Recent Results from the Pierre Auger Observatory

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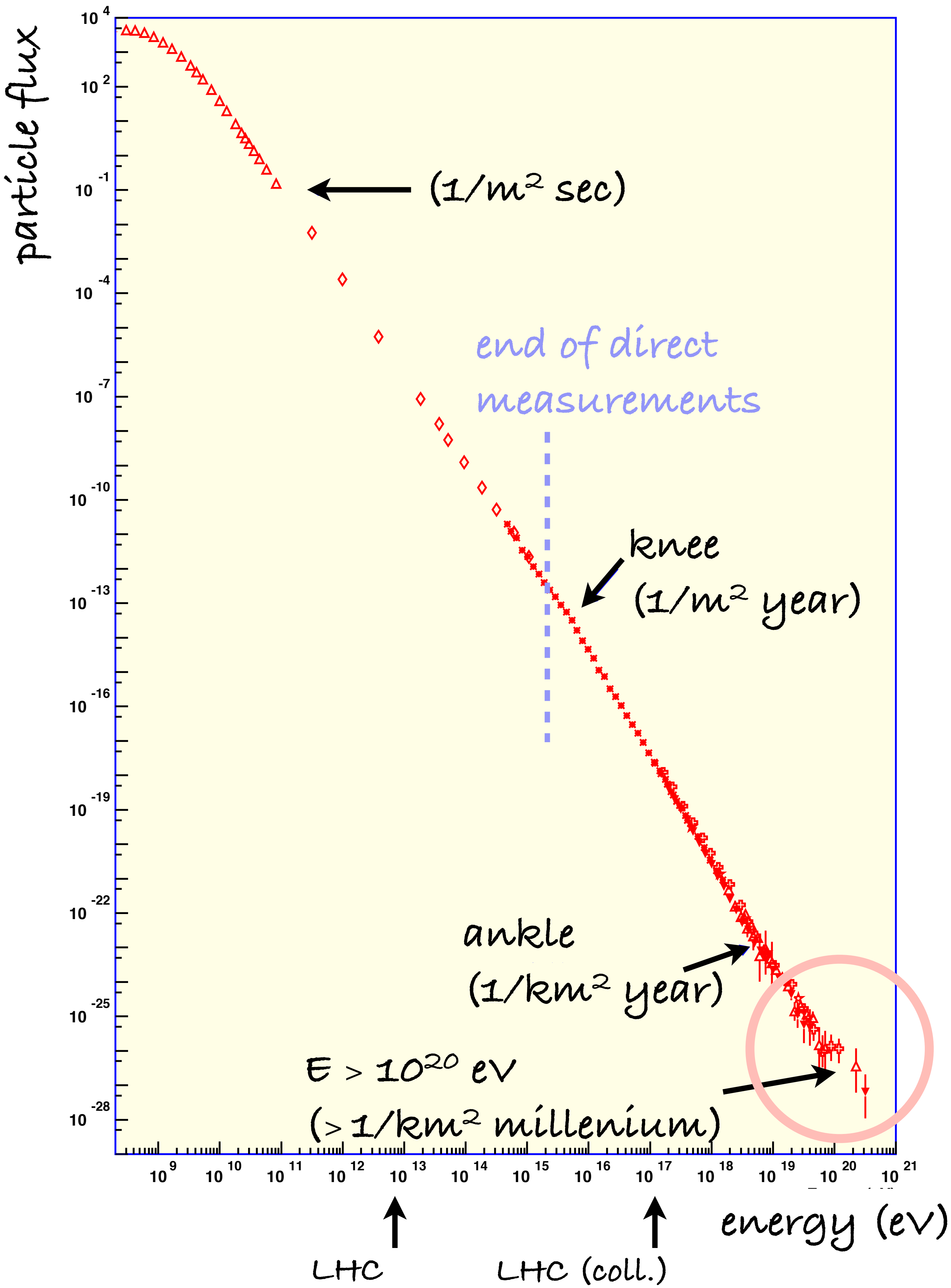
Cosmic Ray Summer School

Nor Amberd, Armenia, June, 2012

Ultra-High Energy Cosmic Rays

Flux of Cosmic Rays



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

10x up in energy, ≈500x down in flux

Highest energy events:
≈ 3 x 10^{20} eV

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?
How do UHE particles interact?

Cosmic Rays: the real high-energy physics

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

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

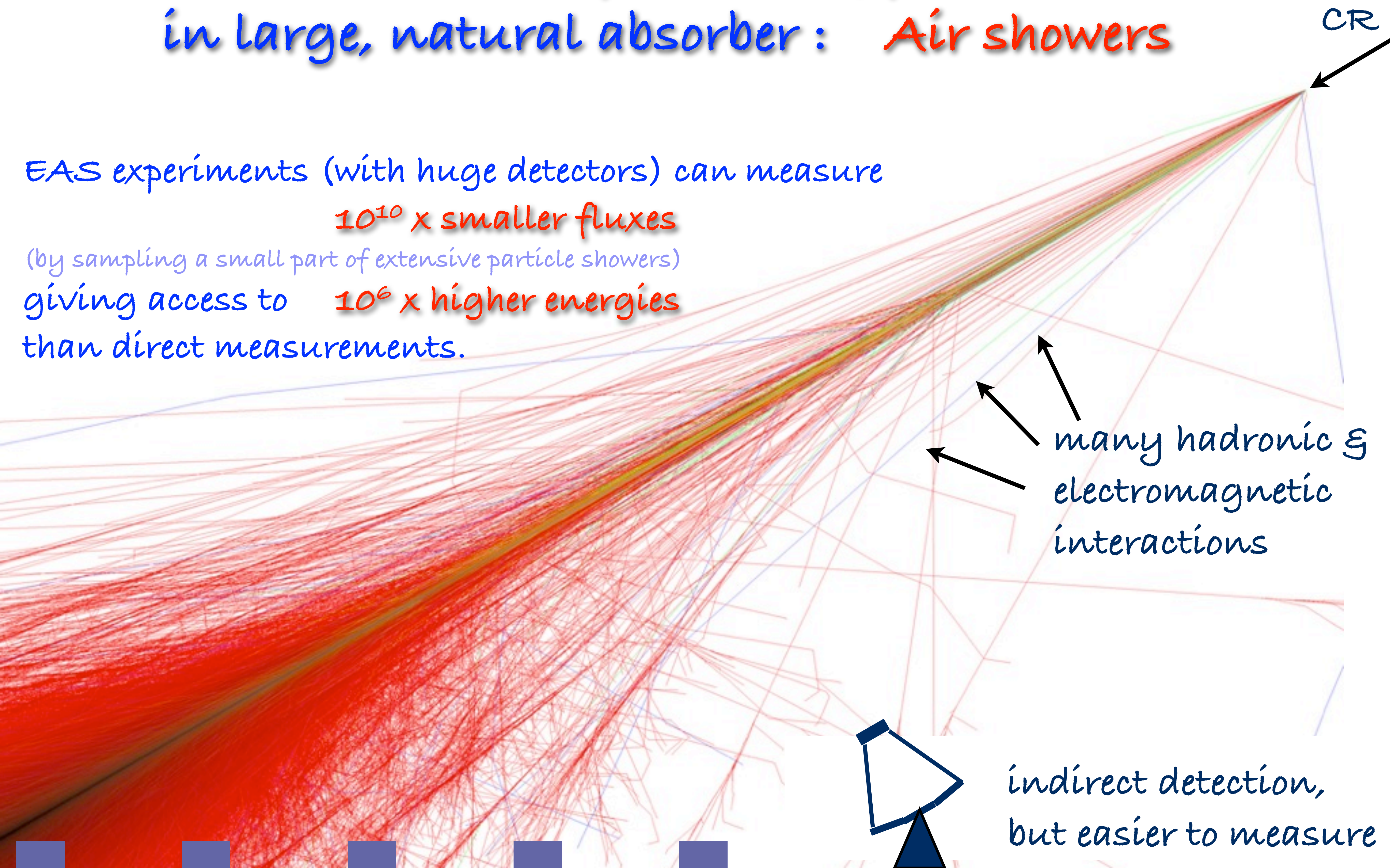
EAS experiments (with huge detectors) can measure

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 :

- CR composition (p, He, O, ... Fe, γ , ν)
- energy spectrum

  get composition from magnetic deflections, features in spectrum,
  well-understood acceleration and environments
  to constrain hadronic interactions.

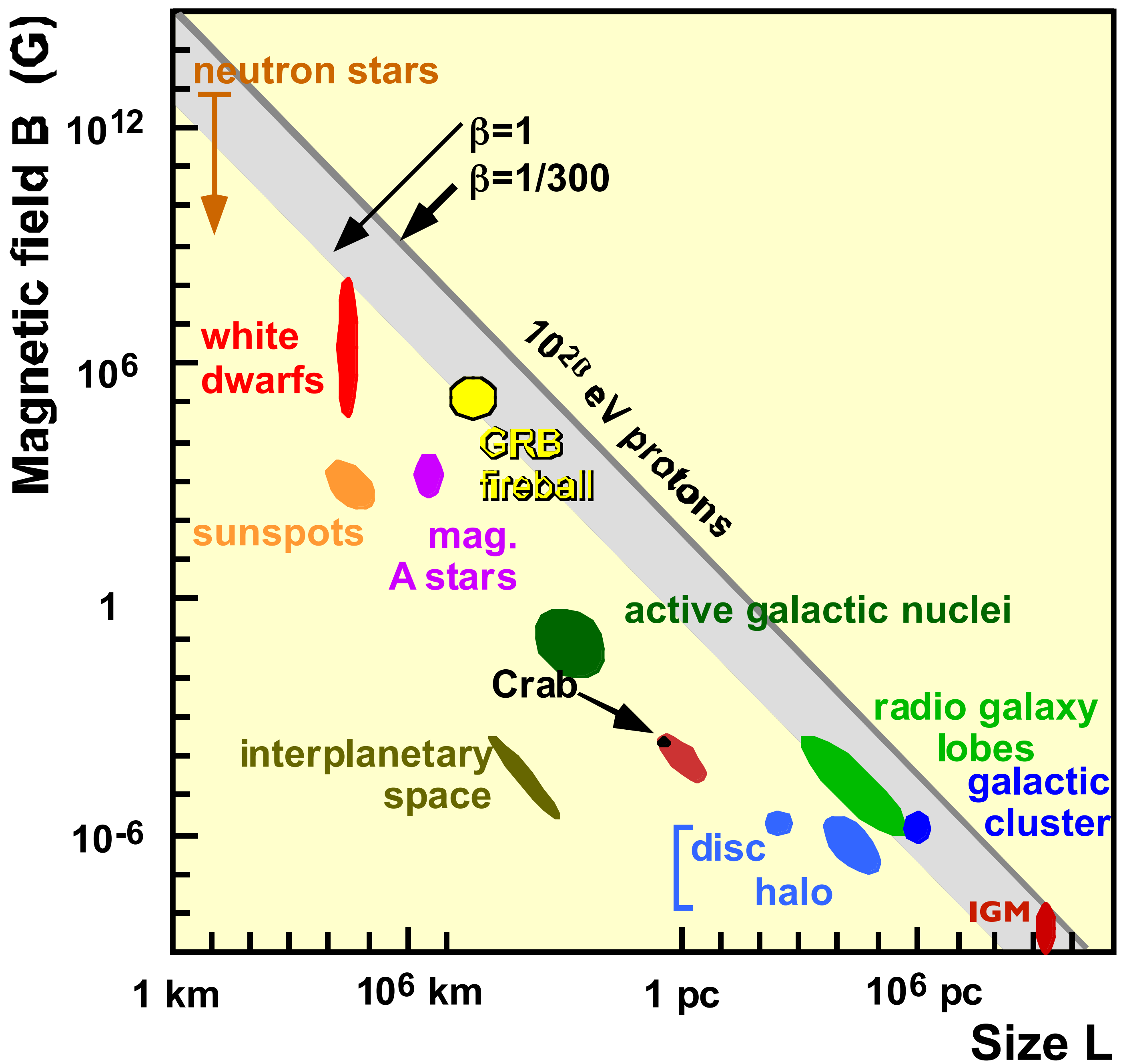
- details of nuclear and hadronic interactions

  Construct an air shower model based on
  particle physics data (LHC ...) and reliable theories.
  Extrapolate to the UHECR regime ($>10^{18}$ eV, very forward)
  to interpret CR composition.

Find consistent description of
Astrophysics and Hadronic physics
simultaneously.

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

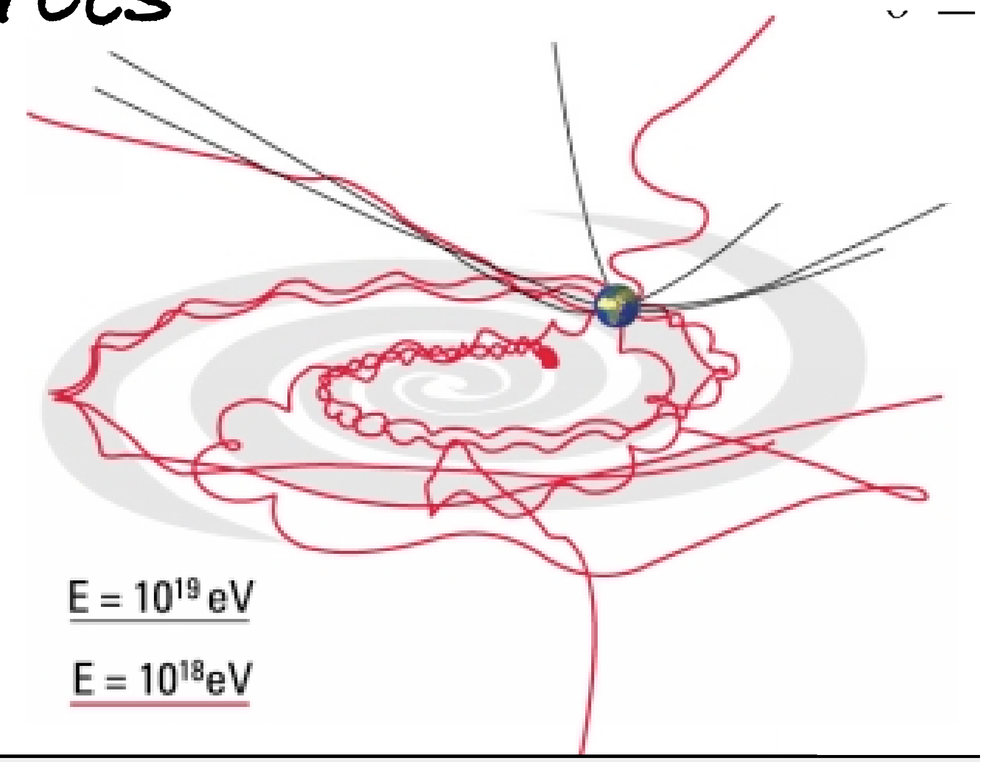
But also:
energy gain should be larger than losses

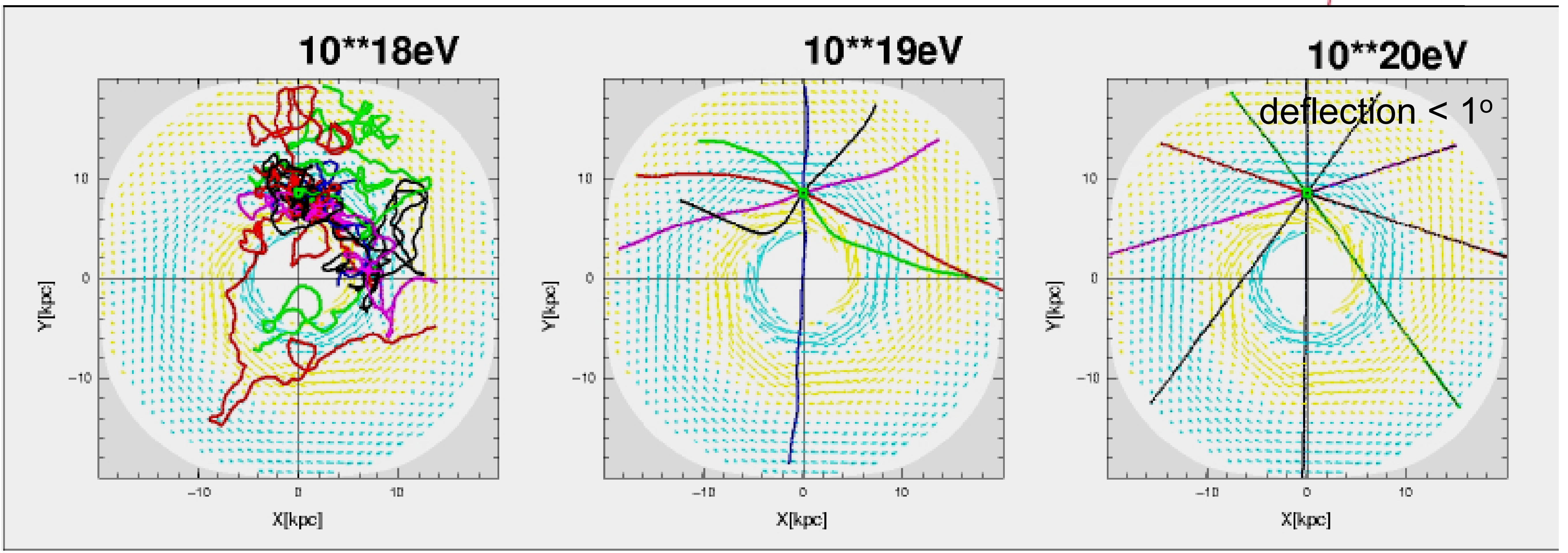
No obvious candidates.

Highest Energy Particles are not deflected much !

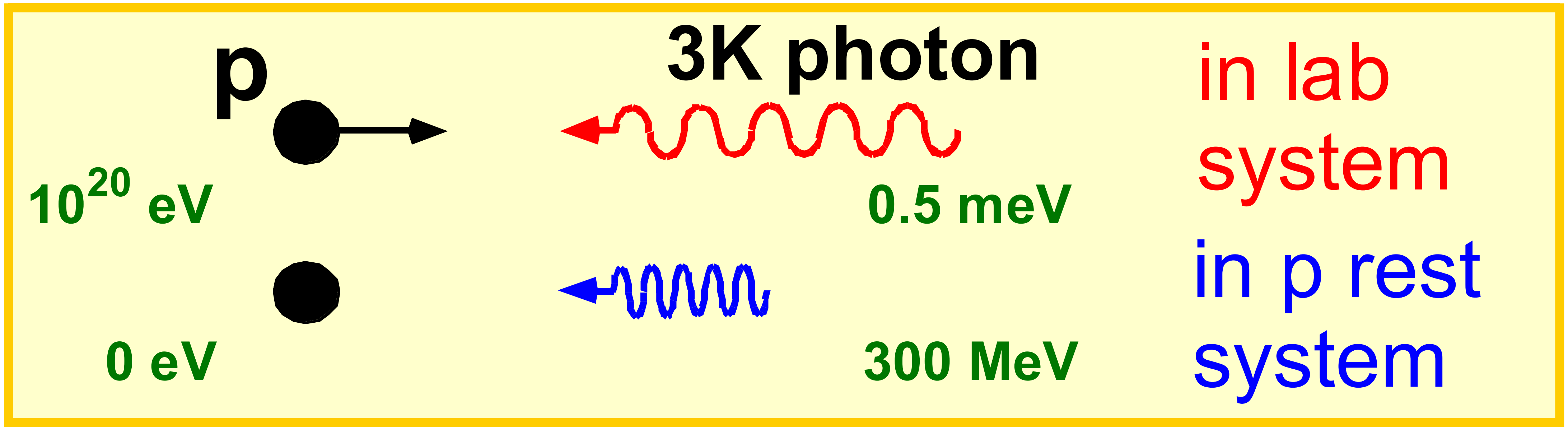
i.e. CR start pointing back at sources

"Charged particle astronomy"





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

The Pierre Auger Observatory

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

(UHECRs: > 10^{18} 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:

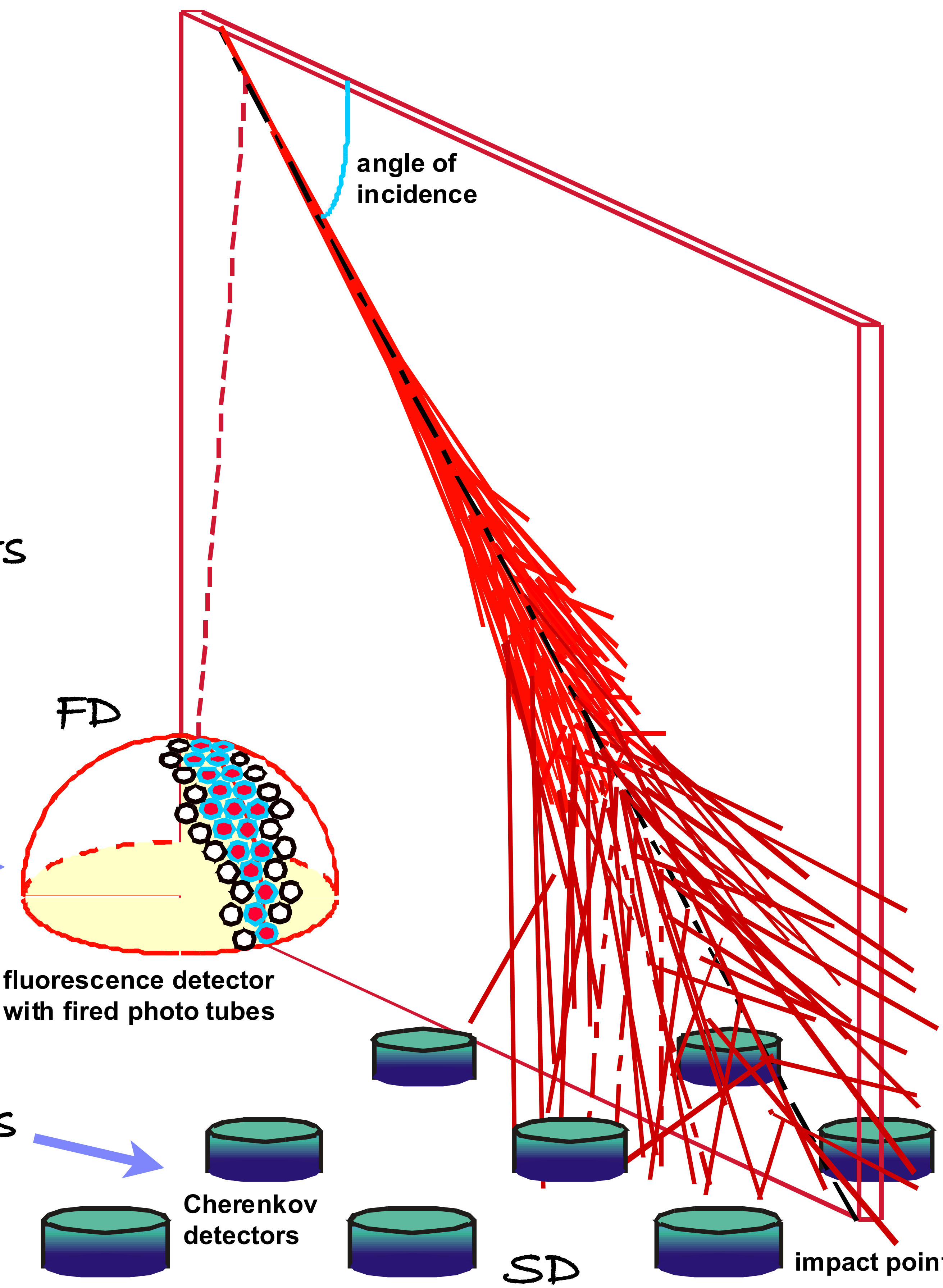
indirect measurement,
shape and particle content of showers

Auger: Hybrid Detector

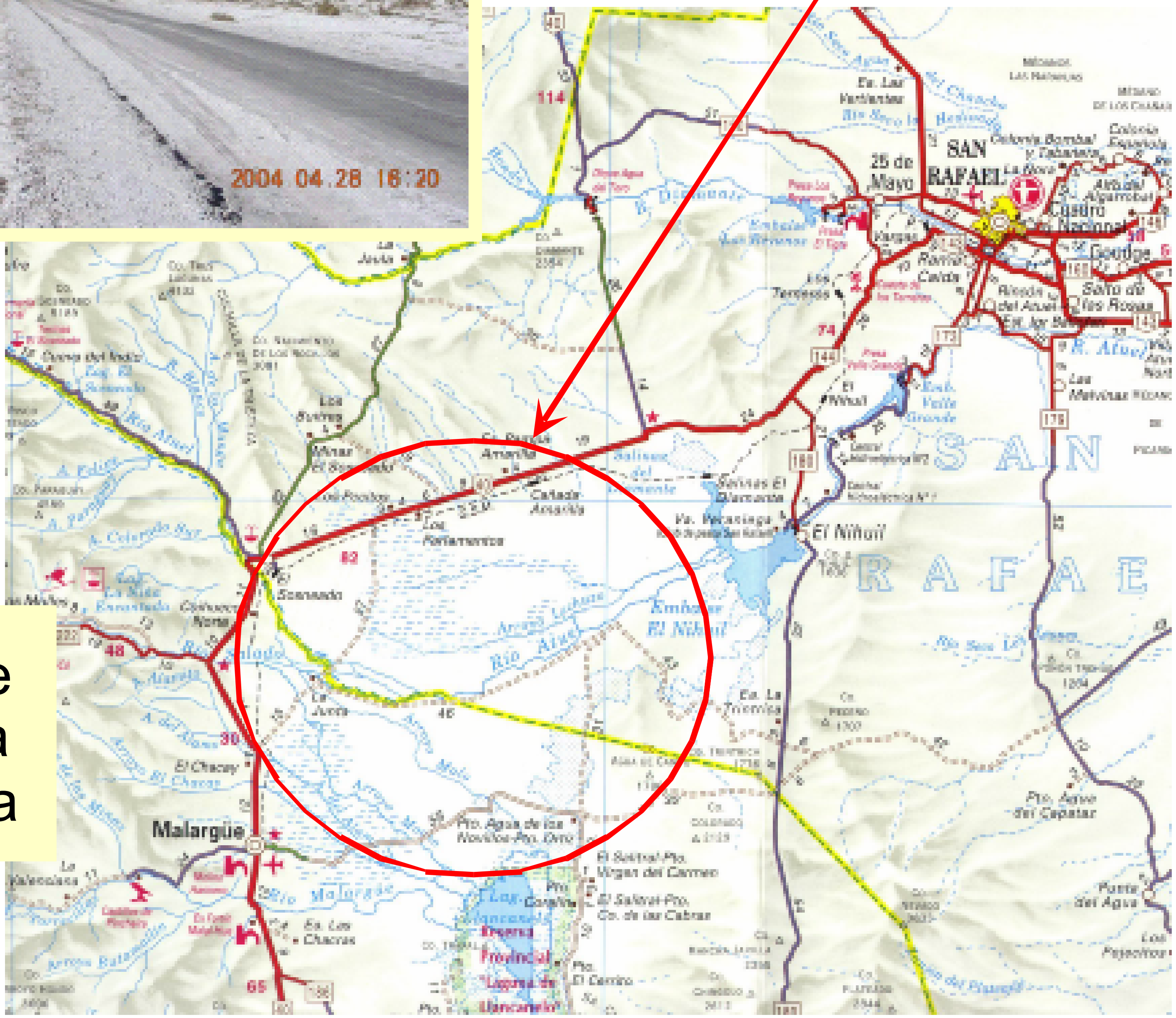
measure extensive air shower with:

24 Fluorescence telescopes
30° x 30° FoV, 10% duty cycle,
good energy resolution

array of 1600 water Cherenkov detectors
on 3000 km², 100% duty cycle,
well-known aperture



Auger South
**(1400 m a.s.l.,
35.2° S, 69.2° W)**

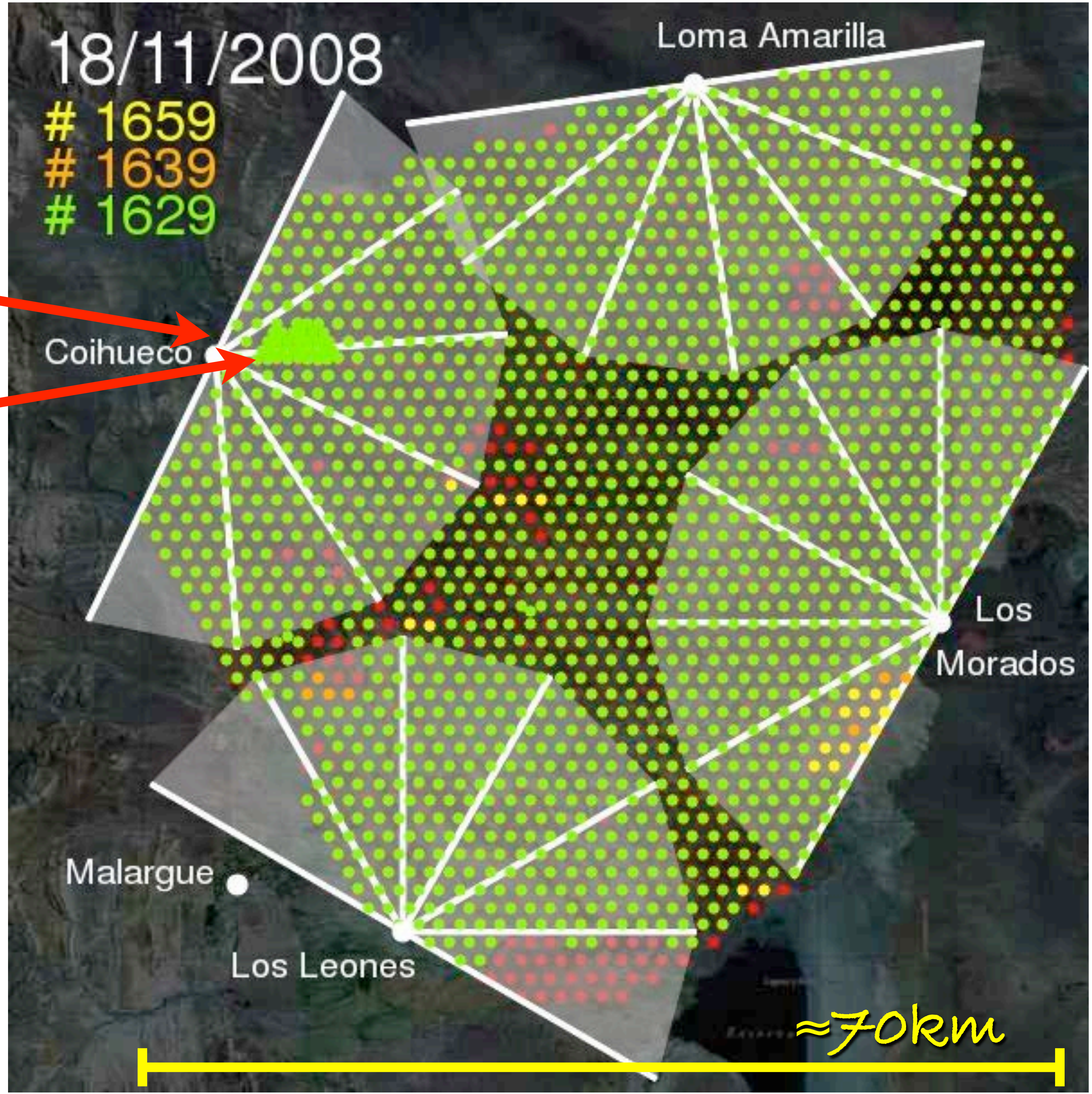


Malargüe
Mendoza
Argentina

Auger layout

HEAT
high elev.
FD tels.

infill
array

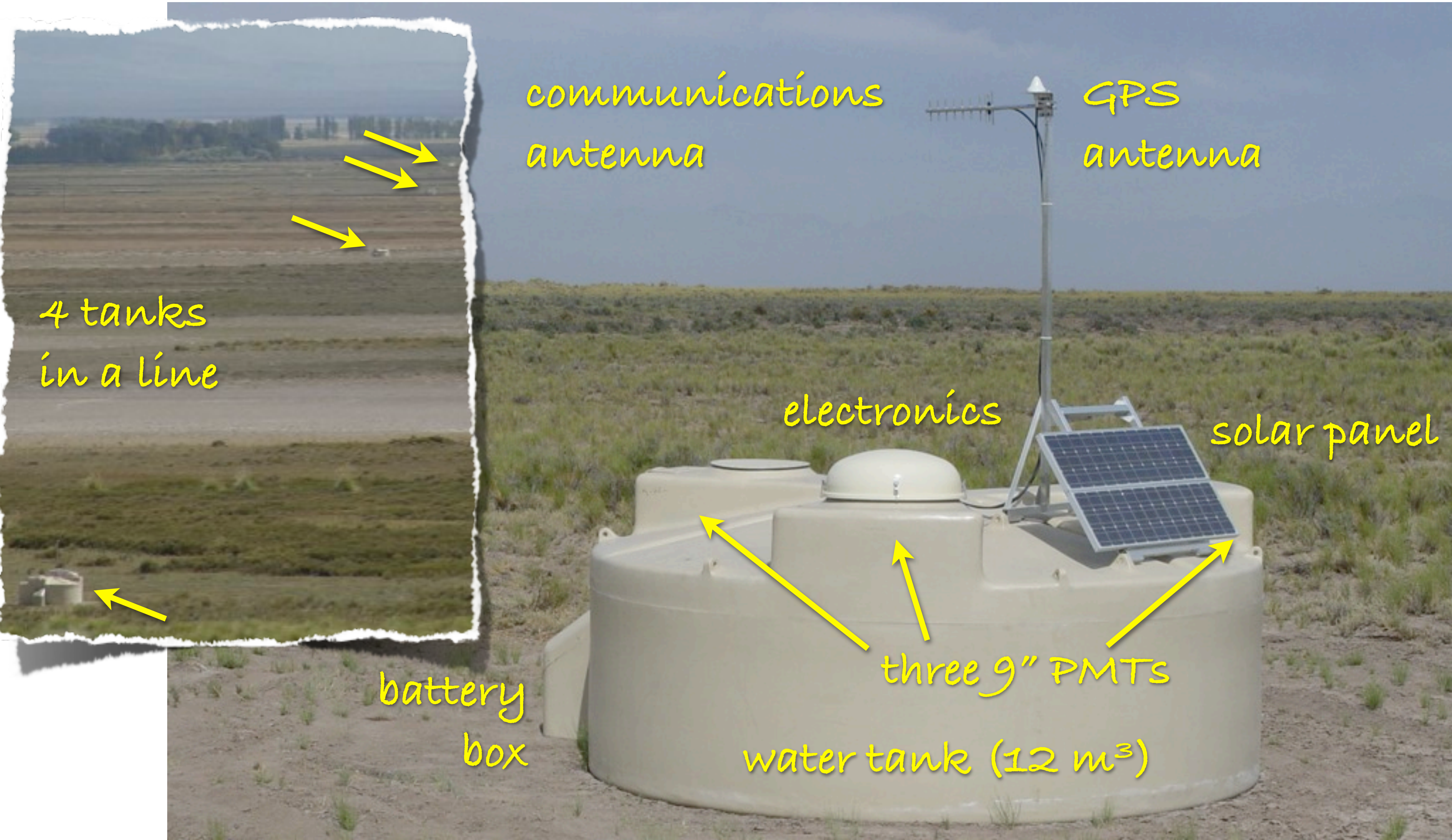


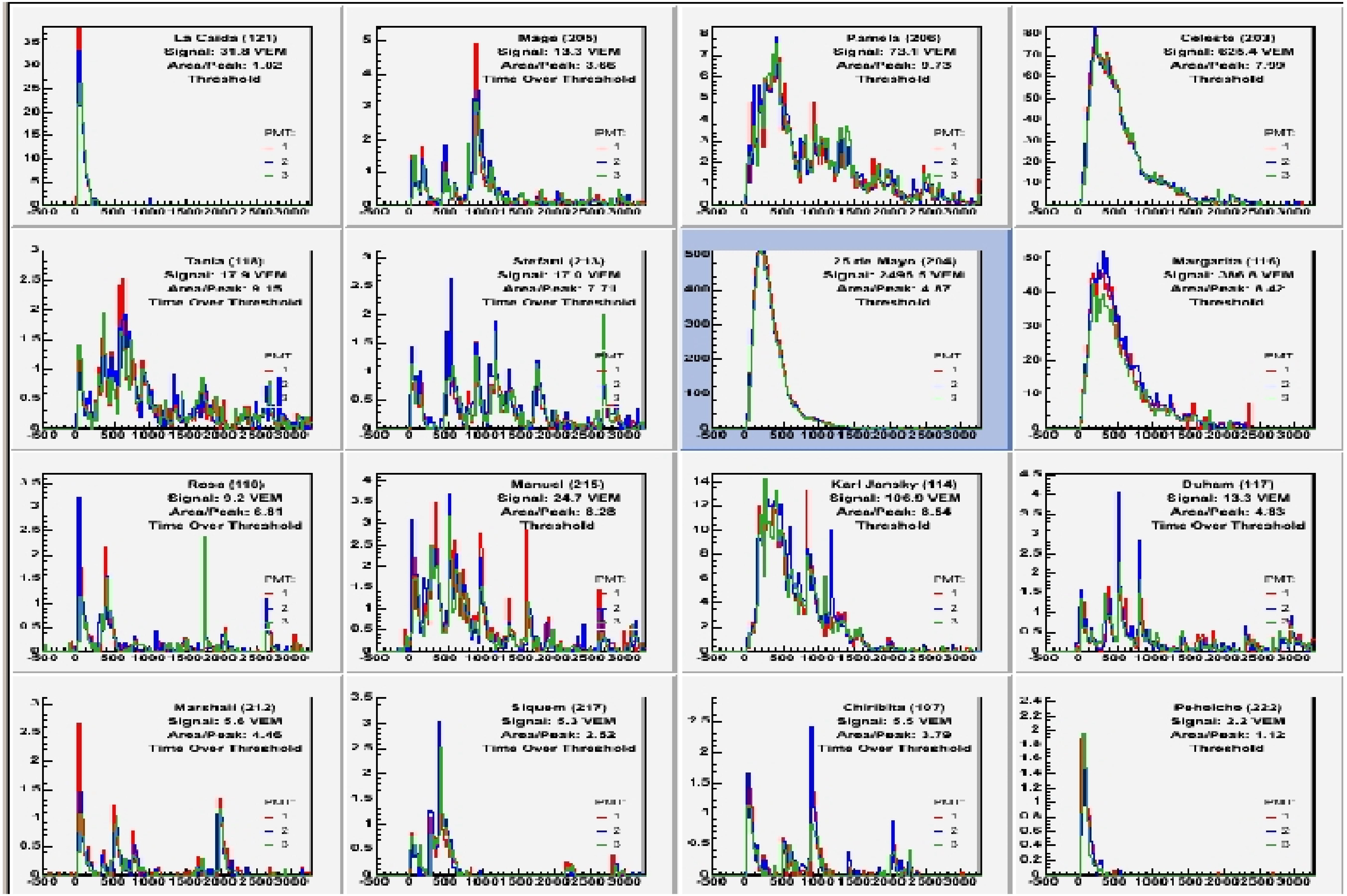
data taking:
since 2004
completion:
Nov 2008

Surface array

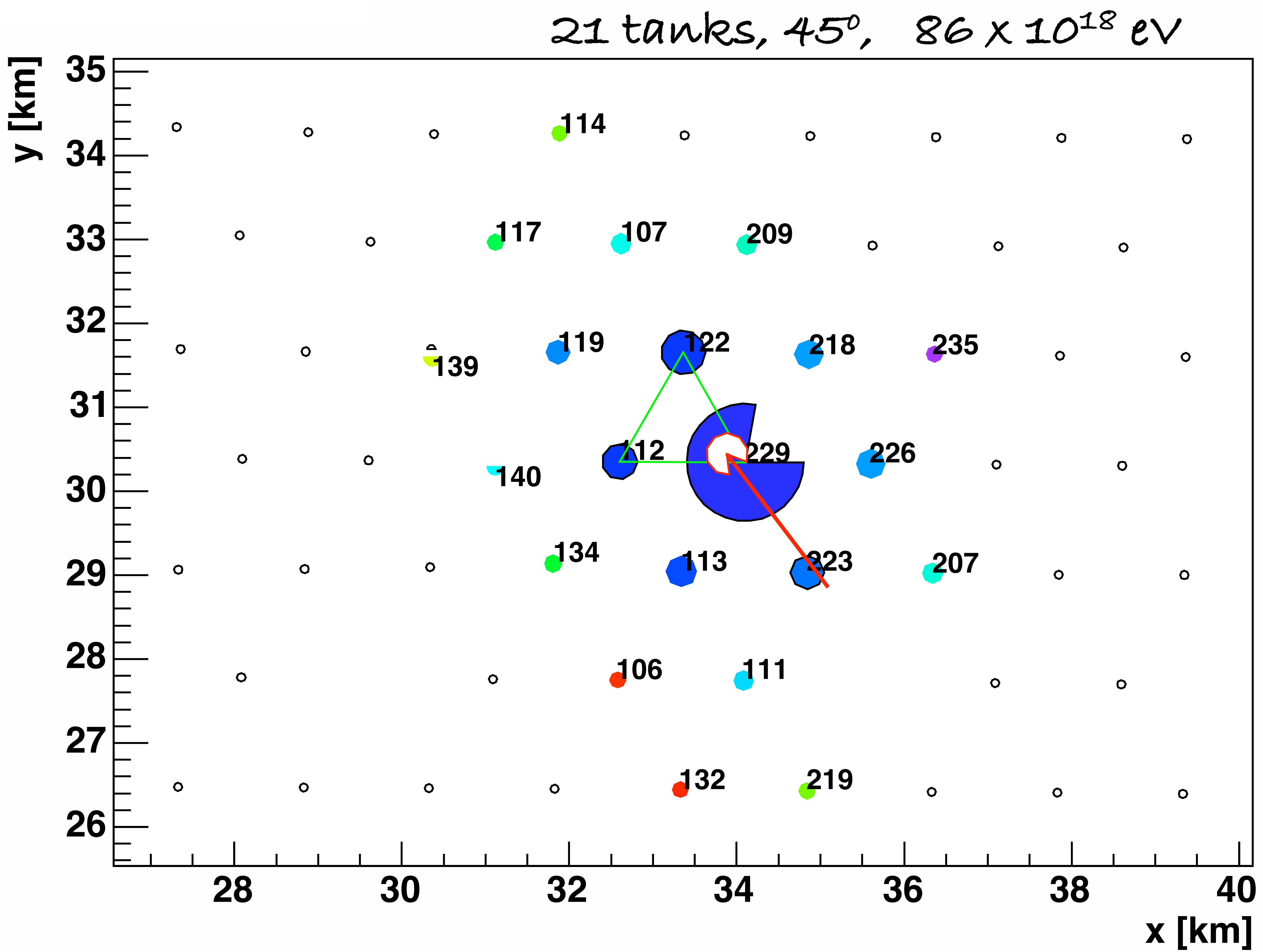
(Water cherenkov detectors)

>1600 tanks deployed over 3000 km^2
triangular grid, 1.5 km distance,
3 PMTs, read out at 40 MHz
solar powered, ≈ 10 W



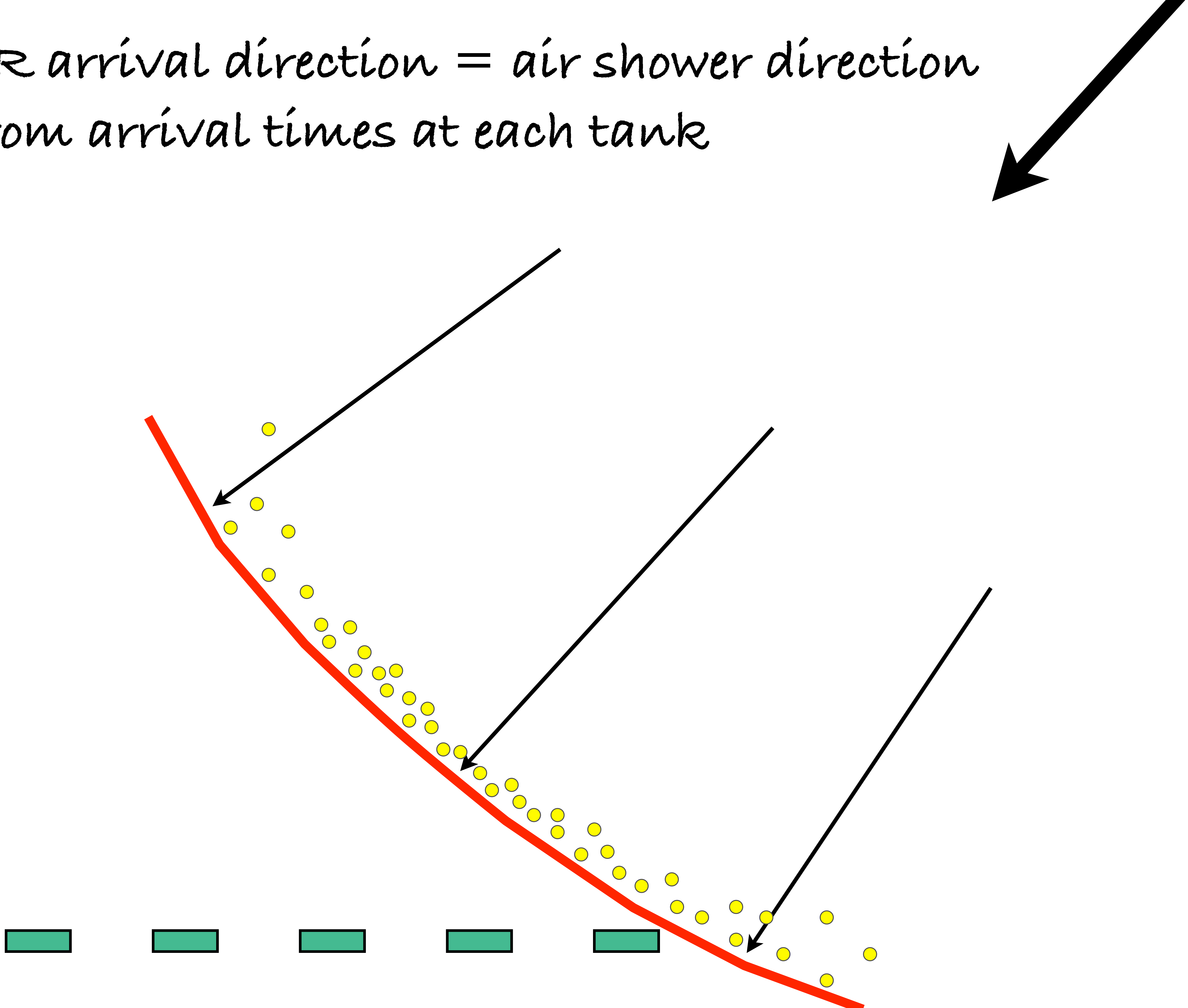


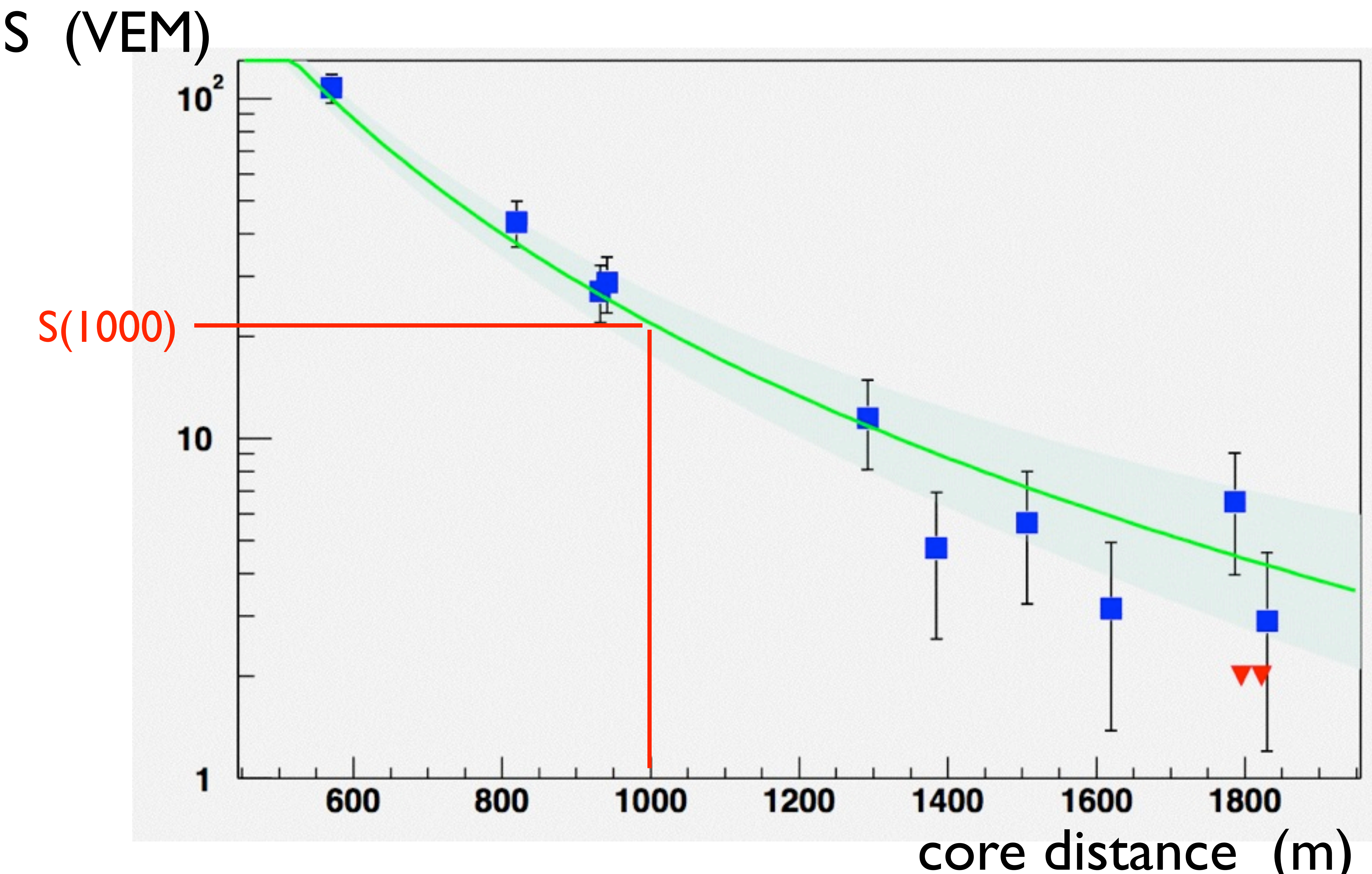
High & smooth pulses close to shower core, low & spiky pulses far away.



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.

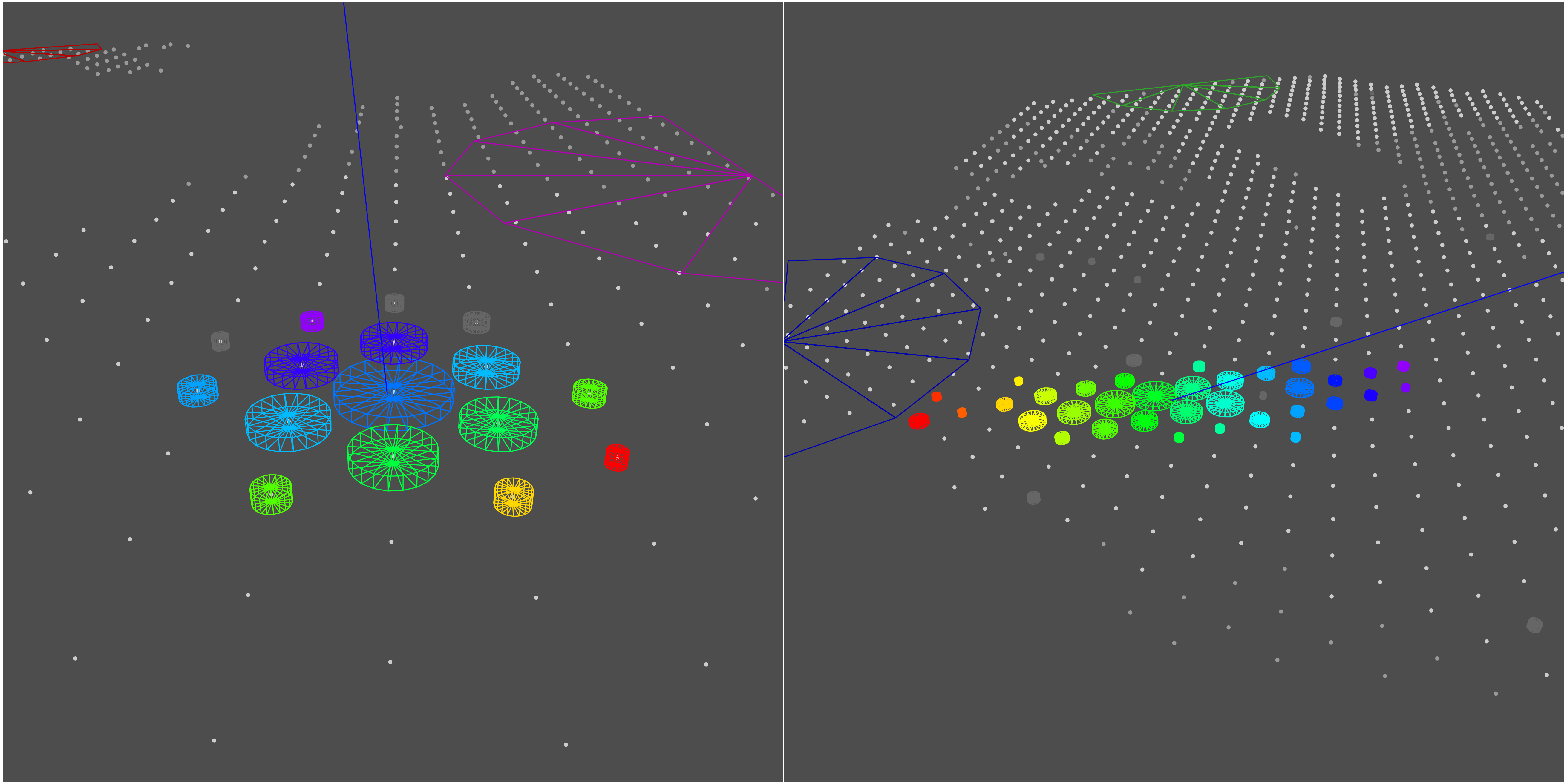
some of the highest-energy SD events:

near vertical

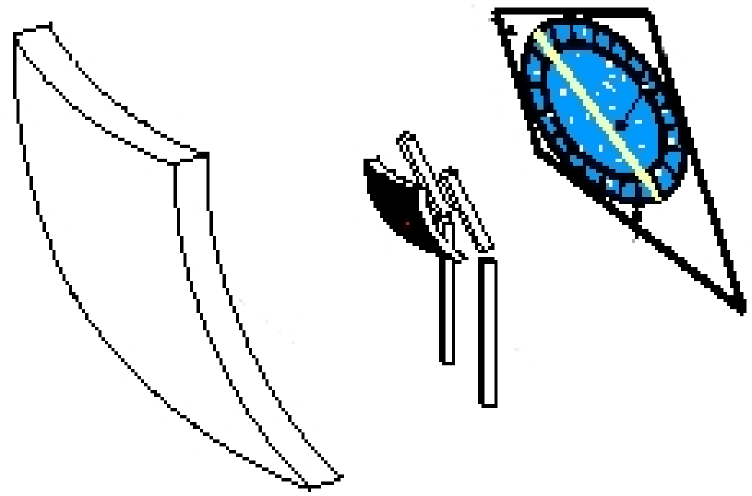
inclined

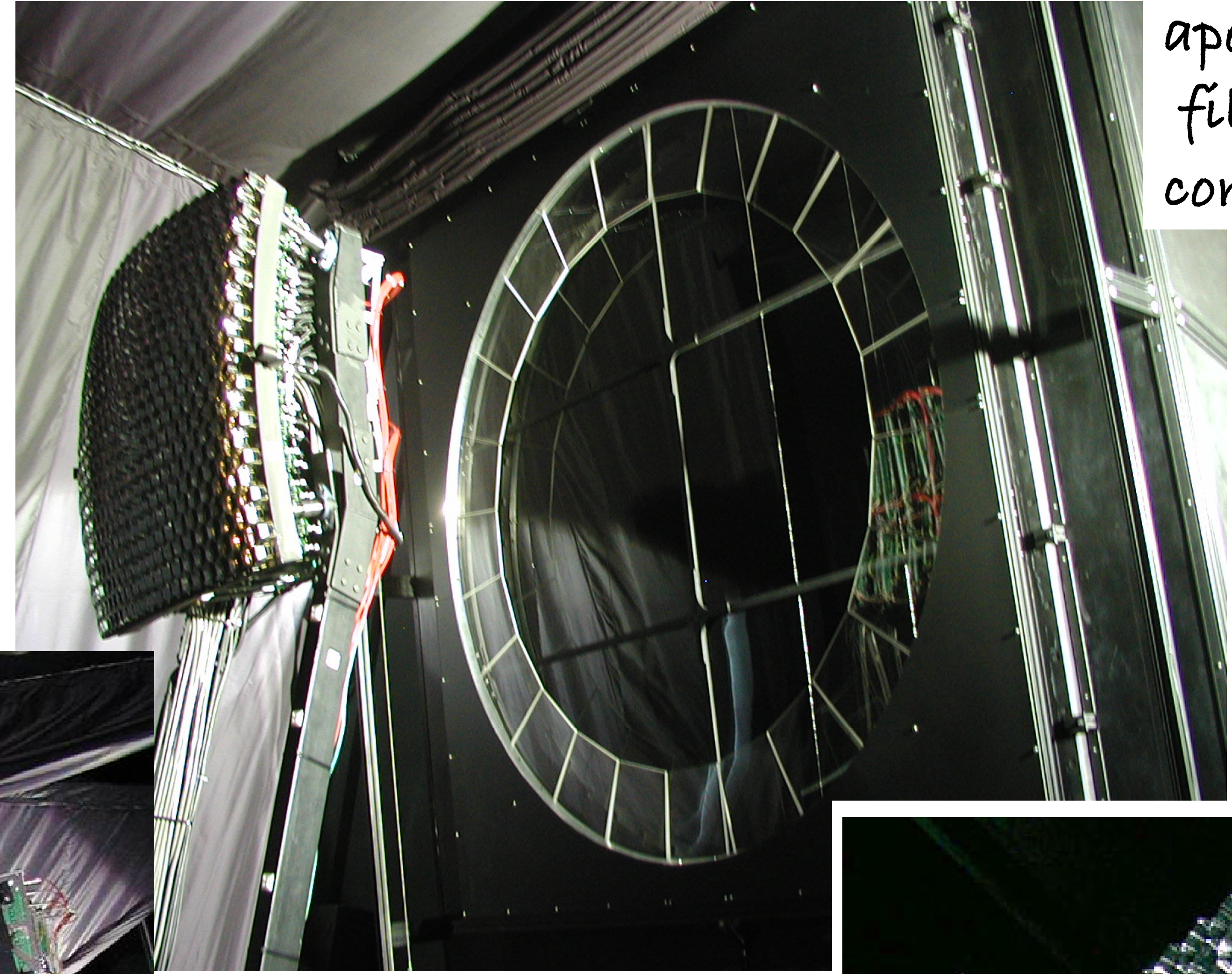
E = 1.67 x 10^{20} eV   θ = 14°

E = 0.37 x 10^{20} eV   θ = 74°

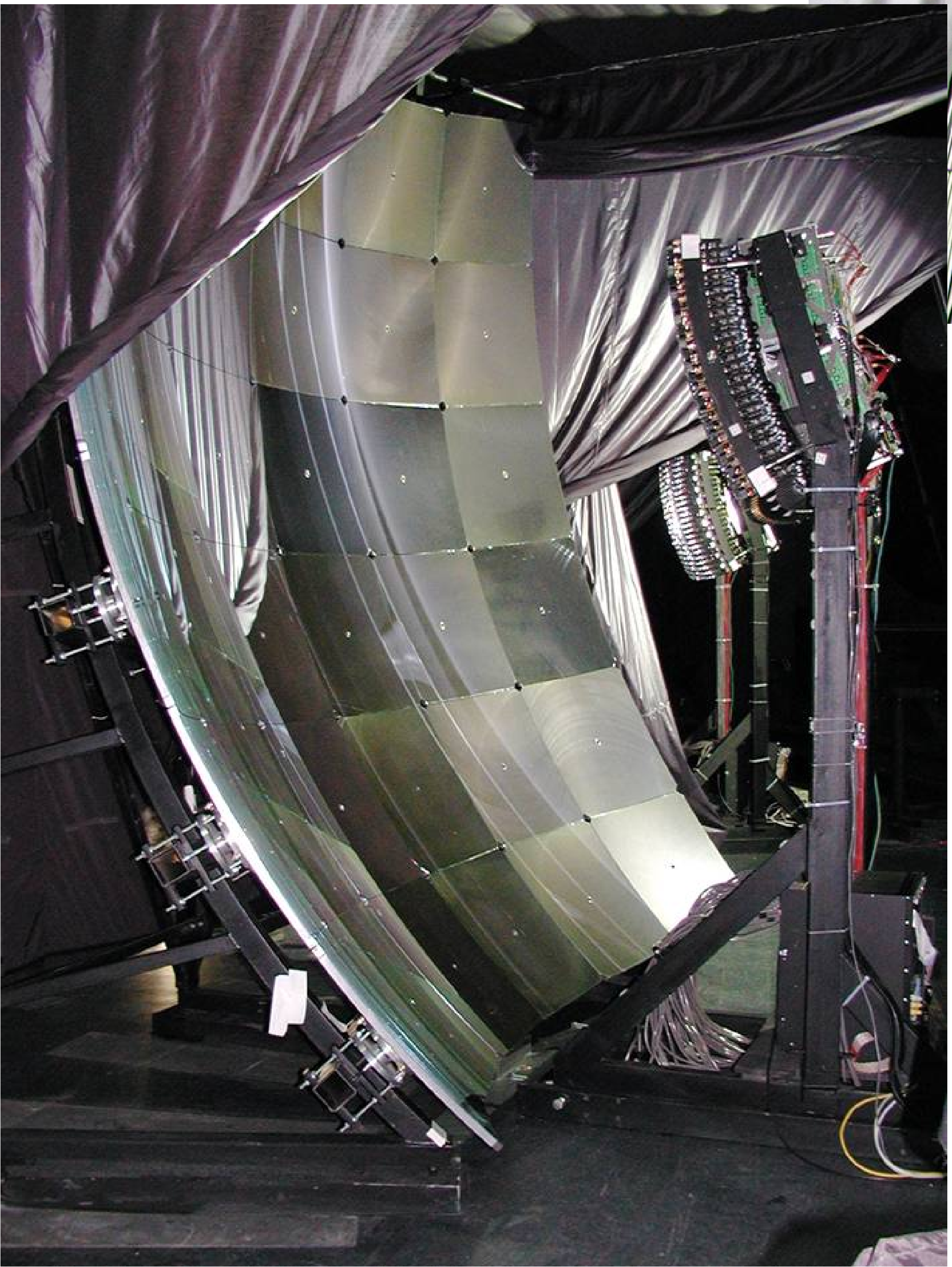


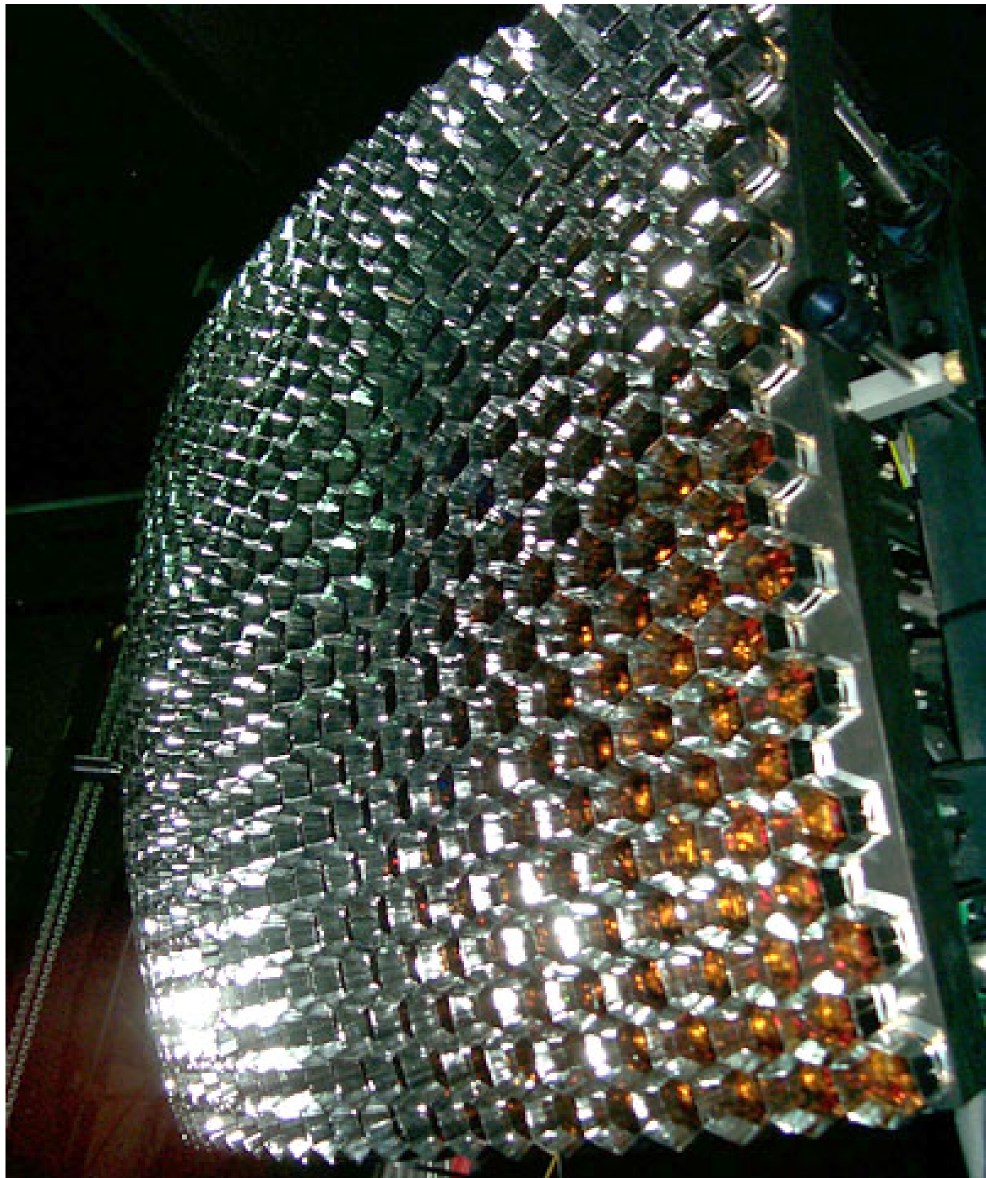
FD telescope:





aperture with shutter, filter and Schmidt corrector lenses





11 m² mirror (Aluminium)

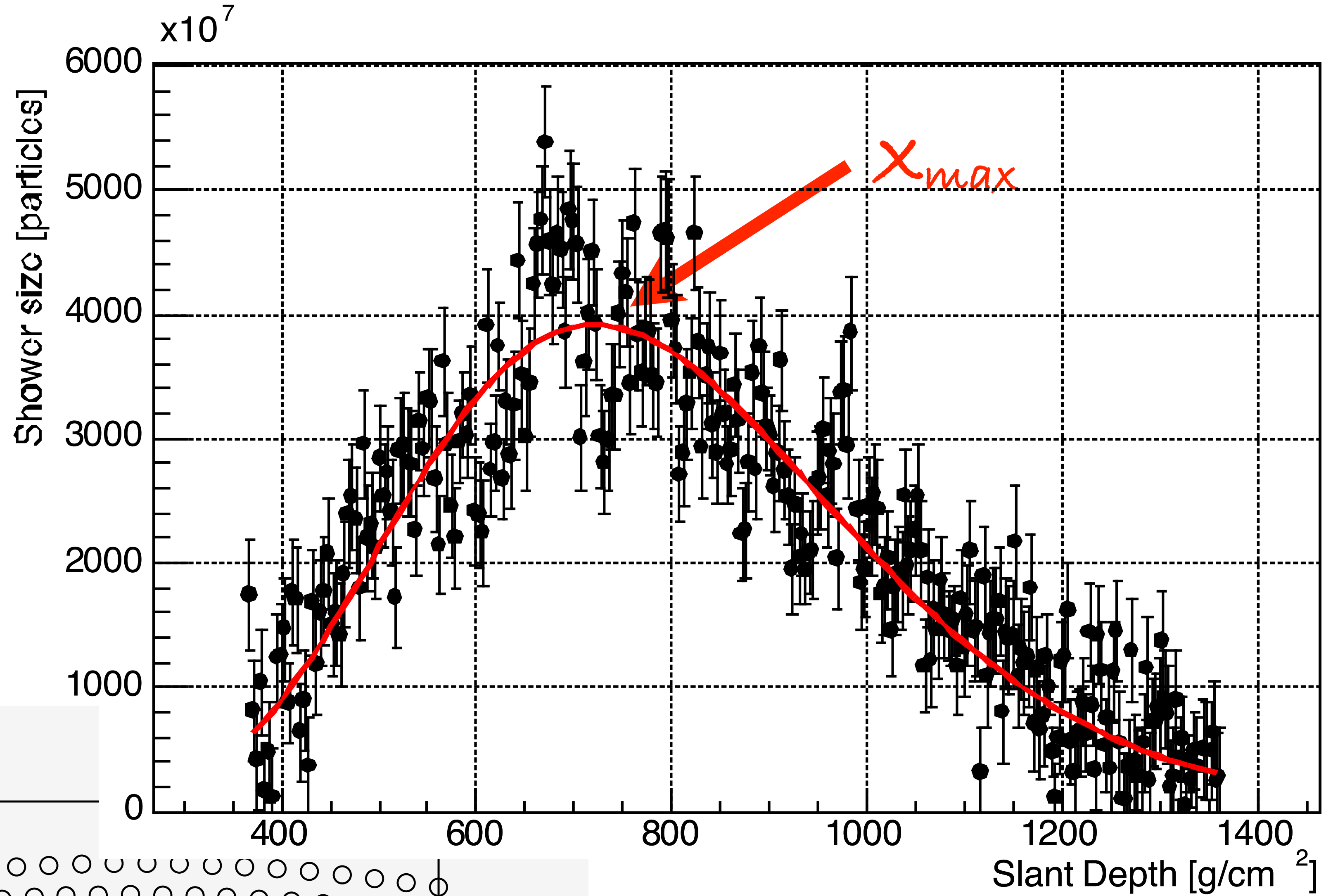
440 PMT camera

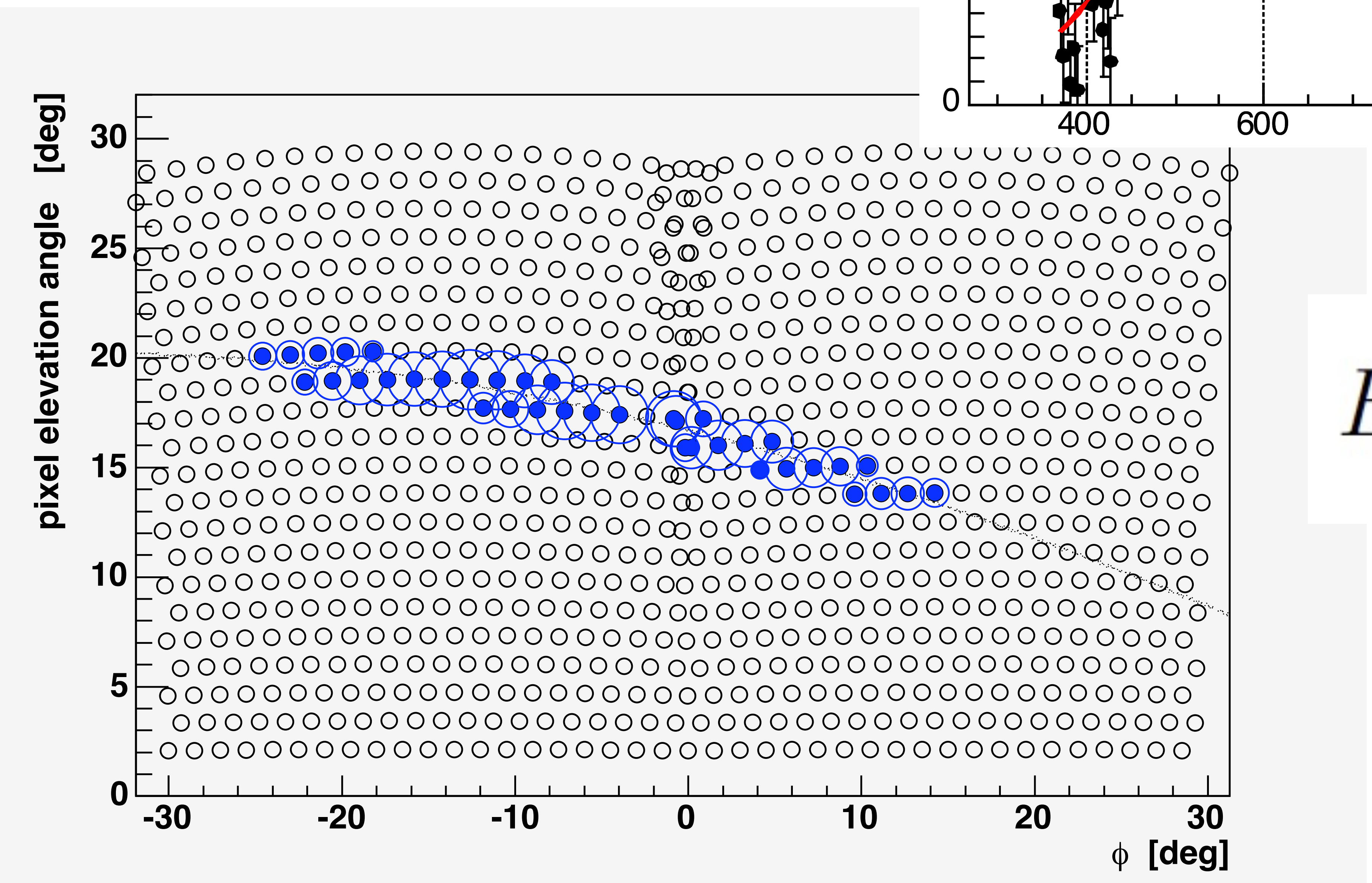
24 telescopes at 4 sites

30°x30° FOV, each

FD:

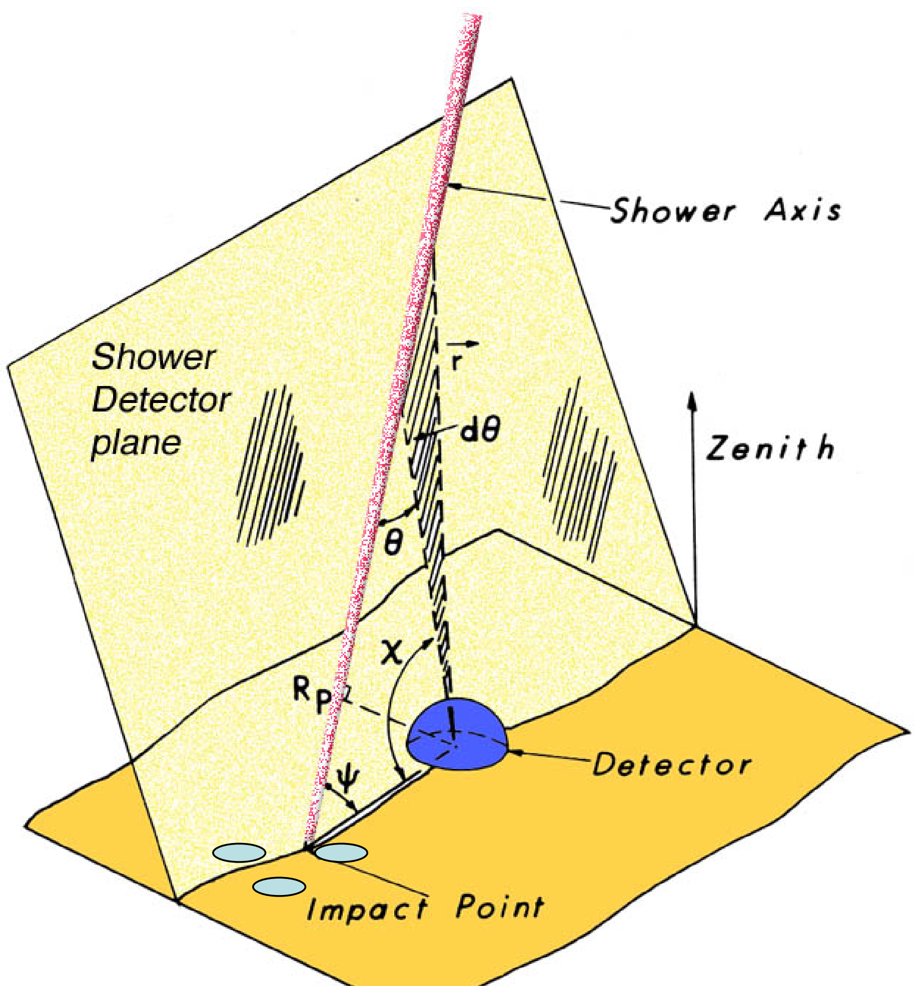
longitudinal profile,
calorimetric energy,
X_{max} for mass comp.

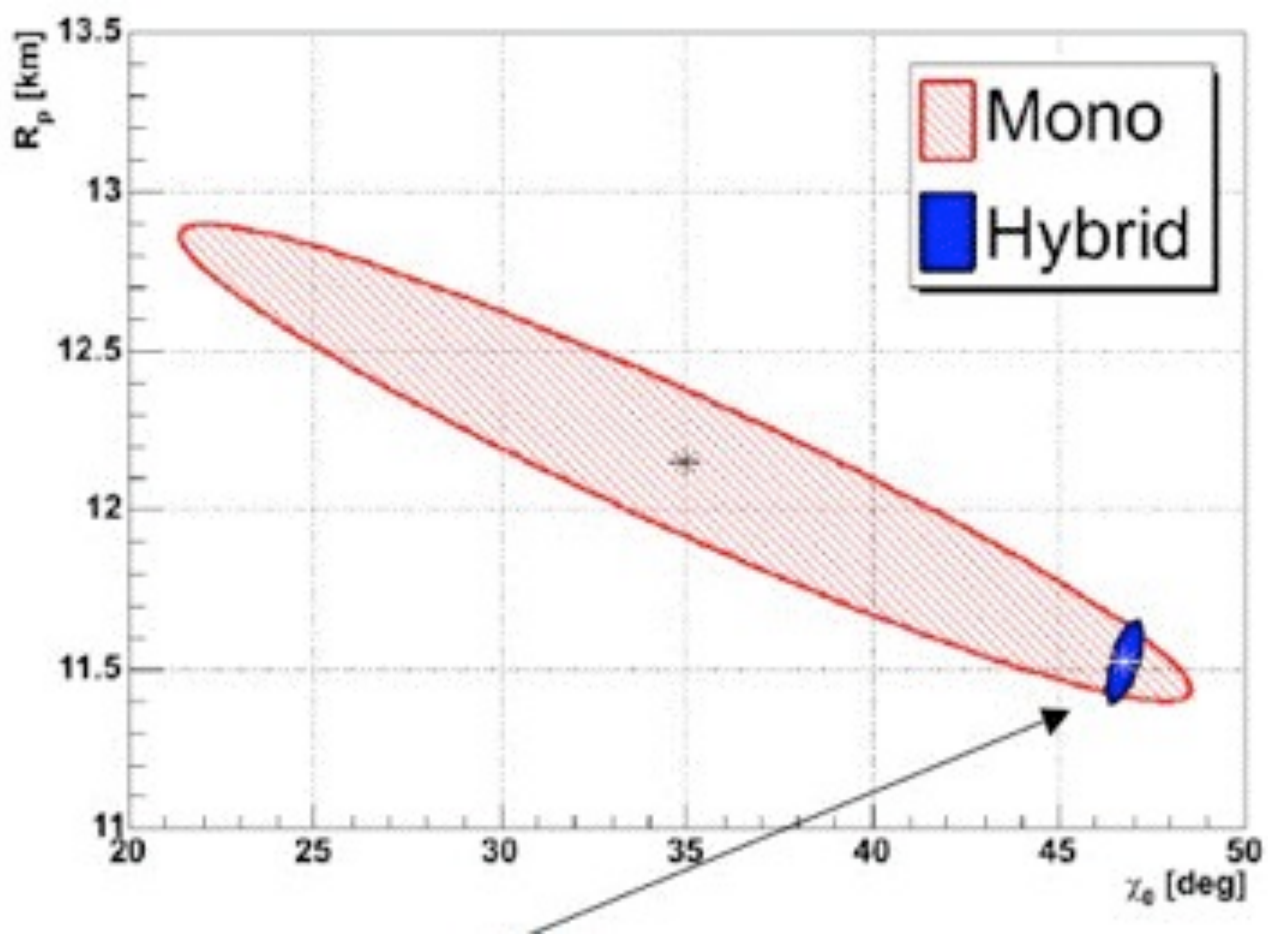




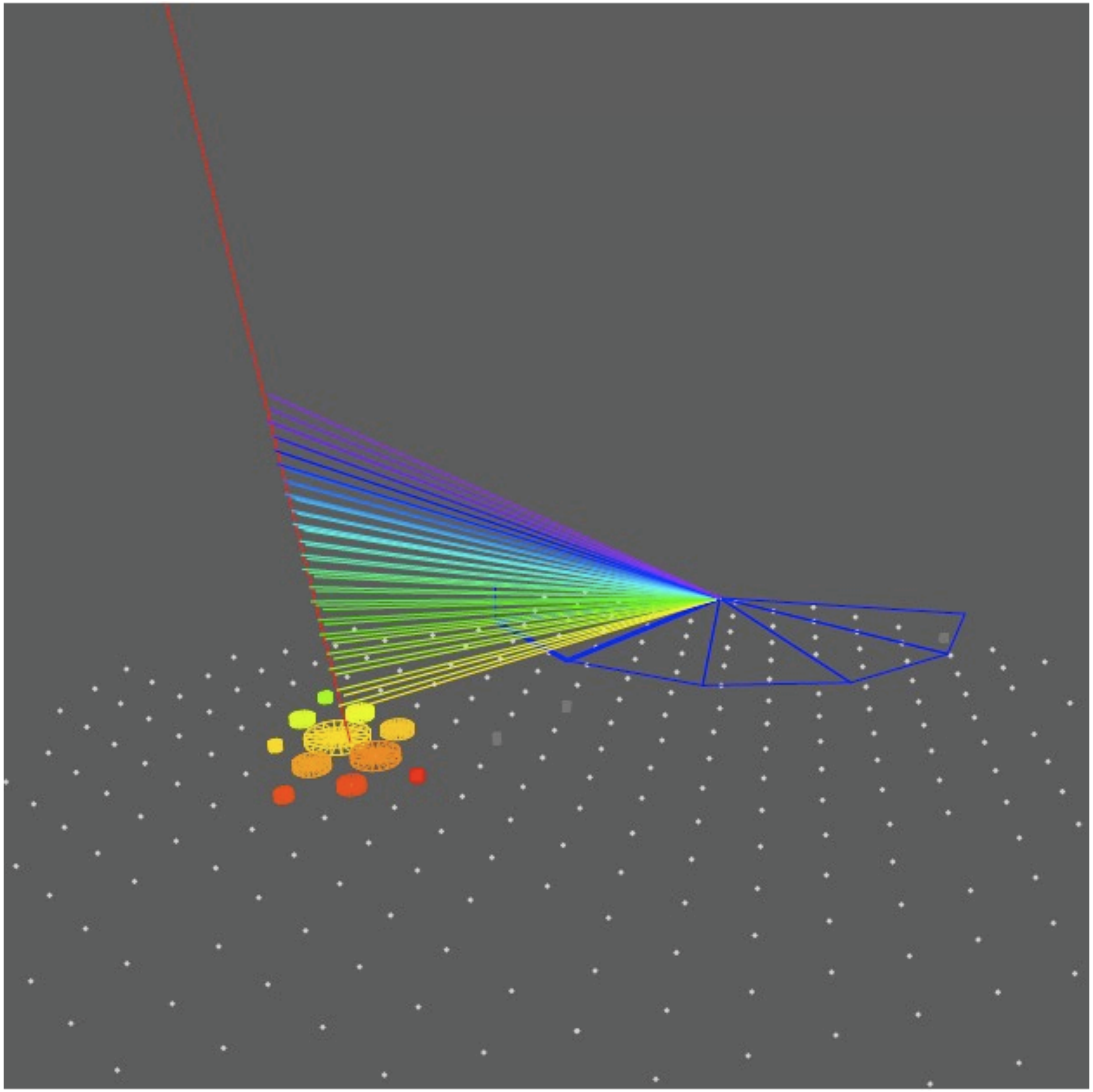
$$E \propto \int_0^\infty N(t)dt$$

	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

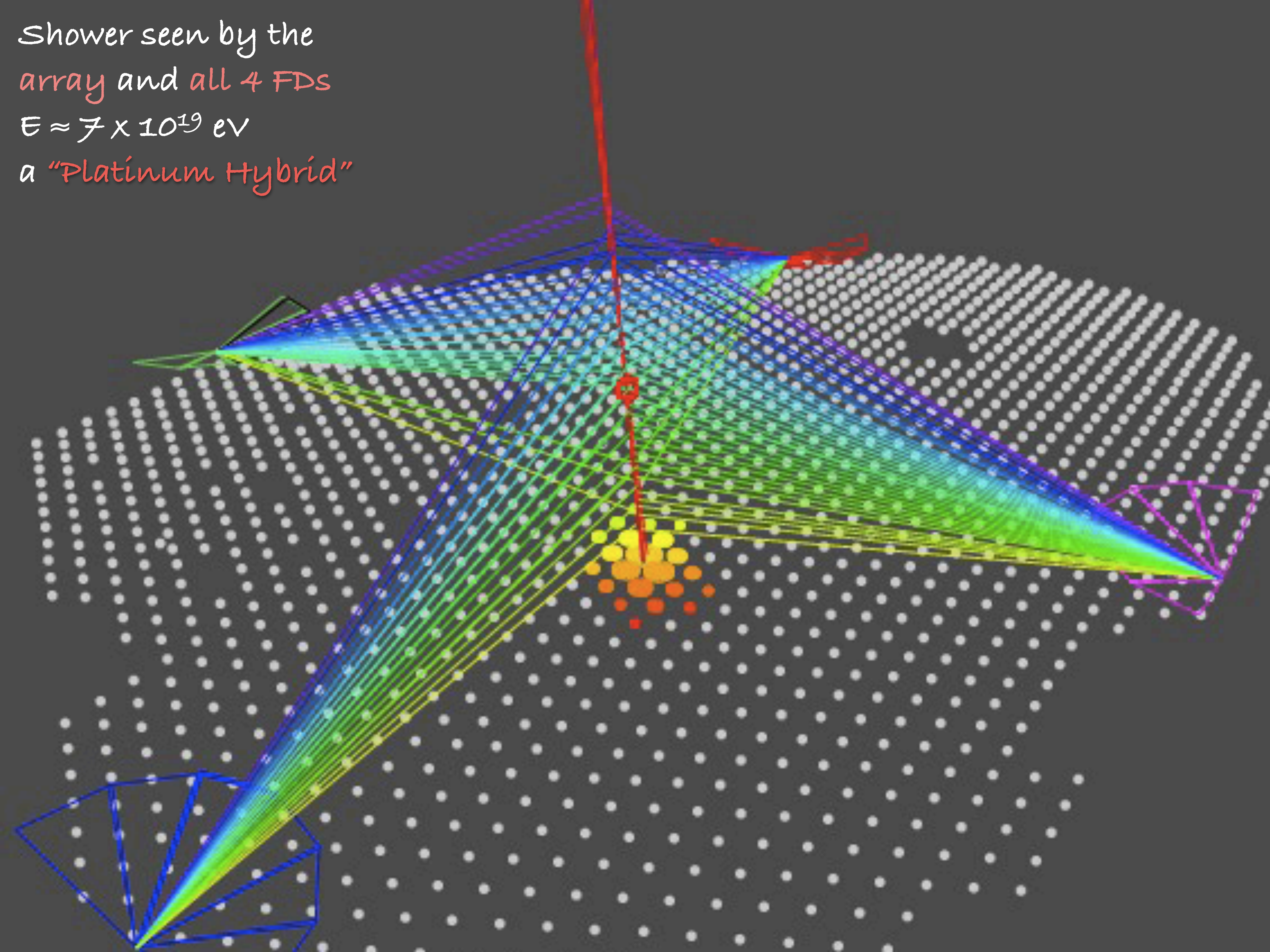


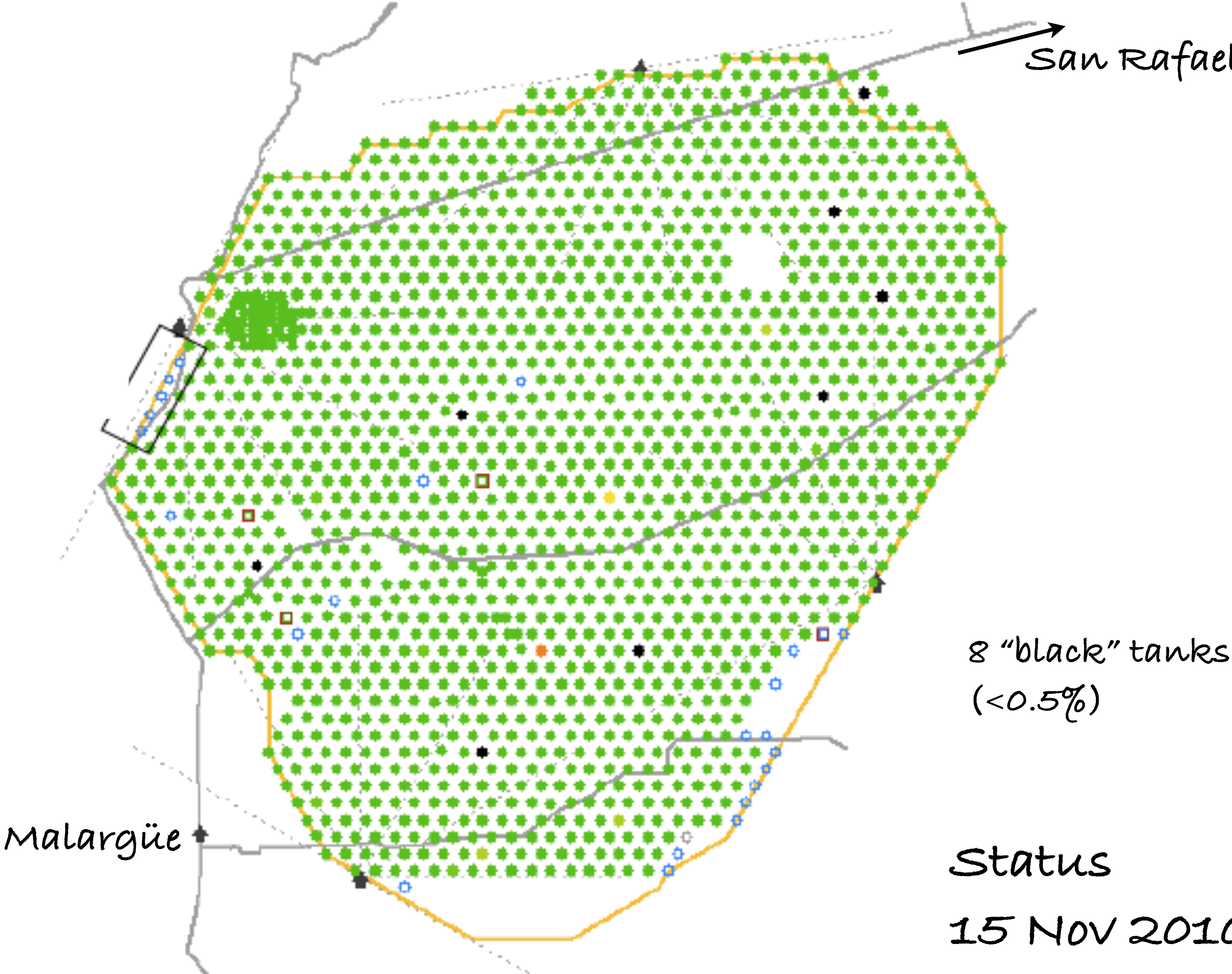


golden hybrid event



Shower seen by the
array and all 4 FDs
$E \approx 7 \times 10^{19}$ eV
a "Platinum Hybrid"





8 “black” tanks (<0.5%)

Status

15 Nov 2010

a truly black tank

(... after a grass fire)

Some Results:

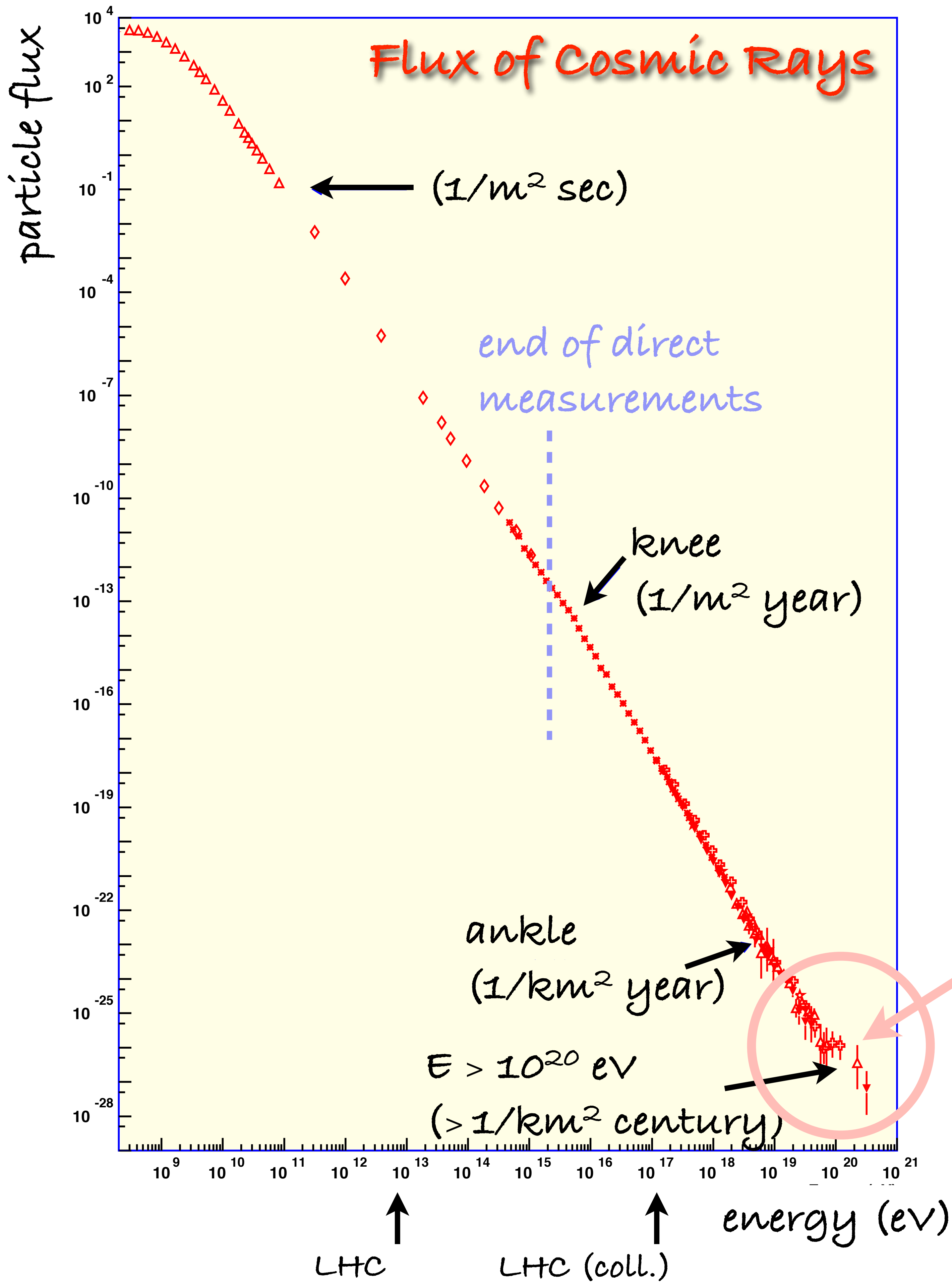
- Spectrum
- Arrival directions
- Composition
- Particle Physics at $>10^{18}$ eV

Data until Dec. 2010

$\approx$ 21000 km^2 yr sr

$\approx$ 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

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

E: straight forward from FD

(but FD only active for 10% of time)

model dependent from SD

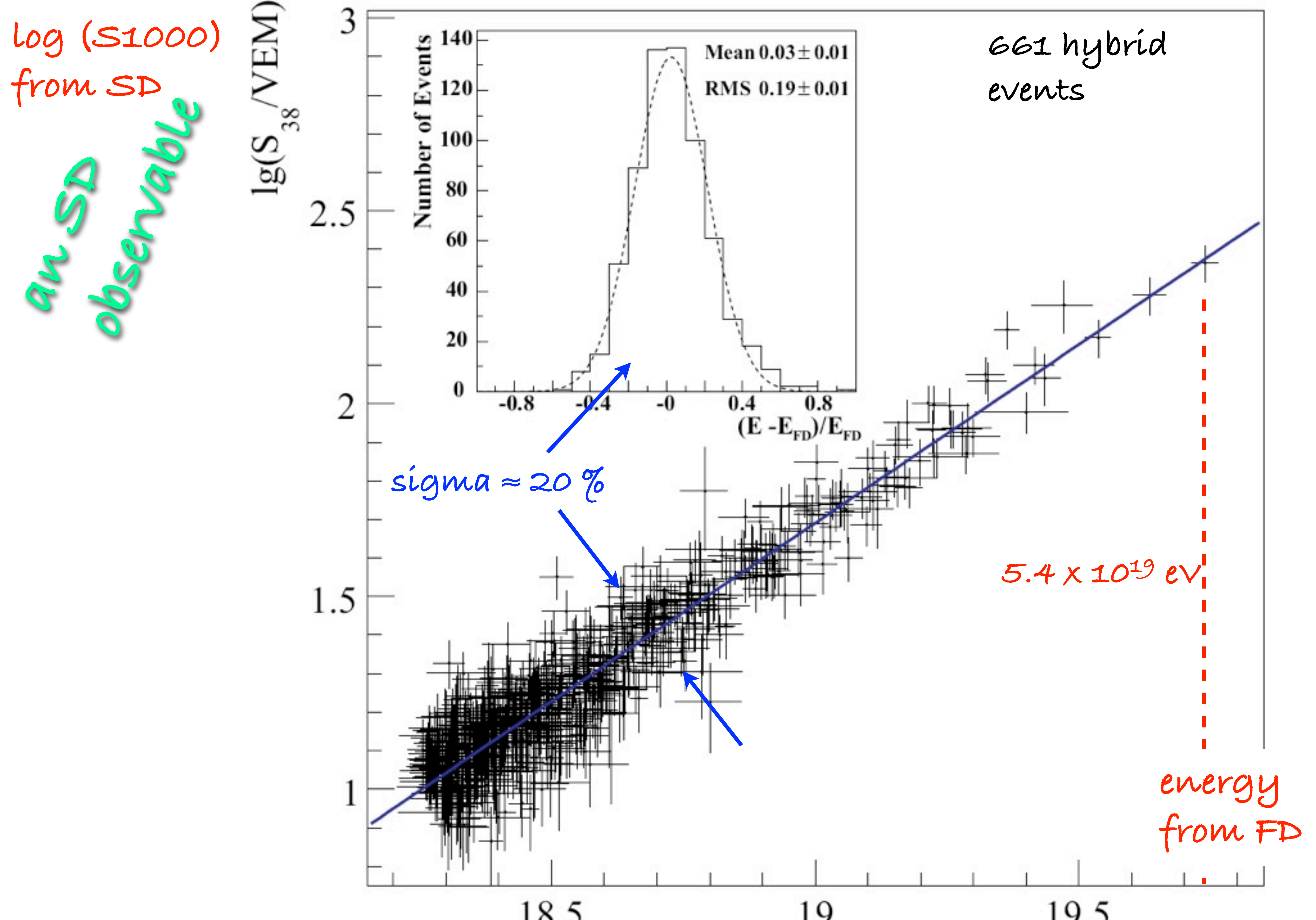
(SD active for 100% of time)

get energy calibration from FD

for high statistics from SD

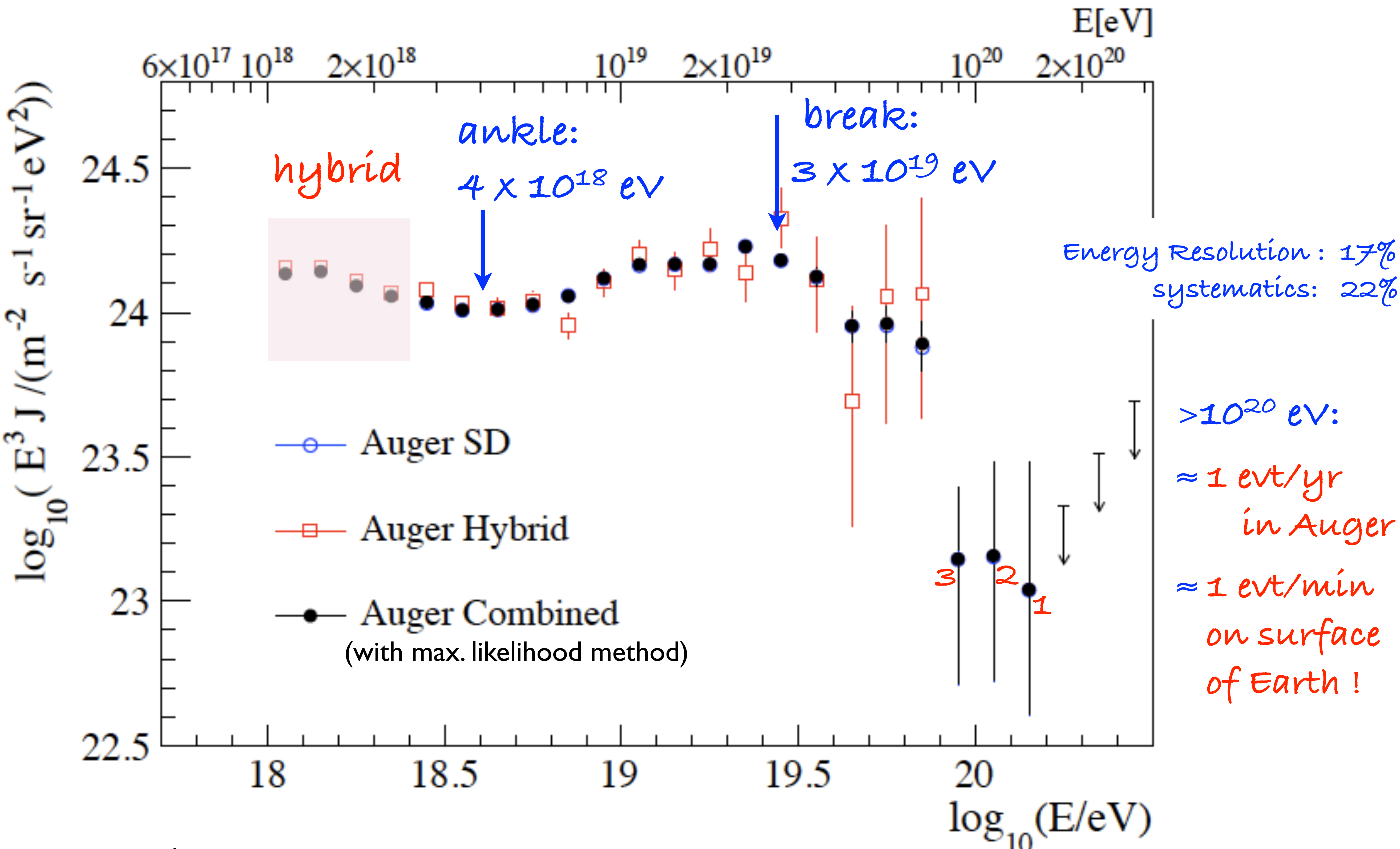
A: directly from size of SD

(above 3×10^{18} eV)



Model independent energy calibration

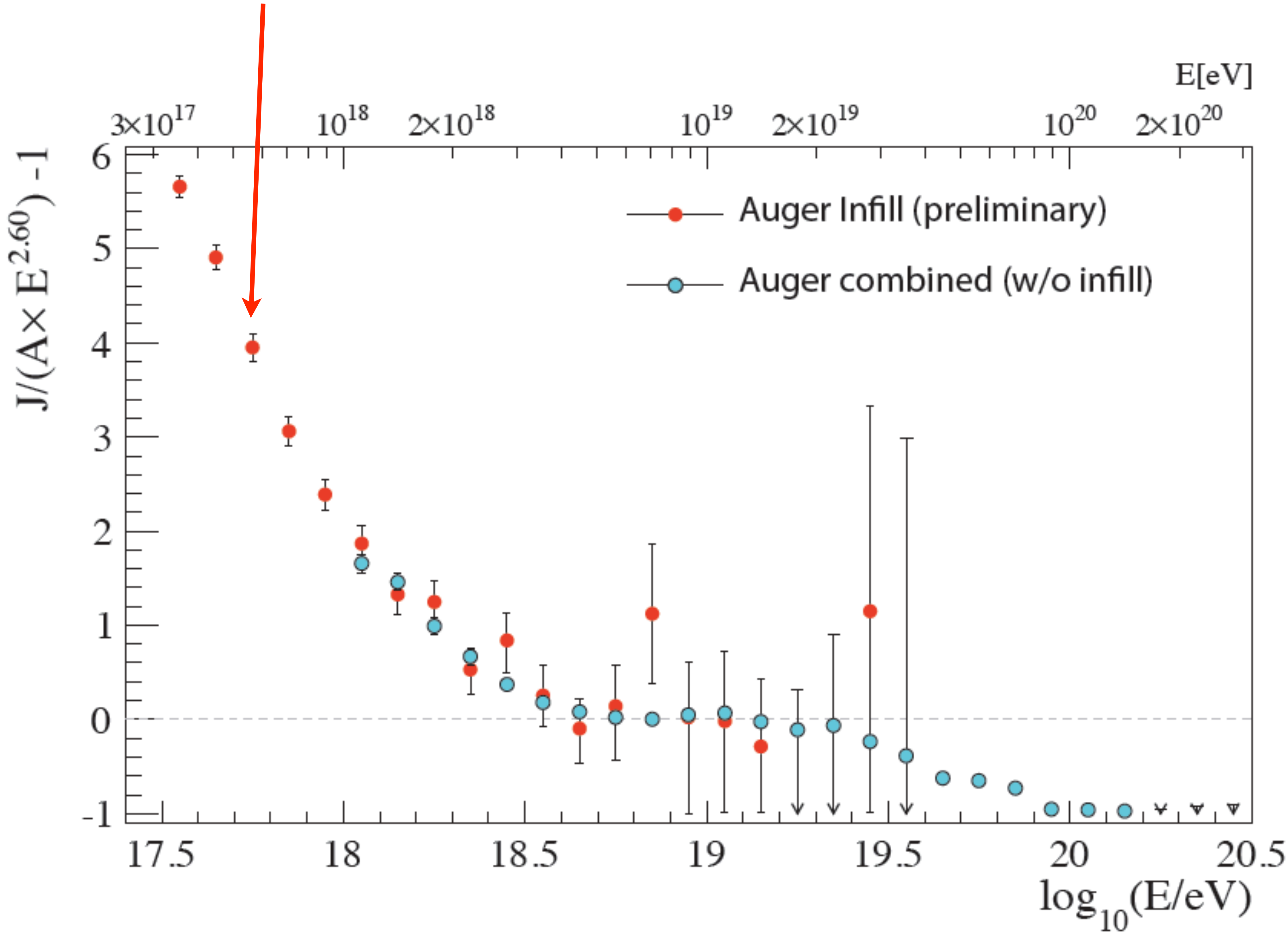
Energy spectrum



$\theta = 0 - 60°$

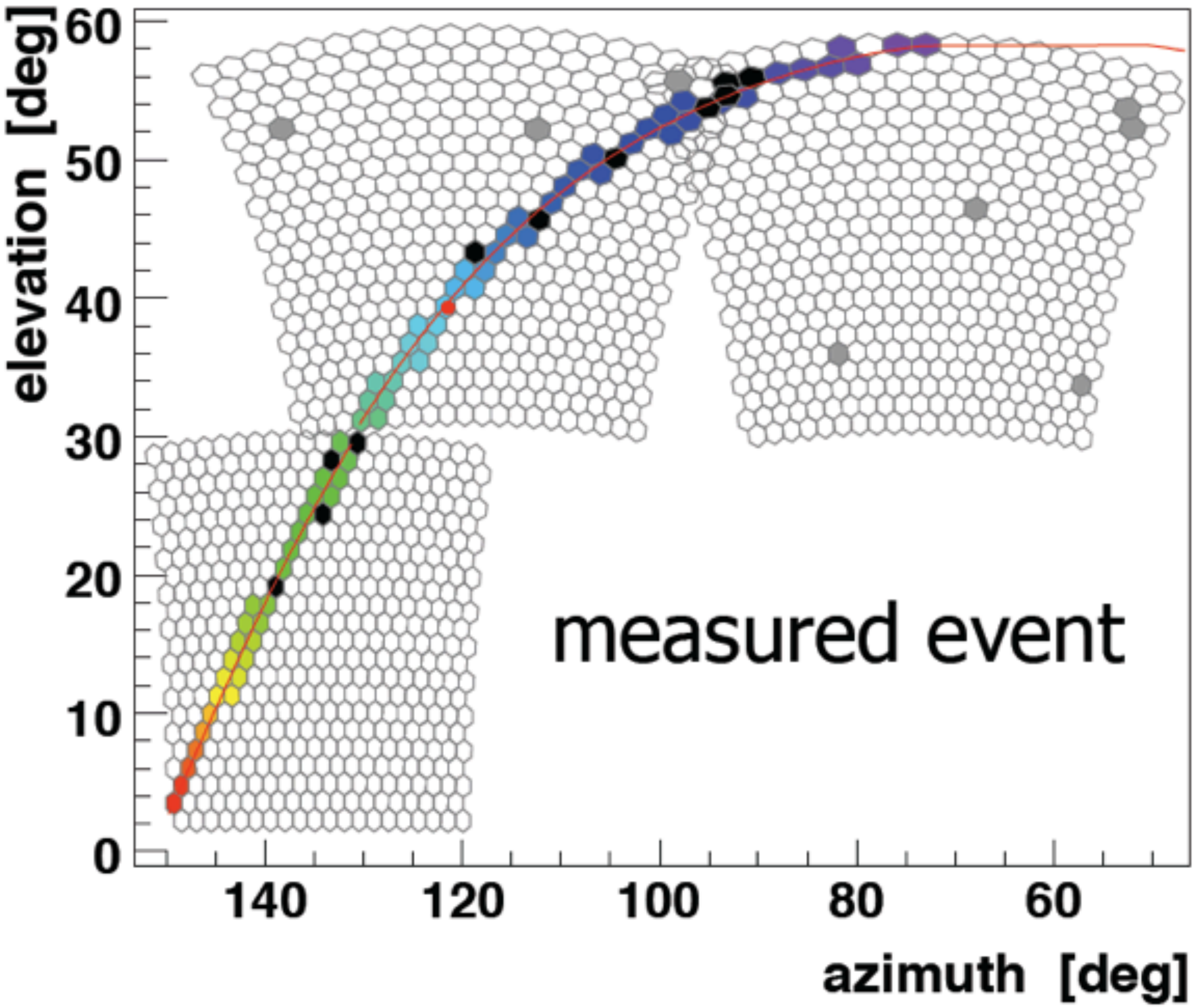
Auger finds "ankle" and a clear (>20 σ) spectral steepening at $E \approx 3 \times 10^{19}$ eV.

Extension to lower energies with the 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 proton rich

Alternatives:

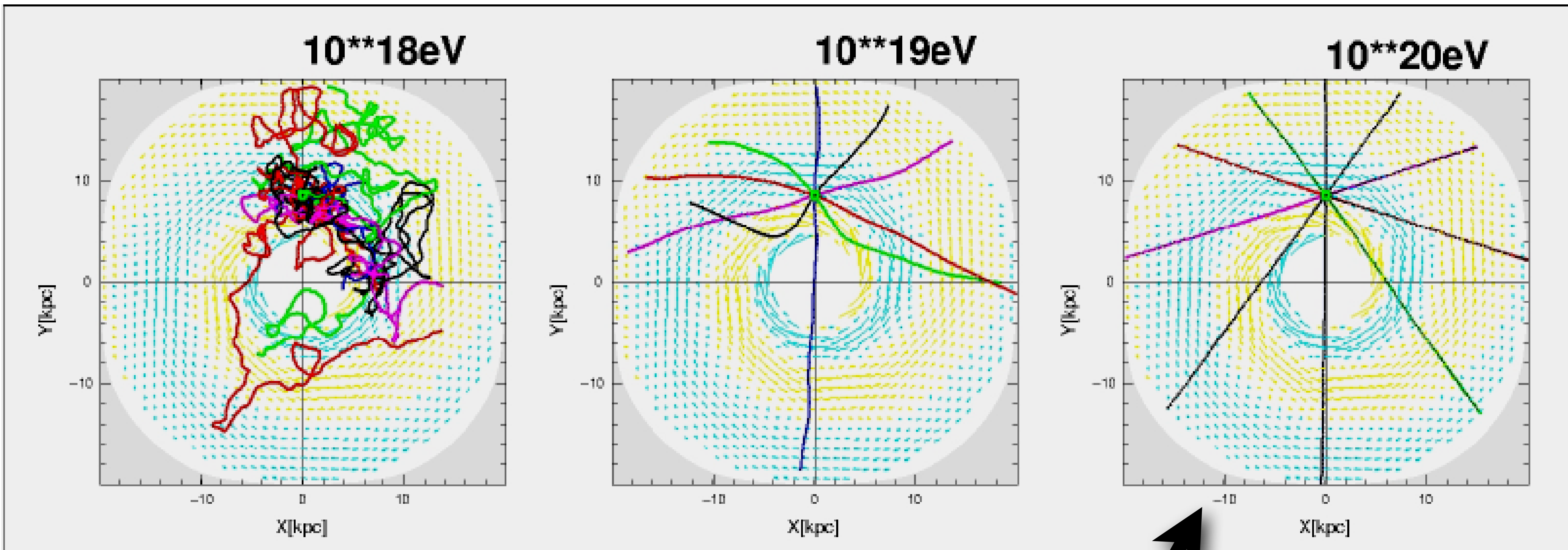
maximum energy of accelerator ?
effect of a local source ?

Is ankle the transition point between galactic and extragalactic CRs ?

... need more info on **composition** ...

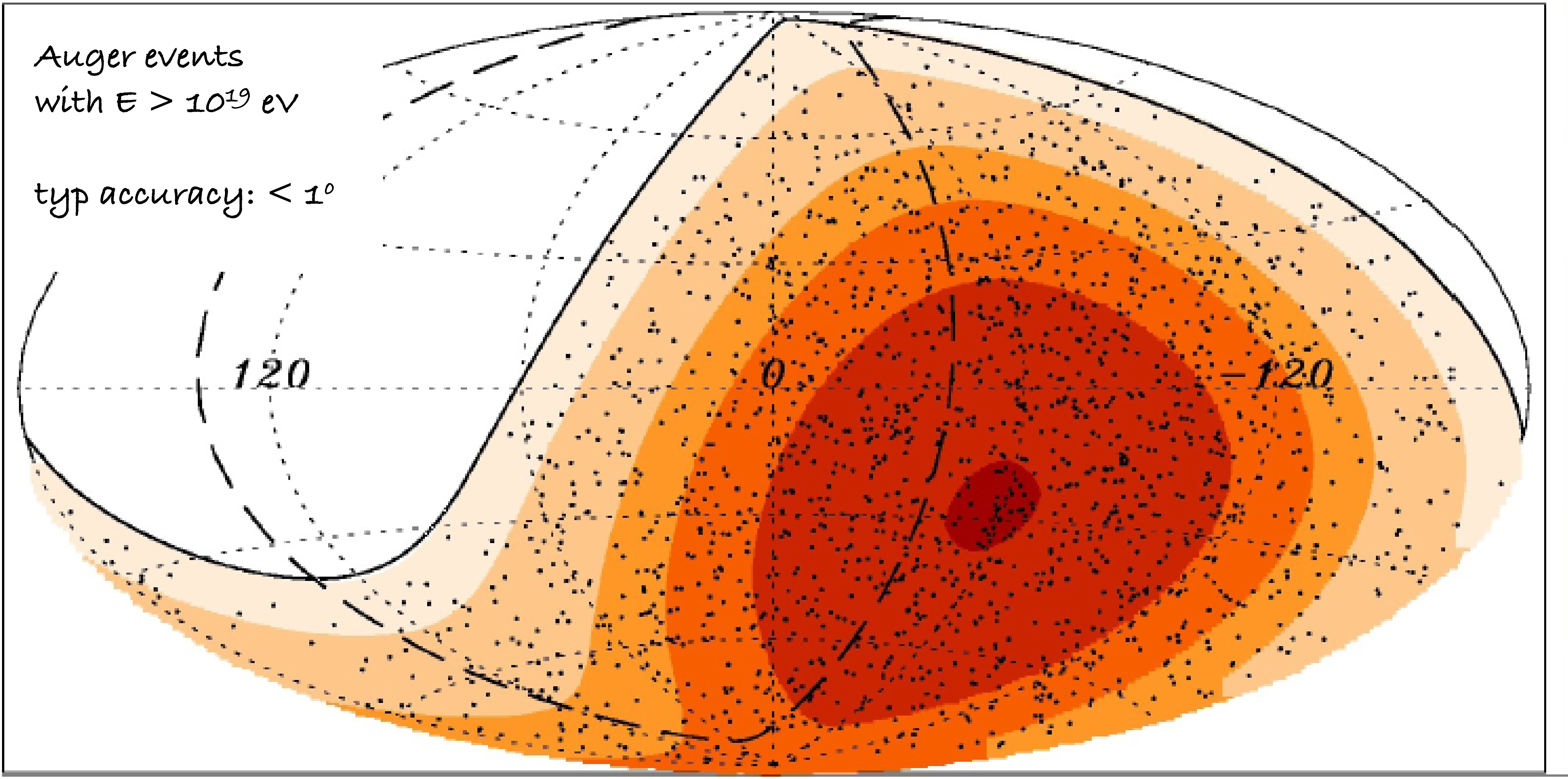
Anisotropy - Sources (?)

Highest Energy Particles are not deflected much !
i.e. CR should start pointing back at sources.



deflection < 1^o

Astronomy with charged particles ?



No enhancement along galactic disk: UHE particles are extragalactic.

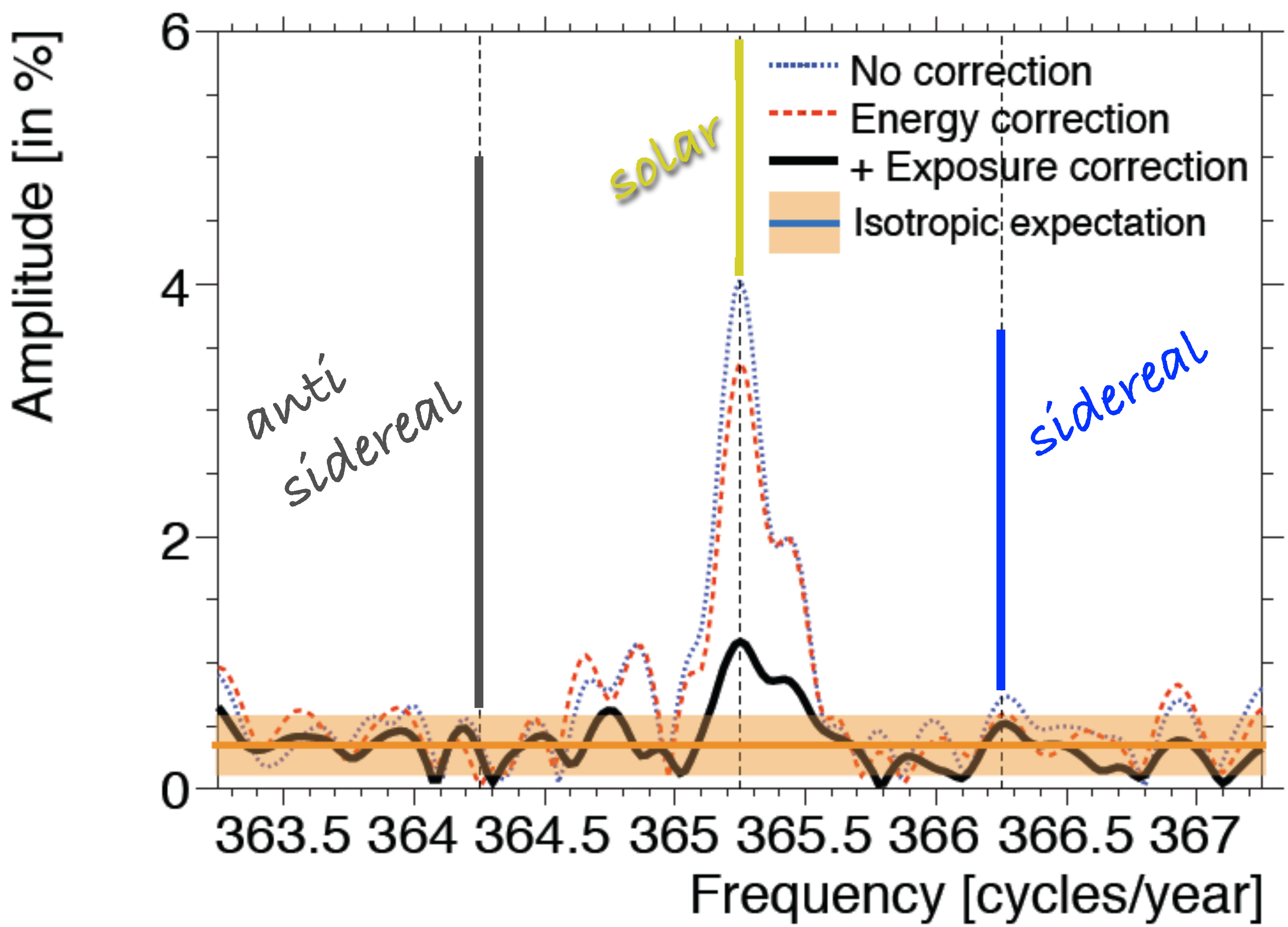
Clusters? Point sources? Large-scale anisotropies? Correlations with source populations?

Large-Scale anisotropy :

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

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

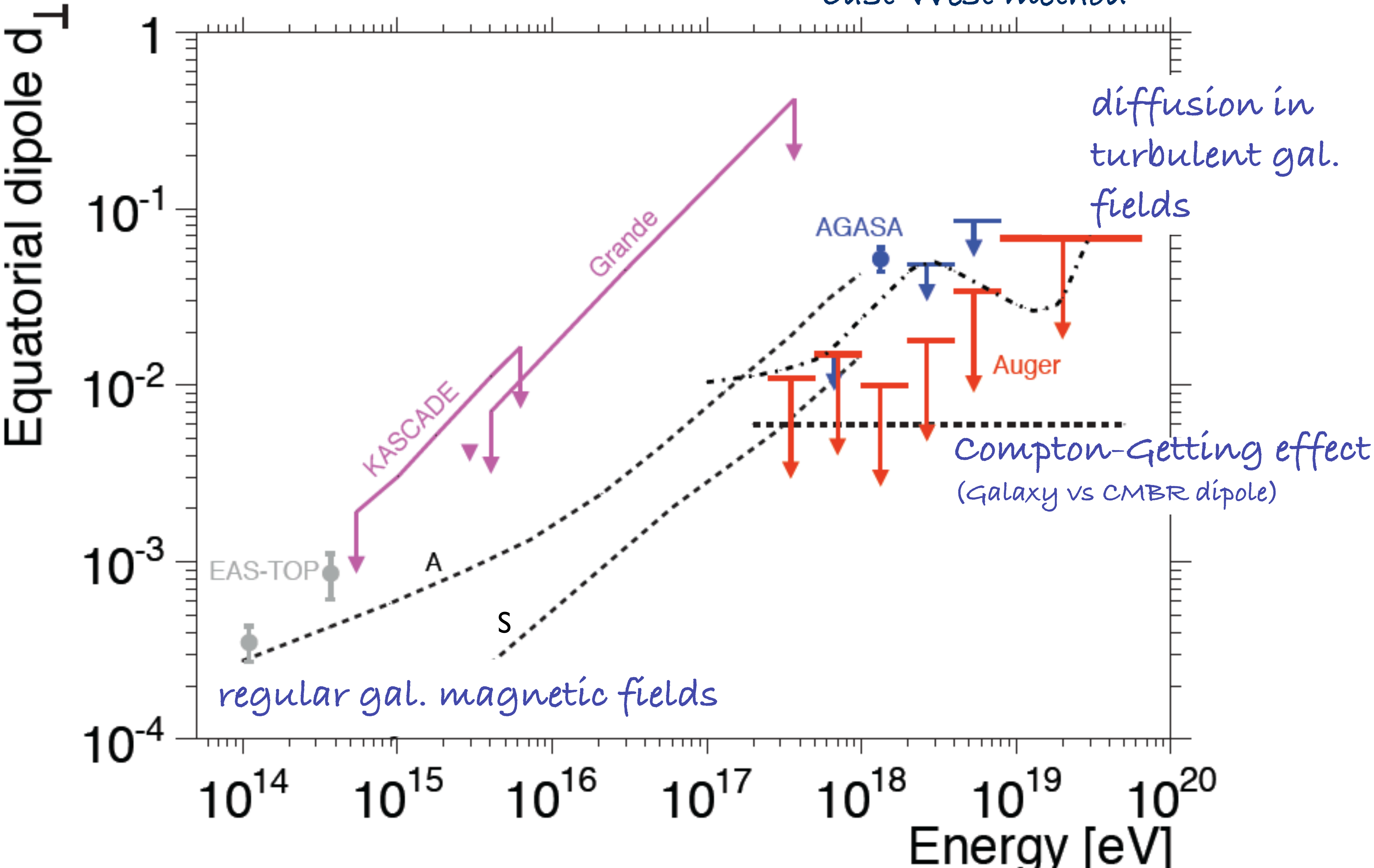
both erase - non-uniformity in acceptance and
- weather effects

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

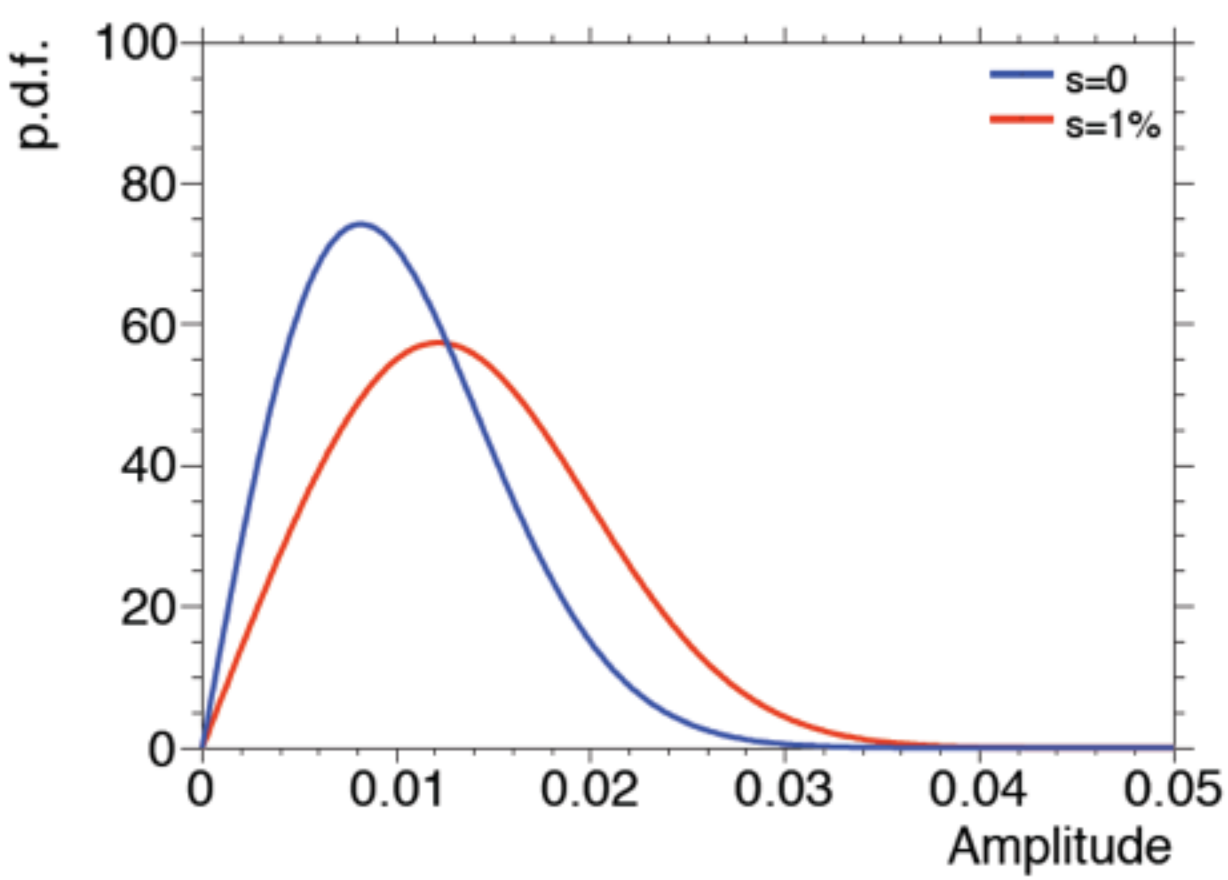


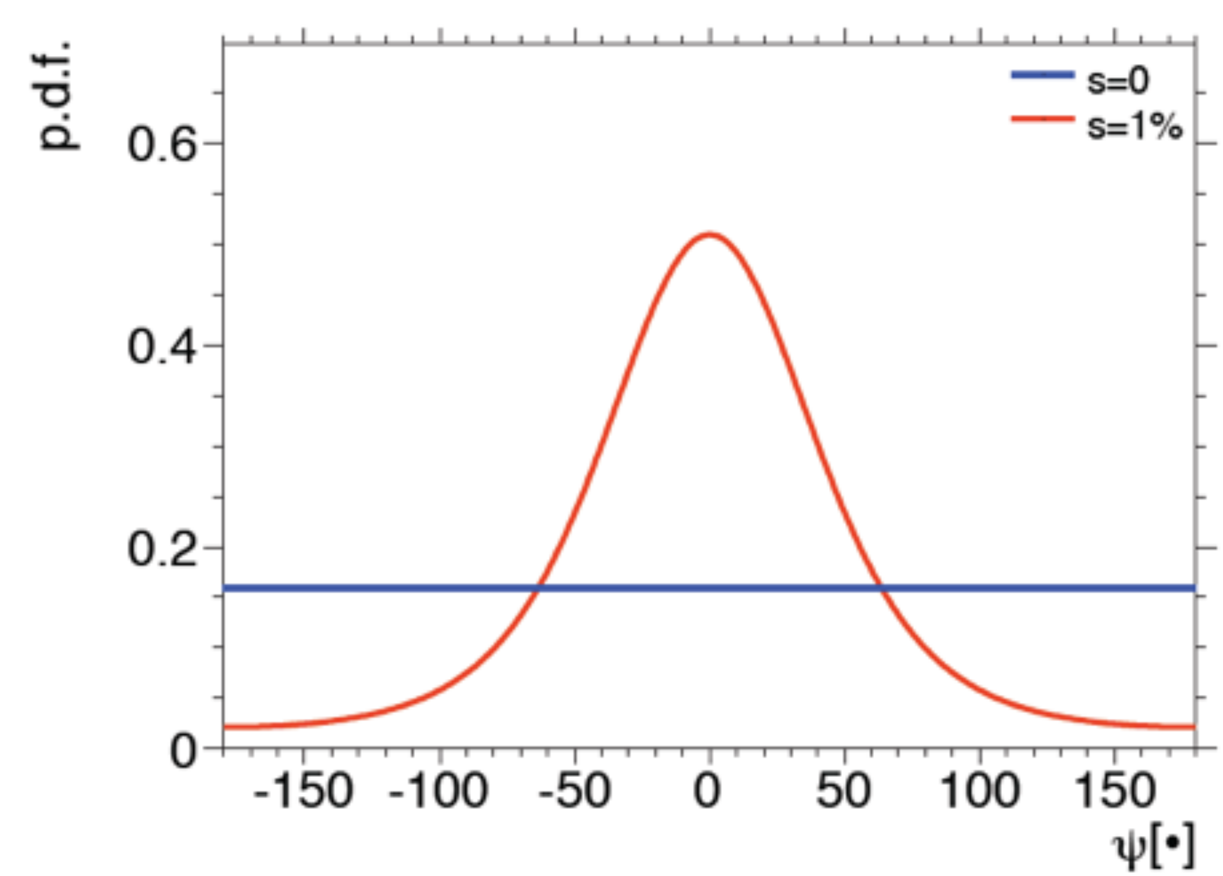
Limits close to / lower than some predicted anisotropies.
More data will give an anisotropy signal or model constraints.

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)

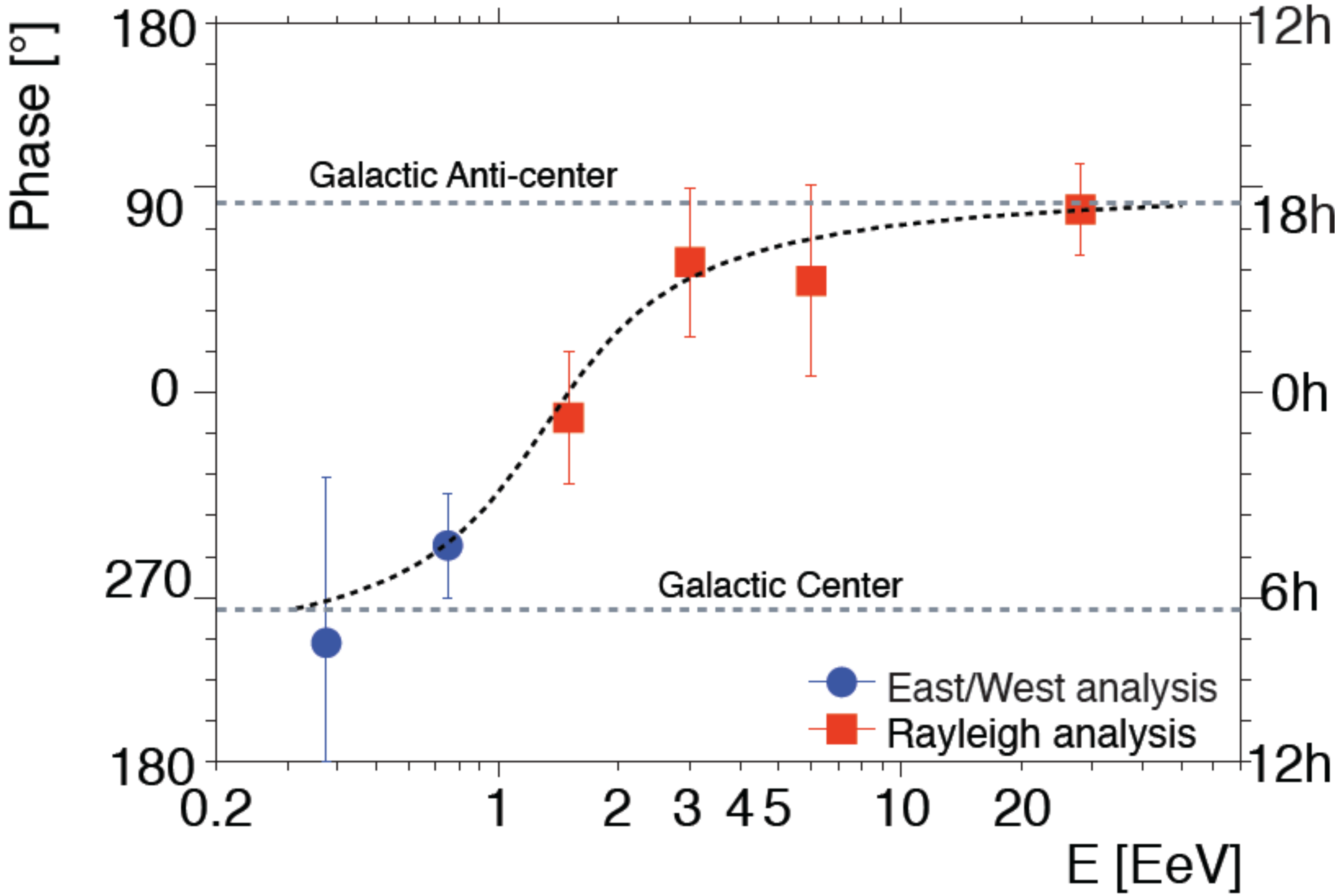




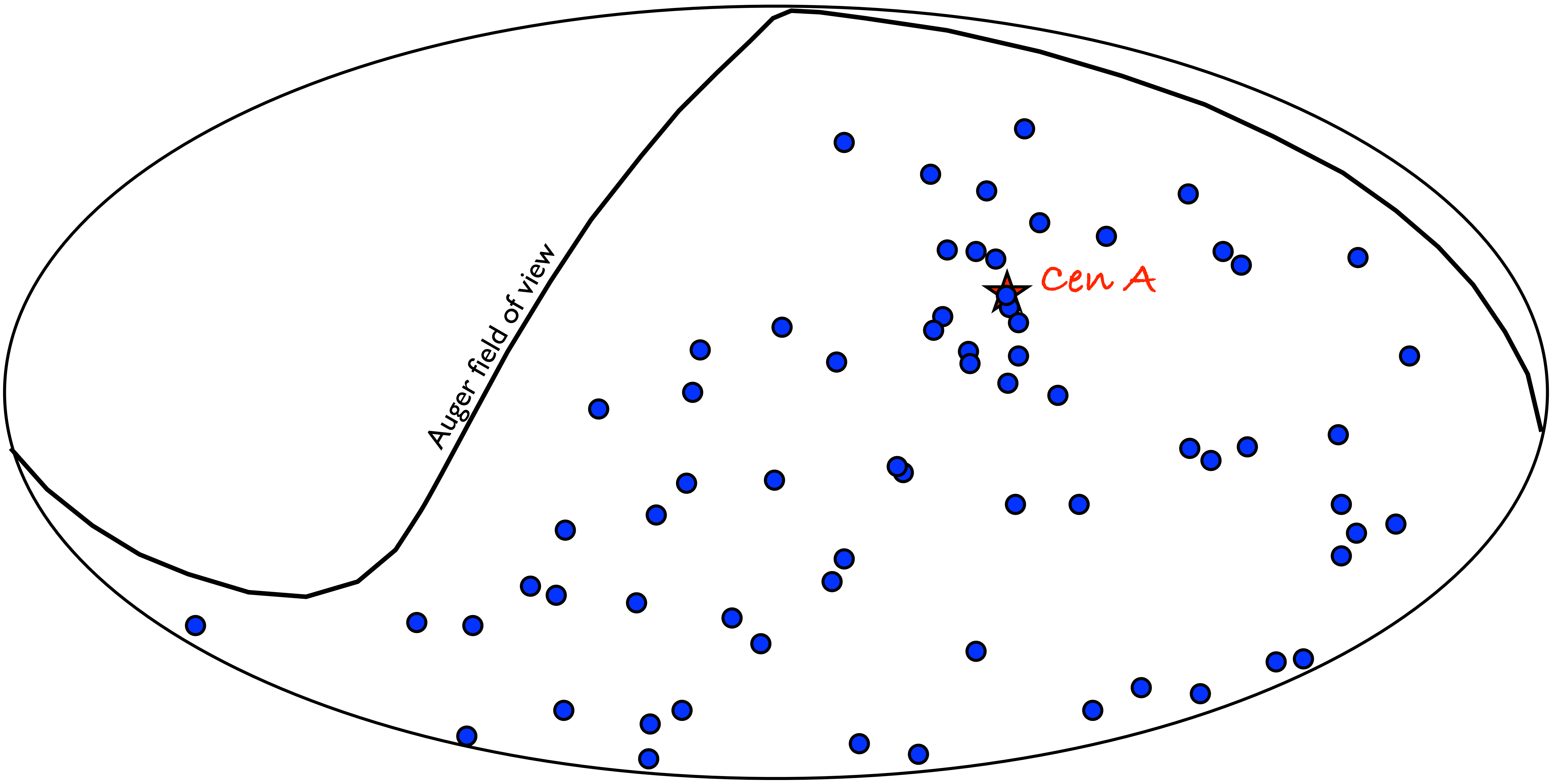
Phase is ≈2.5 x more sensitive than amplitude.

Smooth transition in RA from 270° to 90°

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



69 Highest Energy Events >55 EeV (Dec 2009)

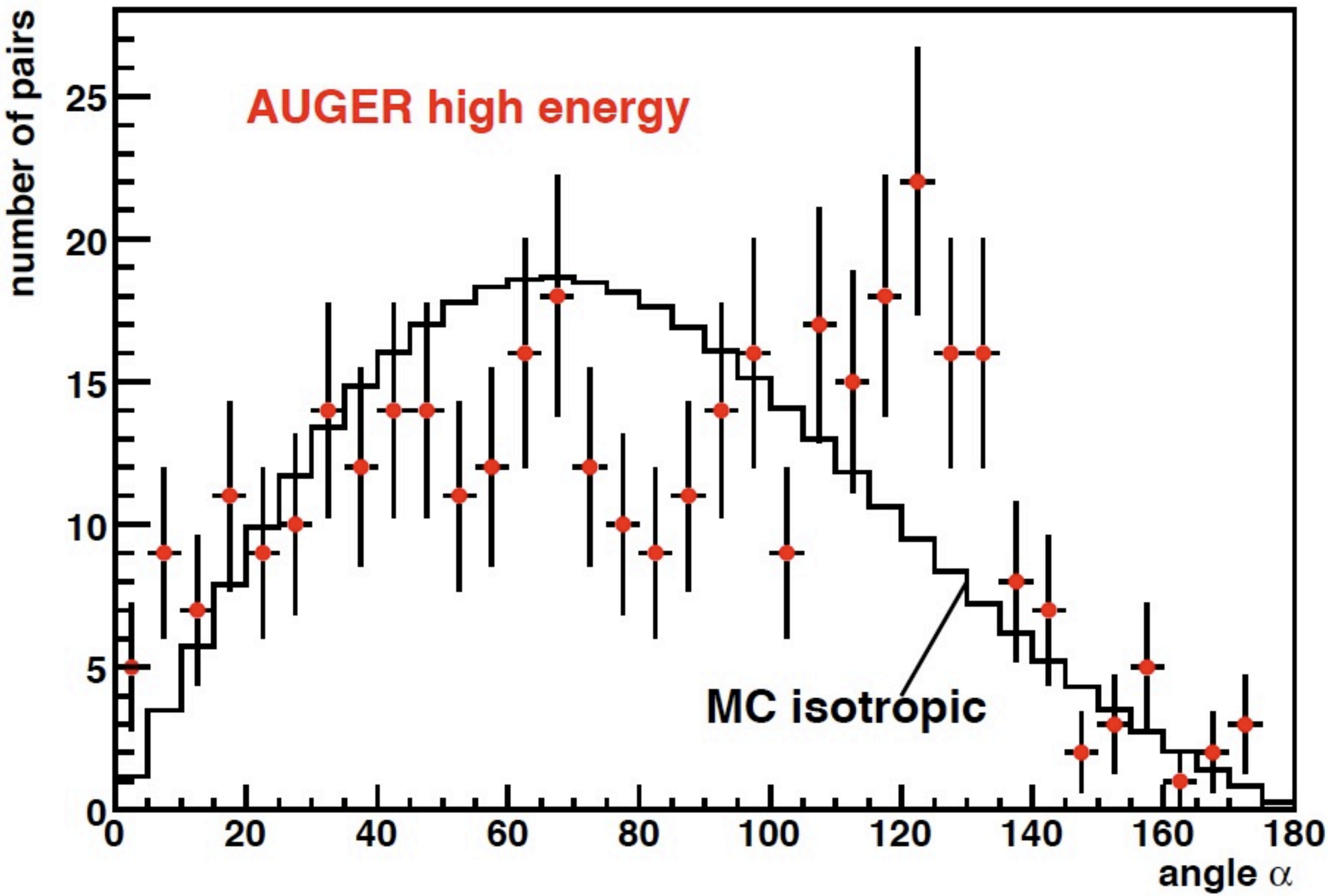


Isotropic ? Clustering ? Is Cen A a source ? ...

How to quantify ?

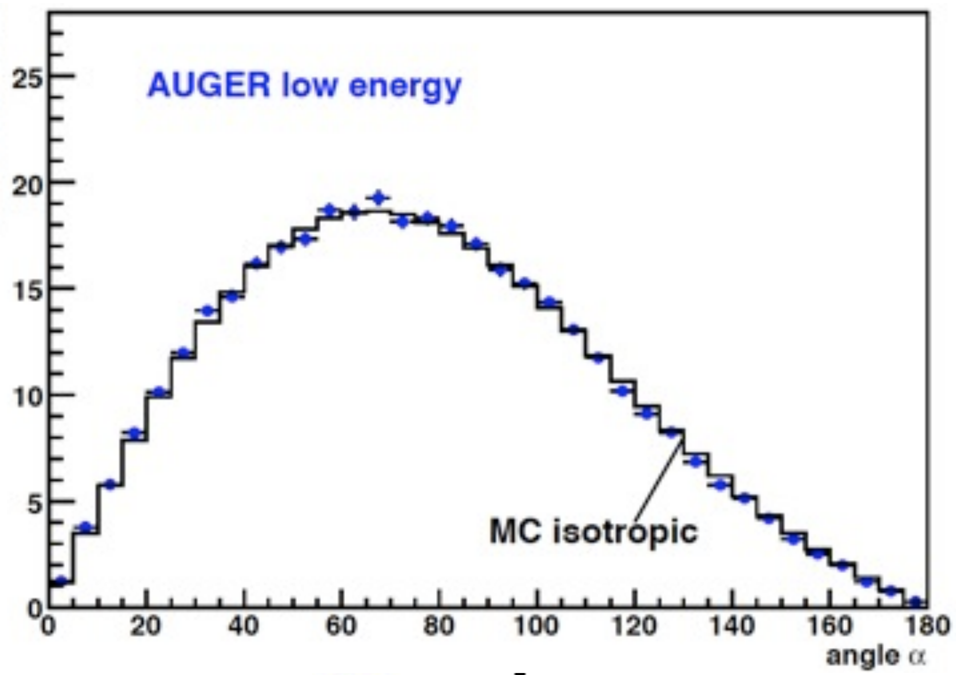
No enhancement from galactic disk. Extragalactic origin!

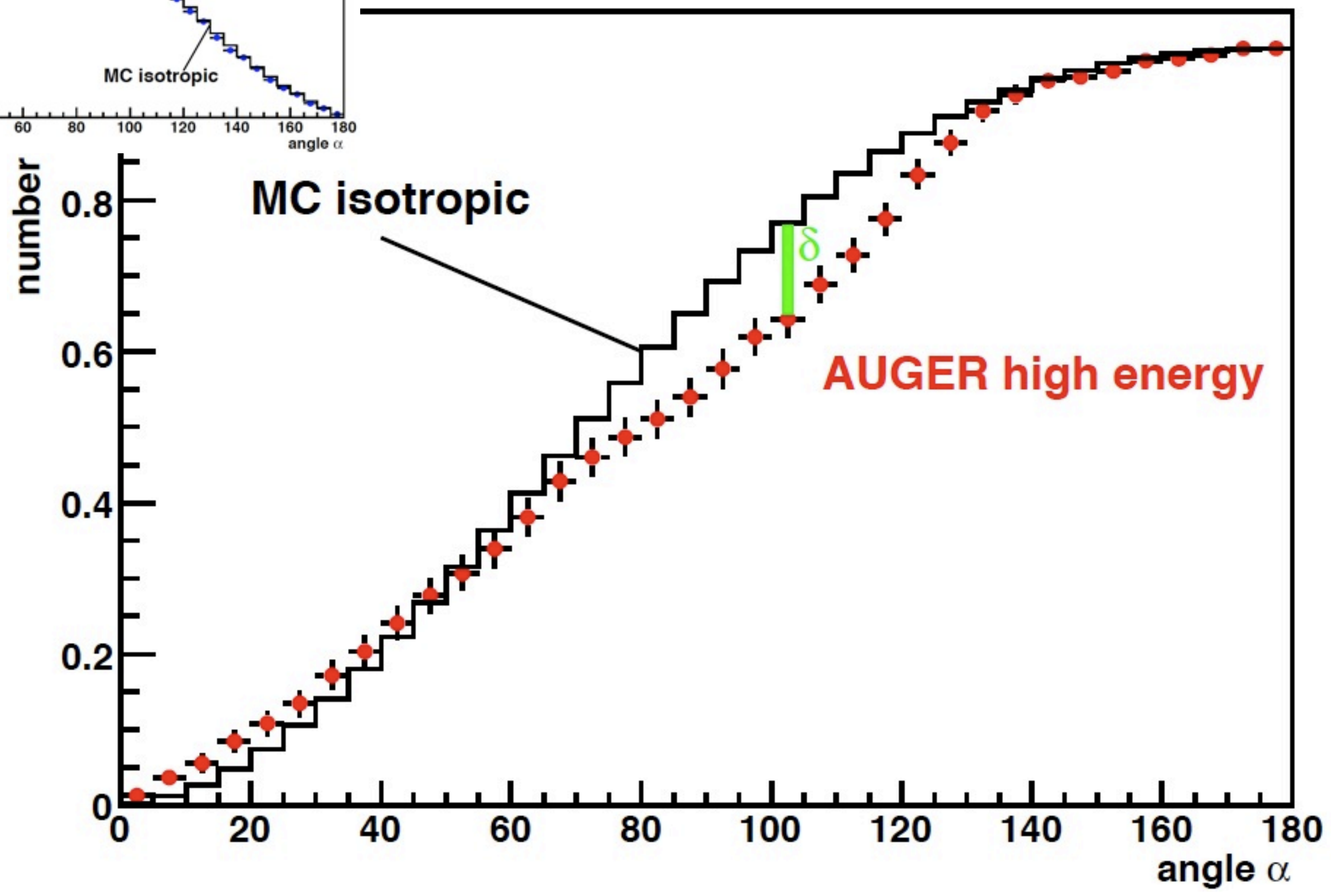
2-point correlation function



Kolmogorov-Smirnov Test

(chance probability ≈ 0.5%)



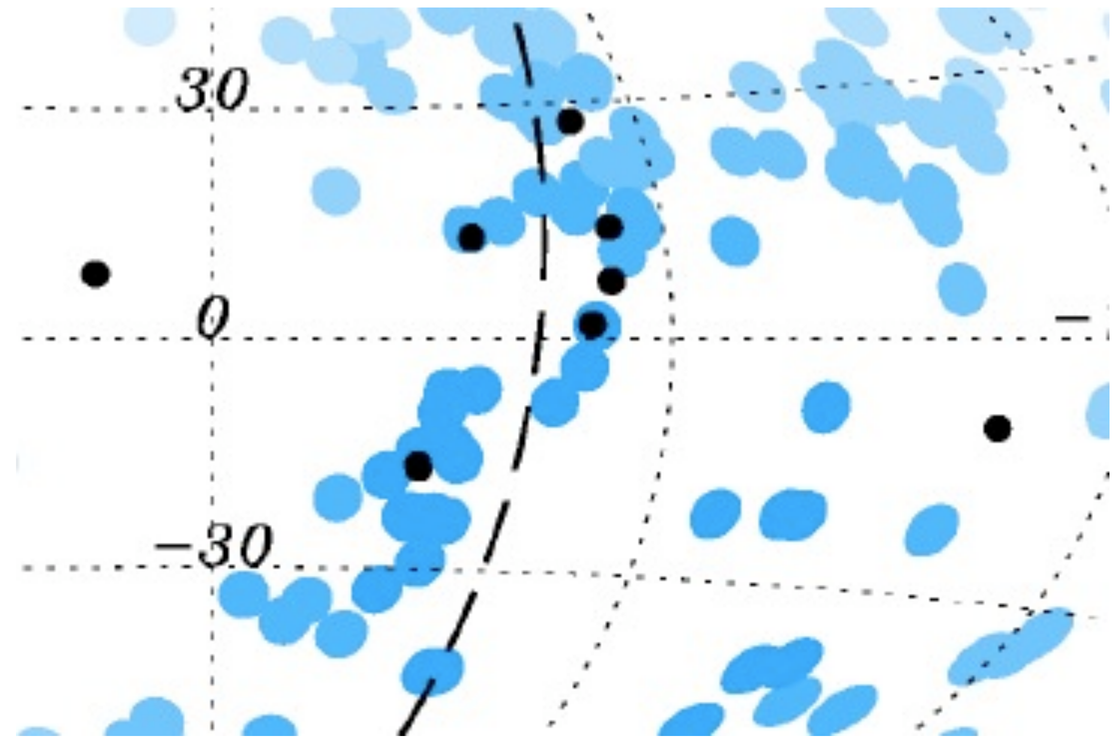


Correlation of CRs with source population :

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

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

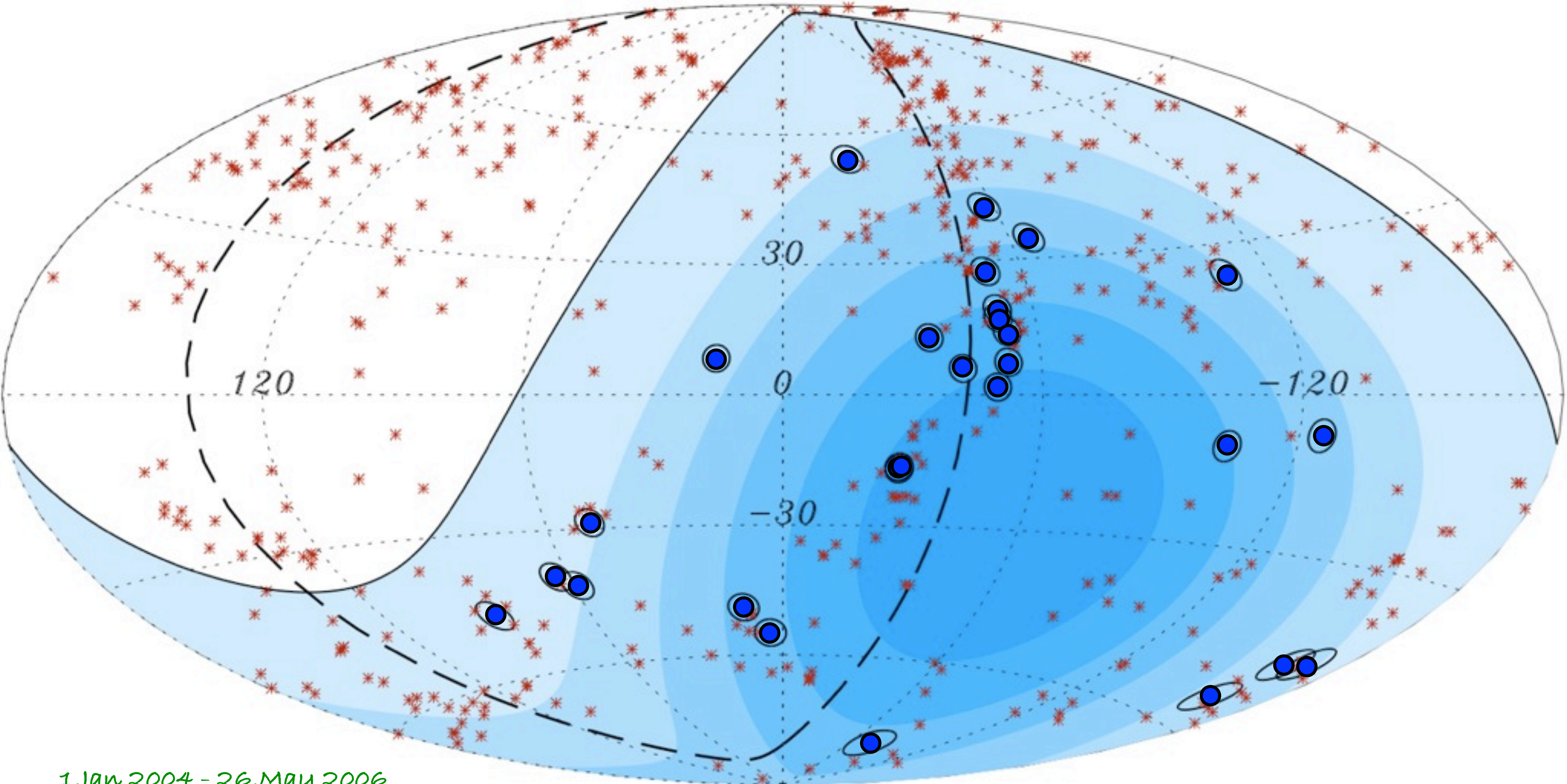
$p \approx 0.21$

AGN 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

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

$p \approx 0.21$



1.Jan 2004 - 26.May 2006

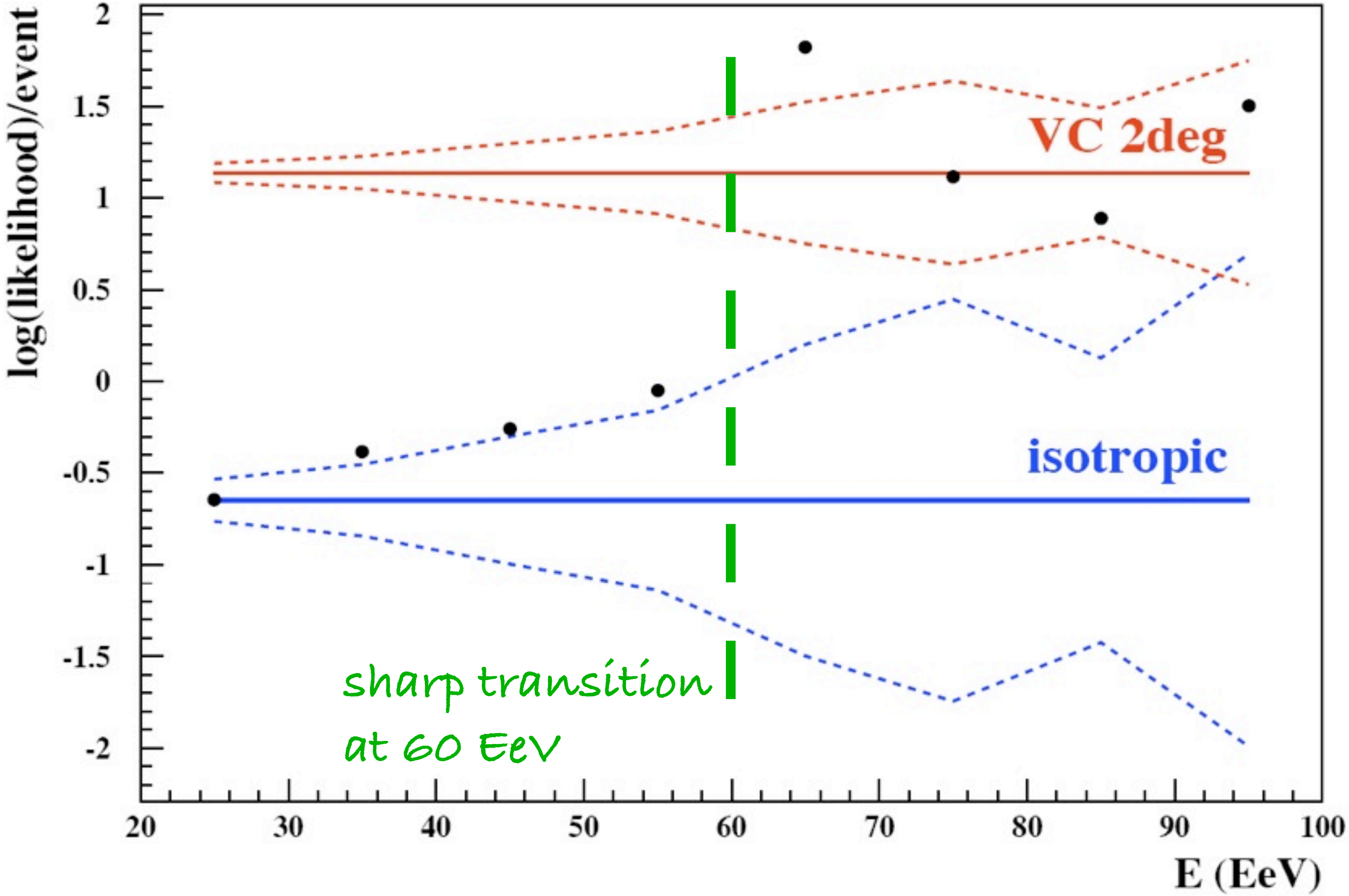
scan: 15 evts, 12 correlate with AGN (3.2 exp.) for R<3.1°, z < 0.018, E > 56 EeV

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.



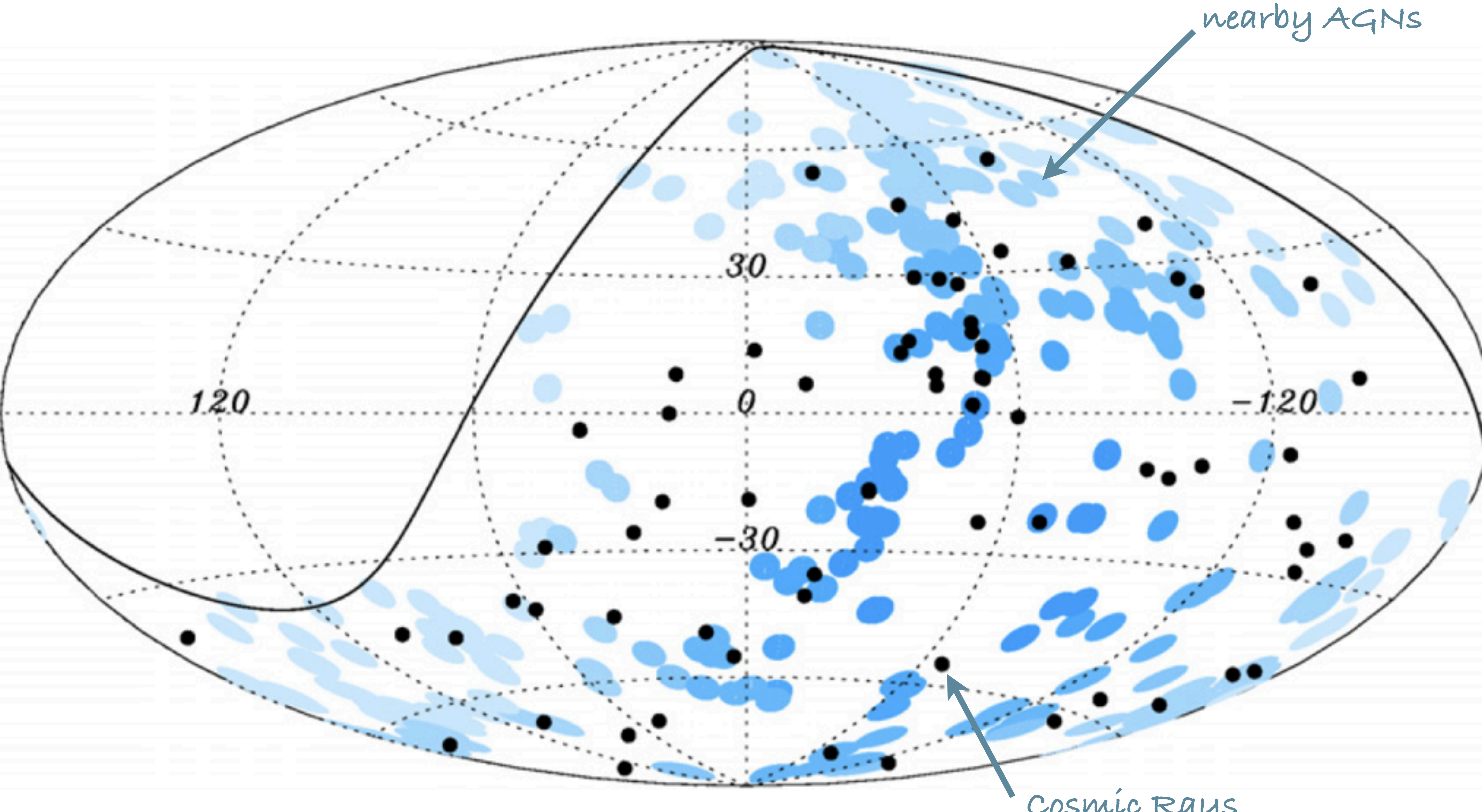
draw random events maps from isotropic dist.
VC catalog

and compare with smoothed VC (d<100 Mpc)

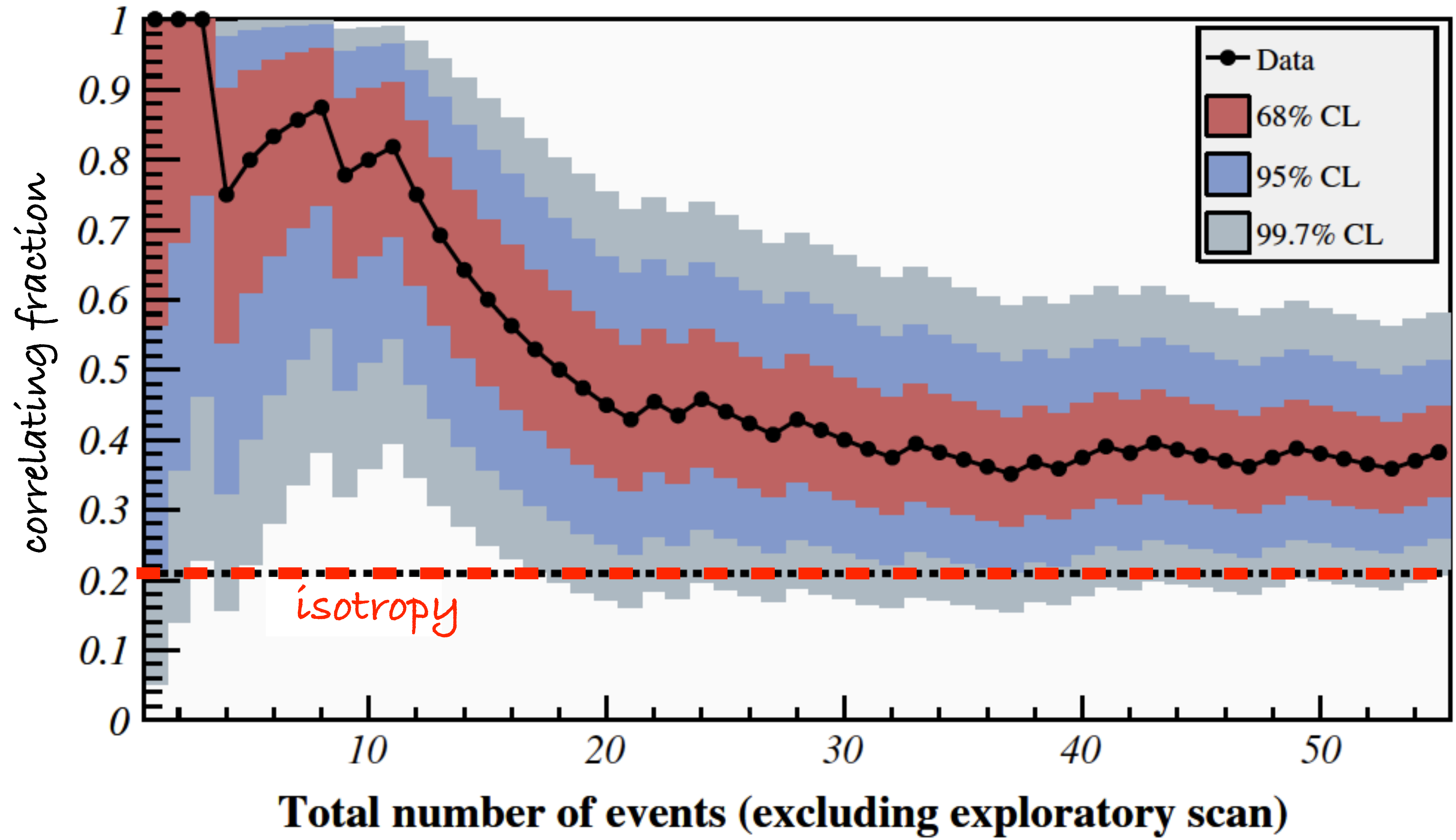
Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects

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

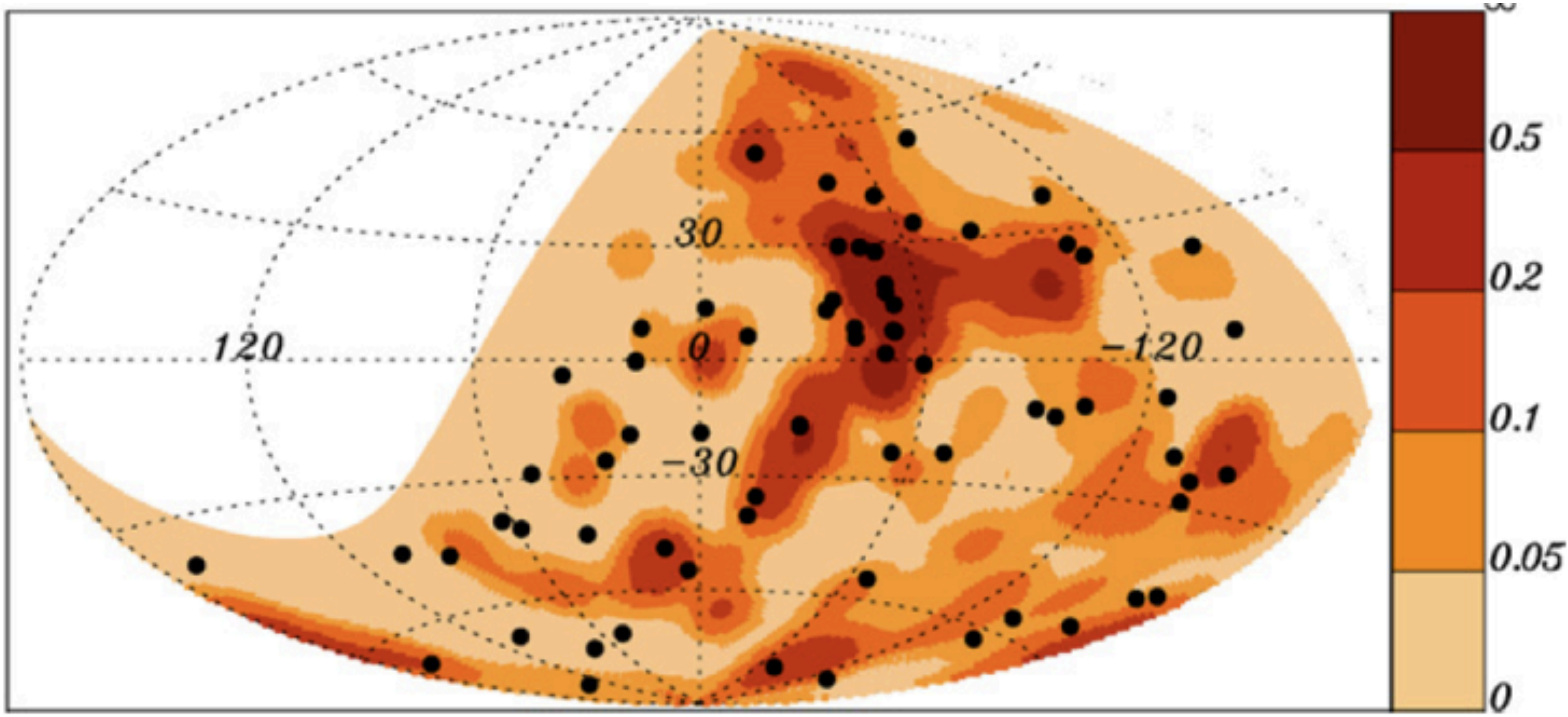
current signal: $p = 0.38^{+0.07}_{-0.06}$

chance probability for isotropic distribution to give this result: 0.006

Swift-BAT

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

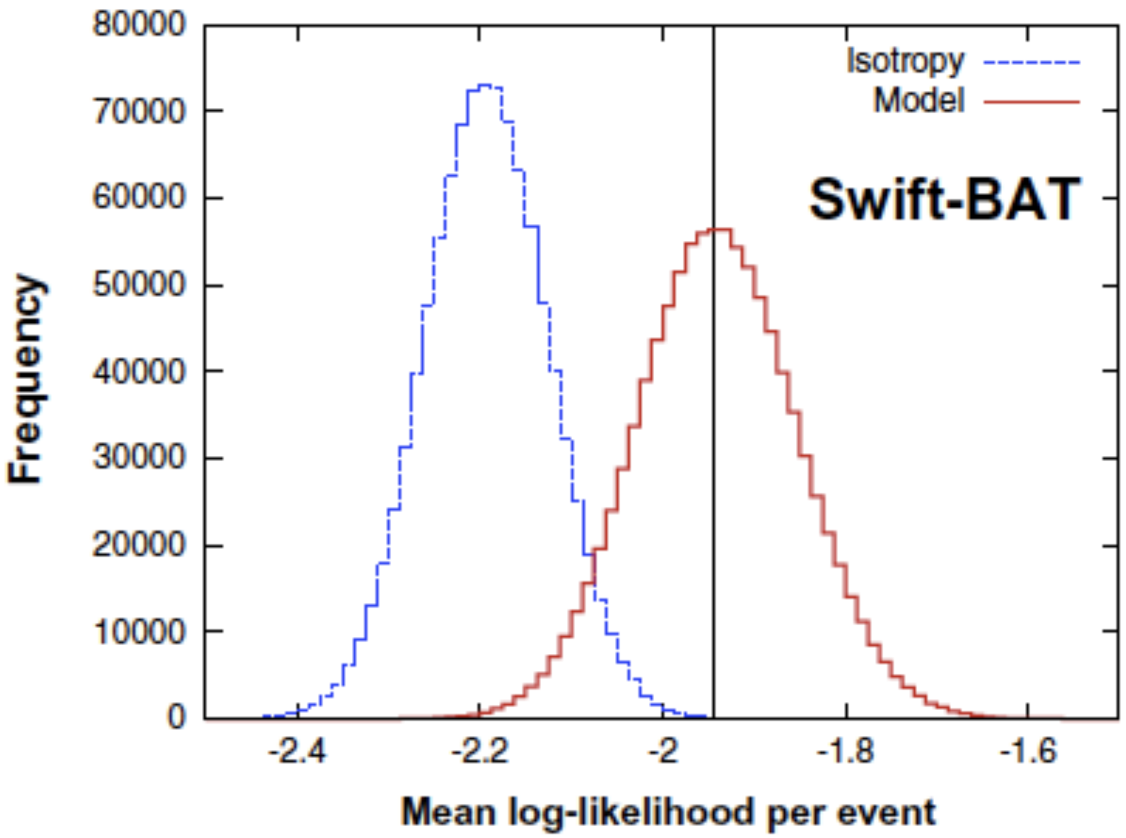
d < 200 Mpc
weighted with X-ray flux,
rel. exposure, GZK effect
5° smoothing



UHE Cosmic rays are
– not isotropic
– of extra-galactic origin.

UHECRs come from
"nearby extragalactic matter"

$\approx 30^{\circ}$ clustering (protons ?)



data
isotropy
model

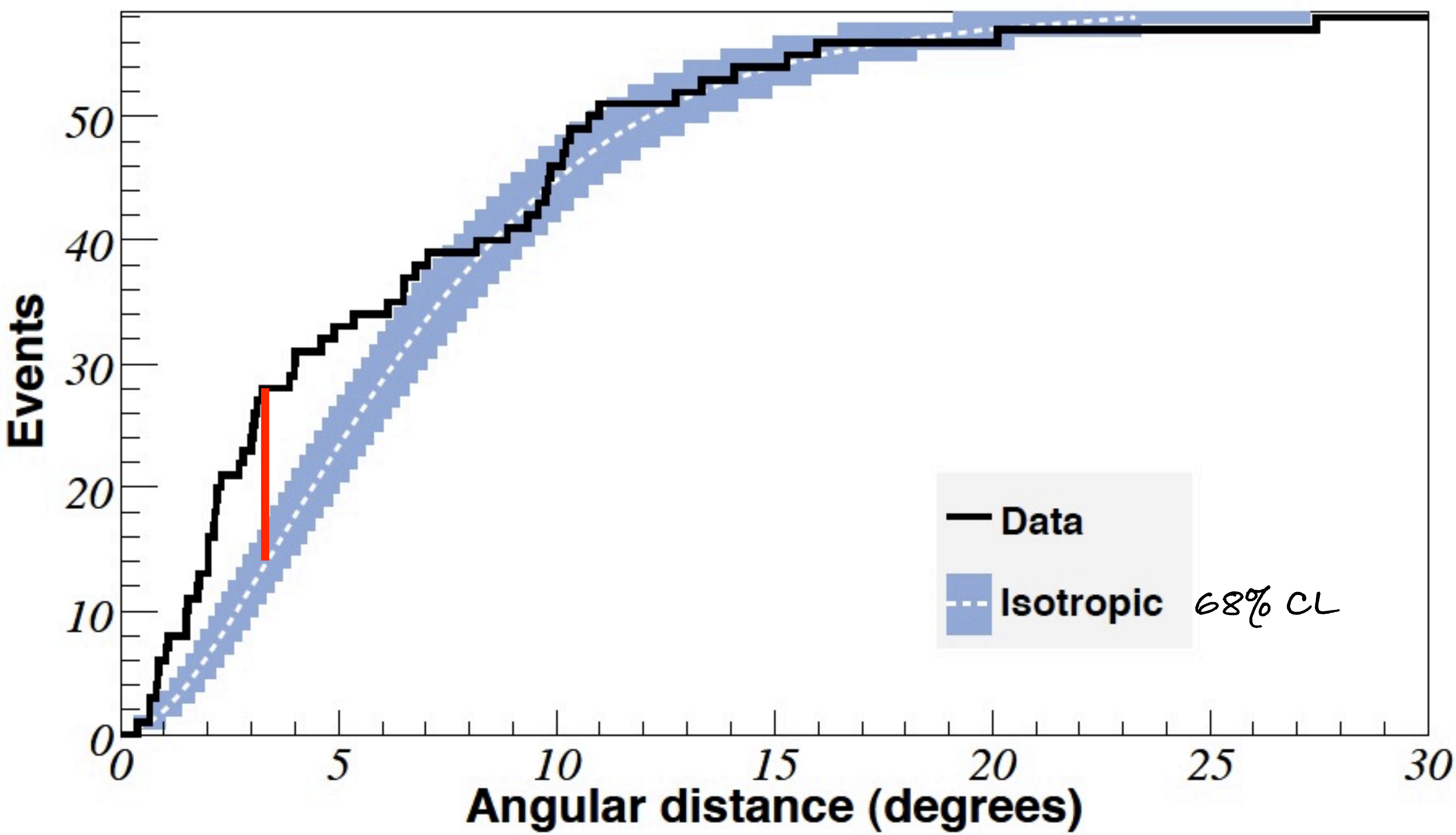
This result is suggestive of

primary protons and a GZK cut-off:

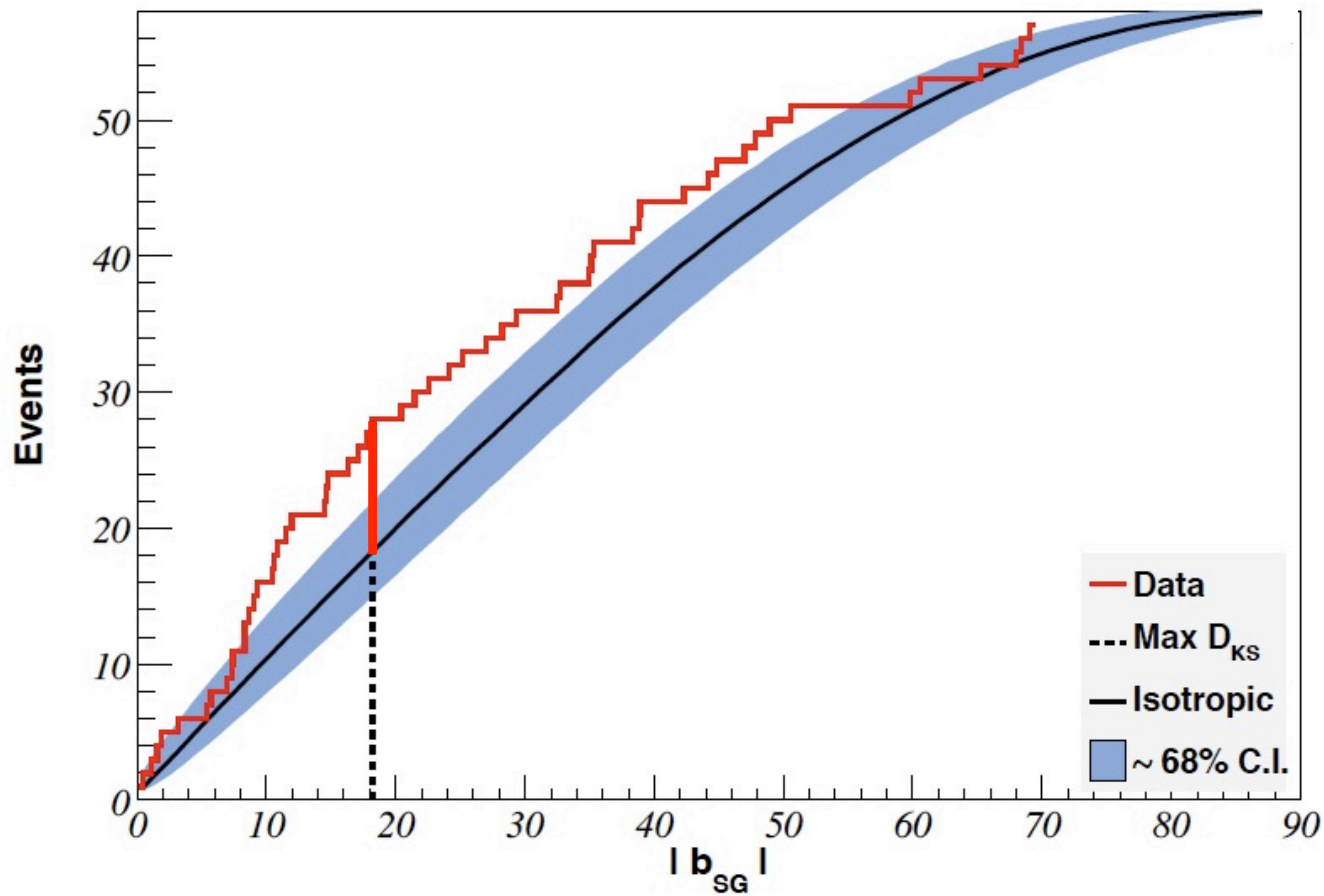
deflection in gal. mag. fields @ 60 EeV: small for protons
big for Iron

correlation only with nearby AGNs

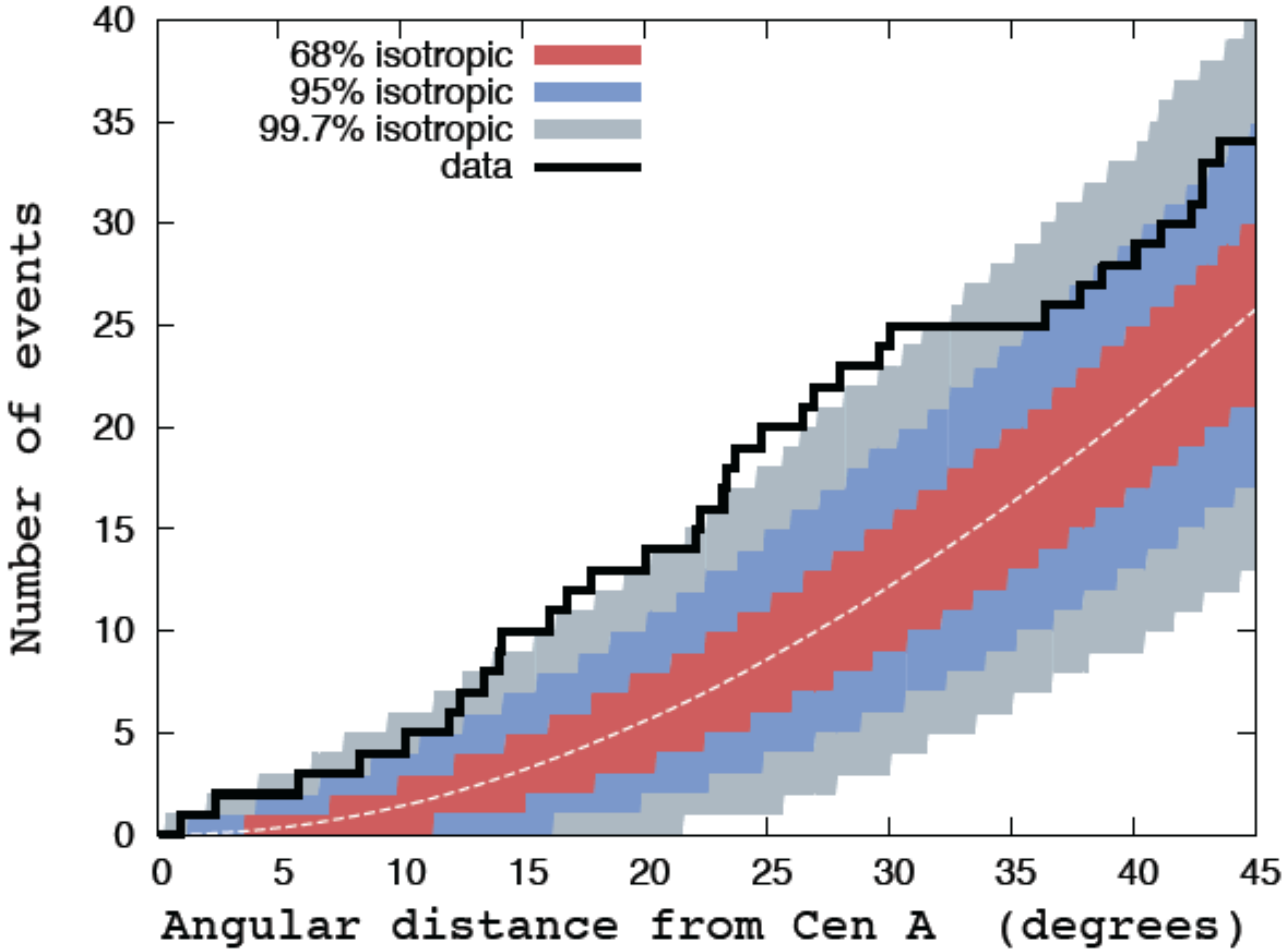
Distance: CR - nearest AGN (z<0.018)



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 ?

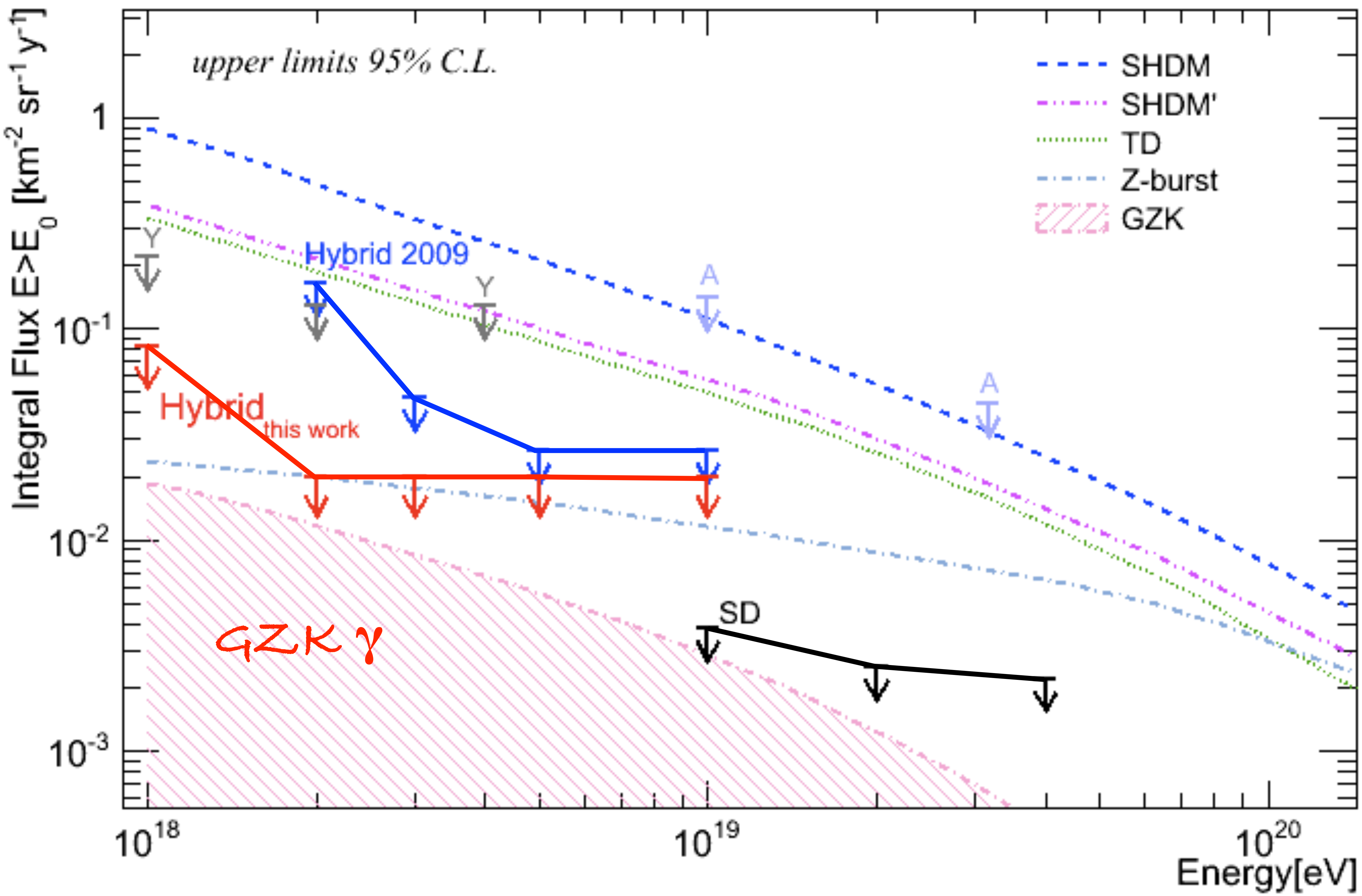
showers do start near top of atmosphere

neutrons ?

from nearby galactic neighbourhood

so far no evidence

Photon limits



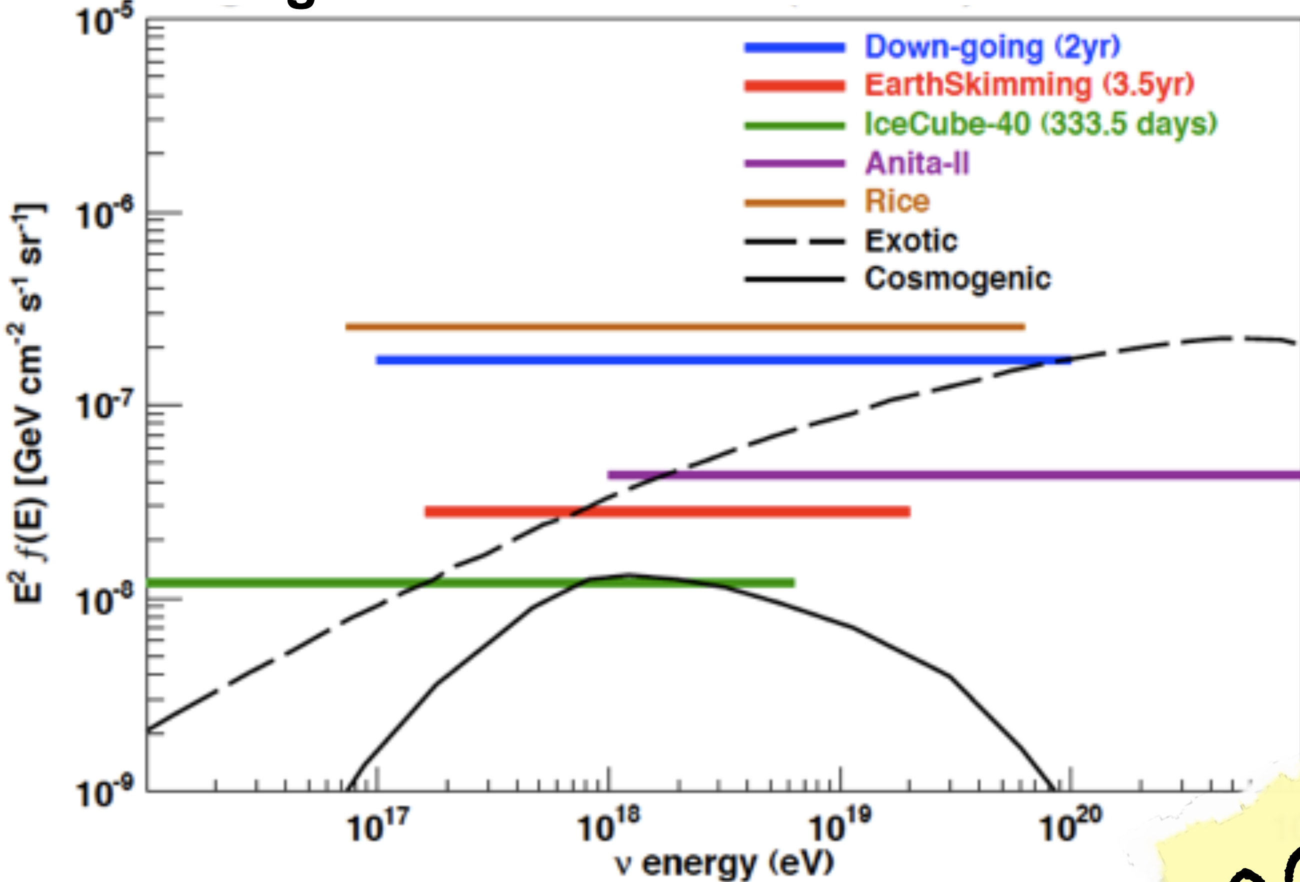
improved limits at lower energies,

approaching the region where GZK γ are expected.

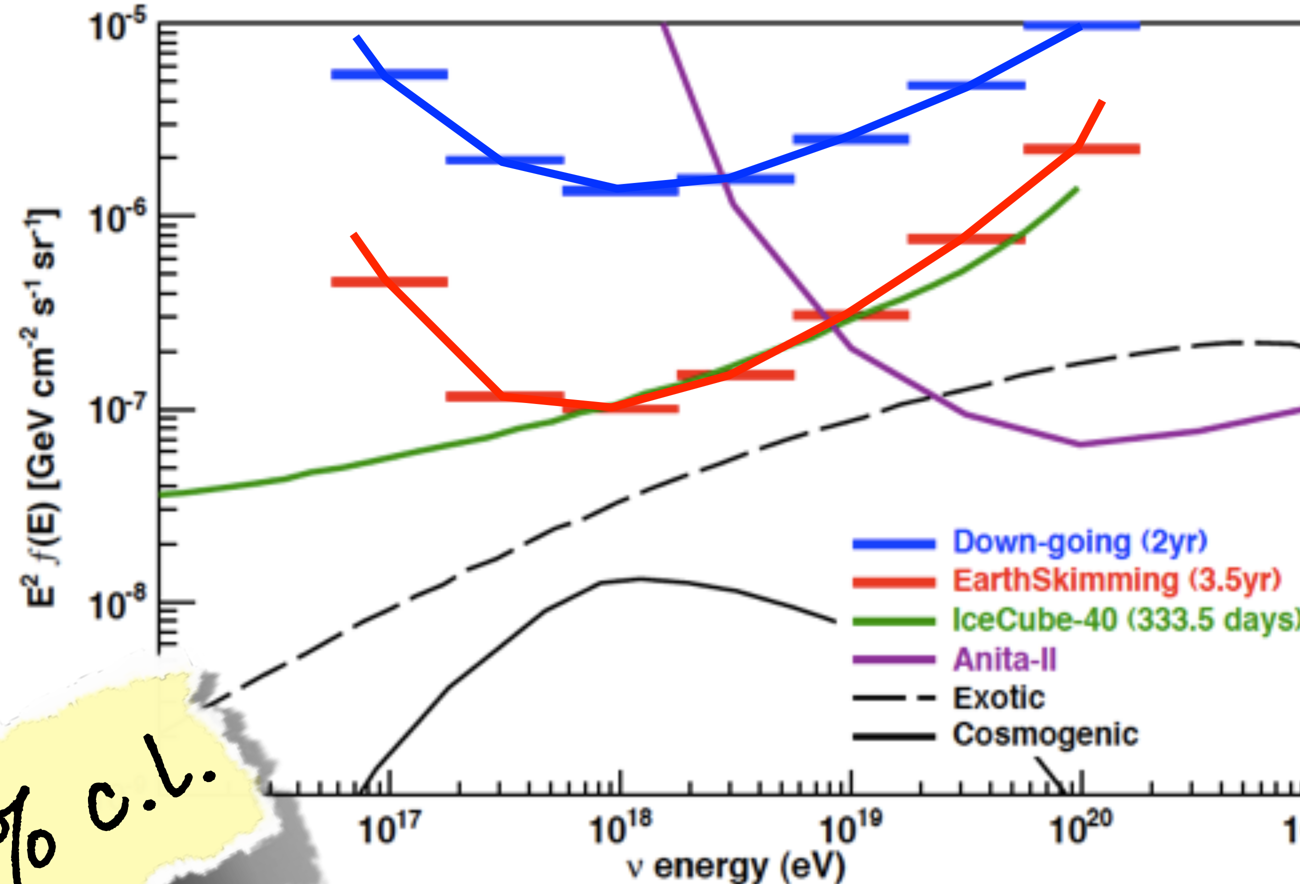
ν limits

90% c.l.

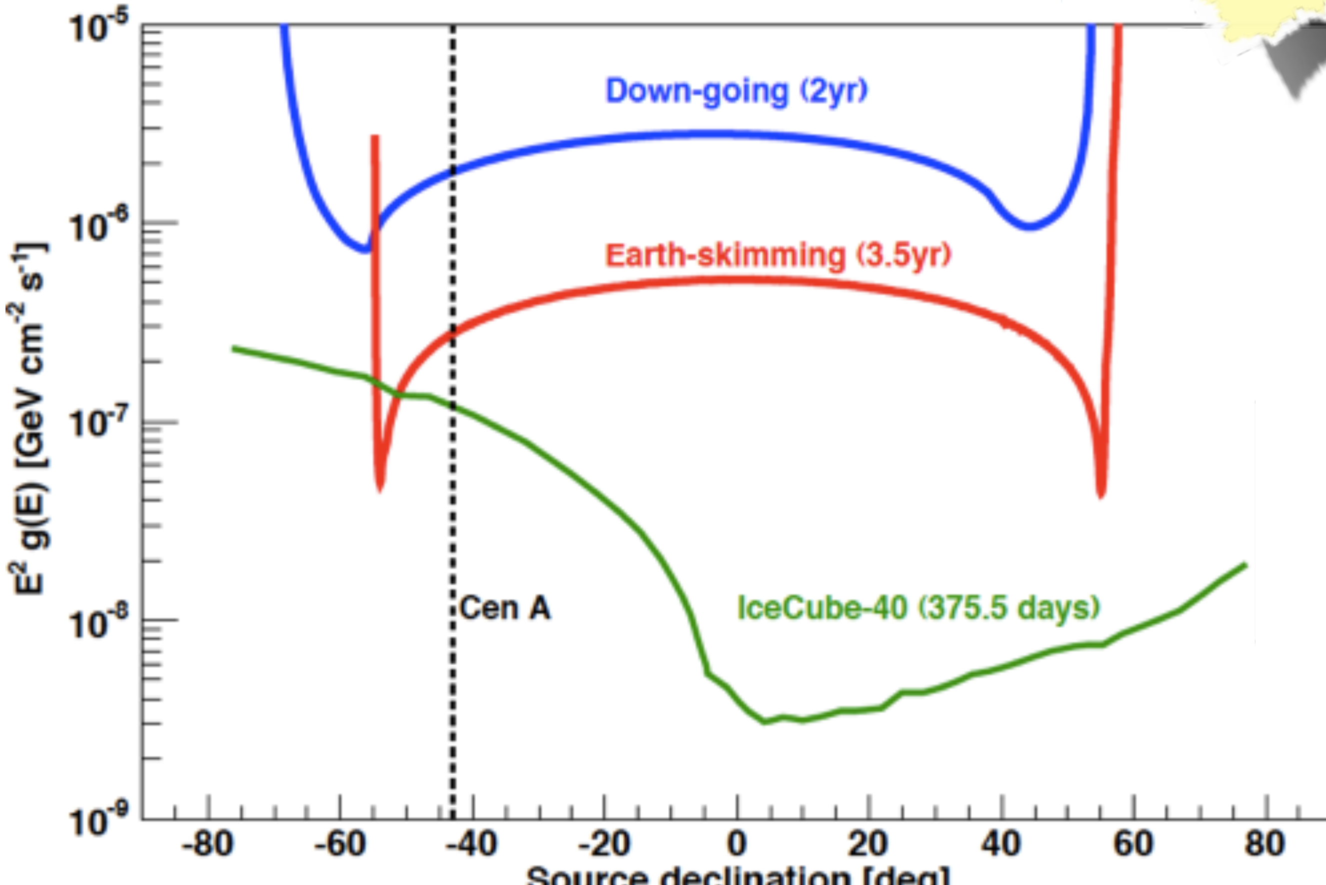
integral



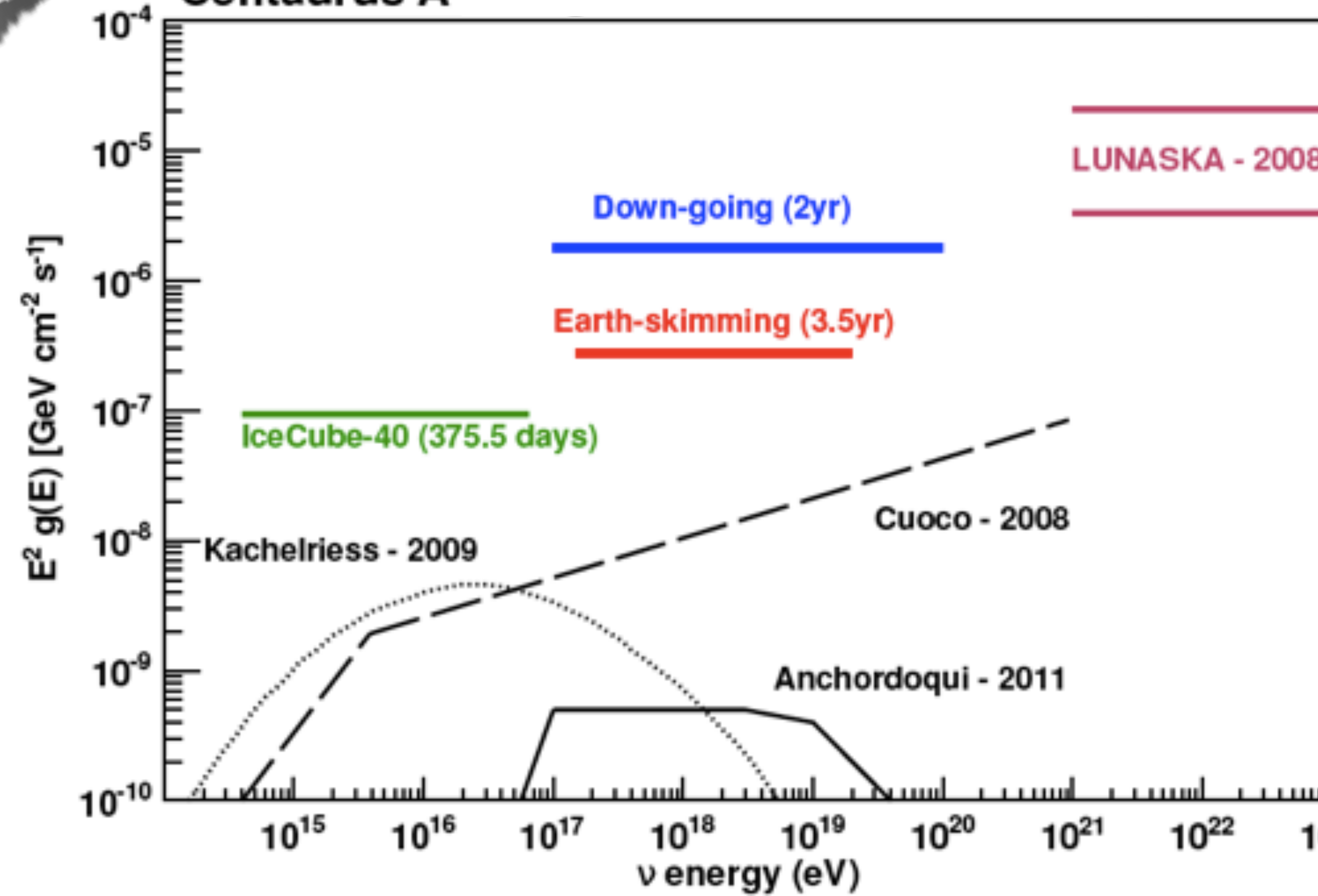
differential



point source



Centaurus A



Composition

Options:

(stable particles)

nuclei :

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

p ... He ... O ... Fe

the only nuclei to survive long travel to earth

difficult !

need shower model for interpretation

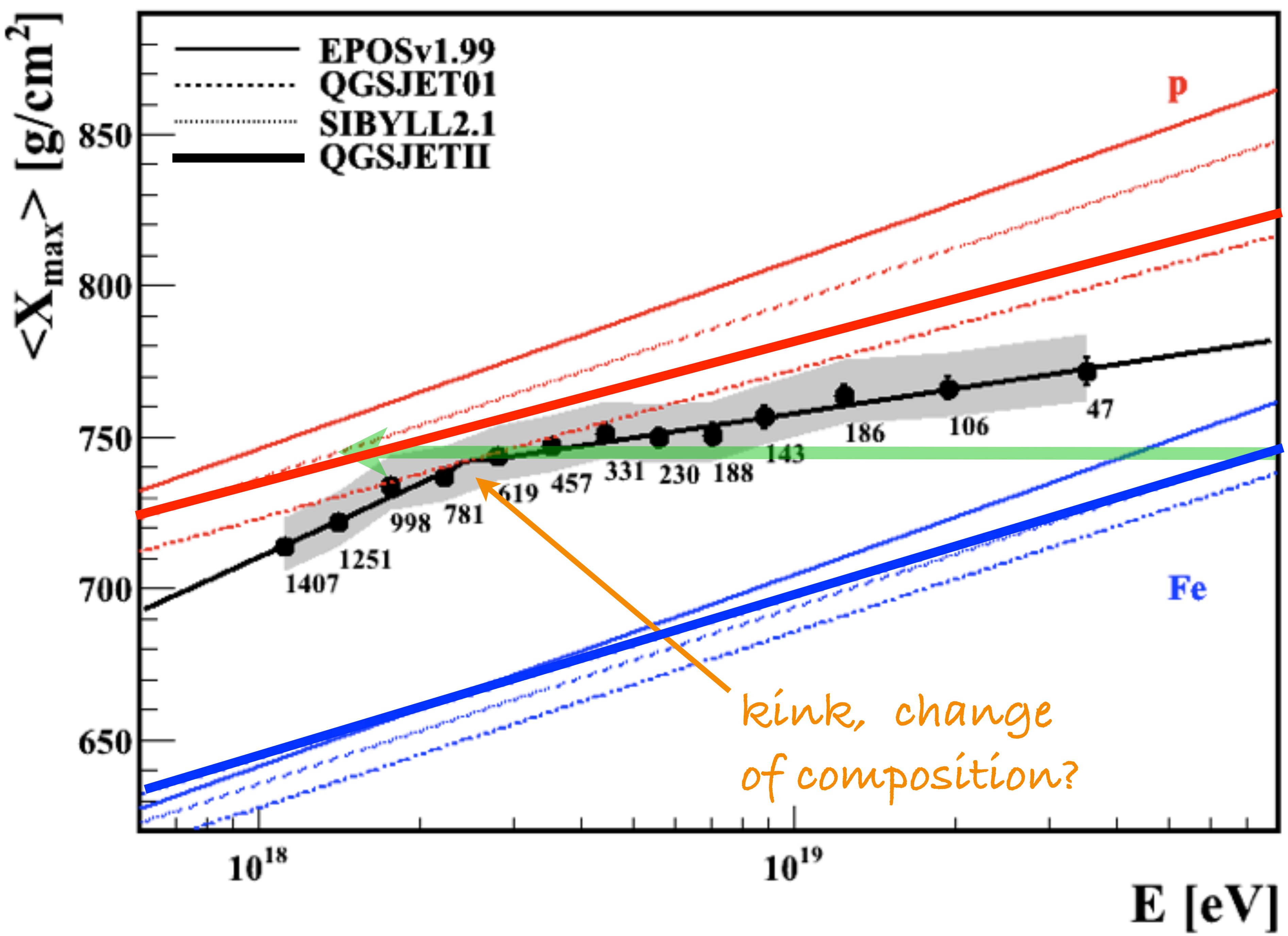
Nuclear Composition

X_{max}: height of shower maximum

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

difficult ! need shower model for interpretation

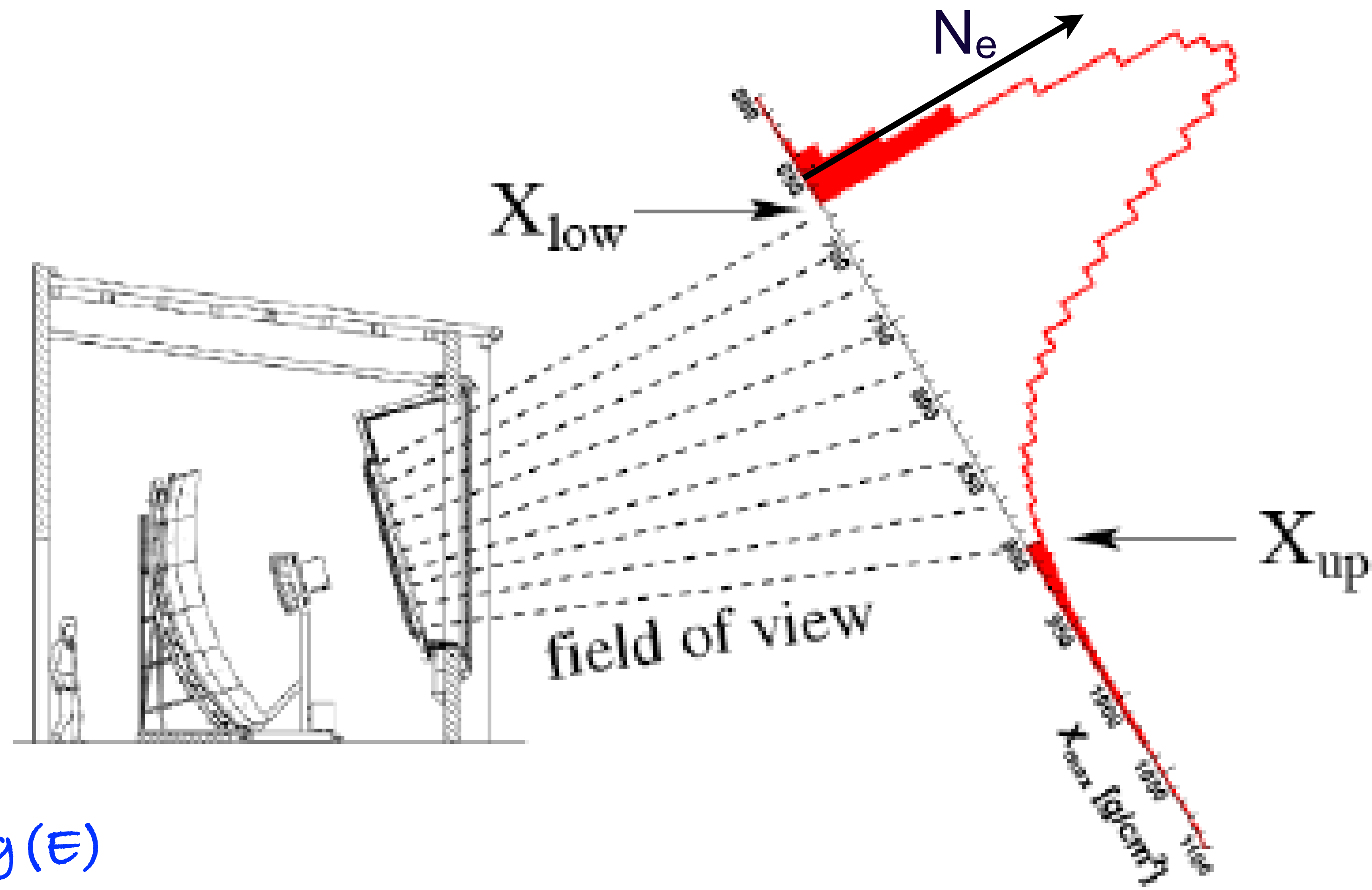
FD:



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

same E/A

same X_{max}



X_{max}: grows with log(E)

p: penetrate deeper, larger X_{max}

Fe: develop earlier, smaller X_{max}

difference about 70 g/cm²

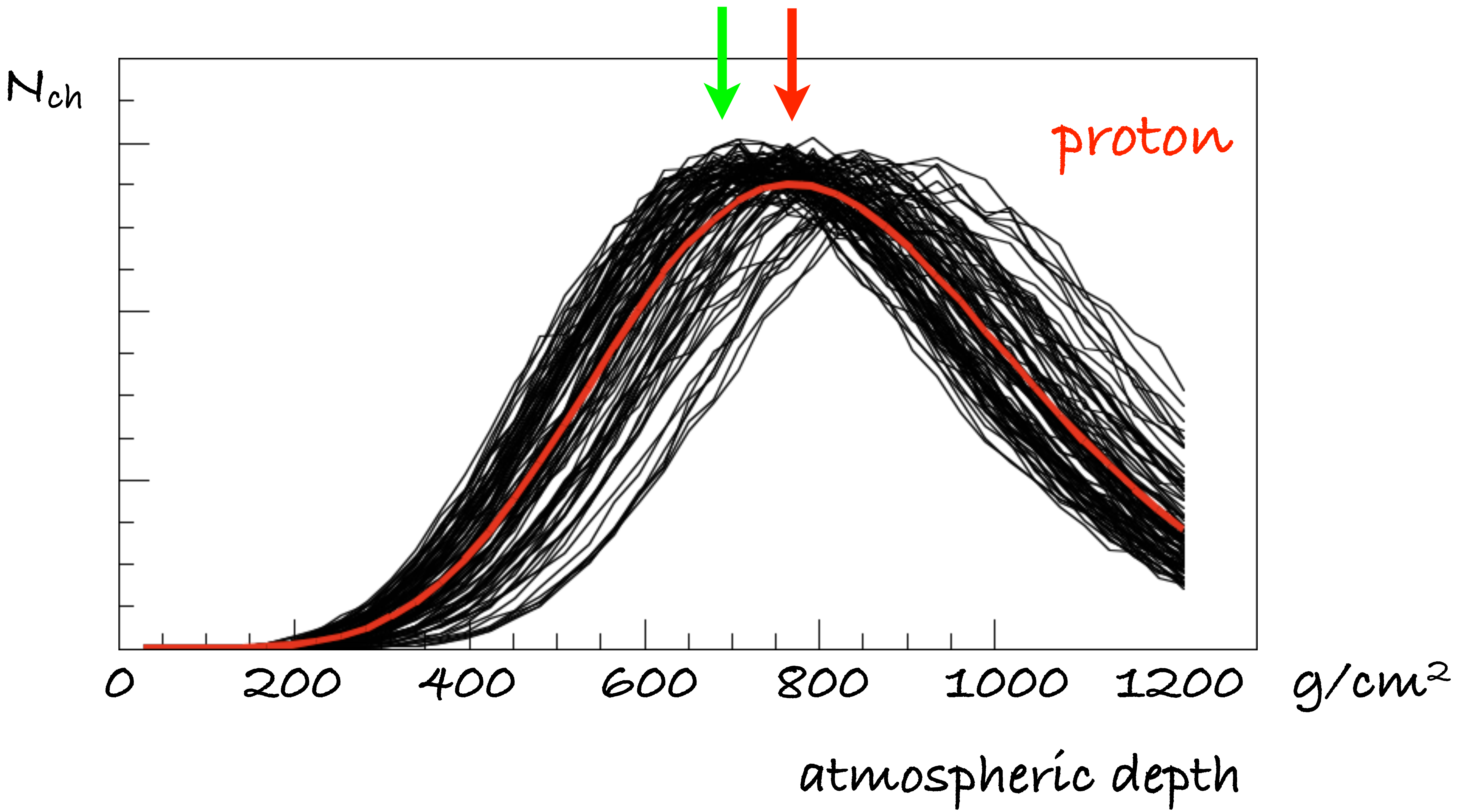
$X_{max}(p)$ fluctuates much more than $X_{max}(Fe)$

$RMS(X_{max}(p)) \approx 60\ g/cm^2$ $RMS(X_{max}(Fe)) \approx 20\ g/cm^2$

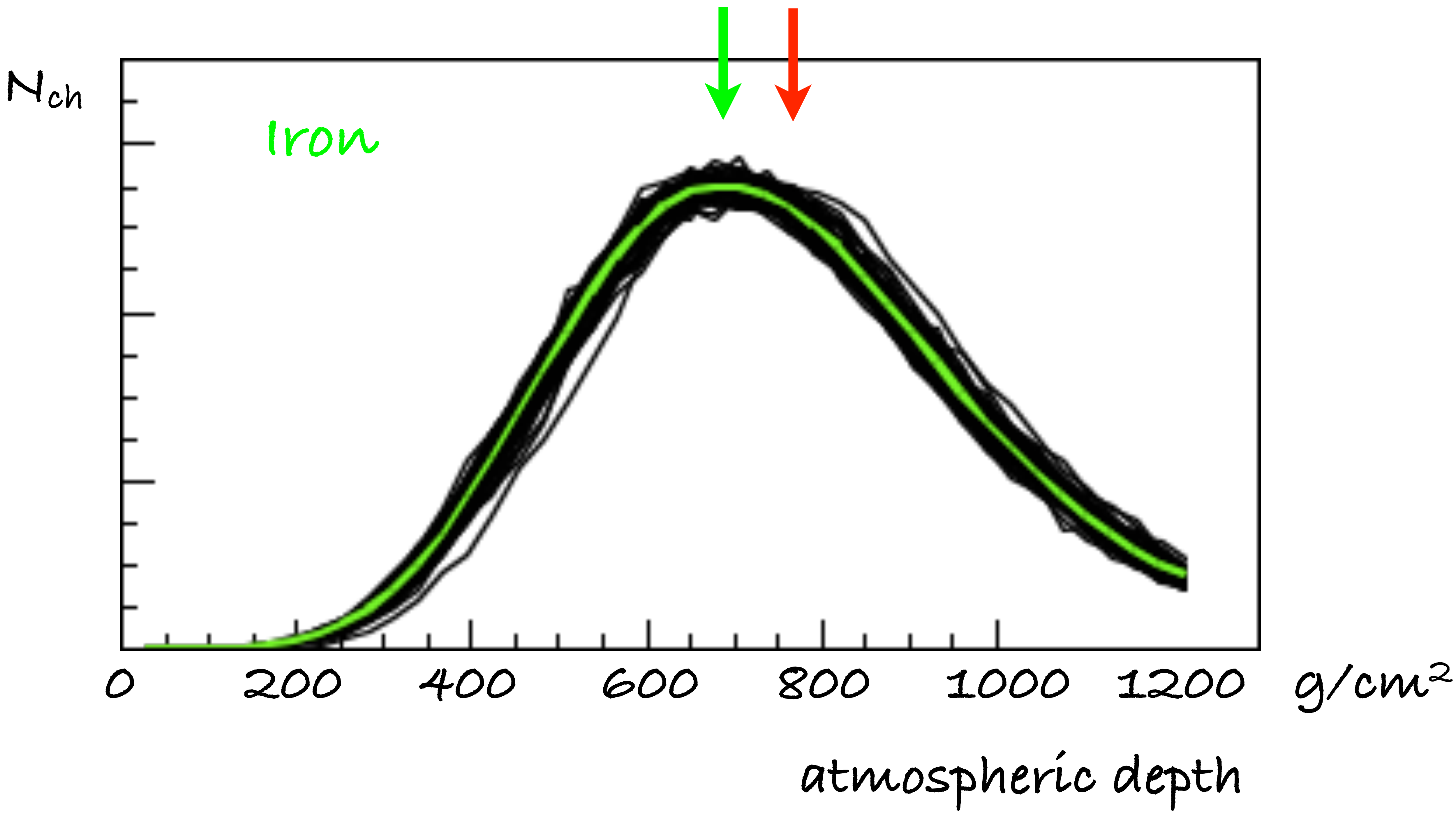
largely due to σ_{inel} of primary particle.

1 Fe $\approx$ 56 protons of $E_0/56$

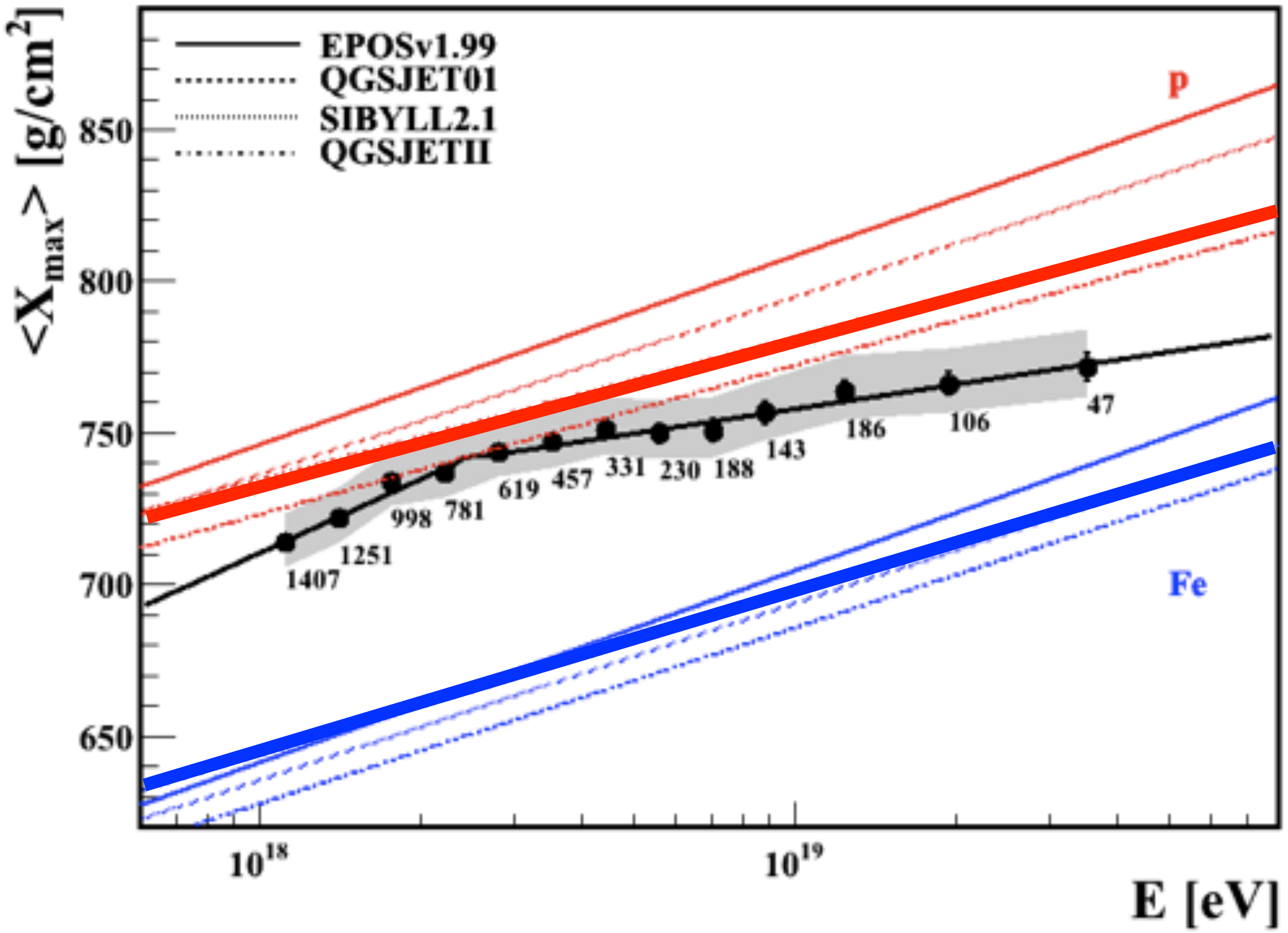
100 proton showers, 10^{19} eV



50 Iron showers, 10^{19} eV

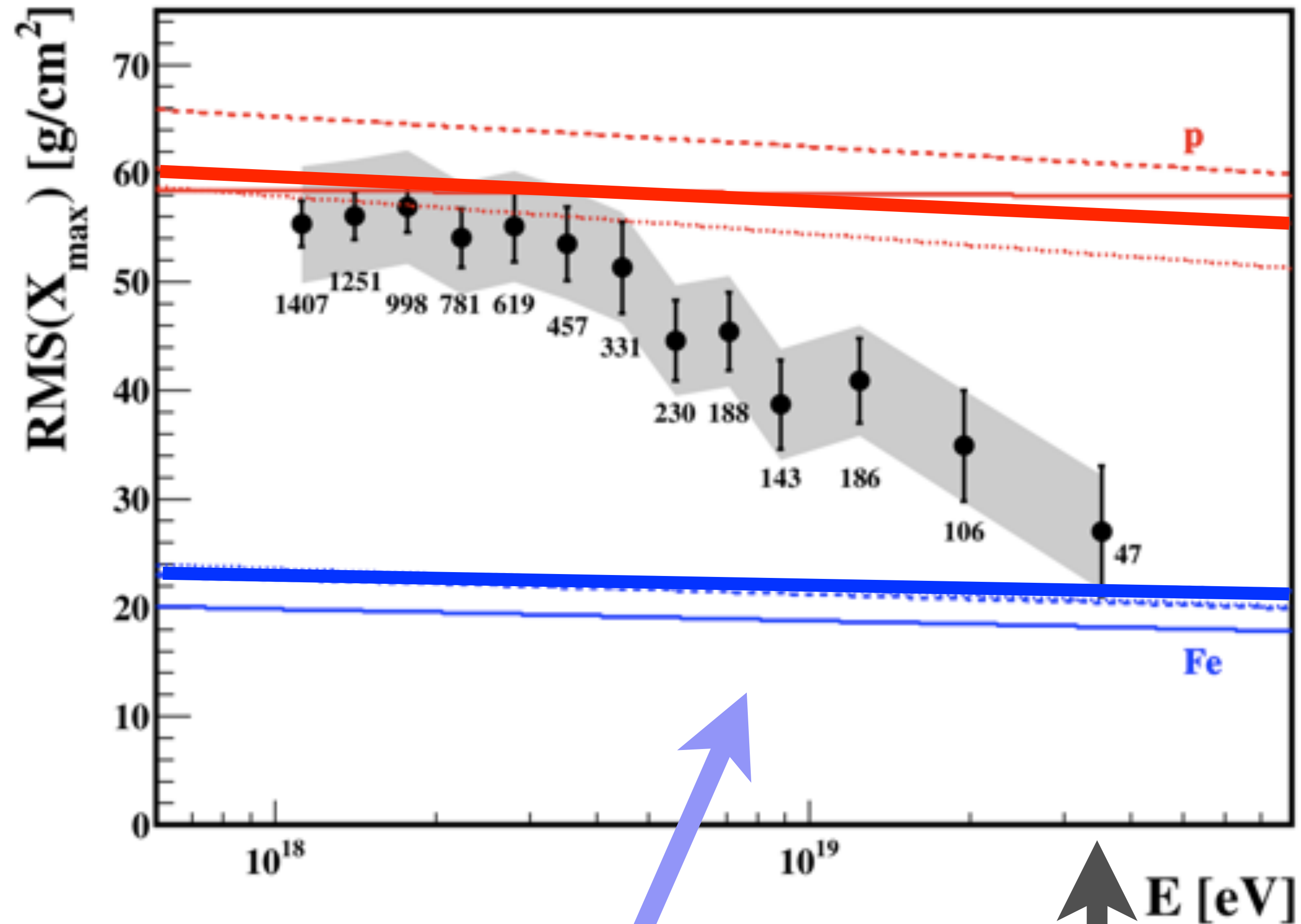


X_{max}



model dependent interpretation

RMS(X_{max})



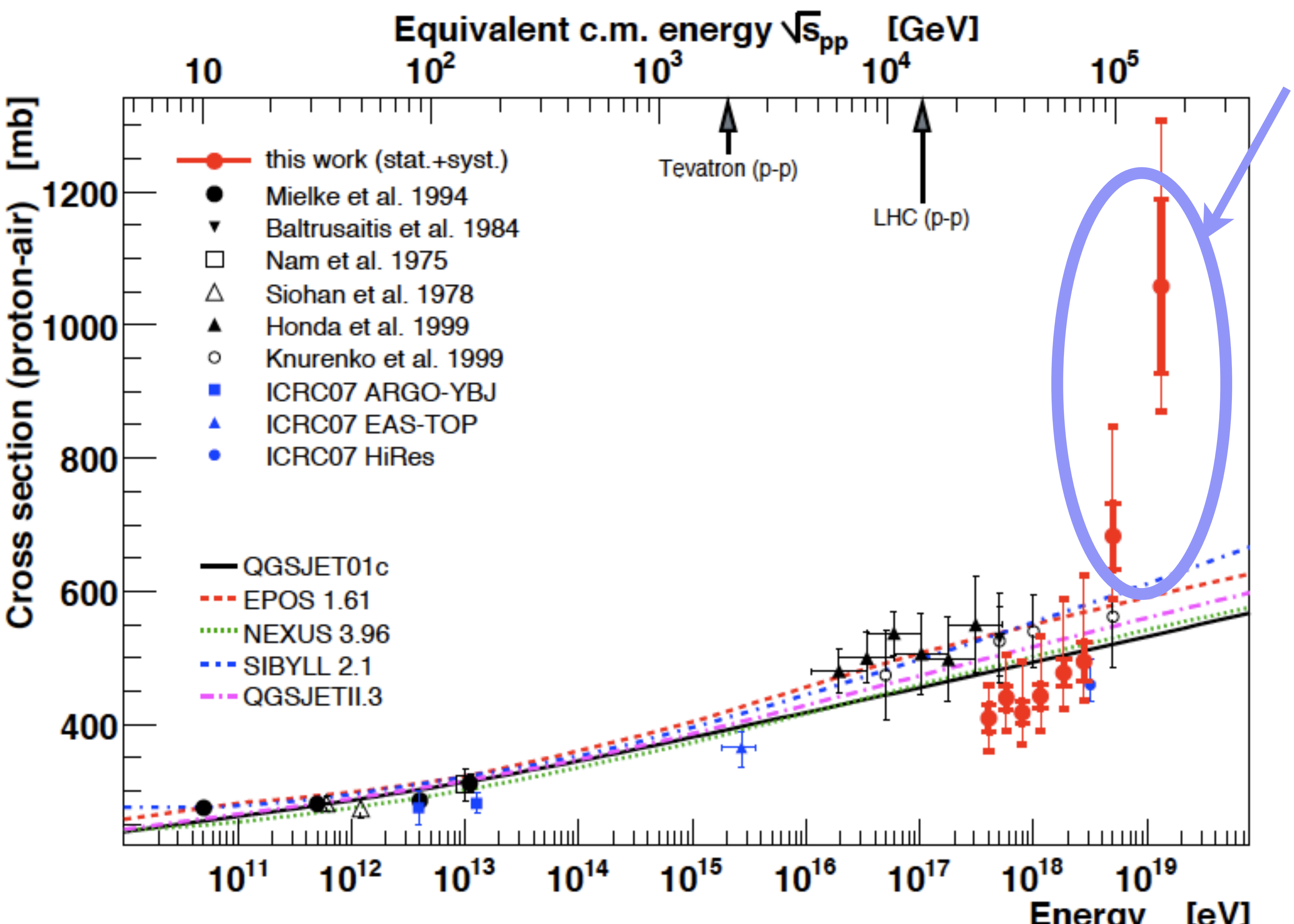
whatever we do to models (within limits), data do not fit to primary proton sims.

$E < 4 \times 10^{19}$ eV

If one trusts the models, then composition turns heavier

(but the two plots are not consistent)

What if CR are protons and physics changes?



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

Composition mis-match ?

Spectrum: GZK cut-off ?

Anisotropy: correlation with nearby matter

p dominated ?

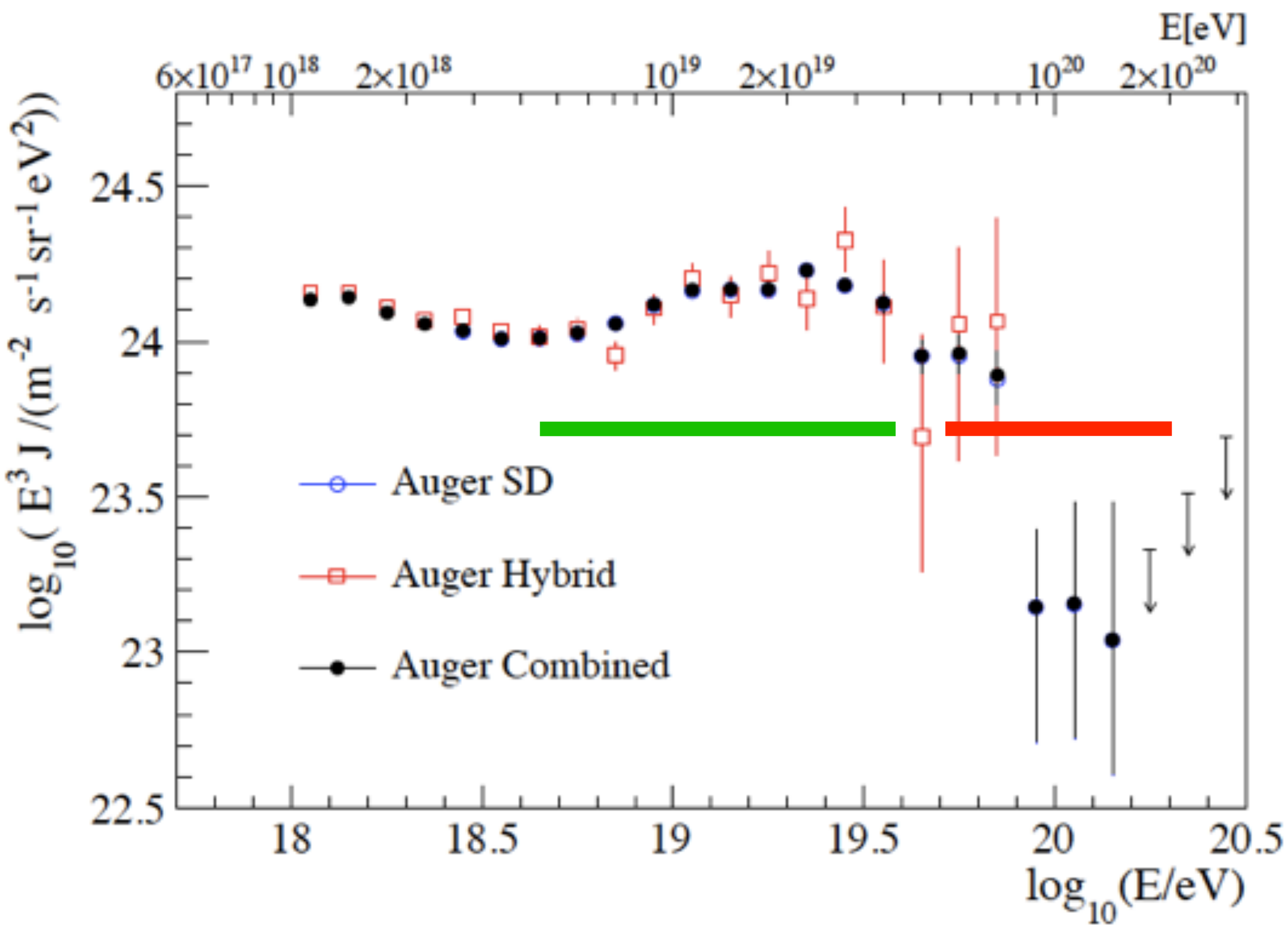
(E > $6x10^{19}$ eV)

Composition: X_{max}, SD variables

mixed/heavy ?

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

strongly model dependent

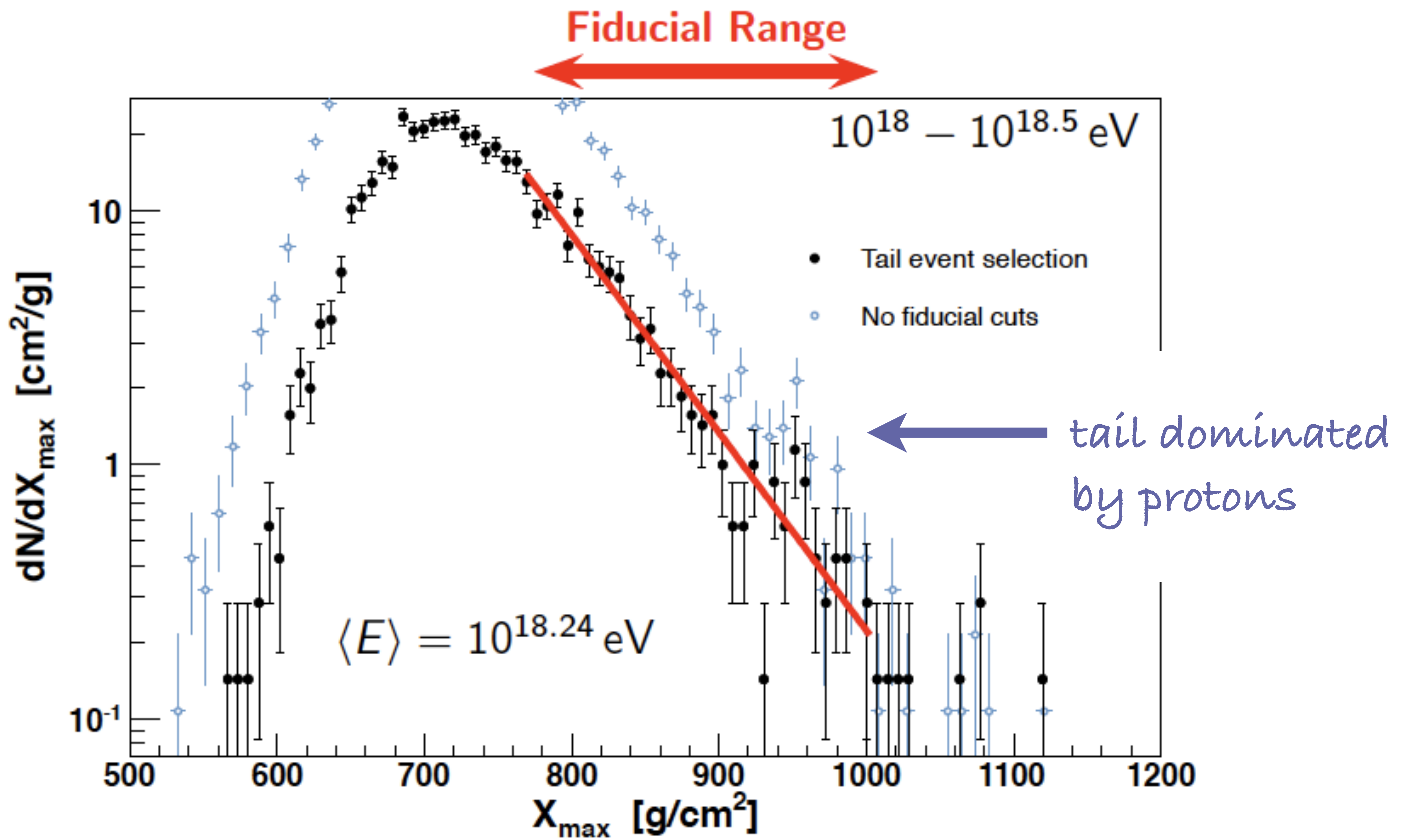


Need hadronic interaction models to be modified ?

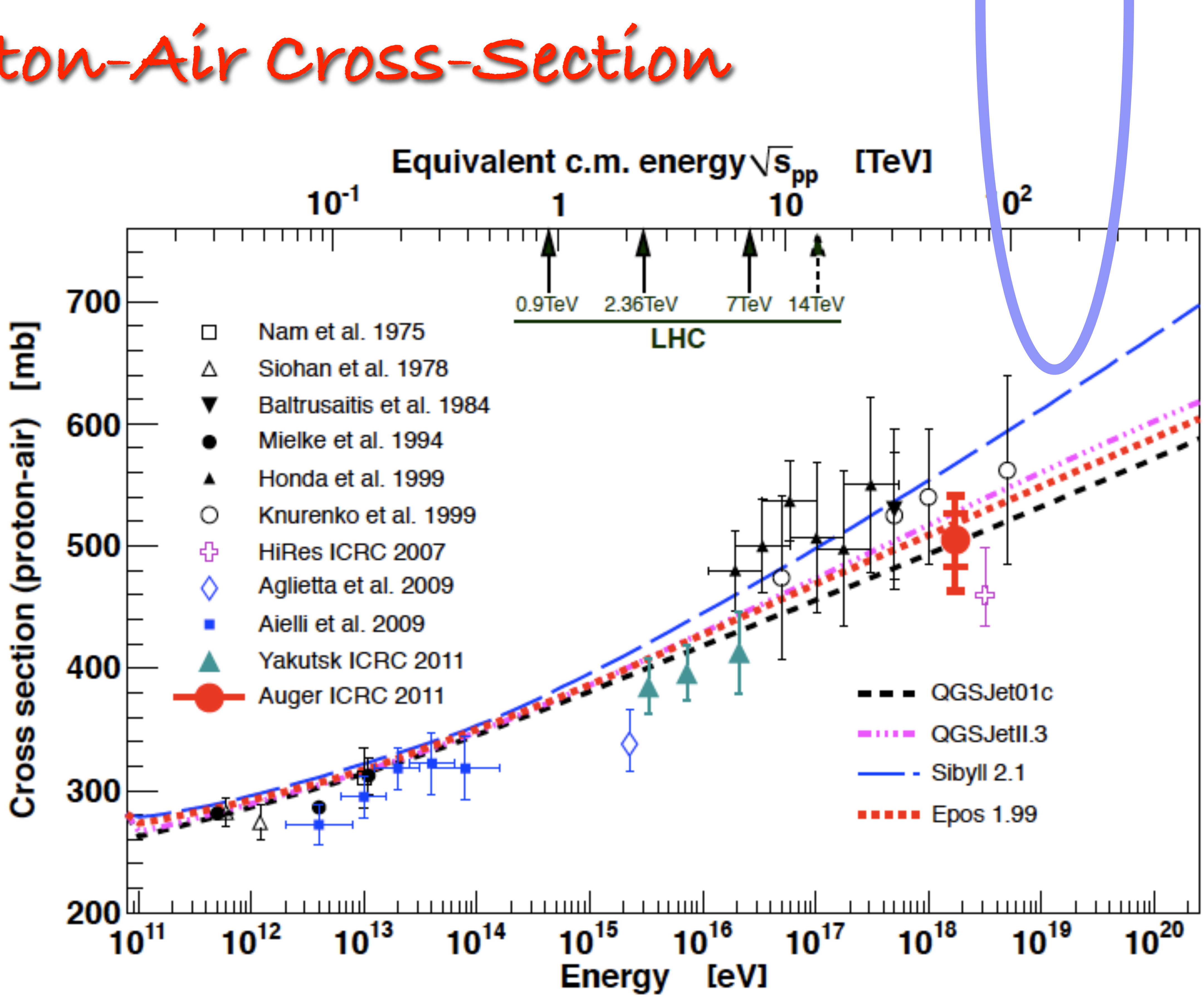
We start to do particle physics at > 10^{18} eV.

Proton-Air Cross-Section

... from tail of X_{max} distribution

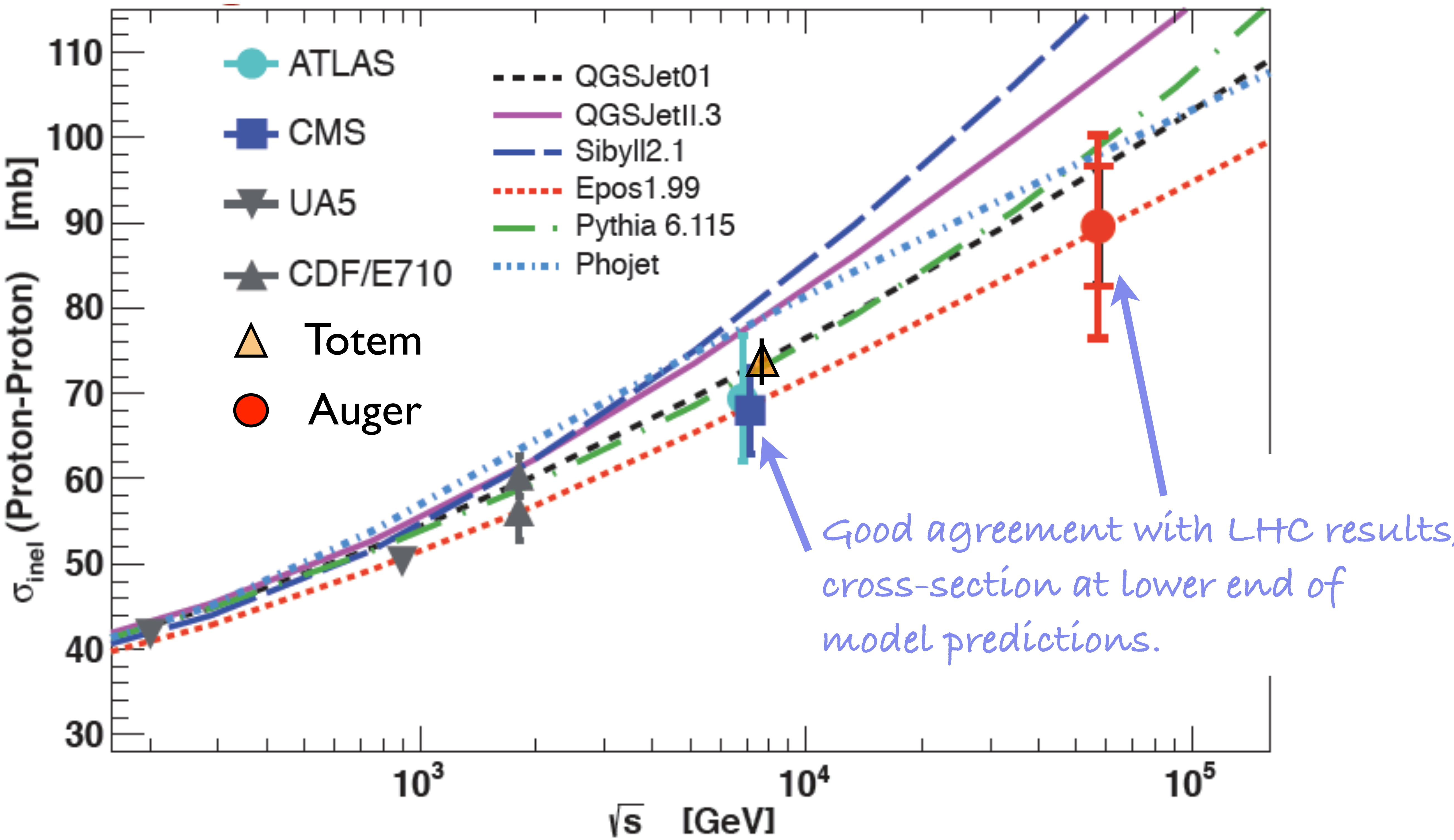


Proton-Air Cross-Section



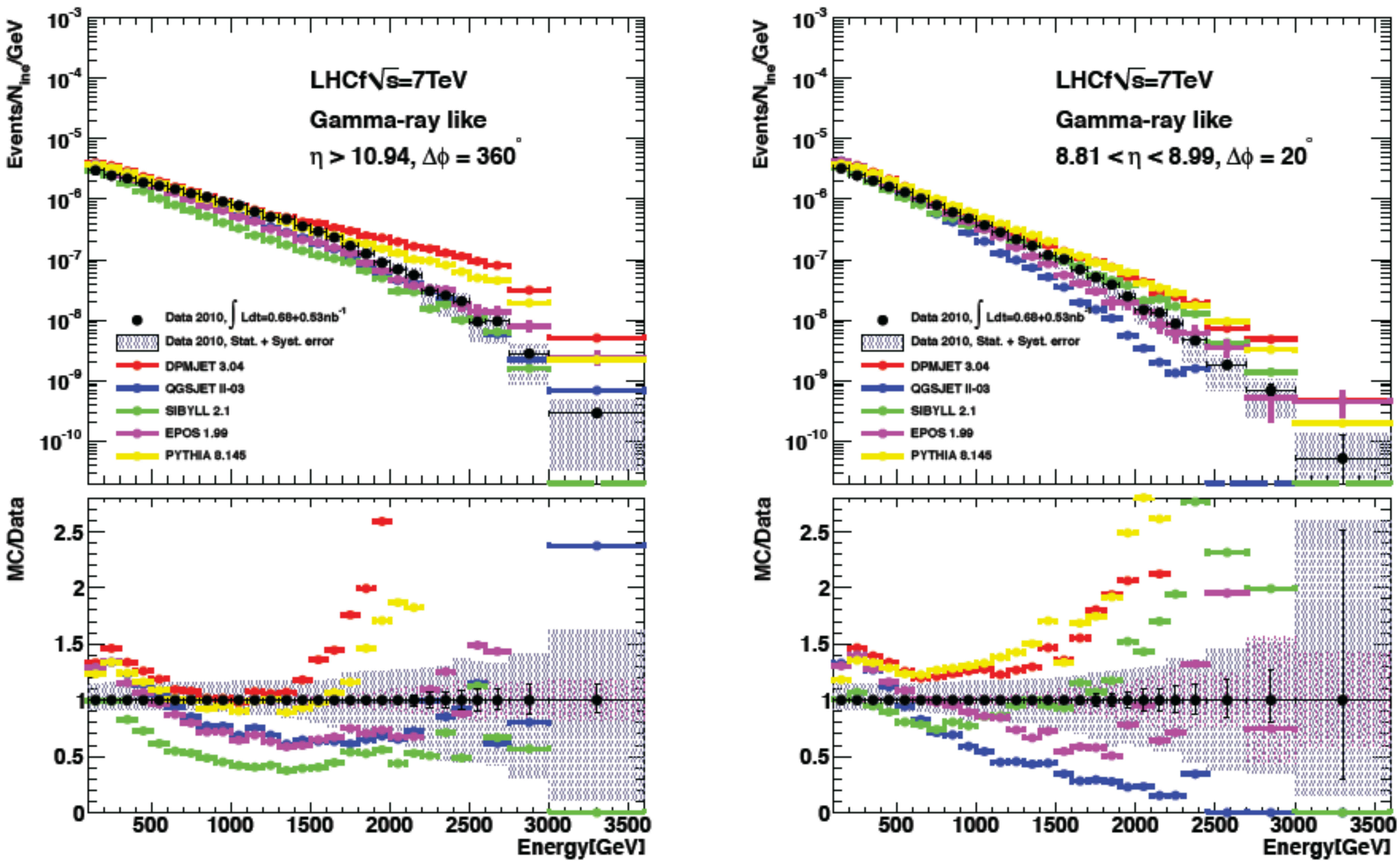
σ(p-air) = 505 ± 22 ± 30 mb (@ 2 EeV)

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



$$\sigma(p\text{-}p) = 90 \pm 7 \pm 10 \text{ mb} \quad (@\ E_{cm} \approx 57 \text{ TeV})$$

LHCf: π^0 production at 0°



models to be modified ...

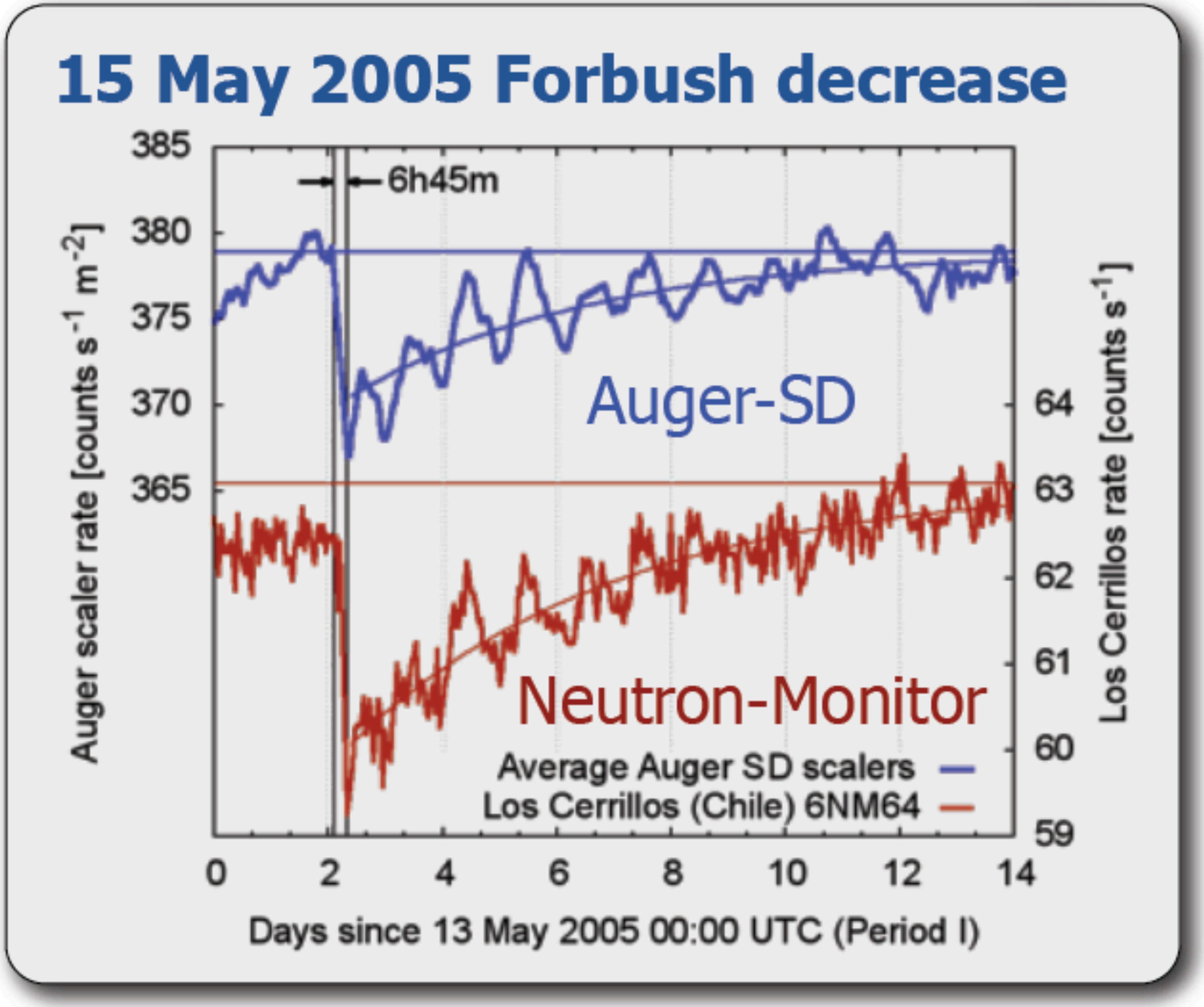
- Much more data from LHC / RHIC expected.
- Model to be revised for a better extrapolation to UHE

- further analysis of Auger data
- extensions for more info per event

.... for a better overall description of
CR composition and hadronic interactions.

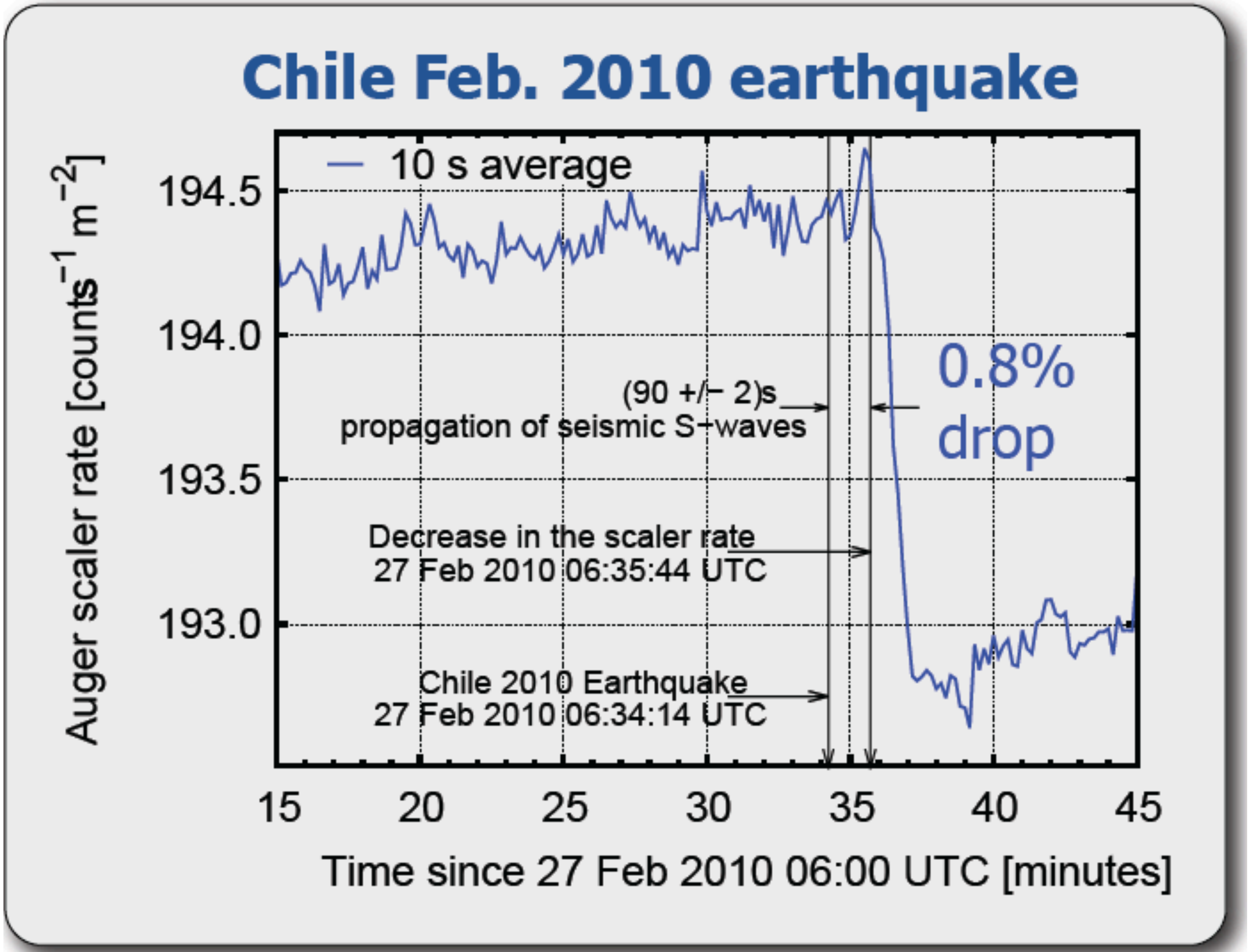
Exotics:

Auger Scaler Rates: read out for monitoring

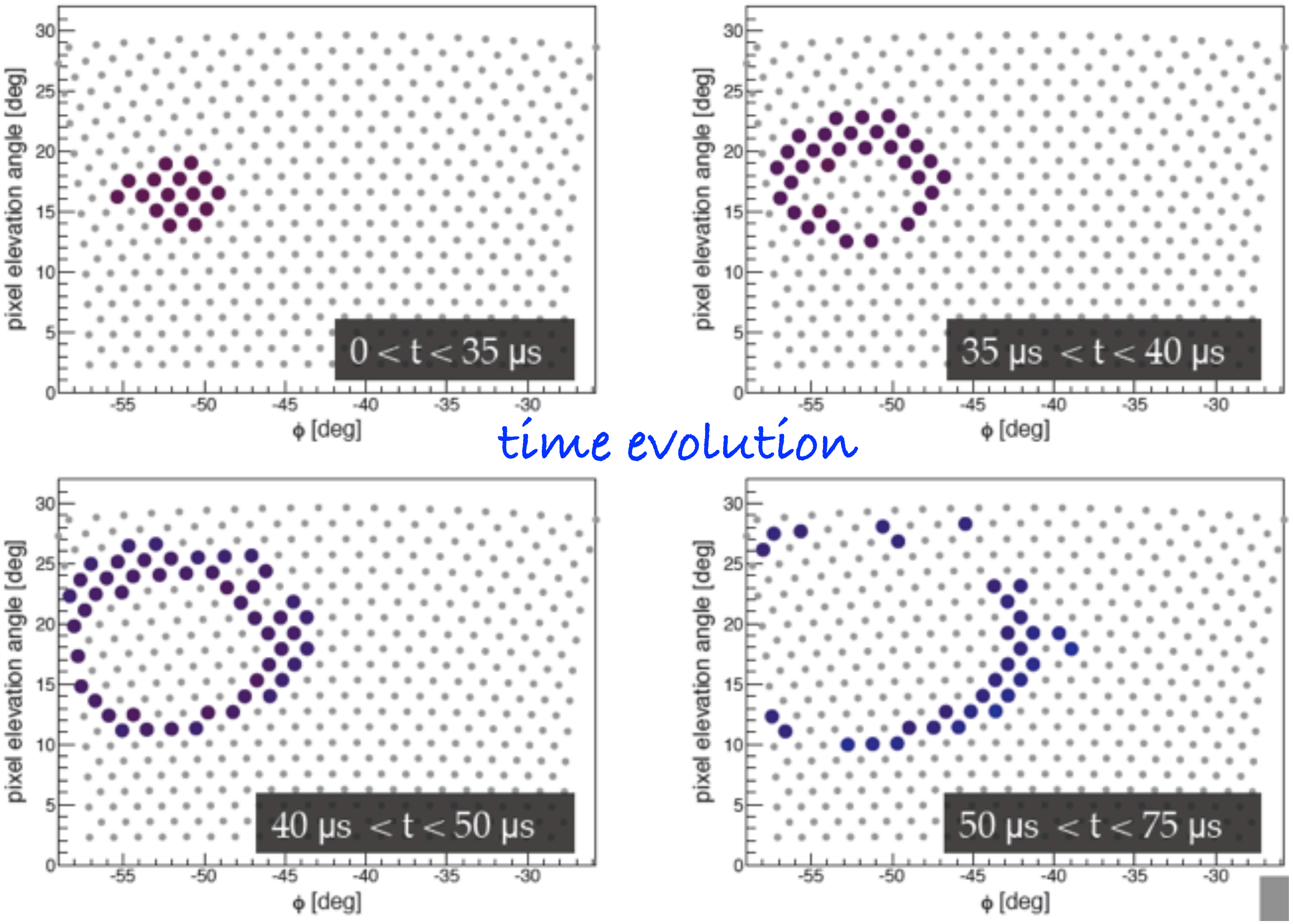


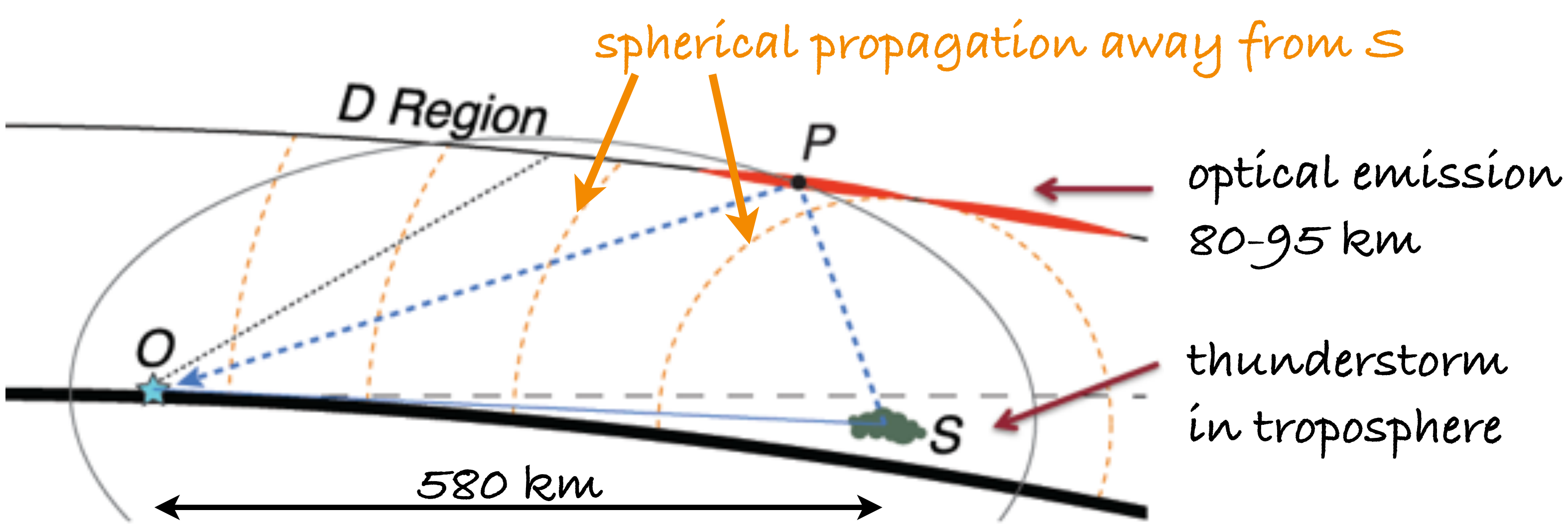
Exotics:

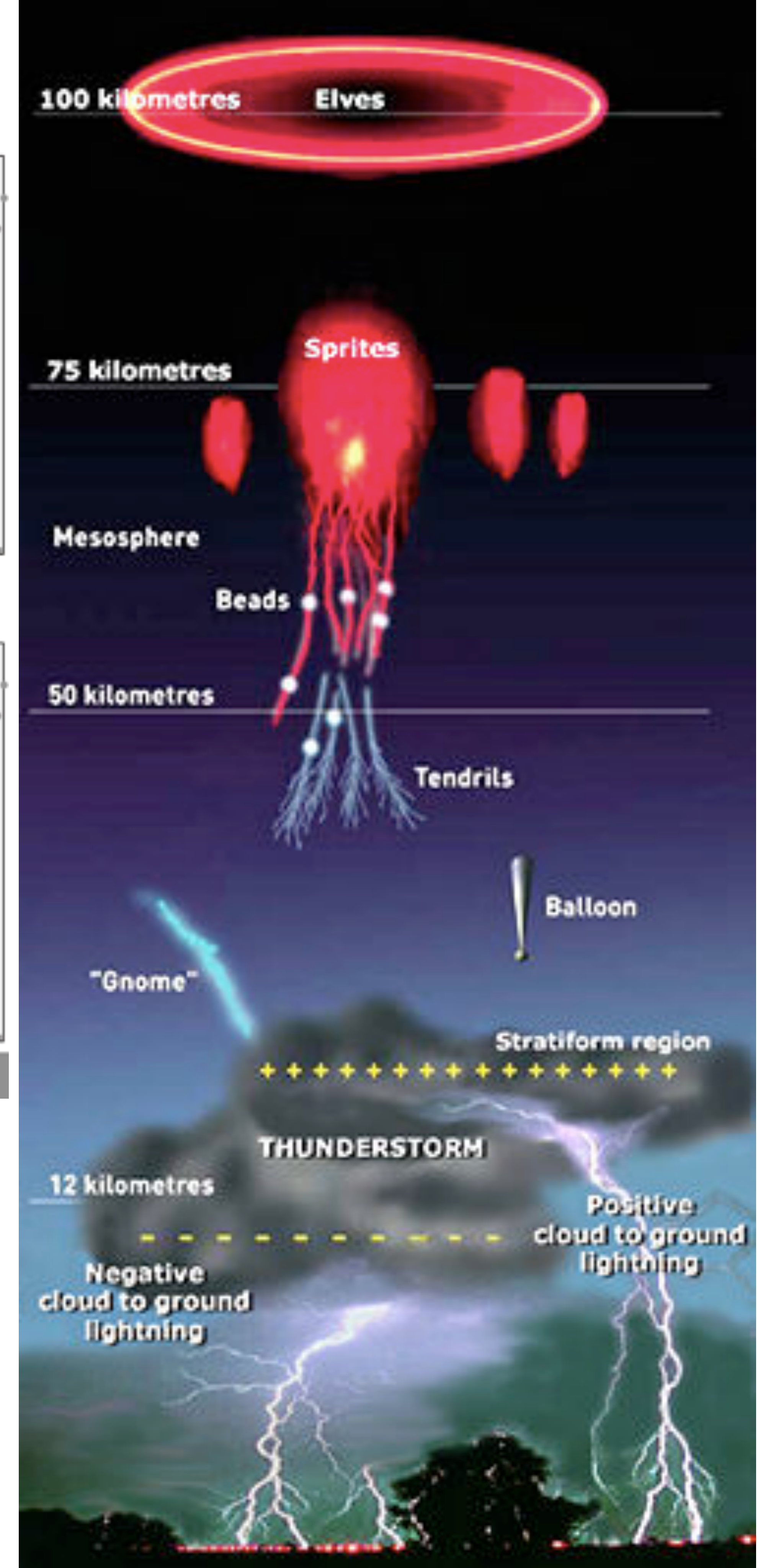
Auger Scaler Rates: read out for monitoring



Elves with the Auger FD







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
Interpretation requires knowledge of composition.

Arrival directions:
CR are extragalactic
Correlation with nearby matter for E > 55 EeV,

Mass composition:
upper limits on photons, neutrinos, and neutrons
reduced fluctuations at $\approx 2 \times 10^{19}$ eV mixed / heavy composition?
with current models, but...

Particle Physics (at $>10^{18}$ eV):
p-air, p-p cross section @ 2×10^{18} eV
Hadronic interaction models in CORSIKA need adaption ...
More muons & ground signal needed for same fluorescence light
Auger results and new collider data constrain shower models

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 techniques needed. Ideas?
Radio detection of air showers not quite ready yet.

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

Jem-EUSO on ISS,	400 km alt.,	$>10^5$ km^2
CROS satellite,	400-800 km alt.	$\approx 10^6$ km^2

The End