Recent Results from the Pierre Auger Observatory

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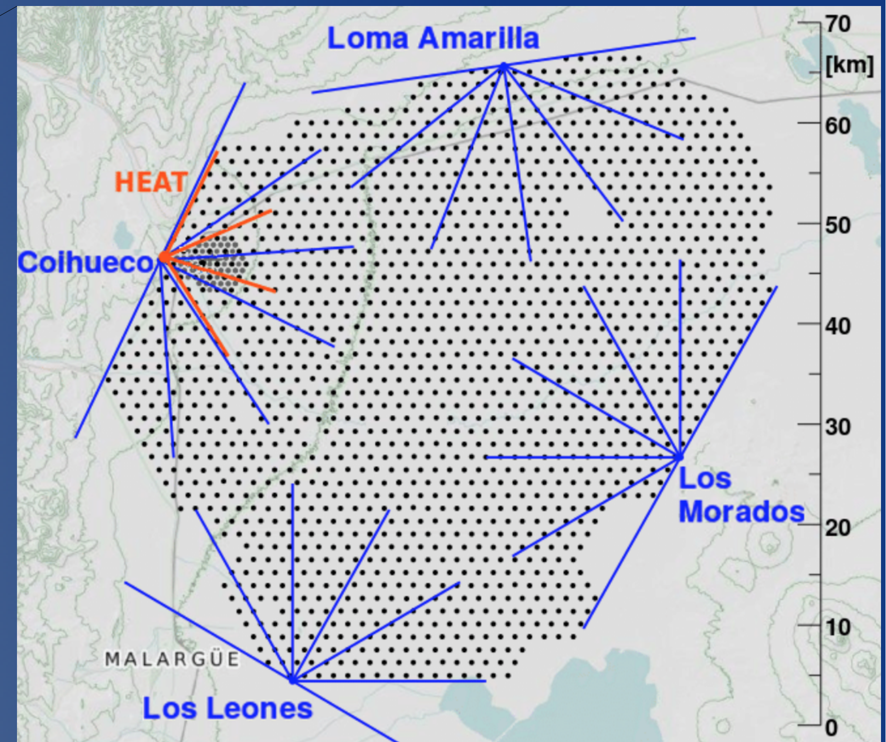
(on behalf of Pierre Auger Collaboration)

41st Erice International School on Nuclear Physics
September 23rd , 2019

Pierre Auger Observatory

~500 members
89 institutions

Malargüe,Mendoza, Argentina, 1.4-1.5 km asl (35°28'S,69°20'W)



Surface detector

SD1500: 1600 tanks,1.5 km spacing, A=3000 km^2

SD750: 61 tanks,0.75 km spacing, A=25 km^2

Detection of Cherenkov light from $\mu^{\pm}$,$e^{\pm}$,γ

12 tons of H_2O, 3 PMTs per tank

100% duty cycle

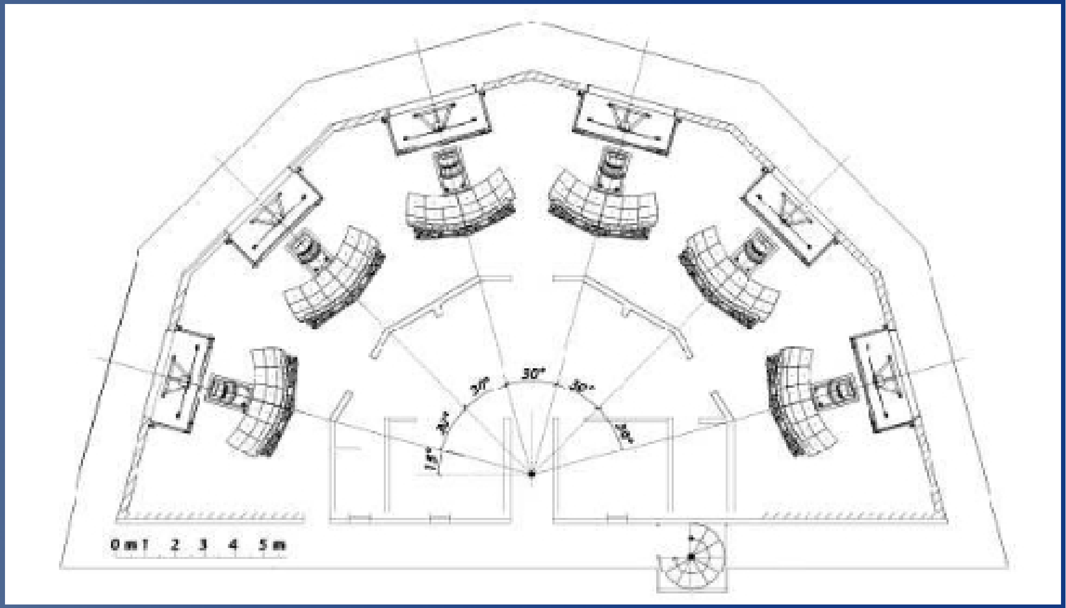
Angular resolution <1°

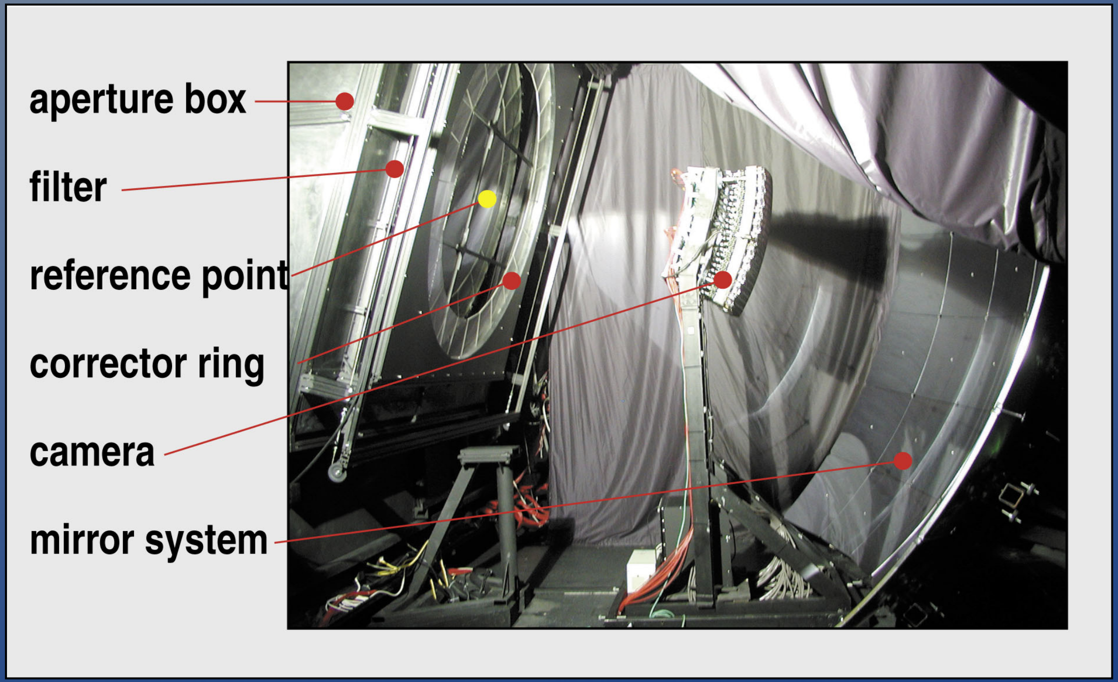
E_{thr}(SD1500): $10^{18.3}$ eV

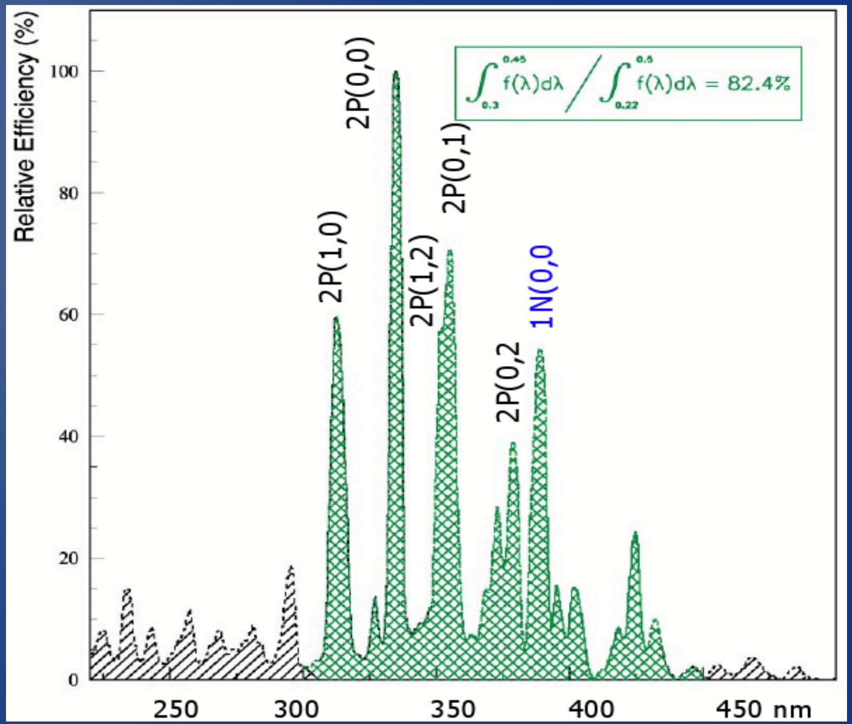
E_{thr}(SD750): 10^{17} eV

Fluorescence Detector

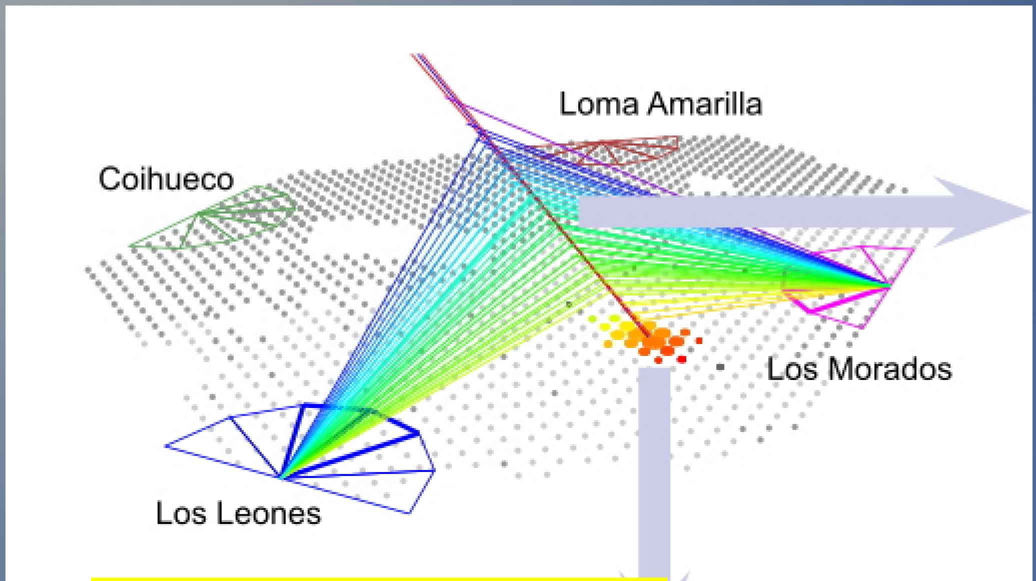
24 telescopes in 4 eyes
FD camera: 440 PMTs / telescope
Mirror area: 11m^2
Field of View: 6x30°x30° for each FD
UV filter: 300-420 nm
Buffering 1000 time bins, 100 ns each
Duty cycle ~12% (1/2 moon cycle)
Angular resolution ~ 0.6°



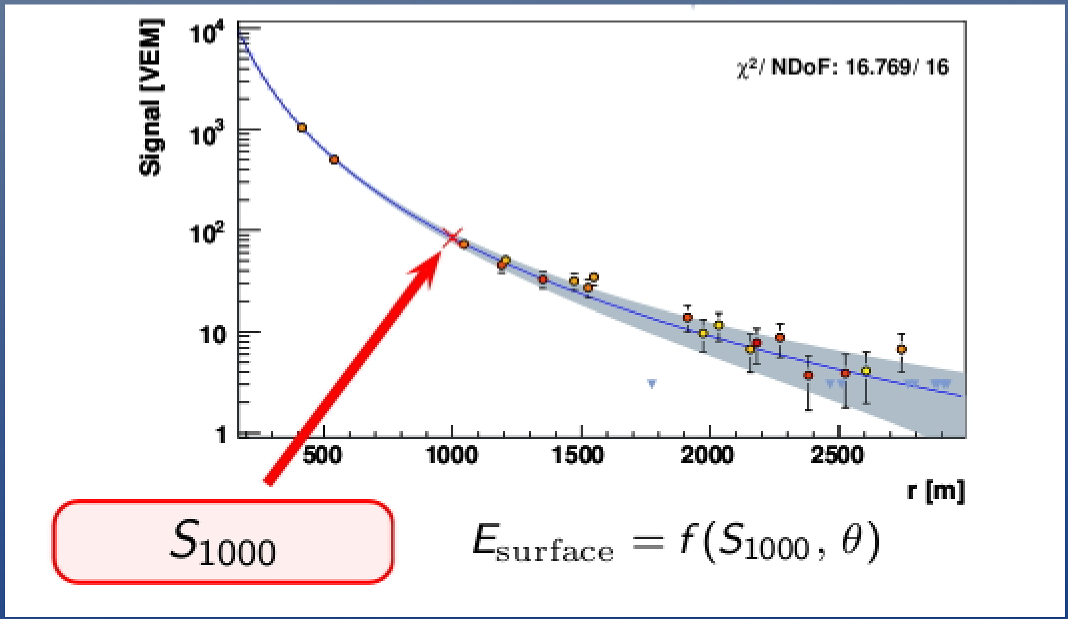




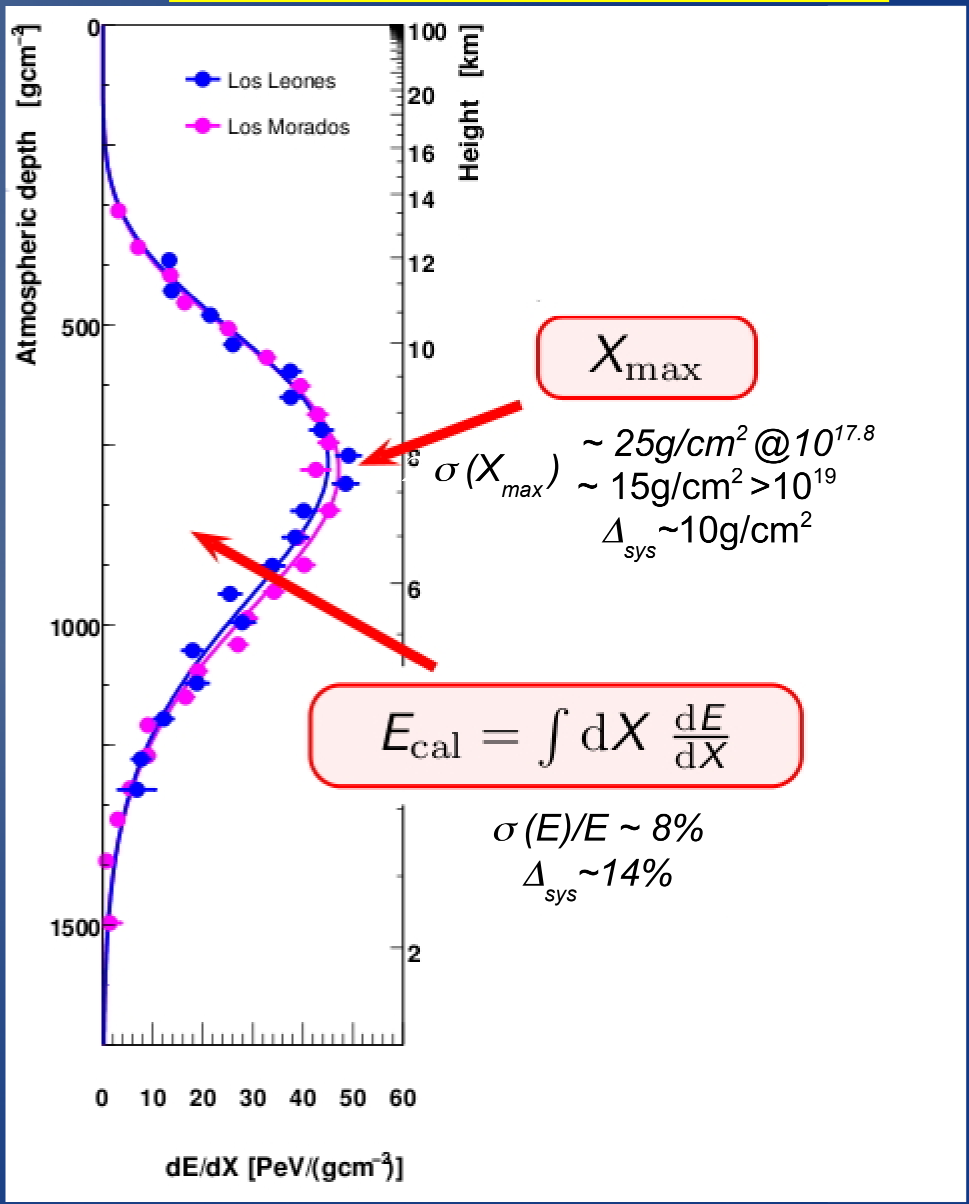
Hybrid Reconstruction of Cosmic Ray Showers



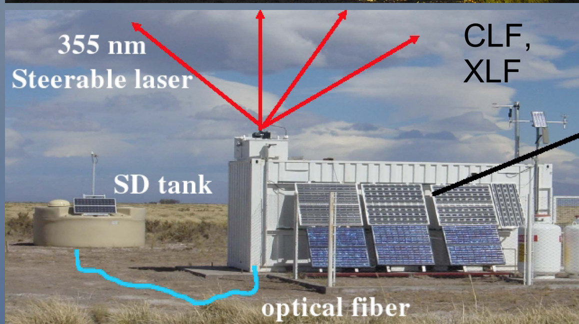
SD : lateral profile

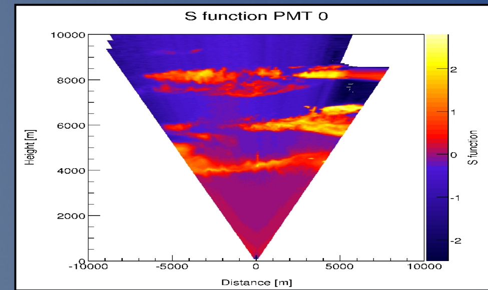


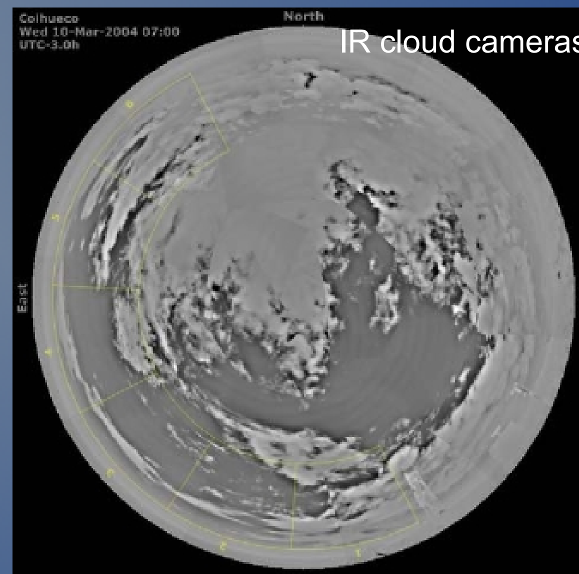
FD : longitudinal profile

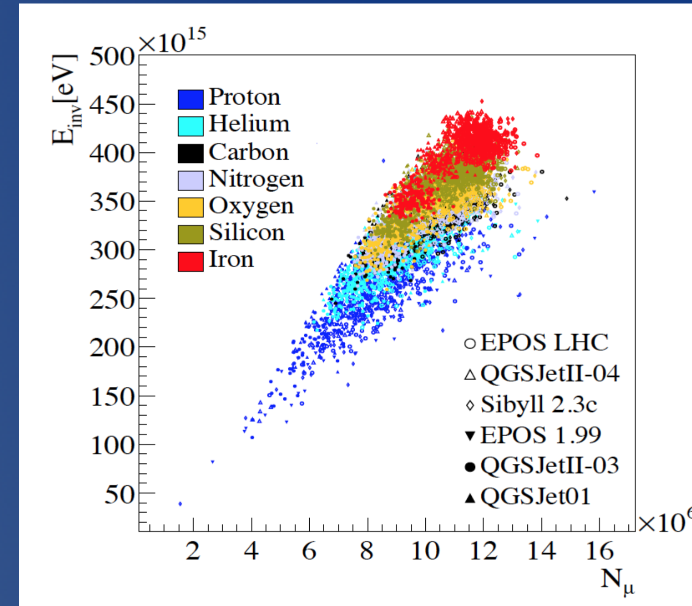


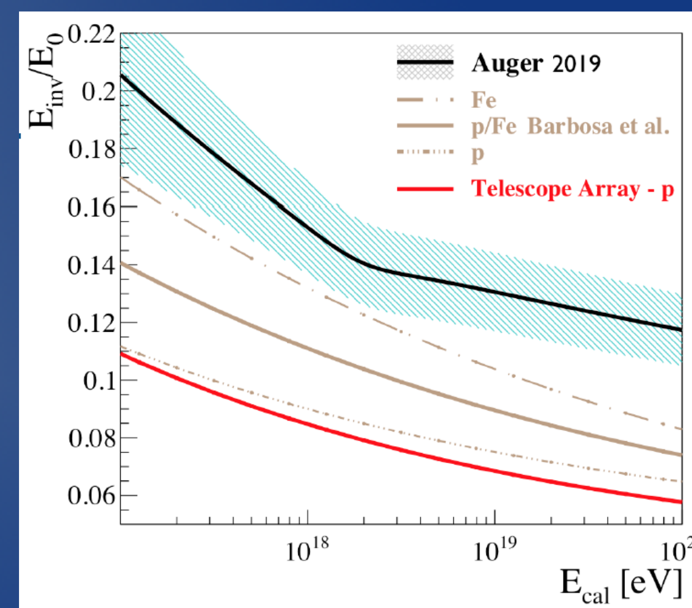
Energy Calibration











E_{FD} calculated correcting for :

- geometry
- atmospheric optical properties (clouds, aerosols)
- invisible energy, proportional to N_μ reaching the ground.

E_{cal} = EM component of the shower, originating from π^0 decay to $\gamma\gamma$

Energy Calibration

For (quasi)vertical showers, FD/SD energy calibration is performed correcting for the polar angle, to account for angular dependence of EAS attenuation.

$S38 = S1000 * f(\cos^2\vartheta 2 \cos^2 38)$

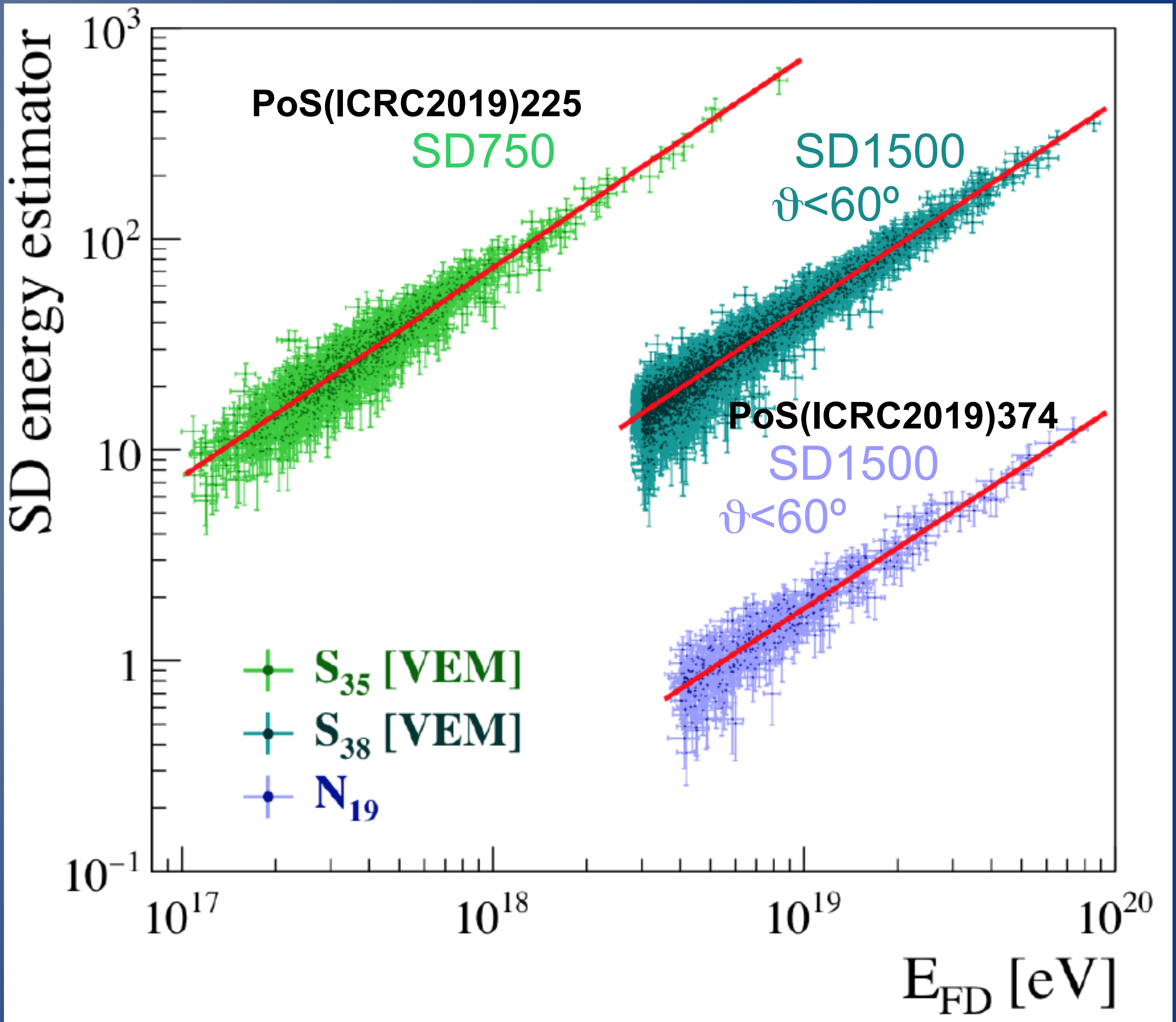
for the main array;

$S35 = S450 * g(\cos^2\vartheta - \cos^2 35)$

for the infill array.

For (quasi) horizontal showers, the energy is obtained counting the number of muons

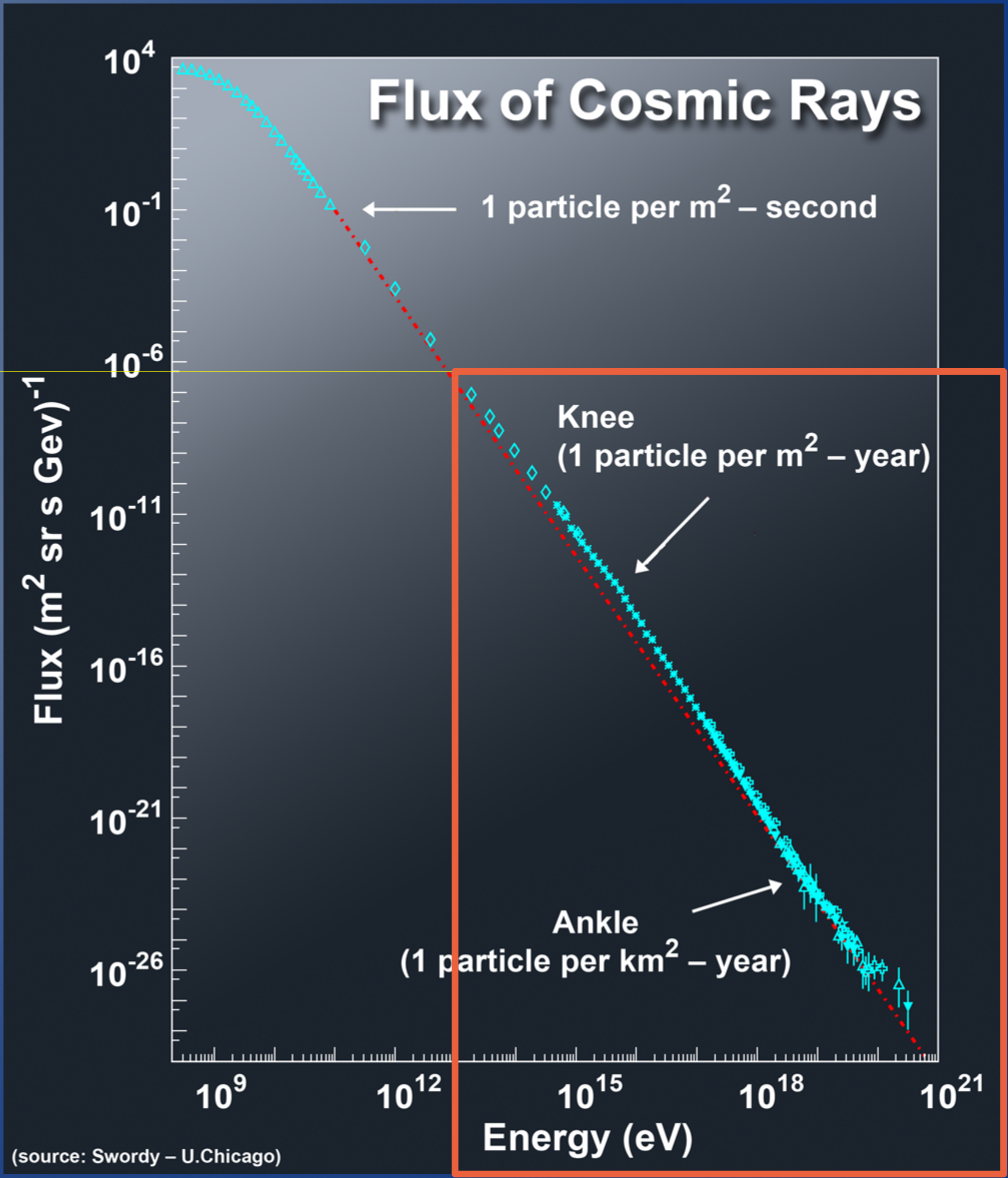
$N19 = N_\mu / N_\mu(E=10^{19}\text{ eV})$



CR Energy Spectrum

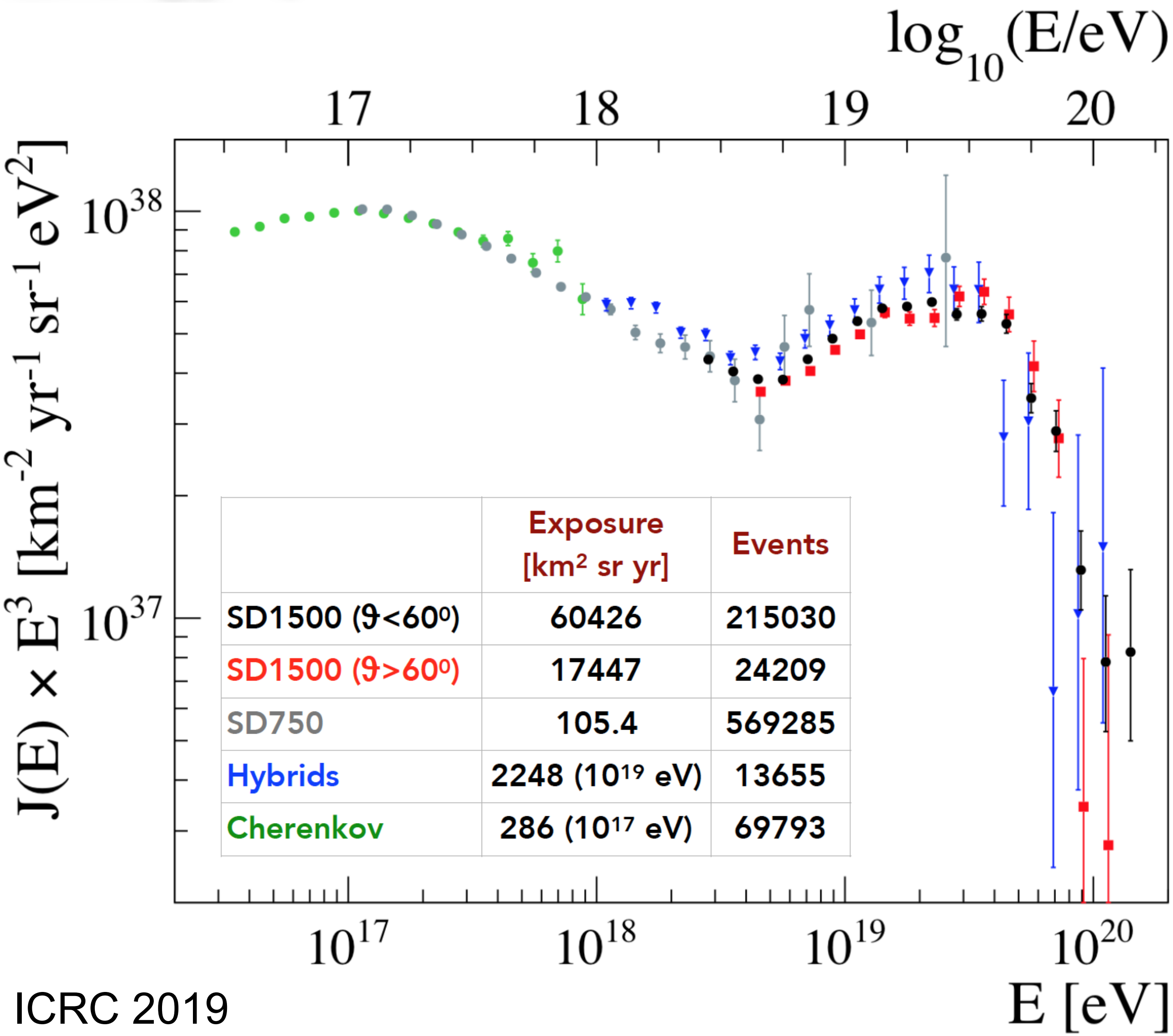
Direct measurements: low energy cosmic rays are observed using detectors in space (e.g. AMS2, FERMI) or on baloons (CREAM)

Indirect measurements: the flux of high energy cosmic rays is too low and direct observation is not possible. Secondaries are detected in the atmosphere or on the Earth surface (e.g. AUGER, Telescope Array)



CR Energy Spectrum

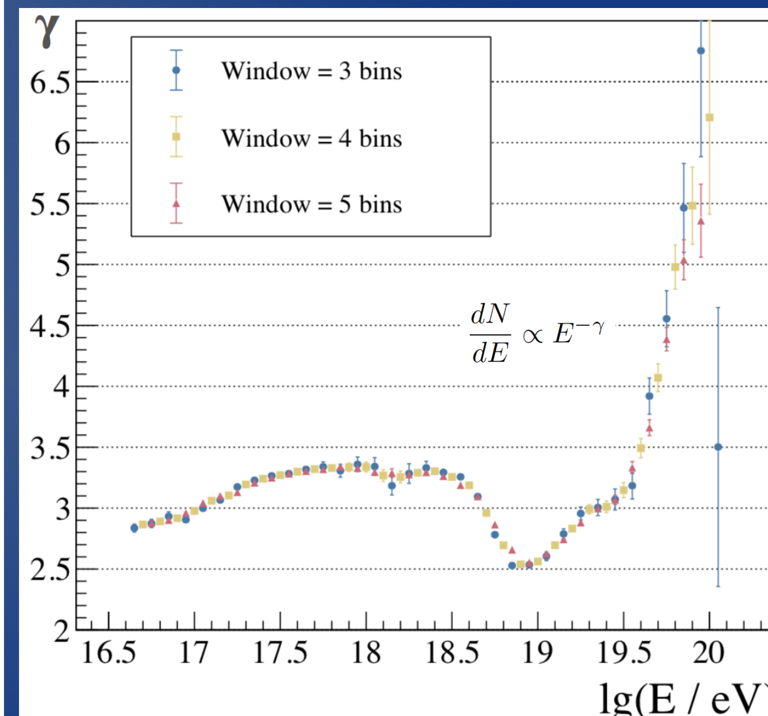
AUGER measures high energy cosmic rays across more than four orders of magnitude.



	Exposure [km² sr yr]	Events
SD1500 (ϑ<60⁰)	60426	215030
SD1500 (ϑ>60⁰)	17447	24209
SD750	105.4	569285
Hybrids	2248 (10^{19} eV)	13655
Cherenkov	286 (10^{17} eV)	69793

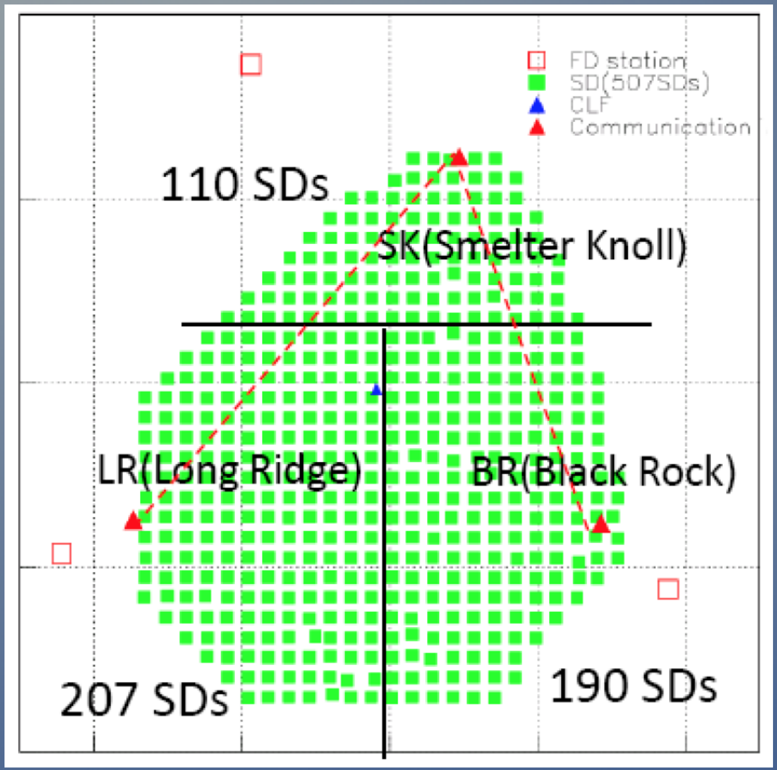
PoS(ICRC2019)450
Comparing all Auger datasets, a consistent picture seems to emerge...

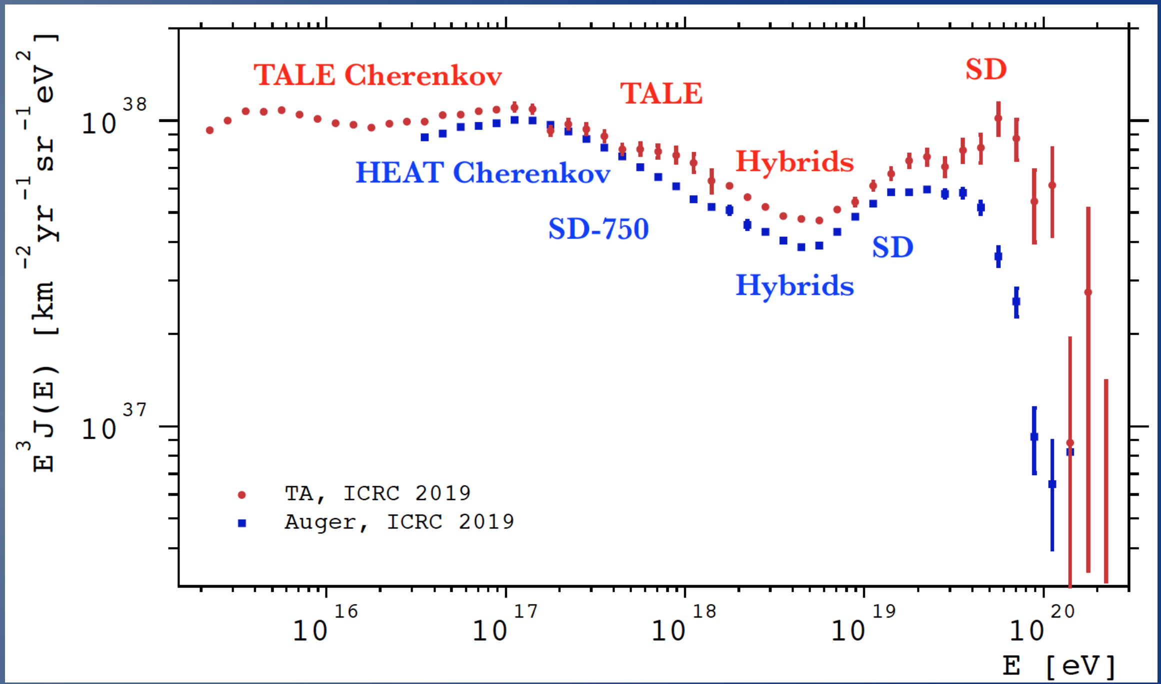
Evolution of the spectral index γ with energy



CR Energy Spectrum: Auger vs Telescope Array

Telescope Array (Delta, Utah)





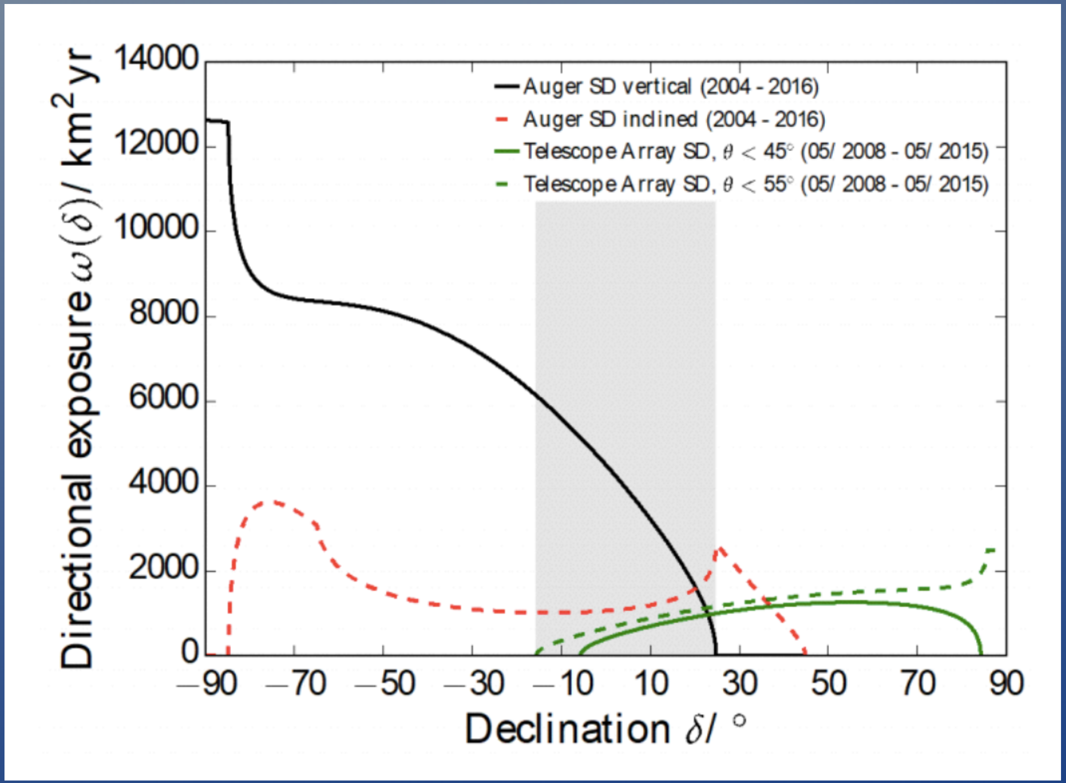
3 FD's
507 SD's, 3m^2 scintillator
608 km^2 total area
11 years operation

Long standing issue: tension between the two measurements still not understood.
A TA-Auger working group has been created to compare calibration methods and systematics.

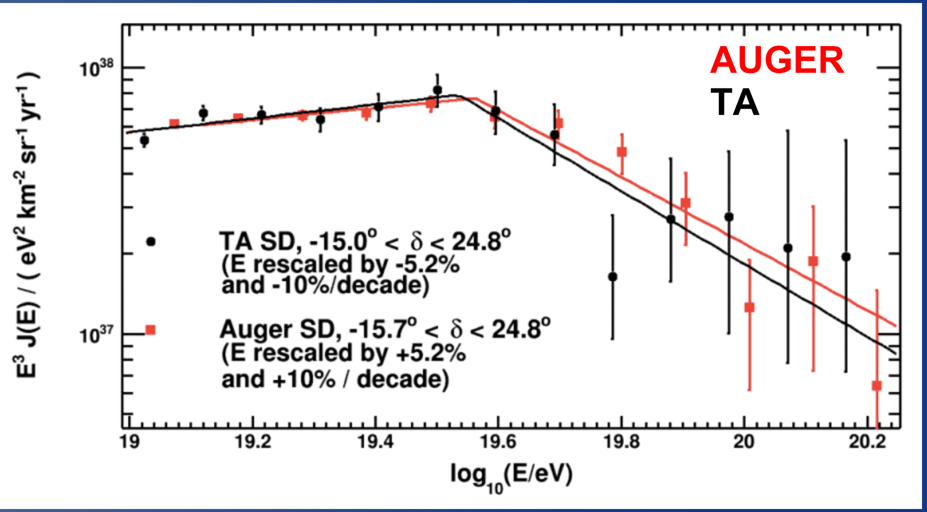
CR Energy Spectrum: Auger vs Telescope Array

Various checks on systematics:
- Energy scale
- FD fluorescence yield
- Invisible energy corrections
- SD angle corrections
- Hybrids systematics

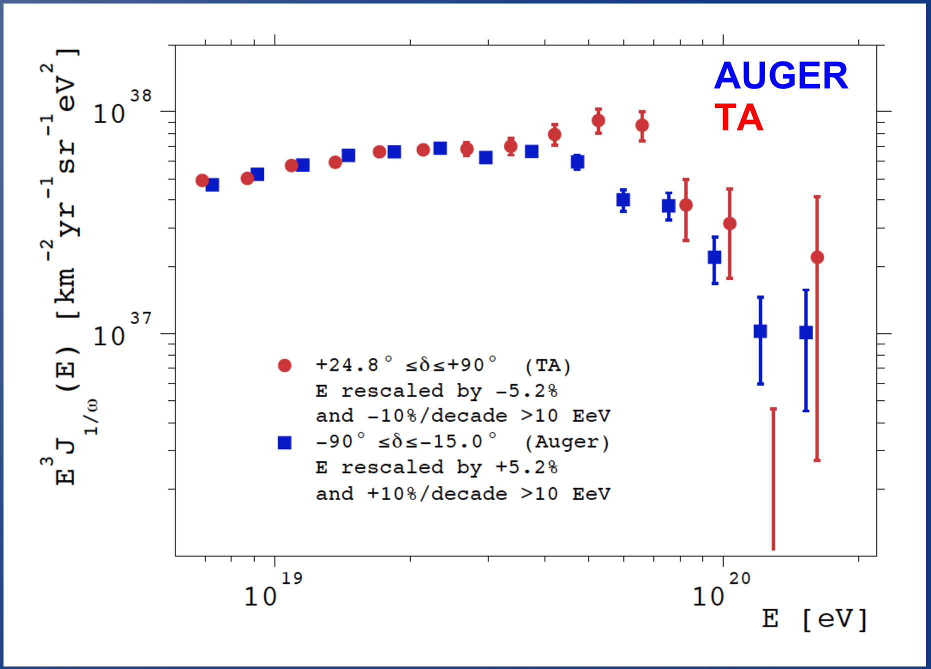
Spectra split in/out common declination band (see below)



Inside common declination band

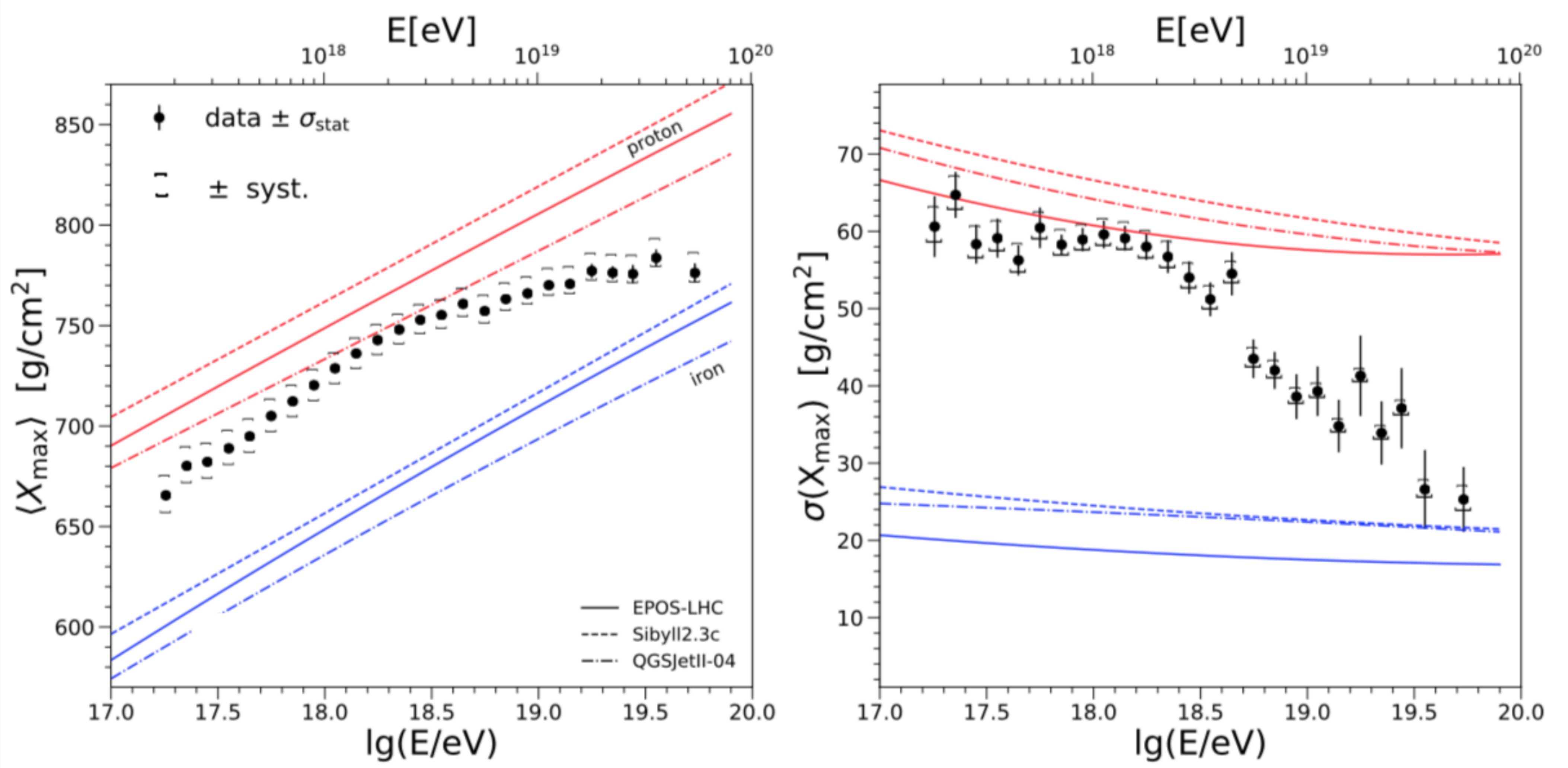


Outside common declination band



CR composition: X_{max} and $\sigma(X_{max})$ from FD

The best proxy for primary CR mass is the depth of maximum development of the shower. Lighter nuclei are more penetrating. FD event statistics does not allow to measure composition above $10^{19.7}$ eV. Beside average penetration depth, also the RMS can be used.

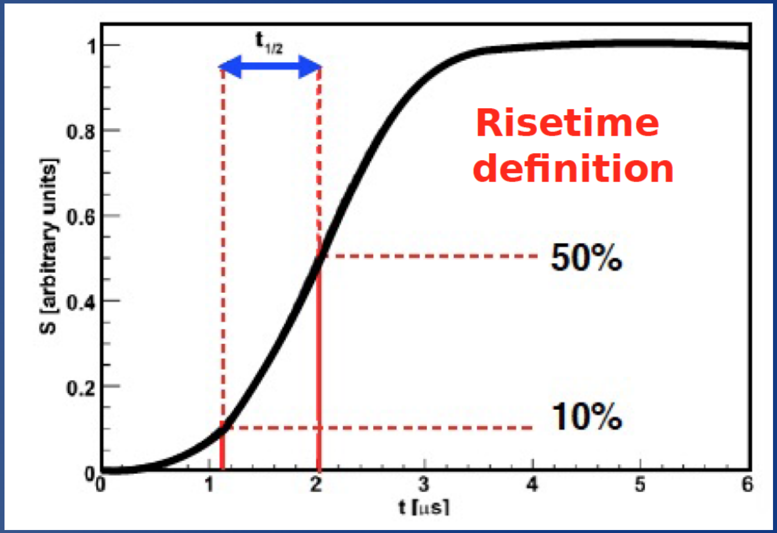


CR composition: X_{max} from SD

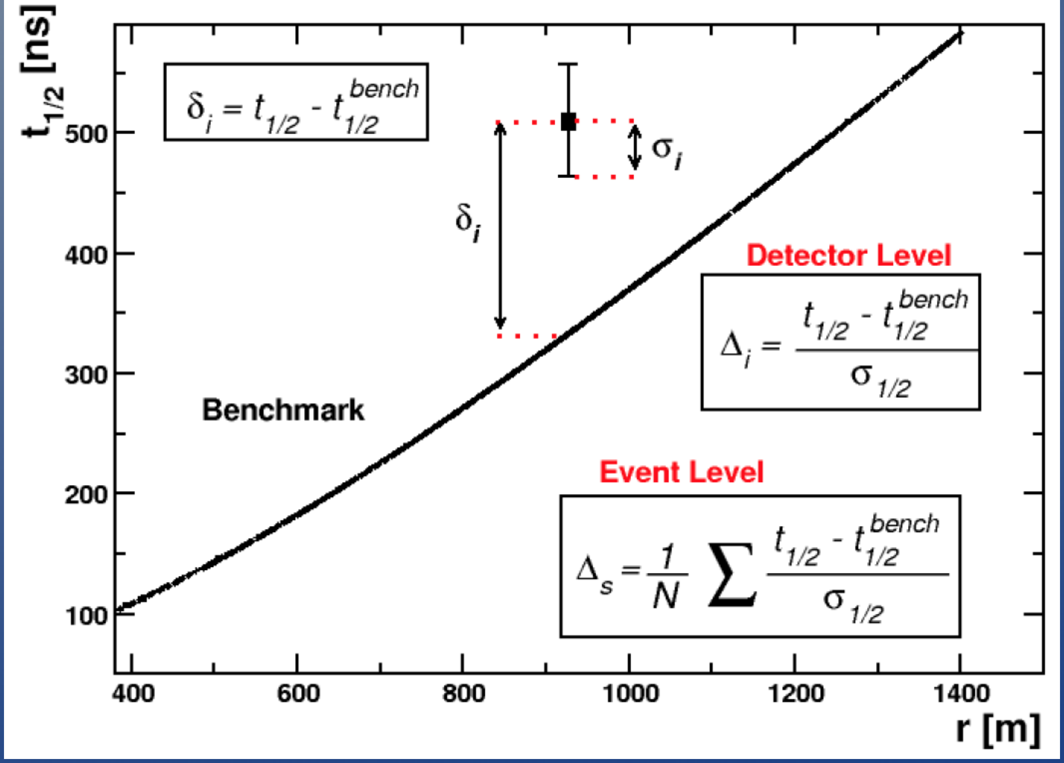
PRD 96 (2017) 122003

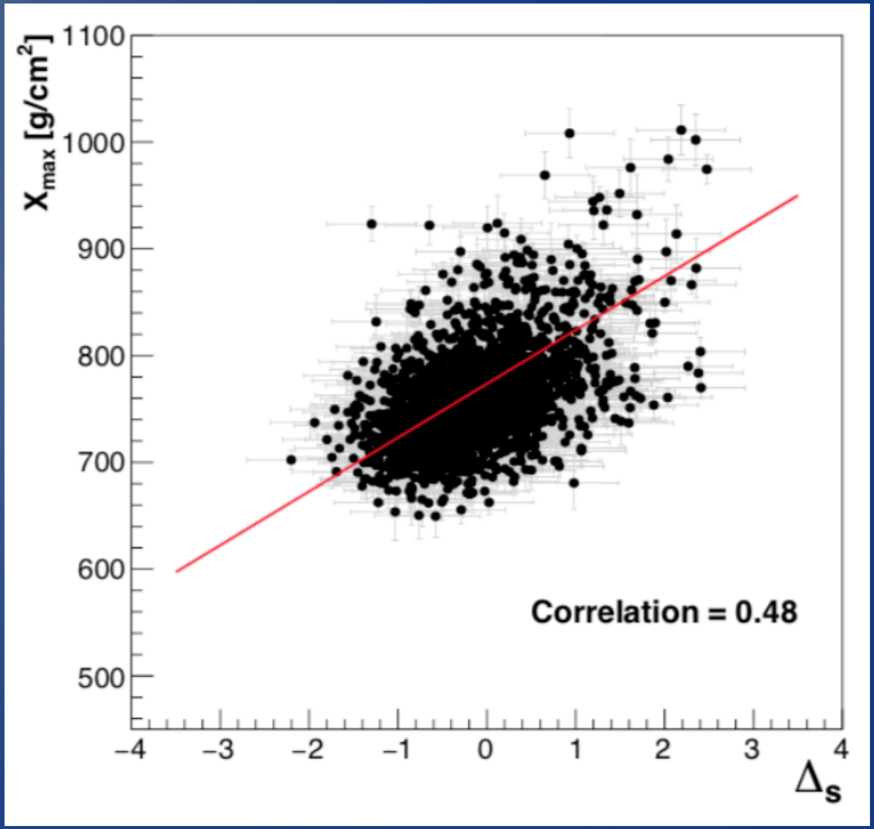
The benchmark risetime is defined as the function $t_{1/2}(r)$ for a primary energy:

- of $10^{19.1}$ eV<E<$10^{19.2}$ eV (in SD1500)
- of $10^{17.7}$ eV<E<$10^{17.8}$ eV (in SD750)

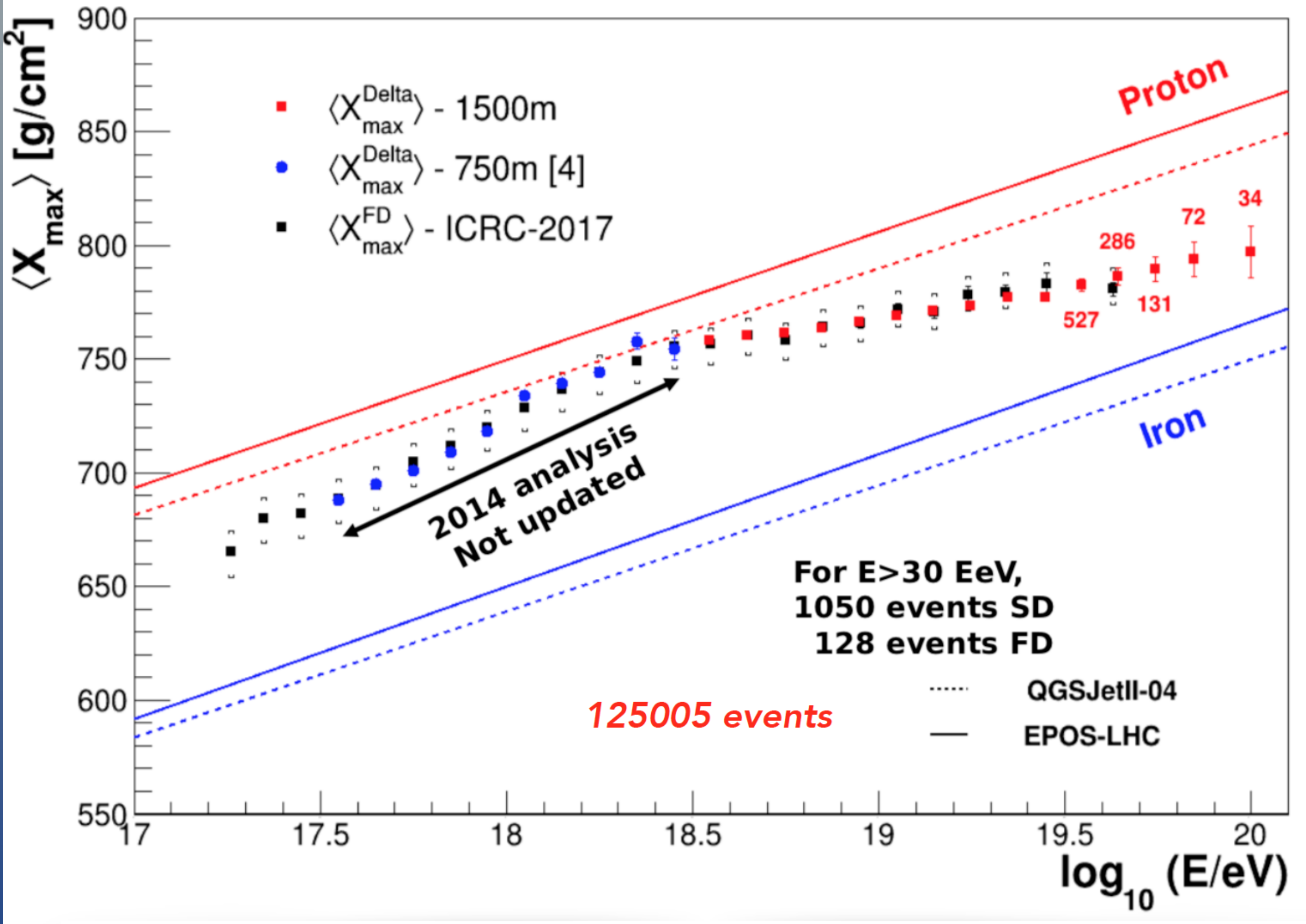


We use hybrid events to correlate Δ_s with the X_{max} measured by FD.





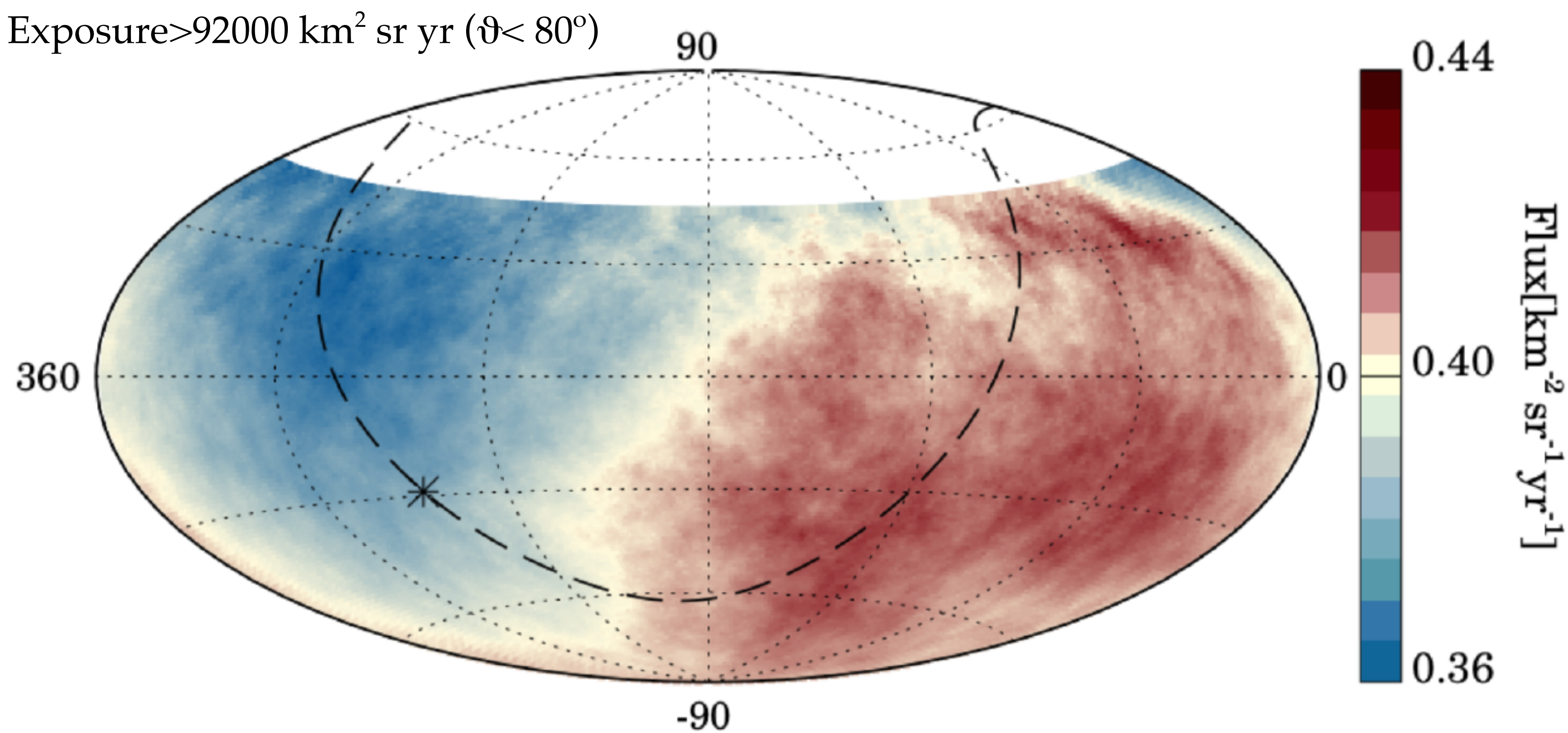
CR composition: X_{max} from SD



Large scale anisotropies: dipolar structure

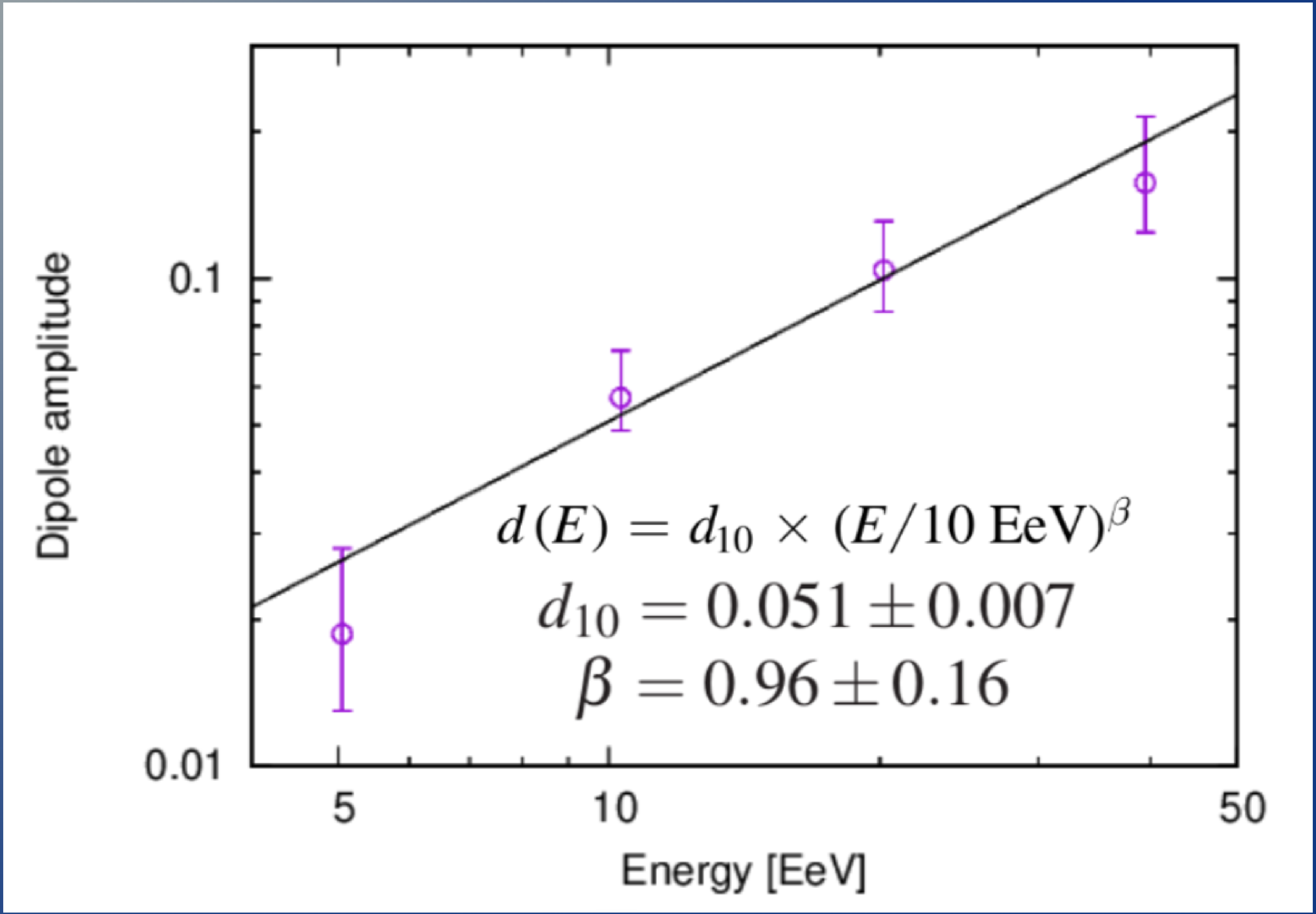
3-D dipole above 8 EeV pointing towards $(\alpha,\delta) = (98^o,-25^o)$ Amplitude = $(6.6^{+1.2}_{-0.8})$%

Consistent with the picture of extra-galactic origin of UHECR above 2 EeV



Energy [EeV] interval	median	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]
4 - 8	5.0	88,317	$0.010^{+0.007}_{-0.004}$	-0.016 ± 0.009	$0.019^{+0.009}_{-0.006}$	70 ± 34	-57^{+24}_{-20}
≥ 8	11.5	36,924	$0.060^{+0.010}_{-0.009}$	-0.028 ± 0.014	$0.066^{+0.012}_{-0.008}$	98 ± 9	-25 ± 11

... growing with energy



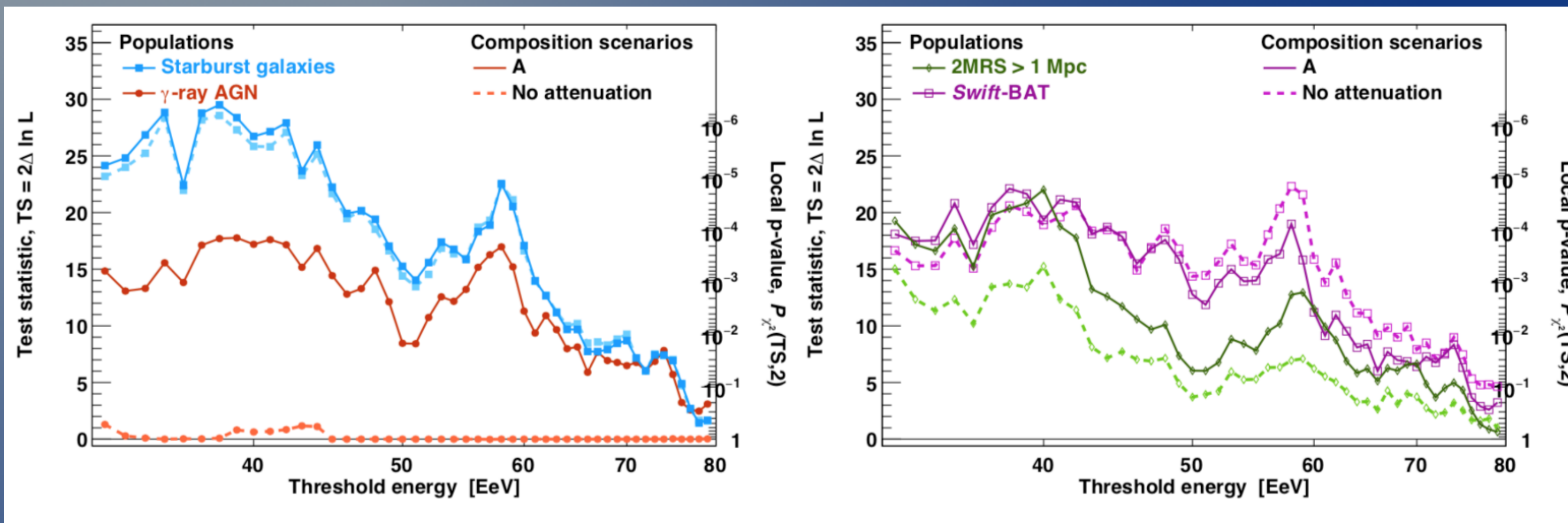
Searching for point sources within 250 Mpc

Active galactic nuclei
33 sources (CenA, Fornax A, M87 ....)

Swift-BAT catalog
> 300 sources (radio loud and quiet)

Starburst Galaxies
32 sources (Circinus, M82, M83, ...)

2MRS catalog
10 k sources with D>1 Mpc



ApJ Letters, 853 (2018) L29

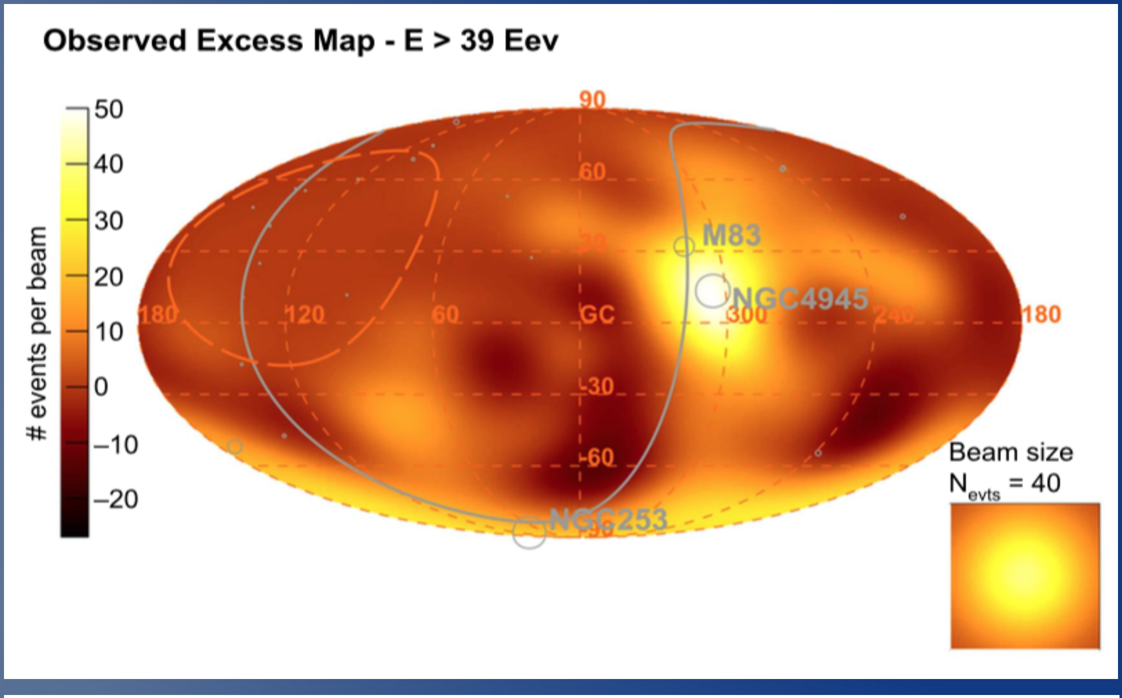
Catalog	E_{th}	TS	Local p-value	post-trial	f_{aniso}	θ
Starburst	38 EeV	29.5	4×10^{-7}	$4.5\ \sigma$	$11^{+5}_{-4}\%$	$15^{+5}_{-4}{}^\circ$
γ–AGN	39 EeV	17.8	1×10^{-4}	$3.1\ \sigma$	$6^{+4}_{-3}\%$	$14^{+6}_{-4}{}^\circ$
Swift-BAT	38 EeV	22.2	2×10^{-5}	$3.6\ \sigma$	$8^{+4}_{-3}\%$	$15^{+6}_{-4}{}^\circ$
2MRS	40 EeV	22.0	2×10^{-5}	$3.6\ \sigma$	$19^{+10}_{-7}\%$	$15^{+7}_{-4}{}^\circ$

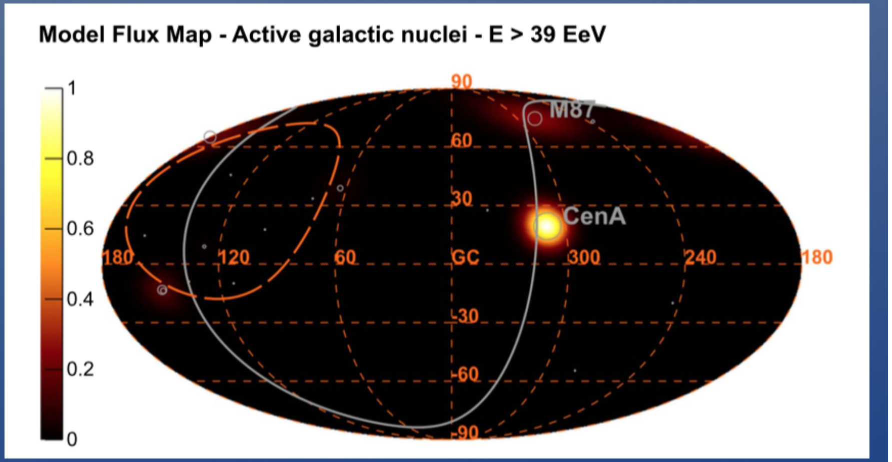
Dominant sources: Starburst galaxies

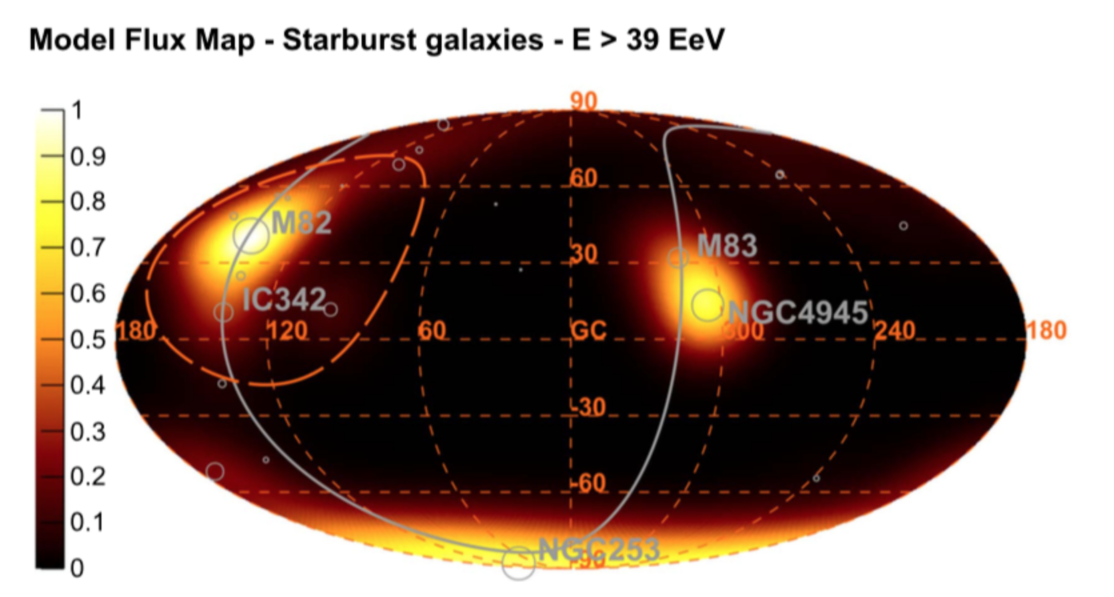
ApJ Letters, 853 (2018) L29

The southern sky is dominated by three starburst galaxies:
NGC 253 (Sculptor galaxy, 2.7 Mpc)
M83,NGC4945 (4 Mpc , in Centaurus)

The northern sky part not visible by Auger, is dominated by one starburst galaxy:
M82 (3.6 Mpc , Ursa Major)
observed by Telescope Array

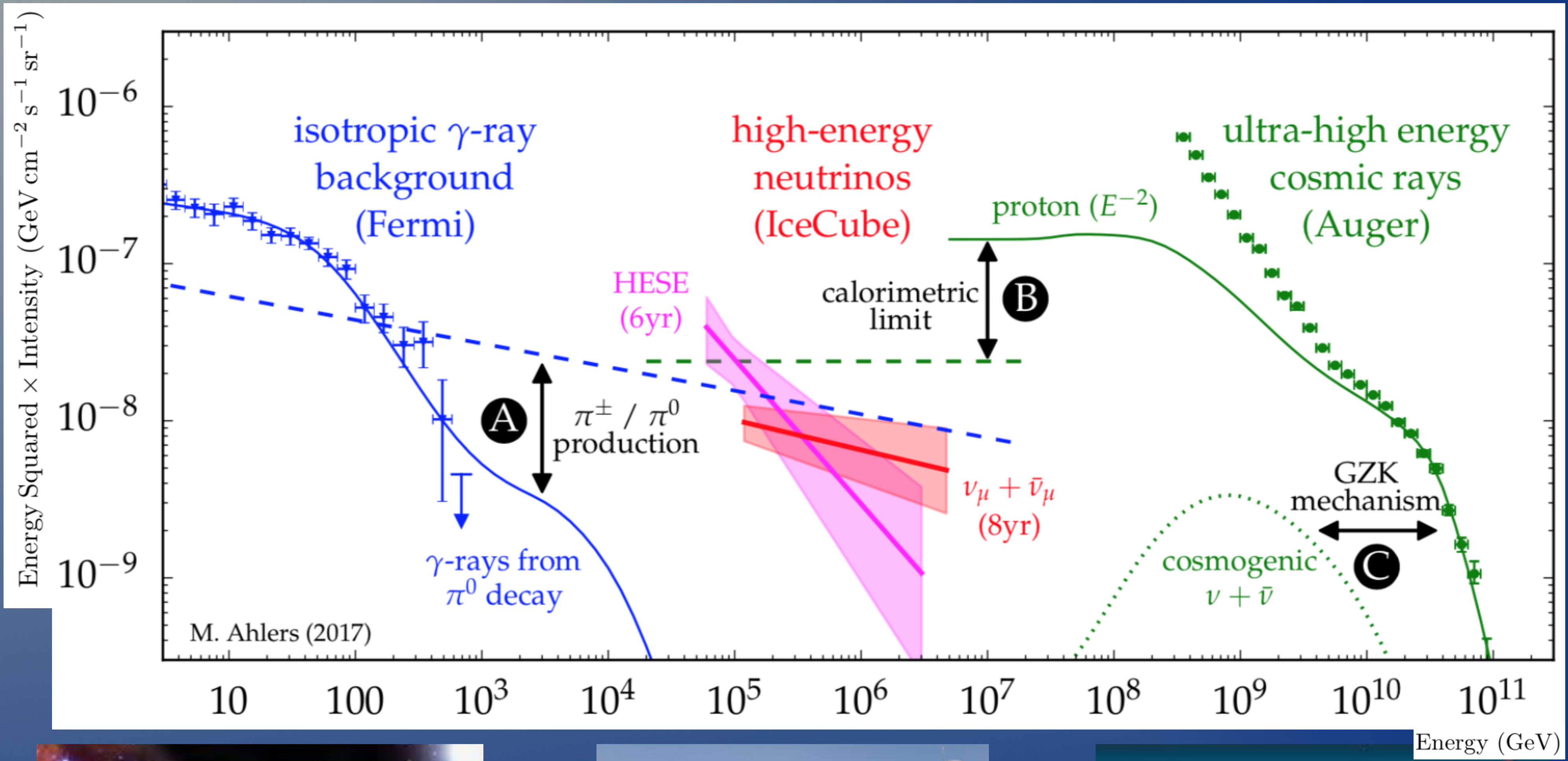


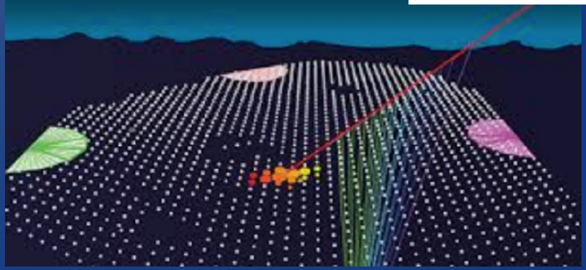




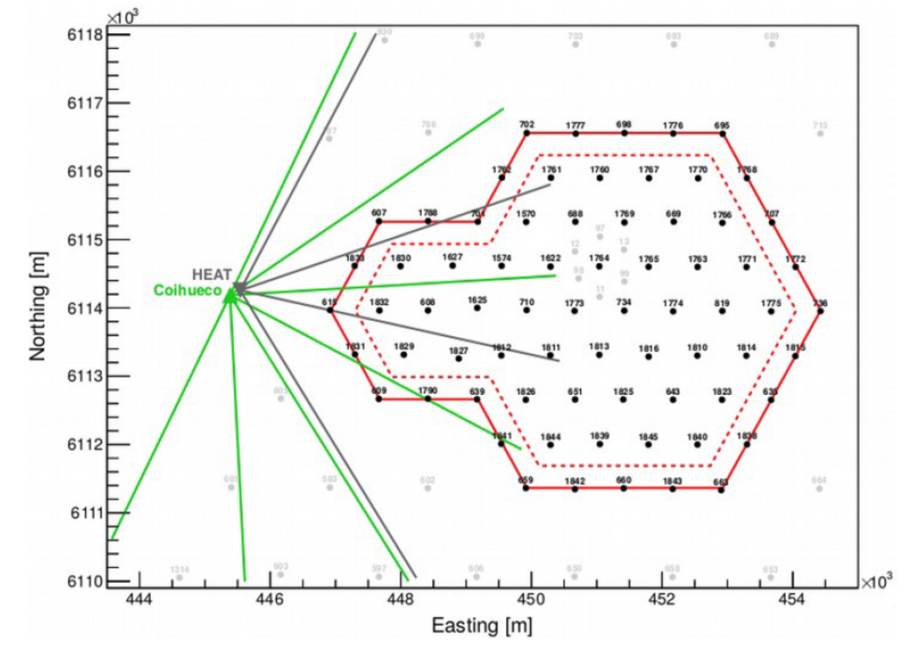
The highest energy photons,neutrinos,CR's

Towards a unified picture? (ArXiV: 1903.04334)

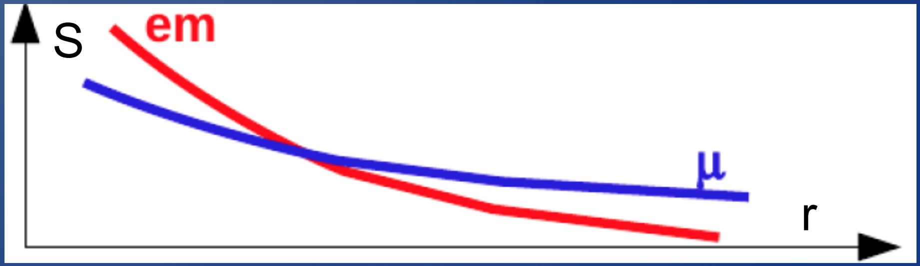




Searching for UHE photons with hybrid events

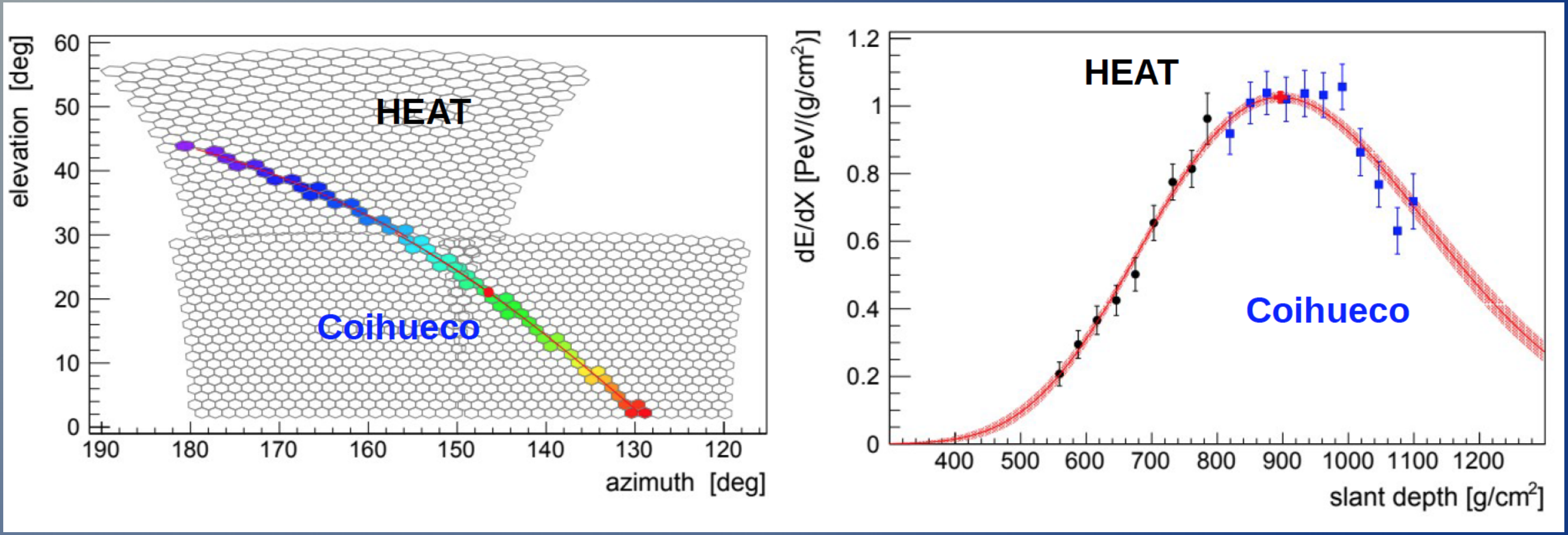


Hybrid selection extension to lower energies
- using SD750 and HEAT Telescopes at Coihueco
- BDT training of proton and photon MC based on these inputs:
  Xmax from FD
  Number of SD750 stations
  Steepness of the lateral distribution in SD



Data sample : 2204 events , 1 candidate found (1.98 exp bkg)

Searching for UHE photons with hybrid events



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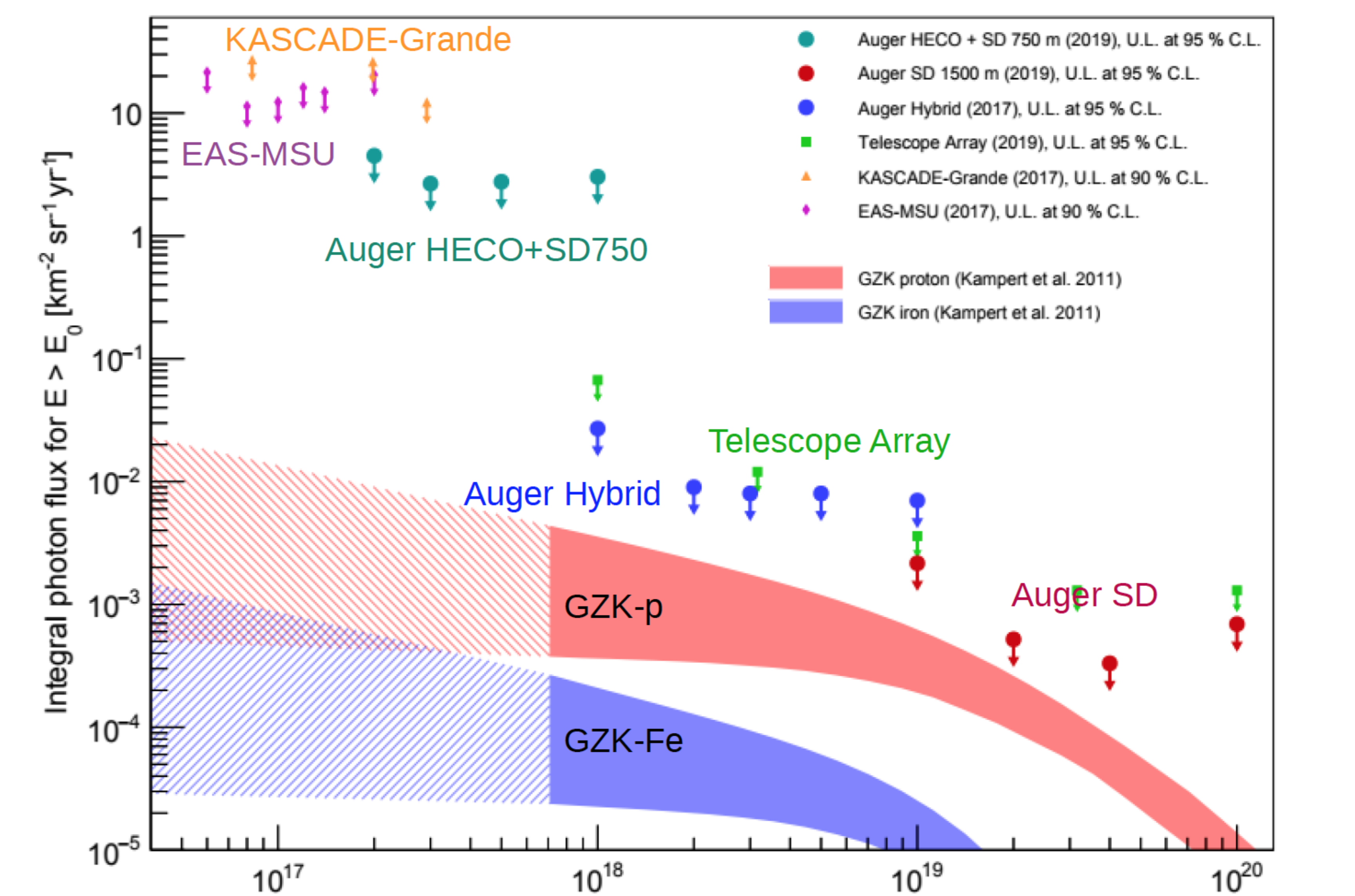
  Steepness of the lateral distribution in SD

Datasample : 2204 events , 1 candidate found (1.98 exp bkg)

Searching for UHE photons with Auger SD



Origin and spectra of cosmogenic neutrinos

UHE protons

a) $p + \gamma_{CMB} \rightarrow n + \pi^+$ (photoproduction)

b) $p + p \rightarrow n + p + \pi^0 + \pi^\pm$ (pp interactions)

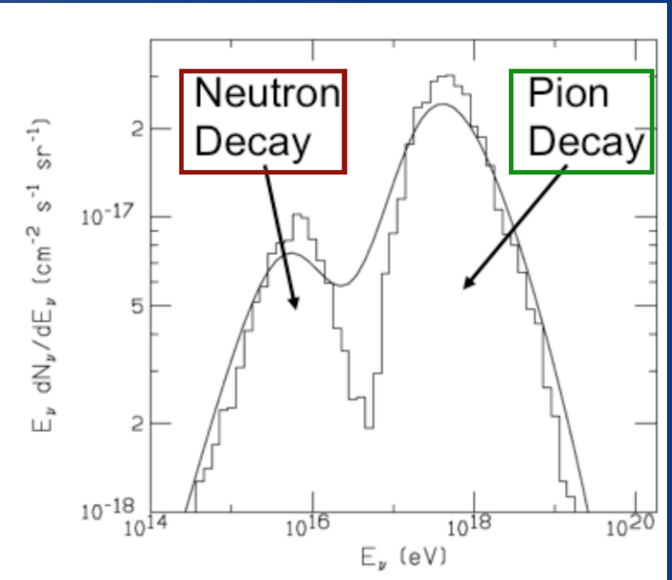
matter at/around source

- $\pi^{+(-)} \rightarrow \mu^{+(-)} + \nu_\mu \; (\bar{\nu}_\mu)$
  - $\mu^{+(-)} \rightarrow e^{+(-)} + \bar{\nu}_e \; (\nu_e) + \nu_\mu \; (\bar{\nu}_\mu)$

$E_\nu \sim 0.05 \, E_p$

- $n \rightarrow p + e^- + \bar{\nu}_J$

$E_\nu \sim 0.001 \, E_p$



UHE nuclei

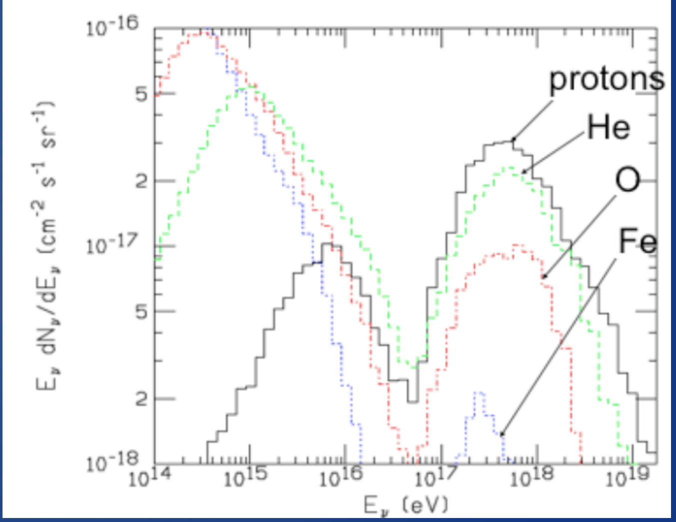
c) $A + \gamma \rightarrow A' + p$ (nucleus photo-disintegration)

$p + \gamma \rightarrow ....\nu$'s

IR/Optical/UV background

With heavier nuclei , the pion peak decrease

$E_\nu \sim 0.05 \, E_A / A$

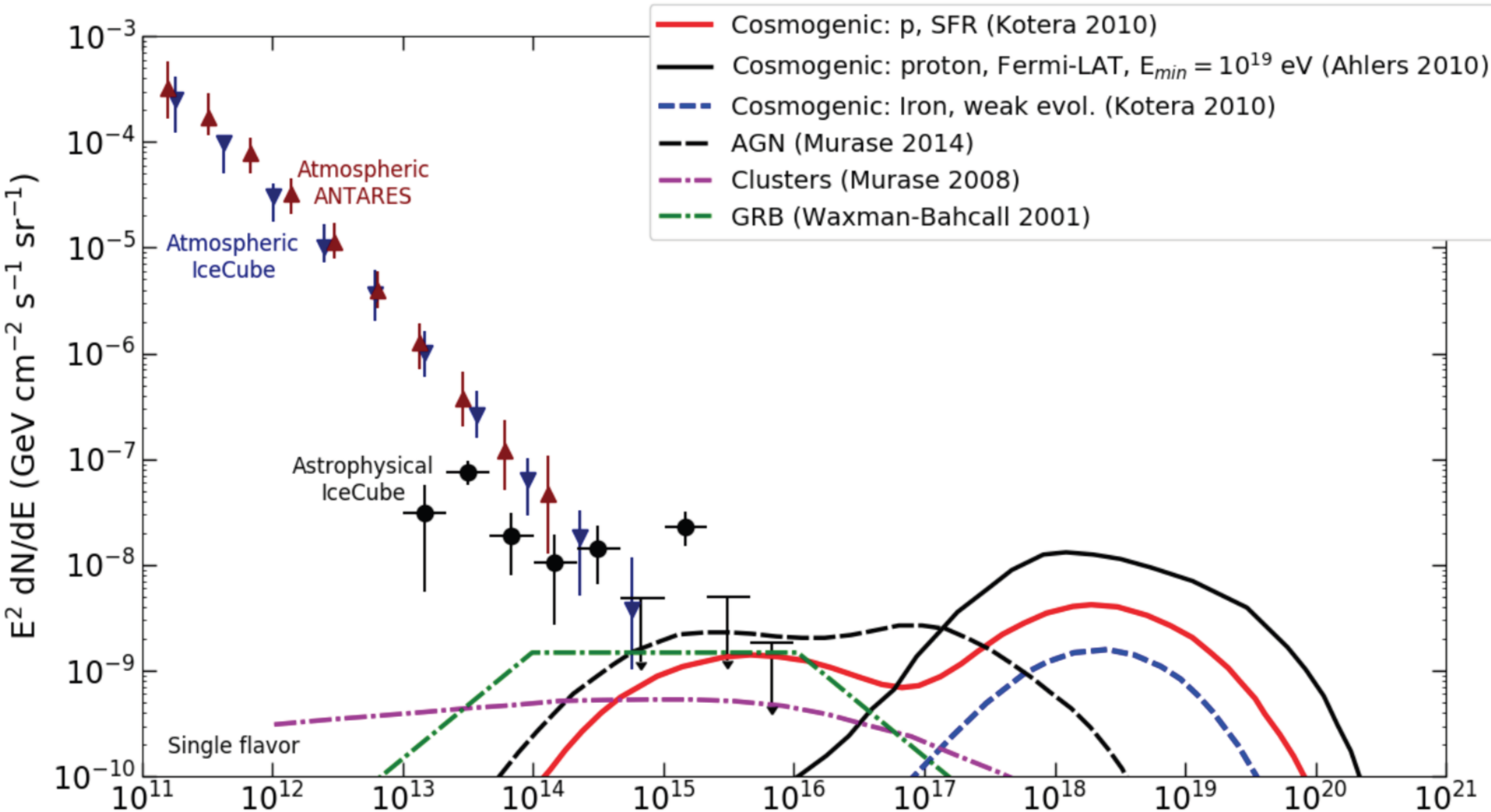


Cosmogenic Neutrino Energy depends on target photons:

$E_\gamma = 10^{-4}$ eV (CMB) $\rightarrow E_\nu \sim 2$ EeV

$E_\gamma = 1$ eV (IR/UV) $\rightarrow E_\nu \sim 0.02$ EeV

Origin and spectra of cosmogenic neutrinos

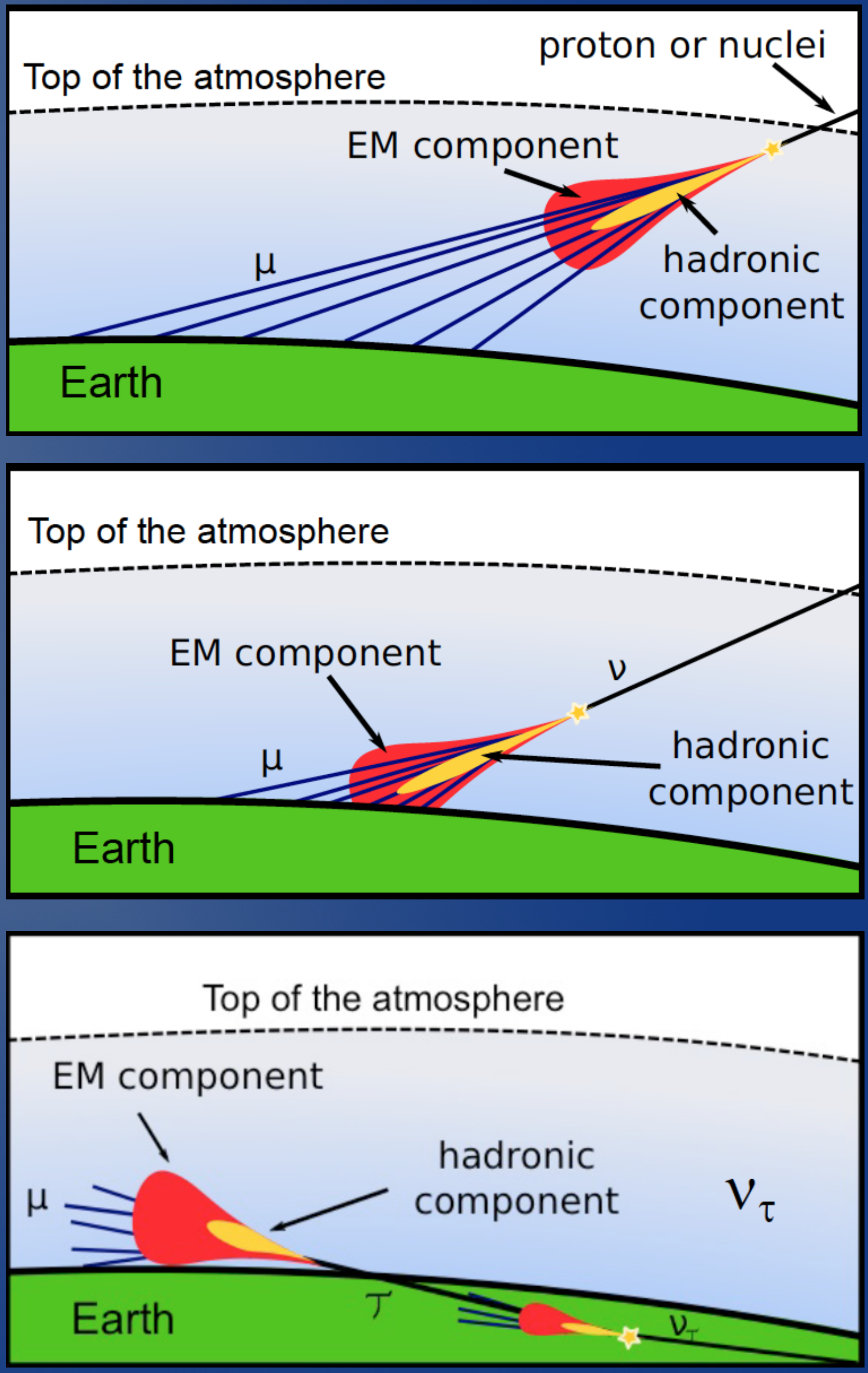


Searching for UHE neutrinos with Auger SD

Essentially we search for inclined showers with large EM component

Protons&nuclei initiate inclined showers high in the atmosphere. Only muons reach the ground.

Neutrinos can initiate showers close to ground, with a large residual EM component



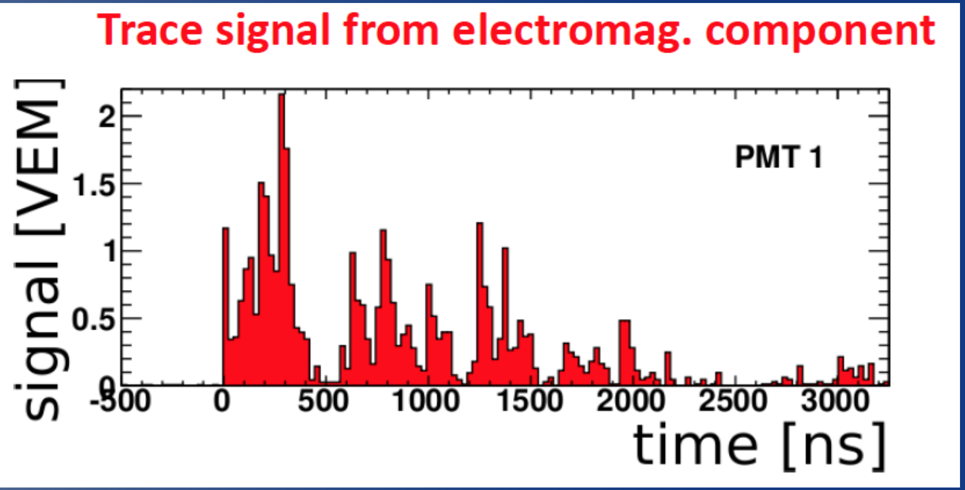
Neutrino signature in Auger SD signals

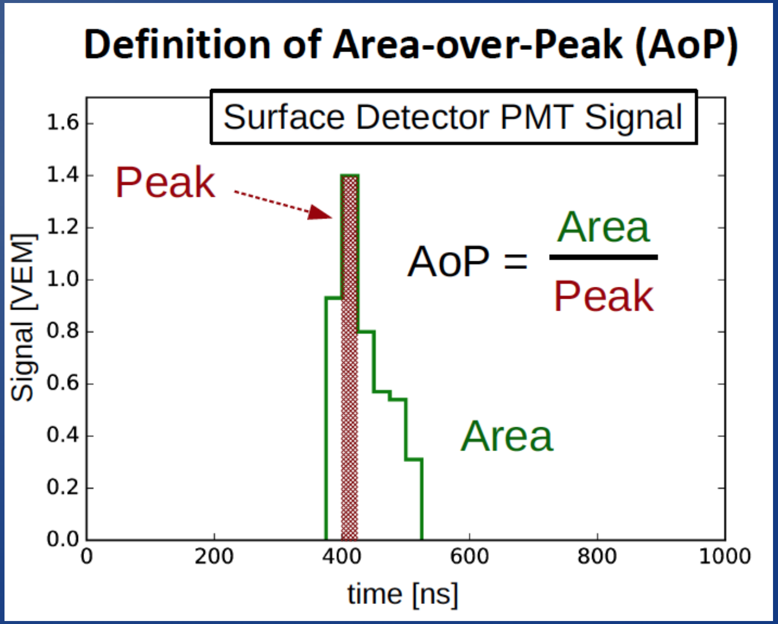
SD signals with high EM component are more extended in time.

At Trigger level , they are required to pass as Time-Over-Threshold (ToT)

In offline reconstruction, have a large Area-over-Peak (AoP) ratio.

A neutrino candidate is identitified as a very inclined shower with large values of Area-over-Peak.

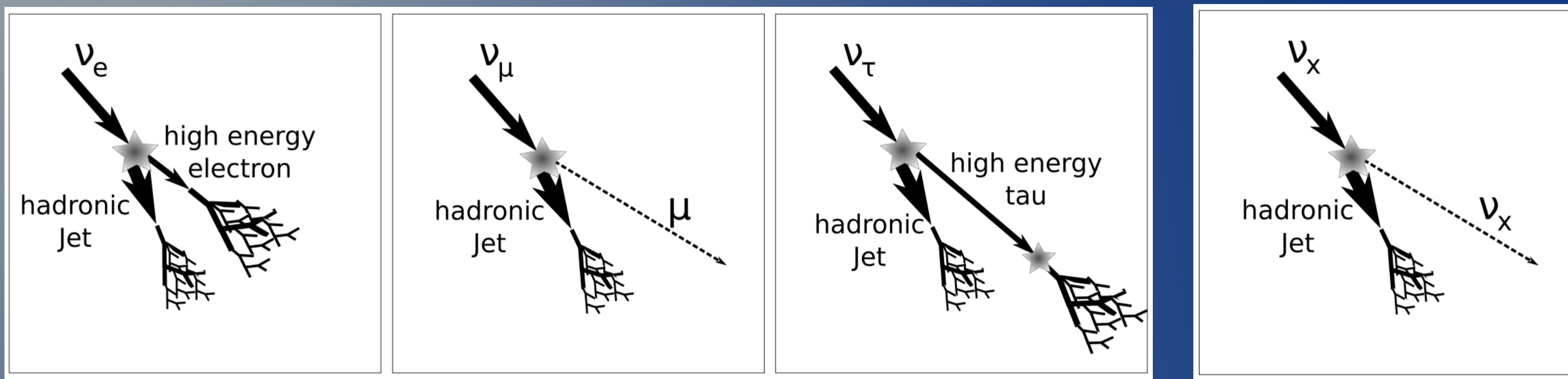


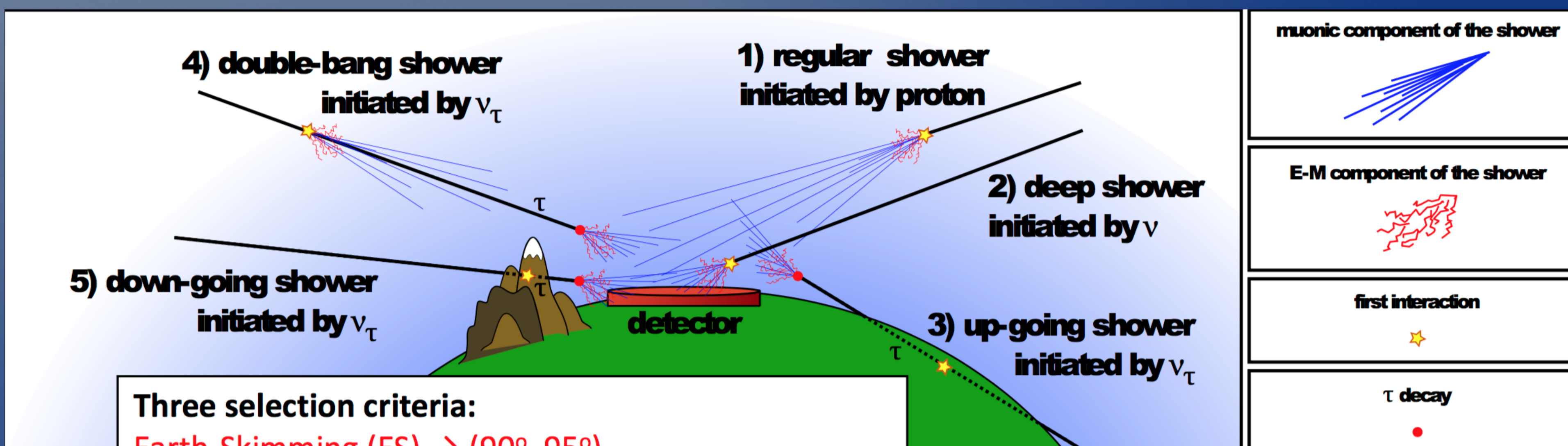


Sensitivity to all ν flavours and current type

Charged current

Neutral current





Three selection criteria:

Earth-Skimming (ES) → (90°, 95°)

Downward-going high-angle (DGH) → (75°, 90°)

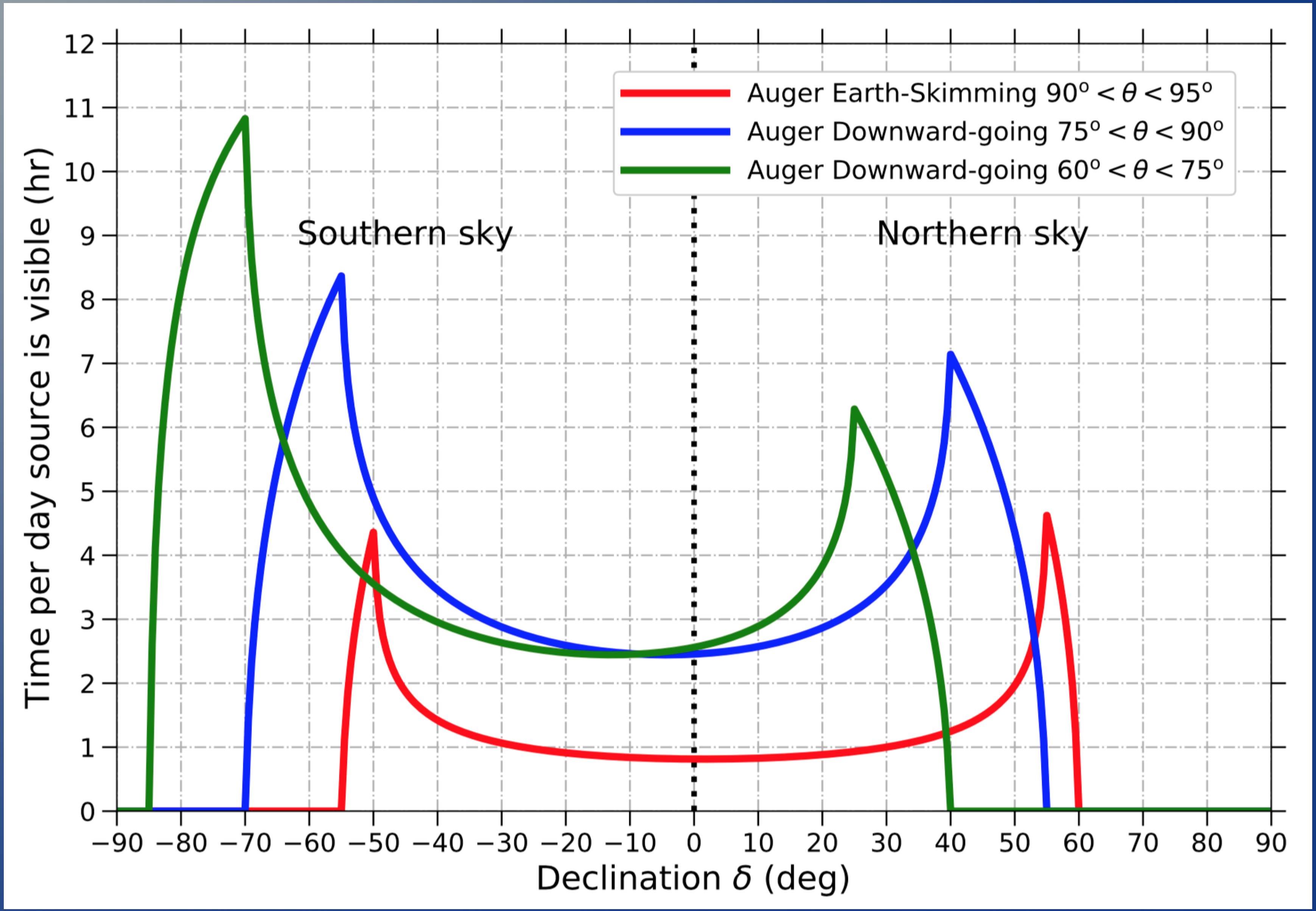
Downward-going low-angle (DGL) → (60°, 75°)

More details on selection in
Pierre Auger Collab., PRD **91**, 092008 (2015)

7

Daily exposure of a given pointlike ν source

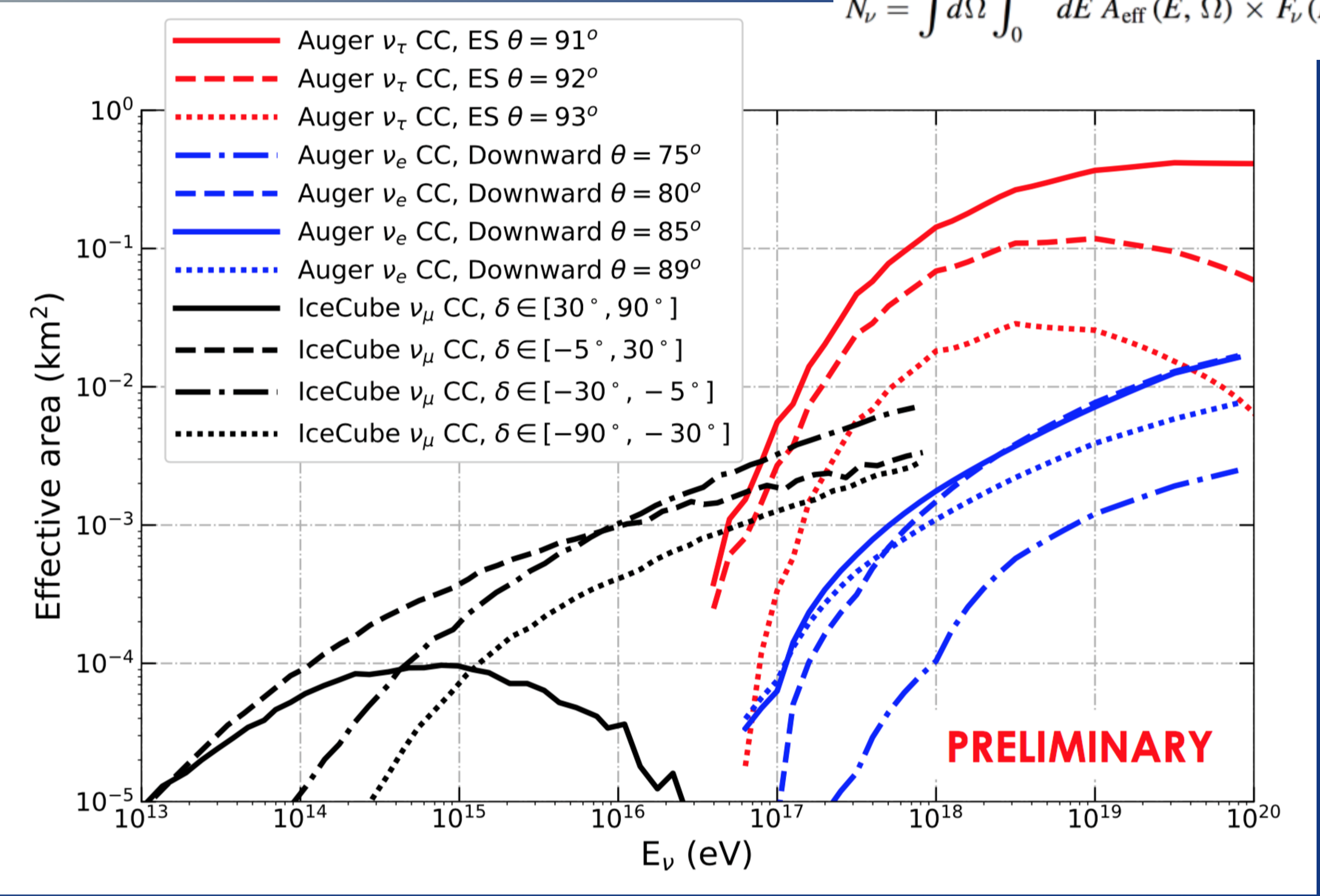
The number of hours per day depends on its declination



Sensitivity to transient sources

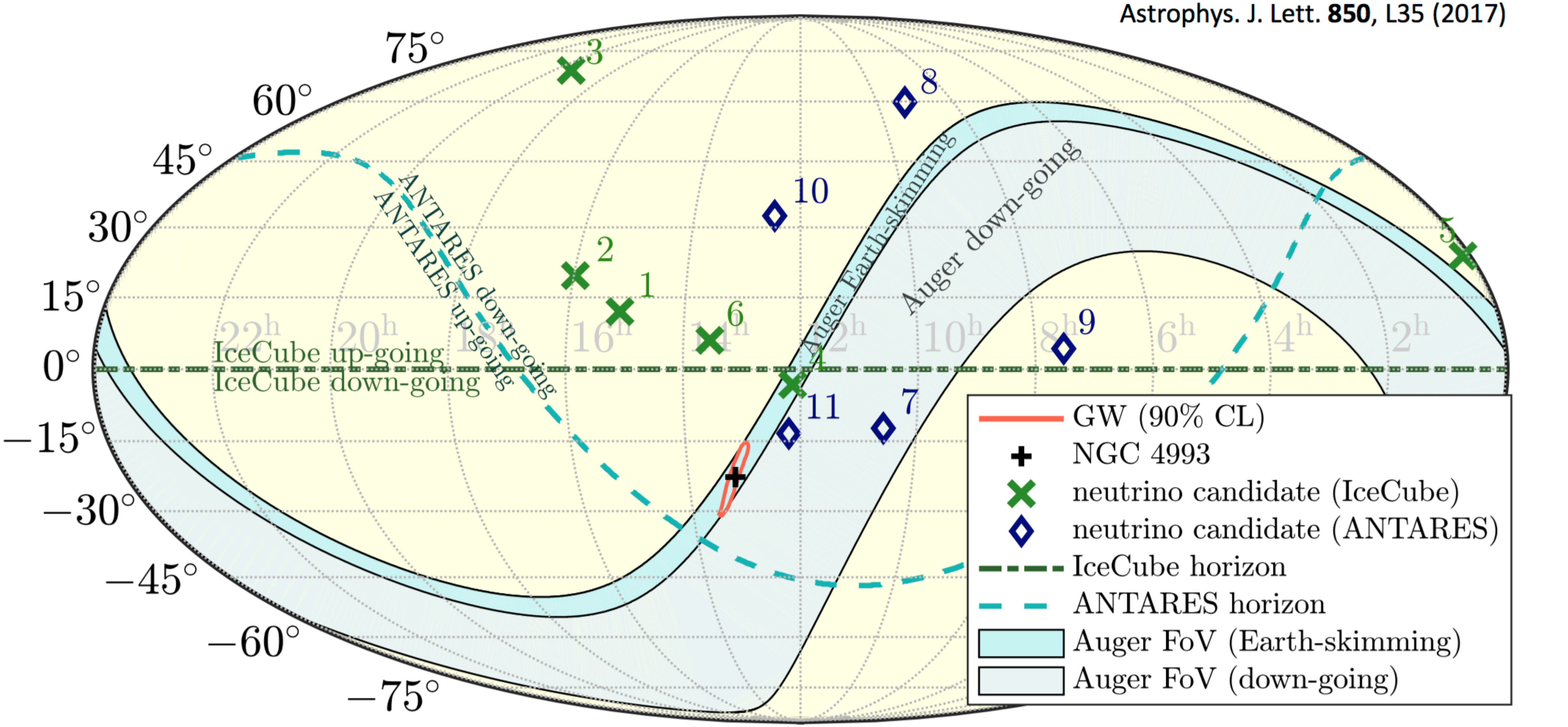
Flux variation depends on the convolution of instantaneous Effective area A_{eff}

$$\dot{N}_\nu = \int d\Omega \int_0^\infty dE\, A_{\rm eff}(E,\Omega) \times F_\nu(E_\nu,\Omega)$$



Follow-up of GW170817 BNS merger

ANTARES, IceCube, Auger, LIGO & Virgo
Astrophys. J. Lett. **850**, L35 (2017)



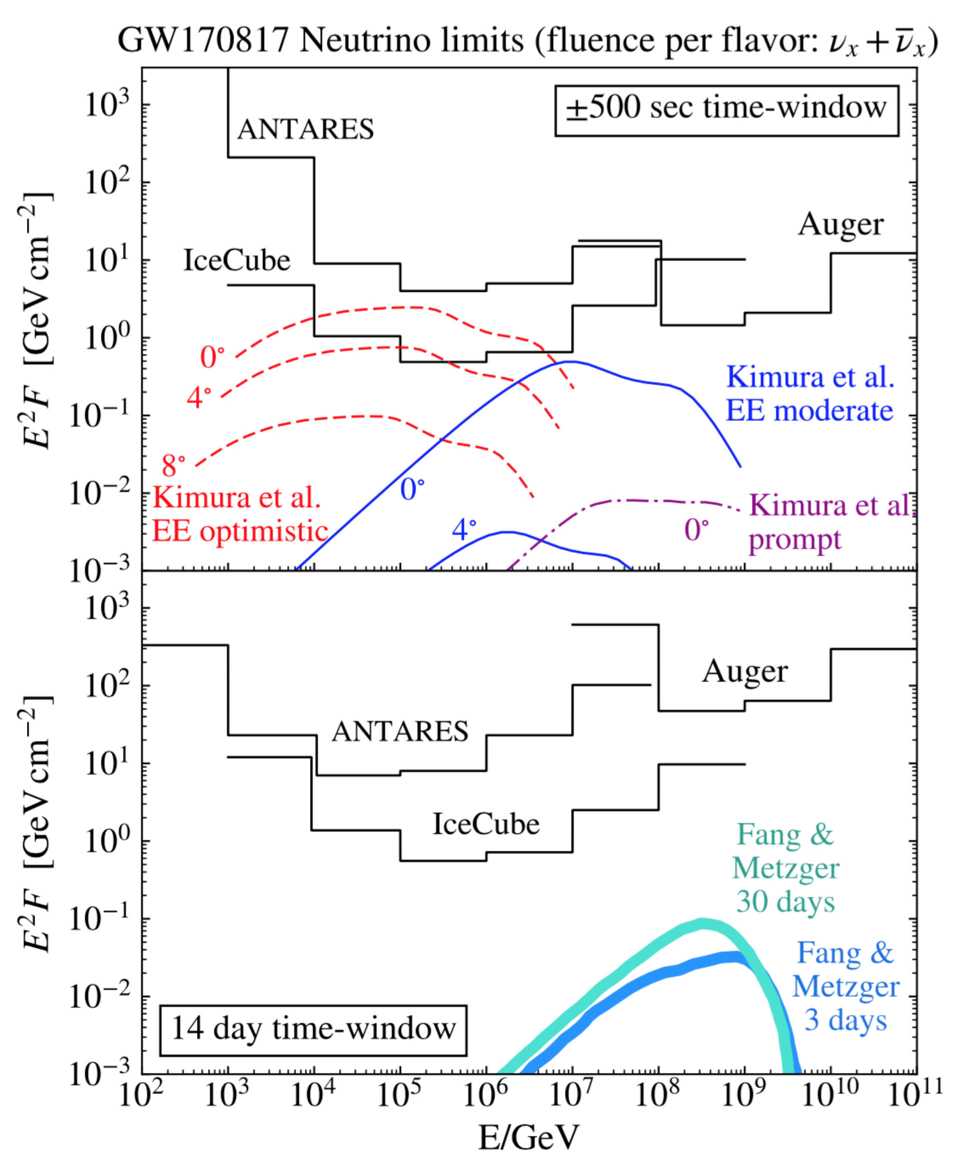
We were EXTREMELY LUCKY: the BNS merger was in the 1% of the sky with optimal acceptance for detection of UHE τ neutrinos in Auger, at the time of arrival of GW170817

Limits on ν fluxes from BNS merger GW170817

Non observation of neutrino candidates from the source location in a ±500 time window about the time of arrival of GW170817, and in the 14 days following the observation.
A short GRB viewed with a large off axis angle (i.e. larger than 20º) is not expected to generated a flux of detectable UHE neutrinos towards Earth.

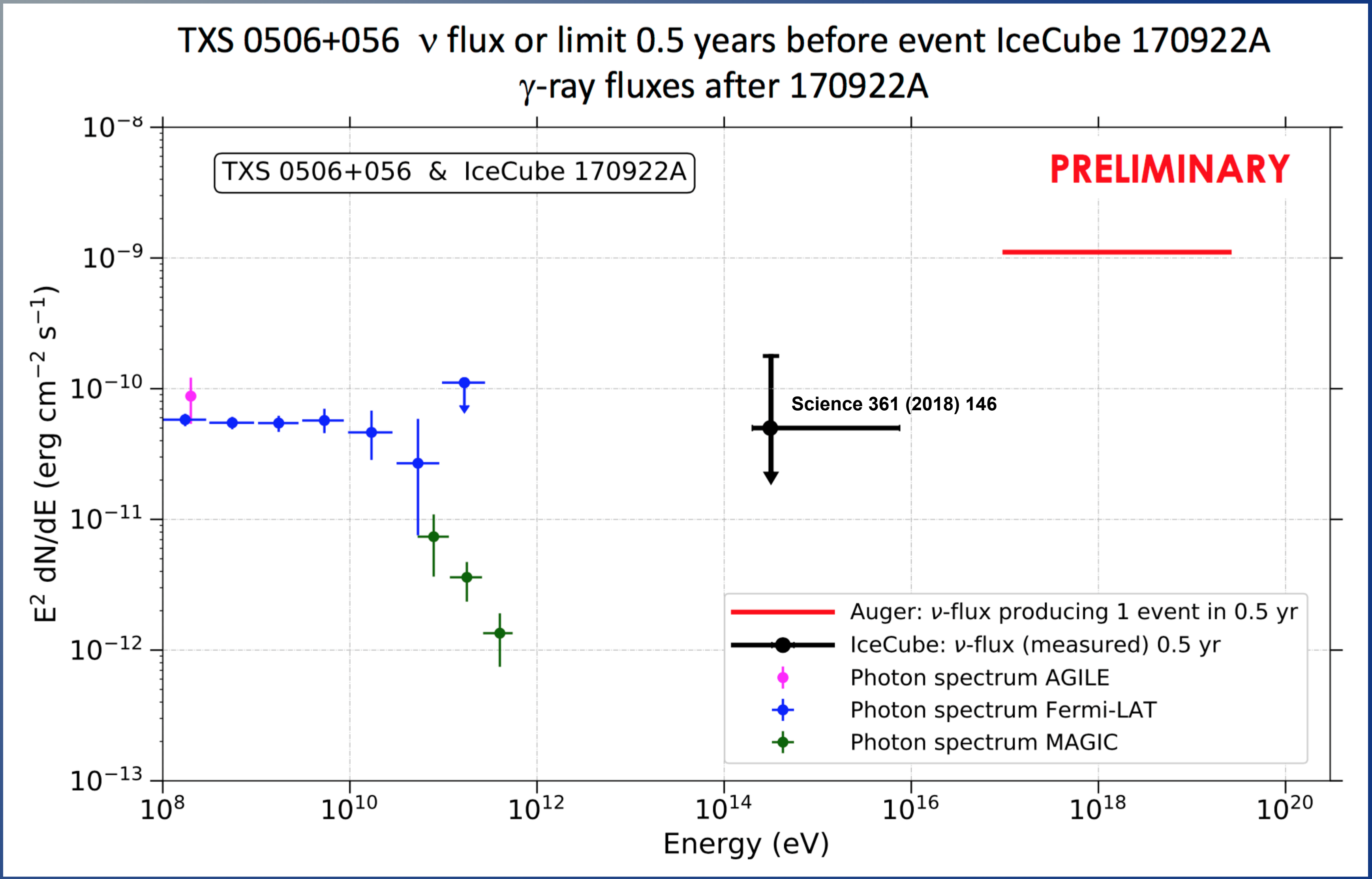
Kimura et al, ApJ 848(2018)L4
- prompt emission: due to internal dissipation in the jet
- Extended Emission (EE): due to forward shocks around the short GRB
- viewable on or off axis
- neutrinos emitted from close GRB or EE

Fang et al, arXiV:1707.04263
- msec Magnetar remnants
- delayed ν 's are produced in CR interactions with close nucleons
- if magnetars are strong sources of UHECR's (light nuclei at $10^{17.5\text{-}18}$ eV) candidate neutrinos are expected



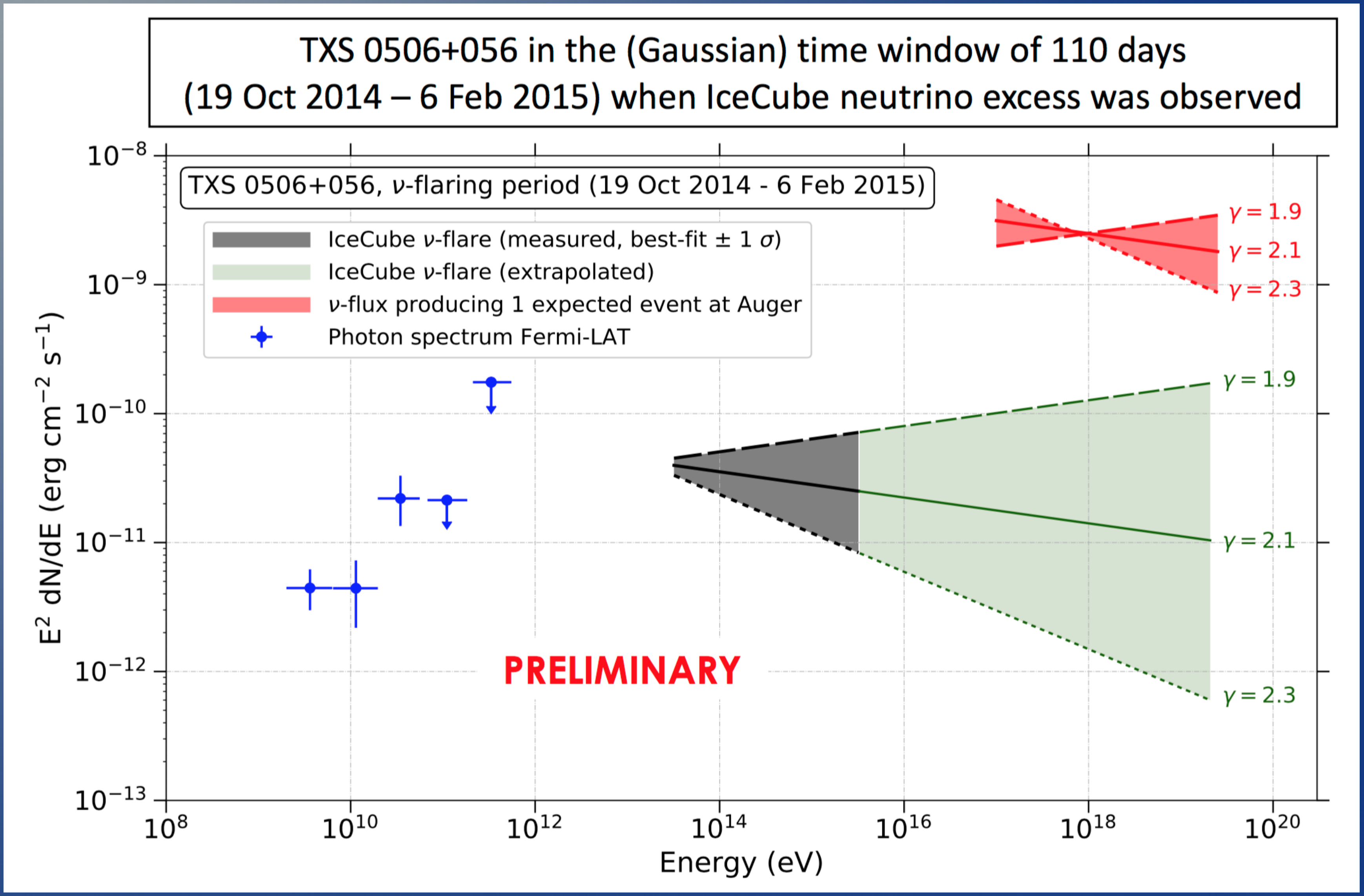
ANTARES, IceCube, Auger, LIGO & Virgo
Astrophys. J. Lett. **850**, L35 (2017)

Flux/limits from Blazar TXS 0506 + 056 (dec ~ 5.7º)



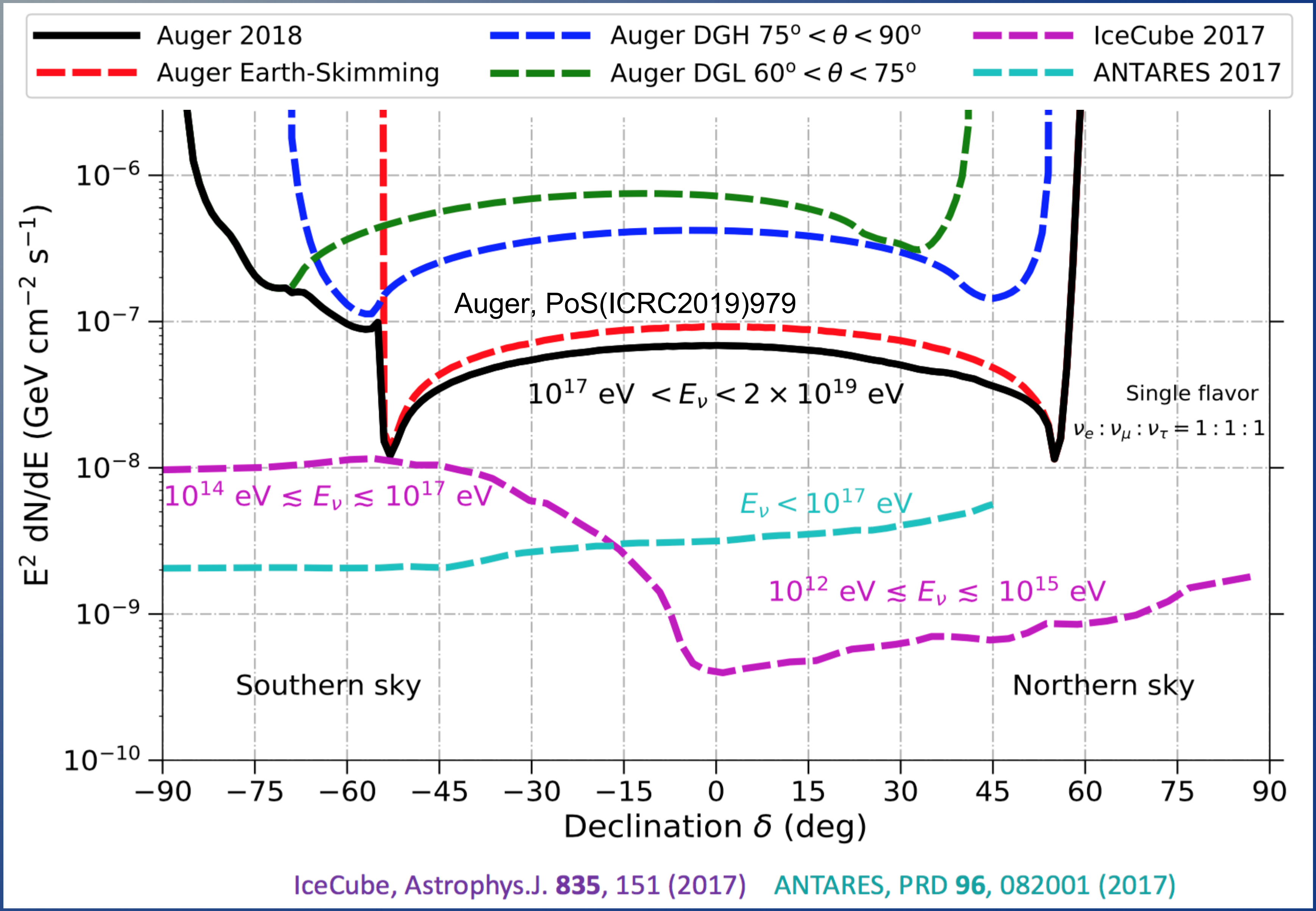
First upper limits to the neutrino flux from TXS 0506+056 at EeV energies

Flux/limits from Blazar TXS 0506 + 056 (dec ~ 5.7º)

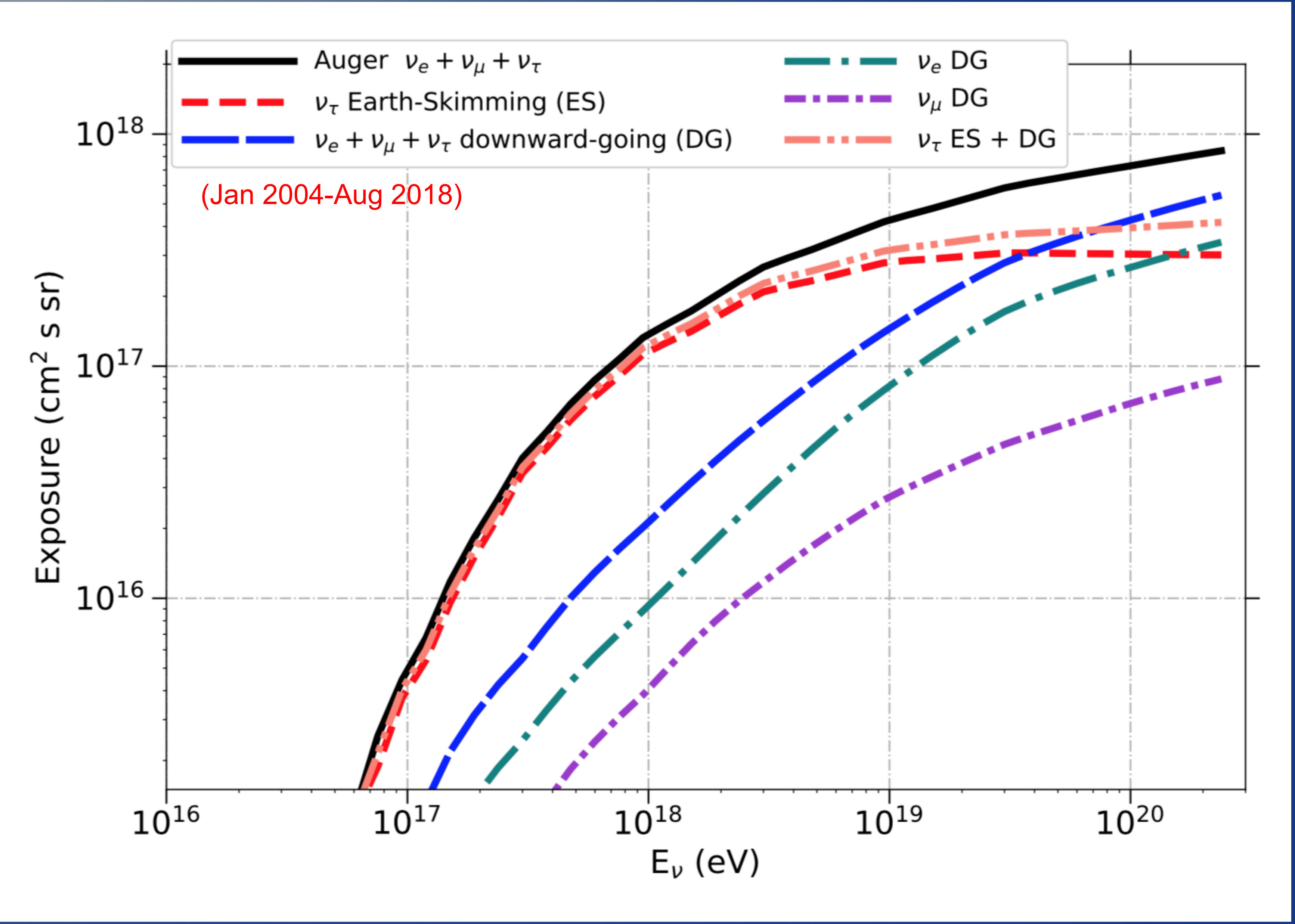


Limits to point-like, steady ν sources

Complementary, in energy range, to IceCube/ANTARES limits

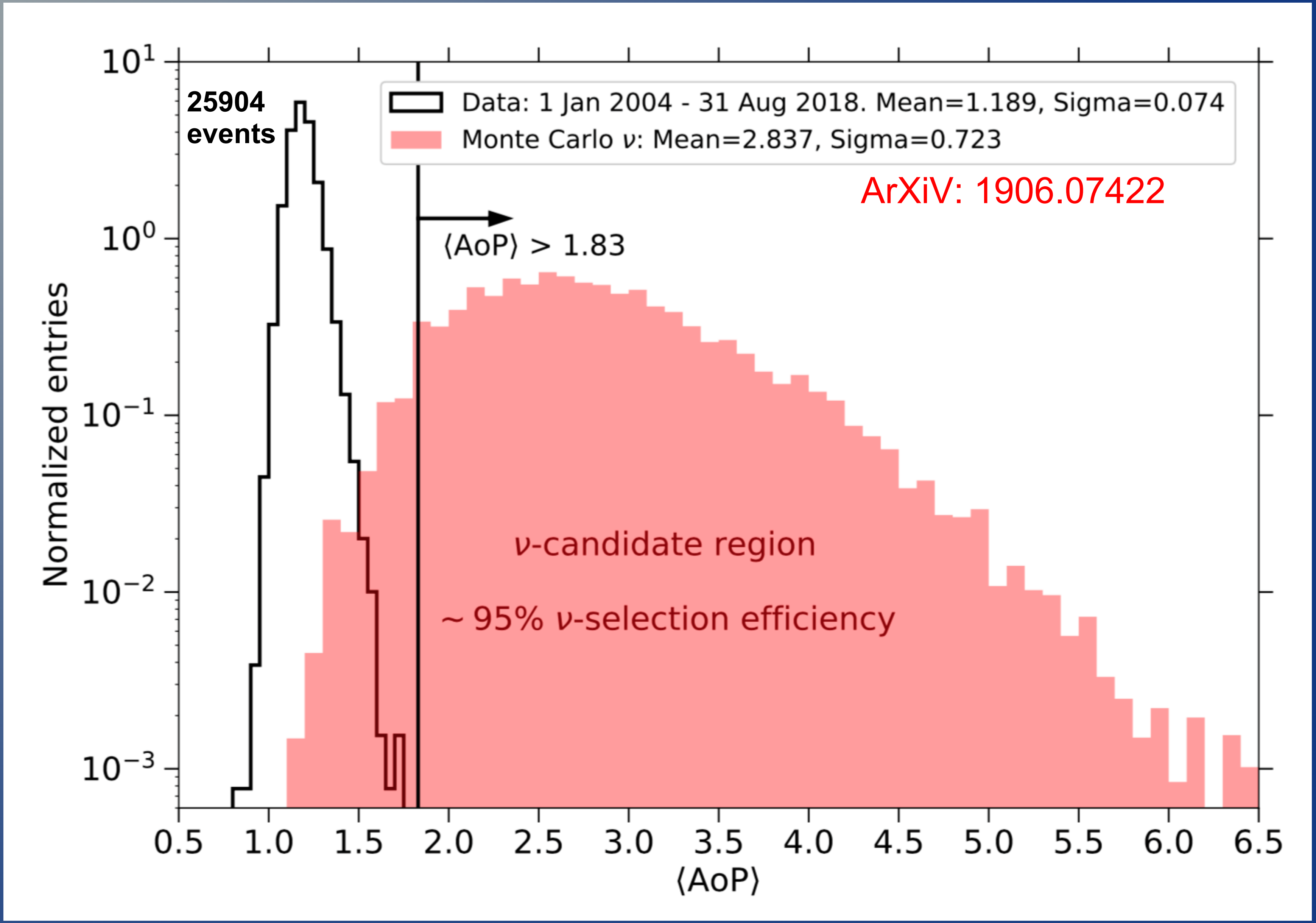


The diffuse flux of UHE ν's: Auger exposure



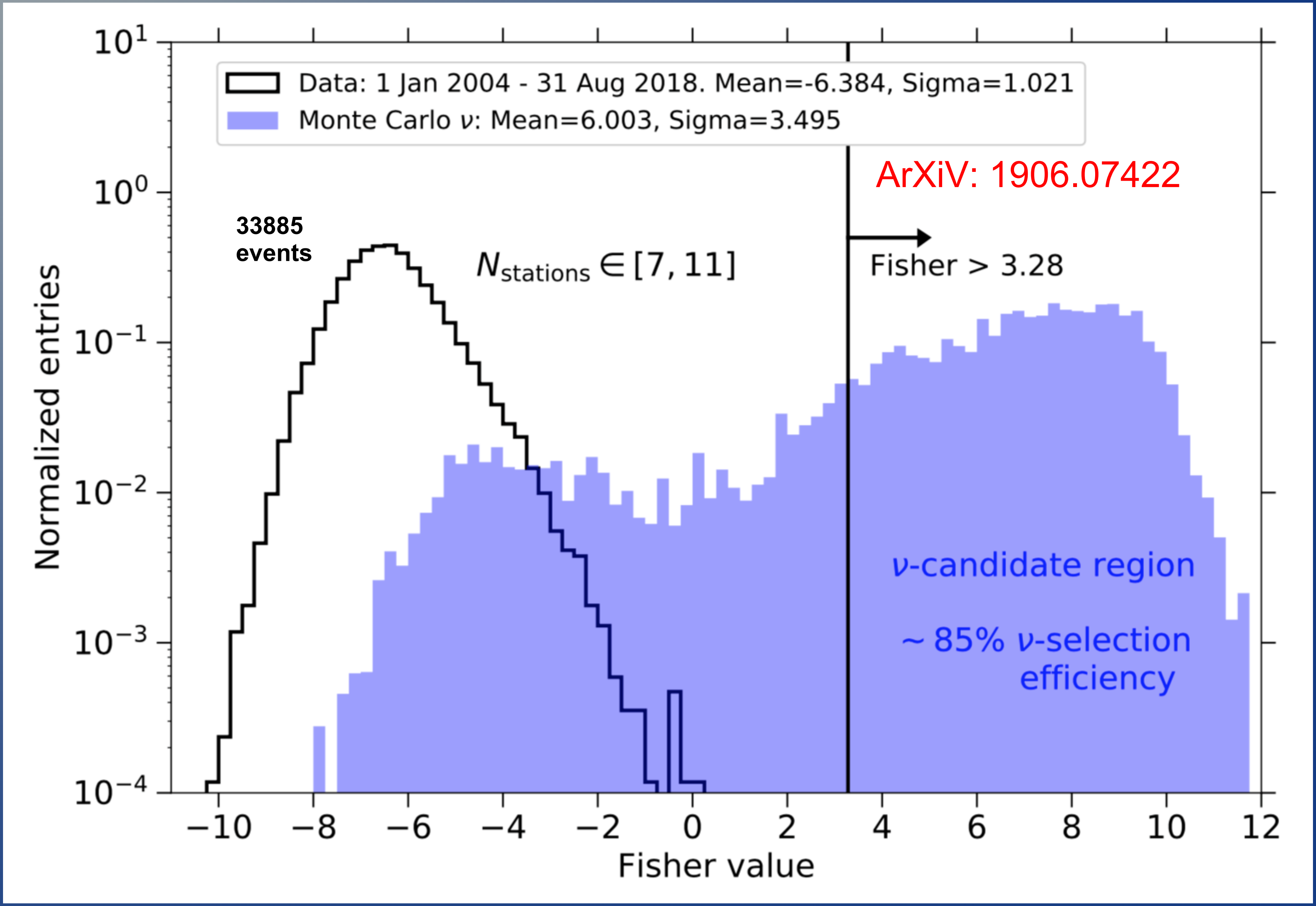
Exposures calculated for all neutrino flavors including CC and NC interactions.

Results on earth skimming neutrinos

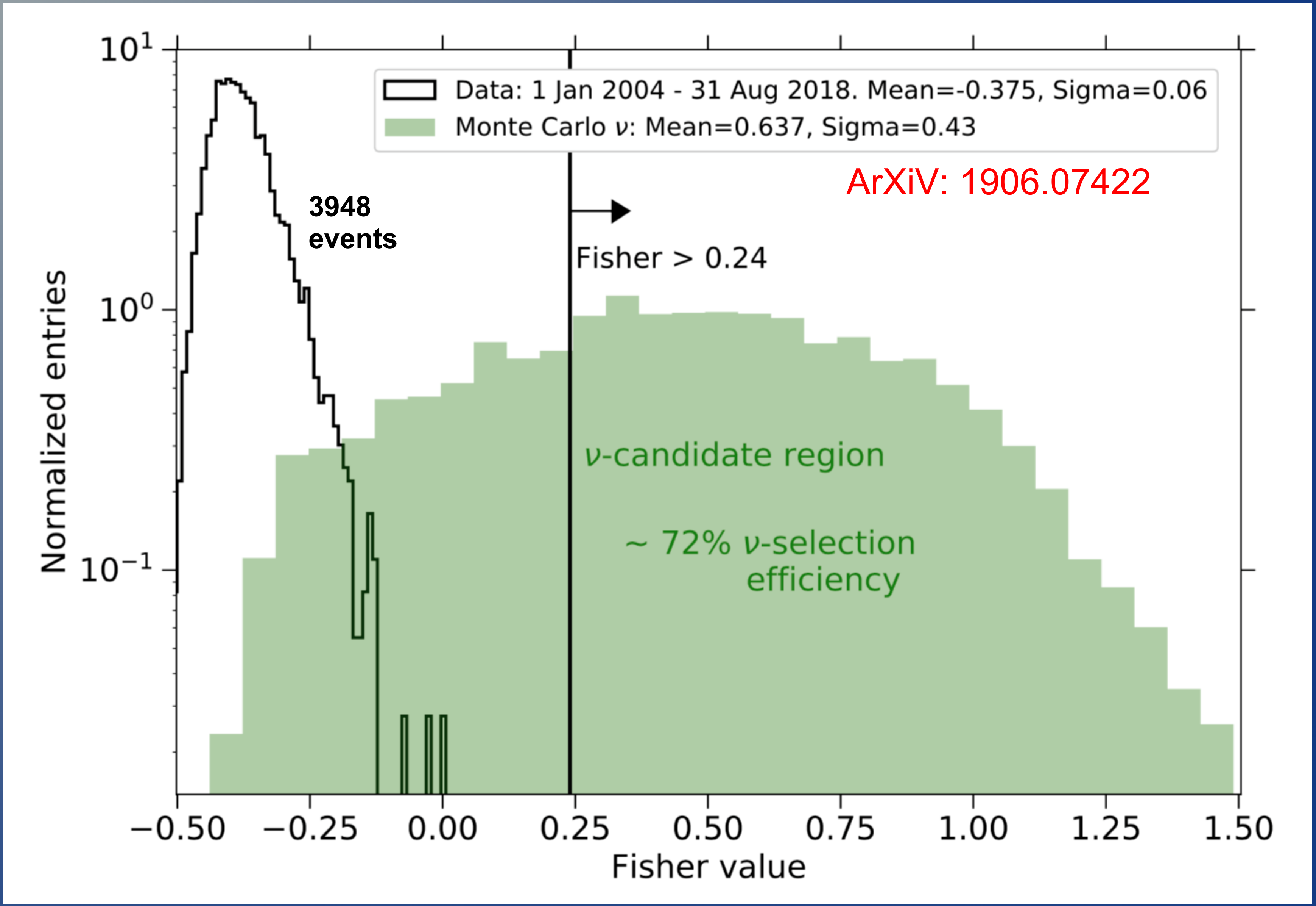


AUGER sensitivity is dominated by exposure, not by background

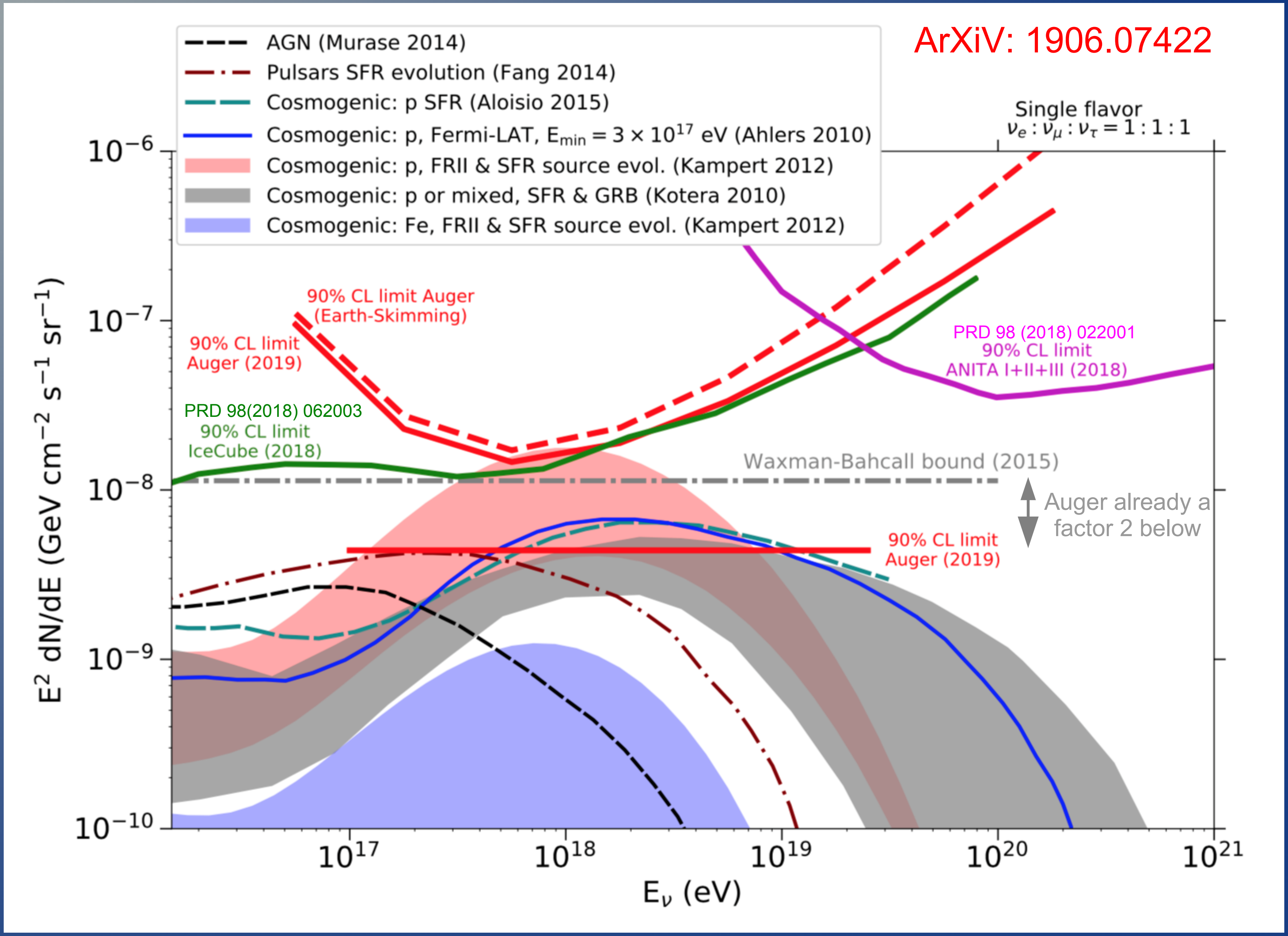
Results on DGH sample (75º<θ <90º)



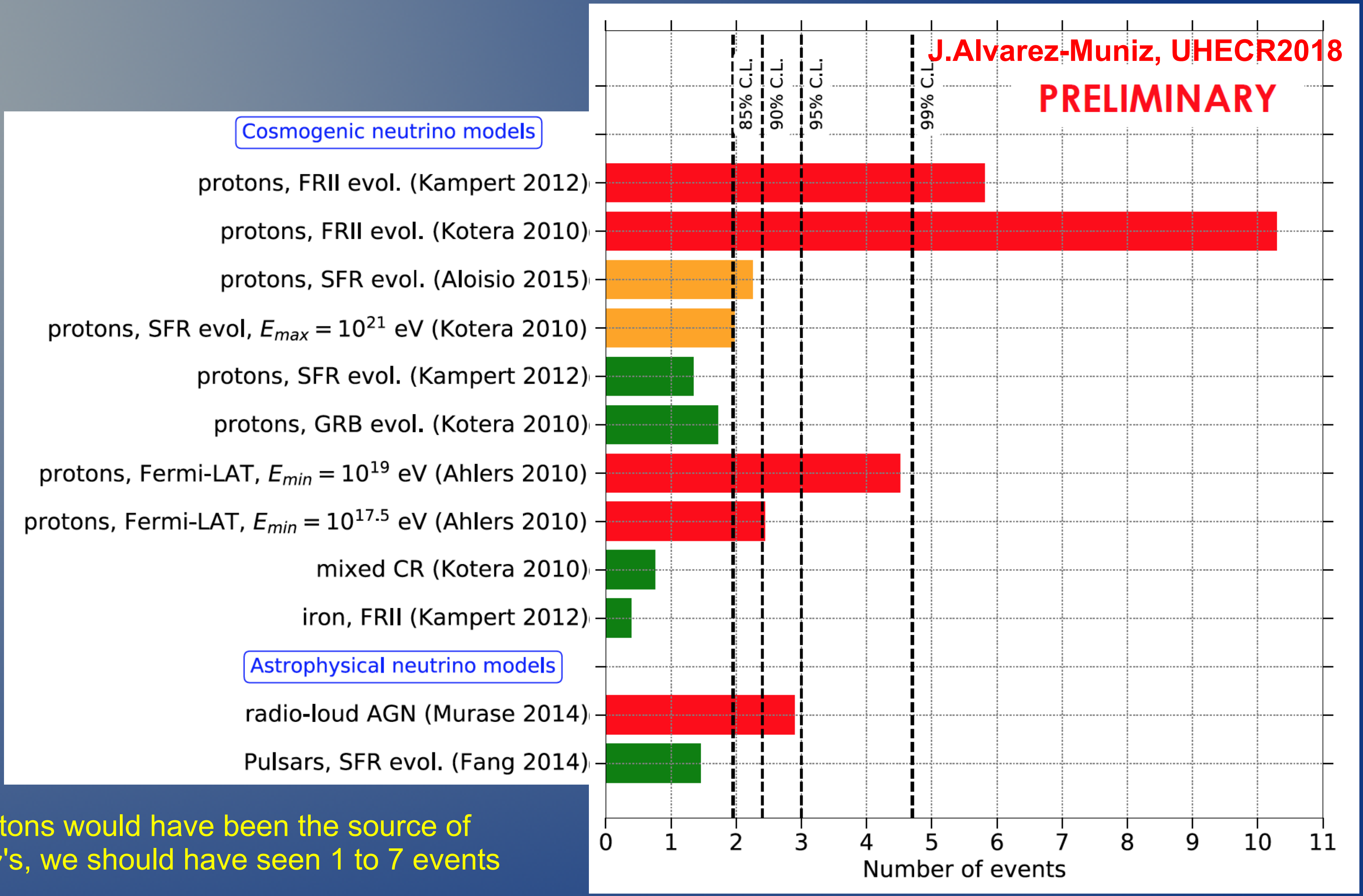
Results on DGL sample (60º<θ <75º)



Limits on the diffuse flux of UHE neutrinos



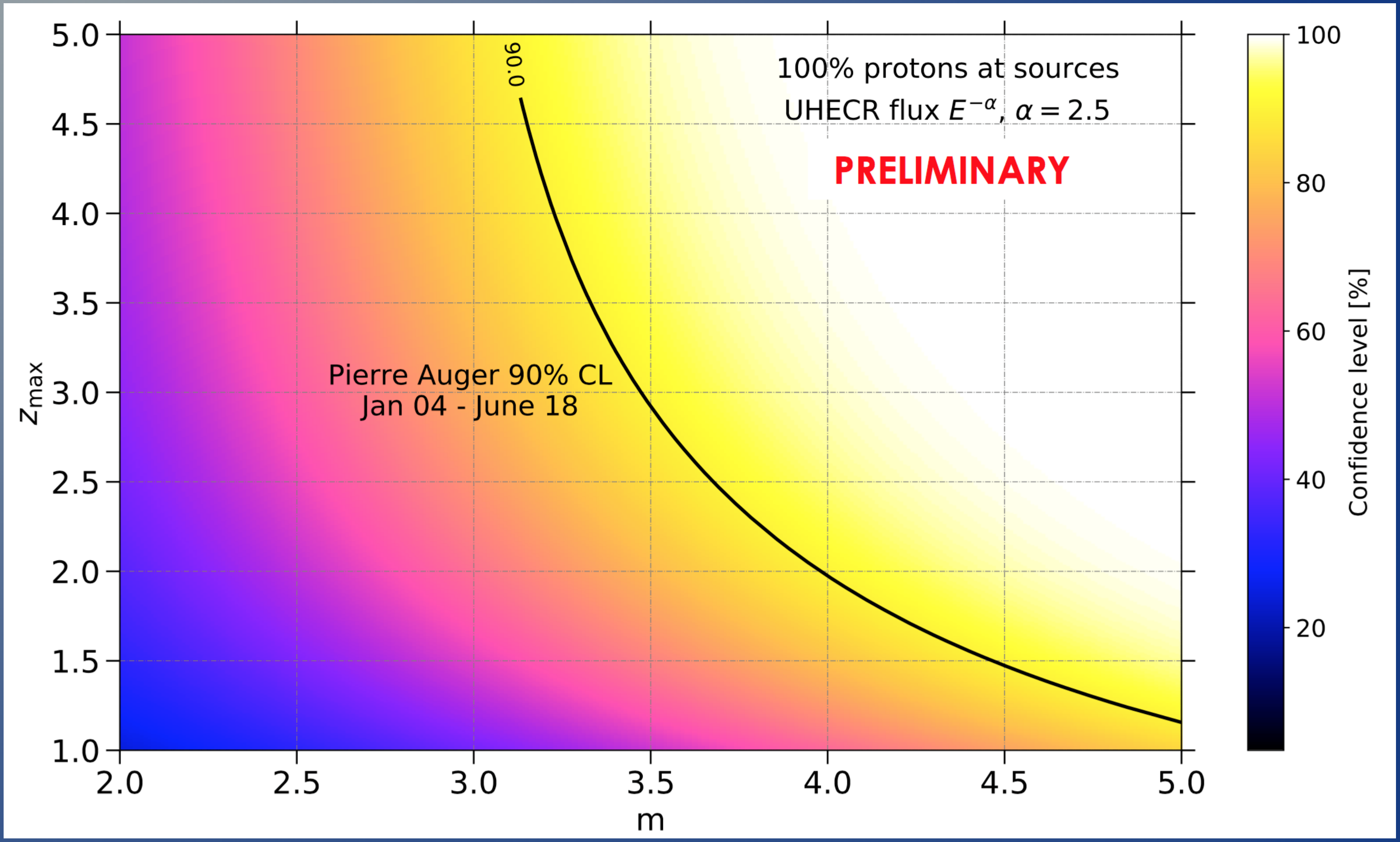
Cosmogenic ν: are we running out of (proton) sources ?



If GZK on protons would have been the source of cosmogenic ν's, we should have seen 1 to 7 events

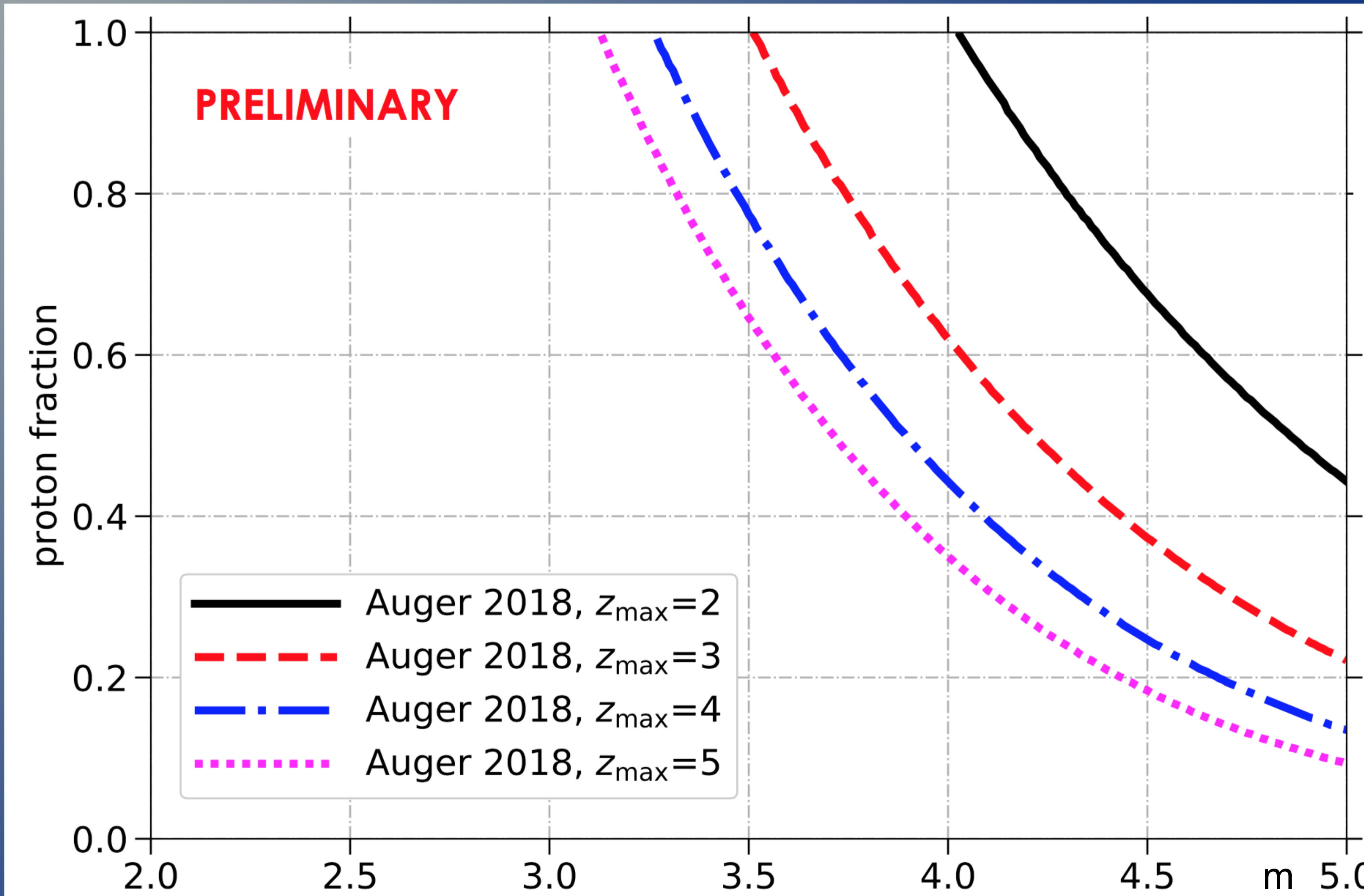
Auger is starting to constrain models of cosmogenic neutrino production based on proton dominance at sources, and assuming **weak** evolution of star formation rate with redshift

Running out of (proton) sources ?



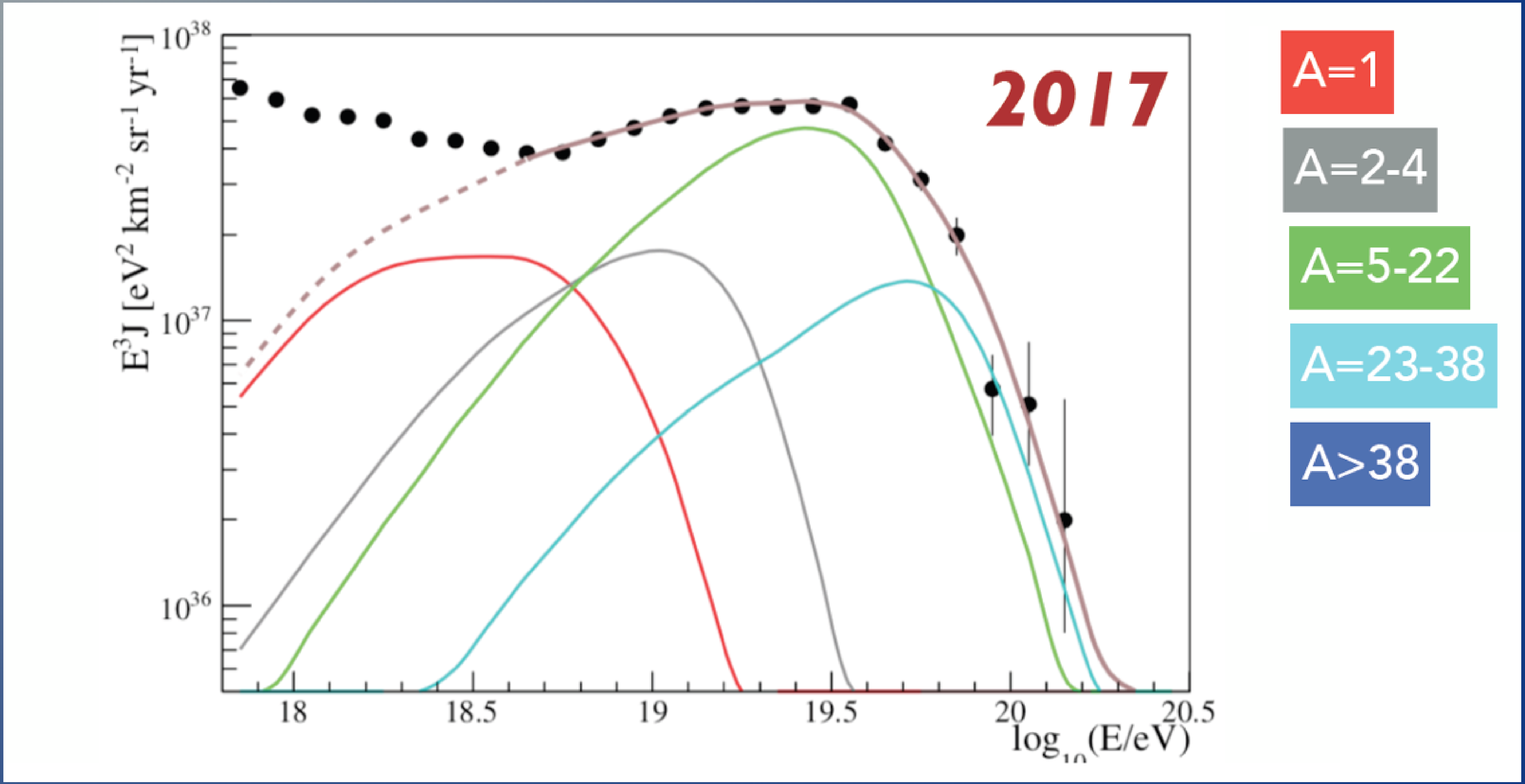
Assuming that the source numbers evolve with redshift as $(1+z)^m$, we can set limits on observable sources below max redshift z_{max} at given value of index m

Running out of (proton) sources ?

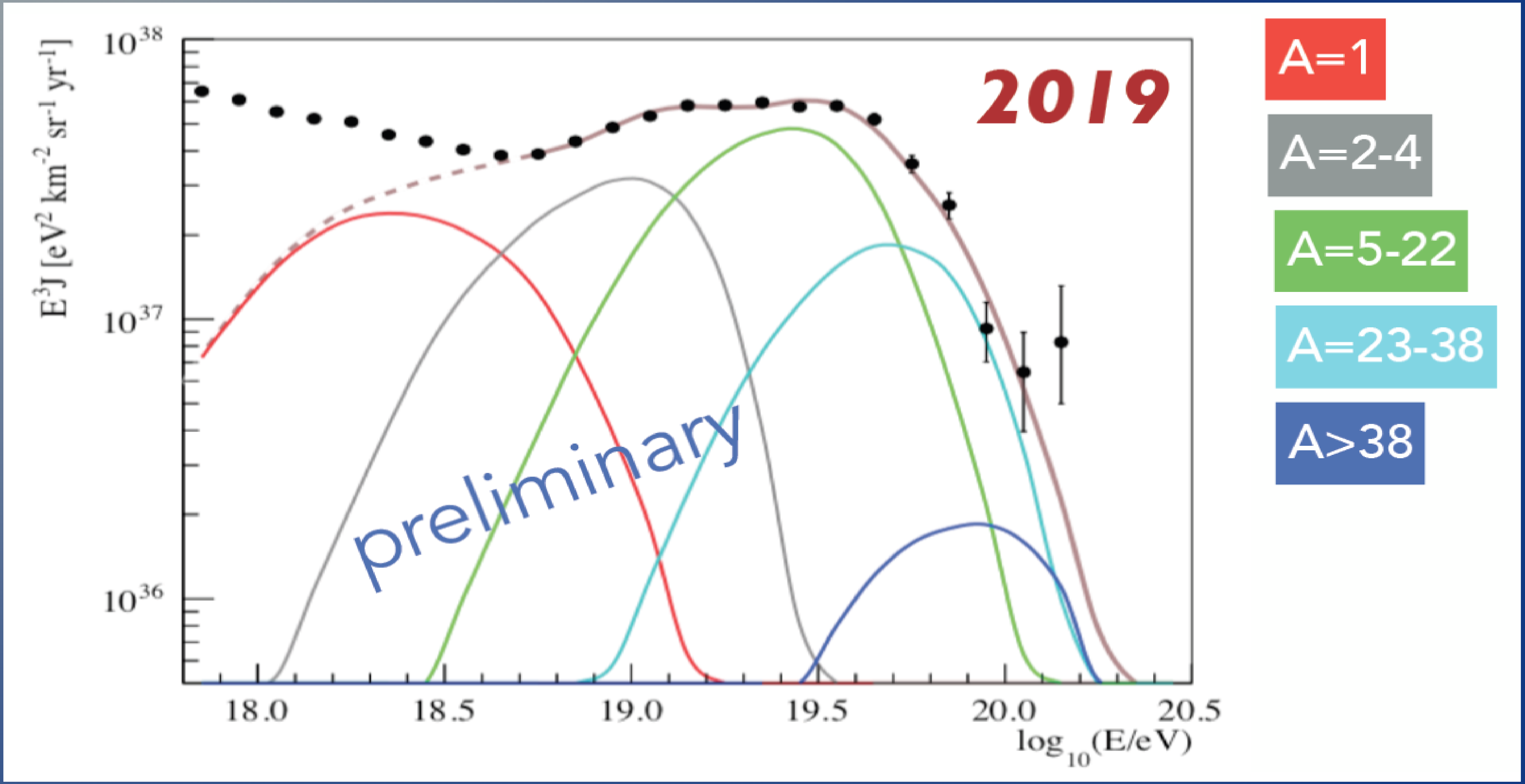


Auger set limits on top right region. Stronger constraints for high proton fraction and fast evolution with redshift z.

Using the composition to understand the spectrum

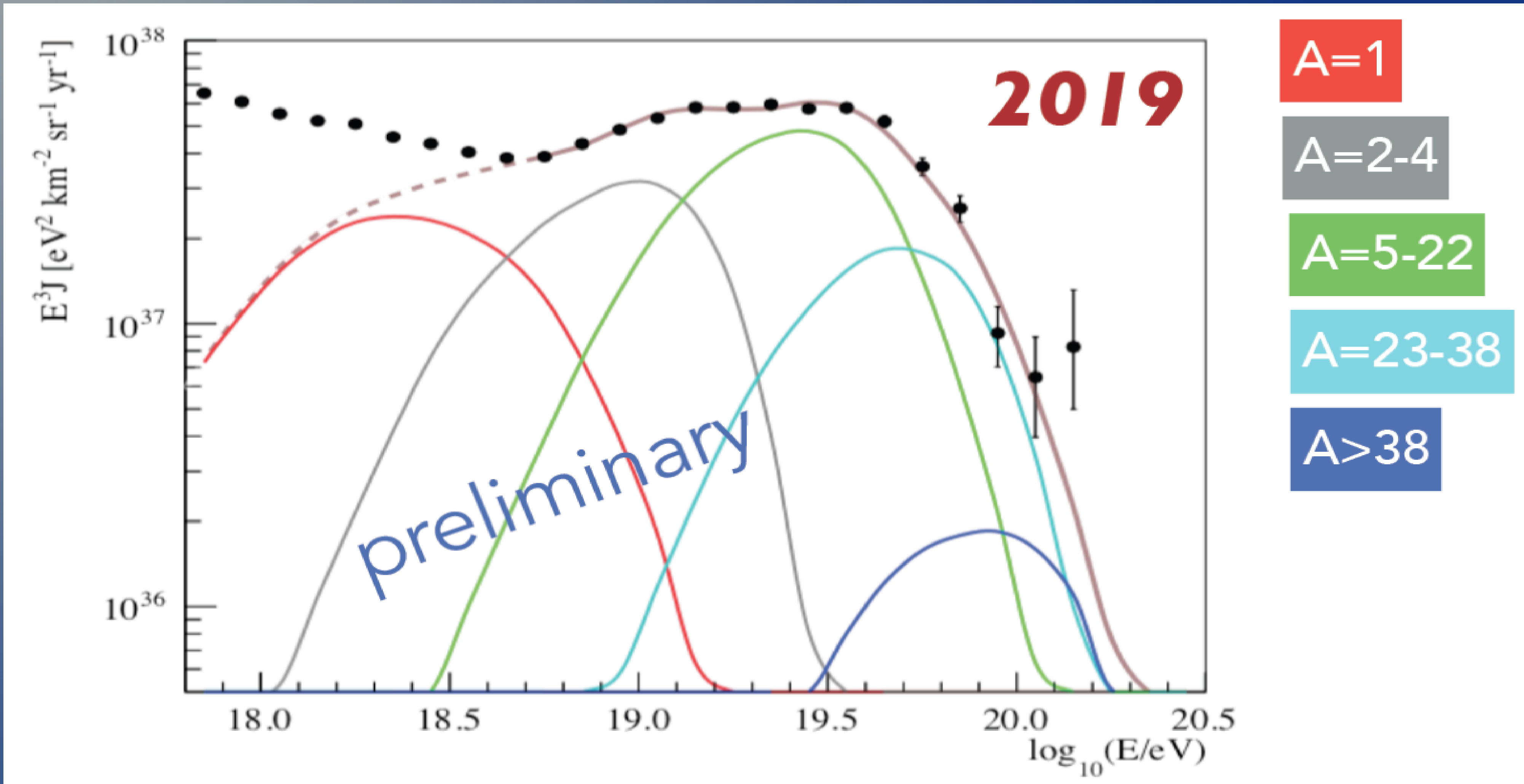


Using the composition to understand the spectrum



As we keep taking data, any structures on the end of the spectrum can be compared to models. Can we isolate the lighter component?

Using the composition to understand the spectrum



AugerPrime: Science case

Improve the sensitivity to the composition, by disentangling EM and muonic components

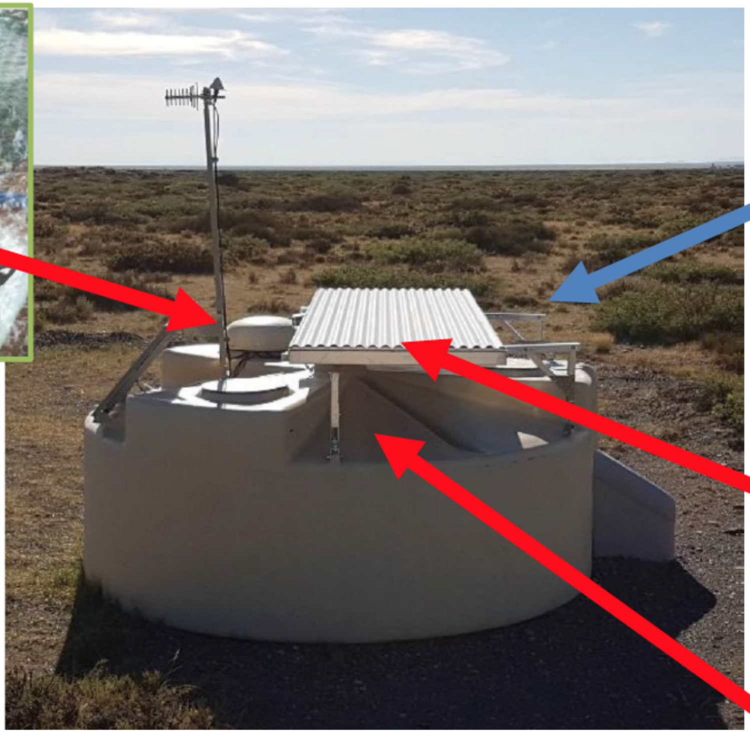
Study the origin of soppression at the end of the spectrum

Study the hadronic interactions at highest energies

Improve estimates on neutrino and photon fluxes

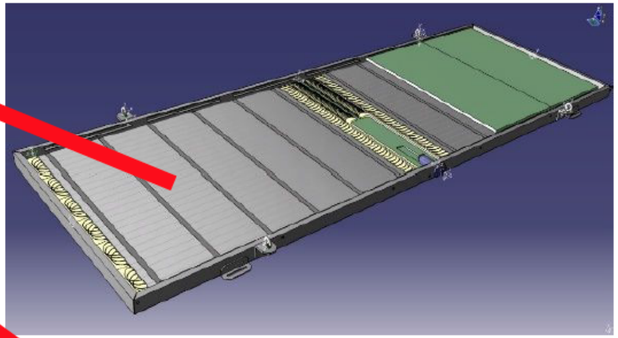
Search for potential sources by selecting light primaries

AugerPrime: Detector Upgrade



Radio detection of cosmic rays

Faster electronics



New Scintillator detectors

Small PMT to increase dynamic range

Experiment lifetime extended until 2024

Increased sensitivity to composition
Increased sensitivity to photons & ν's
Multi-messenger astronomy

AugerPrime: Work in Progress

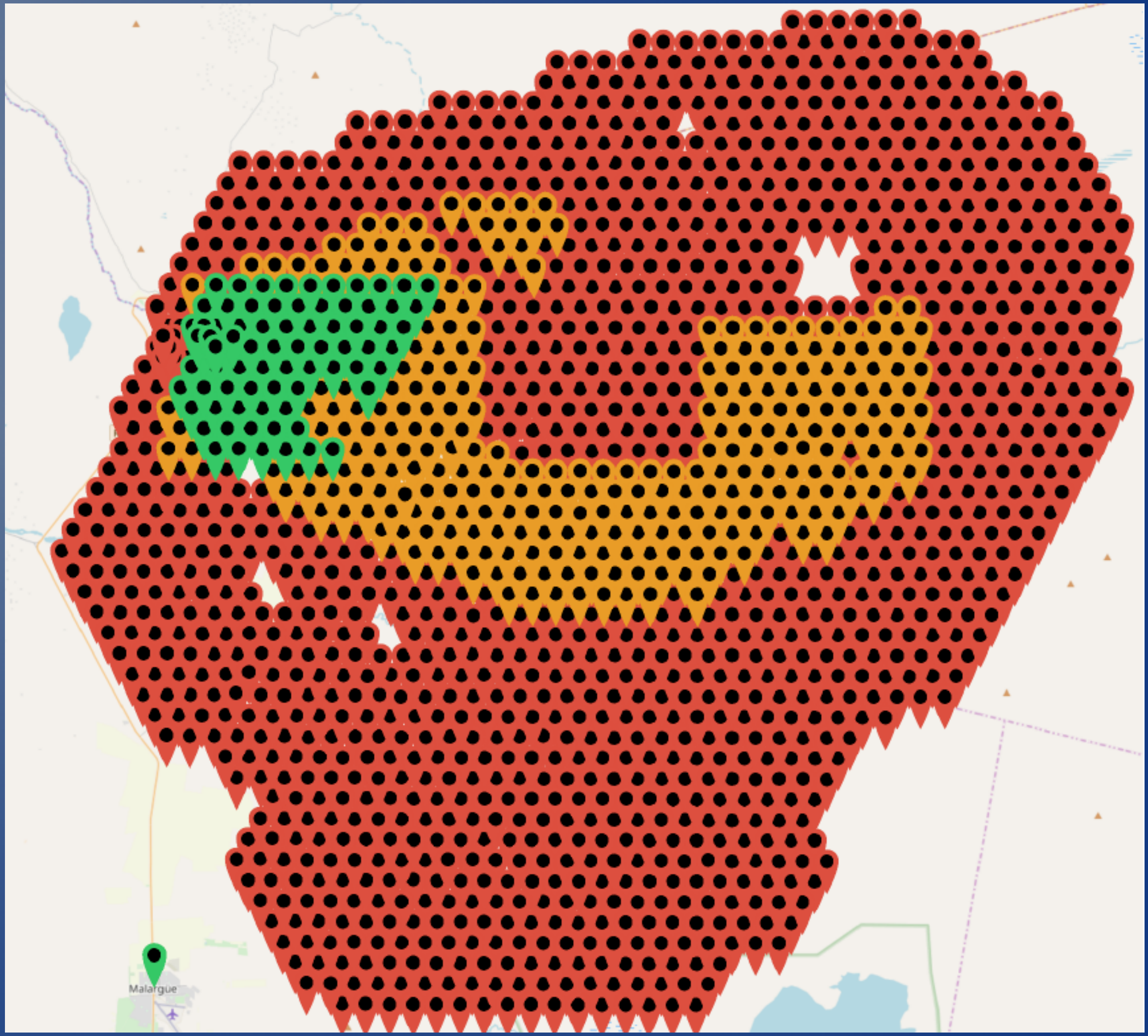
12 upgraded SD's (Engineering Array) operating since 2016 with new electronics: higher sampling rate, larger dynamic range

SSD preproduction array: 80 SD's in operation since 3/2019

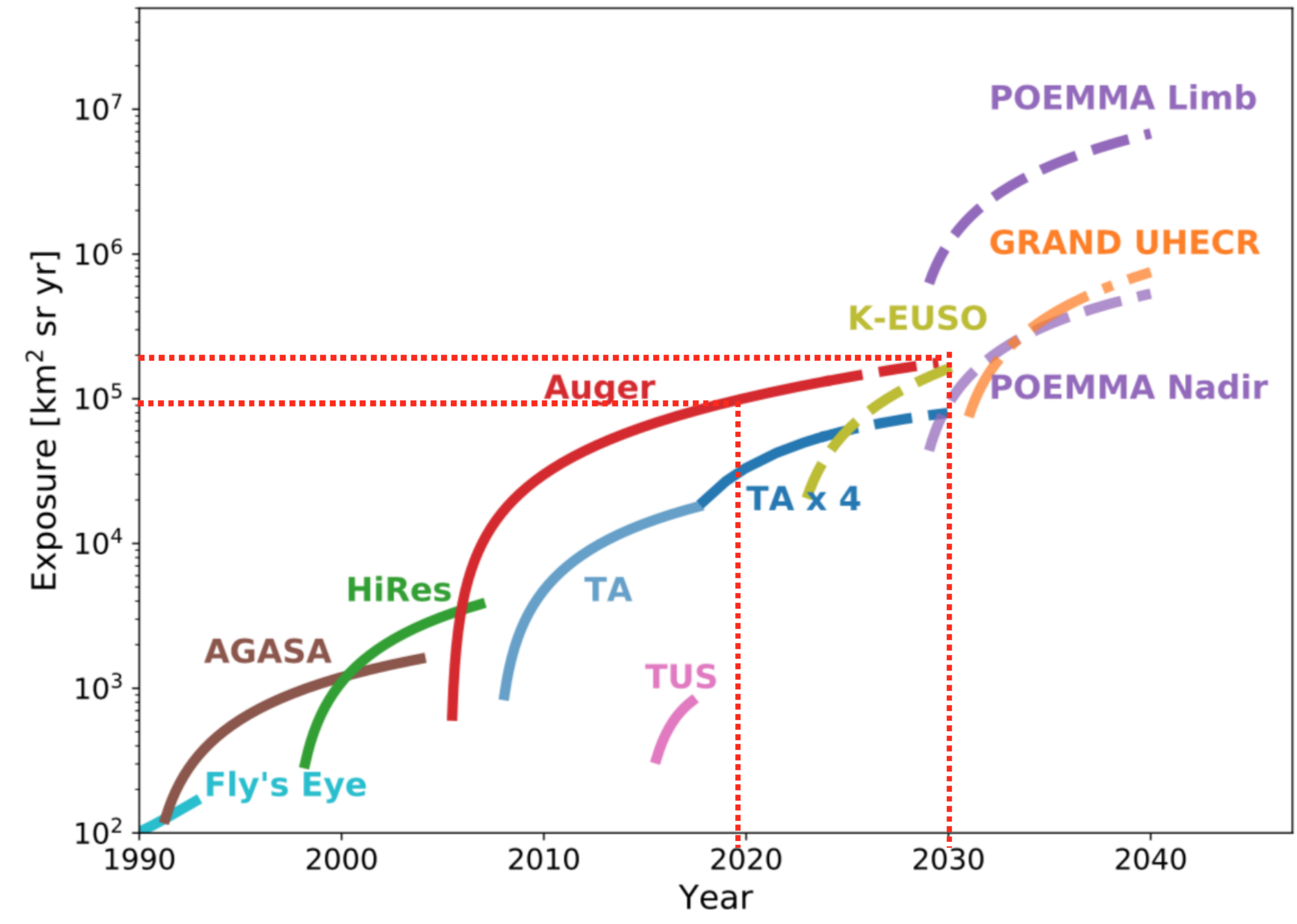
Already deployed: almost 400 SSD stations

Underground Muon Detector in construction

World's largest Radio Detector in preparation (3000 km^2)



The Far Future



R.Batista et al., arXiv:1903.06714

Summary

The Auger Observatory has integrated 15 years of data to address the most important questions in cosmic ray physics at the ultra high energies. Similarly, the Telescope Array experiment is studying the northern sky since 11 years.

The hybrid technique (air fluorescence + water Cerenkov tanks at ground) has allowed to control the absolute energy scale of the UHECR spectrum at 15-20% level; nevertheless, results from the north and south of the sky are not in complete agreement, suggesting residual unknown systematics.

The UHECR composition goes from light to heavy elements in the last two decades of the spectrum. If confirmed, this casts doubts on the extragalactic origin of the CR spectrum.

The recent multimessenger observations (the binary NS merger GW170817 and the burst from the blazar TXS0506+056) have allowed Auger to put limits on the (unlikely) existence of acceleration mechanisms of UHE neutrinos

Auger is already setting limits on the diffuse flux of cosmogenic neutrinos, suggesting that the end of the spectrum may not be caused by GZK effect in propagation, but by the exaustion of accelerating sources.

The observatory is currently upgrading the SD, installing one scintillator and one antenna per tank, to improve the muon-electron discrimination, to gain further insights on the nature of the primaries.

Thank you