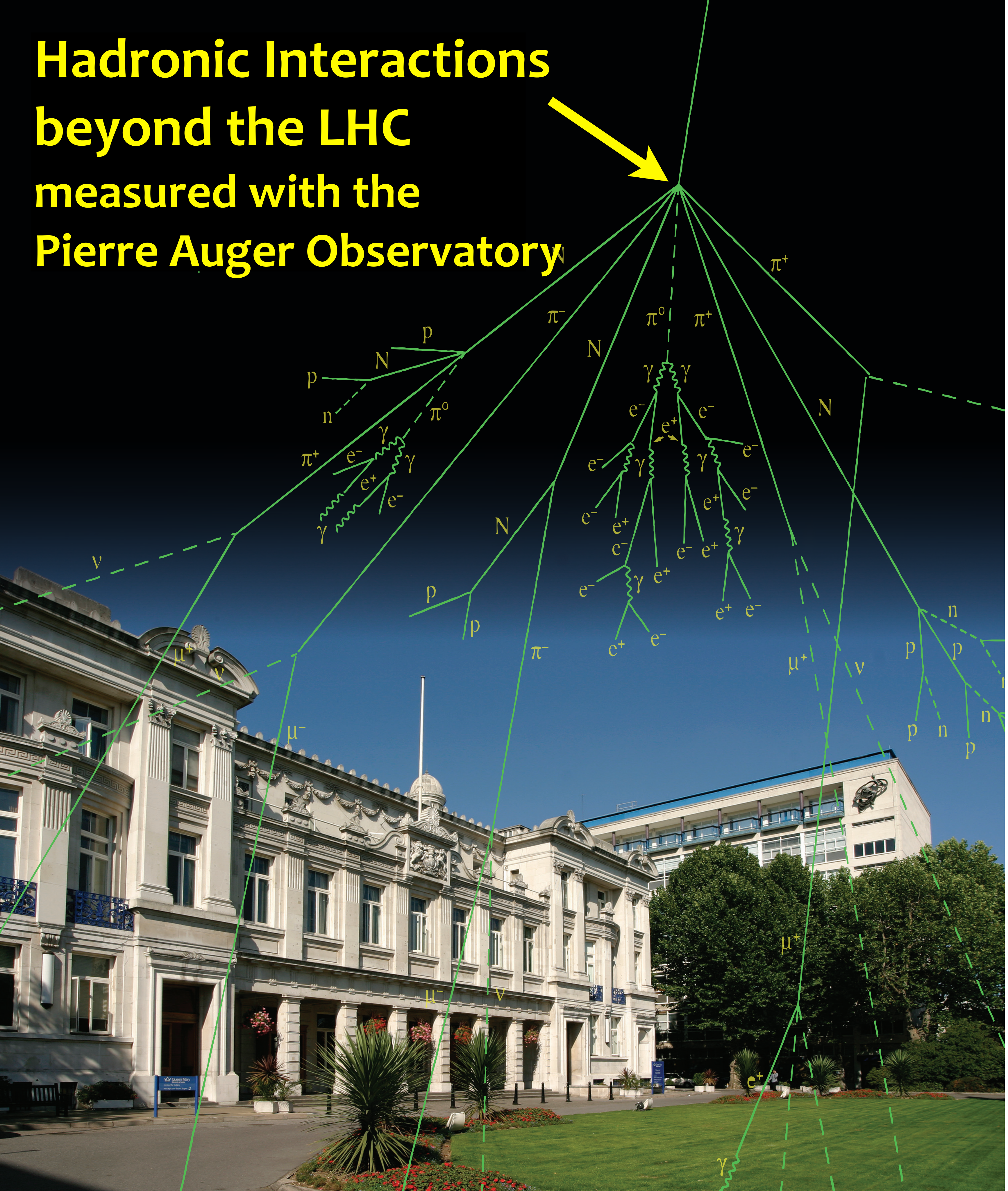
Hadronic Interactions beyond the LHC

measured with the Pierre Auger Observatory



- UHECRs & Auger
- Some results
- Hadronic physics

Johannes Knapp
UNIVERSITY OF LEEDS

Cosmic Rays:

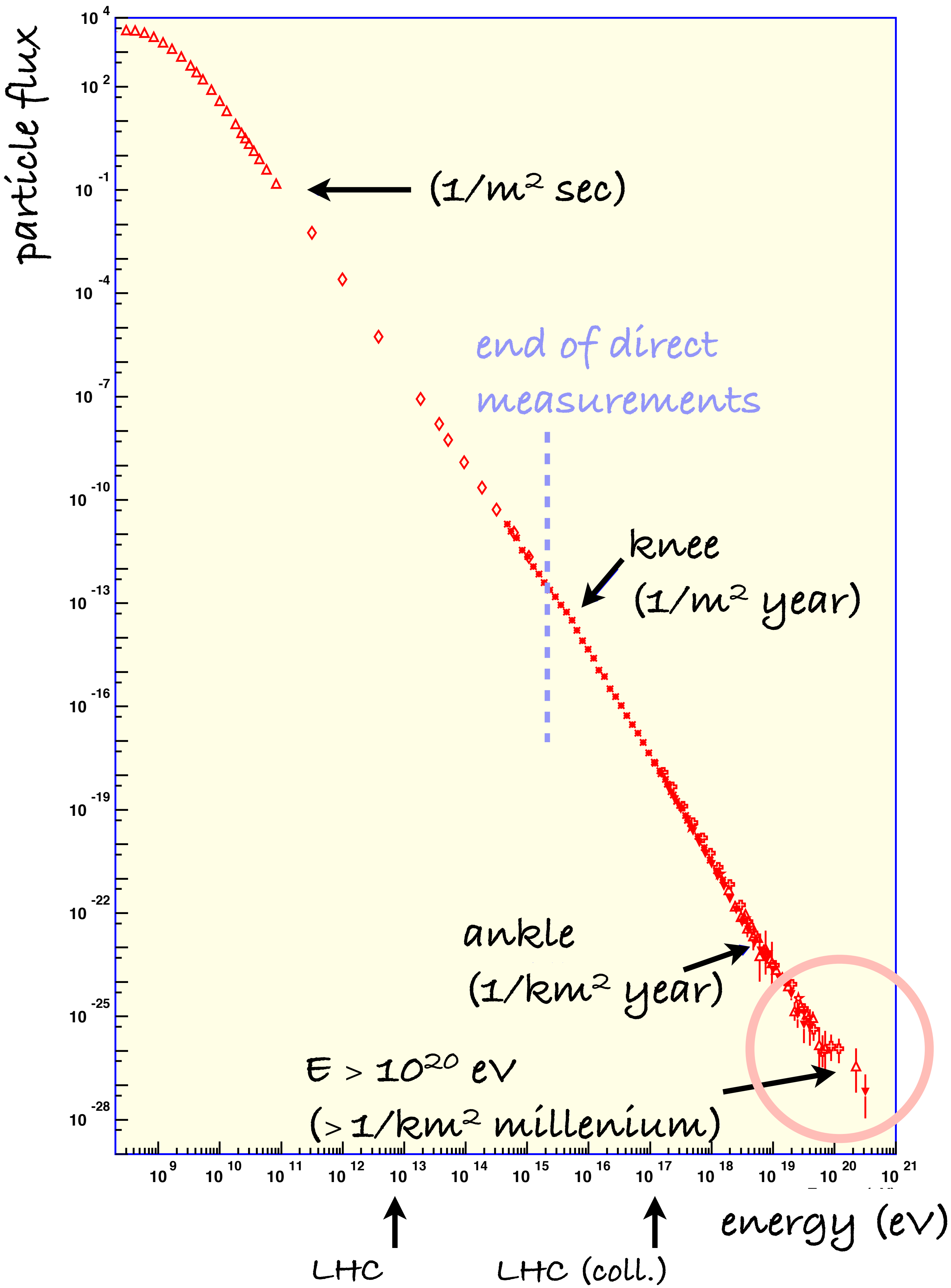
charged particles from astrophysical sources
... the highest energy particles in the universe !

Cosmic Rays: p, He, ... Fe fully ionised nuclei
electrons identified at low energies

Energies: MeV .... $\geq 10^{20}$ eV (UHE: $> 10^{18}$ eV)

Important part of the galaxy / universe

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

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

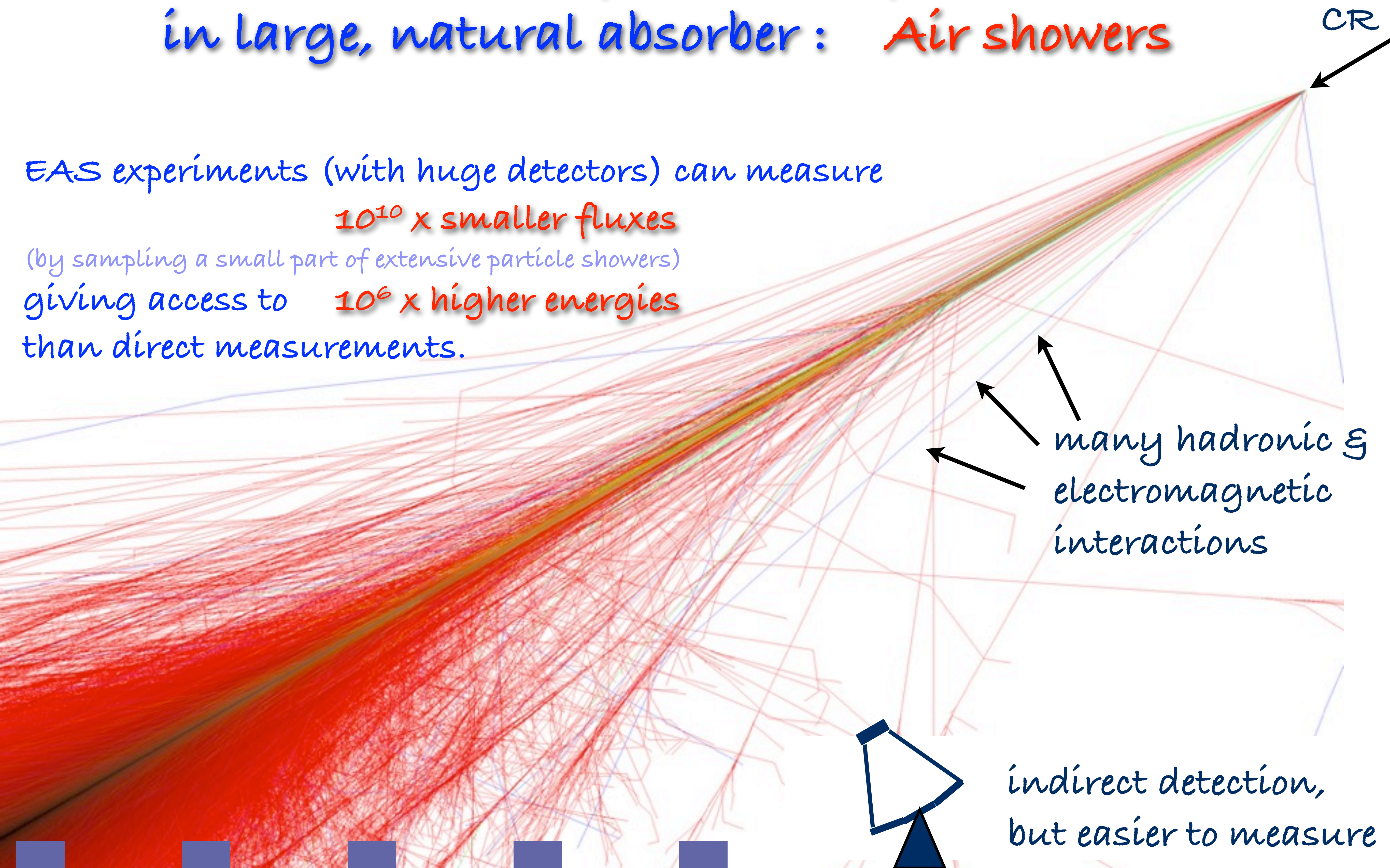
EAS experiments (with huge detectors) can measure

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 ...

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:

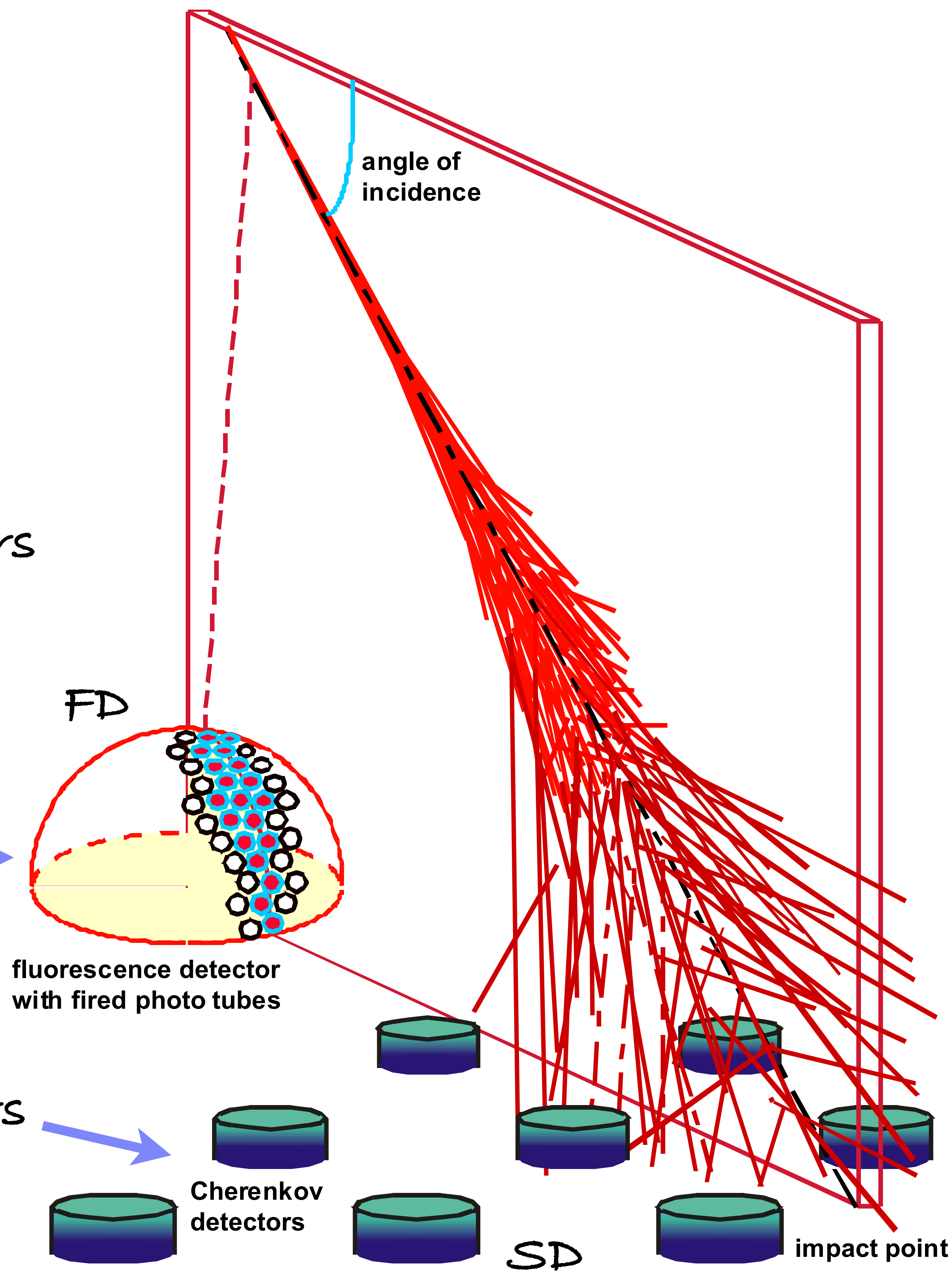
indirect measurement,
shape and particle content of showers

Auger: Hybrid Detector

measure extensive air shower with:

24 Fluorescence telescopes
$30^0 \times 30^0$ FoV, 10% duty cycle,
good energy resolution

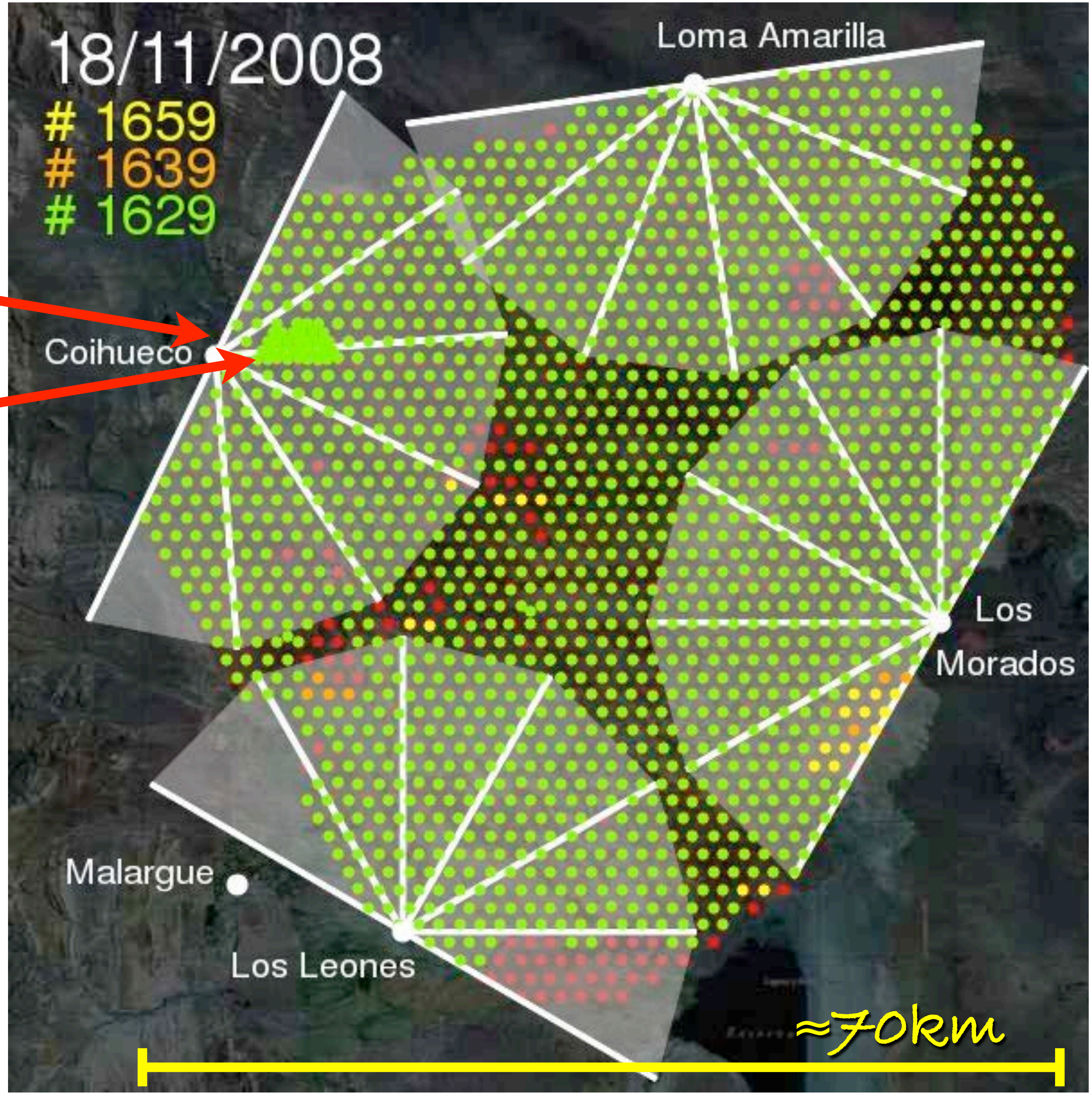
array of 1600 water Cherenkov detectors
on 3000 km², 100% duty cycle,
well-known aperture



Auger layout

HEAT
high elev.
FD tels.

infill
array

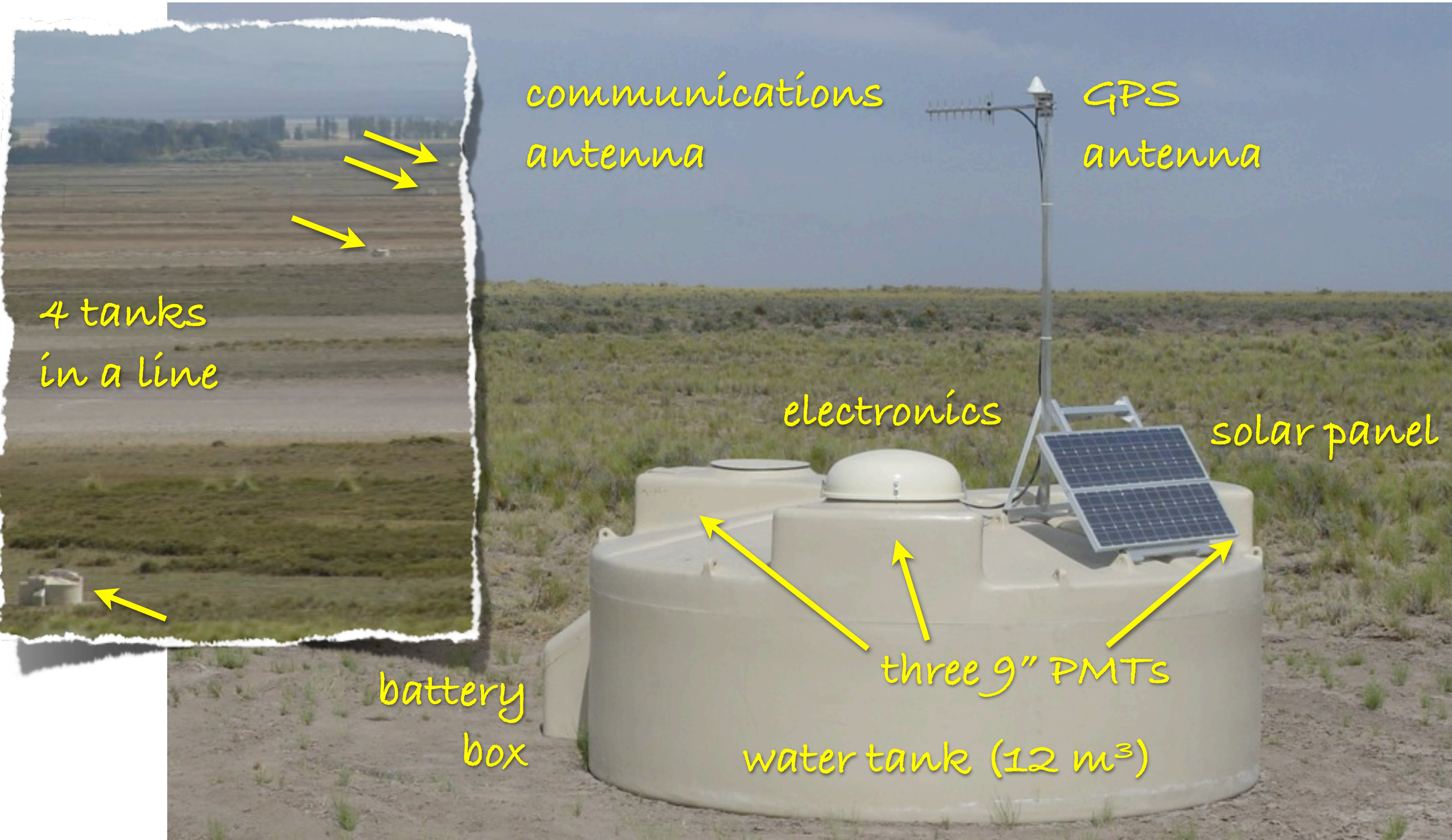


data taking:
since 2004
completion:
Nov 2008

Surface array

(Water cherenkov detectors)

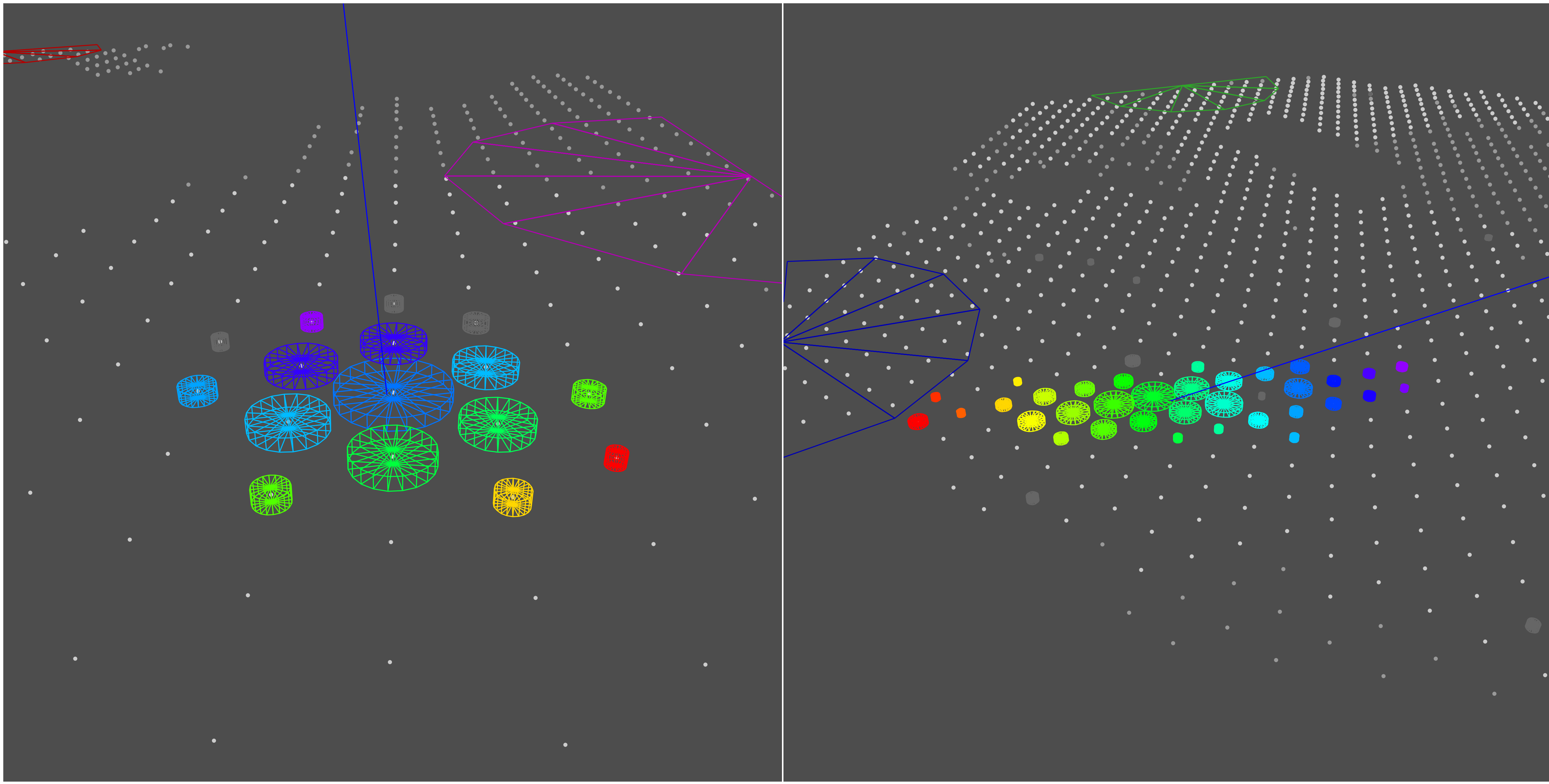
>1600 tanks deployed over 3000 km²
triangular grid, 1.5 km distance,
3 PMTs, read out at 40 MHz
solar powered, ≈ 10 W

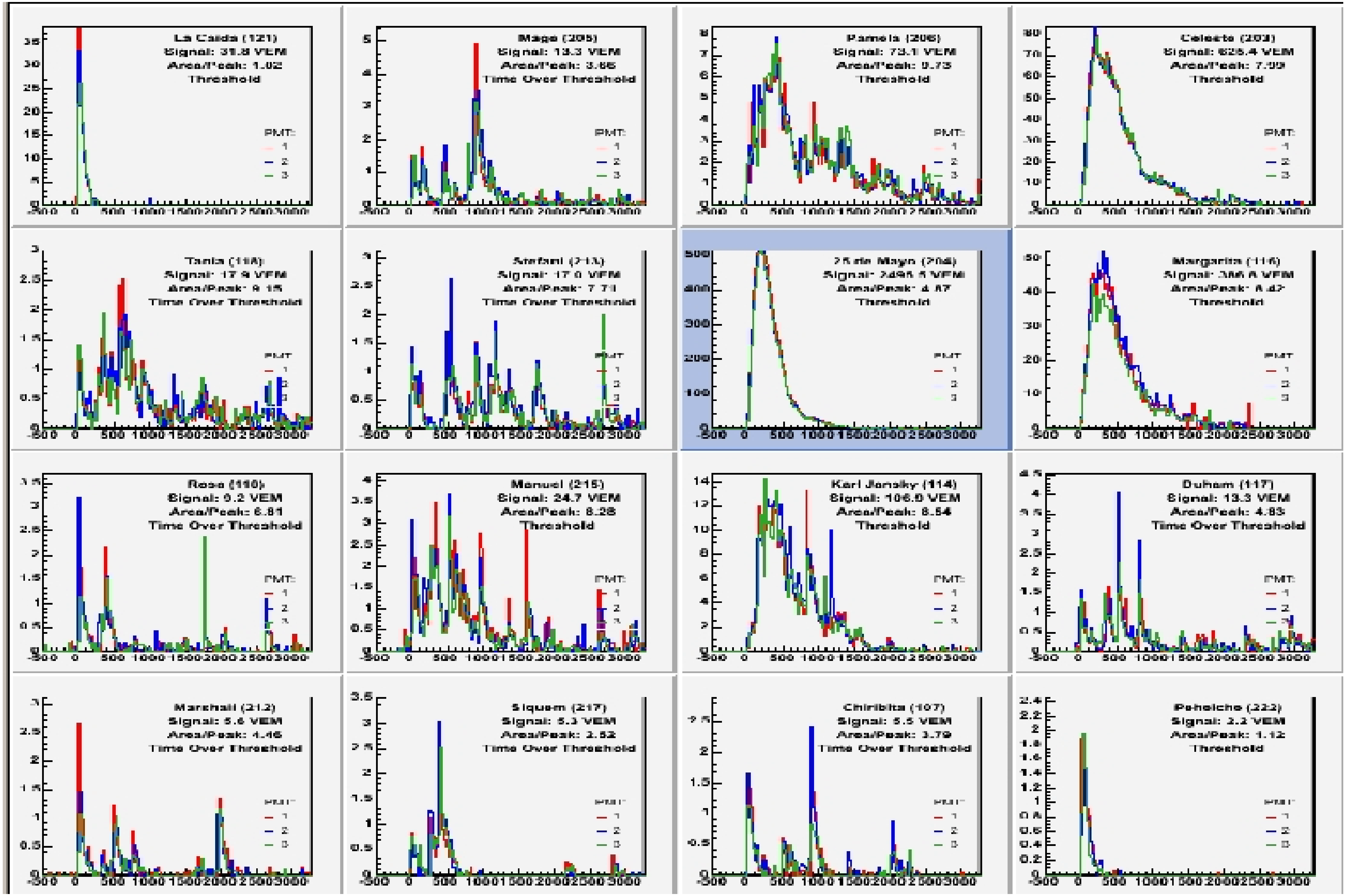


some of the highest-energy SD events:

near vertical — $E = 1.67 \times 10^{20}$ eV $\theta = 14^{o}$

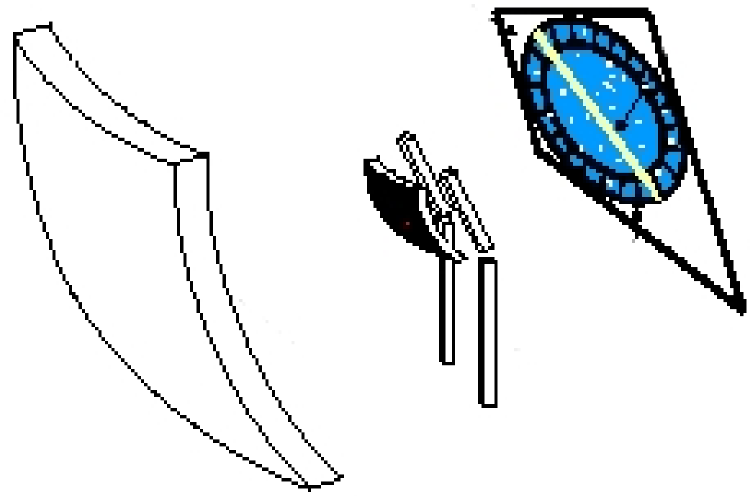
inclined — $E = 0.37 \times 10^{20}$ eV $\theta = 74^{o}$

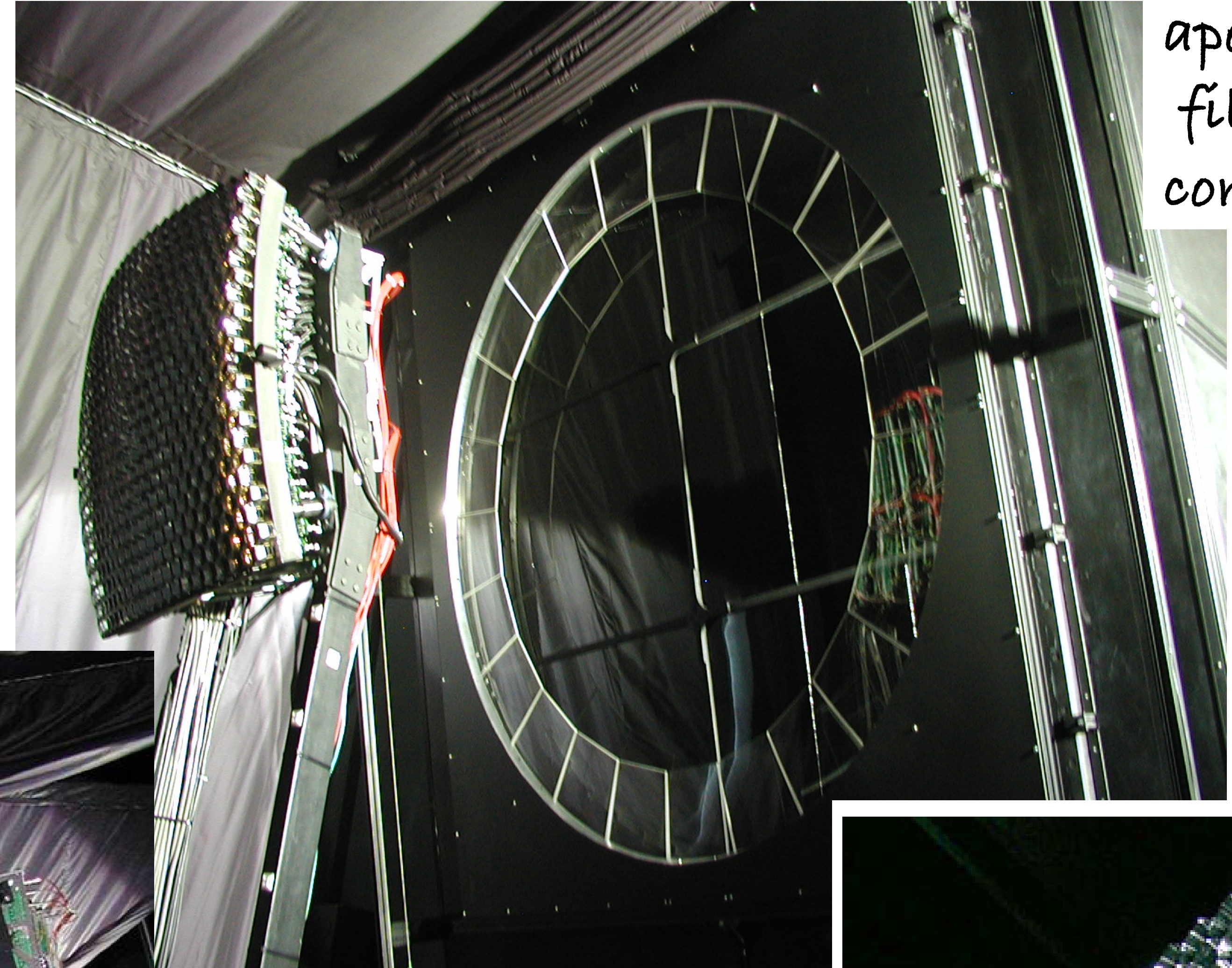




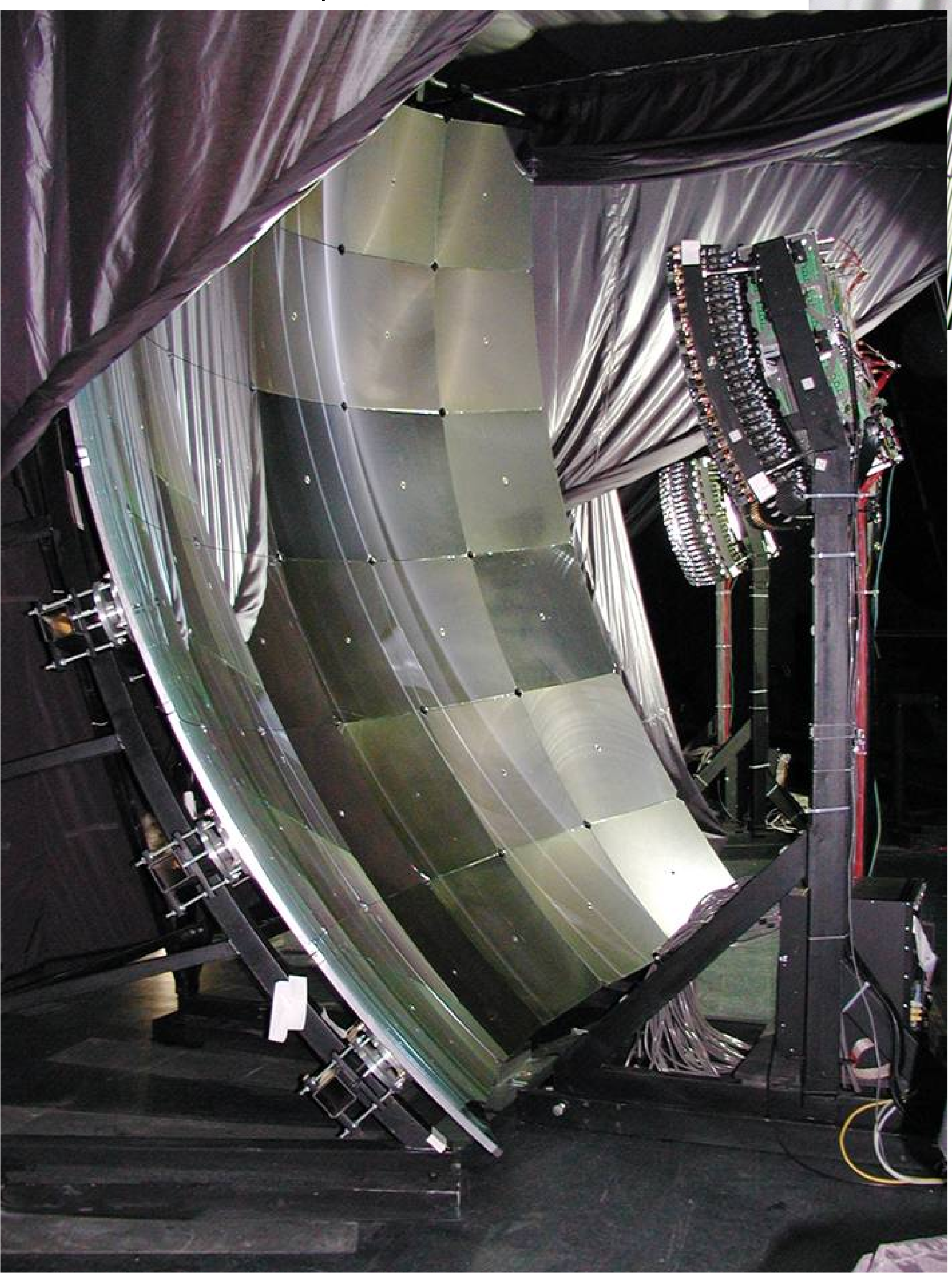
High & smooth pulses close to shower core, low & spiky pulses far away.

FD telescope:



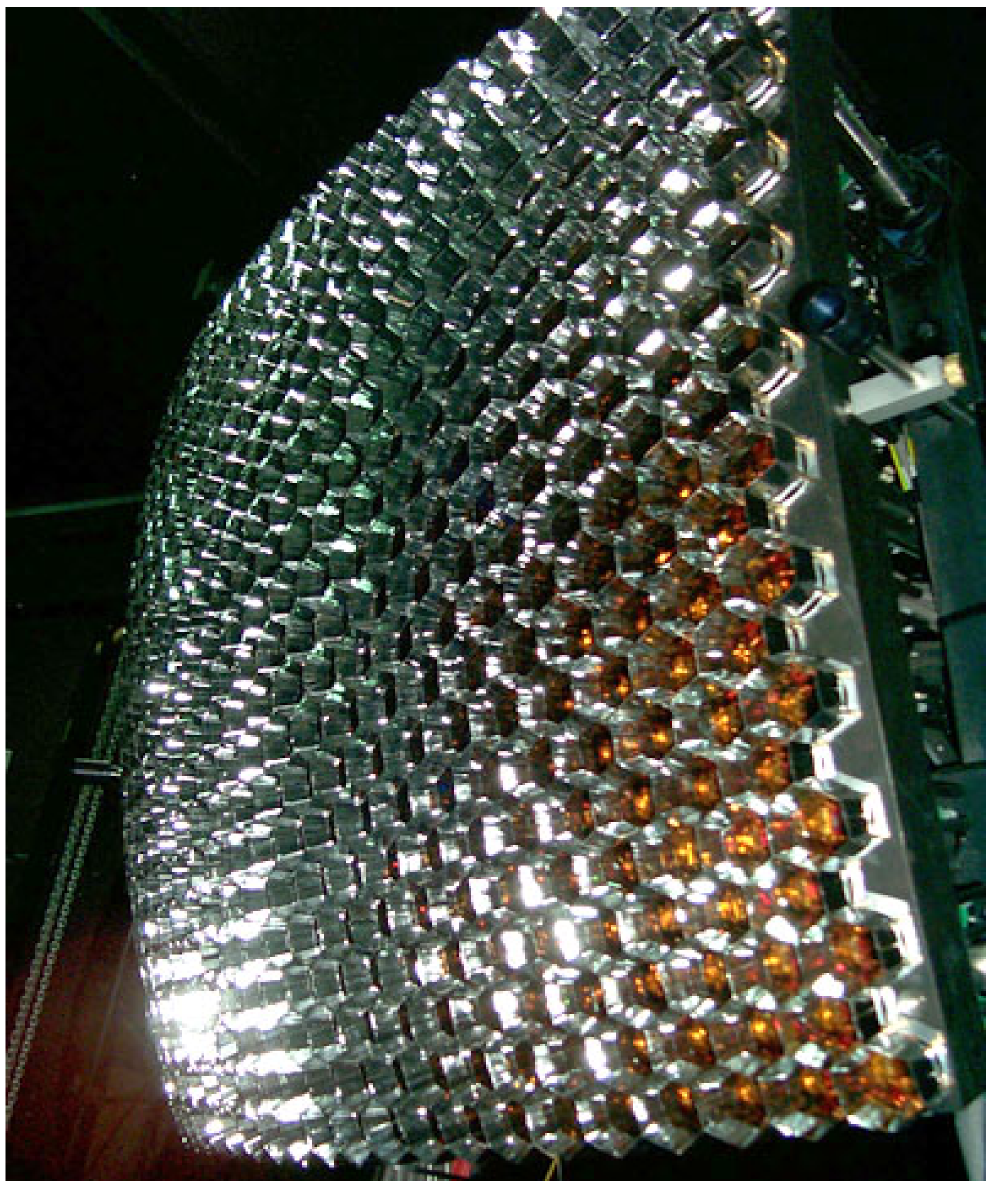


aperture with shutter,
filter and Schmidt
corrector lenses



$11\ m^2$ mirror
(Aluminium)

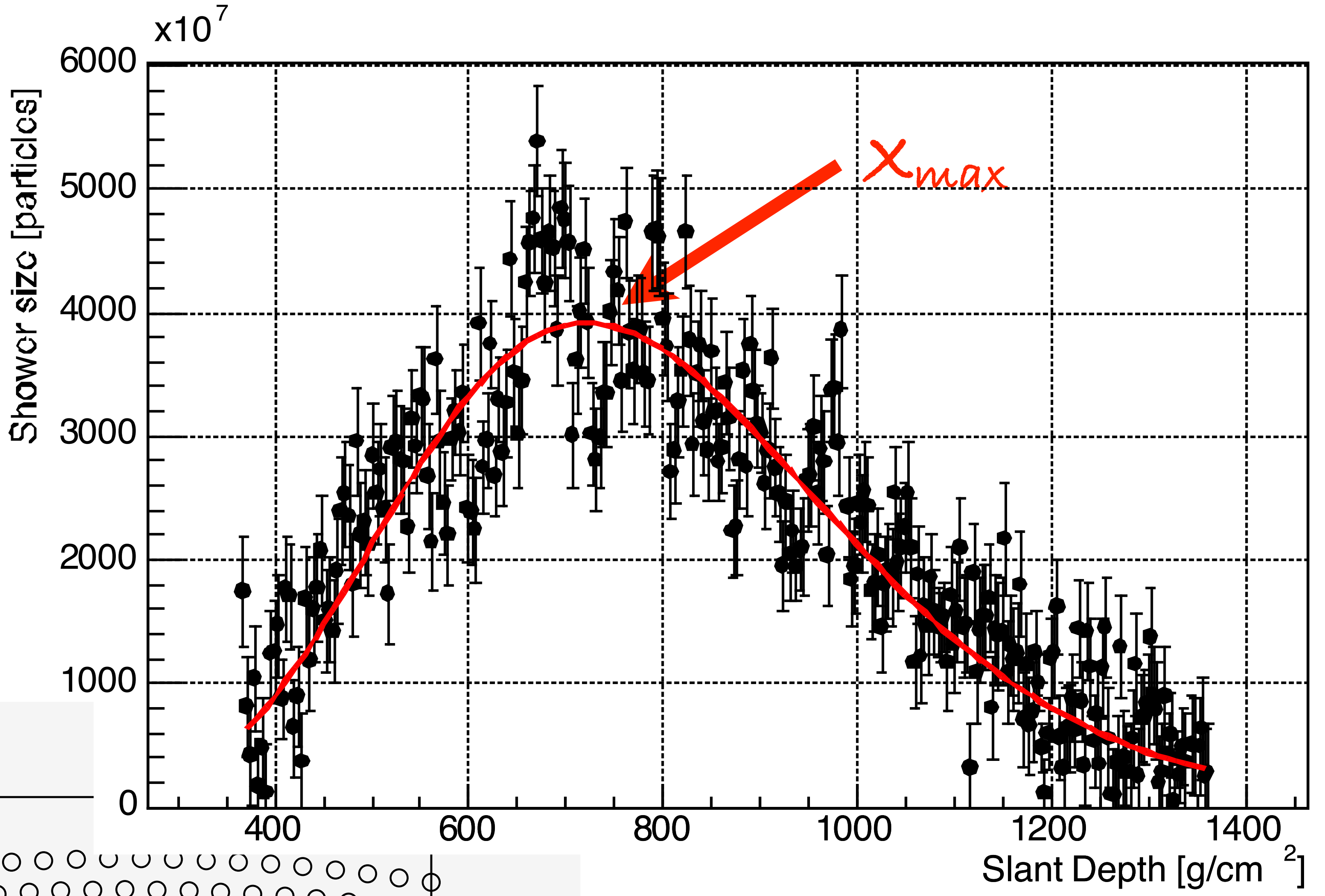
440 PMT camera

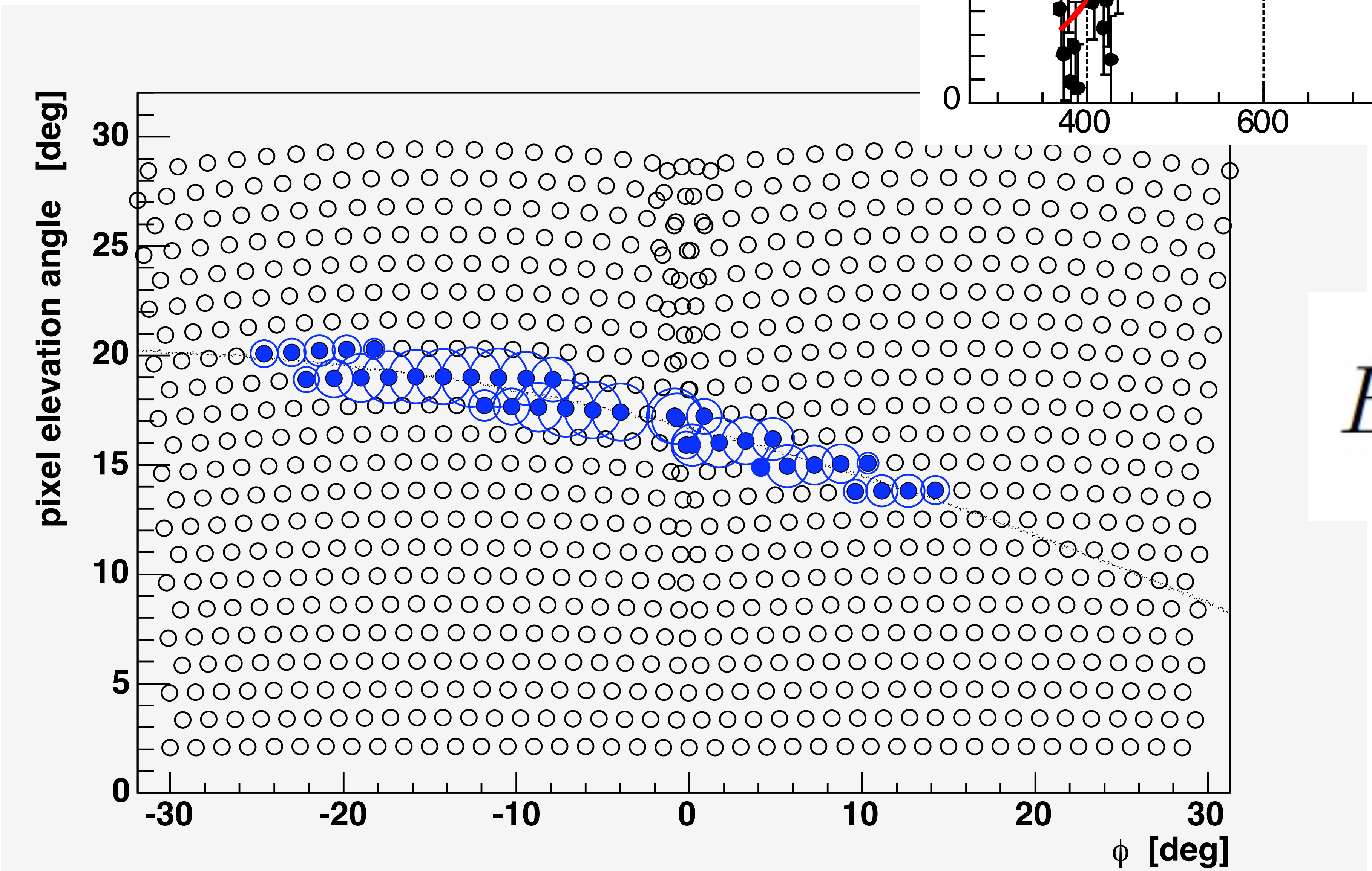


24 telescopes at 4 sites
$30^o \times 30^o$ FOV, each

FD:

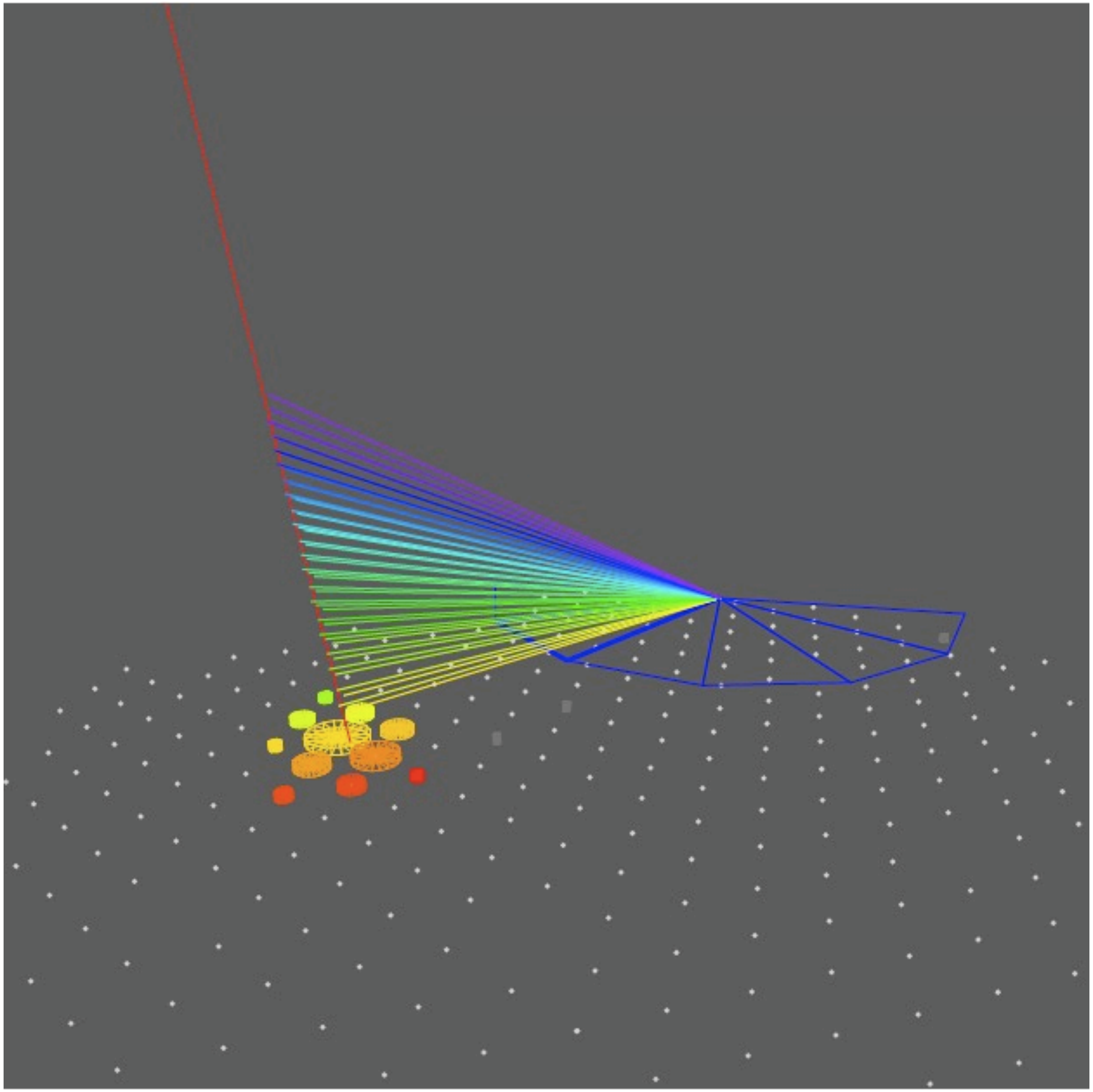
longitudinal profile,
calorimetric energy,
X_{max} for mass comp.



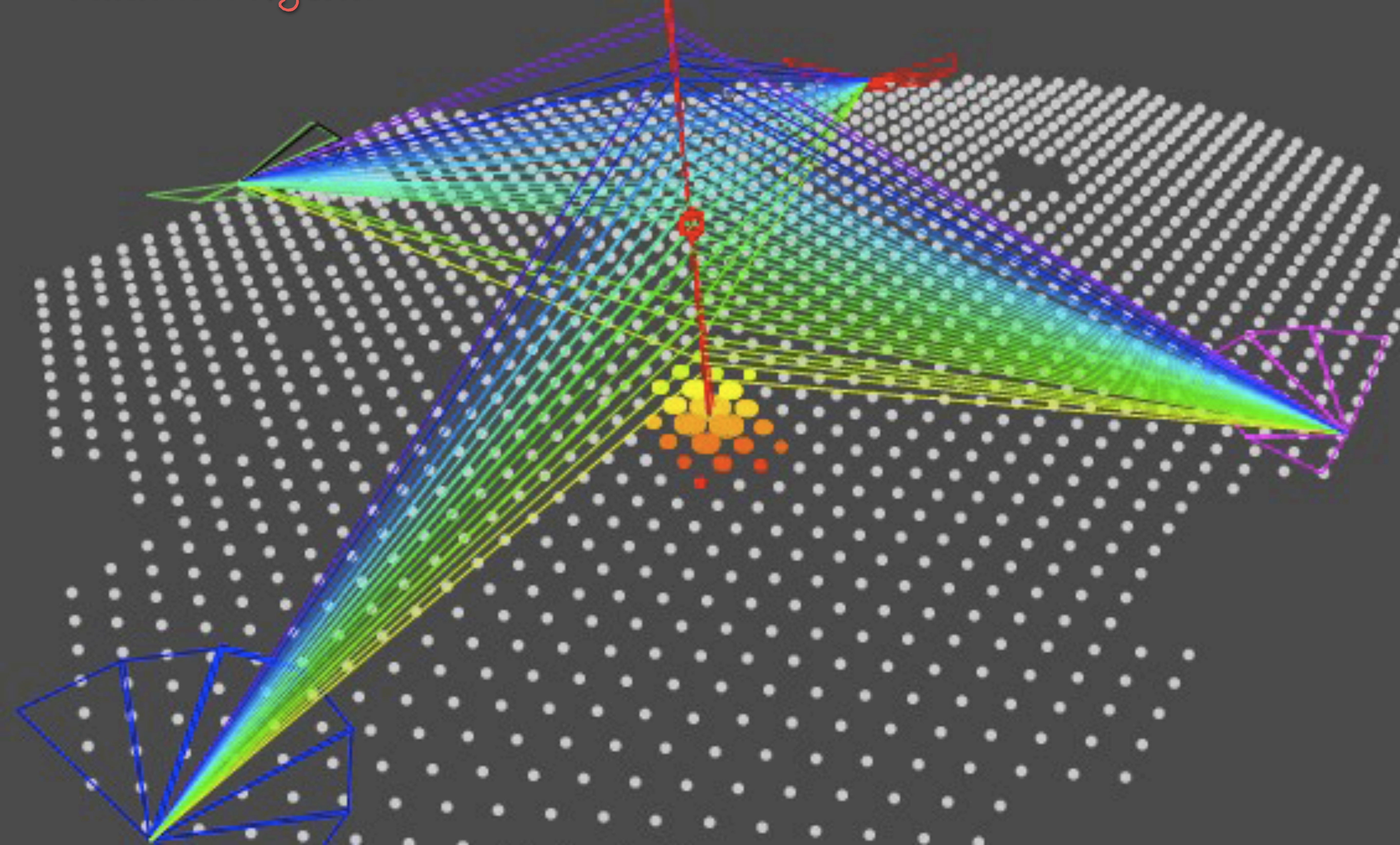


$$E \propto \int_0^\infty N(t)dt$$

golden hybrid event



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



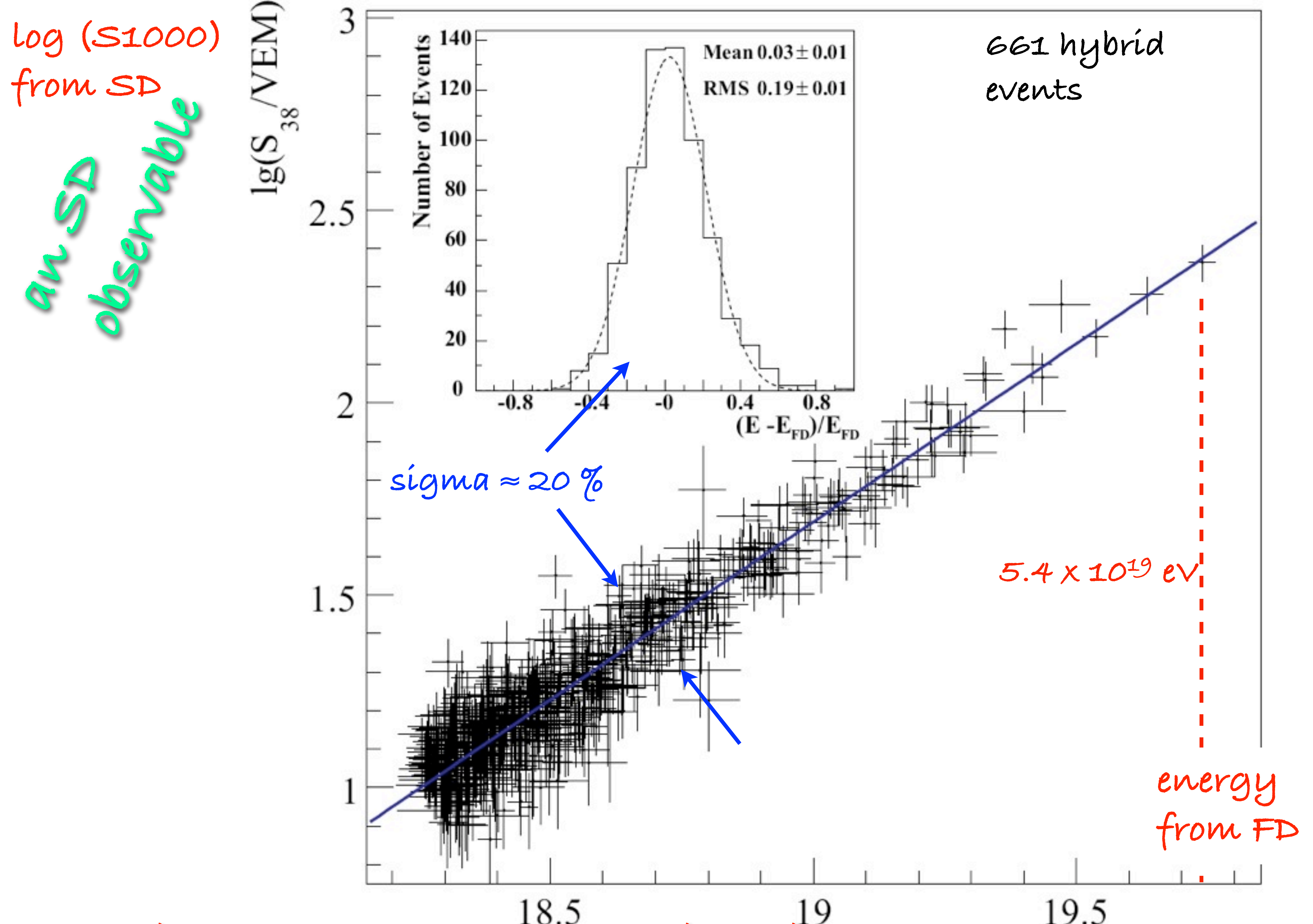
Some Results:

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

Data until Dec. 2010

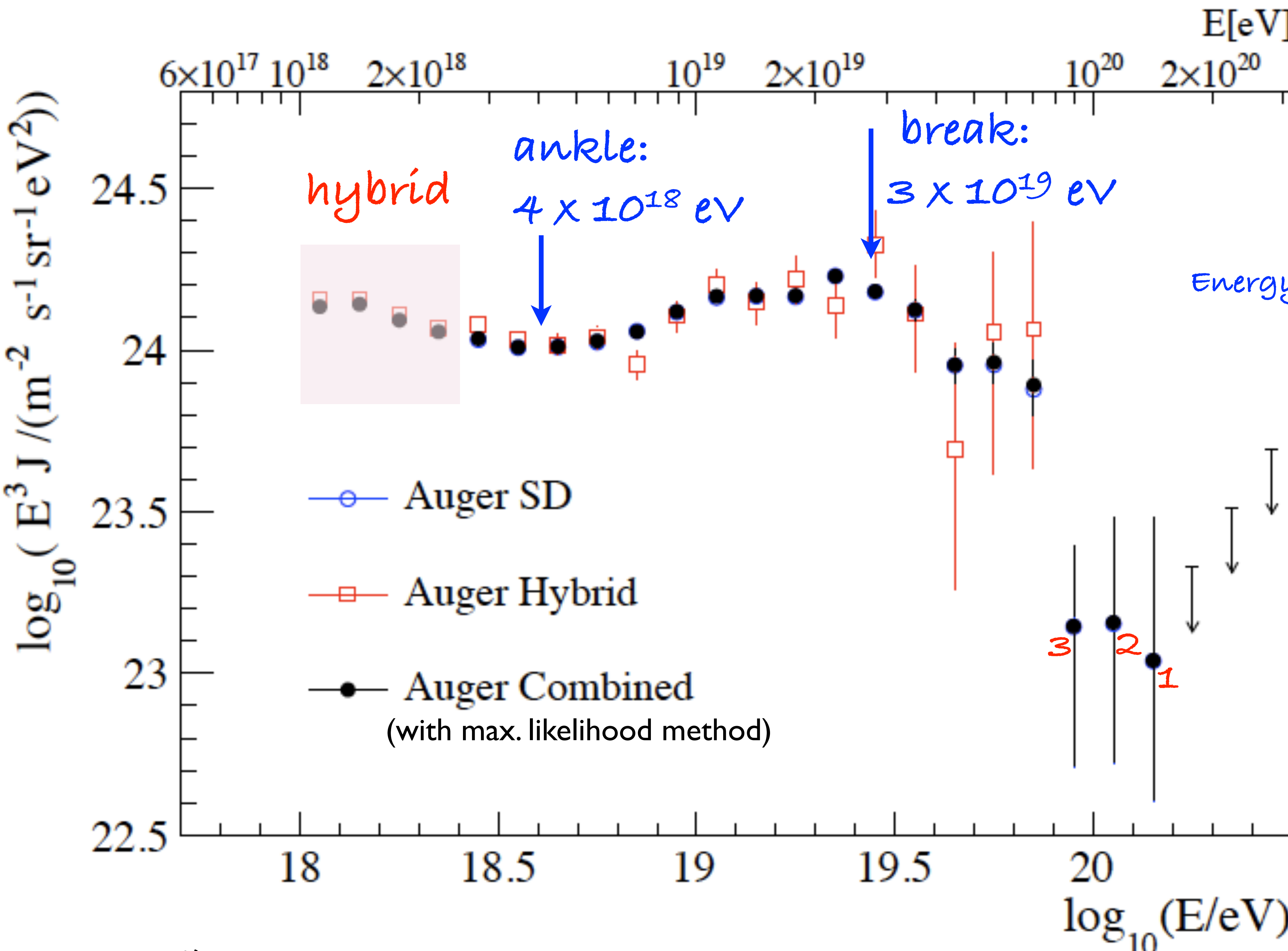
≈ 21000 km^2 yr sr

≈ 3.2 full-Auger yrs



Model independent energy calibration

Energy spectrum



Energy Resolution : 17%
systematics: 22%

$>10^{20}$ eV:

≈ 1 evt/yr in Auger

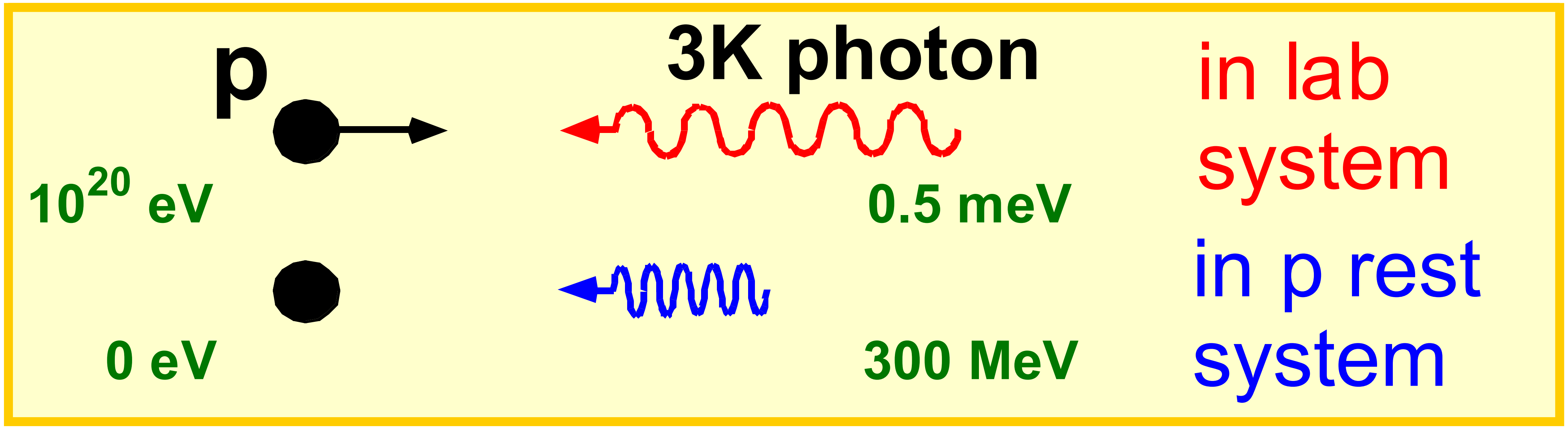
≈ 1 evt/min on surface of Earth !

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

$\theta = 0 - 60^\circ$

GZK Cut-Off

Greisen Zatsepin Kuzmin



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

photo - pion production

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

photo dissociation

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

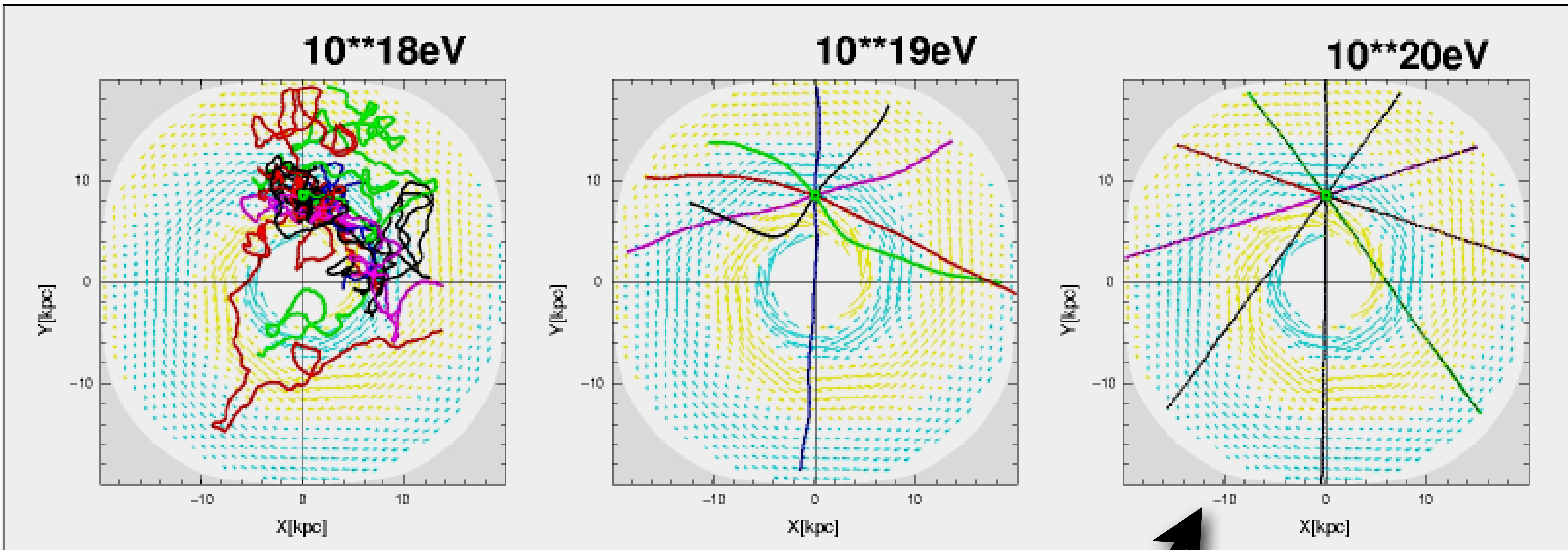
beyond this: **Sources must be close !**

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

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

Anisotropy - Sources (?)

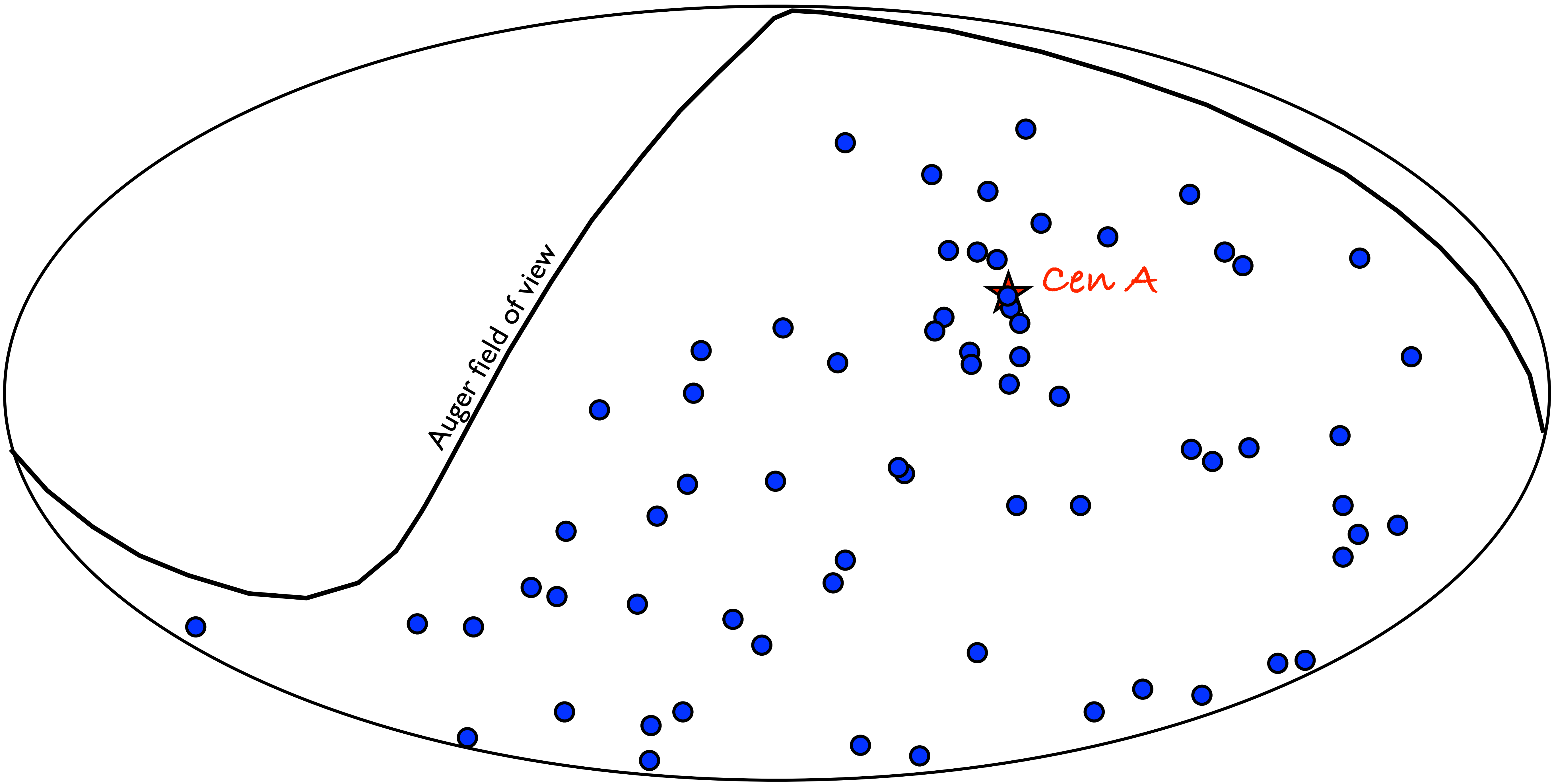
Highest Energy Particles are not deflected much !
i.e. CR should start pointing back at sources.



deflection < 1°

Astronomy with charged particles ?

69 Highest Energy Events >55 EeV (Dec 2009)



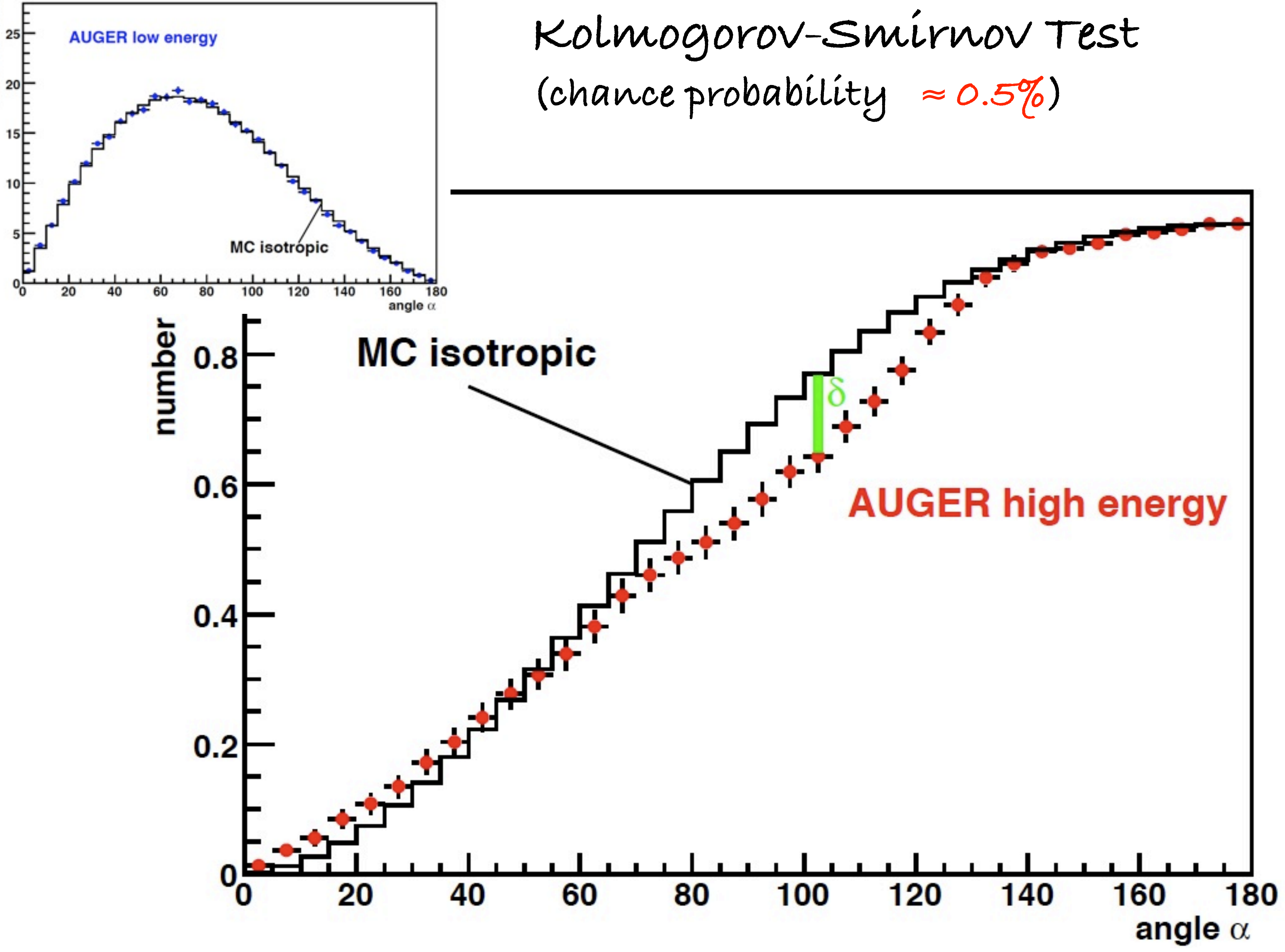
Isotropic ? Clustering ? Is Cen A a source ? ...

How to quantify ?

No enhancement from galactic disk. Extragalactic origin!

Kolmogorov-Smirnov Test

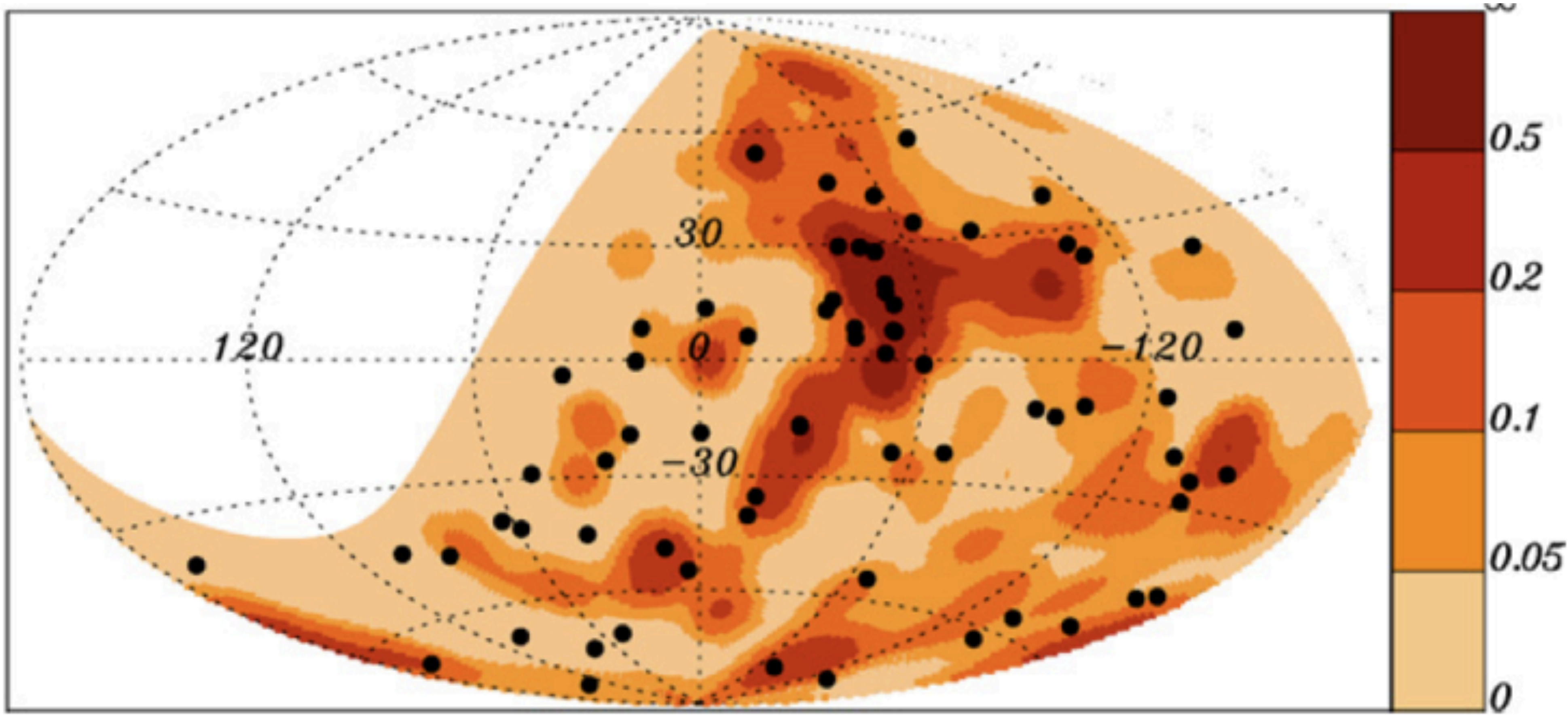
(chance probability $\approx 0.5\%$)



Swift-BAT

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

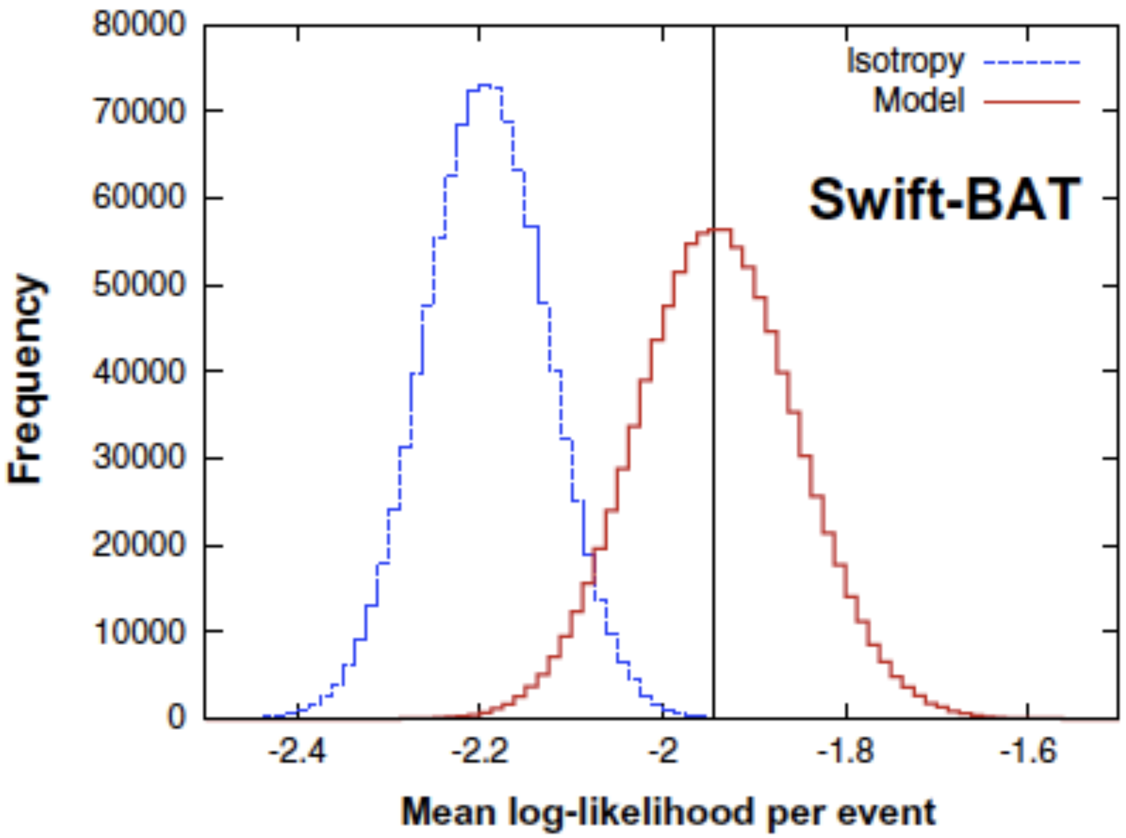
d < 200 Mpc
weighted with X-ray flux,
rel. exposure, GZK effect
5° smoothing



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

UHECRs come from
"nearby extragalactic matter"

≈30° clustering (protons ?)



data
isotropy
model

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

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

The CORSIKA program

http://www-ik.fzk.de/corsika

difficult !
need shower model
for interpretation

Fully 4-dim MC simulation

Hadronic (p-N, π-N, ... A-N)
and electromagnetic interactions.

cross-sections, particle production (at $\approx 0^{0}$).
soft interactions, decays, ...

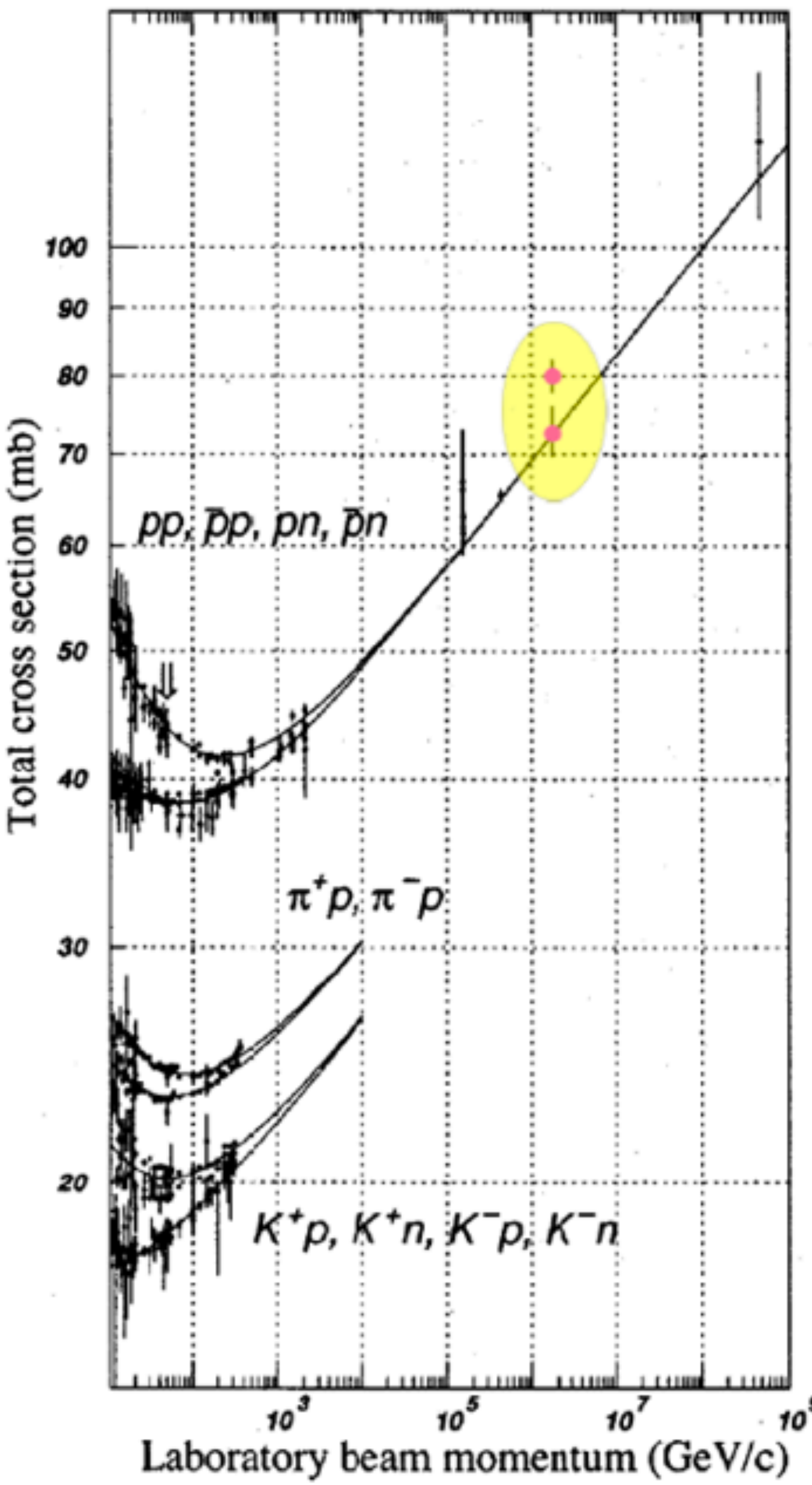
Models based on collider data (< TeV) and
a theory with some predictive power for
extrapolation to 10^{20} eV

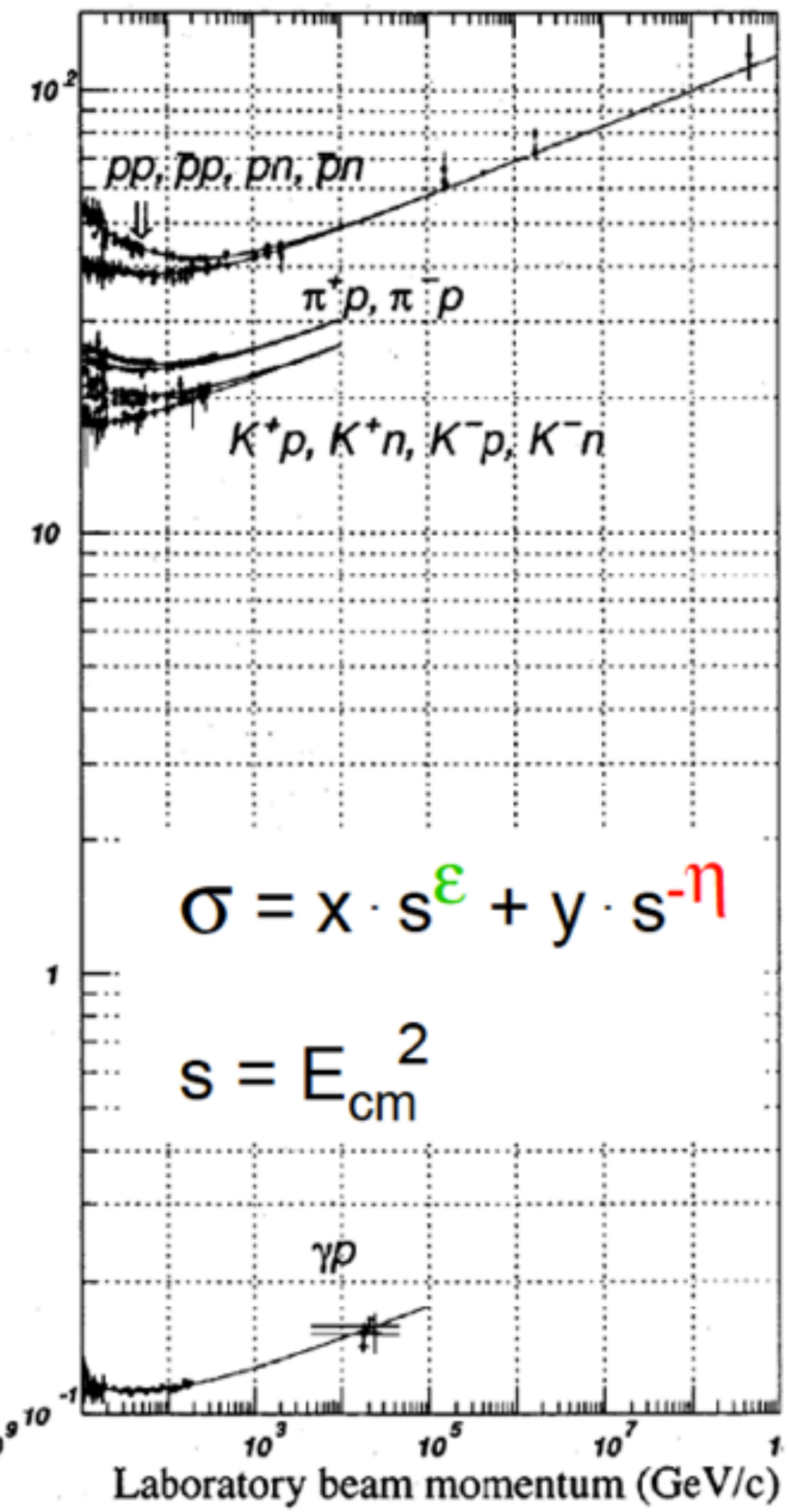
Gribov Regge Theory

Energies: 10^{6} ... 10^{20} eV

UHE Hadronic models are the major source of uncertainty.

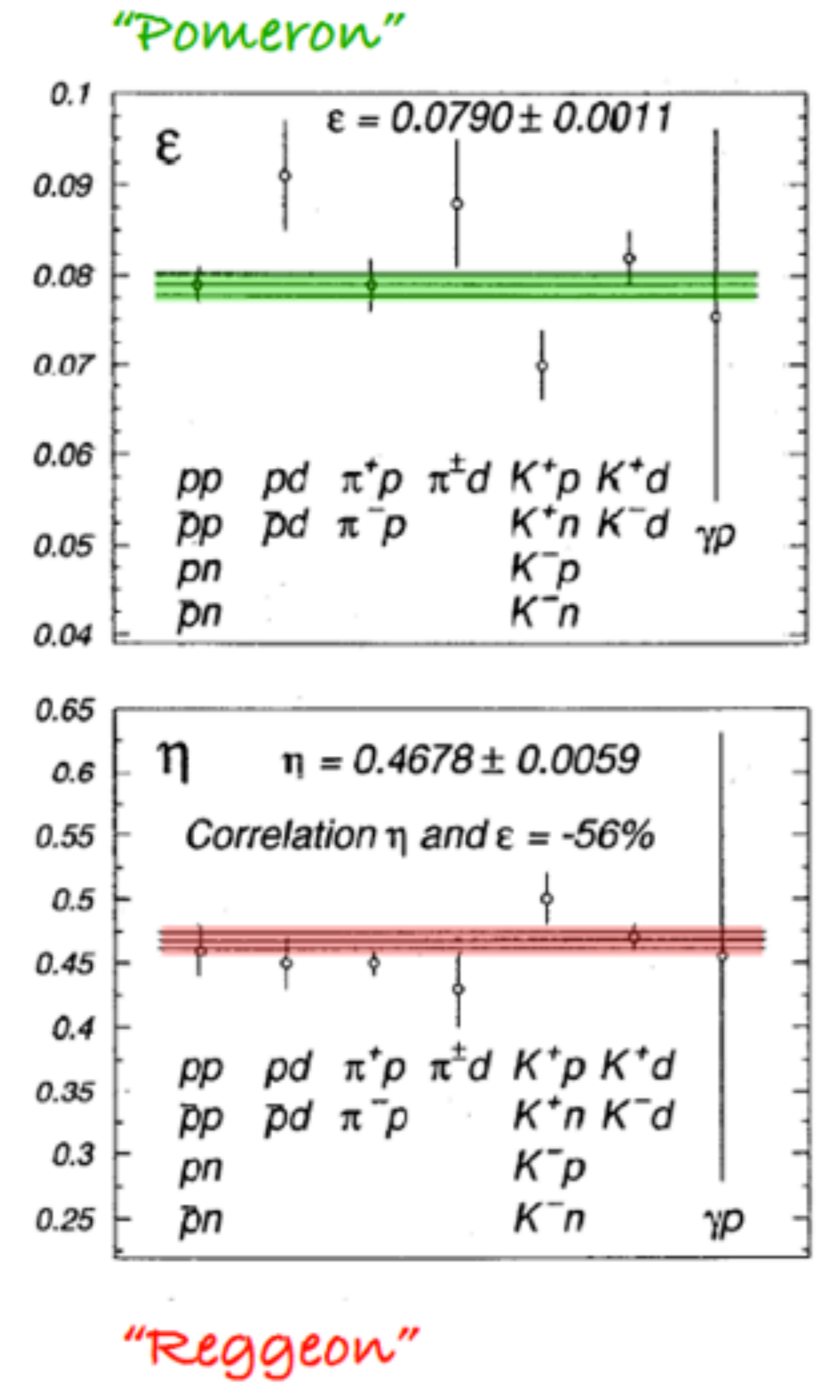
Cross-sections well described by "Reggeon" and "Pomeron" exchange





$$\sigma = x \cdot s^{\varepsilon} + y \cdot s^{-\eta}$$

$$s = E_{cm}^{2}$$



from Particle Data Book 1996

CORSIKA: is not perfect but gives reasonable agreement of simulations with air shower data from 10^{11} eV to 10^{20} eV:

HESS, VERITAS, Magic	γ ray astron.;	10^{11}-10^{14} eV
KASCADE-Grande	CR showers;	10^{14}-10^{17} eV
Haverah Park		10^{17}-10^{18} eV
Auger		10^{18}-10^{20} eV

reasonable agreement: $\sim$ 30% level for $<10^{18}$ eV

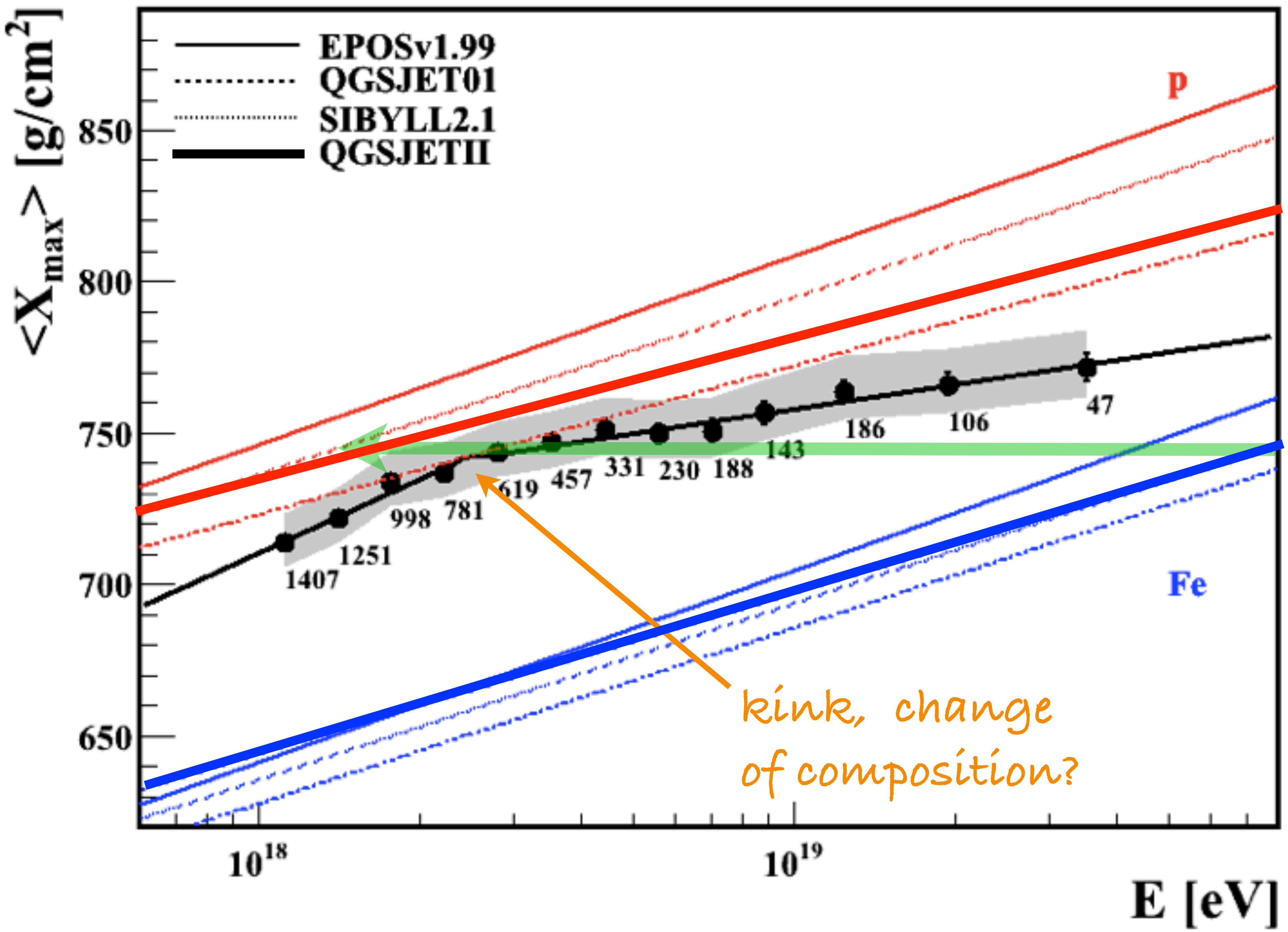
Nuclear Composition

X_{max}: height of shower maximum

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

difficult !
need shower model
for interpretation

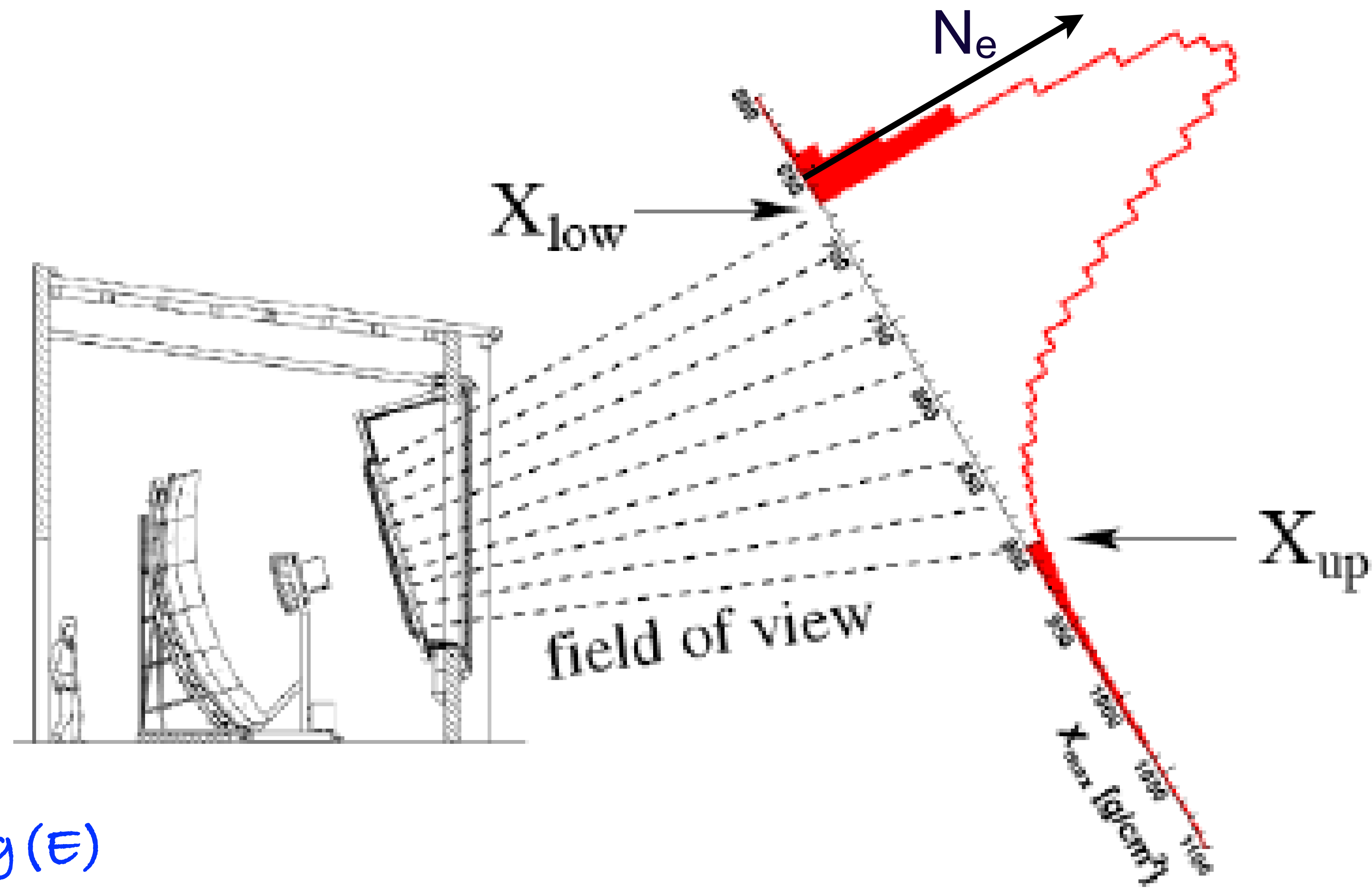
FD:



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

same E/A
same X_{max}

kink, change
of composition?



X_{max}: grows with log(E)

p: penetrate deeper, larger X_{max}

Fe: develop earlier, smaller X_{max}

difference about 70 g/cm²

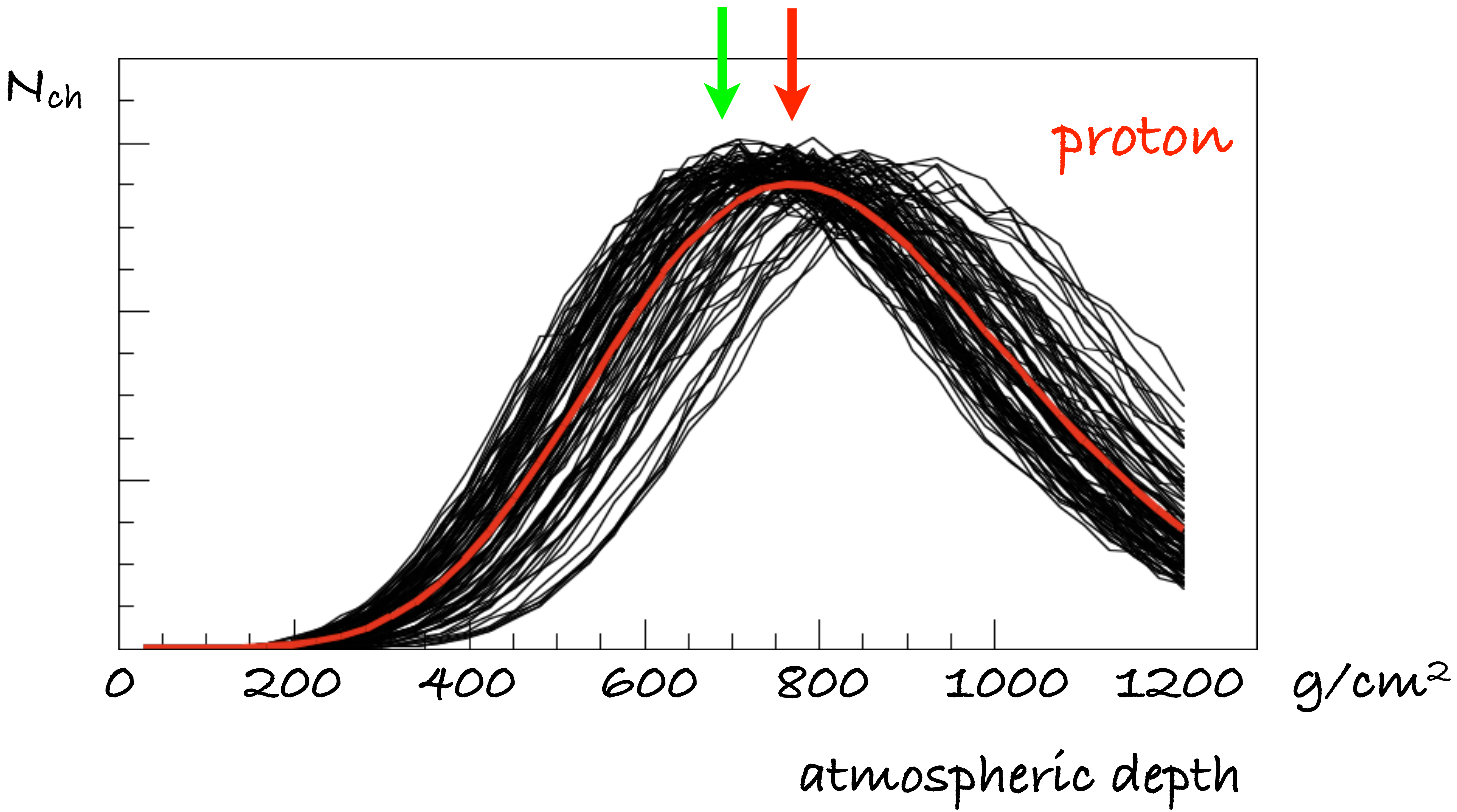
$X_{max}(p)$ fluctuates much more than $X_{max}(Fe)$

$RMS(X_{max}(p)) \approx 60$ g/cm² $RMS(X_{max}(Fe)) \approx 20$ g/cm²

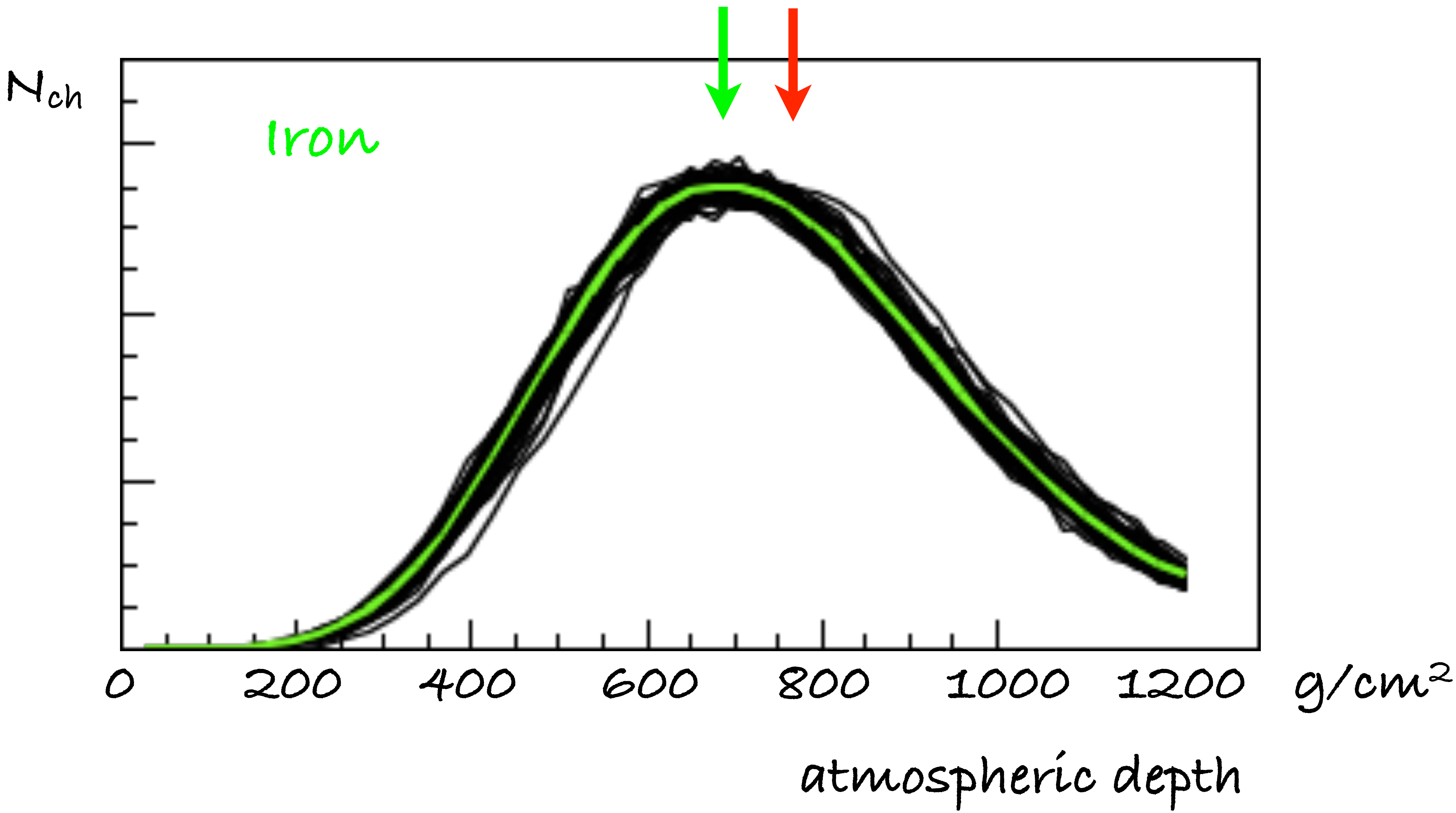
largely due to σ_{inel} of primary particle.

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

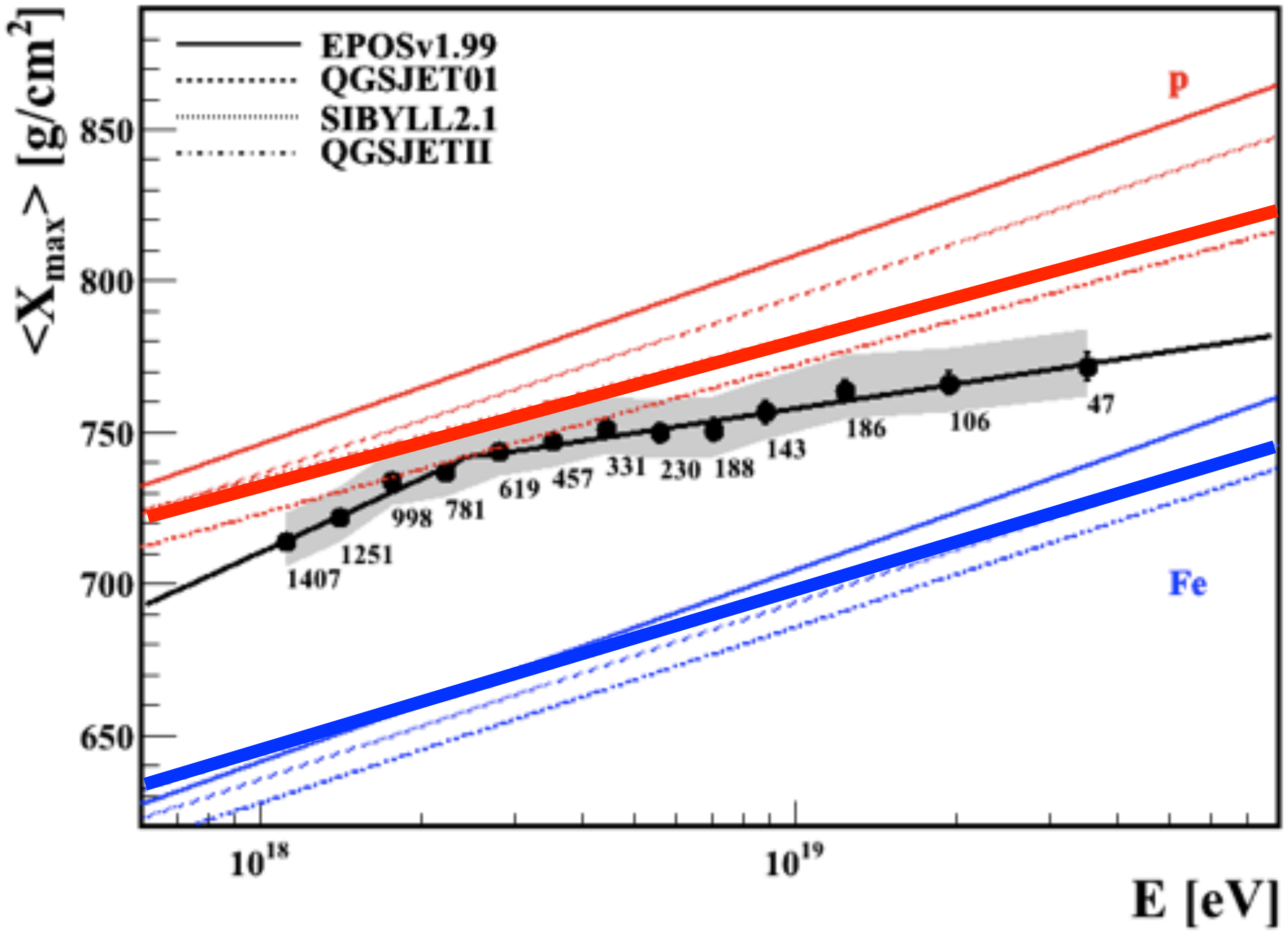
100 proton showers, 10^{19} eV



50 Iron showers, 10^{19} eV

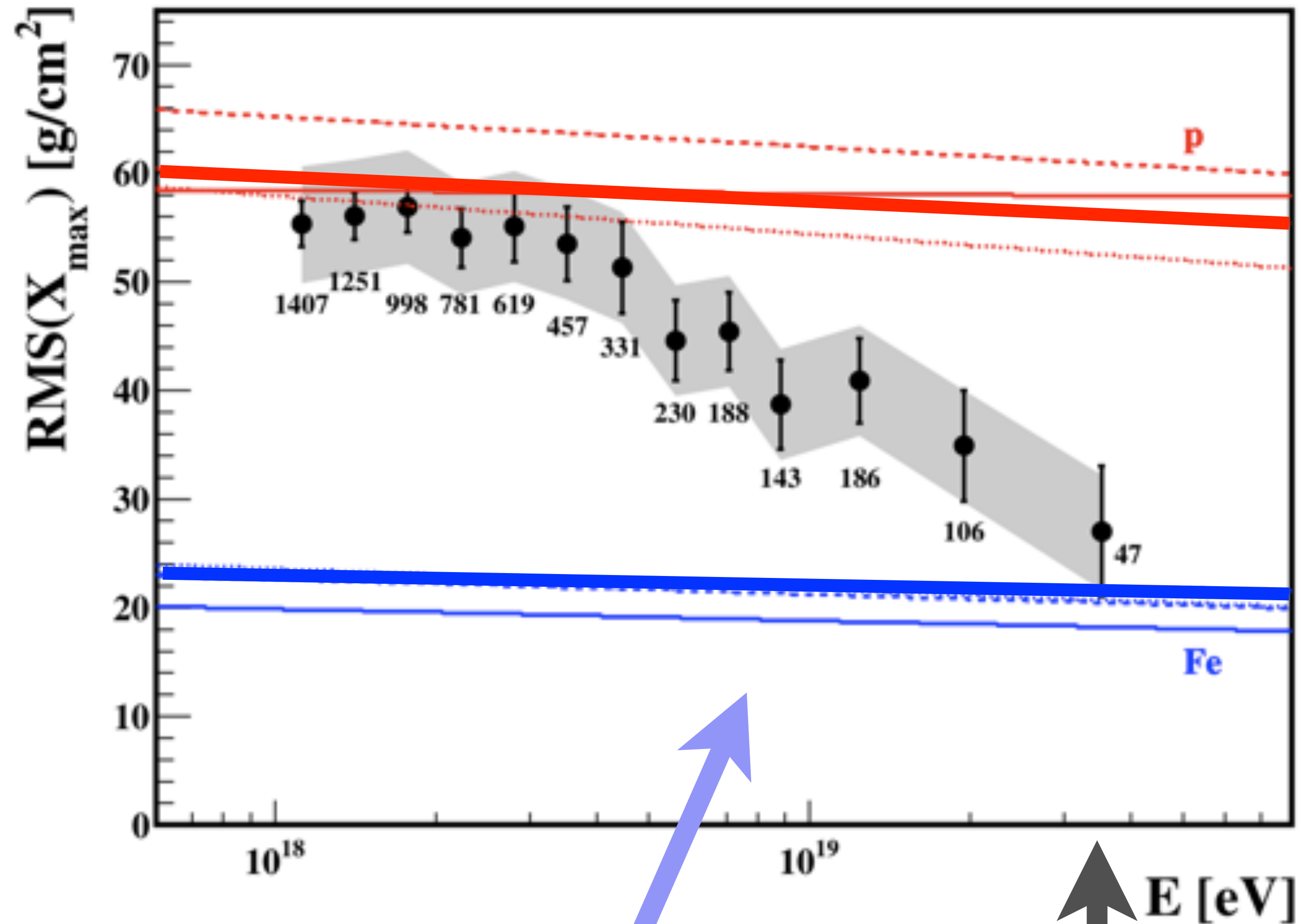


X_{max}



model dependent interpretation

RMS(X_{max})



whatever we do to models (within limits),

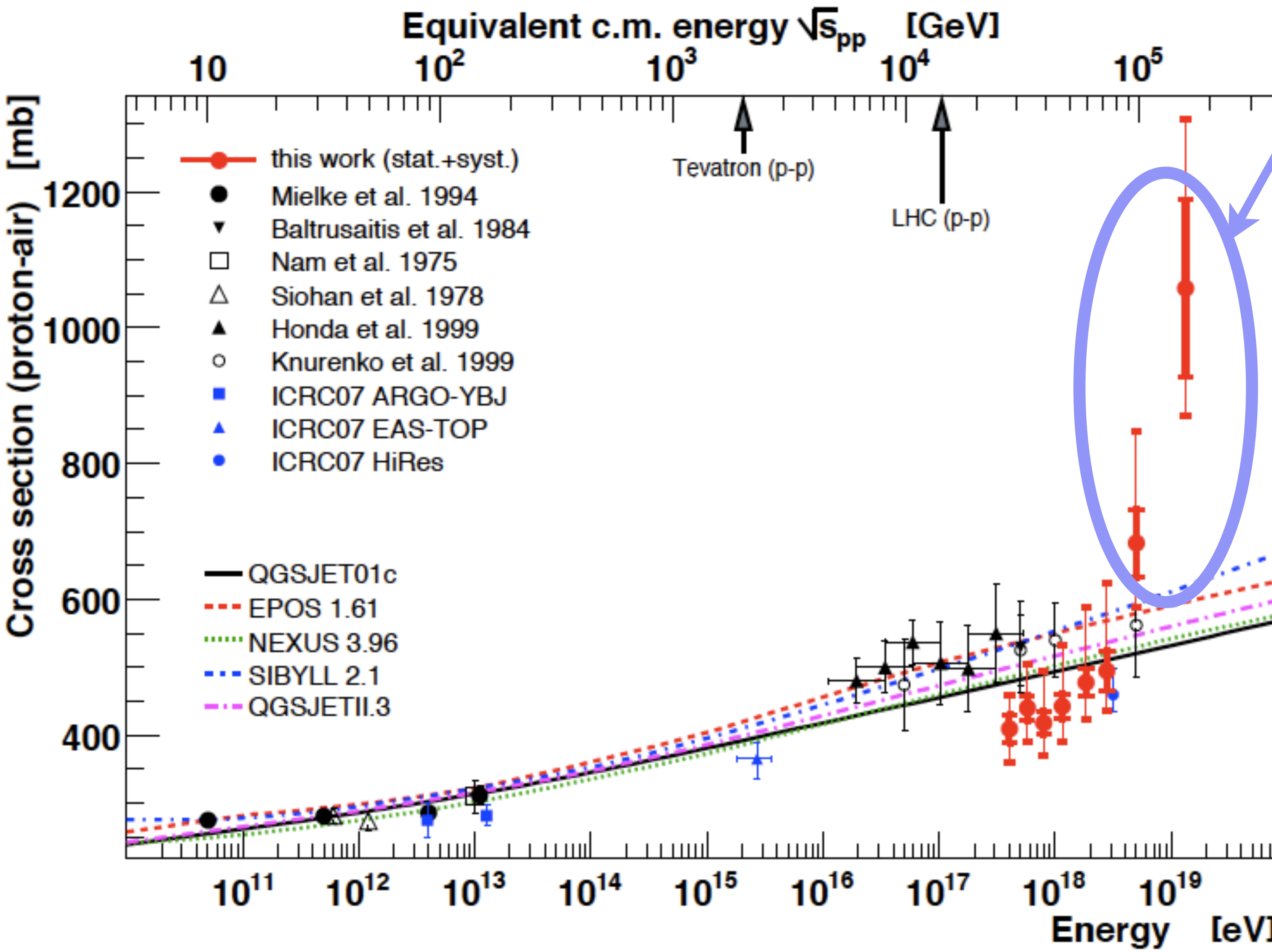
data do not fit to primary proton sims.

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

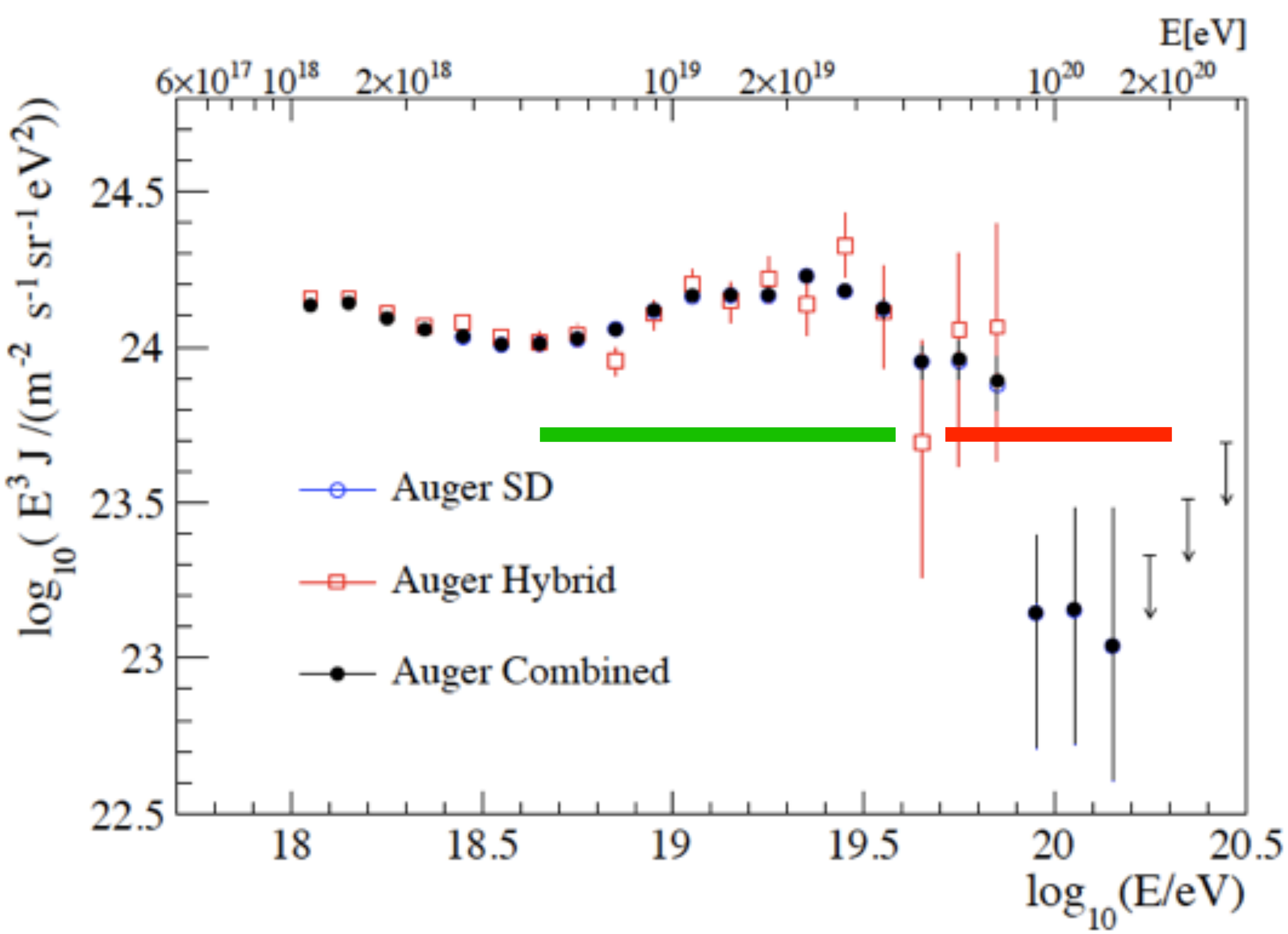
Spectrum: GZK cut-off ?

Anisotropy: correlation with nearby matter

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

Composition: X_{max}, SD variables

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



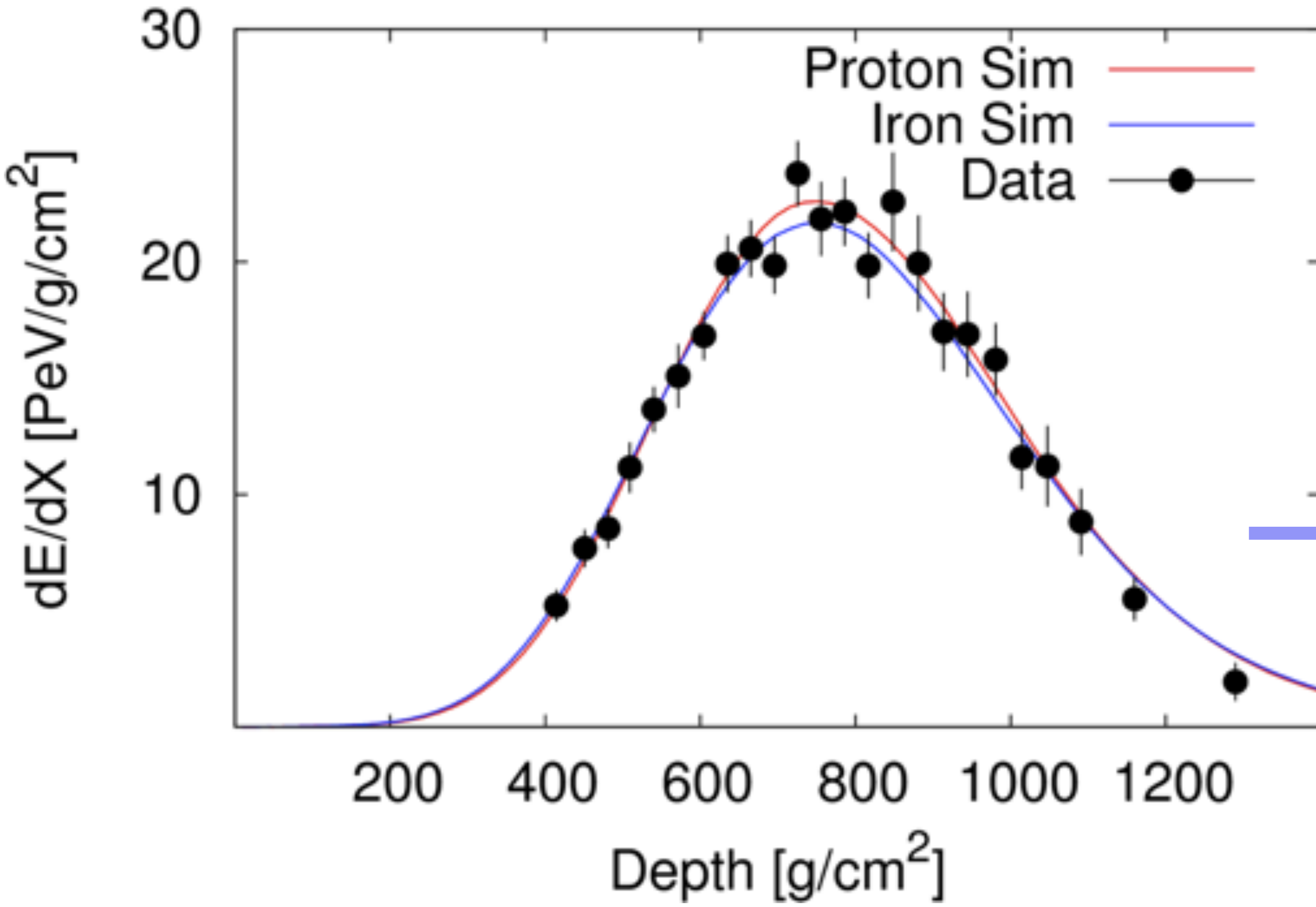
strongly model dependent

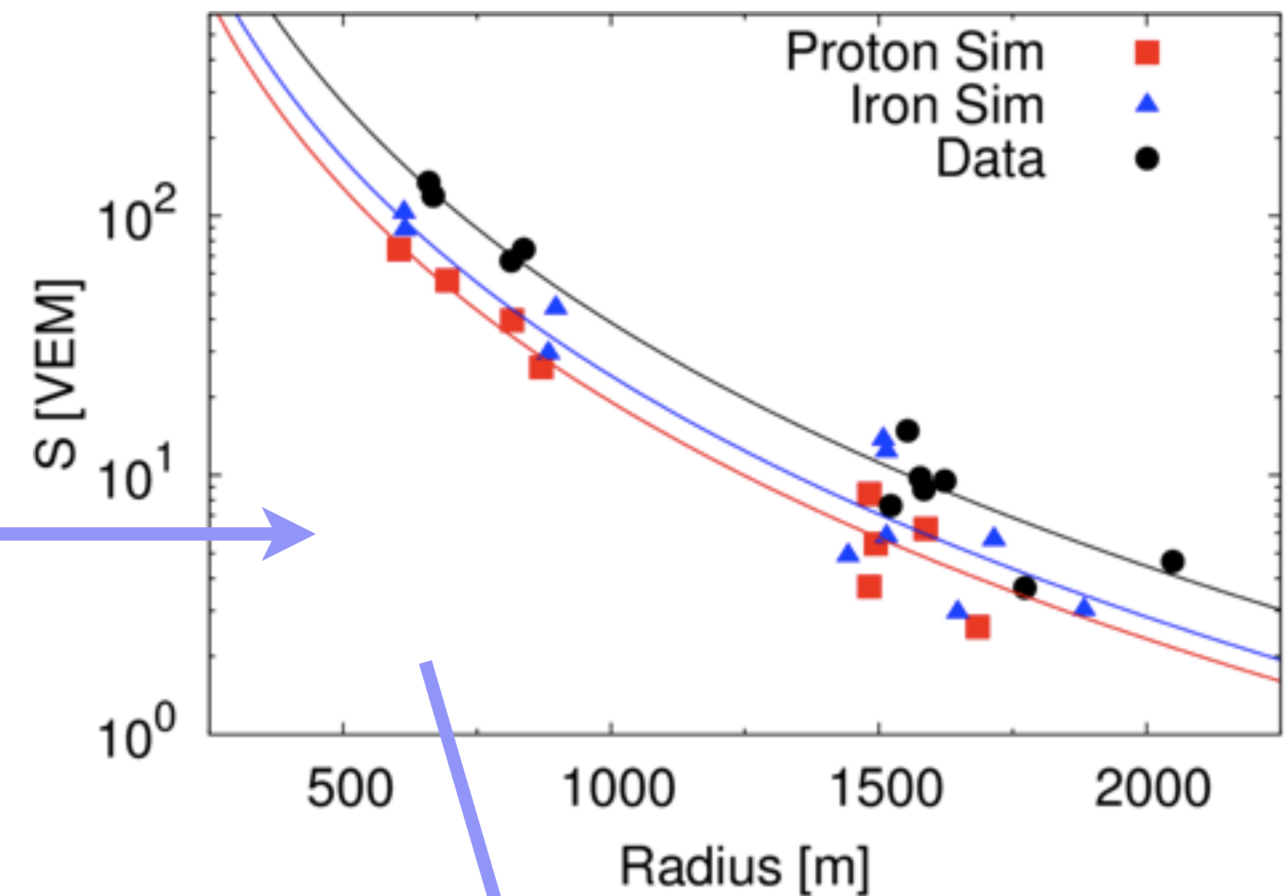
Need hadronic interaction models to be modified ?

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

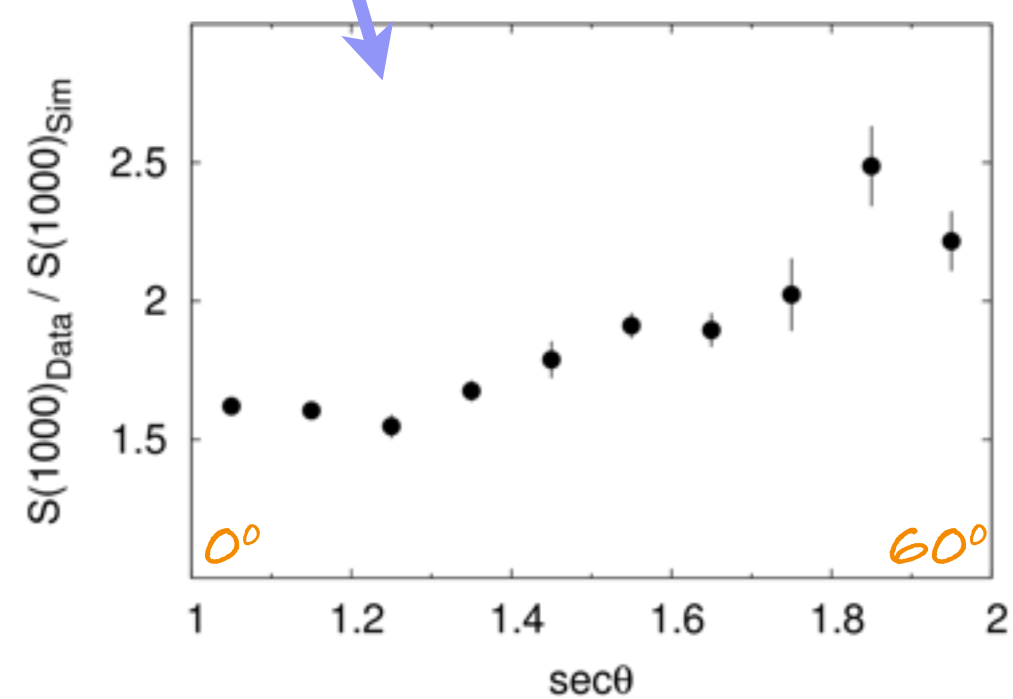
Are the EAS models right ?

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



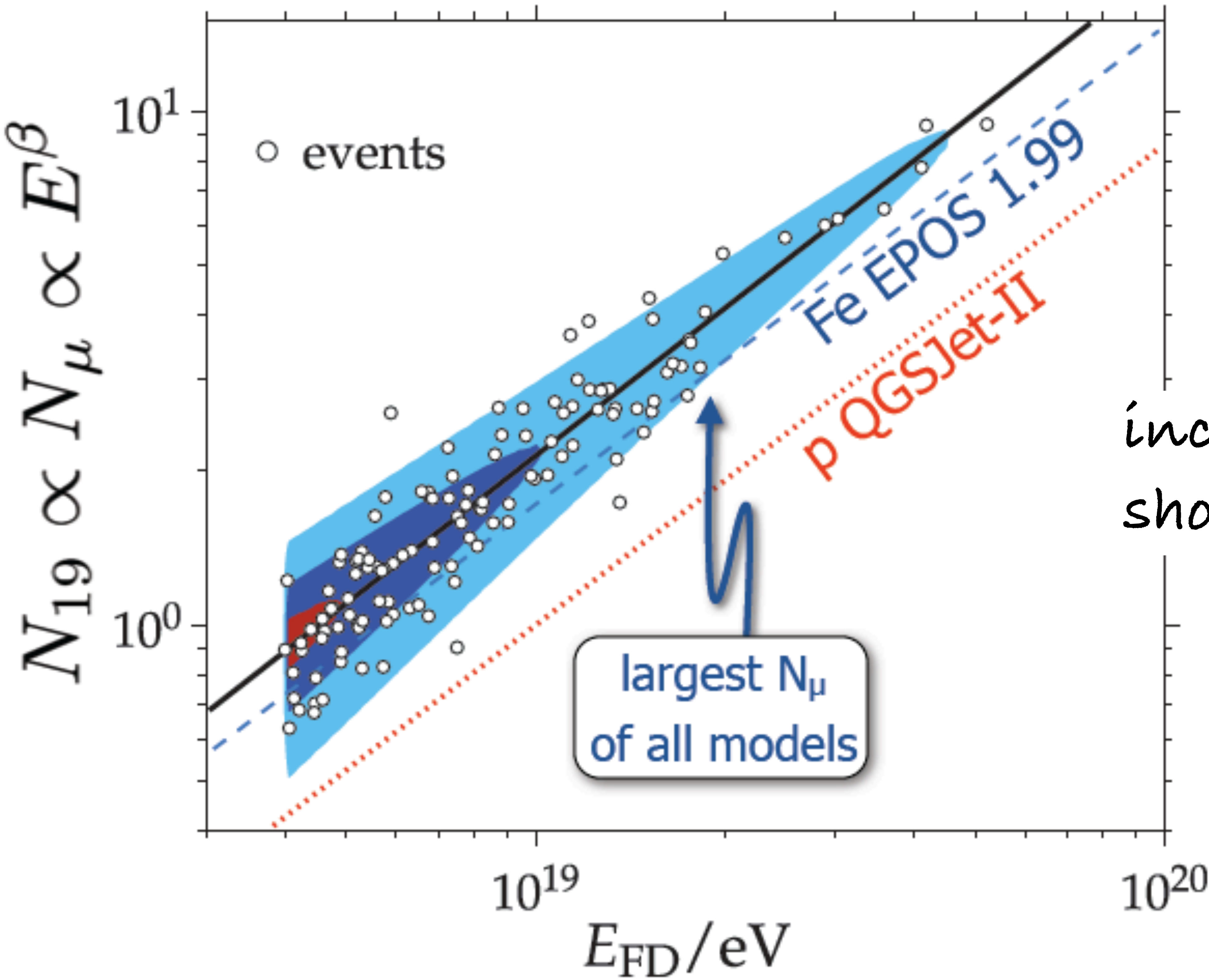


match the long. shower profile (as seen in FD)
of a measured event with
p and Fe simulations



μ content rises with θ

models underestimate
ground signal by 1.5 - 2x



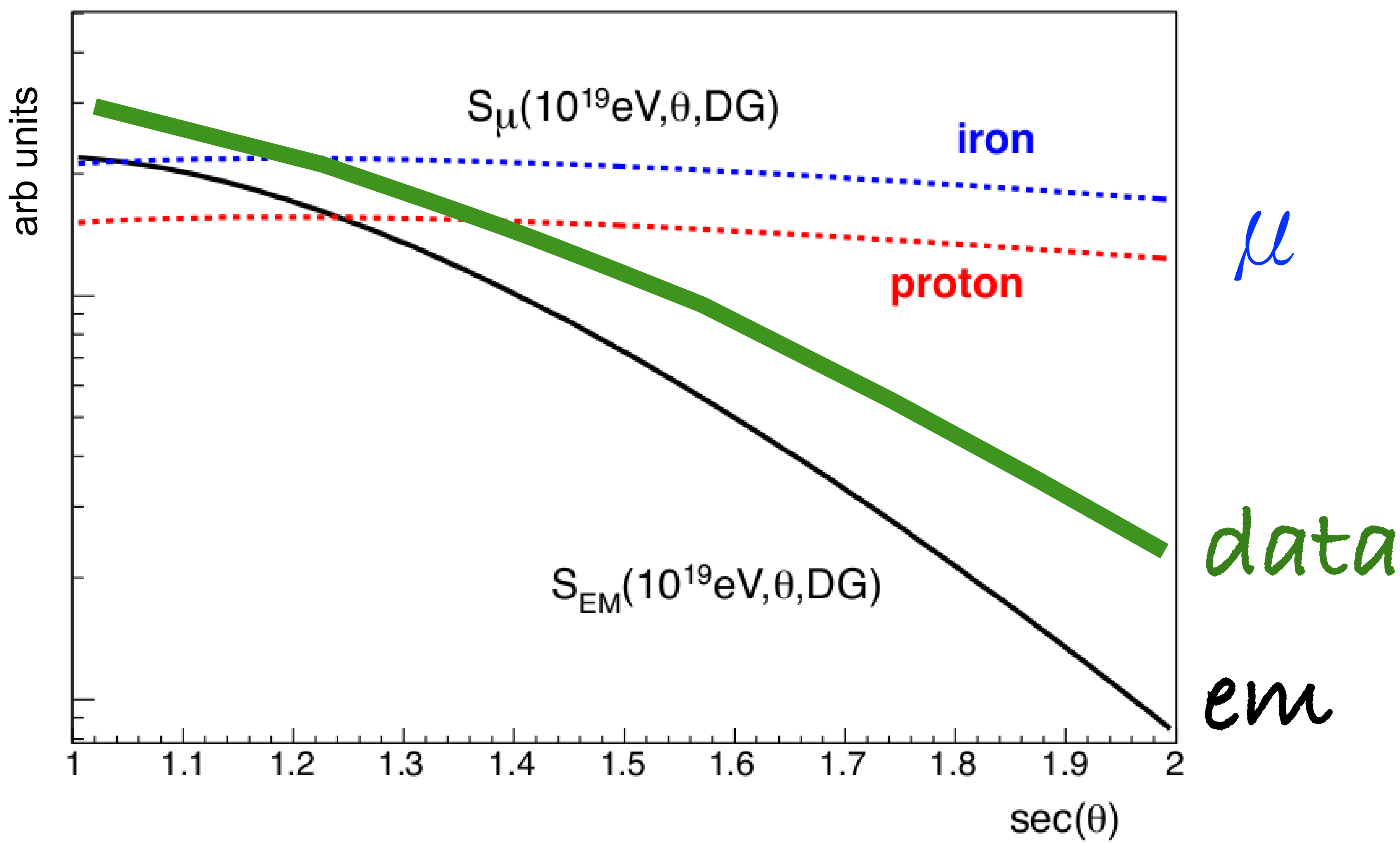
inclined showers

models underestimate N_μ by 25-100%

for Fe for p

Universality:

em and muonic signal depend only on E and shower development (DG)



measure $S_{1000}(\theta)$, compare with simulations

Result: muon deficit (≈ 53%) in simulations

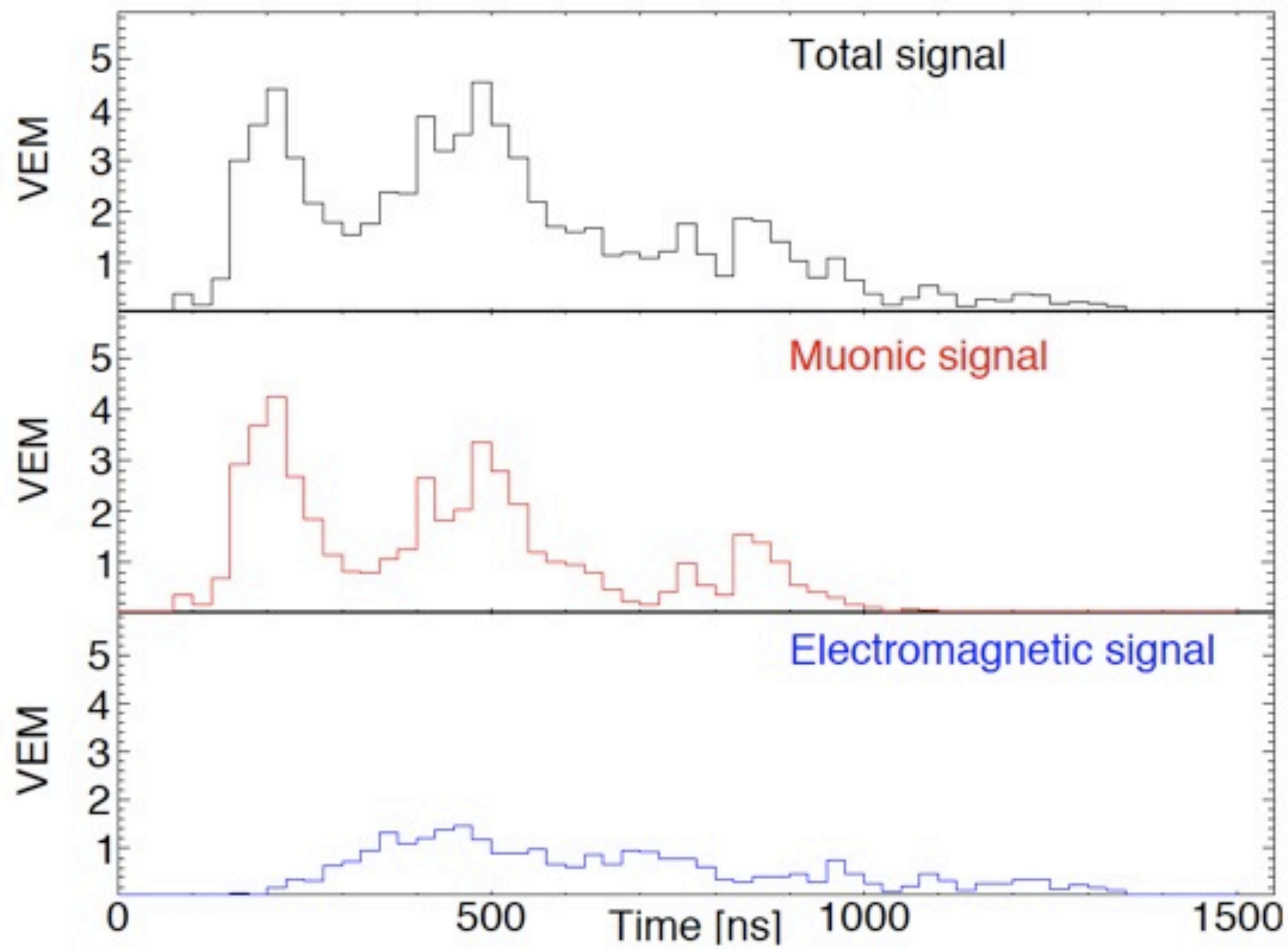
i.e. 26% higher energy estimate than FD

Other methods:

jump method: count muon peaks in time traces

smoothing method: separate e,γ and μ signal

golden hybrid analysis: compare SD with FD reconstruction



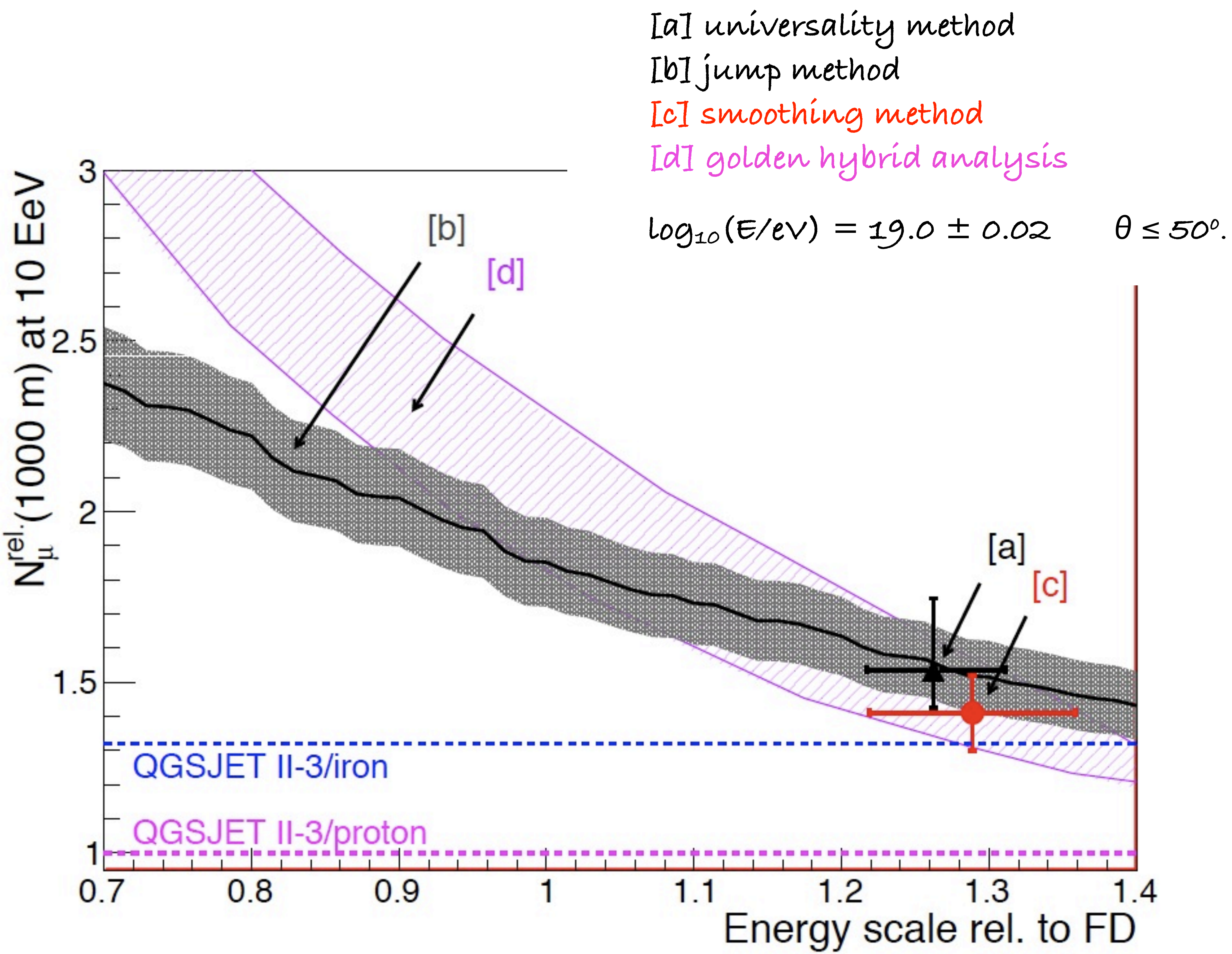
$E_{e,\gamma} \approx$ MeV

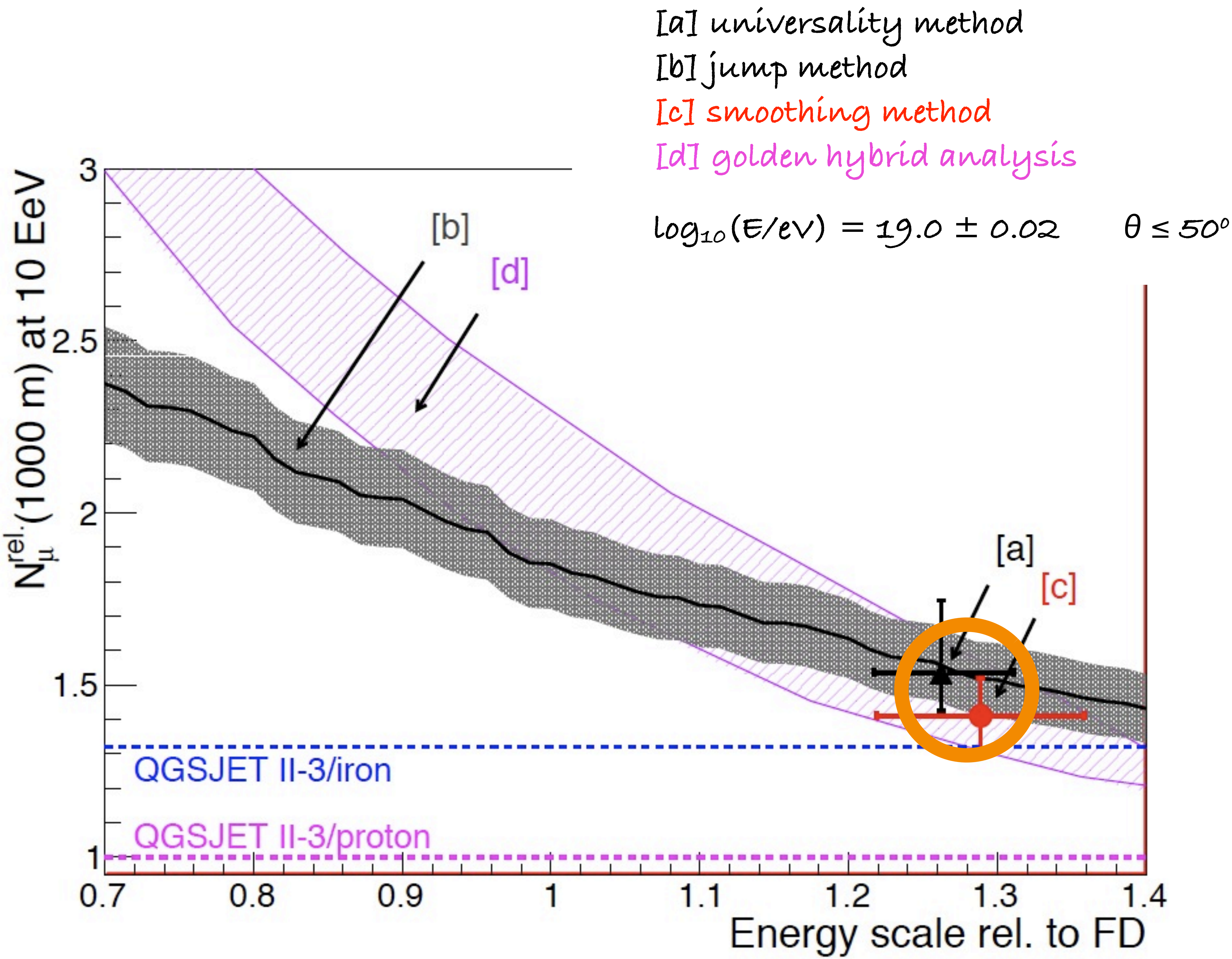
$E_\mu \approx$ GeV

≈ 240 MeV energy deposit

spiky

smooth


[a] universality method
[b] jump method
[c] smoothing method
[d] golden hybrid analysis
$\log_{10}(E/eV) = 19.0 \pm 0.02$ $\theta \leq 50^{\circ}$.
[b]
[d]
[a]
[c]
QGSJET II-3/iron
QGSJET II-3/proton
$N_{\mu}^{rel.}$(1000 m) at 10 EeV
Energy scale rel. to FD
3
2.5
2
1.5
1
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4



[a] universality method
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$\log_{10}(E/eV) = 19.0 \pm 0.02$
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[b]
[d]
[a]
[c]
QGSJET II-3/iron
QGSJET II-3/proton
$N_{\mu}^{rel.}$(1000 m) at 10 EeV
Energy scale rel. to FD
3
2.5
2
1.5
1
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4

Consistent findings:

Air shower models require modifications:

Muons	need ≈ 1.3 - 2x more,	@ 10^{19} eV
ground signal	need ≈ 1.5 - 2x more	

for the same longitudinal profile.

hadronic model ?

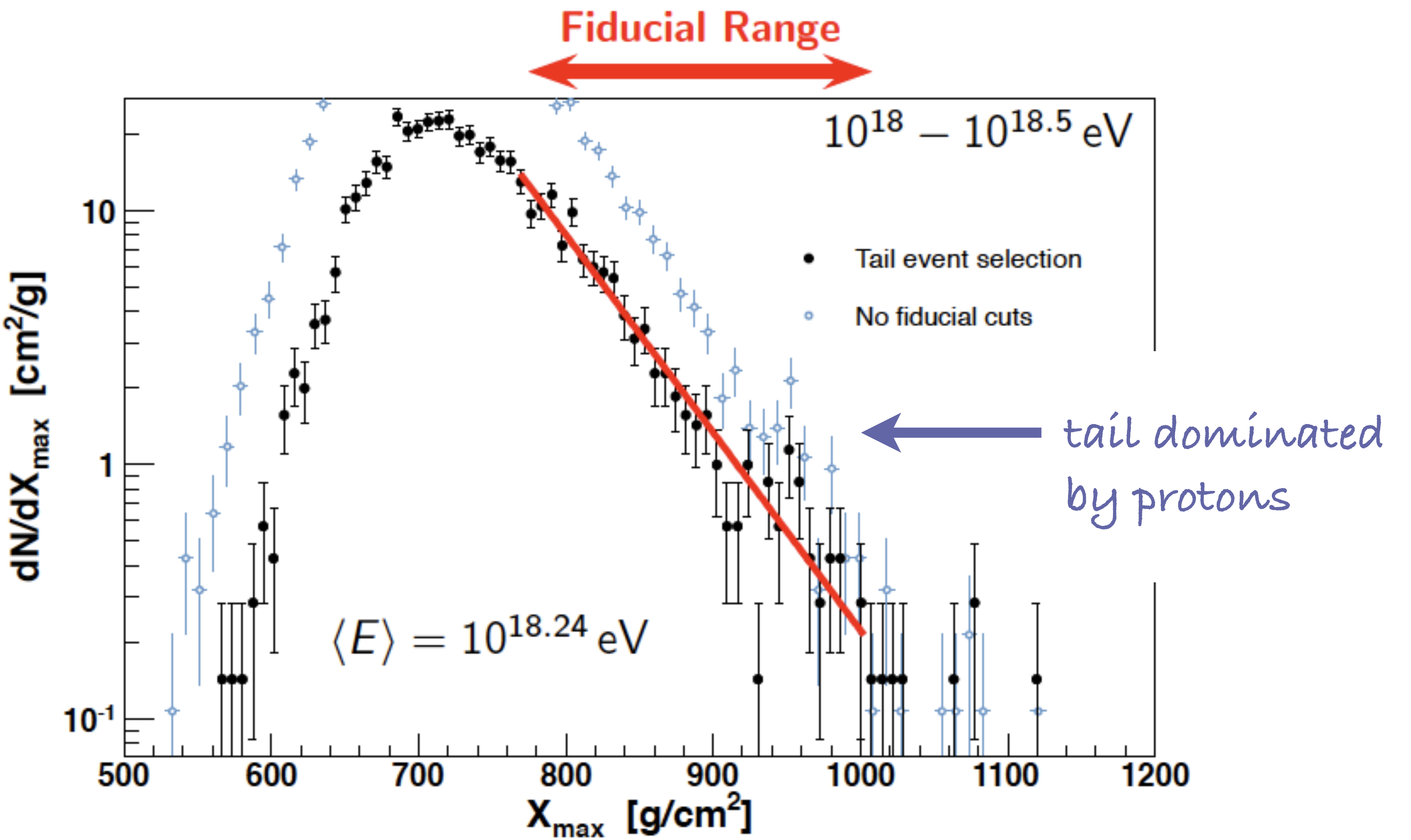
fluorescence yield ?

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

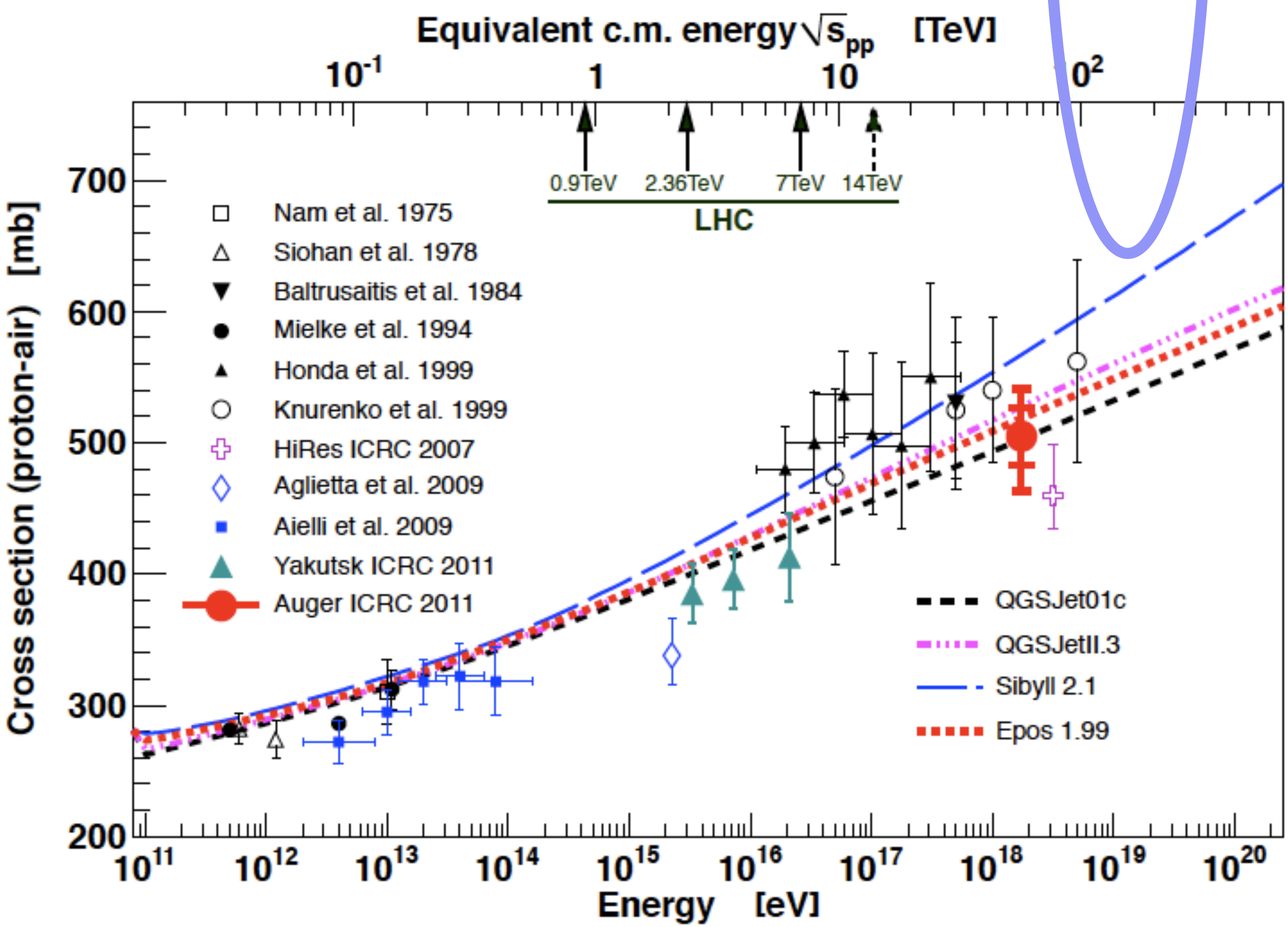
EPOS: a new model, with enhanced baryon production makes about 50% more muons.....

Proton-Air Cross-Section

... from tail of X_{max} distribution

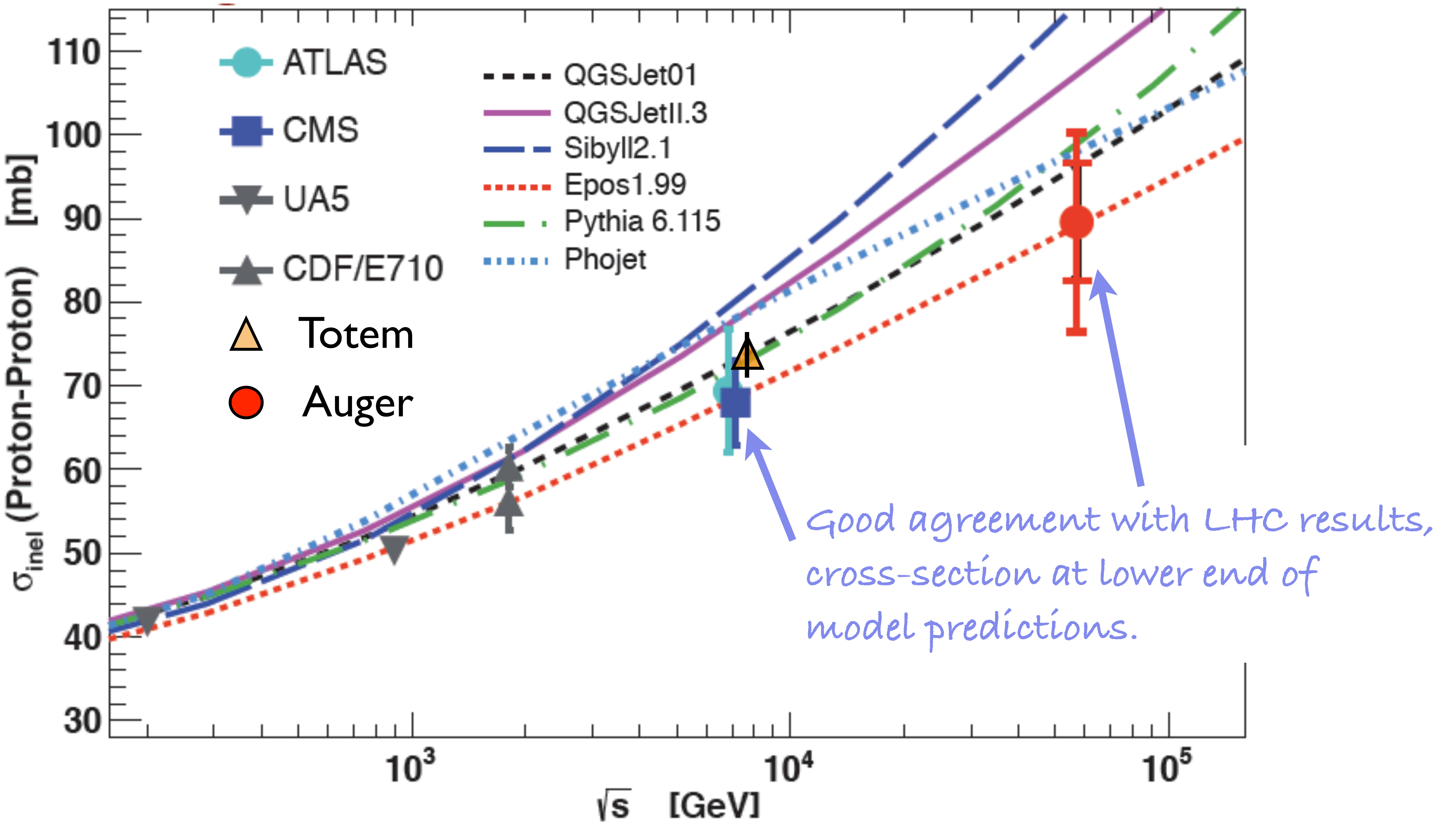


Proton-Air Cross-Section



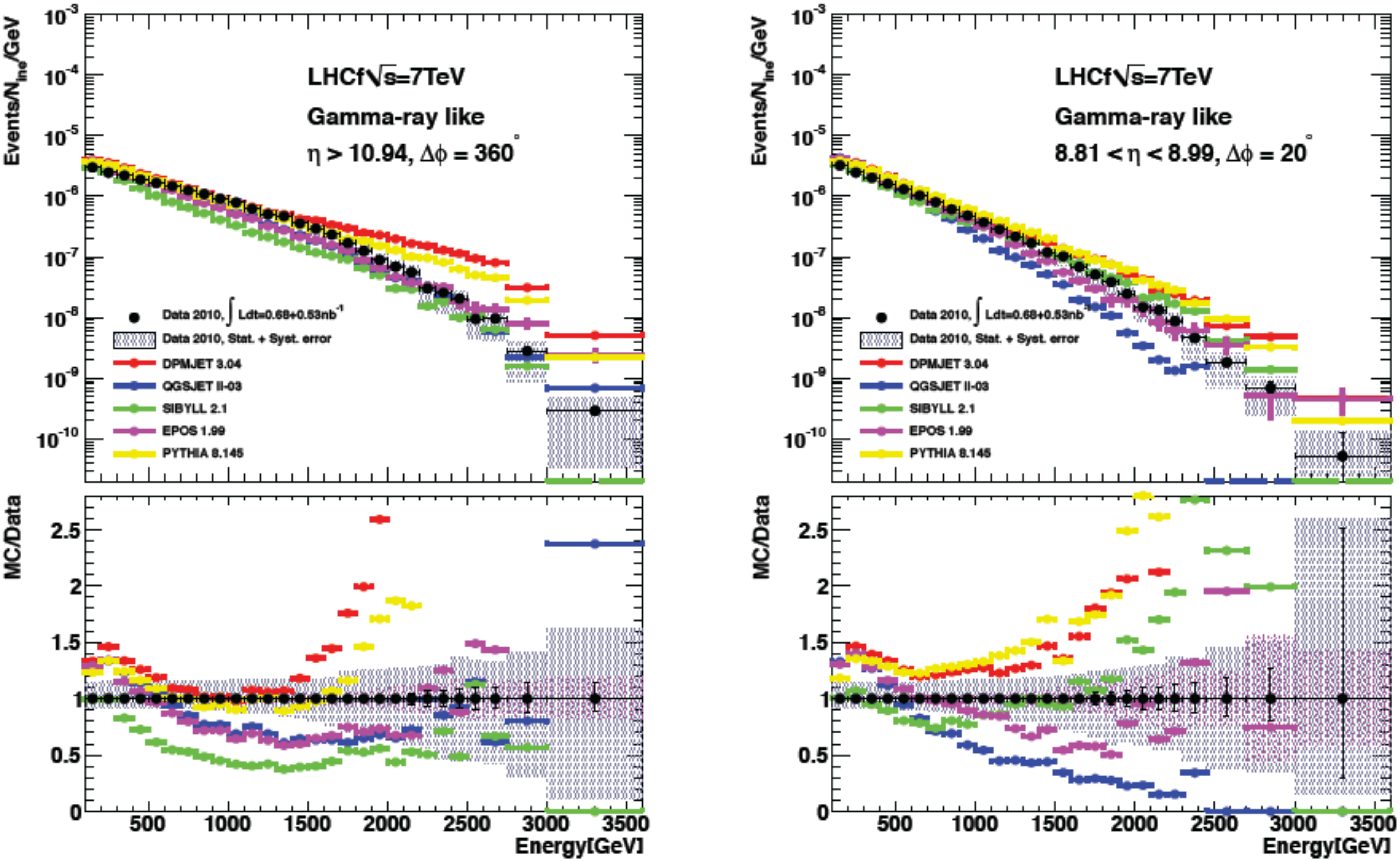
σ(p-air) = 505 ± 22 ± 30 mb (@ 2 EeV)

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



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

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

The End