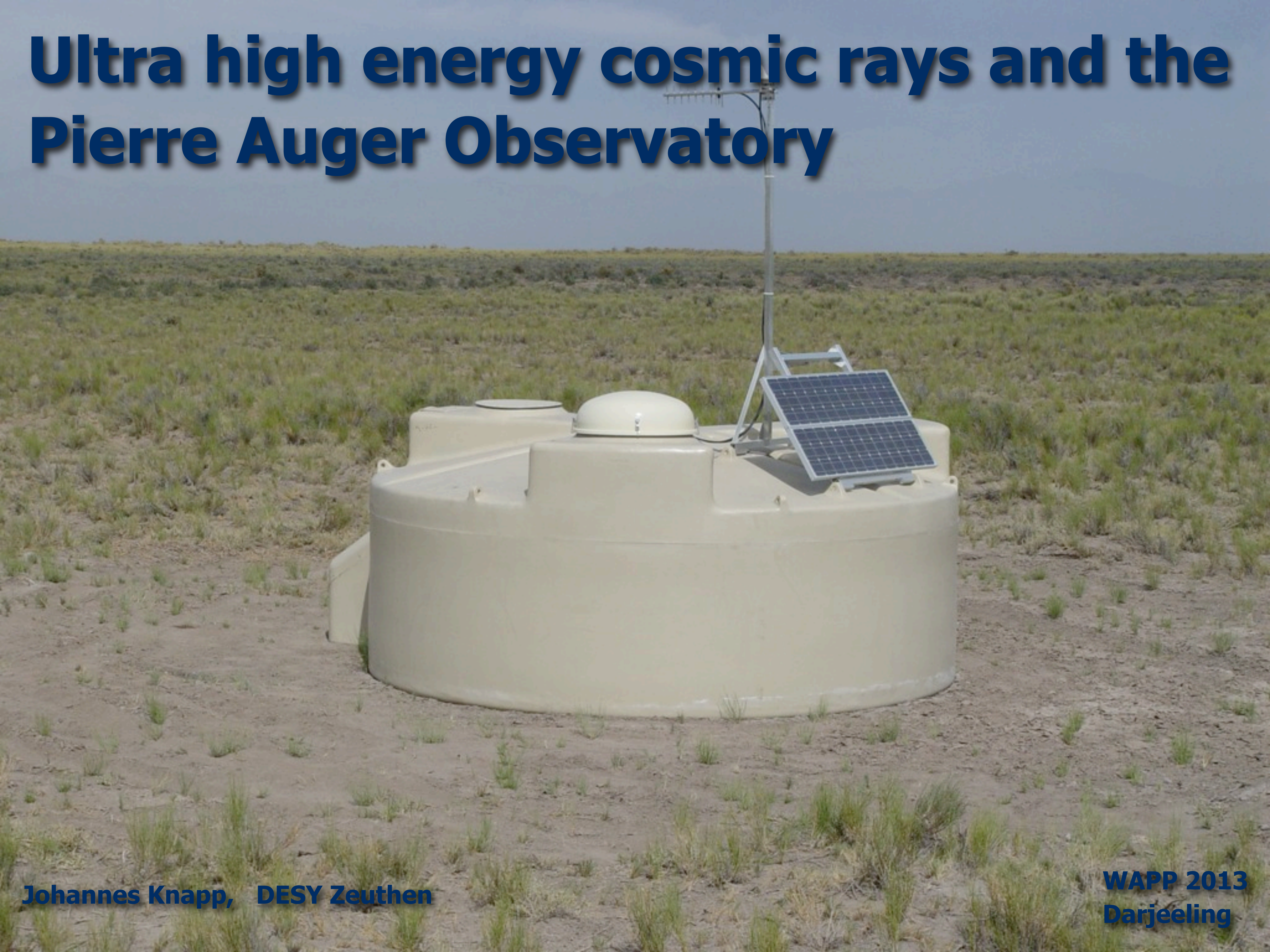
Ultra high energy cosmic rays and the Pierre Auger Observatory



Johannes Knapp, DESY Zeuthen

WAPP 2013
Darjeeling

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

Cosmic Rays:

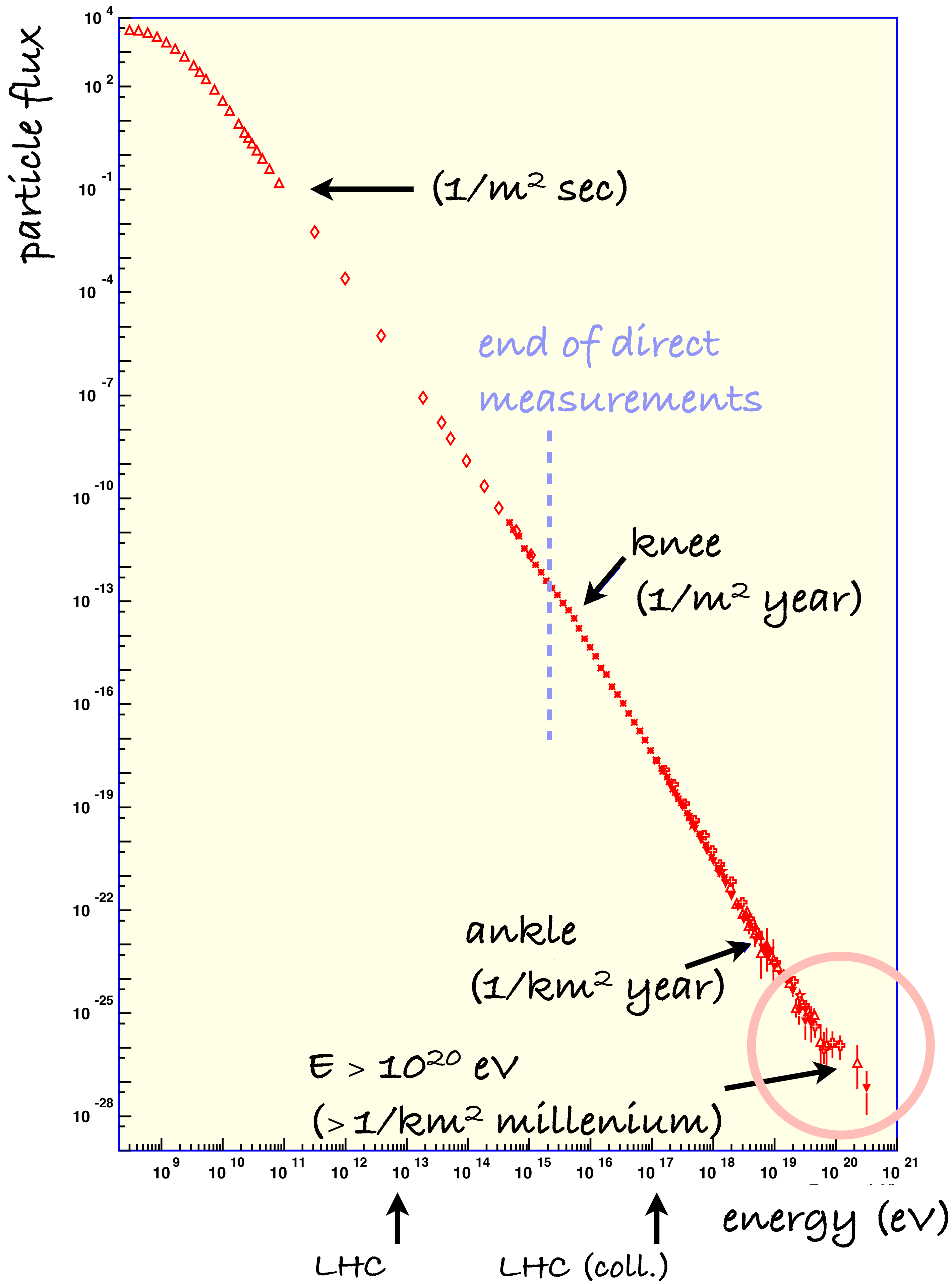
charged particles from astrophysical sources
... the highest energy particles in the universe !

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

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

1962 Volcano Ranch
1995 Fly's Eye

Flux of Cosmic Rays



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

10x up in energy, ≈500x down in flux

Highest energy events:
≈ 3×10^{20} eV

10^{20} eV particles do exist !

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:

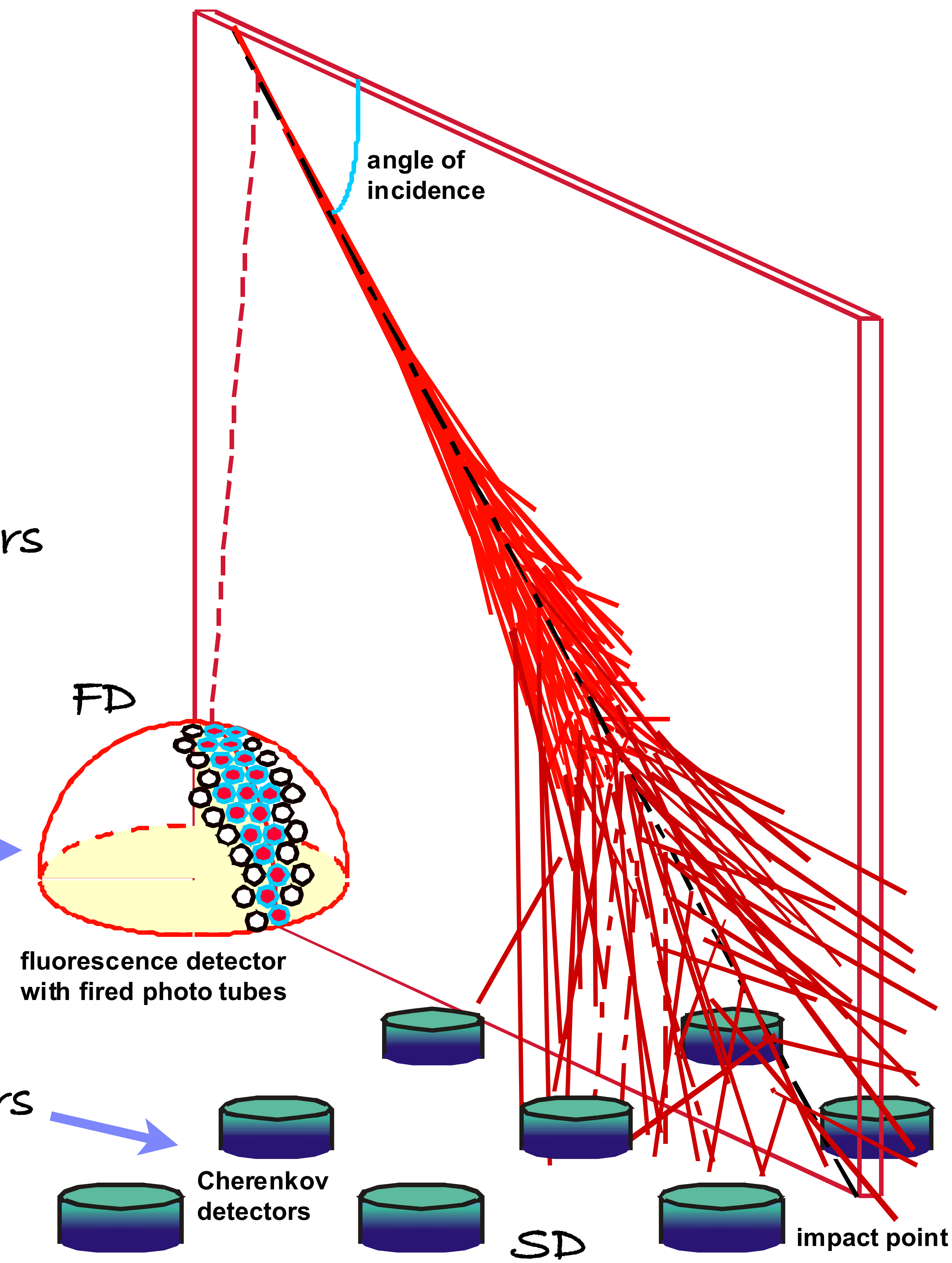
indirect measurement,
shape and particle content of showers

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 km^2, 100% duty cycle,
well-known aperture



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 CORSIKA program

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

Fully 4-dim MC simulation

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

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

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

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

reasonable agreement: (~ 30% level for <10^{18} eV)

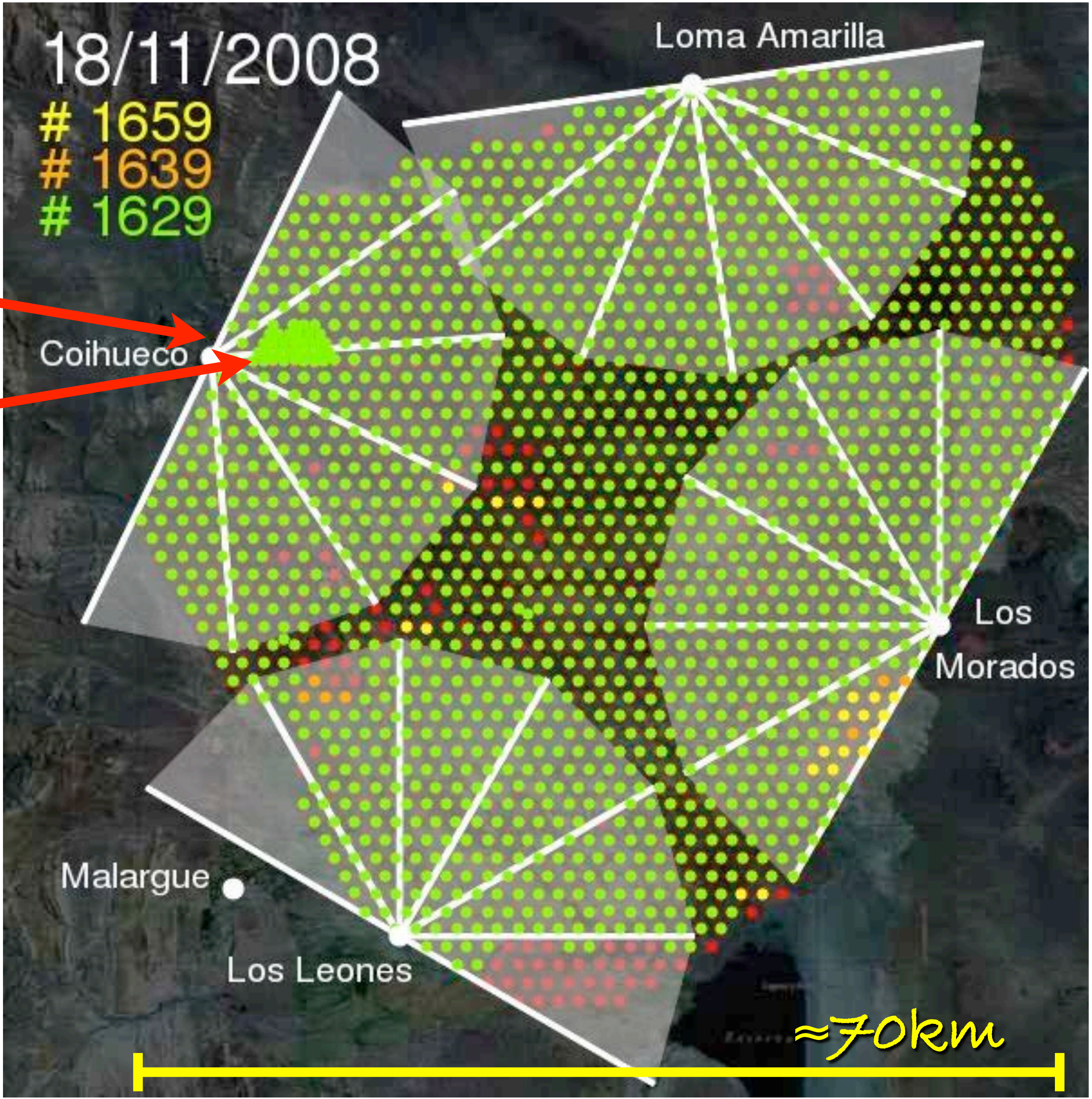
e.g.	HESS, VERITAS, Magic γ ray astron.;	10^{11}-10^{14} eV
	KASCADE-Grande CR showers;	10^{14}-10^{17} eV
	Haverah Park	10^{17}-10^{18} eV
	Auger	10^{18}-10^{20} eV

UHE Hadronic models are the major source of uncertainty.

Auger layout

HEAT
high elev.
FD tels.

infill
array

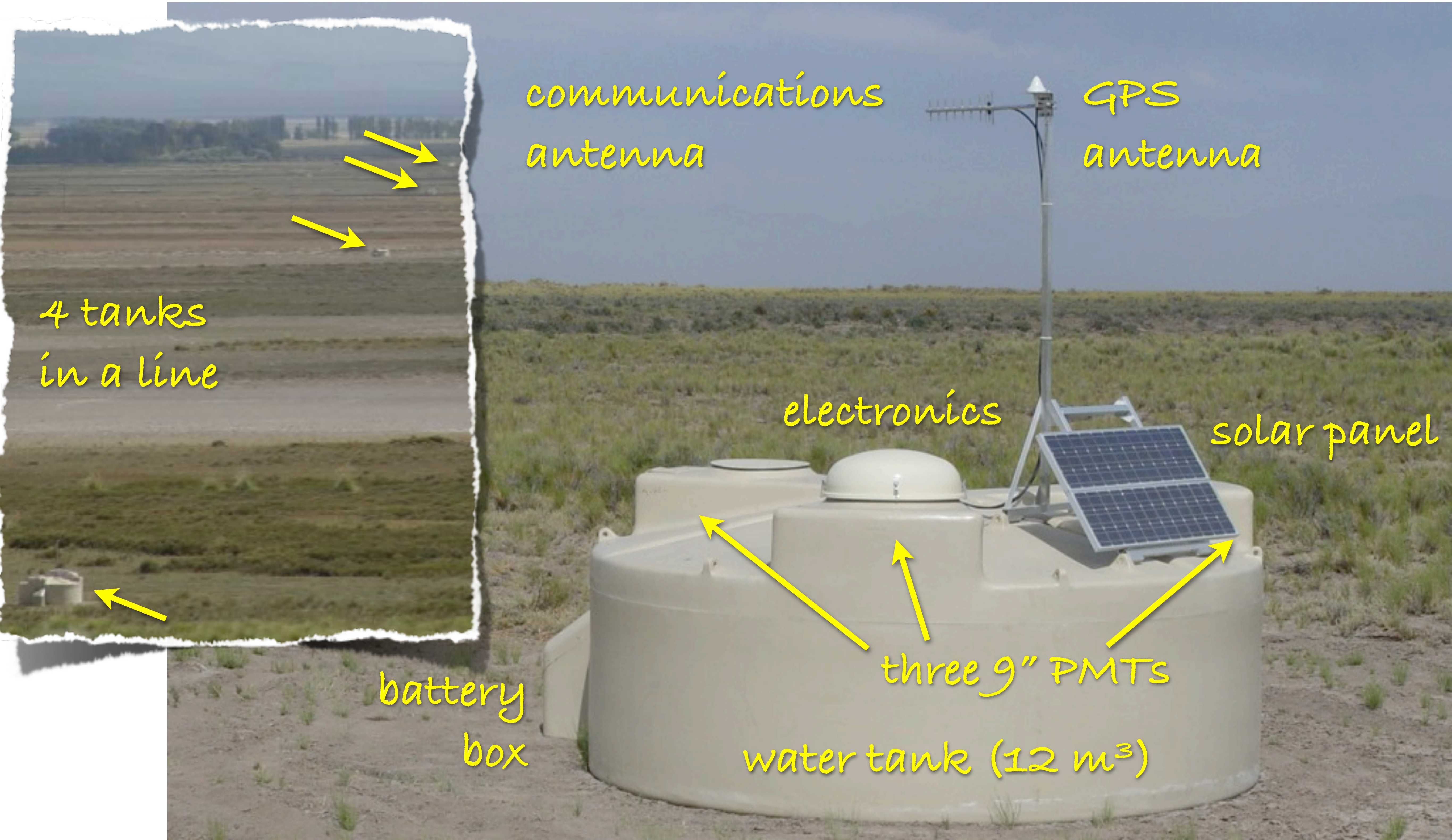


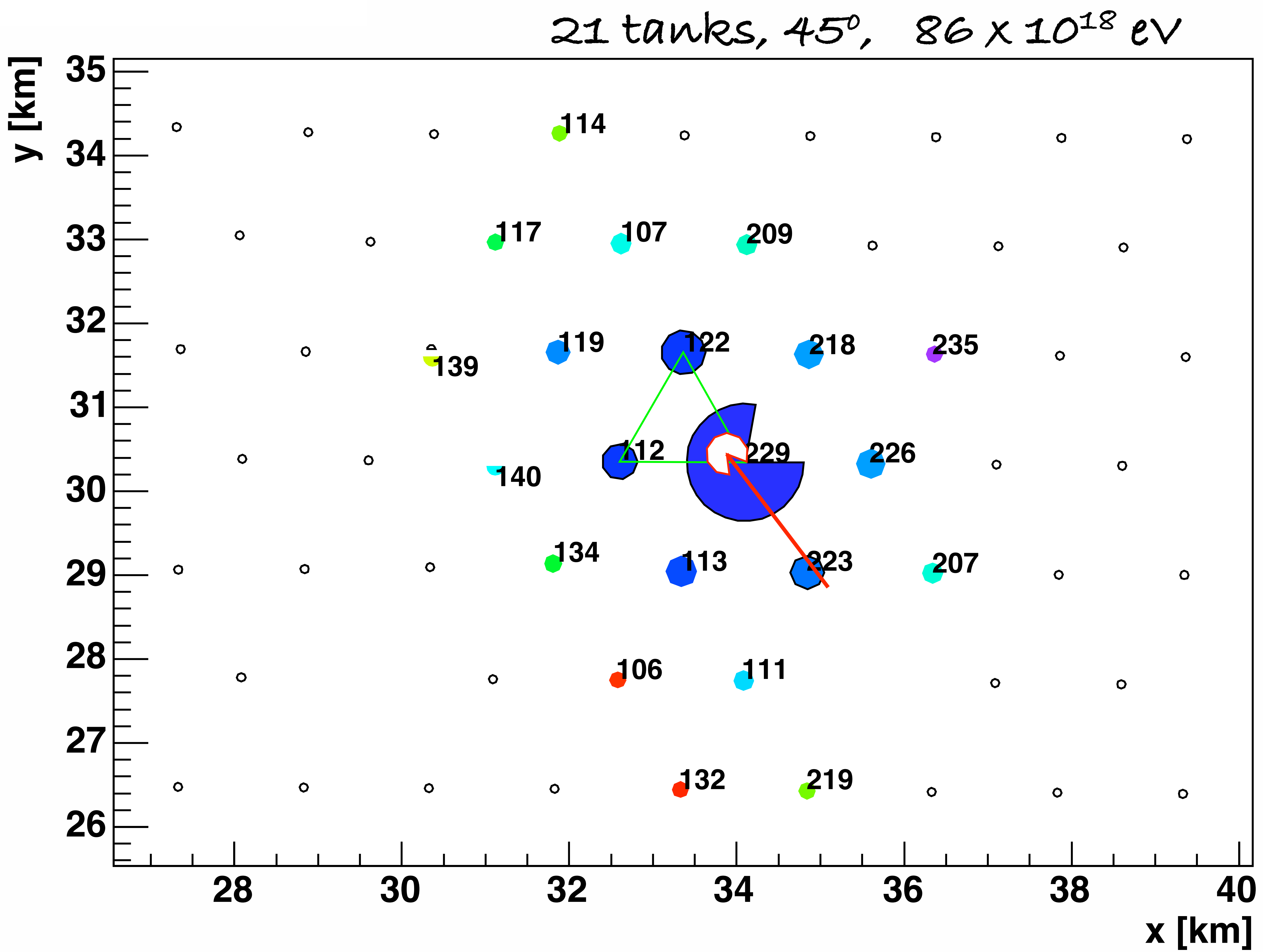
data taking:
since 2004
completion:
Nov 2008

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





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
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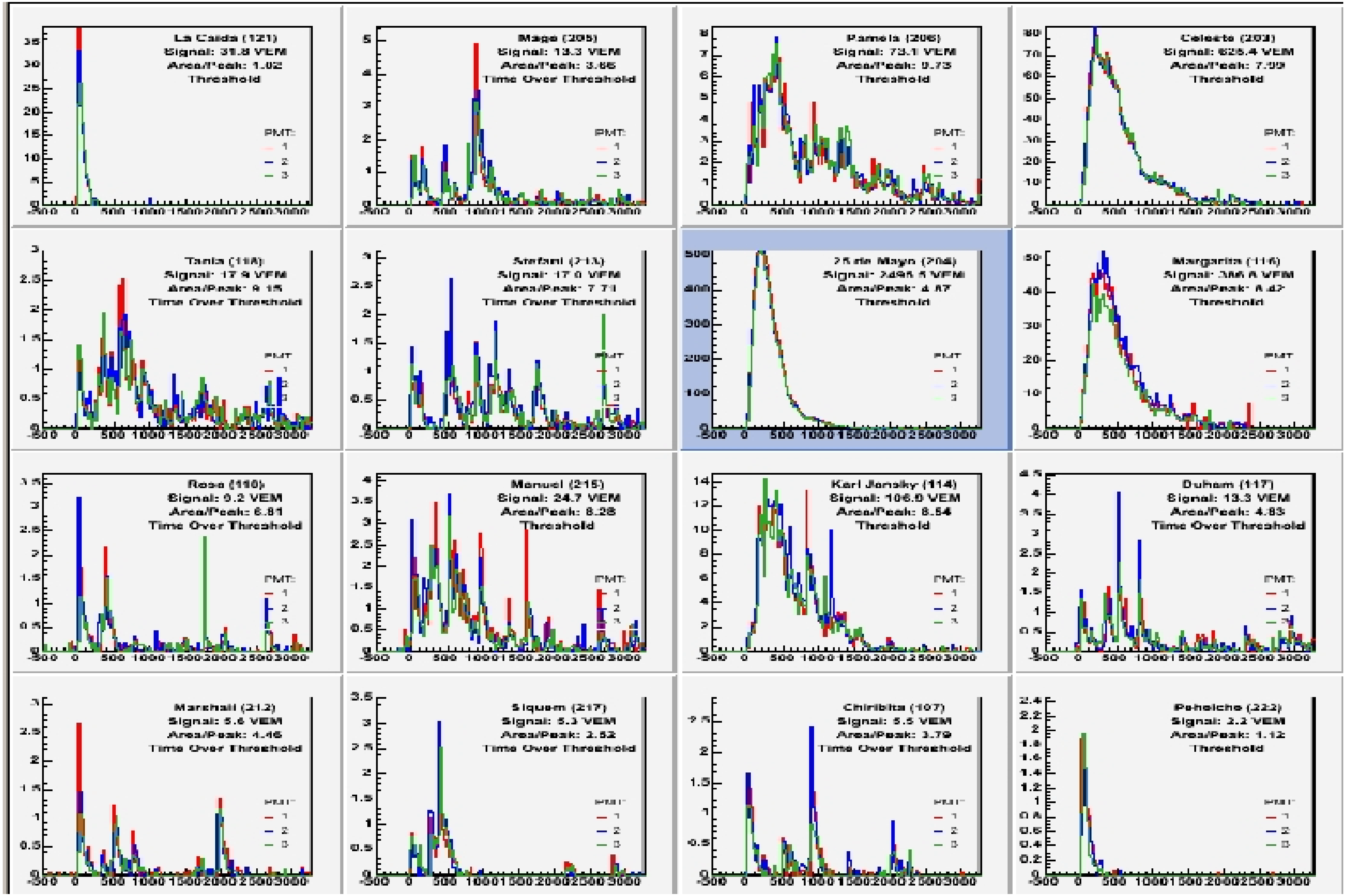
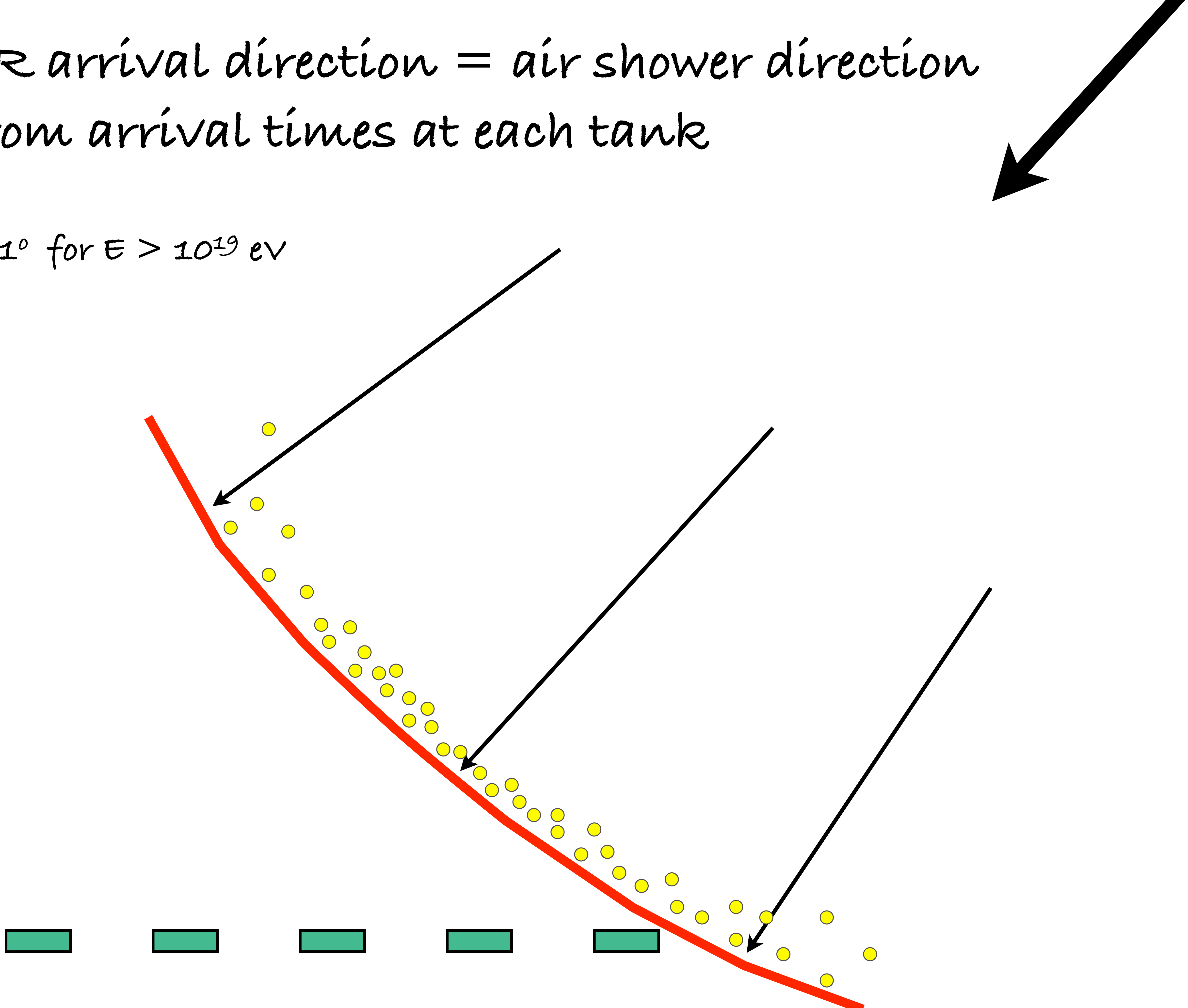
207
106
111
132
219

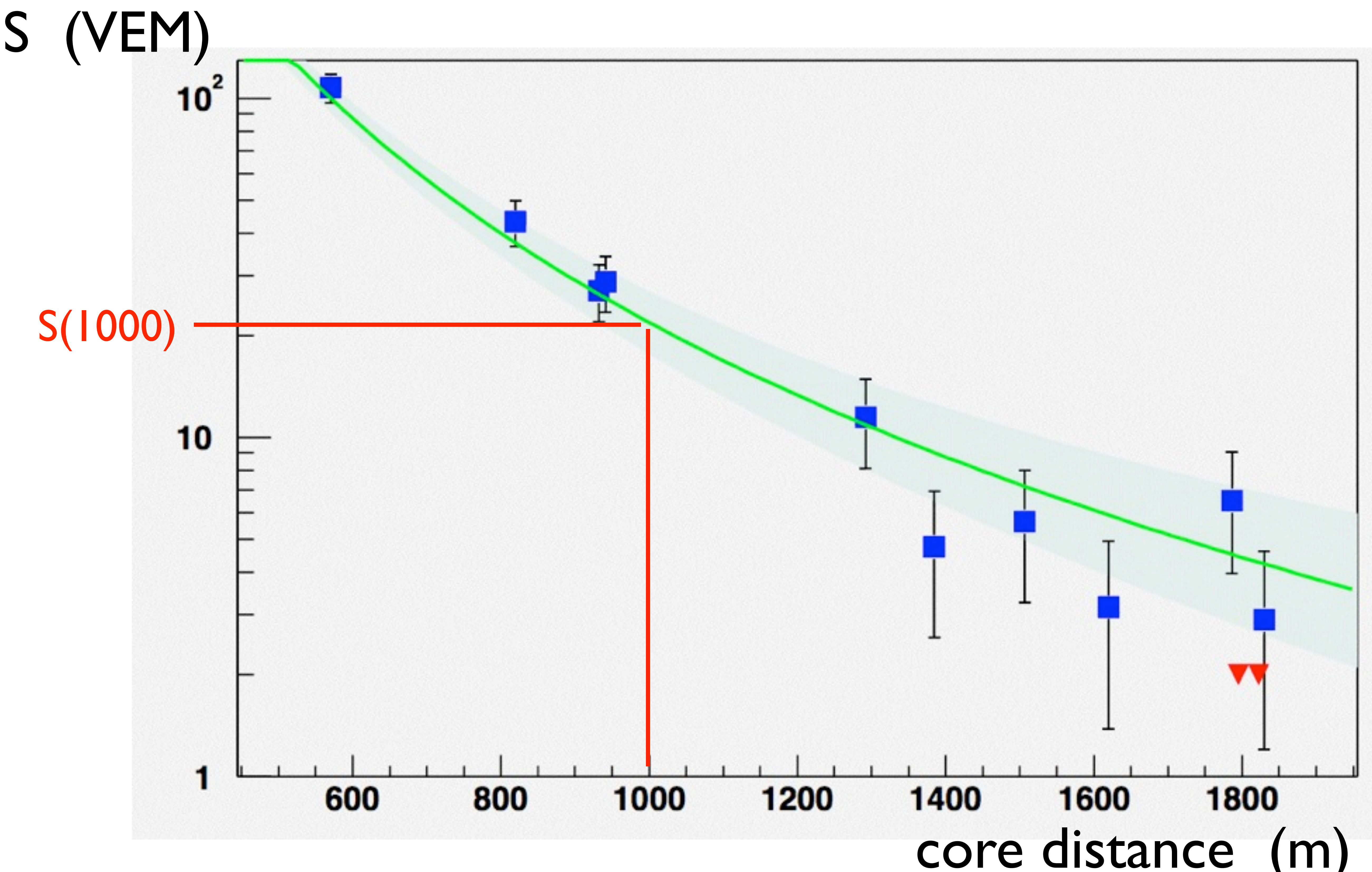


High & smooth pulses close to shower core, low & spiky pulses far away.

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

< 1° for E > 10^{19} eV





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.

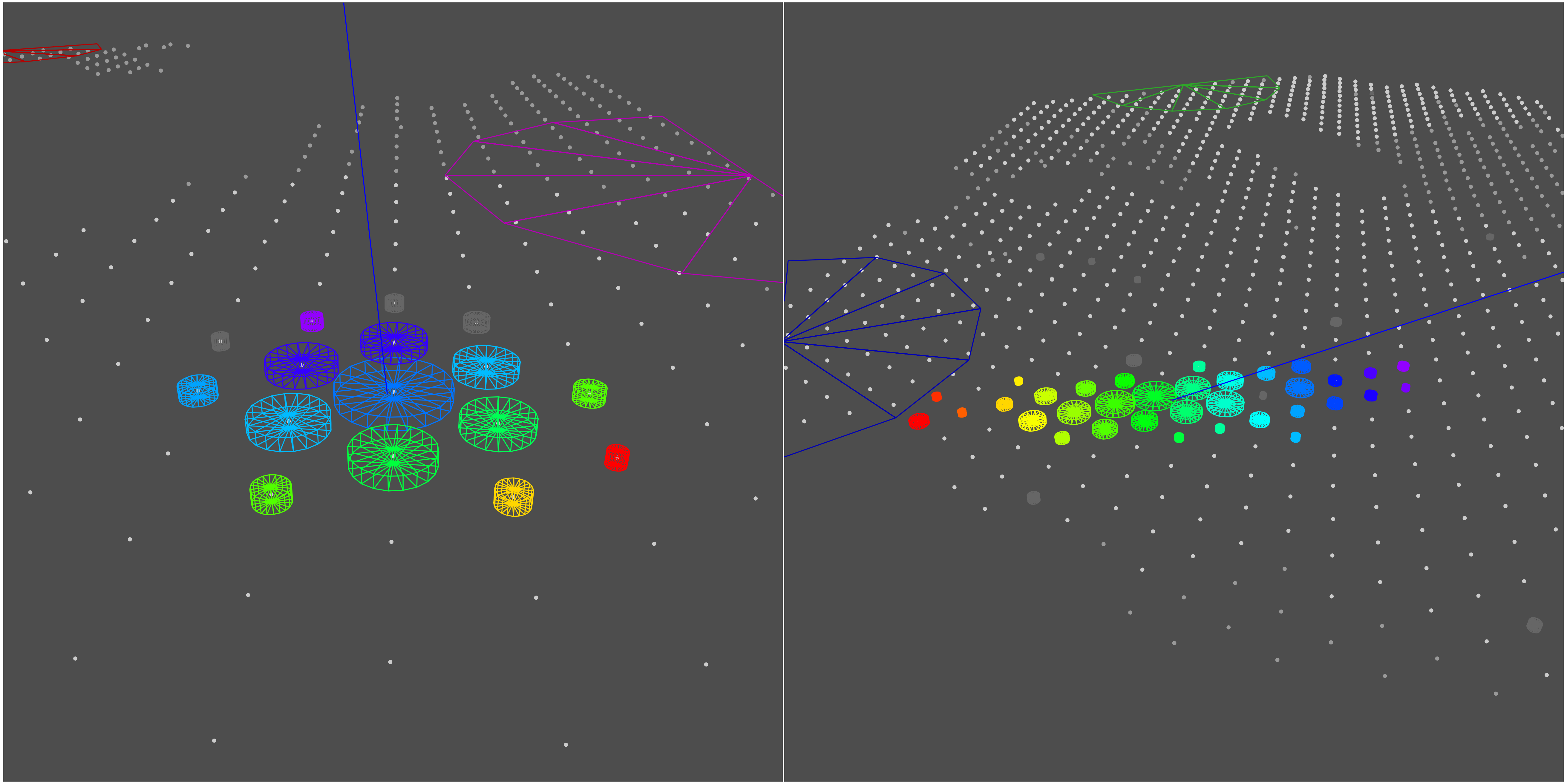
some of the highest-energy SD events:

near vertical

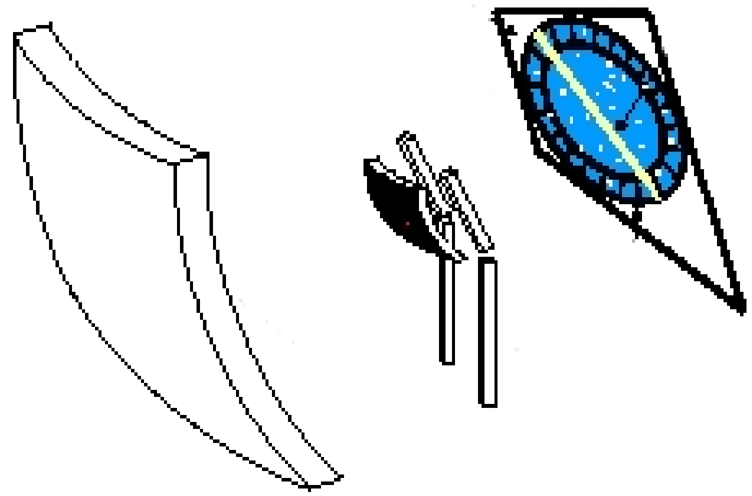
$E = 1.67 \times 10^{20}$ eV $\theta = 14^o$

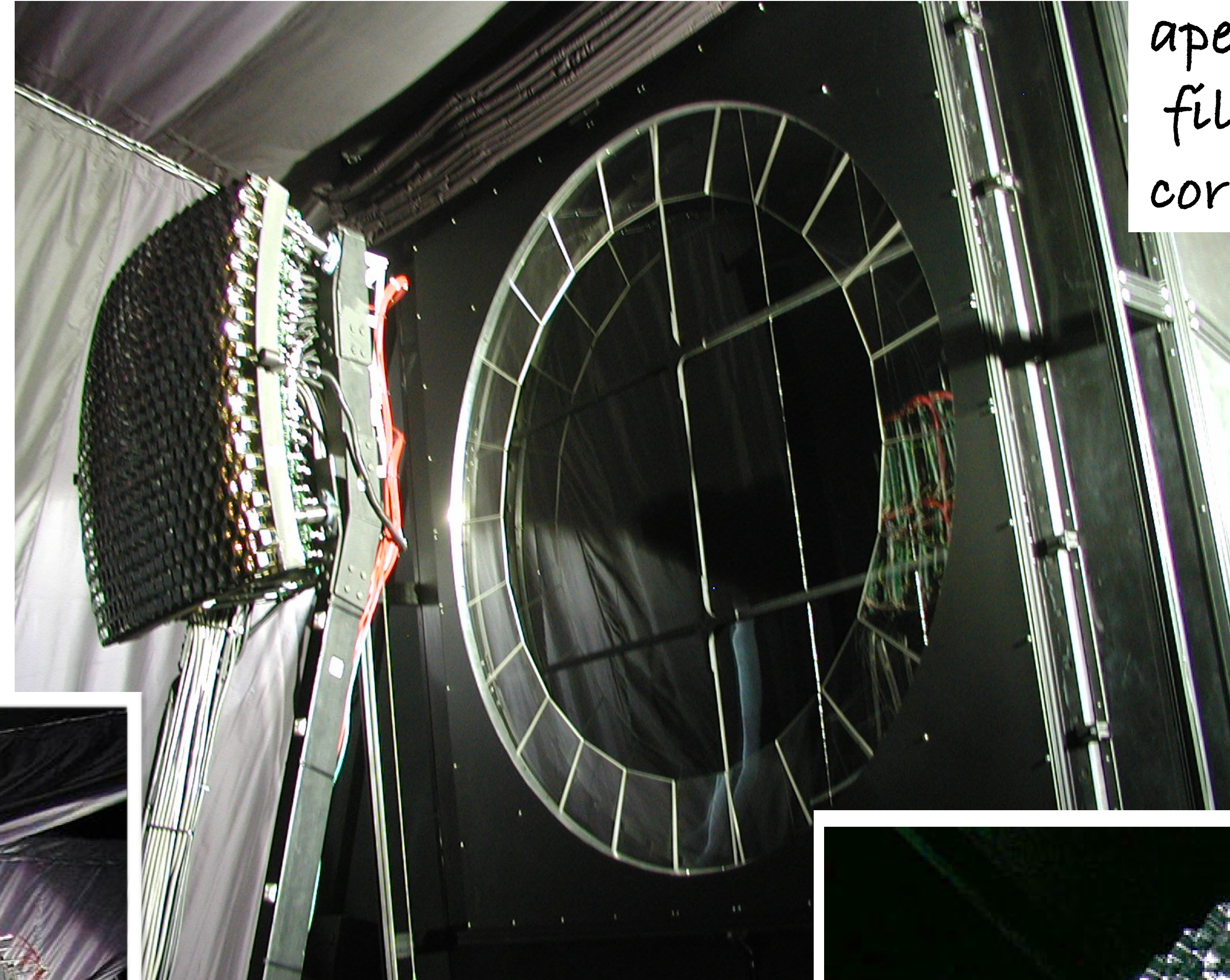
inclined

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

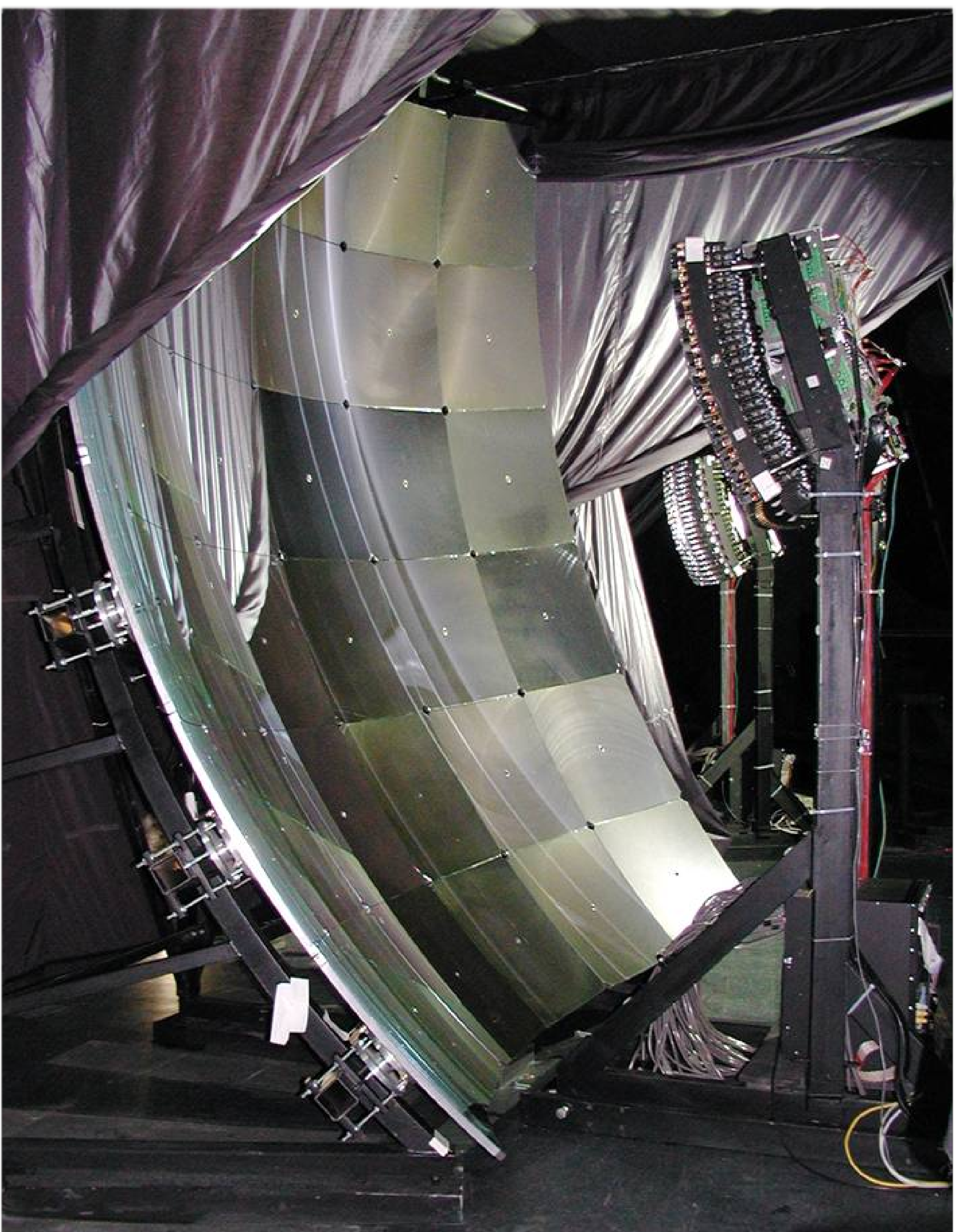


FD telescope:



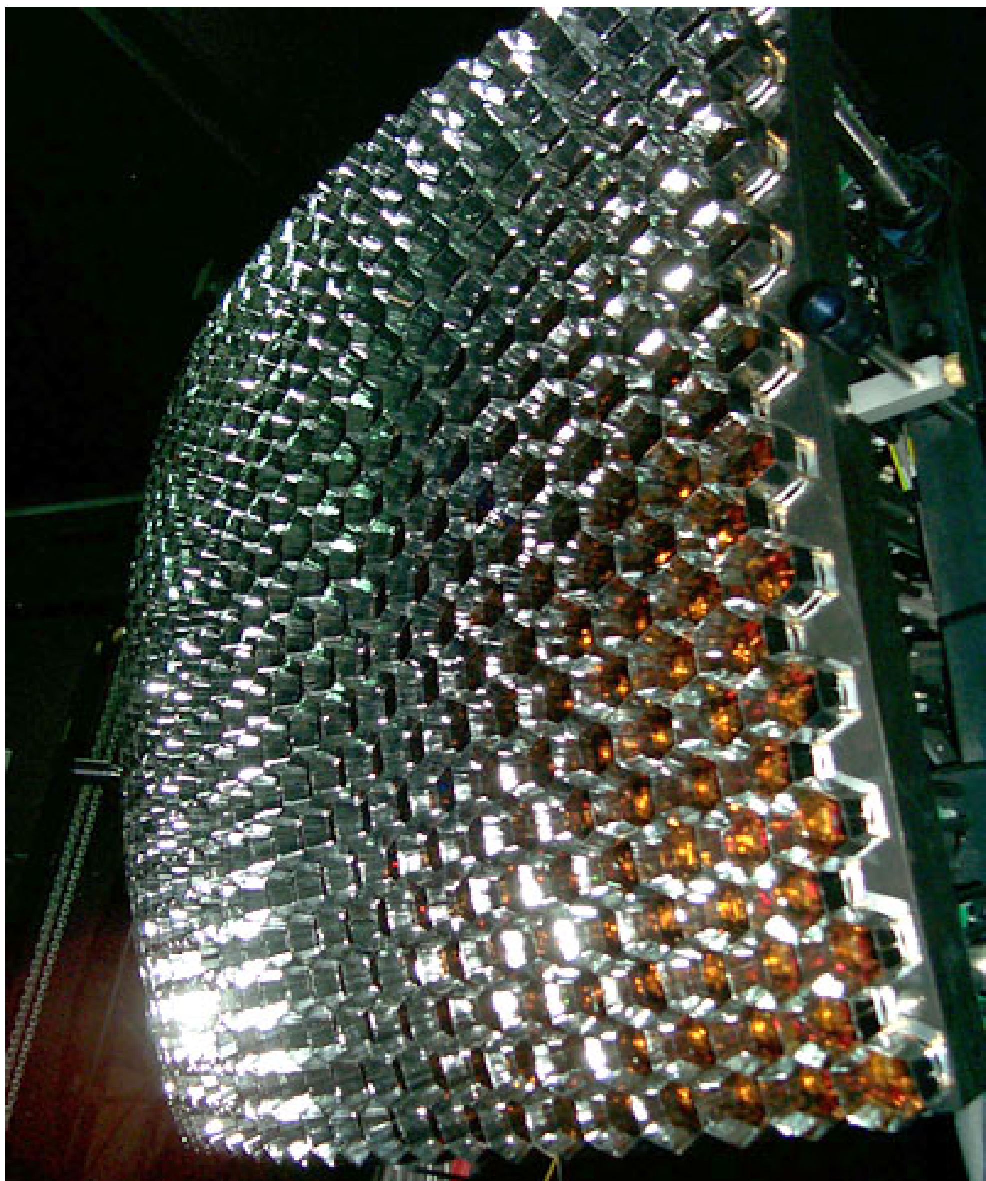


aperture with shutter, filter and Schmidt corrector lenses



11 m² mirror (Aluminium)

440 PMT camera

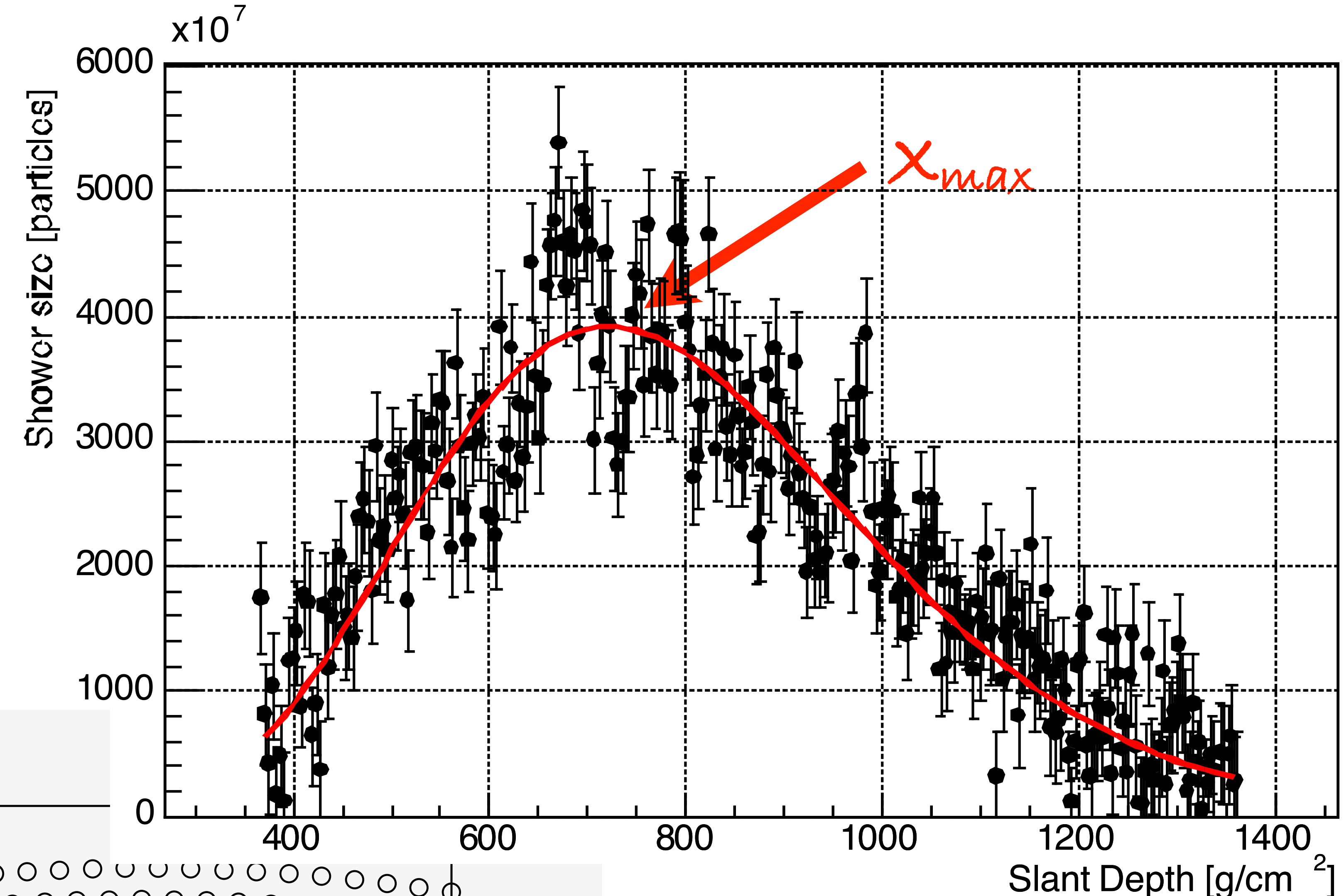


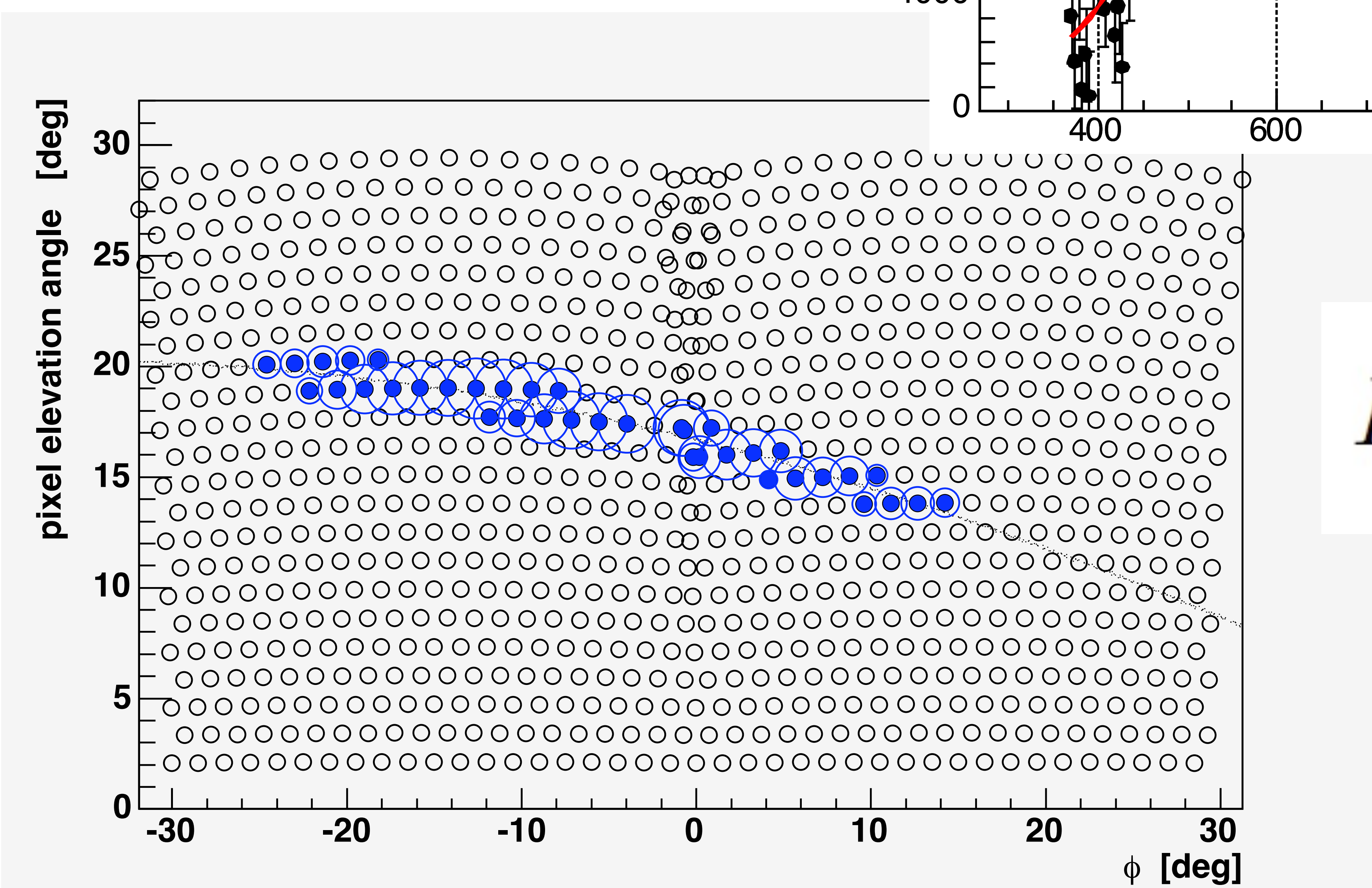
24 telescopes at 4 sites

30°x30° FOV, each

FD:

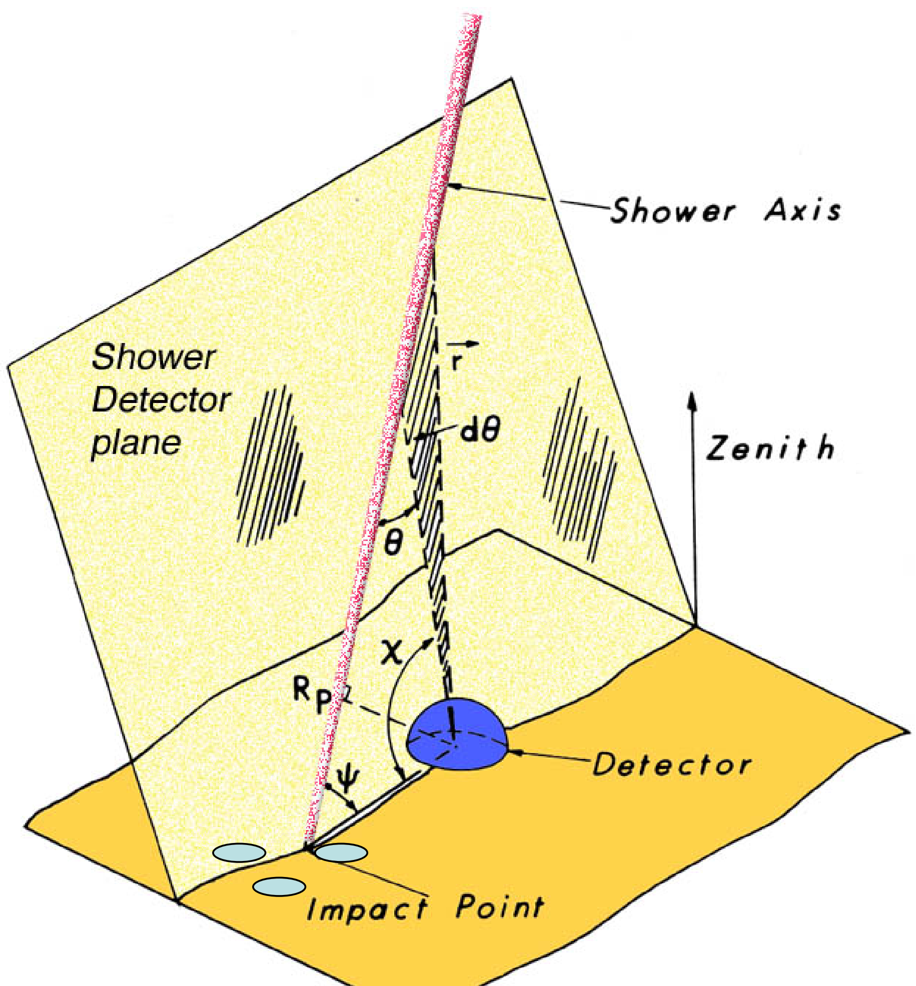
longitudinal profile,
calorimetric energy,
X_{max} for mass comp.

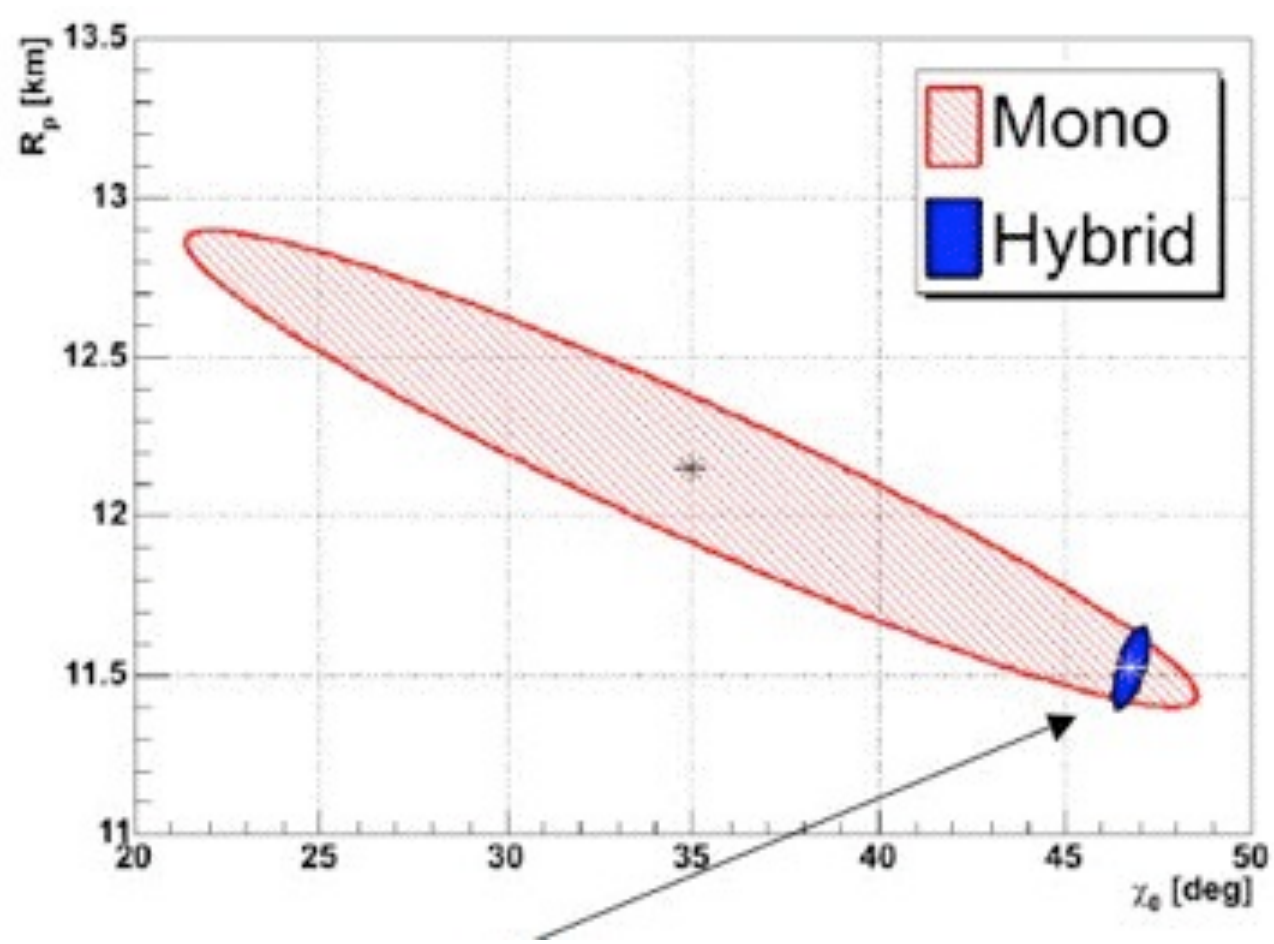




$$E \propto \int_0^\infty N(t)dt$$

	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



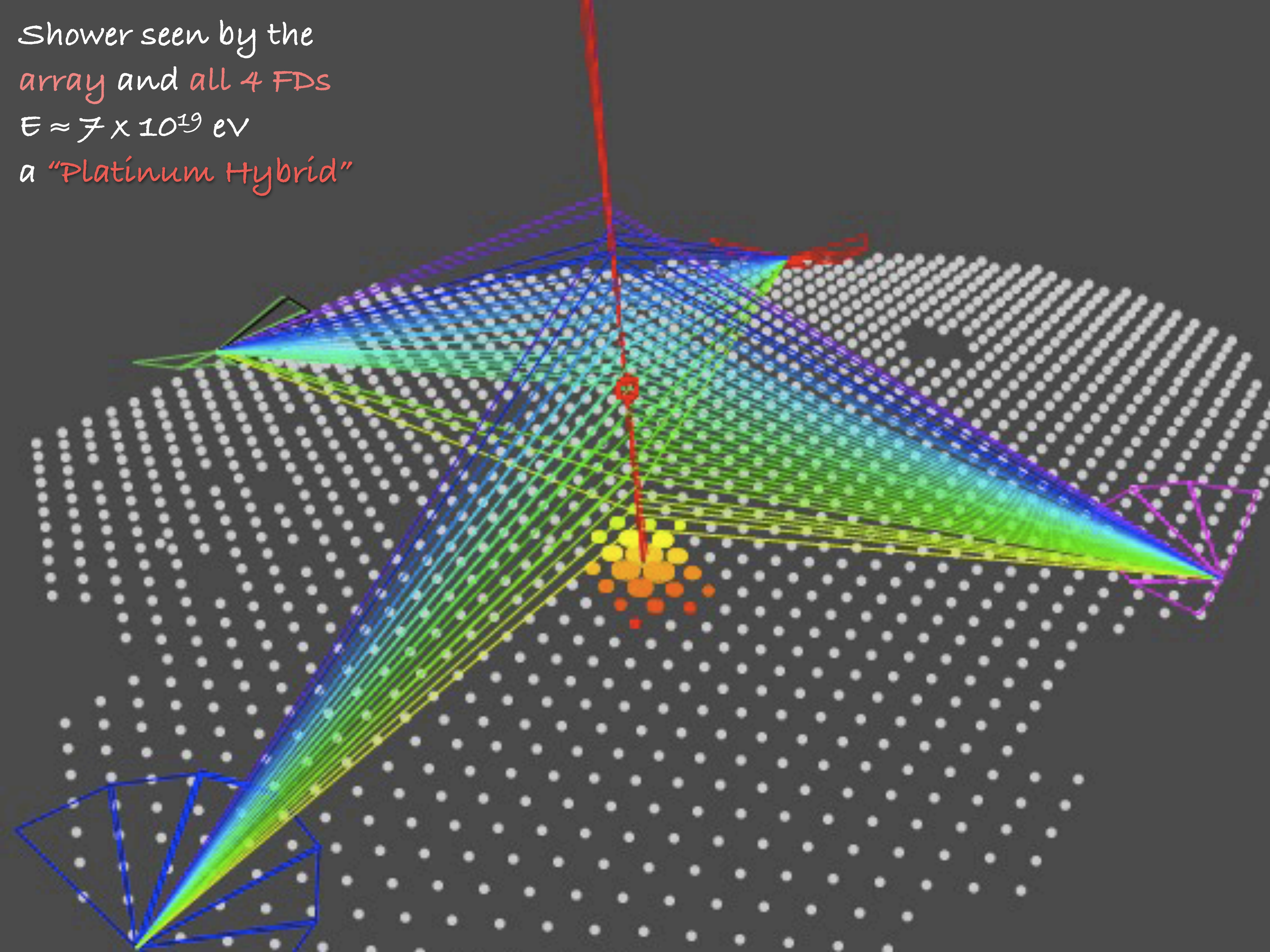


Shower seen by the

array and all 4 FDs

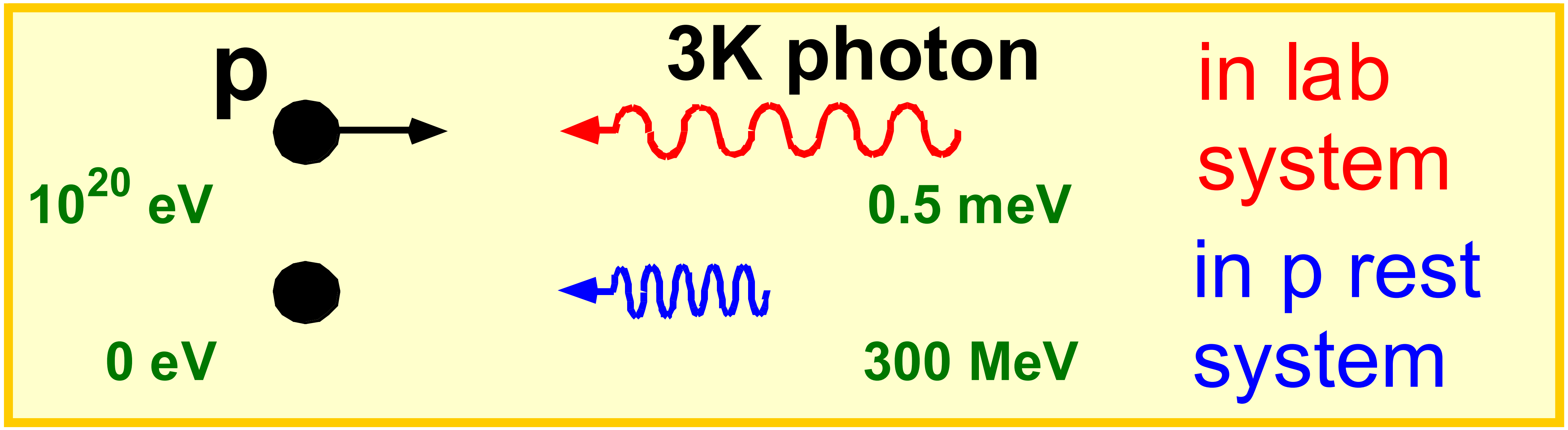
$E \approx 7 \times 10^{19}$ eV

a “Platinum Hybrid”



GZK Cut-Off

Greisen Zatsepin Kuzmin



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

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

photo - pion production

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

photo dissociation

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

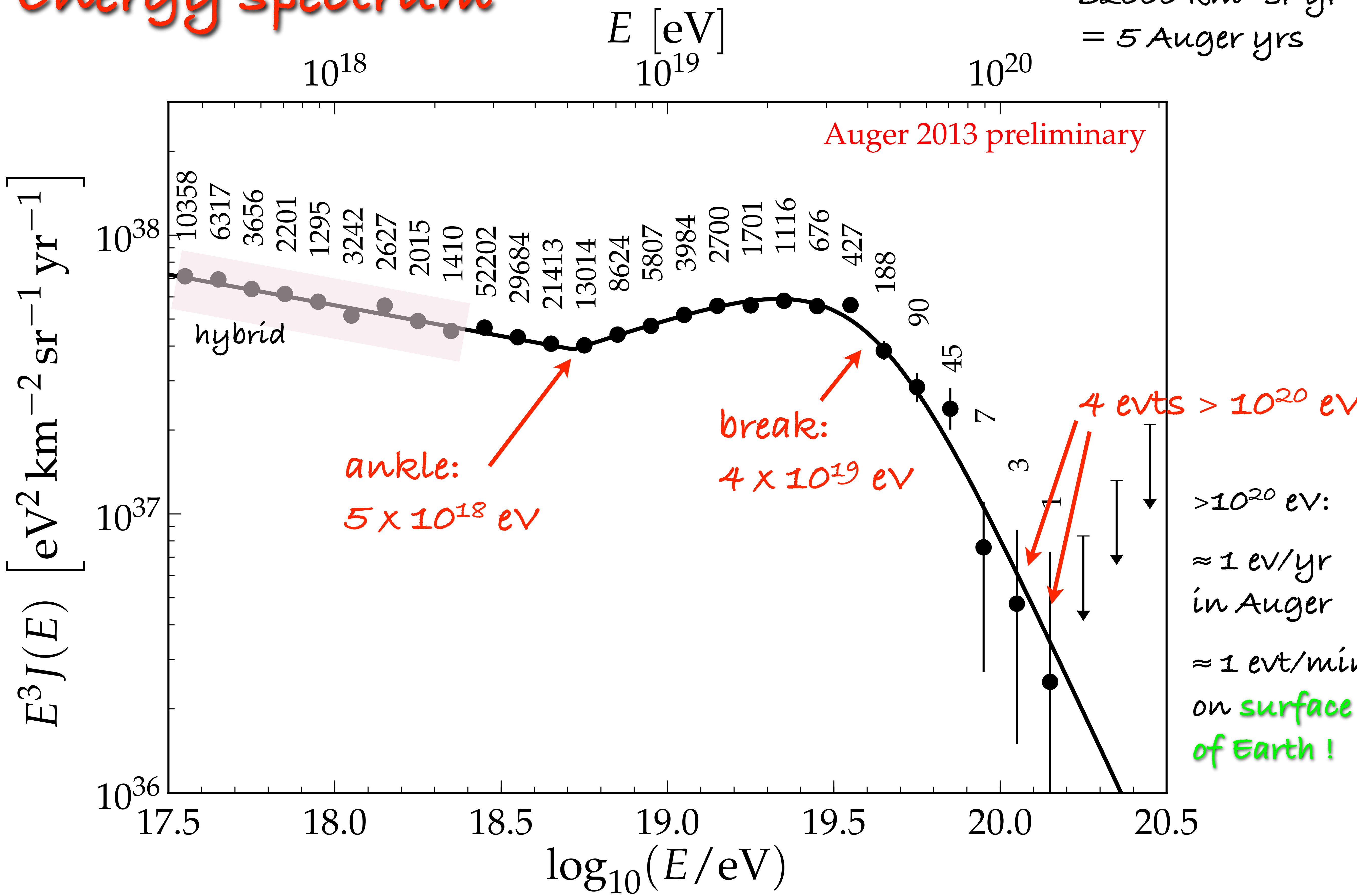
for high statistics from SD

A: directly from size of SD

(above 3x10^{18} eV)

Energy spectrum

32000 km² sr yr
= 5 Auger yrs



>10^20 eV:

≈ 1 ev/yr in Auger

≈ 1 evt/min on surface of Earth !

Auger finds "ankle" and a clear (>20 σ) spectral steepening at E ≈ 3 x 10^19 eV.

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 ≈ few x 10^{19} eV

But also nuclear primaries would be absorbed,
and could produce a similar cut-off.

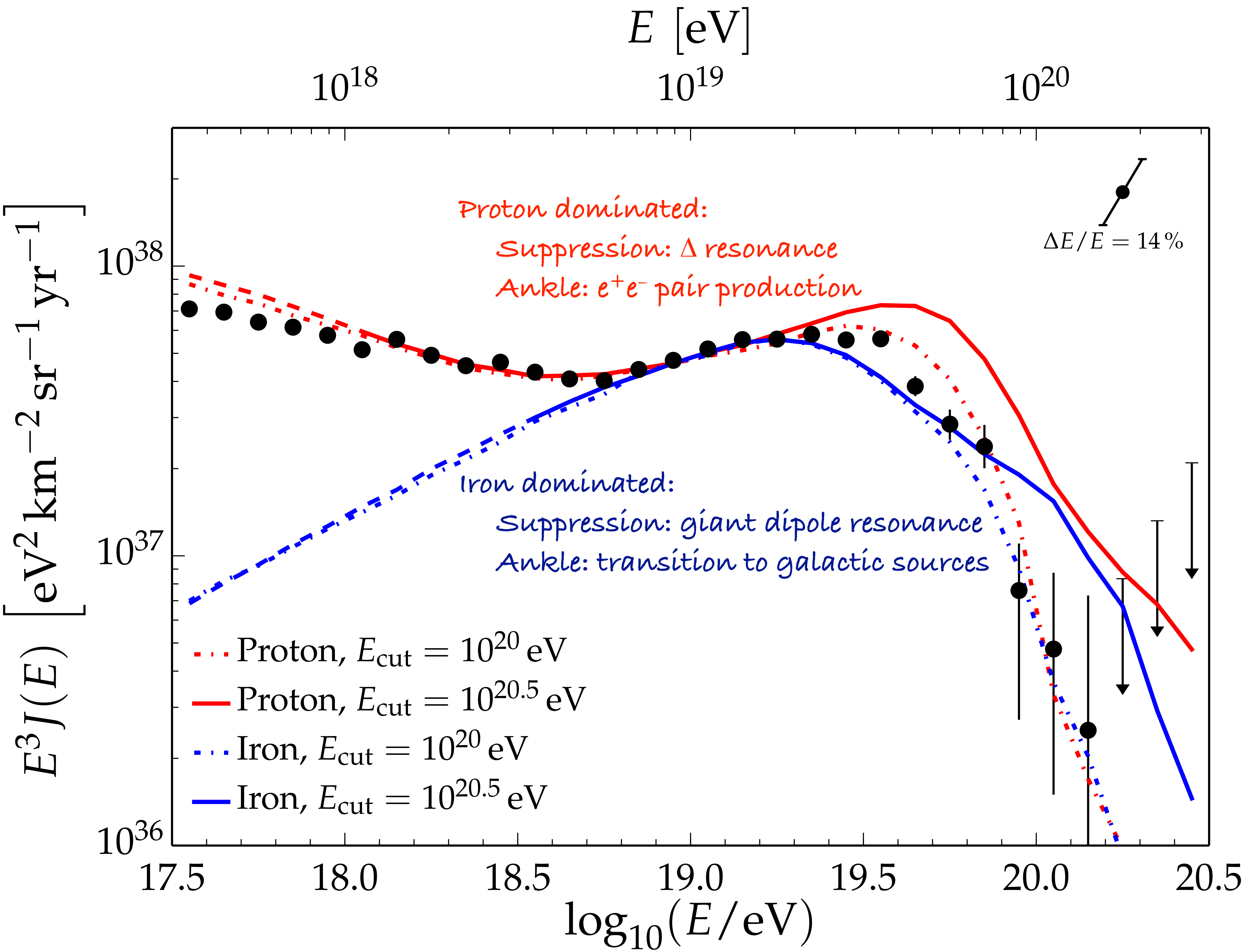
Alternatives:

maximum energy of accelerator ?
effect of a local source ?

Is ankle the transition point between galactic and extragalactic CRs ?

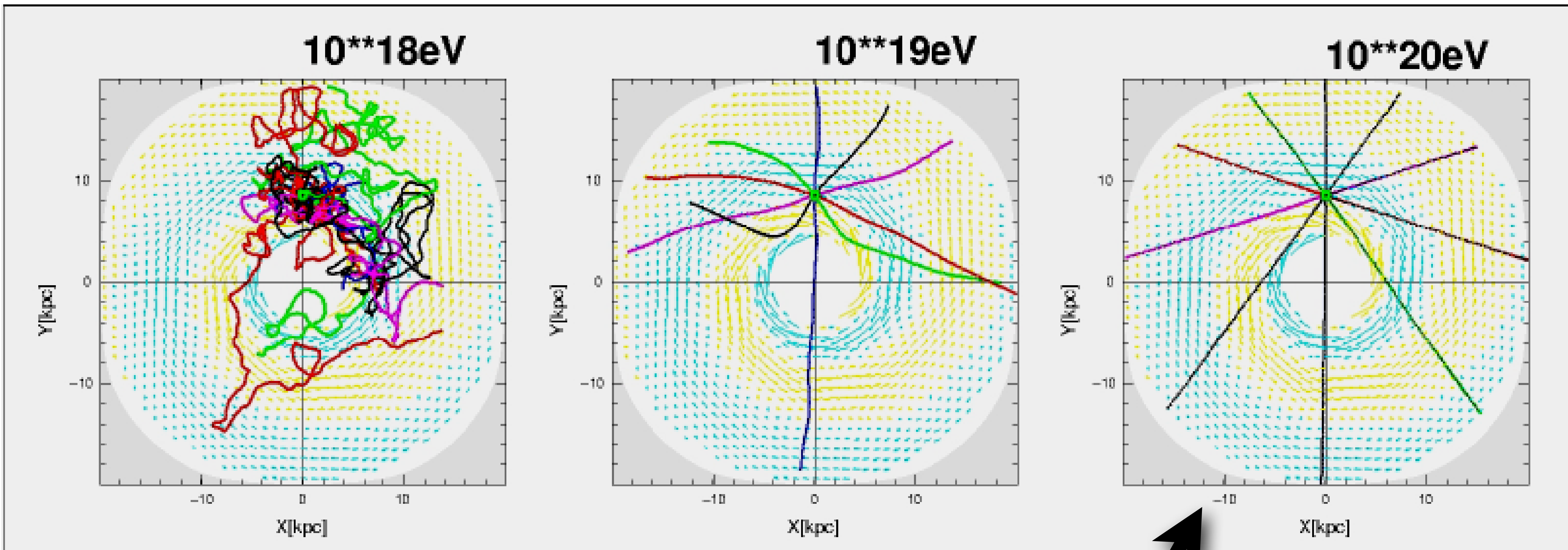
... need more info on composition ...

Interpretation?



Anisotropy - Sources (?)

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

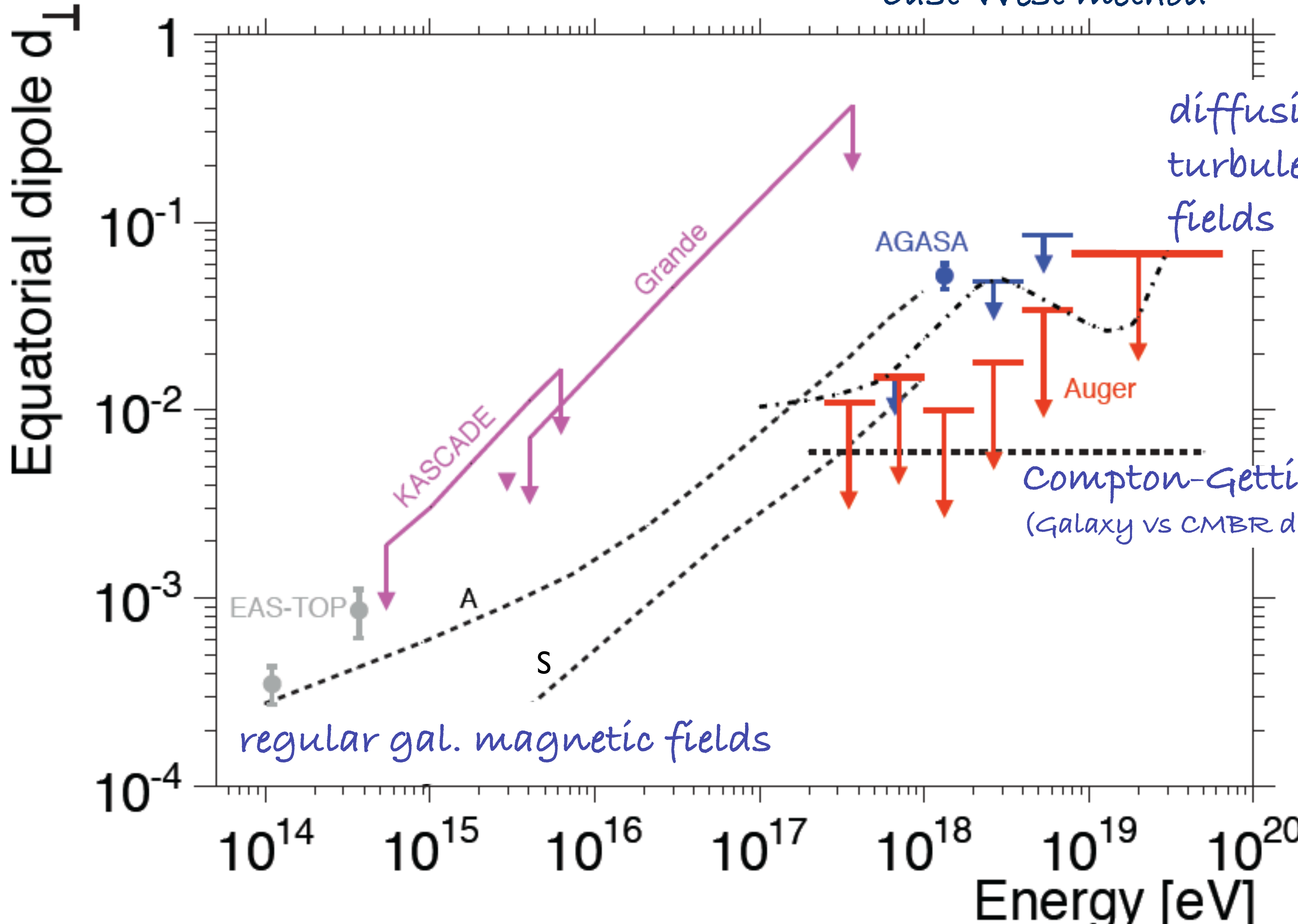


deflection < 1^o

Astronomy with charged particles ?

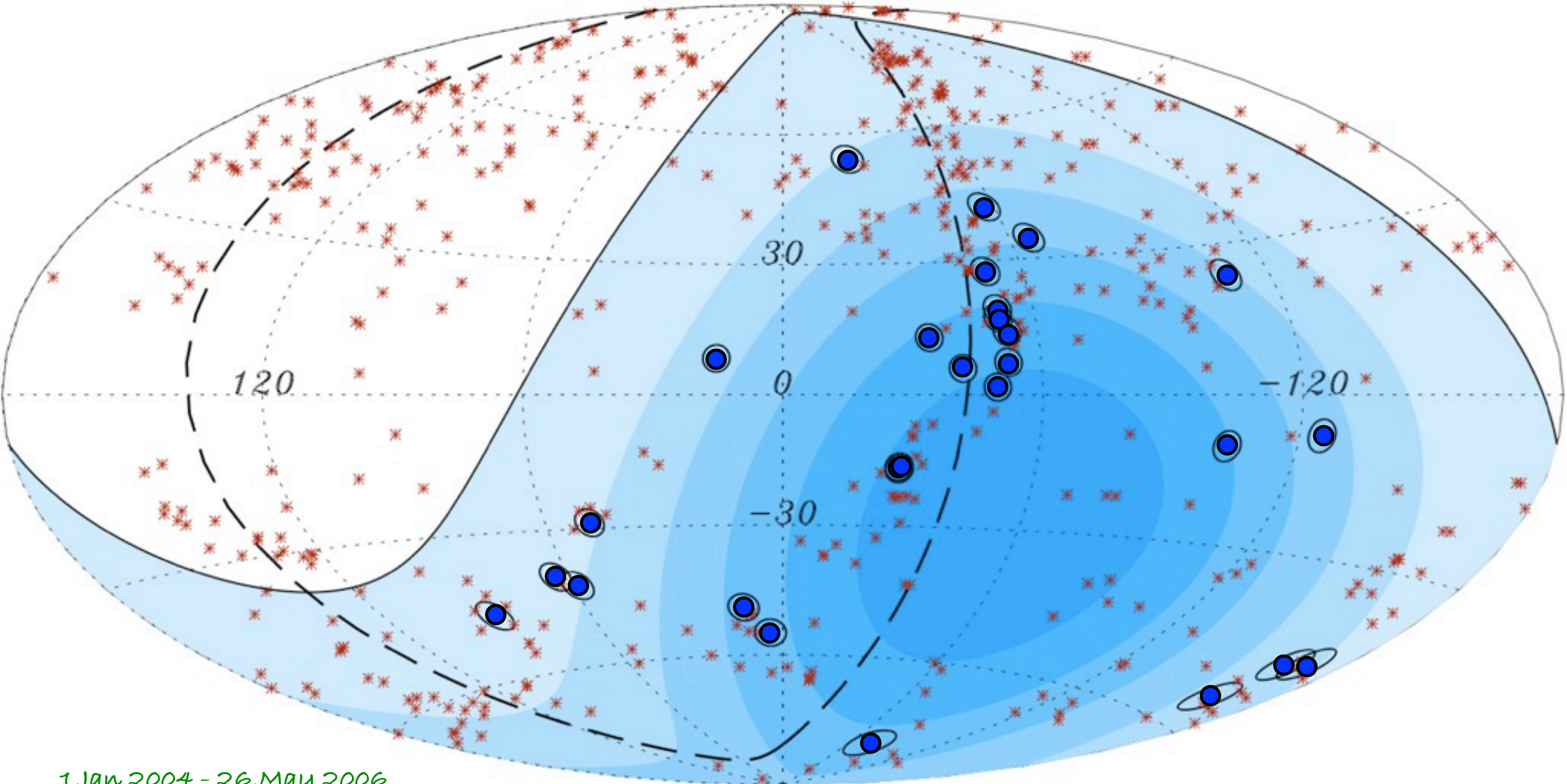
Large-Scale Anisotropy

- 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.



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

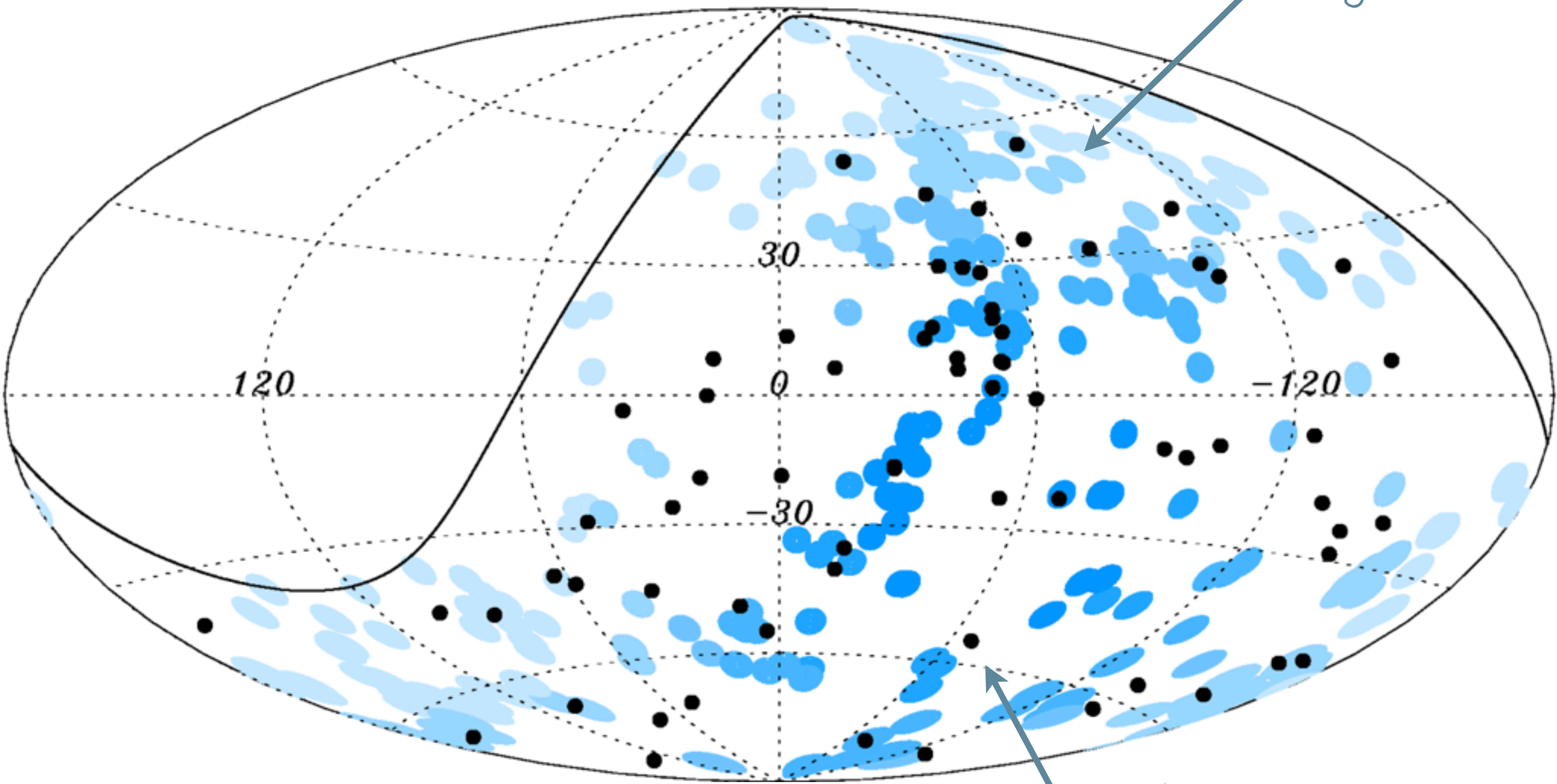
27.May 2006 - 31.Aug 2007 $p < 1.7 \times 10^{-3}$

total data: 1.2 Auger-years

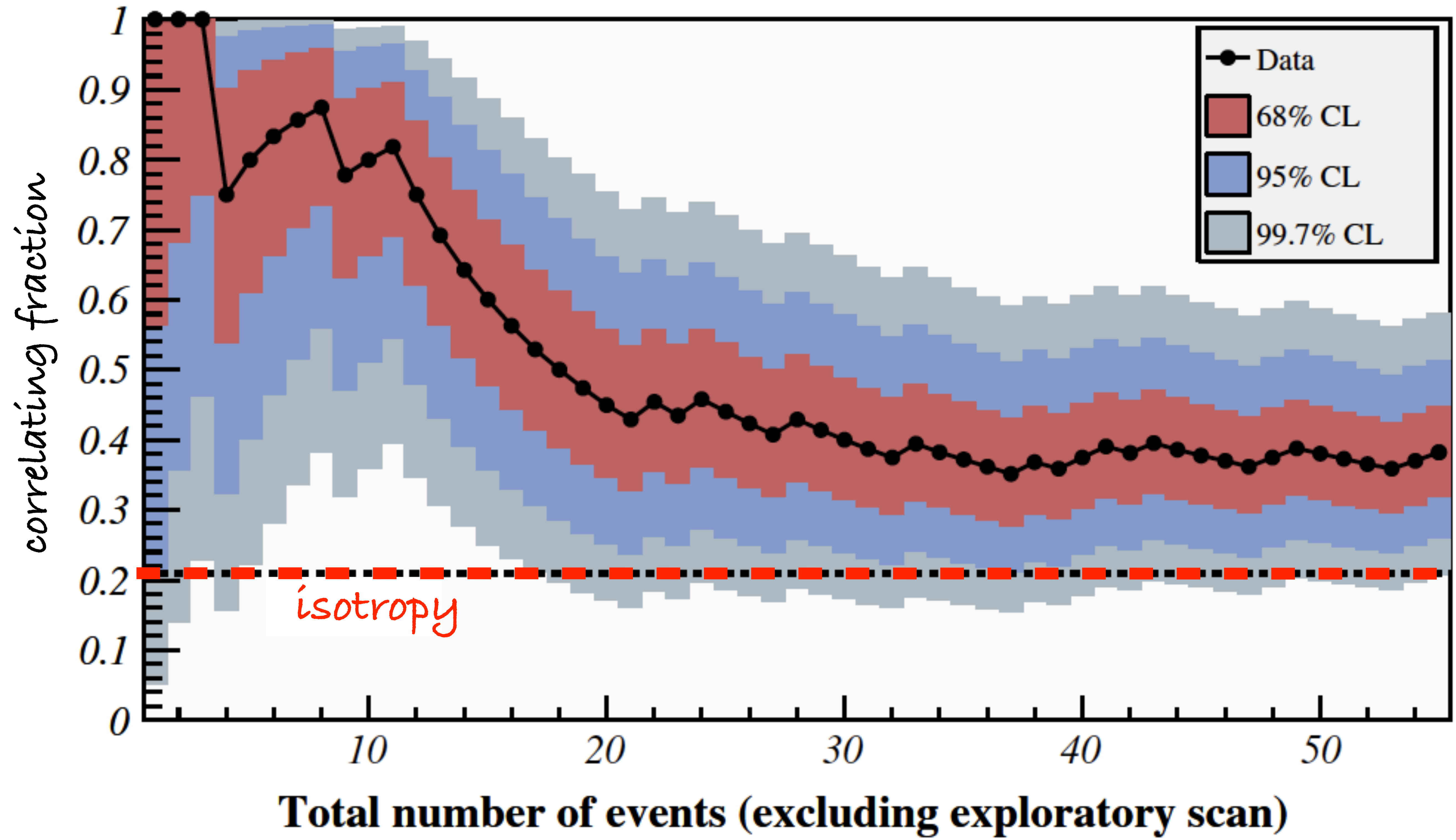
UHECR isotropy rejected with > 99% confidence level, are of extragalactic origin.

84 Highest Energy Events >55 EeV (2011)

(28 correlating)



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

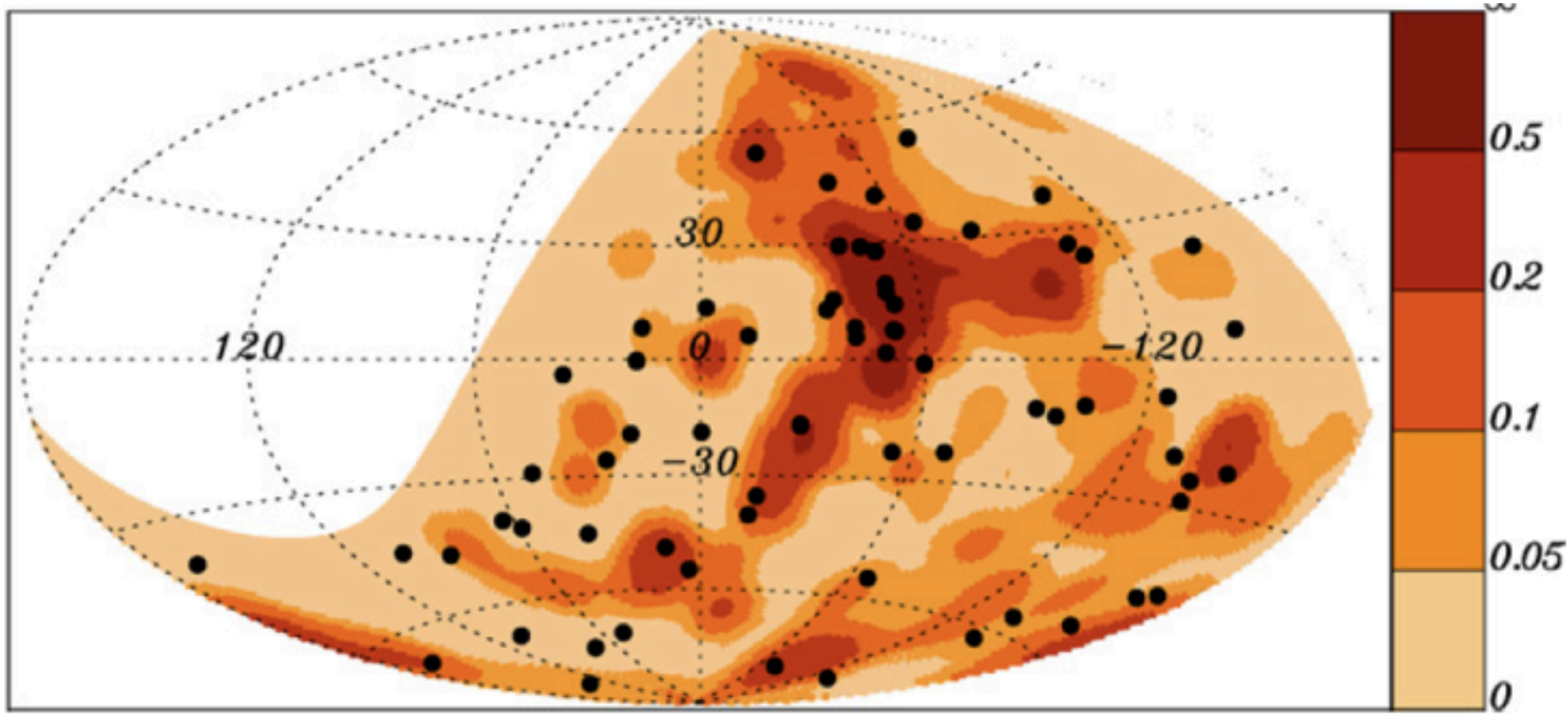
current signal: $p = 0.33 \pm 0.05$

chance probability for isotropic distribution to give this result: 0.006

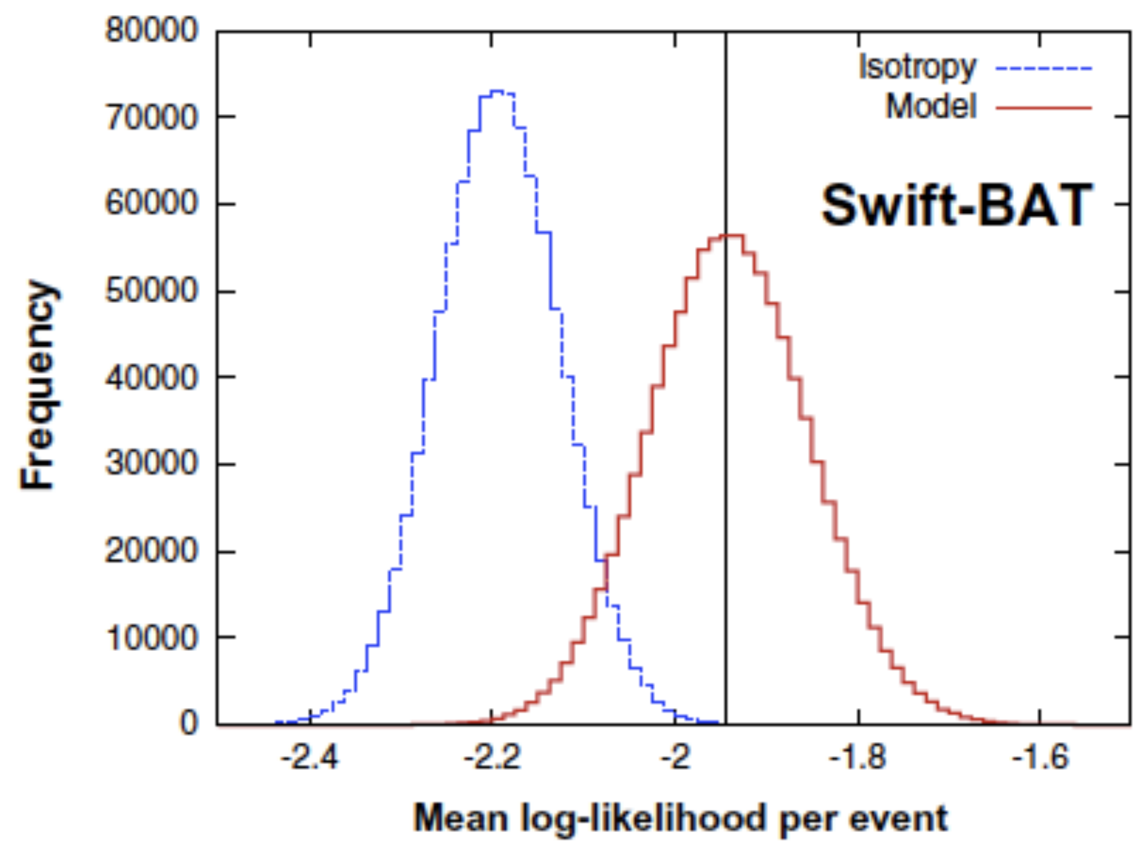
Swift-BAT

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.



data
isotropy
model

UHECRs come from
"nearby extragalactic matter"

≈30° clustering (protons ?)

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

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

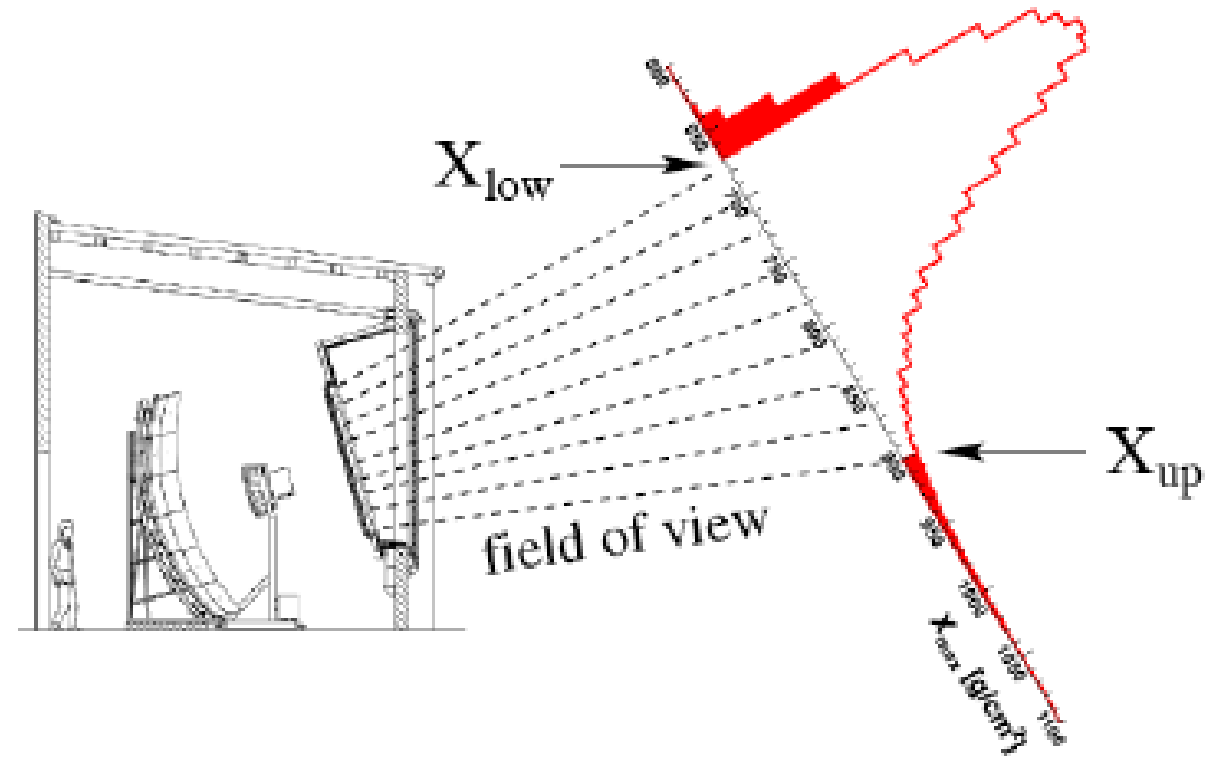
so far no evidence

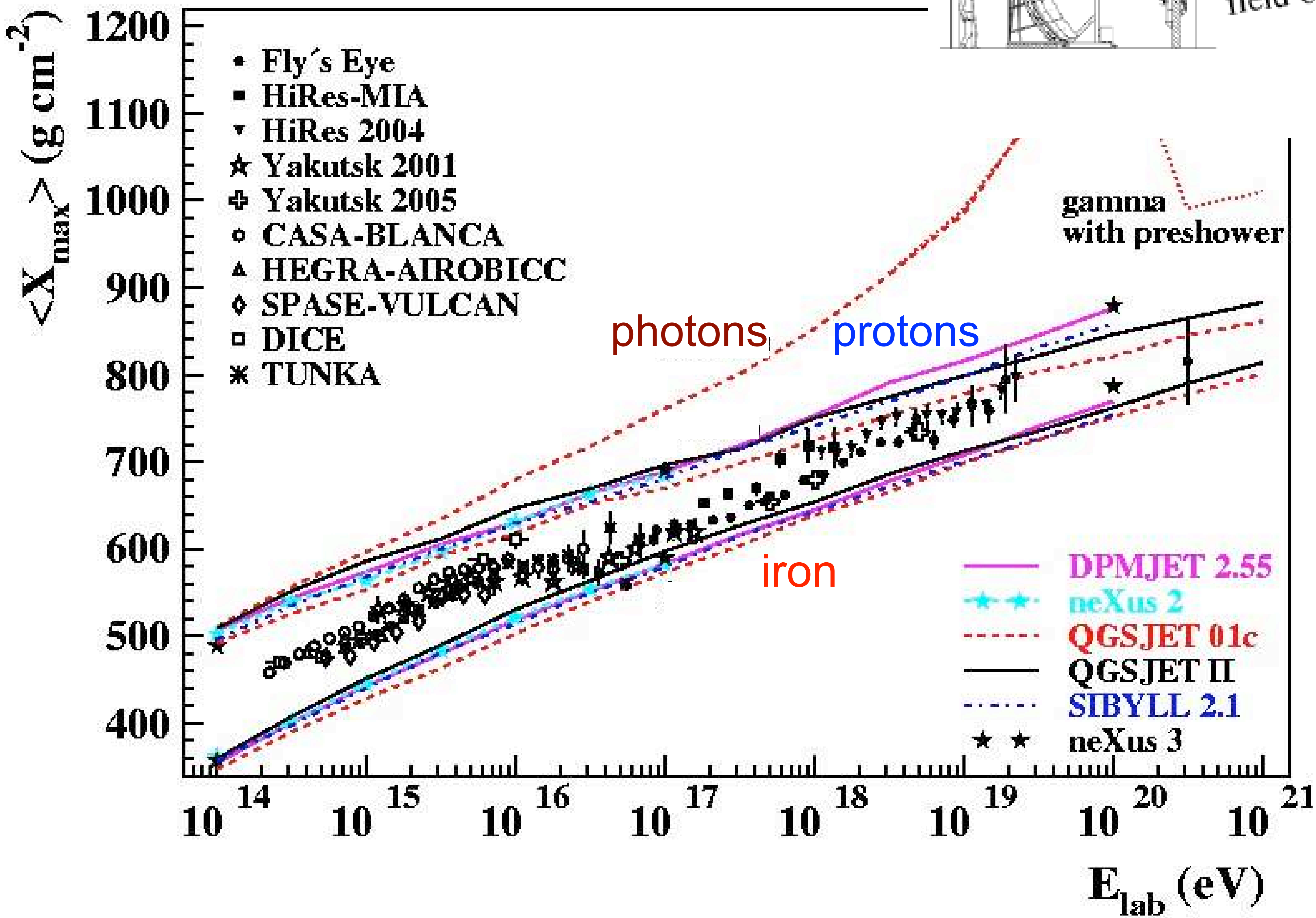
Photons

FD: measure X_{max}

photons maximise deeper than nuclei

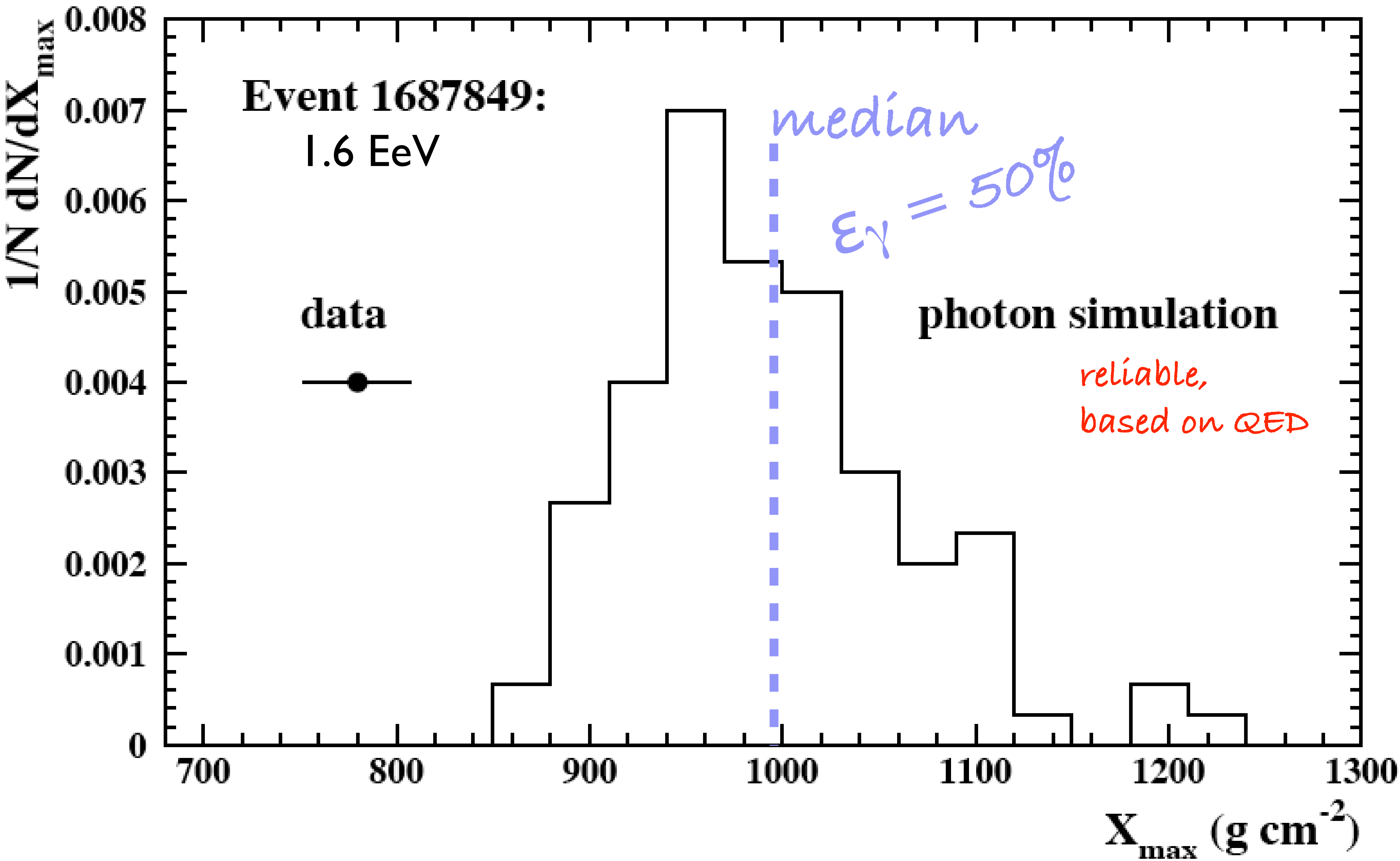
protons maximise deeper than iron



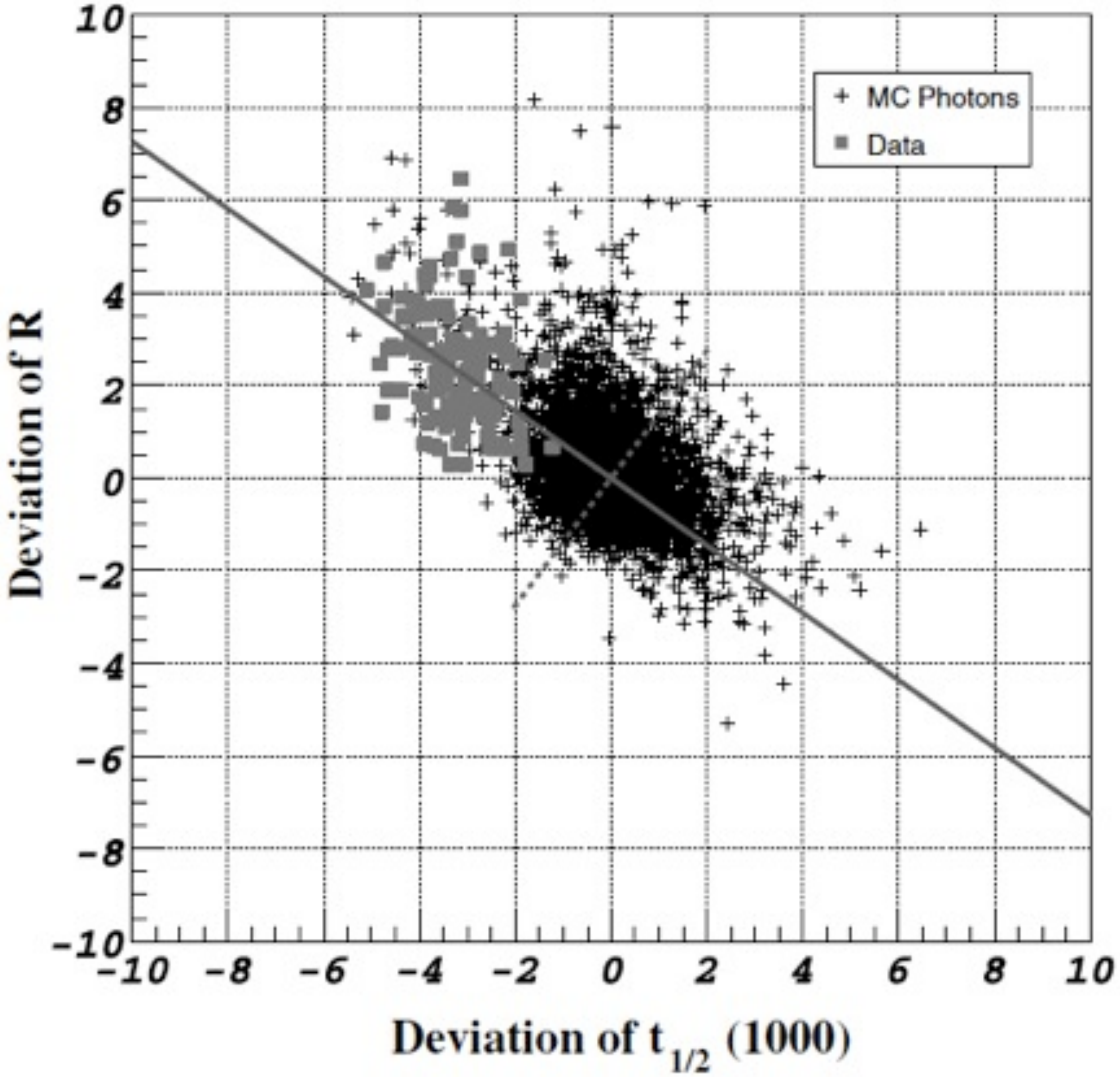


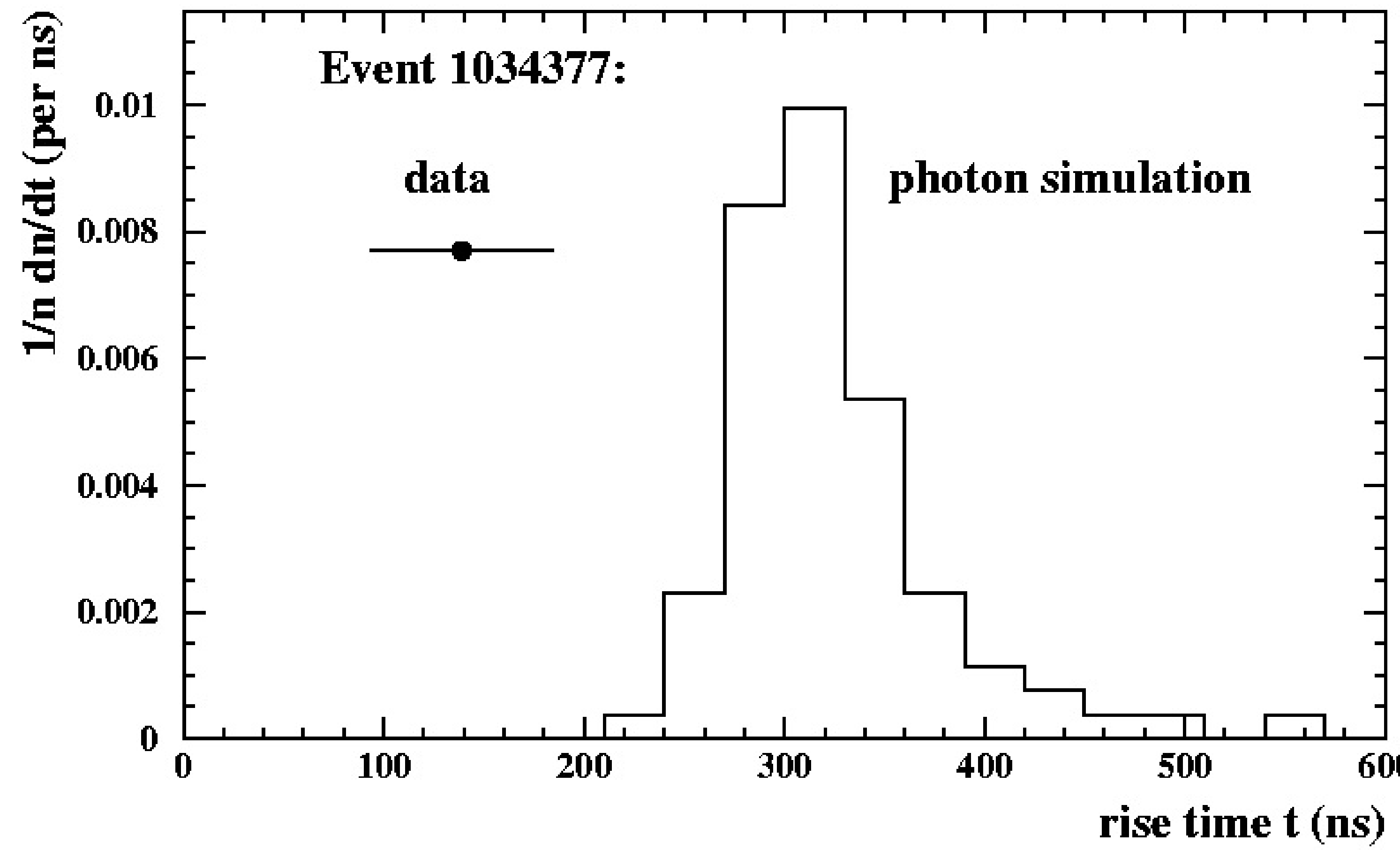
FD events (hybrid), E>10^{19} eV

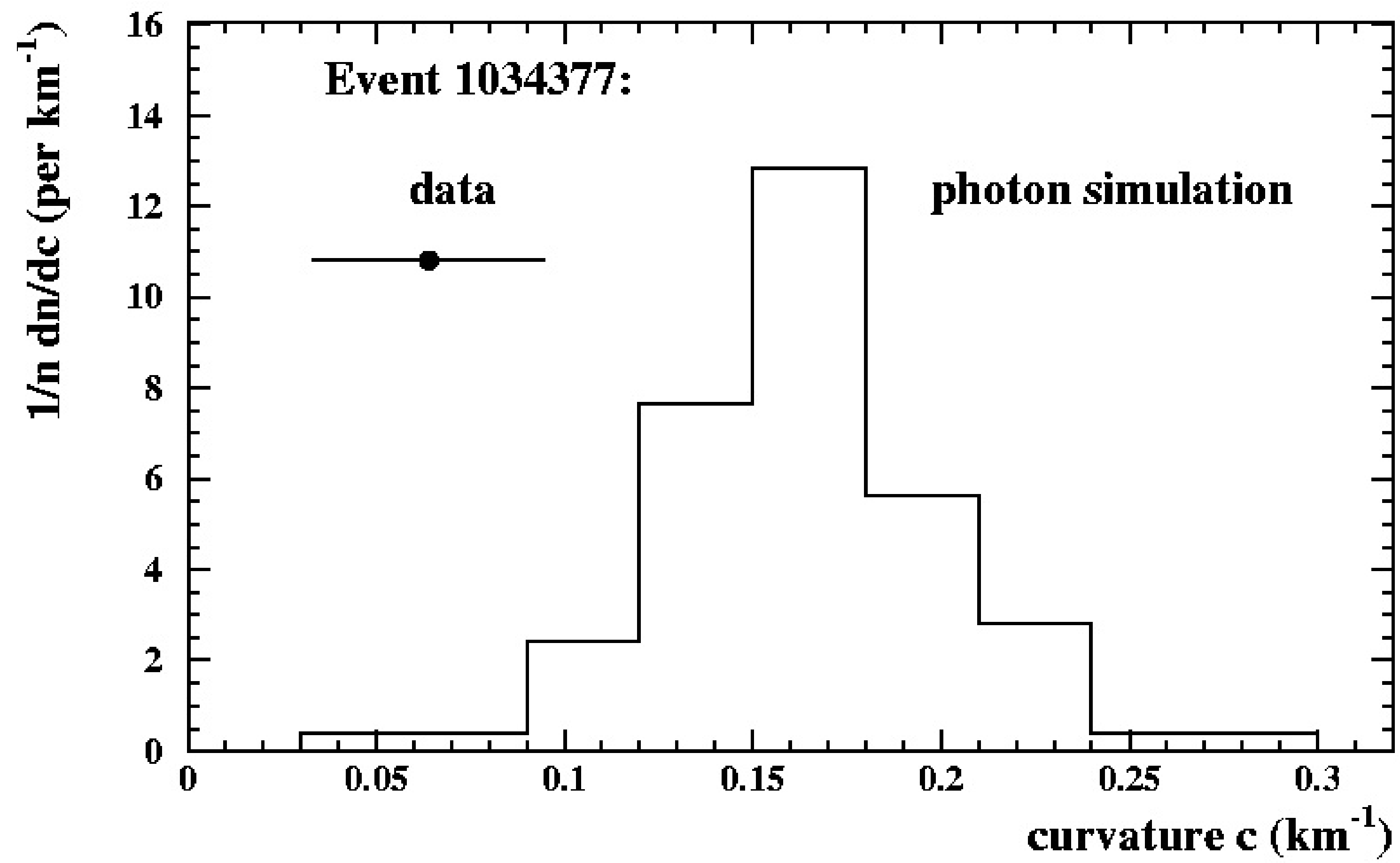
(only 10% of data)



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





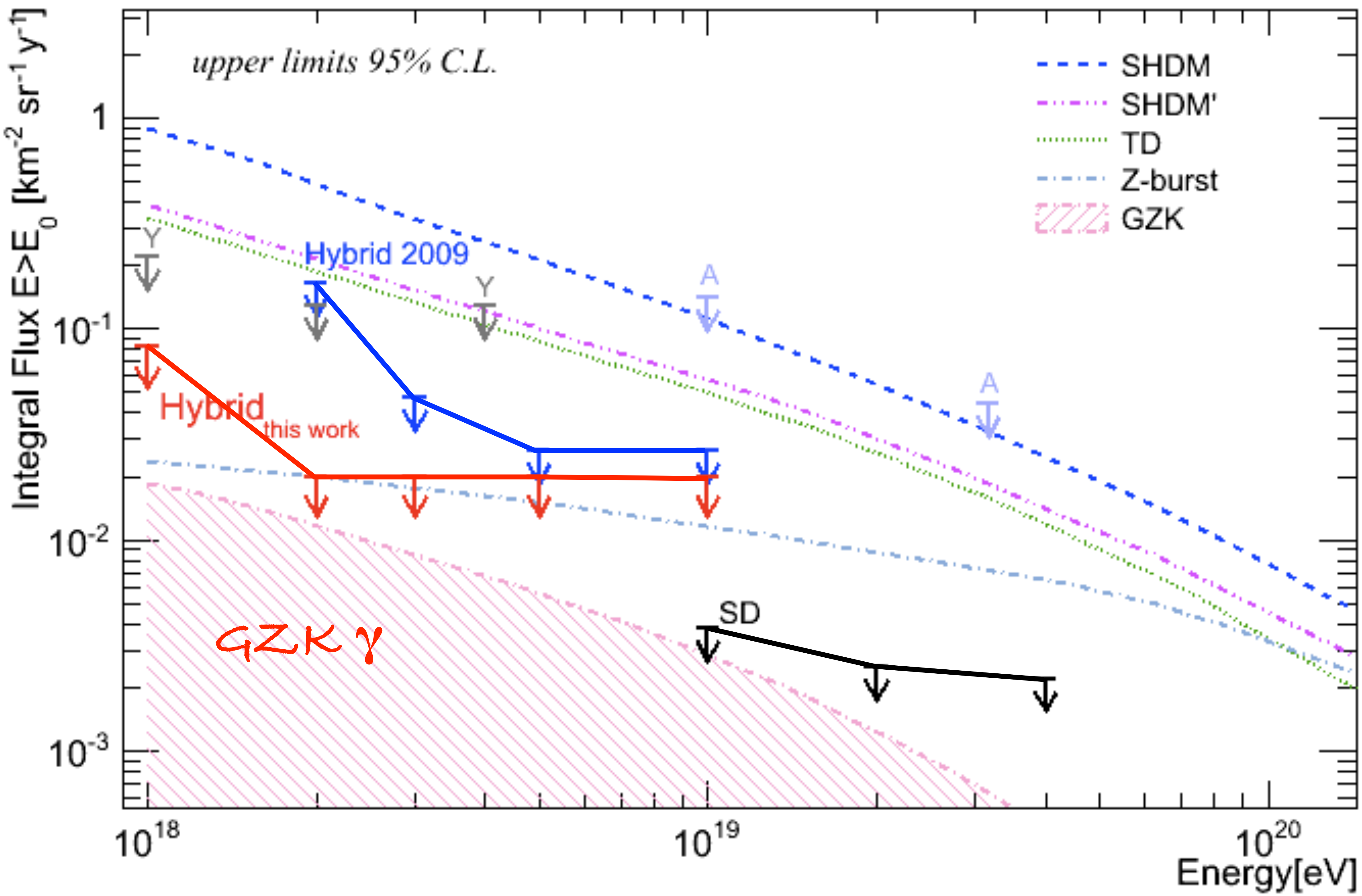


SD only variables:

- signal rise time
- curvature of shower front

SD: much larger statistics, but reconstruction not mass independent

Photon limits



improved limits at lower energies,

approaching the region where GZK γ are expected.

Composition

Options: (stable particles)

nuclei :

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

n, p ... He ... O ... Fe

the only nuclei to survive long travel to earth

difficult !
need shower model for interpretation

Galactic Neutrons

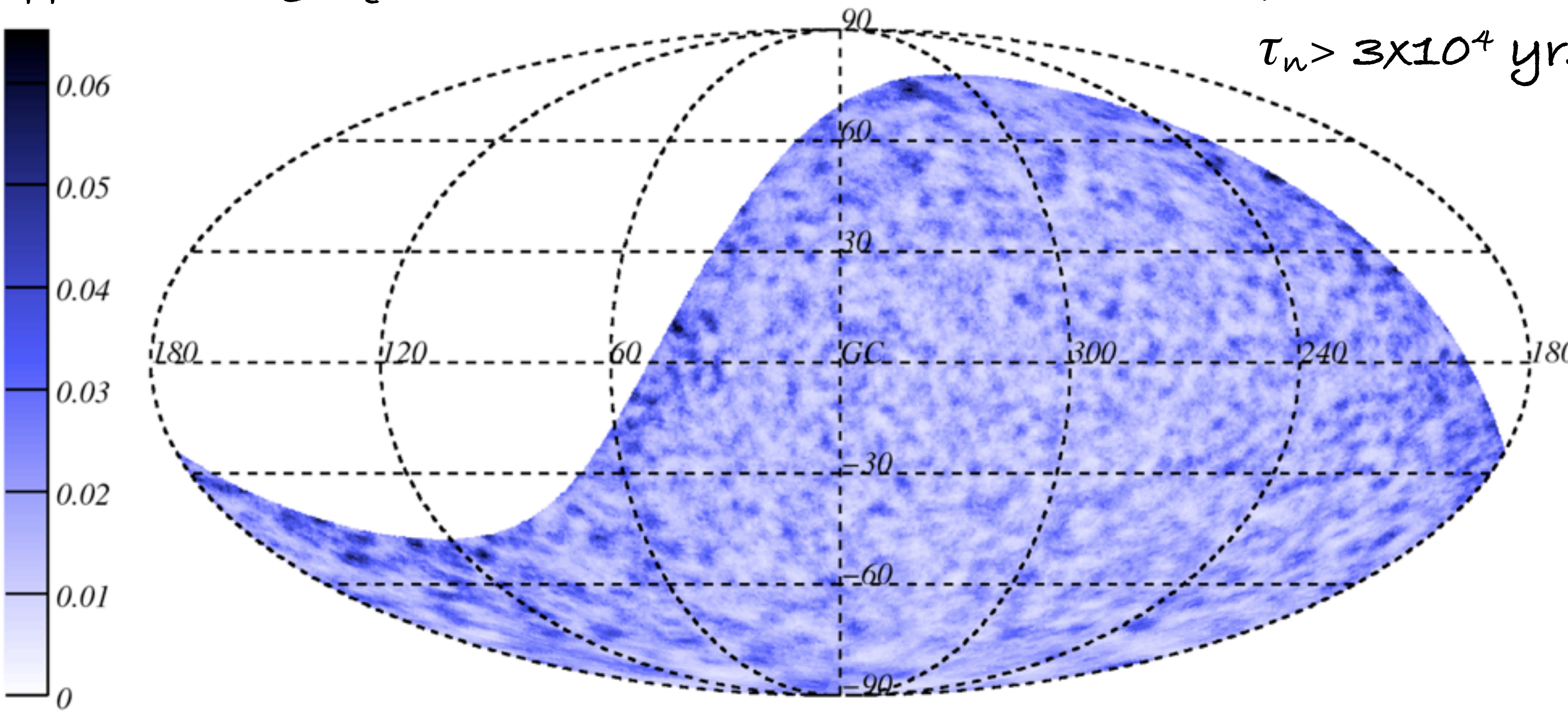
from CR accelerators (expect more n than hadronic γ),
travel in straight lines,
... but decay (can reach us only from our galaxy)
point sources ?

$E > 1\,EeV$

$\gamma > 10^9$

$\tau_n > 3 \times 10^4$ 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

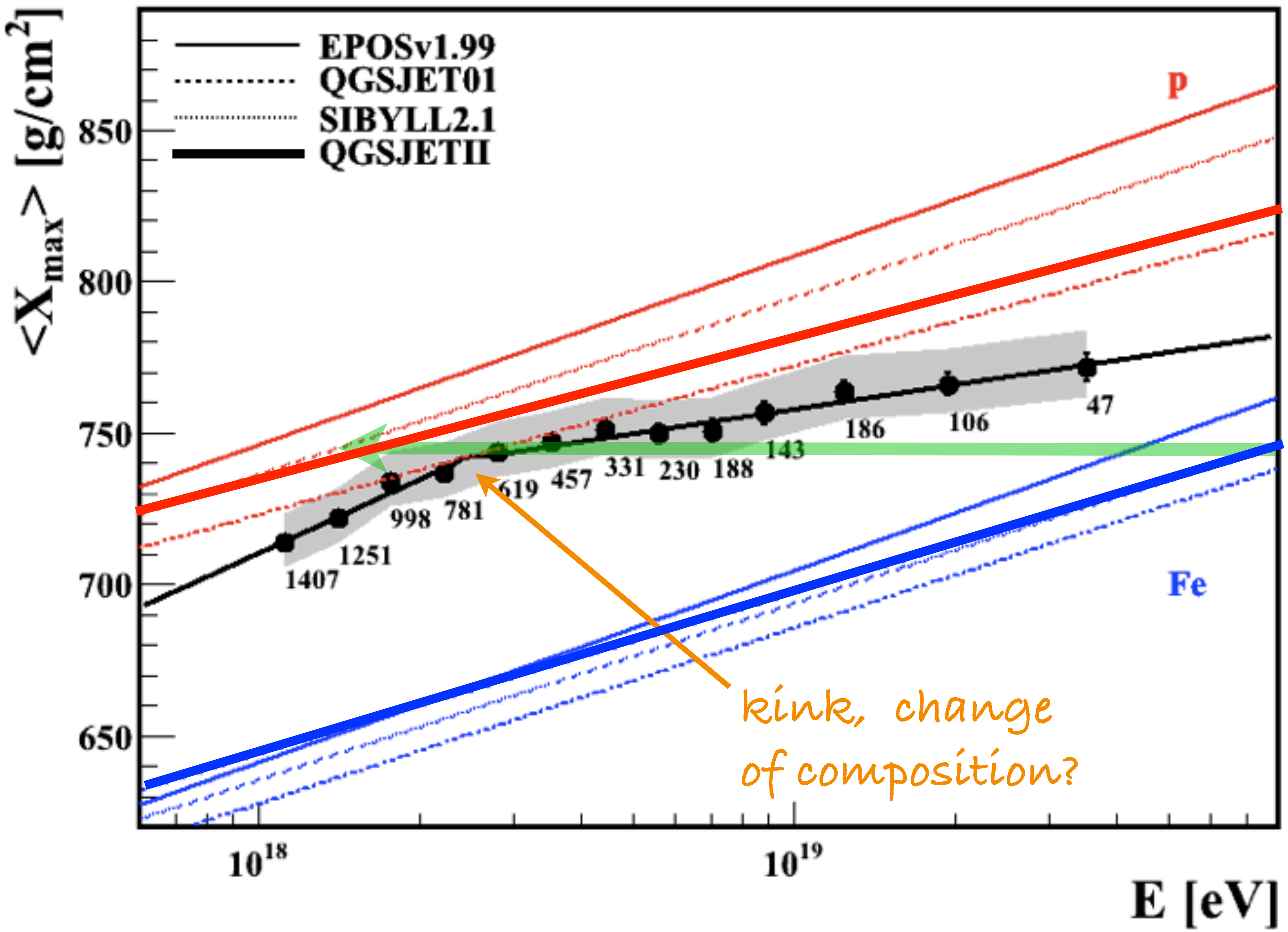
Nuclear Composition

X_{max}: height of shower maximum

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

difficult ! need shower model for interpretation

FD:

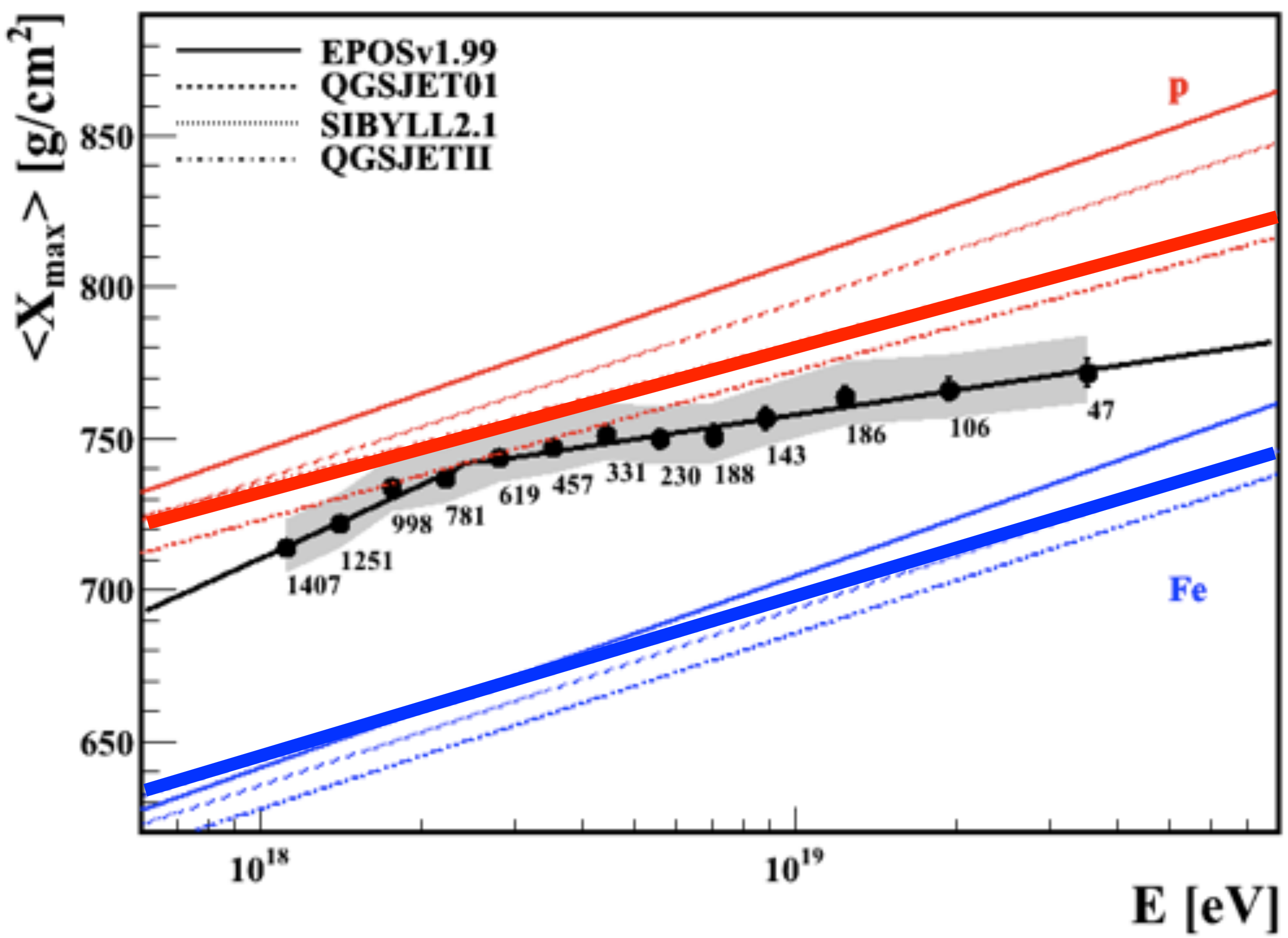


$X_{max} \sim \lg(E/A)$

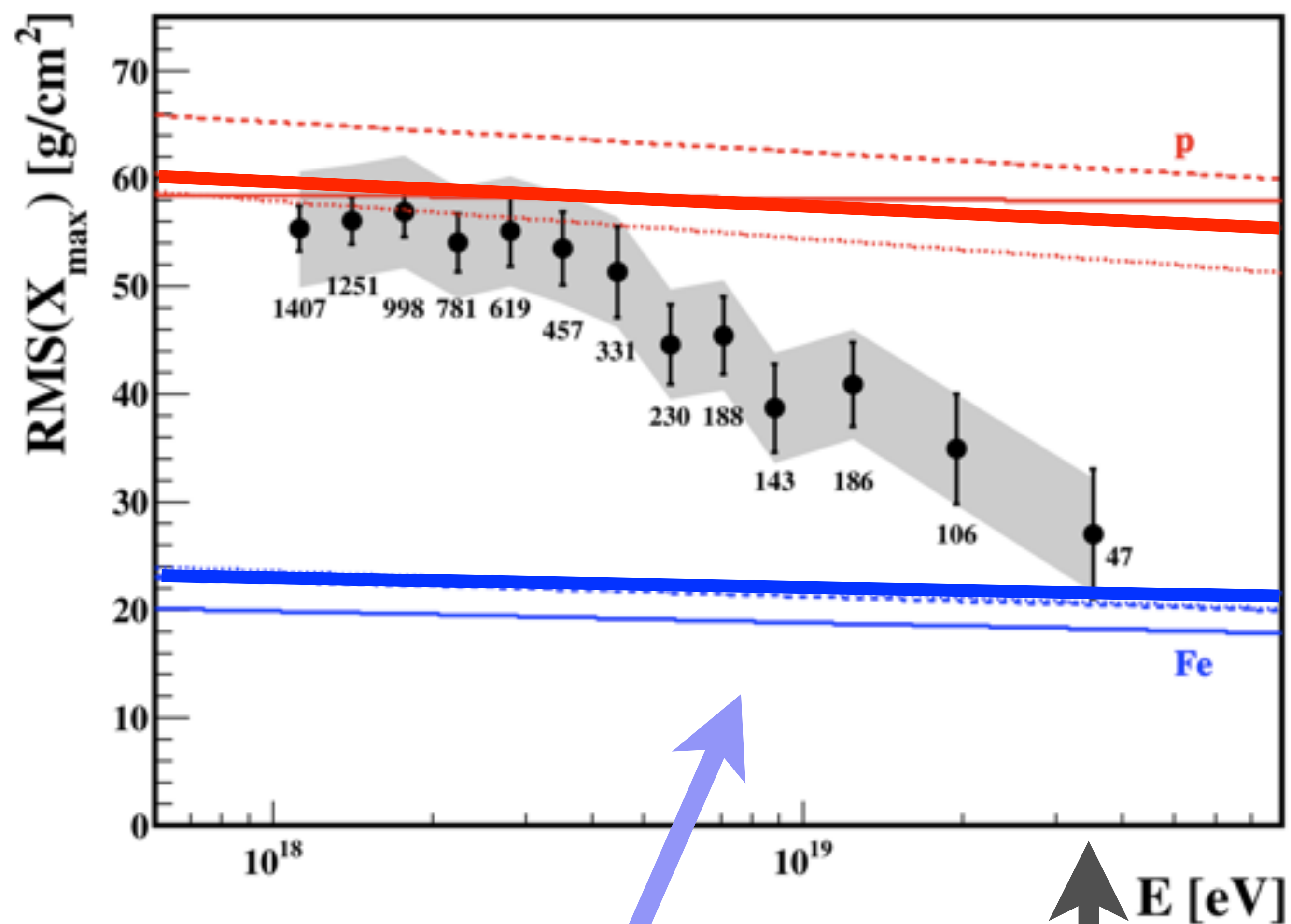
same E/A

same X_{max}

X_{max}



RMS(X_{max})



model dependent interpretation

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

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

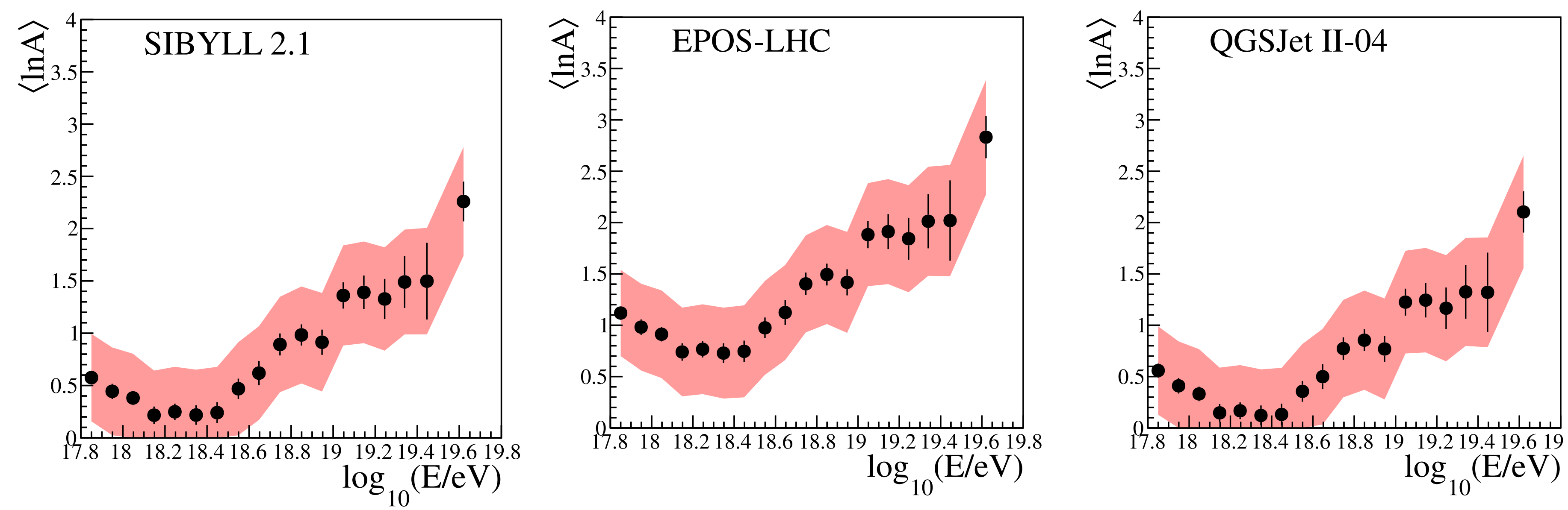
If one trusts the models,
then composition turns heavier
(but the two plots are not consistent)

mixed/heavy ?
(10^{19} eV < E < 4×10^{19} eV)

Composition data: transition to heavier primaries

$$\langle X_{\max} \rangle \approx \langle X^p_{\max} \rangle - D_p \langle \ln A \rangle$$

$\langle \ln A \rangle$: Transition from medium → light → heavy ?

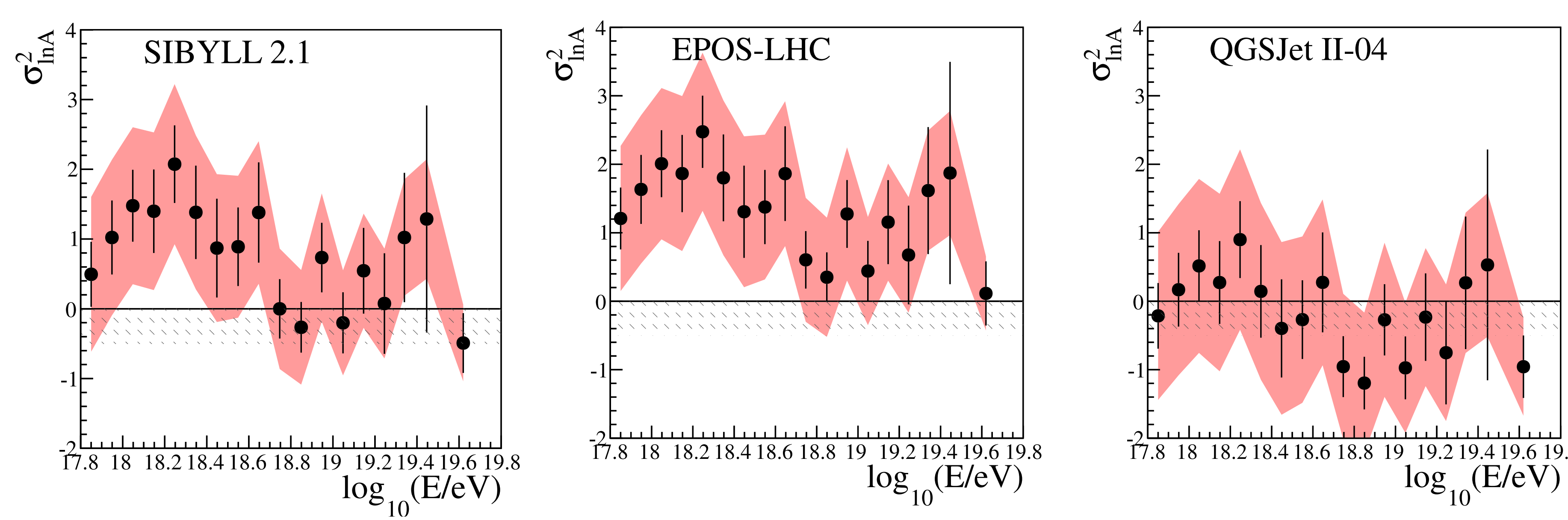


Fe

p

$$\sigma(X_{\max})^2 \approx \langle \sigma_i^2 \rangle + D_p^2 \, \sigma(\ln A)^2$$

σ(ln A): Transition from proton dominated or mixed → approx. pure ?



50:50 p:Fe

pure p

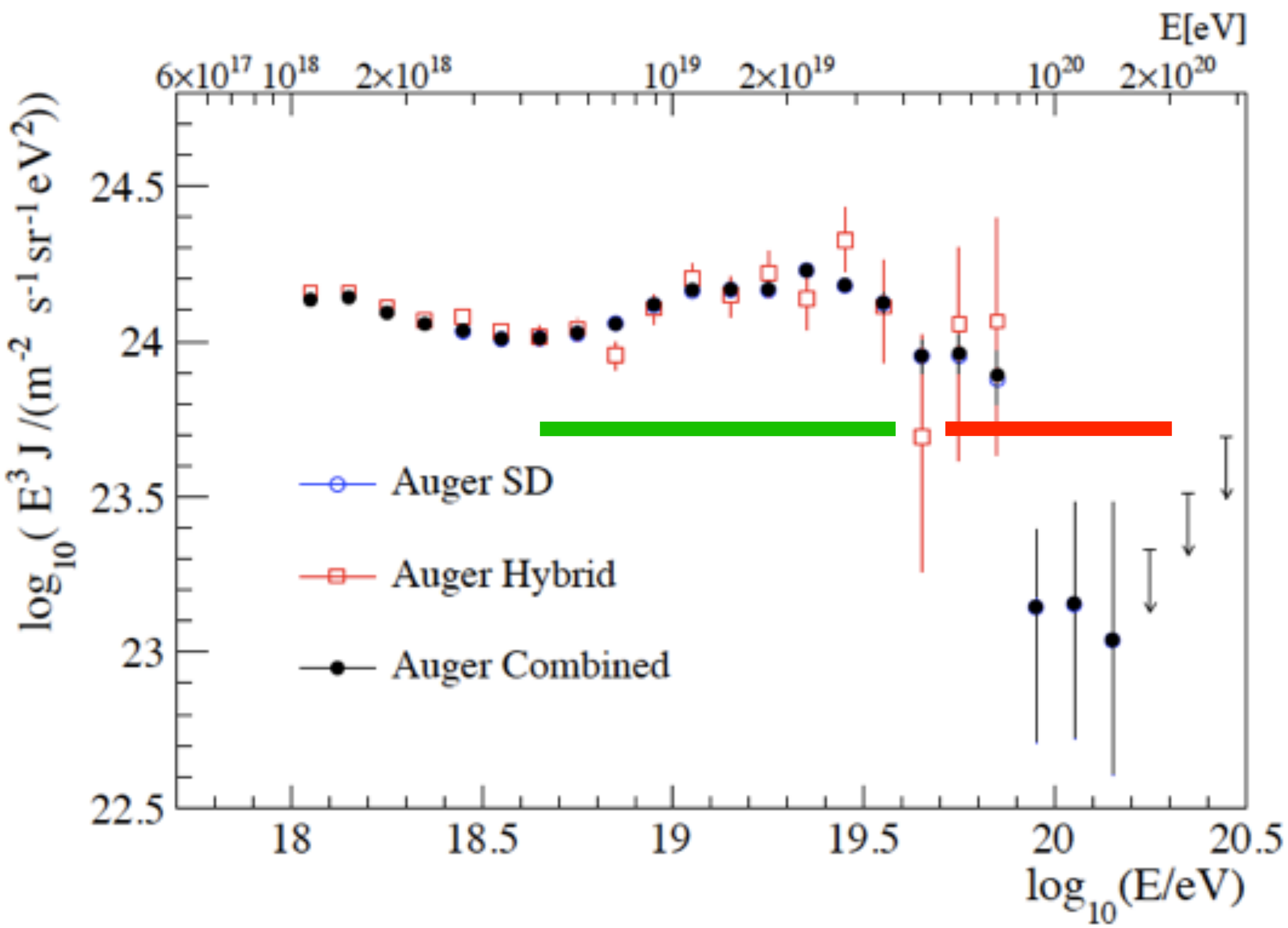
(Auger, JCAP 02 (2013) 026)

Composition mis-match ?

Spectrum: GZK cut-off ?

Anisotropy: correlation with nearby matter — p dominated ? ($E > 6\times10^{19}$ eV)

Composition: X_{max}, SD variables — mixed/heavy ? ($E < 4\times10^{19}$ eV)

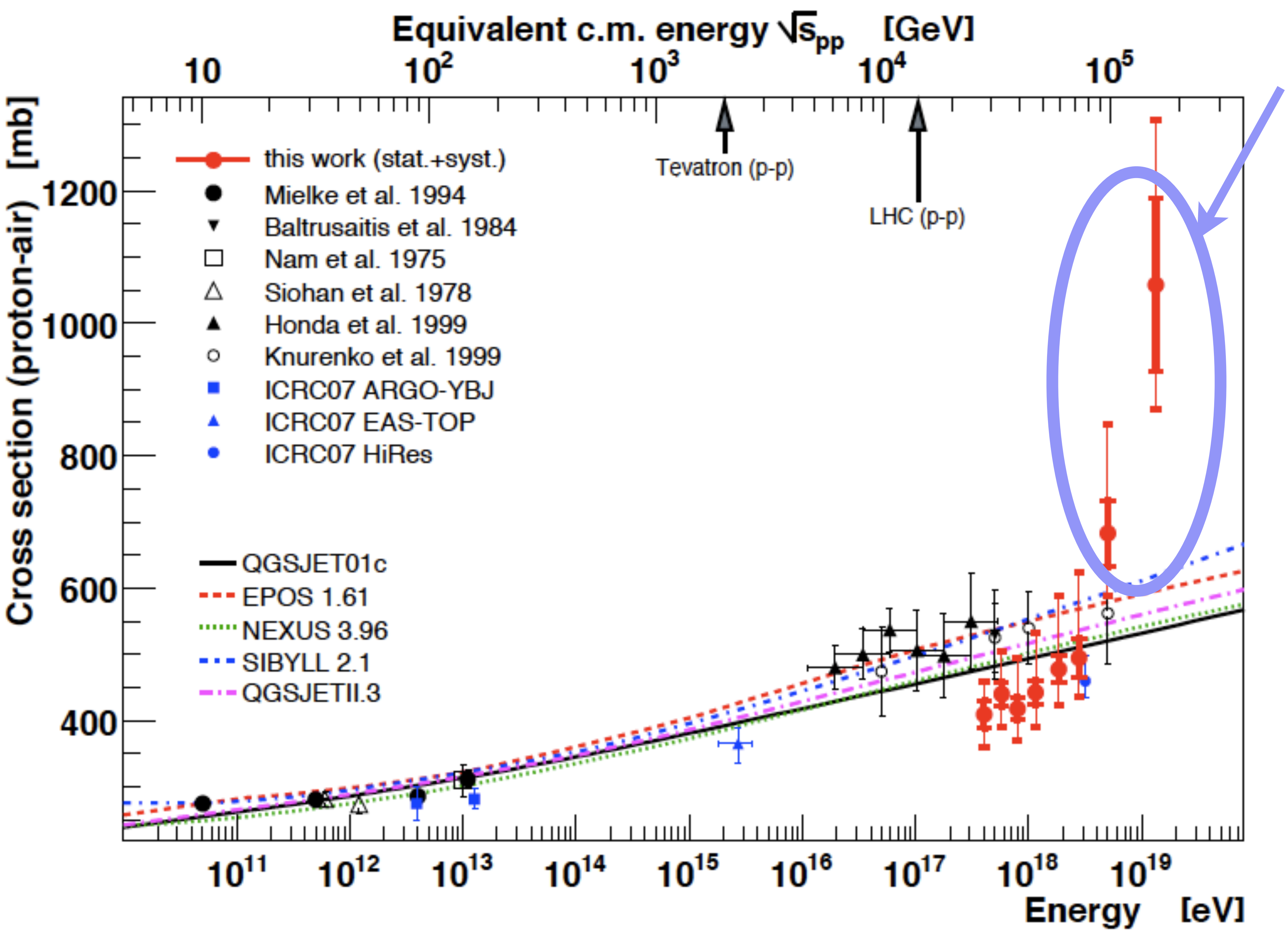


strongly model dependent

Need hadronic interaction models to be modified ?

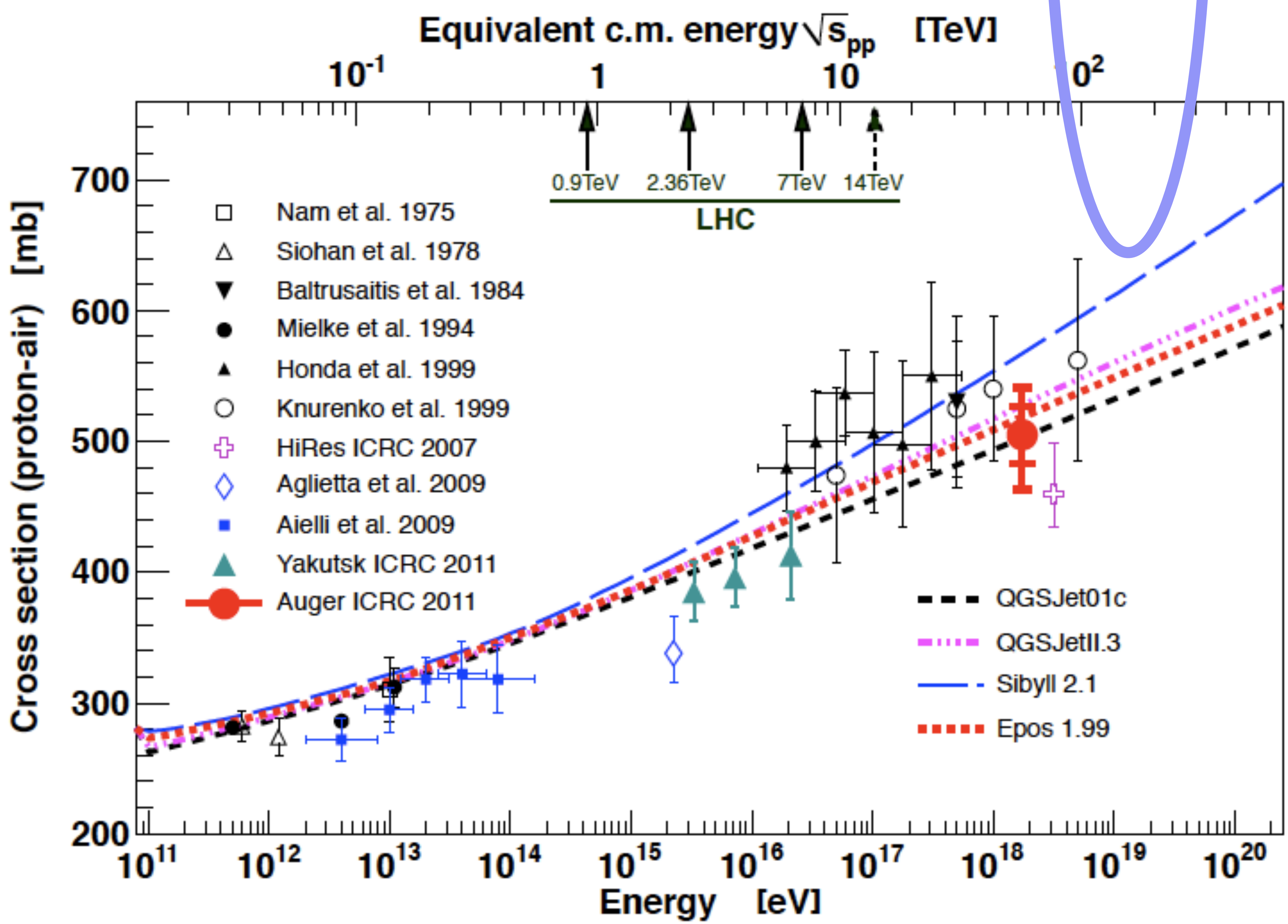
We start to do particle physics at $> 10^{18}$ eV.

What if CR are protons and physics changes?



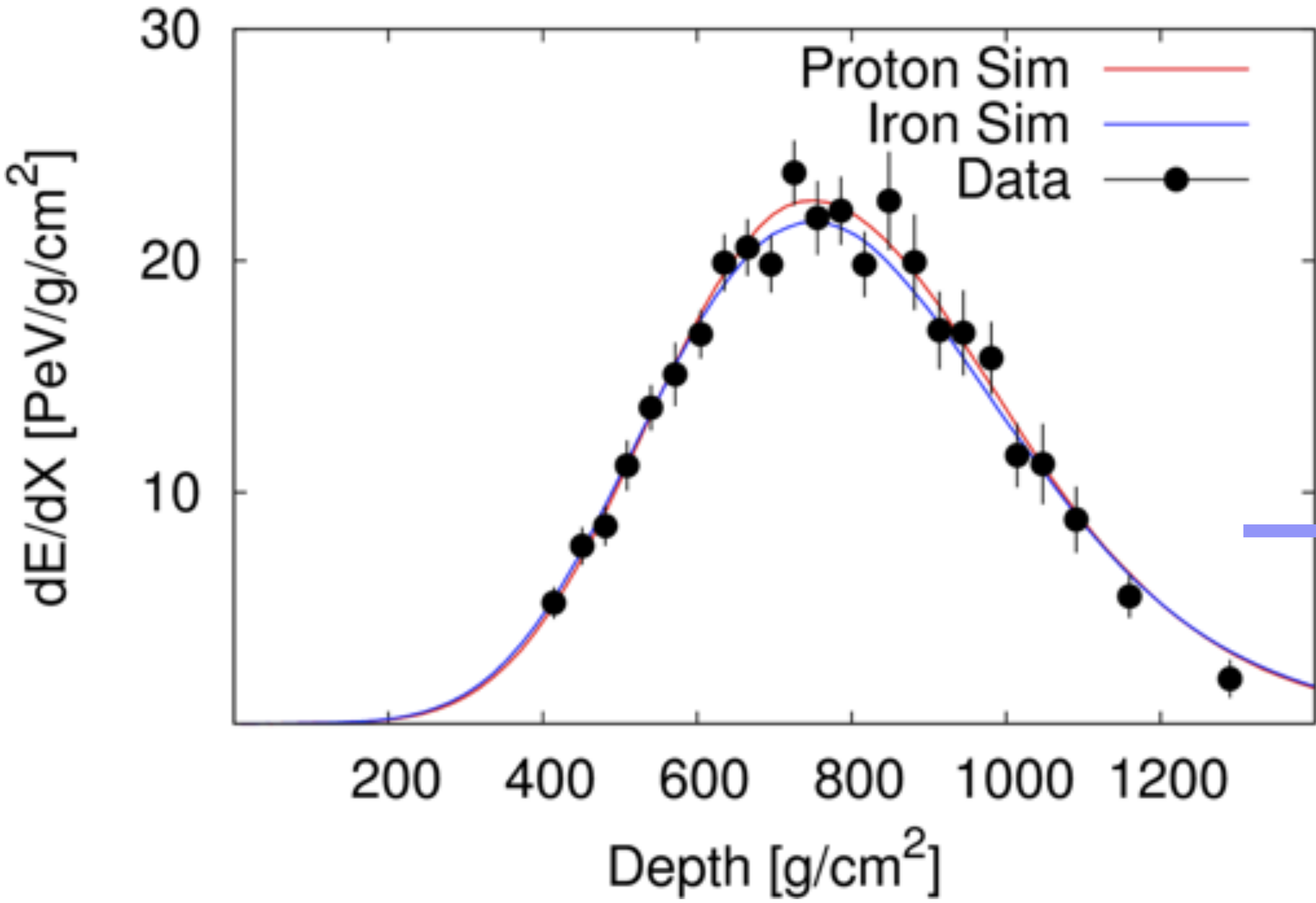
σ(p-air) to rise like this to explain RMS(X_{max}) with prim. p

Proton-Air Cross-Section

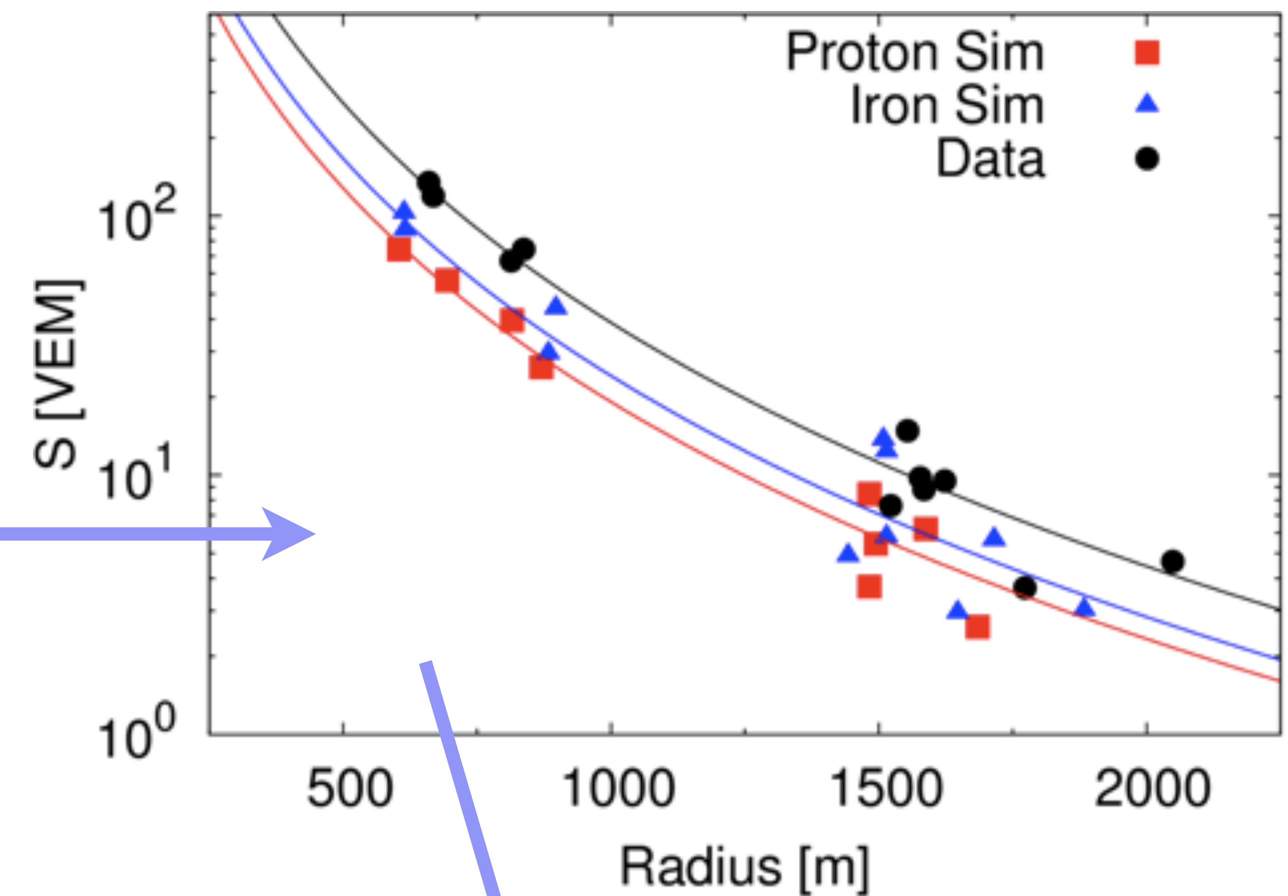


σ(p-air) = 505 ± 22 ± 30 mb (@ 2 EeV)

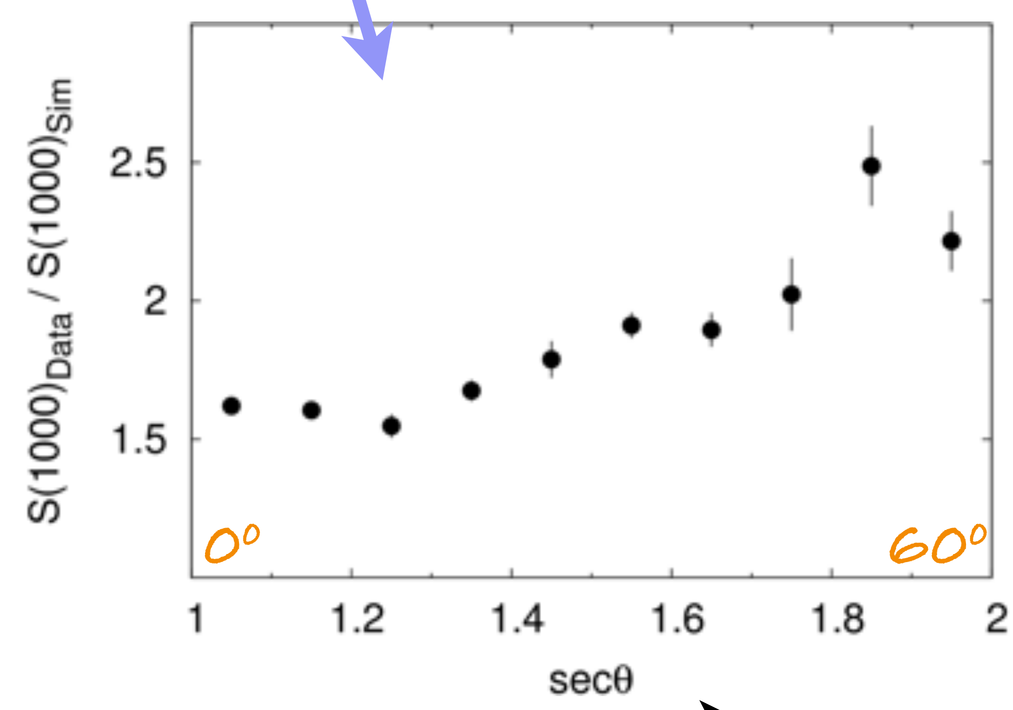
Are the EAS models right ?



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

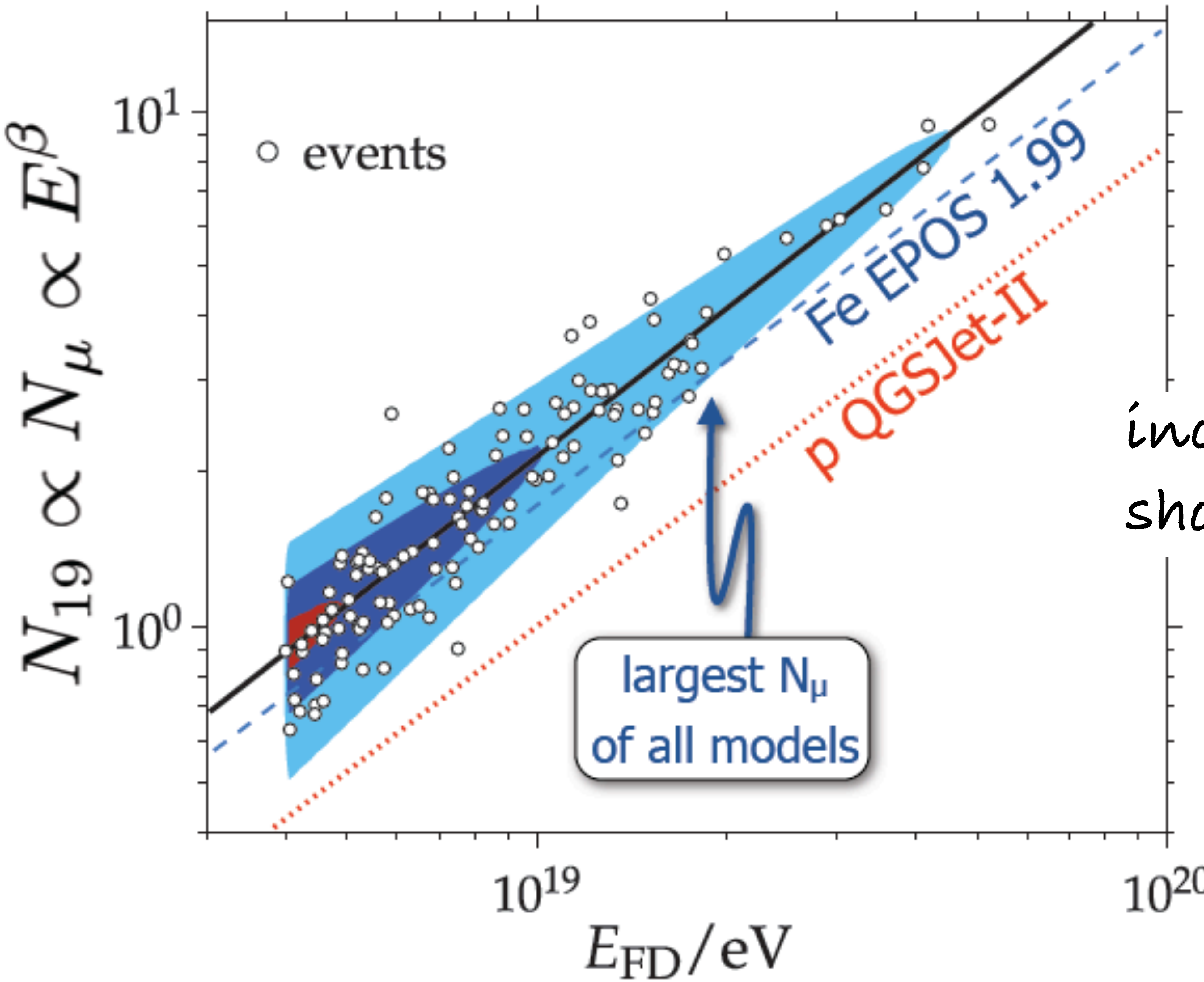


match the long. shower profile (as seen in FD) of a measured event with p and Fe simulations



μ content rises with θ

models underestimate ground signal by 1.5 - 2x



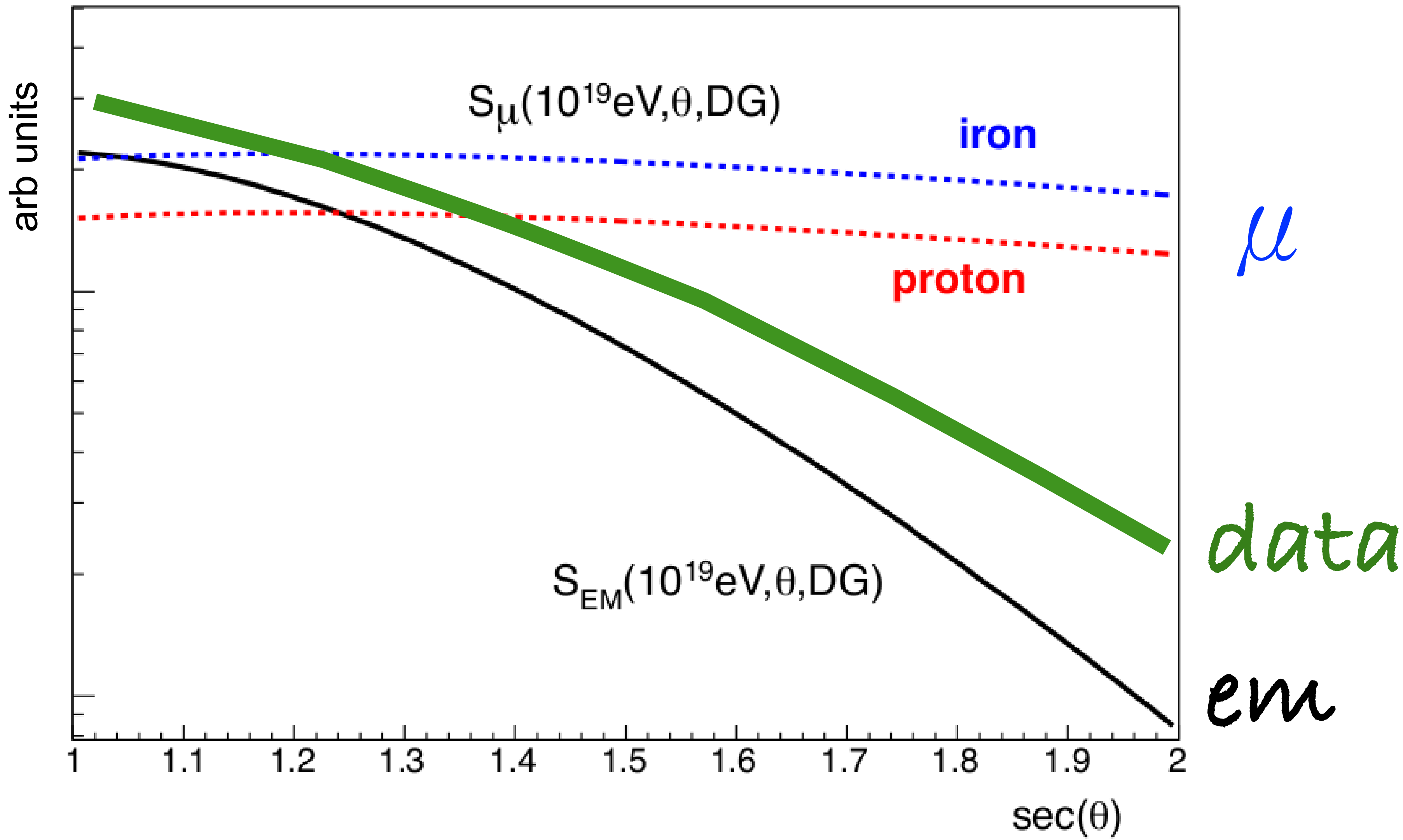
inclined showers

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

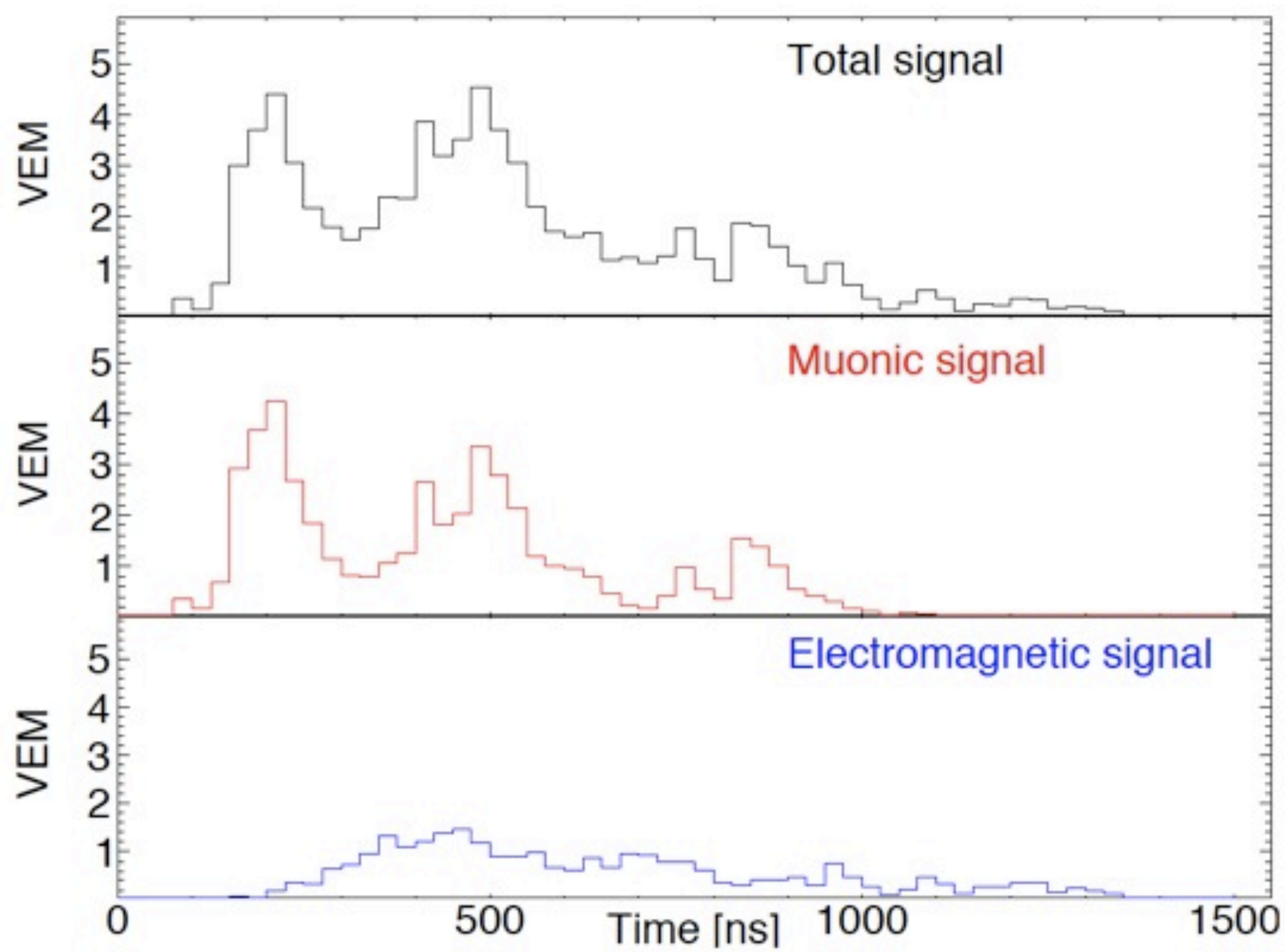
i.e. 26% higher energy estimate than FD

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



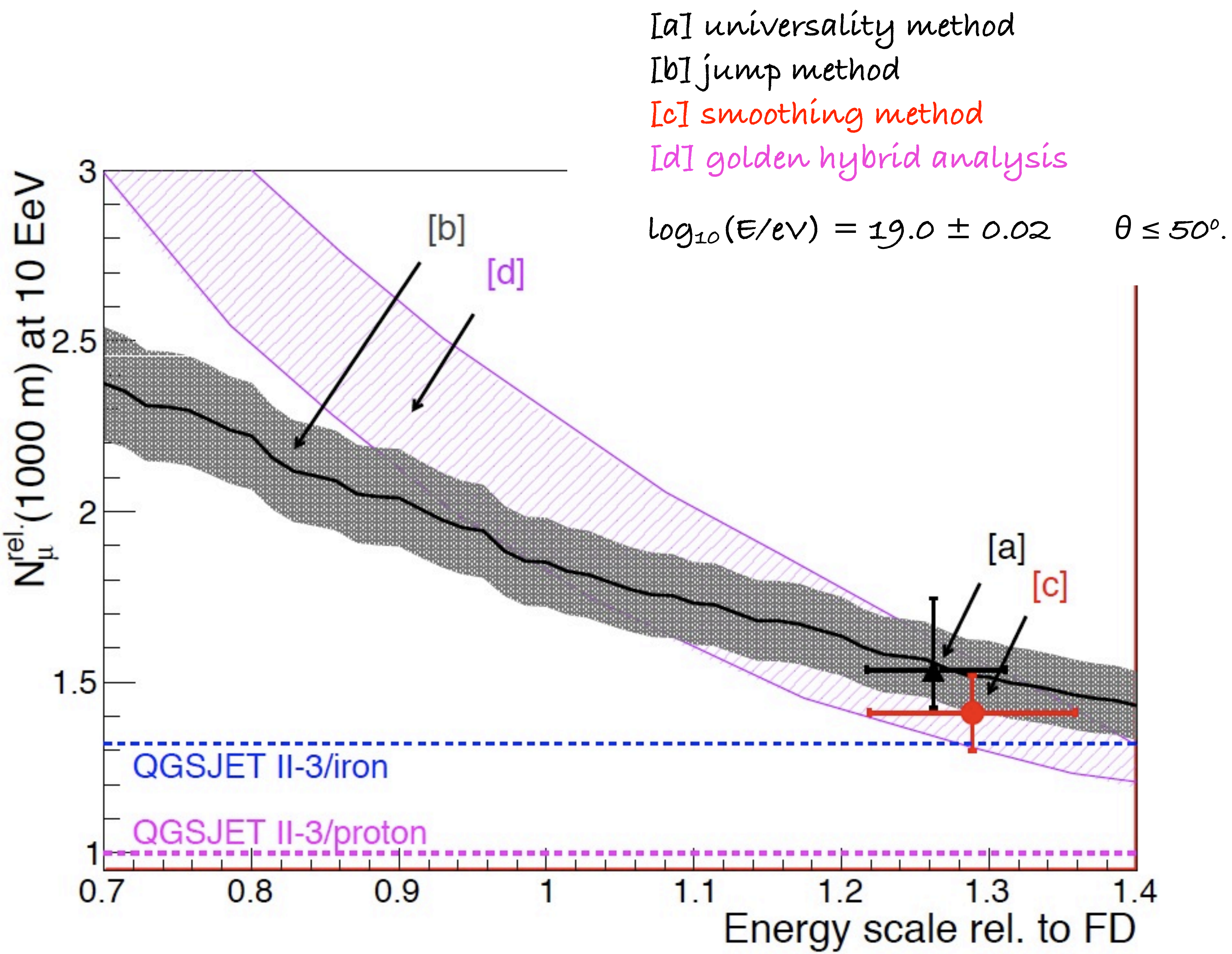
$E_{e,\gamma} \approx$ MeV

$E_{\mu} \approx$ GeV

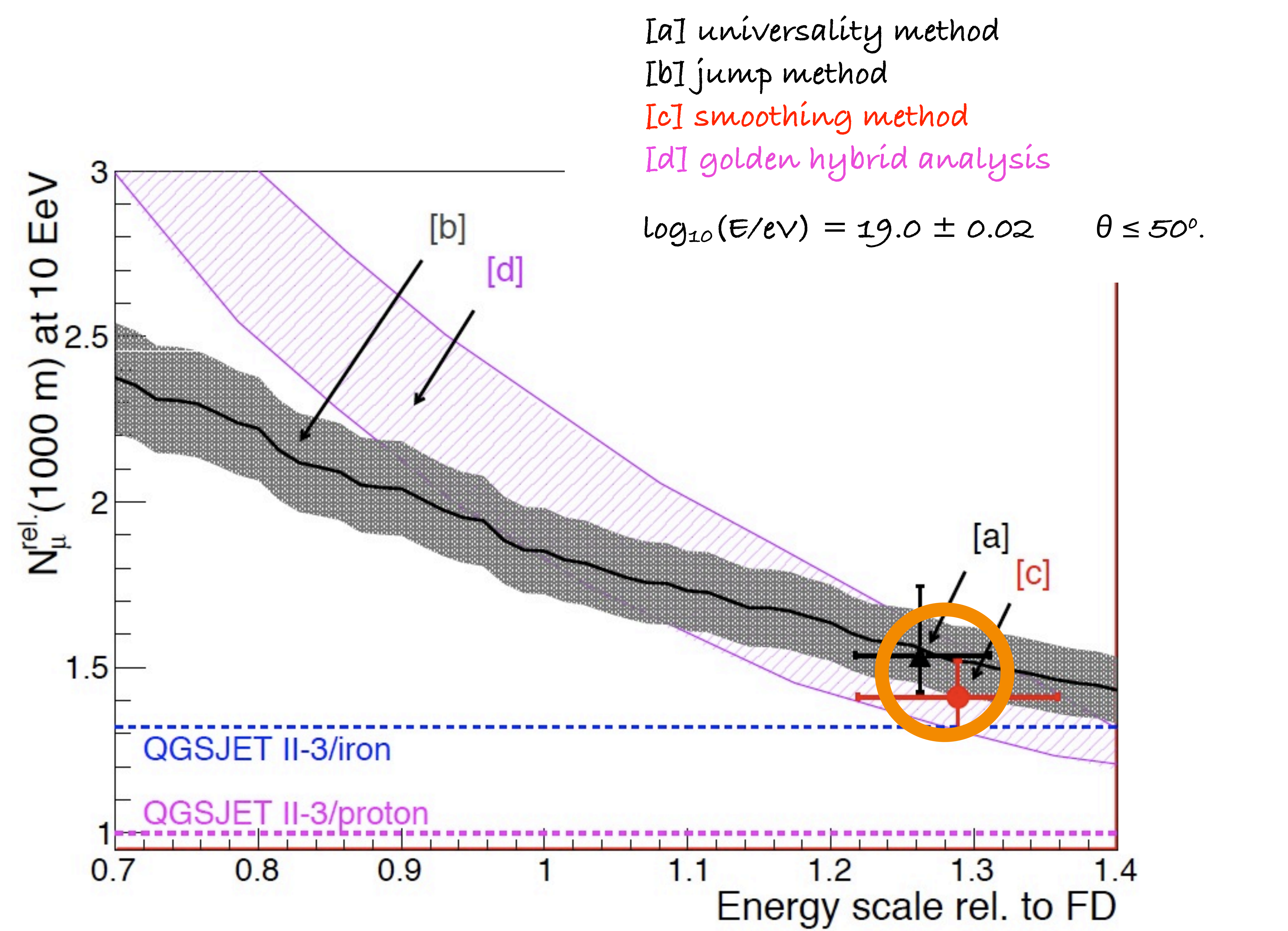
$\approx$ 240 MeV energy deposit

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
[b] jump method
[c] smoothing method
[d] golden hybrid analysis
log10(E/eV) = 19.0 ± 0.02 θ ≤ 50°.
N_μ^rel.(1000 m) at 10 EeV
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QGSJET II-3/iron
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[a]
[b]
[c]
[d]
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
2
2.5
3

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.

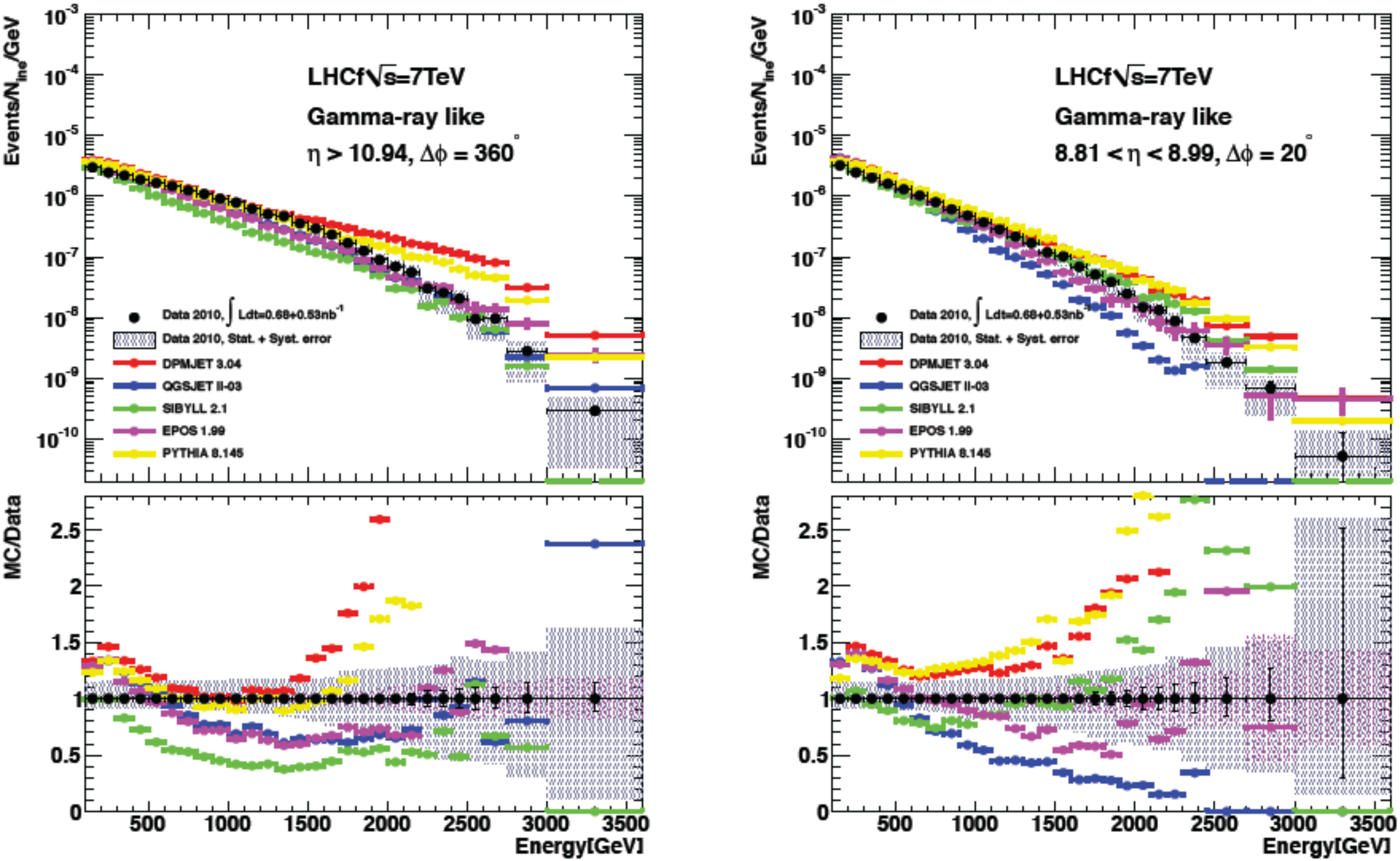
hadronic model ?

fluorescence yield ?

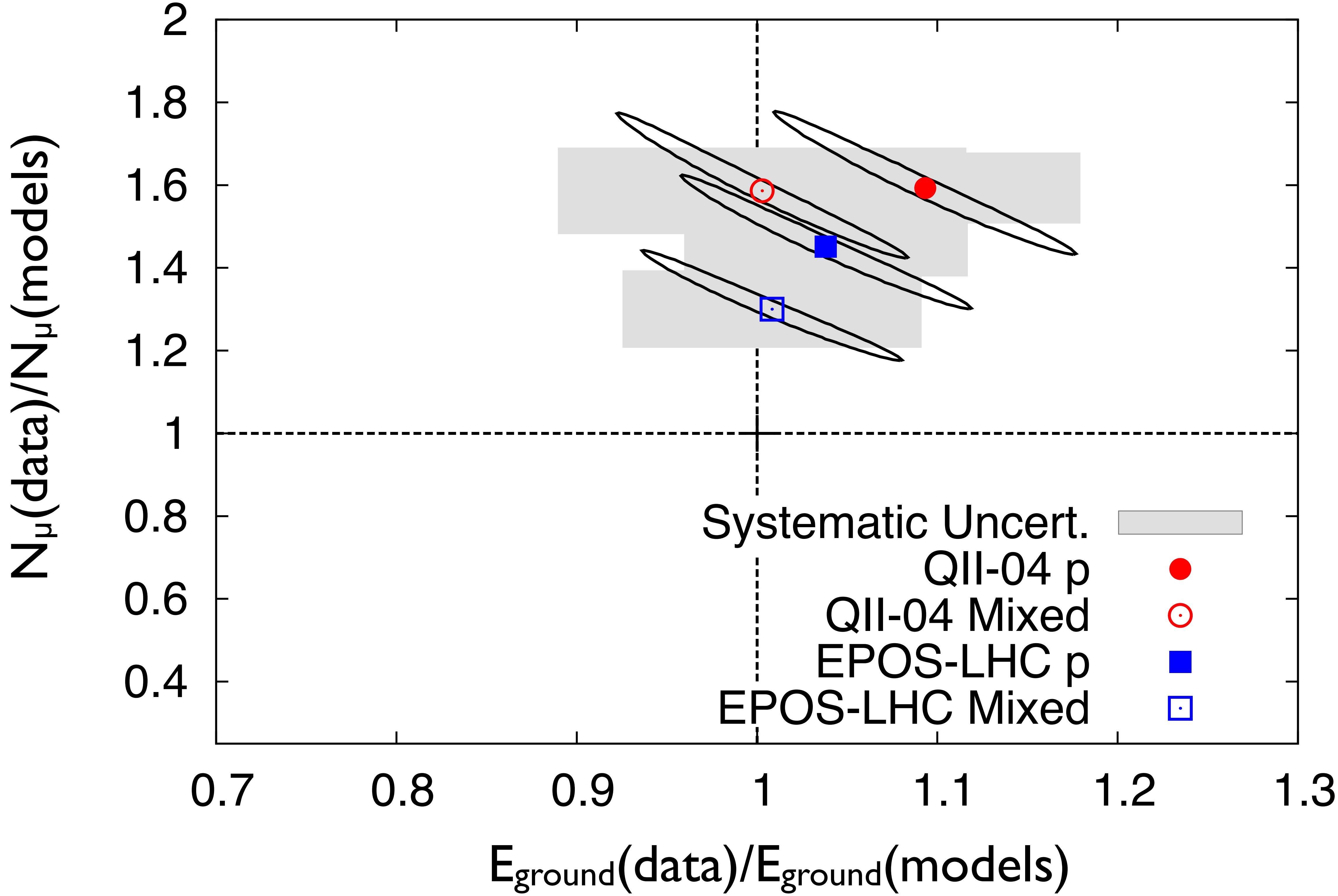
LHC results on cross-sections and particle production (in very forward range) will provide helpful constraints.

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

LHCf: π^0 production at 0°



models to be modified ...



in all models muon number is 30-60% too small

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

- further analysis of Auger data

- extension of Auger for more info per event

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

Why upgrade ?

Extend composition measurements towards higher energies:

→ search for rigidity-dependent suppression of flux

→ verify existence of ~10% p-component at E>55 EeV

→ do proton astronomy & identify sources

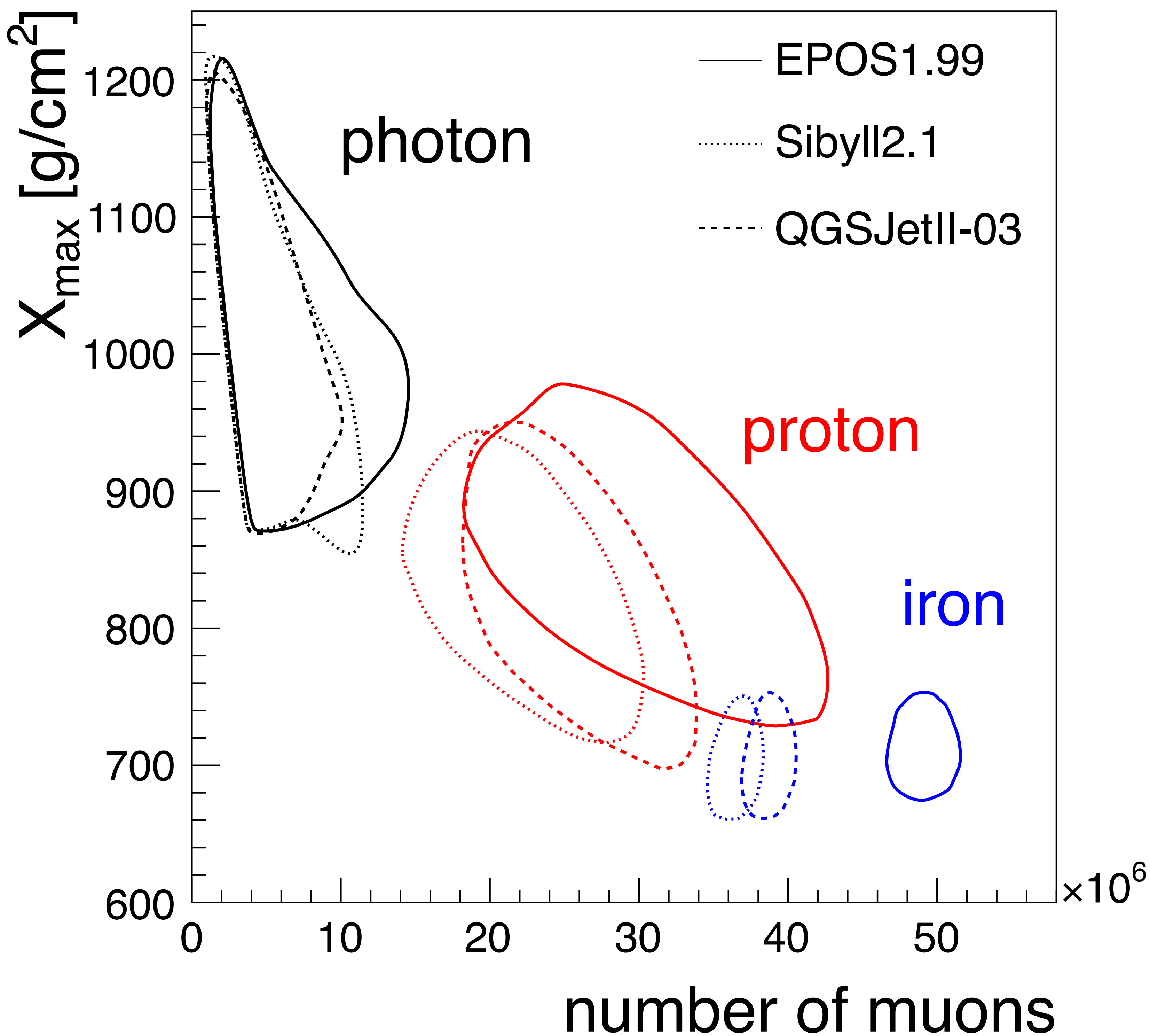
Improve sensitivity to EeV photons:

photons from GZK-effect ("smoking gun")

→ prove/disprove p-dominated composition at highest E
that may possibly be masked by rapid change of had-interactions

Study features of hadronic interactions above E_{cm} = 70 TeV

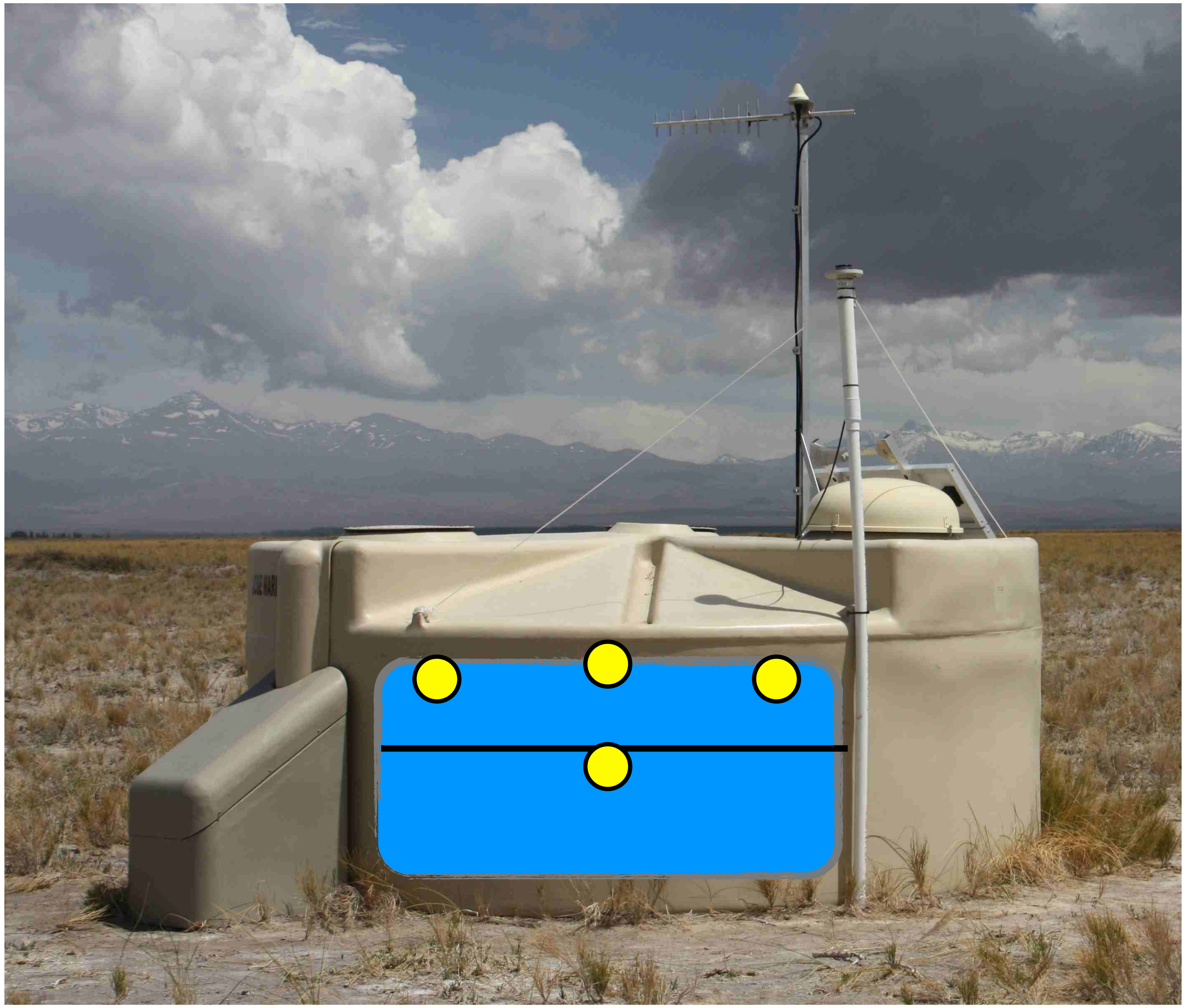
Composition measurement at energies where the cutoff is observed



measure μ comp. with SD

(100% duty cycle)

Various options ...
... to improve on em/mu separation in EAS

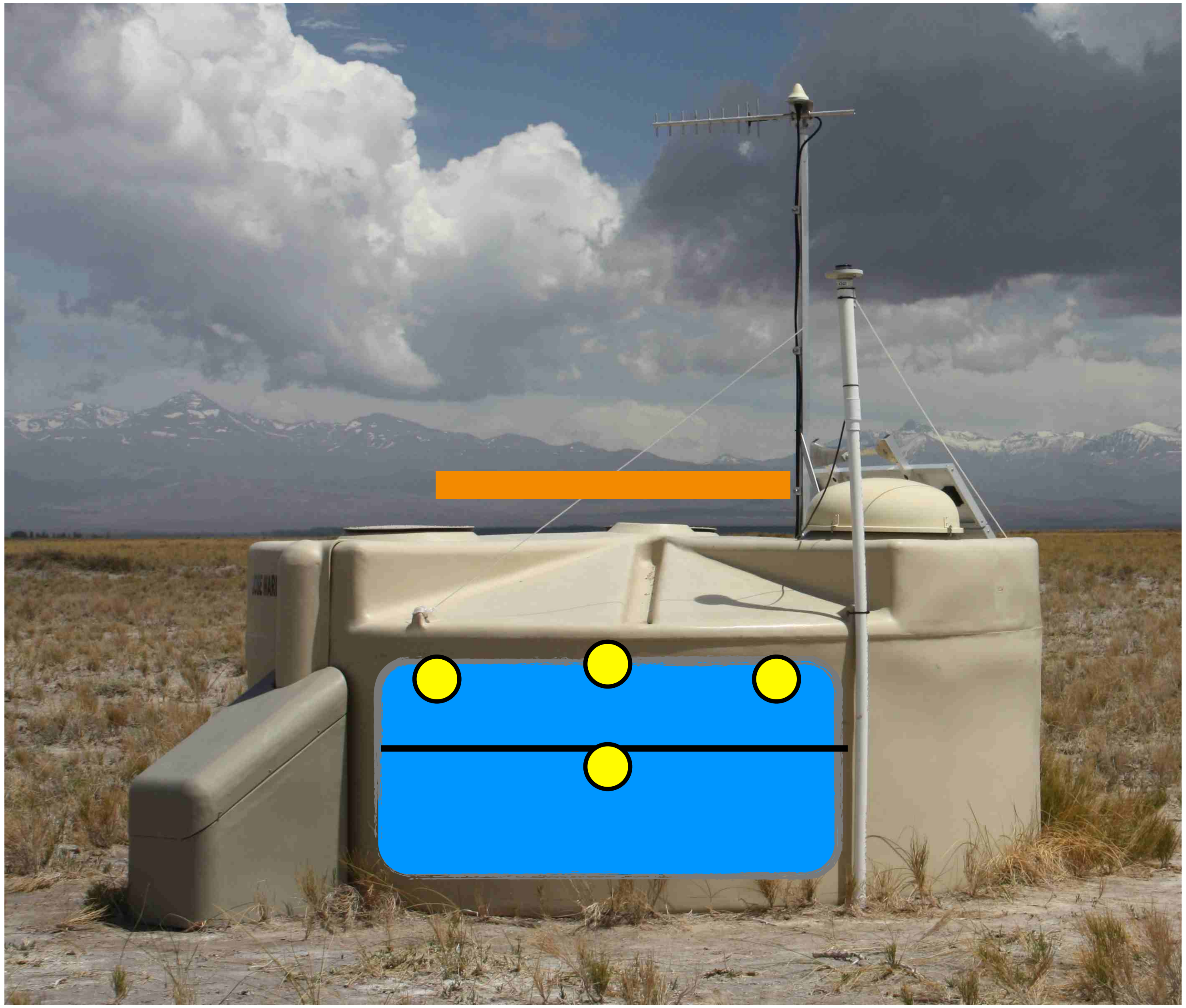


segmented tank
(LSD)

+improved tank
read-out

Various options ...

... to improve on em/mu separation in EAS

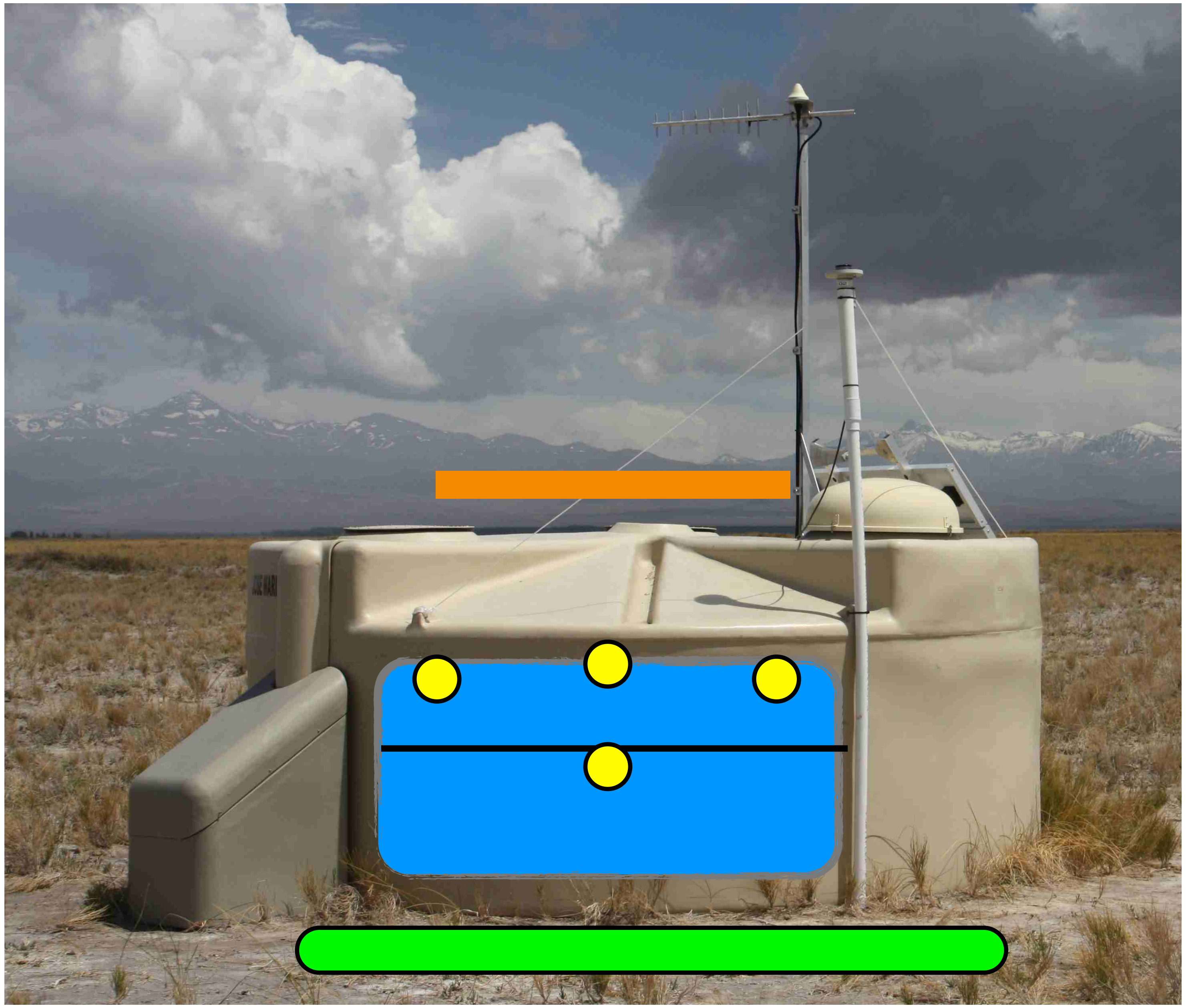


Scintillator on top (ASCII)

segmented tank (LSD)

+improved tank read-out

Various options ...
... to improve on em/mu separation in EAS



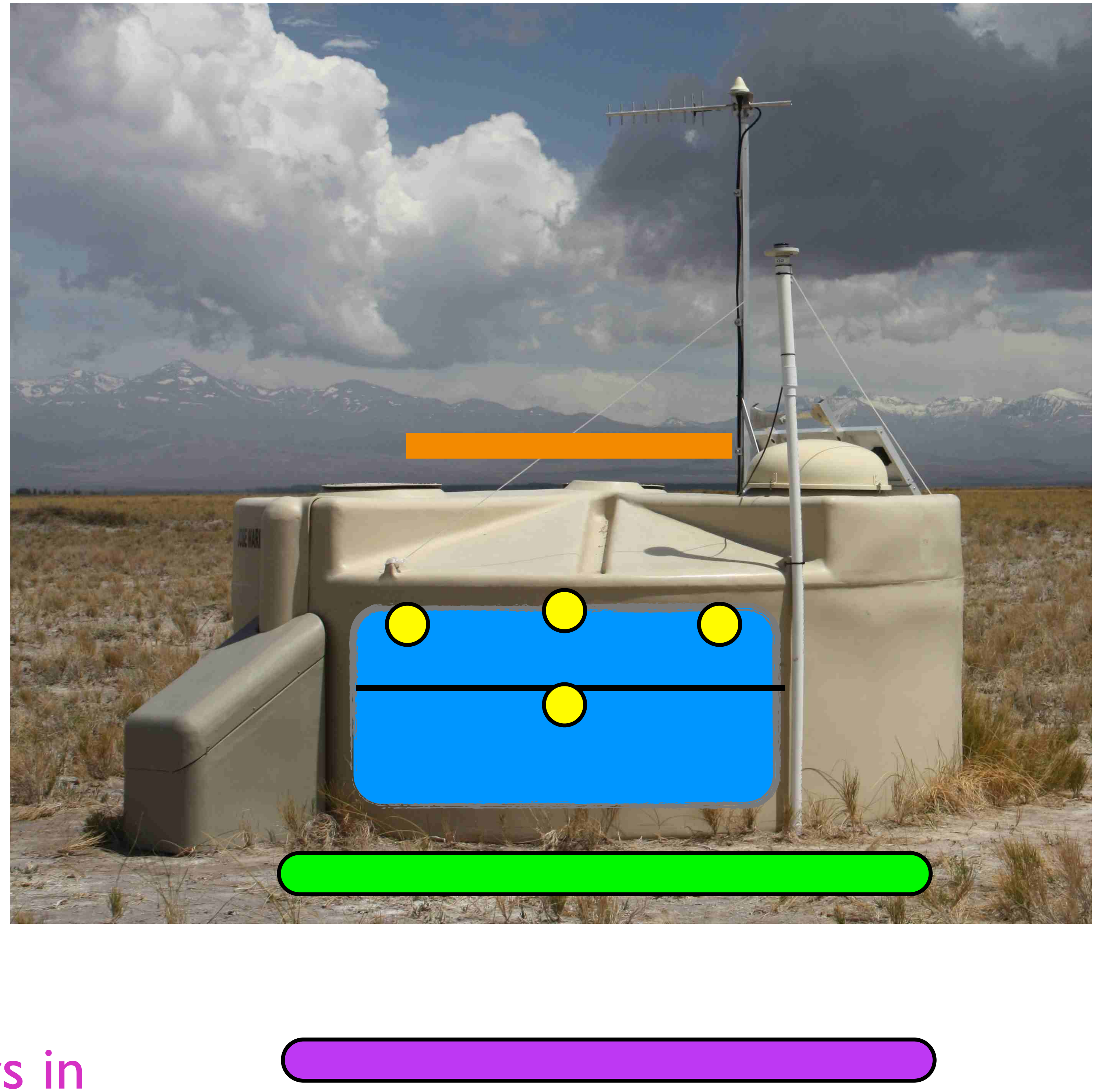
Scintillator on top
(ASCII)

segmented tank
(LSD)

RPCs below
(Marta)

+improved tank
read-out

Various options ...
... to improve on em/mu separation in EAS



Scintillator on top (ASCII)

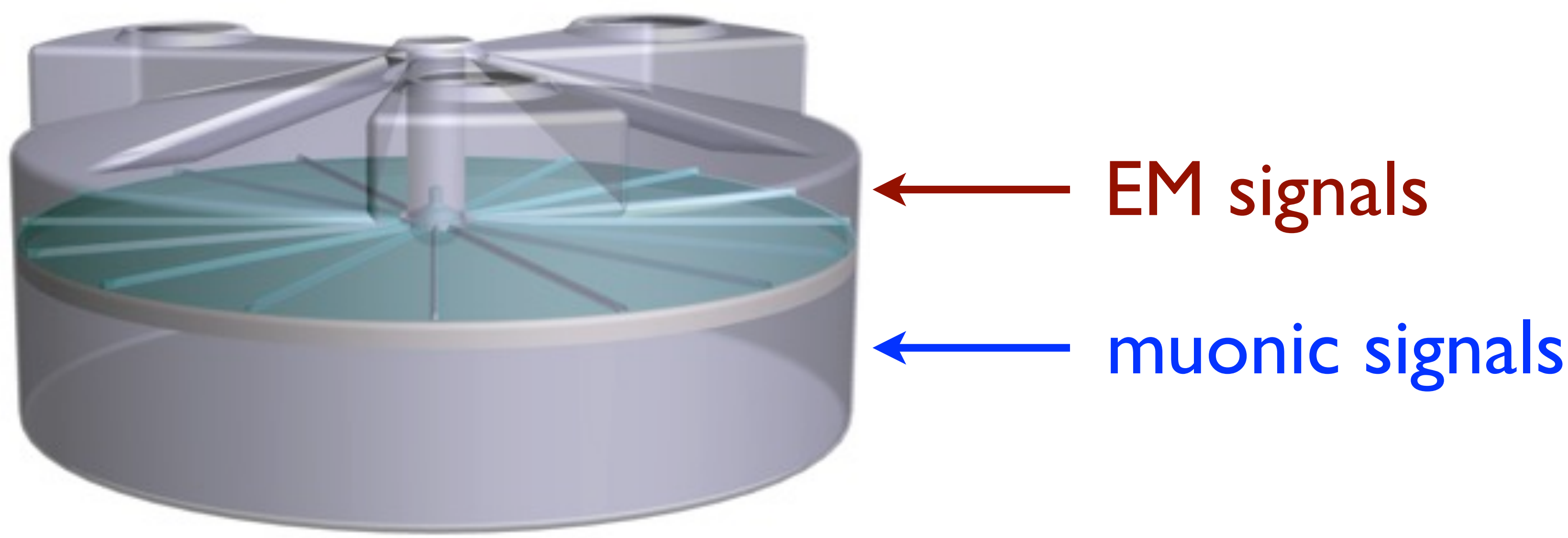
segmented tank (LSD)

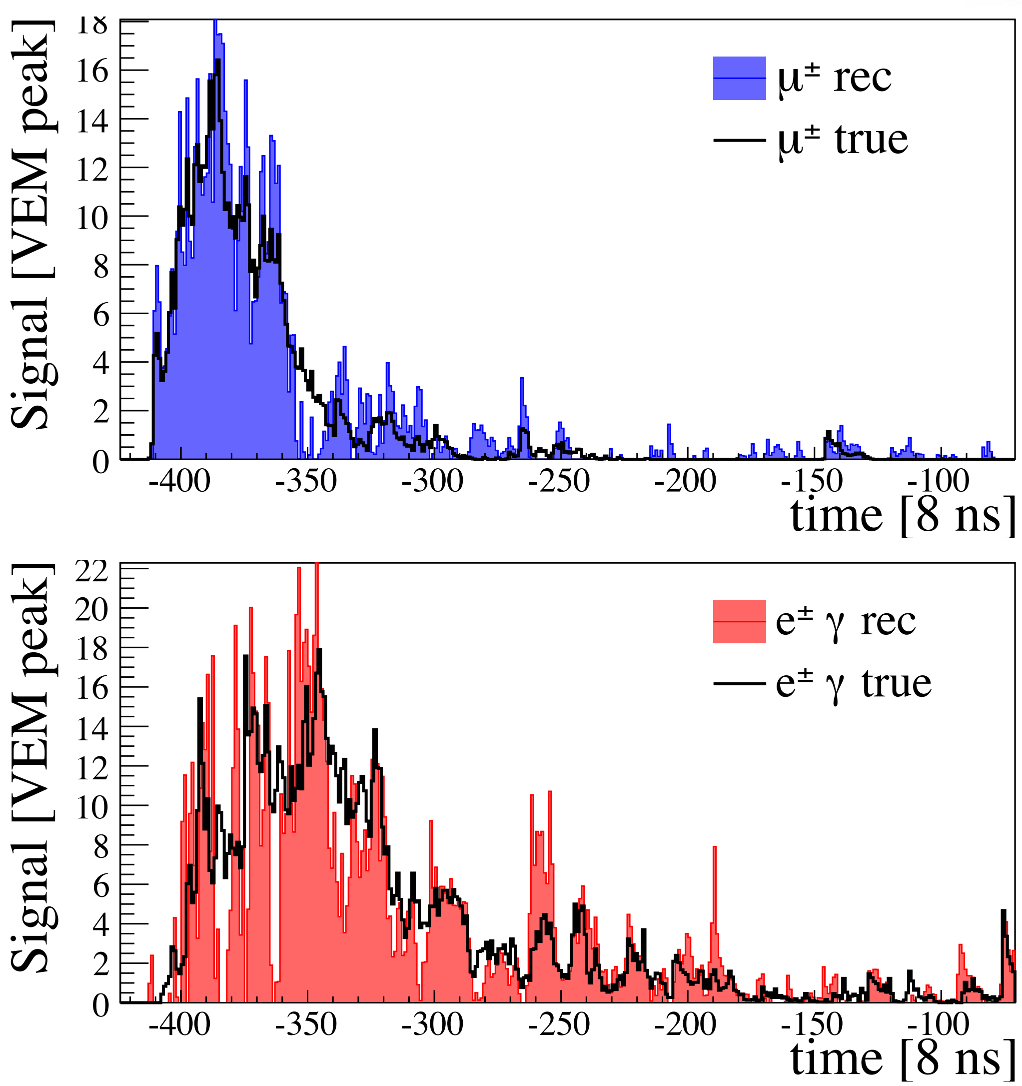
RPCs below (Marta)

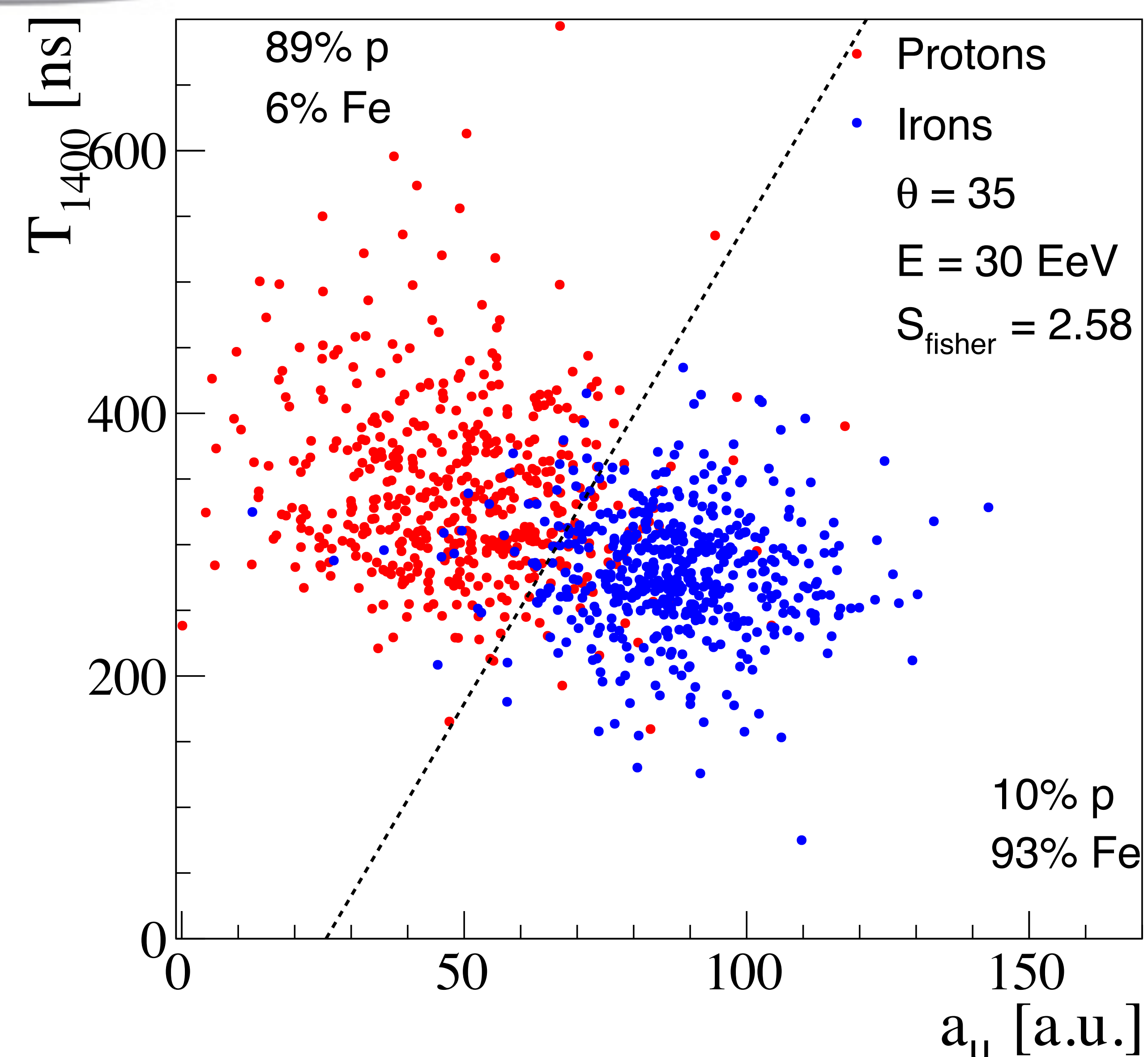
+improved tank read-out

Scintillators in ground (AMIGA-Grande, TOSCA)

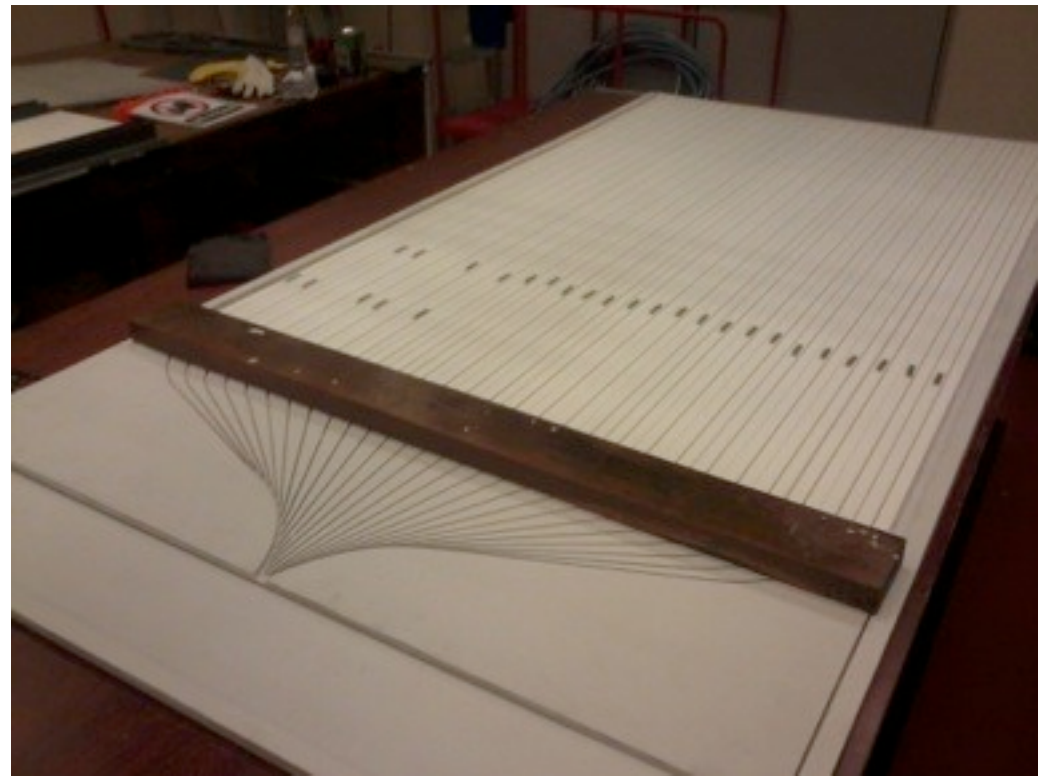
Segmented tanks



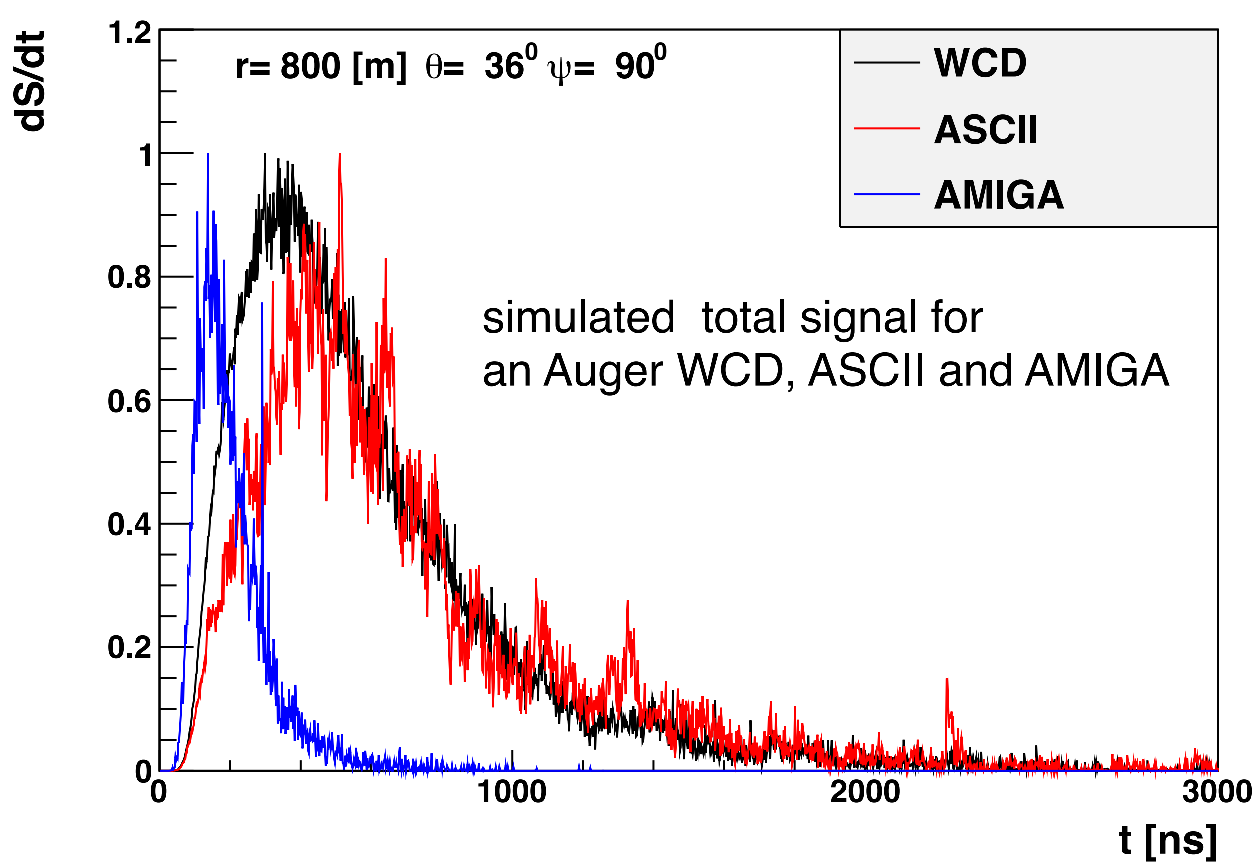


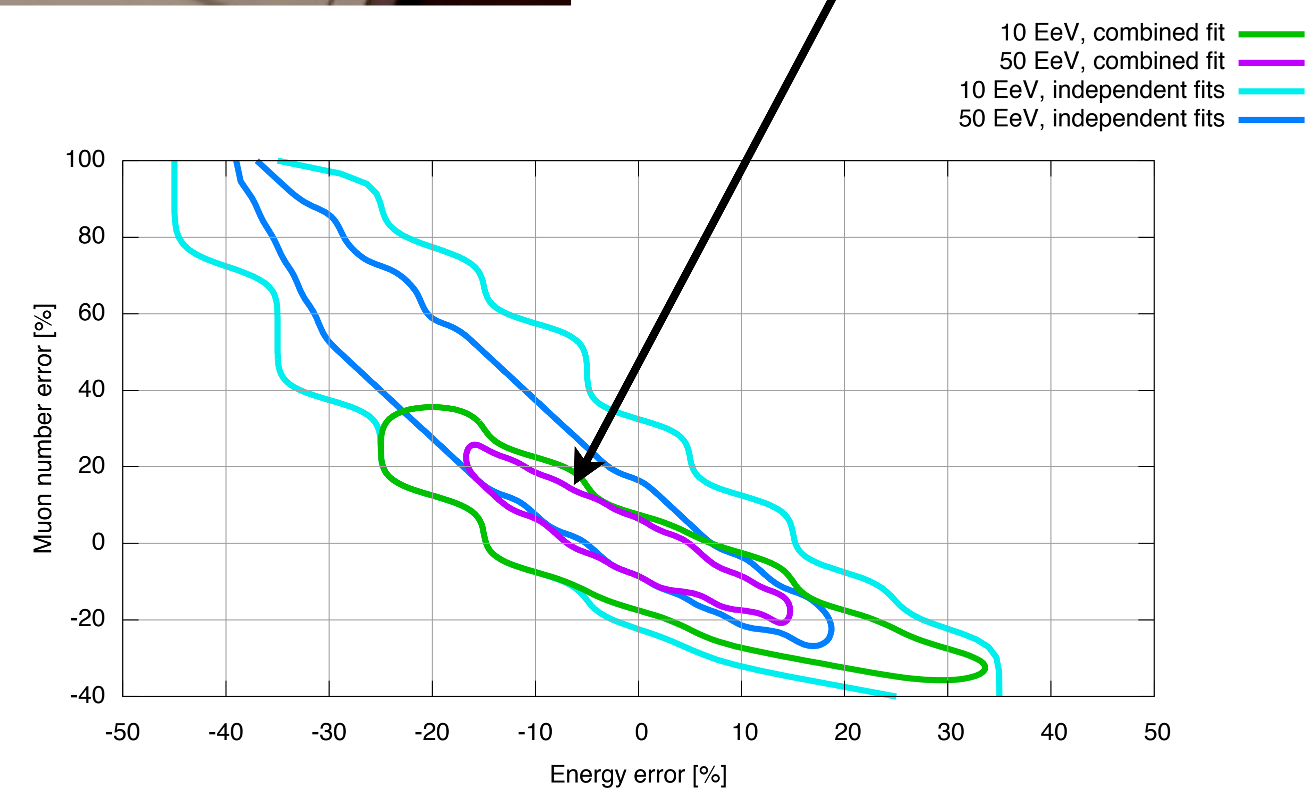


Scintillators on top of tank



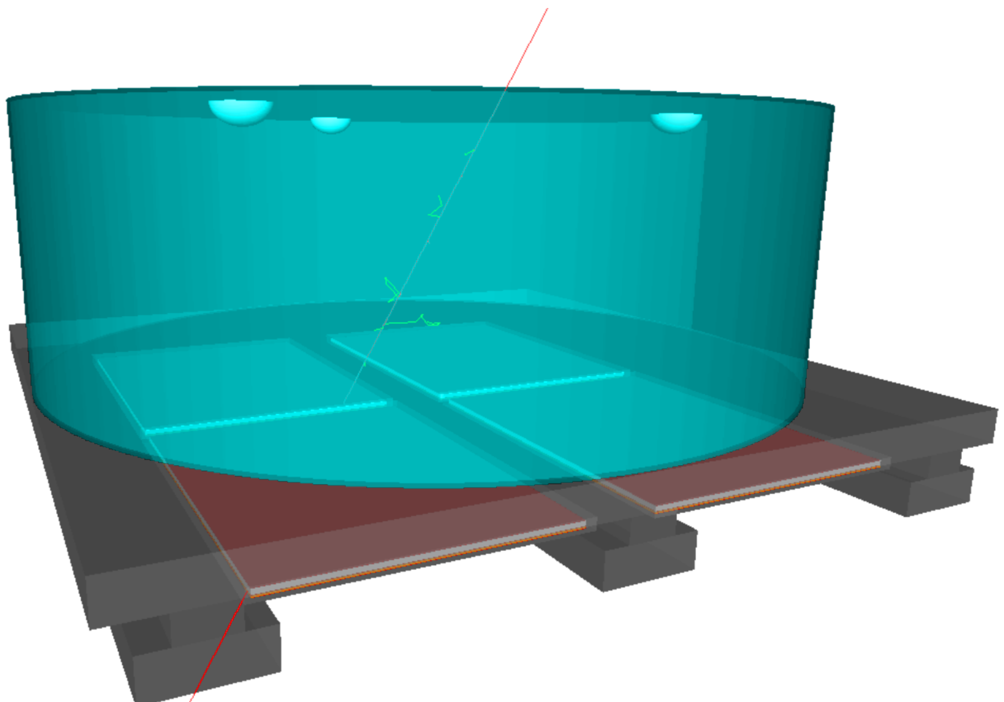
combined LDF fit of WCD and ASCII

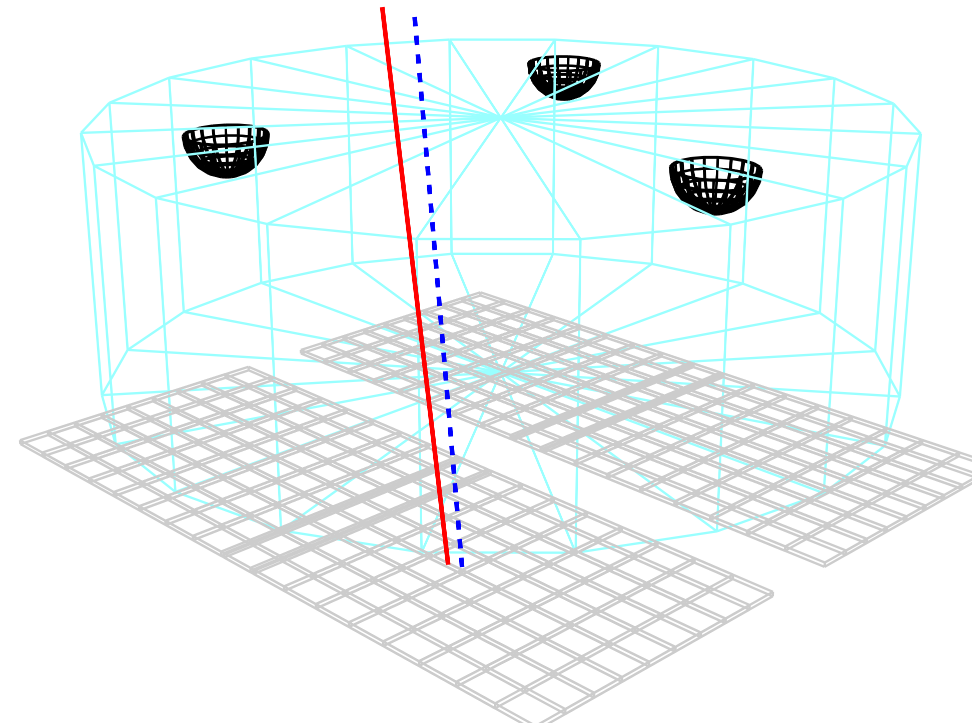




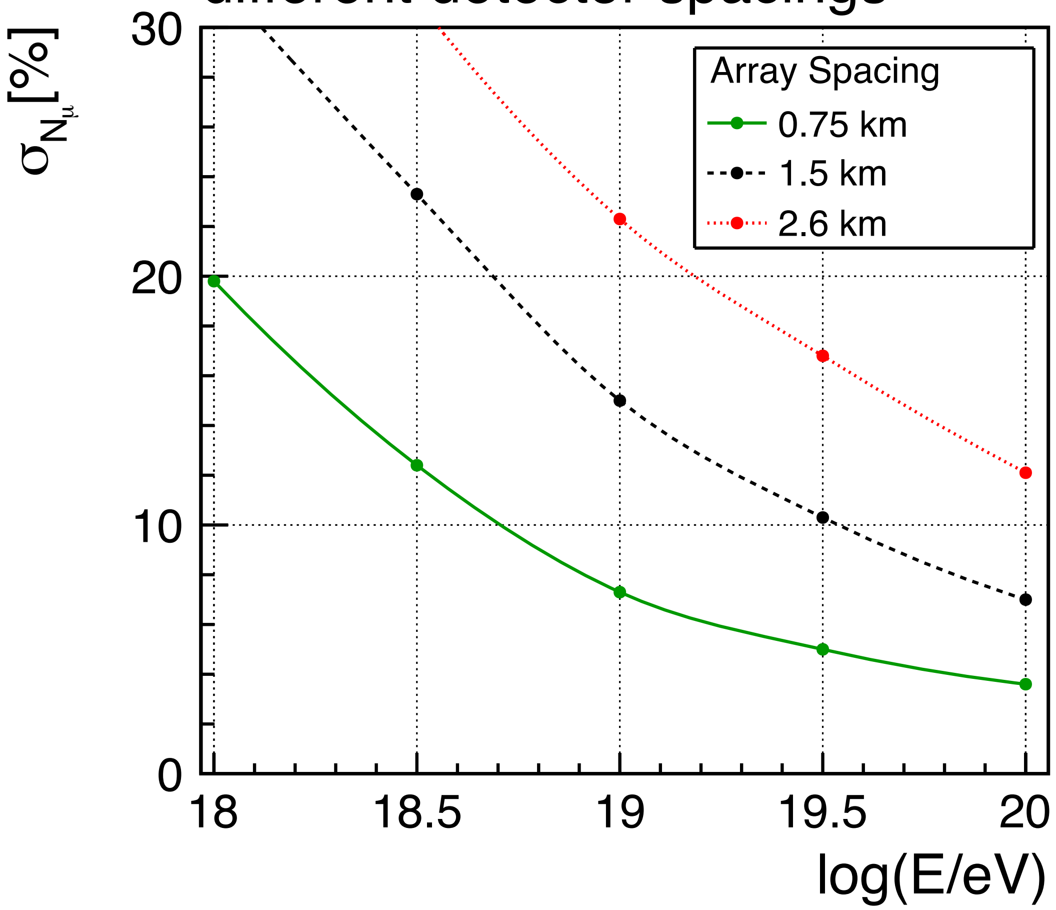
energy vs N_μ errors

RPCs below tanks

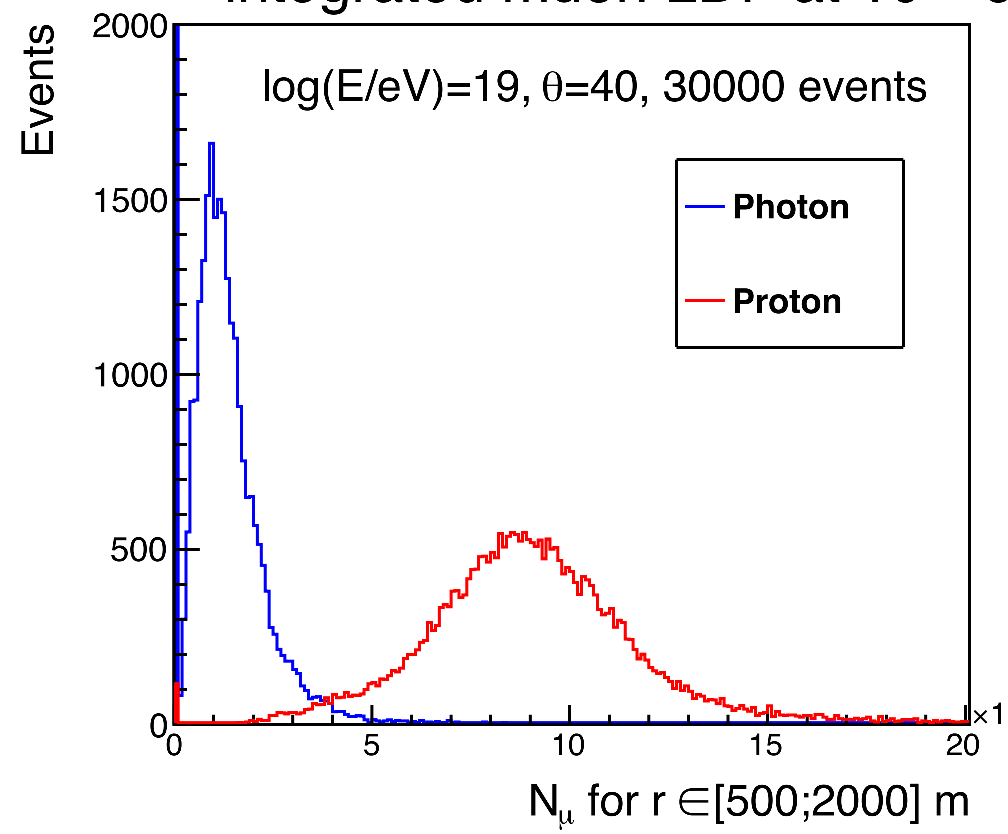




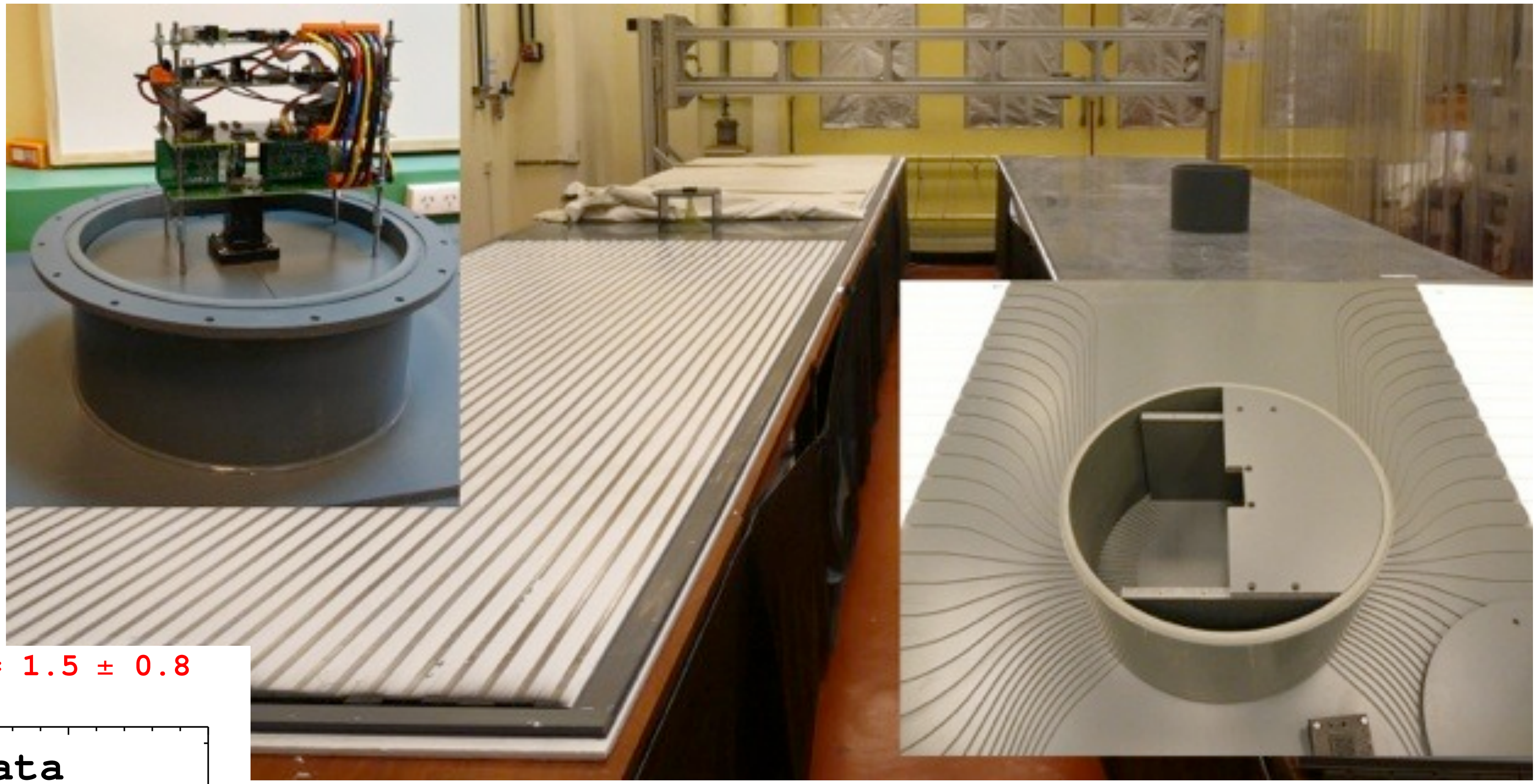
resolution of μ-numbers for different detector spacings

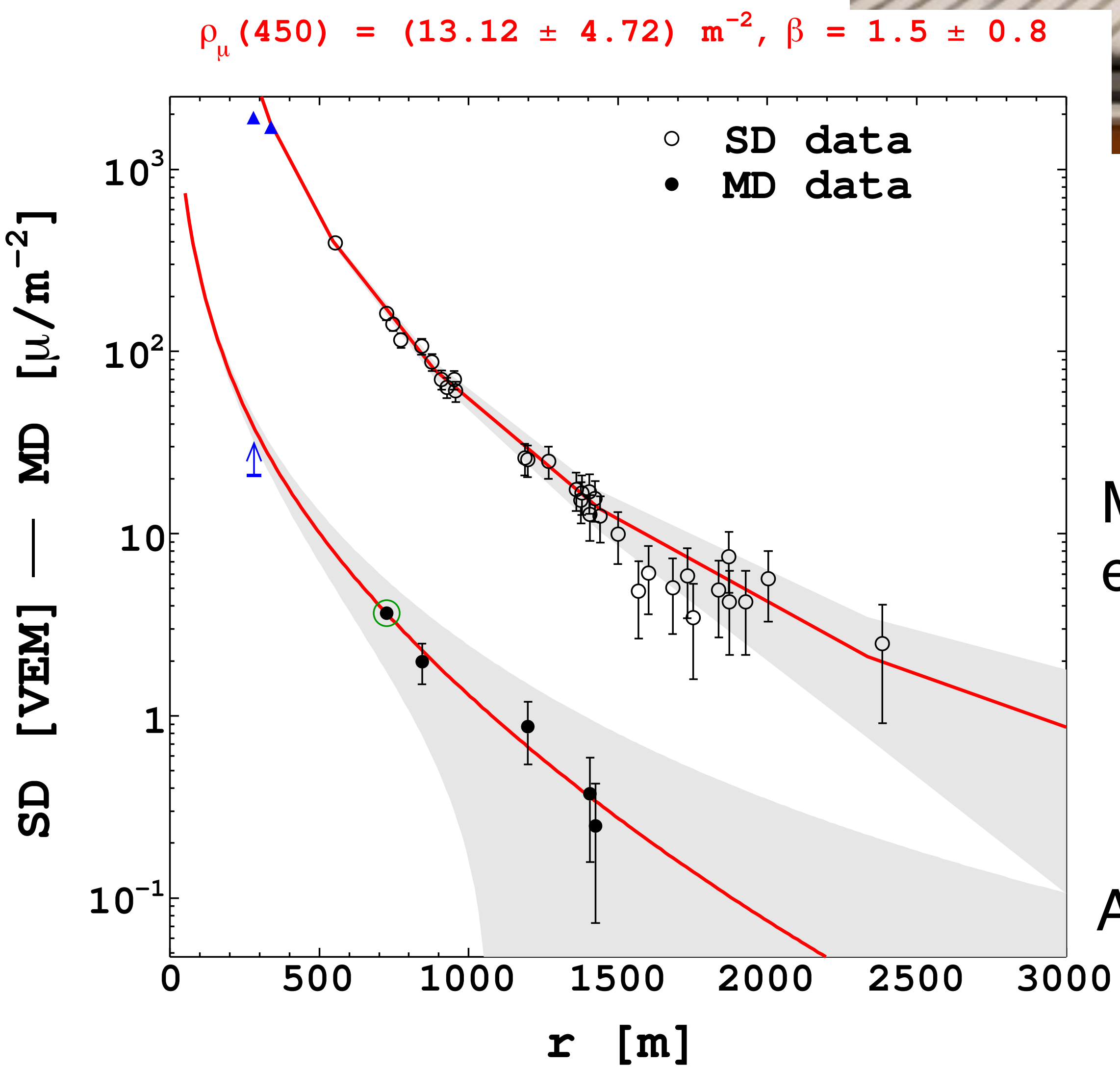


discrimination power of the integrated muon LDF at 10^{19} eV



Scintillators underground 1





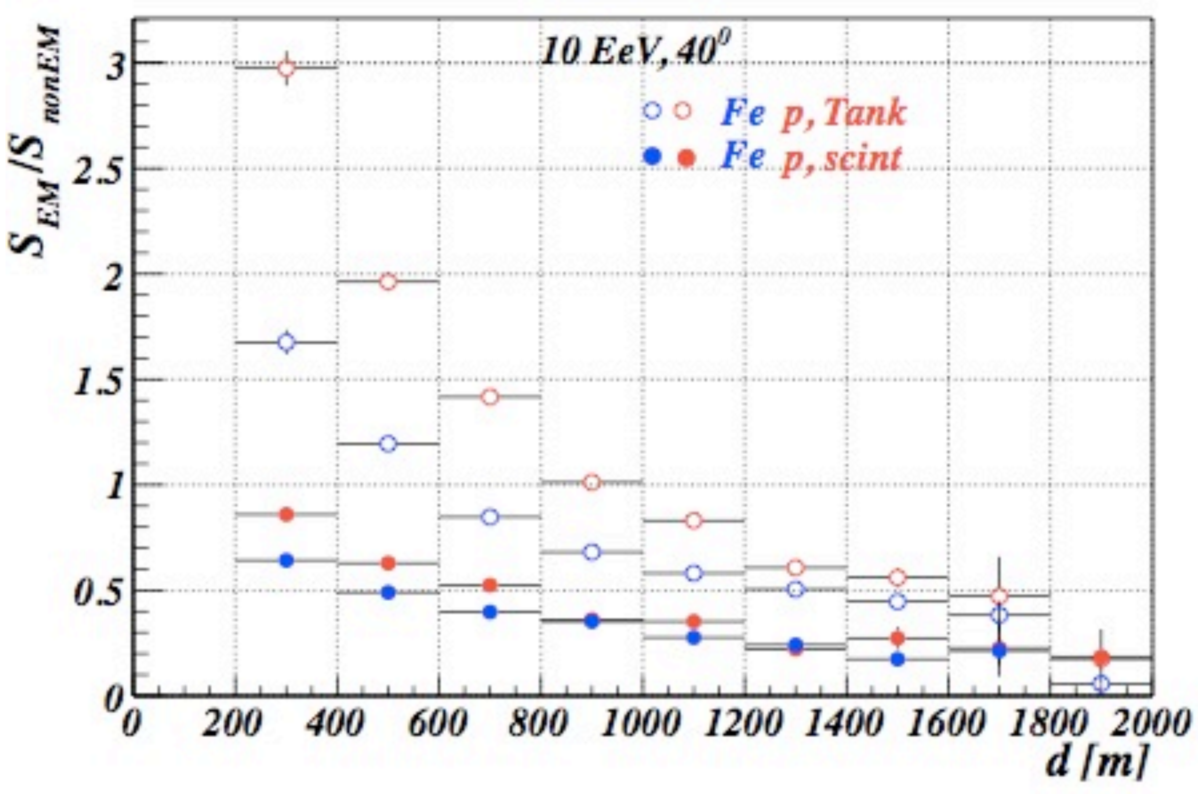
Measured LDF for a shower with reconstructed energy of $1.1 \cdot 10^{19}$ eV

WCD

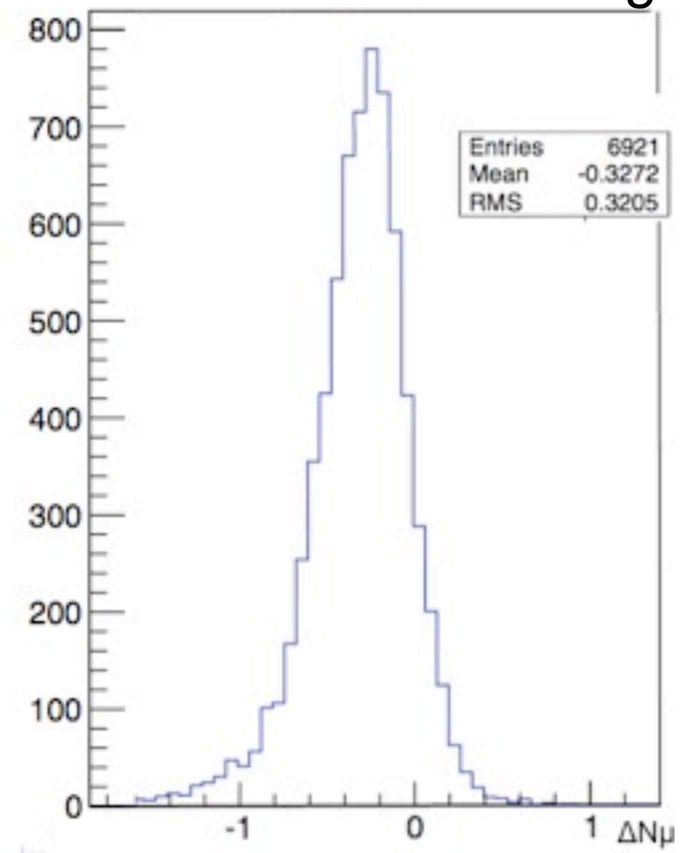
AMIGA

Scintillators underground 2

AMIGA like scintillator bar



expected N_μ -resolution
for 4 m² muon coverage



Planned Cost Target: US$ 10-12M (≈ € 8-10M)

(≈ 20 % of initial investment)

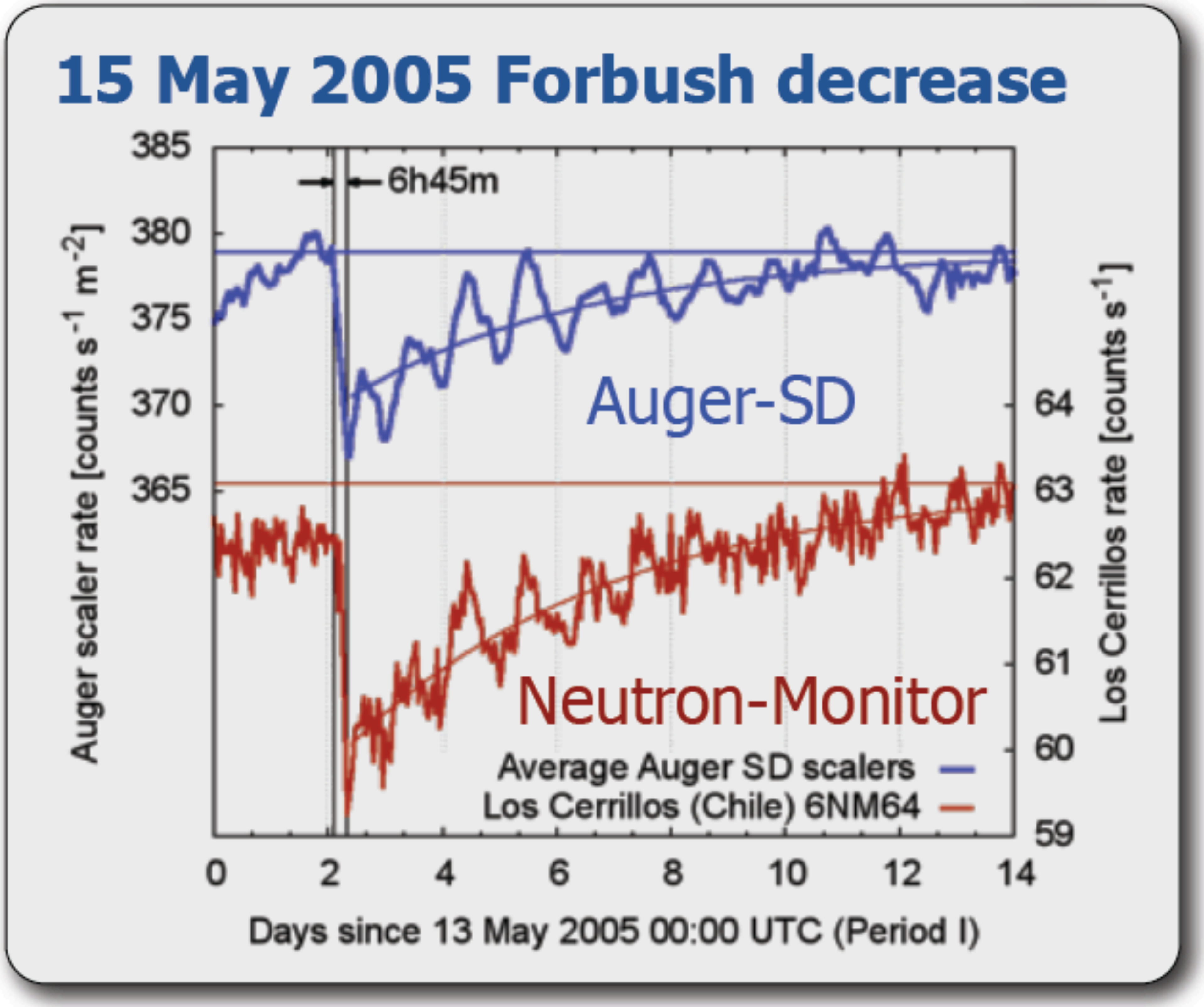
Time Line:

	2013				2014				2015				2016				2017				2018			
Science Proposal subm			●																					
Review of Science Proposal					●																			
Prototyping in field			X	X	X	X																		
Selection of Prototype																								
Submission of TDR							●																	
Final Evaluation							X	X																
Seeking funds / **construction**							●	●	X	X	X	X	X	X	X	X	X	X						
take data												X	X	X	X	X	X	X	X	X	X	X	X	→
upgrade finished																					●			

data taking into 2023 will double the statistics of all data up to 2015

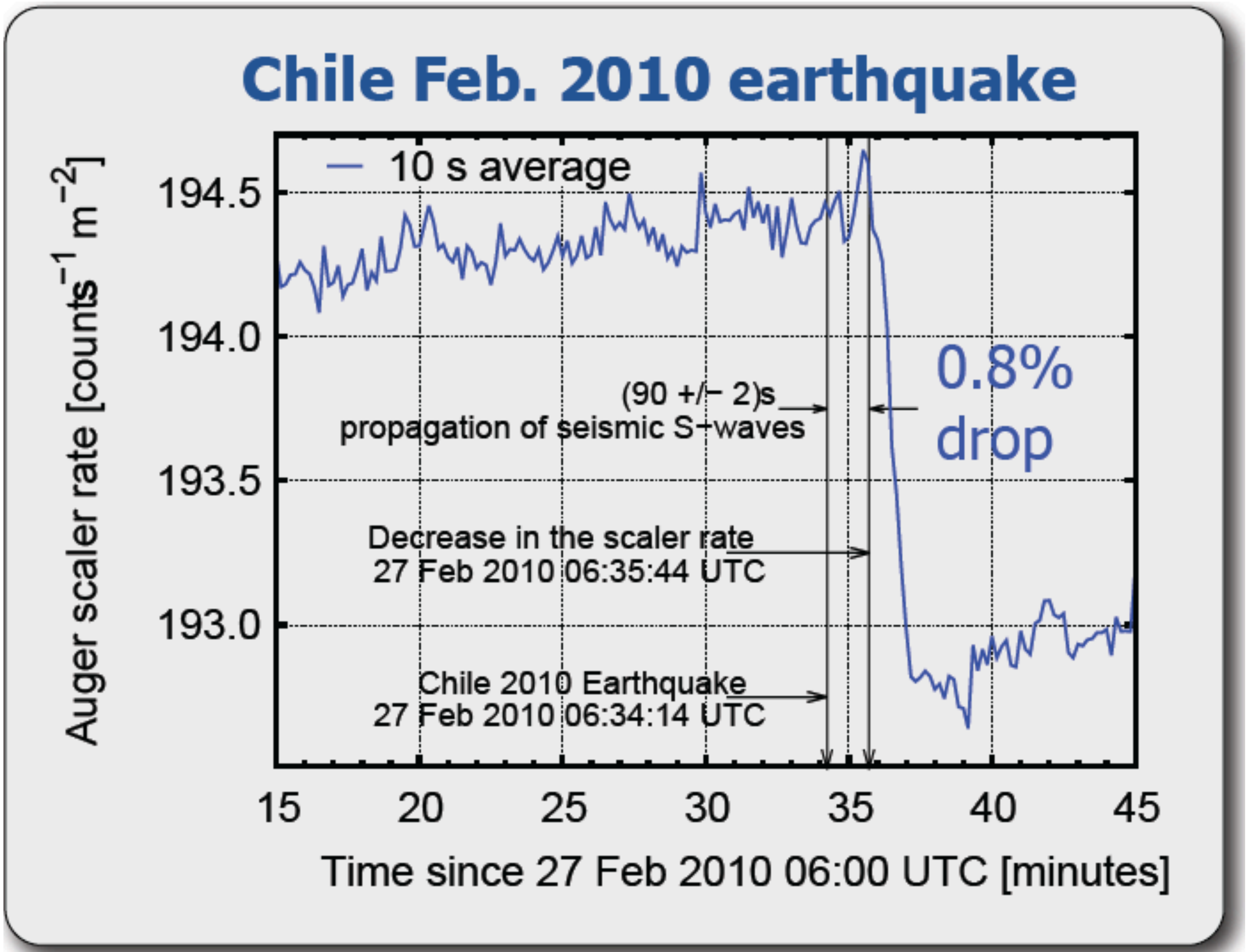
Exotics:

Auger Scaler Rates: read out for monitoring

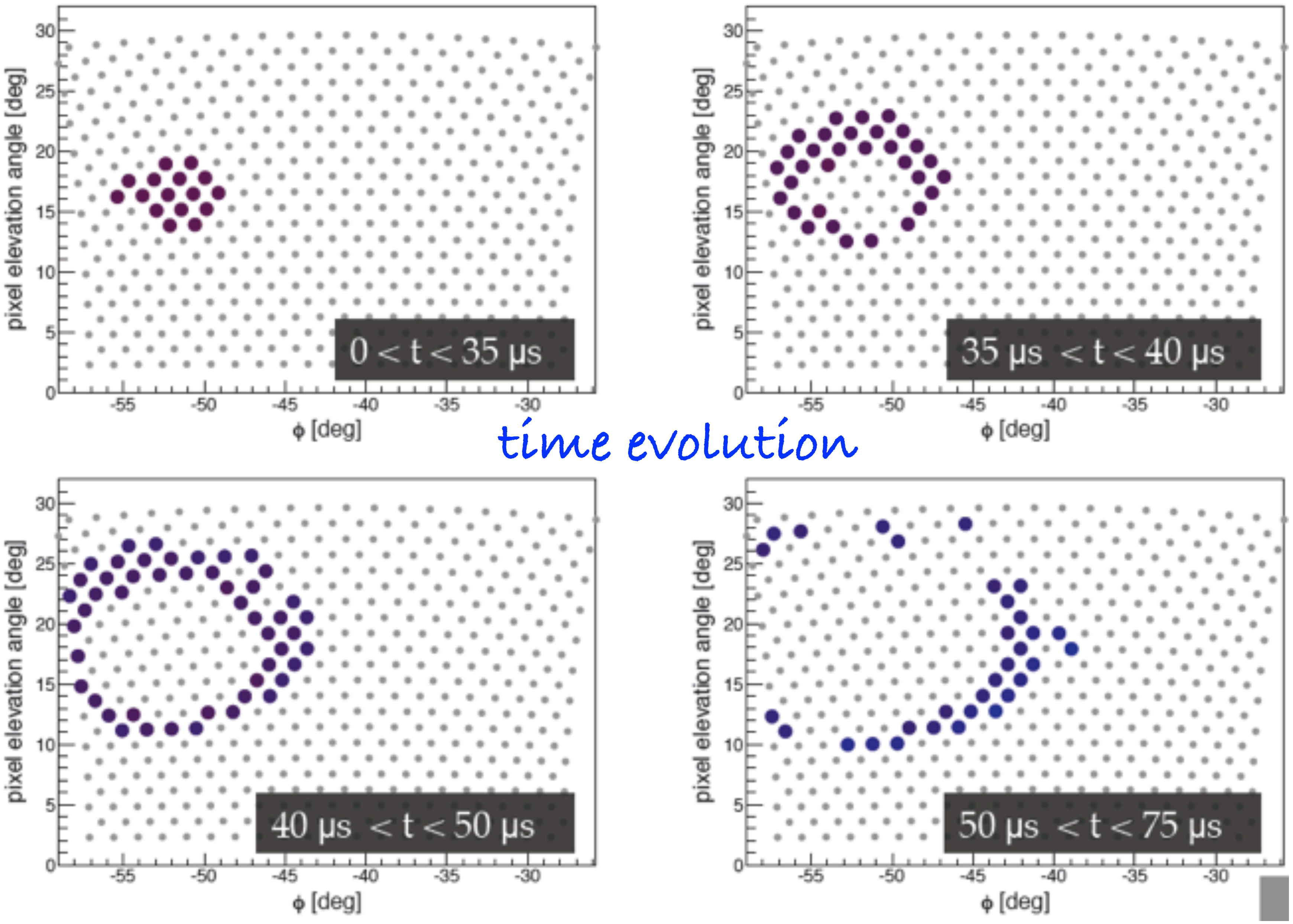


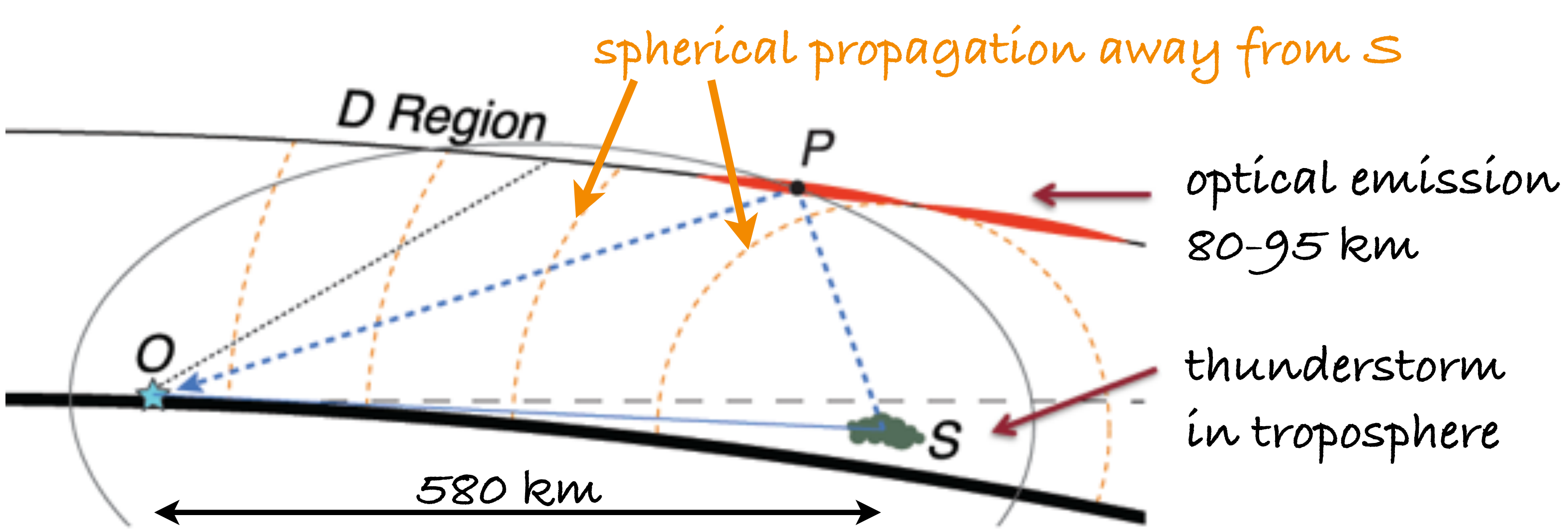
Exotics:

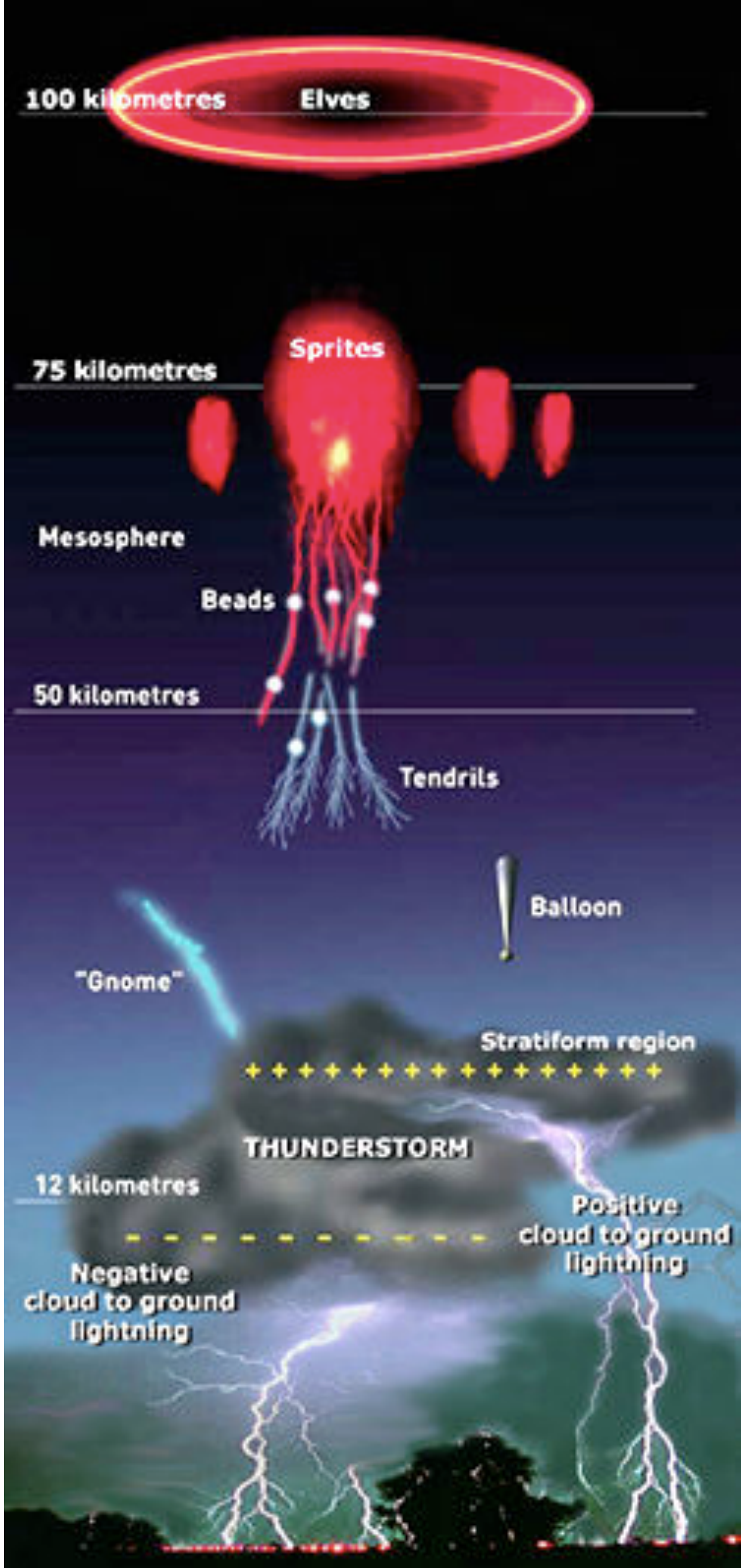
Auger Scaler Rates: read out for monitoring



Elves with the Auger FD







Summary:

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

Spectrum: ankle and steepening seen at $\approx 5 \times 10^{18}$ and $\approx 4 \times 10^{19}$ eV
with model-independent measurement and analysis
Interpretation requires knowledge of composition.

Arrival directions:
CR are extragalactic
some 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 (as is) will provide a few more years of reliable experimental data & a solid basis for future work.
Operation at least until 2015 (then total exposure: 7 Auger yrs)

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

— Prolongation and upgrade (?) for better composition measurements
2015 - 2025

— 3000 km^2 turns out to be still too small for the energies ~10^{20} eV
"Auger next"? > 30000 km^2 ??? new, cheaper techniques needed.
Ideas? Radio detection of air showers not quite ready yet.

— CRs, ν from space: >3 x 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.	≈10^6 km^2

The End