Multi-Messenger Astrophysics at Ultra-High Energy with the Pierre Auger Observatory

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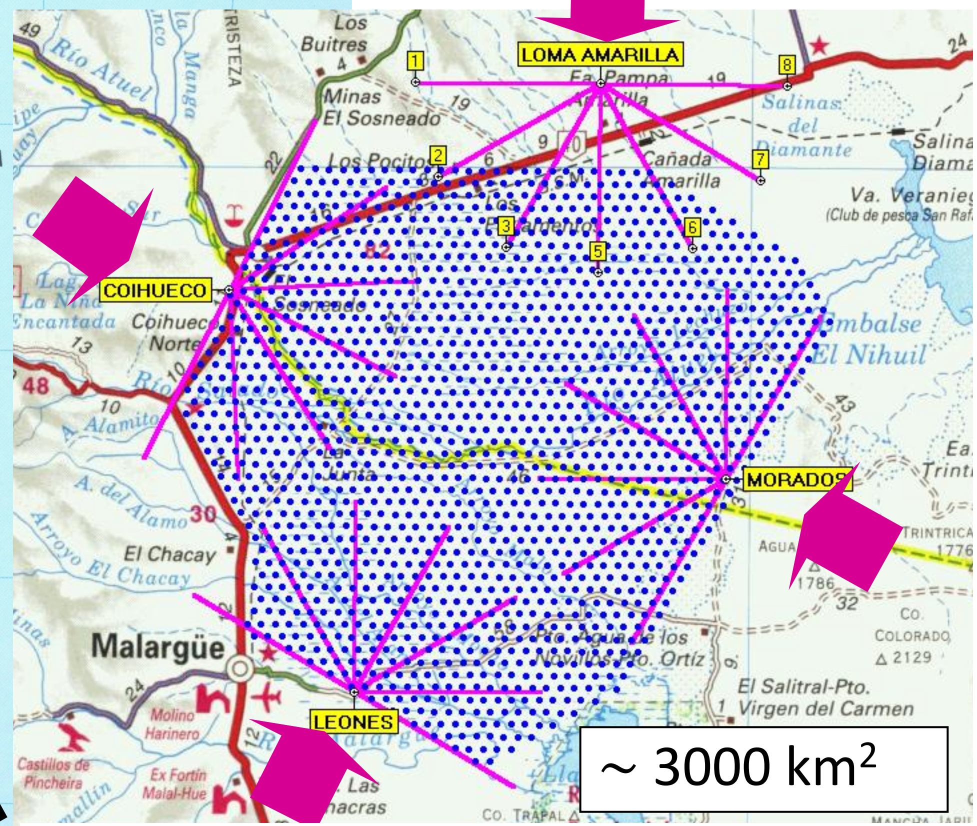
The Pierre Auger Observatory

Malargüe, Mendoza (Argentina)

35.5º S, 69.3º W
1400 m a.s.l. (880 g cm^{-2})

SD 1500 = Surface Detector array of 1600 water Cherenkov stations (3000 km^2)

FD = 4 Fluorescence buildings (24 + 3) detectors



+ SD 750 = 61 water Cherenkov stations (~ 25 km^2)
+ AERA = Array of 153 antennas (~ 17 km^2)
+ AMIGA = Array of 61 buried muon detectors (~ 23.5 km^2)

Pierre Auger, Nuclear Instruments & Methods in Physics Research A **798** (2015) 172–213

Take-home message:

- The **Pierre Auger Observatory is a key detector in the field of Multi-messenger Astrophysics at EeV energies.**
- With Auger we can:
  - **discriminate** photons & ν in the background of charged CR at EeV energies,
  - with **large identification efficiency** (50% photons, > 85% neutrinos),
  - with **good angular resolution**: 2.5°...0.5° improving with energy and zenith angle (< 0.5° for θ > 60° and E > 3 EeV),
  - **monitor continuously** a **large fraction of sky** (-80° to 60° in equatorial declination),
  - with **unrivalled sensitivity to transient sources** if located at "right" position in the sky

UHE neutrinos in Auger

Data in this work:
1 January 2004 - 30 June 2018*

*$\simeq$ 14.5 years of operation
*$\simeq$ 9.5 ”full Auger” equivalent years

Search for UHE neutrinos with Auger Surface Detector

Searching for neutrinos ⇒
searching for **inclined showers**
with **electromagnetic component**

- Protons & nuclei initiate inclined showers high in the atmosphere =>

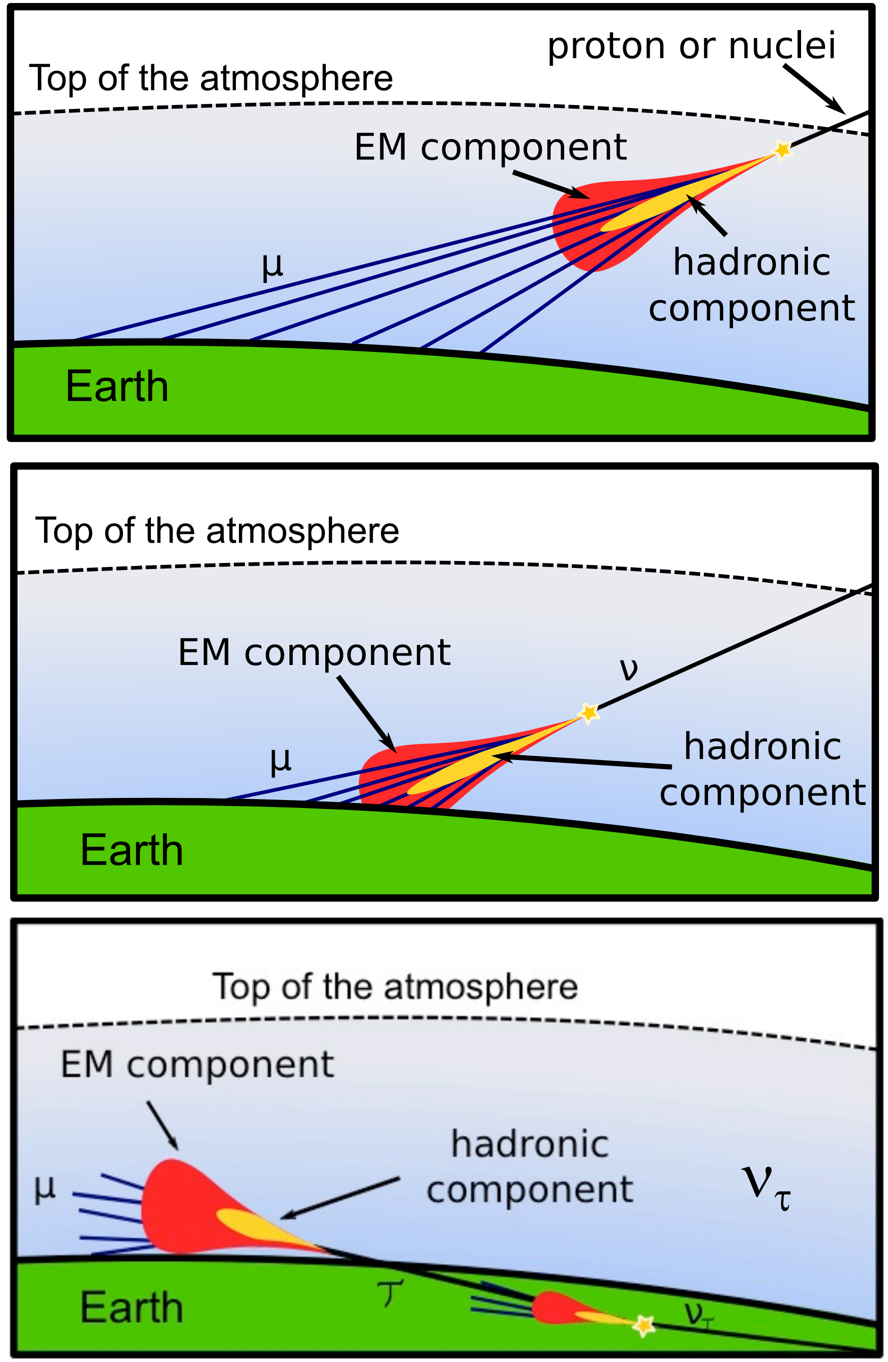
  Shower front at ground mainly composed of muons

  (electromagnetic component absorbed in atmosphere).

- Neutrinos can initiate “deep” showers close to ground =>

  Shower front at ground:

  electromag. + muonic components



Identifying neutrinos in data collected at Auger Surface Detector

From the observational point of view, **signals due to electrom. component are extended in time**:

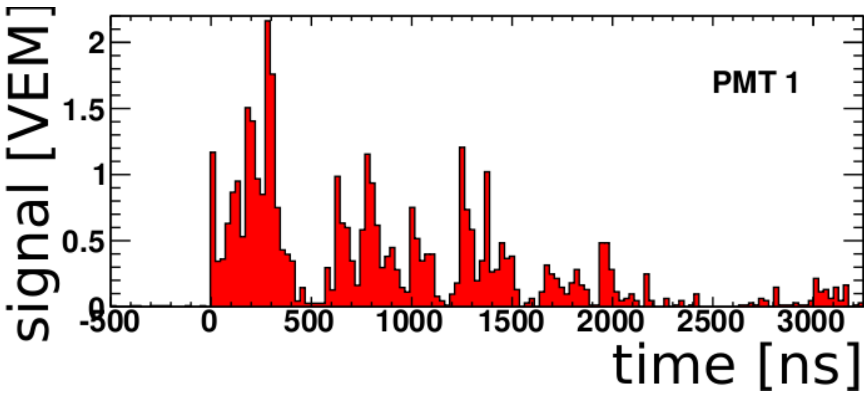
- Induce Time-over-Threshold (ToT) triggers in the SD stations

and/or

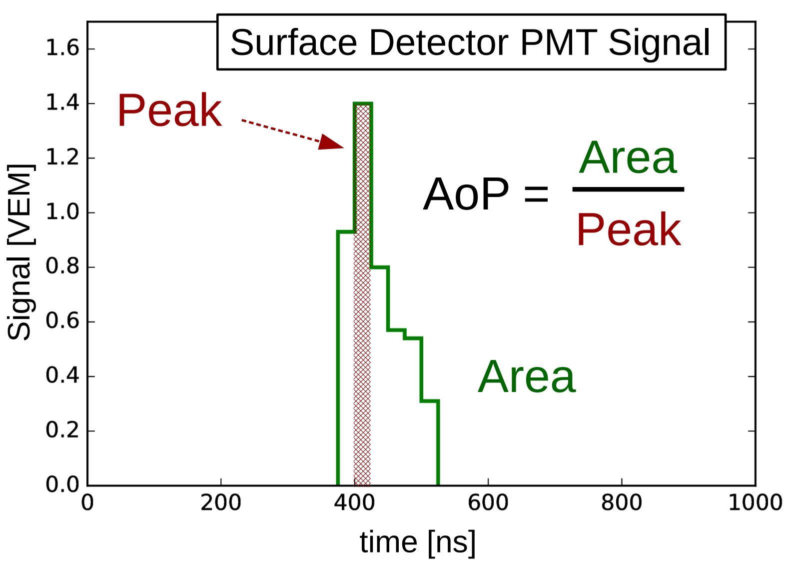
- Have large **Area-over-Peak** (AoP) value (AoP ∼ 1 muonic front)

Searching for neutrinos ⇒
Searching for inclined showers with stations with large values of Area-over-Peak

Trace signal from electromag. component

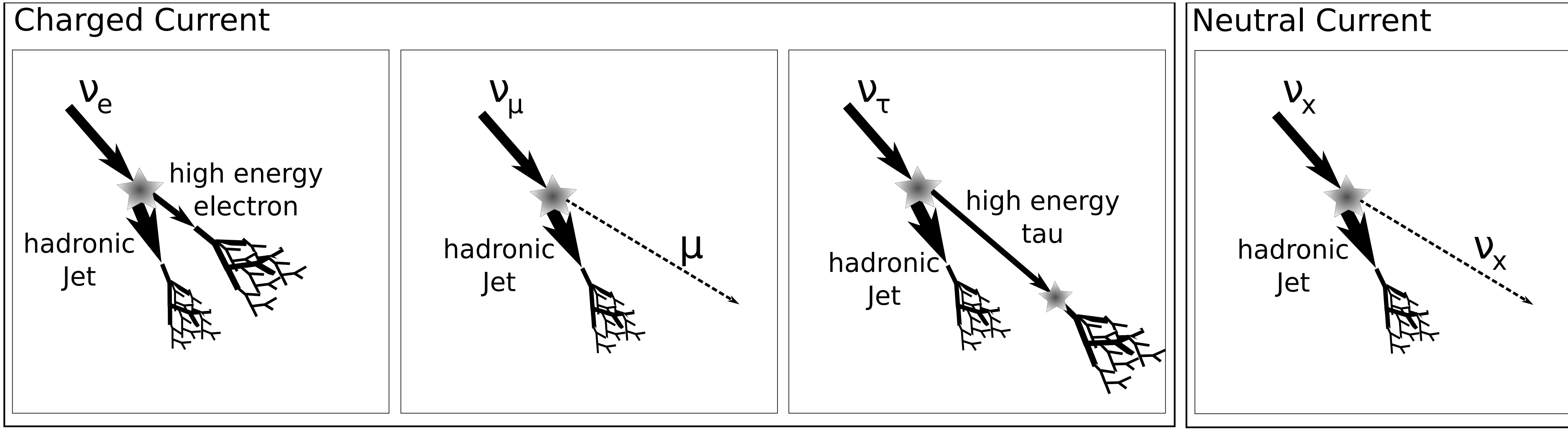


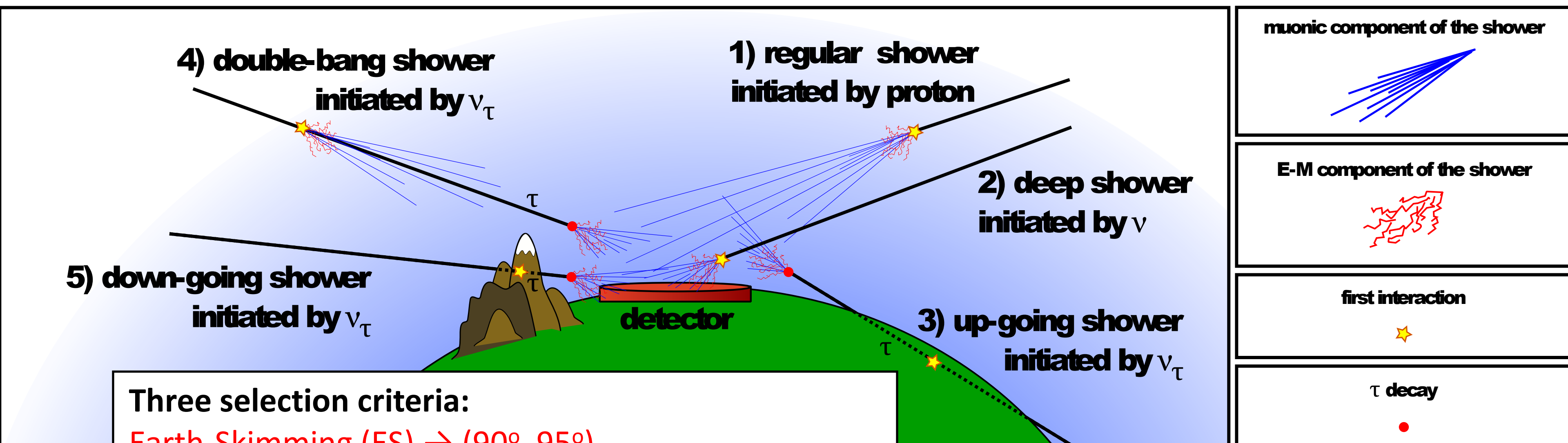
Definition of Area-over-Peak (AoP)



Pierre Auger, PRD **91**, 092008 (2015)

Sensitivity to all flavours & channels in Auger





Three selection criteria:

Earth-Skimming (ES) → (90°, 95°)

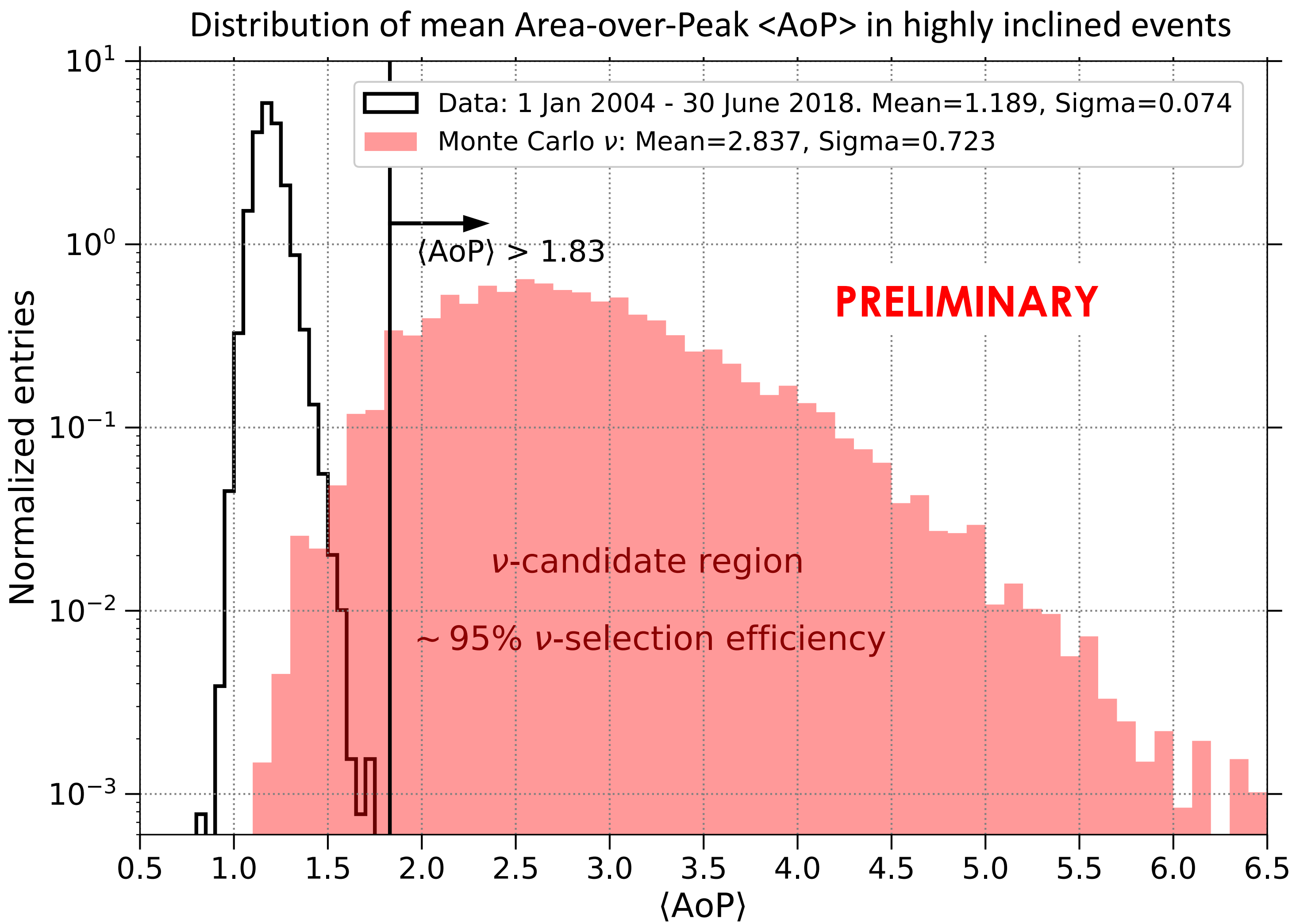
Downward-going high-angle (DGH) → (75°, 90°)

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

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

Data unblinding: Earth-Skimming channel

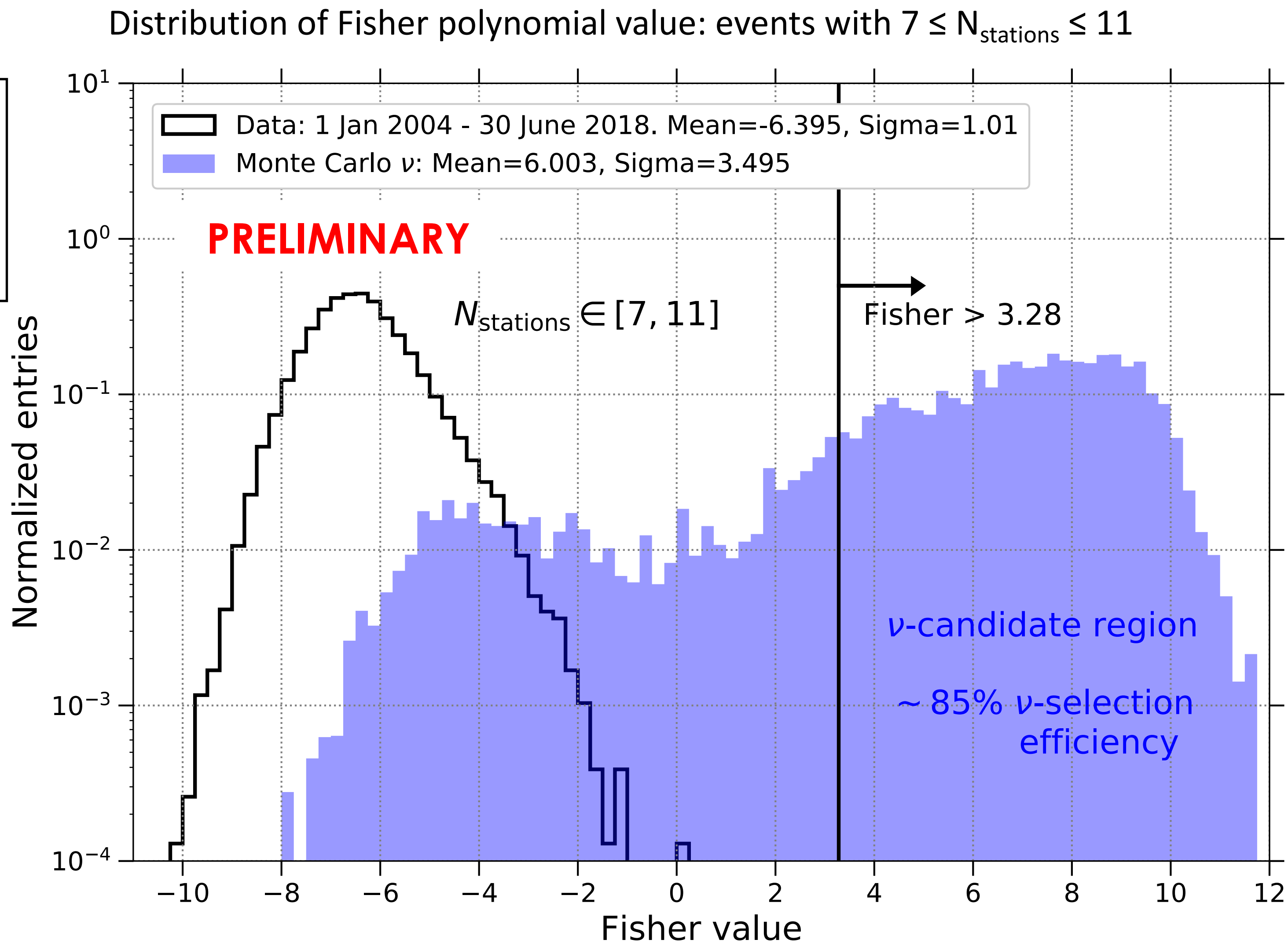
Auger data up to 30 June 2018



No neutrino candidates in the Earth-Skimming channel
Large ν-selection efficiency => sensitivity dominated by exposure, NOT by background

Unblinding: Downward-going (75° < θ < 90°) channel

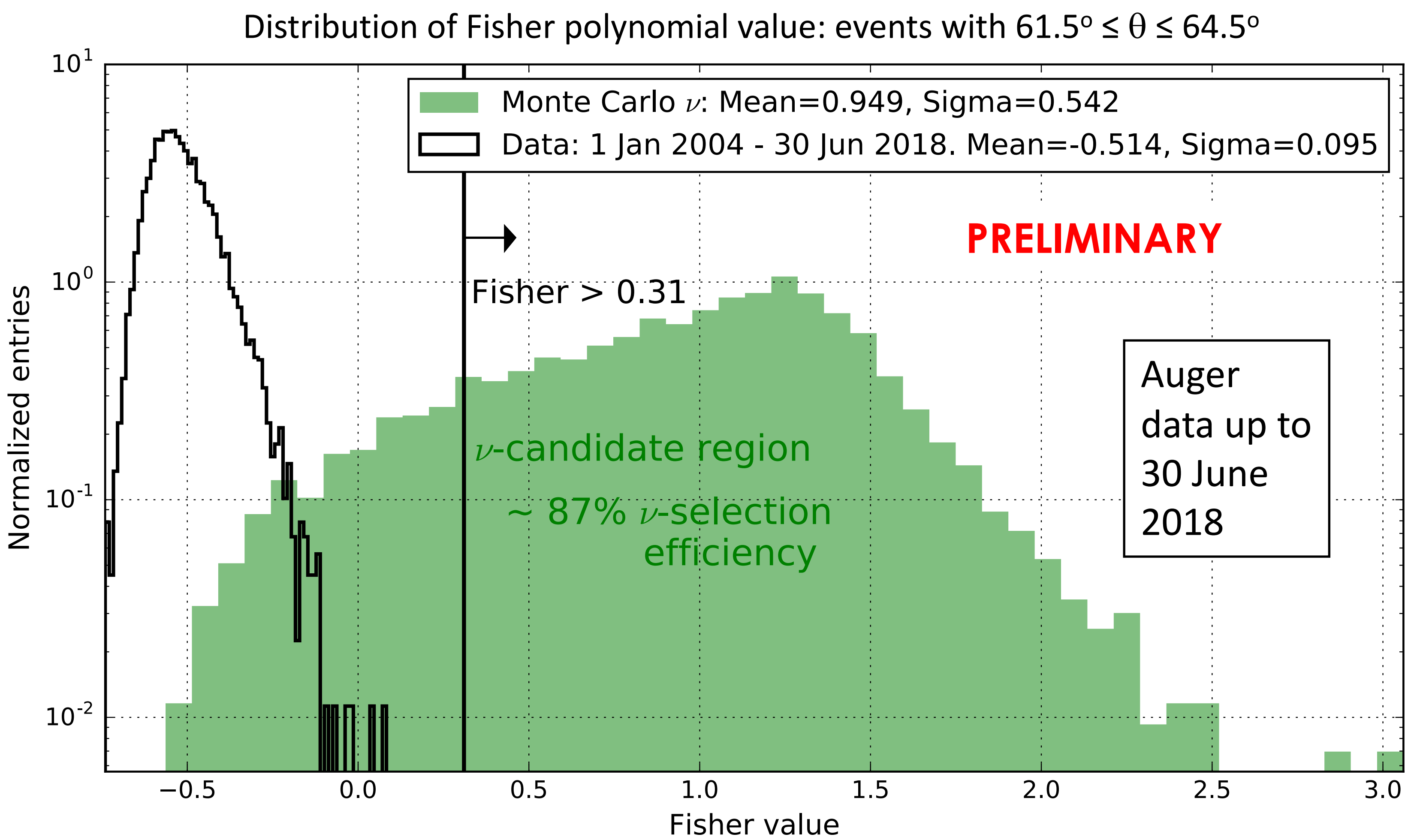
Auger data up to 30 June 2018



No neutrino candidates in Downward-going (75° < θ < 90°) channel for any number of stations

Large ν-selection efficiency => sensitivity dominated by exposure, NOT by background

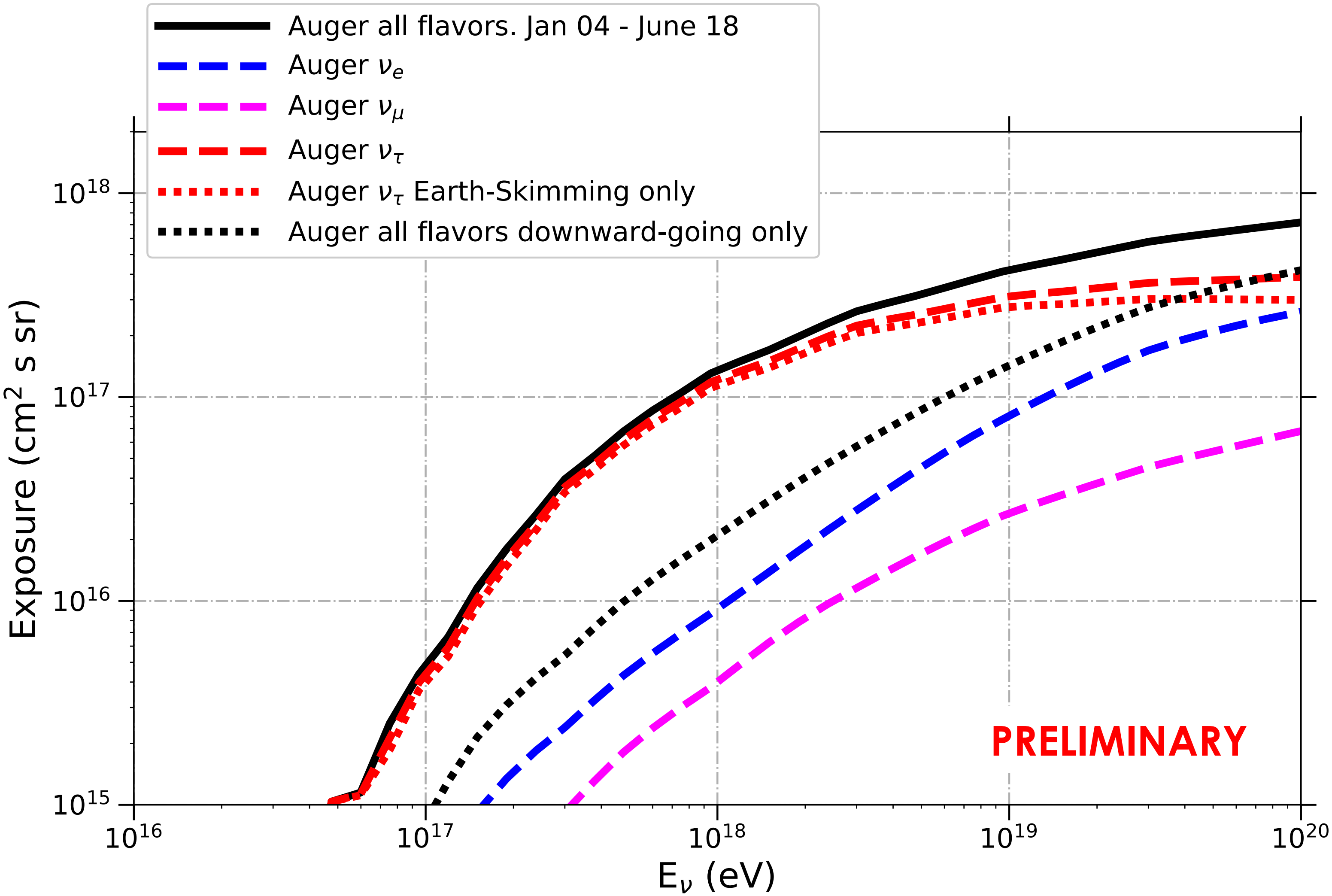
Unblinding: Downward-going (60º < θ < 75º) channel



No neutrino candidates in Downward-going (60º < θ < 75º) channel
Large ν-selection efficiency => sensitivity dominated by exposure, NOT by background

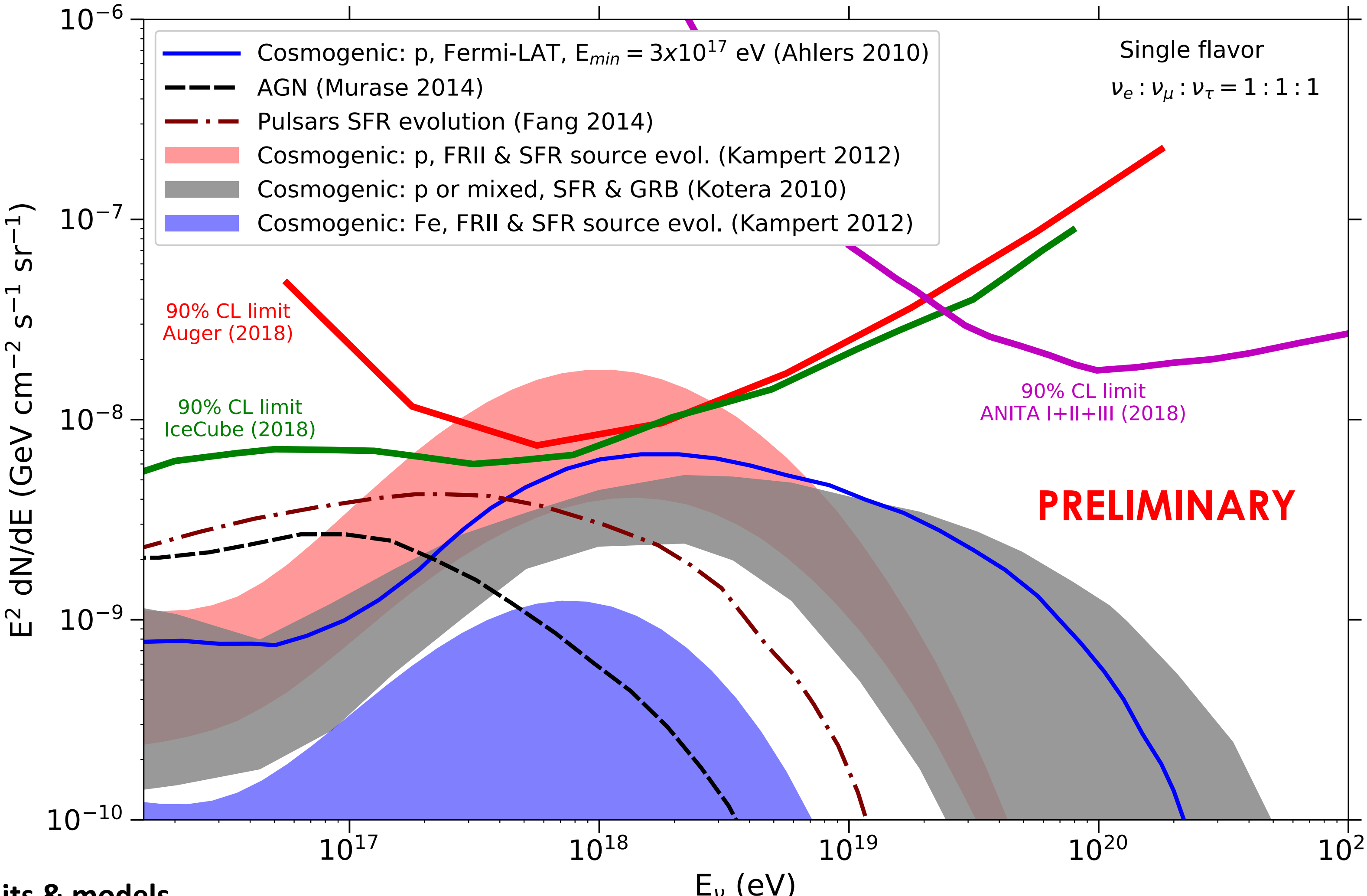
Limits to diffuse fluxes of UHE neutrinos

Auger exposure to diffuse flux of UHE neutrinos



Sensitivity dominated by **Earth-Skimming tau neutrino** channel alone up to E $\simeq$ 4 x 10^{19} eV when **Downward-going** channels take over

Differential limits to diffuse flux of UHE neutrinos

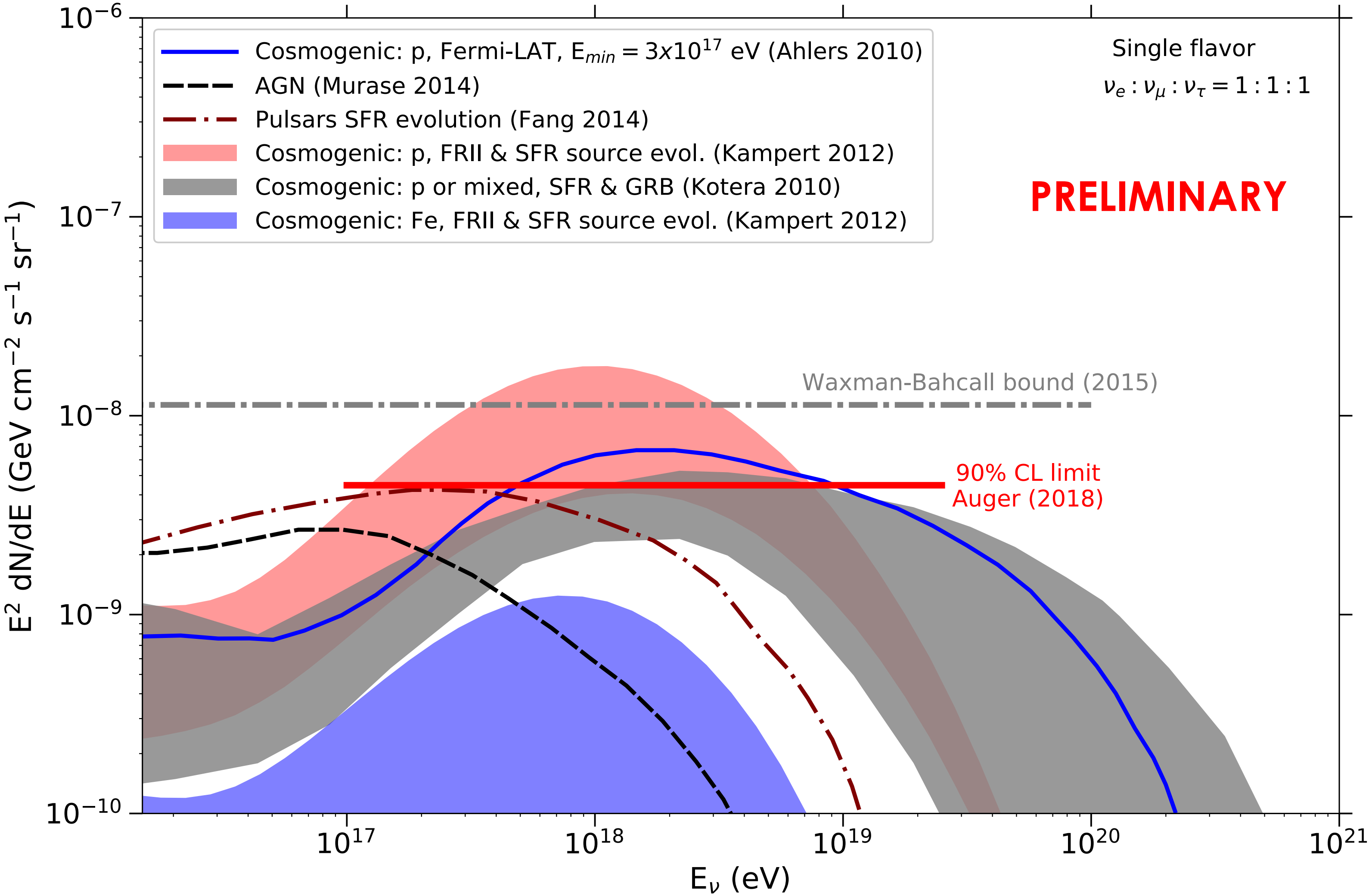


NOTE: limits & models converted to single flavor. Differential limits in one decade in energy

Auger sensitivity to UHEν is maximum around EeV energies and is comparable to that of IceCube

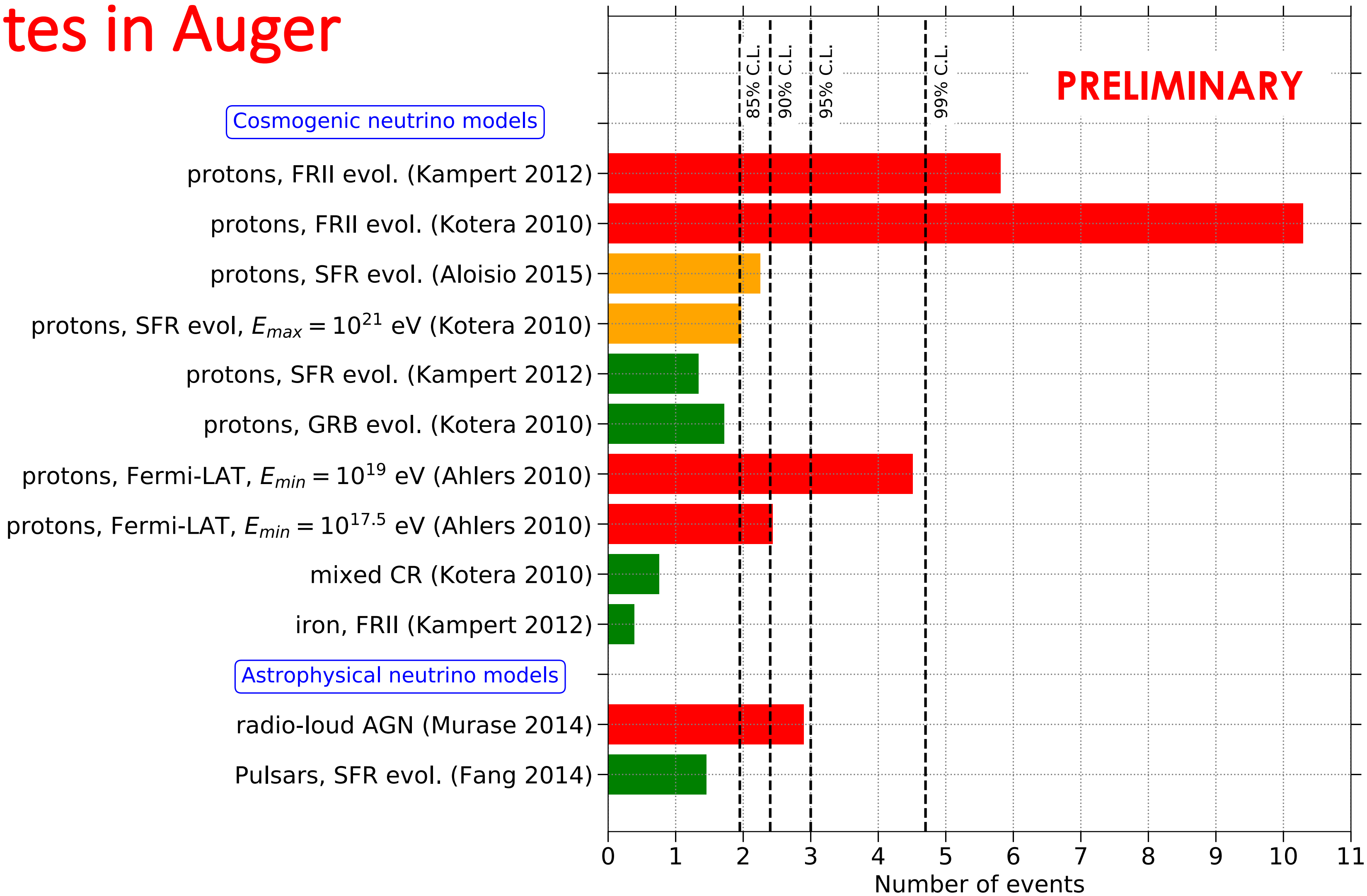
IceCube, PRD **98**, 062003 (2018)
ANITA, PRD **98**, 022001 (2018)

Auger integrated limit to diffuse flux of UHEν



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

Expected event rates in Auger

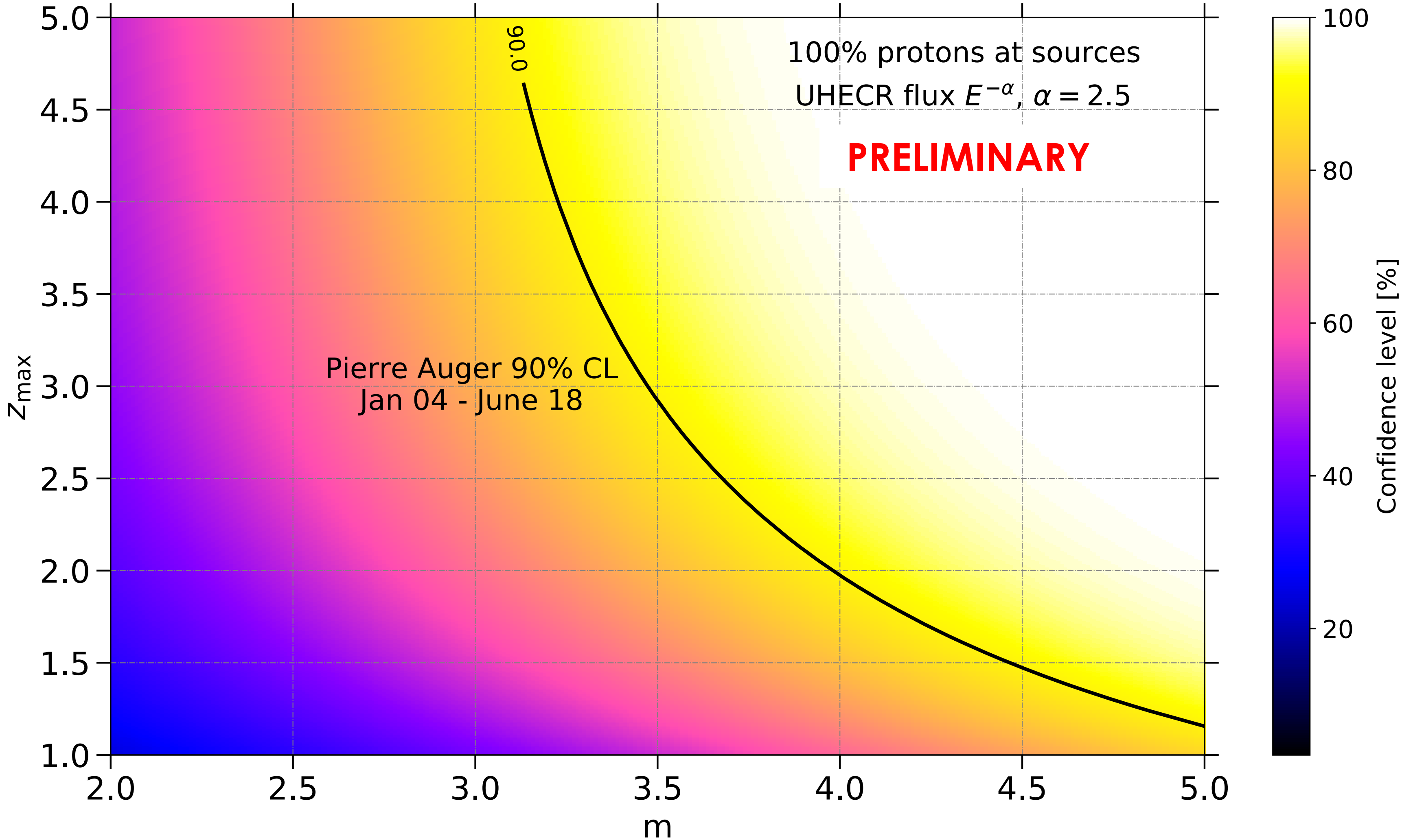


With Auger we are starting to constrain models of cosmogenic ν production assuming **protons** dominate at sources & Star-Formation Rate (**weak**) evolution with redshift *z*

Auger constraints on sources of UHECR

Non-observation of UHE neutrinos in Auger => disfavors (at 90% C.L.) a large parameter space in z_{max} and **m** [sources evolving as $(1+z)^m$]

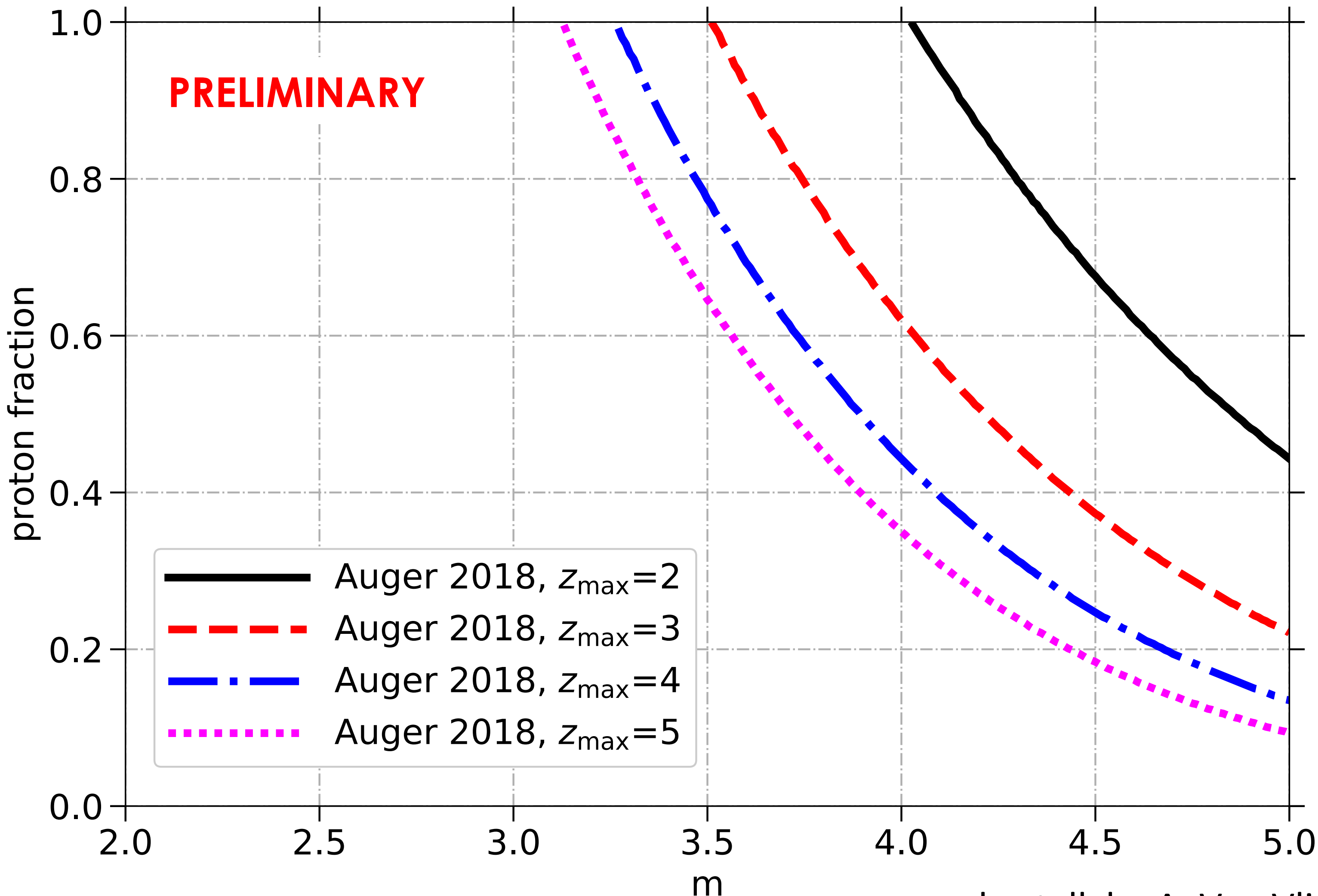
Region above black solid line excluded at 90% CL



ν fluxes obtained as in S. Yoshida et al. PRD **85**, 063002 (2012)

Auger constraints on sources of UHECR

Large proton fraction at sources & strong source evolution disfavored at > 90% C.L.
Auger constraints weaken as the proton fraction is diminished



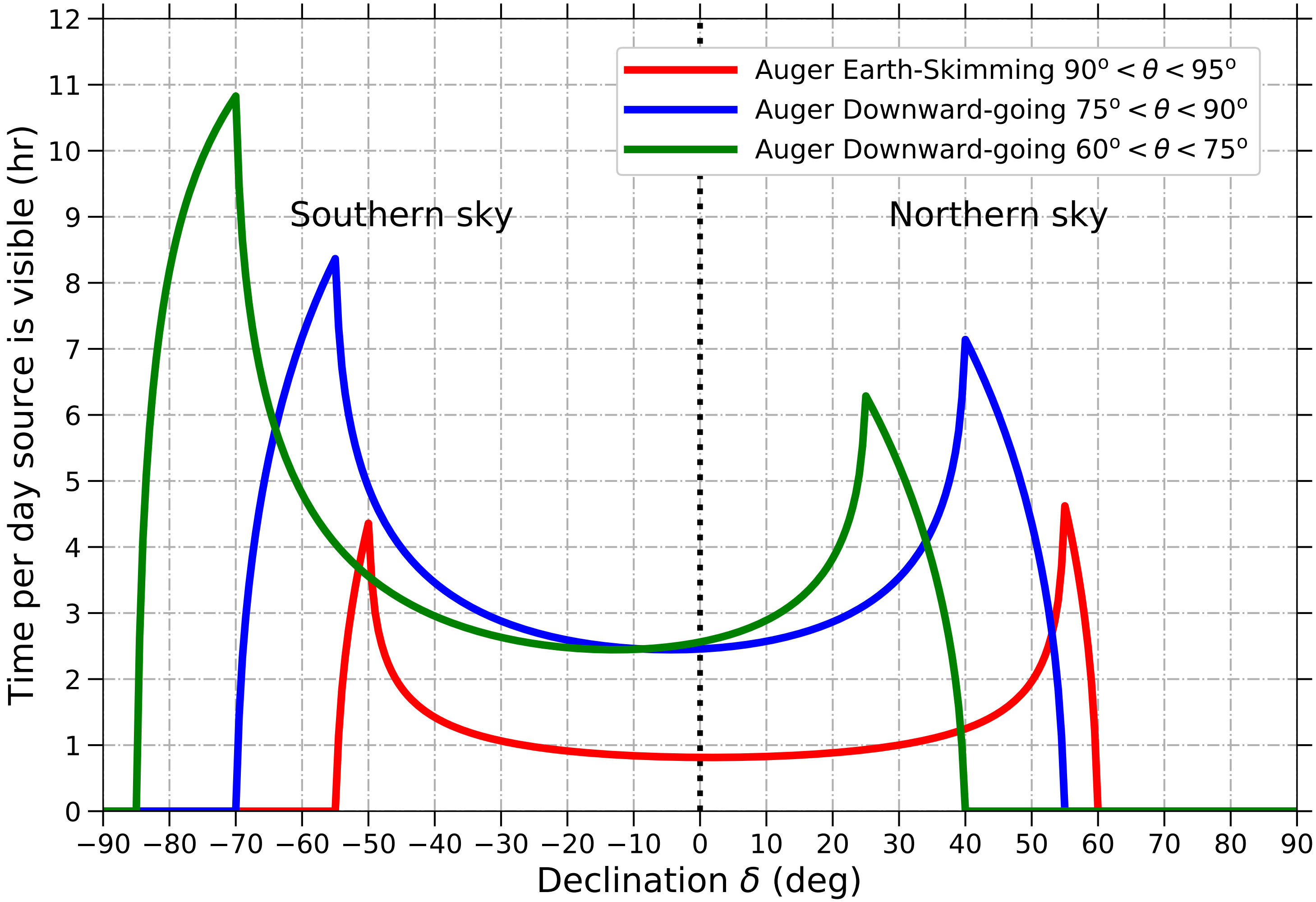
Region above each line excluded at 90% CL

see also talk by A. Van Vliet today

Point-like sources of UHE neutrinos (steady & transient)

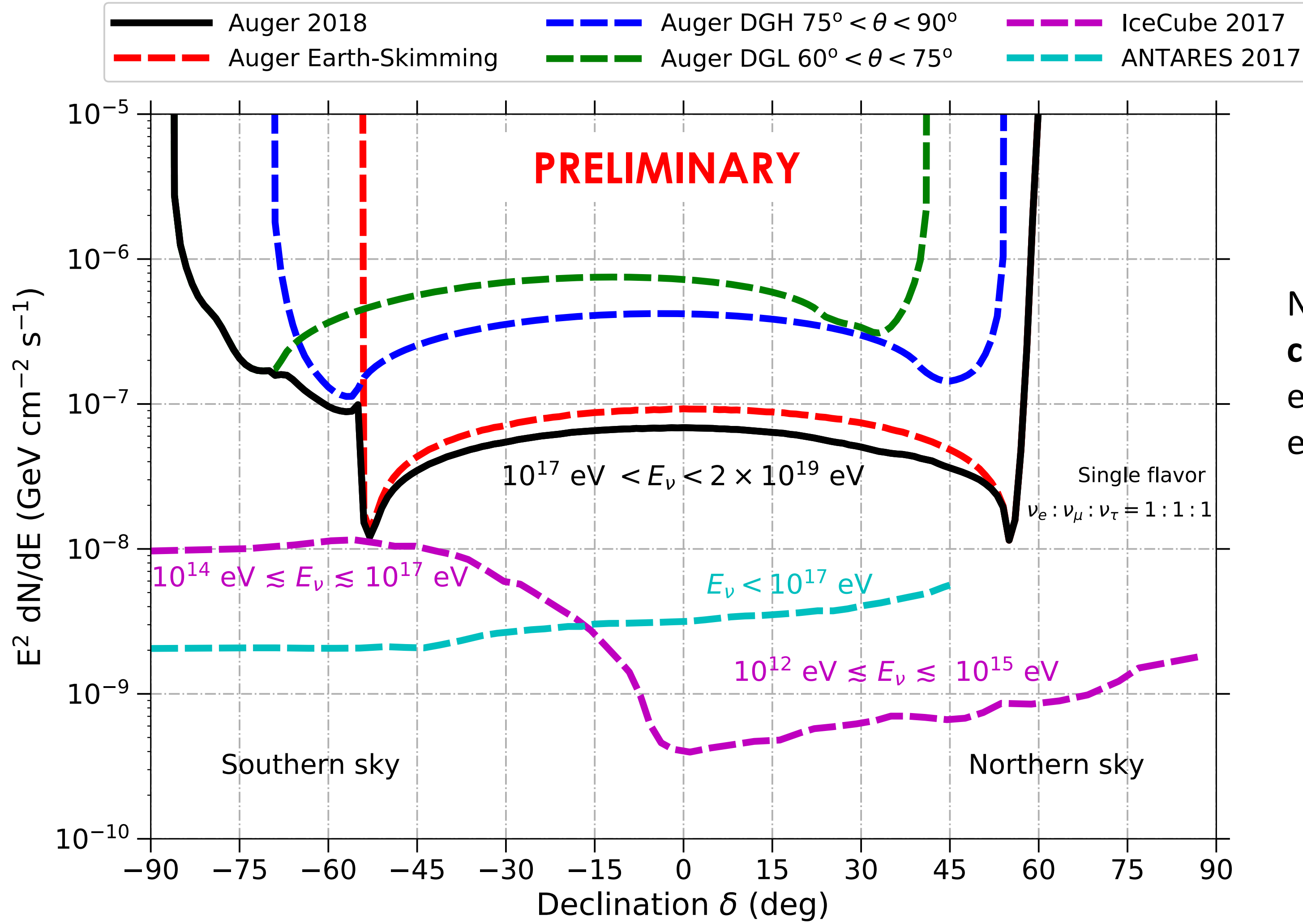
UHE neutrinos:

Time per day a source is visible in the field-of-view of Earth-Skimming & Downward-going neutrino channels as a function of source declination



Limits to point-like & steady neutrino sources

Broad range in declination where ν can be efficiently identified with Auger: two ”sweet” spots around declinations -55º and +55º

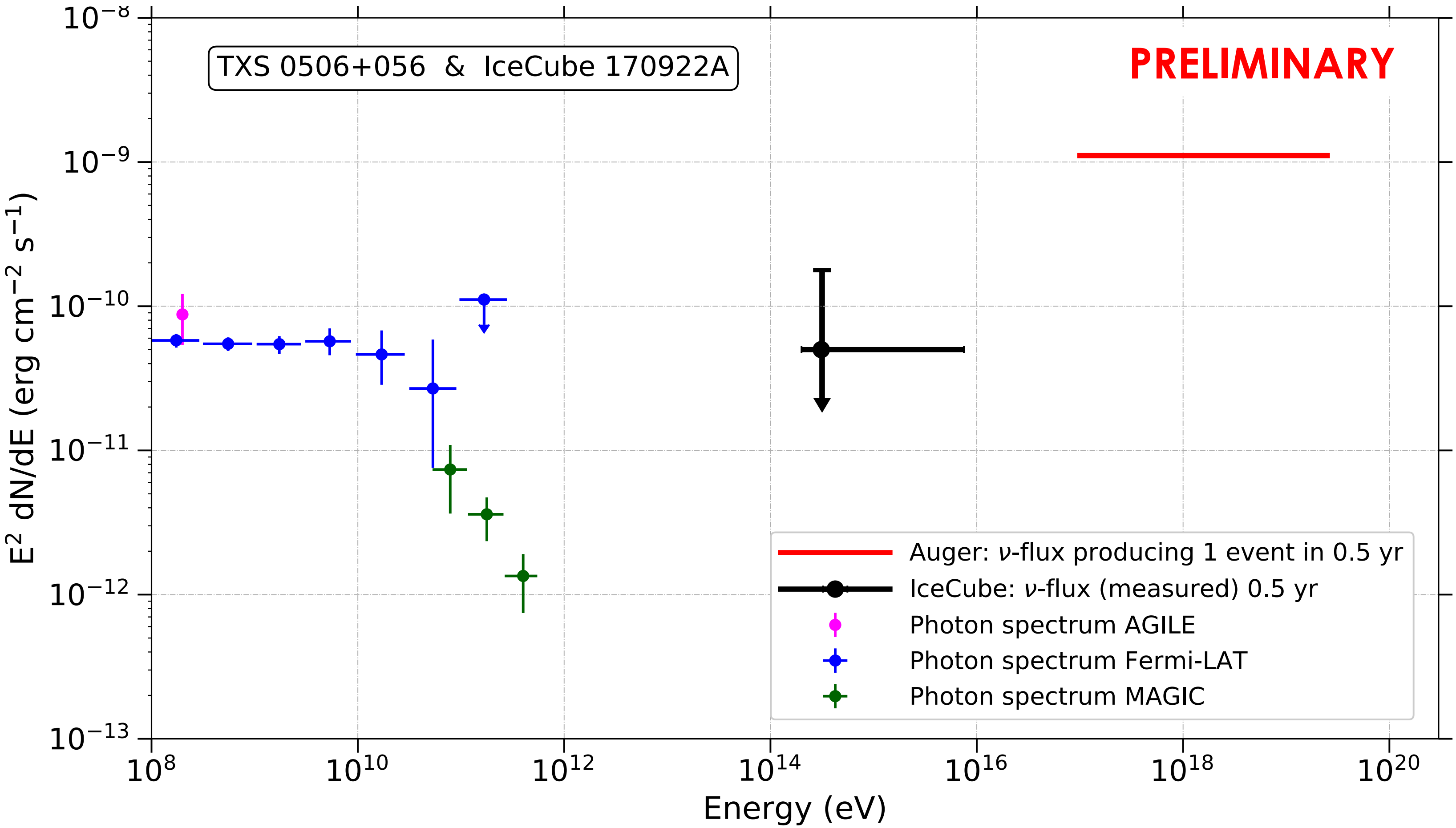


NOTE
complementary
energy ranges of
experiments

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

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

TXS 0506+056 ν flux or limit 0.5 years before event IceCube 170922A
γ-ray fluxes after 170922A

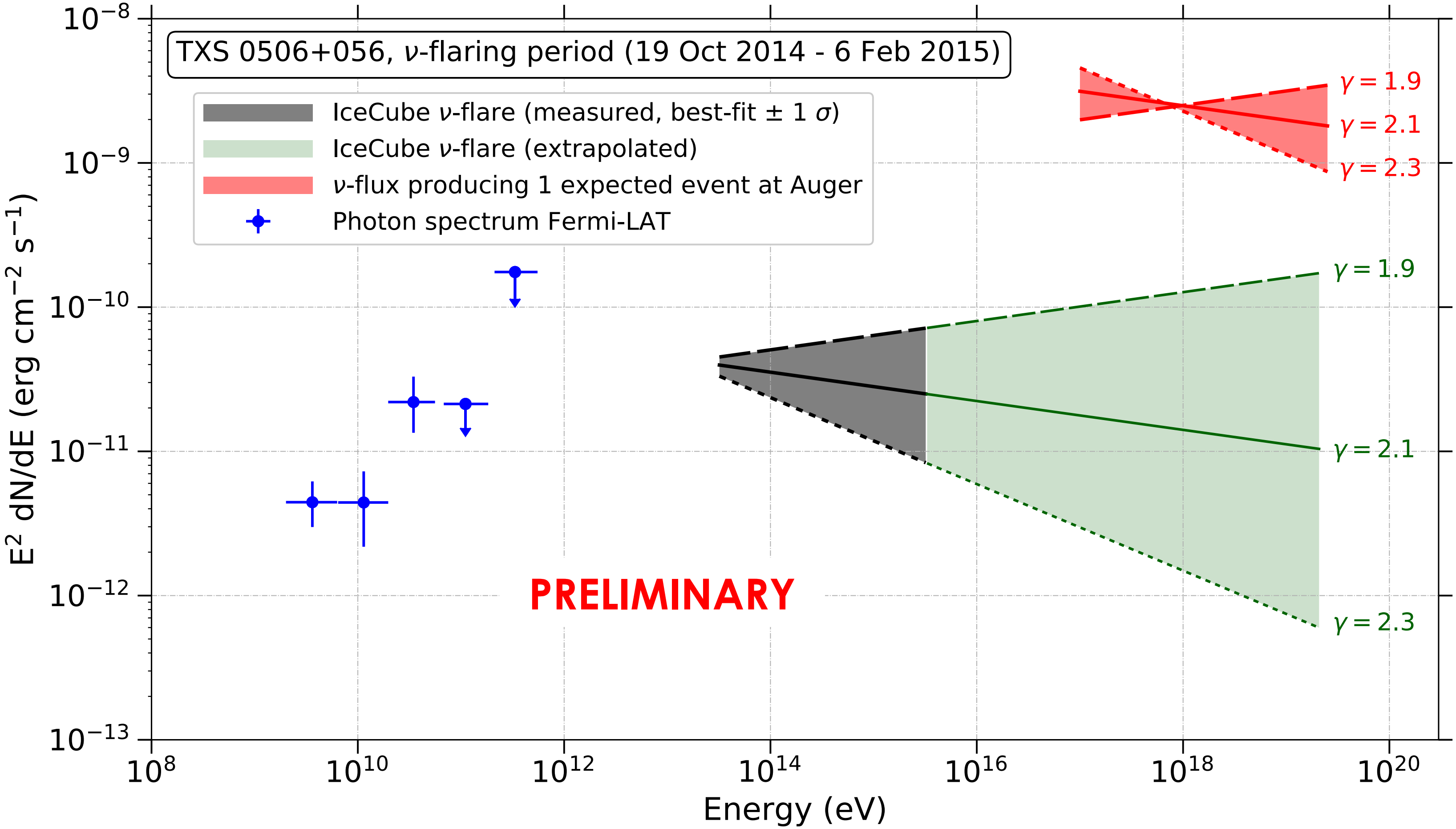


First upper limits to the neutrino flux from TXS 0506+056 at EeV energies

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

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

TXS 0506+056 in the (Gaussian) time window of 110 days
(19 Oct 2014 – 6 Feb 2015) when IceCube neutrino excess was observed



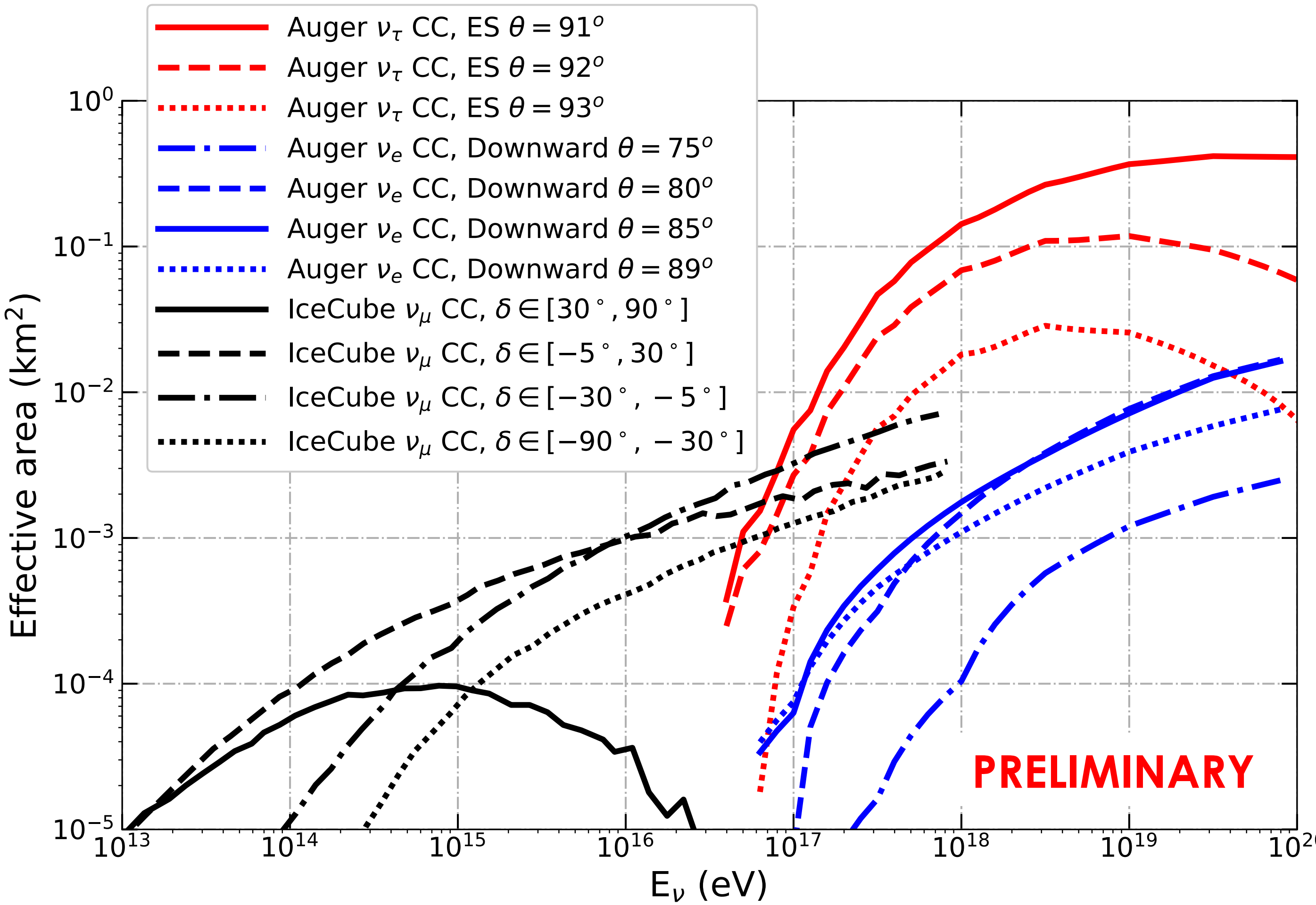
First upper limits to the neutrino flux from TXS 0506+056 at EeV energies

IceCube, Science **361**, 147 (2018). P. Padovani et al. MNRAS **480**, 192 (2018)

Instantaneous effective area A_{eff}: sensitivity to transient sources

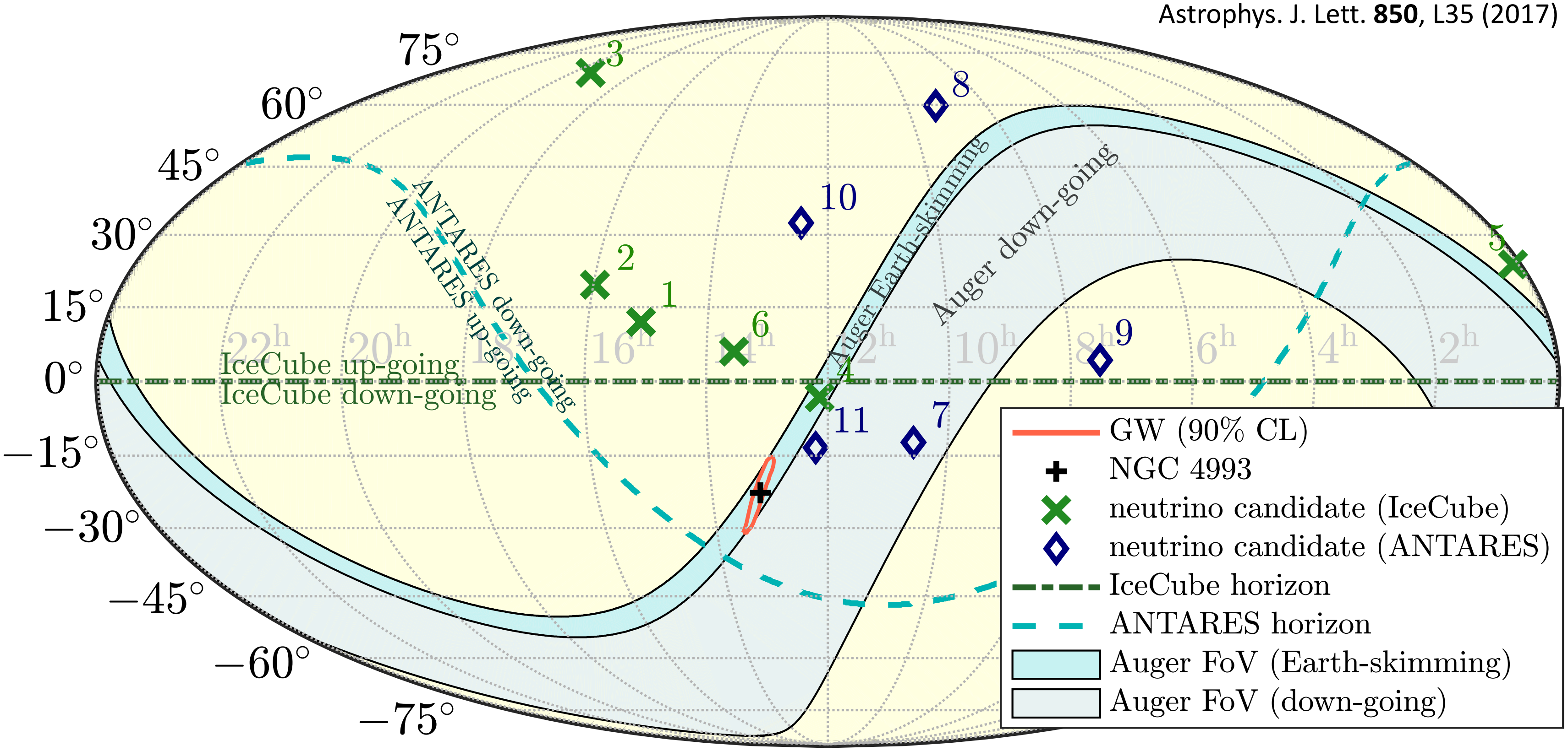
$$\dot{N}_\nu = \int d\Omega \int_0^\infty dE\, A_{\rm eff}\,(E,\, \Omega) \times F_\nu\,(E_\nu,\, \Omega)$$

Large area of SD of Auger => **unrivalled sensitivity to transient point-like sources at EeV** (as long as source is located in sky in the FoV of Earth-Skimming channel.



Follow-up of GW170817
Binary Neutron Star Merger + short GRB

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

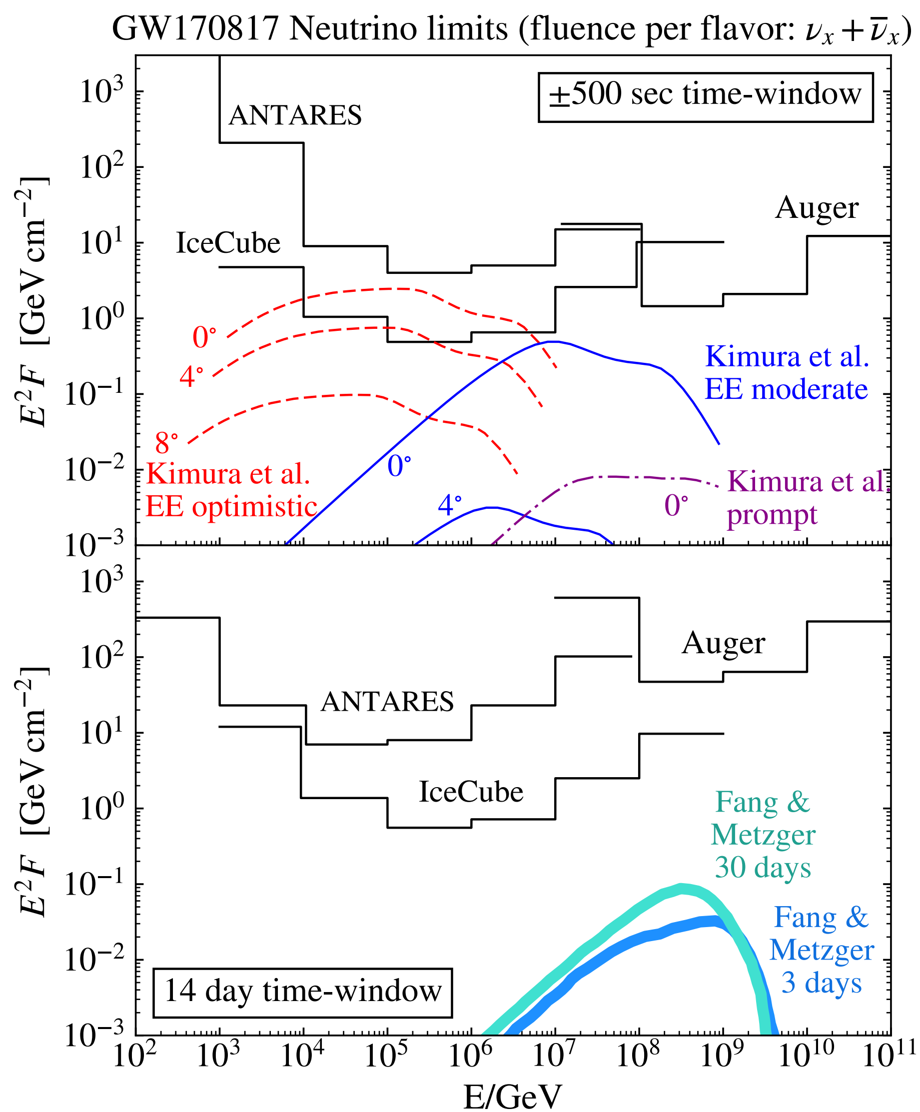


The NS-NS merger was in an **optimal position** for the detection of UHE tau neutrinos from Auger at the instant of emission of GW170817

Limits to ν from Binary NS-NS event GW170817: ANTARES, Auger & IceCube

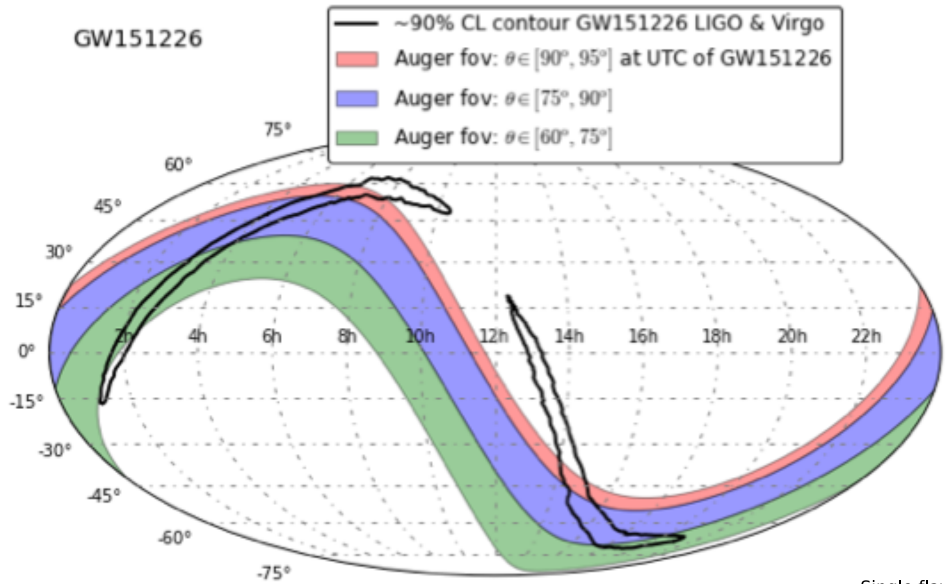
- Neutrino limits based on non-observation in ± 500 sec & +14 days-time windows

- Lack of neutrino detection consistent with expectations from a short GRB viewed at a large off-axis angle ≳ 20º (in agreement with LIGO/Virgo & GRB observations)



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

Limits to Binary Black Hole mergers: GW151226



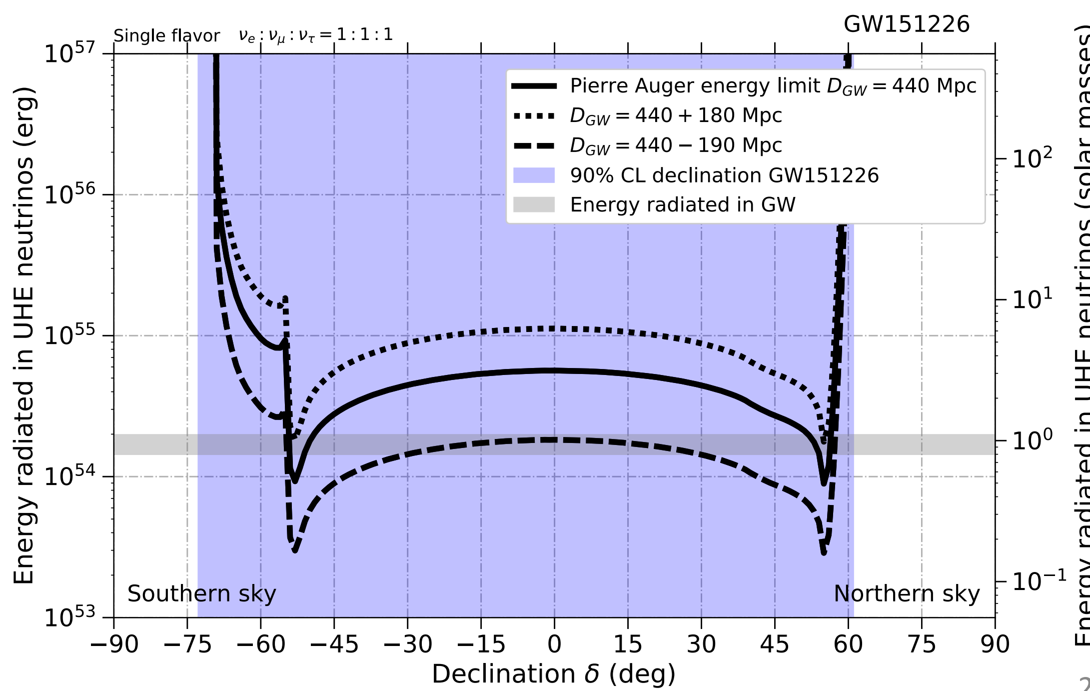
Skymap (equatorial coords.):

- Localization of GW151226
- field-of-view of Auger in inclined directions at instant GW151226 occurred

Pierre Auger , PRD **94**, 122007 (2016)

Limits to energy emitted in the form of UHEν from non-observation of ν candidates in Auger 1 day after GW151226:

- Less than a few solar masses in the form of neutrinos.
- Compatible with expectations of absence of ν production in “naked” BH-BH mergers.



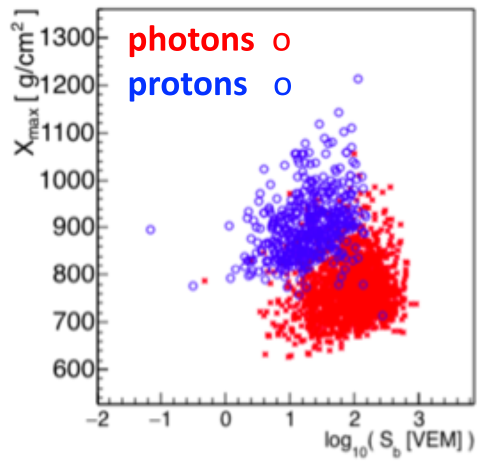
UHE photons in Auger

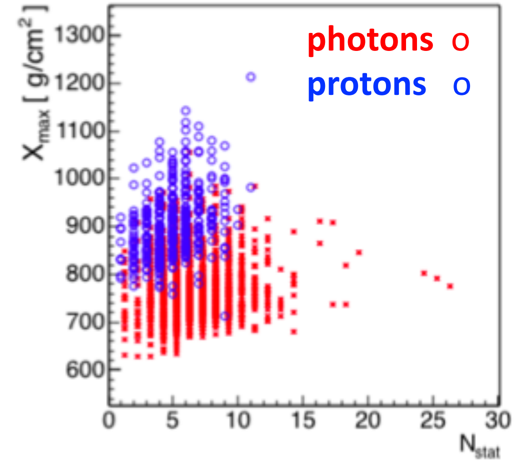
Search for UHE photons with Auger FD + SD

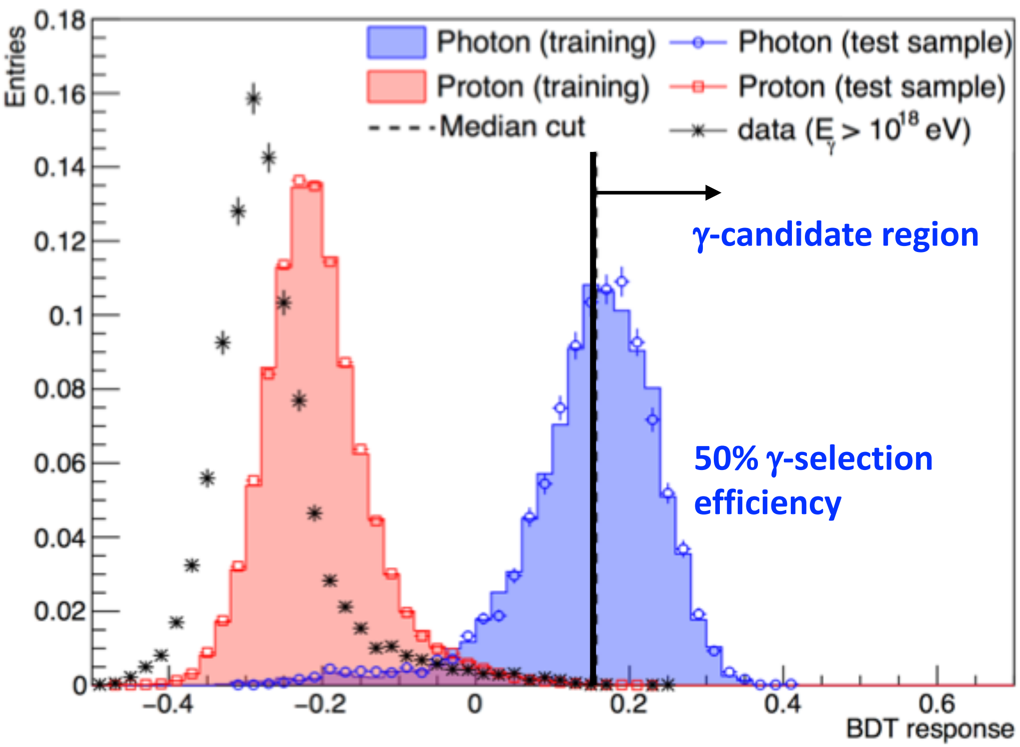
γ-induced showers have deeper X_{max} and less muons than proton showers =>

- Steeper Lateral Distribution at ground.
- Less triggered stations

M. Niechciol for the
Pierre Auger Collab. PoS (ICRC 2017) 517







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

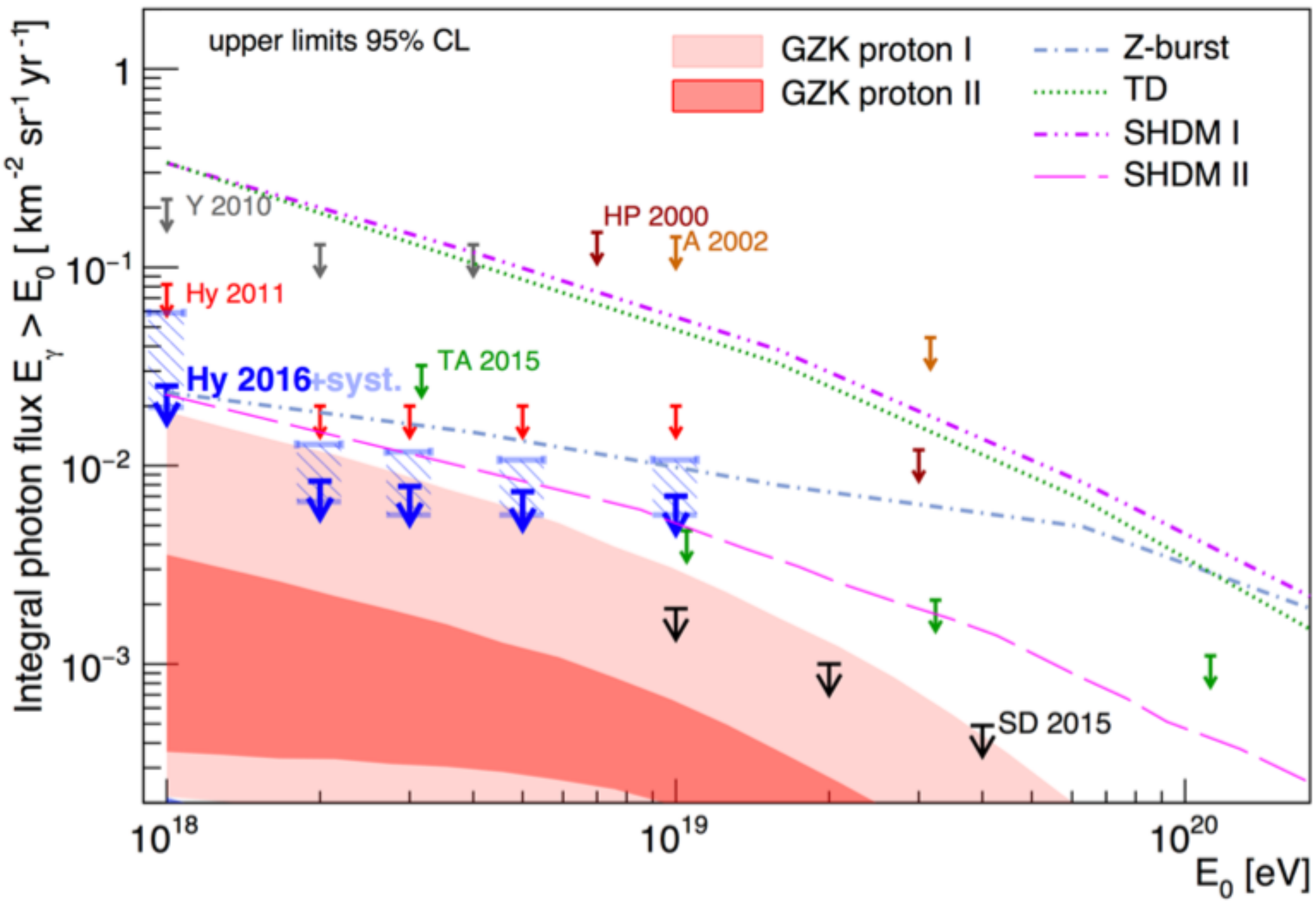
Multivariate analysis using:

X_{max}, $N_{stations}$ and S_b

- 50% γ-selection efficiency
- 3 events above cut

(compatible with background expectations)

Limits to diffuse flux of UHE photons



Blue arrows:
Hybrid (FD+SD) data
Jan 2005 – Dec 2013

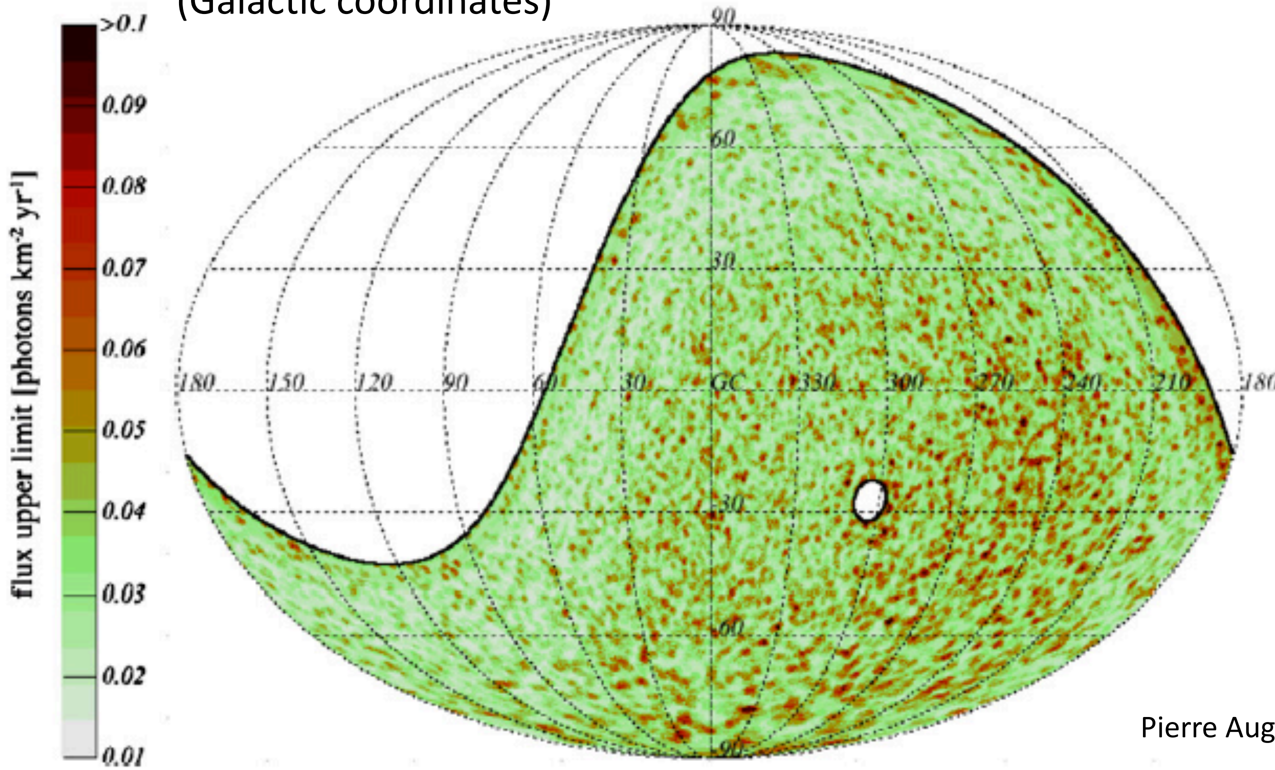
Black arrows:
SD data only
Jan 2004 – May 2013

M. Niechciol for the
Pierre Auger Collaboration
ICRC 2017

- “top-down” models of UHECR production severely constrained
- Constraints on optimistic cosmogenic fluxes assuming 100% protons at sources

Limits to point-like & steady sources of UHE γ

Upper limits to γ-fluxes
(Galactic coordinates)



Multi-variate analysis using **hybrid data (X_{max}, …)** to select enriched samples of photon-like events

Hybrid data:
Jan. 2005 – Sept. 2011
0.2 EeV < E < 3 EeV

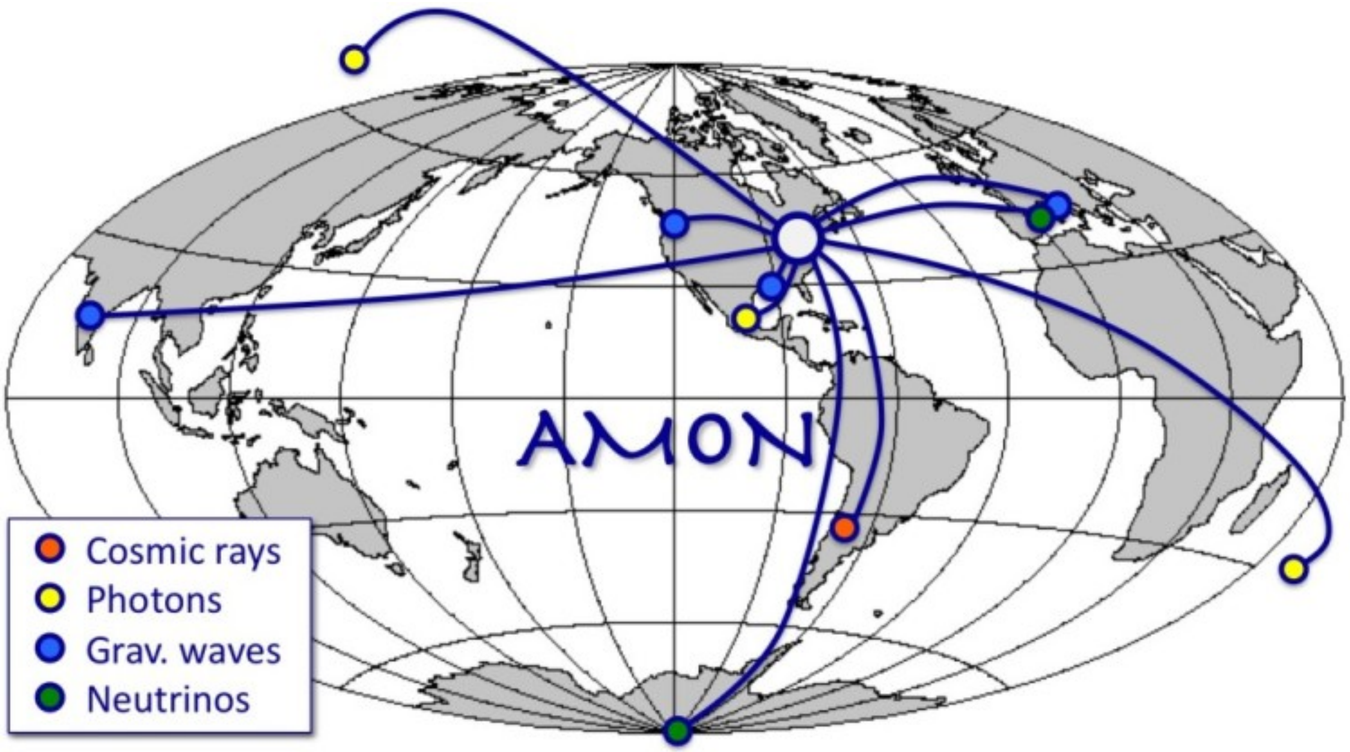
Pierre Auger, Astrophys. J. **789**, 160 (2014)

- No significant excess of γ-like events from **any point in sky** => **upper limits**
- Upper limits compatible with:
  - Sources are extragalactic & farther than ~ 5 Mpc (photons absorbed)
  - Sources are Galactic but transient and/or beamed (beam NOT pointing to us)
  - Sources have a small optical depth (small photon production efficiency)

See Pierre Auger, Astrophys. J. Lett. **837**, L25 (2017) for photon limits to targeted sources

AMON: Astrophysicsl Multimessenger Observatory Network

- Auger sends all vertical events with energy ≥ 3 EeV to AMON with the goal of real-time coincidence analysis with IceCube, HAWC, etc…
- 2 or more events observed within 100 s and < 3 deg. generate an AMON alert for other AMON-partner observatories to follow-up on.



https://www.amon.psu.edu/

Summary & Conclusions:

1. With the Pierre Auger Observatory we are contributing to **Multi-Messenger Astrophysics at EeV energies** using photons & neutrinos.

2. Updated search for UHEν in Auger data up to 30 June 2018 – **NO candidates**

3. **Competitive photon & ν diffuse flux limits**: constraining sources of UHECR.

4. Sensitivity to UHEν in a **large fraction of sky** from -80º to 60º in equatorial declination that is being **monitored continuously**.

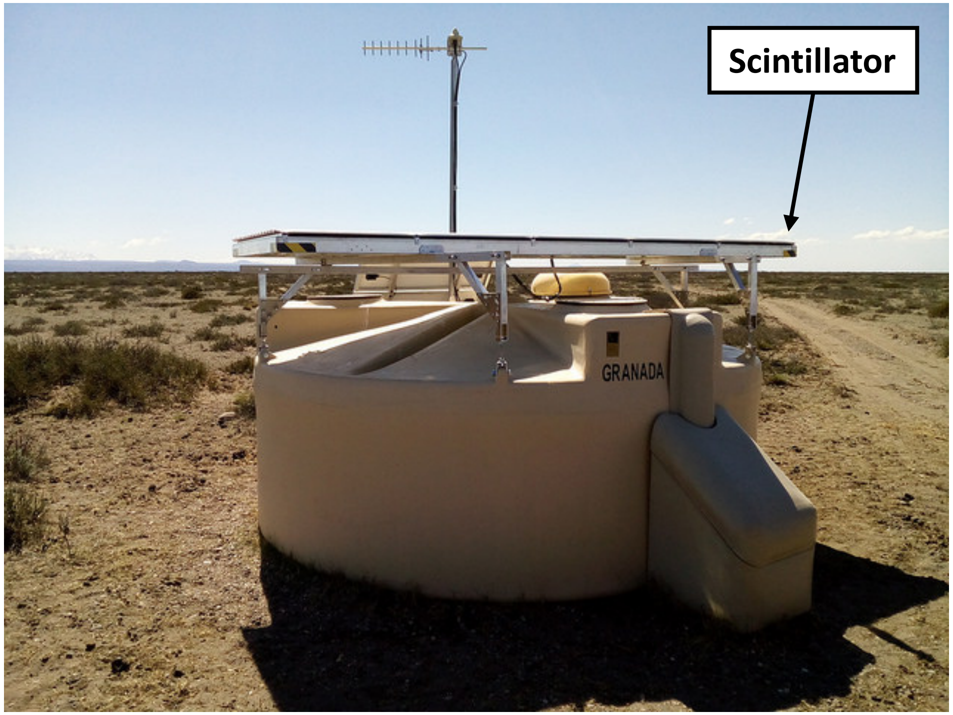
5. First upper limits to the neutrino flux from **TXS 0506+056 at EeV energies.**

6. **Unrivalled sensitivity to transient sources** if located at the right position in the sky: e.g. GW170817 BNS merger.

More information

AugerPrime

D. Martello, Pierre Auger Collab. PoS (ICRC2017) 383
See also A. Castellina's talk on Friday at 9:20 am



- **Upgrade** of Pierre Auger Observatory:

- Instrument water-Cherenkov stations

with ~ 4 m^2 **scintillators on top:**

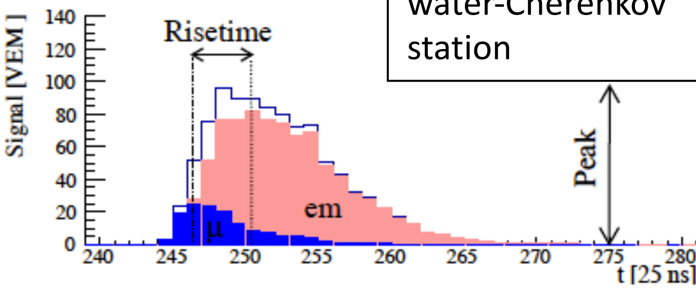
  - ✓ 3x faster sampling of signal traces
  - ✓ ~ 2x better timing (5 ns accuracy)
  - ✓ 32x larger dynamic range (small PMT)
  - ✓ lower energy trigger threshold.

- Engineering array (12 stations) working since 2016

- Goal: **Improve muon/electromagnetic separation in showers**
  - Improve **composition p/Fe determination** on a shower-by-shower basis
  - Enhance **photon/proton** discrimination power.
  - Good also for **neutrino searches** - work in progress…
    - New triggers => Lower energy threshold => enhance sensitivity in the 0.1 EeV energy range
    - Enhanced neutrino/proton discrimination: Deep neutrino showers have a large electrom. content

Search for UHE γ with Auger SD-only

Time trace in water-Cherenkov station



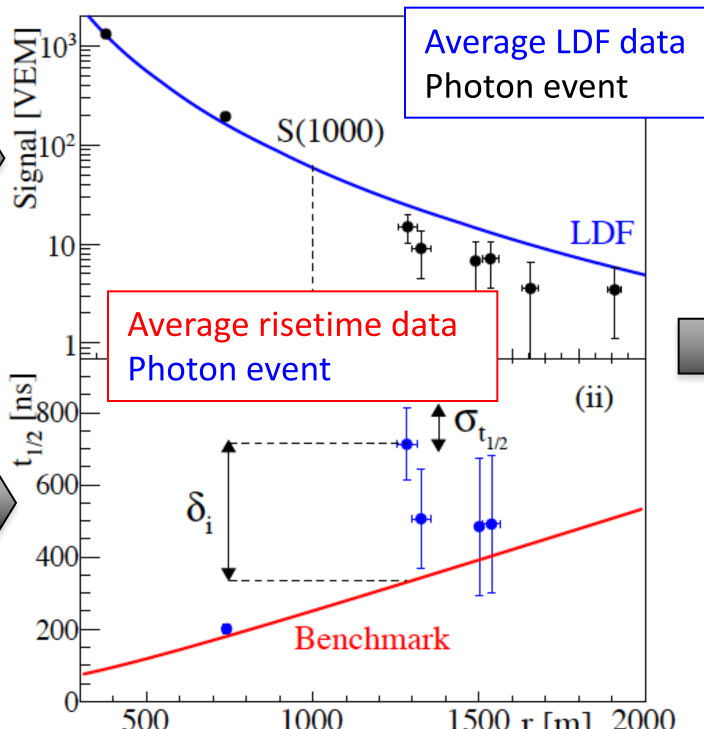
Carla Bleve, Pierre Auger Collab. ICRC 2015

γ-induced showers: deeper X_{max} than p showers & less muons =>

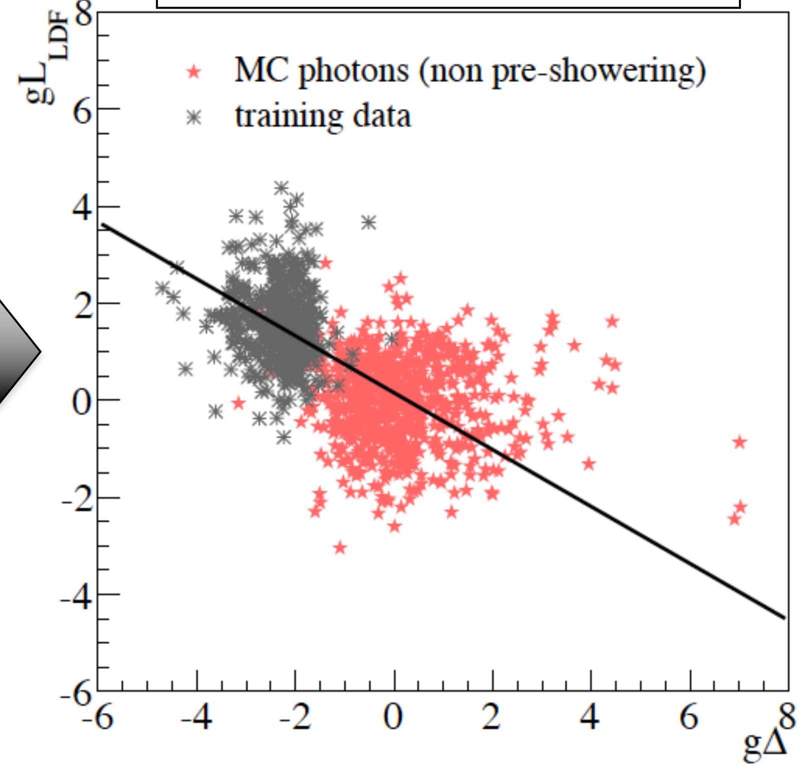
- Signals more spread in time: larger risetime
- Steeper Lateral Distribution at ground.

Lateral Distribution of signal

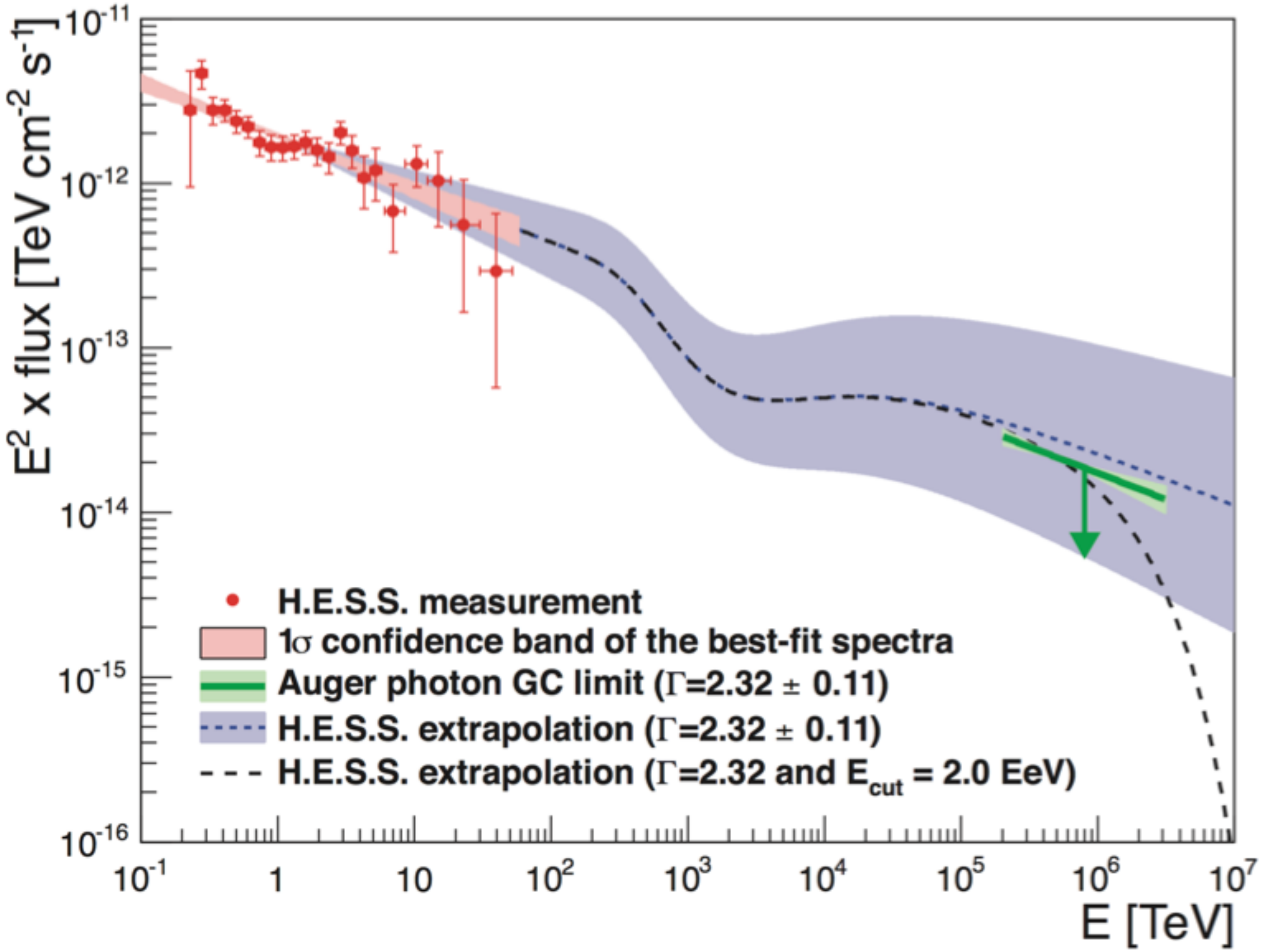
Risetime vs distance to shower core



Multi-variate
Principal Component Analysis



Targeted sources of UHEγ: Galactic Center

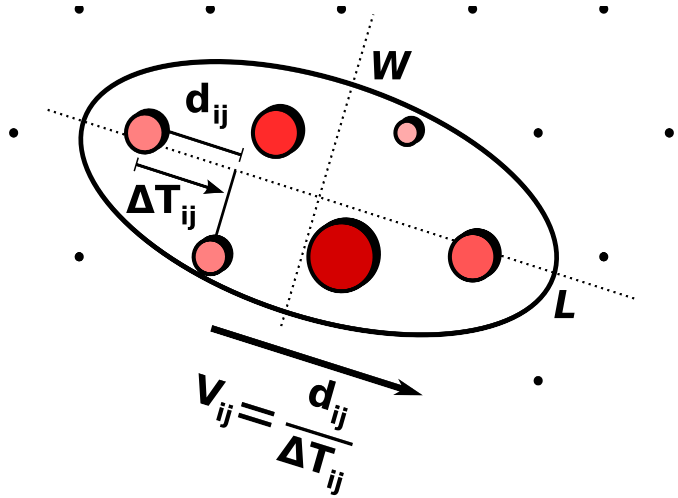


- Connection of Auger limits on γ from Galactic Center to measurements at TeV energy
- Auger limit constrains allowed parameter space for extrapolation of HESS data:

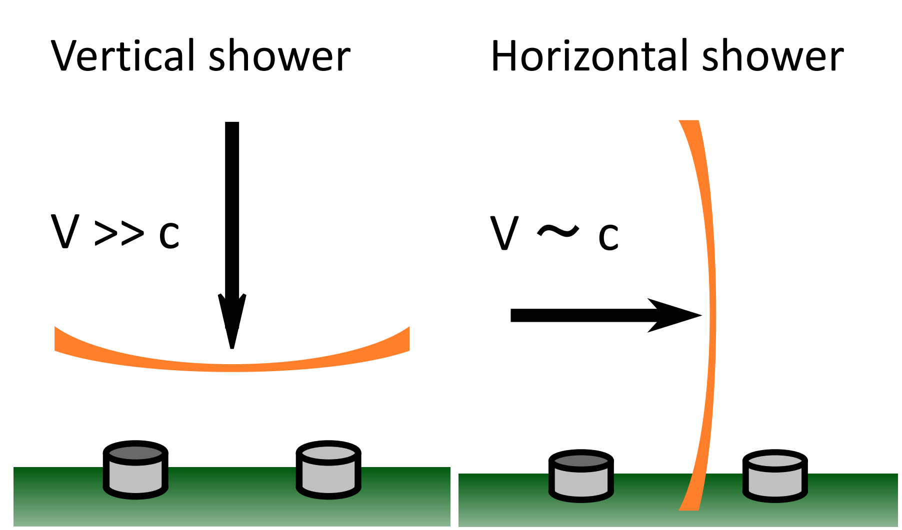
An upper limit on the cutoff energy of 2 EeV can be placed.

Selection of inclined showers: 3 observables

(1) Elongated footprint



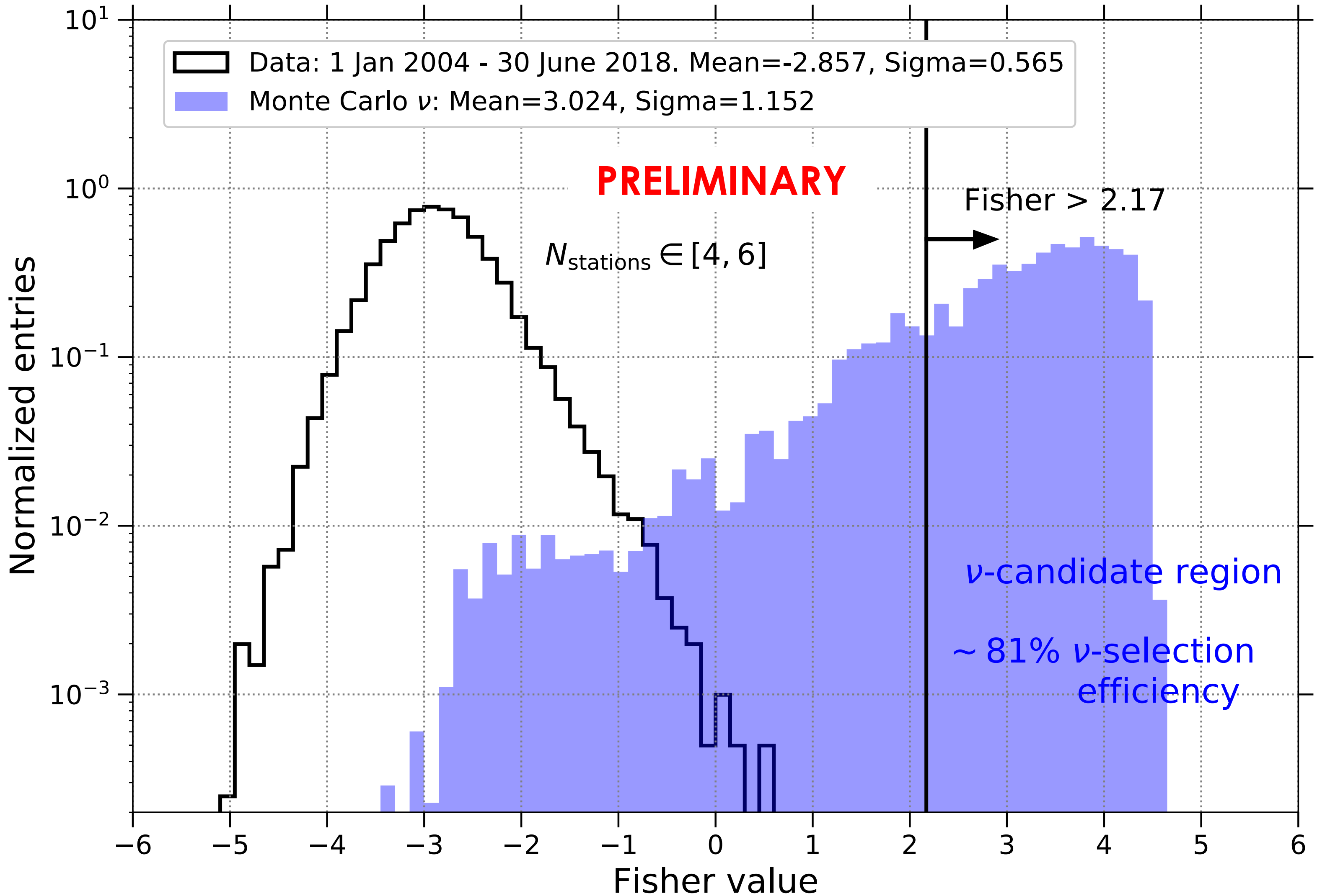
(2) Apparent velocity V of propagation of shower front at ground along major axis L



(3) Reconstructed θ

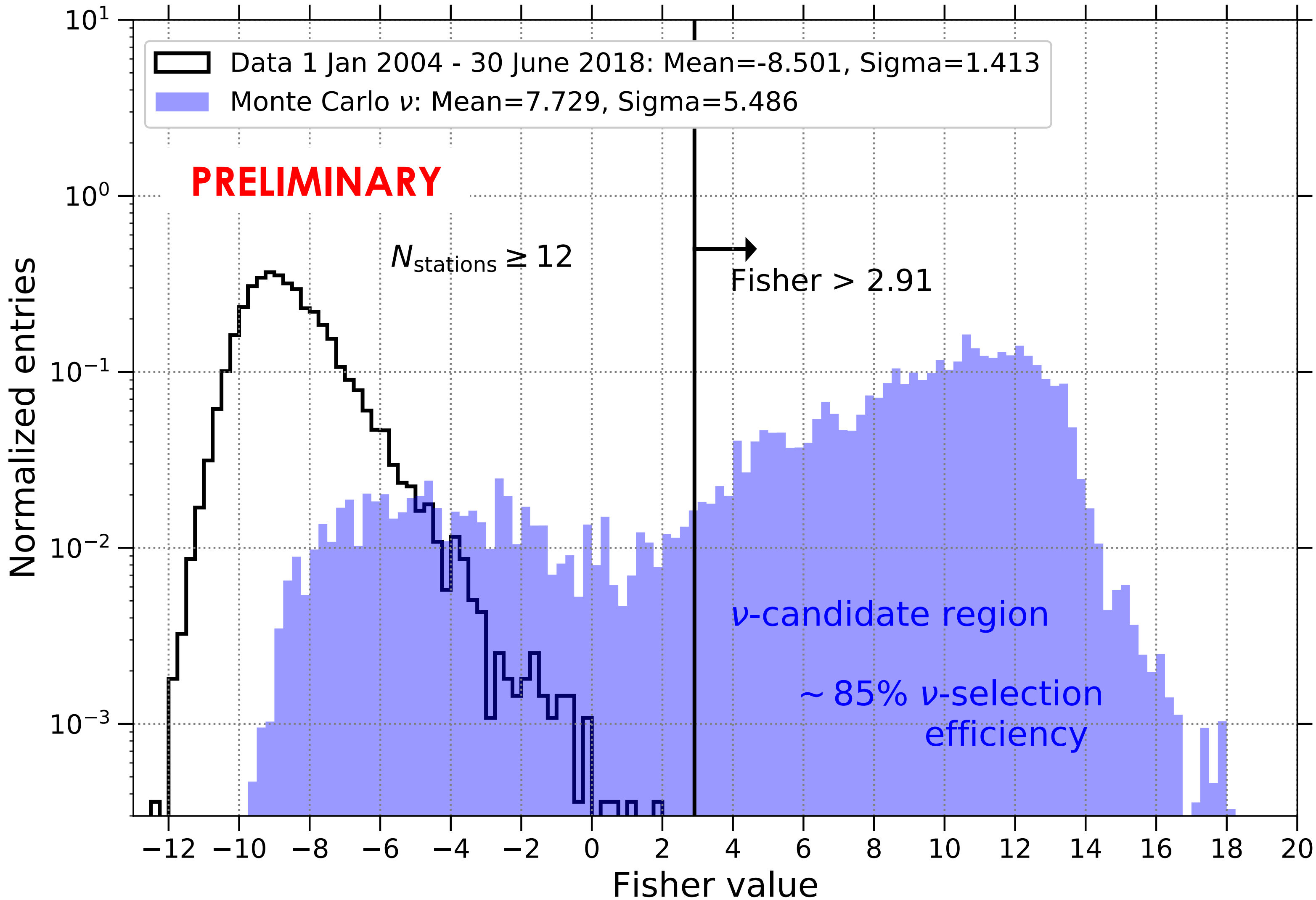
Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$	Down-going Low $(65°, 75°)$
$L/W > 5$	$L/W > 3$	–
$\langle V \rangle \in (0.29,\ 0.31)$ m ns^{-1}	$\langle V \rangle\ <\ 0.313$ m ns^{-1}	–
$\mathrm{RMS}(V) <\ 0.08$ m ns^{-1}	$\mathrm{RMS}(V)/\langle V \rangle < 0.08$	–
–	$\theta_{\mathrm{rec}}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

Unblinding: Downward-going (75º < θ < 90º) channel



Distribution of Fisher polynomial value: events with $4 \leq N_{stations} \leq 6$

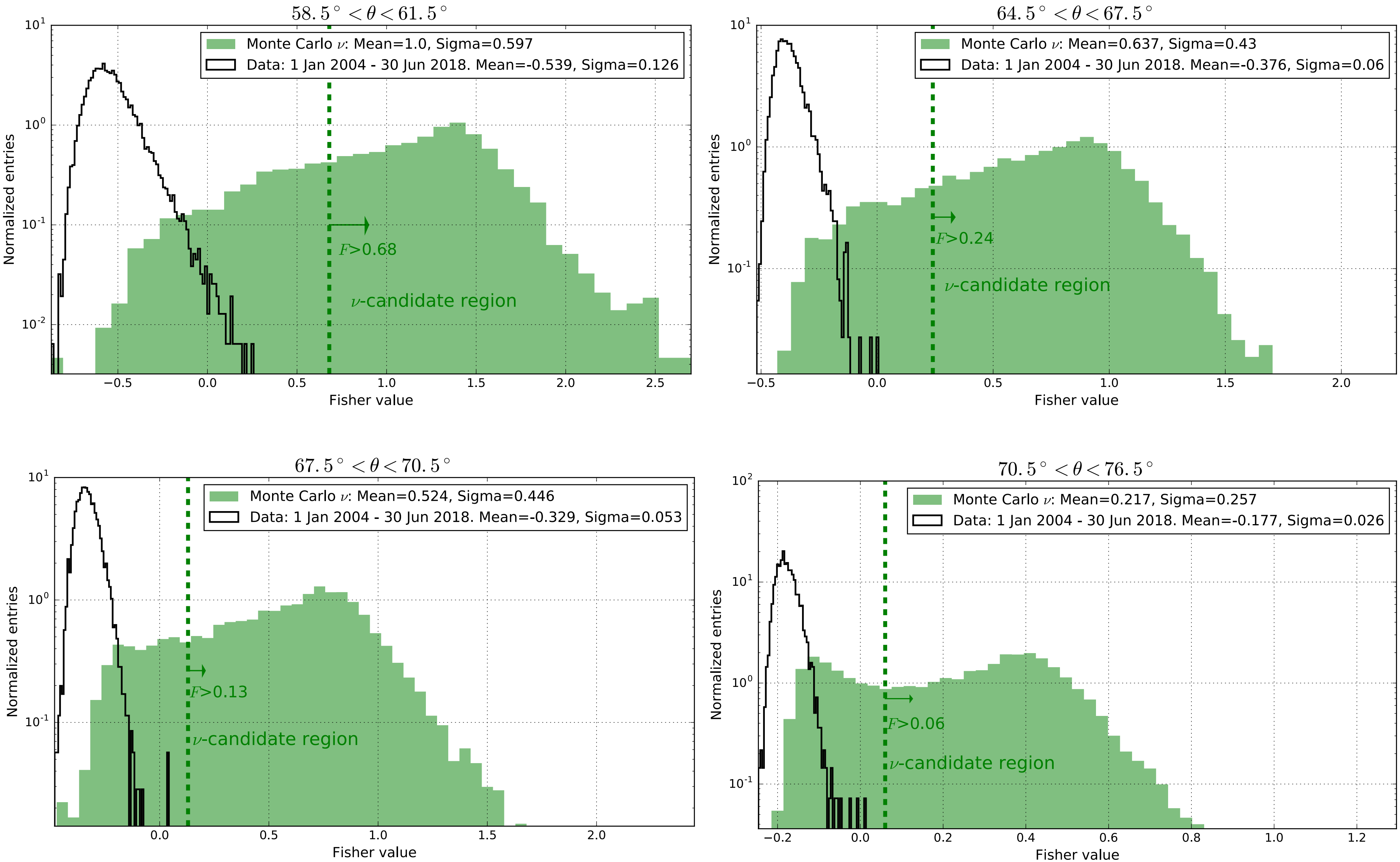
Unblinding: Downward-going (75° < θ < 90°) channel



Distribution of Fisher polynomial value: events with $N_{stations} \geq 12$

Unblinding: Downward-going (60º < θ < 75º) channel

PRELIMINARY



Systematic uncertainties: ν limits

Fractional contribution of channels to the expected neutrino event rate:

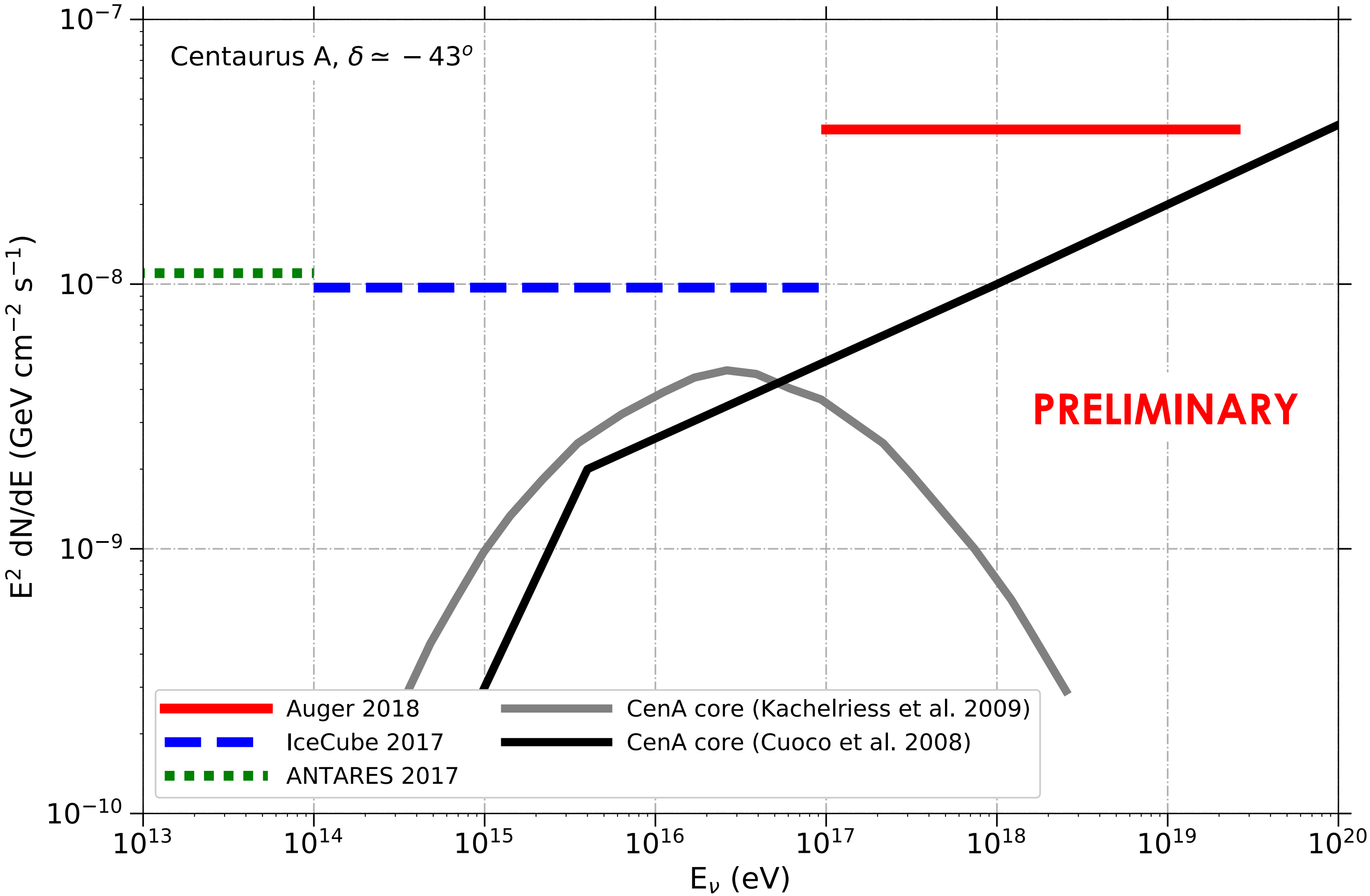
Earth-skimming $\longrightarrow$ 84%
Downward-going $\longrightarrow$ 16%

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	$\sim +37\%, -28\%$

Uncertainties incorporated in the limit following the well-known Conrad approach.

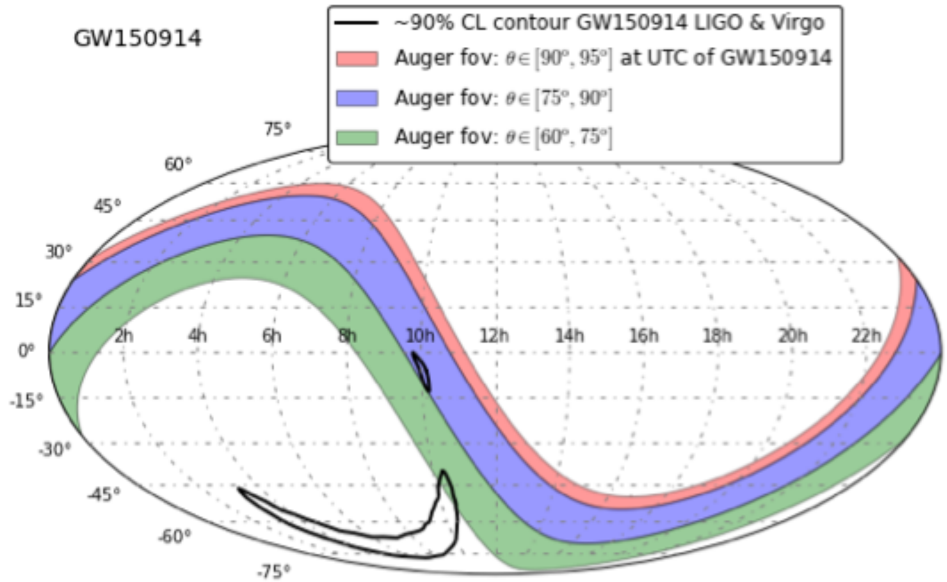
Auger Collaboration
Phys. Rev. D 91, 092008 (2015)

Limits to Centaurus A (dec ~ – 43º)



Auger limit approaching models of ν production in CenA
≃ 0.7 events expected from CenA (Cuoco et al 2008)

Limits to Binary Black Hole mergers: GW150914

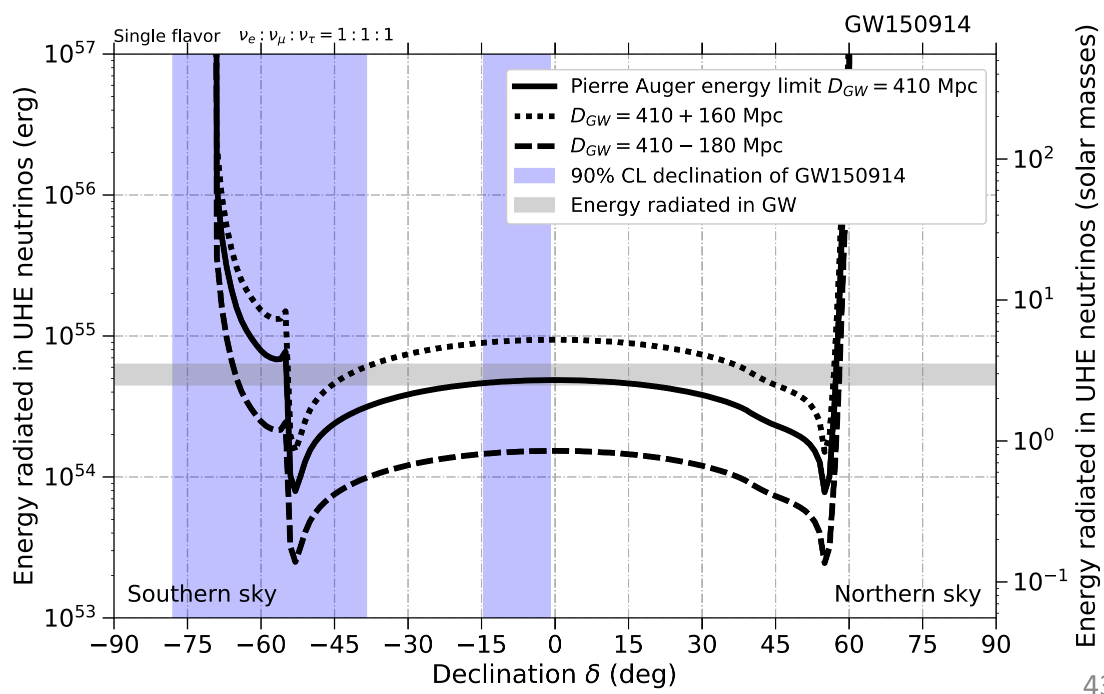


Skymap of localization of GW150914 and field-of-view of Auger in the inclined directions at the instant the BBH merger occured

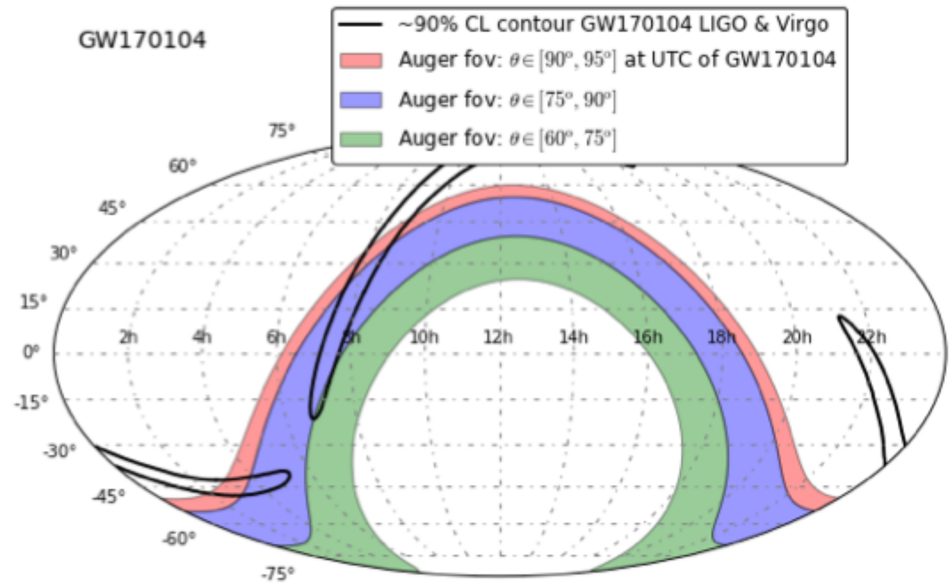
Pierre Auger Collab. PRD **94**, 122007 (2016)

Limits to energy emitted in the form of UHEν from the non-observation of ν candidates 1 day after GW150914 BBH merger:

Less than a few solar masses can be emitted in the form of neutrinos



Limits to Binary Black Hole mergers: GW170104



Skymap of localization of GW151226 and field-of-view of Auger in the inclined directions at the instant the BBH merger occurred

Pierre Auger Collab. PRD **94**, 122007 (2016)

Limits to energy emitted in the form of UHEν from the non-observation of ν candidates 1 day after GW151226 BBH merger:

Worse limit than GW150914 and GW151226 because source is roughly 2 times farther away.

PRELIMINARY