Multi-messenger astrophysics with the Pierre Auger Observatory

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Neutrino Week - GDR Neutrino
Strasbourg, 5-6 November 2018

Outline

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

Pierre Auger Observatory:
nuclei, photons and neutrinos

The Pierre Auger Observatory

The Pierre Auger Observatory

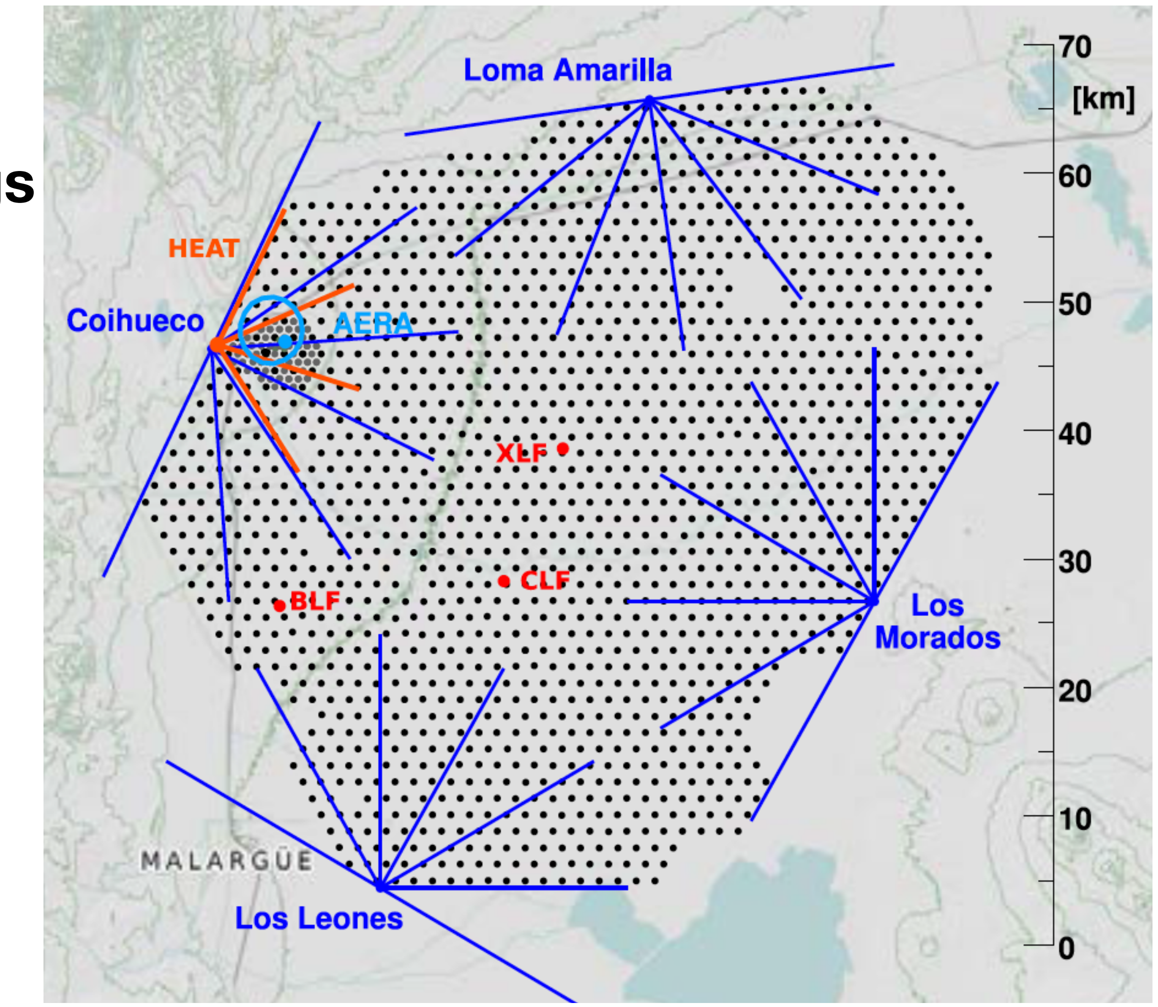
Two independent and complementary detector systems

Fluorescence Detector (FD)

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

~13% duty cycle

longitudinal profile



Surface detector (SD)

1660 water cerenkov detec. (WCD) in 3000 km^2

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 km^2

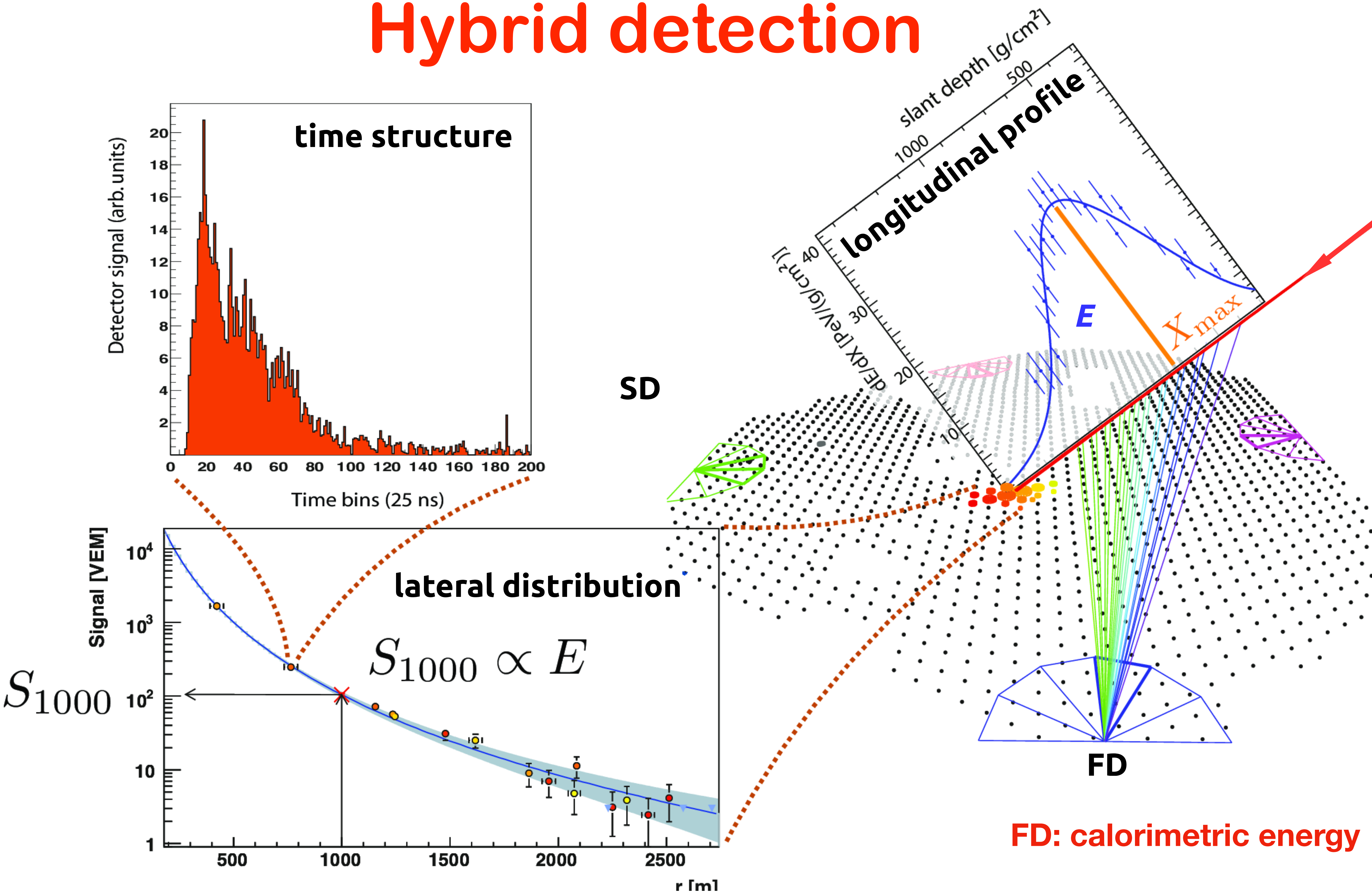
Underground muon detectors

Atmospheric monitoring stations

Auger: data since 2004, completed in 2008

NIM A 2015, arXiv:1502.01323

Hybrid detection

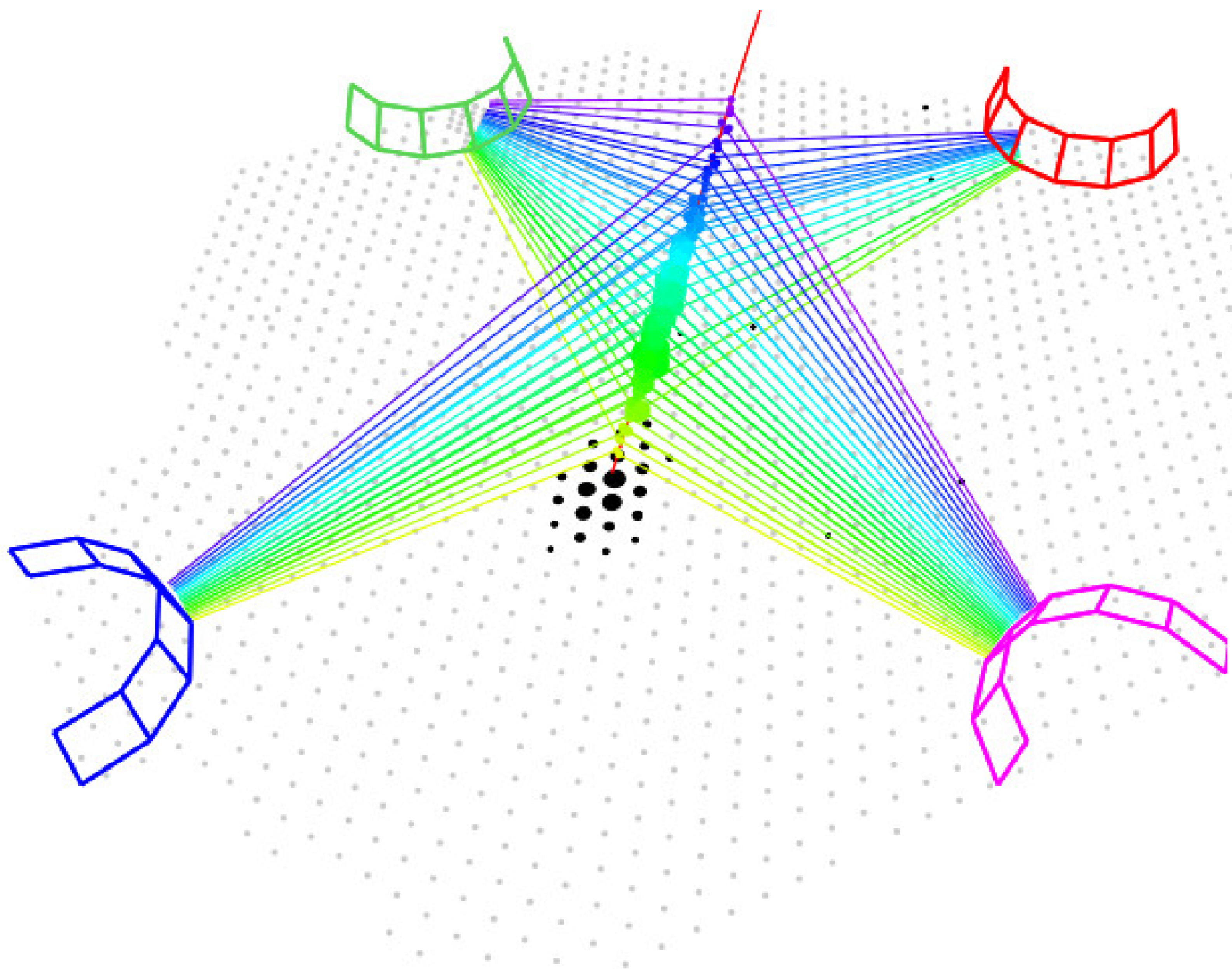


FD: calorimetric energy

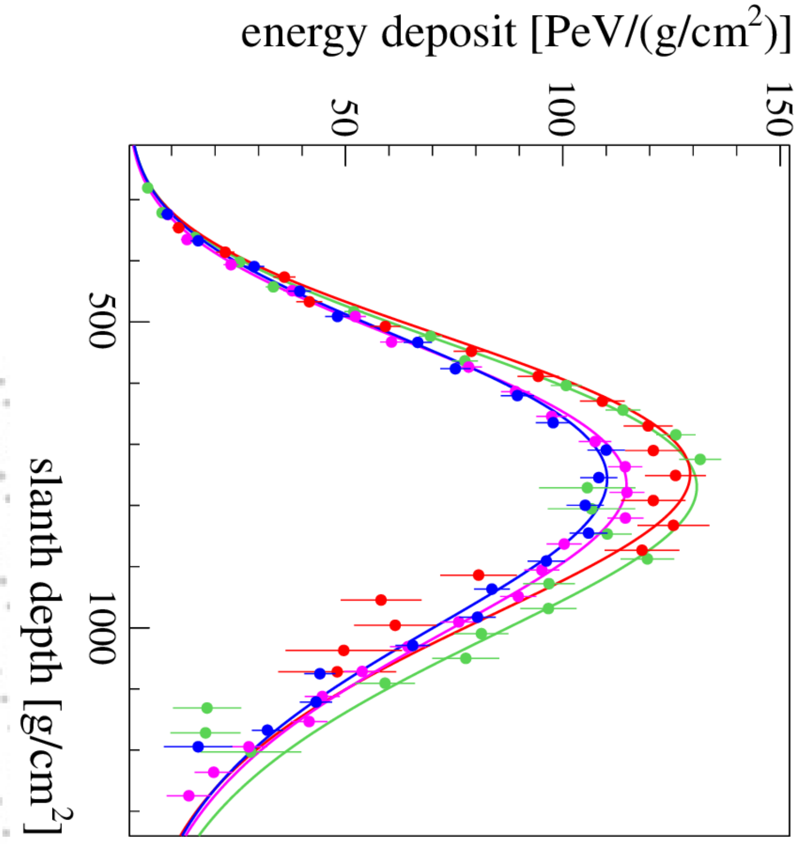
SD ⋆ signal at 1000 m, S_{1000} energy estimator

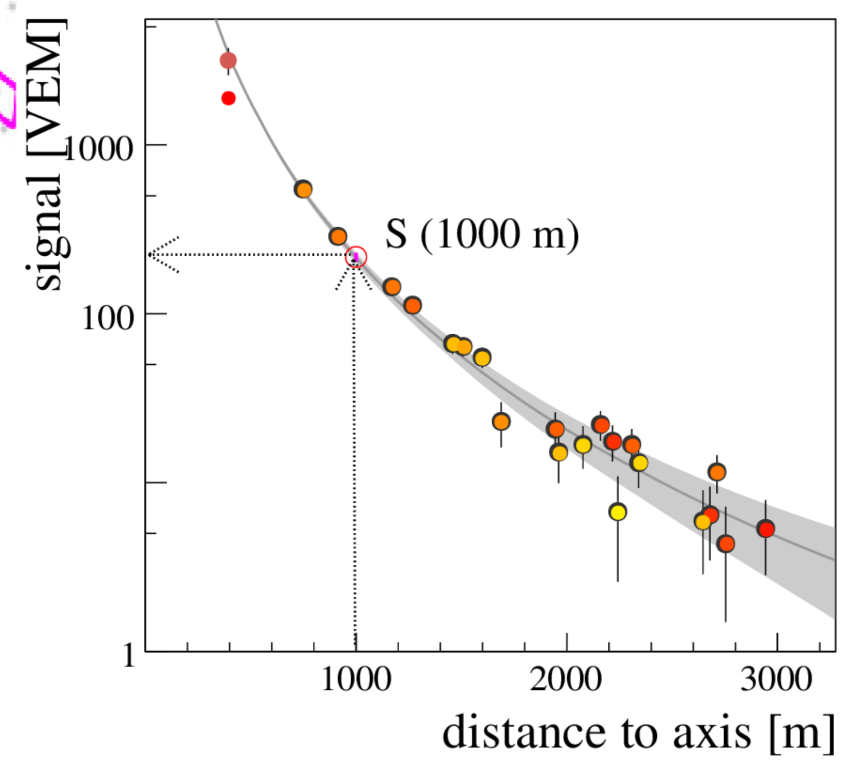
⋆ energy calibration from FD in hybrid events

Quadruple hybrid event

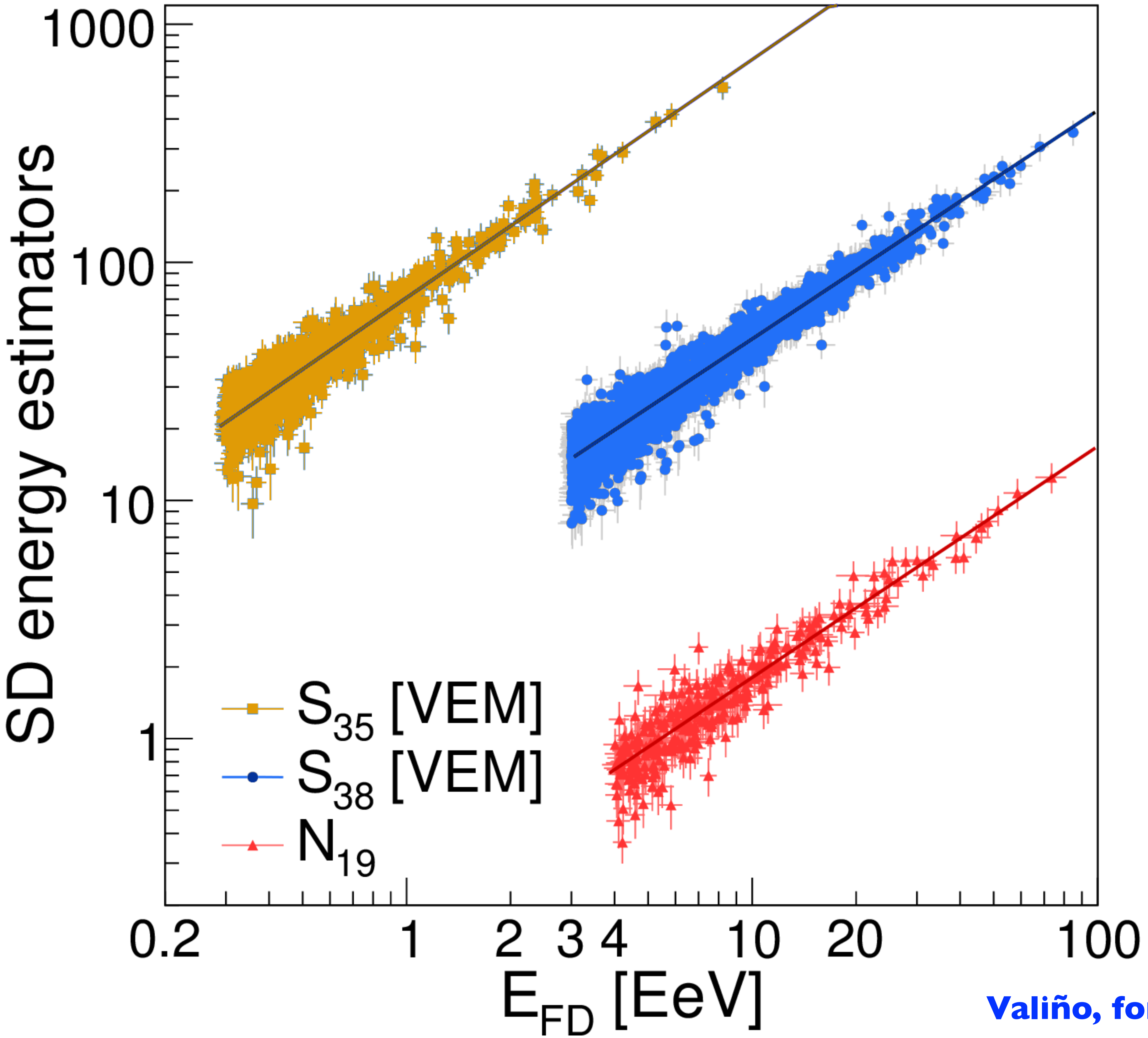


65 km between FD





Hybrid energy calibration



Vertical Equivalent Muon

FD: σ_E = 8%, σ_{syst} = 14%
SD: σ_E = 10% (at 10^{19} eV)

Valiño, for the Pierre Auger Collab., ICRC2015 ArXiv 1509.03732

The search for primary photons

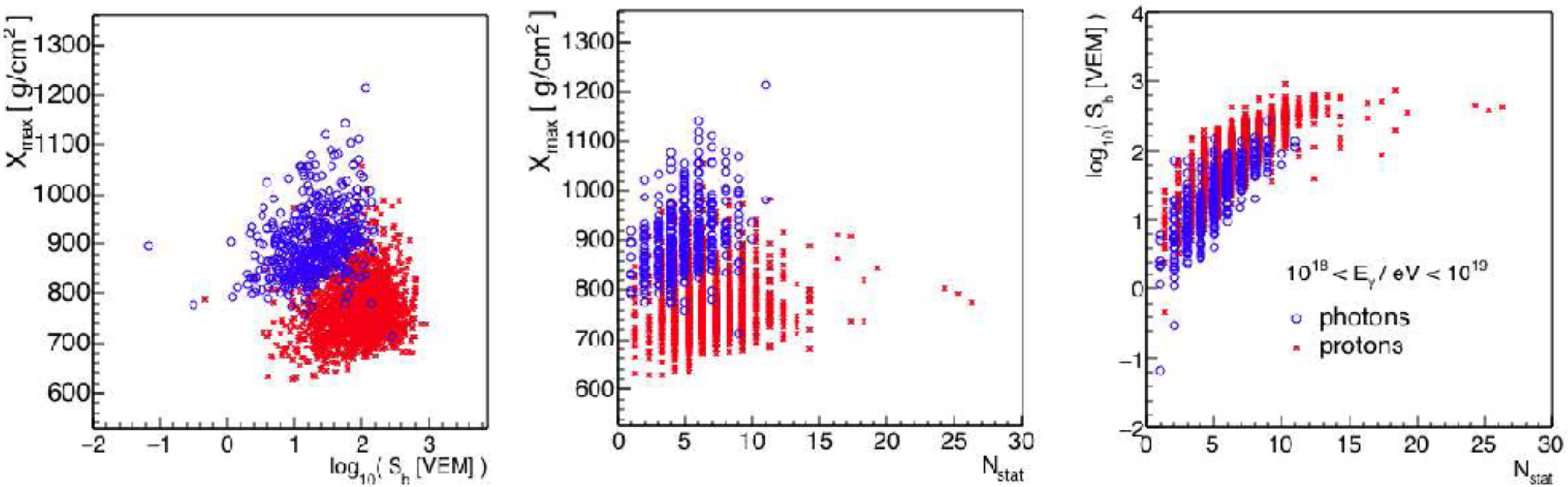
Photon showers x hadronic showers

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

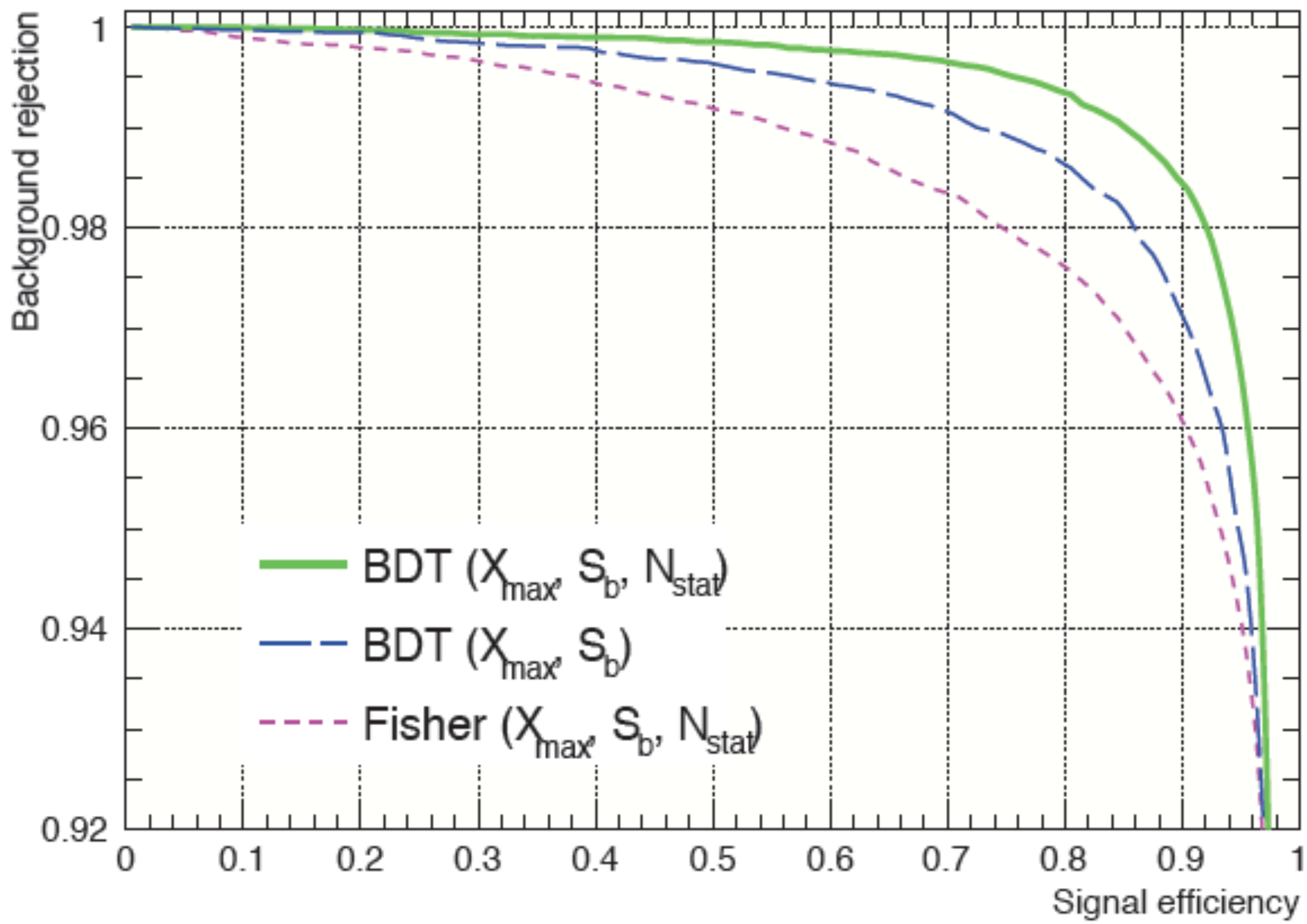
$$S_b = \sum_{i}^{N_{\mathrm{stat}}} S_i \left(\frac{r}{r_0}\right)^b$$

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



Niechciol, for the Pierre Auger Colab., ICRC 2017

Background rejection and signal efficiency



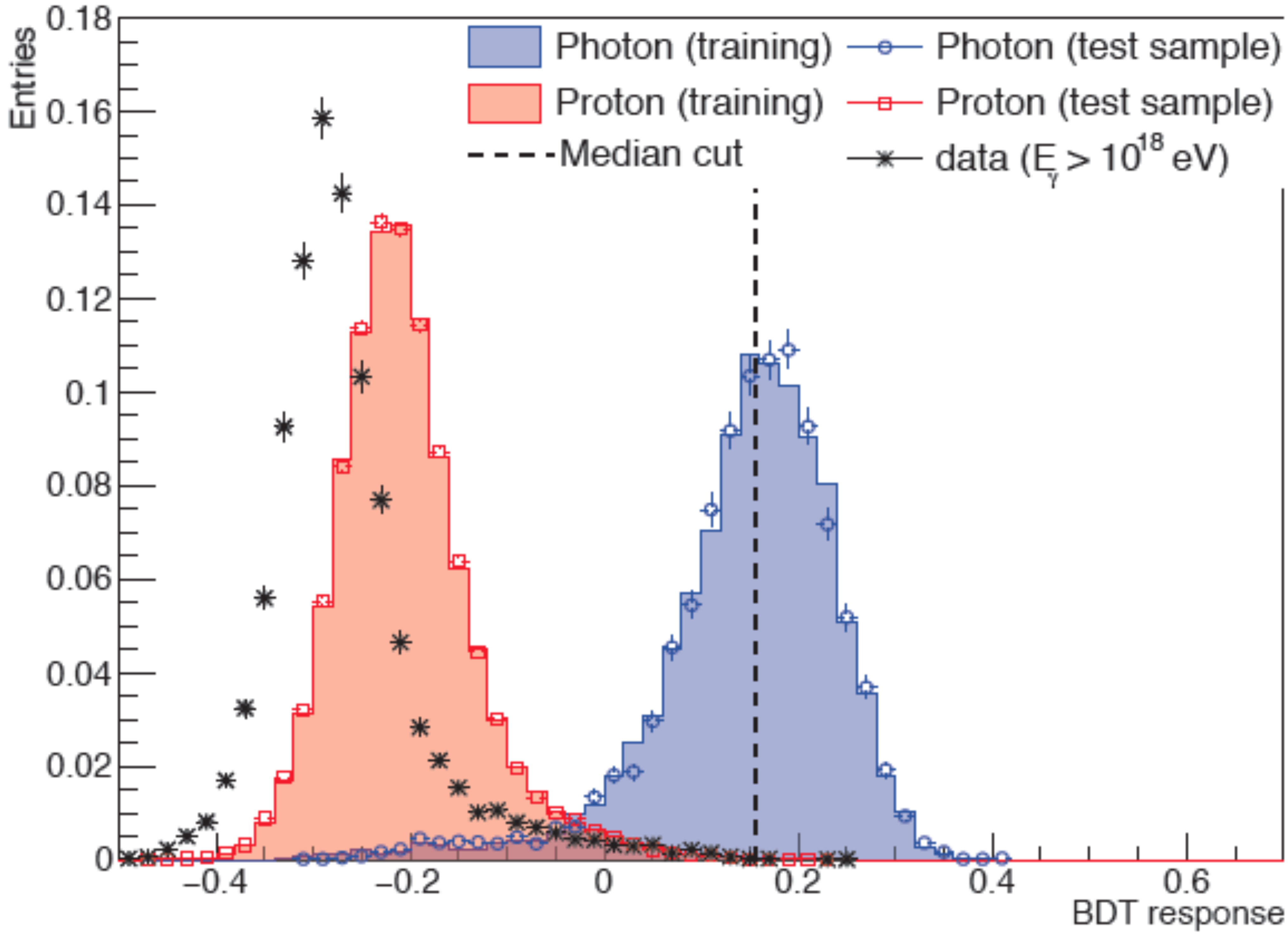
Different algorithms and combinations of input variables

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%**

Niechciol, for the Pierre Auger Colab., ICRC 2017

BDT photon selection

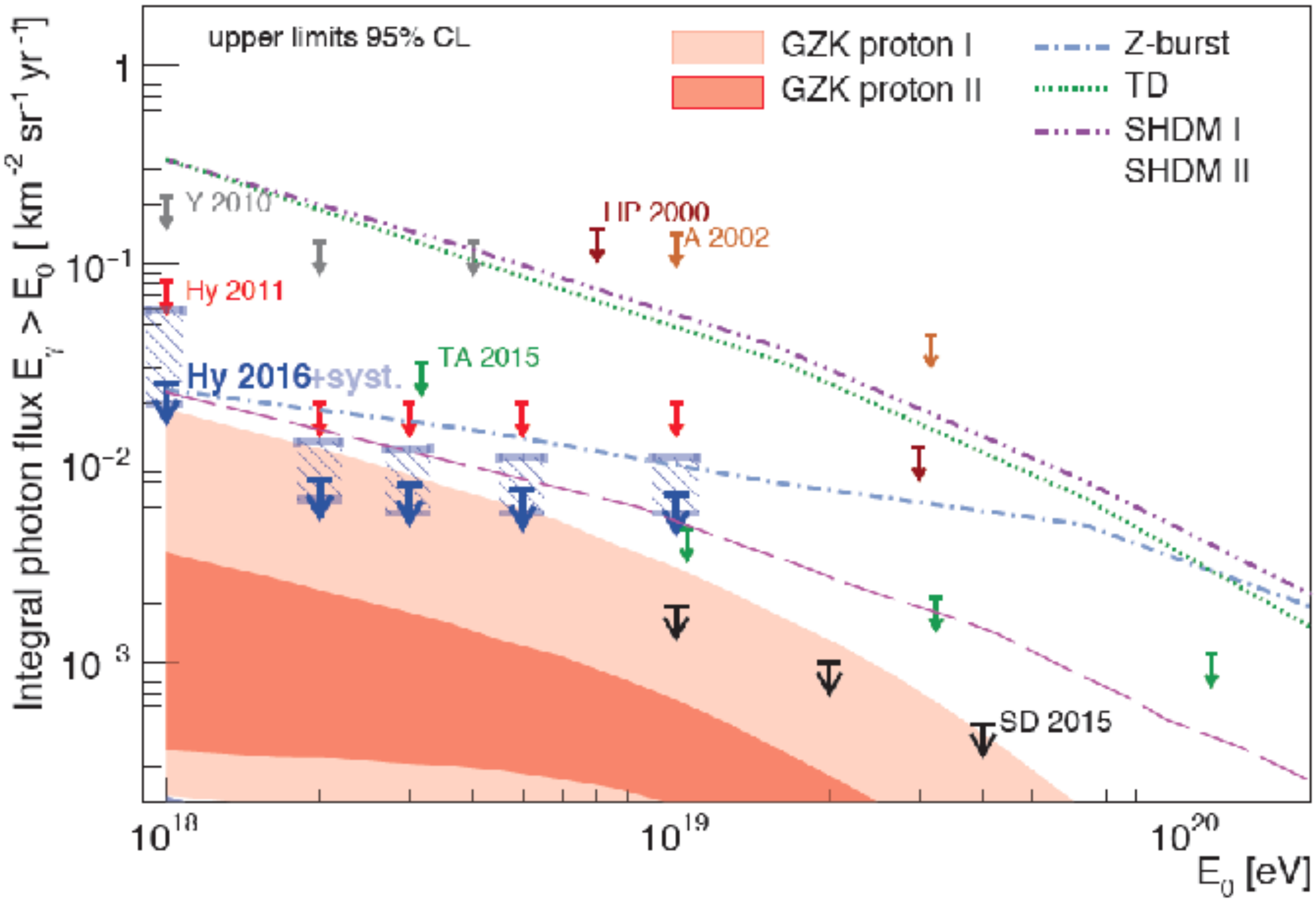


- ⋆ **Three events pass the cut, with 11.4 (3.3) expected for pure-proton (mixed) backg.**
- ⋆ **Candidates compatible with background expectations, upper limits on the integral photon flux at 95% C.L. are derived.** **Niechciol, for the Pierre Auger Colab., ICRC 2017**

Upper limits on photon flux

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

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

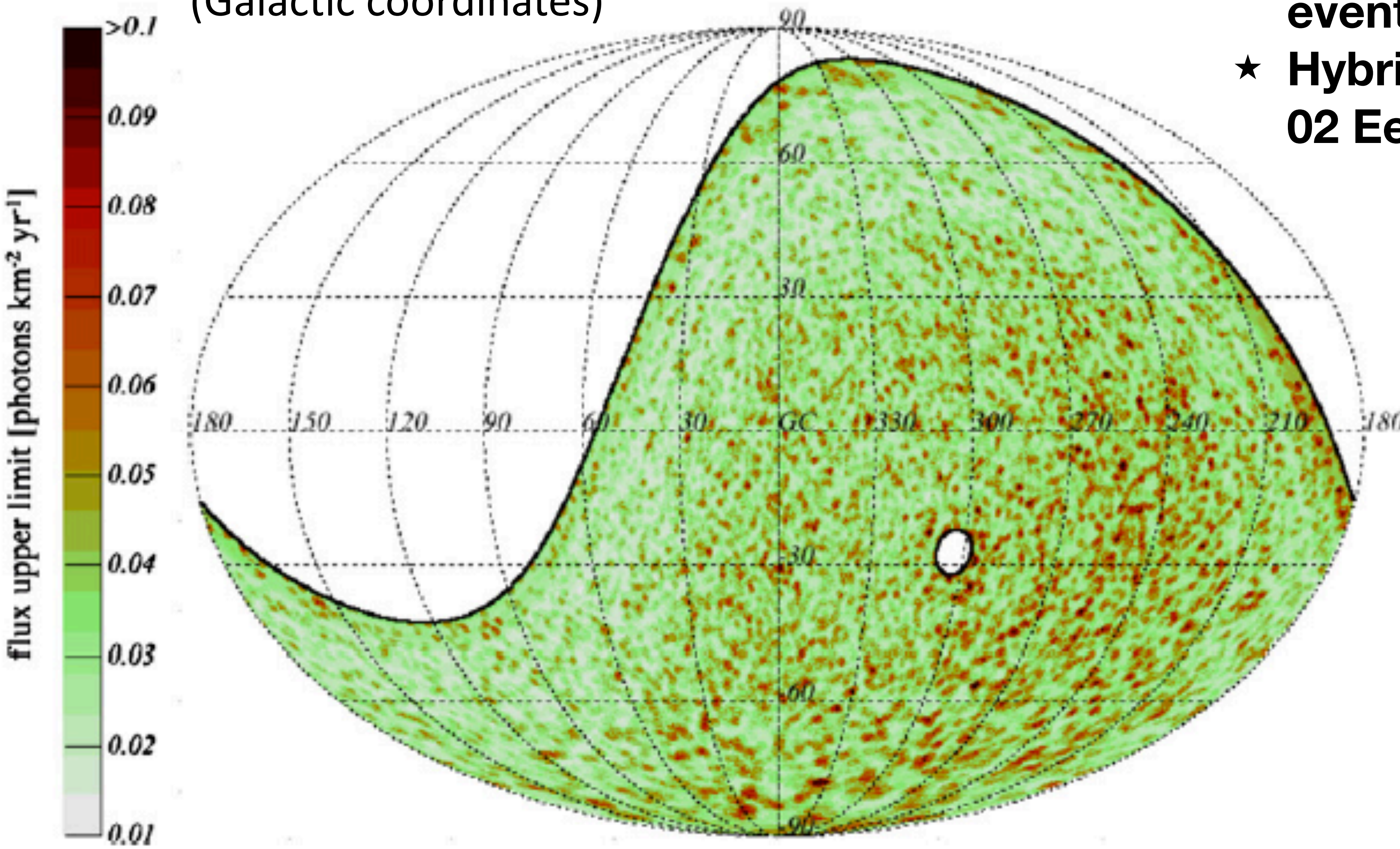


- ⋆ Tight constraints on current top-down scenarios to explain the origin of UHE CR
- ⋆ Sensitivity to photon fractions of about 0.1% for 1 EeV
- ⋆ Exploring the region of photon fluxes predicted in astrophysical scenarios

Niechciol, for the Pierre Auger Colab., ICRC 2017

Limits to sources of UHE photons

Upper limits to γ-fluxes
(Galactic coordinates)



- ⋆ **Multi-variate analysis, hybrid data, enriched samples of photon-like events**
- ⋆ **Hybrid data: Jan 2005 - Sept 2011, 02 EeV < E < 3 EeV**

No significant excess of γ-like events from any point in the sky
Set upper limits

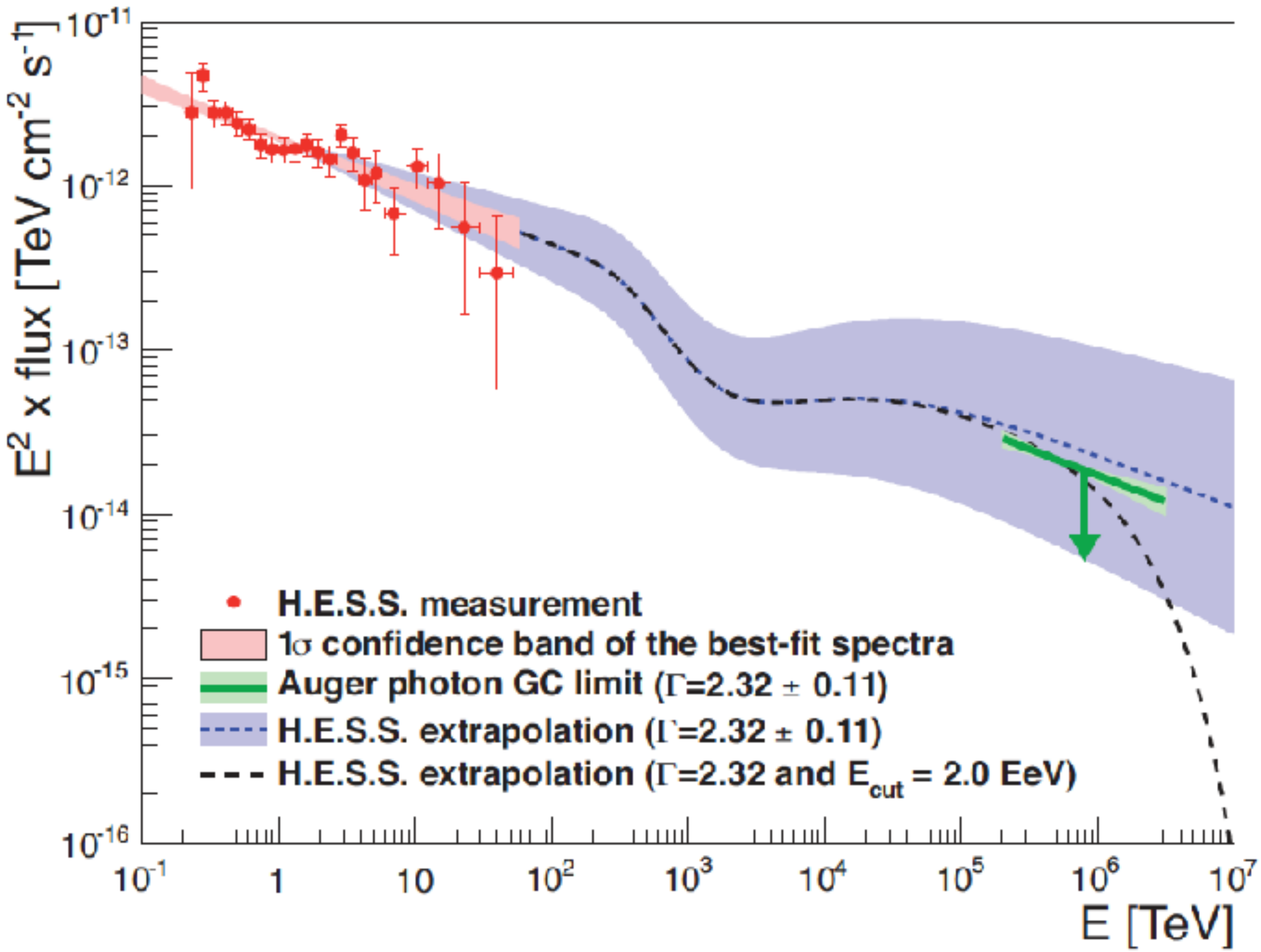
Pierre Auger, Astrophys. J. 789, 160 (2014)

Targeted search upper limits:

- ⋆ **EeV photons might be produced in transient sources, such as gamma-ray bursts or supernovae, or aligned in jets not pointing to us.**
- ⋆ **EeV protons escape from a source more freely than protons that produce TeV photon fluxes (small production of of EeV photons)**

Pierre Auger, Astrophys. J. Lett. 837, L25 (2017)

Photon flux from Galactic center

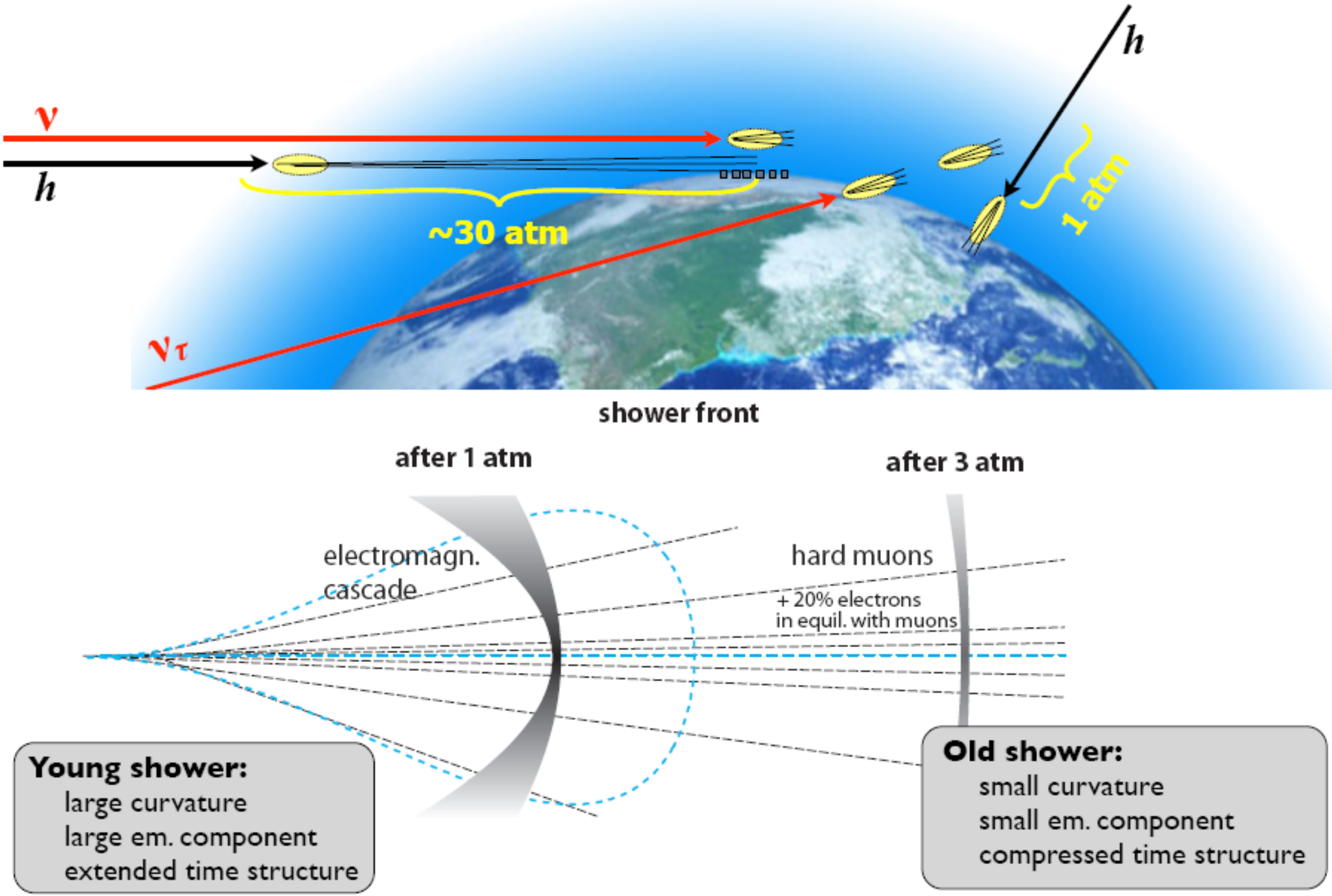


- ★ HESS collaboration: acceleration of TeV protons in the GC
- ★ Extrapolation to EeV takes into account interactions with CMB
- ★ Power law with exponential cuttof: upper limit on the cutoff energy of 2 EeV
- ★ The connection to measurements from the TeV range enables new multi-messenger studies

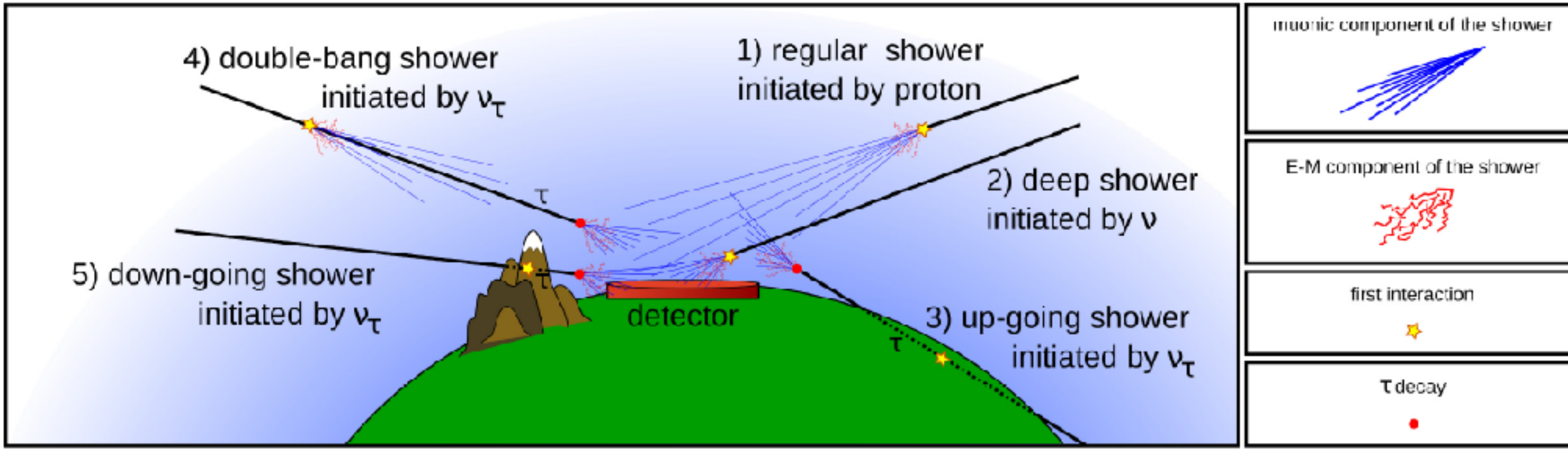
The HESS Collab. Nature, 2016 Niechciol, for the Pierre Auger Colab., ICRC 2017

The search for neutrinos

Neutrino search: old and young showers



Sensitivity: all flavours and channels

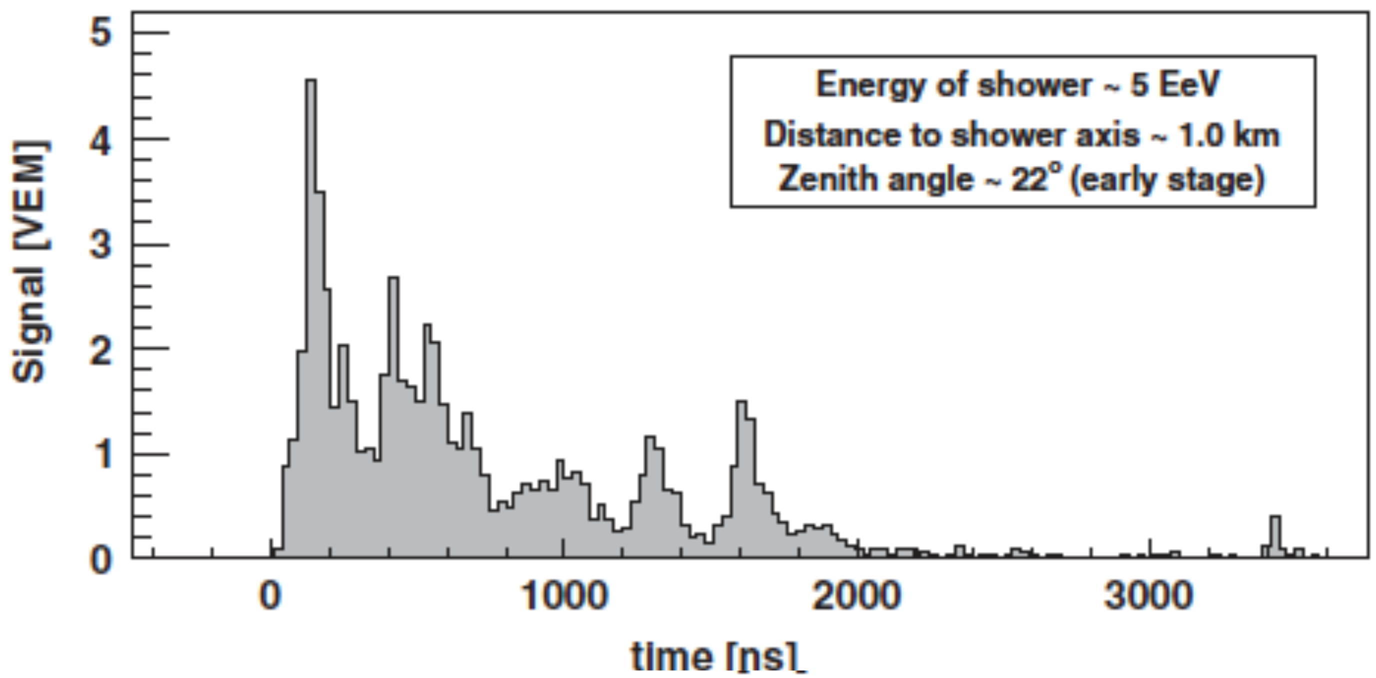


Three selection criteria

★ **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: young showers

Signals produced by the passage of shower particles are digitized with Flash ADCs with 25 ns resolution.

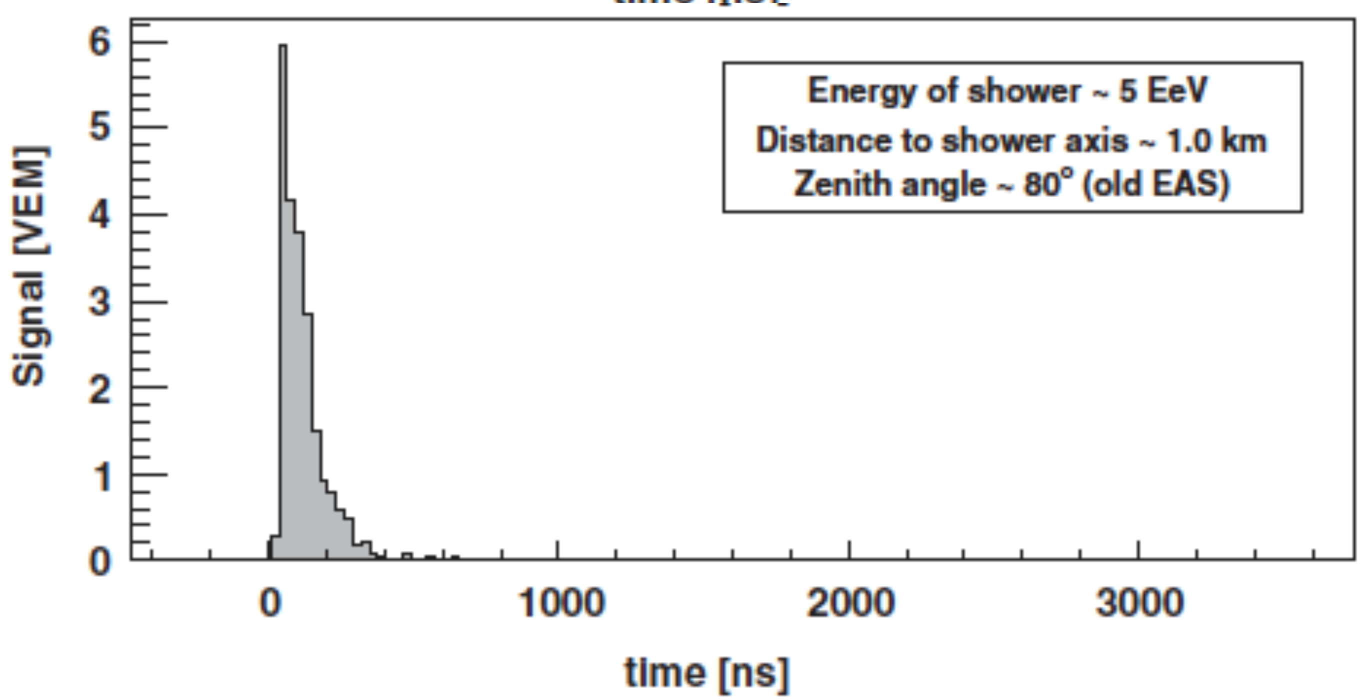


Select young showers

Broad EM component

<AOP> area over peak of digitized signal

large <AOP>

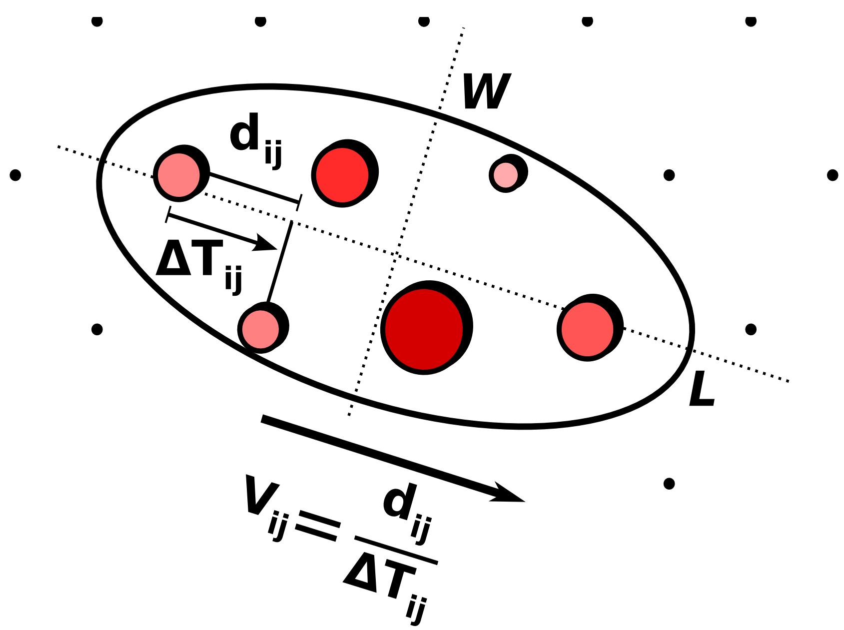


small <AOP>

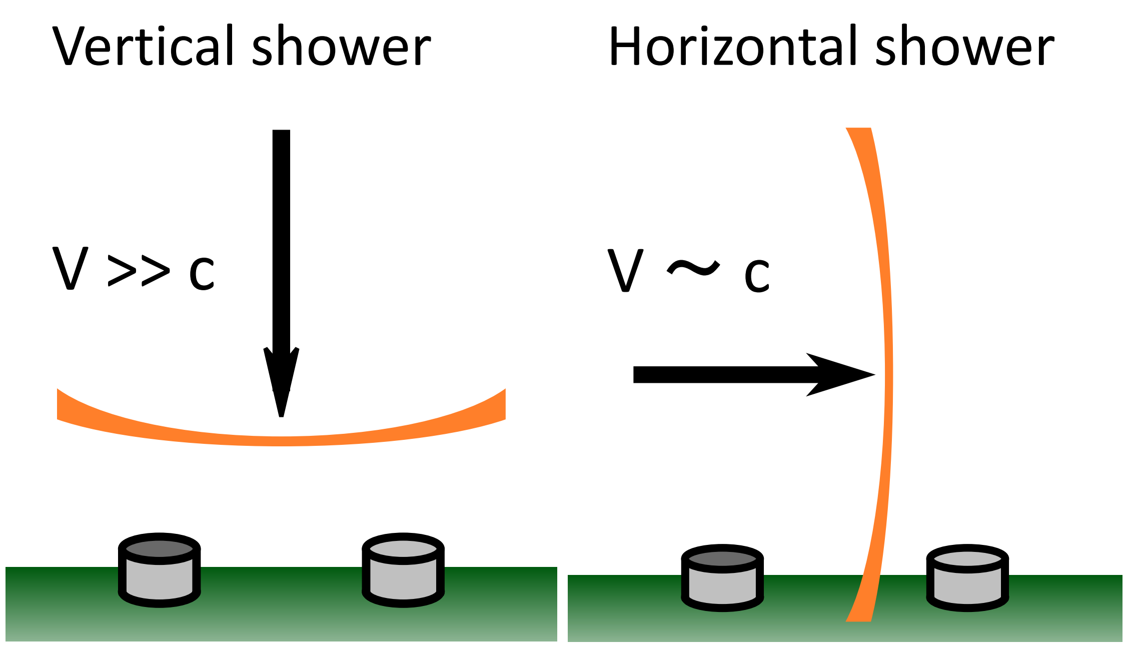
Pierre Auger Coll., Phys. Rev. D 91, 092008 (2015); Ap JL 755:L4 (2012)

Selecting ν in data: horizontal showers

Elongated pattern: L > W



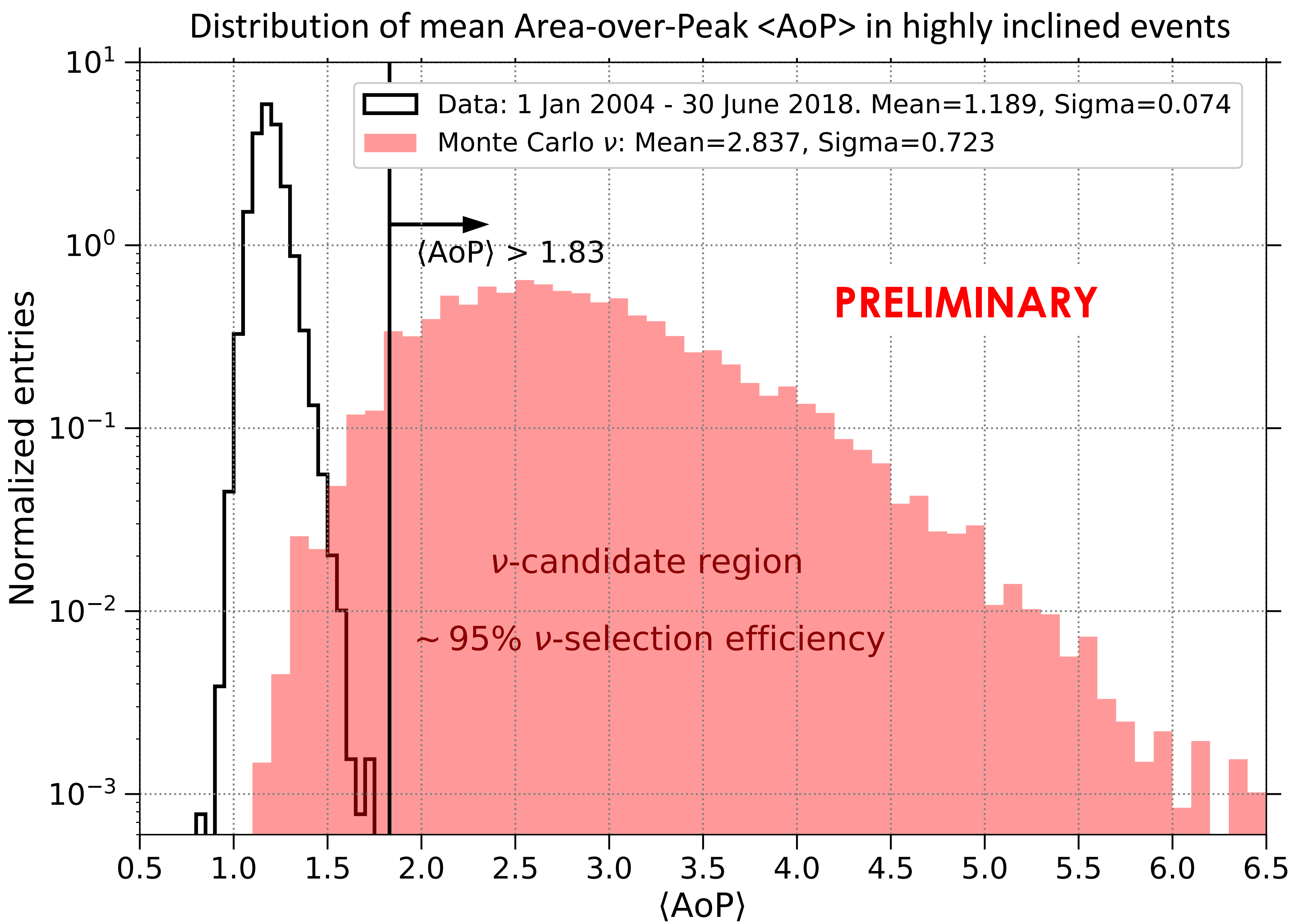
Apparent speed signal ≈ c



Zenith angle reconstruction

Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$	Down-going Low $(65°, 75°)$
$L/W > 5$	$L/W > 3$	–
$\langle V \rangle \in (0.29,\ 0.31)$ m ns^{-1}	$\langle V \rangle < 0.313$ m ns^{-1}	–
$\mathrm{RMS}(V) < 0.08$ m ns^{-1}	$\mathrm{RMS}(V)/\langle V \rangle < 0.08$	–
–	$\theta_{\mathrm{rec}} > 75°$	$\theta_{\mathrm{rec}} \in (58.5°,\ 76.5°)$

ν search: ES Earth skimming



<AOP> cut

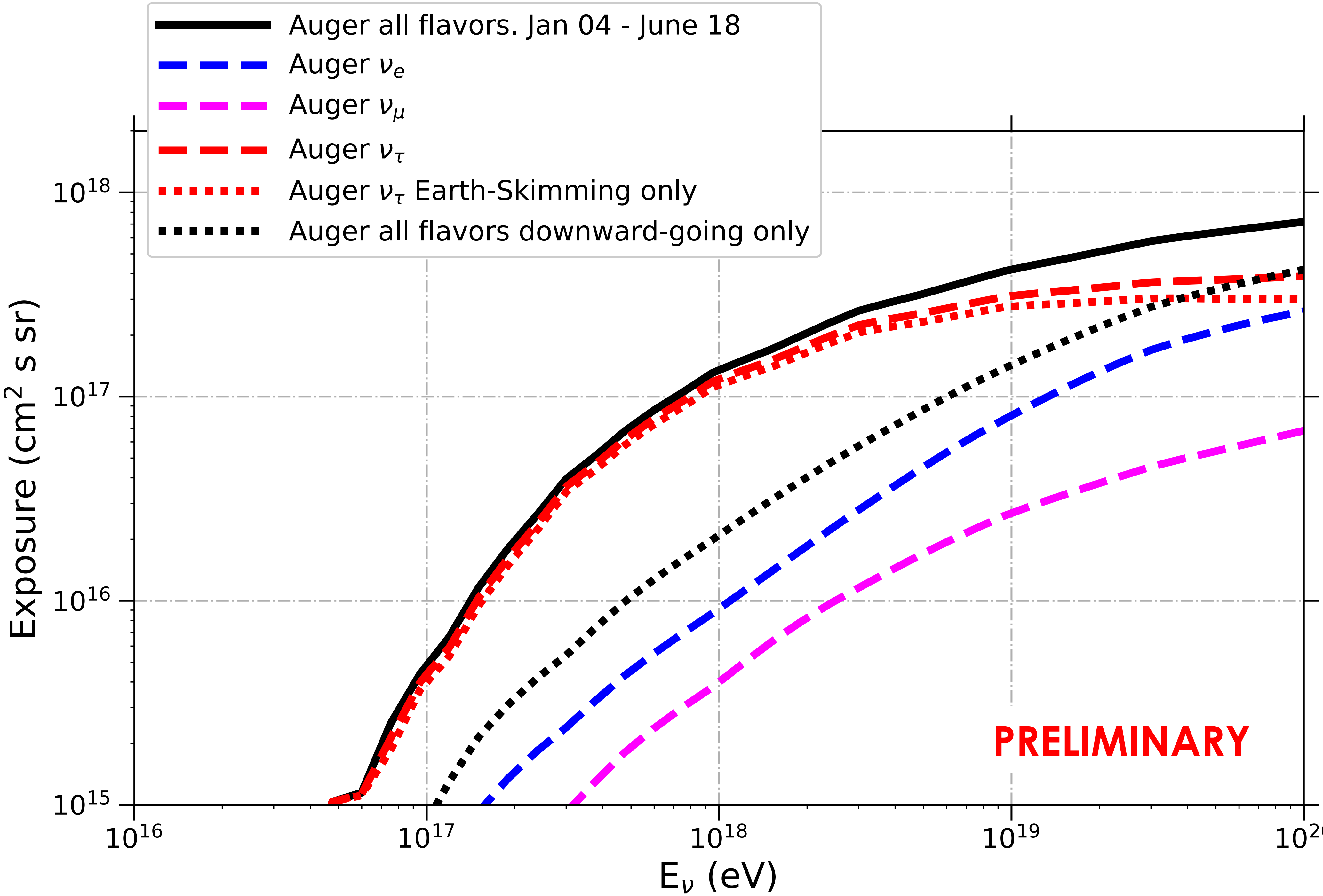
- ⋆ less than one bckg event in 50 years of SD data
- ⋆ large ν-selection efficiency

No candidates

- ⋆ sensitivity dominated by exposure, not by background

Alvarez-Muniz, for the Pierre Auger Collab., UHECR2018

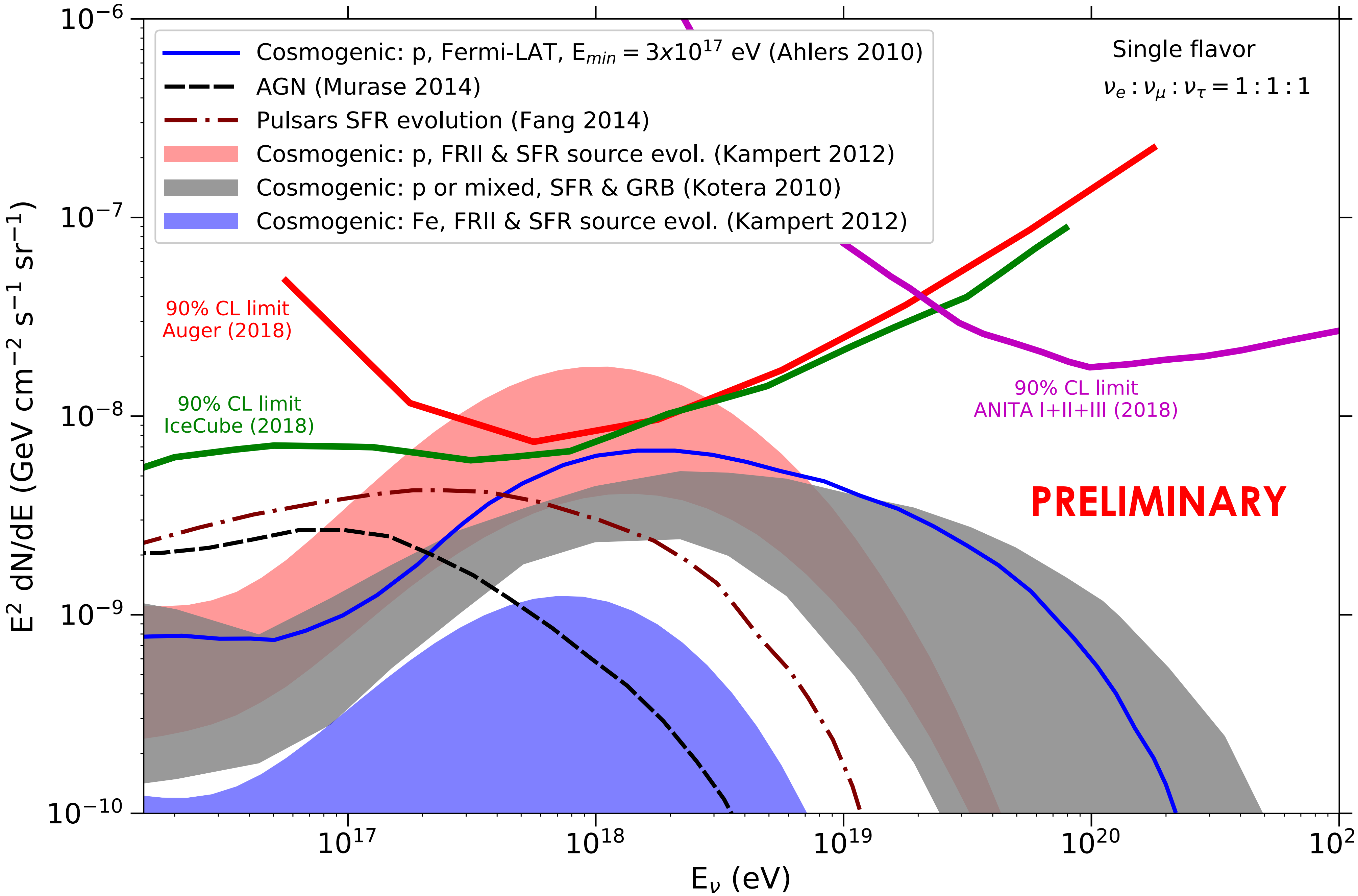
Exposure to diffuse flux of UHE ν



Earth-skimming neutrinos dominate the exposure in spite of the reduced solid angle to which the detector is sensitive to them: larger neutrino conversion in the Earth's crust

Alvarez-Muniz, for the Pierre Auger Collab., UHECR2018

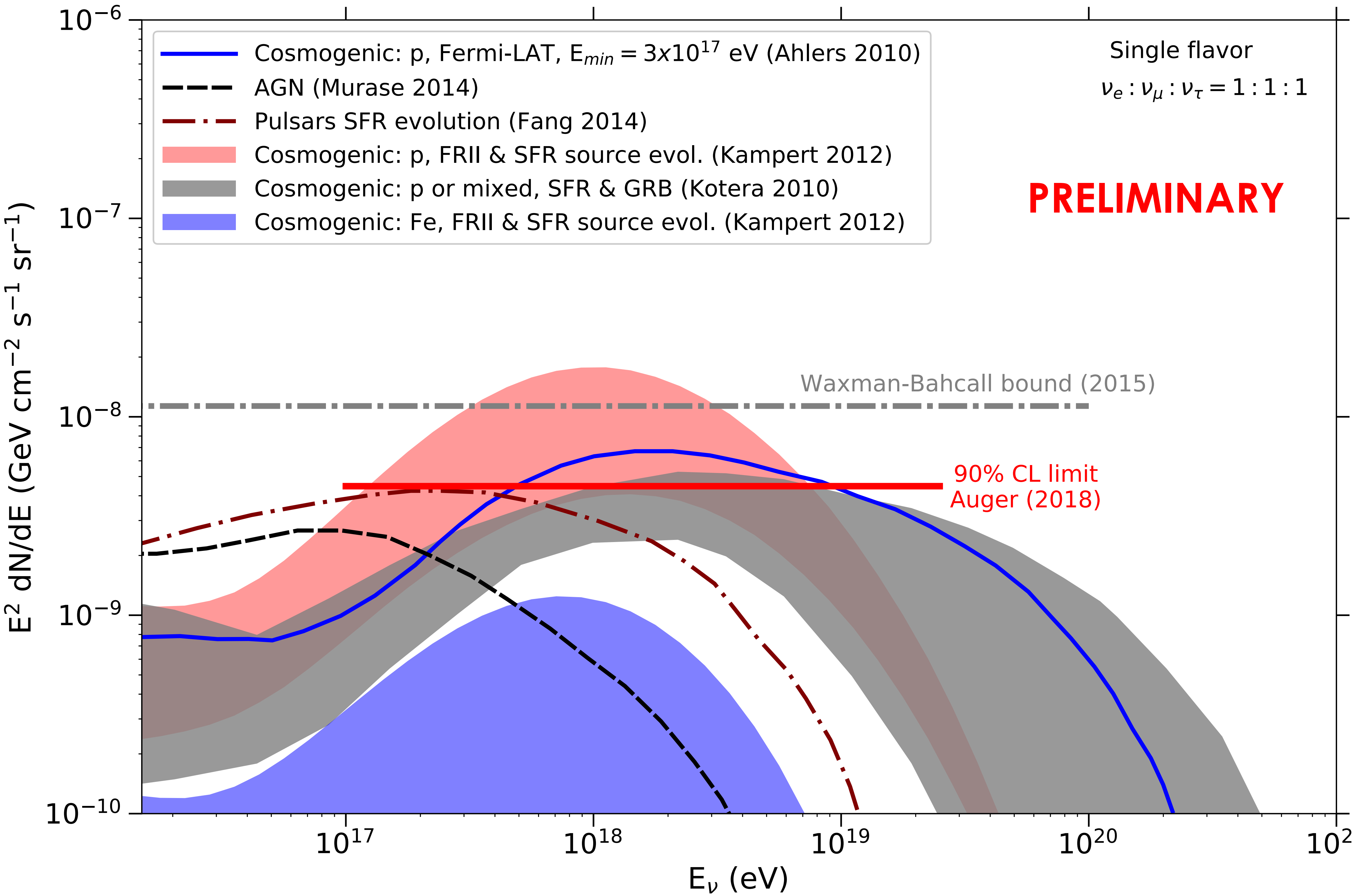
Differential limits to diffuse ν flux



- ⋆ **Limits and models converted to single flavour**
- ⋆ **Differential limits in one decade of energy**
- ⋆ **Auger maximum around EeV, comparable to IceCube**
- ⋆ **Complementary measurements !**

Alvarez-Muniz, for the Pierre Auger Collab., UHECR2018

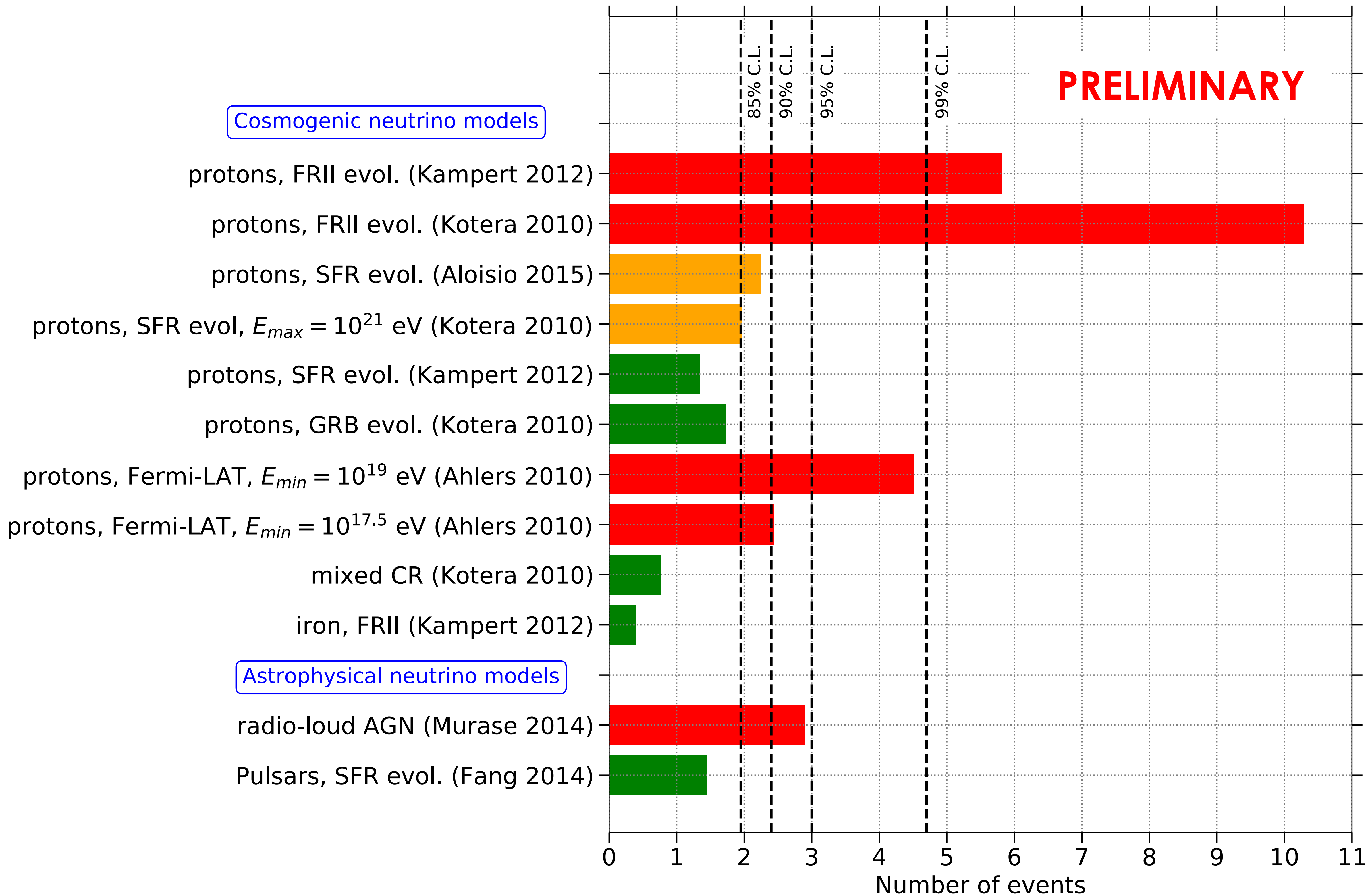
Integrated limits to diffuse ν flux



- **Auger integrated limit ~ 4.4 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}**
- **factor ~ 2 below Waxman-Bahcall upper bound**

Alvarez-Muniz, for the Pierre Auger Collab., UHECR2018

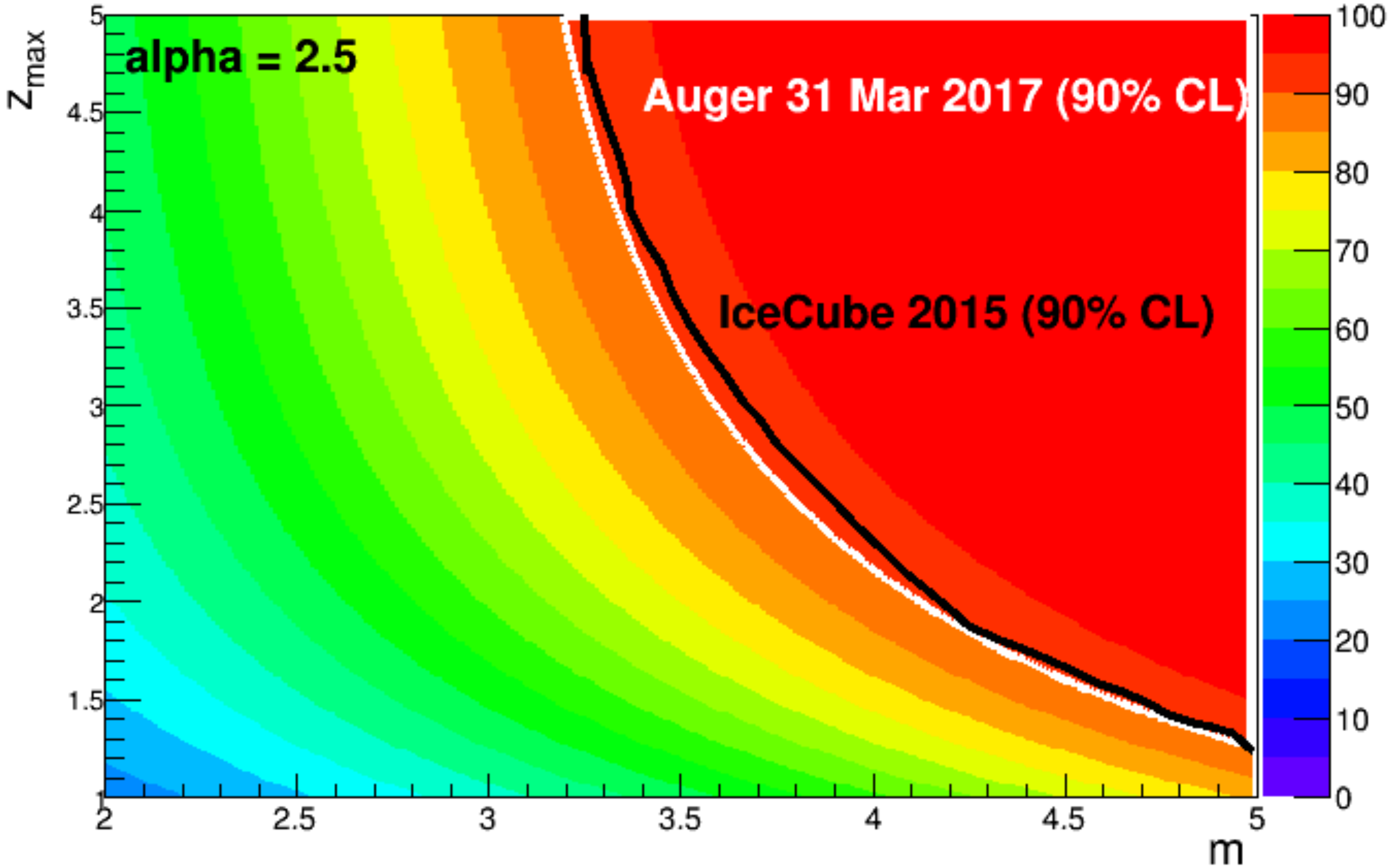
Expected event rates



- ⋆ **constrain models of cosmogenic ν production**
- ⋆ **protons dominate at sources and weak Star-Formation Rate evolution with redshift *z***

Alvarez-Muniz, for the Pierre Auger Collab., UHECR2018

Proton dominated sources



- ★ 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)

Data

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

Cosmogenic flux depend on:

- ★ m Source evolution

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

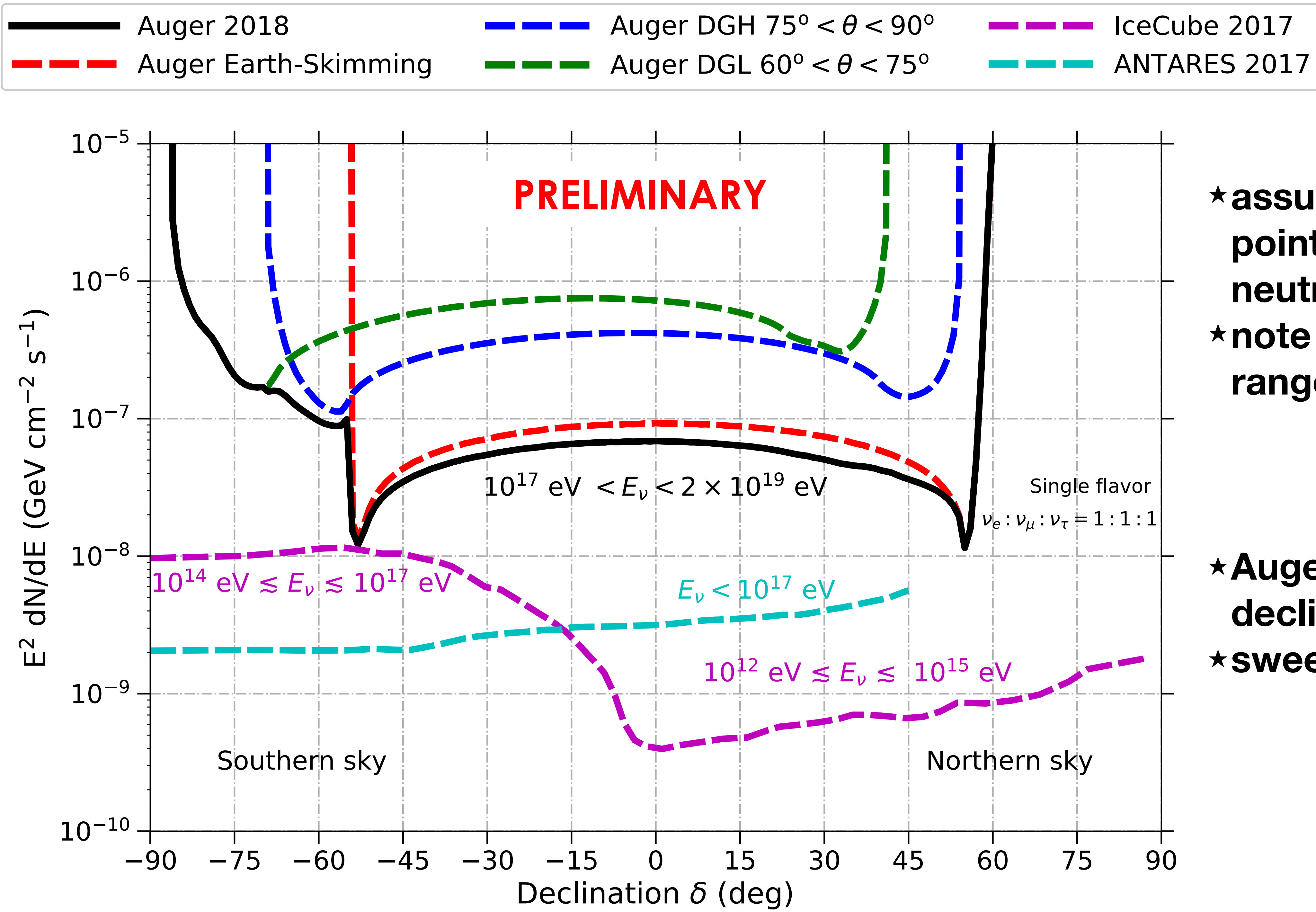
- ★ $z_{\max}$ Maximum z
- ★ α Spectral index of injection at source

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

Zas, for the Pierre Auger Collab., ICRC2017

Steady sources, blazars and GW events

Limits to point-like steady ν sources



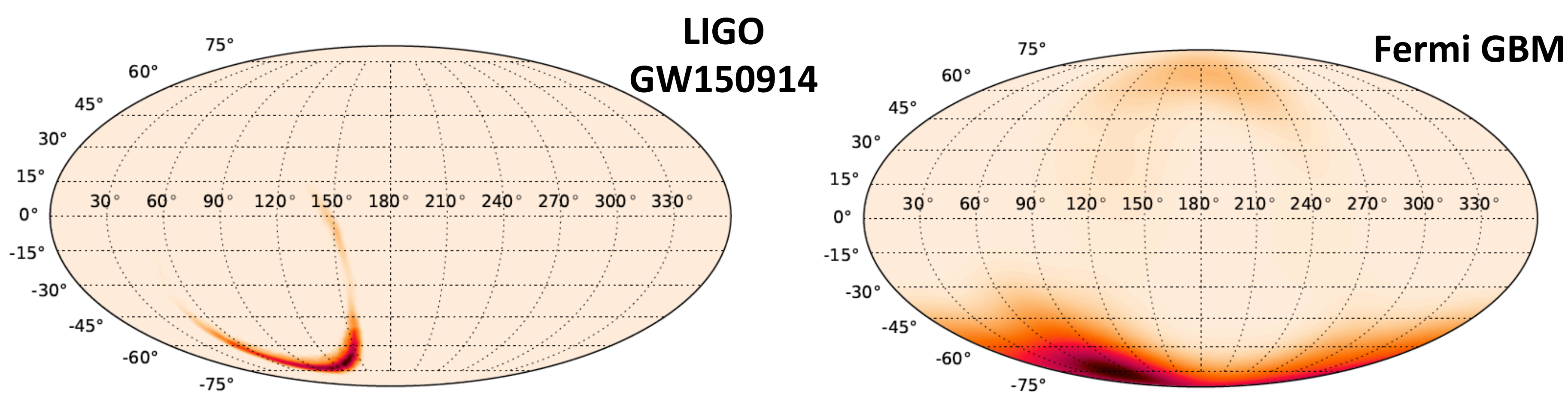
- ⋆assuming a single flavor point-like flux of UHE neutrinos dN/dE = k^{PS} E^{-2}
- ⋆note the different energy ranges
- ⋆Auger: broad range of declination
- ⋆sweet spot: θ = -55º, +55º

IceCube, Astrophys.J. 835, 151 (2017)
ANTARES, PRD 96, 082001 (2017)

Alvarez-Muniz, for the Pierre Auger Collab., UHECR2018

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

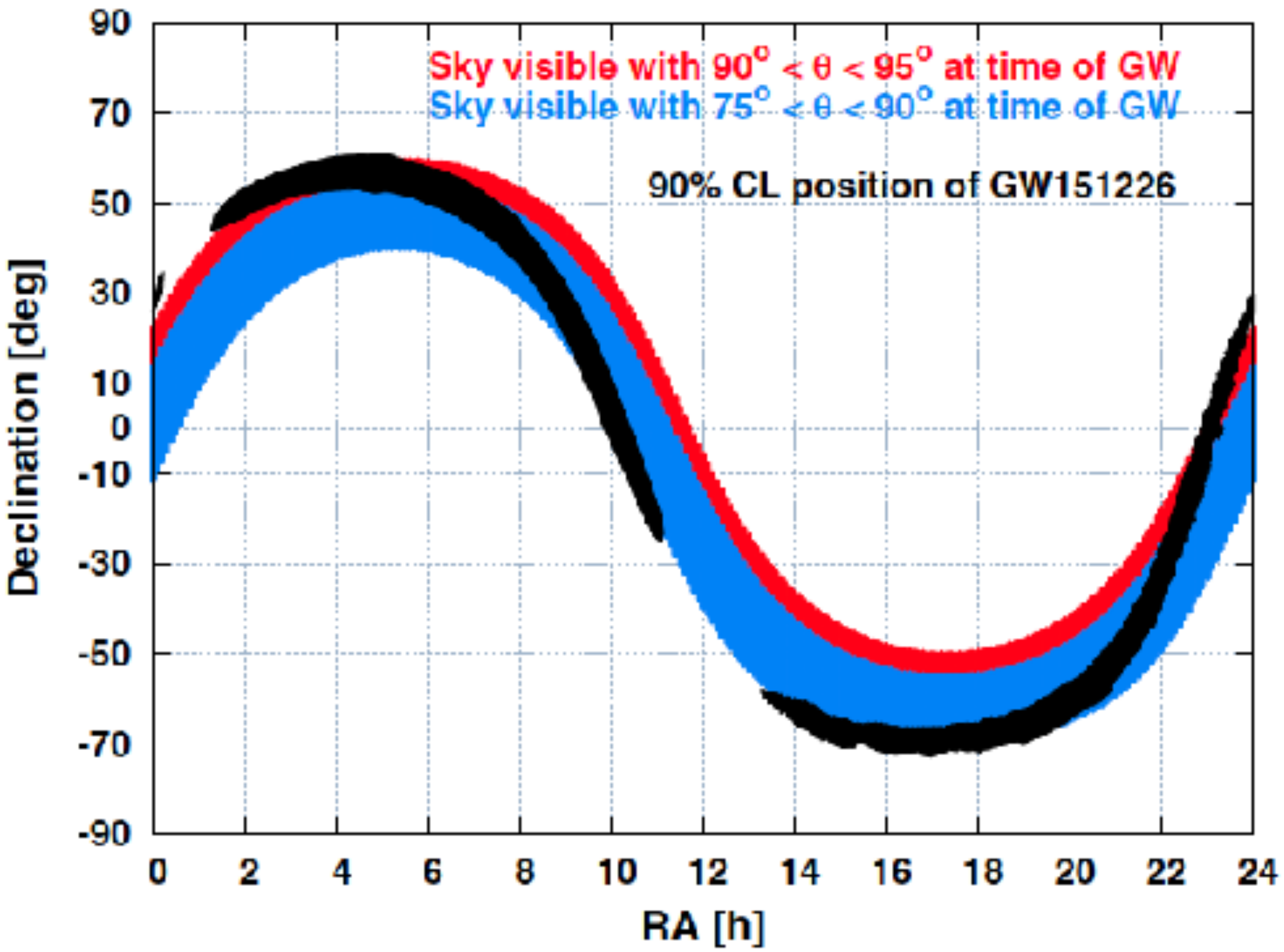
- **Conservative upper limit on the duration of GRB afterglows**
- **UHE neutrinos may be produced in interactions of UHECRs with the lower-energy photons of the GRB afterglow**

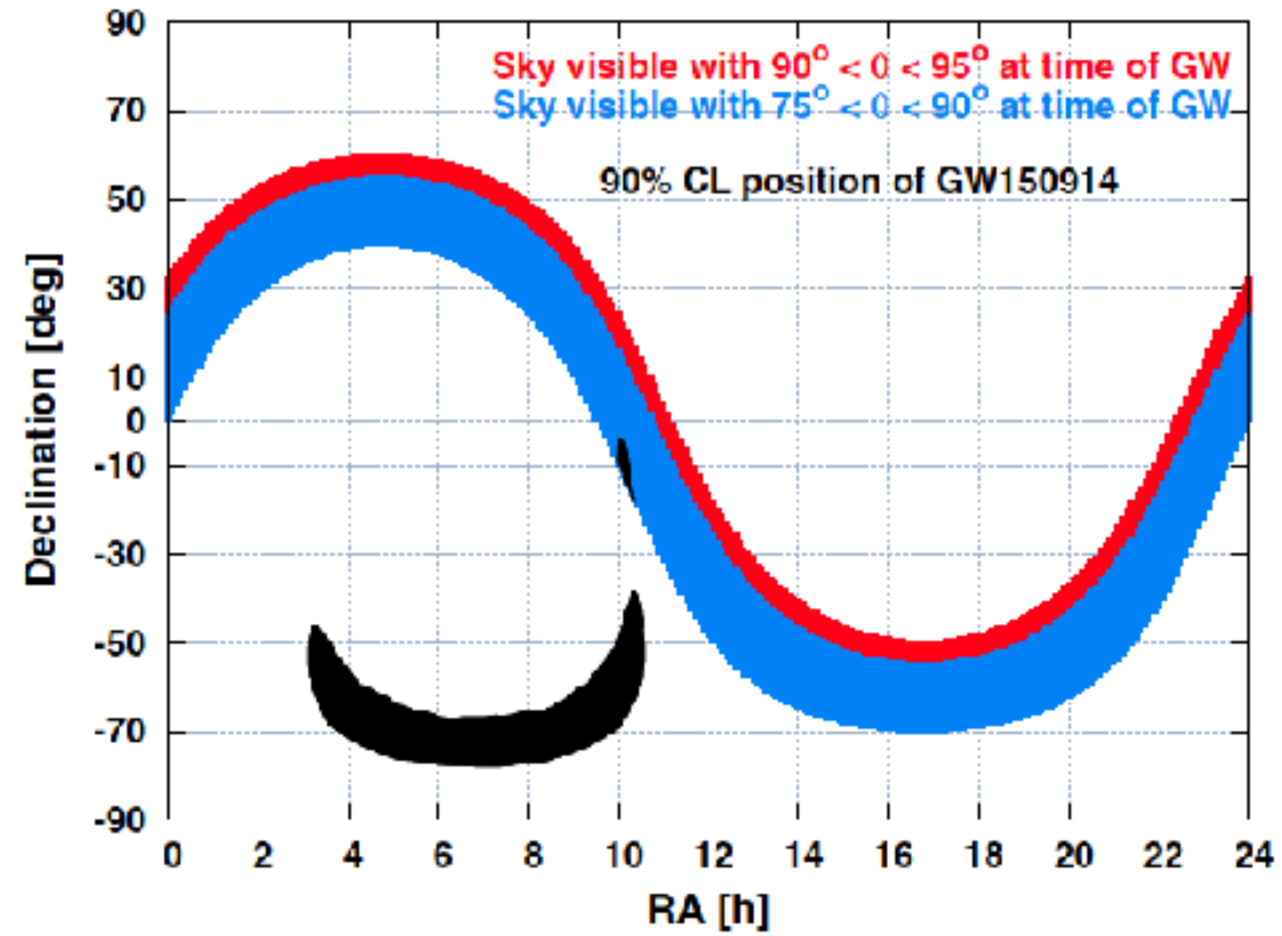
Same identification criteria to neutrinos as discussed previously

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**

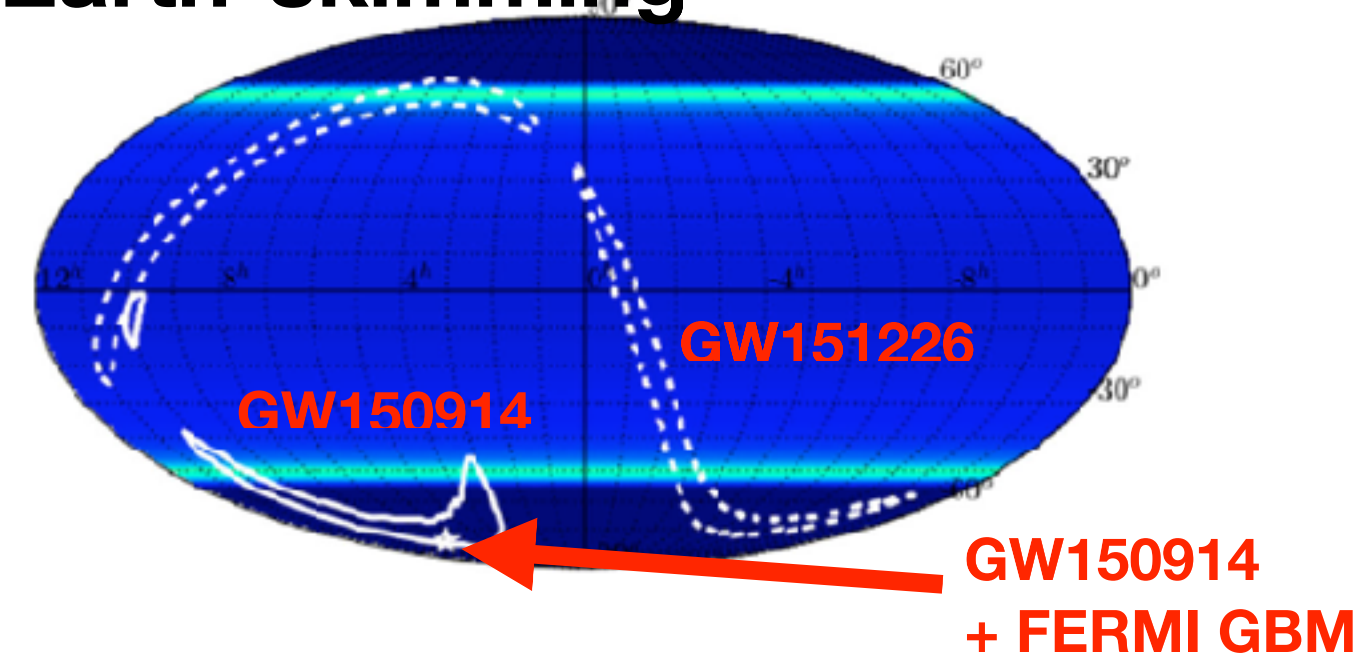




No candidate was detected in the window of ± 500 s around the GRB event

Visibility time fraction in one sidereal day

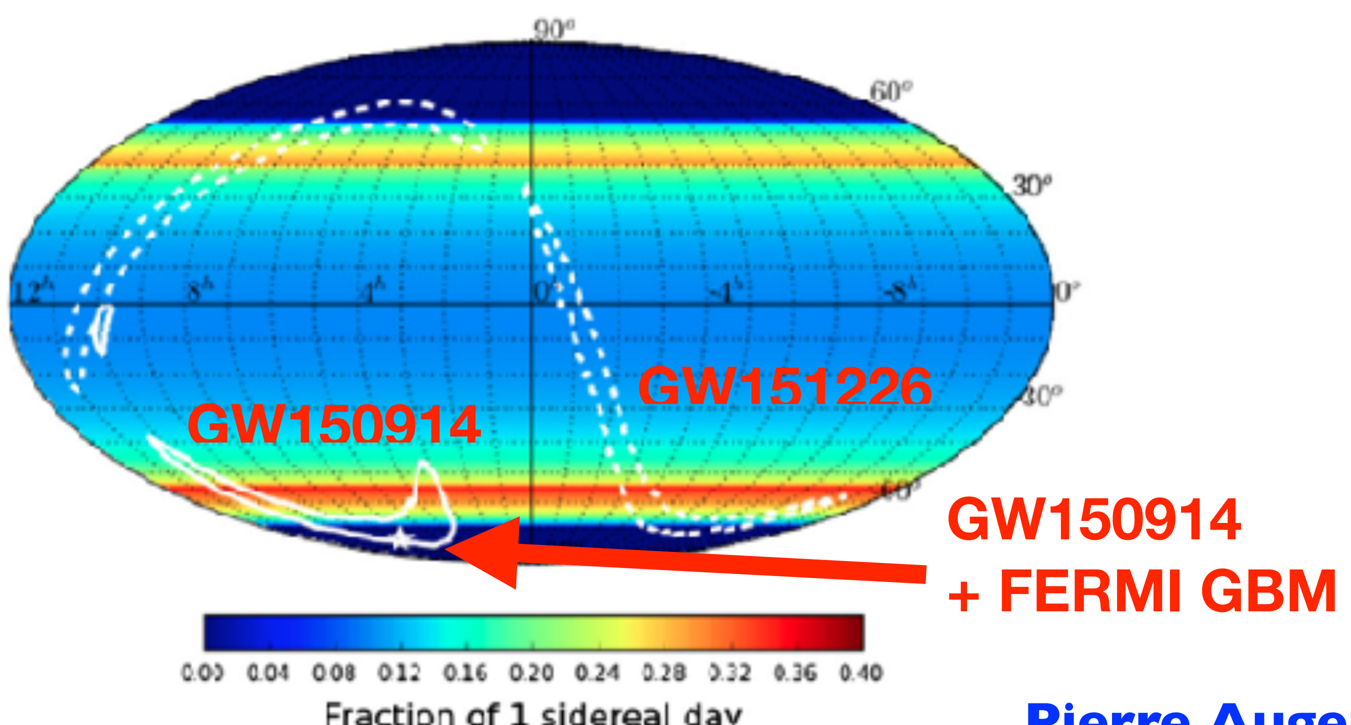
Earth-skimming



equatorial coordinates

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

Down-going high



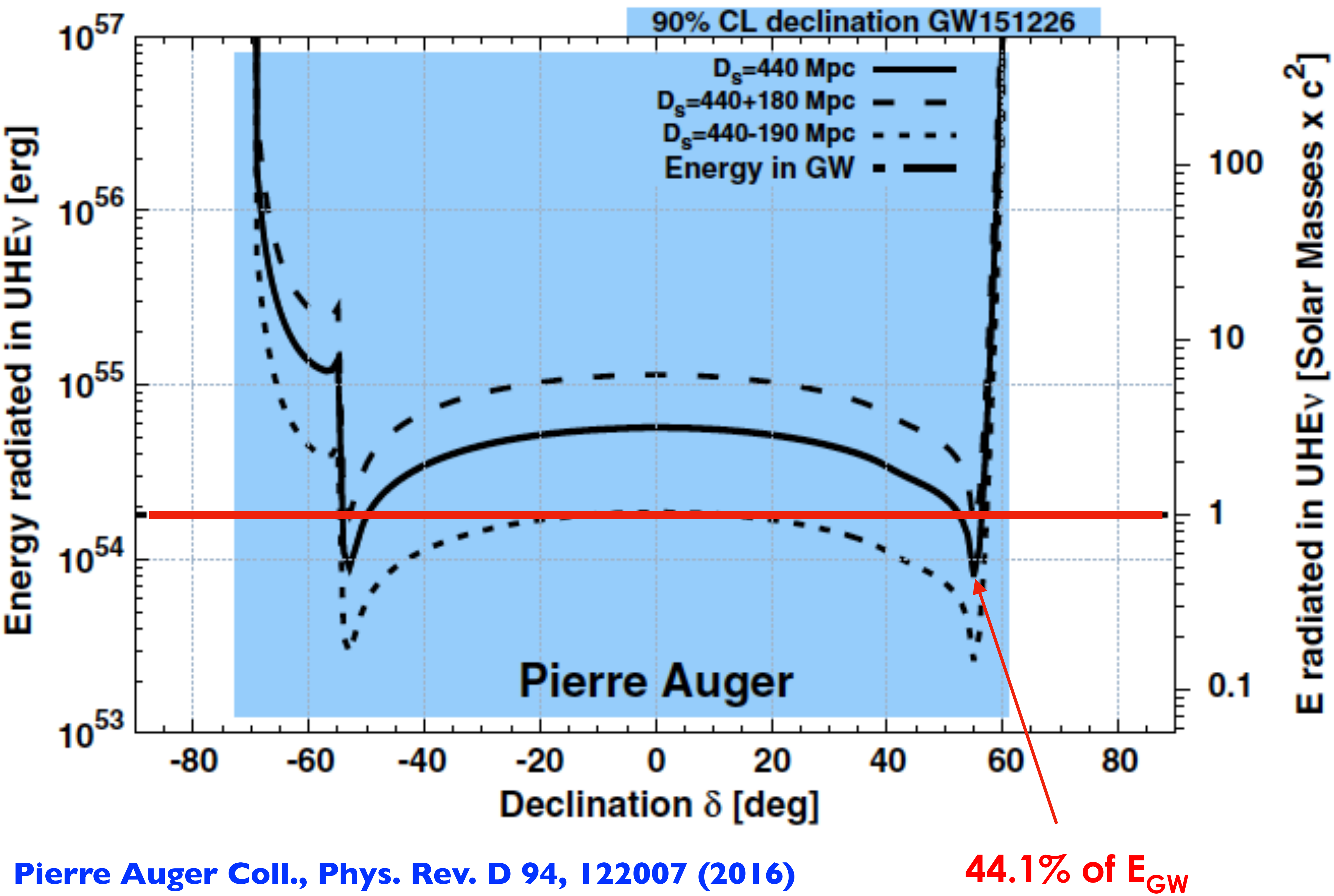
$$N^{\rm GW}_{\rm event} = \int_{E_\nu} \frac{dN^{\rm GW}_\nu}{dE_\nu}(E_\nu)\mathcal{E}_{GW}(E_\nu,\delta)dE_\nu$$

$$\frac{dN^{\rm GW}_\nu}{dE_\nu}(E_\nu) = k^{\rm GW} E_\nu^{-2}$$

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

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

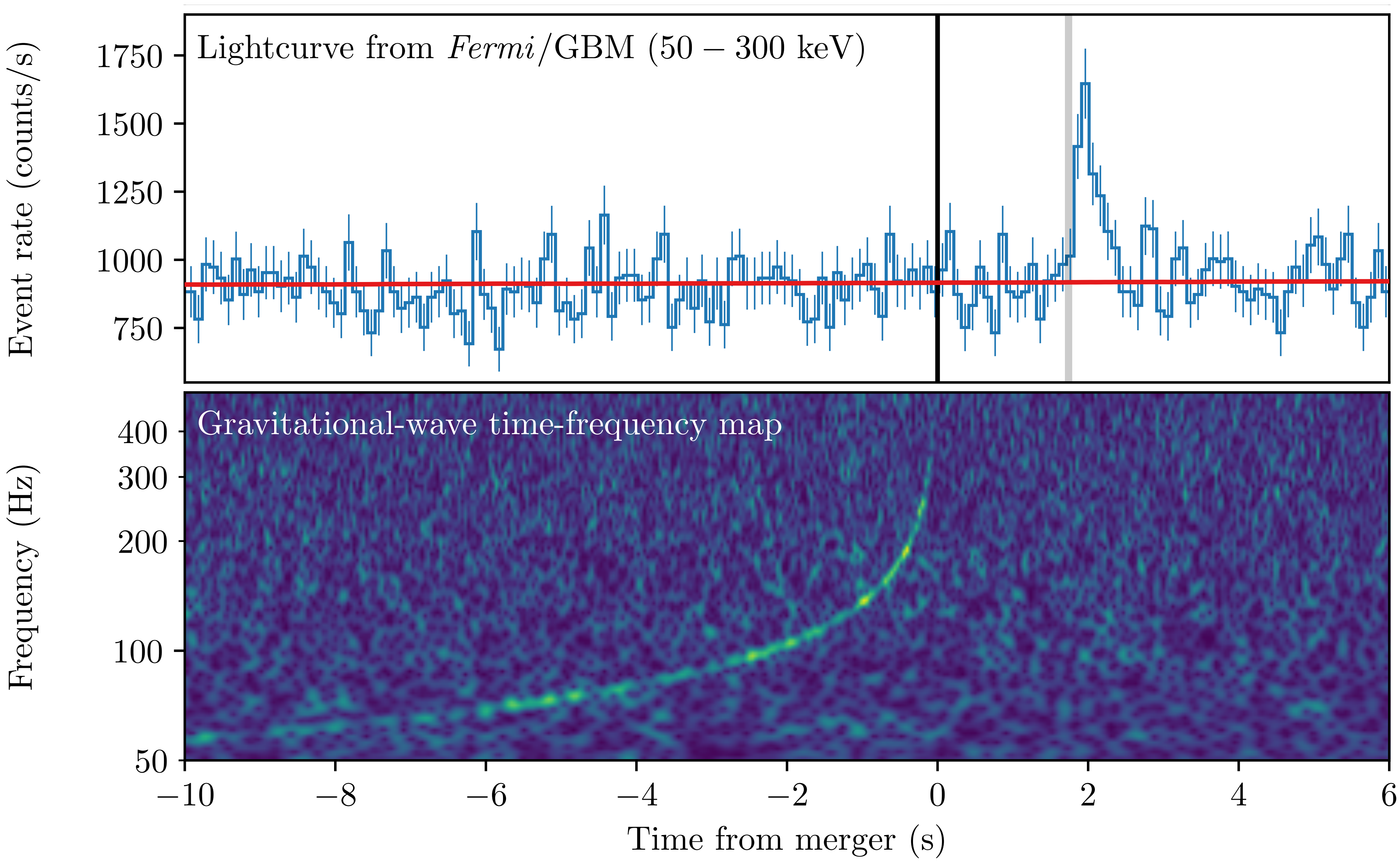
Constraints on energy radiated from GW151226 in UHE ν ($E_\nu > 0.1$ EeV)



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

A binary neutron star merger

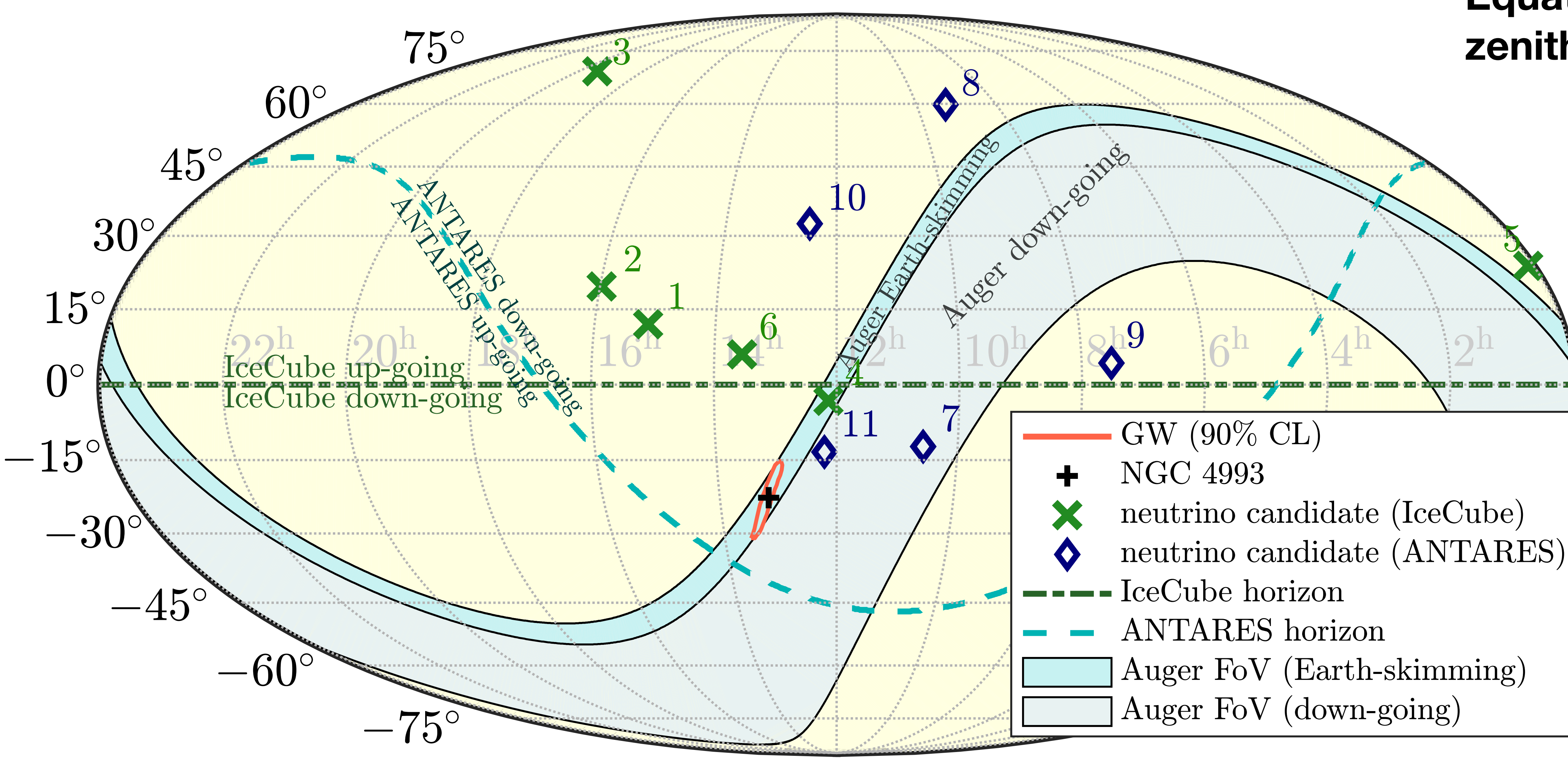
- ⋆ GW170817: a NS-NS merger seen in gravitational waves
- ⋆ GRB170817A: confirmed as short GRB (Fermi GBM, Integral)
- ⋆ UV, optical and IR observation located the merger in NGC 4993
- ⋆ Fermi LAT, H.E.S.S., HAWC observe region later



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

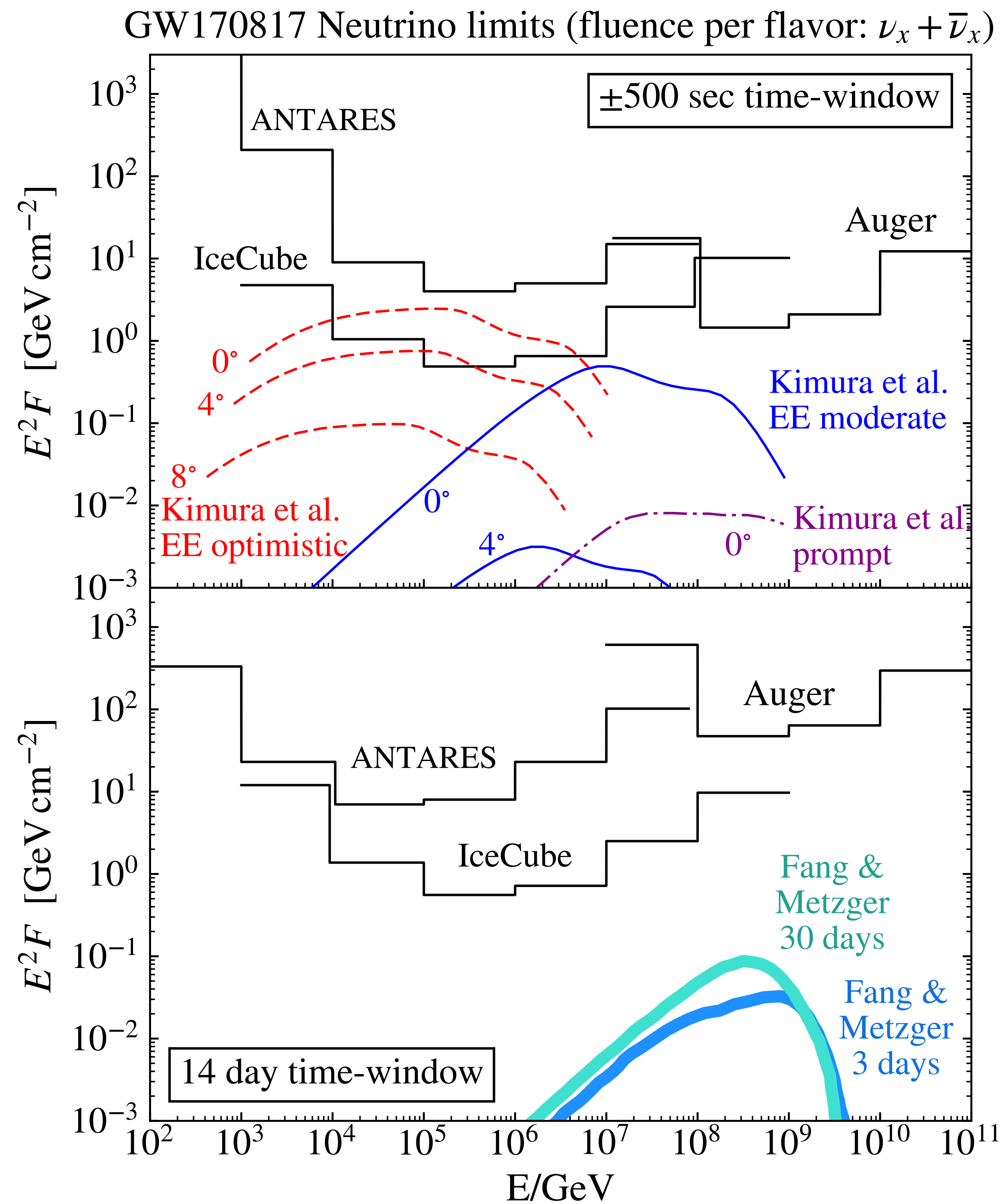


LiGO/VIRGO, ANTARES, IceCube and the Pierre Auger Observatory, AJL, 2017

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**



LiGO/VIRGO, ANTARES, IceCube and the Pierre Auger Observatory, AJL, 2017

Blazar TXS 0506 + 056

Blazar TXS 0506+056:

- ⋆ BL Lac type, Dec=5.68 deg, RA = 05:09:25.96 hh:mm:ss
- ⋆ z = 0.3365 => Luminosity distance ~ 1.78 Gpc

Paiano et al., Astrophys. J. Lett. 854, L32, 2018

IceCube:

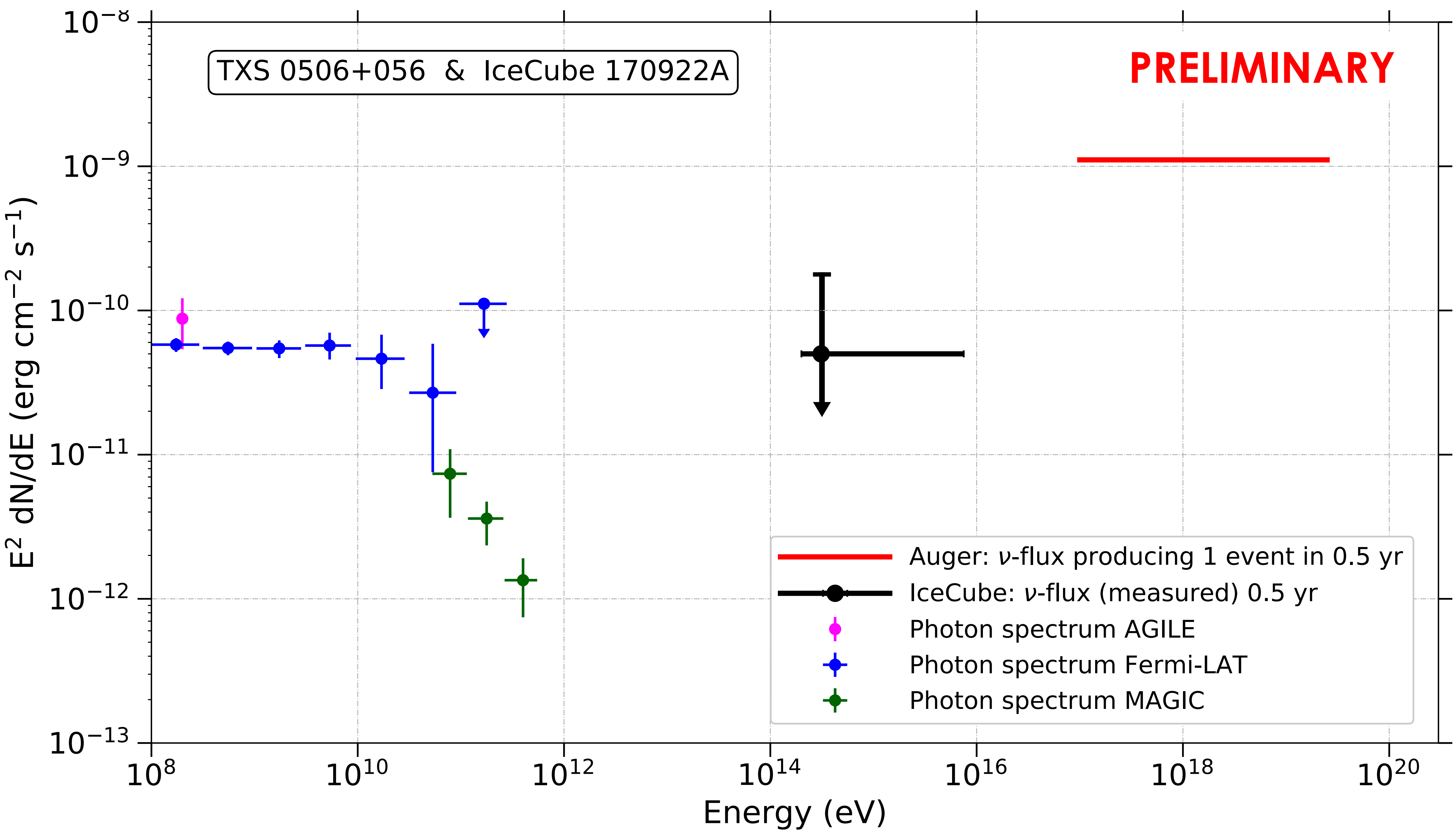
- ⋆ Event 170922A (Sep.22, 2017 at 20:54:30.43 UTC)
- ⋆ Track-like event (angular resolution ~0.1deg). Estimated E_n~ 300 TeV
- ⋆ Fermi-LAT reported association (within 0.1 deg) with TXS 0506+056 in a state of enhanced emission
- ⋆ Chance association with blazar disfavored at ~ 3.σ level
- ⋆ High-energy neutrino emission from same blazar in archival data prior to 2017: 13 ± 5 events

Follow-up campaign triggered by IceCube observation:

- ⋆ Gamma-Rays: Fermi-LAT, AGILE and MAGIC detection of enhanced emission
- ⋆ No neutrino detection in ANTARES

ν flux limits from Blazar TXS 0506 + 056

ν flux or limit 0.5 years before event IceCube 170922A
γ-ray fluxes after 170922A



IceCube et al., Science 361, 146 (2018)

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

Alvarez-Muniz, for the Pierre Auger Collab., UHECR2018

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)

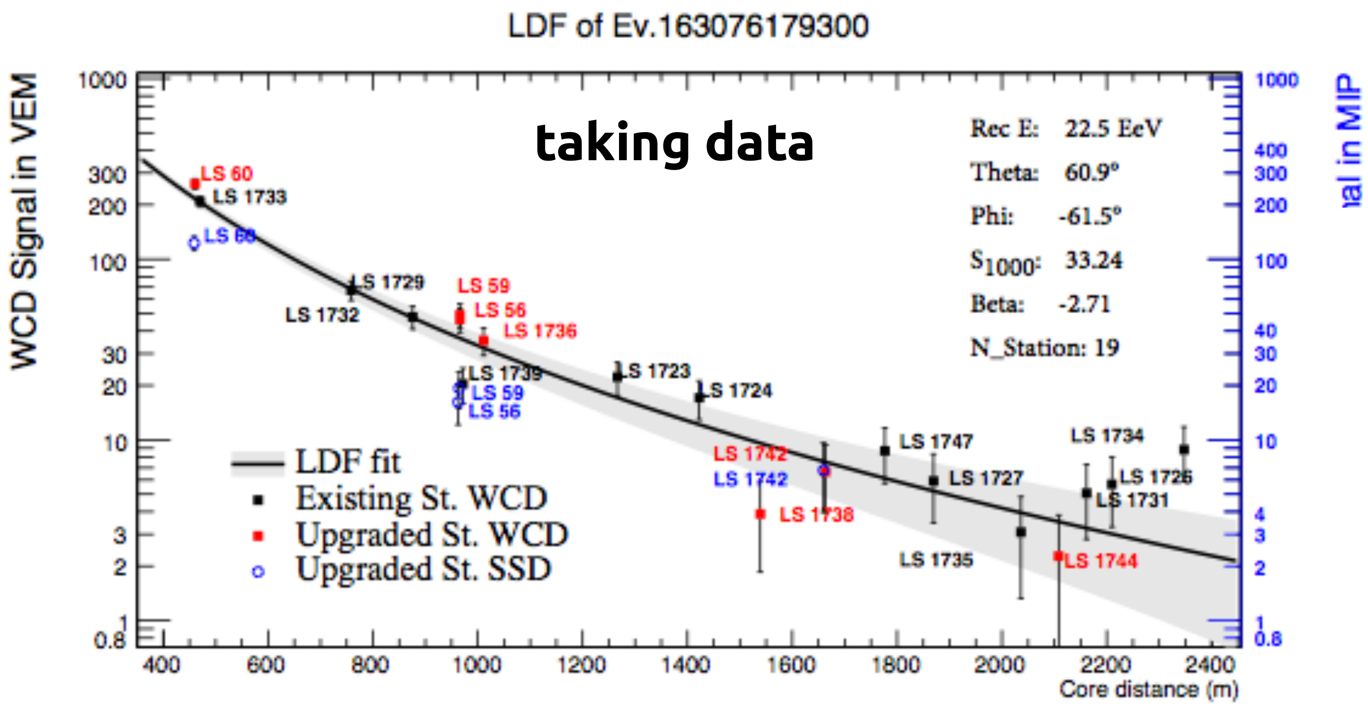
2016:
Engineering Array

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

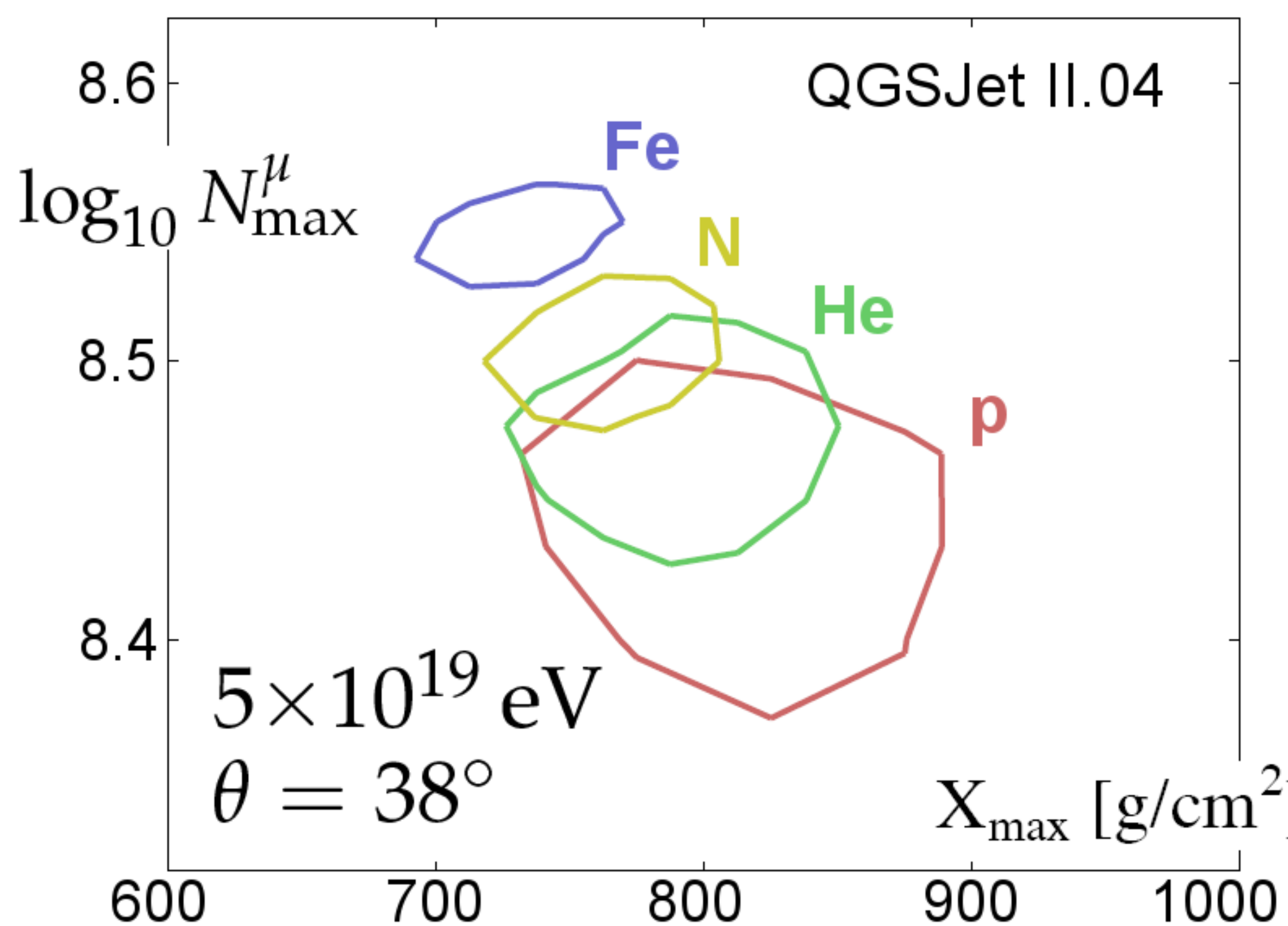
★ Lateral distribution function determination

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 GW and Blazar 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
- ★ First high energy neutrino limits for Blazar TXS 0506 + 056

Active role in multimessenger era!

Backup slides