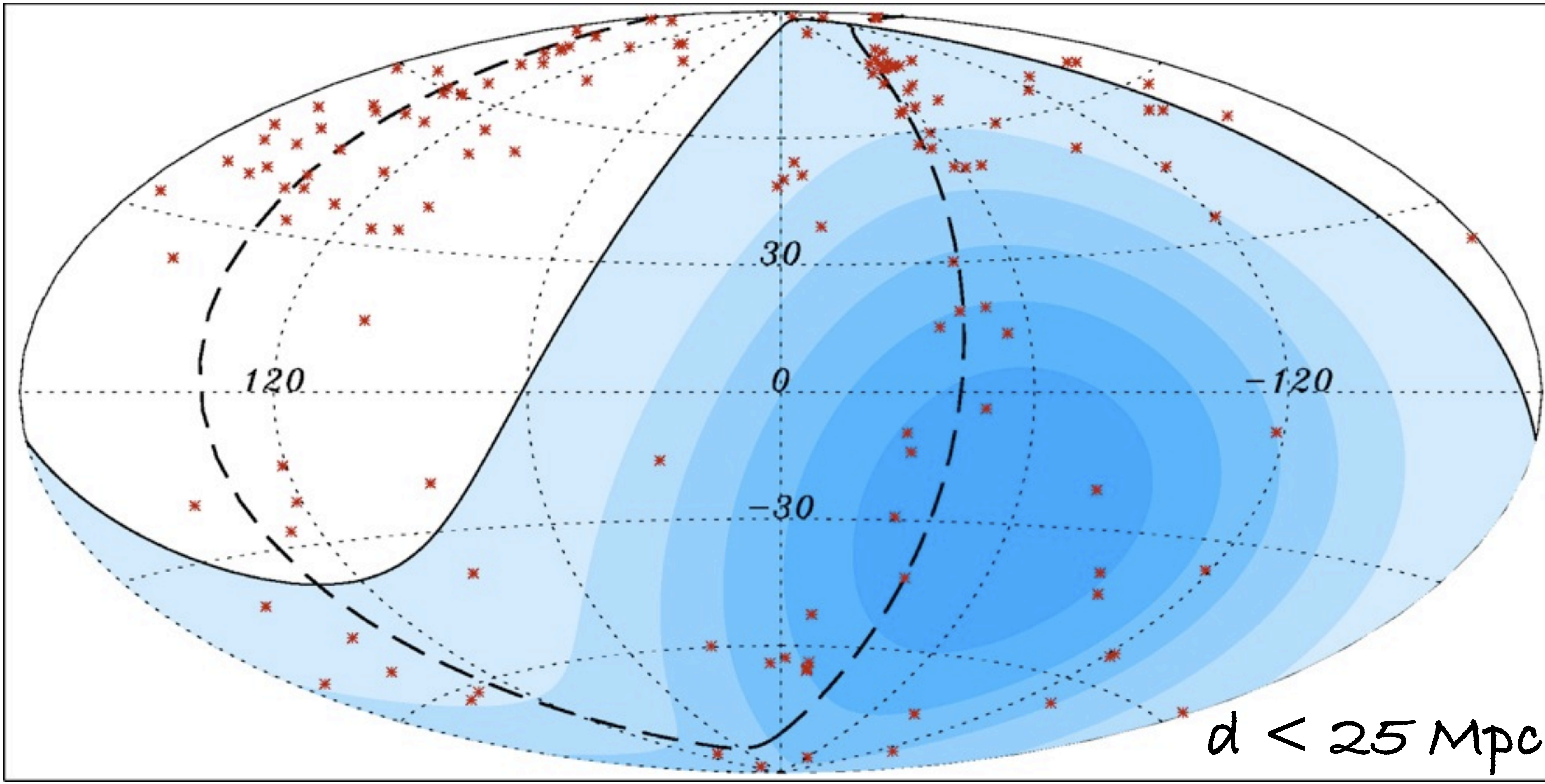
(chance probability < 0.5%)





Correlation with potential source population ?

12^{th} Veron-Cetty catalogue: 694 AGN with d < 100 Mpc (2006)



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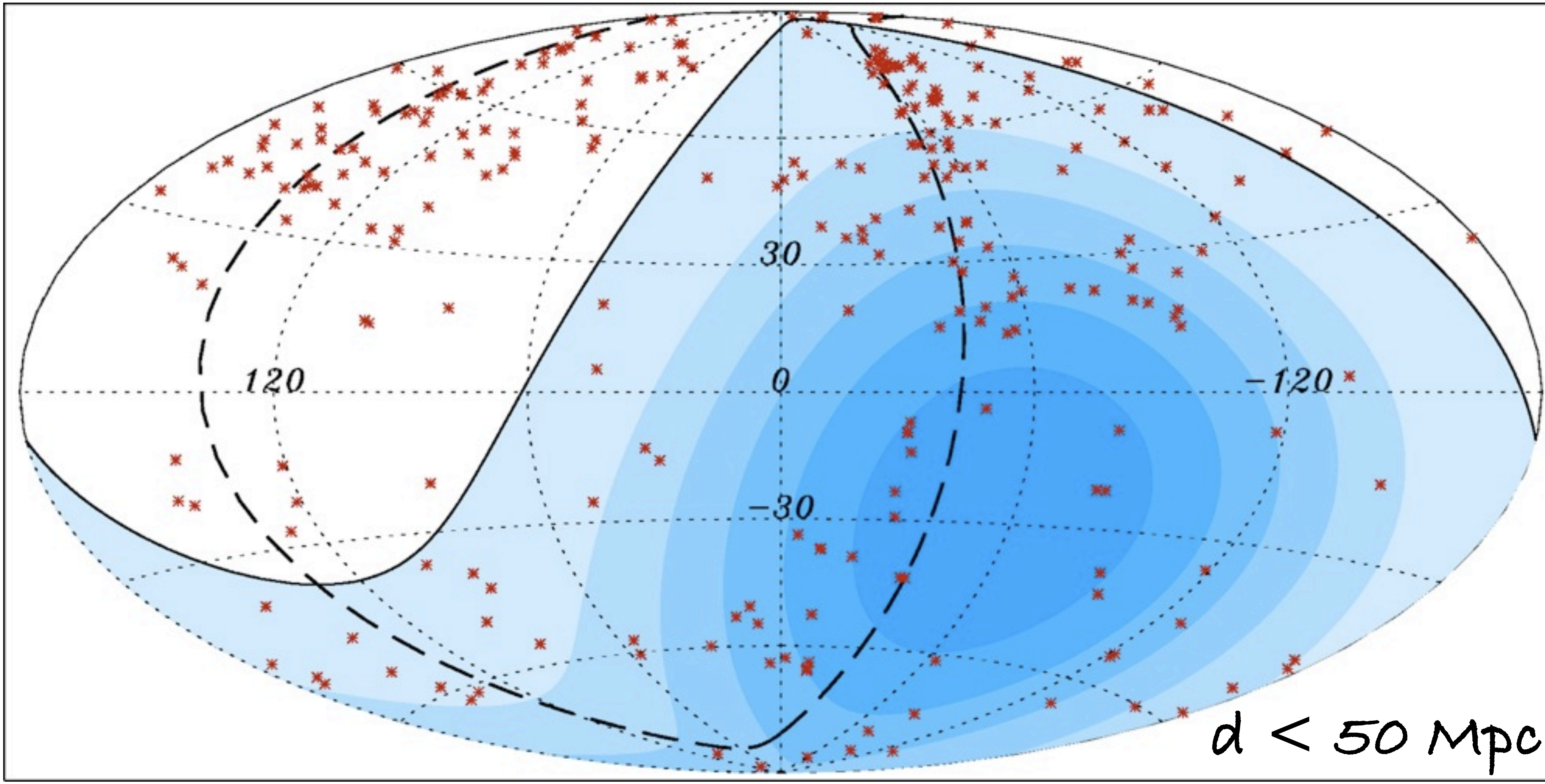
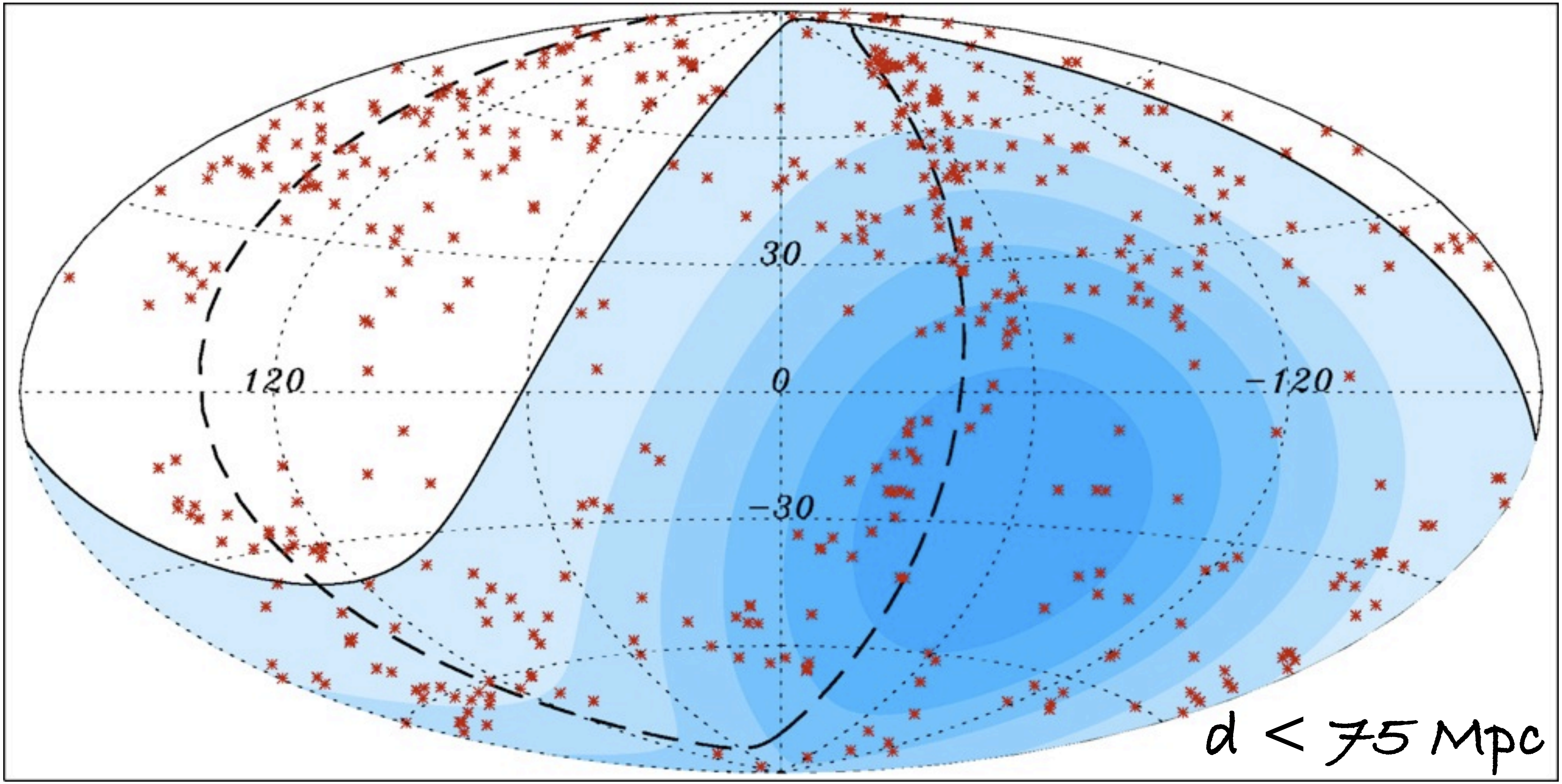
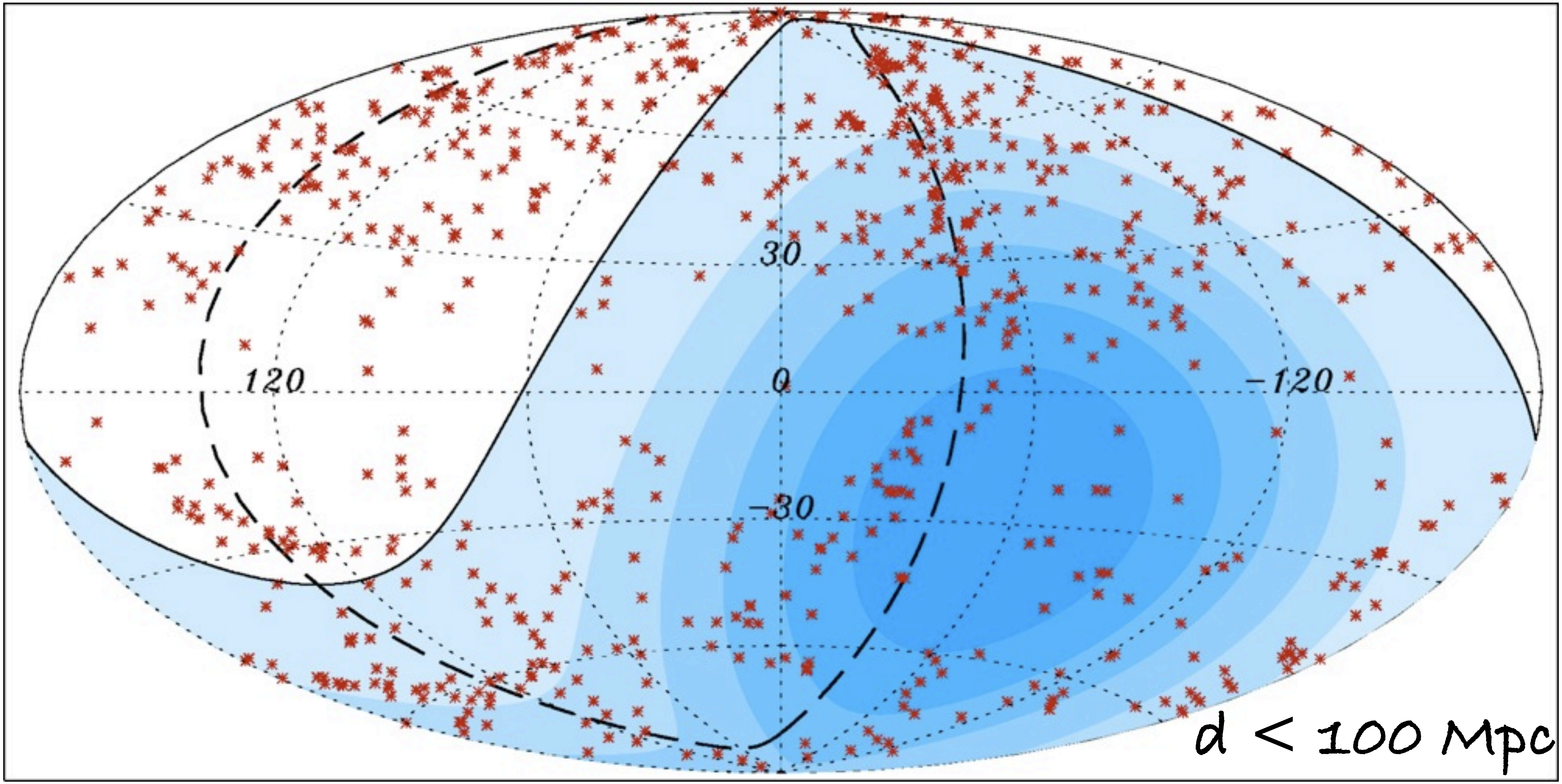


12th Veron-Cetty catalogue: 694 AGN with d < 100 Mpc (2006)



12th Veron-Cetty catalogue: 694 AGN with d < 100 Mpc (2006)

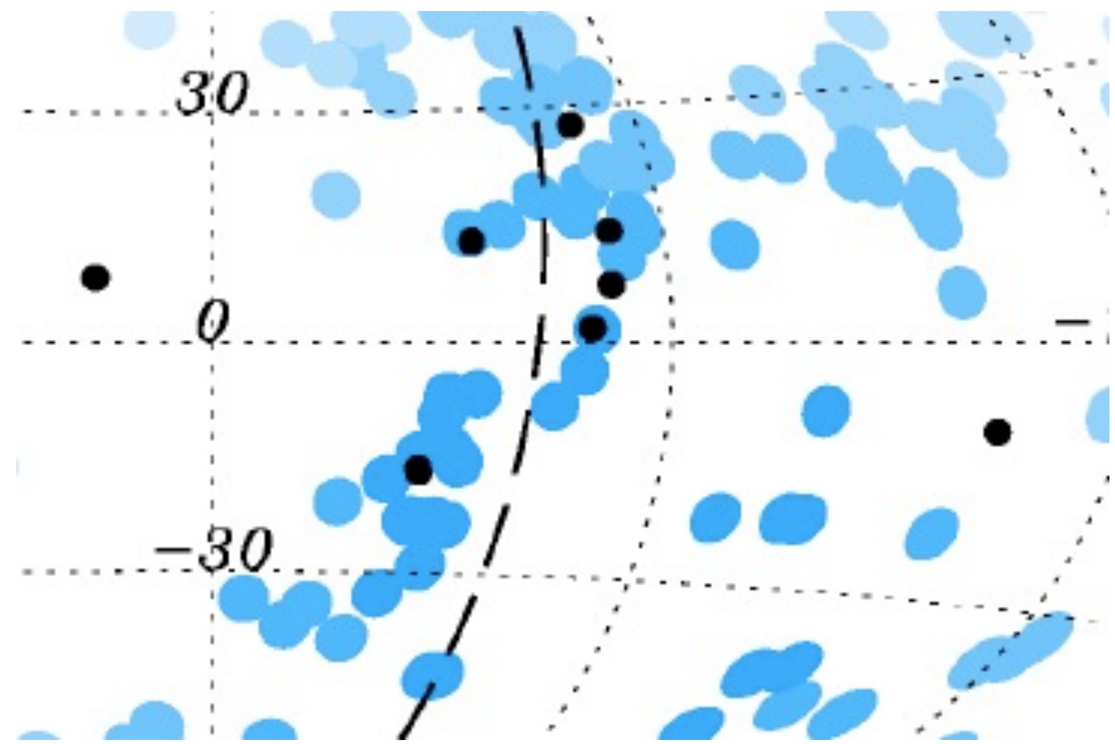


Correlation of CRs with source population :

Vary: max distance to source
max disc around sources
min CR energy

... to correlate CRs with AGNs

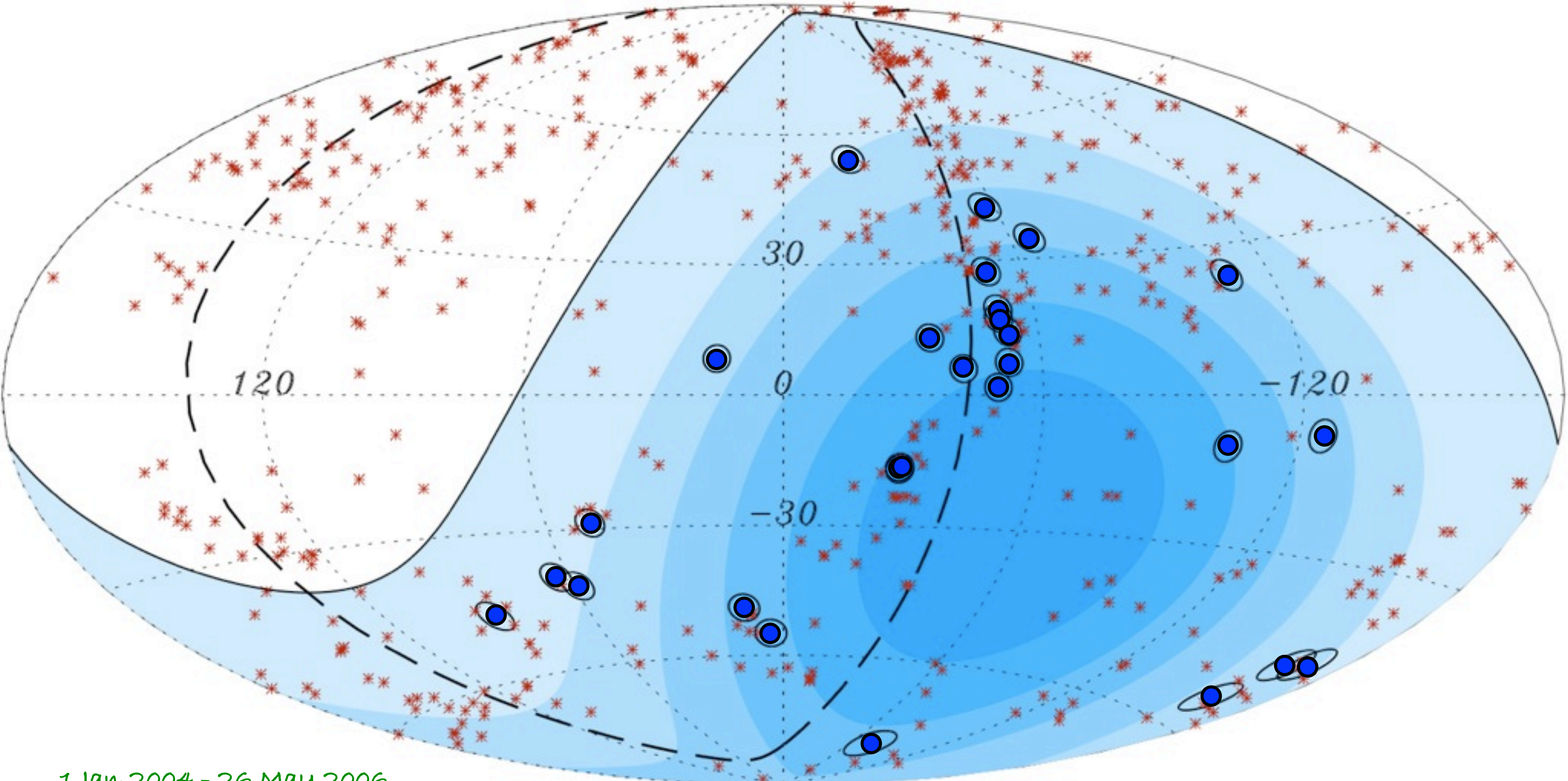
AGNs with disc size R cover a fraction p of the sky (exposure-weighted).



Probability P to find k or more of N random CRs in the area around the AGNs

$$P = \sum_{j=k}^{N} \binom{N}{j} p^j (1-p)^{N-j}$$

p≈0.21



1.Jan 2004 - 26.May 2006

scan: 15 evts, 12 correlate with AGN (3.2 exp.) for R<3.1°, z < 0.018, E > 56 EeV

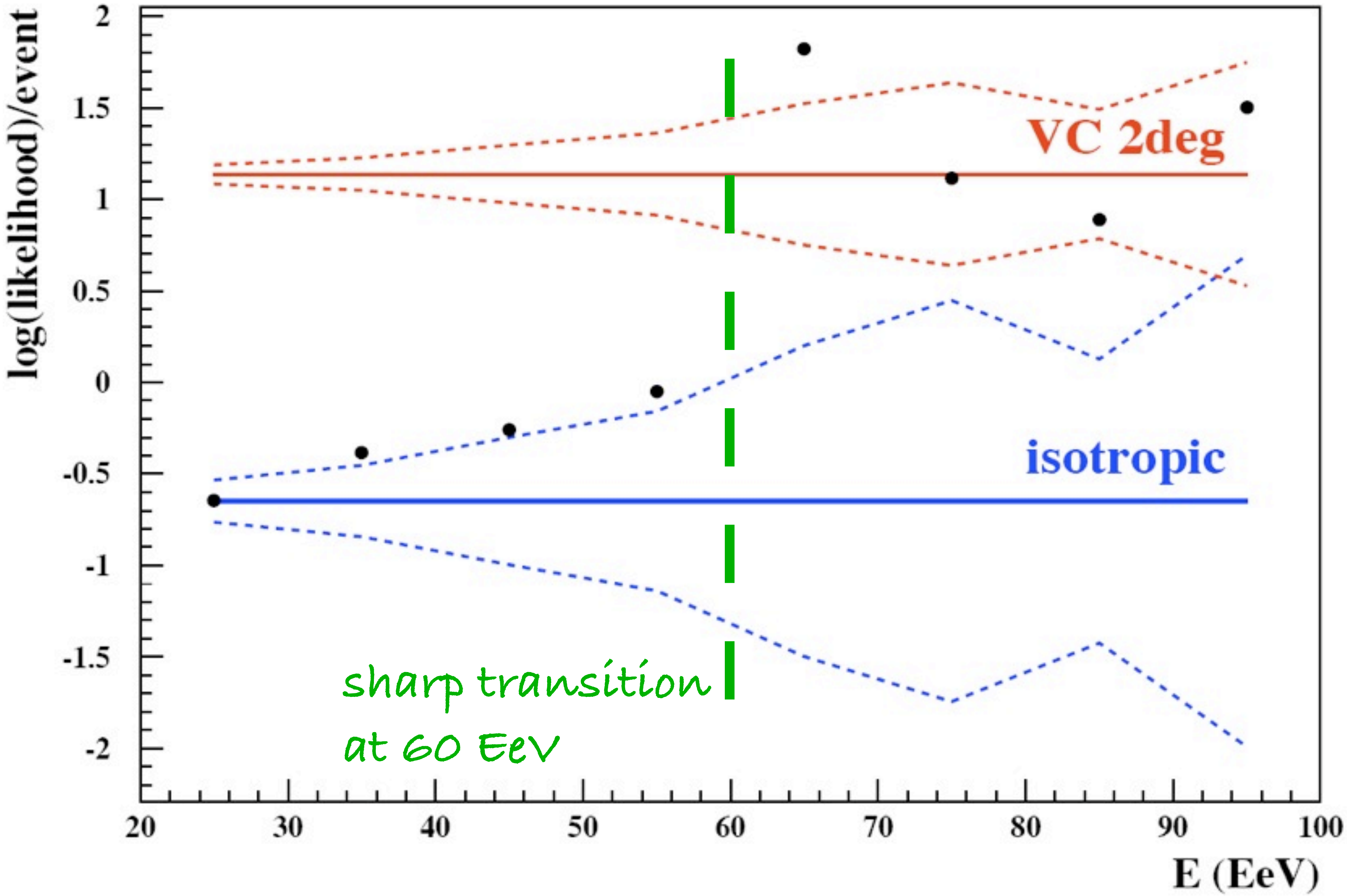
no scan: 13 evts, 8 correlate with AGN (2.7 exp.) independent sample

27.May 2006 - 31.Aug 2007 $p < 1.7 \times 10^{-3}$

total data: 1.2 Auger-years

UHECR isotropy rejected with > 99% confidence level,

are of extragalactic origin.



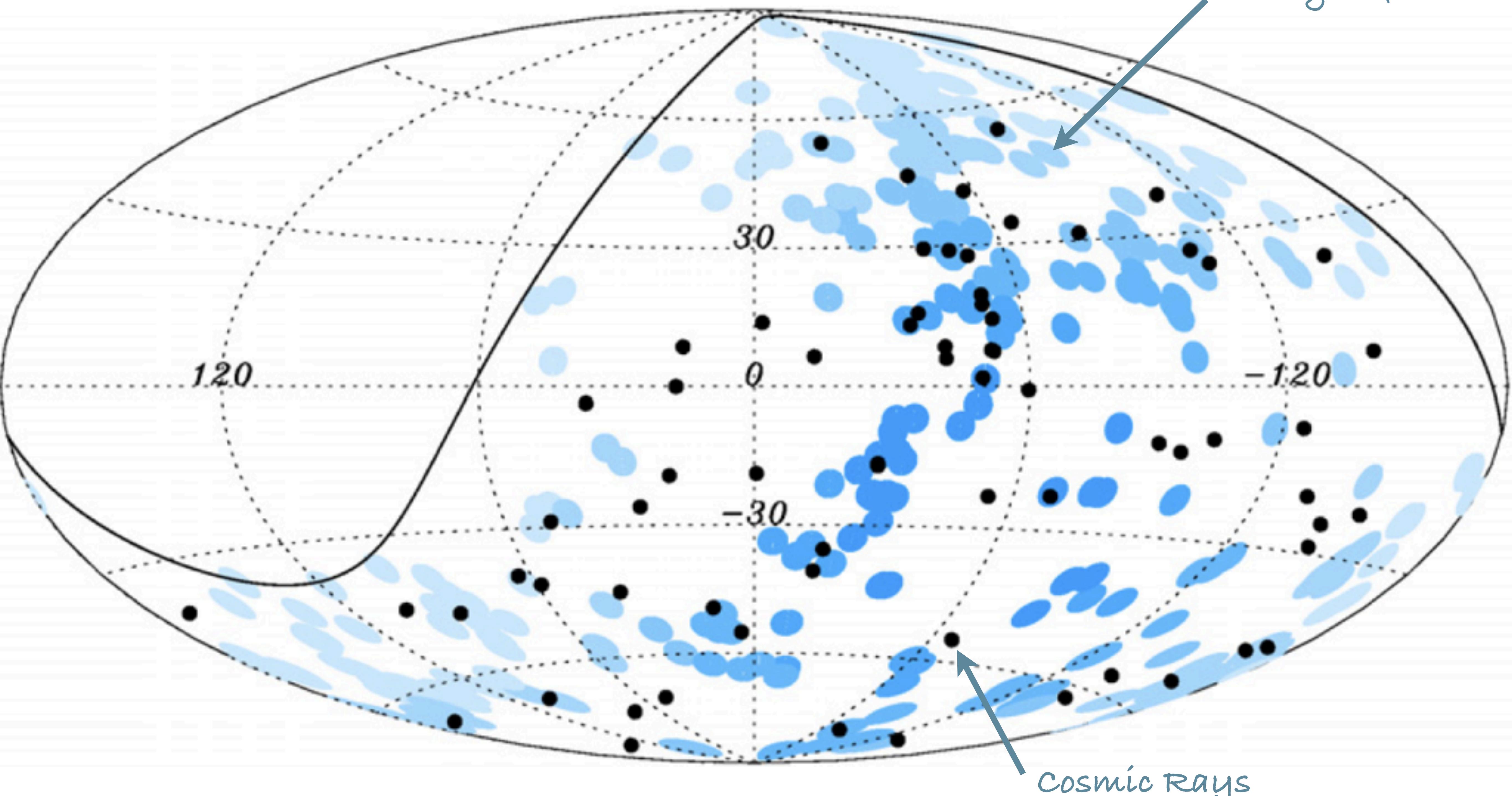
draw random events maps from isotropic dist.
VC catalog

and compare with smoothed VC (d<100 Mpc)

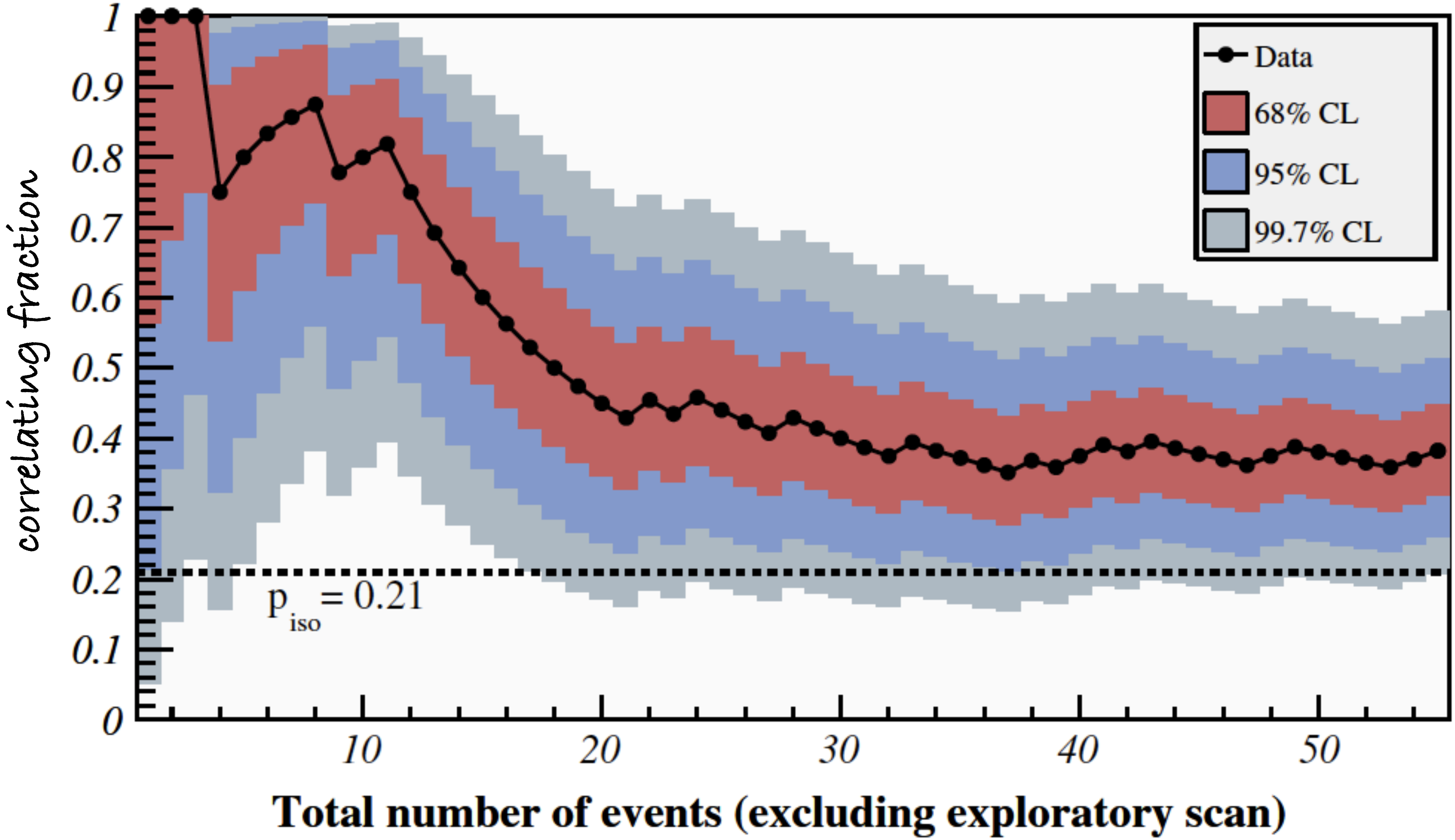
Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects

Auger Collaboration, Science 318, (2007) 938

69 Highest Energy Events >55 EeV (Dec 2009)



Update of the correlation of the highest energy cosmic rays with nearby galaxies (V-C catalog).



parameters fixed a priori: $E_{min} > 55$ EeV, $\psi < 3.1°$, $d_{max} = 75$ Mpc

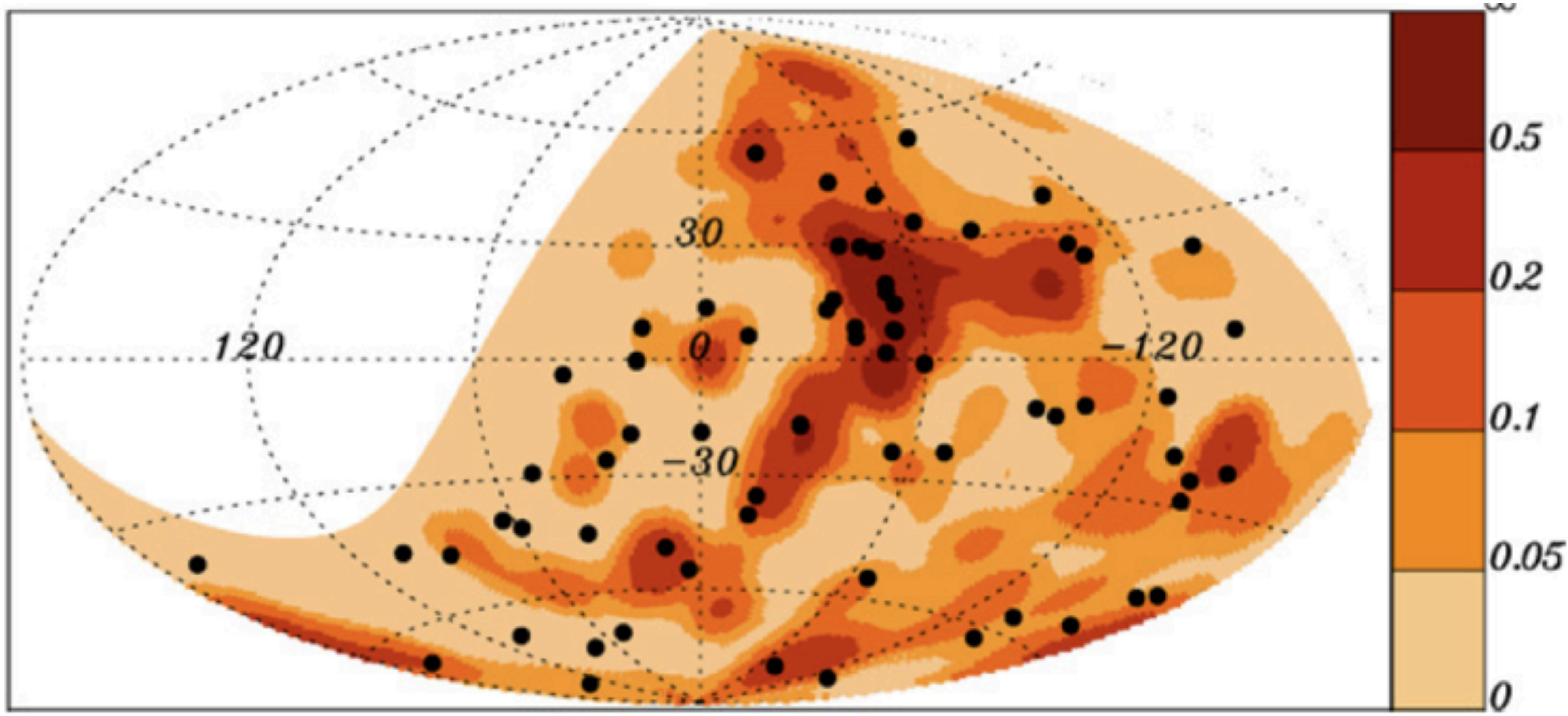
current signal: $p = 0.38^{+0.07}_{-0.06}$

chance probability for isotropic distribution to give this result: 0.006

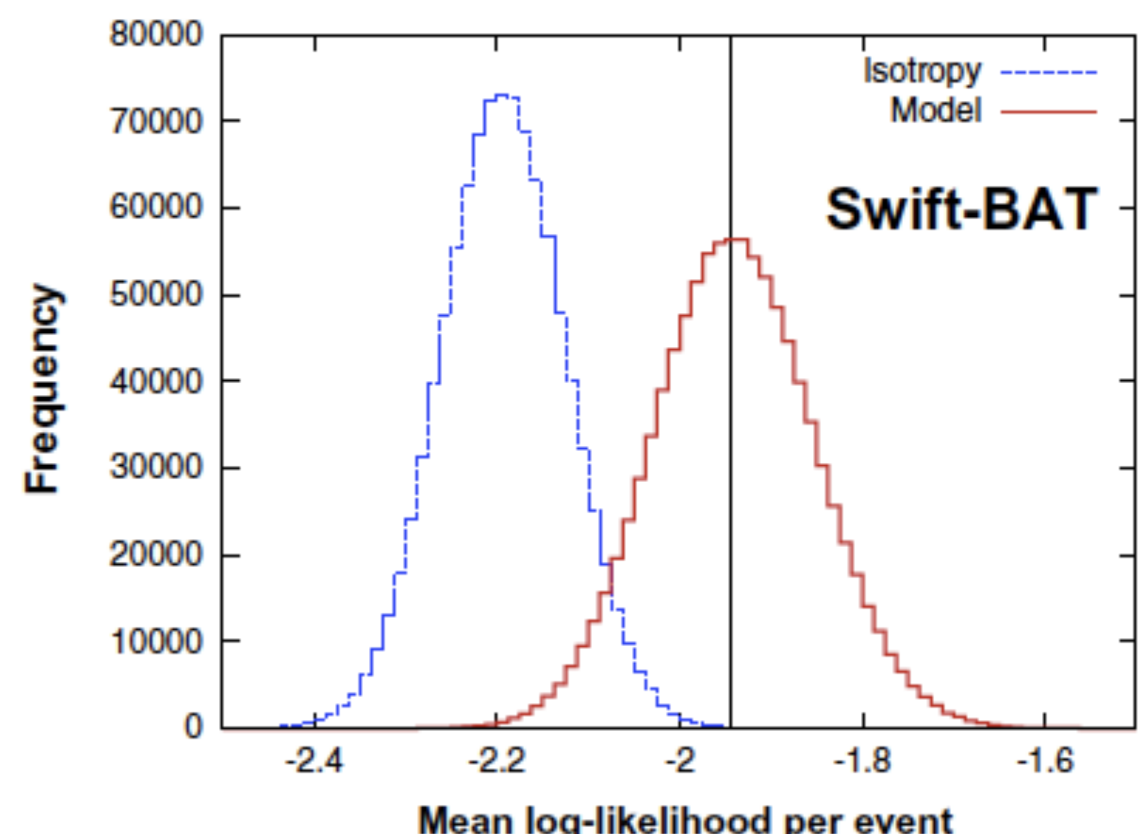
Swift-BAT

58-months catalog,
(uniform, hard X-rays
261 Seyfert galaxies)

d < 200 Mpc
weighted with X-ray flux,
rel. exposure, GZK effect
5° smoothing



UHECRs come from
"nearby extragalactic matter"

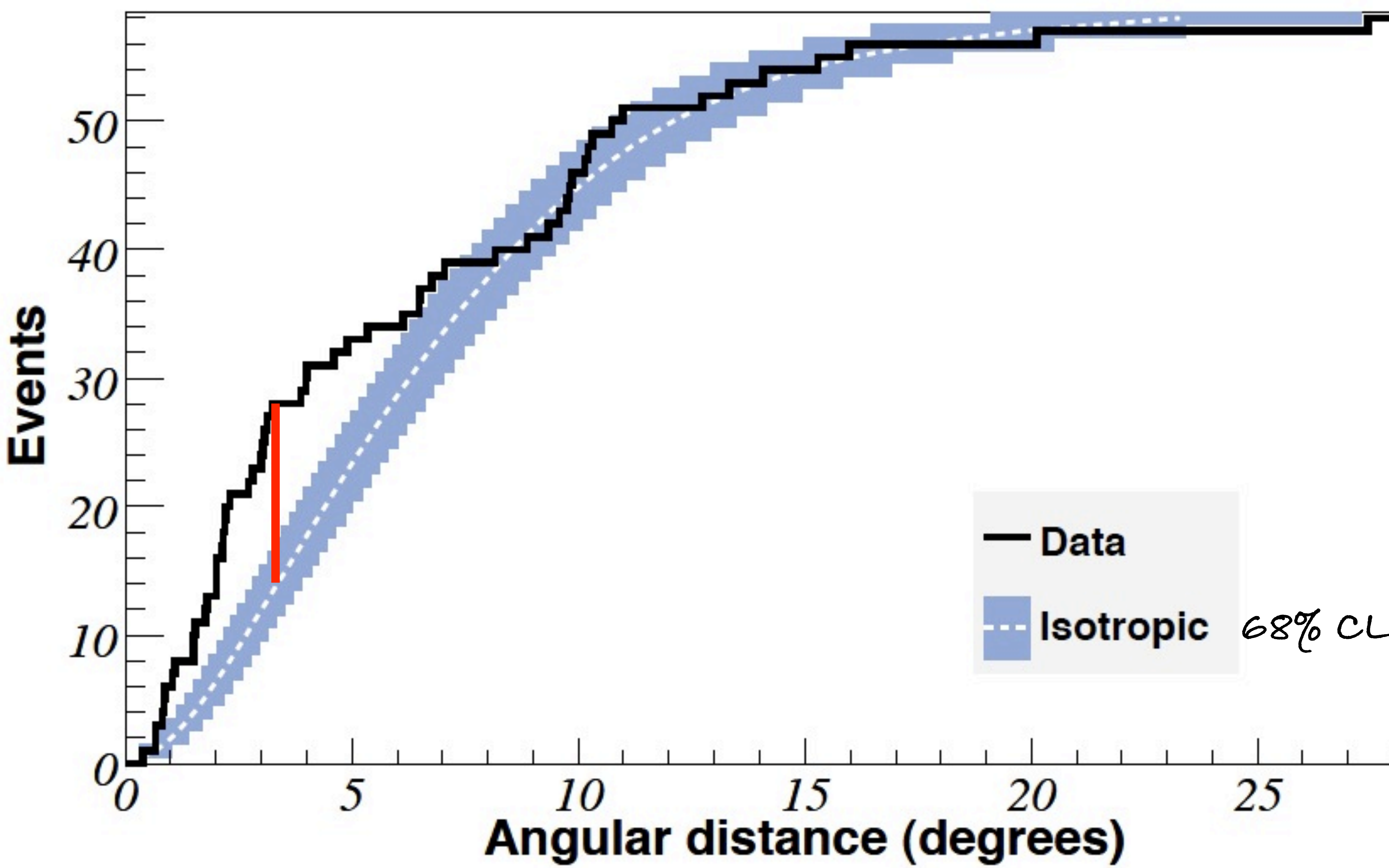


data
isotropy
model

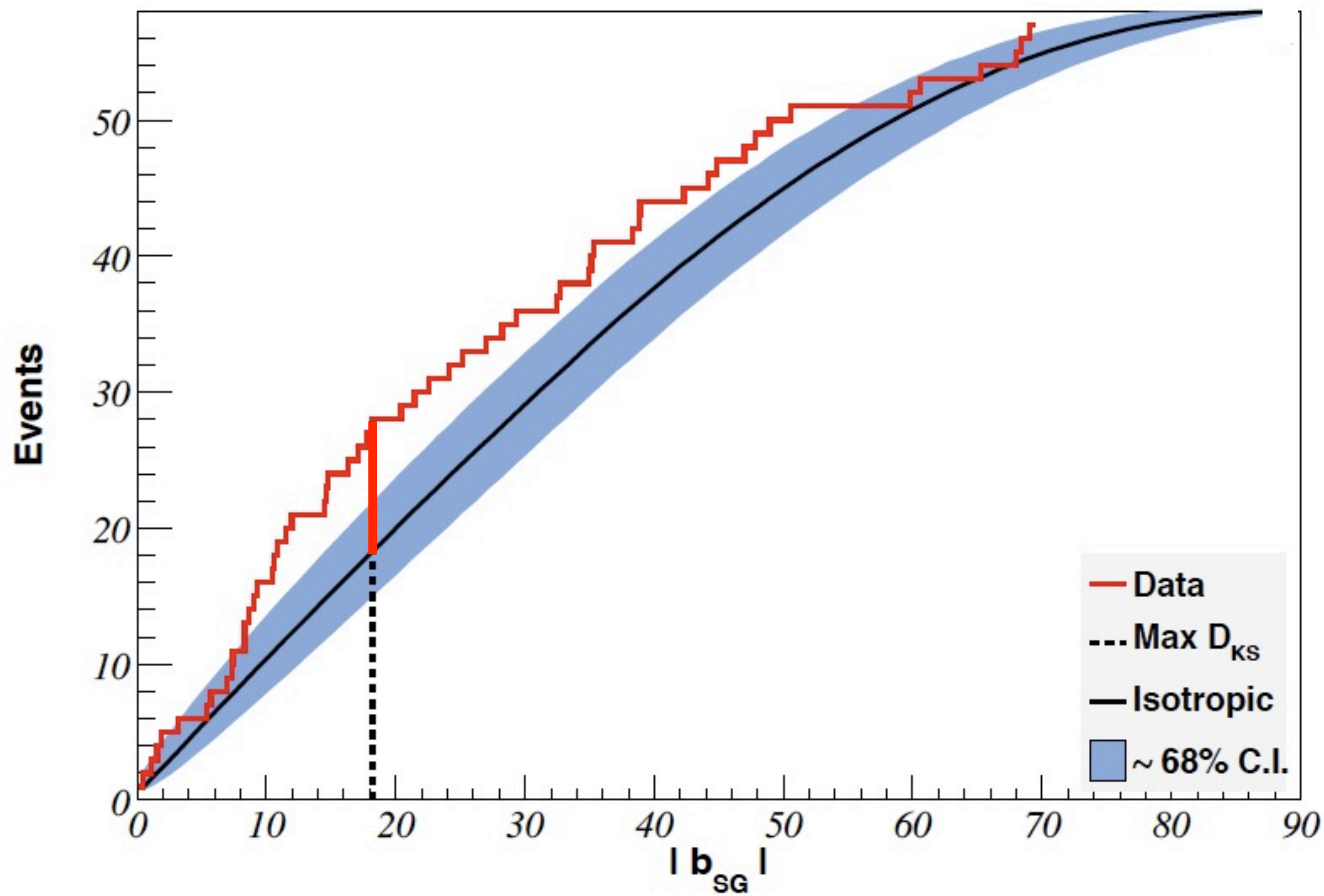
suggestive of primary protons

as deflection in gal. magnetic fields @ 60 EeV:
should be small for protons
big for Iron

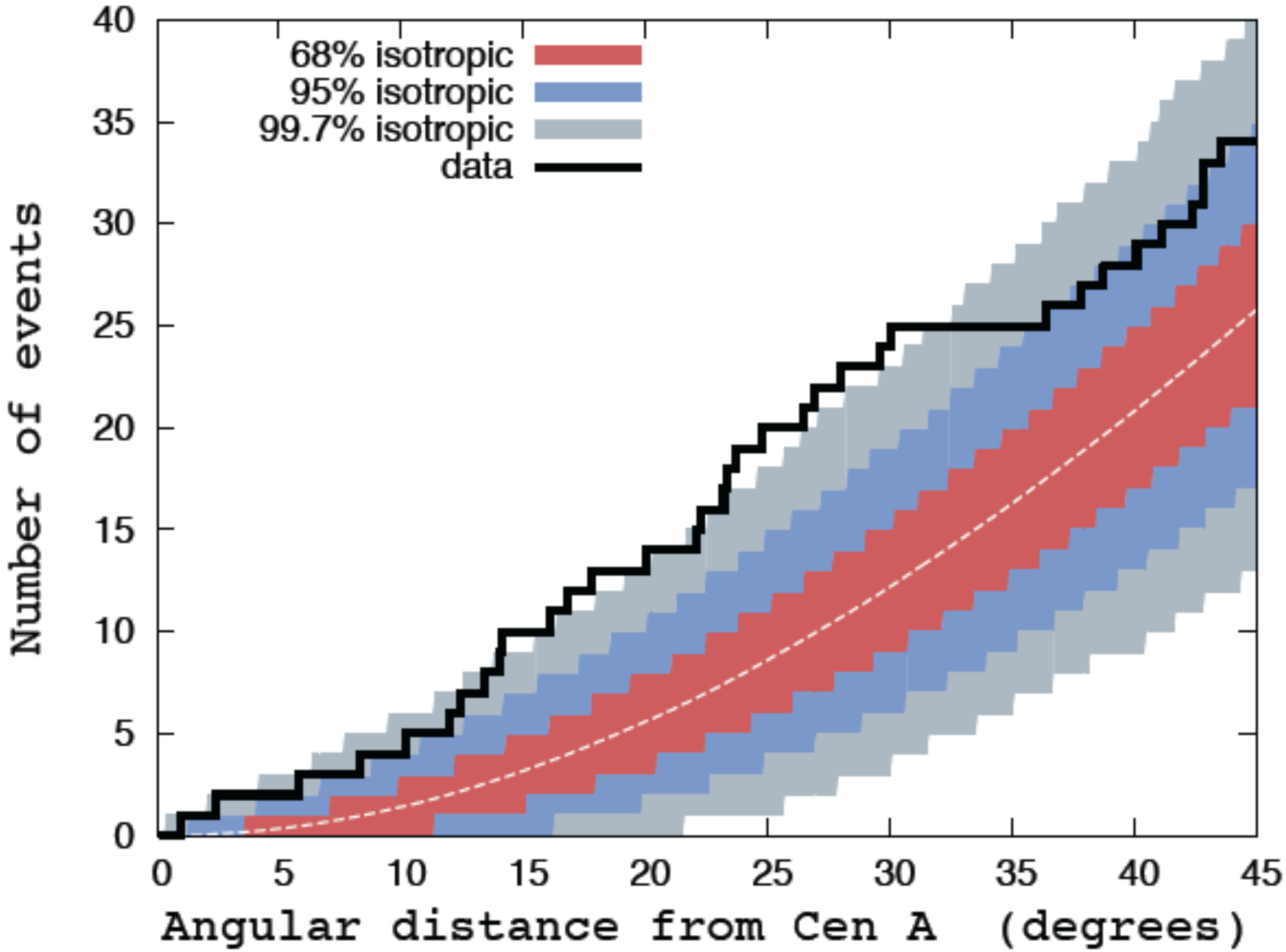
Distance: CR - nearest AGN (z<0.018)



Distance: CR - Supergalactic Plane



Distance: CR - Cen A



4% chance prob. for isotropic distribution

Composition

Options: (stable particles)

photons ?

shower shape is different from expectation for photons
(electromagnetic interaction is well known; QED)

neutrinos ?

showers do start near top of atmosphere

so far no γ or ν candidates found

Showers look like showers from p and nuclei at lower energies, ... just much larger.

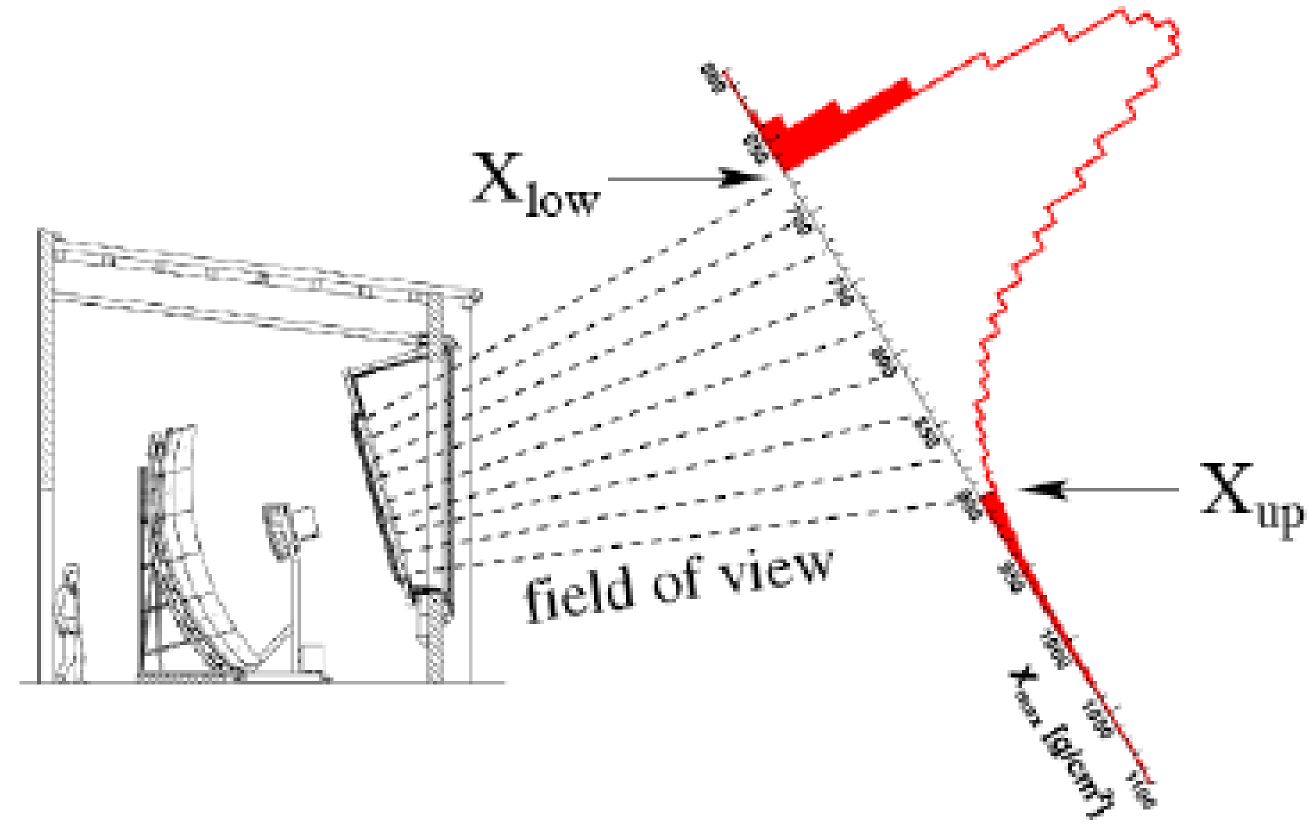
p ... He ... O ... Fe n (?)

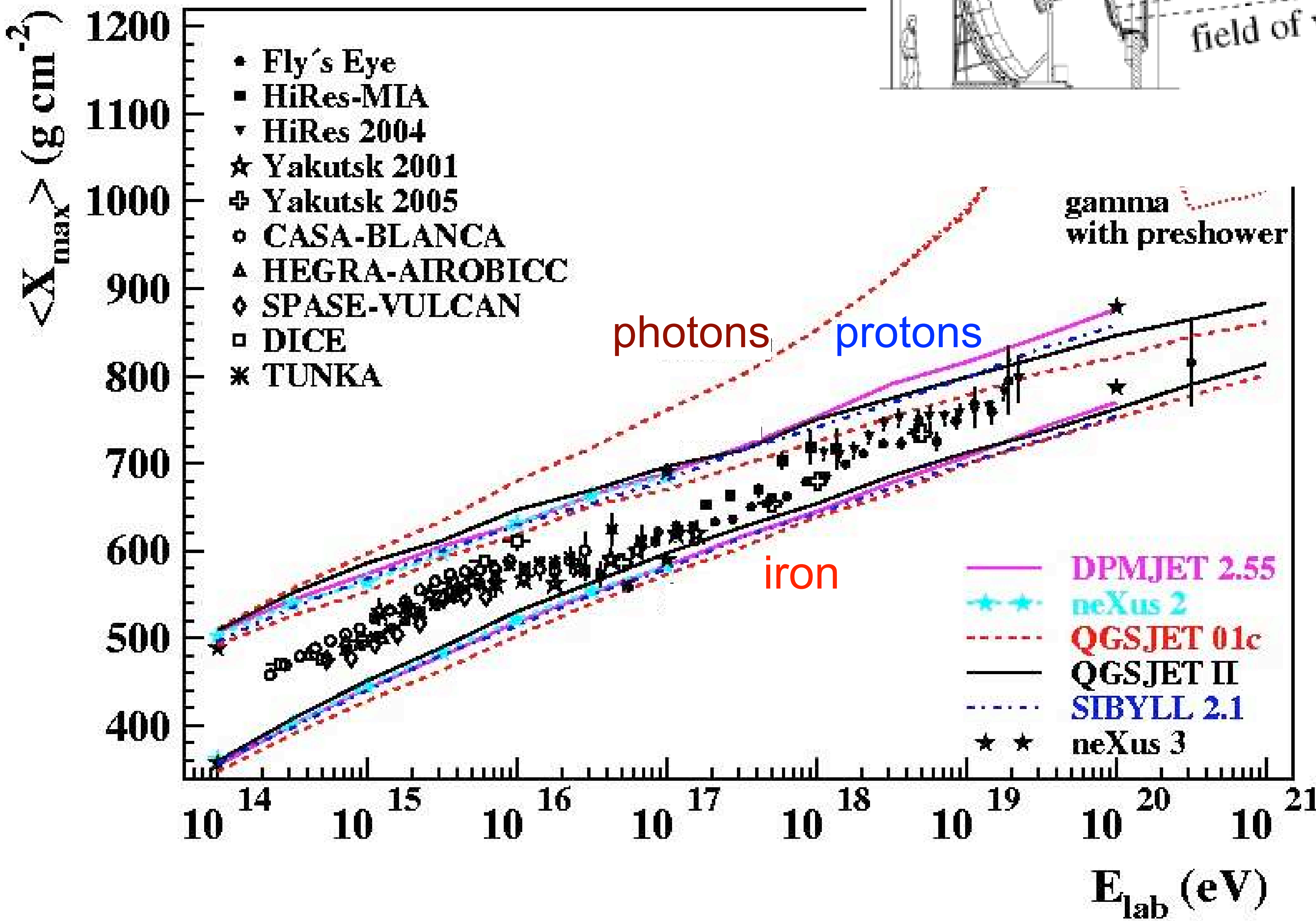
Photons

FD: measure X_{max}

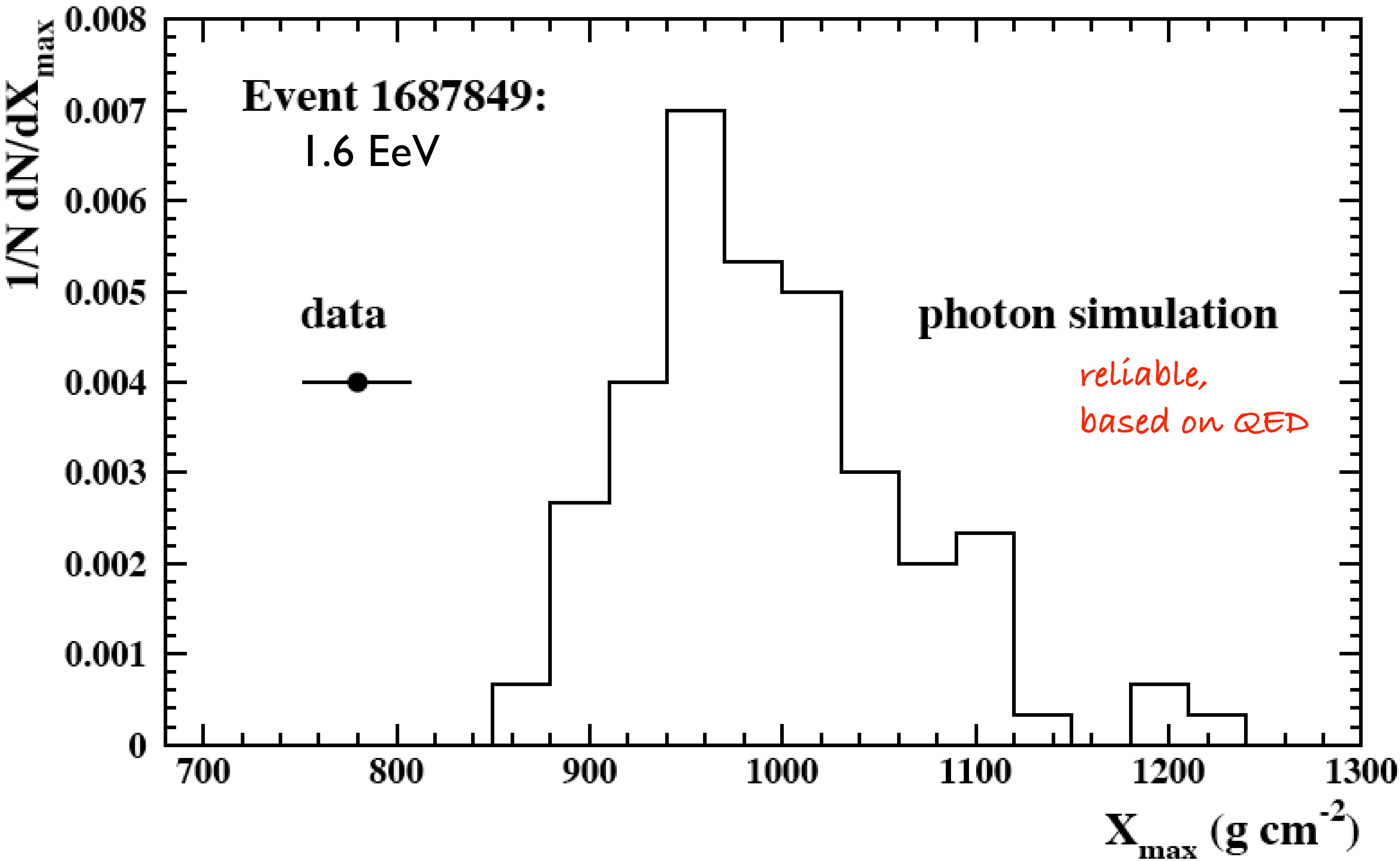
photons maximise deeper than nuclei

protons maximise deeper than iron

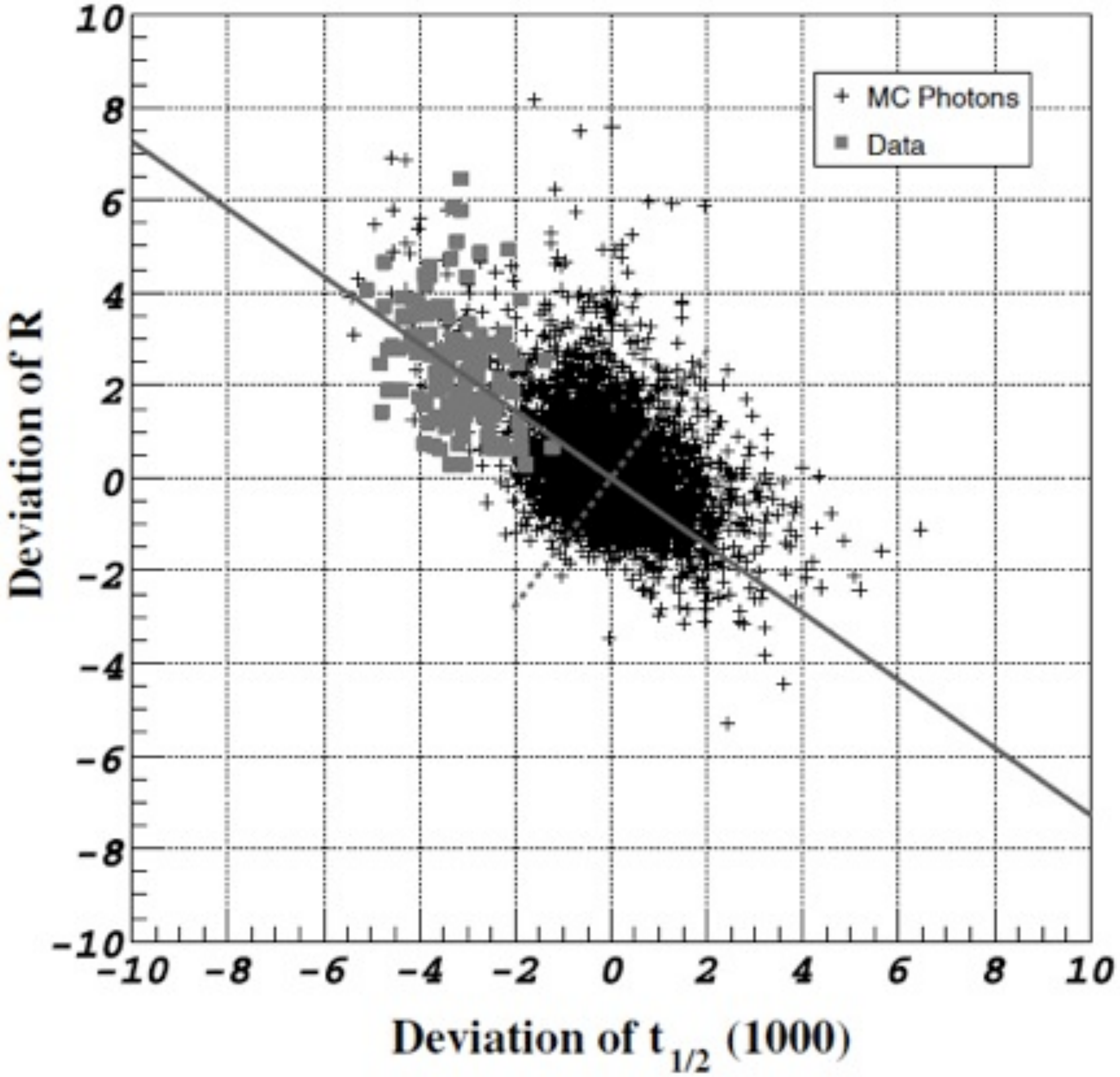


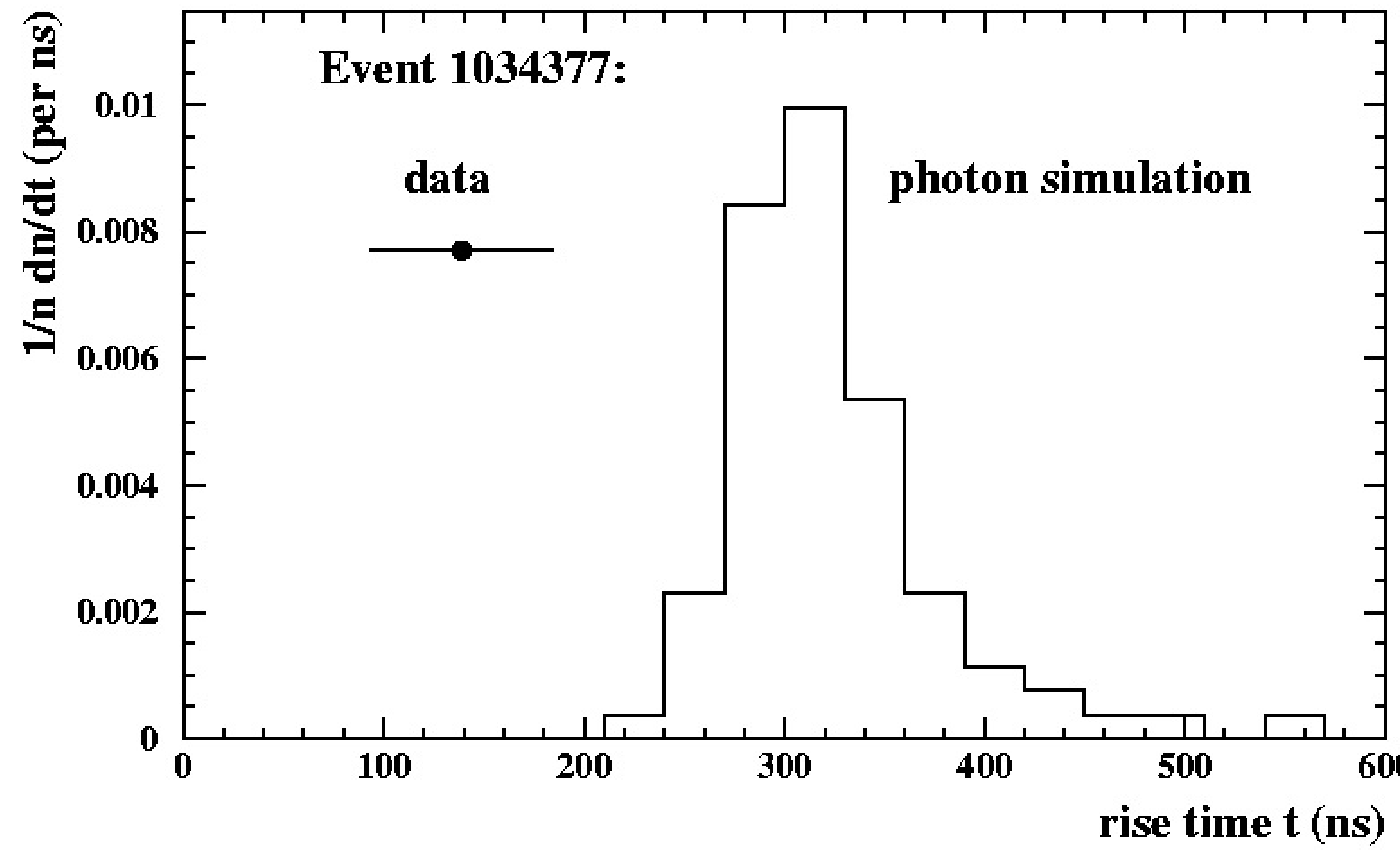


Hybrid events, E>10^{19} eV



compare each event with photon simulations,
combine probabilities for all events

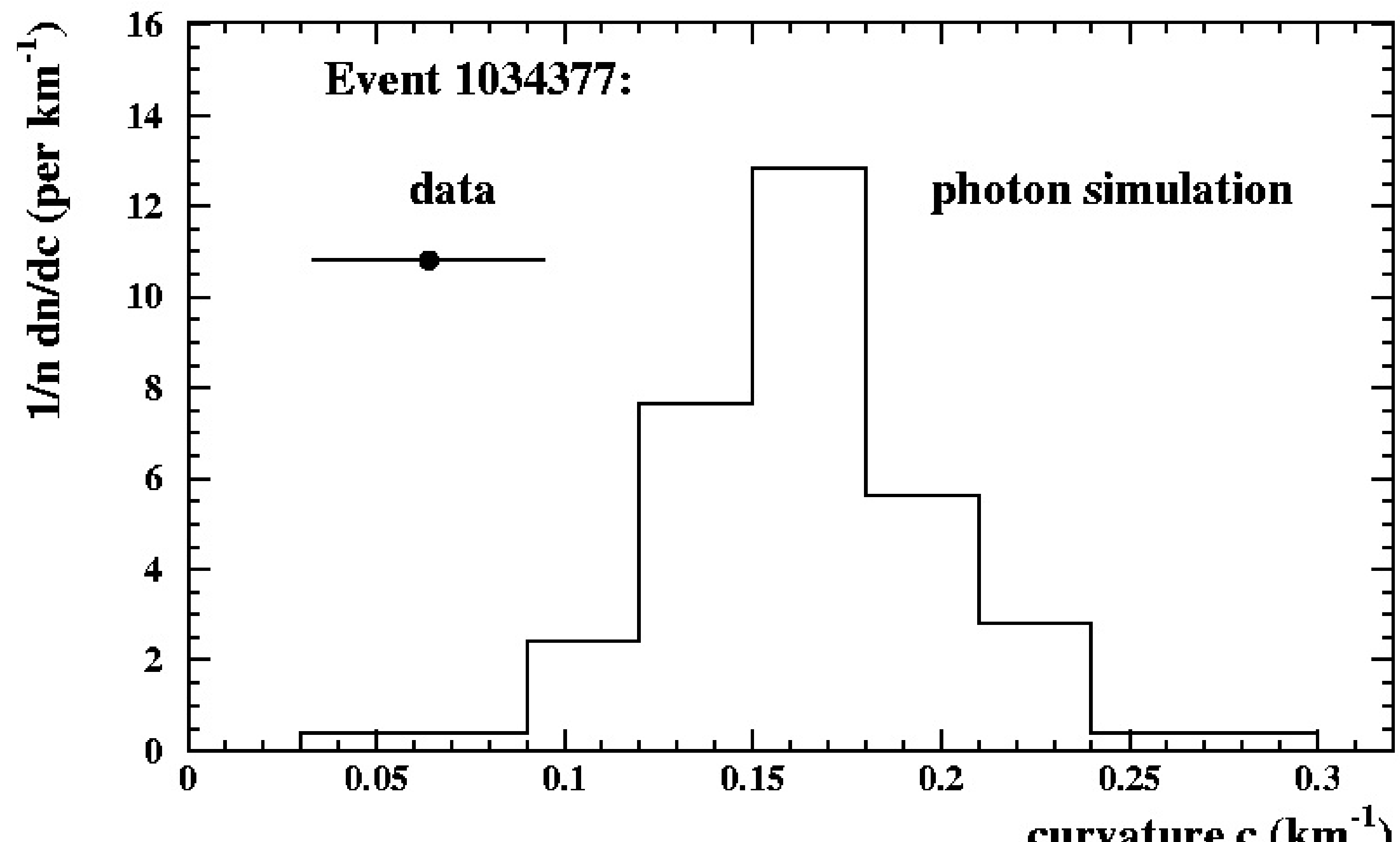




SD only variables:

- signal rise time
- curvature of shower front

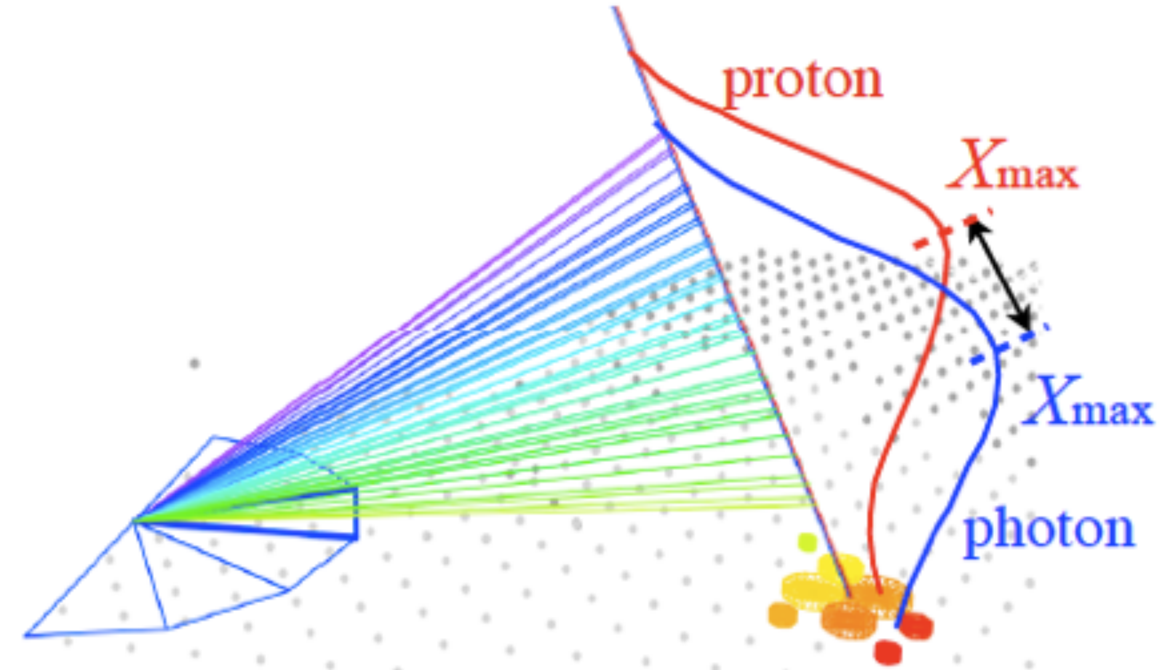
SD: much larger statistics, but reconstruction not mass independent

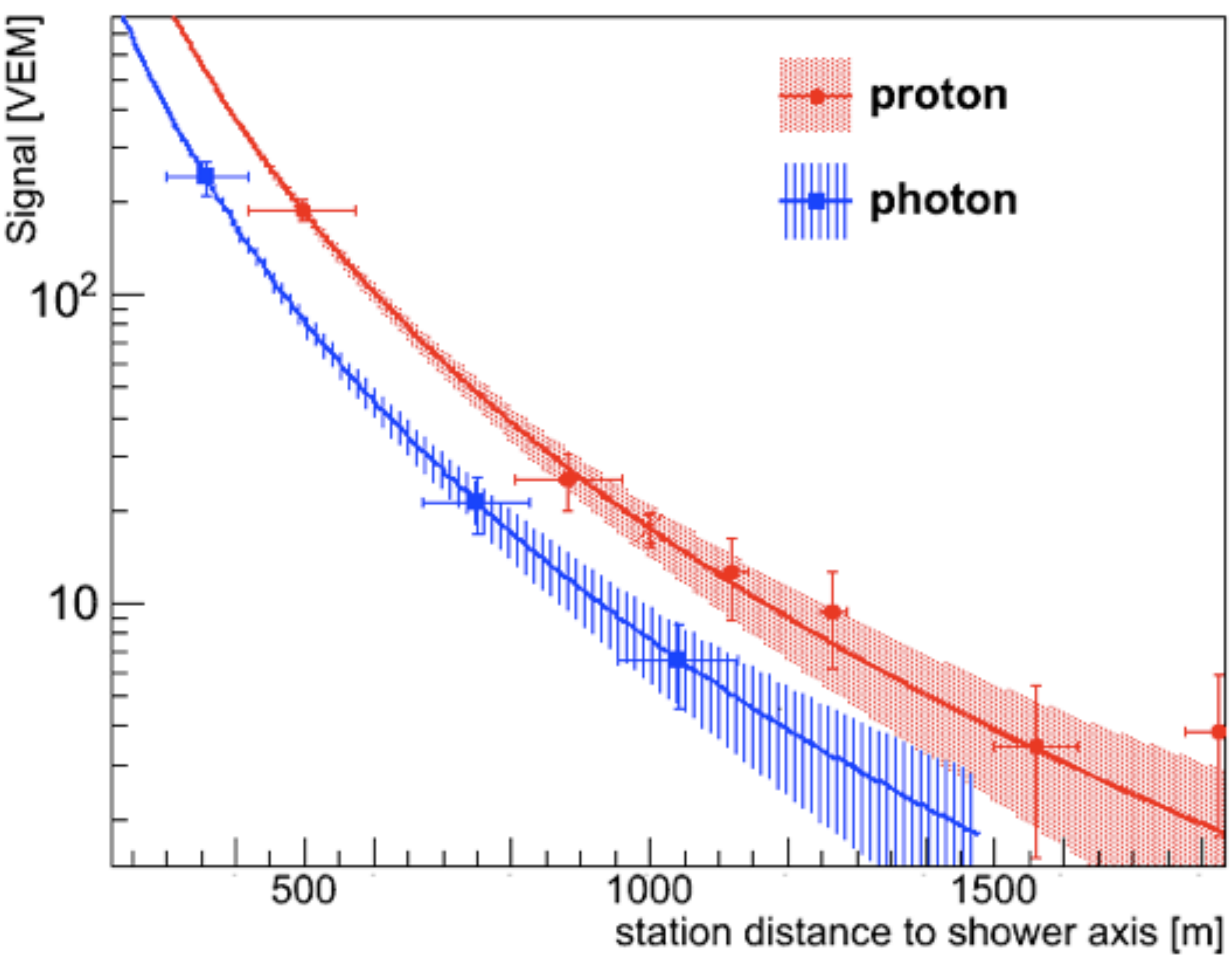


Photons

FD: measure X_{max}

γ maximise deeper than p, Fe

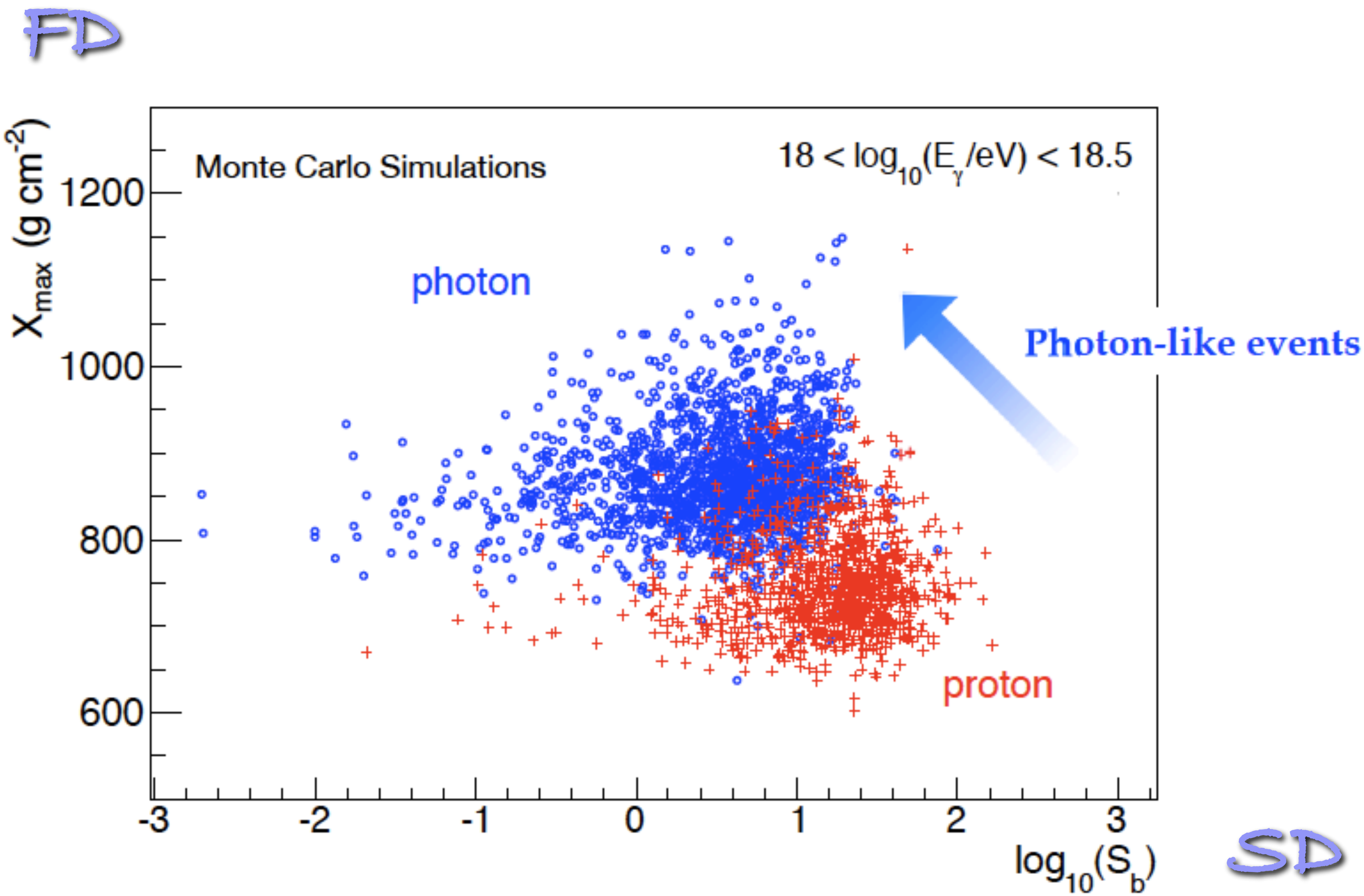




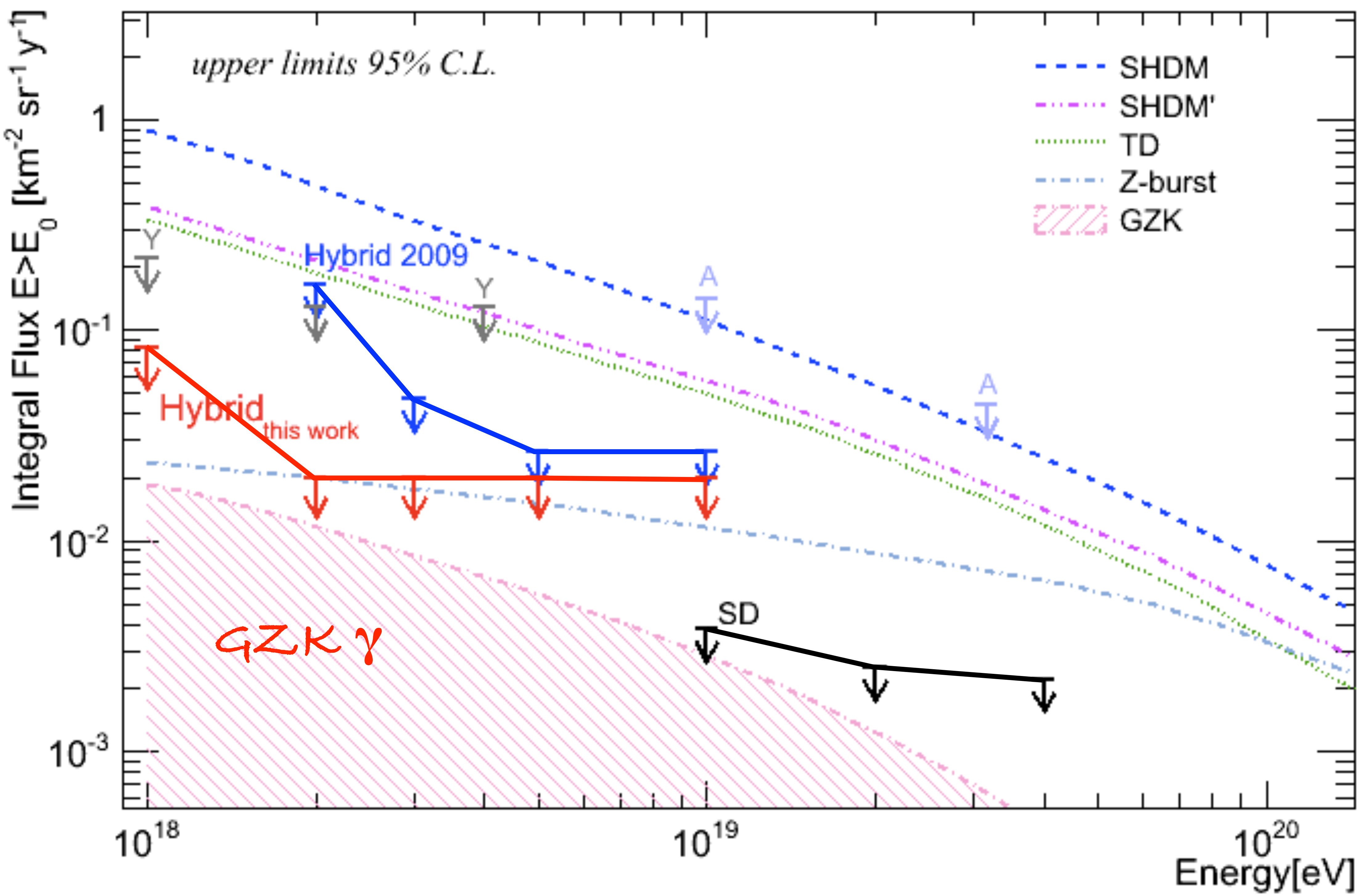
SD: measure S(r)

photons have smaller signals

(for the same FD energy)



$$S_b = \sum_i S_i \left(\frac{R_i}{1000} \right)^4$$



improved limits at lower energies,

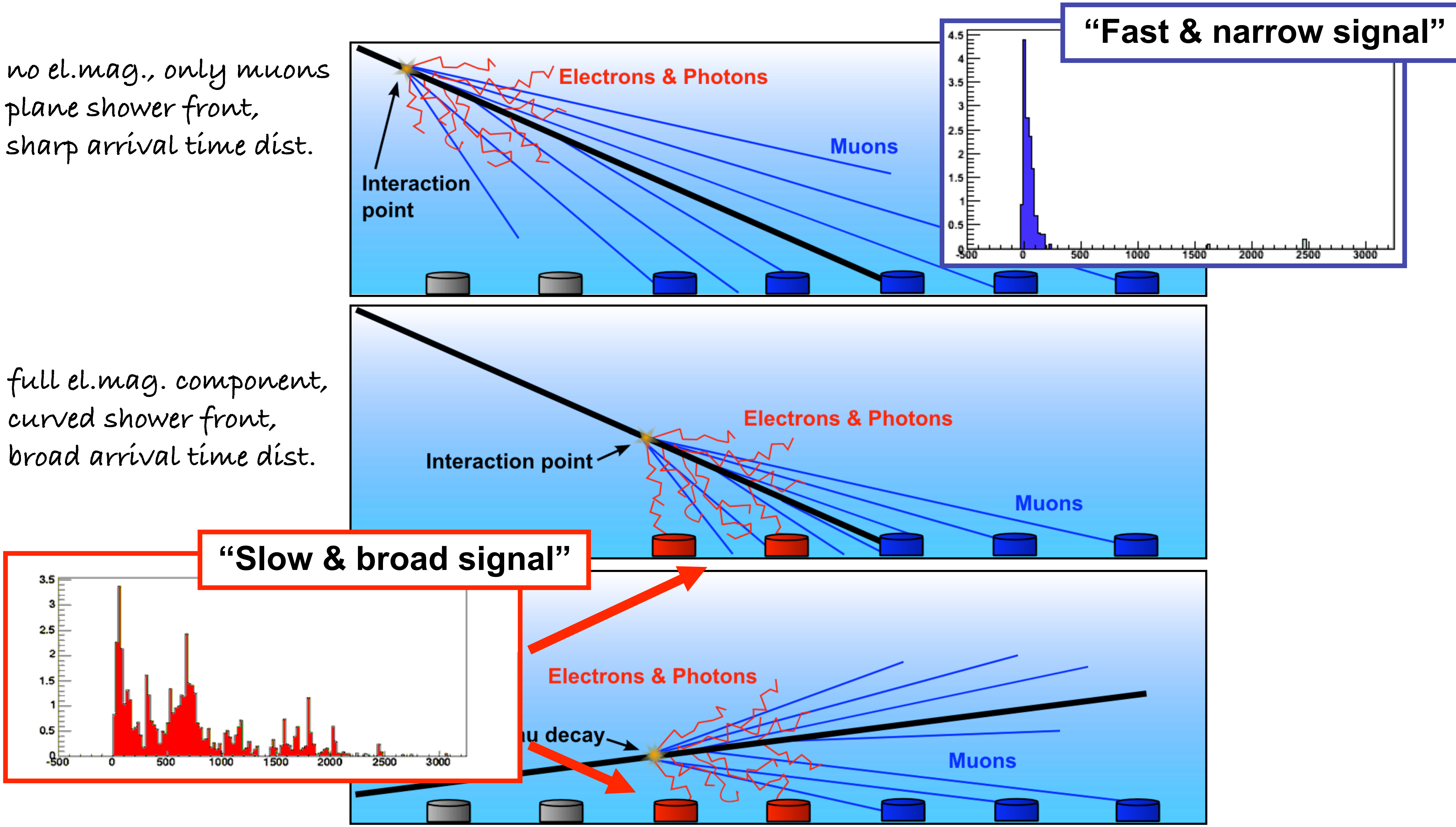
approaching the region where GZK γ are expected.

Neutrino detection with Auger

nearly horizontal showers : atmosphere » 1000 g/cm²

no el.mag., only muons
plane shower front,
sharp arrival time dist.

full el.mag. component,
curved shower front,
broad arrival time dist.

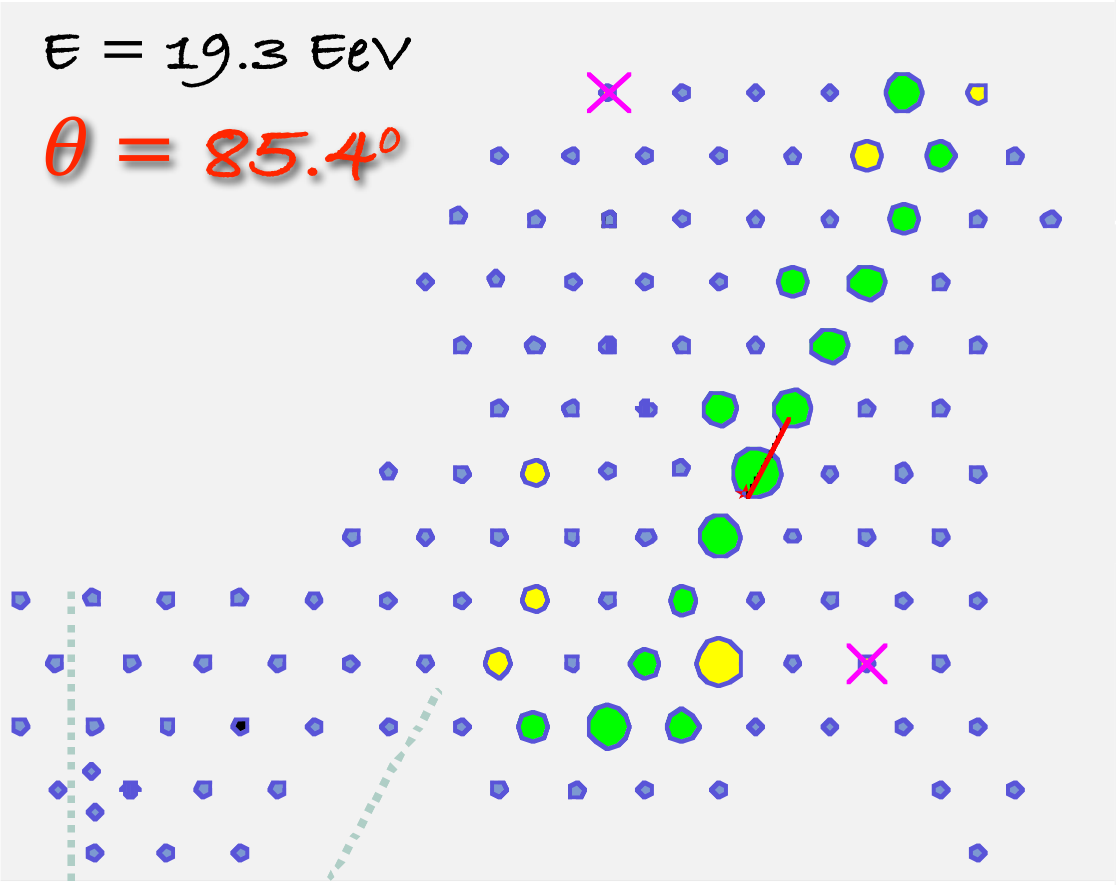


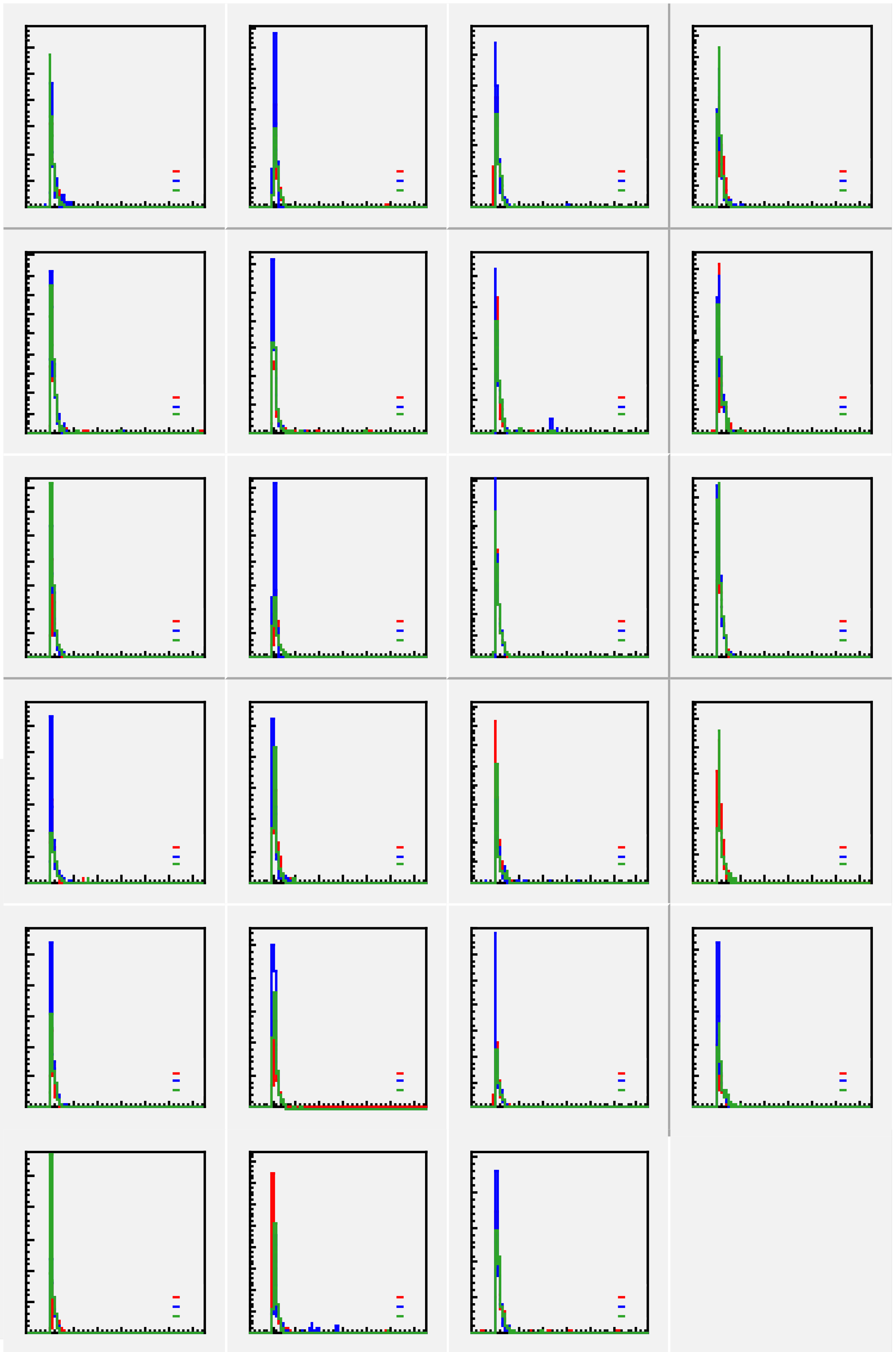
PRL 100 (2008) 211101

horizontal neutrino showers look like CR showers after ~ 1 atm.

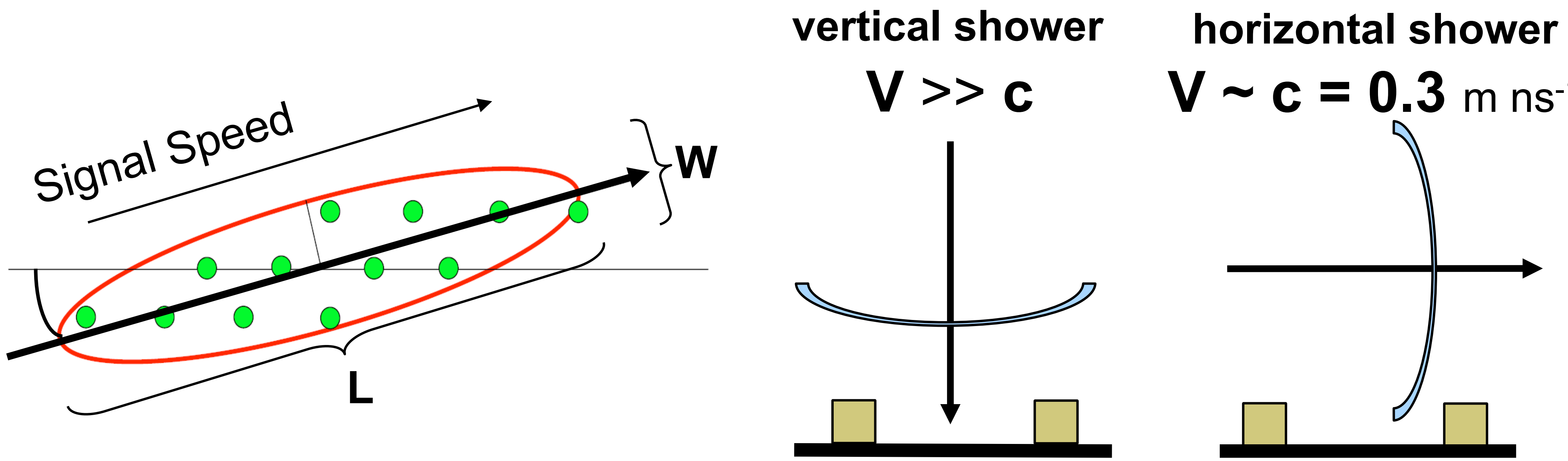
Horizontal showers:

- increase sky coverage and aperture
- give neutrino sensitivity



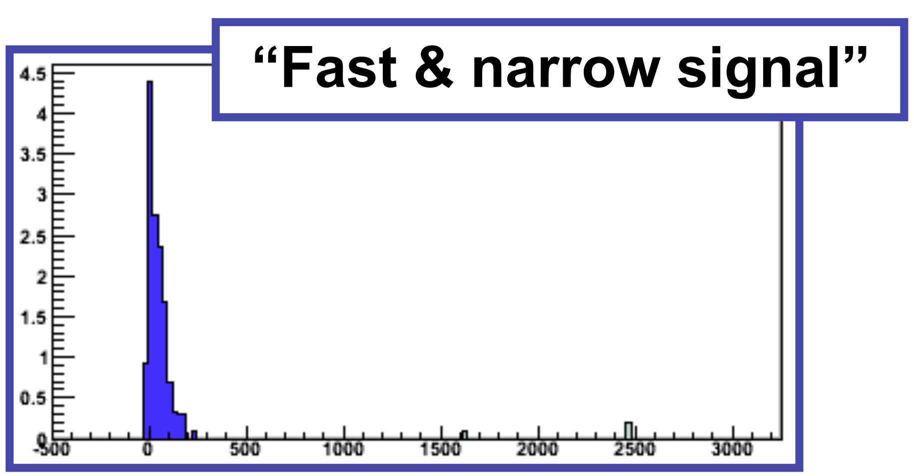


quality cuts



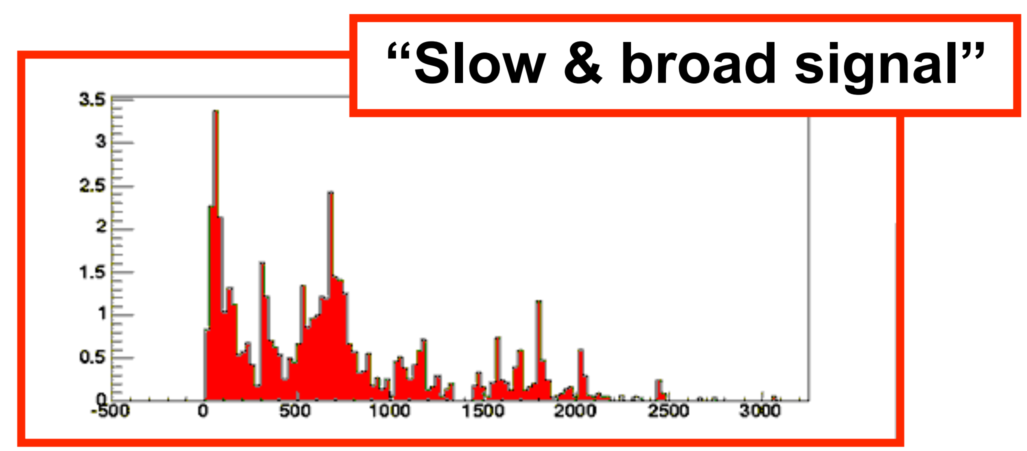
area over peak to select ν events

Muons



Small AOP (~ 1)

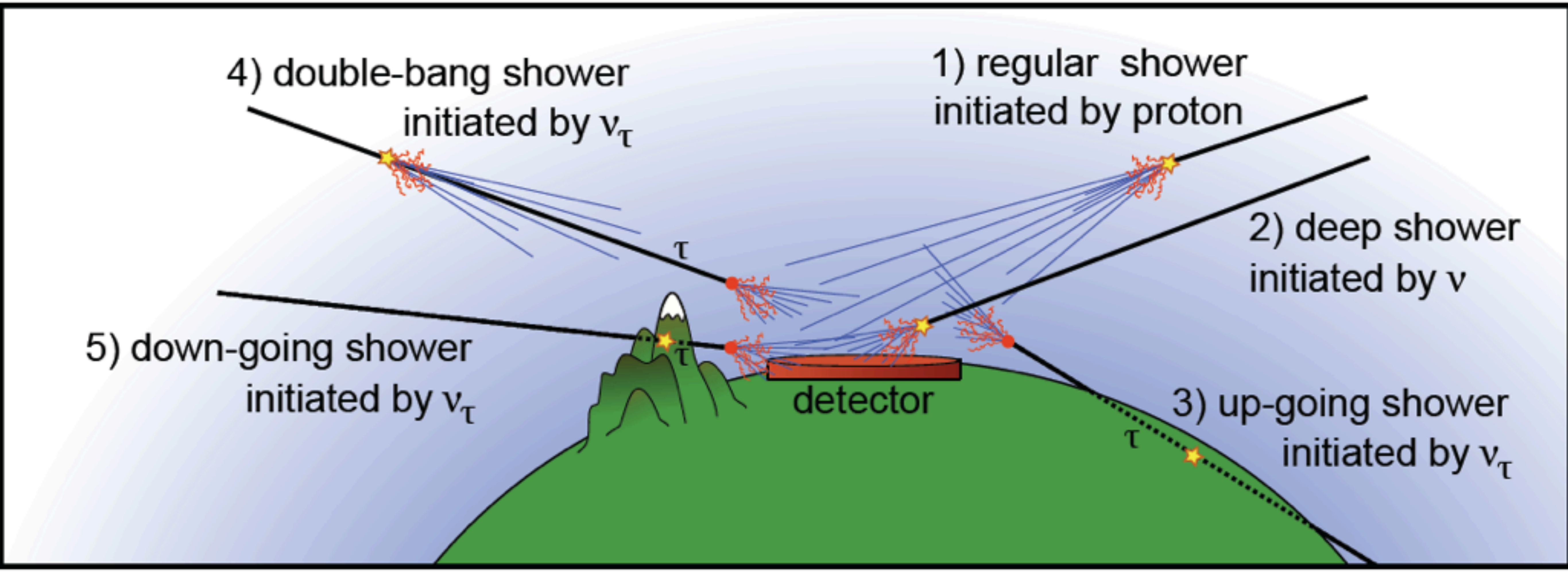
Electrons + photons



Large AOP (> 3)

combine AOPs of different tanks with Fisher method

Neutrinos



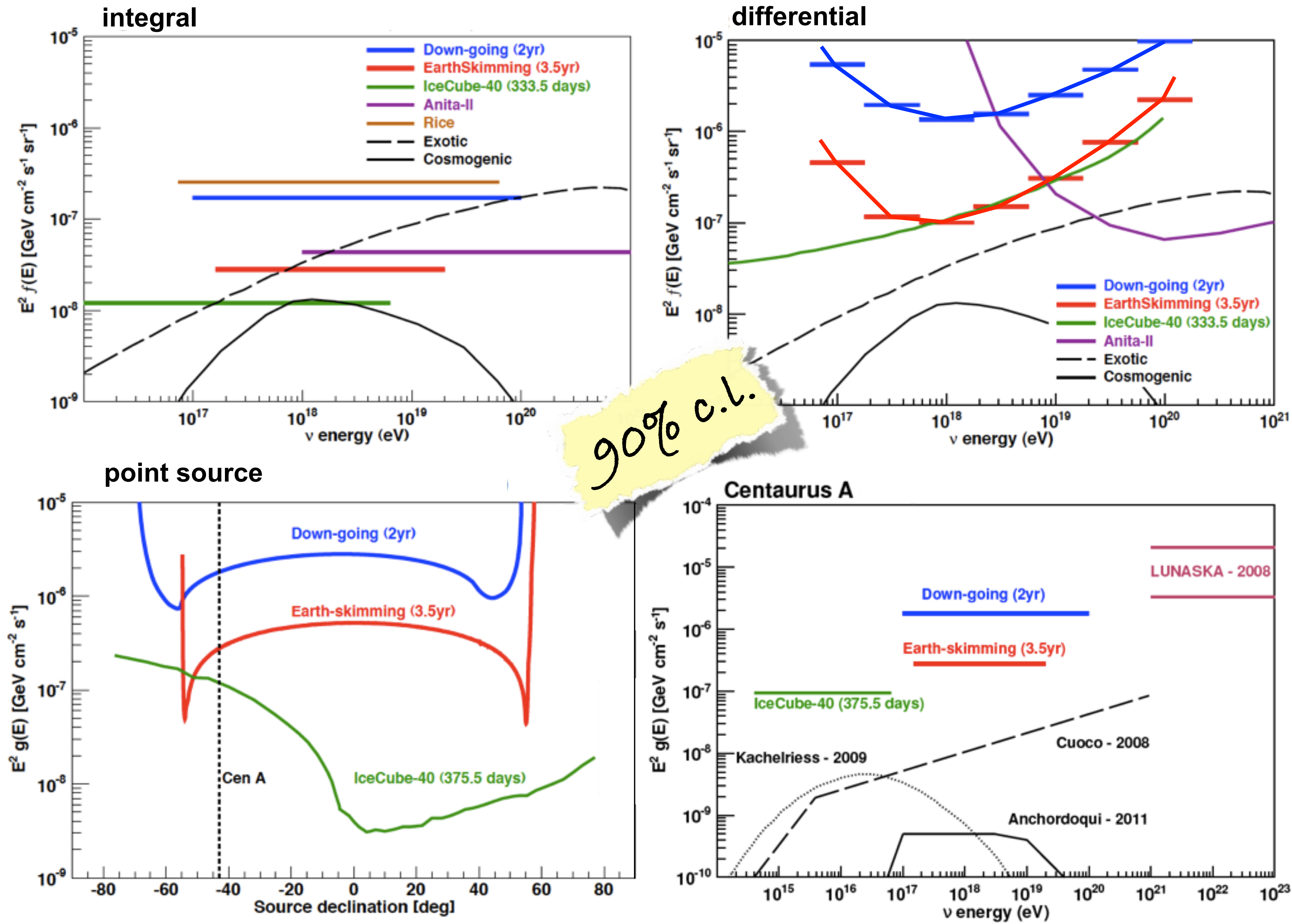
τ neutrinos have distinctive signatures:

- enhanced rate from Andes
- Earth skimming neutrinos

expected event rates:

GZK: ≈ 0.5 /yr
WB: ≈ 0.3 /yr
TD: ≈ 3 /yr

so far: no ν candidates found


integral
Down-going (2yr)
EarthSkimming (3.5yr)
IceCube-40 (333.5 days)
Anita-II
Rice
Exotic
Cosmogenic
$E^2 f(E)$ [GeV cm^{-2} s^{-1} sr^{-1}]
ν energy (eV)
differential
Down-going (2yr)
EarthSkimming (3.5yr)
IceCube-40 (333.5 days)
Anita-II
Exotic
Cosmogenic
$E^2 f(E)$ [GeV cm^{-2} s^{-1} sr^{-1}]
ν energy (eV)
90% c.l.
point source
Down-going (2yr)
Earth-skimming (3.5yr)
IceCube-40 (375.5 days)
Cen A
E^2 g(E) [GeV cm^{-2} s^{-1}]
Source declination [deg]
Centaurus A
LUNASKA - 2008
Down-going (2yr)
Earth-skimming (3.5yr)
IceCube-40 (375.5 days)
Cuoco - 2008
Kachelriess - 2009
Anchordoqui - 2011
E^2 g(E) [GeV cm^{-2} s^{-1}]
ν energy (eV)

Galactic Neutrons

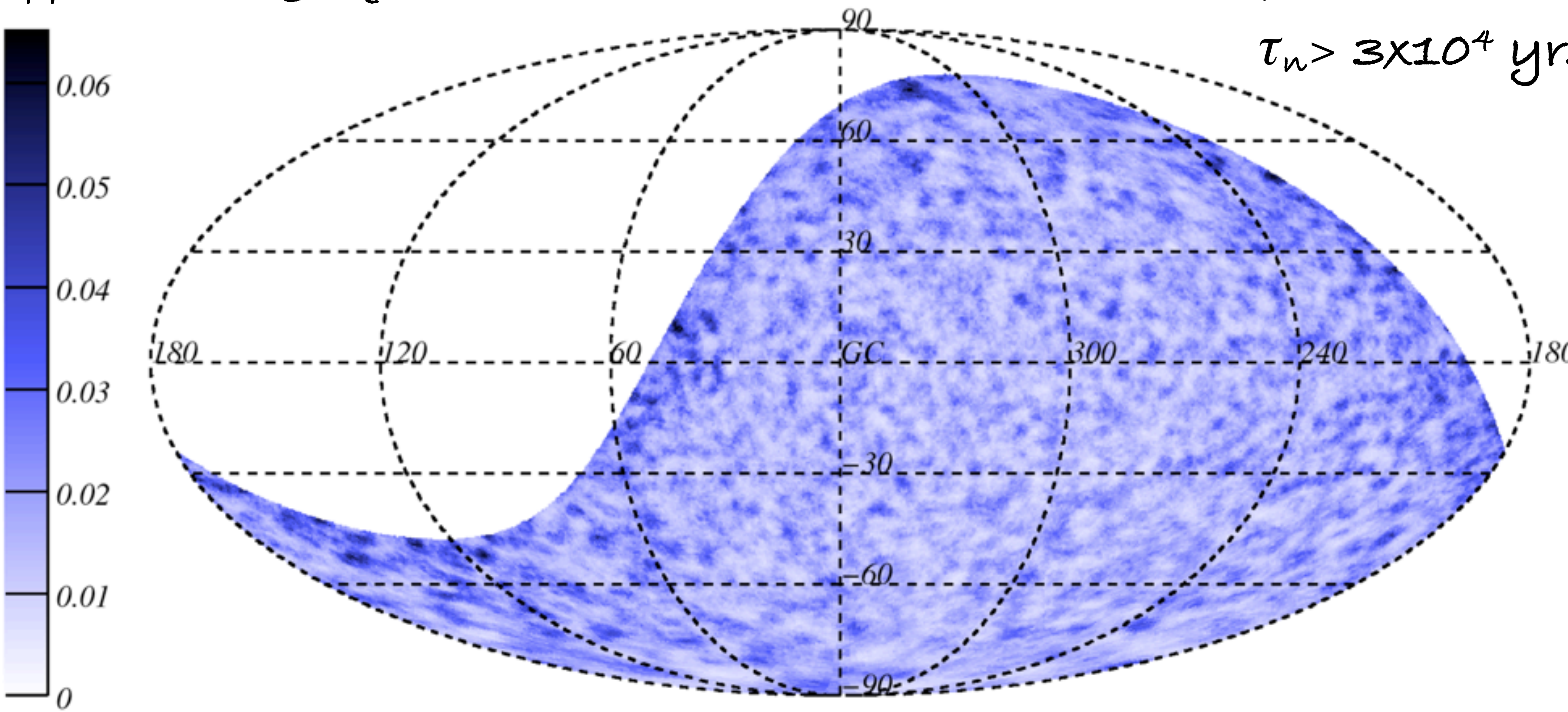
from CR accelerators (more n than hadronic γ),
travel in straight lines,
... but decay (can reach us only from own galaxy)
point sources ?

$E > 1$ EeV

$\gamma > 10^9$

$\tau_n > 3 \times 10^4$ yrs

upper limits (95% cl)



(/ km² yr)

no excess, nothing from gal. disc or gal. plane

Name 1FGL	l [deg]	b [deg]	distance [kpc]
J0835.3-4510	263.55	-2.79	0.29 ± 0.02
J1709.7-4429	343.10	-2.69	$1.4 - 3.6$
J1856.1+0122	34.70	-0.42	2.8
J1809.8-2332	7.39	-1.99	1.7 ± 1.0
J1801.3-2322c	6.57	-0.21	1.9
J1420.1-6048	313.54	0.23	5.6 ± 1.7
J1018.6-5856	284.32	-1.70	2.2
J1028.4-5819	285.06	-0.49	2.3 ± 0.7
J1057.9-5226	285.98	6.65	0.7 ± 0.2
J1418.7-6057	313.33	0.14	$2 - 5$

Fermi LAT

Name HESS	l [deg]	b [deg]	distance [kpc]
J0852-463	266.28	-1.24	0.2
J0835-455	263.85	-3.09	0.29
J1713-397	347.28	-0.38	1
J1616-508	332.39	-0.14	6.5
J1825-137	17.82	-0.74	3.9
J1708-443	343.04	-2.38	2.3
J1514-591	320.33	-1.19	5.2
J1809-193	10.92	0.08	3.7
J1442-624	315.41	-2.30	2.5
J1640-465	338.32	-0.02	8.6

H.E.S.S.

bright γ sources, $d < 9$ kpc ($\approx \lambda_n$ @EeV)

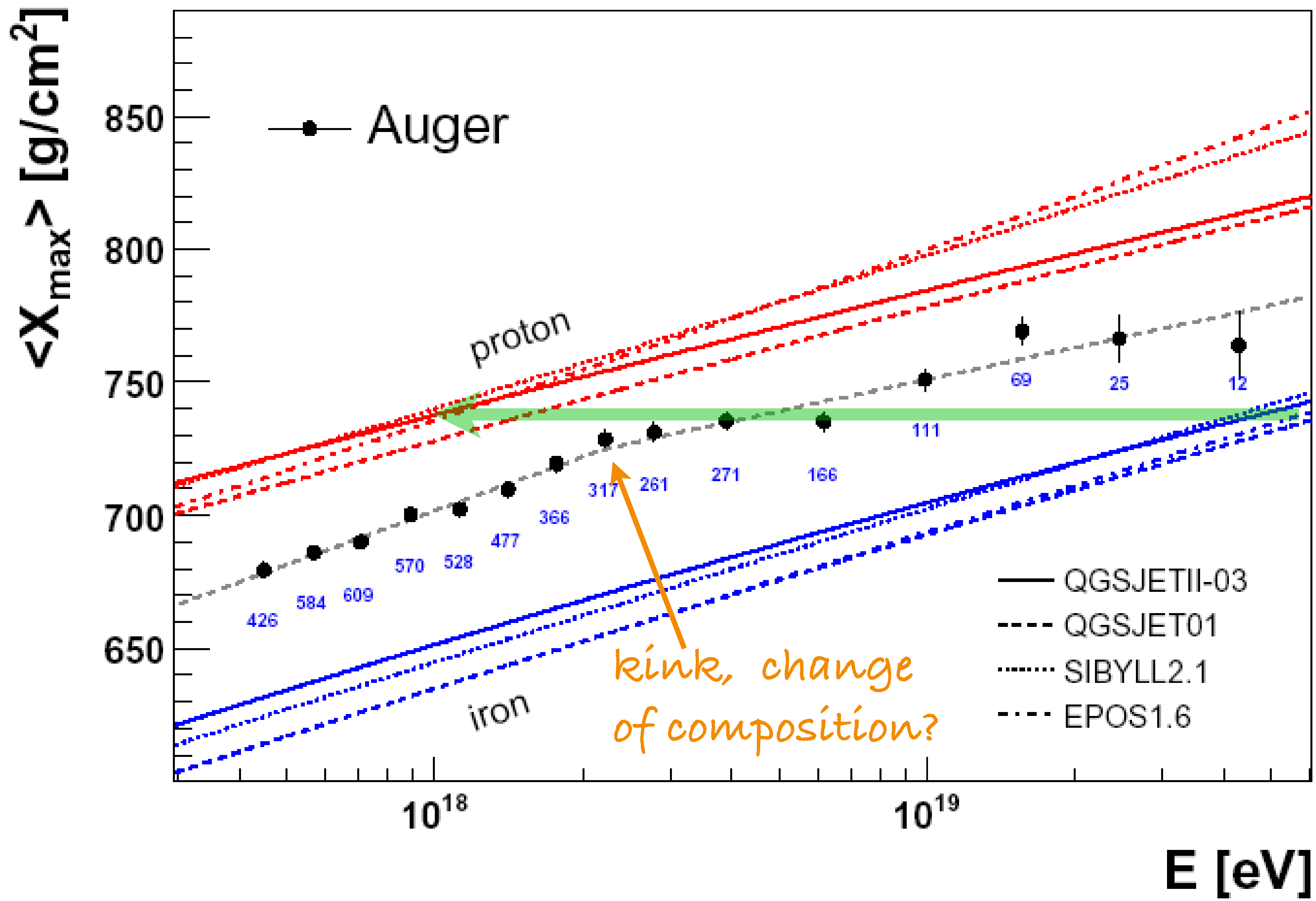
Set of sources	Energy bin [EeV]	S_{stacked}
Fermi LAT	$[1 - 2]$	2.07
Fermi LAT	$[2 - 3]$	0.51
Fermi LAT	≥ 1	2.35
H.E.S.S.	$[1 - 2]$	-0.75
H.E.S.S.	$[2 - 3]$	-0.40
H.E.S.S.	≥ 1	-0.89

no excess found

Nuclear Composition

difficult !
results strongly model dependent

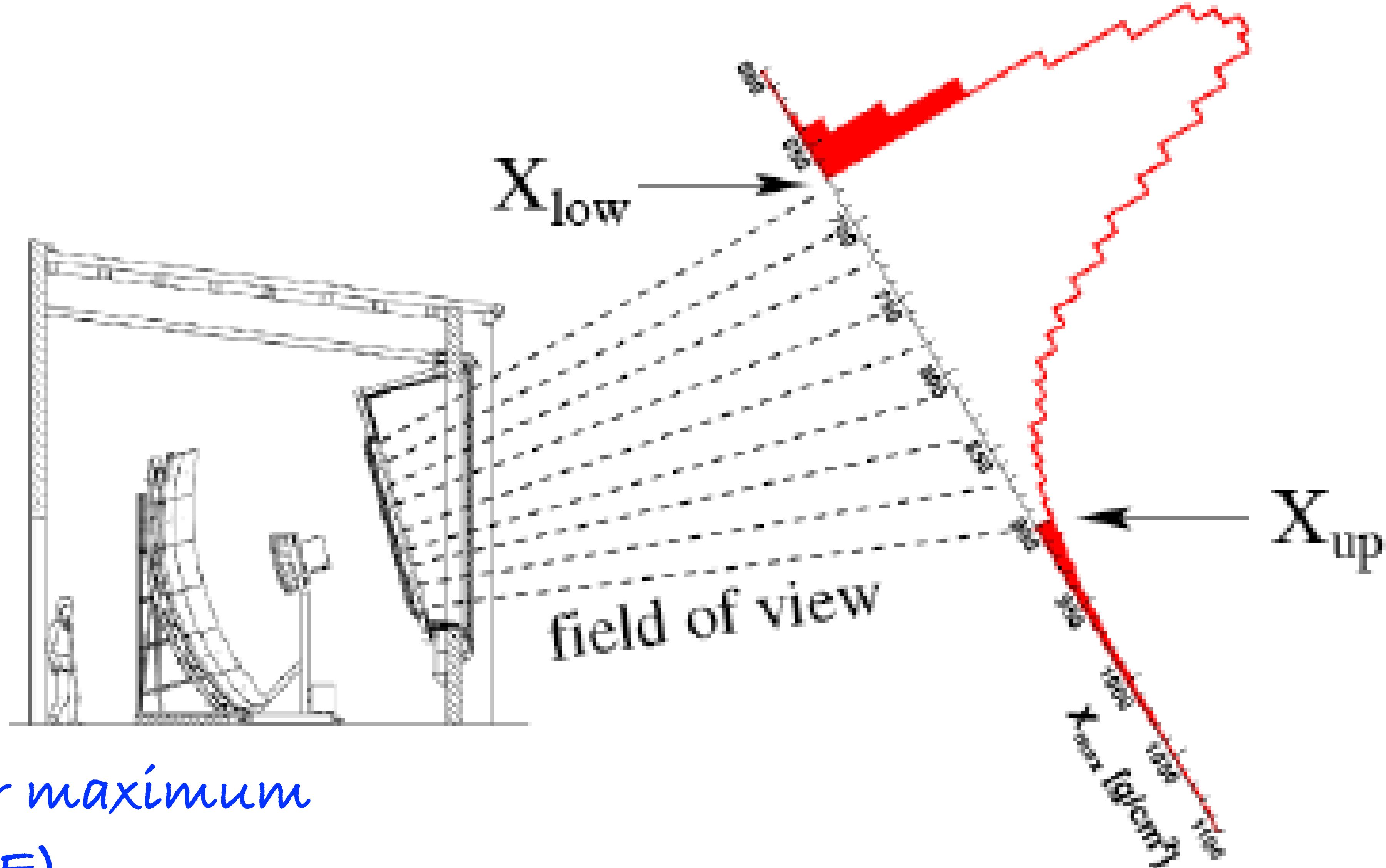
FD:



$X_{max} \sim lg(E/A)$

same E/A

X_{max} and RMS(X_{max}) are mass sensitive



X_{max}: height of shower maximum
grows with log (E)

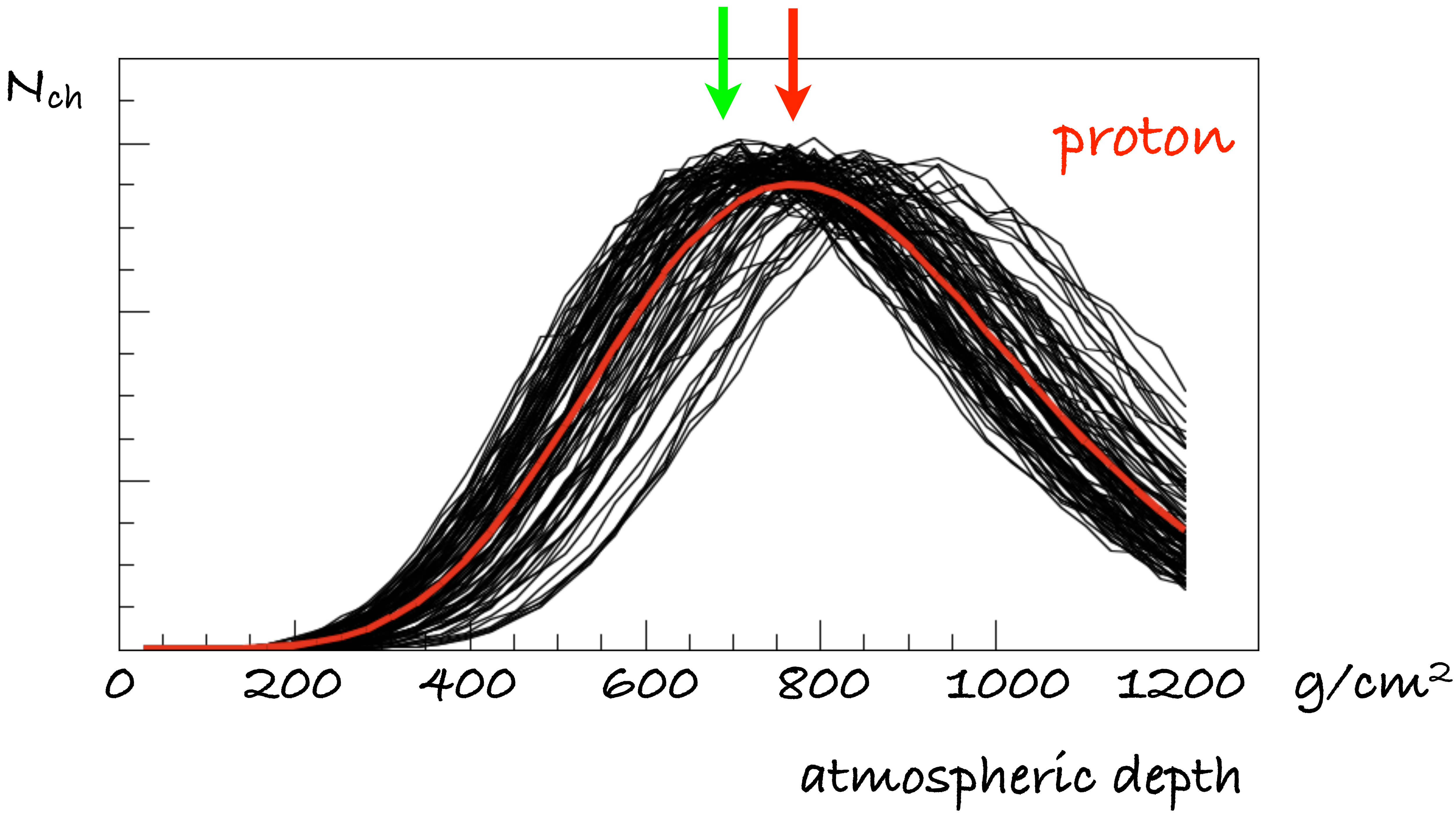
p: penetrate deeper, larger X_{max}
Fe: develop earlier, smaller X_{max}
difference about 70 g/cm²

X_{max}(p) fluctuates much more than X_{max}(Fe)
RMS(X_{max}(p)) ≈ 60 g/cm²   RMS(X_{max}(Fe)) ≈ 20 g/cm²

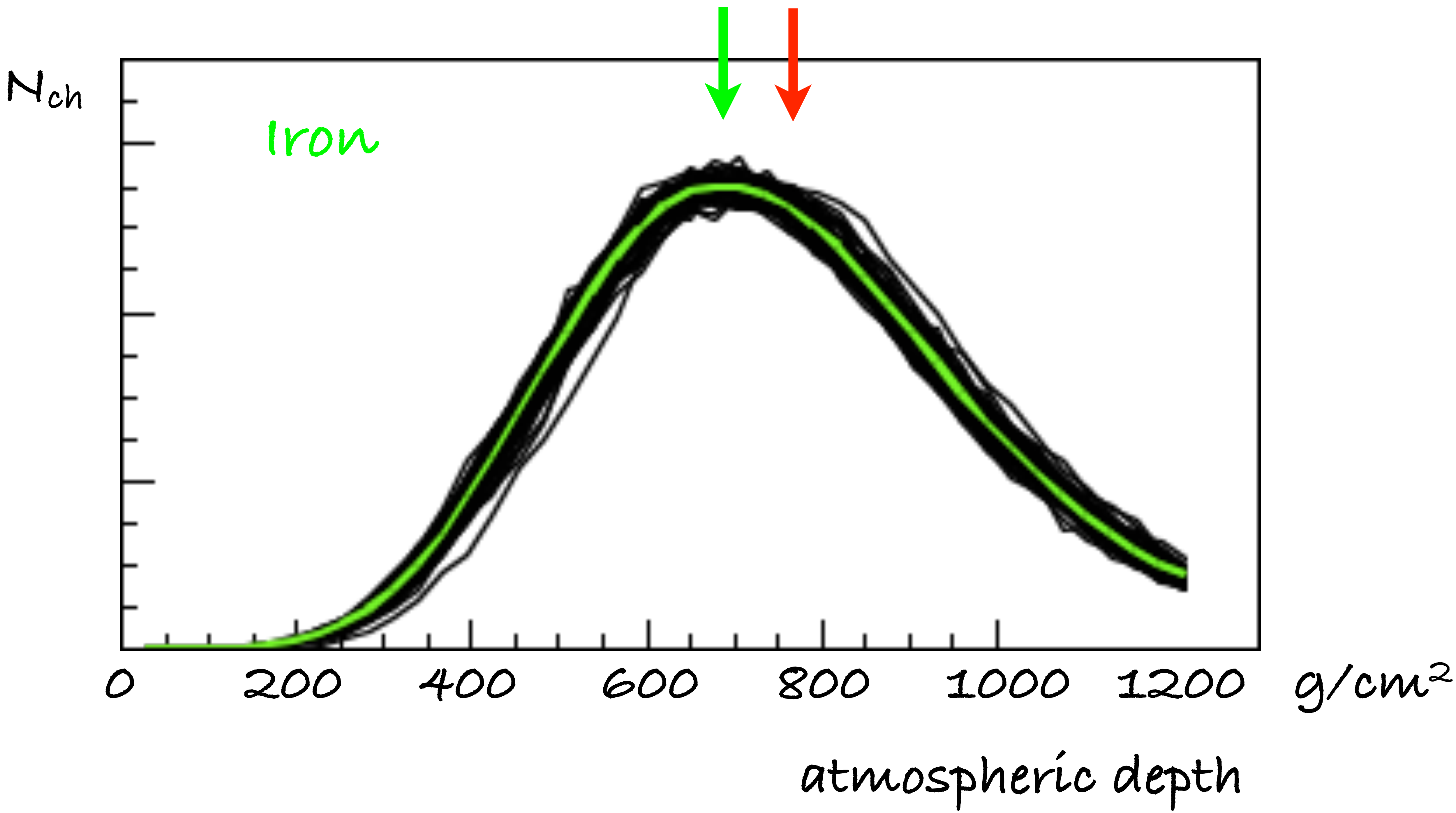
largely due to σ_{inel} of primary particle.

1 Fe ≈ 56 protons of $E_0/56$

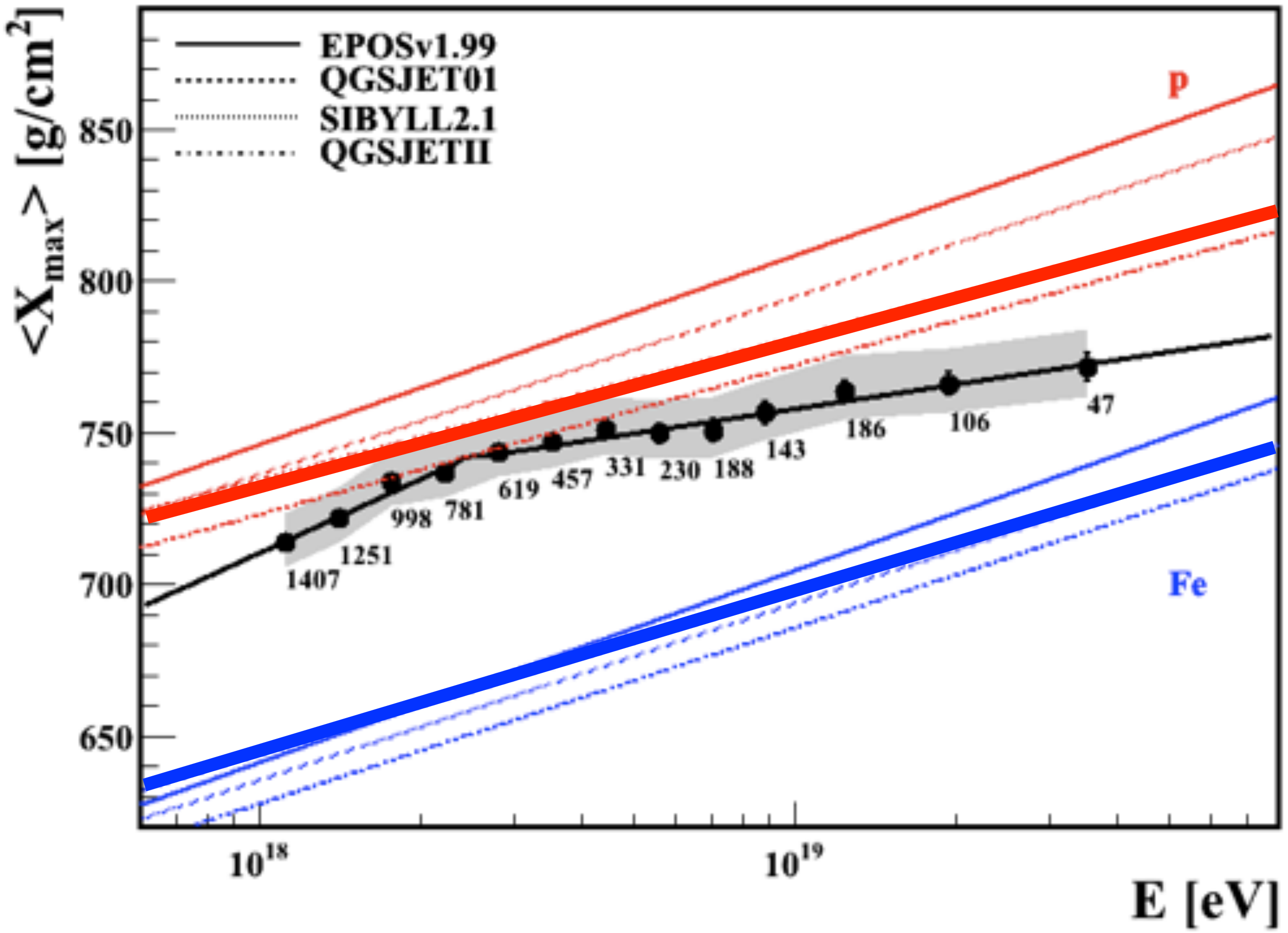
100 proton showers, 10^{19} eV



50 Iron showers, 10^{19} eV

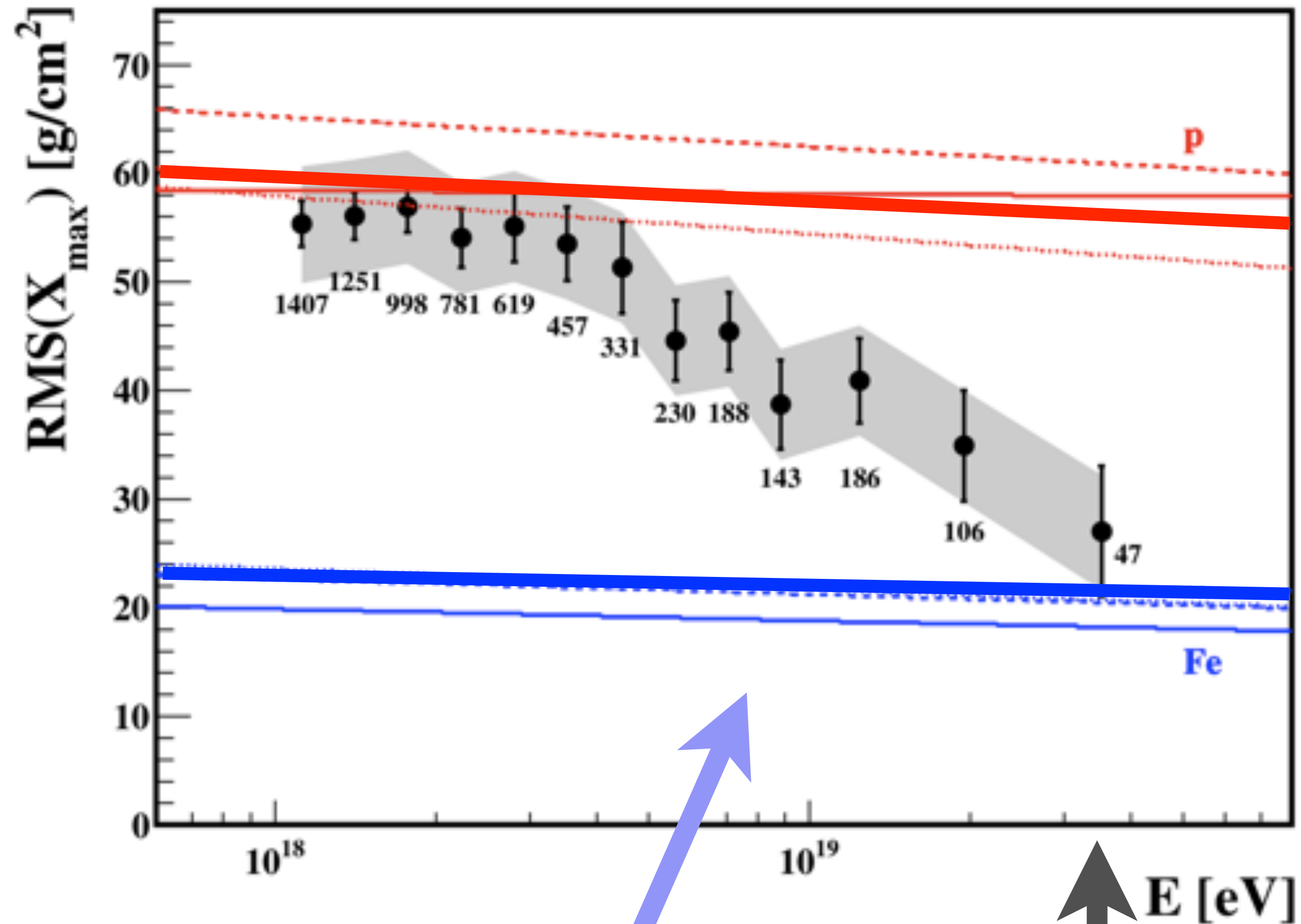


X_{max}



model dependent interpretation

RMS(X_{max})

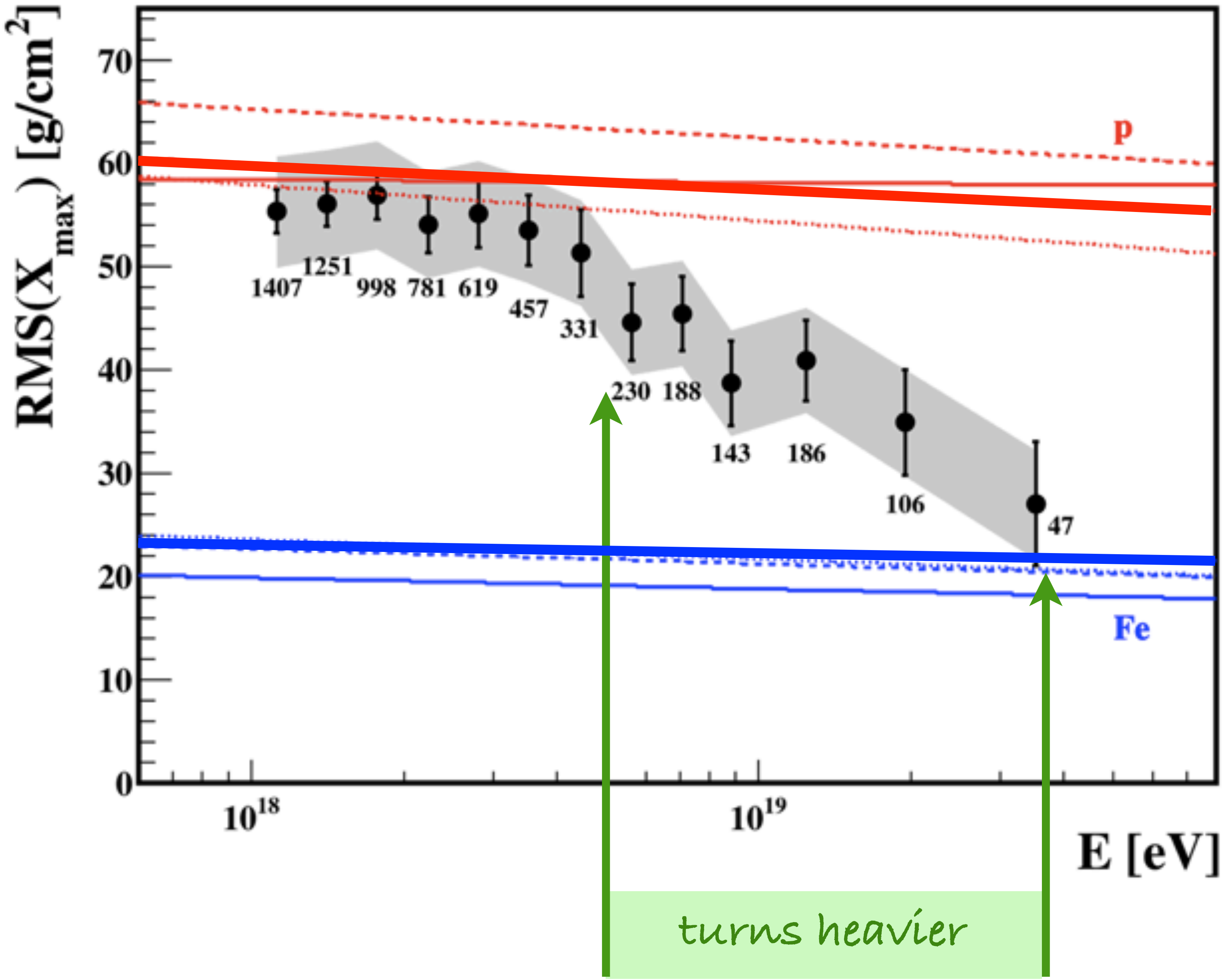


difficult to influence with model changes

$E < 4 \times 10^{19}$ eV (below spectral cut-off)

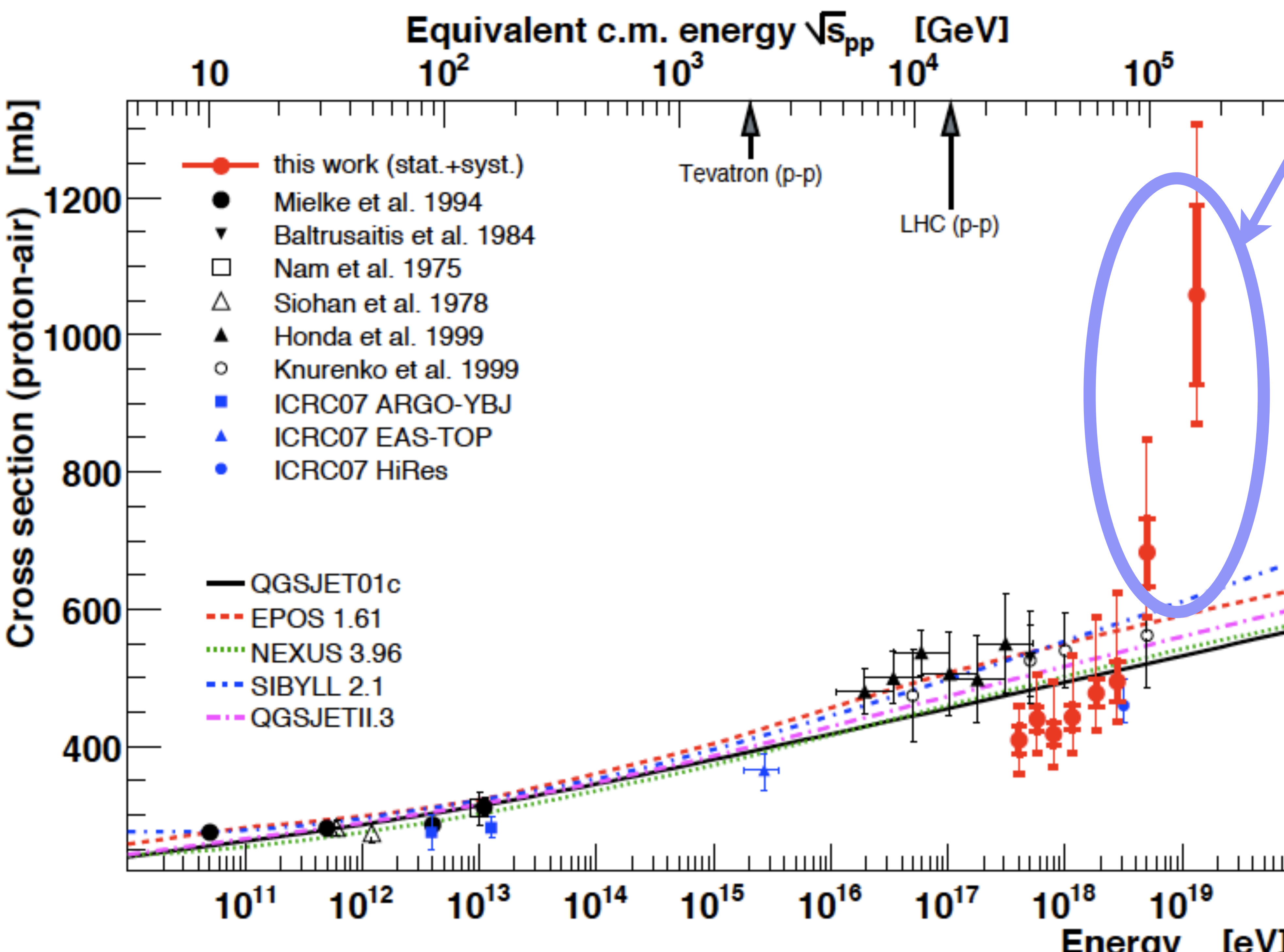
If one trusts the models, then composition turns heavier.

RMS(X_{max})



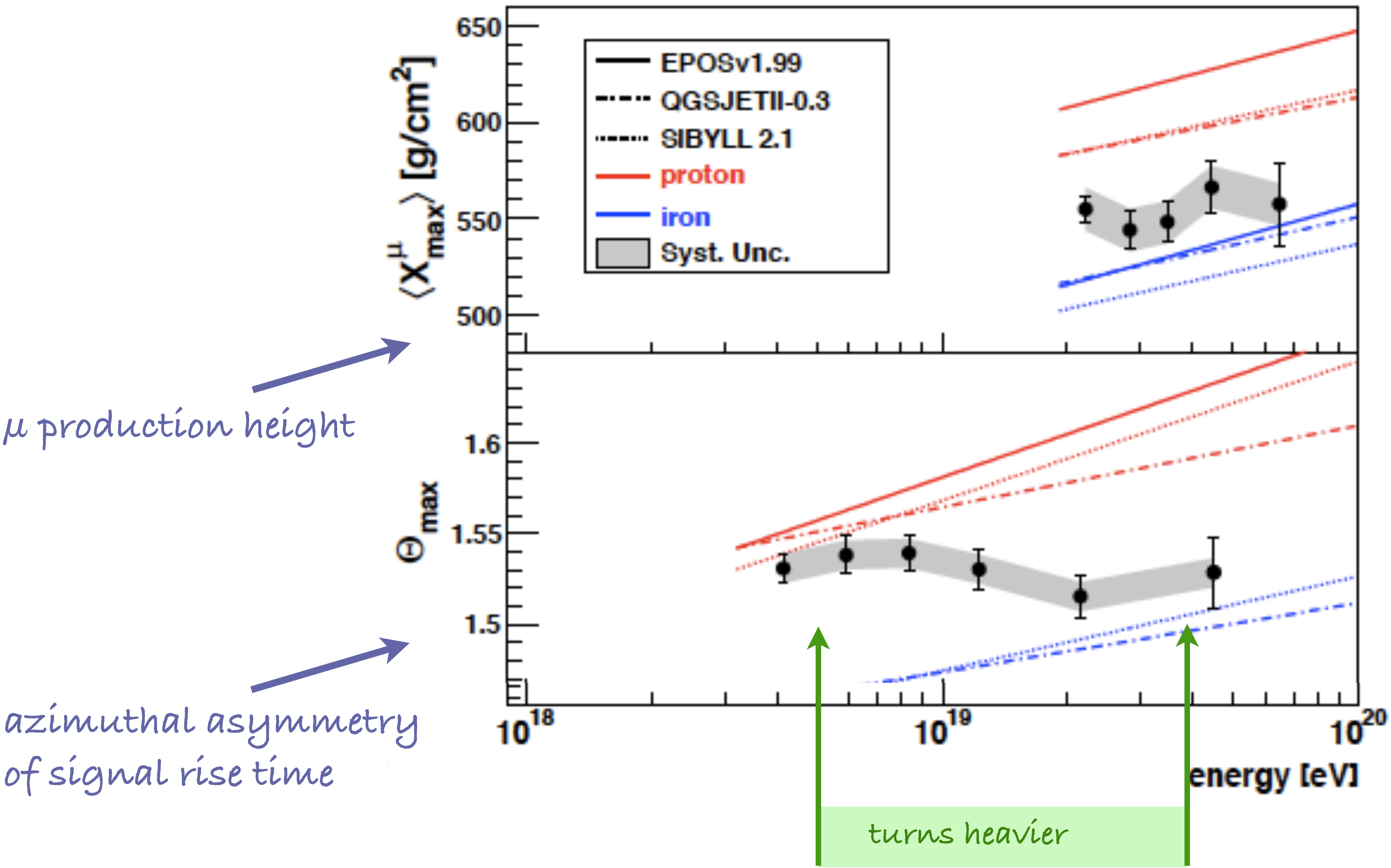
whatever we do to models (within limits), data do not fit to primary proton sims.

If UHECR were protons, one needs a dramatic rise of the p-air cross-section at E >10^{18} eV to explain this data.



σ(p-air) to rise like this to explain RMS(X_{max}) with prim. p

more mass sensitive SD variables:



Composition mis-match ?

Spectrum: GZK cut-off
Anisotropy: correlation with nearby matter

p dominated ? ($E > 6x10^{19}$ eV)

Composition: X_{max}, SD variables

mixed/heavy ($E < 4x10^{19}$ eV)

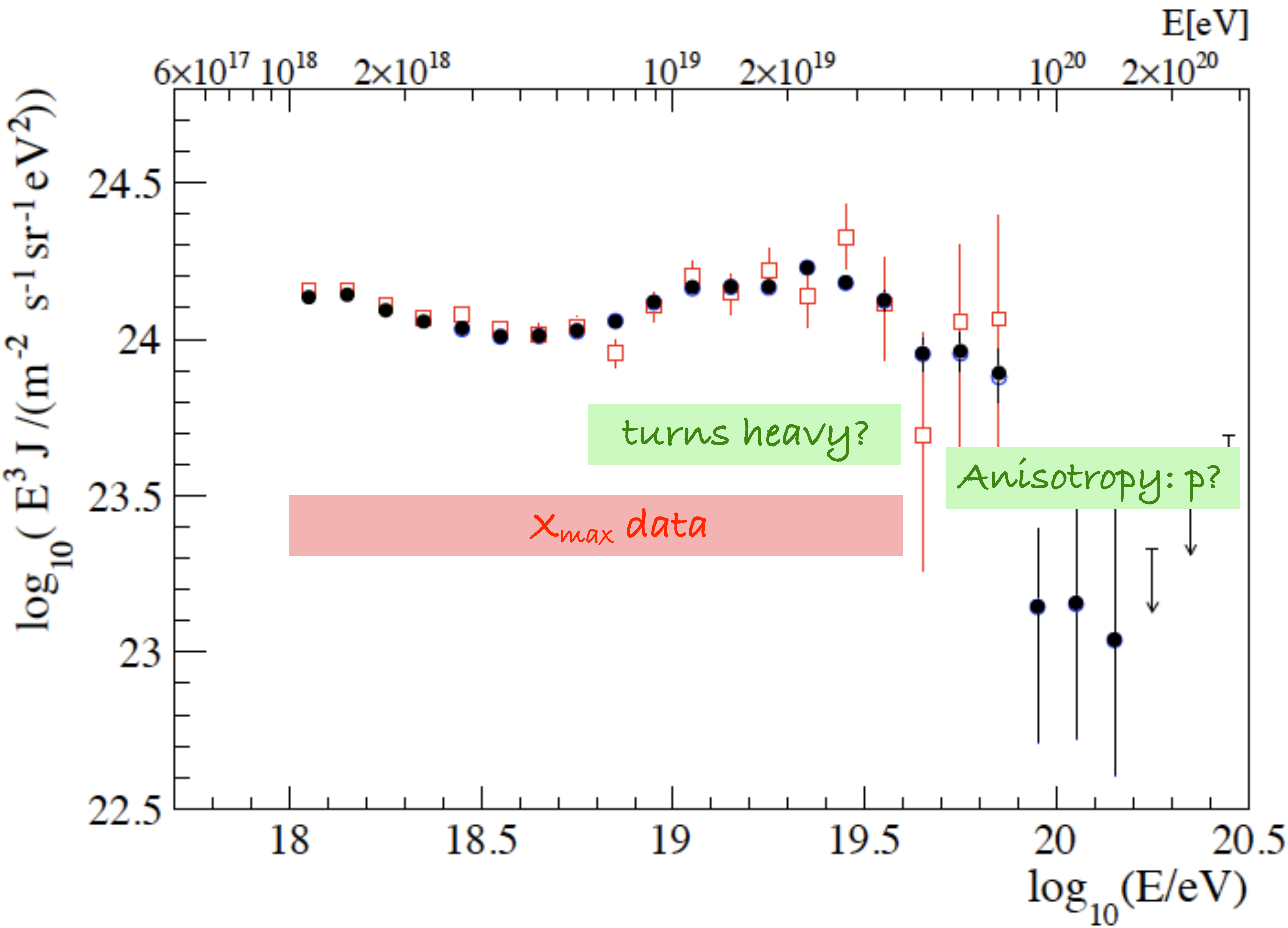
strongly model dependent

Need hadronic interaction models to be modified to make p-sims look more like data ???

(e.g. cross sections, particle production, ...)

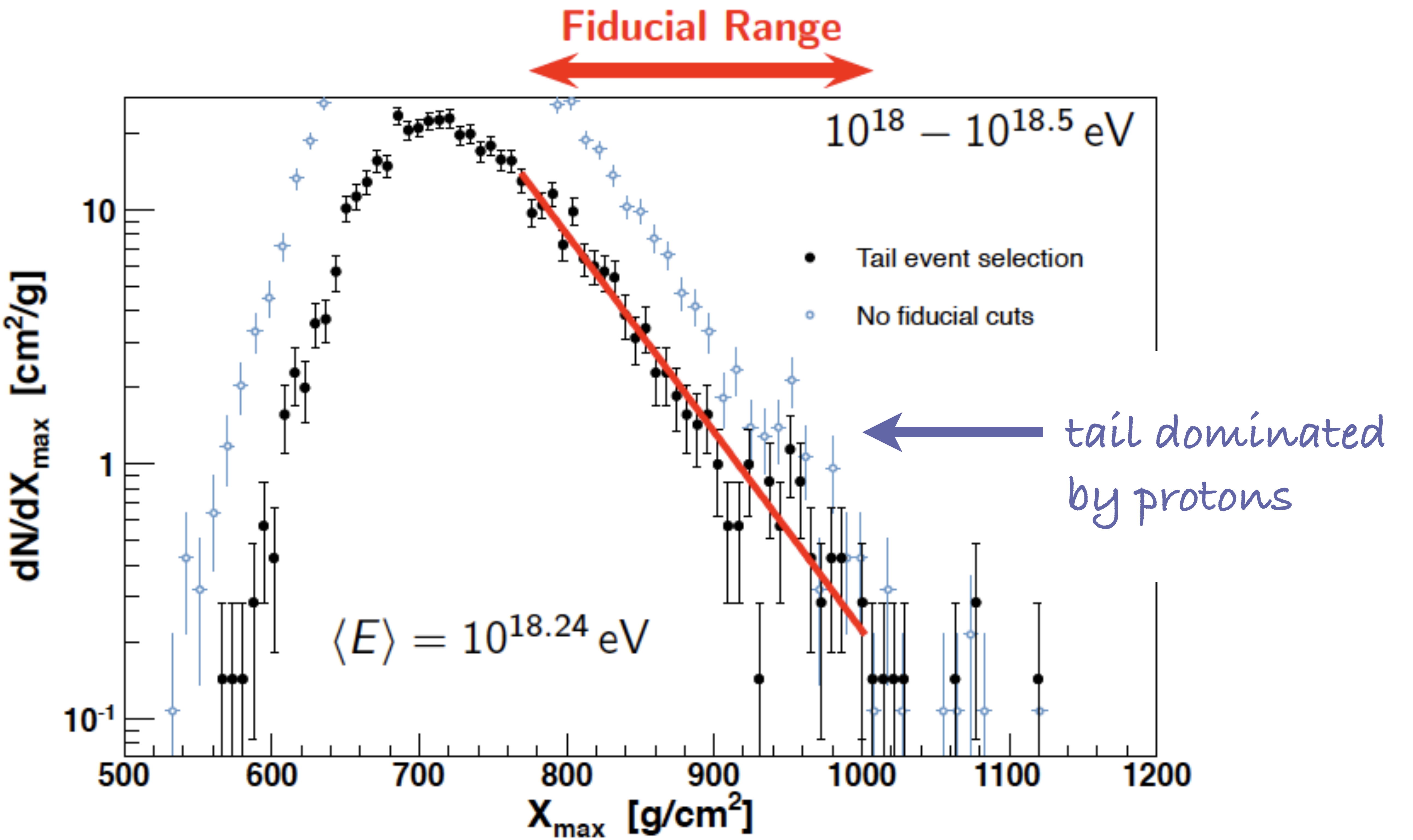
We start to do particle physics at $>10^{19}$ eV.

Puzzles remain ....

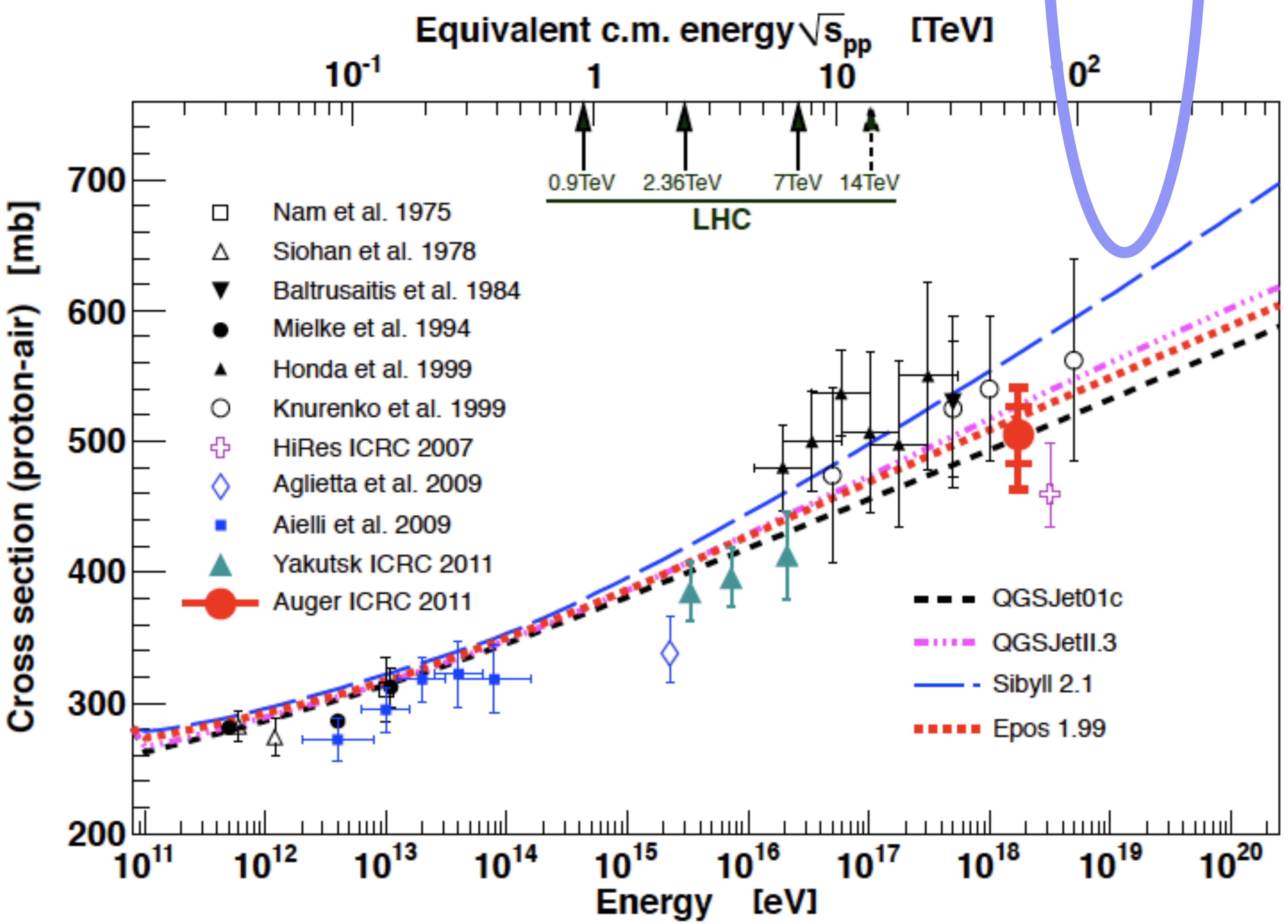


Proton-Air Cross-Section

... from tail of X_{max} distribution

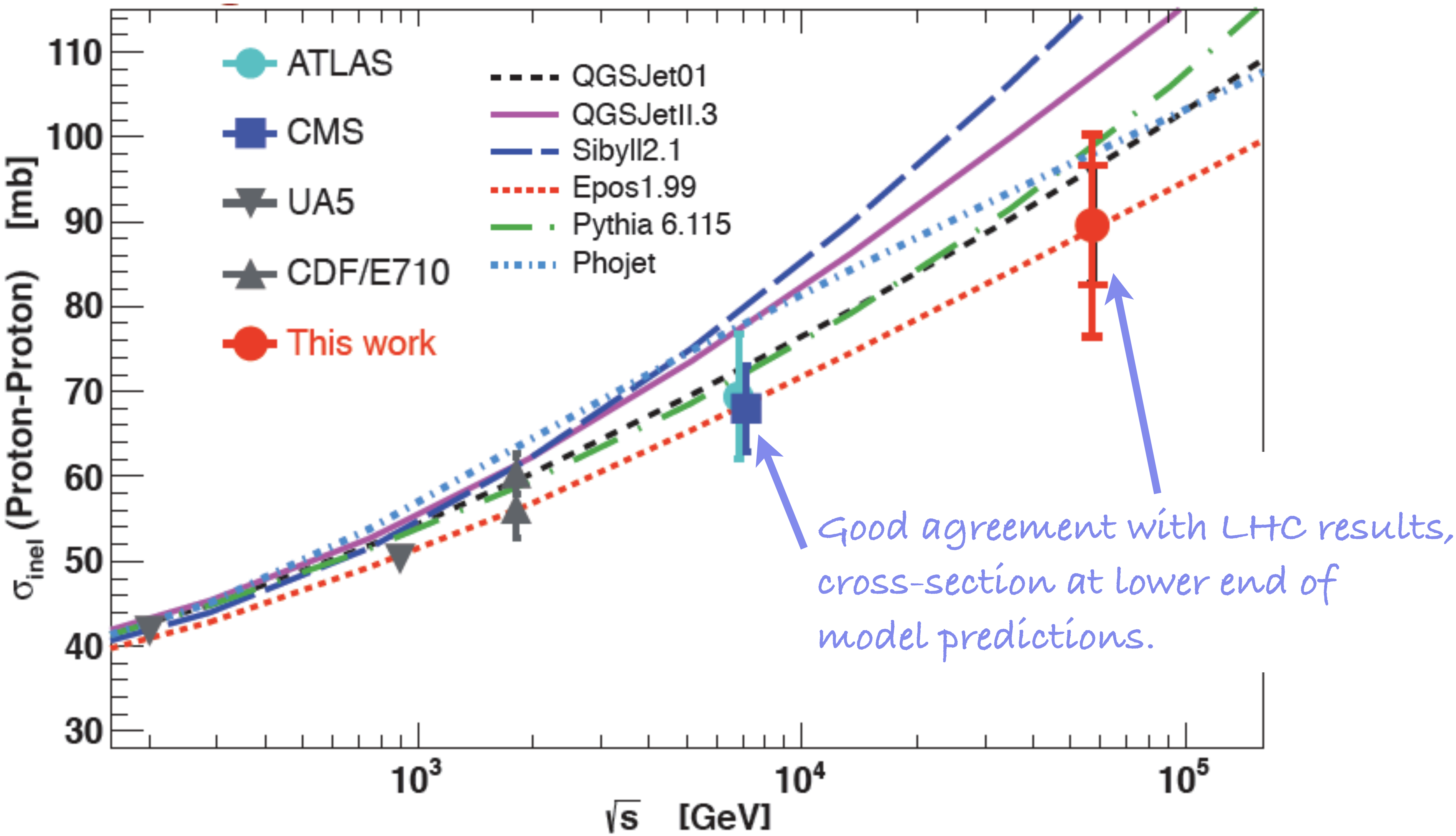


Proton-Air Cross-Section



σ(p-air) = 505 ± 22 ± 30 mb (@ 2 EeV)

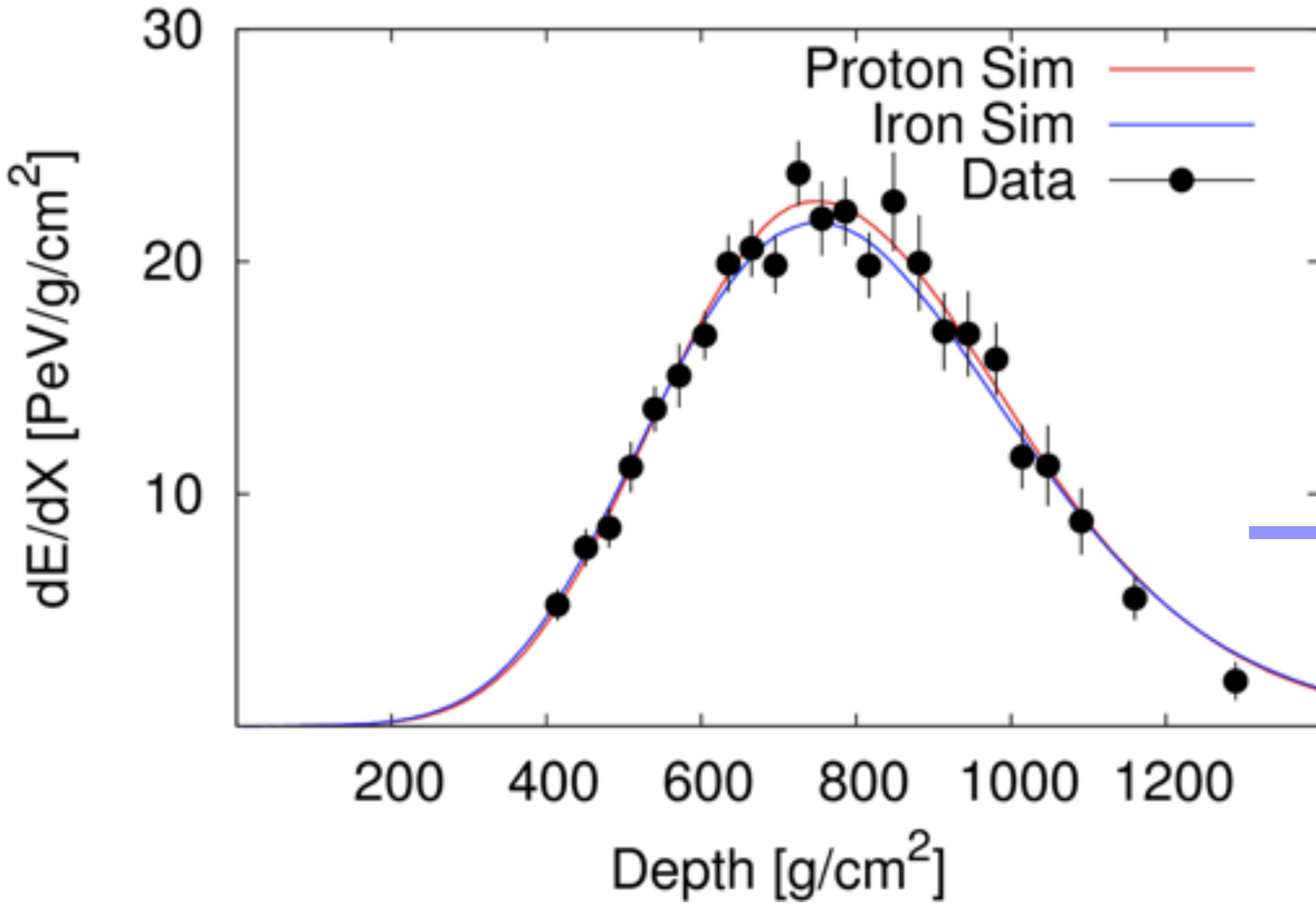
p-p cross-section (using Glauber model for conversion)

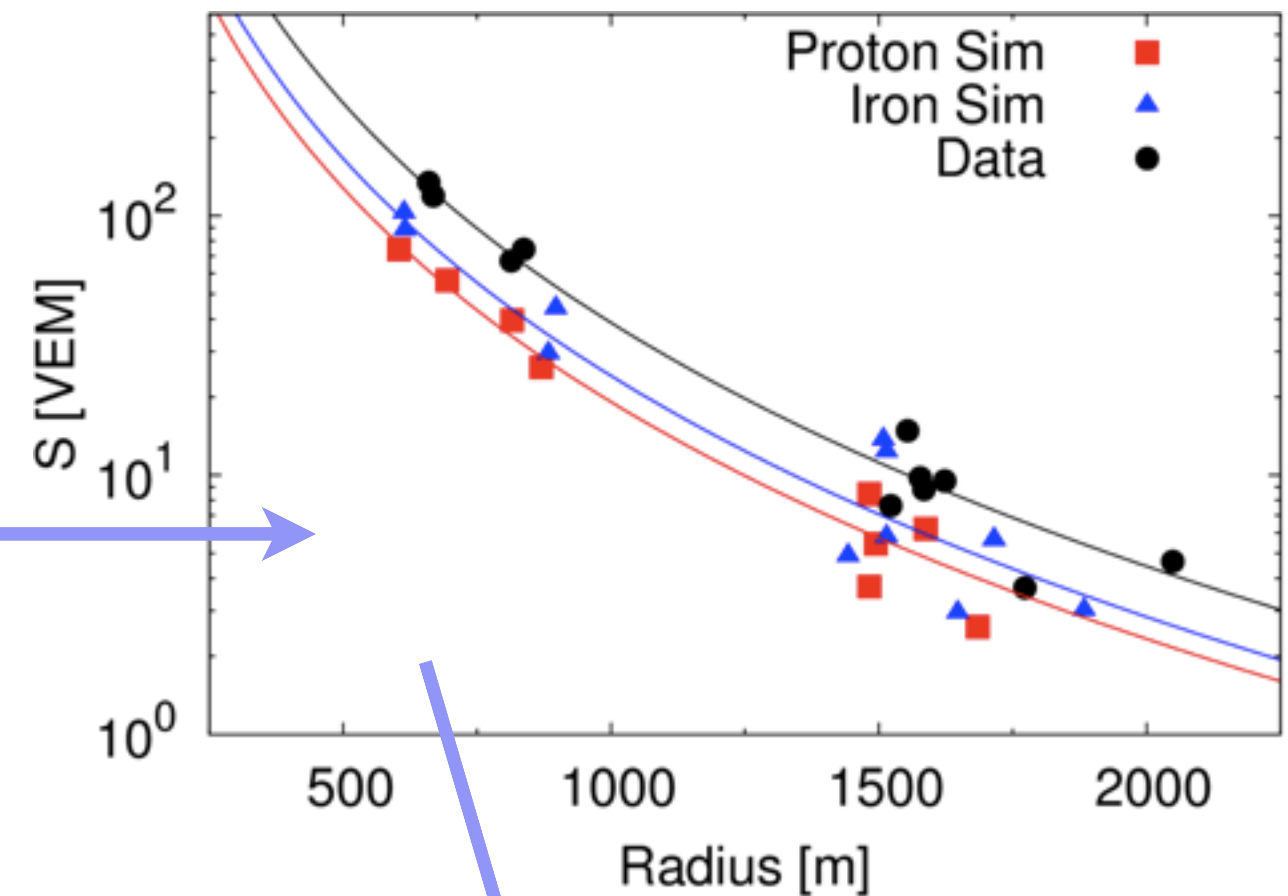


σ(p-air) = 90 ± 7 ± 10 mb (@ $E_{cm} \approx 57$ TeV)

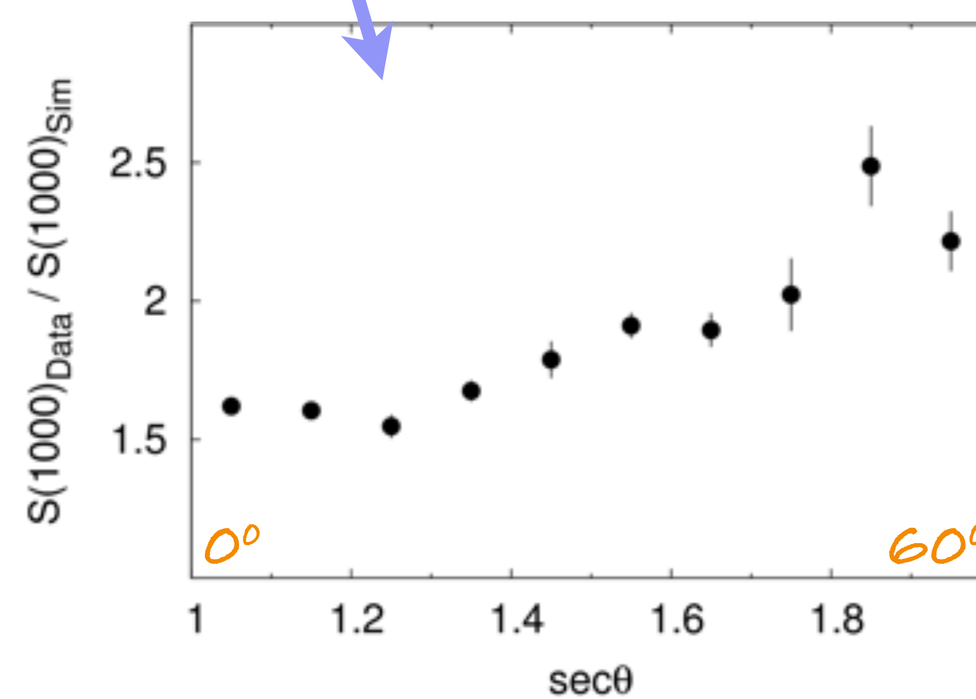
Are the EAS models right ?

same simulated events
have less signal in SD
than the measured ones.



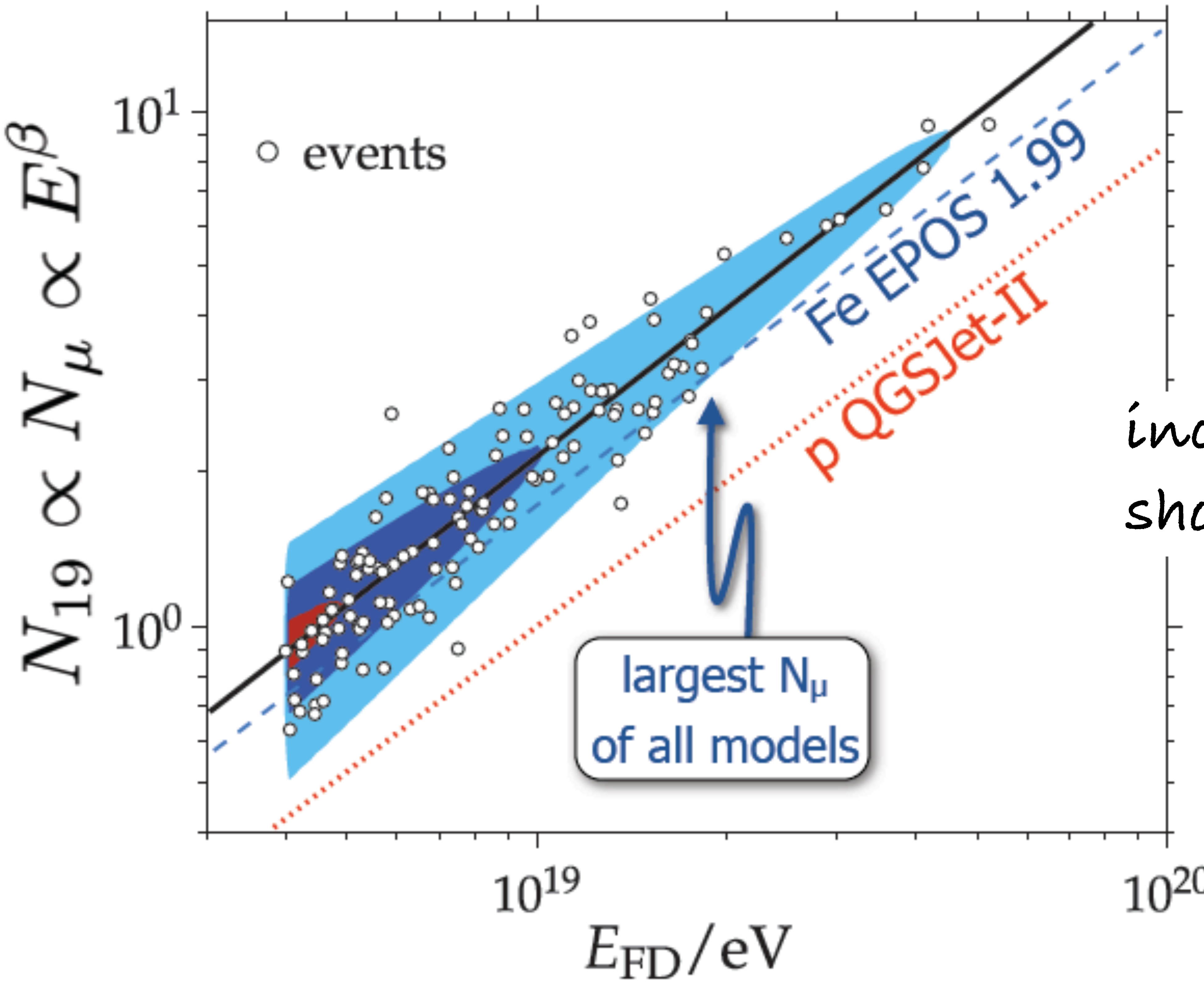


match the long. development (as seen in FD)
of a measured event
with p and Fe simulations



μ content rises with θ

models underestimate
ground signal by **1.5 - 2x**



inclined showers

models underestimate N_μ by 25-100%

for Fe for p

Consistent findings:

Air shower models require modifications:

Muons	need ≈ 1.3 - 2x more,
ground signal	need ≈ 1.5 - 2x more

for the same longitudinal profile.

hadronic model ???

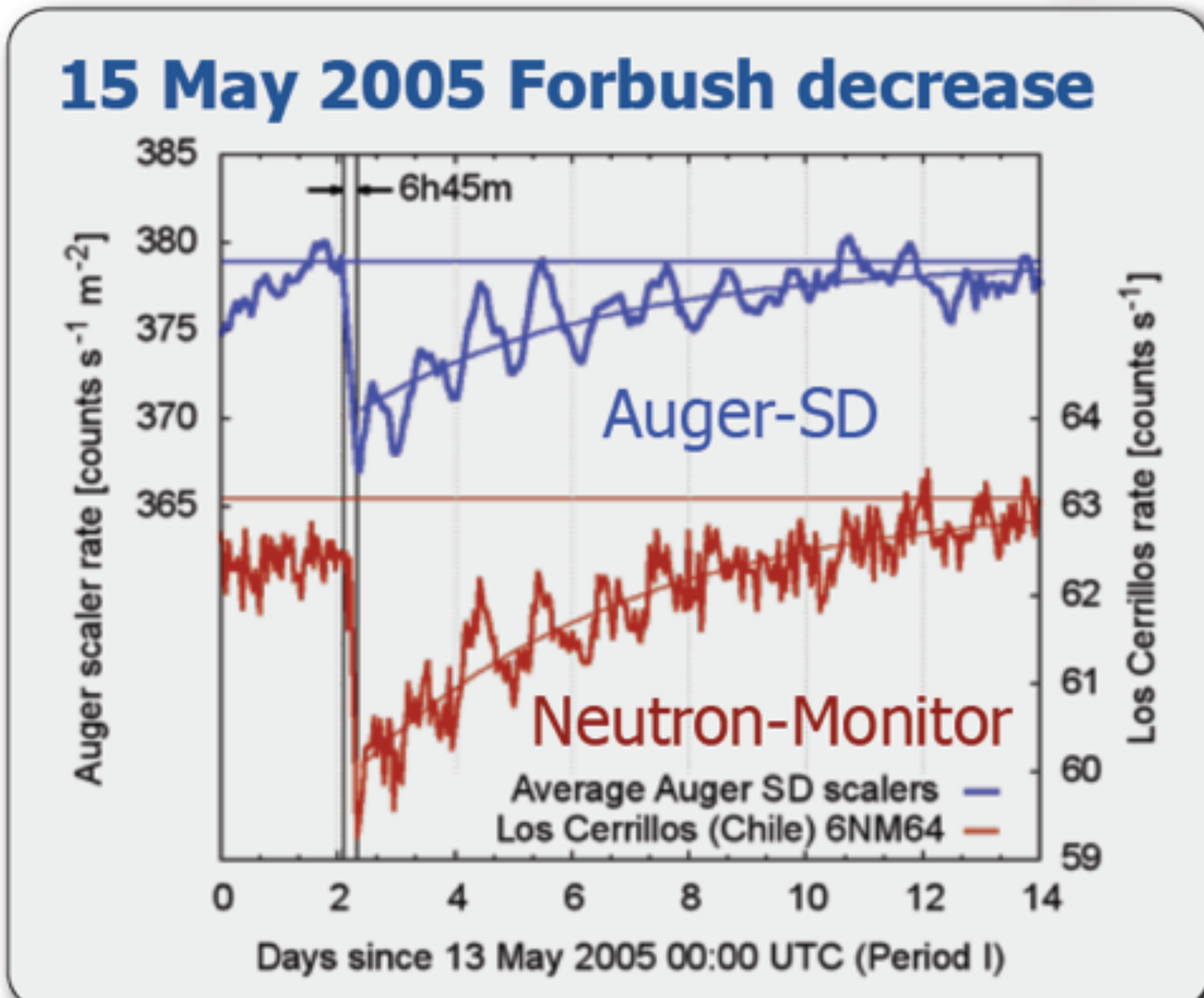
fluorescence yield ???

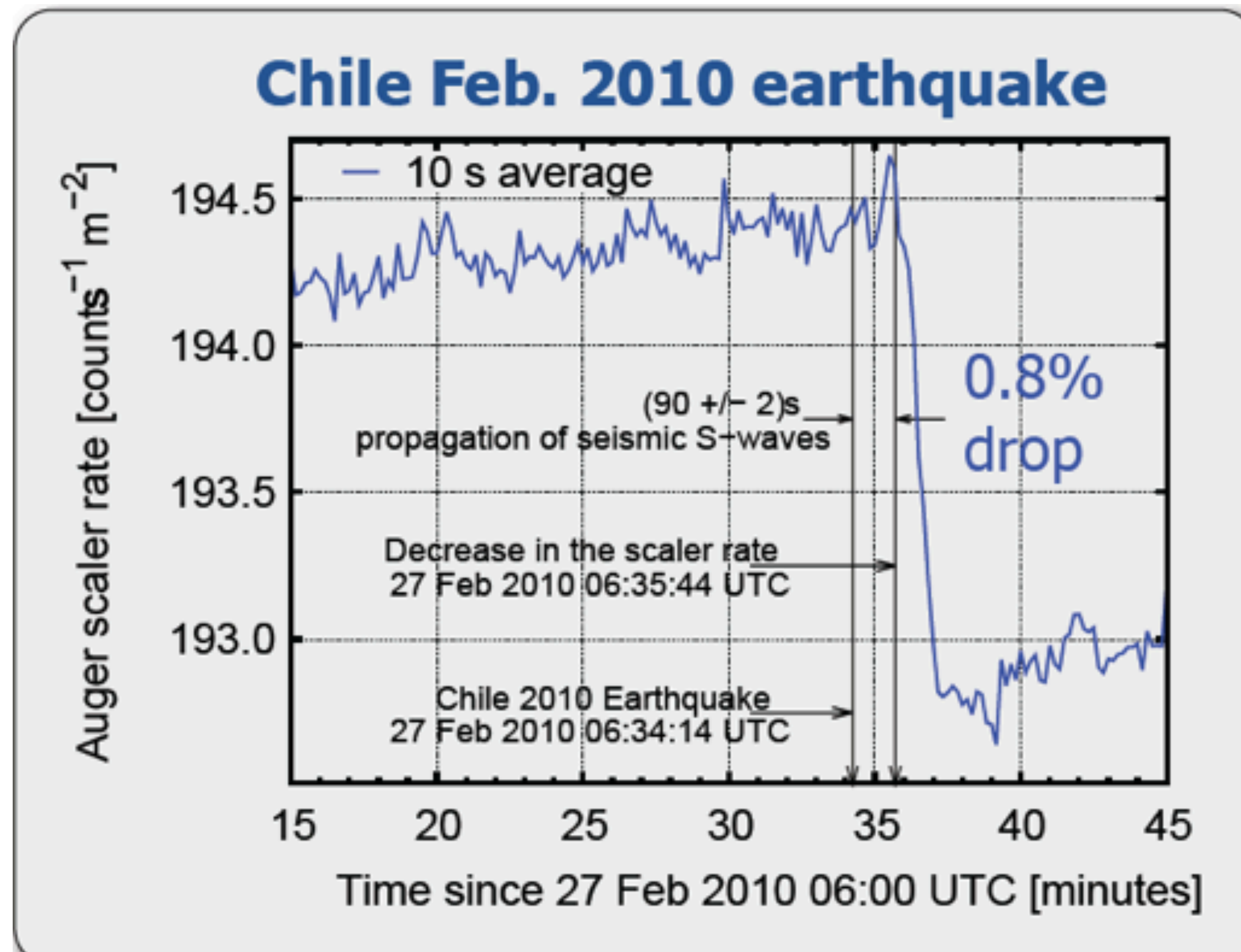
LHC results on cross-sections and particle production (in very forward range) will provide helpful constraints.

EPOS: a new model, with enhanced baryon production makes about 50% more muons.....

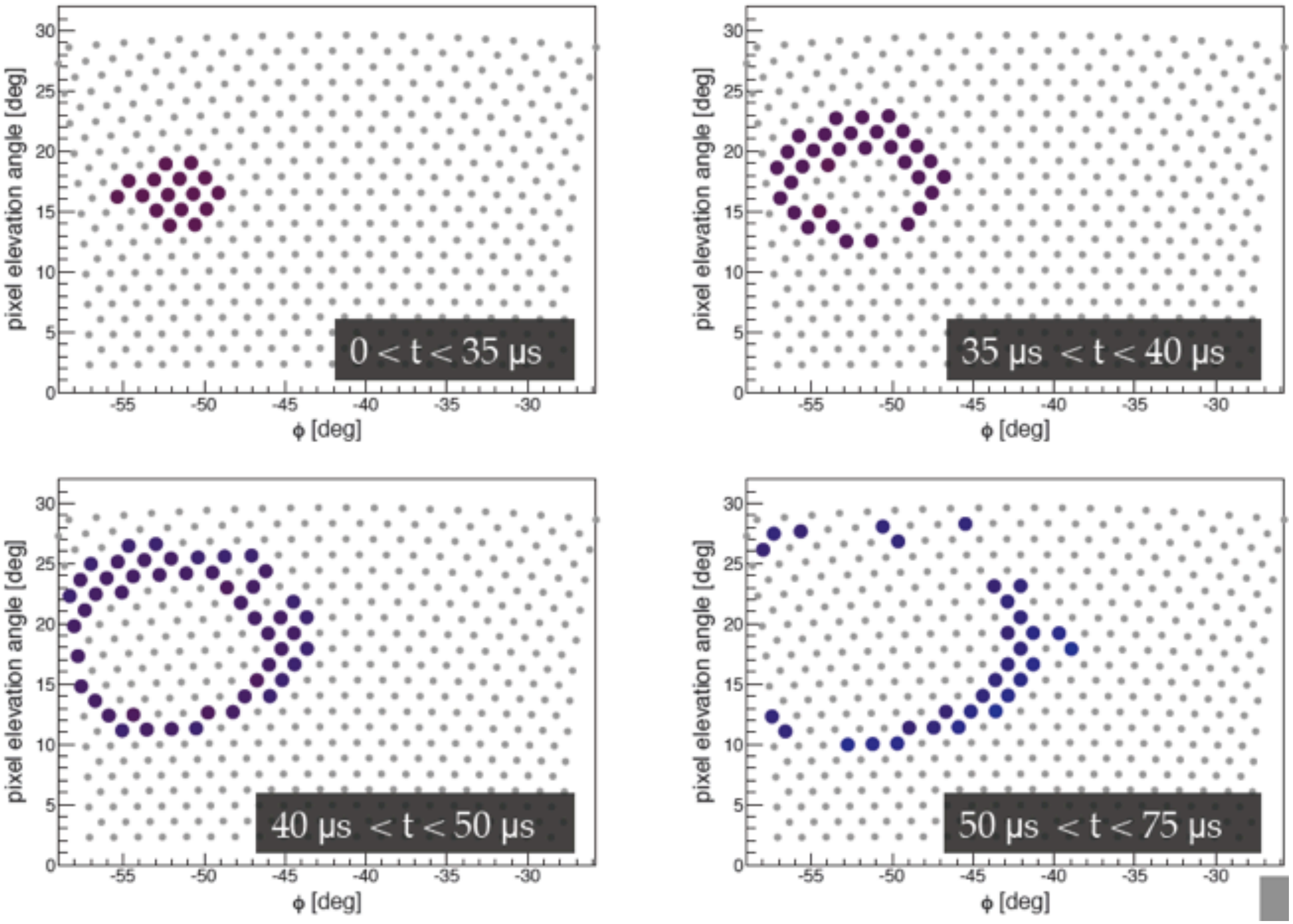
Exotics:

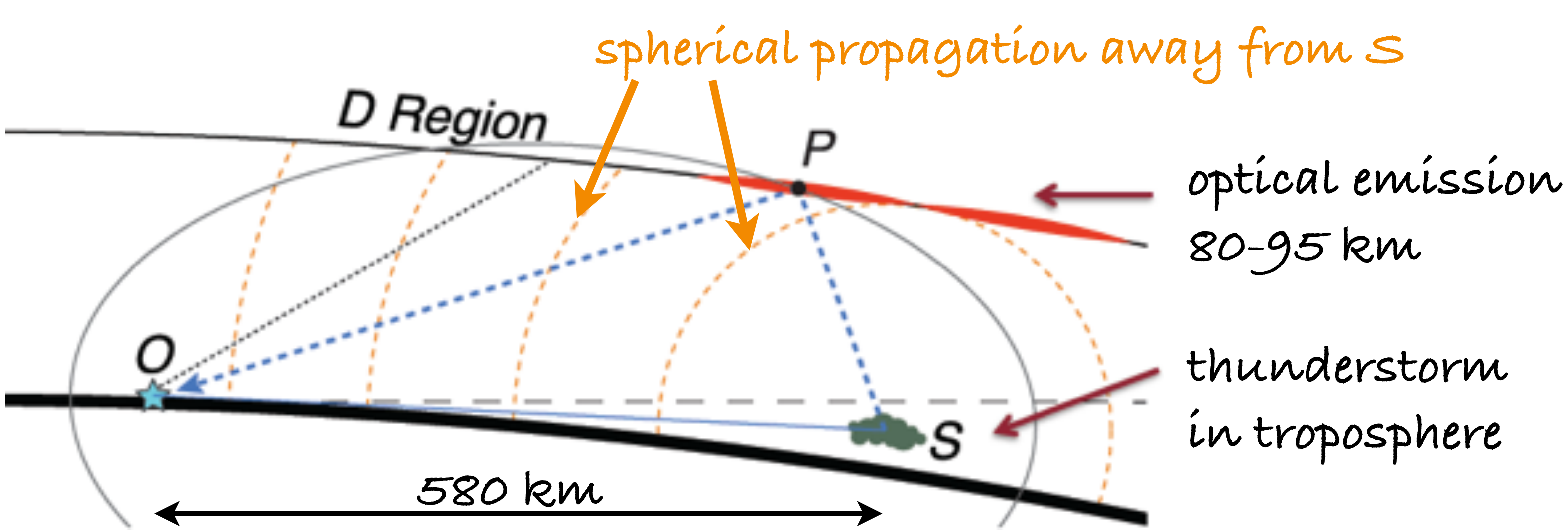
Auger Scaler Rates: read out for monitoring

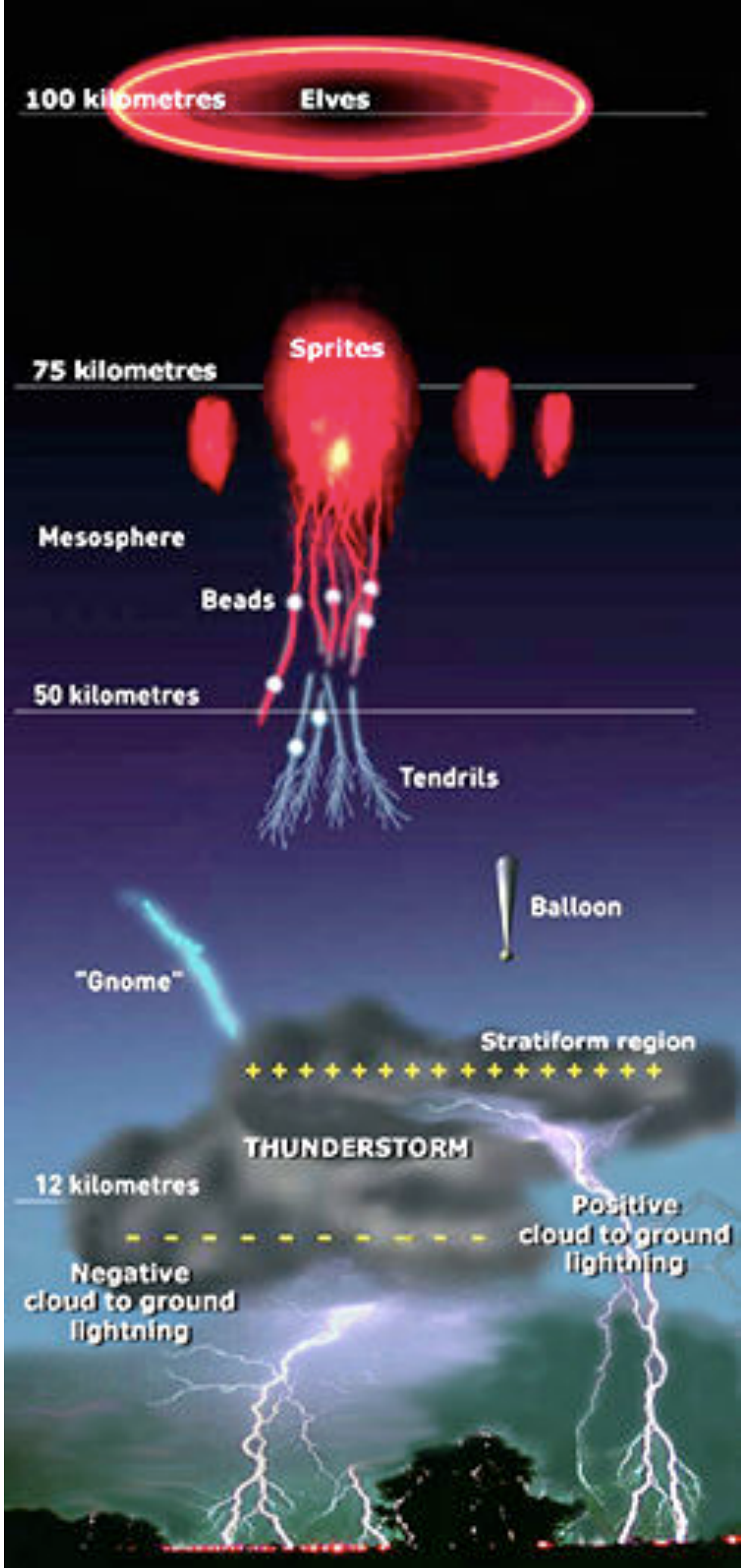




Elves with the Auger FD







Auger Results

see: http://www.auger.org/technical_info/

- Anisotropy studies around the galactic centre at EeV energies with the Auger Observatory
  Astroparticle Physics 27 (2007) 244
- An upper limit to the photon fraction in cosmic rays above 10^{19} eV from the Pierre Auger Observatory
  Astroparticle Physics 27 (2007) 155
- Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects
  Science 318 (2007) 938
- Correlation of the highest-energy cosmic rays with the positions of nearby active galactic nuclei
  Astroparticle Physics 29 (2008) 188
- Upper limit on the cosmic-ray photon flux above 10^{19} eV using the surface detector of the Pierre Auger Obs.
  Astroparticle Physics 29 (2008) 243
- Upper Limit on the Diffuse Flux of Ultrahigh Energy Tau Neutrinos
  Physical Review Letters 100 (2008) 211101
- Observation of the suppression of the flux of cosmic rays above 4×10^{19} eV
  Physical Review Letters 101 (2008) 061101
- Limit on the diffuse flux of ultrahigh energy tau neutrinos with the surface detector of the Pierre Auger Observatory
  Physical Review D79 (2009), 102001
- Upper limit on the cosmic-ray photon fraction at EeV energies from the Pierre Auger Observatory
  Astroparticle Physics 31 (2009) 399
- Measurement of the energy spectrum of cosmic rays above 10^{18} eV using the Pierre Auger Observatory
  Physics Letters B 685 (2010) 239
- Measurement of the Depth of Maximum of Extensive Air Showers above 10^{18} eV
  Physical Review Letters (2010)
- Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter
  Astroparticle Physics 34 (2010) 314
- Search for First Harmonic Modulation in the Right Ascension Distribution of Cosmic Rays Detected at the Pierre Auger Observatory
  Astroparticle Physics 34 (2011), 627-639

Spectrum Anisotropy Composition

Summary:

Auger is taking high-quality data at $> 10^{17}$ eV.

Spectrum: ankle and steepening seen at $\approx 4 \times 10^{18}$ and $\approx 3 \times 10^{19}$ eV
with model-independent measurement and analysis

But what is the interpretation?

cut-off: likely GZK cut-off, protons?

ankle: transition galactic to extra-galactic ?

Arrival directions:

CR are extragalactic

Correl. with nearby matter for E > 55 EeV, protons?

Mass composition:

upper limits on photons and neutrinos,

reduced fluctuations at $\approx 2 \times 10^{19}$ eV

mixed / heavy composition?

with current models, but...

Particle Physics (at $>10^{18}$ eV):

Hadronic interaction models need adaption ...

More muons & different energy scale needed

Auger and collider data constrain models

Extensions (to lower energies) - HEAT, infill array:

... may help to clarify composition

What next ?

Auger-South will provide a few more years of reliable experimental data & a solid basis for future work.

3000 km^2 turns out to be still too small for the highest energies.

Good test environment for alternative techniques
(MHz, GHz Radio detection of EAS, atmospheric physics, ...)

Operation at least until 2015 (total: 7 Auger years)
then prolongation (?)

a next step? > 30000 km^2 ??? new, cheaper technique needed.
Ideas?

CRs, ν from space: Jem-EUSO $< 3 \times 10^6$ km^2 sr, launch in 2014?

ISS,	400 km alt.,	surveys	10^5 km^2
CROS satellite,	400-800 km alt.		10^6 km^2

Are you interested in the future of
ultra high energy cosmic rays?

International Symposium on Future Directions in UHECR Physics
UHECR 2012 CERN (Geneva), February 13-16, 2012
http://2012.uhecr.org

Review of the science and future challenges of UHE cosmic rays
Main objectives:

- UHECR physics questions for the future
- New detection techniques and detector designs

The End