Ultra High Energy Cosmic Rays & Current Results from the ...

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The most energetic 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, ...)

Cosmic rays produce Photons and Neutrinos

Auger

"What is the origin of the
Ultra High Energy Cosmic Rays ?"
(UHECRs: > 10^{19} eV)

Measure them with unprecedented statistics and quality.

Auger: unprecedented statistics and precision

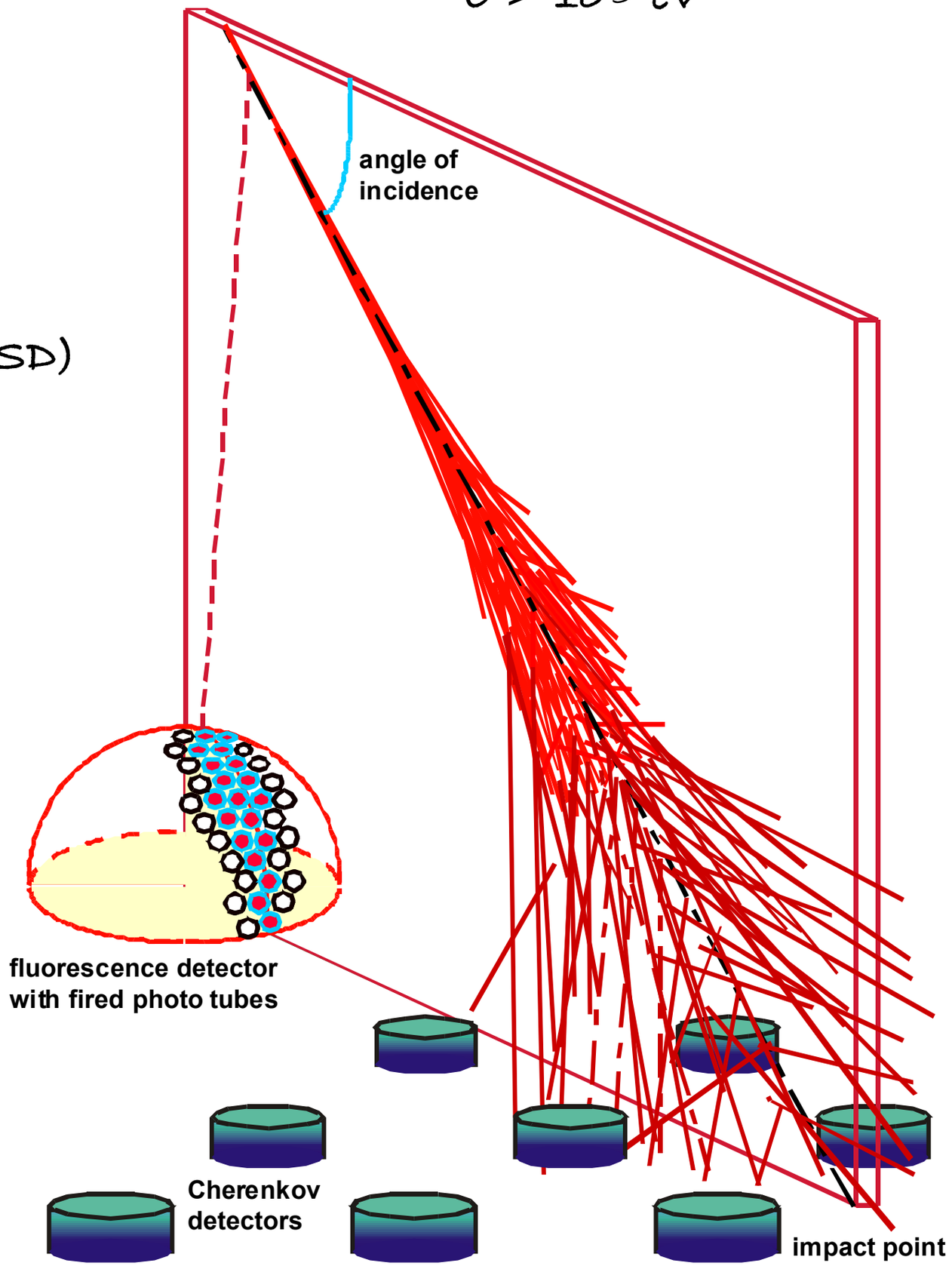
≈ 3000 evts/yr with $E > 10^{19}$ eV

Hybrid Detector:

Array of 1600 water Cherenkov detectors (SD)
covering 3000 km²
duty cycle: 100%

Fluorescence telescopes (FD)
24 FDs (30°x30° each)
duty cycle: 10%

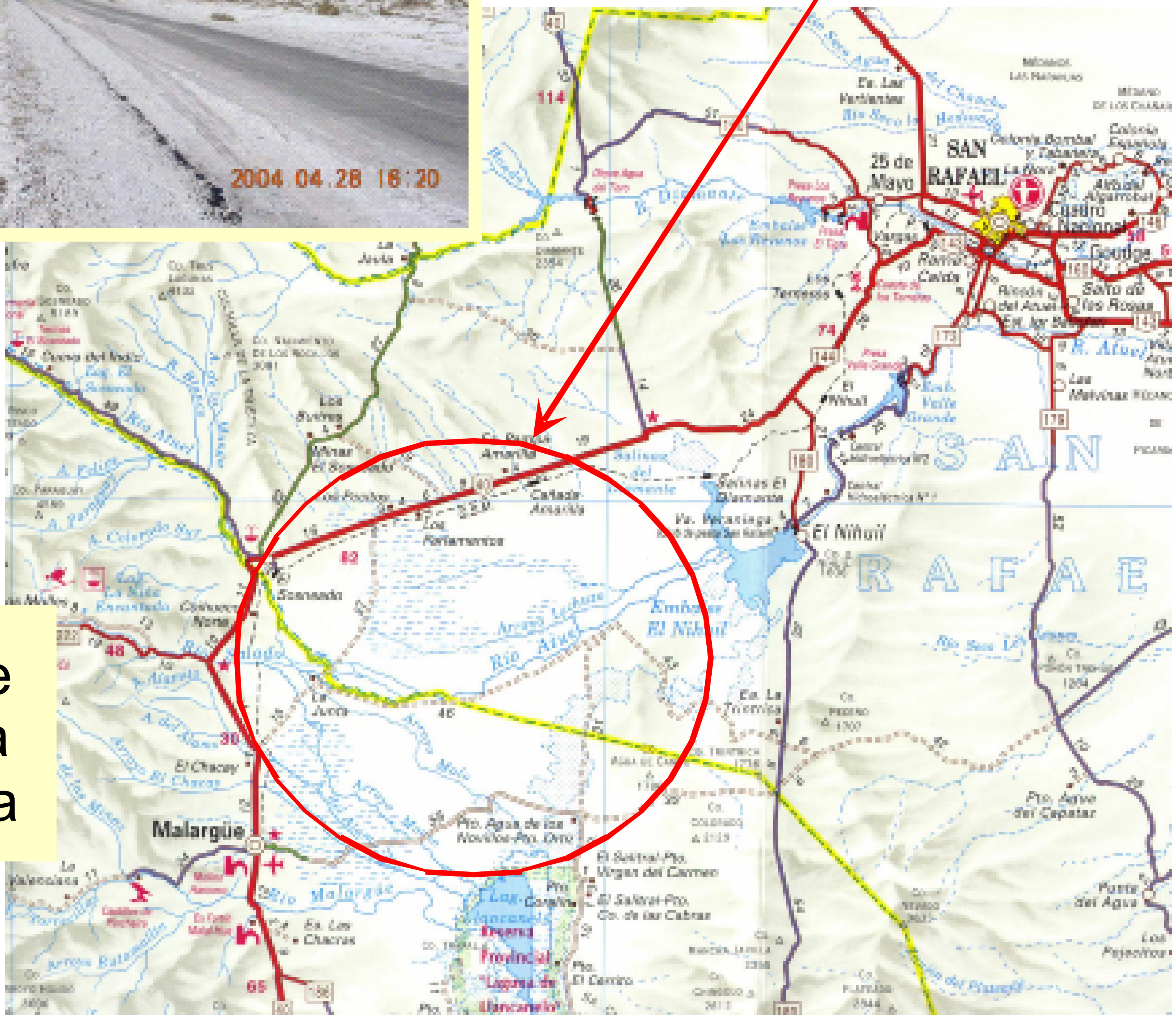
Better geometric reconstruction,
cross-calibration, control of systematics.



Shape of the spectrum? Cut-off?
Anisotropy in arrival directions?
Mass composition ?

Auger South

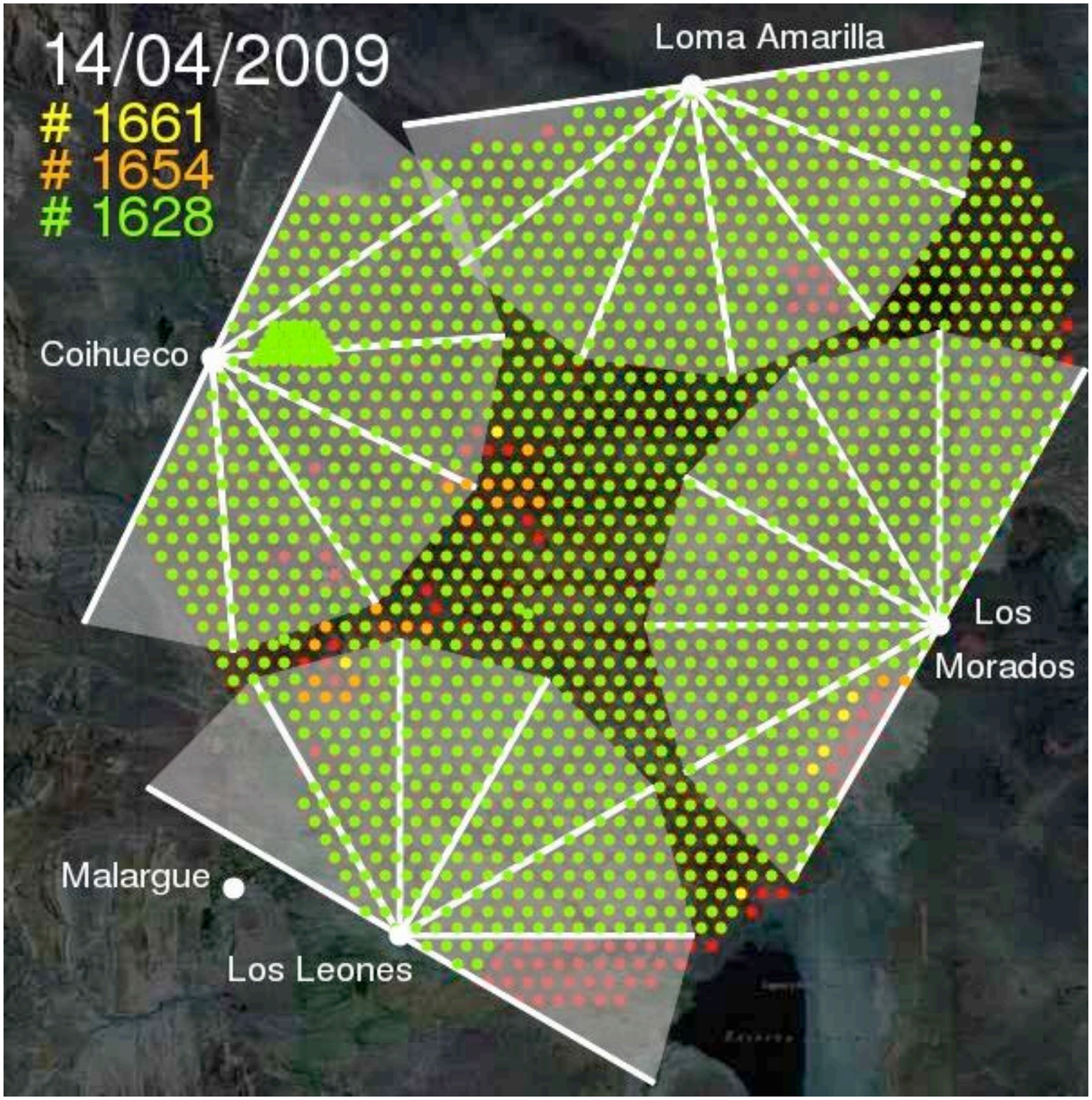
(1400 m a.s.l., 35.2° S, 69.2° W)



Malargüe
Mendoza
Argentina

Auger array (almost) complete:

planned
tank deployed
with water
send data



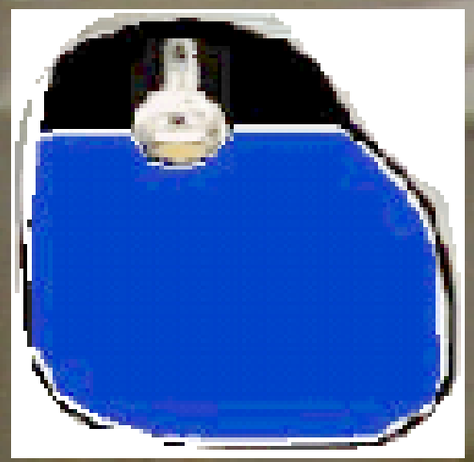
Inauguration: 14-15 Nov 2008

Communications antenna

GPS antenna

Electronics enclosure

Solar Panels



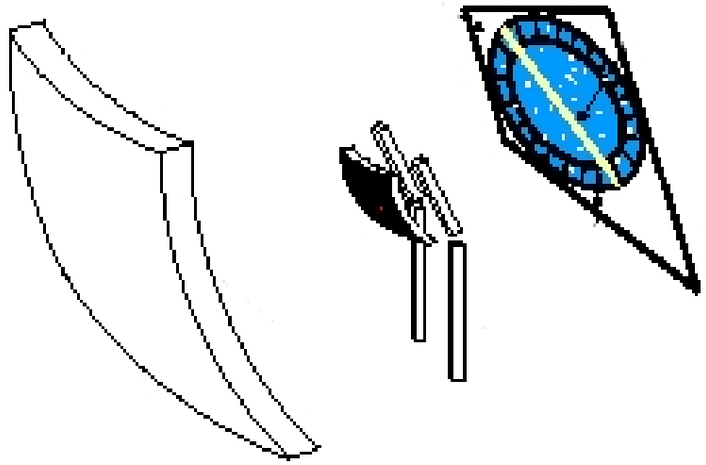
3 x 9" PMTs

Plastic tank
12 m^3 water

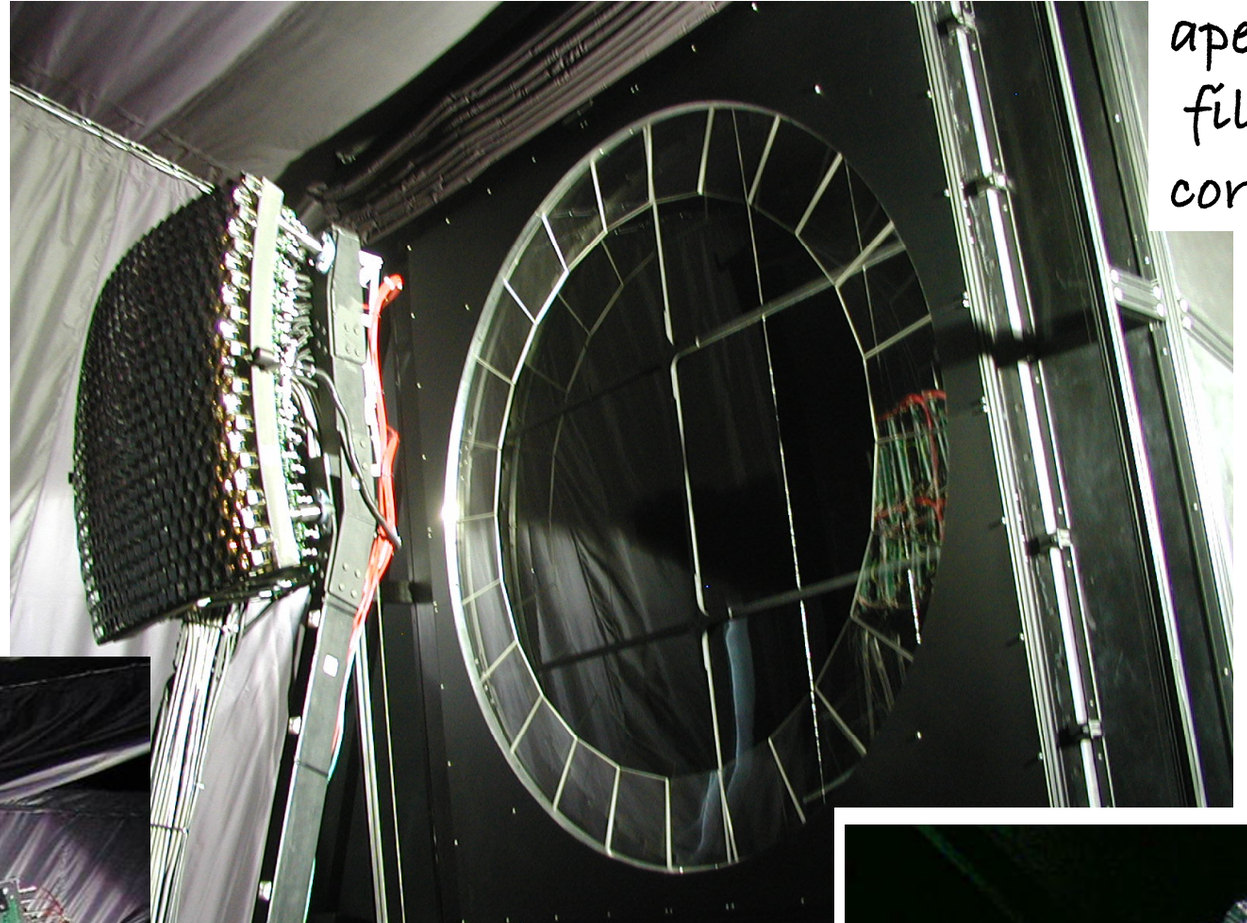
Battery box

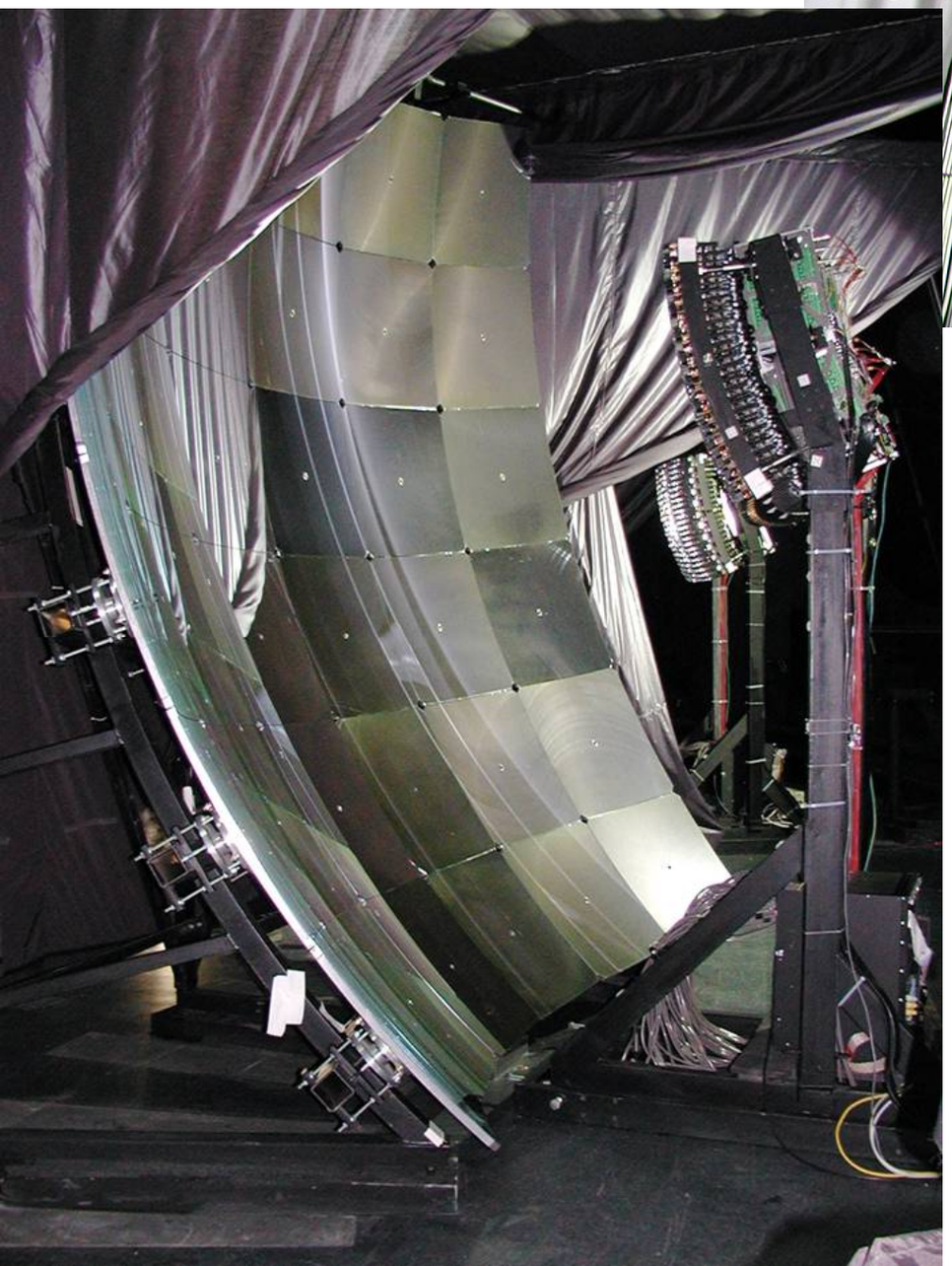
1600 water Cherenkov detectors over 3000 km^2

FD telescope:



aperture with shutter, filter and Schmidt corrector lenses

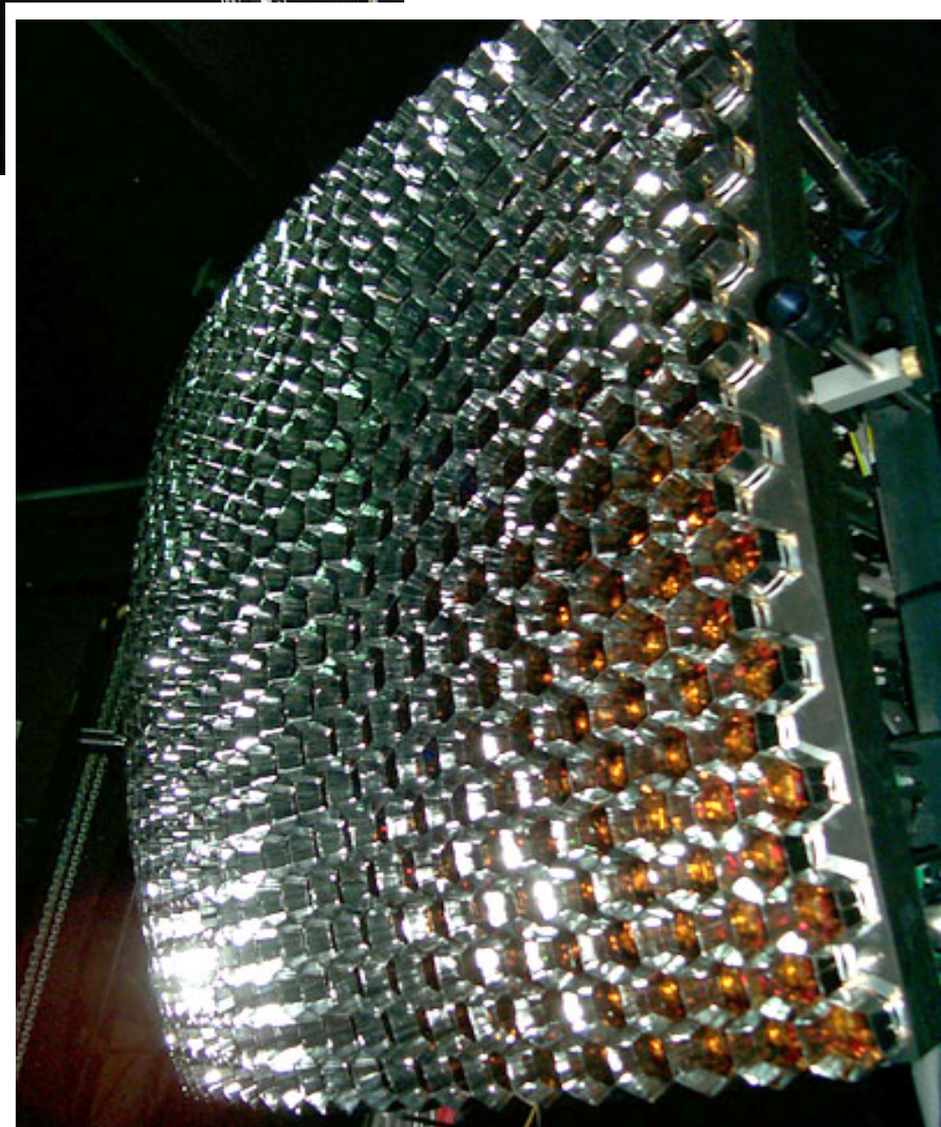


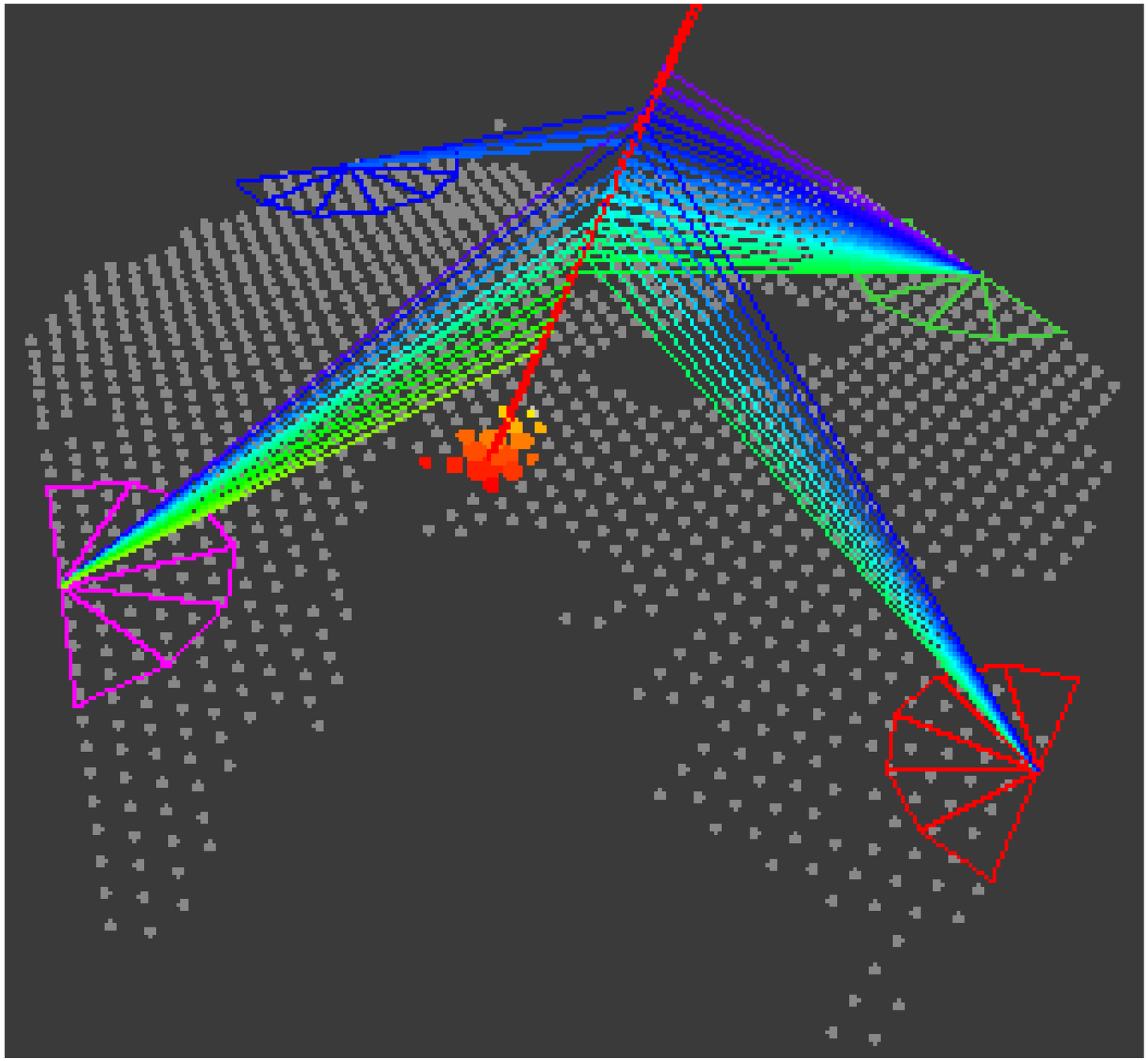


11 m² mirror (Aluminium)

440 PMT camera

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





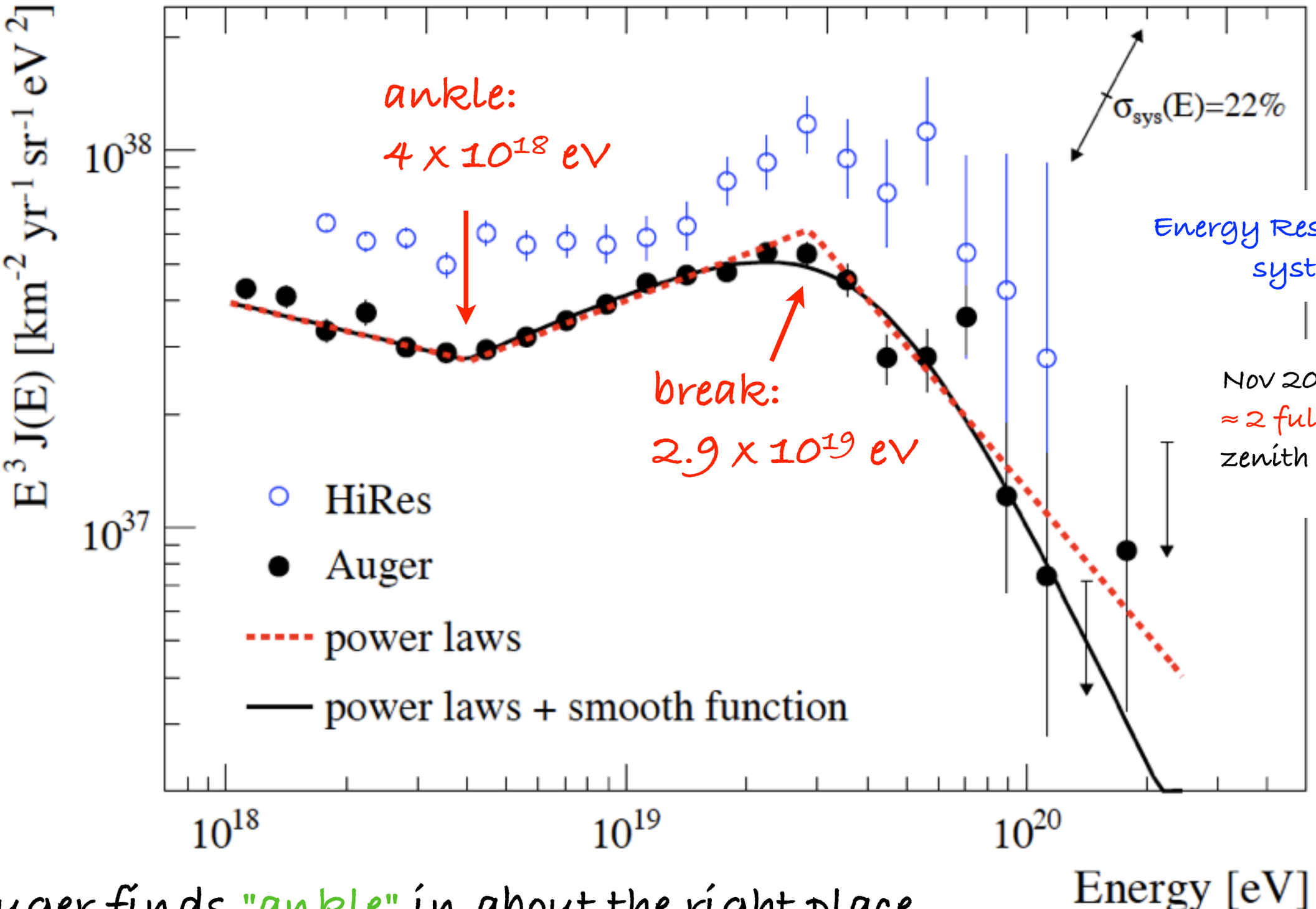
20 May '07: 1st 4-fold event:
seen by the array & all 4 FDs
$E \sim 10^{19}$ eV

SD only:
full event statistics

Hybrid (i.e. FD + SD):
great event quality for
≈ 10% of data

Energy Spectrum : hybrid + SD

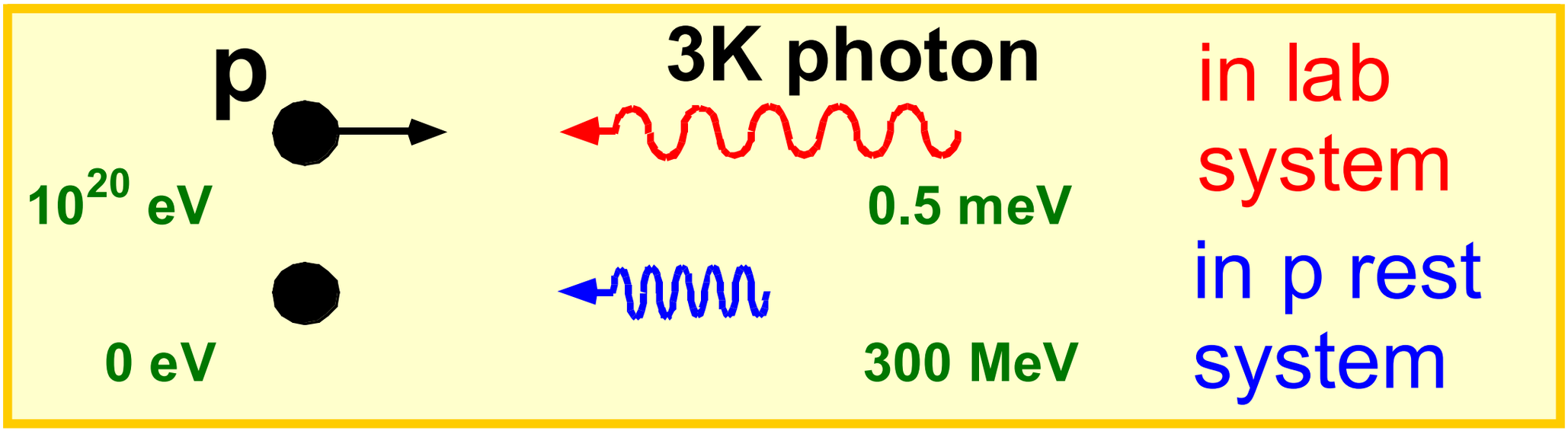
$$\text{Flux} = \frac{N_{evts(>E)}}{t \cdot A \cdot \Omega}$$



Auger finds "ankle" in about the right place and a spectral steepening at $E \approx 3 \times 10^{19}$ eV.

GZK Cut-Off

Greisen Zatsepin Kuzmin



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

$\longrightarrow n + \pi^+$ → ν

$^{56}Fe + \gamma \longrightarrow {}^{55}Fe + n$ 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 $\gamma \approx 10^{11}$!

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 in flux at $\approx$ few x 10^{19} eV

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

Alternatives:

Heavier nuclei ? would also be absorbed, but require some fine tuning

maximum energy of accelerator ?

effect of a local source ?

Is ankle the transition point between galactic and extragalactic CRs ?

... need more info on composition ...

Composition: Particle Type ?

Showers look like showers from p and nuclei

neutrinos ?

penetrative, showers could start anywhere

photons ?

shower shape is different from that of nuclei
(electromagnetic interaction is well known; QED)

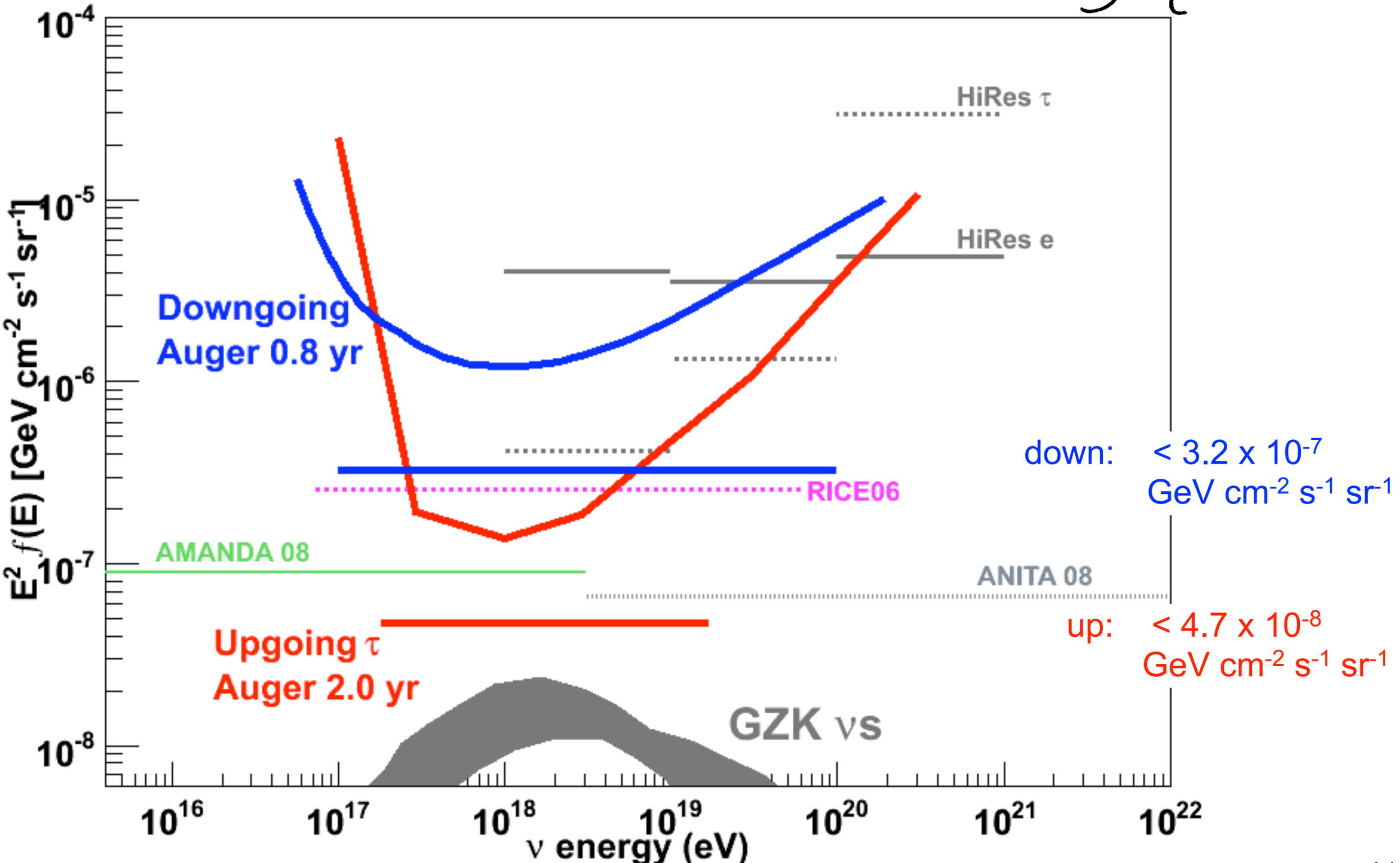
separate p, He, O, Fe ?

difficult,
indications that composition turns heavier
between 2×10^{18} and 2×10^{19} eV

see talk by
Ronald Bruijn

so far: no neutrino candidates found

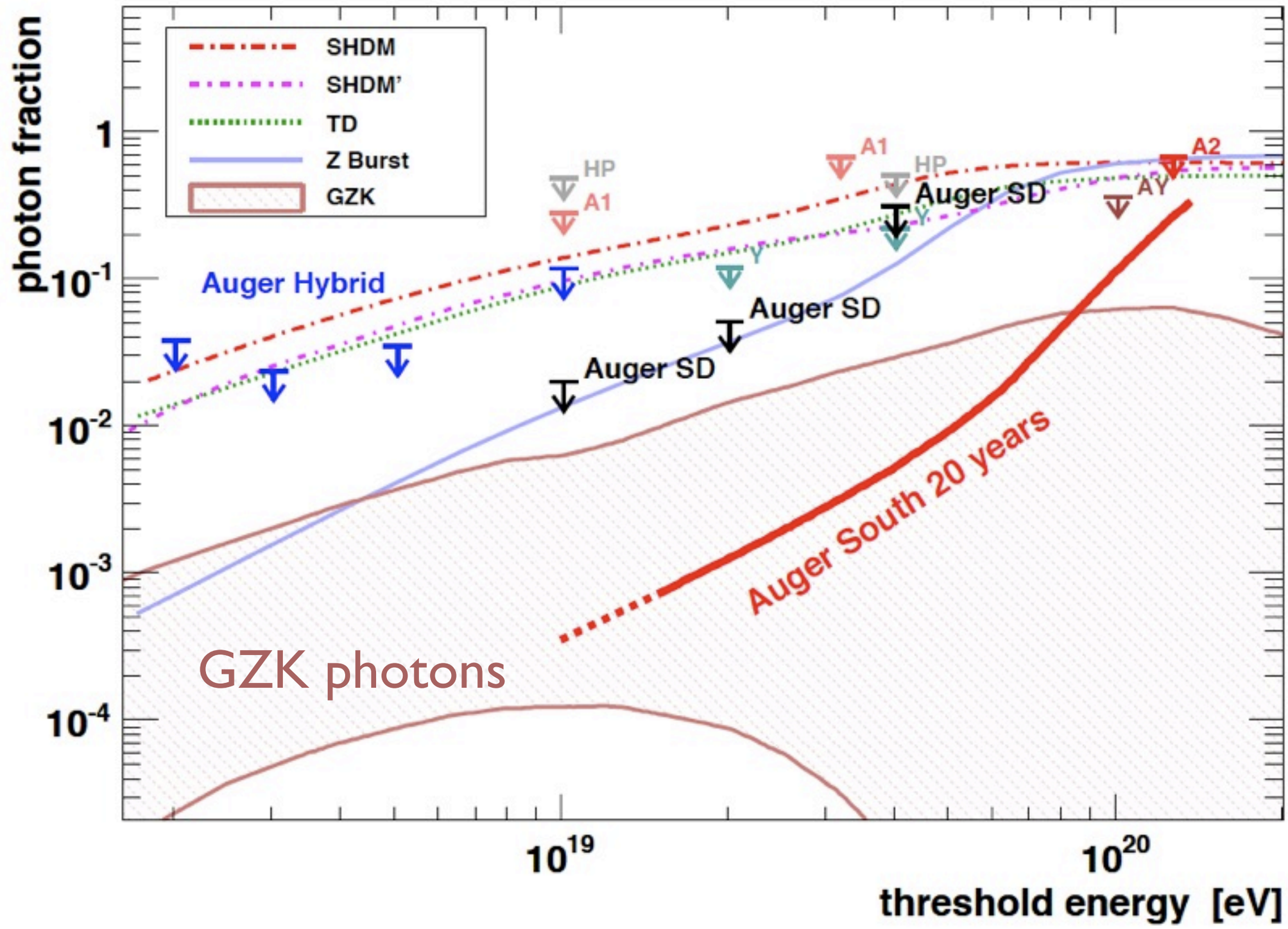
limits: 90% c.l.



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}

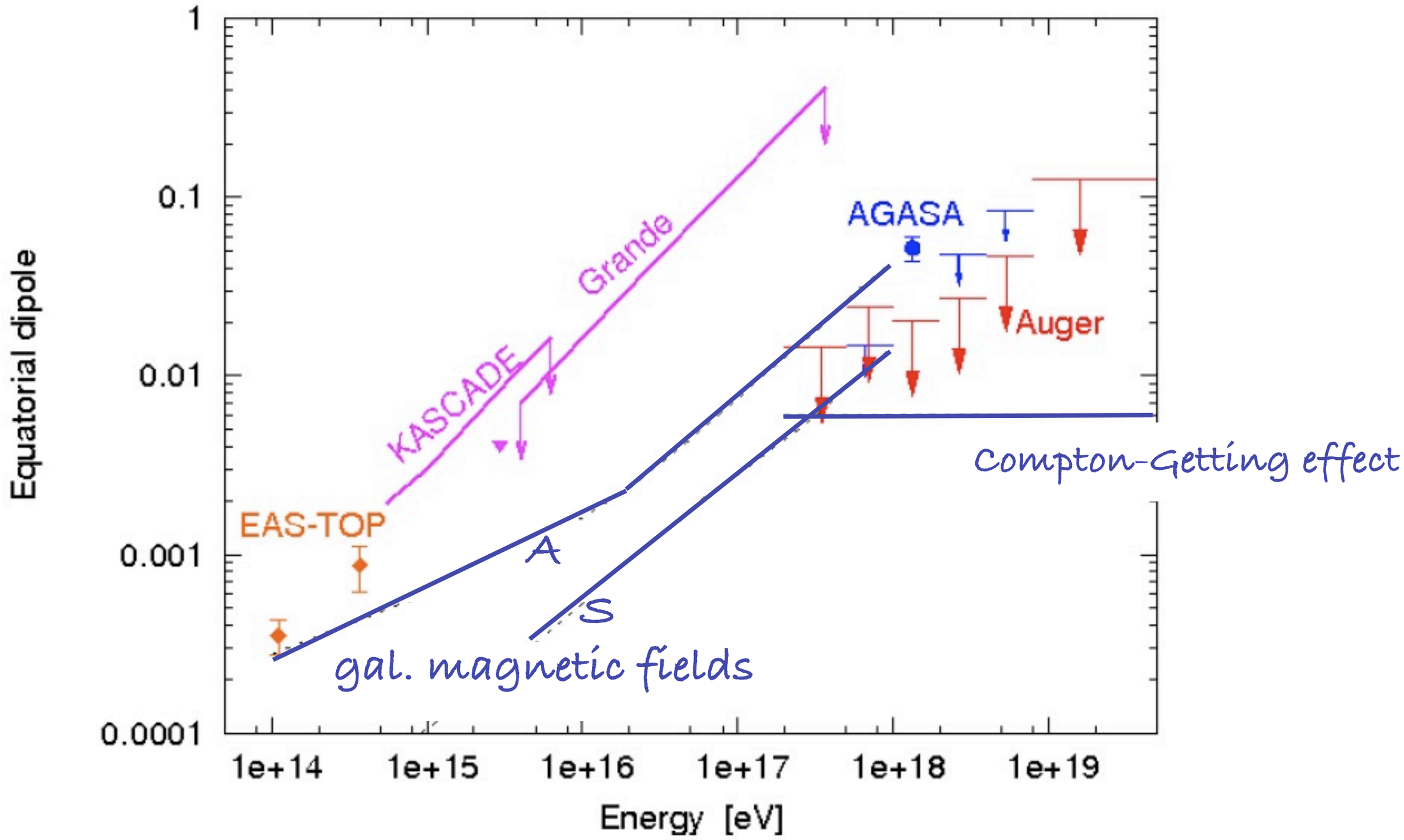
Upper limits on photons



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

Large-Scale Anisotropy:

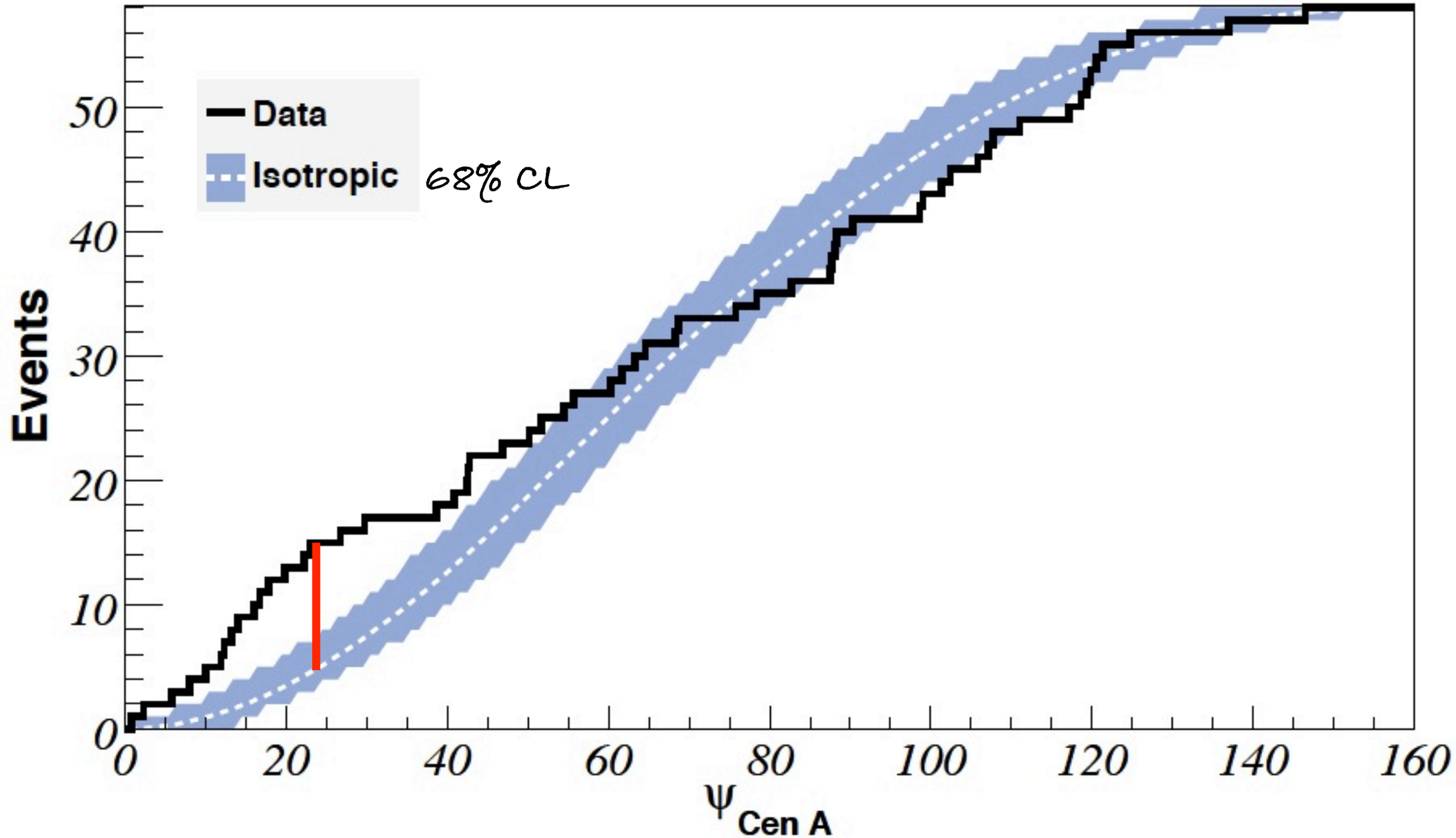
Transition galactic-extragalactic should induce large-scale anisotropy of CRs.



Limits close to predicted anisotropies.

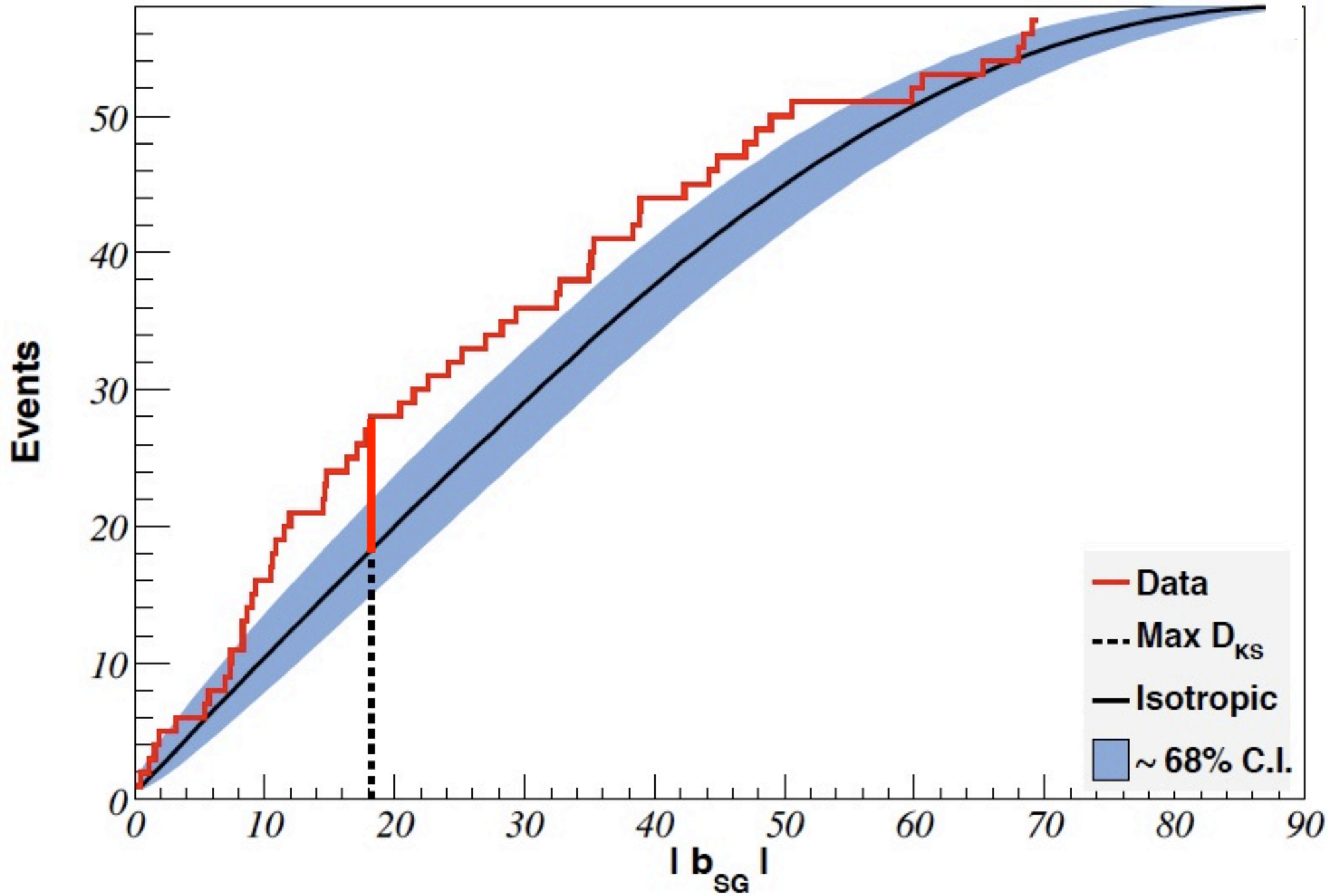
More data will give an anisotropy signal or model constraints.

Distance: CR - Cen A



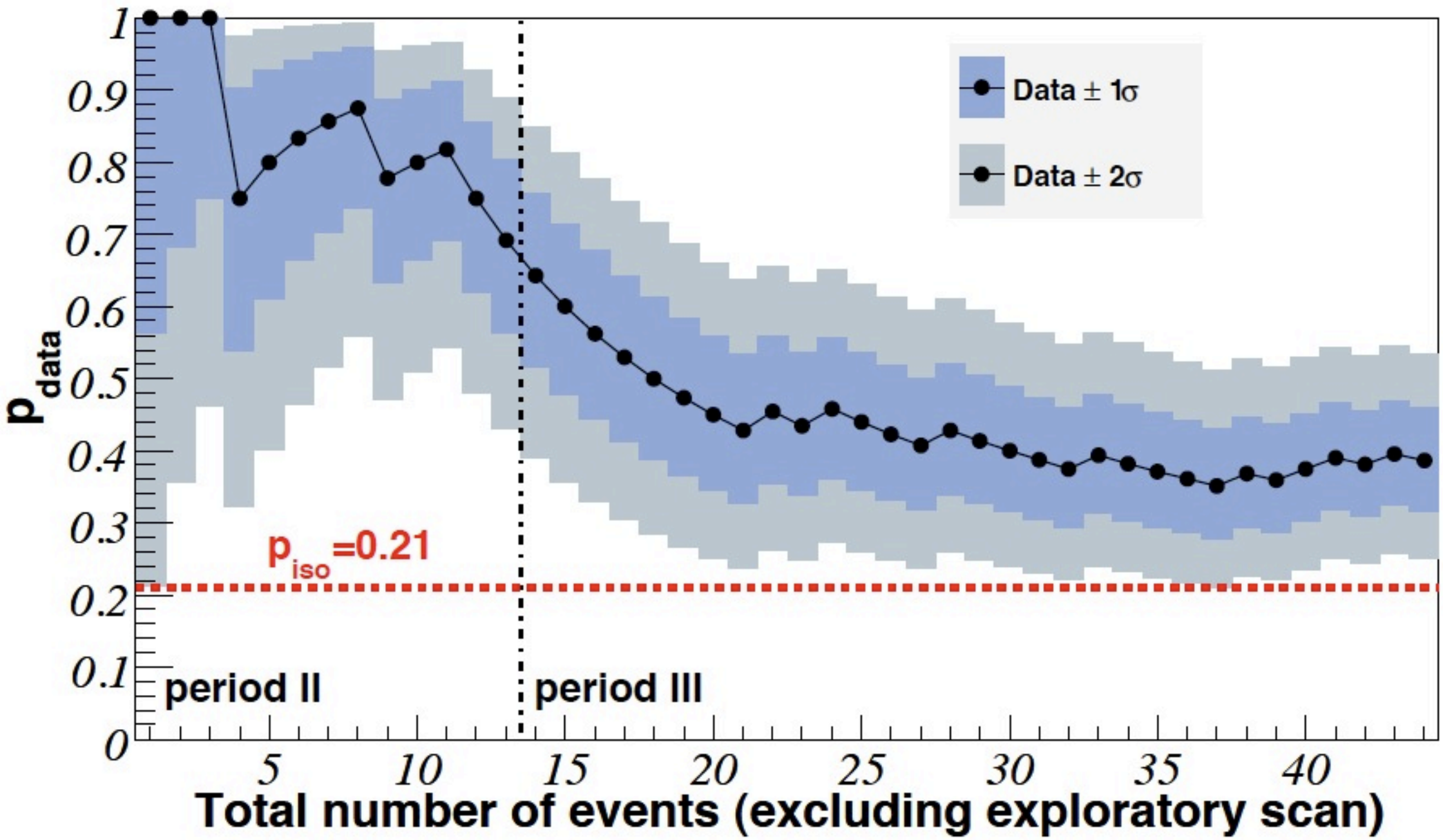
2% chance prob. for isotropic distribution

Distance: CR - Supergalactic Plane



Comparison with objects from Veron-Cetty Catalog

(as published in Science 318)



UHECRs appear to arrive anisotropically,
allows inference about sources and composition.

see talk by
Rebecca Gozzini

Composition mis-match ?

Spectrum:	GZK cut-off	p dominated ($E > 6 \times 10^{19}$ eV)
Anisotropy:	correlation with nearby matter	
Composition:	X_{max}, $t_{1/2}$, ...	mixed / heavy ($E < 3 \times 10^{19}$ eV)

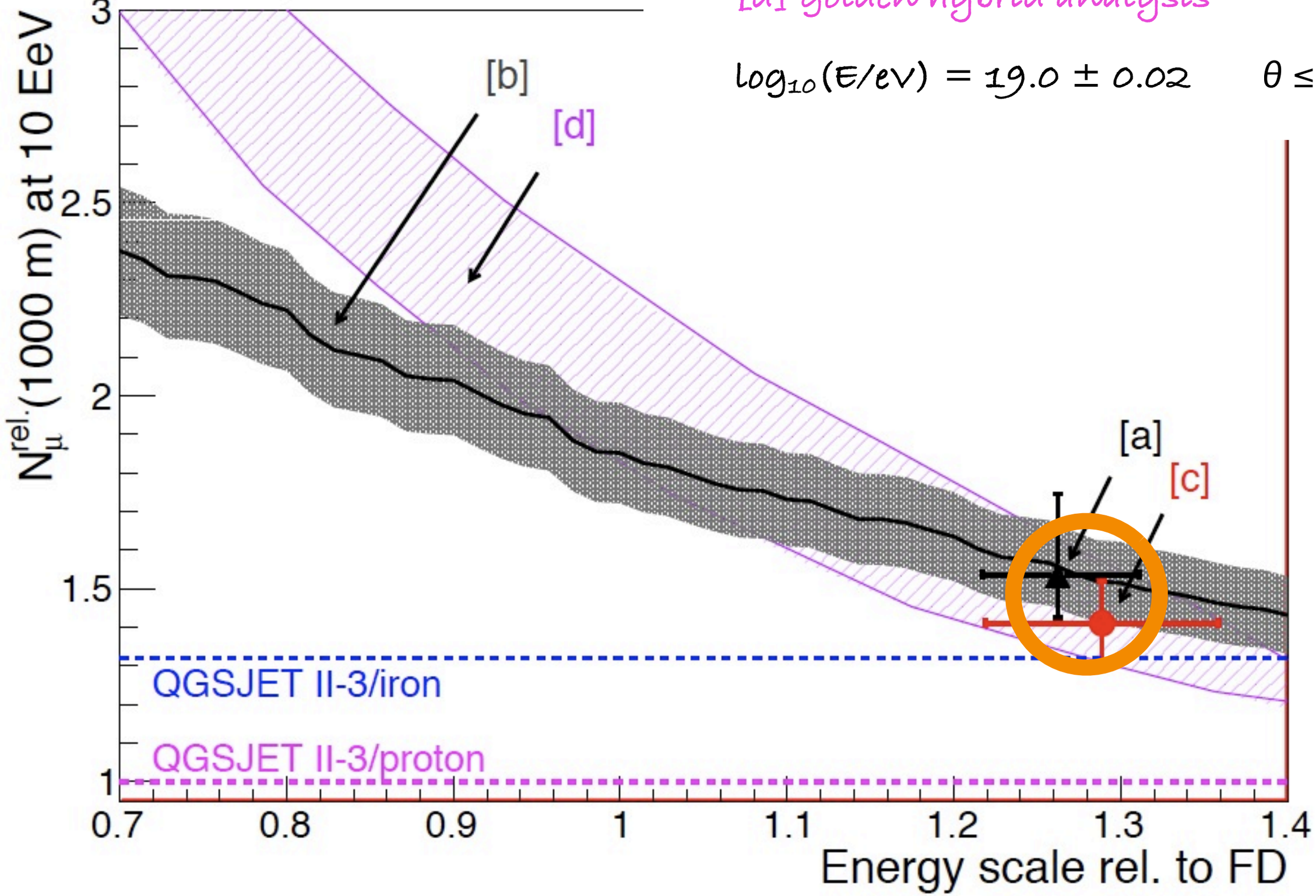
strongly model dependent

Need hadronic interaction models to be modified (within their uncertainties) to make data look more p-like ??? (cross sections, inelasticity, ...)

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

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

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



Conclusion & Outlook:

Auger-South is complete and works very well.

Exposure so far ≈ 20000 km² sr year

to come > 70000 km² sr year

Auger will provide many years of good experimental data & many exciting results on UHE astro particles.

Results so far ...

Spectrum
Anisotropy
Composition

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

+ many technical papers and ICRC contributions