Multi-messenger astrophysics with the Pierre Auger Observatory

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GEMMA
Gravitational-waves, ElectroMagnetic and dark_MAtter
Lecce, 4-7 June 2018

Outline

- ⋆ Introduction
- ⋆ The Pierre Auger Observatory
- ⋆ Search for photons
- ⋆ Search for neutrinos
- ⋆ GW follow-ups
- ⋆ Observatory upgrade
- ⋆ Conclusions

Pierre Auger Observatory:
nuclei, photons and neutrinos

The Pierre Auger Observatory

The Pierre Auger Observatory

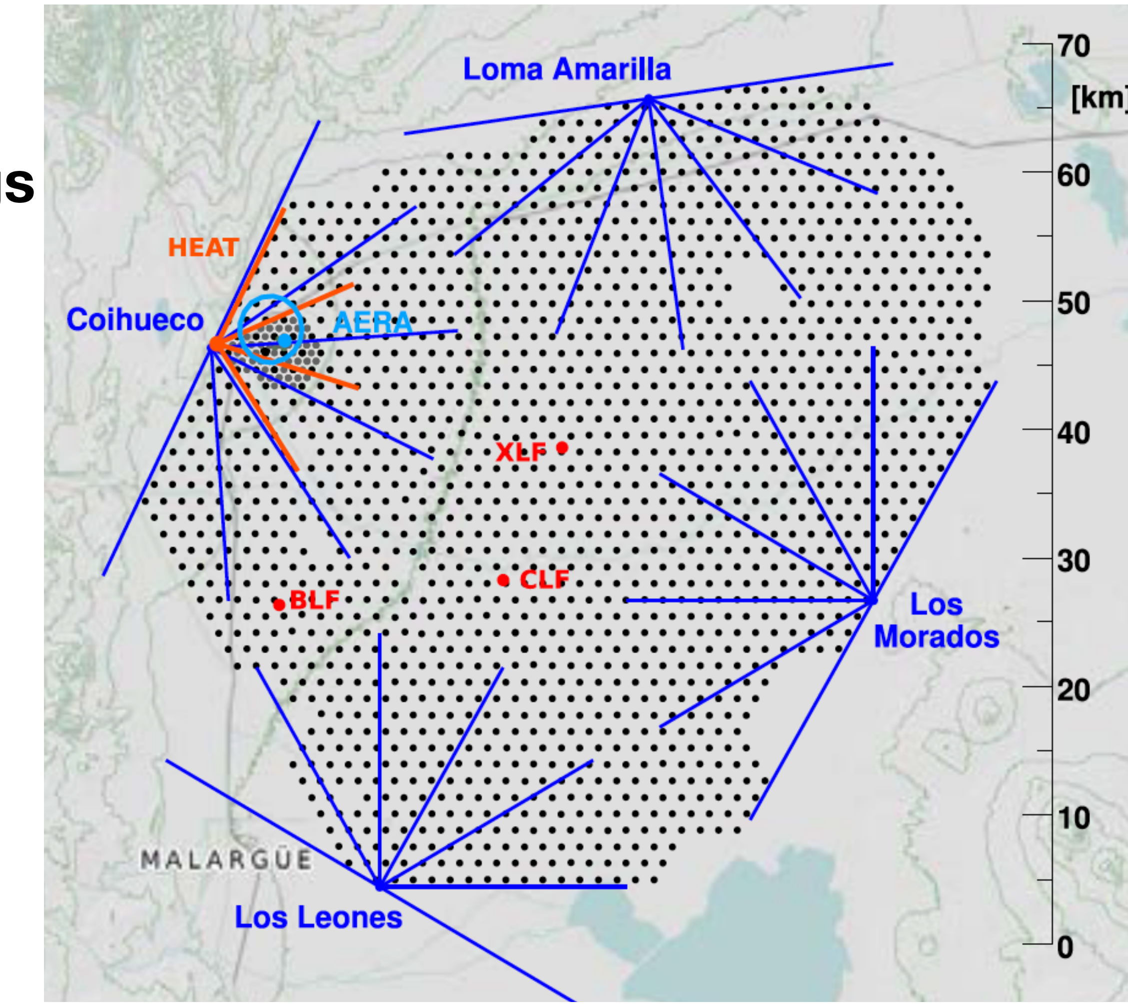
Two independent and complementary detector systems

Fluorescence Detector (FD)

24 telescopes in four buildings
FoV: 1°-30° in elevation
3 High Elevation Auger Telescopes (HEAT)
FoV: 30°-60° in elevation

~13% duty cycle

longitudinal profile



Surface detector (SD)

1660 water cerenkov detec. (WCD) in 3000 km²

1.5 km spacing

Denser array, 750 m

100% duty cycle

particle density at ground

Hybrid events: at least one WCD + FD

AERA 124 antennas in 6 km²

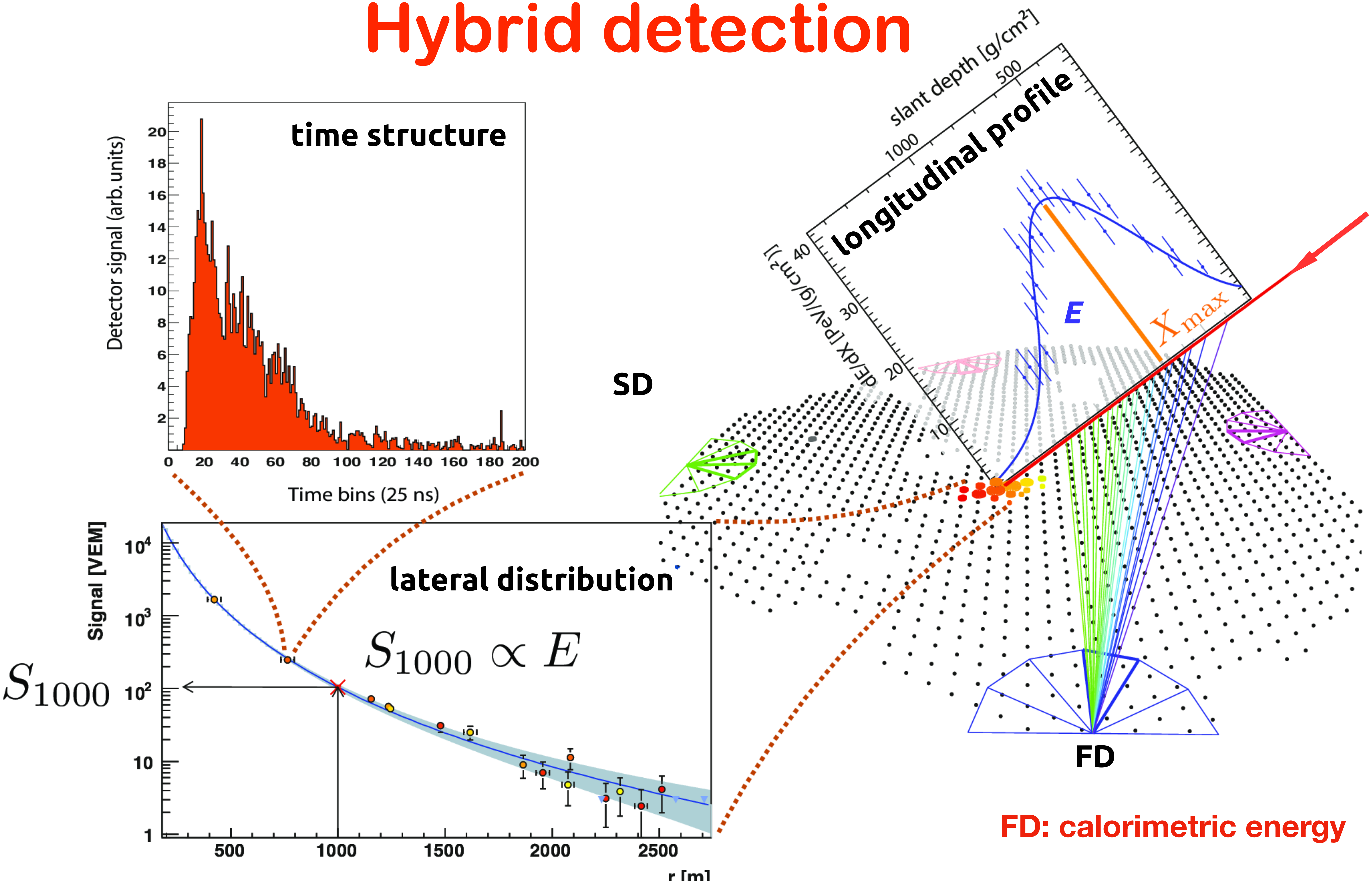
Underground muon detectors

Atmospheric monitoring stations

Auger: data since 2004, completed in 2008

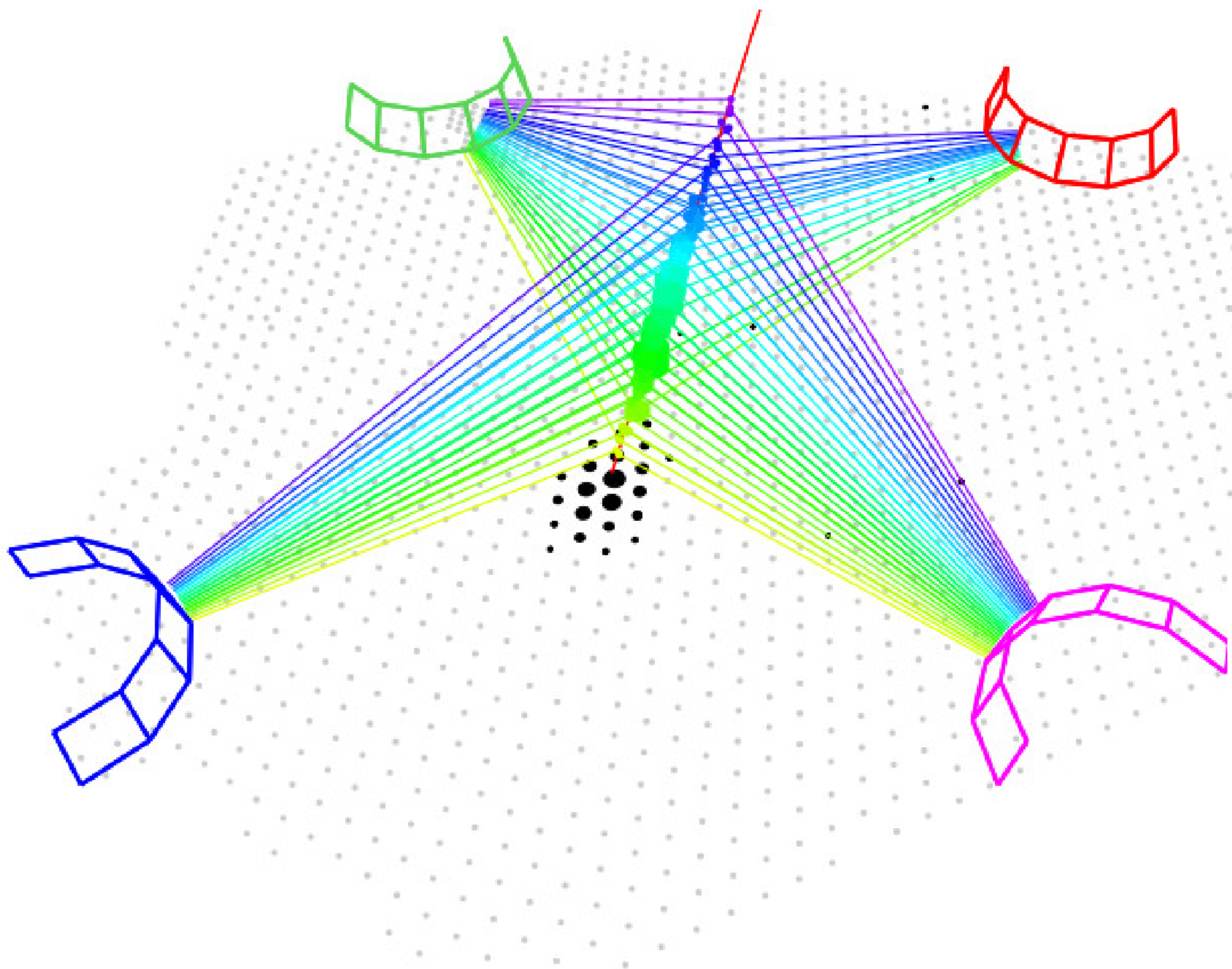
NIM A 2015, arXiv:1502.01323

Hybrid detection

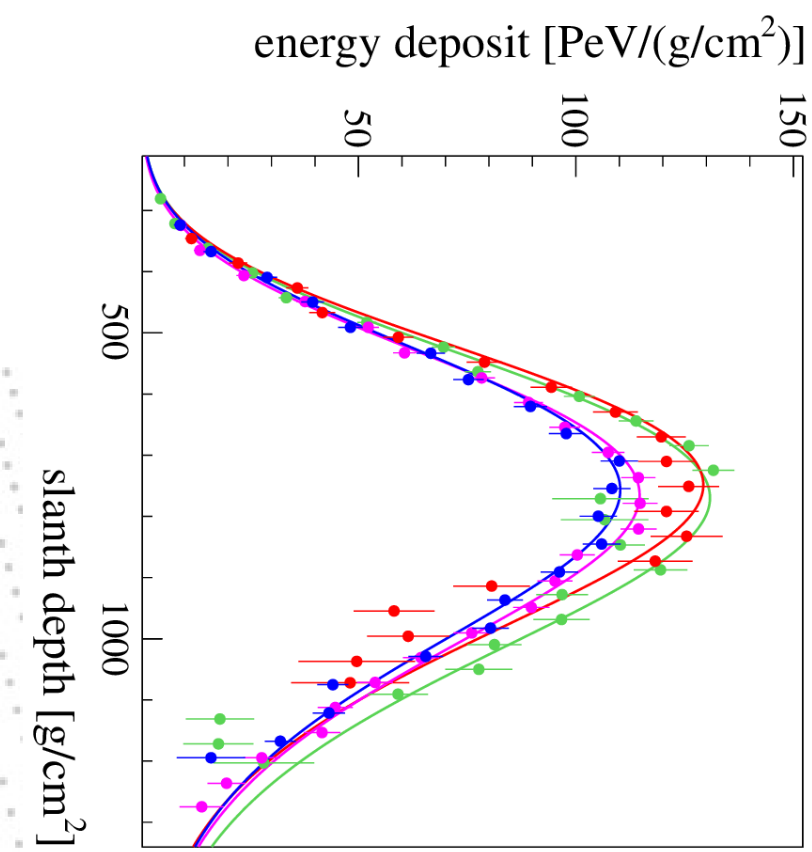


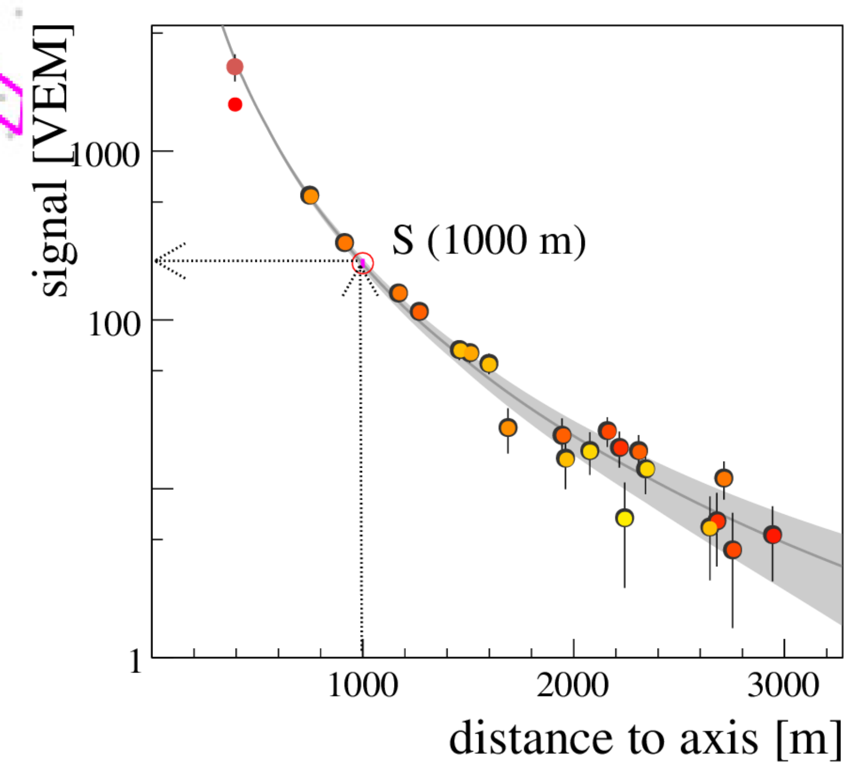
SD ⋆ signal at 1000 m, S_{1000} energy estimator
⋆ energy calibration from FD in hybrid events

Quadruple hybrid event



65 km between FD





The search for primary photons

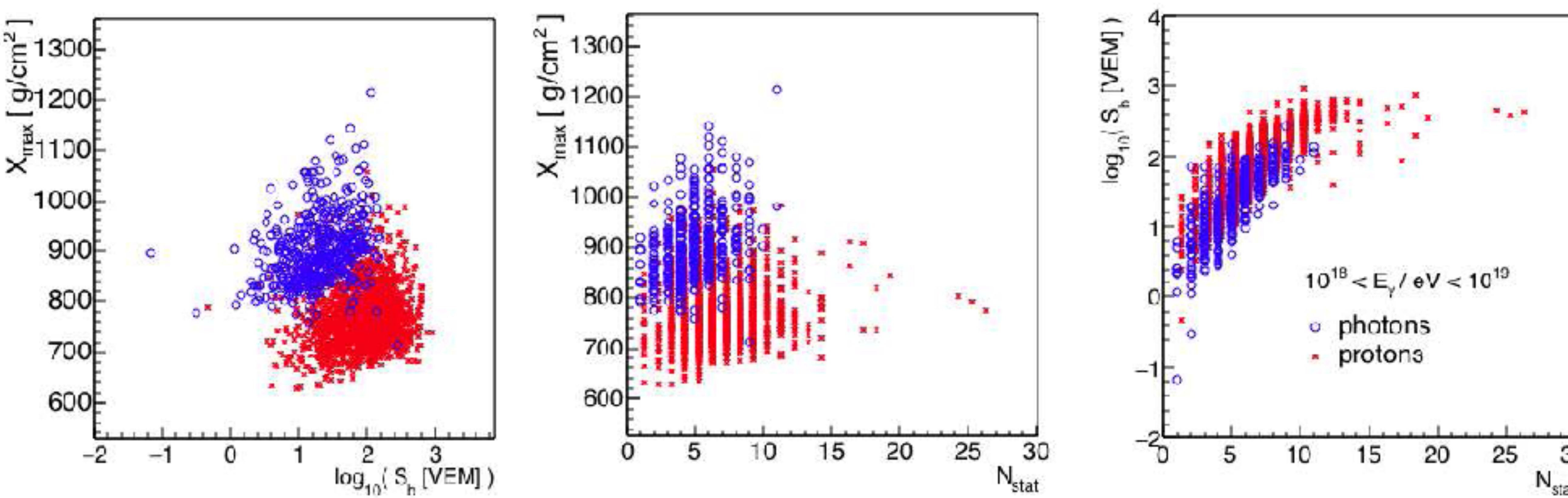
Photon showers x hadronic showers

Identification of photon showers

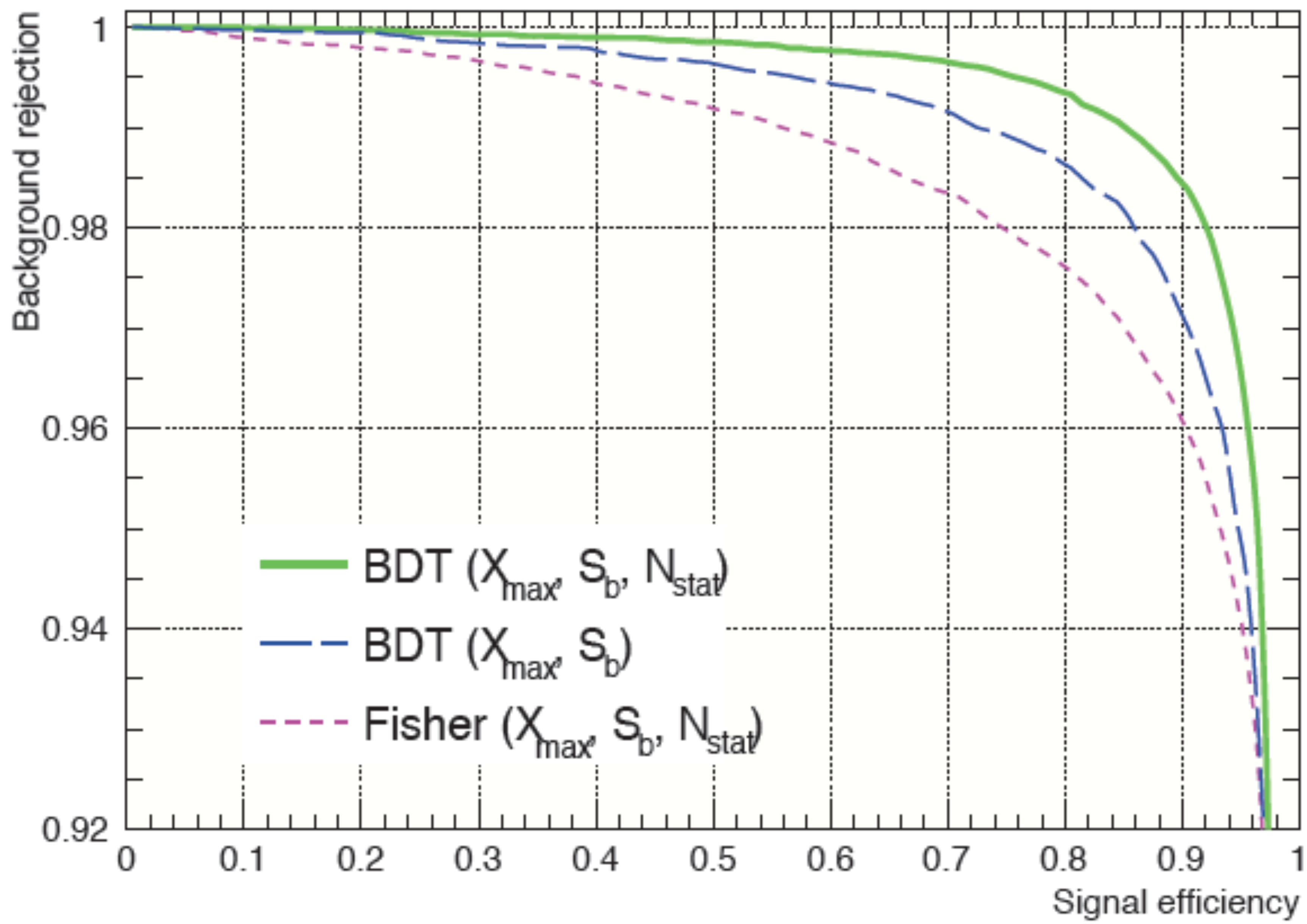
- ★ UHE photon showers develop deeper in the atmosphere than showers of same energy induced by hadrons (smaller multiplicity of electromagnetic interactions) Xmax
- ★ Photon showers smaller footprint on ground (smaller number of triggered stations) Nstat
- ★ Steeper lateral distribution function

$$S_b = \sum_{i}^{N_{\mathrm{stat}}} S_i \left(\frac{r}{r_0}\right)^b$$

Detailed MC simulations 10^{17} and 10^{19} eV



Background rejection and signal efficiency

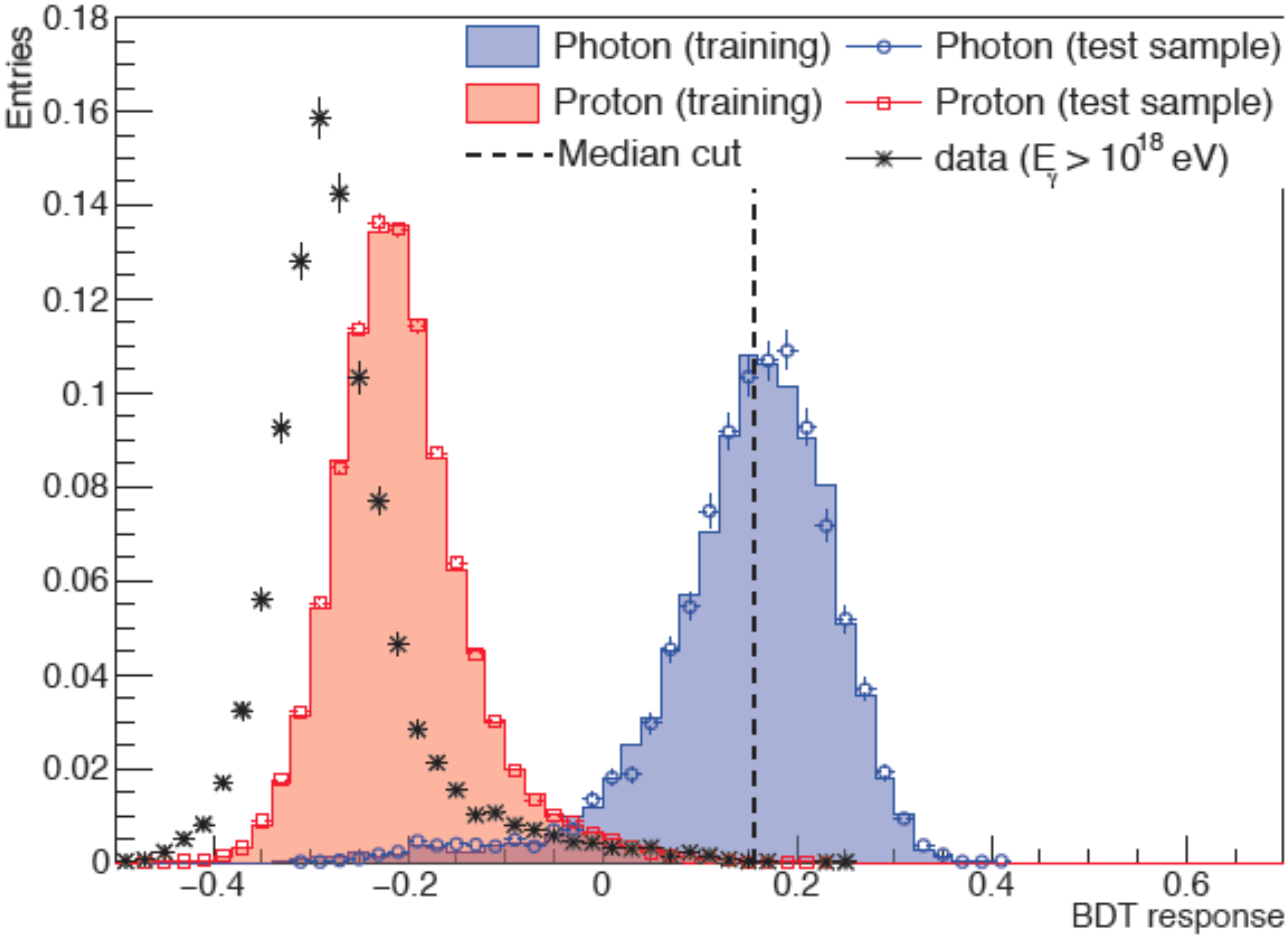


Different algorithms and combinations of input variables

Boosted decision tree and Fisher multivariate analysis

- ★ **Energy and zenith angle are included in the BDT**
- ★ **background contamination 0.14% for a photon selection efficiency of 50%**

BDT photon selection

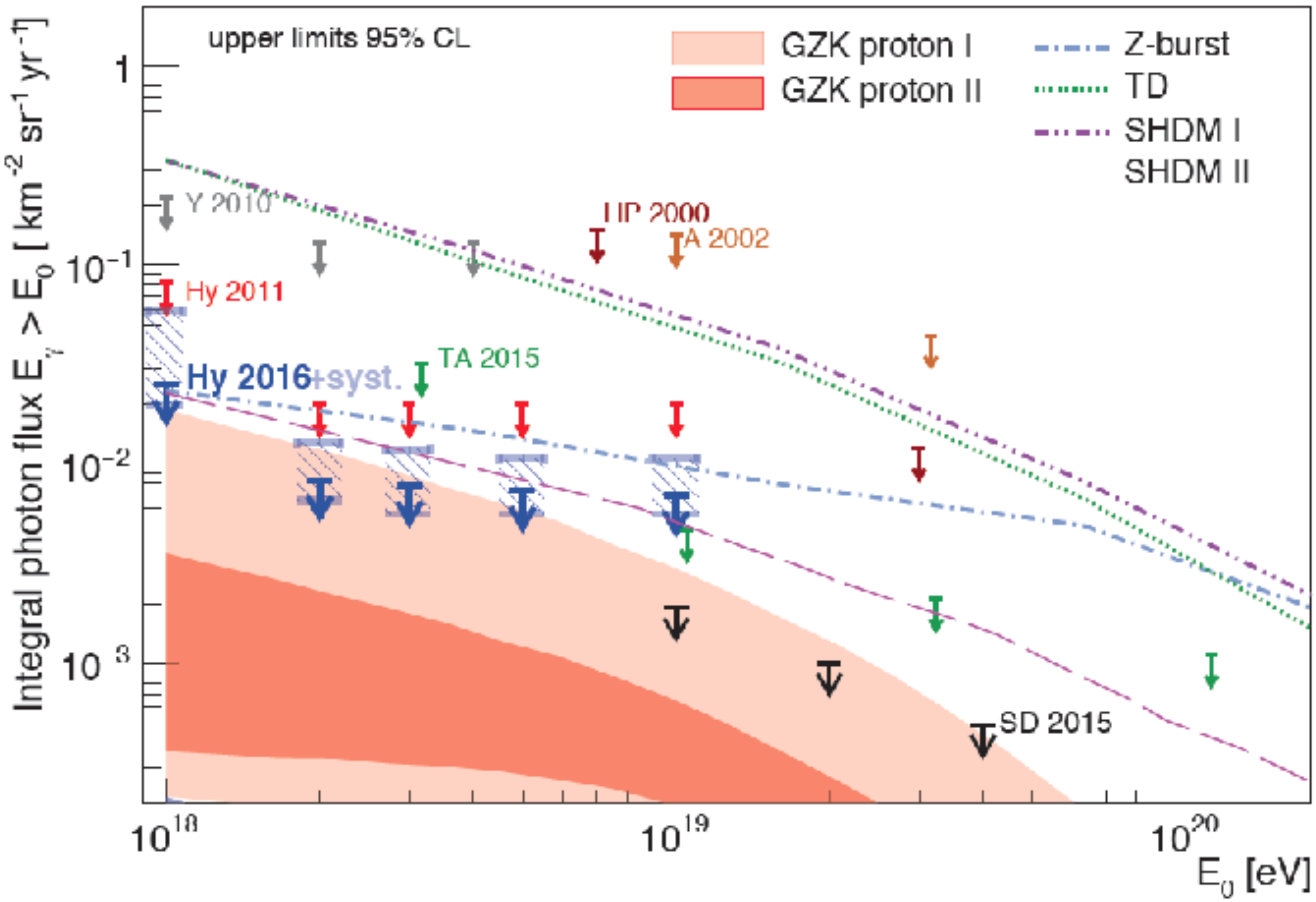


- ⋆ **Three events pass the cut, with 11.4 (3.3) expected for pure-proton (mixed) backg.**
- ⋆ **Candidates compatible with background expectations, upper limits on the integral photon flux at 95% C.L. are derived.**

Upper limits on photon flux

$$\Phi_{UL}^{0.95}(E_\gamma > E_0) = \frac{N_\gamma^{0.95}(E_\gamma > E_0)}{\mathcal{E}_\gamma(E_\gamma > E_0 | E_\gamma^{-\Gamma})}$$

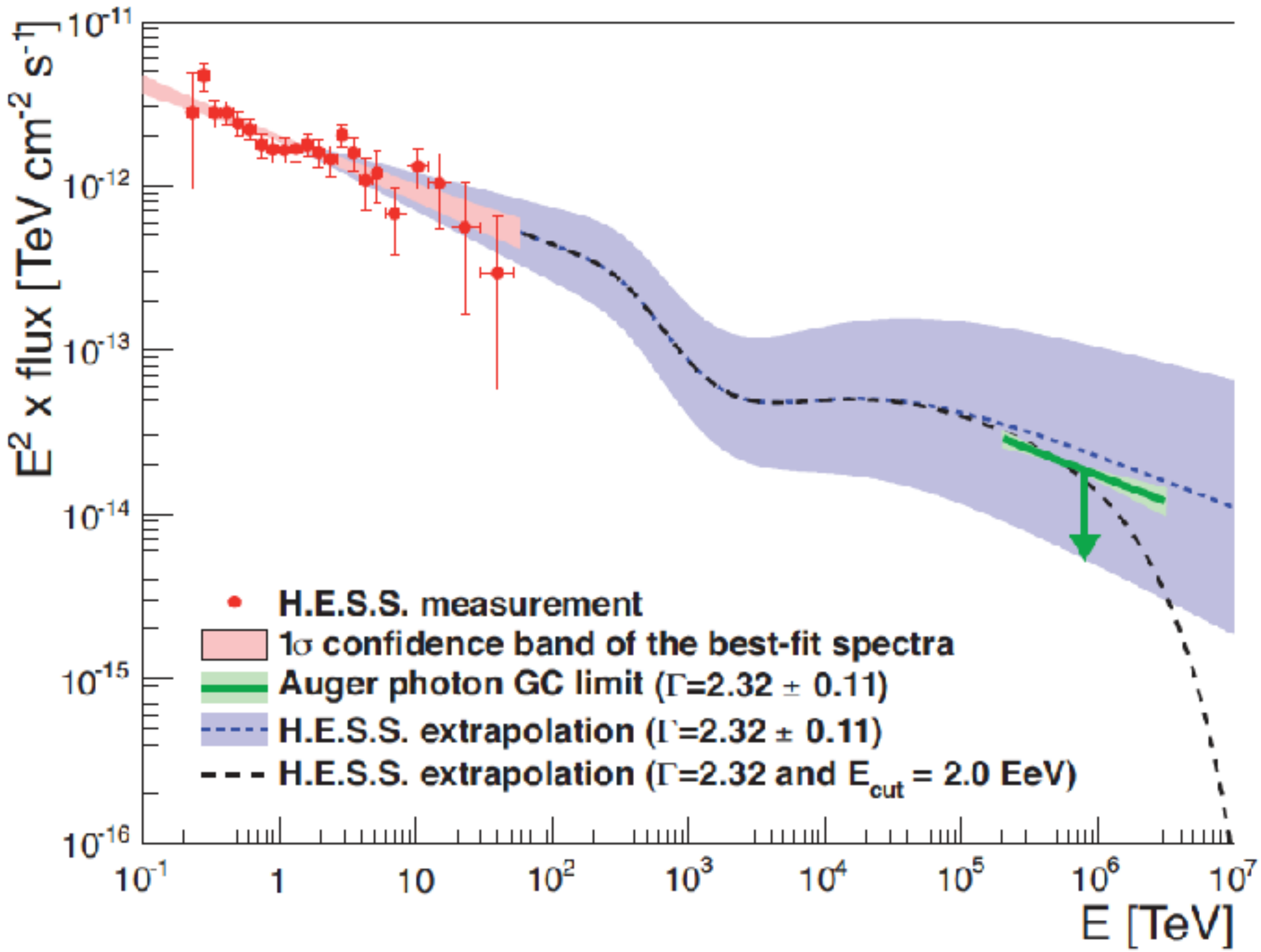
- ⋆ **Number of candidates at 95% CL**
- ⋆ **Integrated exposure assuming a power law spectrum**



- ⋆ **Tight constraints on current top-down scenarios to explain the origin of UHE CR**
- ⋆ **Sensitivity to photon fractions of about 0.1% for 1 EeV**
- ⋆ **Exploring the region of photon fluxes predicted in astrophysical scenarios**

Niechciol, for the Pierre Auger Colab., ICRC 2017

Photon flux from Galactic center

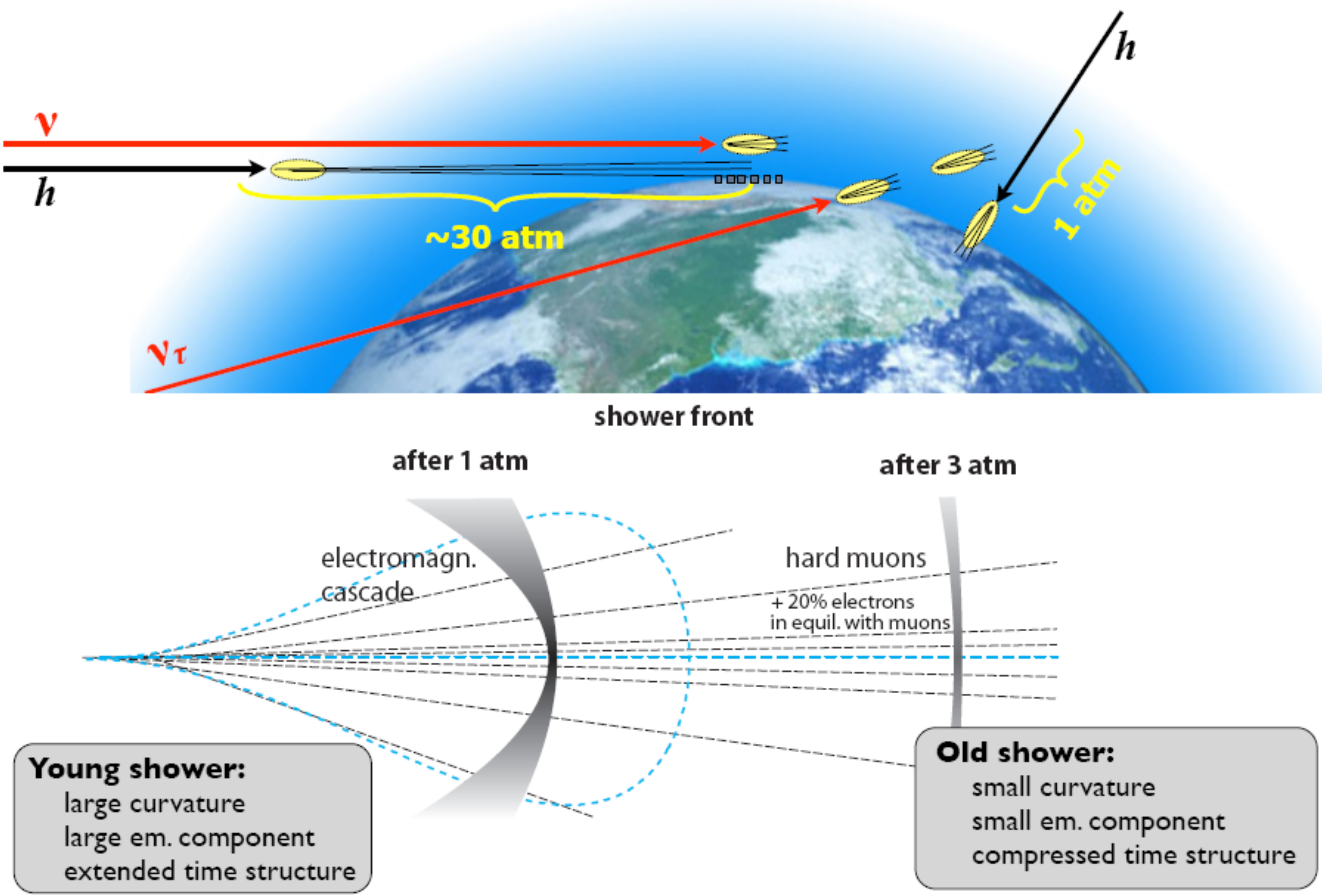


- ★ HESS collaboration: acceleration of TeV protons in the GC
- ★ Extrapolation to EeV takes into account interactions with CMB
- ★ Power law with exponential cuttof: upper limit on the cutoff energy of 2 EeV
- ★ The connection to measurements from the TeV range enables new multi-messenger studies

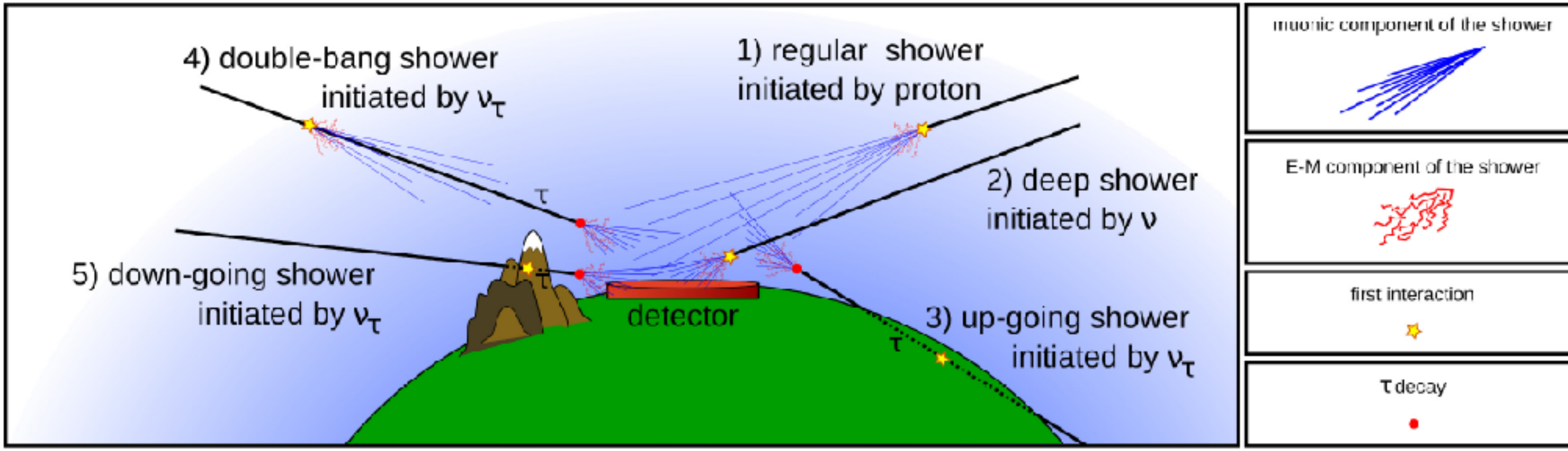
The HESS Collab. Nature, 2016

The search for neutrinos

Neutrino search: old and young showers



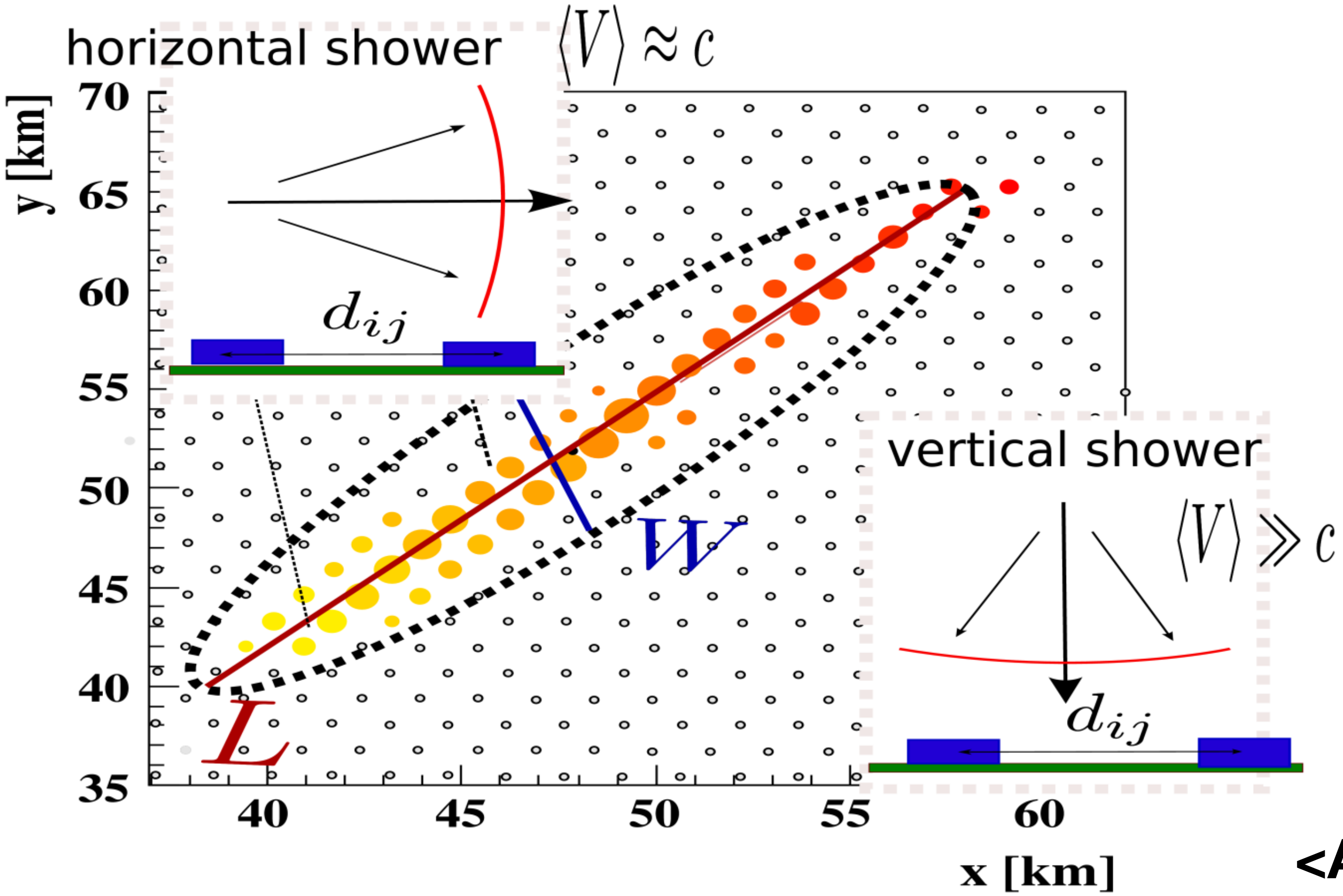
Sensitivity: all flavours and channels



Three selection criteria

★ Downward-going low zenith (2 and 4)	DGL (60º - 75º)	}	all flavours
★ Downward-going high zenith (2, 4 and 5)	DGH (75º - 90º)		
★ Earth-skimming (3)	ES (90º - 95º)		ν_τ

Selecting ν in data



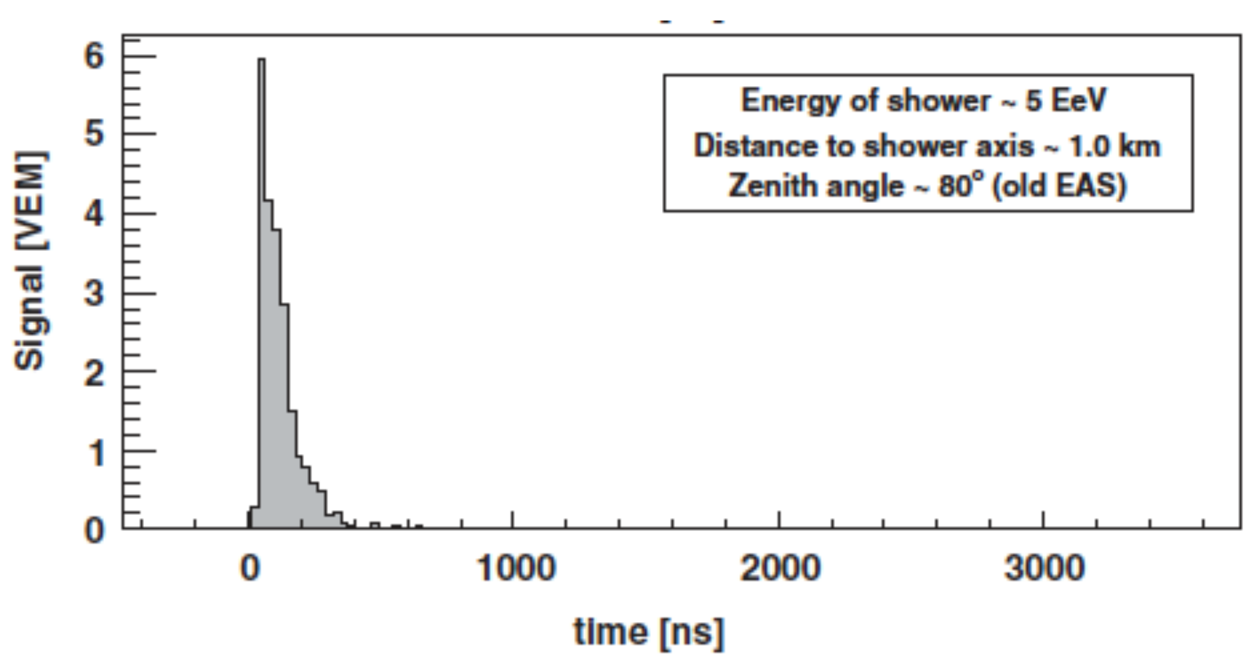
Inclined selection

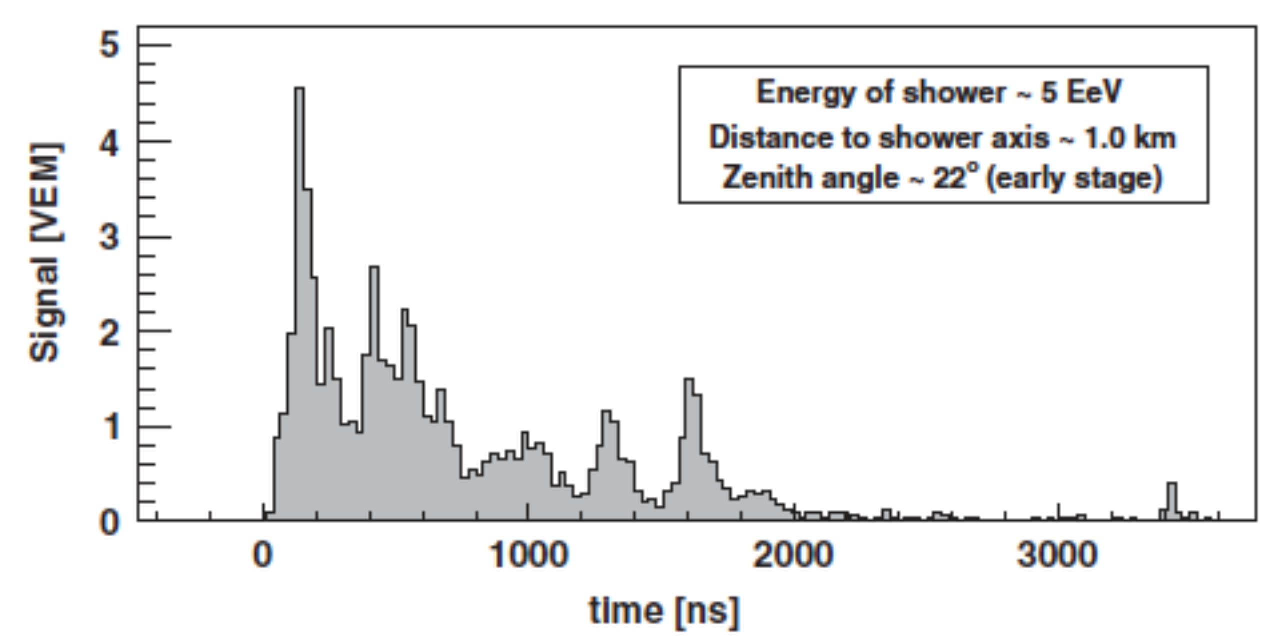
- ★ Elongated pattern: L > W
- ★ Apparent speed signal ≈ c
- ★ Angular reconstruction
  60º - 75º & 75º - 90º

Select young showers

- ★ Broad EM component

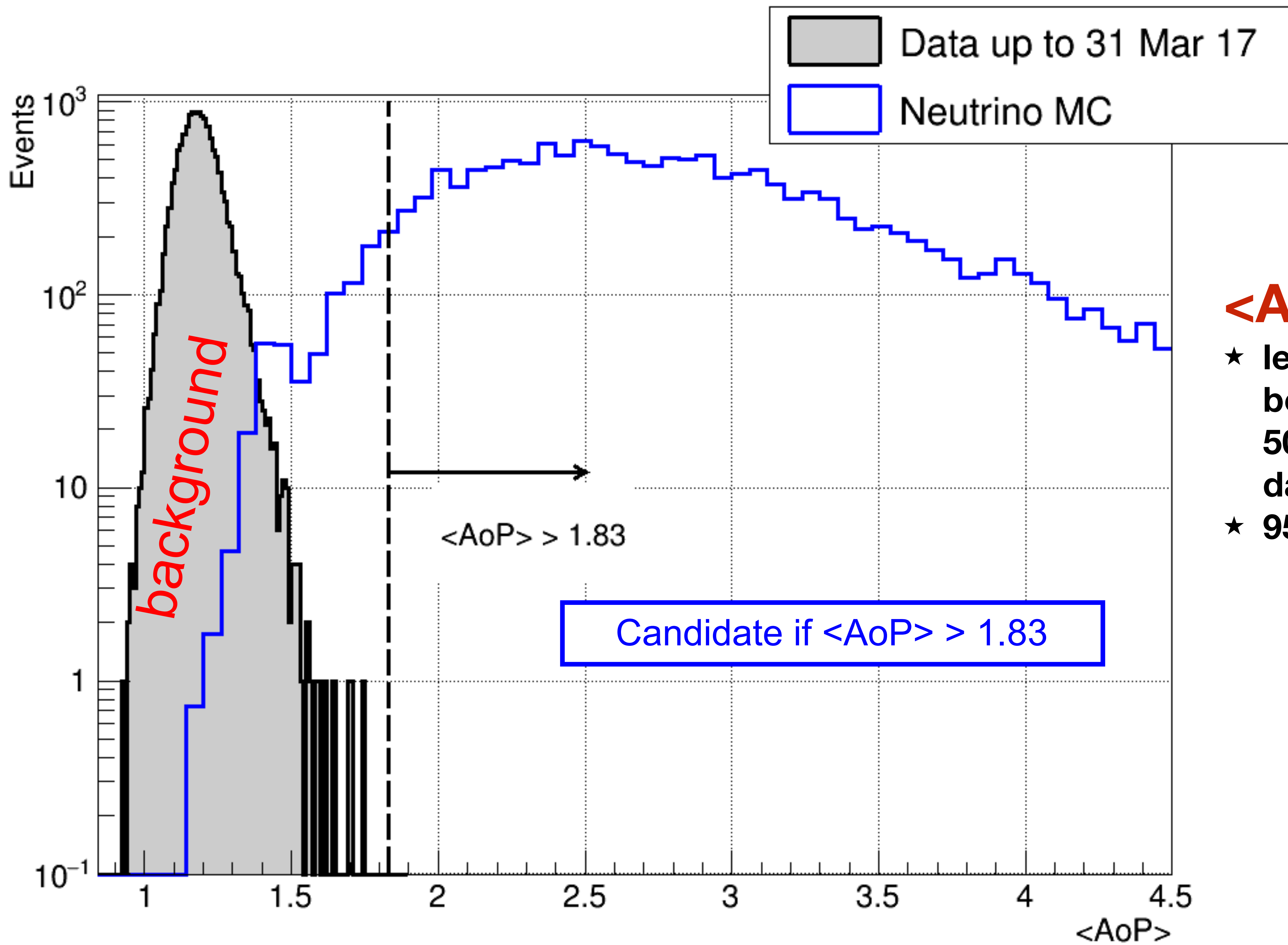
<AOP> area over peak of digitized signal





Pierre Auger Coll., Phys. Rev. D 91, 092008 (2015); Ap JL 755:L4 (2012)

ν search: ES Earth skimming

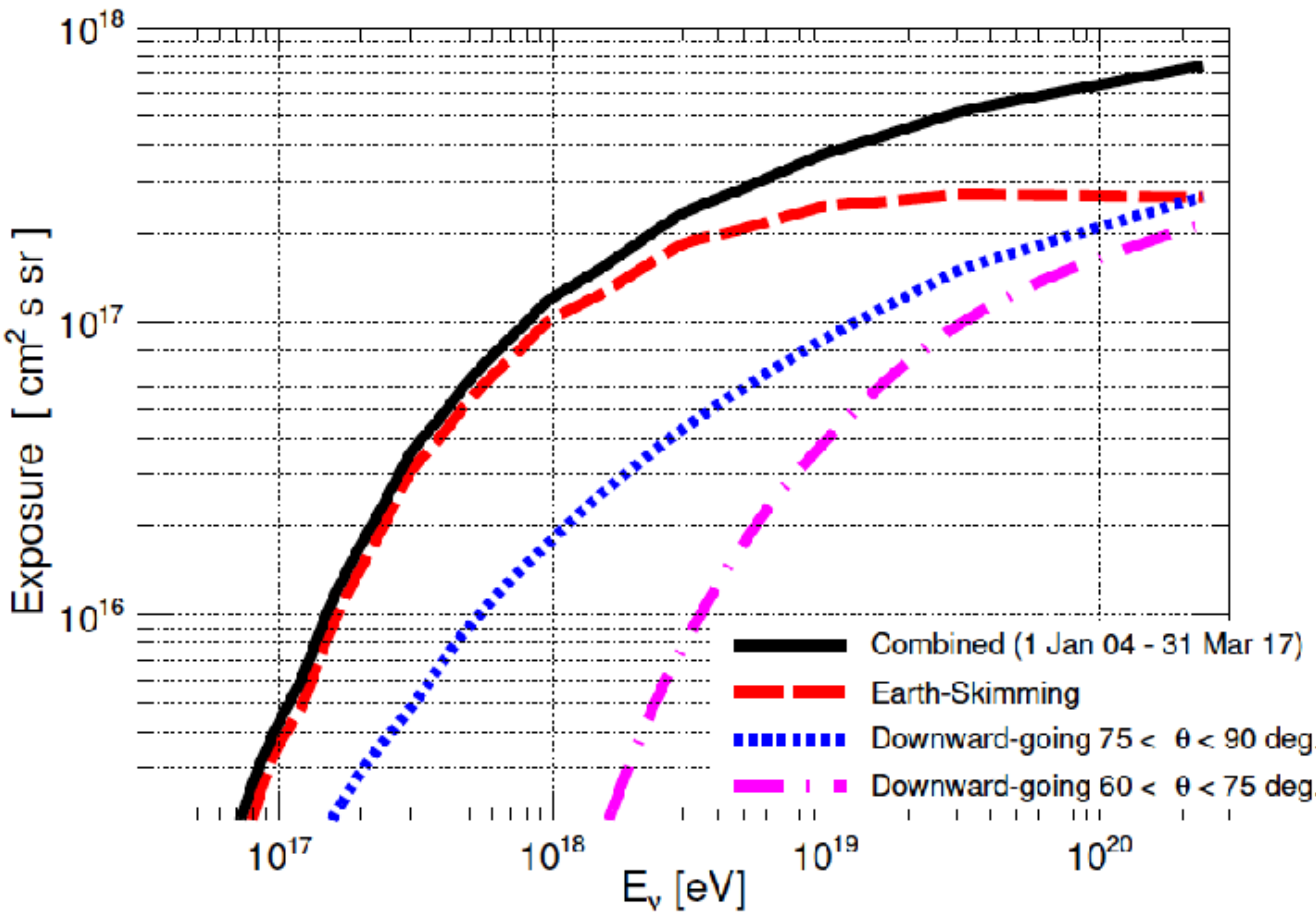


<AOP> cut

- ★ **less than one bckg event in 50 years of SD data**
- ★ **95% efficient**

Zas, for the Pierre Auger Collab., ICRC2017

Exposure 01 Jan 2004 - 31 Mar 2017



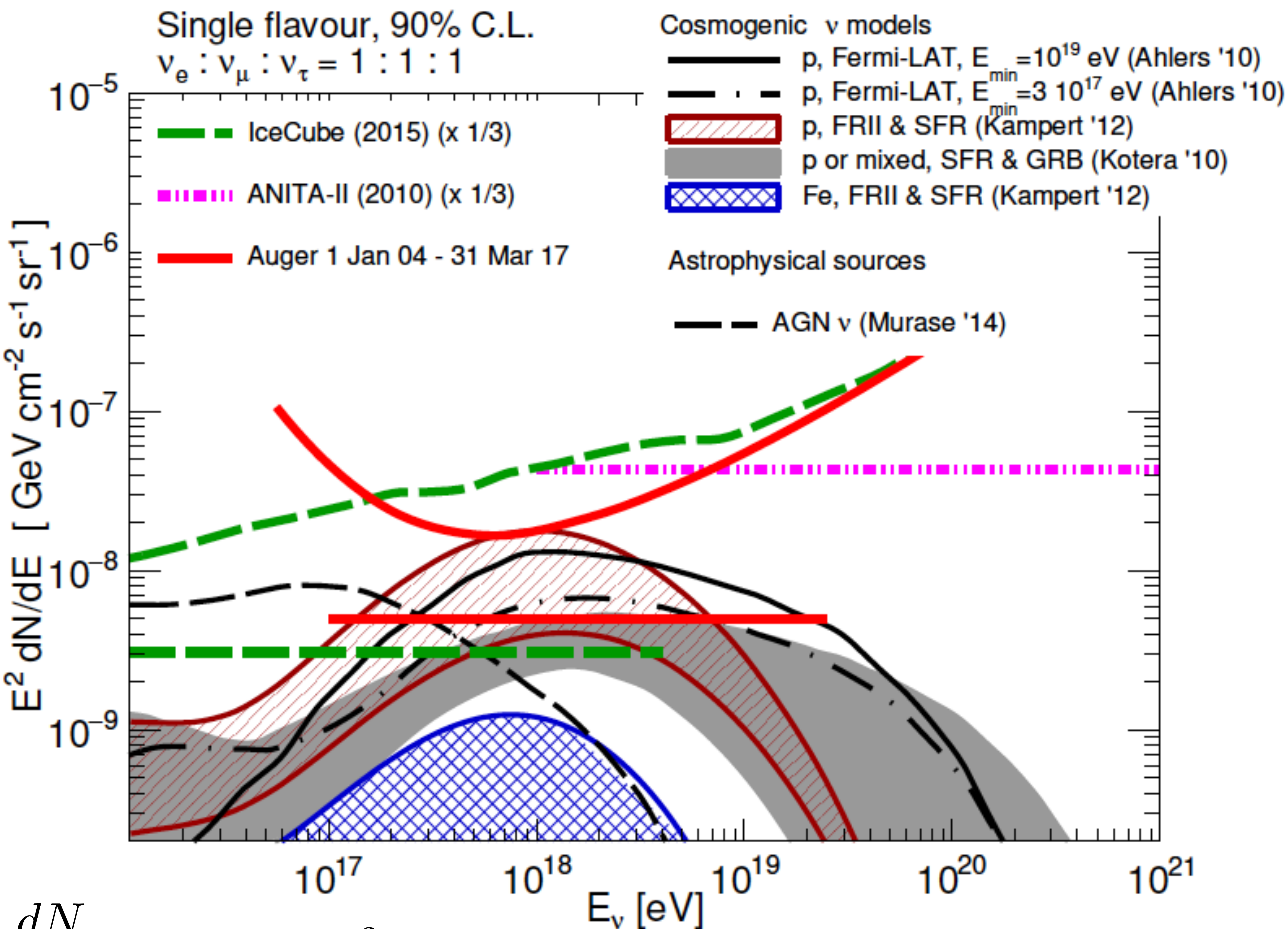
Relative contribution of channels & flavours to event rate (E^{-2} flux)

ES	79.4%
DGH	17.6%
DGL	3.0%

Electron	10.1%
Muon	3.8%
Tau	86.1%

Earth-skimming neutrinos dominate the exposure in spite of the reduced solid angle to which the detector is sensitive to them

ν limits



$$\frac{dN}{dE_\nu}(E_\nu) = kE_\nu^{-2}$$

$$k \leq 5 \times 10^{-9}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Complementary measurements !

Zas, for the Pierre Auger Collab., ICRC2017

Expected events: 01 Jan 04 - 31 Mar 17

Diffuse flux neutrino model	Expected events (1 Jan 04 - 31 Mar 17)
Cosmogenic - proton - strong source evolution	
Cosmogenic - proton, FRII evol. (Kampert 2012)	~ 5.2
Cosmogenic - proton, FRII evol. (Kotera 2010)	~ 9.2
Cosmogenic - proton - moderate source evolution	
Cosmogenic - proton, SFR evol (Aloisio 2015)	~ 2.0
Cosmogenic - proton, SFR evol, $E_{\max} = 10^{21}$ eV (Kotera 2010)	~ 1.8
Cosmogenic - proton, SFR evol. (Kampert 2012)	~ 1.2
Cosmogenic - proton, GRB evol. (Kotera 2010)	~ 1.5
Cosmogenic - proton - normalized to Fermi-LAT GeV γ-rays	
Cosmogenic - proton, Fermi-LAT, $E_{\min} = 10^{19}$ eV (Ahlers 2010)	~ 4.0
Cosmogenic - proton, Fermi-LAT, $E_{\min} = 10^{17.5}$ eV (Ahlers 2010)	~ 2.1
Cosmogenic - mixed and iron	
Cosmogenic - mixed (Galactic) UHECR composition (Kotera 2010)	~ 0.7
Cosmogenic - iron, FRII (Kampert 2012)	~ 0.35
Astrophysical sources	
Astrophysical - radio-loud AGN (Murase 2014)	~ 2.6
Astrophysical - Pulsars - SFR evol. (Fang 2014)	~ 1.3

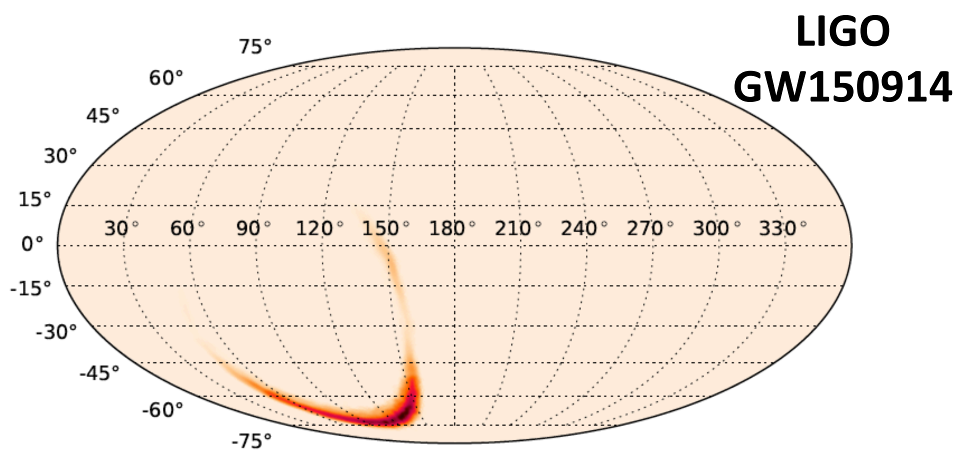
EXCLUDED (> 90% CL), **DISFAVORED** (85% < CL < 90%), **ALLOWED**

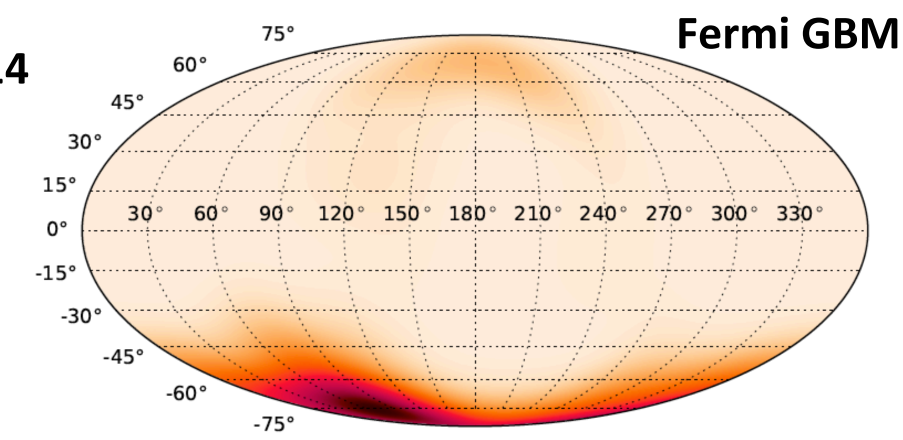
Zas, for the Pierre Auger Collab., ICRC2017

The follow-up of GW events

Binary-BH mergers and neutrinos

- ⋆ LIGO GW150914, GW151226, GW170104 (& LVT151012)
- ⋆ Fermi GBM: transient source above 50 keV 0.4s after GW150914
- ⋆ possible association with a short gamma-ray burst





Mergers of BH are a potential environment where UHE cosmic rays can be accelerated

- ⋆ UHECR accelerated by Fermi mechanism in presence of relic B-fields and debris from BH
  ➔ formation of BHs could imply emission of UHE ν´s and γ´s

K. Kotera, J. Silk, ApJL 823, L29 (2016)

- ⋆ If accretion disk present, UHECR can be accelerated by electric fields in disk dynamo
  ➔ UHE ν´s from interaction with photon backgrounds and gas around BH

L. Anchordoqui, Phys. Rev. D 94, 023010, 2016

ν in coincidence with BH mergers ?

Energy range: E > 100 PeV, complementary to IceCube-Antares follow up

LIGO&VIRGO, Icecube, ANTARES coll. PRD 93, 122010 (2016)

Auger Earth-Skimming and Downward-going neutrino selection to data in spatial and temporal proximity to GW150914, GW151226 (and LVT151012):

Two search periods (motivated by the association of mergers of compact systems and GRBs

+/- 500 s around each GW event
- **to an upper limit on the duration of the prompt phase of the GRBs**
- **PeV neutrinos are thought to be produced in interactions of accelerated cosmic rays and the gamma rays with the GRB itself**

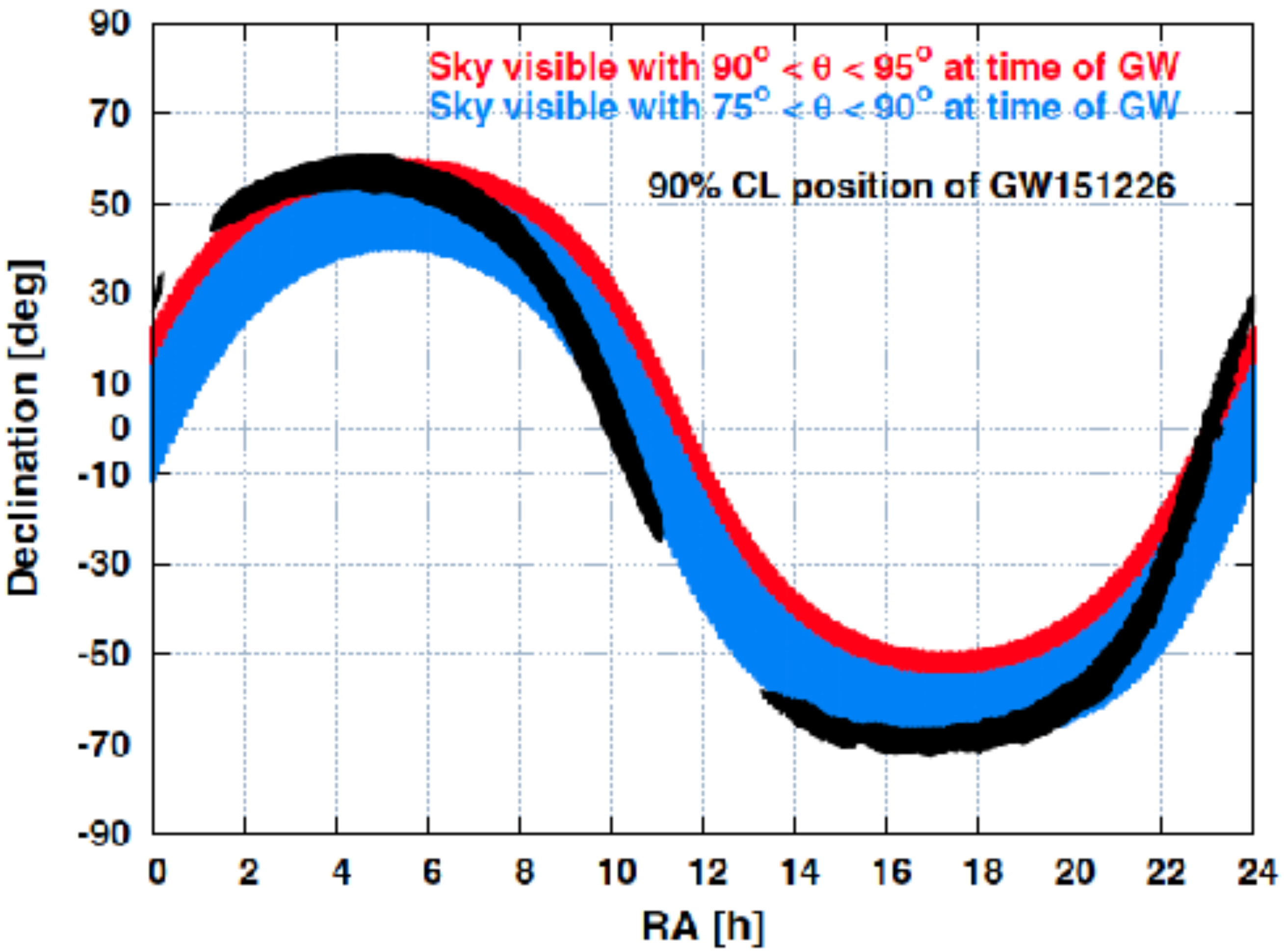
One day after the event
- **Conservative upper limit on the duration of GRB afterglows**
- **UHE neutrinos may be produced in interactions of UHECRs with the lower-energy photons of the GRB afterglow**

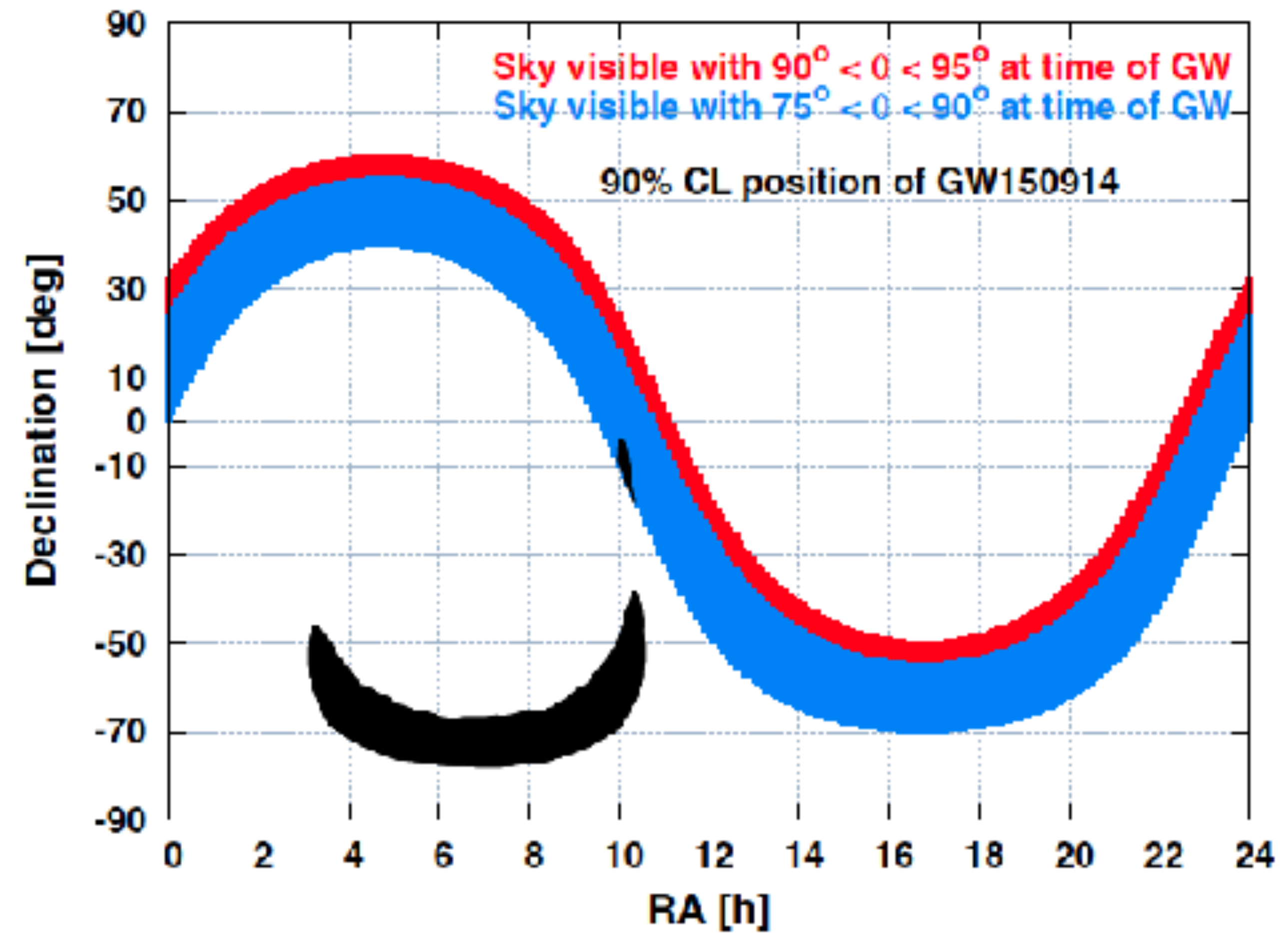
Same identification criteria to neutrinos as discussed previously

Instantaneous field of view

Auger Latitude: λ = -35.2°

- **Auger sensitivity limited to large zenith angles : at each instant in time neutrinos can be detected efficiently only from a specific portion of sky.**
- **Instantaneous field of view of the SD array is limited**
- **Covered region has very good sensitivity to earth-skimming tau neutrinos**

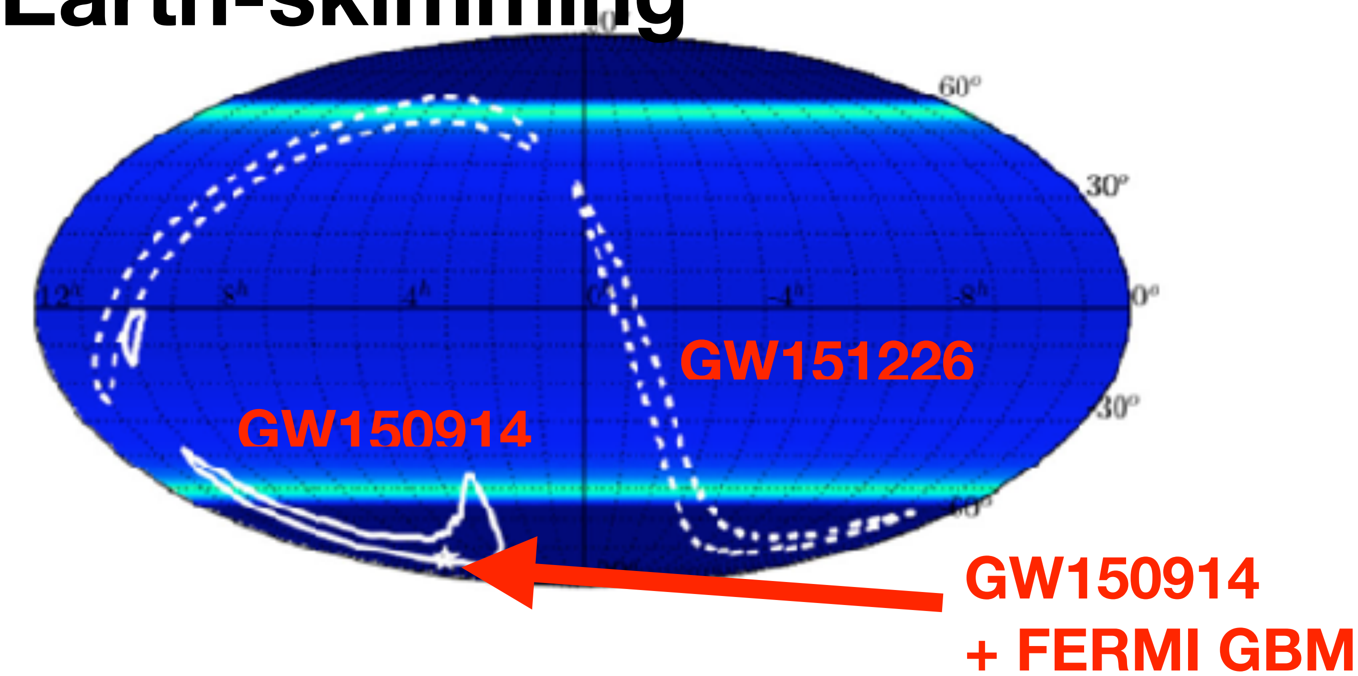




No candidate was detected in the window of ± 500 s around the GRB event

Visibility time fraction in one sidereal day

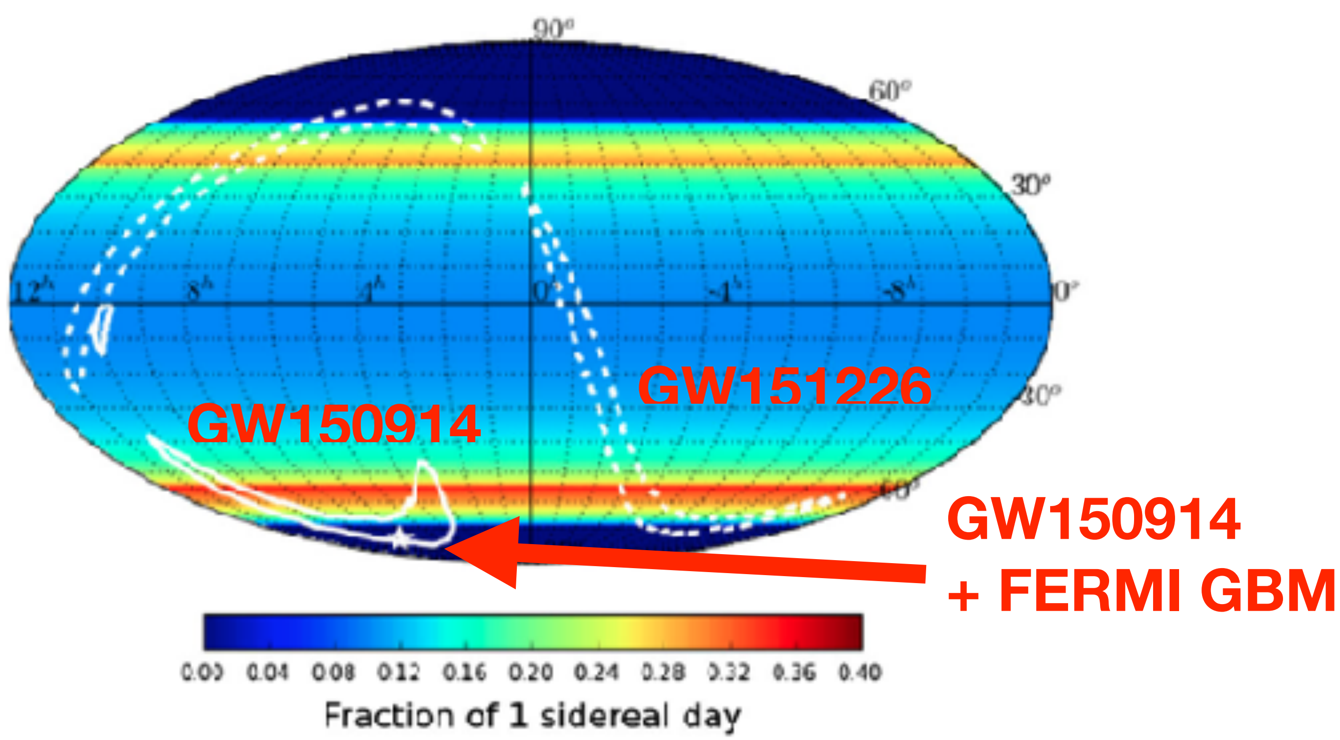
Earth-skimming



equatorial coordinates

No candidate was detected in the window of one day after the GRB event

Down-going high



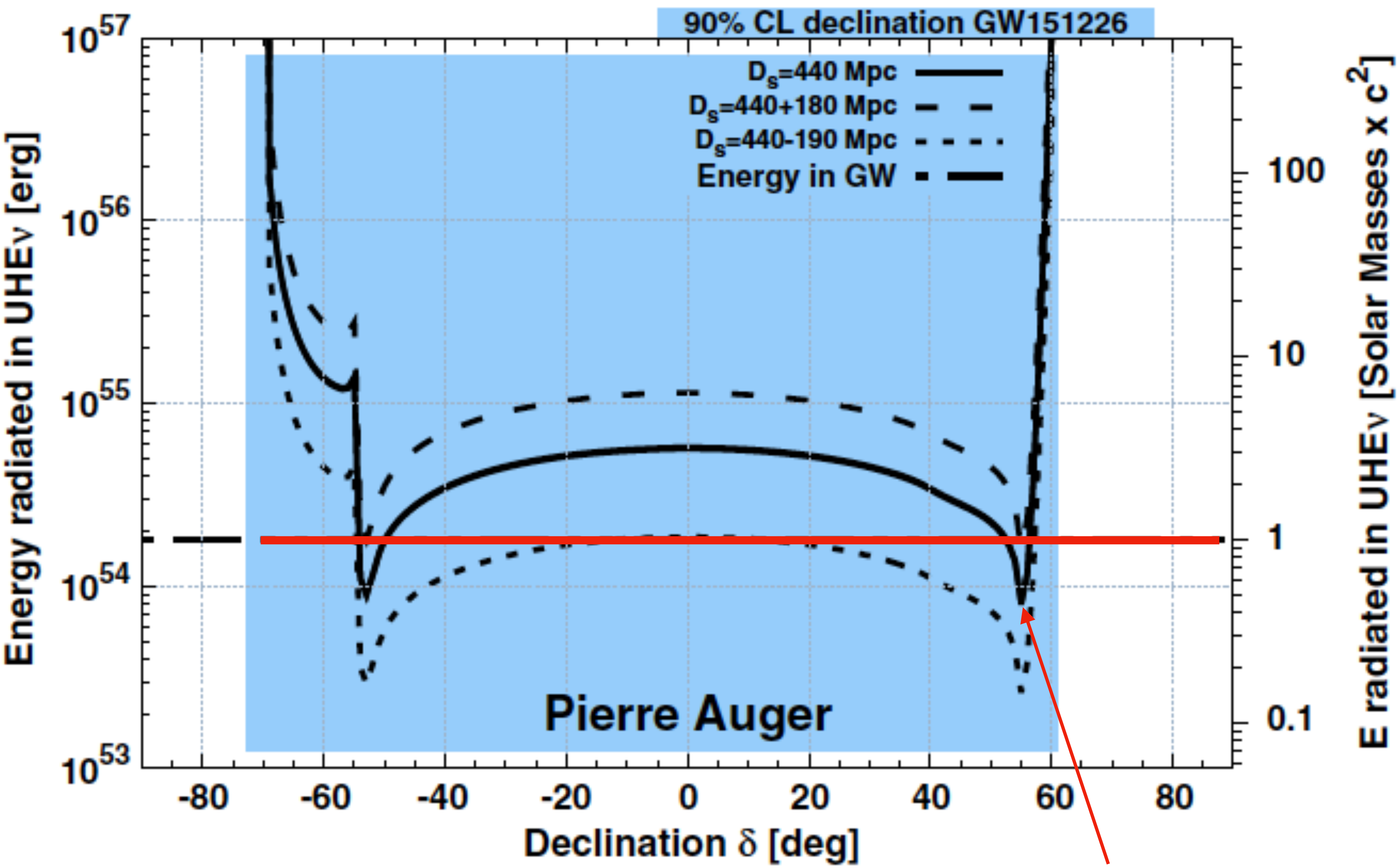
$$N_{\text{event}}^{\text{GW}} = \int_{E_\nu} \frac{dN_\nu^{\text{GW}}}{dE_\nu}(E_\nu)\mathcal{E}_{GW}(E_\nu,\delta)dE_\nu$$

$$\frac{dN_\nu^{\text{GW}}}{dE_\nu}(E_\nu) = k^{\text{GW}} E_\nu^{-2}$$

$$k^{\text{GW}}(\delta) = \frac{2.39}{\int_{E_\nu} E_\nu^{-2}\mathcal{E}_{\text{GW}}(E_\nu,\delta)dE_\nu}$$

Pierre Auger Coll., Phys. Rev. D 94, 122007 (2016)

Constraints on energy radiated from GW151226 in UHE ν ($E_\nu > 0.1$ EeV)

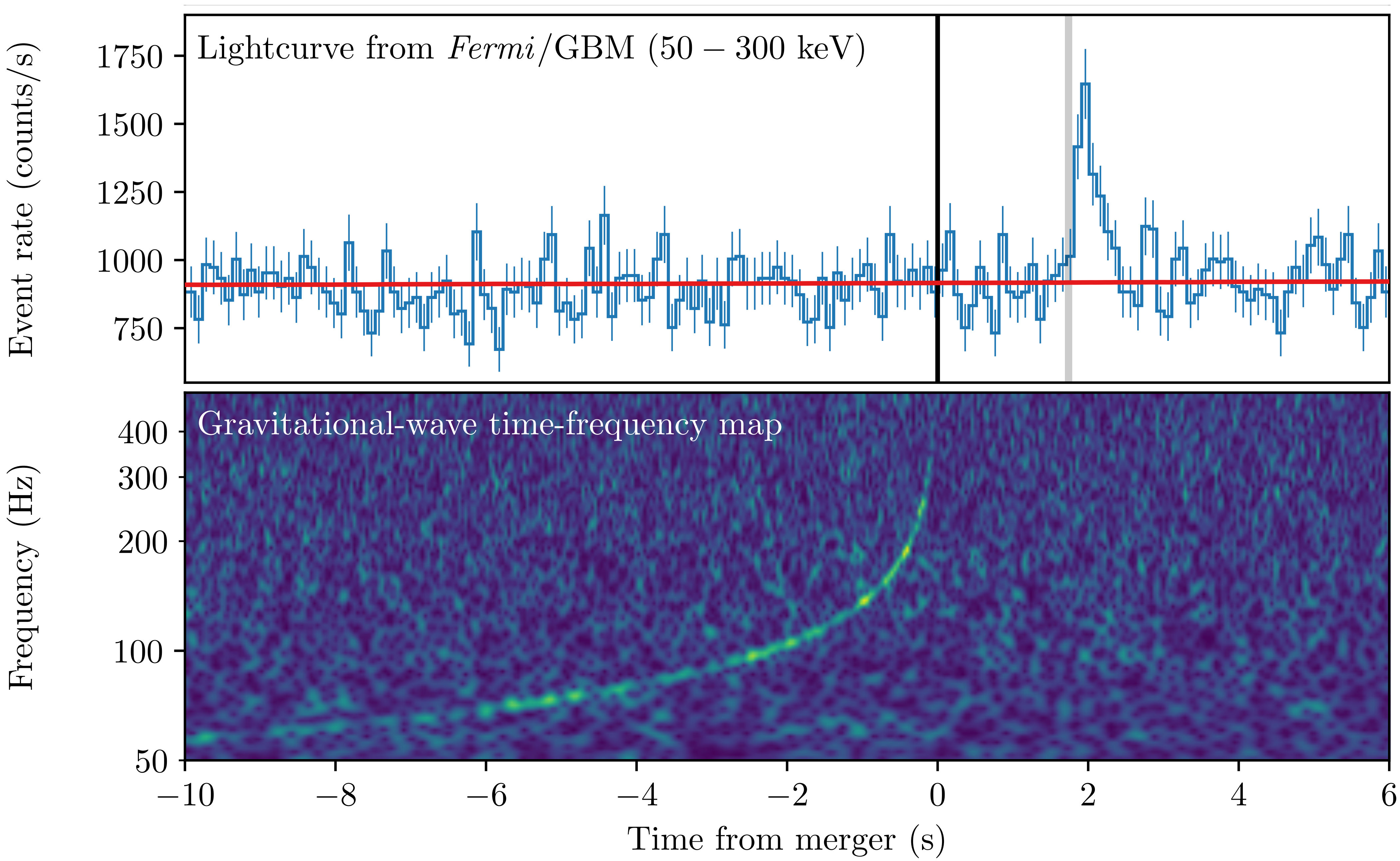


44.1% of E_{GW}

Pierre Auger Coll., Phys. Rev. D 94, 122007 (2016)

A binary neutron star merger

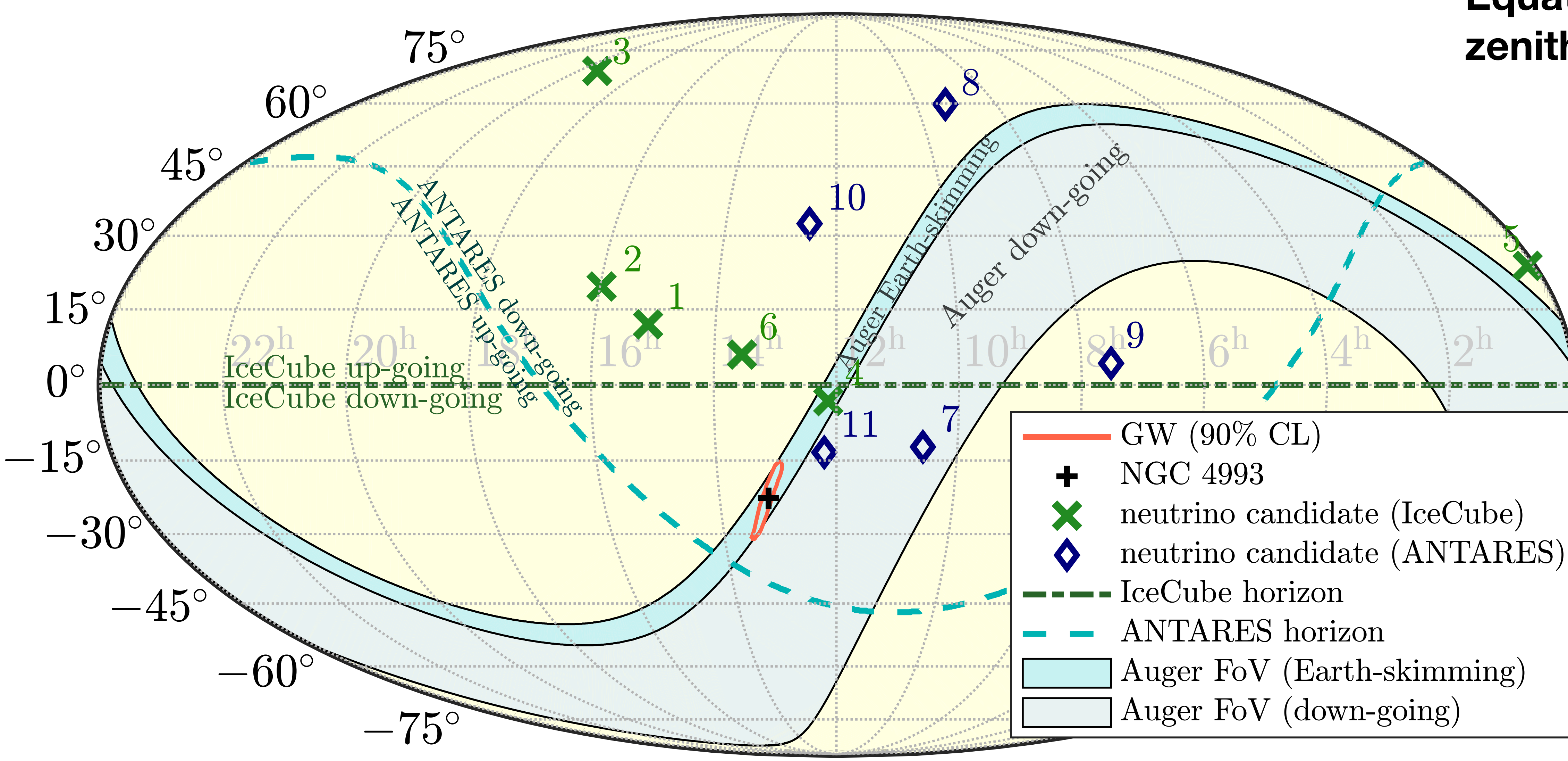
- ⋆ **GW170817: a NS-NS merger seen in gravitational waves**
- ⋆ **GRB170817A: confirmed as short GRB (Fermi GBM, Integral)**
- ⋆ **UV, optical and IR observation located the merger in NGC 4993**
- ⋆ **Fermi LAT, H.E.S.S., HAWC observe region later**



ν in coincidence with GW170817

- ⋆ ν follow up: Antares, IceCube and Pierre Auger Observatory
- ⋆ At time of GW trigger: event in region of maximum sensitivity for Auger

Equatorial coord.
zenith: 91.9º

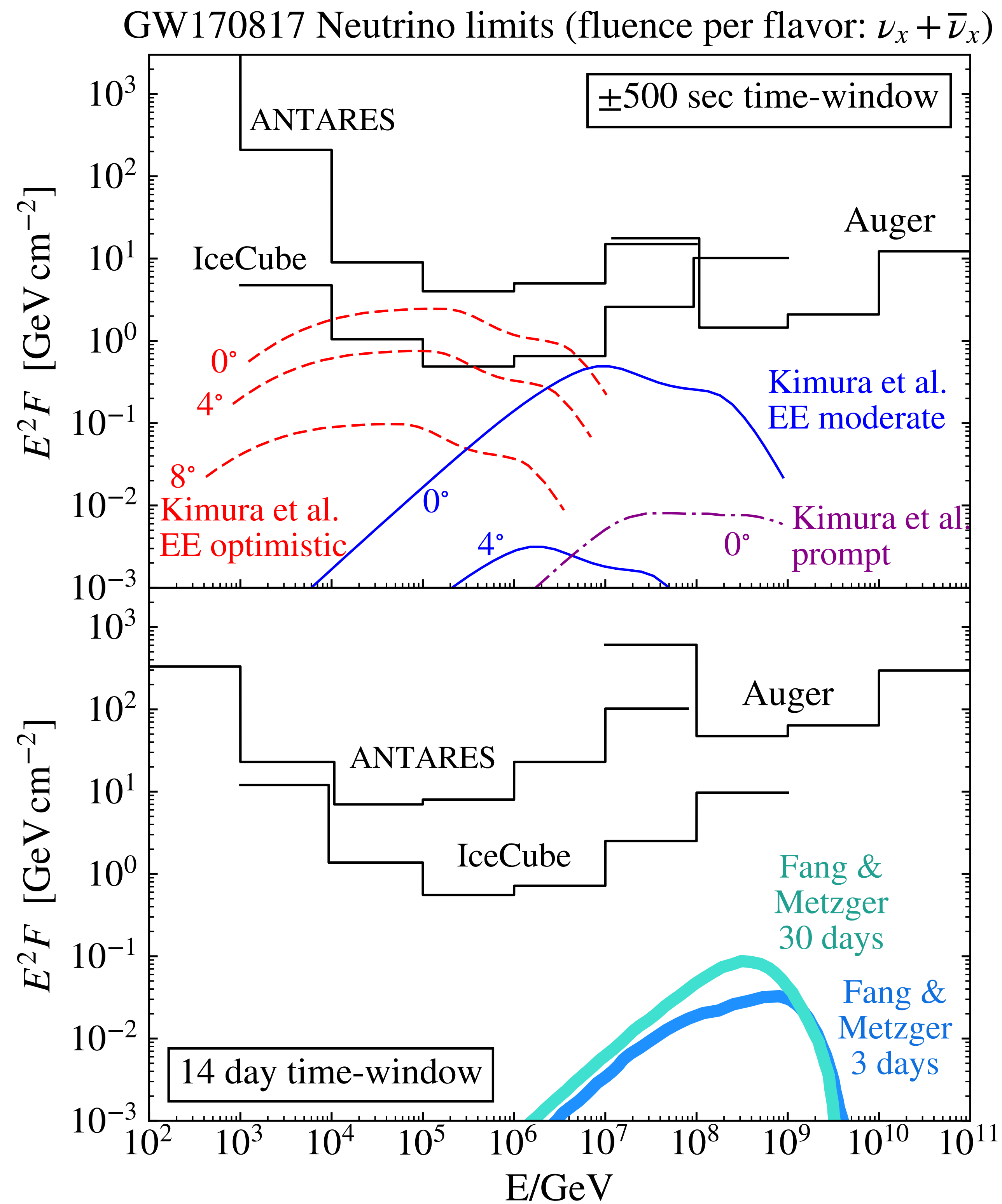


ANTARES, IceCube and the Pierre Auger Observatory, AJL, 2017

GW170817 ν limits

- ★ Time windows: ±500 s, 14-days
- ★ No neutrino candidate found
- ★ Only optimistic model constraint by observations
- ★ Consistent with model predictions of short GRB observed off-axis and low luminosity GRB

- ★ Complementary searches
- ★ An unprecedented joint effort of experiments sensitive to high-energy neutrino



ANTARES, IceCube and the Pierre Auger Observatory, AJL, 2017

The Pierre Auger Observatory upgrade

The Pierre Auger Observatory Upgrade

Increased composition with SD!

A new detector is needed

- ⋆ add a thin scintillator on top of each WCD to enhance em/muon separation
- ⋆ New electronics (120 MHz, three times the current rate)

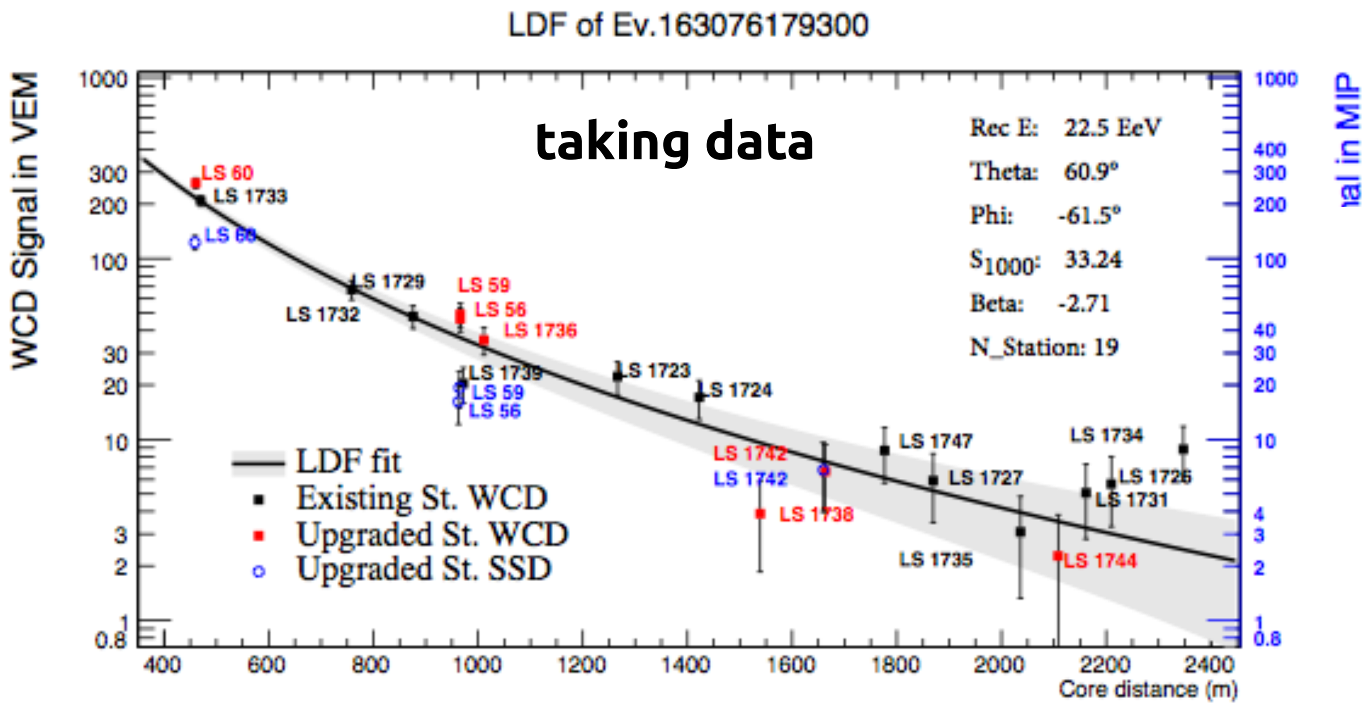
2016:
Engineering Array

2018-2019:
deployment of 1200 SSD

2019-2025:
data taking
(almost double exposure)

Pierre Auger Collaboration, arXiv:1604.03637

The Pierre Auger Observatory Upgrade

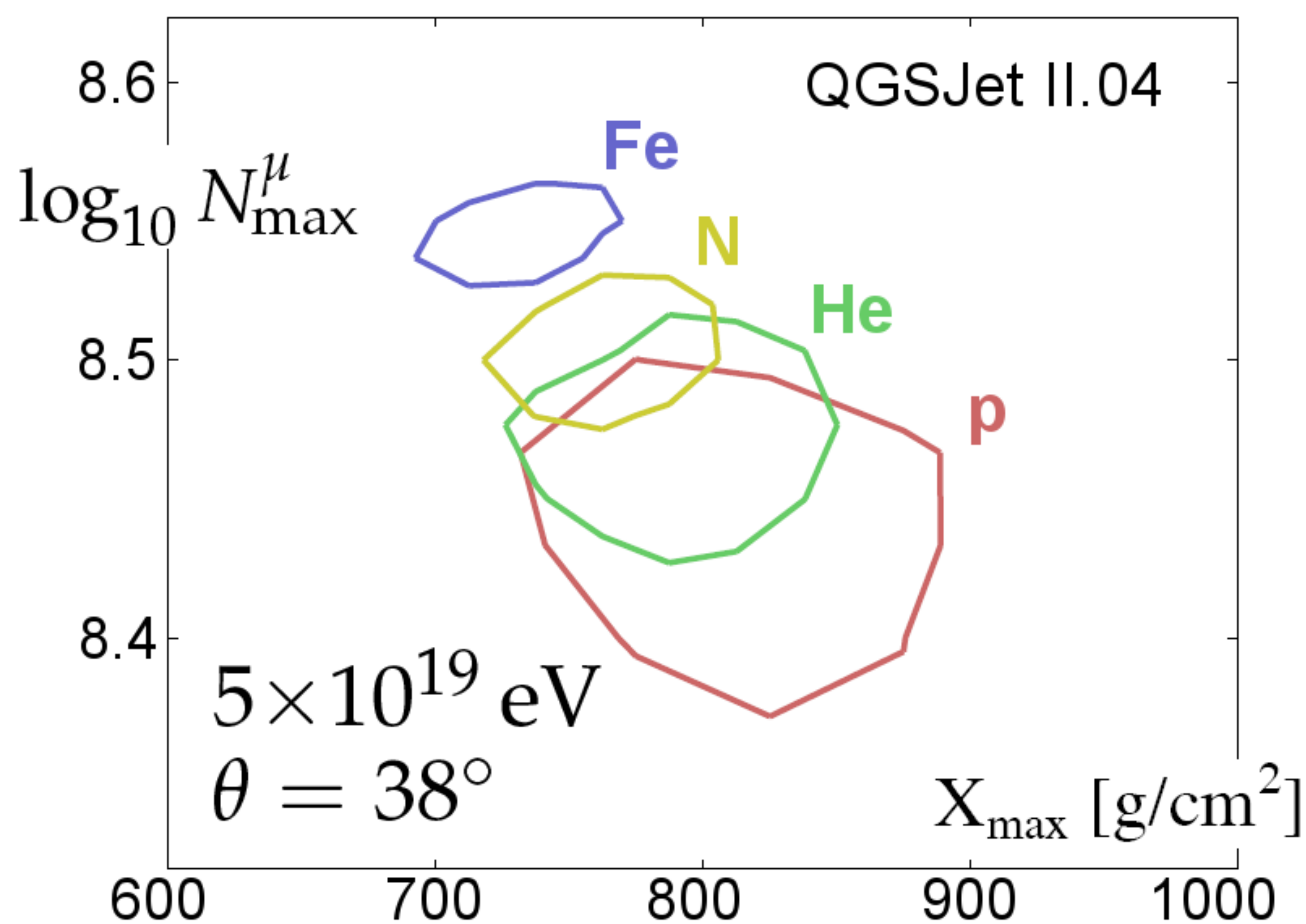


WCD and SSD data

★ Lateral distribution function determination

Physics goals

★ composition measurement at 10^{20} eV
★ composition-enhanced anisotropy studies
★ particle physics with air showers



Martello, for the Pierre Auge Collab., ICRC 2017

Conclusions

Photons

- ⋆ No photons with EeV energies detected so far
- ⋆ Search for a diffuse flux of photons: upper limits impose severe constraints on non-acceleration models for the origin of UHECRs and the predictions from some GZK-based models are within reach
- ⋆ Targeted search: no evidence for EeV photon emitters and the connection with the TeV energy regime enables new multi-messenger studies

Neutrinos

- ⋆ No neutrino found
- ⋆ UHE neutrinos easy to identify: inclined showers with broad time fronts
- ⋆ Search not limited by background but by exposure
- ⋆ Sensitivity peaks at ~ EeV (peak of cosmogenic neutrinos)
- ⋆ Diffuse bounds constrain UHE neutrinos models

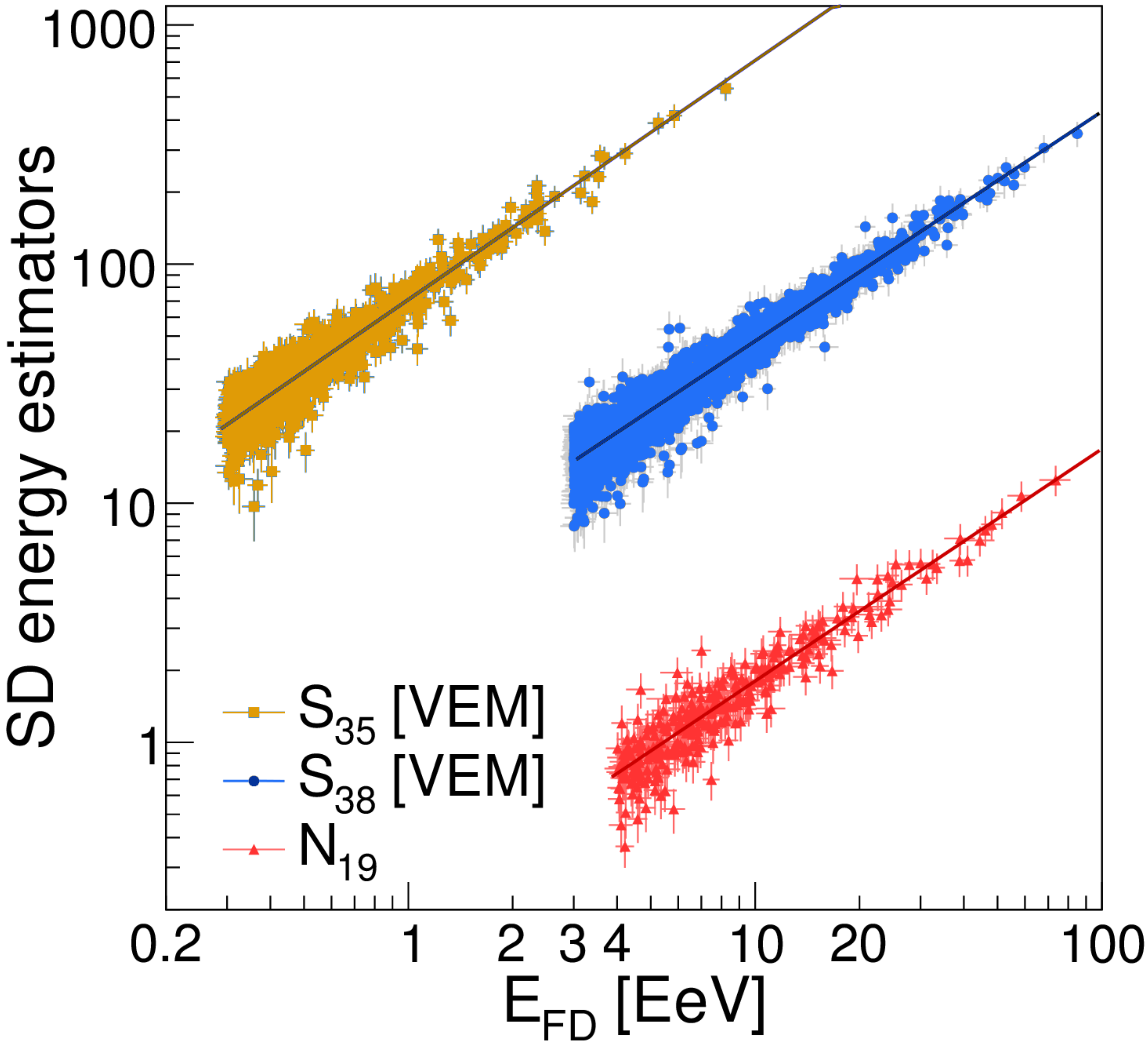
Follow-up of Gravitational-Wave events:

- ⋆ Upper limits on UHE neutrinos in correlation with LIGO GW 2015 events:
  First limits above 10^{17} eV (complementary to IceCube limits)
- ⋆ GW170817: upper limits with Antares and IceCube
- ⋆ Active role in multimessenger era!

Backup slides

Neutrinos

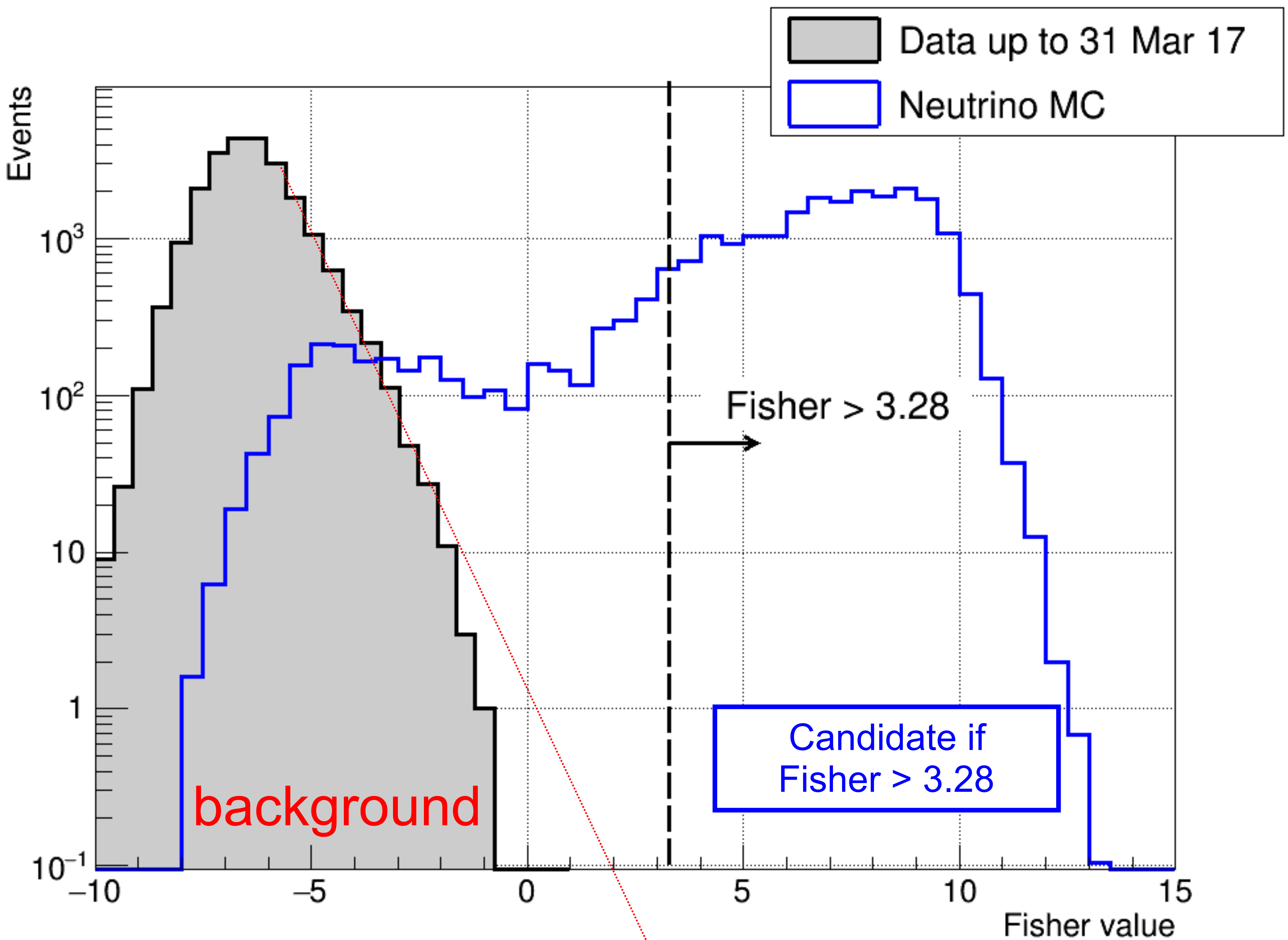
Hybrid energy calibration



FD: σ_E = 8%, σ_{syst} = 14%

SD: σ_E = 10% (at 10^{19} eV)

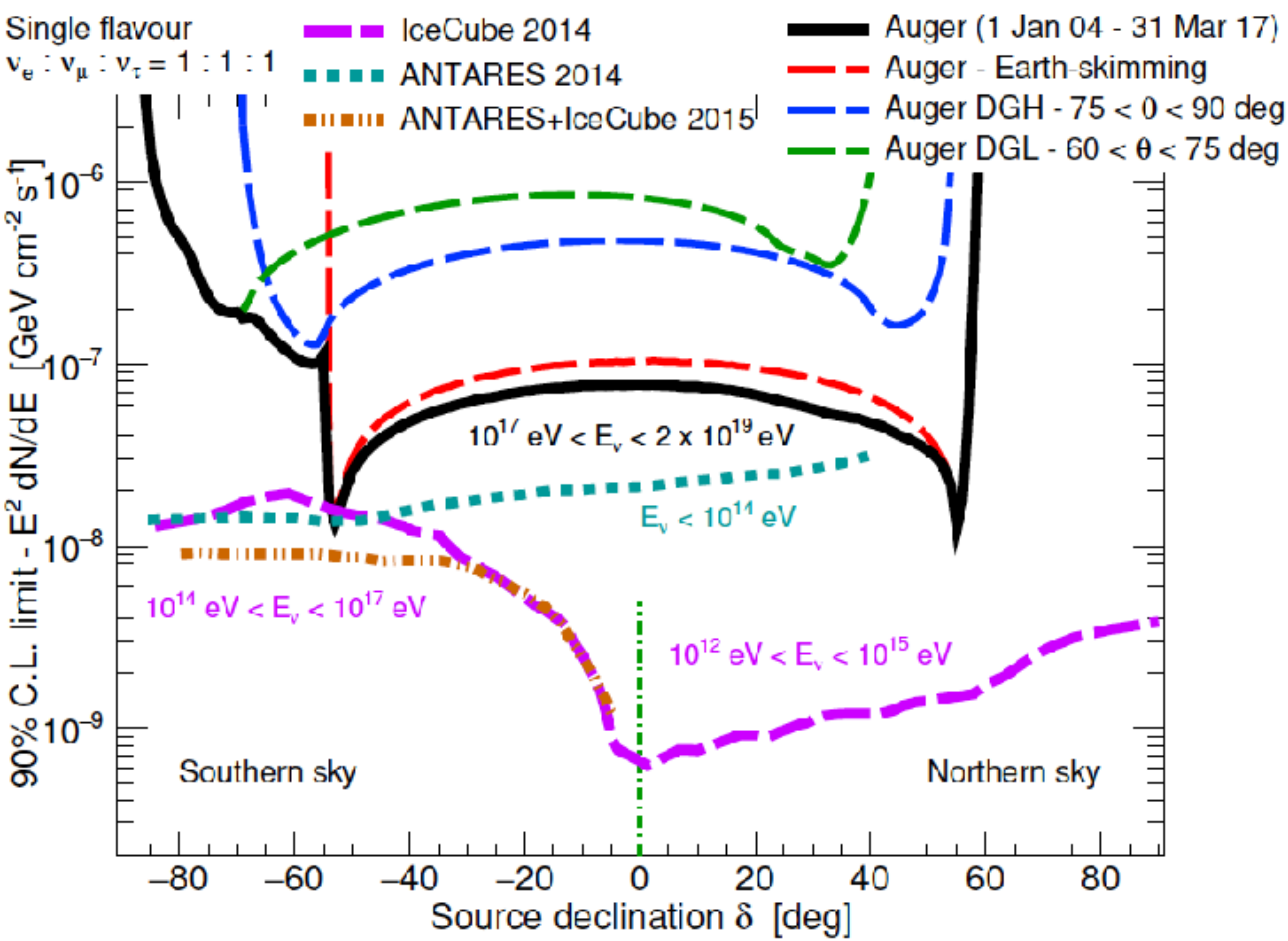
ν search: DGH $75^o < \theta < 90^o$



Fisher

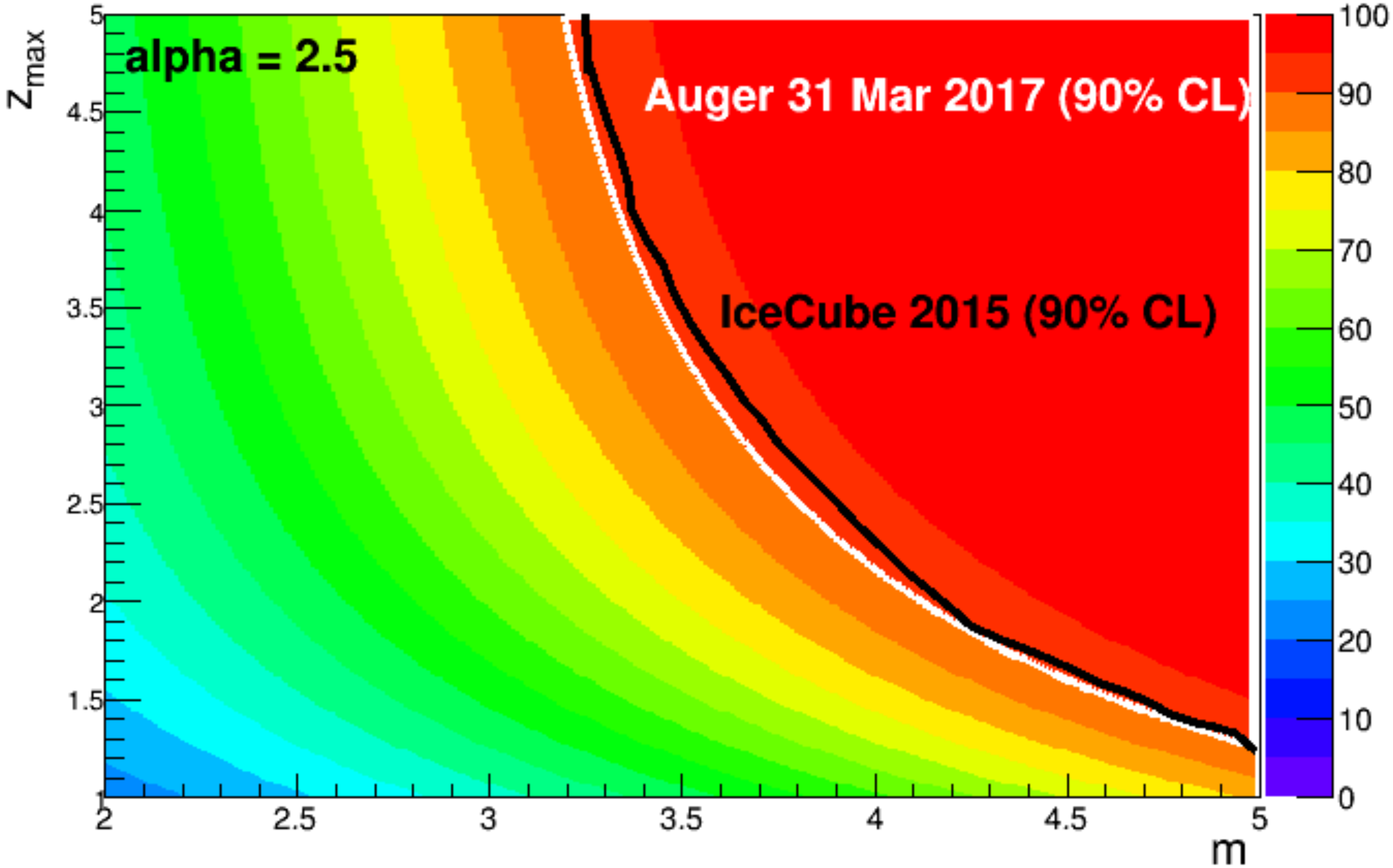
- less than one bckg event in 50 years of SD data
- 85% efficient

Limits to point sources of UHE ν



- ⋆ **assuming a single flavor point-like flux of UHE neutrinos dN/dE = k^{PS} E_ν^{-2}**
- ⋆ **note the different energy ranges**

Proton dominated sources



Data

- ★ Auger Jan 04 - Mar 17
- ★ IceCube April 08 - May 15

Cosmogenic flux depend on:

- ★ m Source evolution

$$\Phi(z) \sim (1+z)^m$$

- ★ $z_{\max}$ Maximum z
- ★ α Spectral index of injection at source

$$\frac{dN}{dE} \sim E^{-\alpha}$$

- ★ Above black line: excluded at 90% by IceCube (7 yrs of data) PRL 2016
- ★ Above white line: excluded at 90% by Auger 2016 (8.4 yrs of full Auger)

Zas, for the Pierre Auger Collab., ICRC2017

ν search: inclined and young showers

TABLE I. Observables and numerical values of cuts applied to select *inclined* and *young* showers for Earth-skimming and downward-going neutrinos. See text for explanation.

Selection	Earth-skimming (ES)	Downward-going *high* angle (DGH)	Downward-going *low* angle (DGL)
Flavours and interactions	ν_τ CC	ν_e, ν_μ, ν_τ CC & NC	ν_e, ν_μ, ν_τ CC & NC
Angular range	$\theta > 90°$	$\theta \in (75°, 90°)$	$\theta \in (60°, 75°)$
N° of stations (N_{st})	$N_{\mathrm{st}} \geq 3$	$N_{\mathrm{st}} \geq 4$	$N_{\mathrm{st}} \geq 4$
Inclined showers	$L/W > 5$ $\langle V \rangle \in (0.29, 0.31)$ m ns^{-1} $\mathrm{rms}(V) < 0.08$ m ns^{-1}	$\theta_{\mathrm{rec}} > 75°$ $L/W > 3$ $\langle V \rangle < 0.313$ m ns^{-1} $\mathrm{rms}(V)/\langle V \rangle < 0.08$	$\theta_{\mathrm{rec}} \in (58.5°, 76.5°)$
Young showers	Data: 1 January 2004–31 May 2010 $\geq 60\%$ of stations with ToT trigger and AoP > 1.4 Data: 1 June 2010–20 June 2013 $\langle \mathrm{AoP} \rangle > 1.83$ $\mathrm{AoP}_{\mathrm{min}} > 1.4$ if $N_{\mathrm{st}} = 3$	Fisher discriminant based on AoP of *early* stations	$\geq 75\%$ of stations close to shower core with ToT trigger and Fisher discriminant based on AoP of *early* stations close to shower core

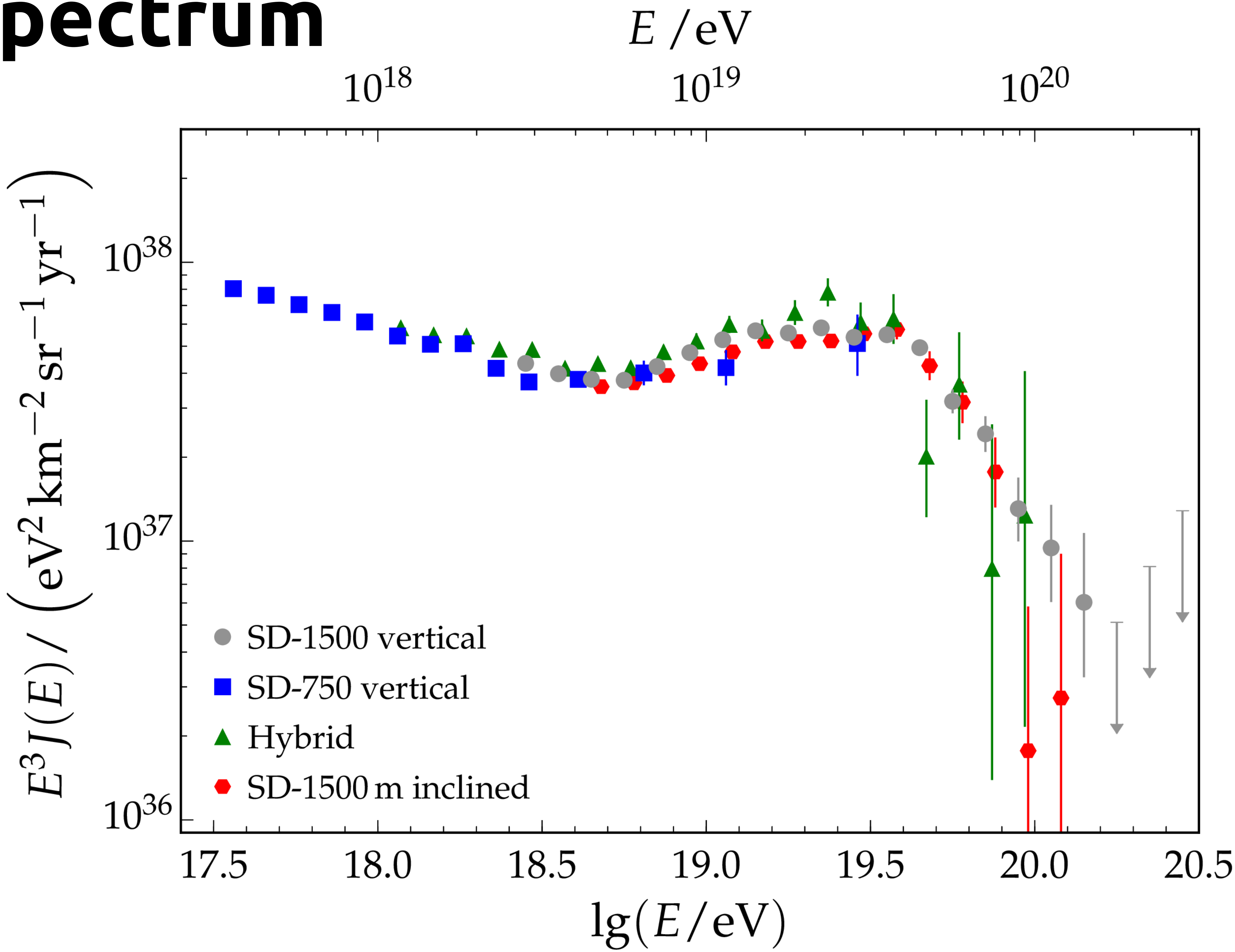
Phys. Rev. D 91, 092008 (2015)

Systematic uncertainties

Source of systematic	Combined uncertainty band
Simulations	$\sim +4\%, -3\%$
ν cross section and τ E-loss	$\sim +34\%, -28\%$
Topography	$\sim +15\%, 0\%$
Total	$\sim +37\%, -28\%$

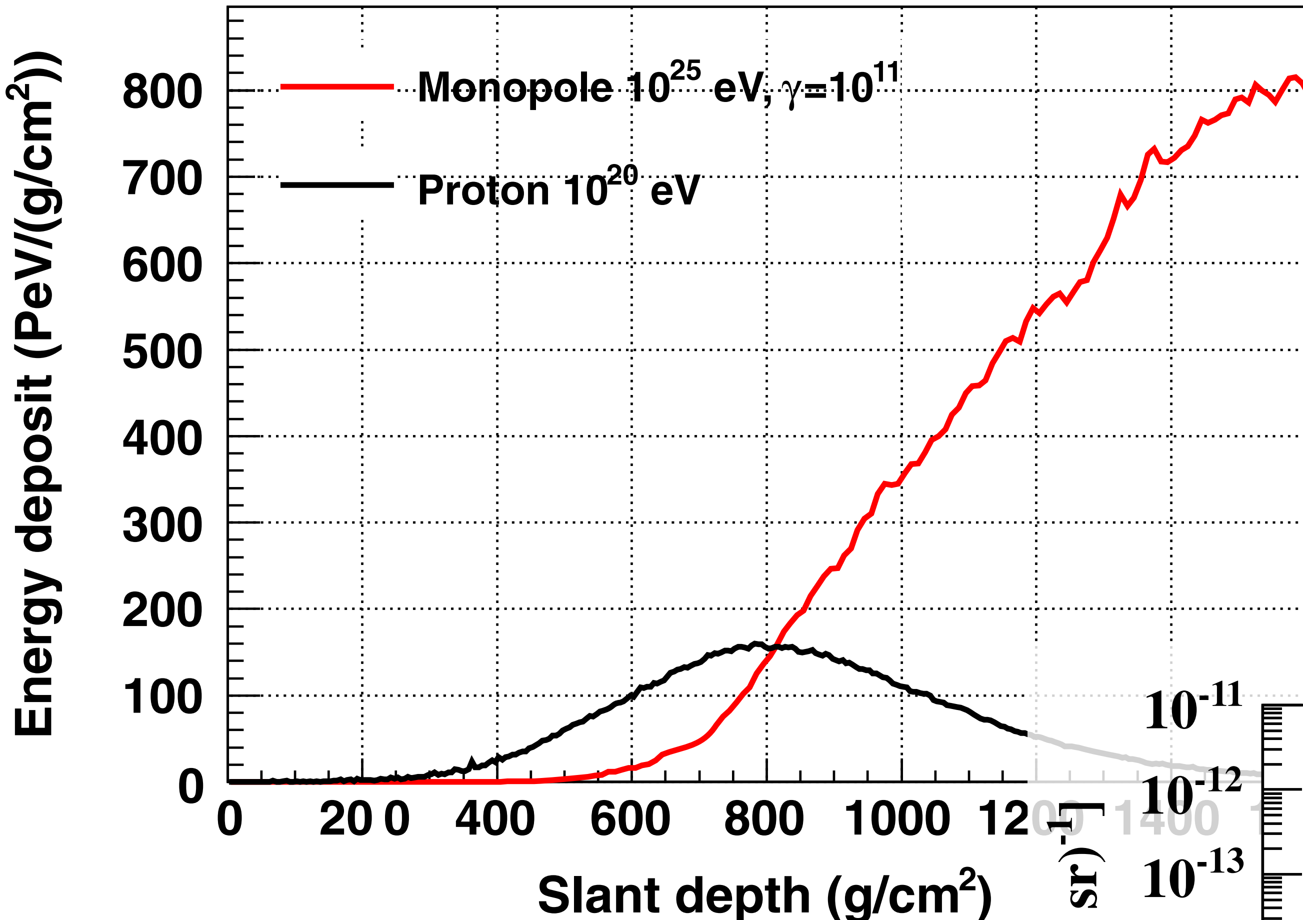
Auger highlights

Spectrum



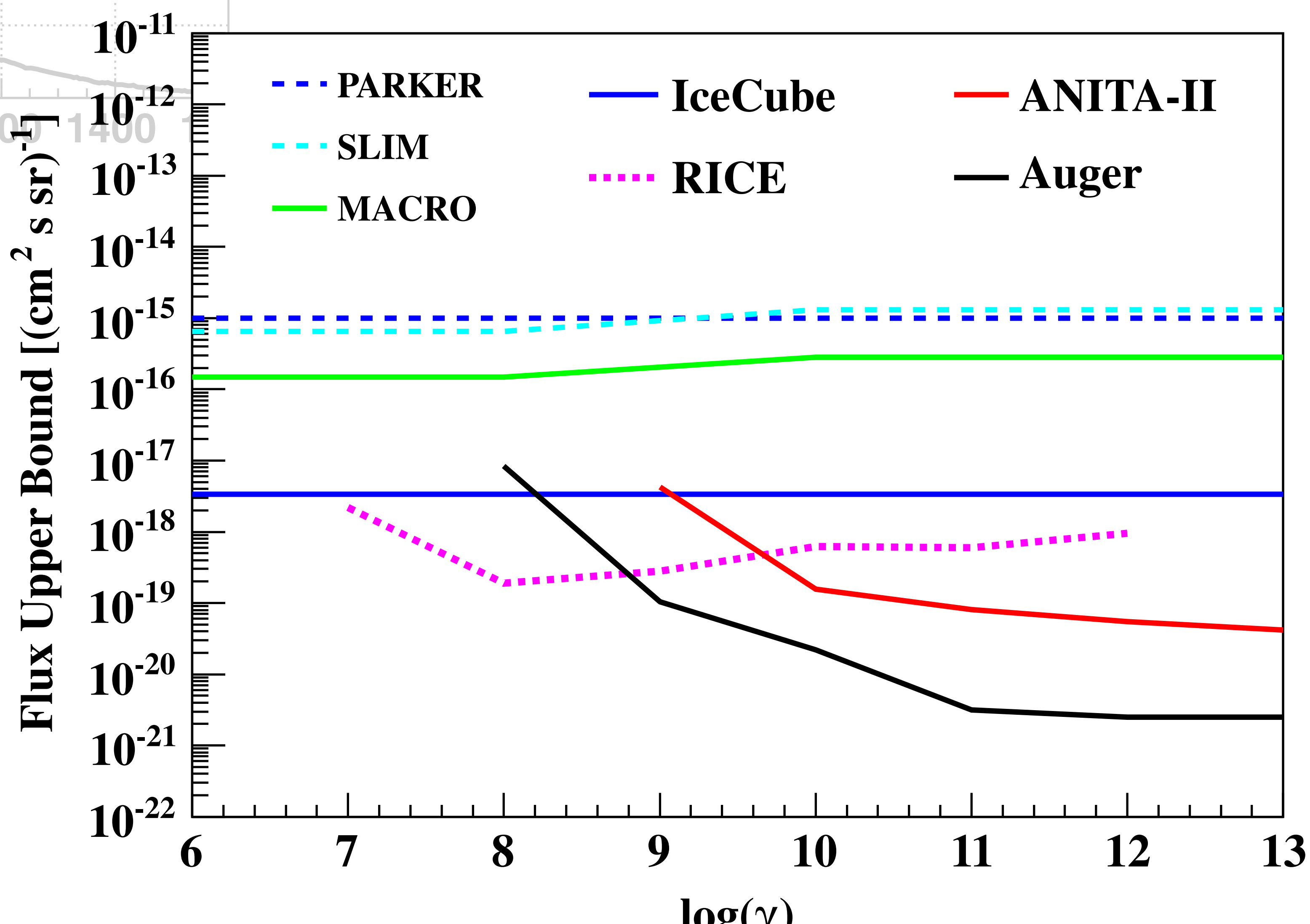
E /eV
10^{18}
10^{19}
10^{20}
10^{38}
10^{37}
10^{36}
$E^3 J(E) / \left(\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right)$
SD-1500 vertical
SD-750 vertical
Hybrid
SD-1500 m inclined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\lg(E/\mathrm{eV})$

Magnetic monopoles



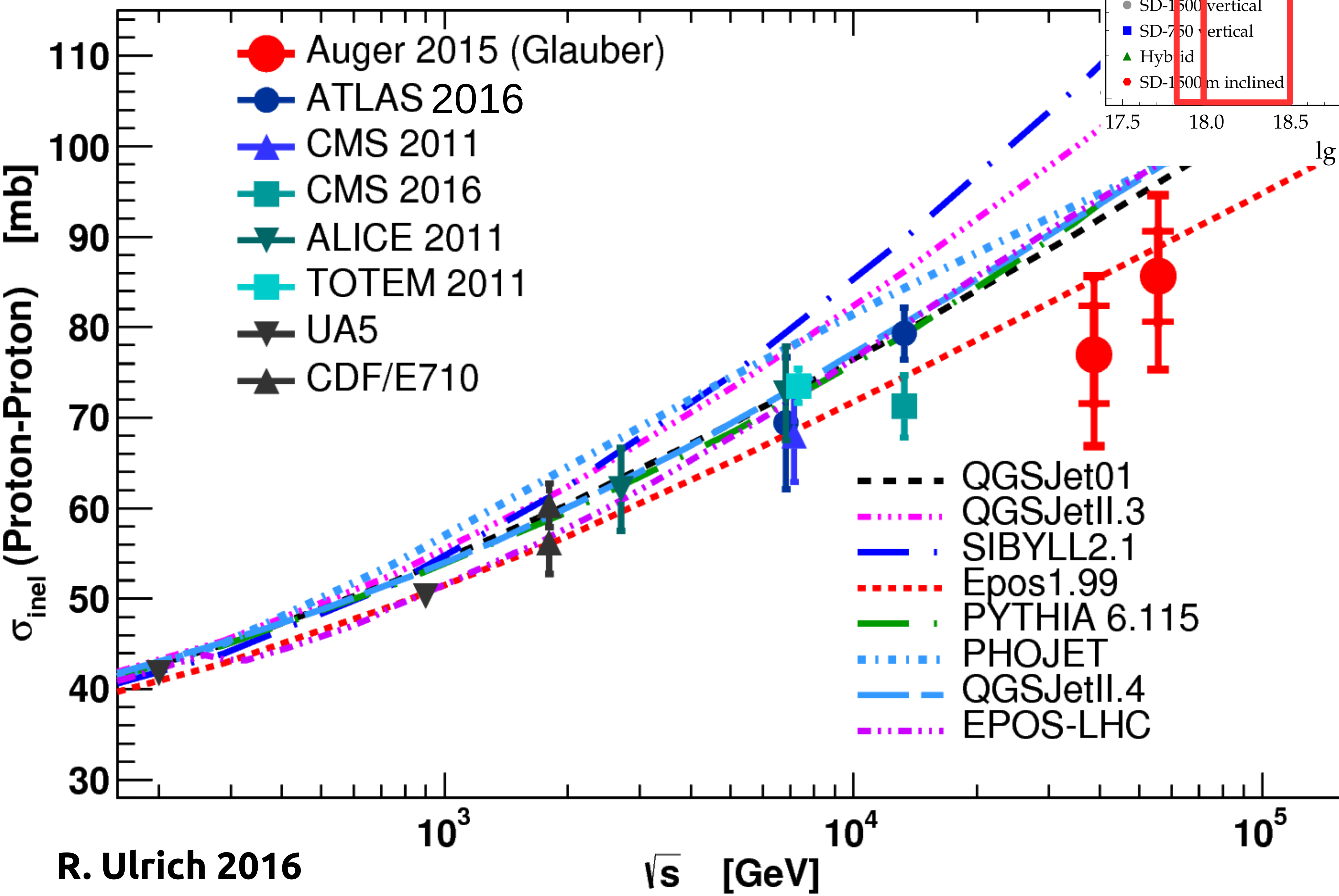
Energy deposit different from hadronic shower

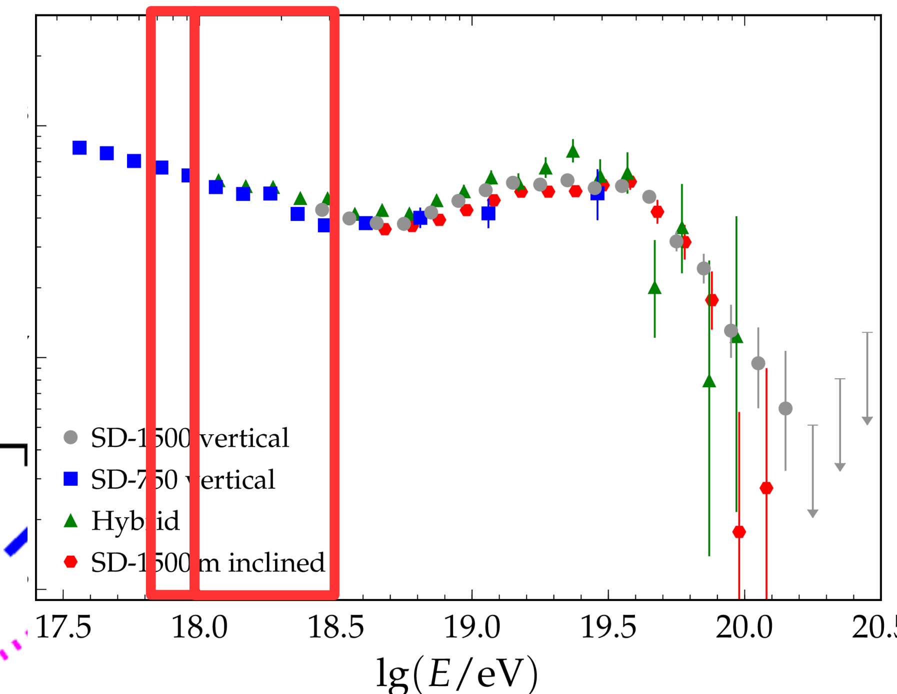
Auger: strongest limits at high E



Pierre Auger Collab, Phys Rev D, 2016

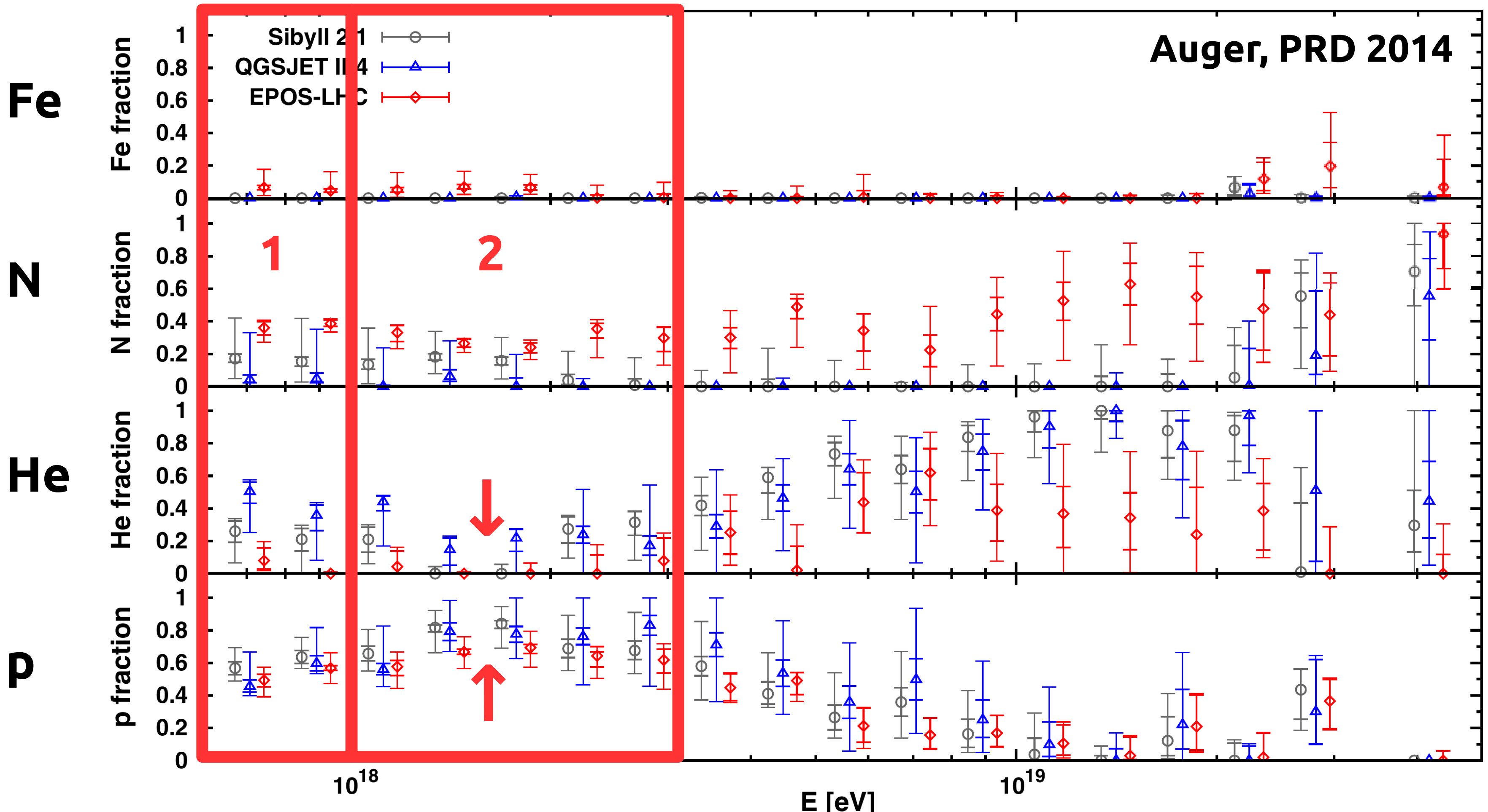
Cross Section

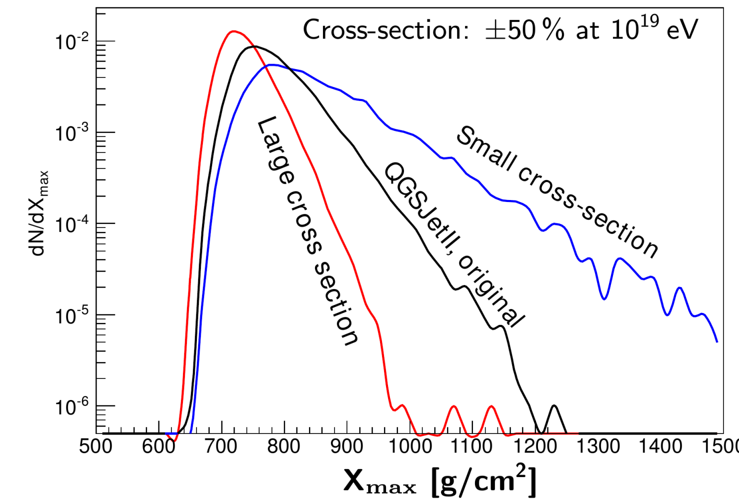




R. Ulrich 2016

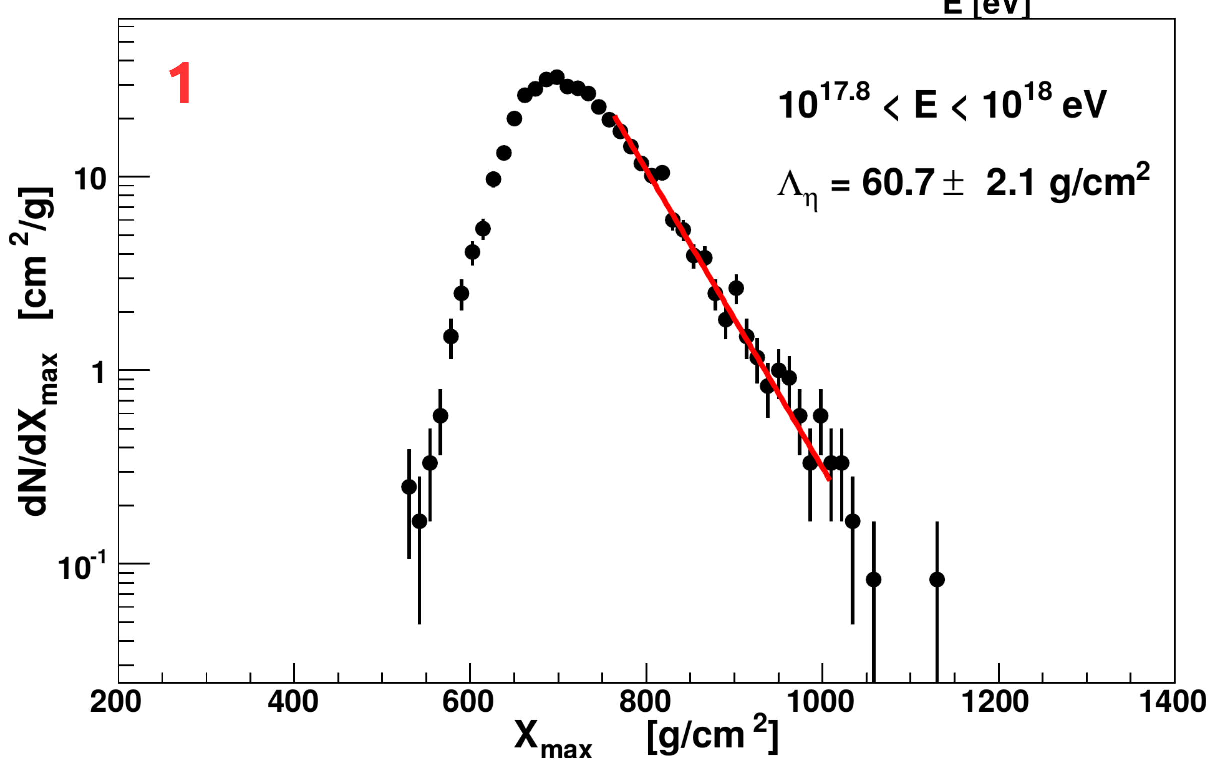
Cross Section

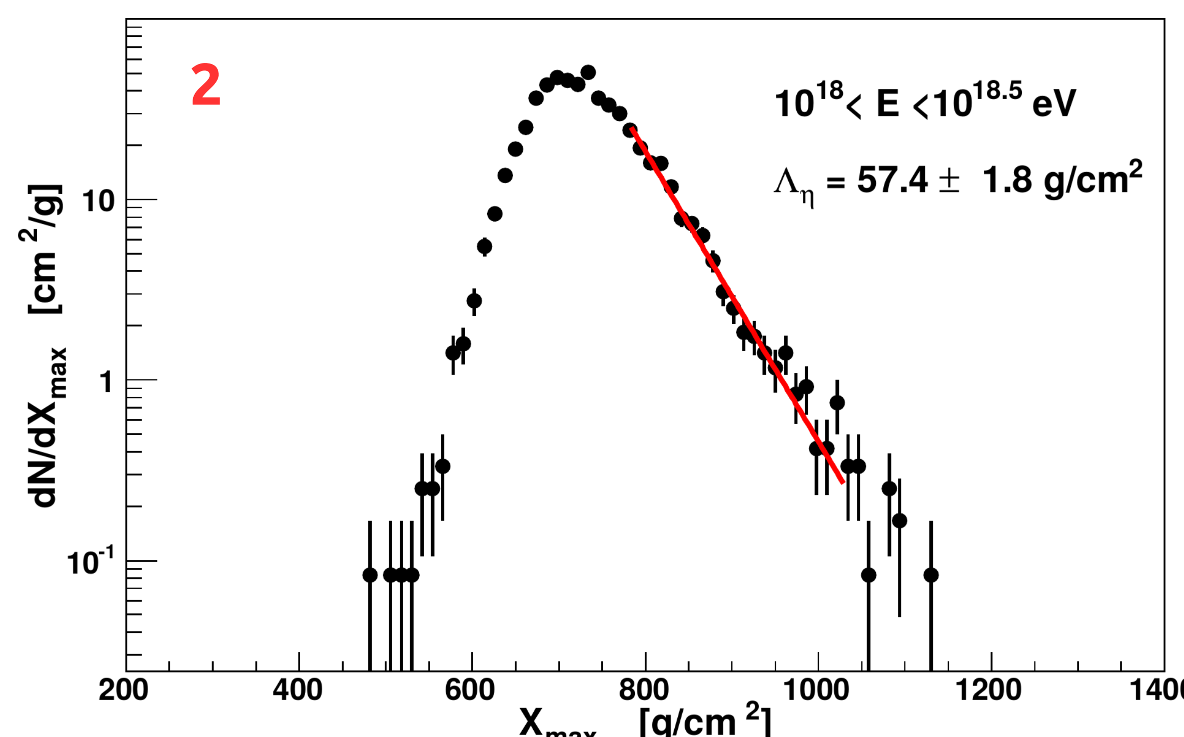




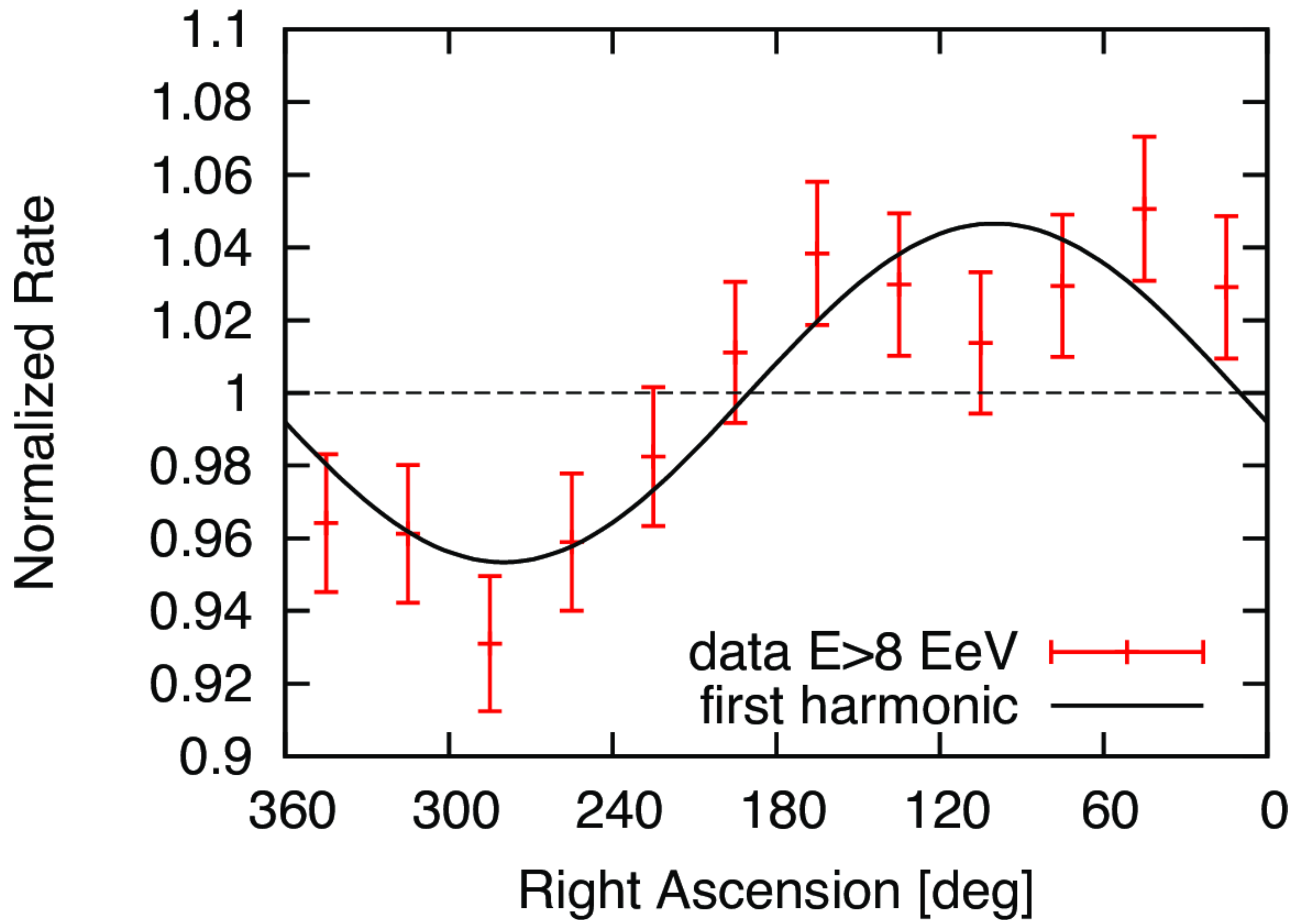
slope at large X_{max} depends on cross-section

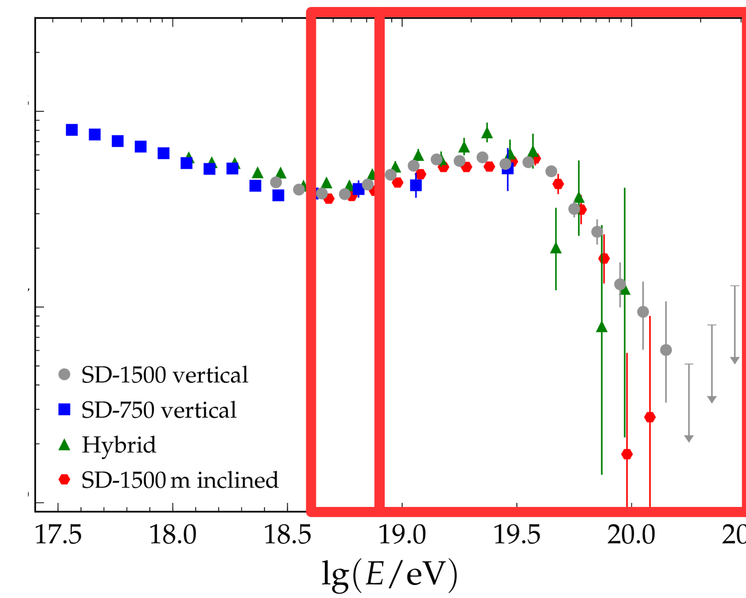
selected so that systematics (dominated by He contamination) is the same as statistical uncertainty





Large-scale Anisotropy





Science
AAAS

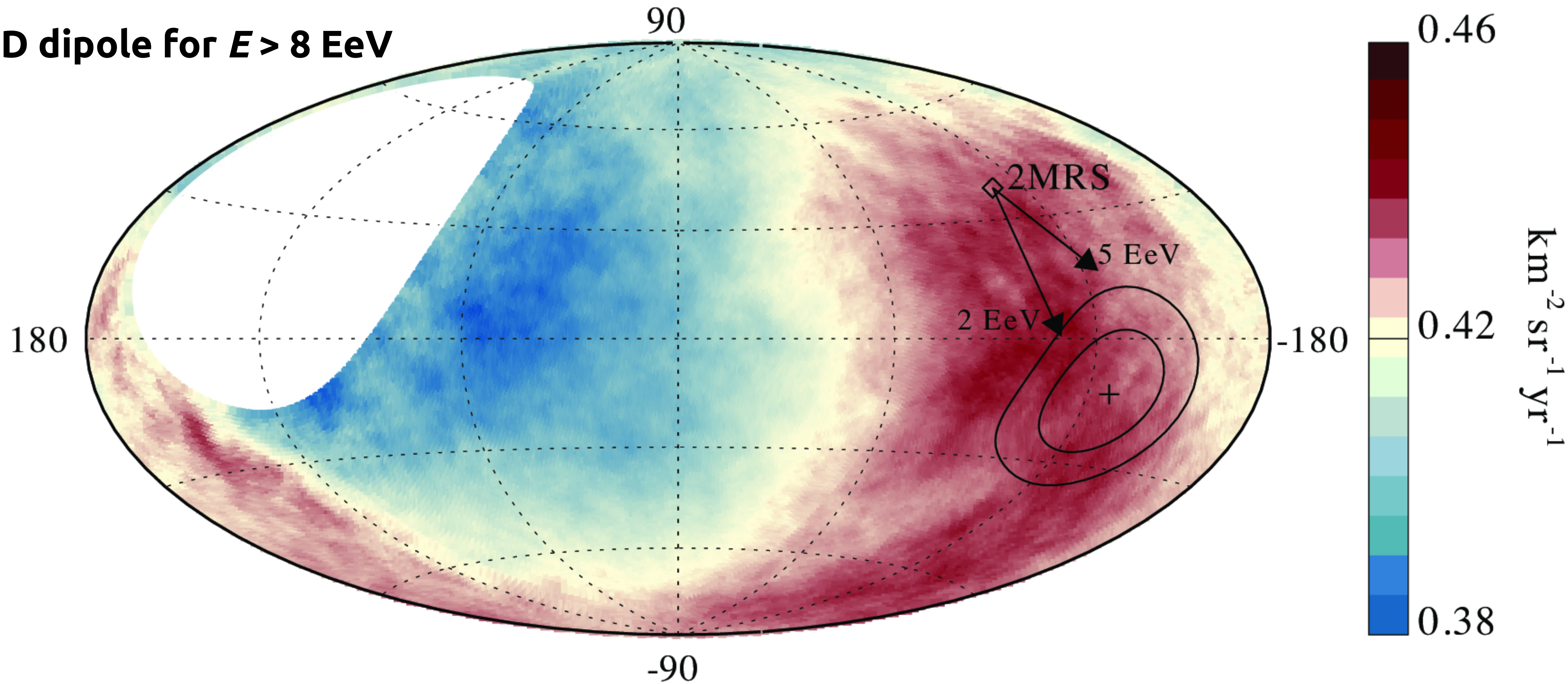
harmonic analysis in right ascension α (exposure symmetrical):

Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

modulation significance 5.3σ (5.6σ before penalization)

Large-scale Anisotropy

3D dipole for *E* > 8 EeV

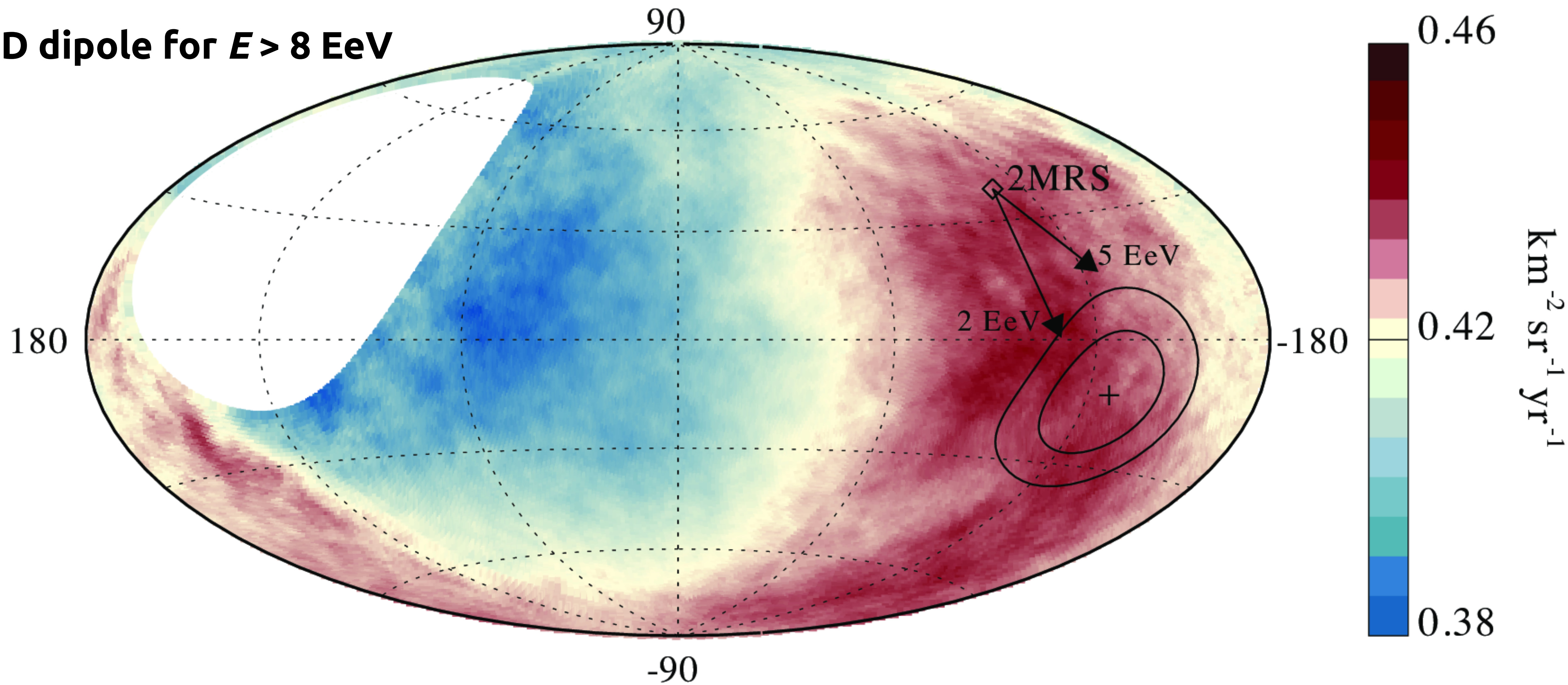


Energy (EeV)	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination δ_d (°)	Dipole right ascension α_d (°)
4 to 8	-0.024 ± 0.009	$0.006^{+0.007}_{-0.003}$	$0.025^{+0.010}_{-0.007}$	-75^{+17}_{-8}	80 ± 60
≥8	-0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10

galactic coordinates (*l*, *b*) = (233°, -13°)

Large-scale Anisotropy

3D dipole for *E* > 8 EeV



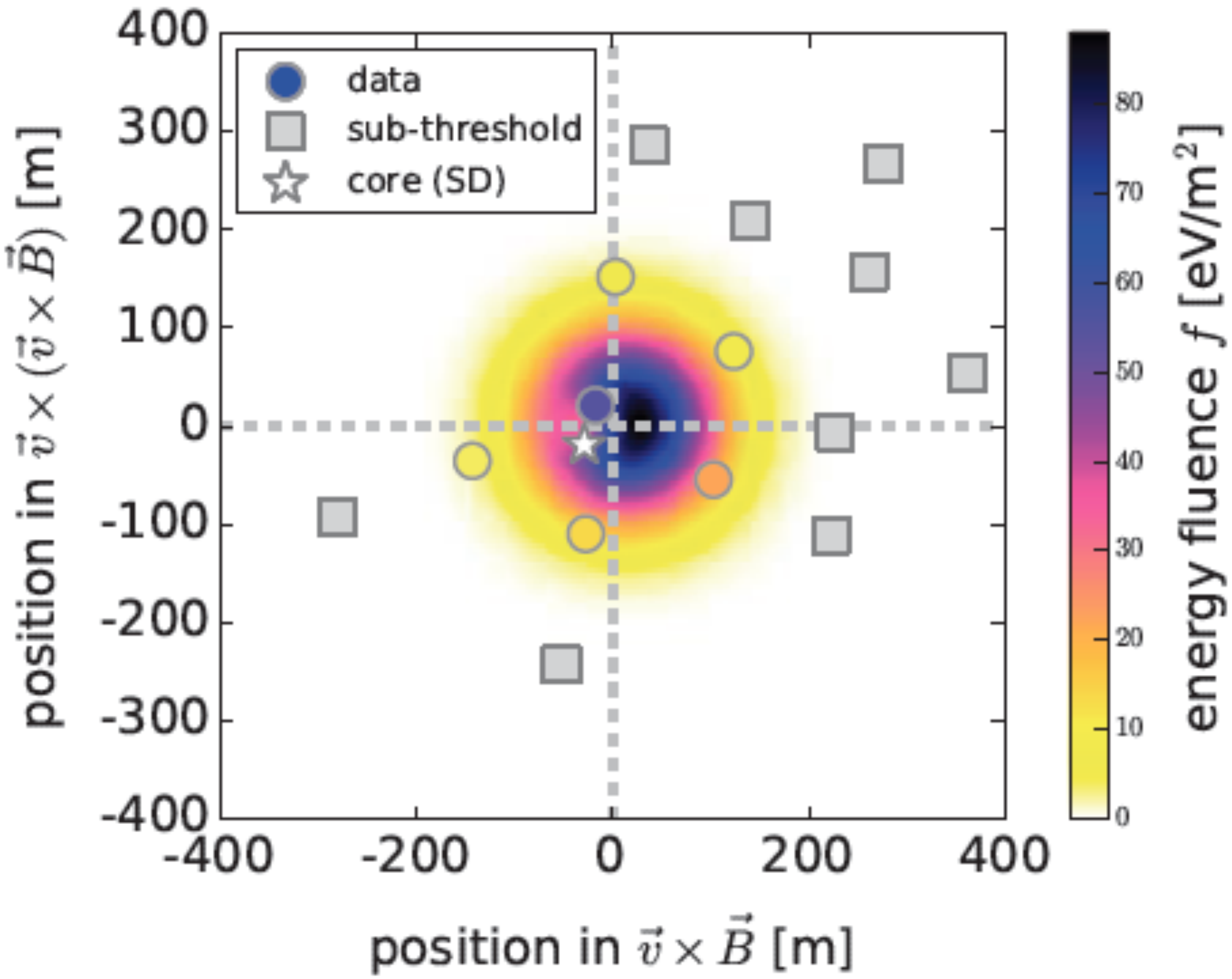
expected if sources distributed as nearby galaxies (2MRS catalog)

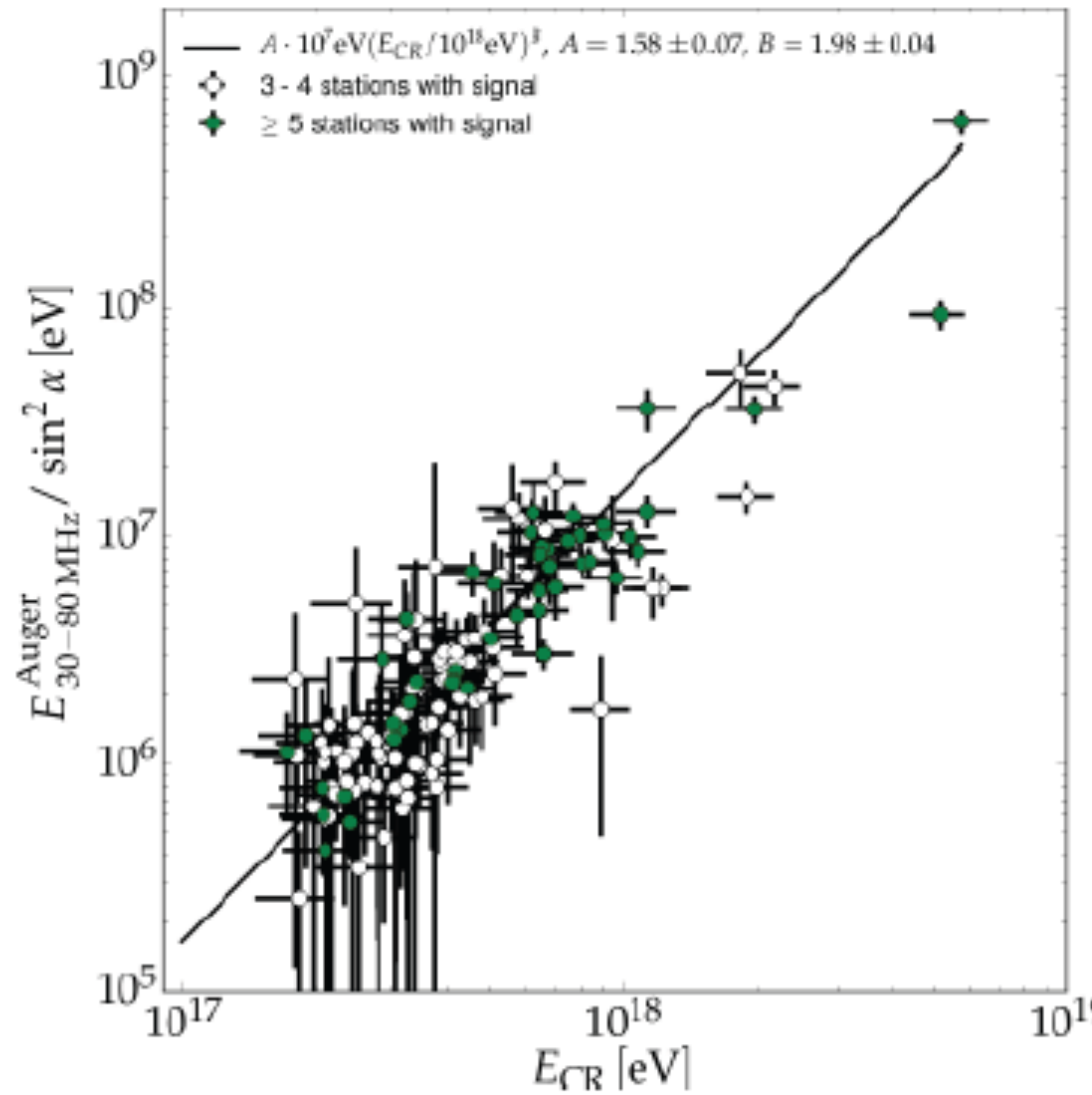
deflection in galactic magnetic field

strong indication for extragalactic origin

physicsworld BREAKTHROUGH OF THE YEAR 2017

Radio array: energy determination





Energy fluence for an extensive air shower with an energy of 4.4 x 10^{17} eV and a zenith angle of 25° measured with AERA (colored circles). The center indicates the shower core reconstructed with the radio data. The colored background indicates the two-dimensional LDF fit. The white star marksthe shower core reconstructed using the surface detector data of the Pierre Auger Observatory

The corrected radiation energy in relation to the cosmic-ray energy measured with the baseline detectors of the Pierre Auger Observatory.