The Puzzle of Ultra-High Energy Cosmic Rays

... and Recent Results from the

Ooty
Dec 2010

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Ultra-High Energy Cosmic Rays

(UHECRs: > 10^{19} eV)

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 .....

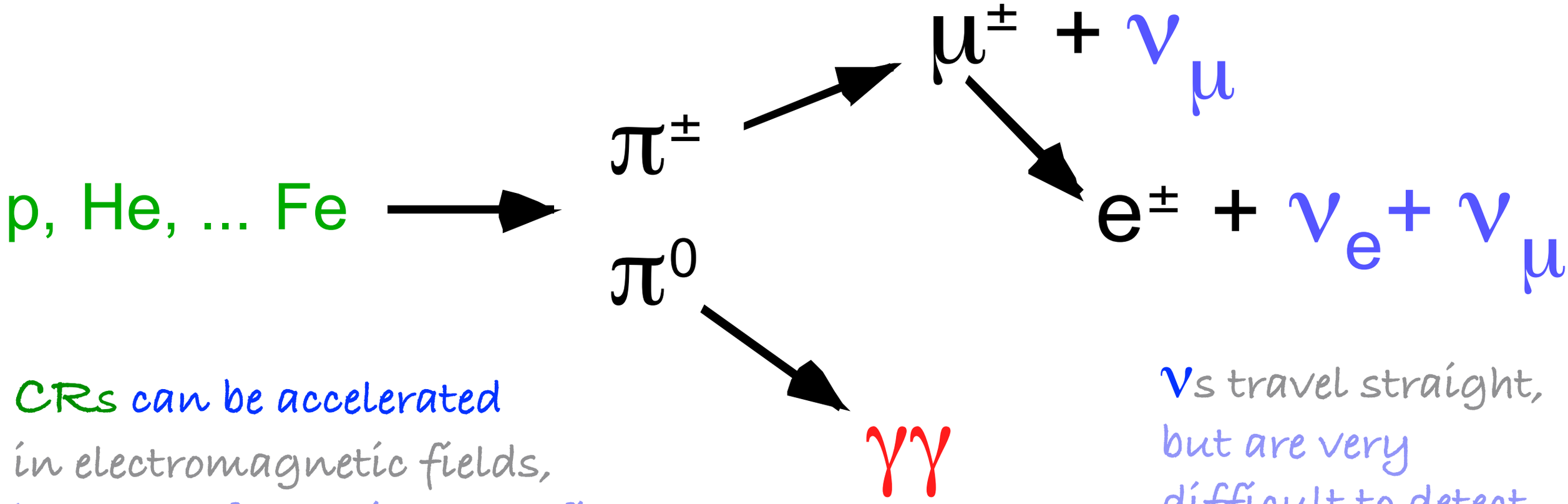
Photons: classical astronomy + high-energy γ-rays

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

There are Cosmic Particle Accelerators out there that go up to $> 10^{20}$ eV !!

What/where are the accelerators? What are the CRs?

Cosmic Rays, Gamma Rays and Neutrinos are linked



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 ν and γ must exist

at similar energies.

But can they be detected above backgrounds ???

γ : >1000 x more cosmic rays

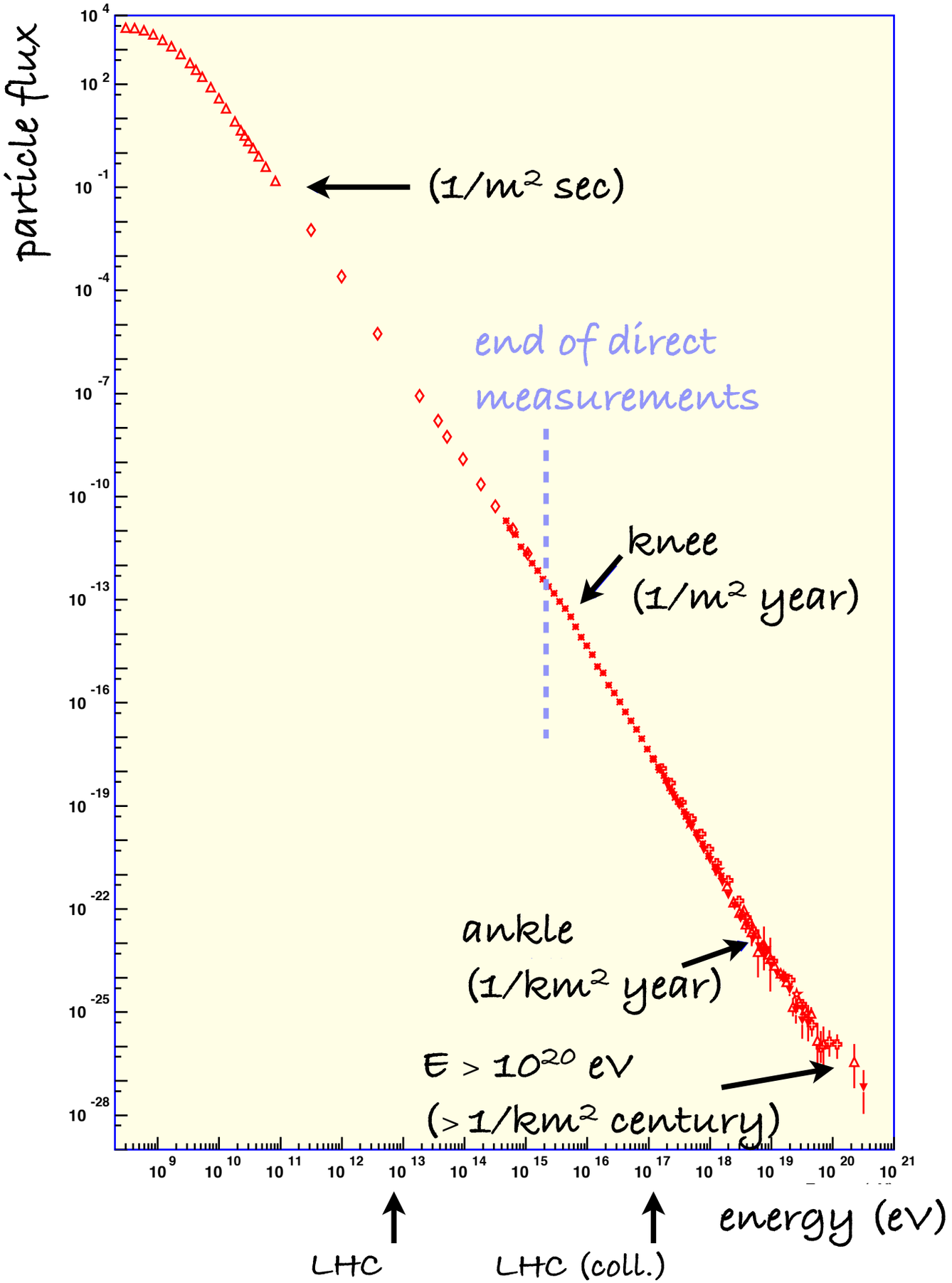
ν : very low interaction cross sections,

atmospheric ν background

To study the most powerful accelerators one must study

Cosmic Rays

Flux of Cosmic Rays



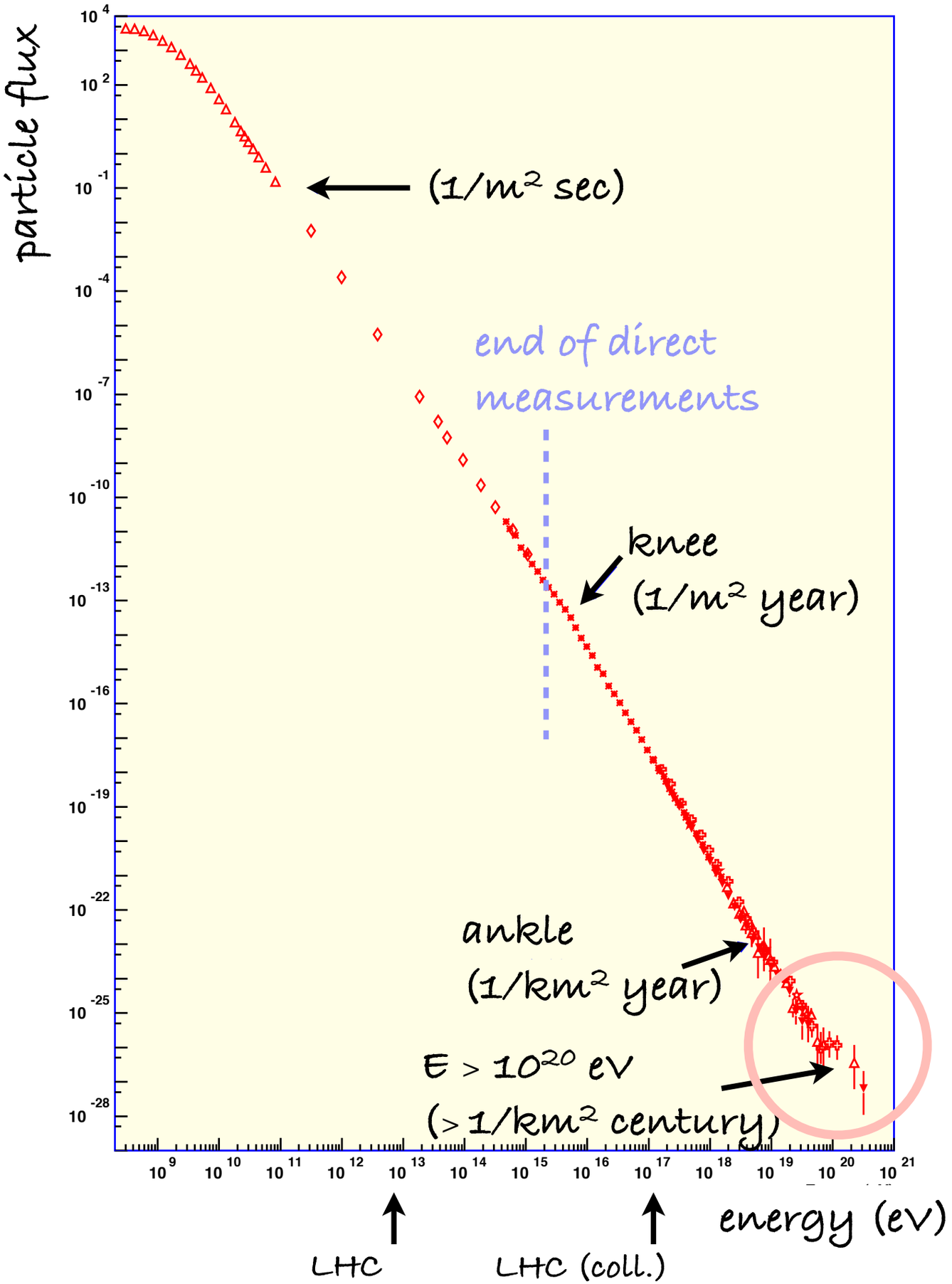
12 orders of magnitude in energy,
33 in flux !

10x up in energy, 500x down in flux

Highest energy events:

$\approx 3 \times 10^{20}$ eV

Flux of Cosmic Rays



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

real high-energy physics

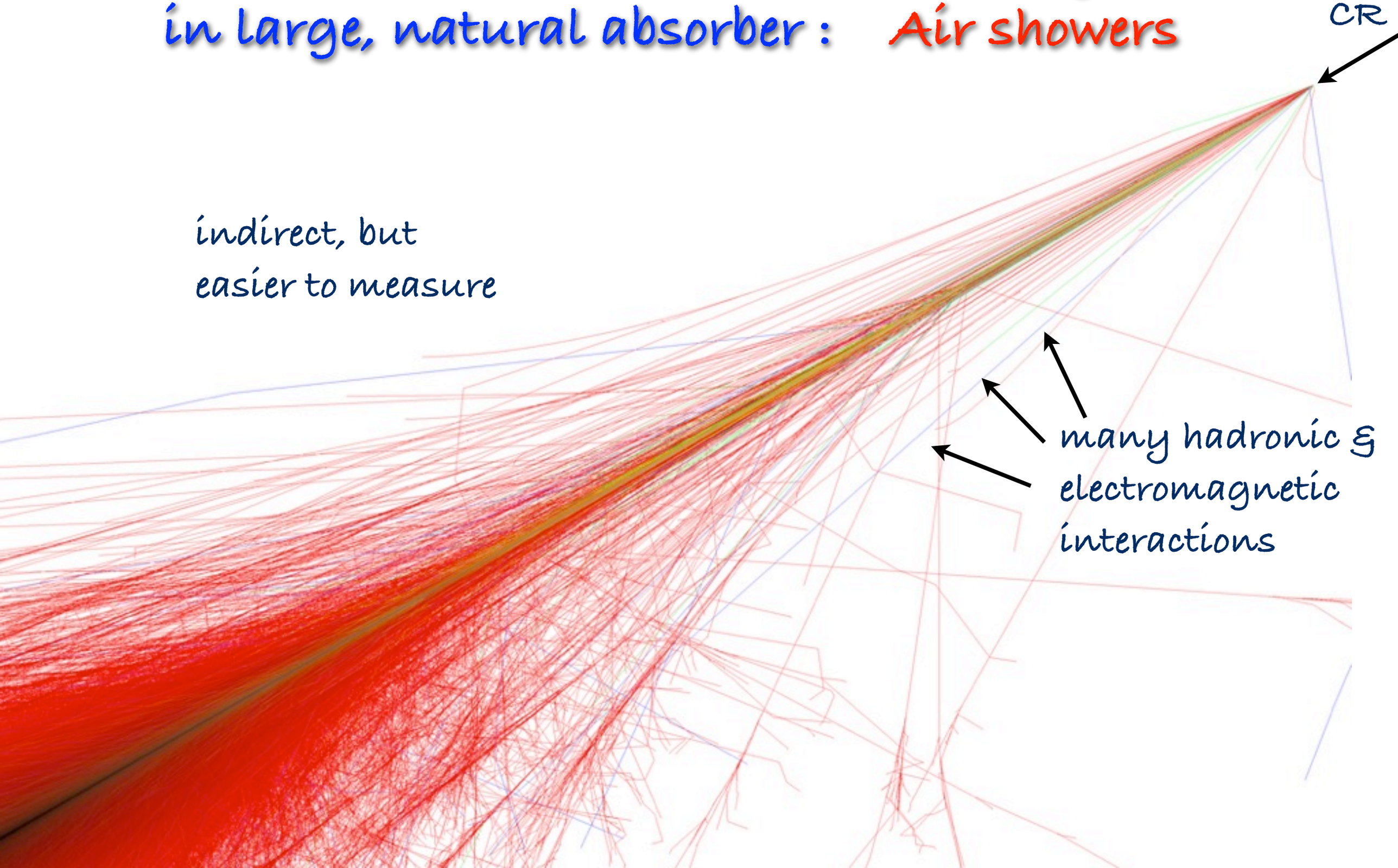
UHECRs require
the most powerful accelerators ...

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

measure reaction products of primary

in large, natural absorber : Air showers

indirect, but
easier to measure



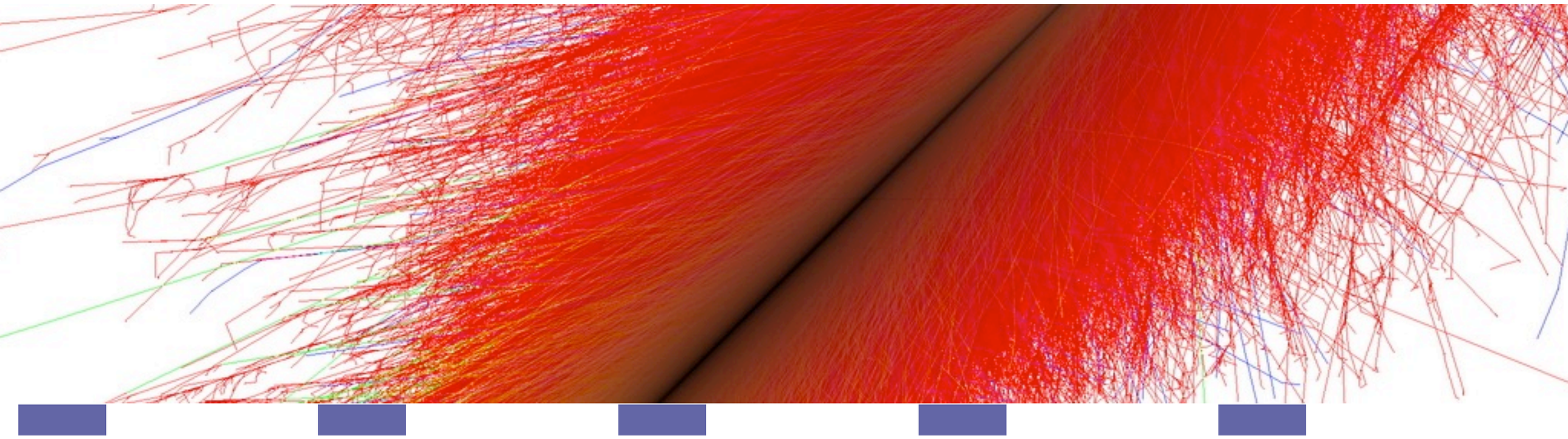
Air shower experiments

- allow measurement of 10^{10} x smaller fluxes

  (by sampling a small part of extensive particle shower)

- give access to 10^{6} x higher energies

than direct measurements on satellites or balloons.



Unknown at high energies :

- elemental composition
- 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 ...

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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.

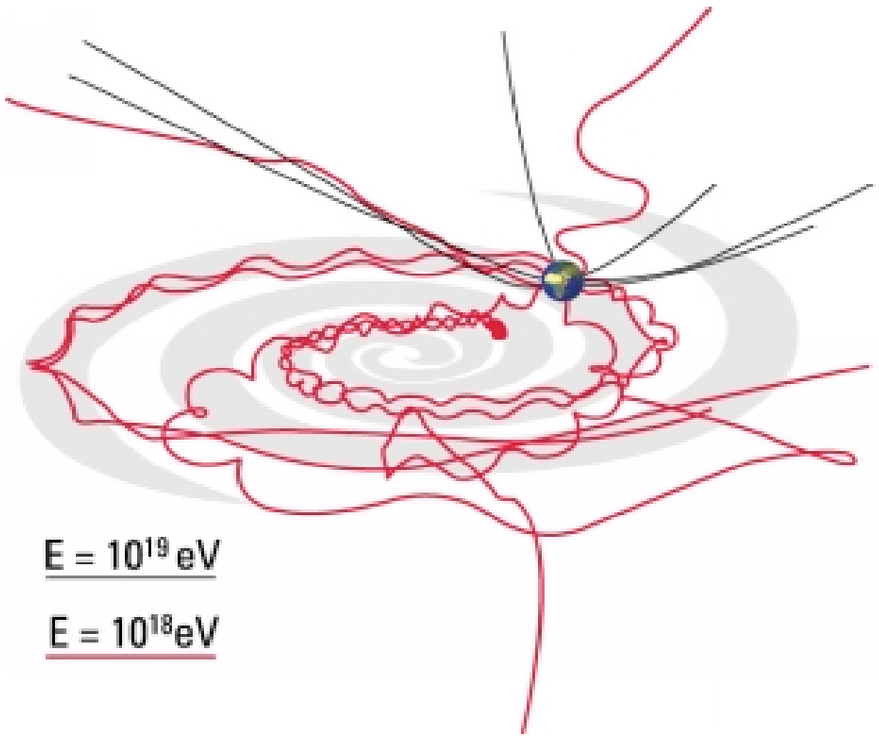
Requires some iteration ...

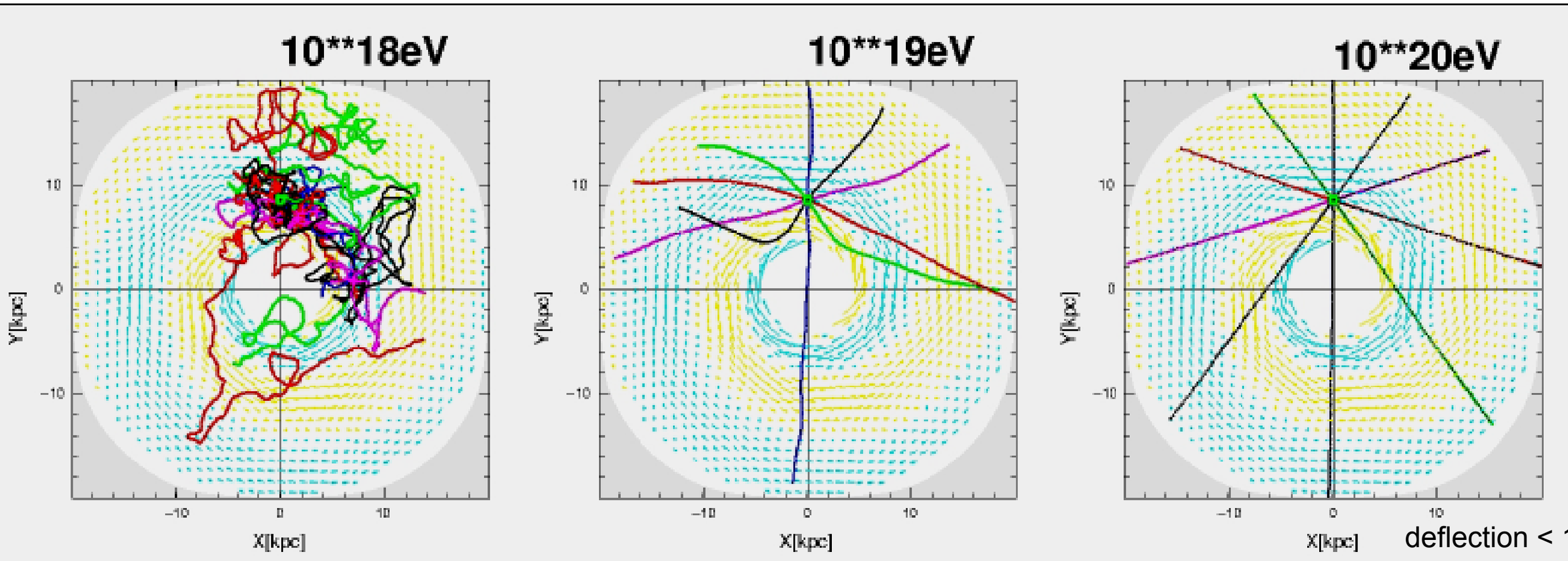
A seriously difficult problem ...

Highest Energy Particles are very rare ...

... but they are not deflected much !
They should start pointing back
at their sources

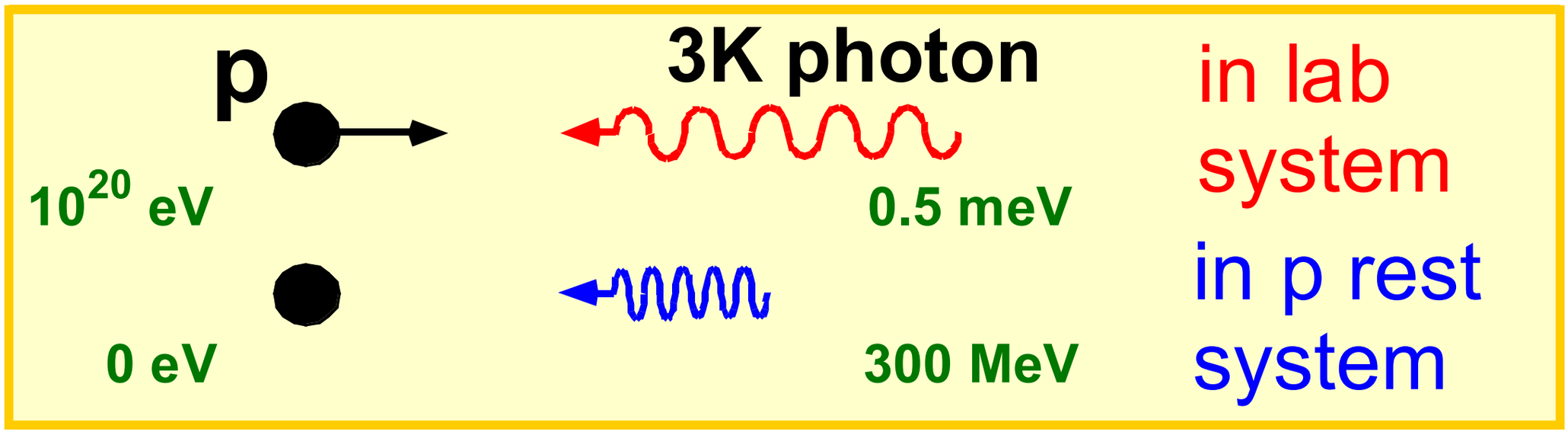
"Charged particle astronomy ?"





deflection < 1°

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



$p + \gamma_{3K} \longrightarrow \Delta^{+} \longrightarrow p + \pi^0$ → γ Photo-pion production

$\longrightarrow n + \pi^+$ → ν

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

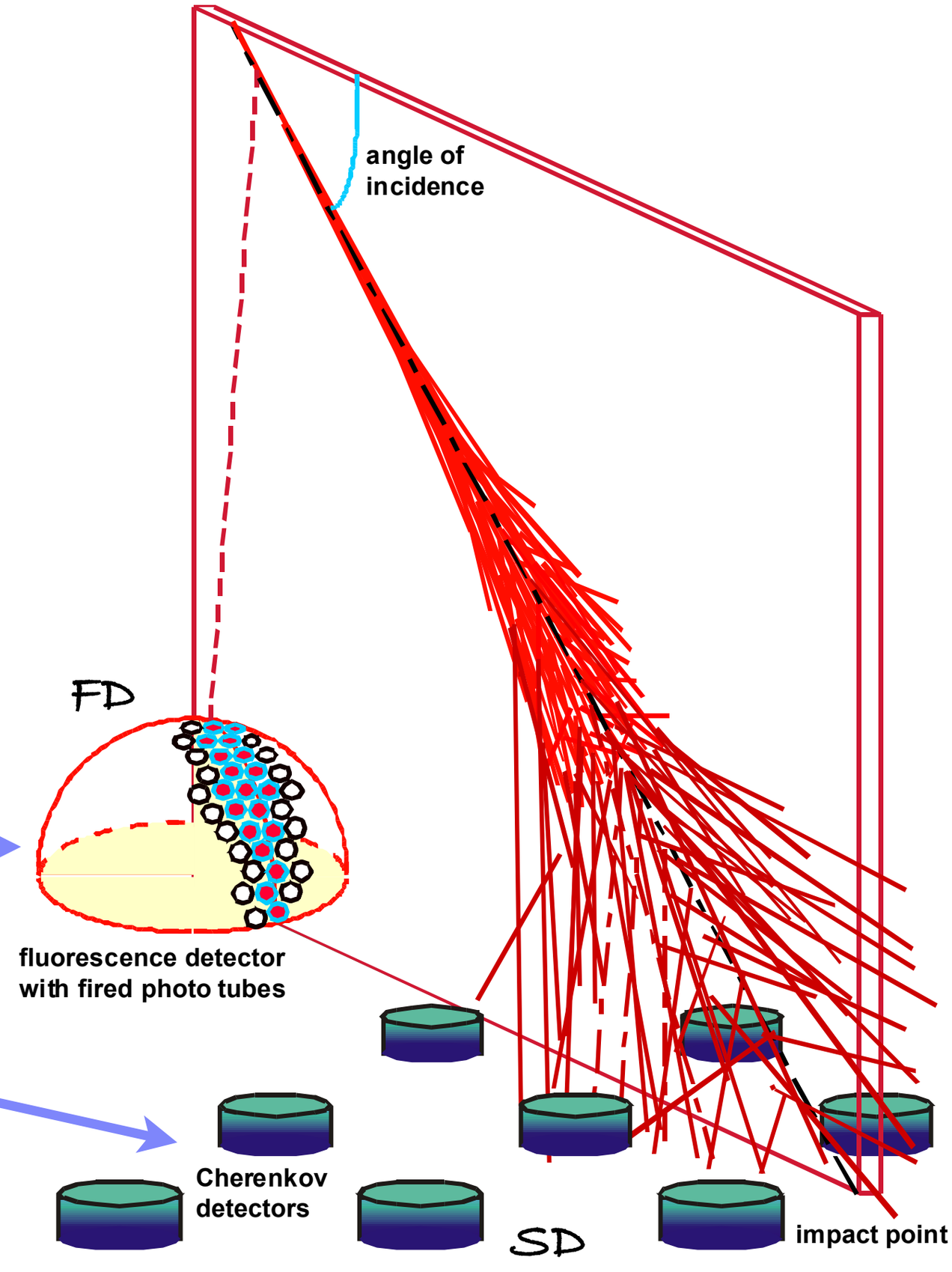
indirect measurement,
shape and particle content

Auger: Hybrid Detector

measure extensive air shower with:

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

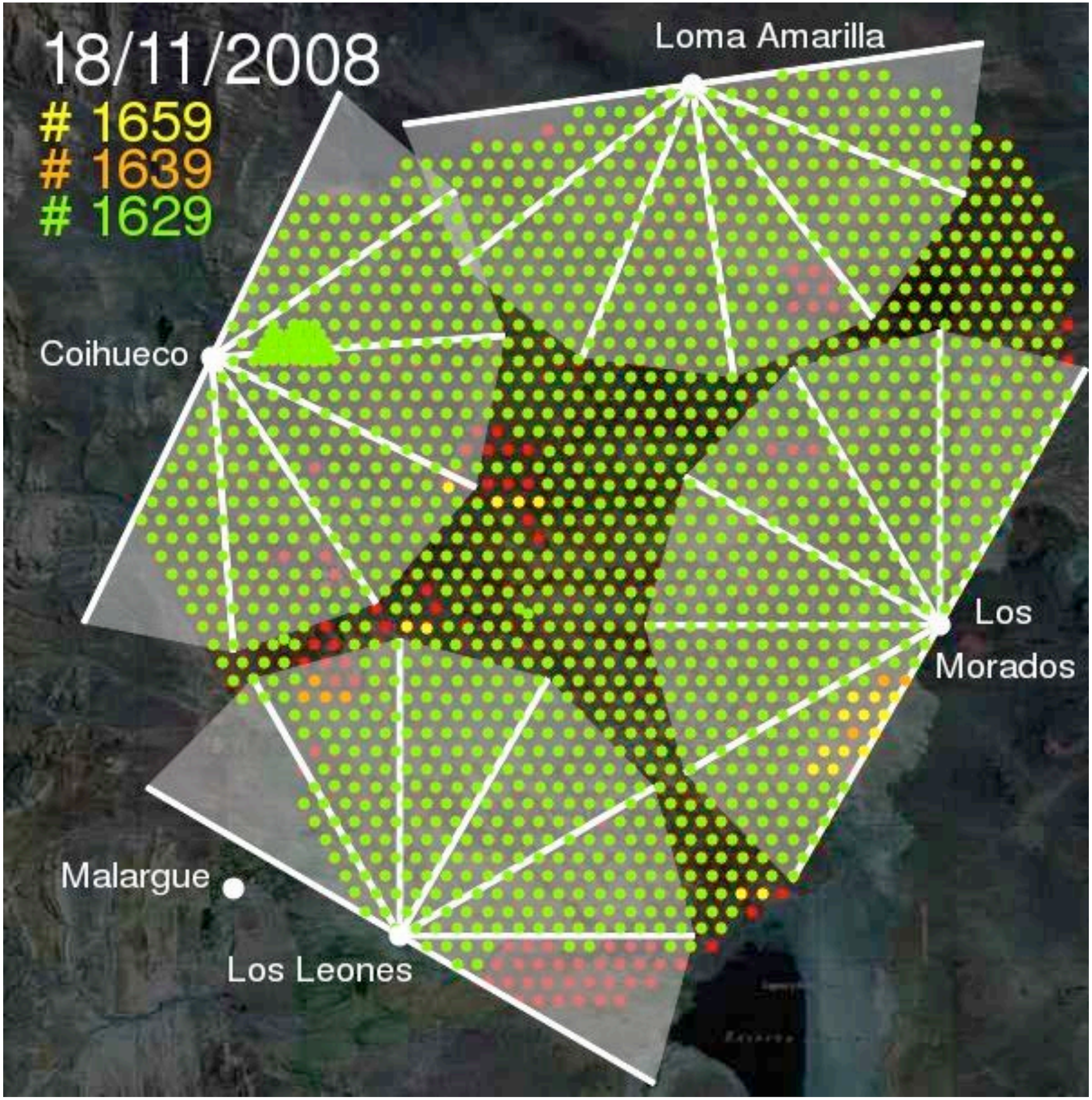
array of 1600 water Cherenkov tanks
on 3000 km², 100% duty cycle,
well-known aperture



The Pierre Auger Observatory

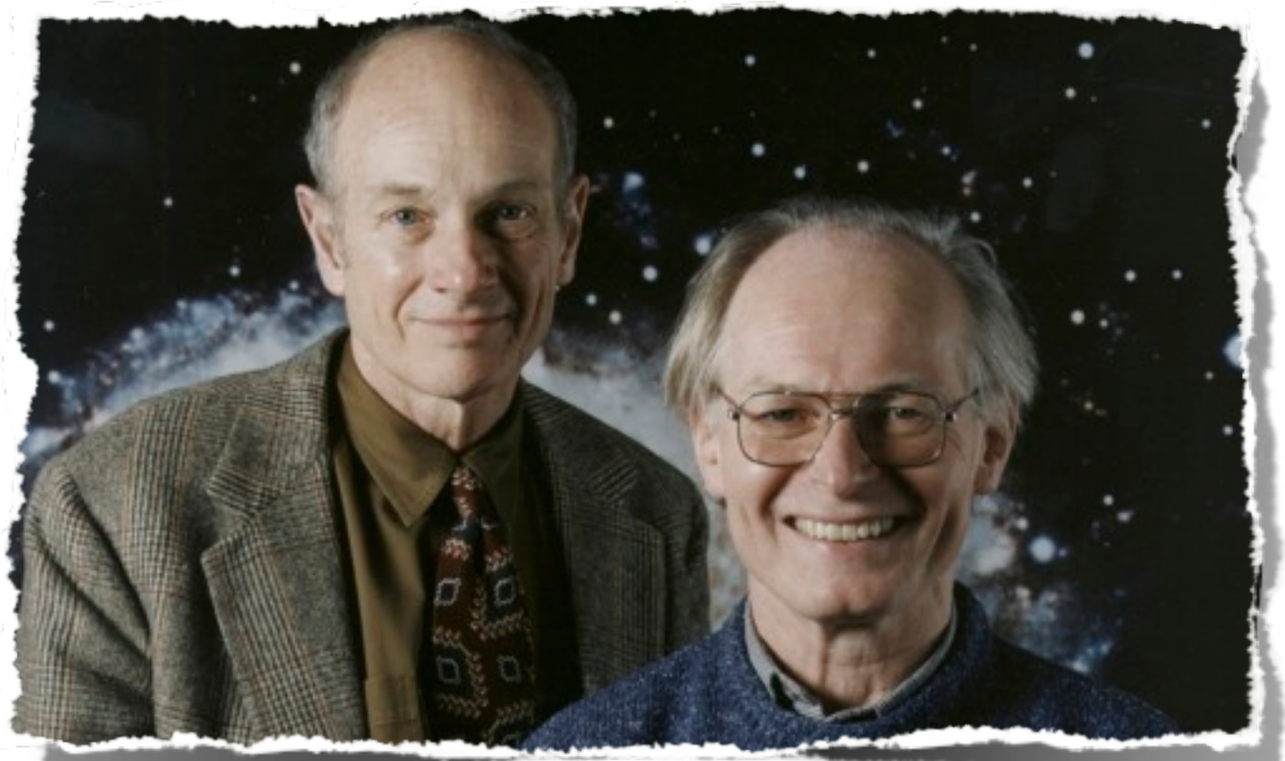
60 km

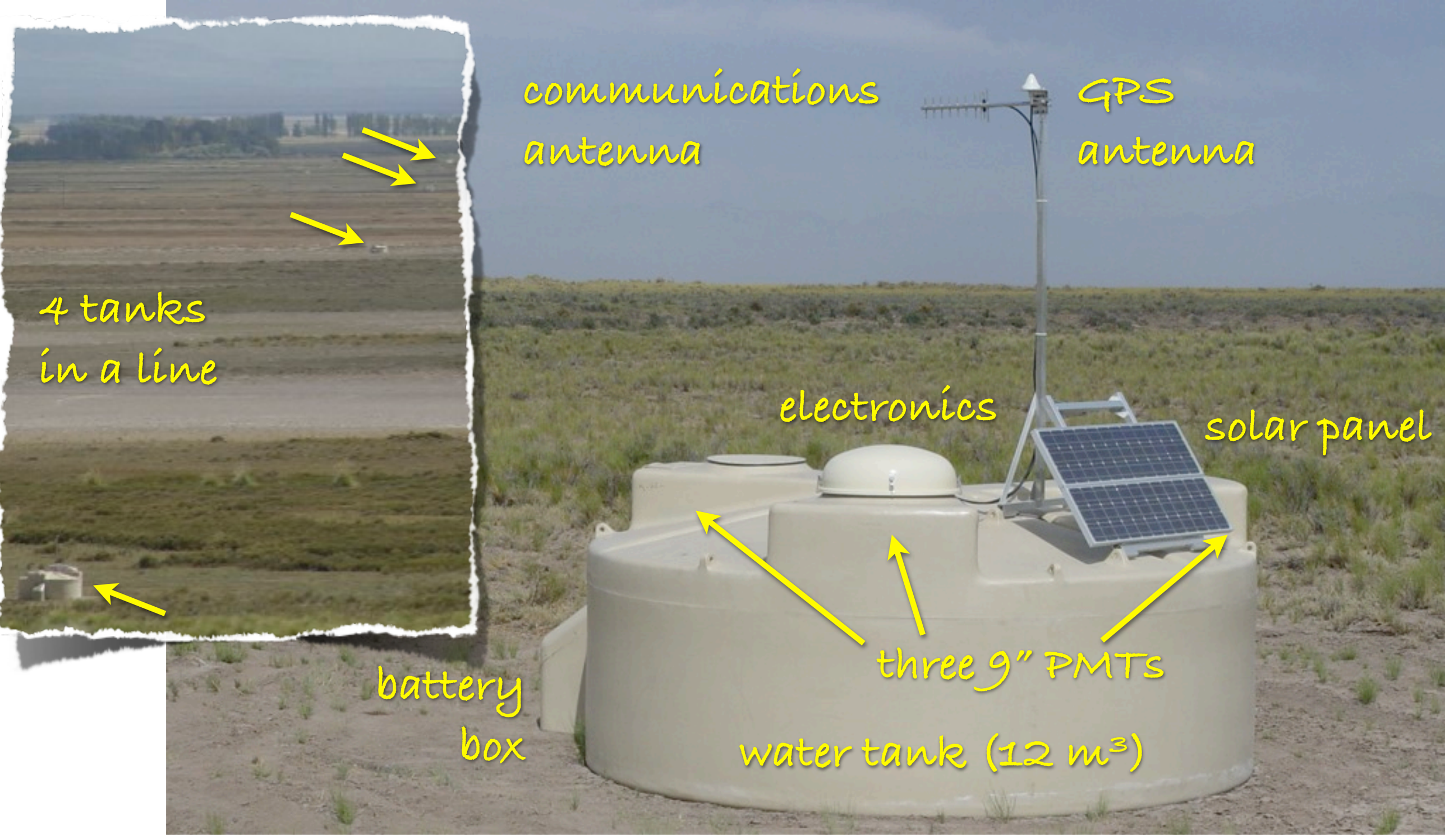
"Completion" Nov 2008



Inauguration Nov 2008

the "founding fathers"





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

21 tanks hit, 45°, 86 x 10^{18} eV

y [km]

35
34
33
32
31
30
29
28
27
26

114
117
107
209
139
119
122
218
235
112
229
226
140
134
113
223
207
106
111
132
219

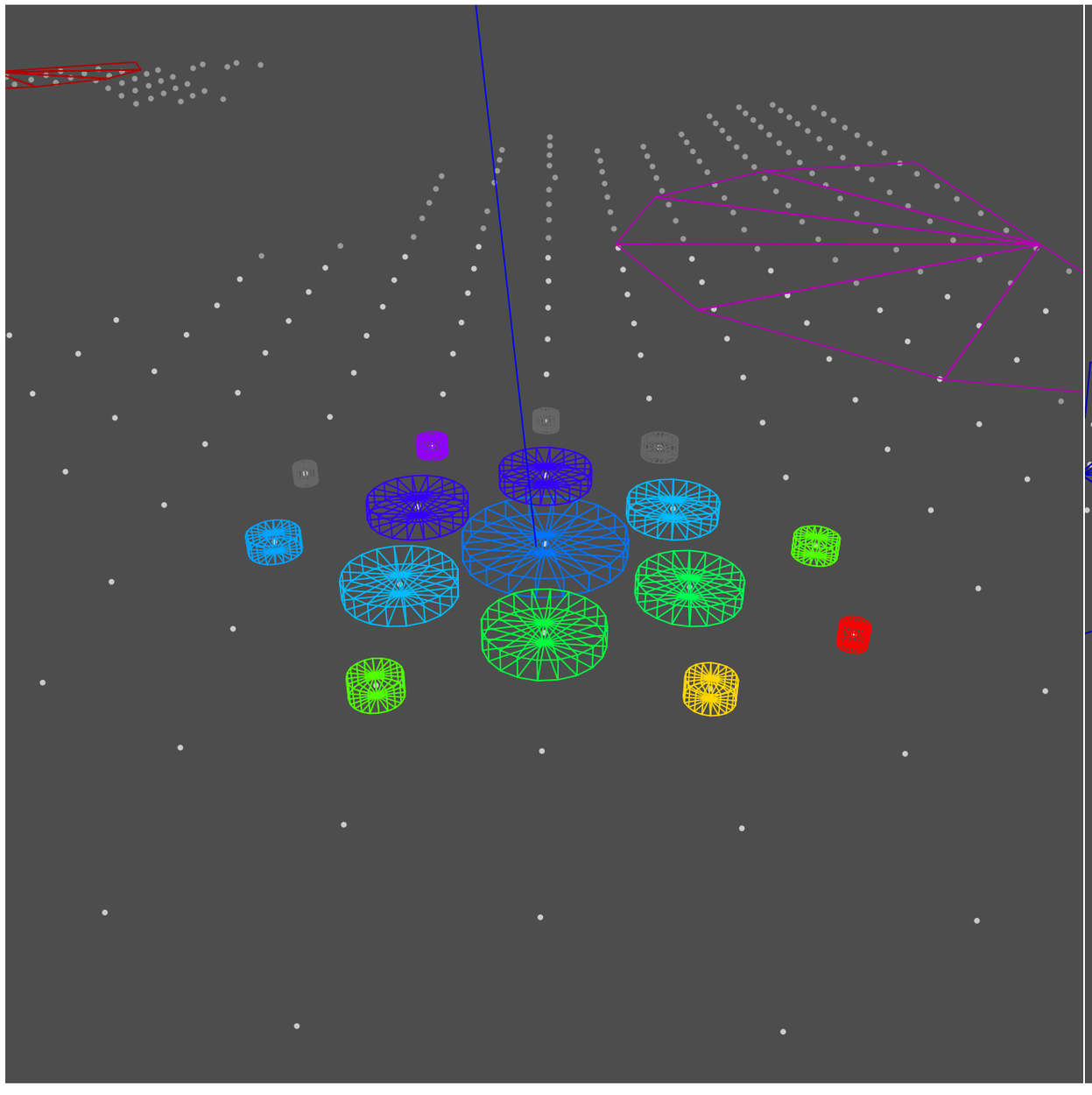
28
30
32
34
36
38
40

x [km]

some of the highest energy SD events:

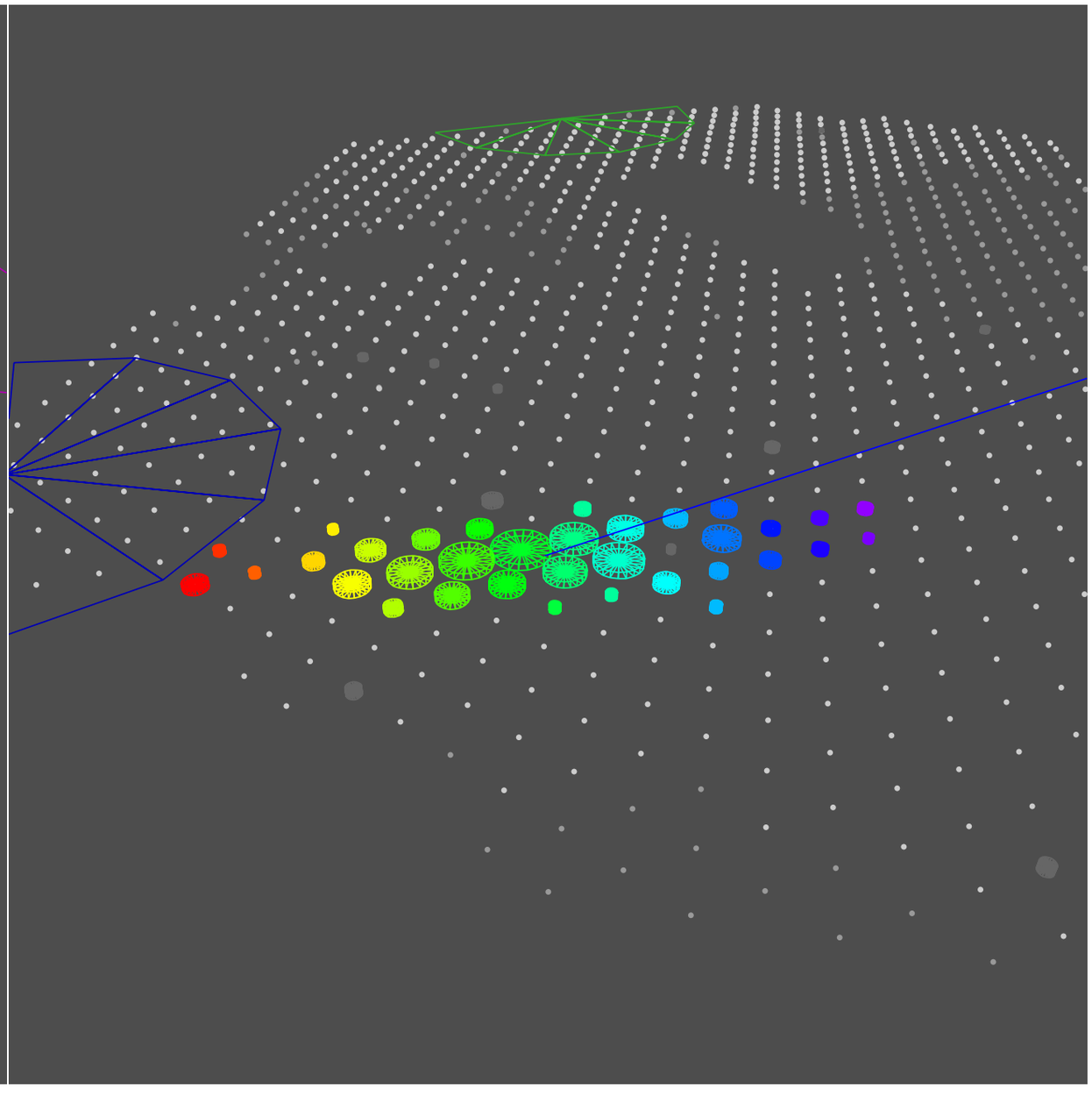
near vertical

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

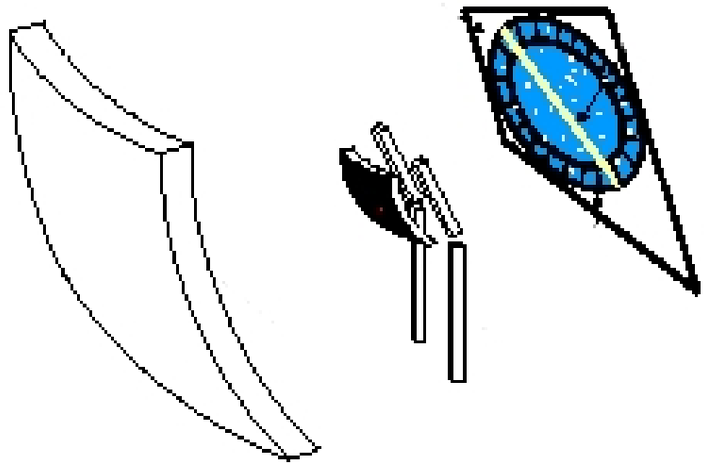


inclined

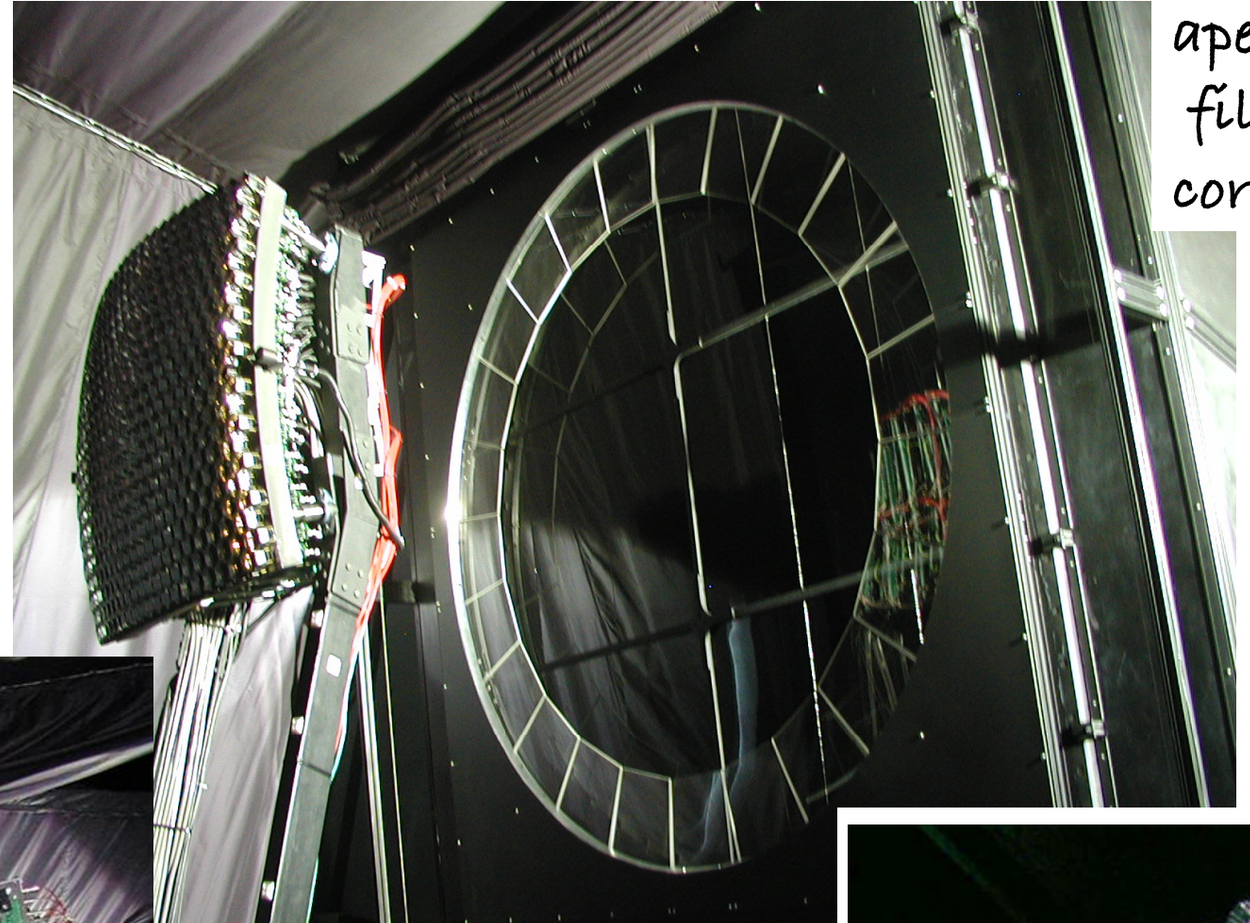
$E = 0.37 \times 10^{20}$ eV $\theta = 74^{o}$

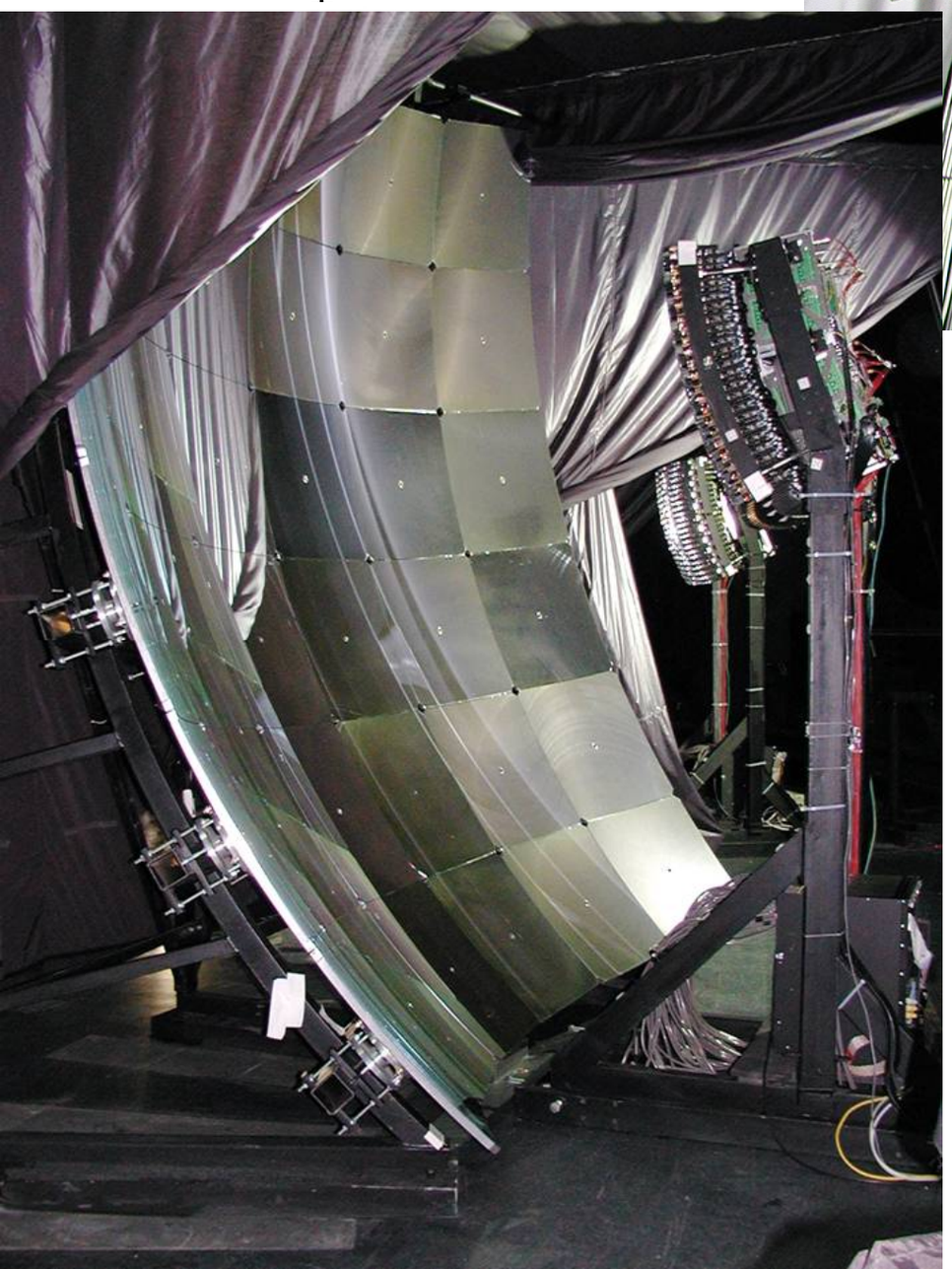


FD telescope:



aperture with shutter, filter and Schmidt corrector lenses

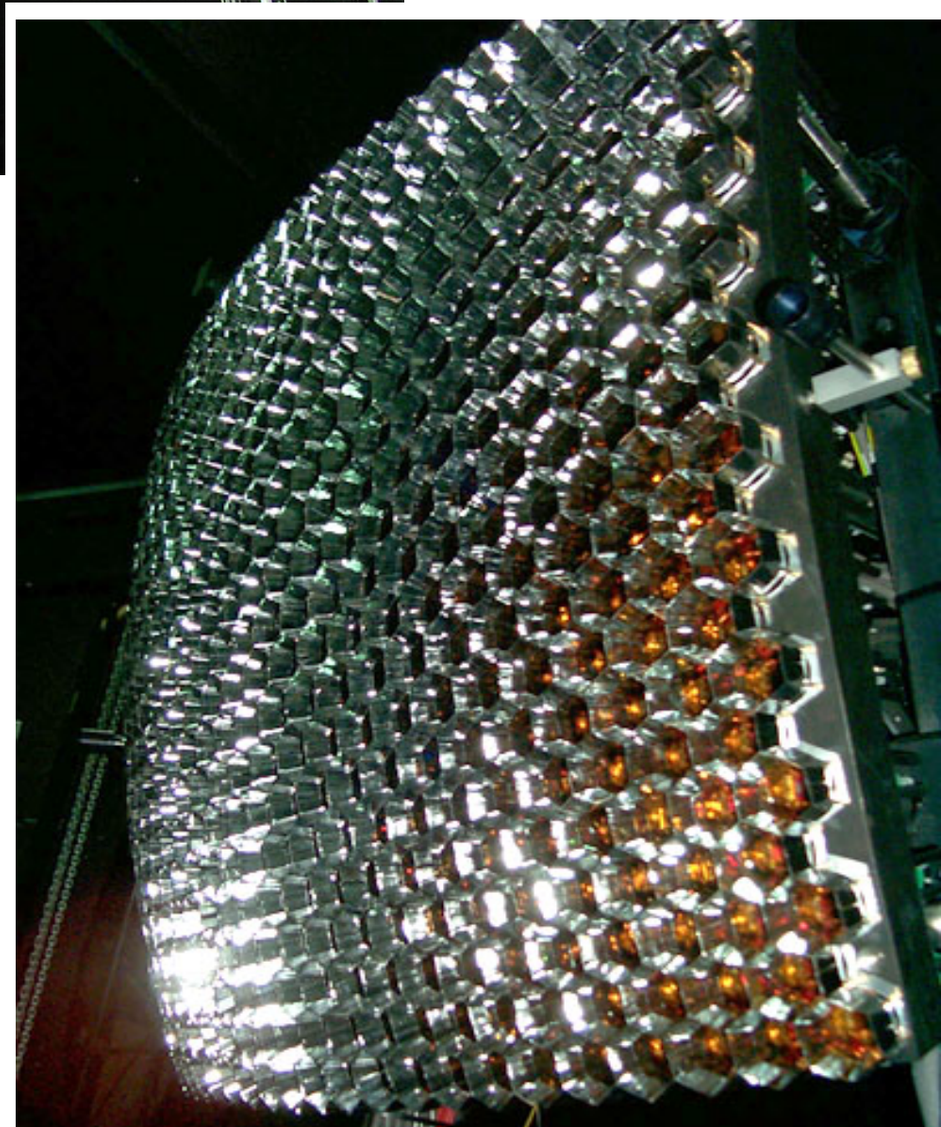




11 m² mirror (Aluminium)

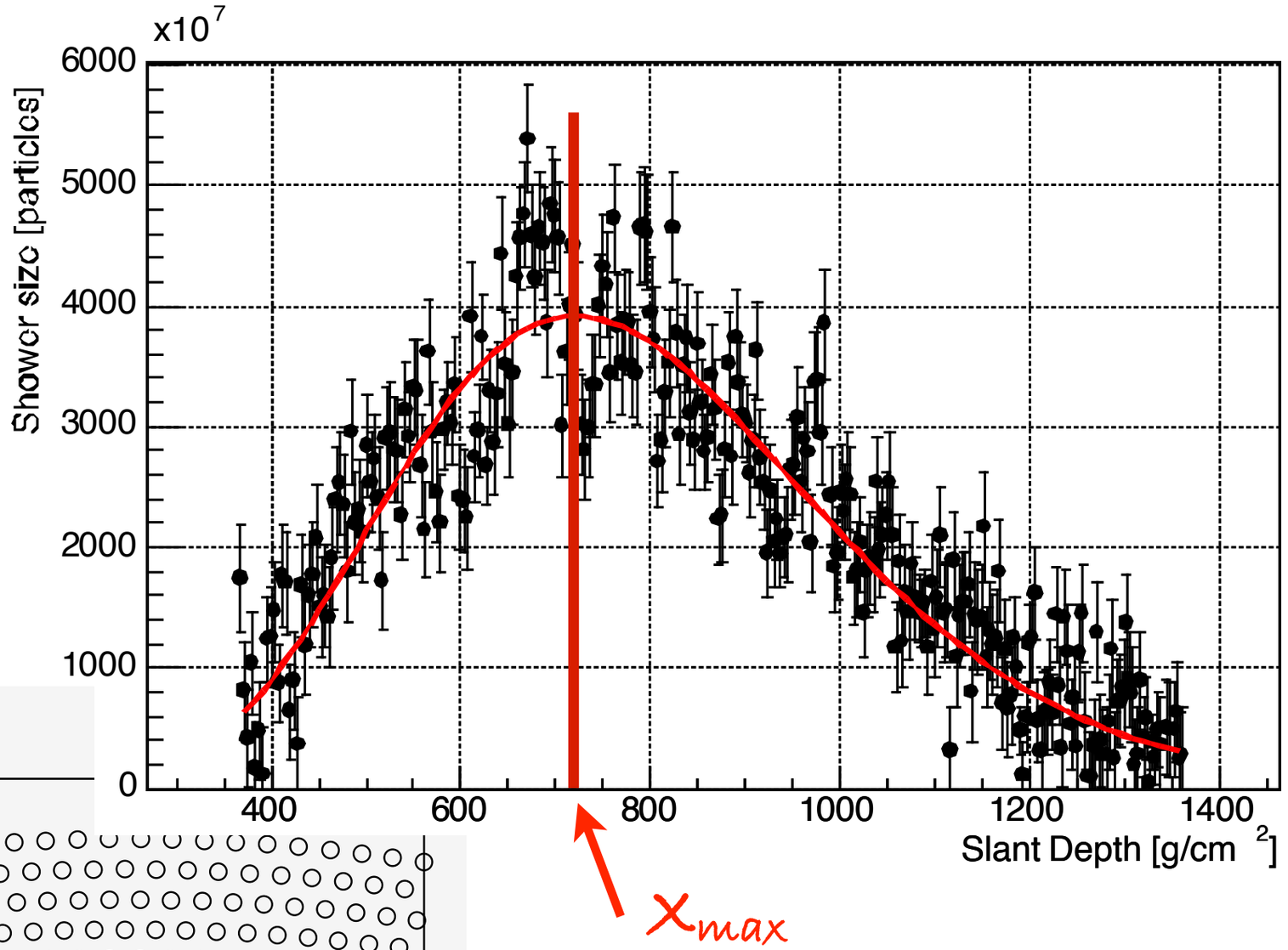
440 PMT camera

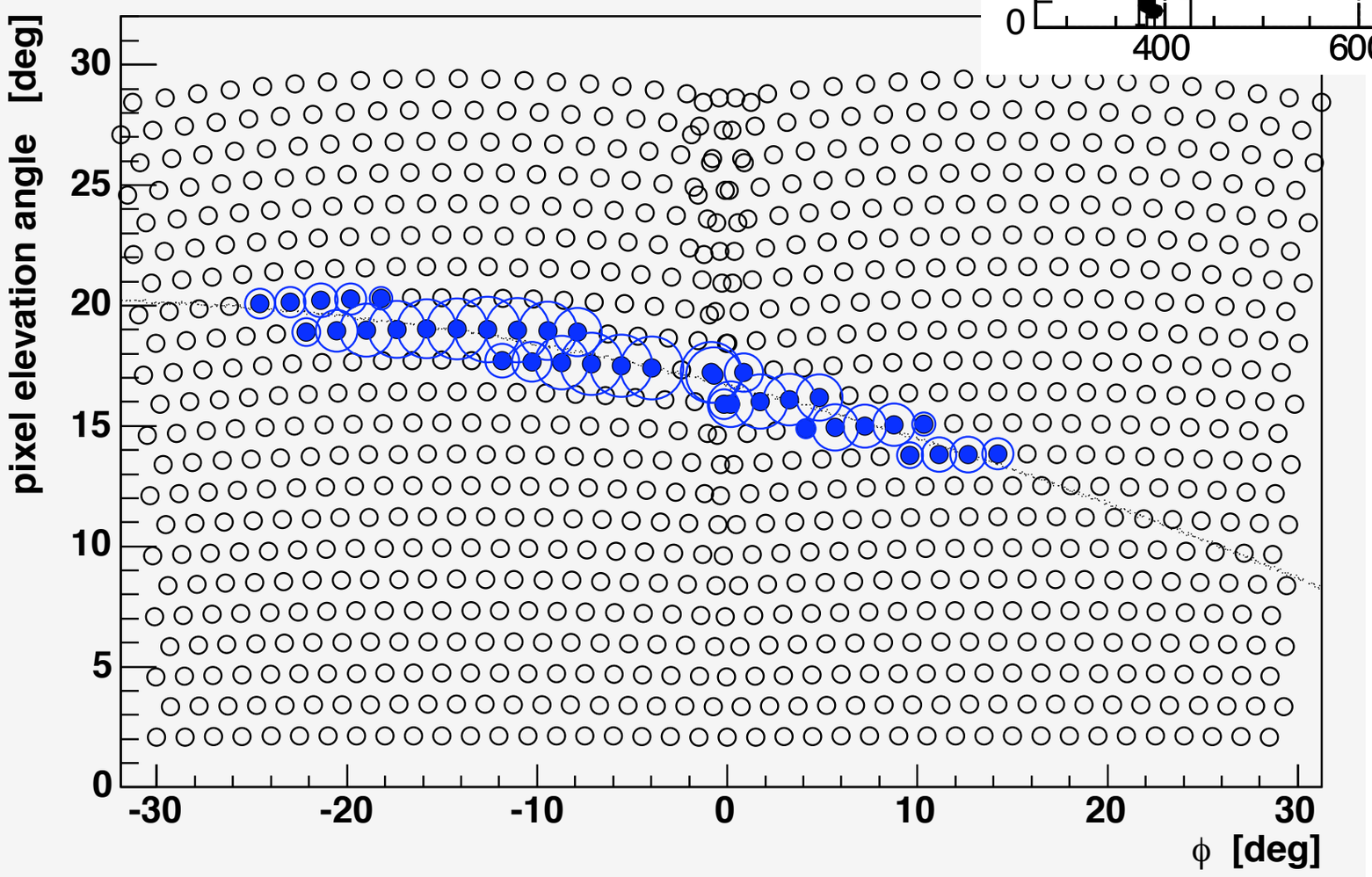
24 telescopes at 4 sites
30°x30° FOV, each



FD:

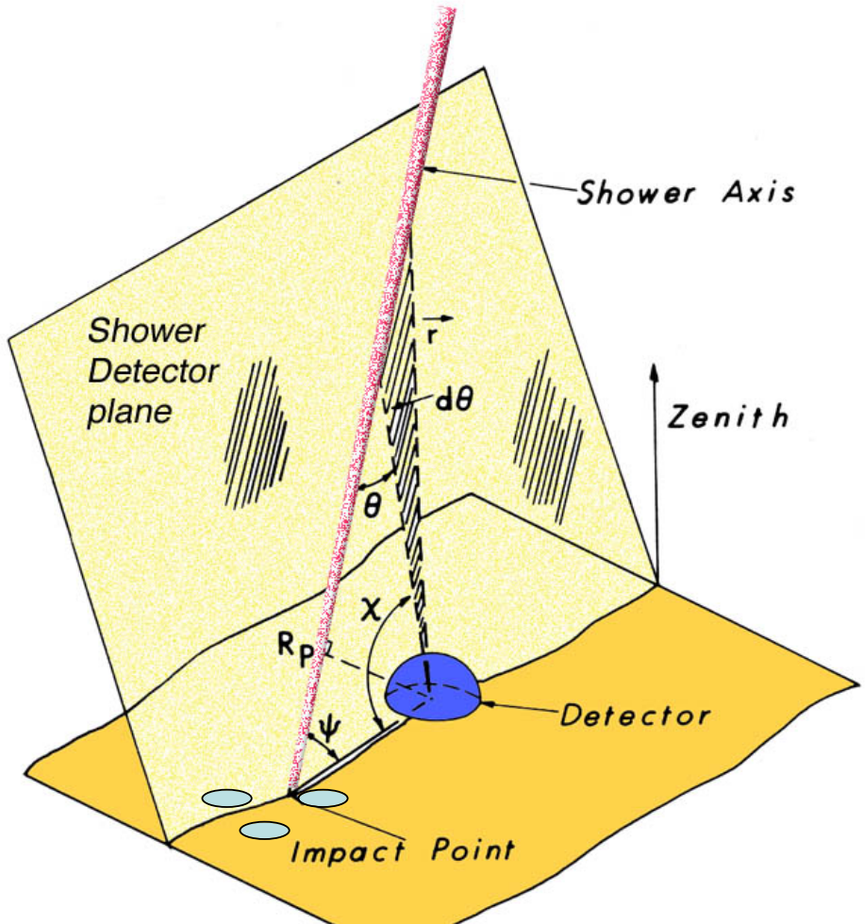
longitudinal profile,
calorimetric energy,
X_{max} for mass comp.

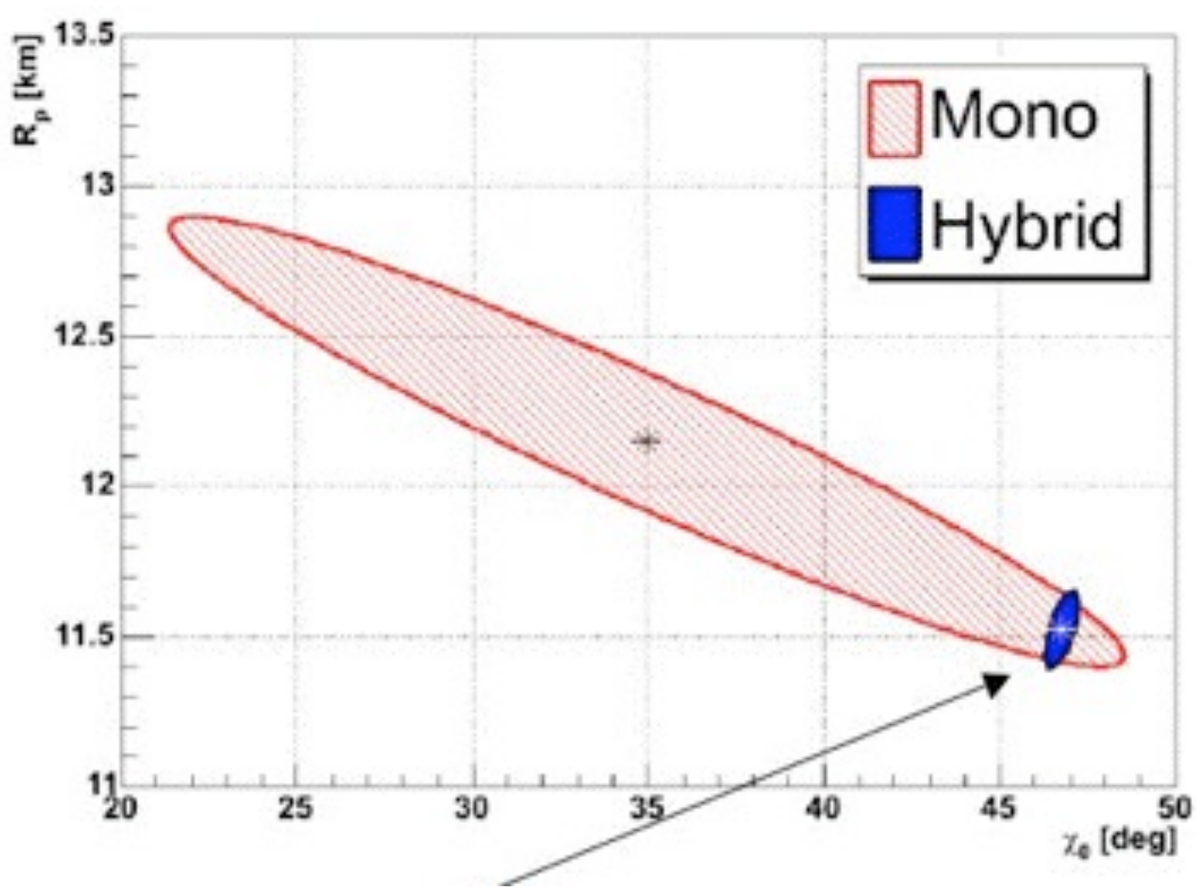




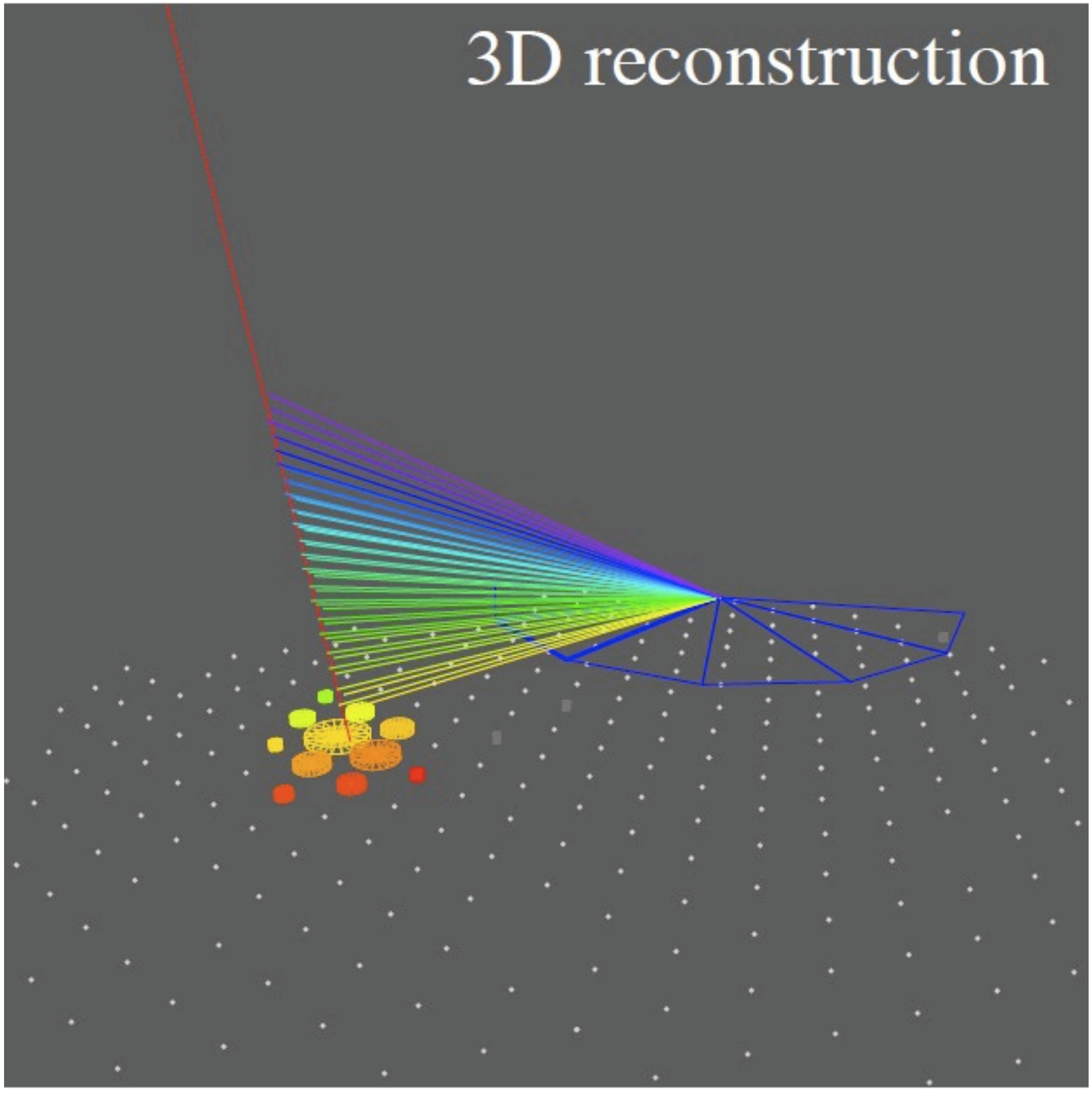
$$E \propto \int_0^\infty N(t)dt$$

	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



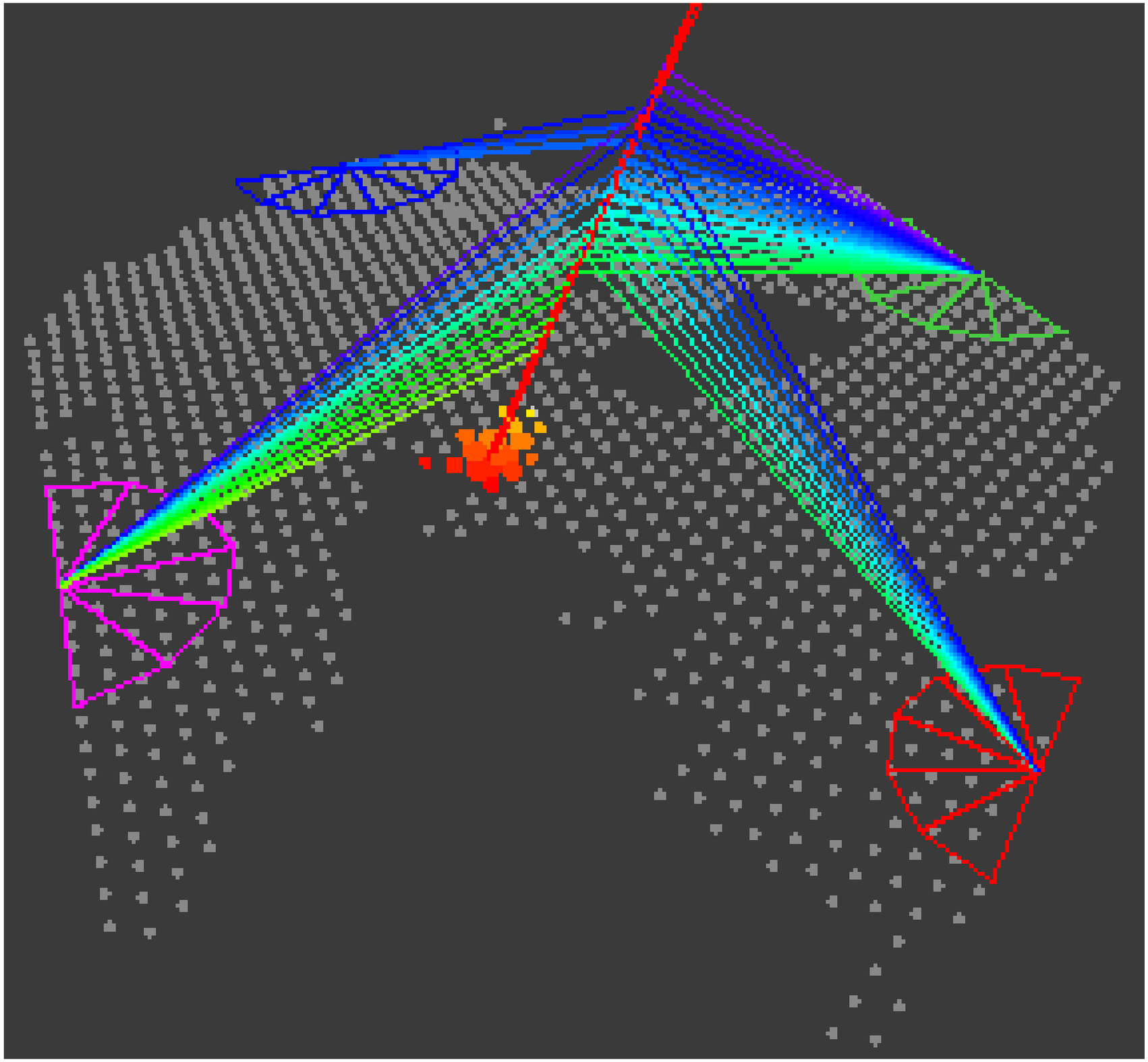


golden hybrid event



20 May 2007 $E \sim 10^{19}$ eV

Shower seen by the array and all 4 FDs



San Rafael

Malargüe

8 "black" tanks
(<0.5%)

Status

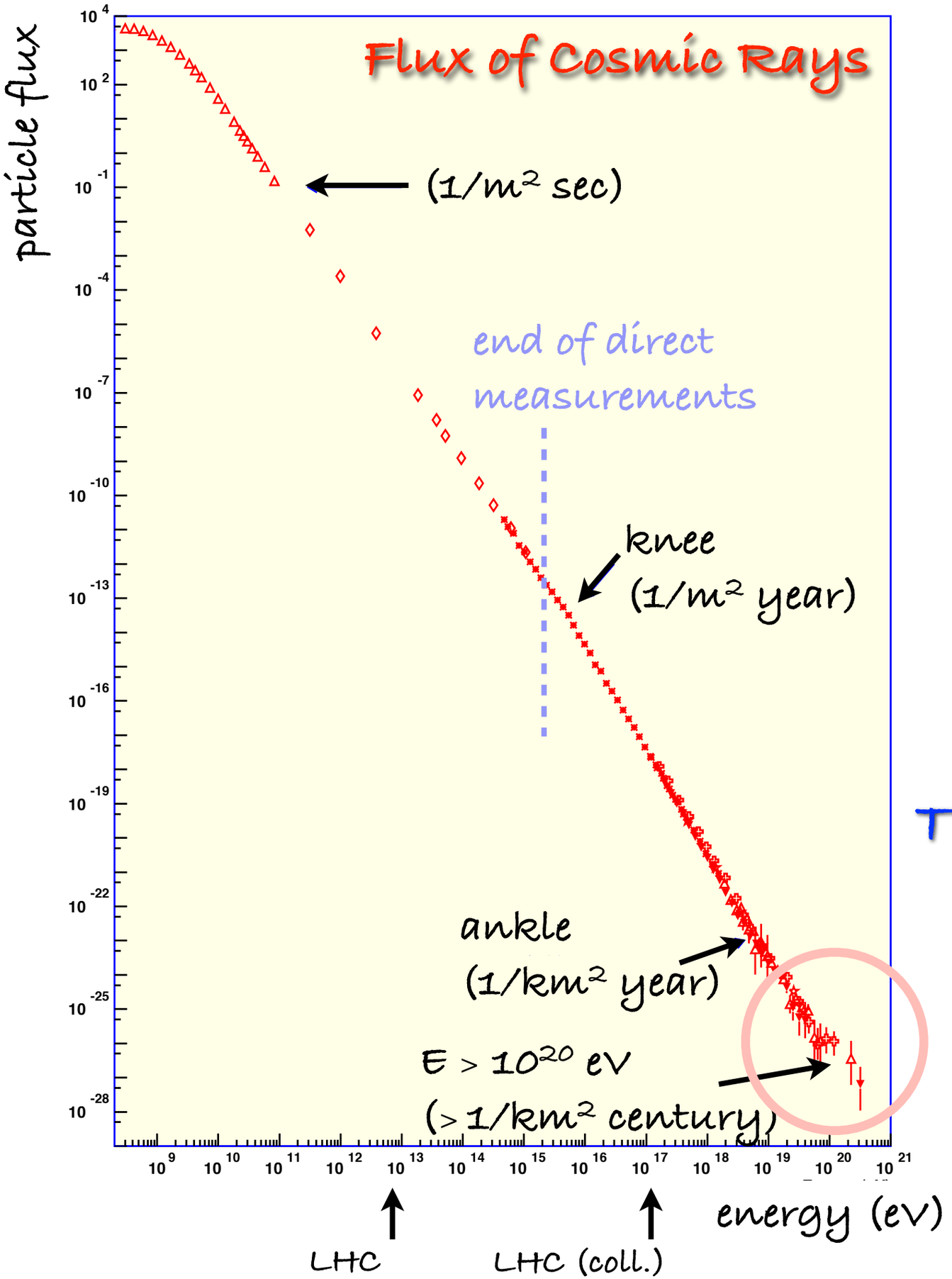
15 Nov 2010

a truly black tank
(... after a grass fire)

Results

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

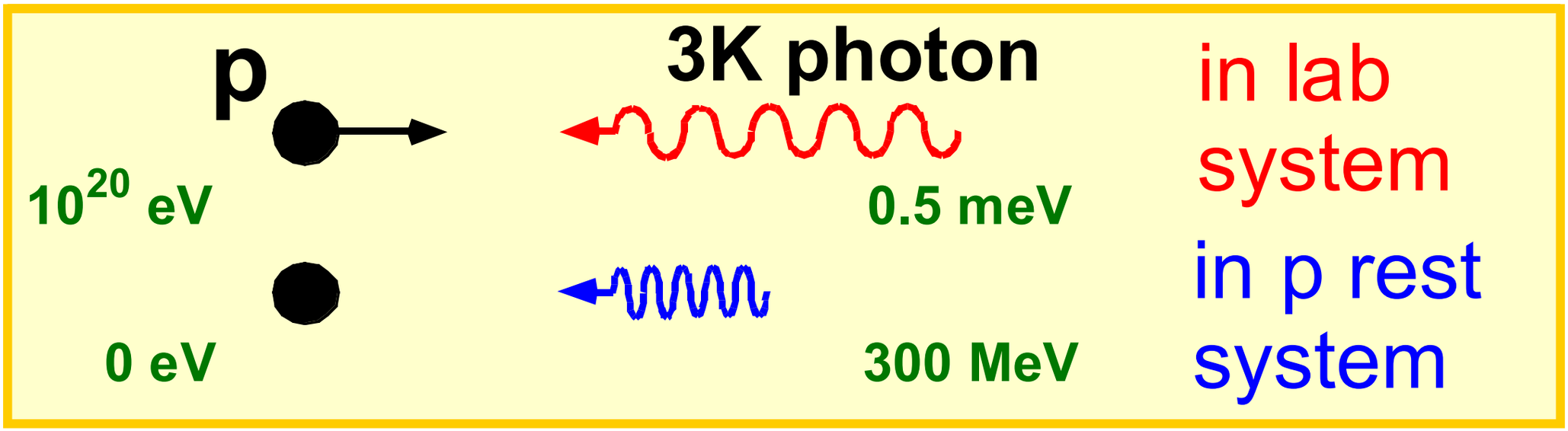
Spectrum



The Auger range ...
with a firm prediction of a spectral feature:
the GZK cut-off

GZK Cut-off

Greisen (1966)
Zatsepin & Kuzmin (1966)



$p + \gamma_{3K} \longrightarrow \Delta^+ \longrightarrow p + \pi^0$ → γ

$\longrightarrow n + \pi^+$ → ν

$^{56}Fe + \gamma \longrightarrow {}^{55}Fe + n$

Photo-pion production

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 $\gamma \approx 10^{11}$!

GZK Cut-off

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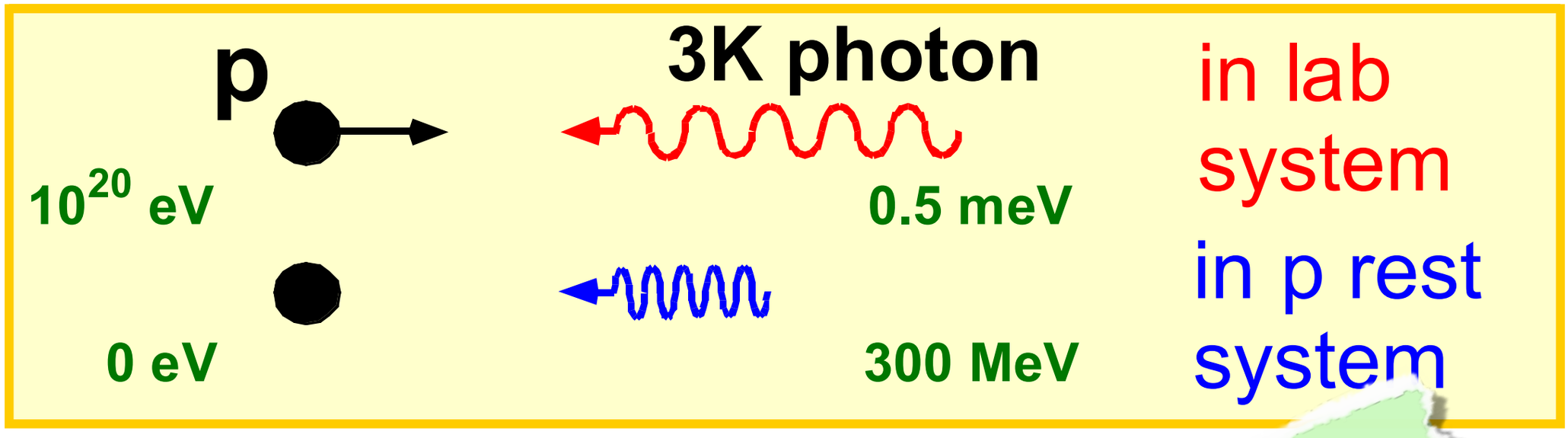

$$p + \gamma_{3K} \longrightarrow \Delta^{+} \longrightarrow p + \pi^{0} \quad \nearrow \gamma$$

$$\longrightarrow n + \pi^{+}$$

$$^{56}Fe + \gamma \longrightarrow$$

Photo-pion production

Photo dissociation

but details depend on source distribution and source spectra and mass composition ...

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

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If source 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)

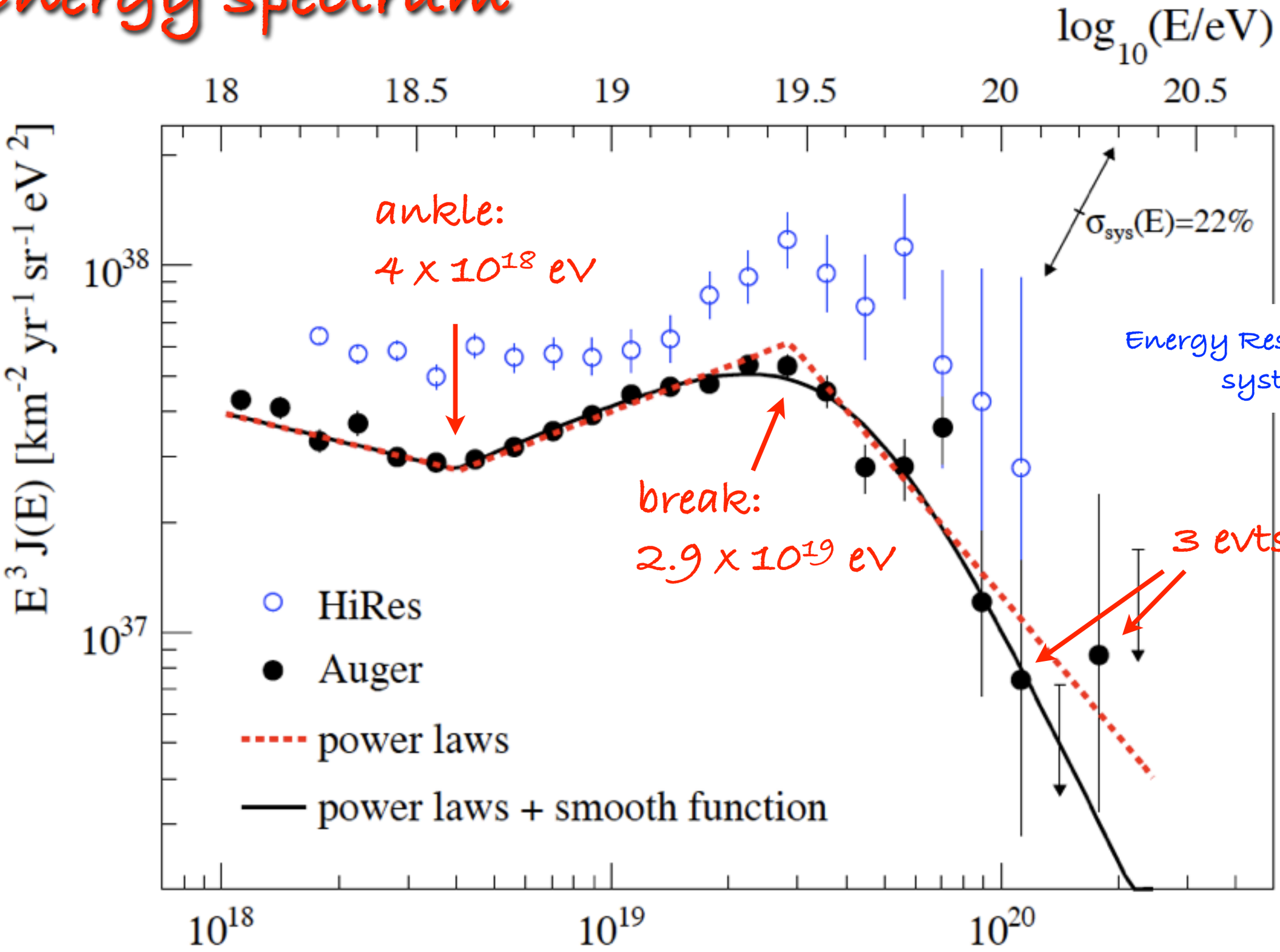
get energy calibration from FD

for high statistics from SD

A: directly from size of SD

(above 3×10^{18} eV)

Energy spectrum



Energy Resolution : 17%
systematics: 22%

>10^{20} eV:
1 evt/min
on surface
of Earth !

Auger finds "ankle" and a clear (>20 σ)
spectral steepening at E ≈ 2.9 x 10^{19} eV.

12790 km² sr yr ≈ 2 full-Auger years
zenith angle: 0-60°

There is a cut-off ... but is it 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 in spectrum at Earth at $\approx$ few x 10^{19} eV

Alternatives:

Also nuclear primaries would be absorbed (but not quite in the same way)
mixed composition with similar cut-off ?
maximum energy of accelerator ?
....

The cut-off is suggestive of protons

(but mixed composition cannot be ruled out)

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

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Hint 1

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(but mixed composition cannot be ruled out)

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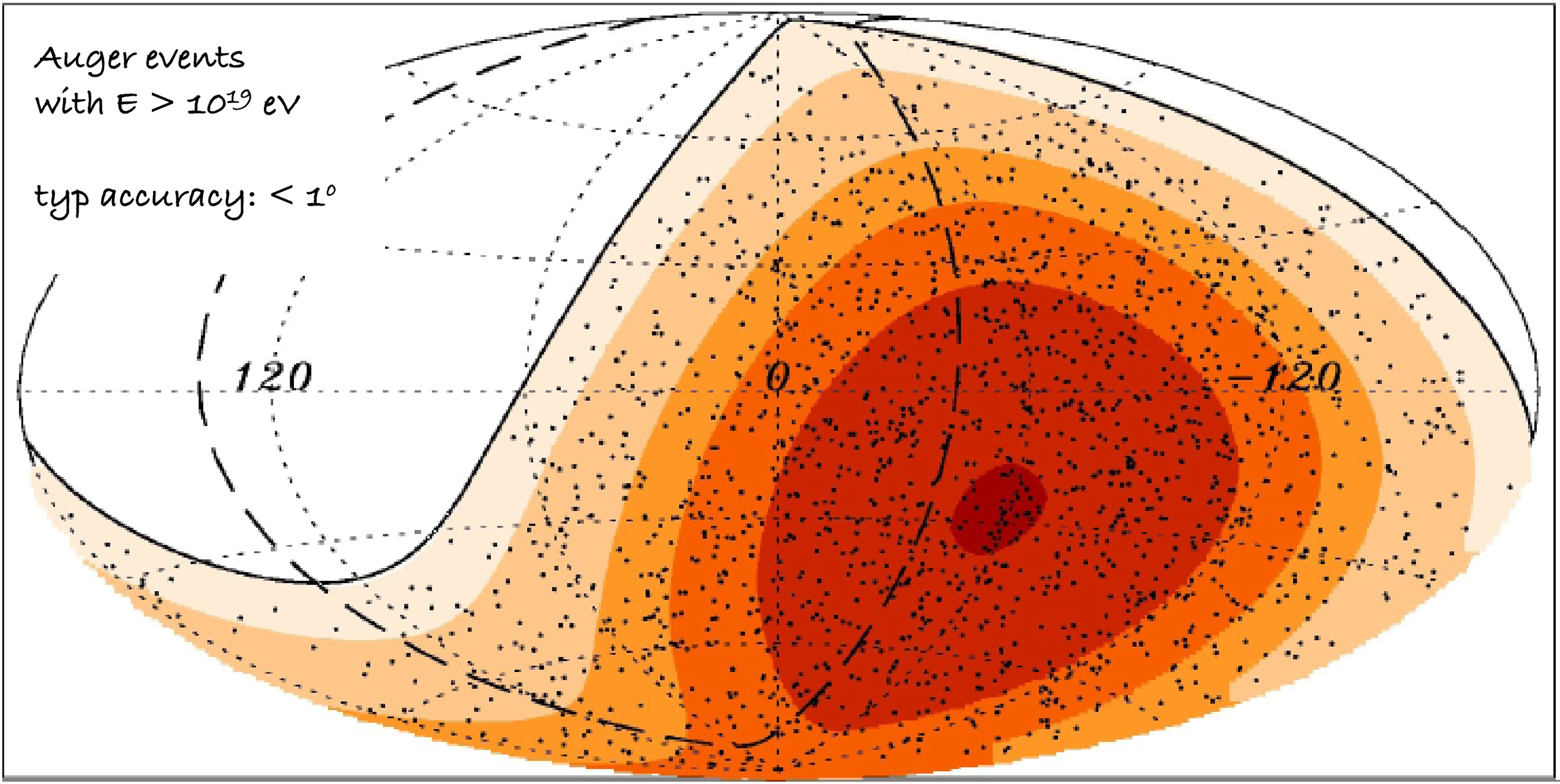
Anisotropy

Auger events
with $E > 10^{19}$ eV

typ accuracy: < 1°

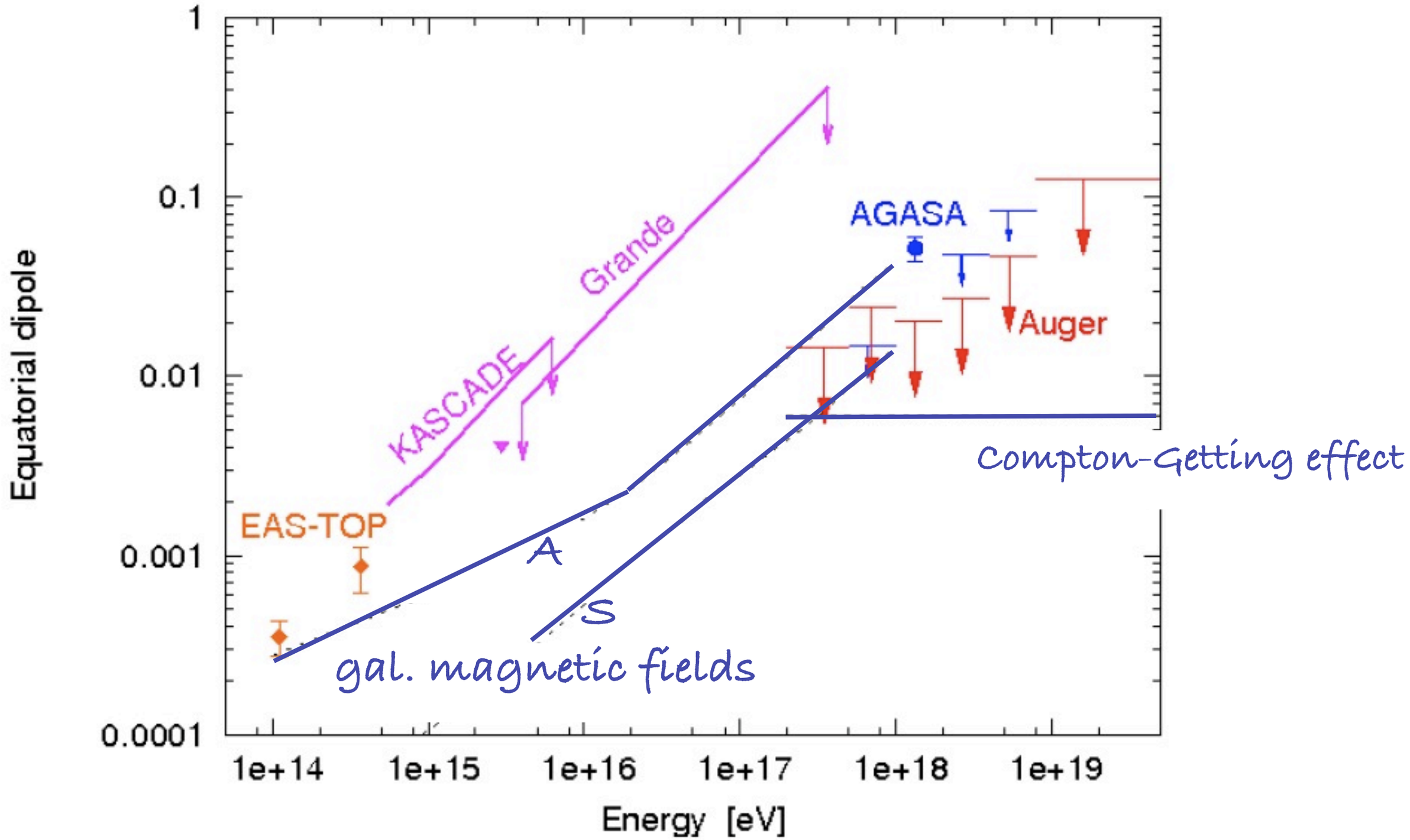


No enhancement along galactic disk: UHE particles are extragalactic.

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

Large-Scale Anisotropy

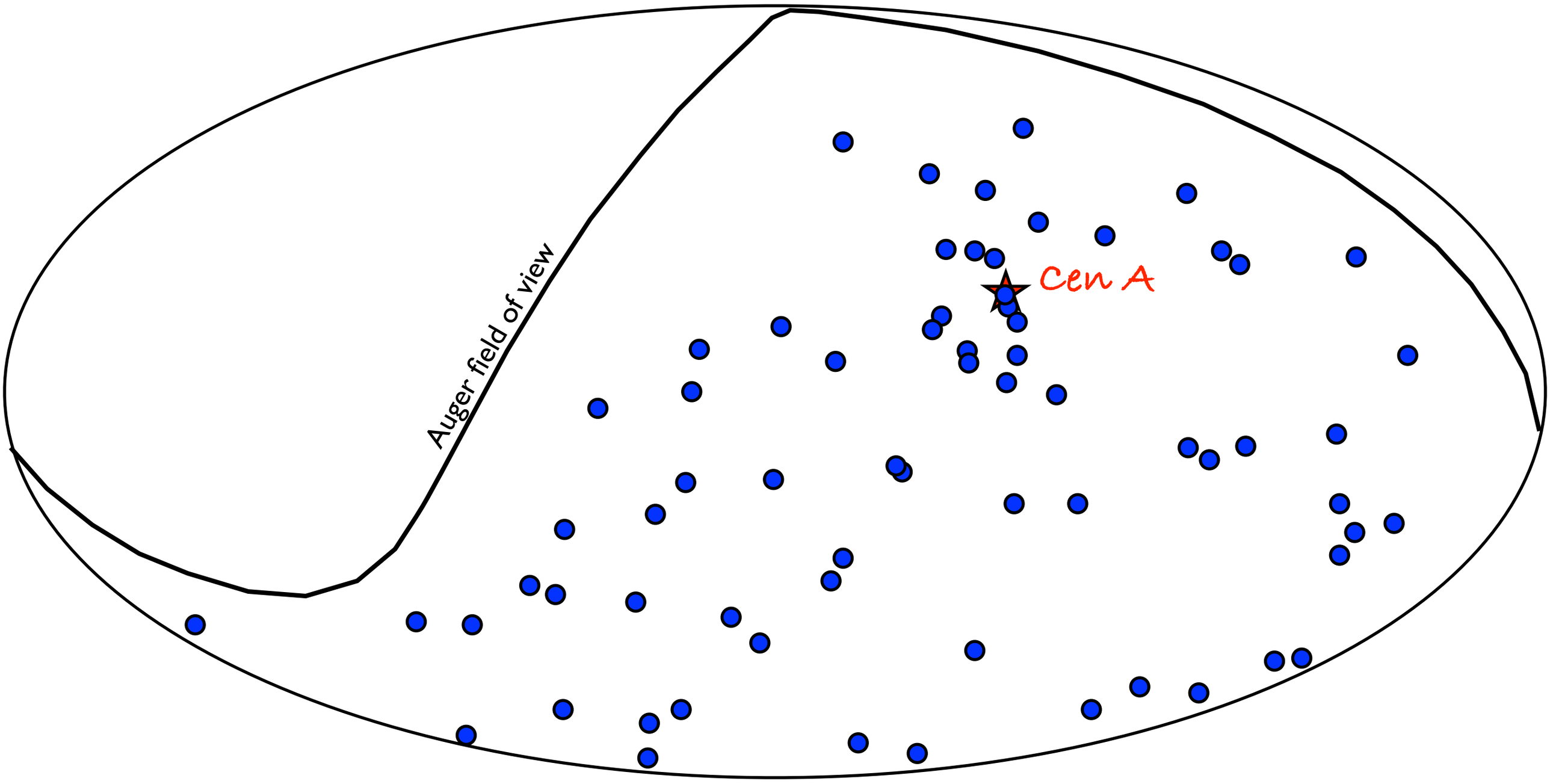
- Fourier analysis of arrival times
- Generalised Rayleigh Method
- East-West method



Limits close to predicted anisotropies.

More data will give an anisotropy signal or model constraints.

69 Highest Energy Events >55 EeV (Dec 2009)



Isotropic ? Clustering ? ... how to quantify ?

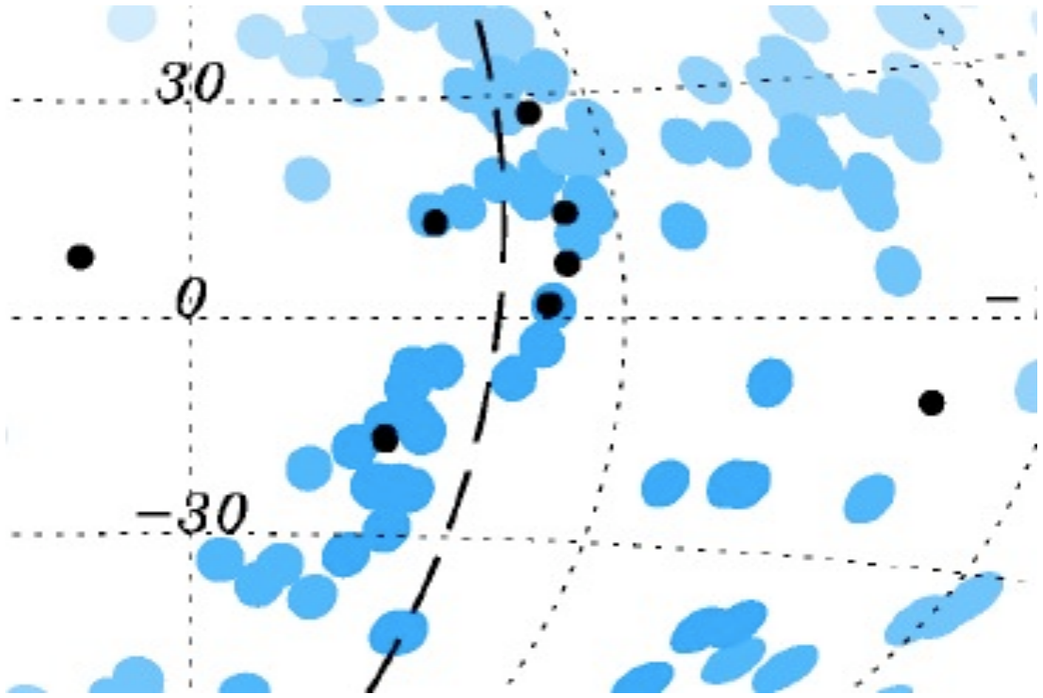
Is Cen A a source of UHECRs ?

Correlation of CRs with source population ?

(1st trial: nearby AGN from the 12th VC-V catalogue)

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

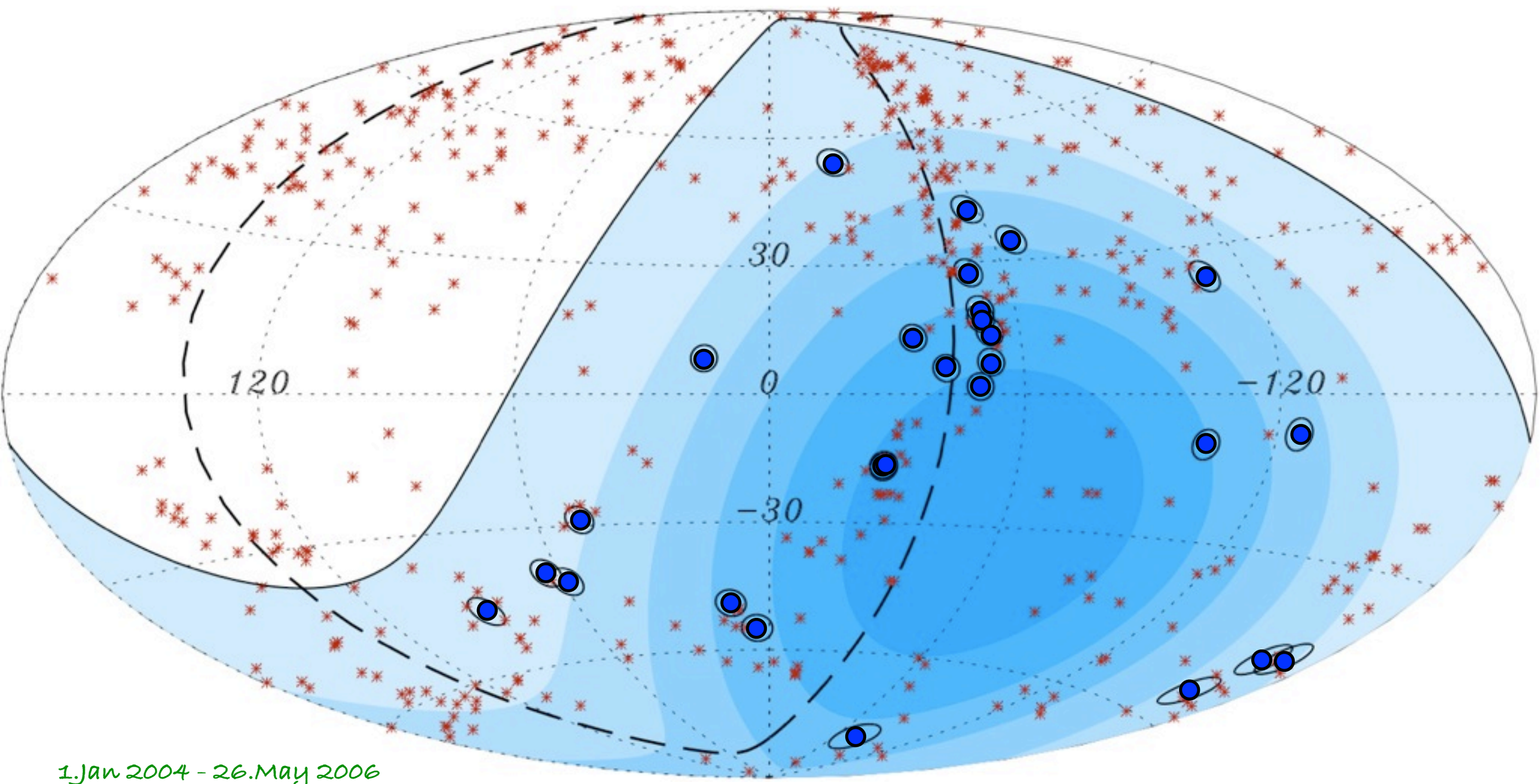
... to correlate CRs with AGNs



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

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



1 Jan 2004 - 26 May 2006

scan: 15 evts, 12 correlate with AGN (3.2 exp.) for $R<3.1^\circ$, $z<0.018$, $E>56$ 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.

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

Auger Collaboration,
Science 318, (2007) 938

This result was suggestive of
primary protons and a GZK cut-off:

deflection in galactic magnetic fields @ 60 EeV:
small for protons
big for Iron
correlation only with nearby AGNs

This result was suggestive of

primary protons and a GZK cut-off:

Hint 2

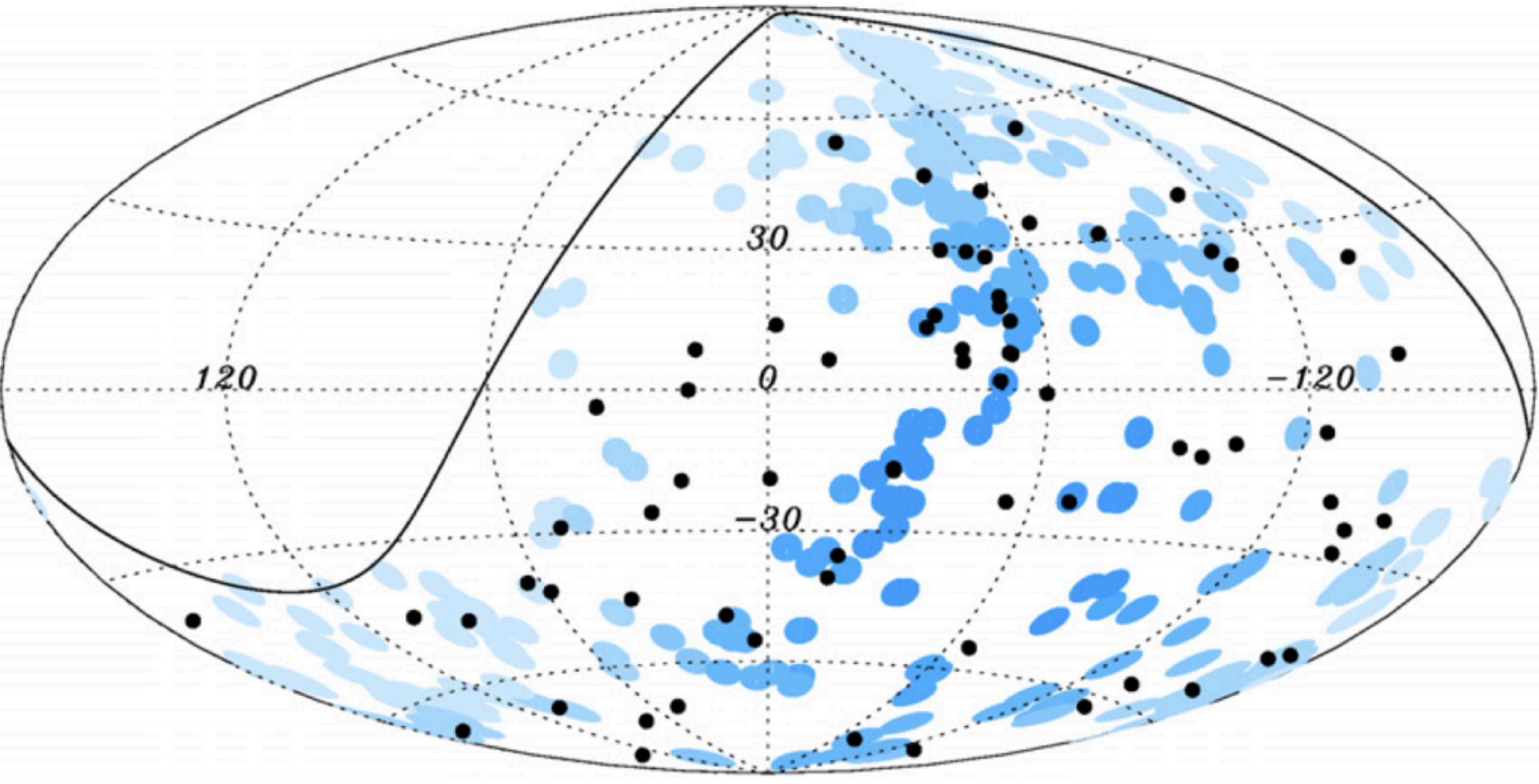
deflection in galactic magnetic fields @ 60 EeV:

small for protons

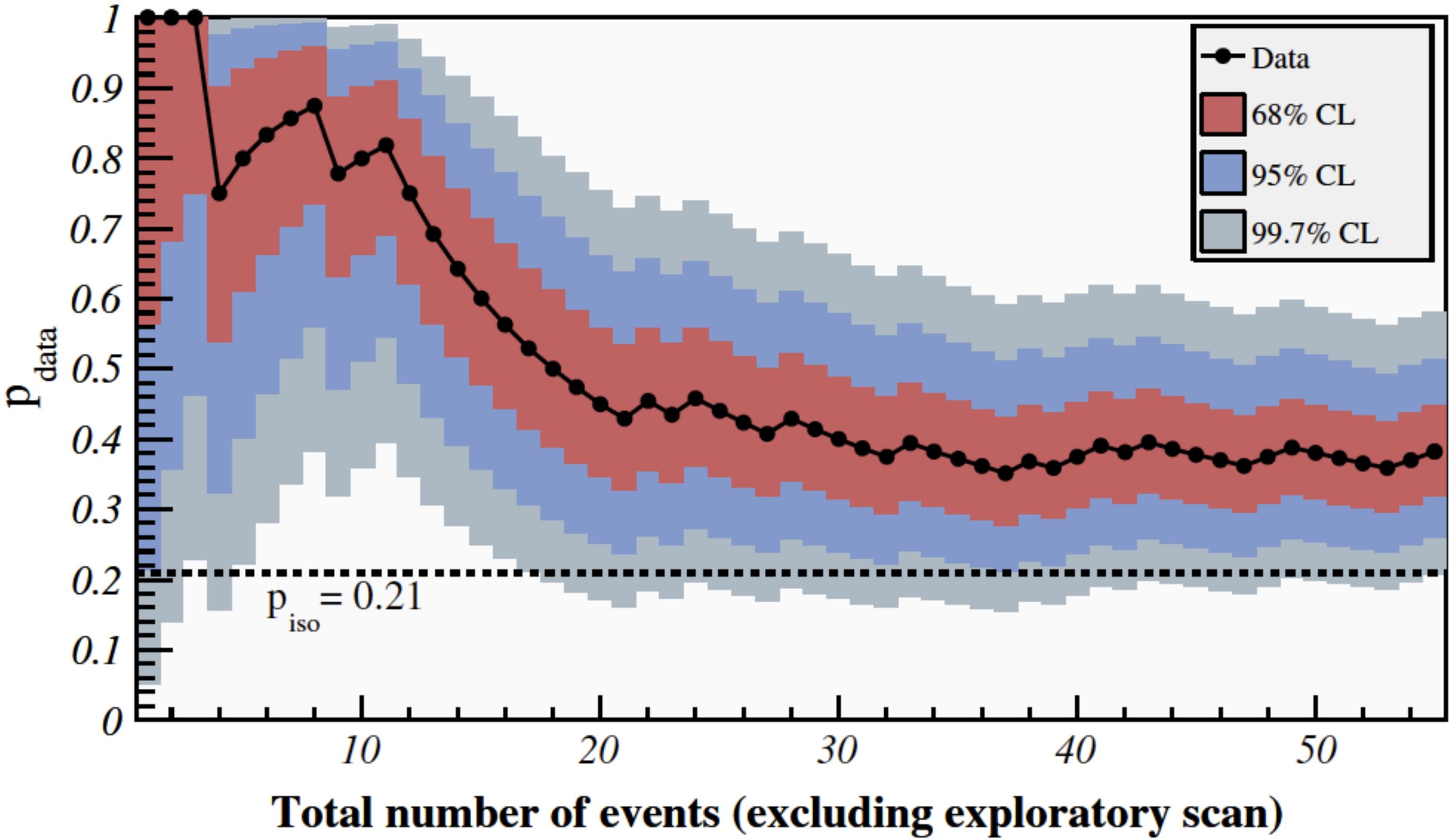
big for Iron

correlation only with nearby AGNs

69 Highest Energy Events >55 EeV (Dec 2009)



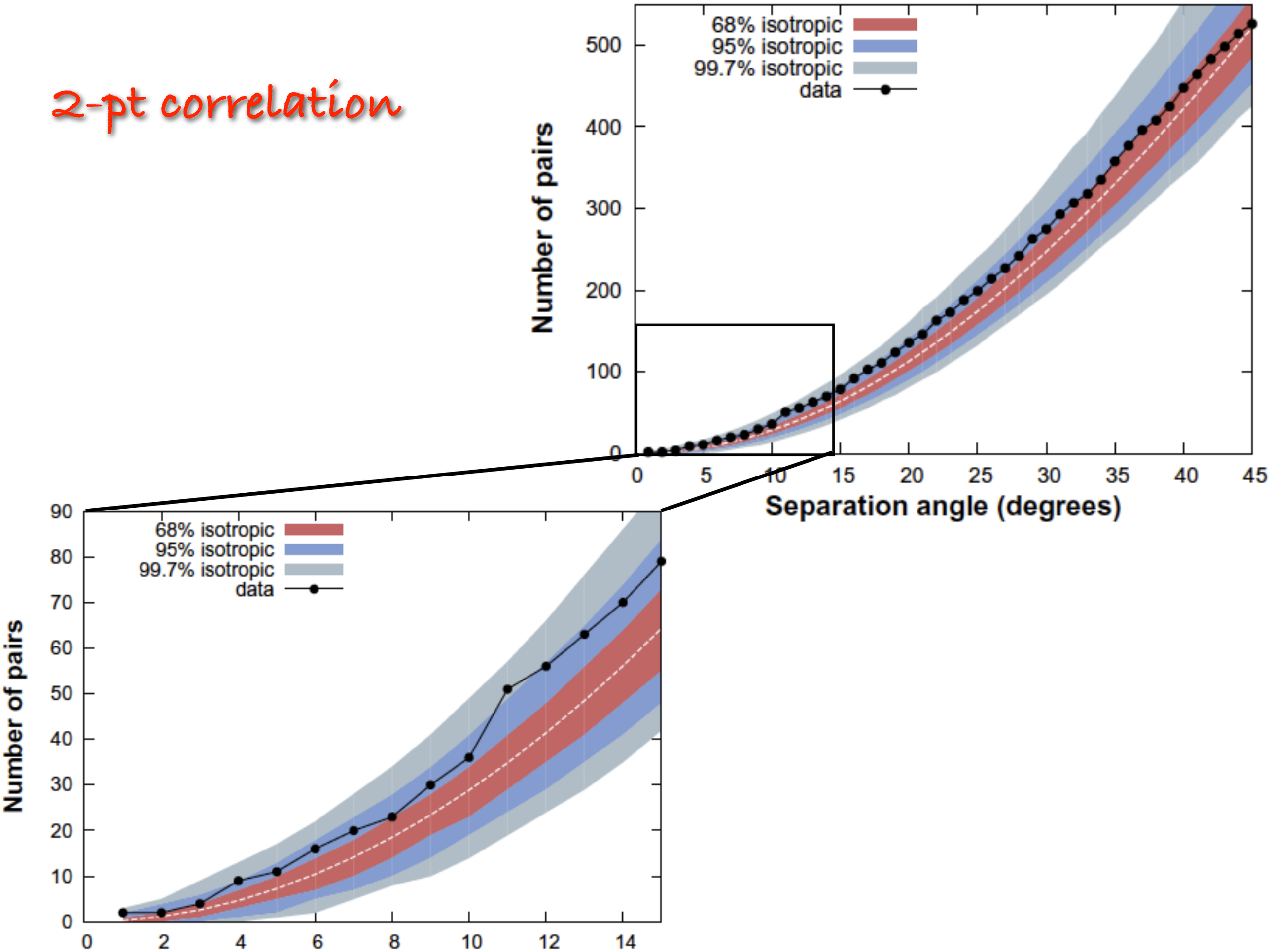
Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter
Astroparticle Physics 34 (2010) 314



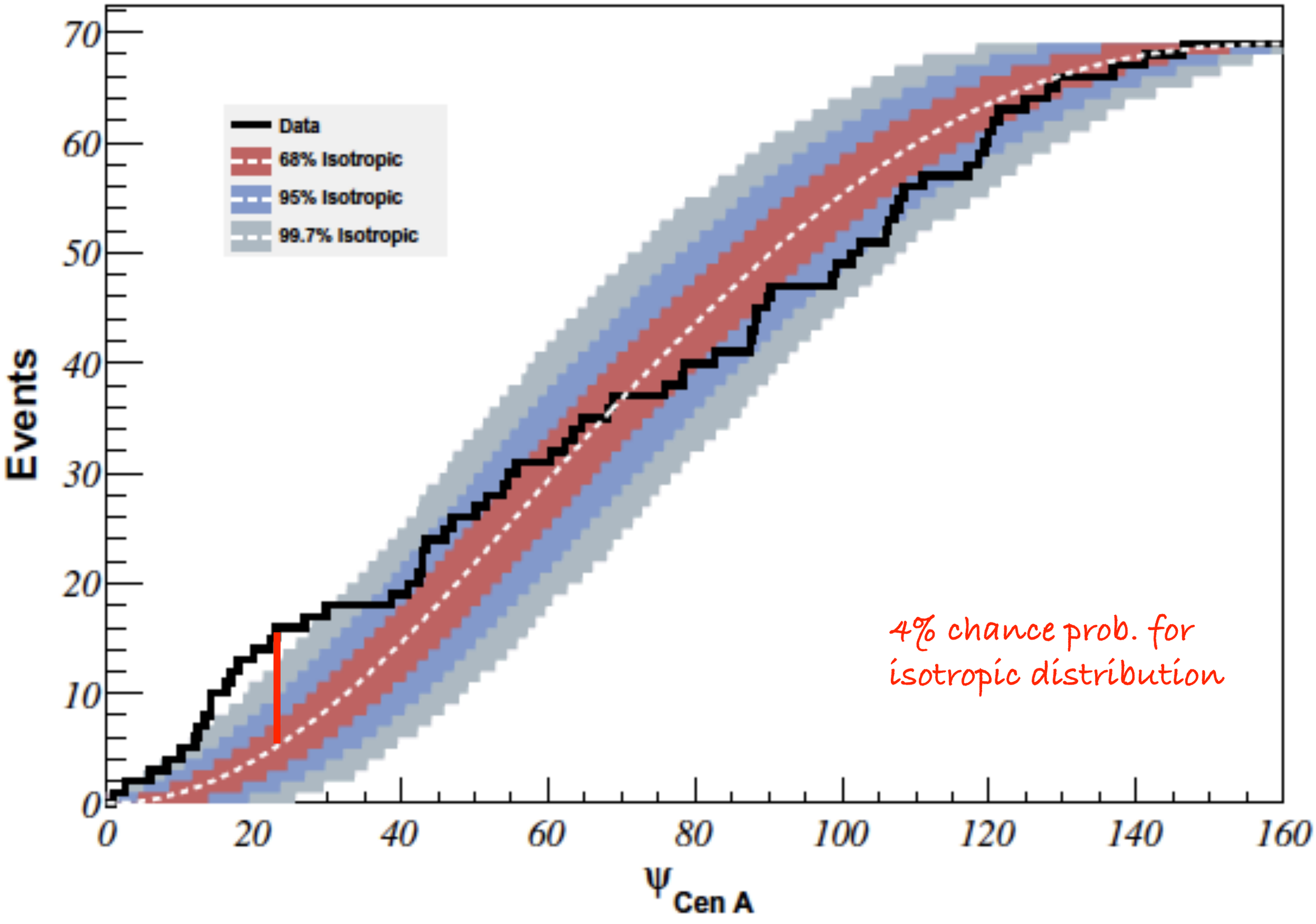
current signal: $p = 0.38^{+0.07}_{-0.06}$

P. Abreu et al. / Astroparticle Physics 34 (2010) 314–326

2-pt correlation

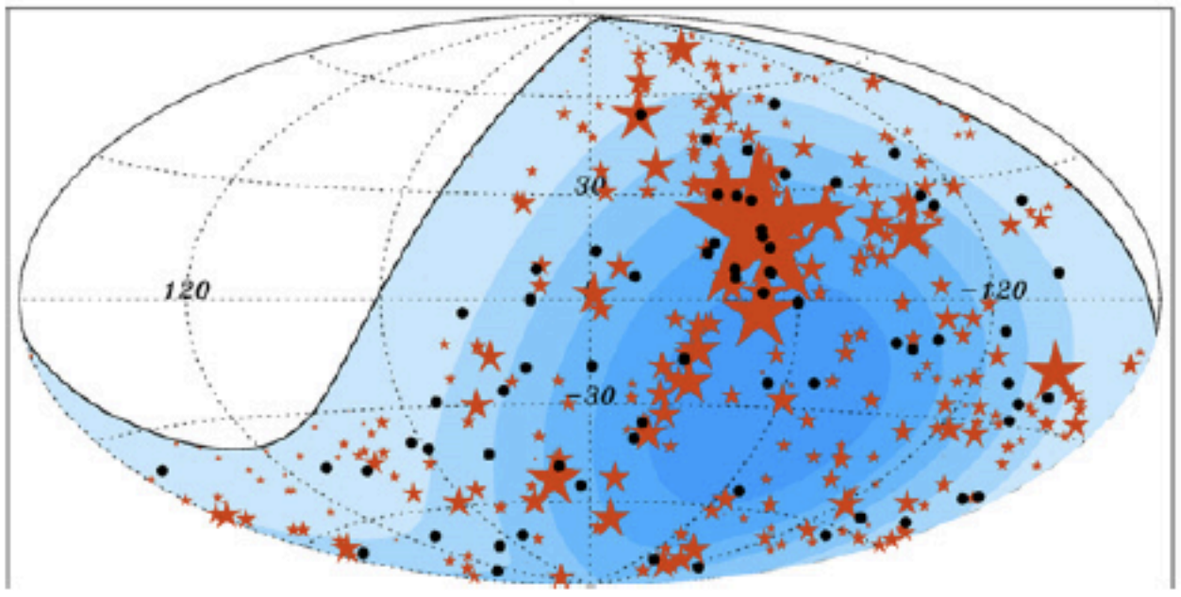


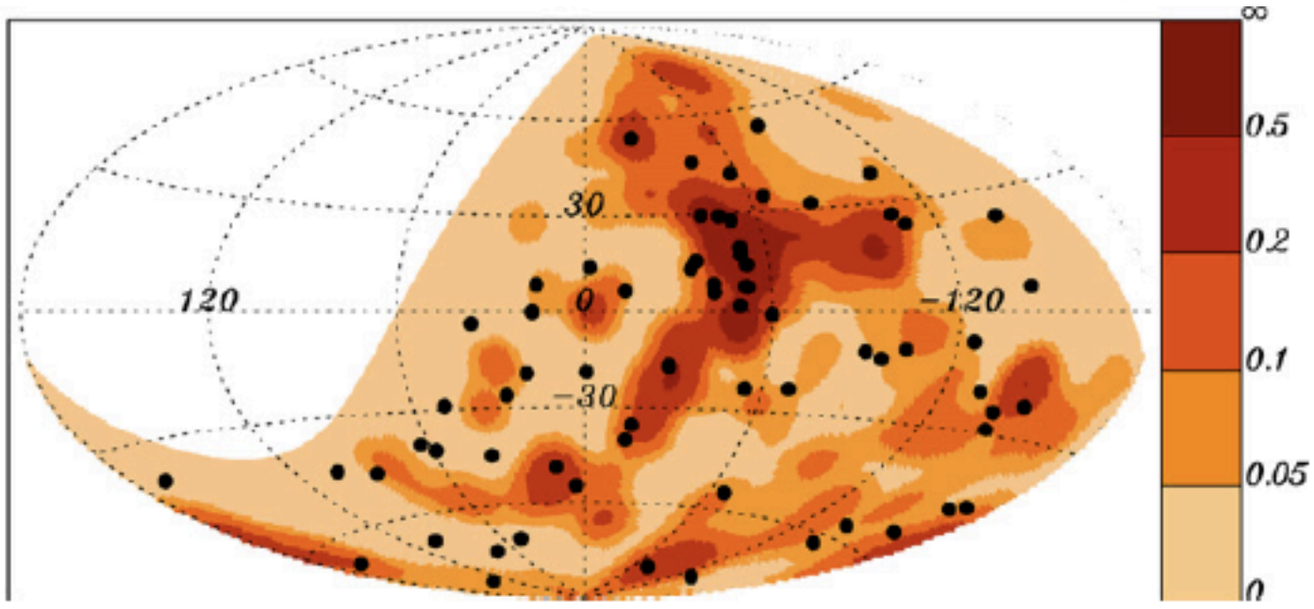
Distance: CR – Cen A



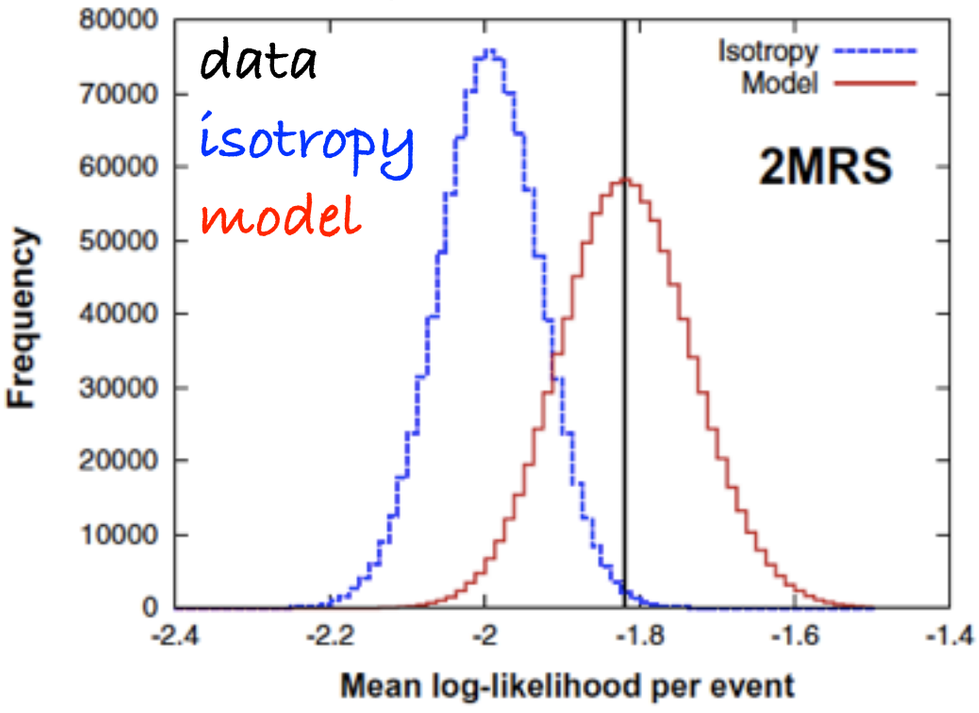
58-months Swift-BAT catalog, d < 200 Mpc
weighted with X-ray flux, rel. exposure, GZK effect

5° smoothing

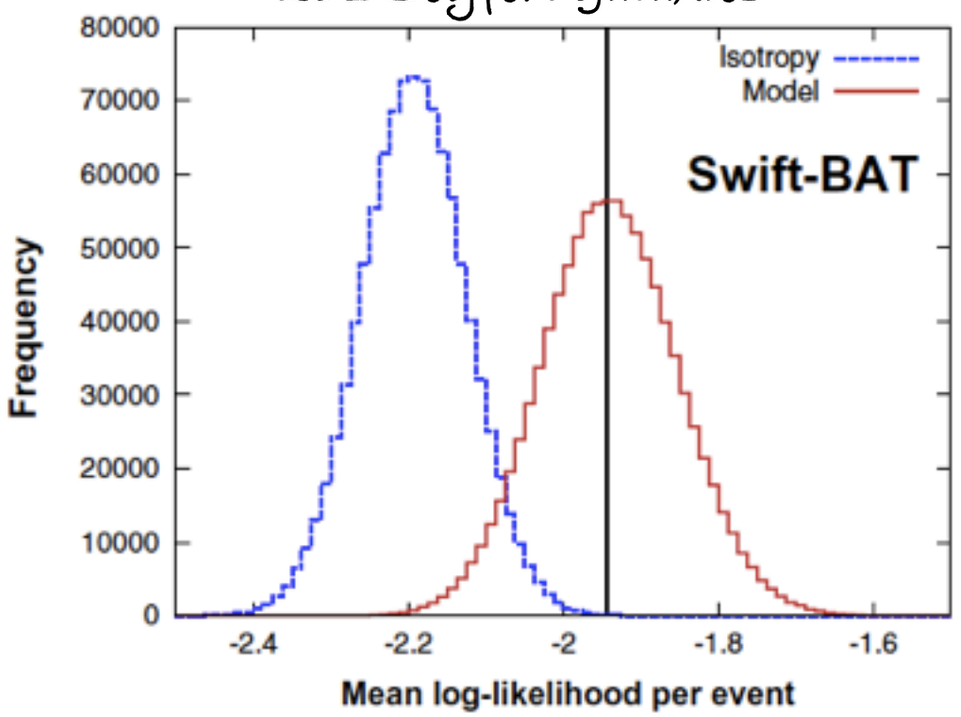




2MRS vol selected
1940 brightest from
2MASS cat.



Swift-BAT
uniform, hard X-ray
261 Seyfert galaxies



AGN correlation (as defined in Science paper) has weakened.

New data do not strengthen the case for anisotropy,
but they do not contradict the earlier result either.

Other catalogues / analyses confirm anisotropy and
the correlation of CRs with "nearby matter"

more data needed to identify actual sources...

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

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

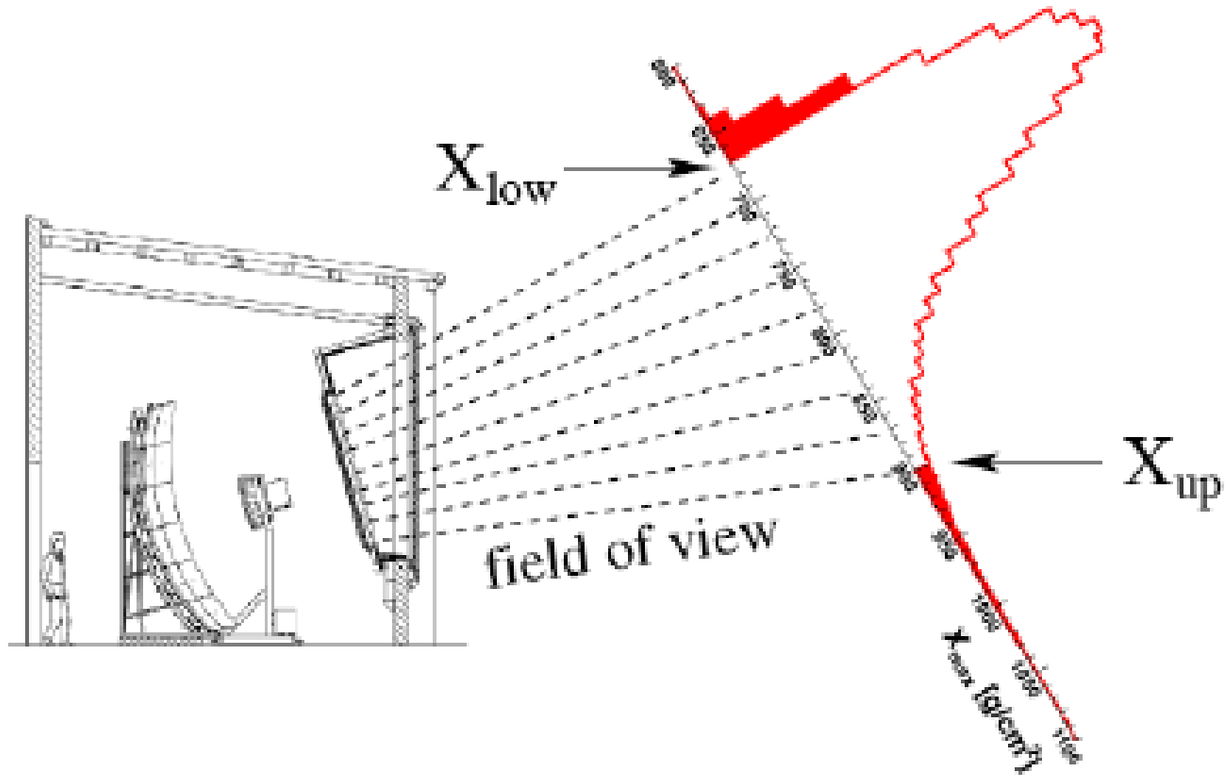
p ... He ... O ... Fe

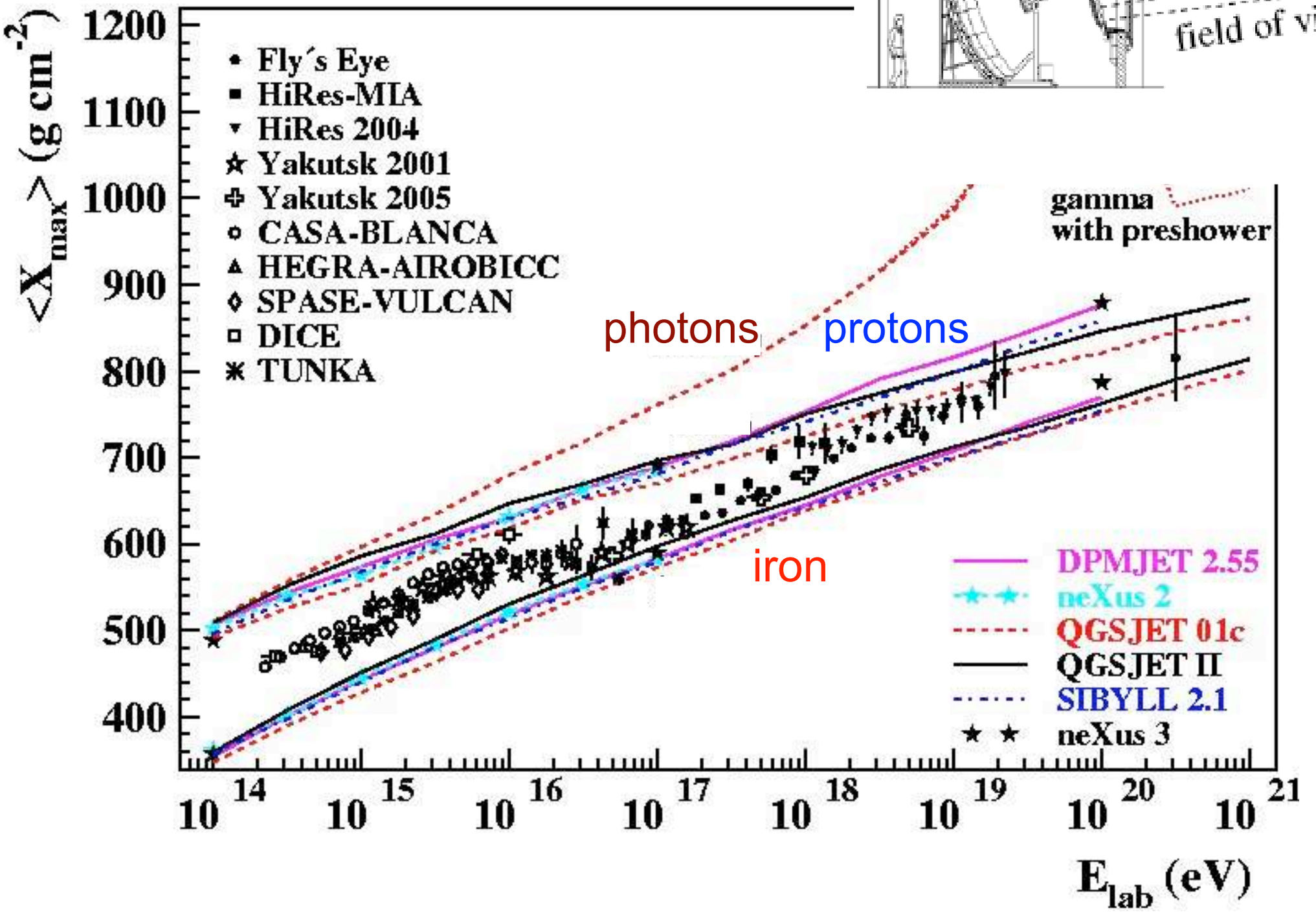
Photons

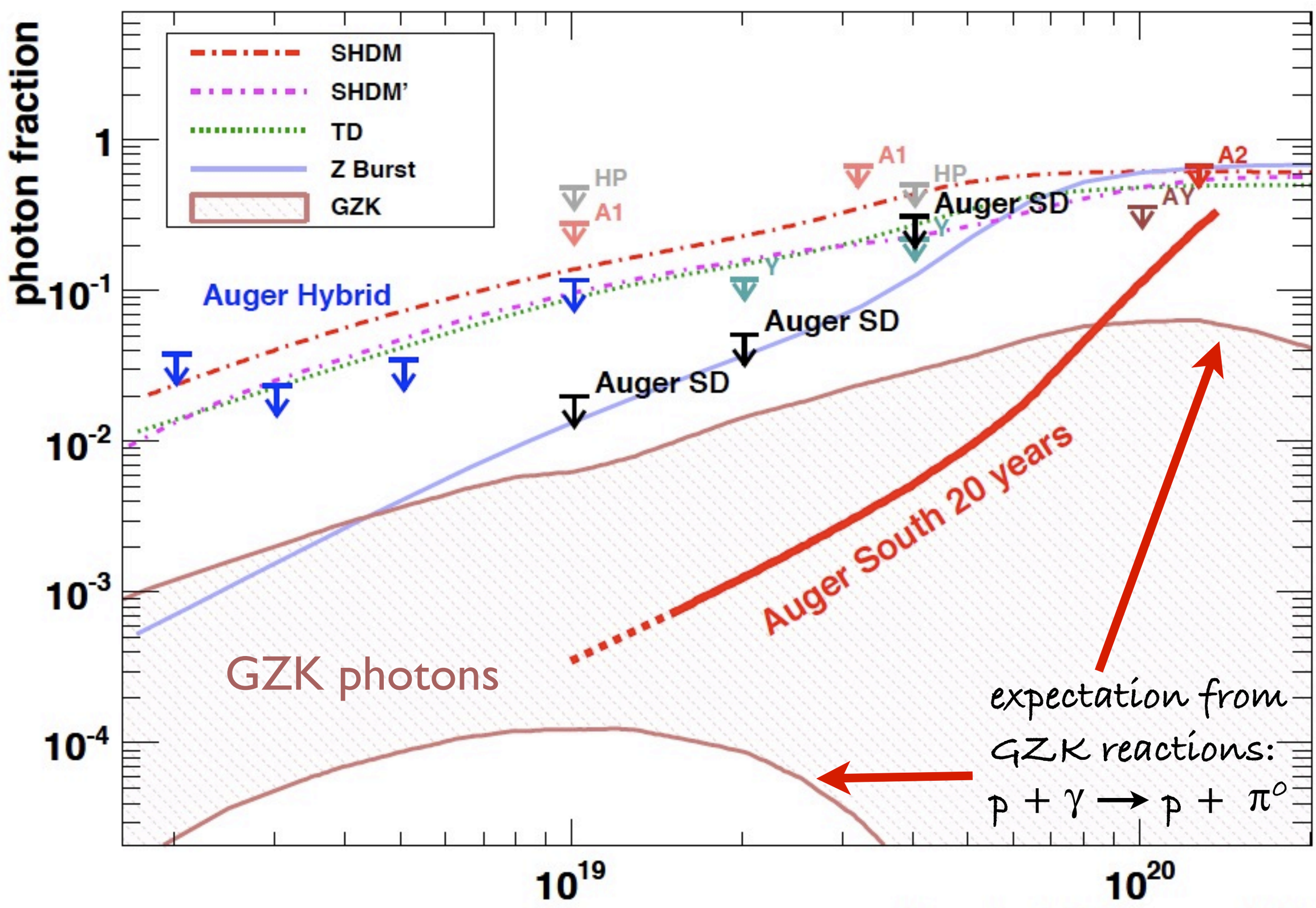
FD: measure X_{max}

photons maximise deeper than nuclei

protons maximise deeper than iron







most top-down models are ruled out,
limits improve with statistics.

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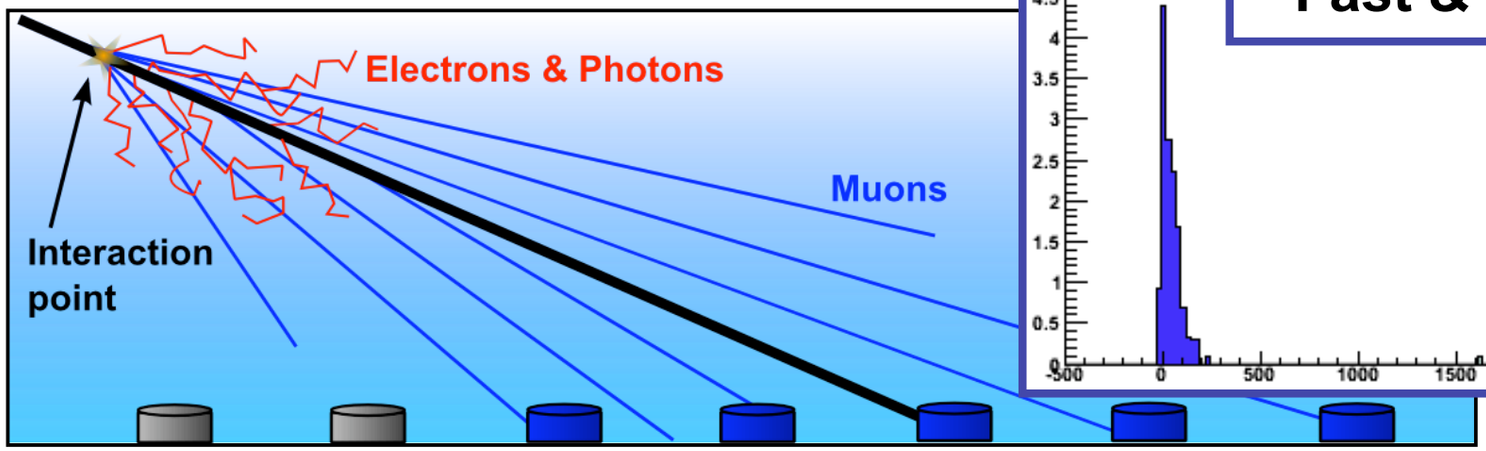
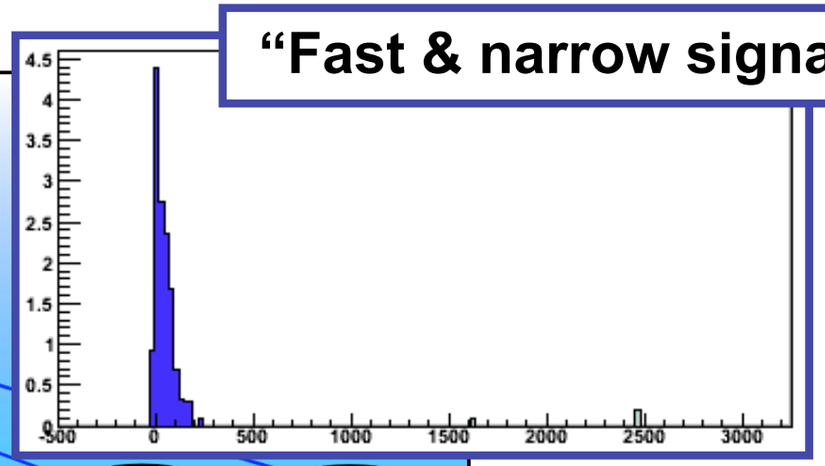
Neutrino detection with Auger

nearly horizontal showers : atmosphere » 1000 g/cm²

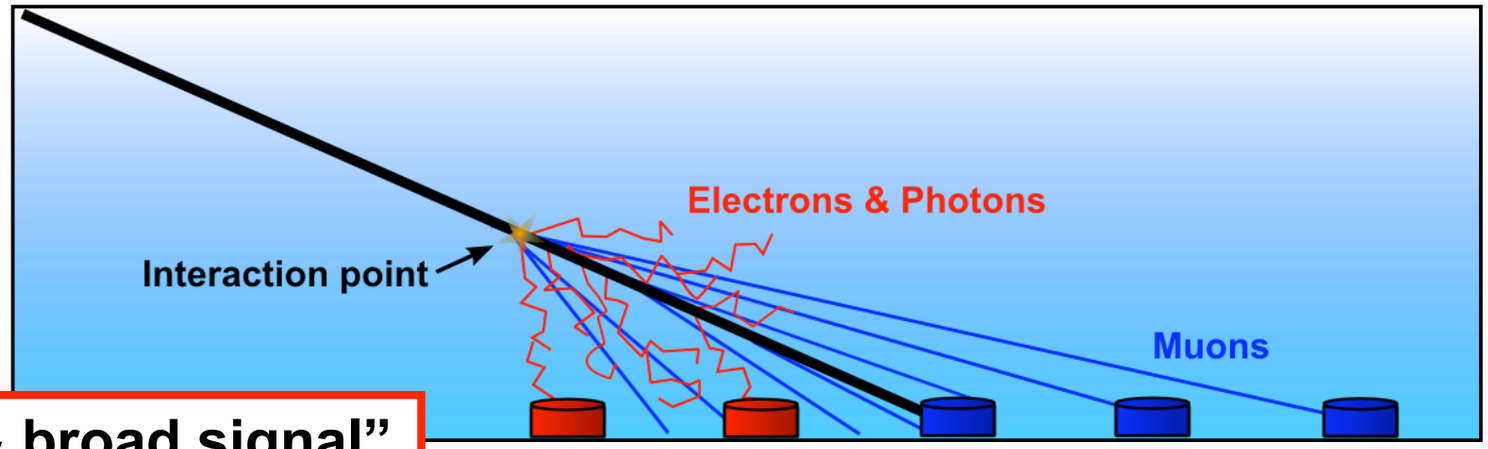
no el.mag., only muons
plane shower front,
sharp arrival time dist.



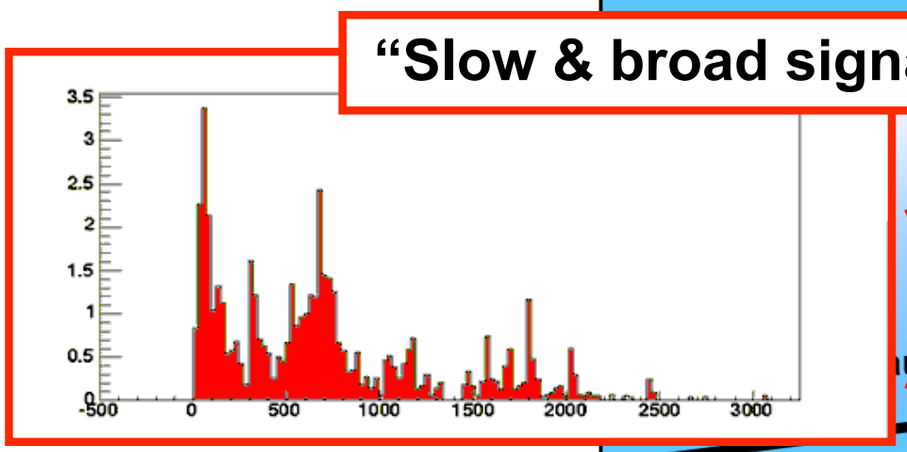


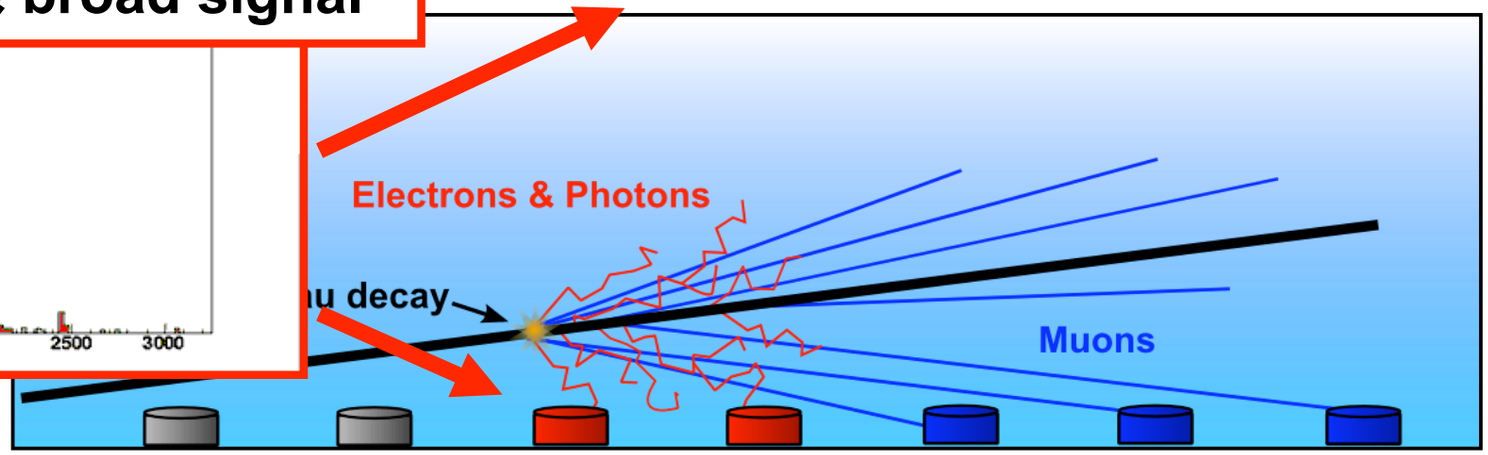
p … Fe

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



ν





ν

PRL 100 (2008) 211101

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

τ neutrinos have distinctive signatures:

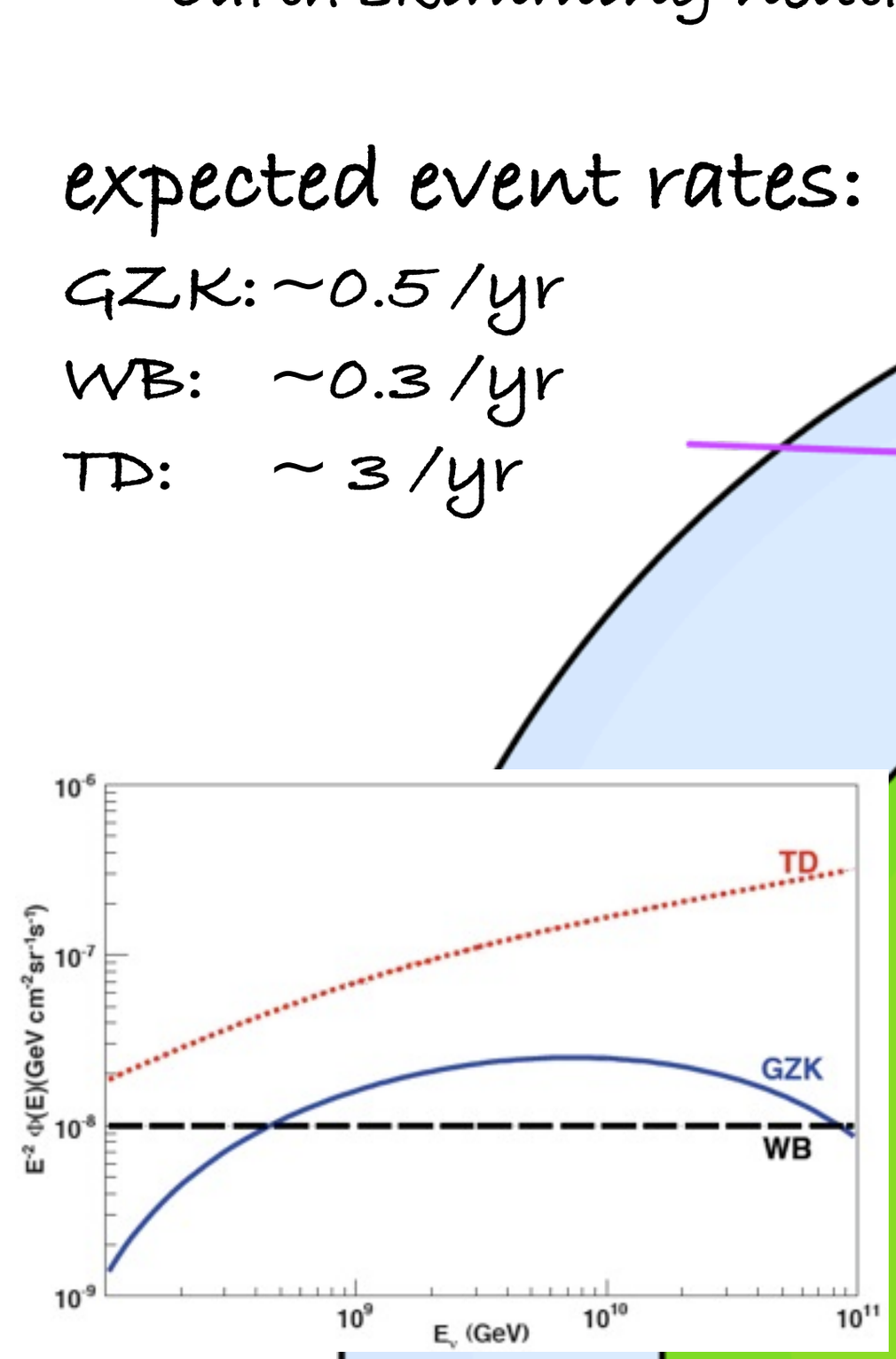
- enhanced rate from Andes
- Earth skimming neutrinos

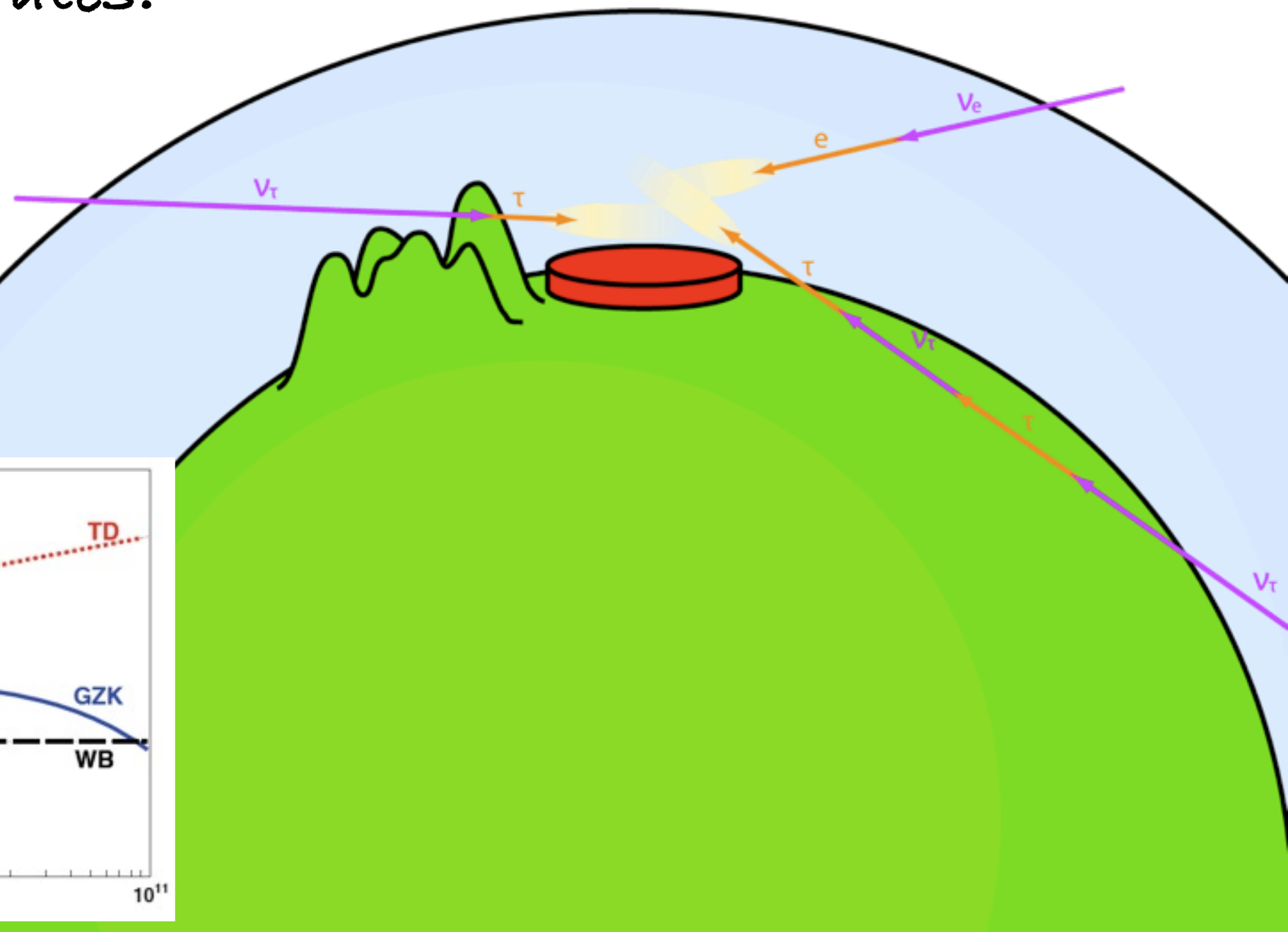
expected event rates:

GZK: ~0.5 /yr

WB: ~0.3 /yr

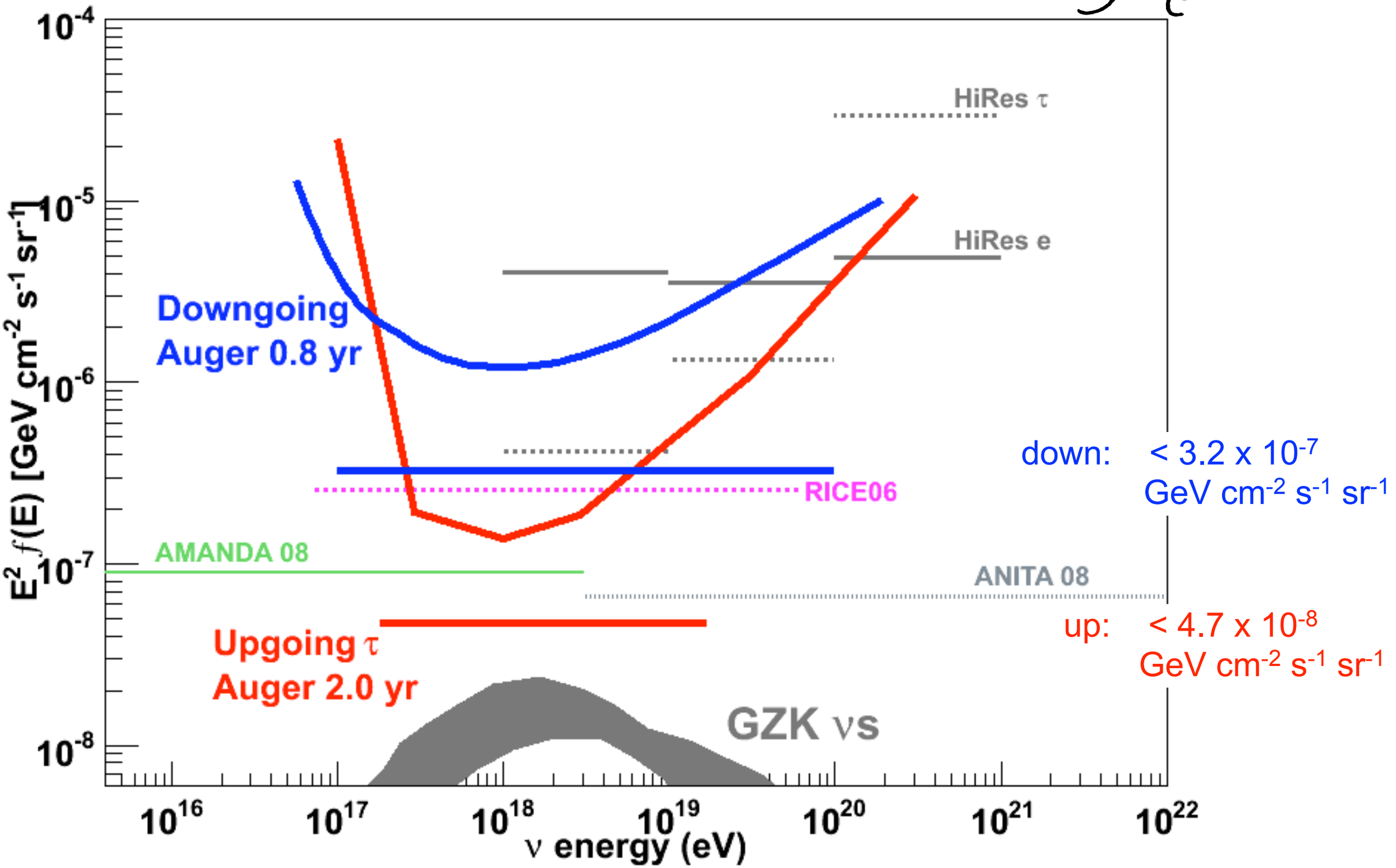
TD: ~3 /yr





so far: no neutrino candidates found

limits: 90% c.l.



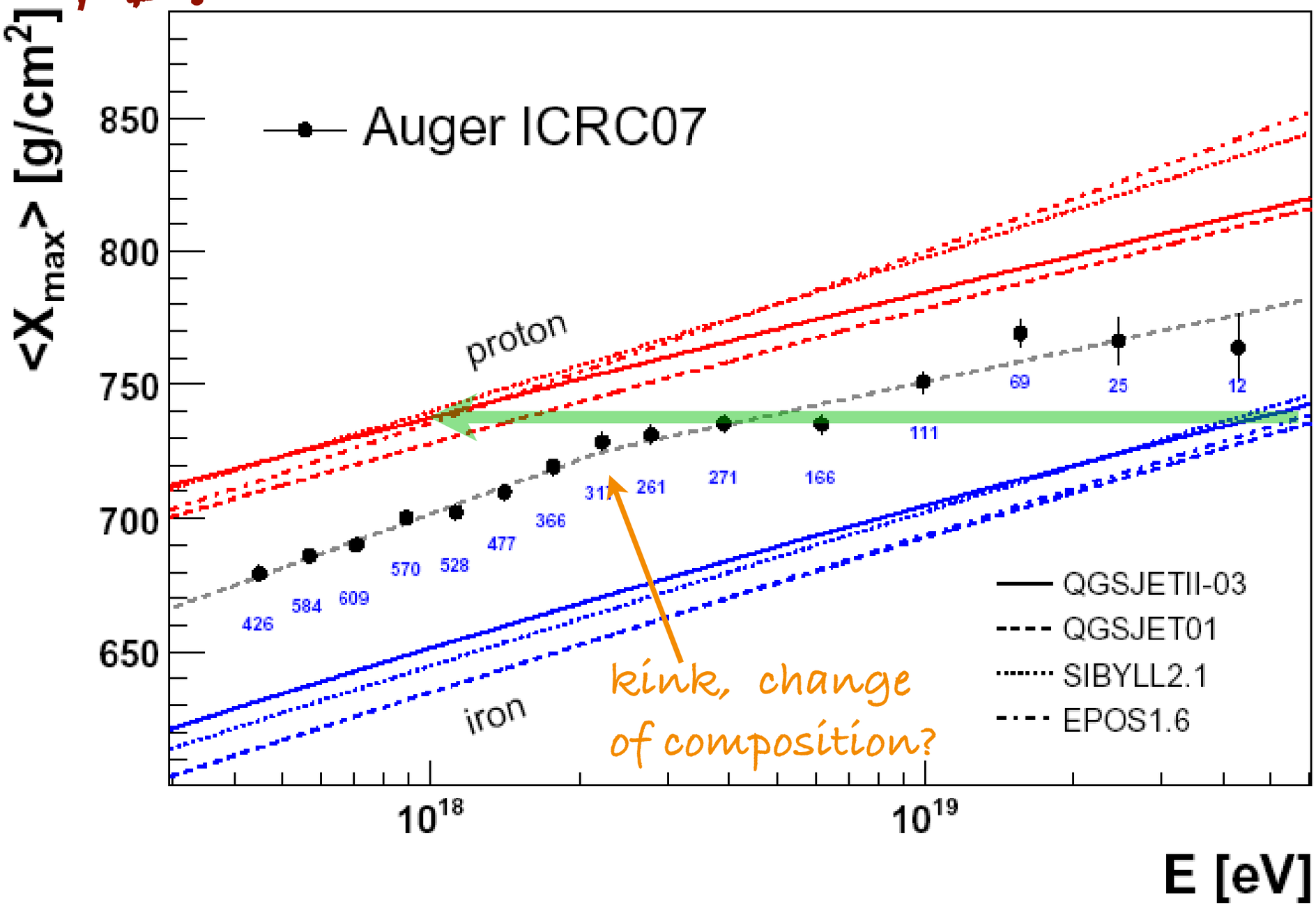
down: $< 3.2 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}

up: $< 4.7 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

CR Nuclei: Hadronic composition

difficult !
results strongly model dependent

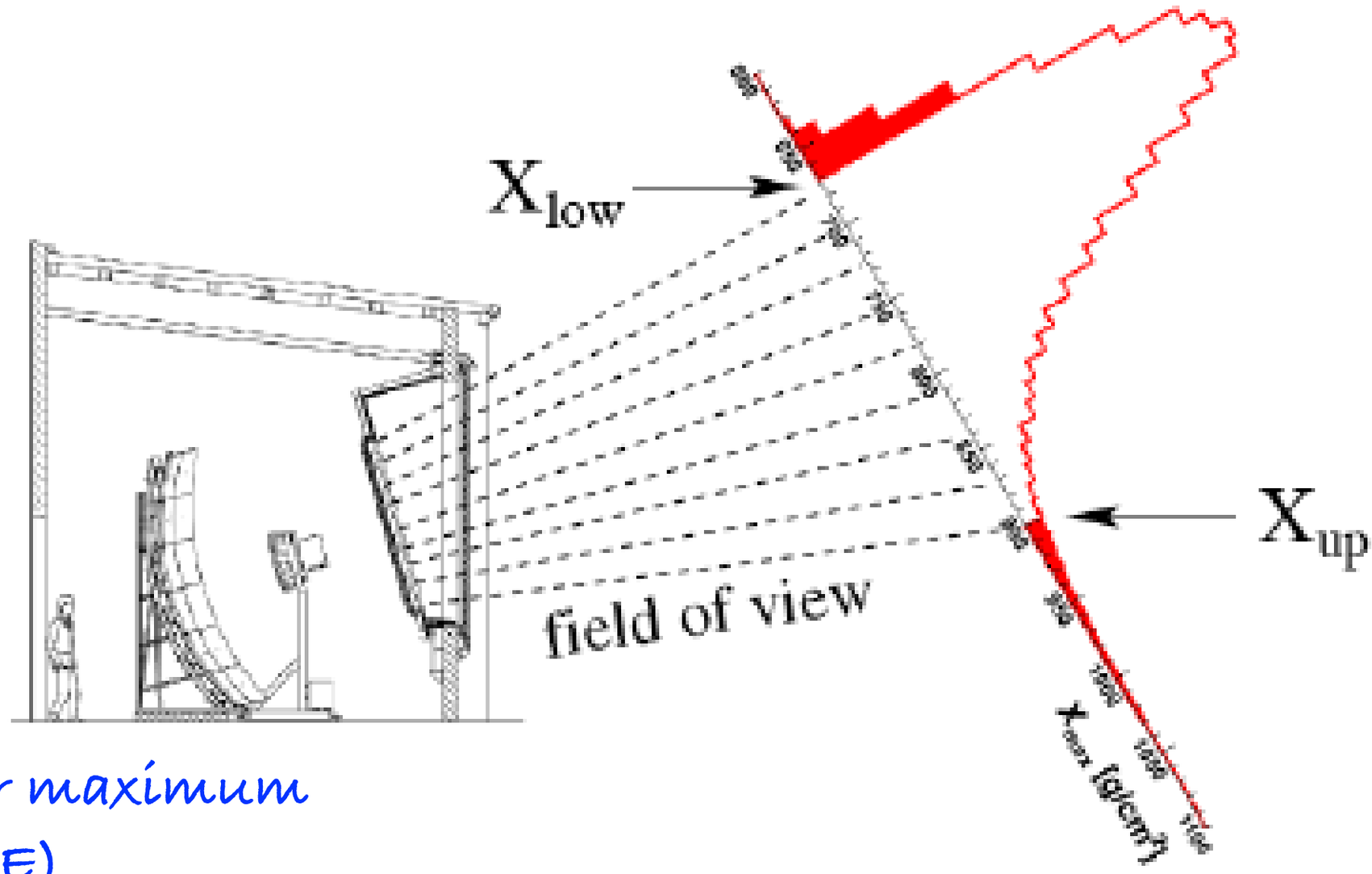
FD:



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

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

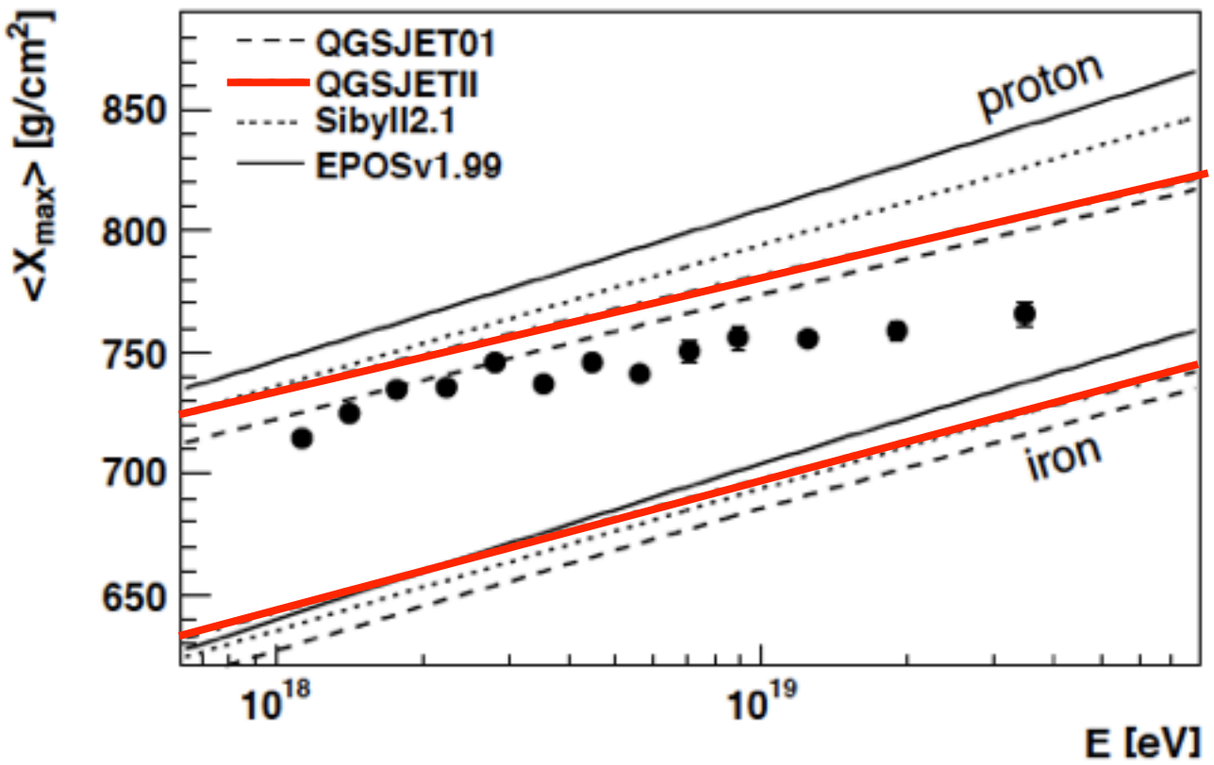
X_{max}(p) fluctuates much more than X_{max}(Fe)

RMS(X_{max}(p)) ≈ 60 g/cm² RMS(X_{max}(Fe)) ≈ 20 g/cm²

largely due to σ_{inel} of primary particle.

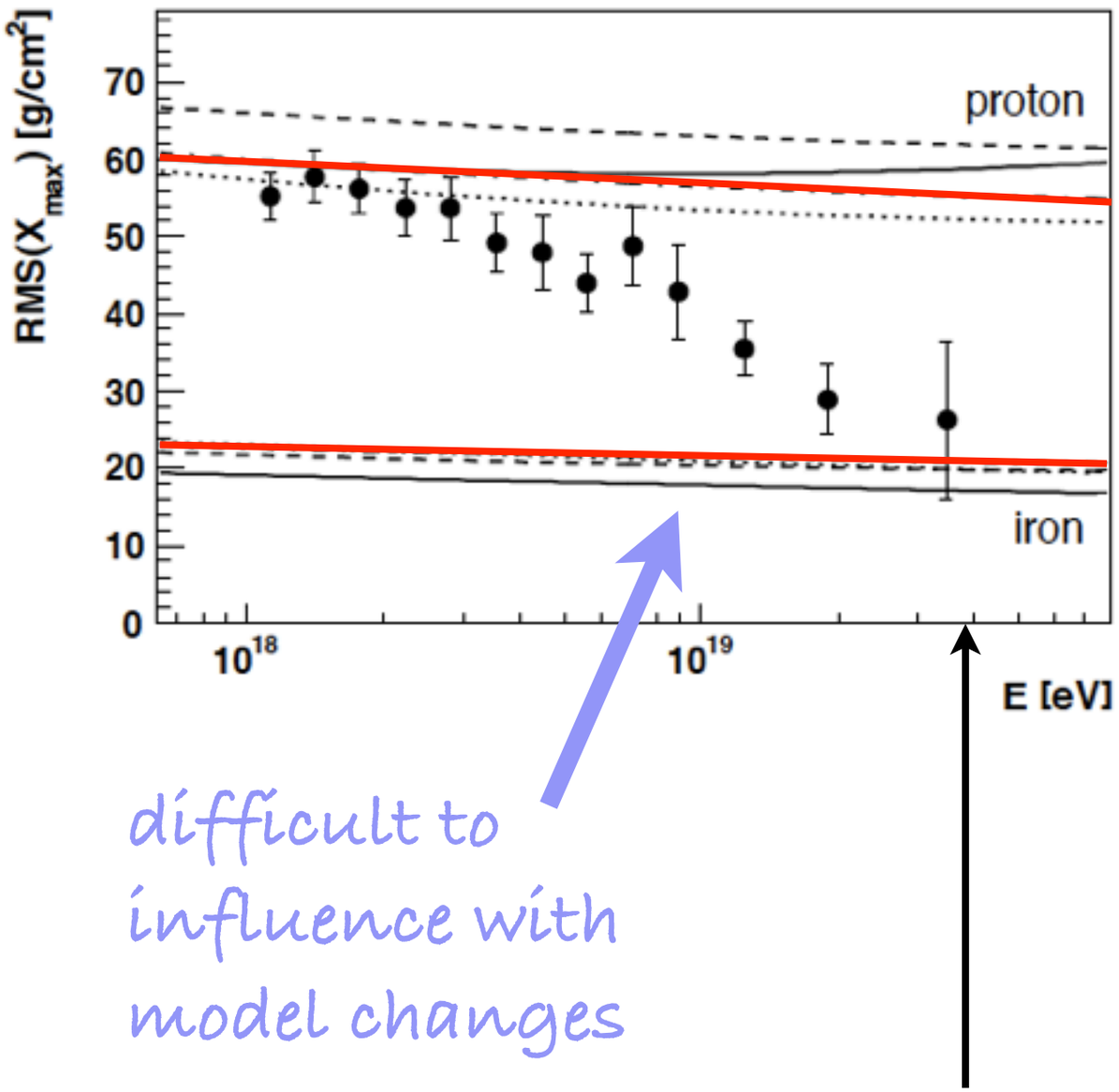
1 Fe ≈ 56 protons of $E_0/56$

X_{max}



model dependent interpretation

RMS(X_{max})

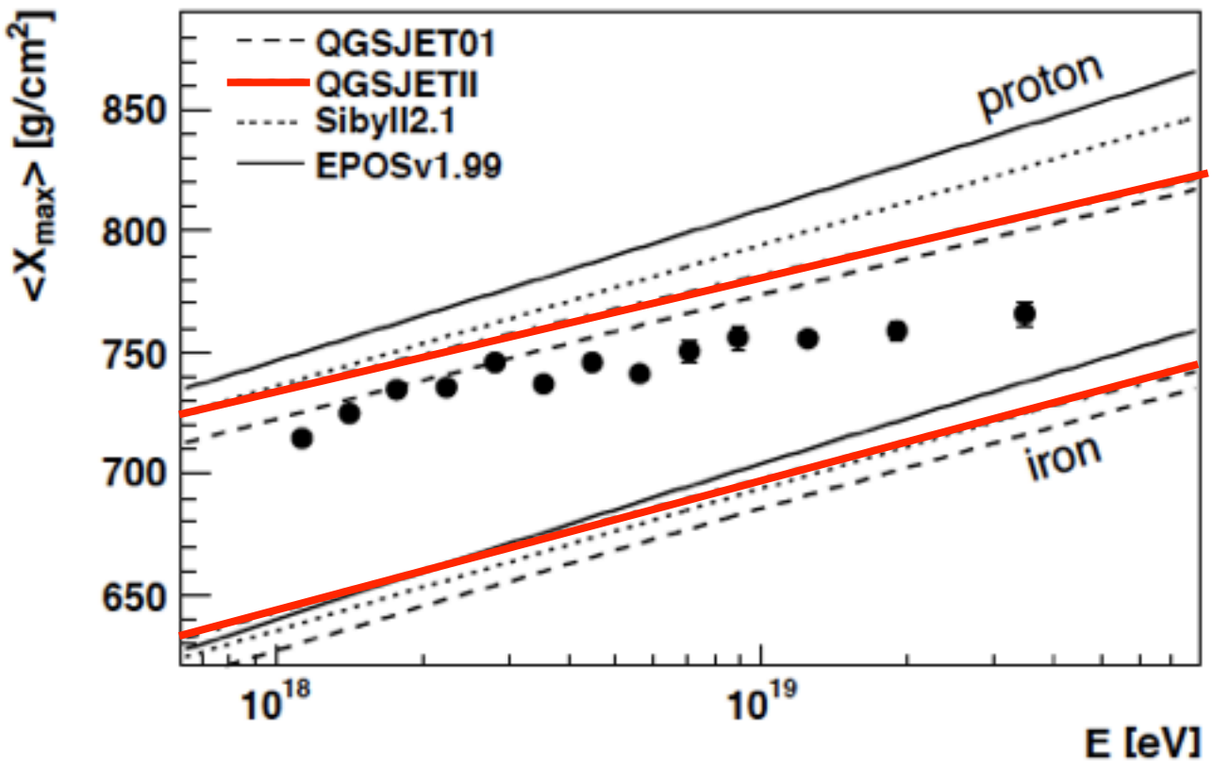


difficult to influence with model changes

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

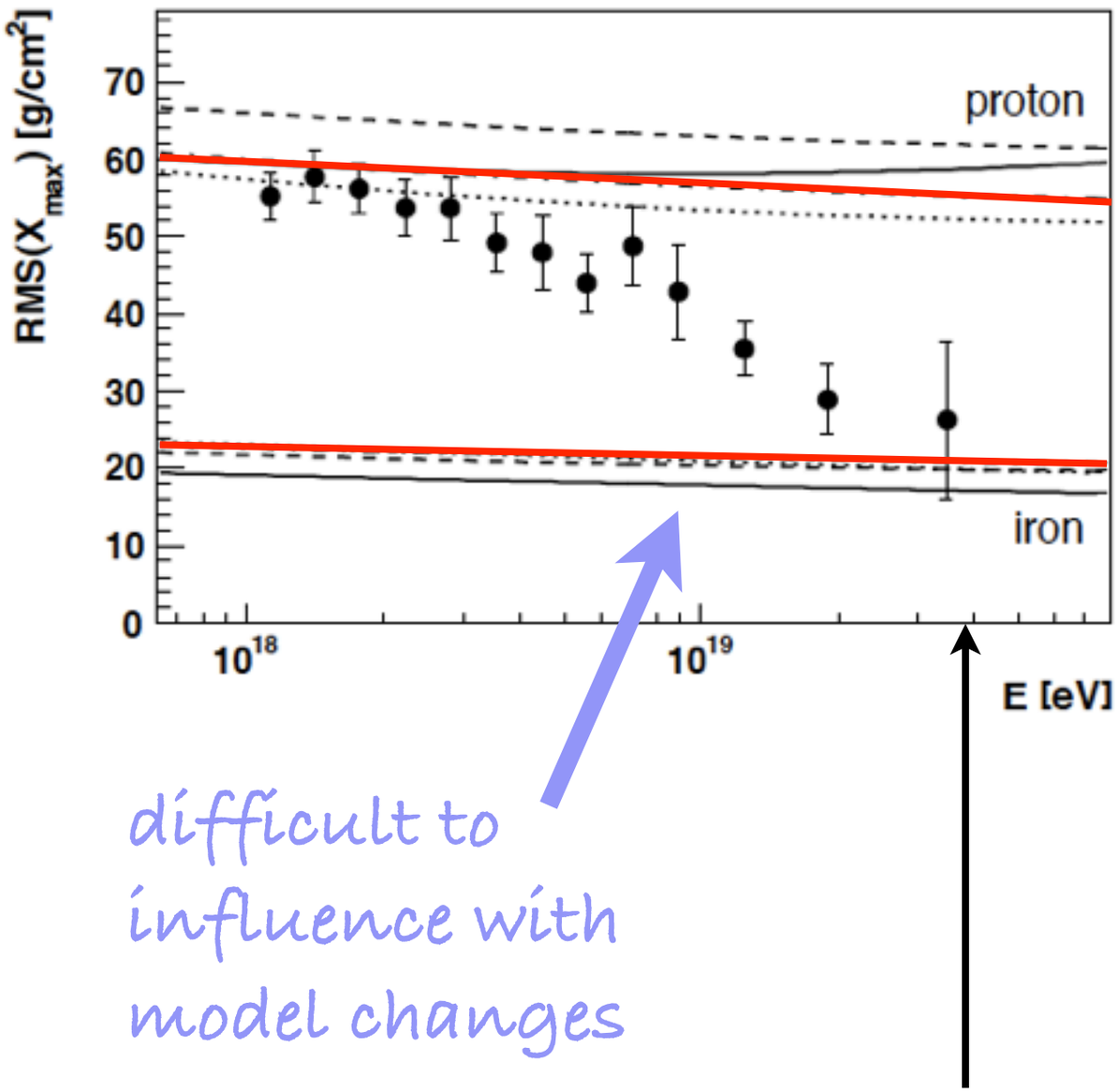
composition turns heavier ?

X_{max}



model dependent interpretation

RMS(X_{max})



difficult to influence with model changes

composition **turns heavier ?**

Hint 3

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

Composition mis-match ?

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

→ p dominated ($E > 6 \times 10^{19}$ eV)

Composition: X_{max}, $t_{1/2}$, ...

→ mixed/heavy ($E < 4 \times 10^{19}$ eV)

strongly model dependent

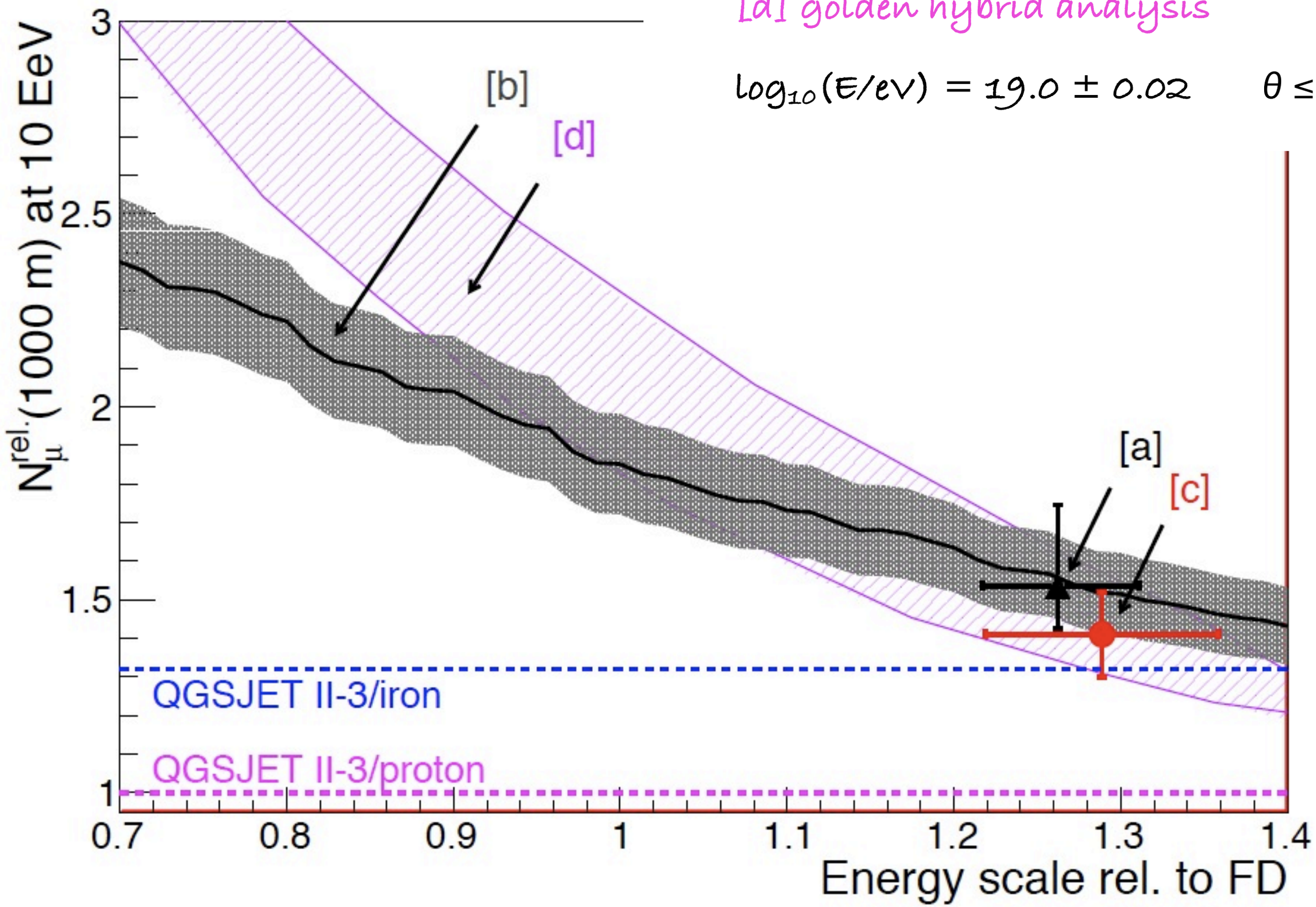
Need hadronic interaction models to be modified
to make p-sims look more like data ???

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

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

[a] universality method
[b] jump method
[c] smoothing method
[d] golden hybrid analysis

$\log_{10}(E/eV) = 19.0 \pm 0.02$ $\theta \leq 50°$.



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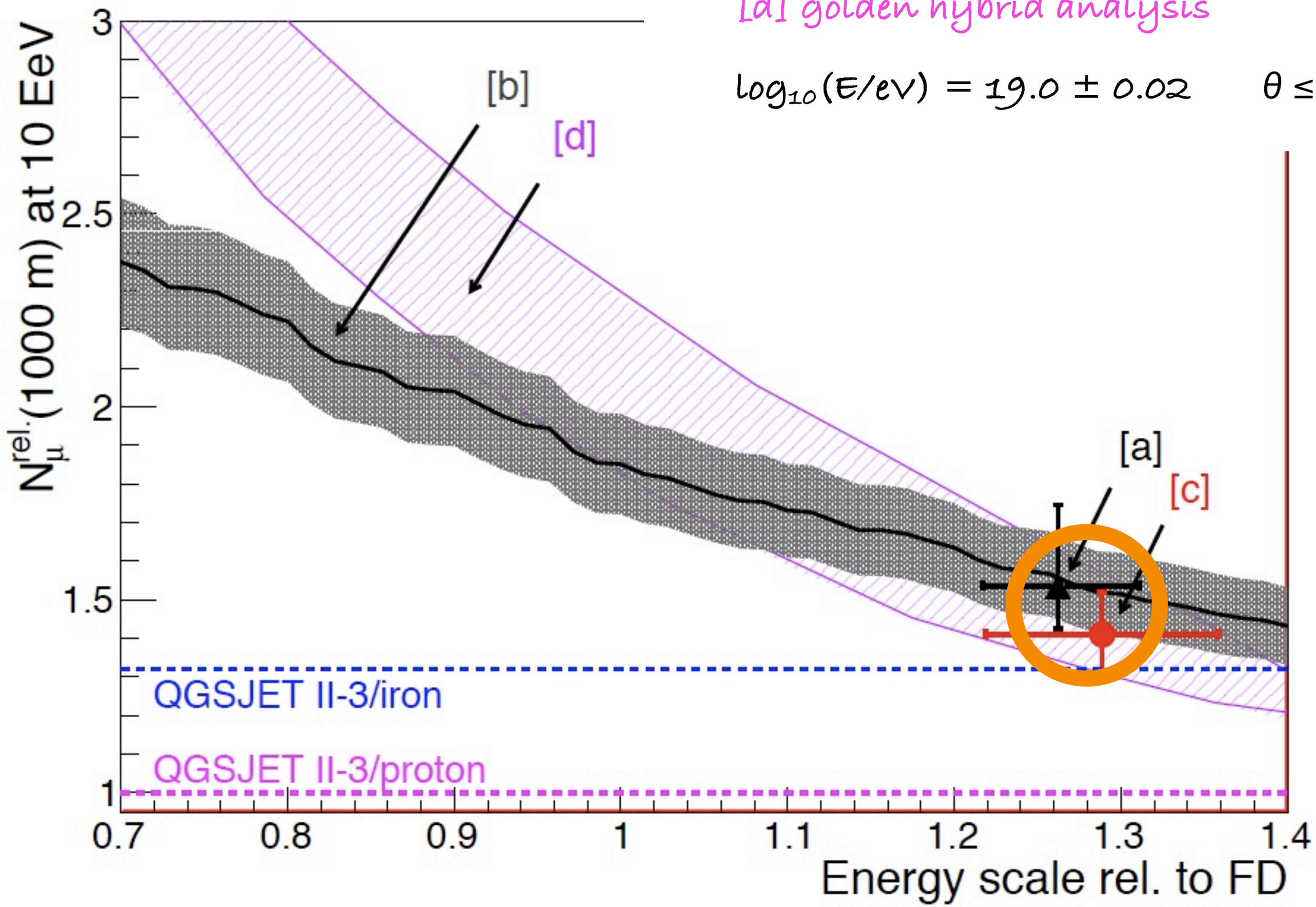


Consistent findings:

Air shower models need modifications:

Muons : about 50% too low,

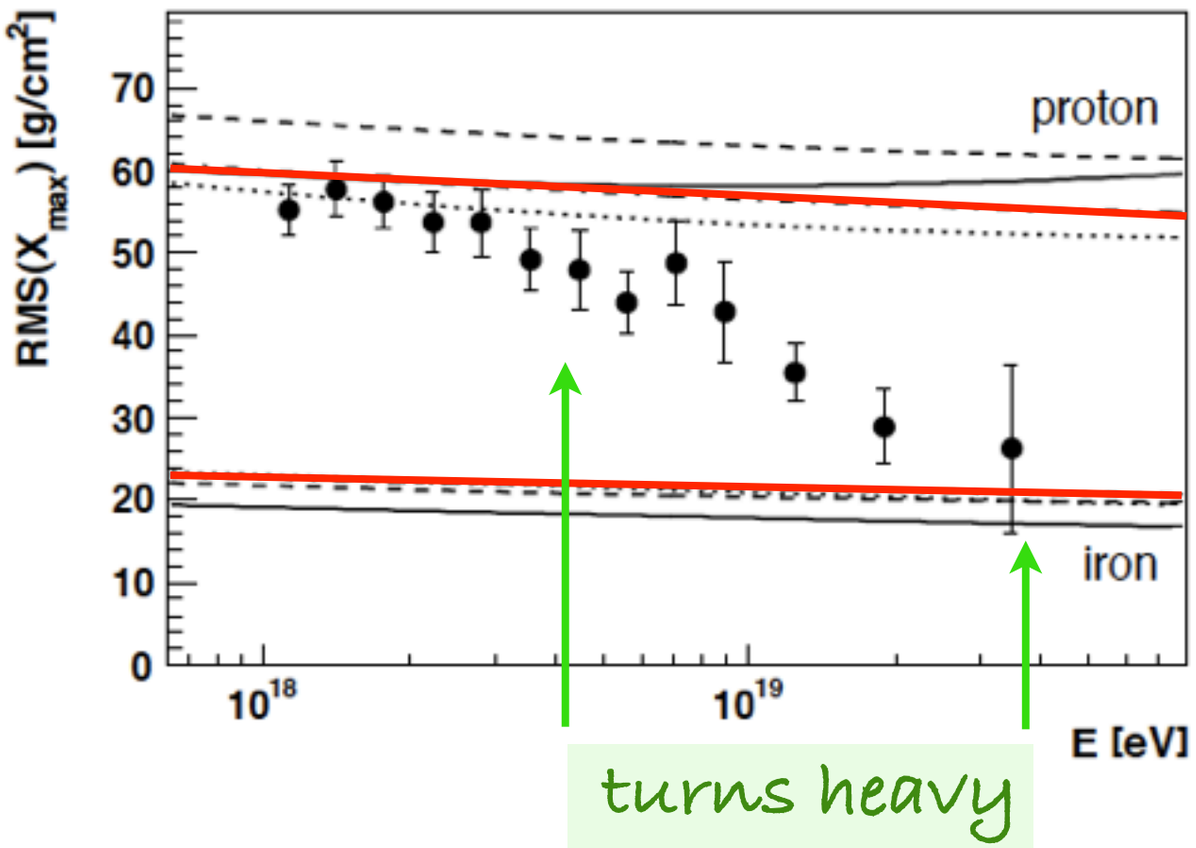
hadronic model ???

Energy reconstruction: about 30% too low.

fluorescence yield ???

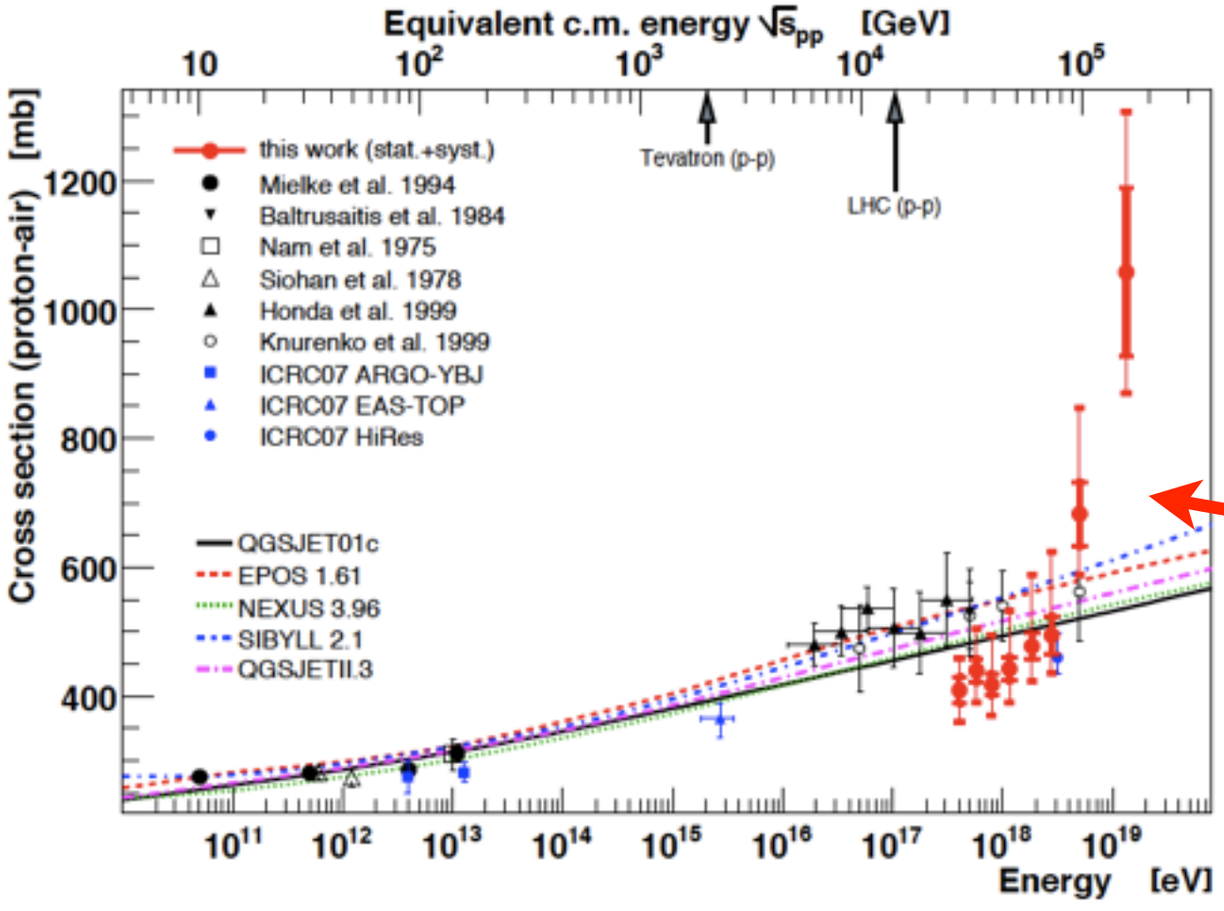
EPOS: a new model, with enhanced baryon production makes about 50% more muons.....

RMS(X_{max})



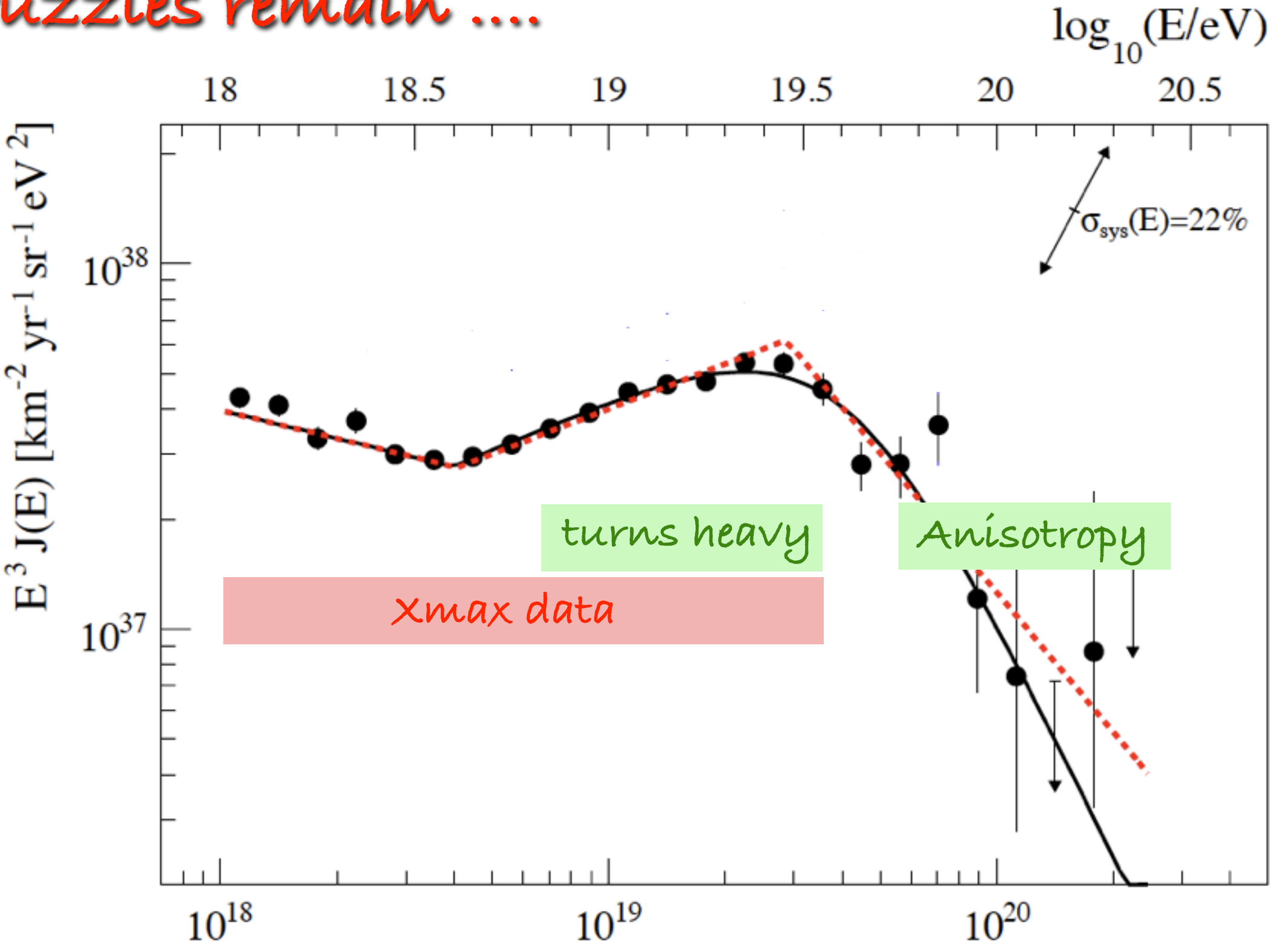
turns heavy

But whatever we do to models (within limits), data do not fit to primary protons.



p cross-section would have to rise like this to explain the RMS(X_{max}) data.

Puzzles remain ....



Summary:

Auger South is taking high-quality data at $>10^{18}$ eV.

Spectrum: ankle and steepening seen at $\approx 4 \times 10^{18}$ and $\approx 2.9 \times 10^{19}$ eV
with model-independent measurement and analysis

But what is the interpretation?

cut-off: likely GZK cut-off, hint that UHECRs are protons?
ankle: transition galactic to extra-galactic ?

Arrival directions:

CR are extragalactic
Correlation with nearby matter for E > 55 EeV,
hint that UHECR are protons?

Mass composition:

upper limits on photons and neutrinos,
reduced fluctuations at $\approx 2 \times 10^{19}$ eV
hint at mixed / heavy composition?

with current models, but...

Particle Physics (at $>10^{19}$ eV):

Hadronic interaction models need adaption ...
More muons & different energy scale needed
Auger and collider data constrain models

Auger takes reliable experimental data on UHECRs.
By far best understood experiment of its kind.

Intriguing findings ...
but interpretation of data is not yet clear.

Extensions (infill, HEAT, Amiga) will help with composition studies.

Many years of data taking to come.