Ultra-high energy neutrinos at the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

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Neutrinos above 0.1 EeV

- If protons and/or heavier nuclei :
  - are accelerated to energies above EeV in Galactic and/or extragalactic sources
  - interact within sources and/or in propragation through Universe

then we expect ~ **EeV neutrinos**

Photo-production:
$E_\nu \sim 0.05\ E_{proton}$

$$p + \gamma \longrightarrow n + \pi^+$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

low-E photons at source or CMB photons (γ)

Nuclear interactions

$$p + p \longrightarrow p + p + n's + \pi's$$

Matter at source (target p)

Cosmogenic neutrinos

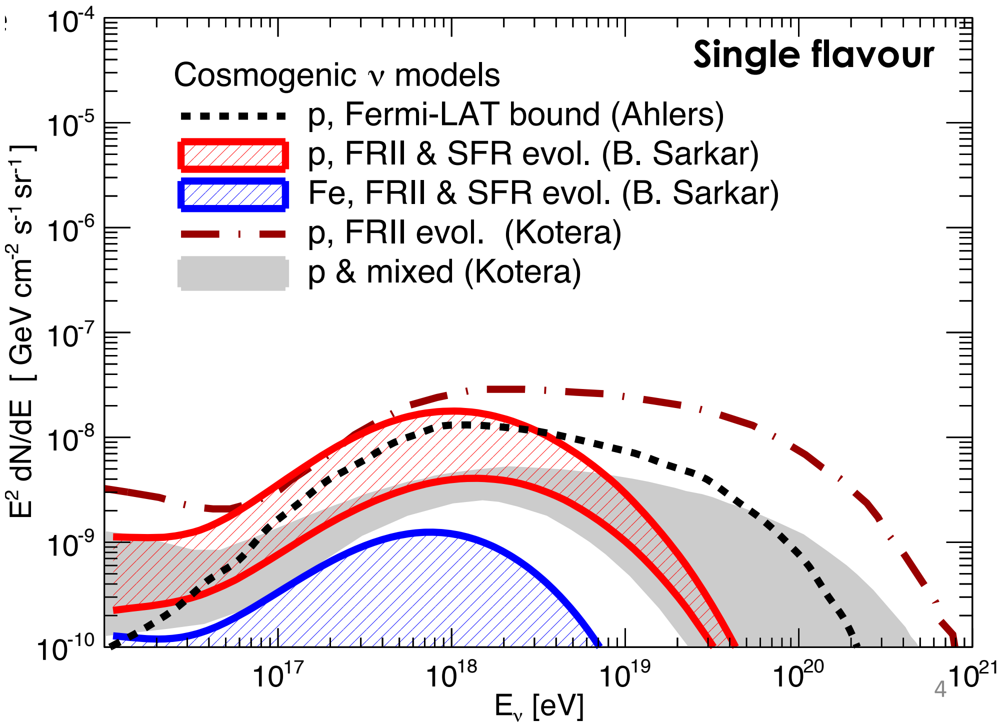
come from interaction of UHECR protons above 50 EeV with CMB photons via GZK (Greisen-Zatsepin-Kuzmin) mechanism:

$$p + \gamma_{CMB} \rightarrow \Delta(1232) \rightarrow n + \pi^+$$

"guaranteed flux"

Detection in EeV range may provide complementary **information** on:

- **UHECR nature** :
  - p or Fe dominated?
  - mixed composition?
- **UHECR origin** :
  - evolution of sources with redshift
  - max. energy attainable in sources



Unlike charged UHECR, neutrinos travel undeflected by magnetic fields and essentially unattenuated :

- reveal the sources of UHECRs at cosmological distances
- extension of astronomy to the EeV (10^{18} eV) range?

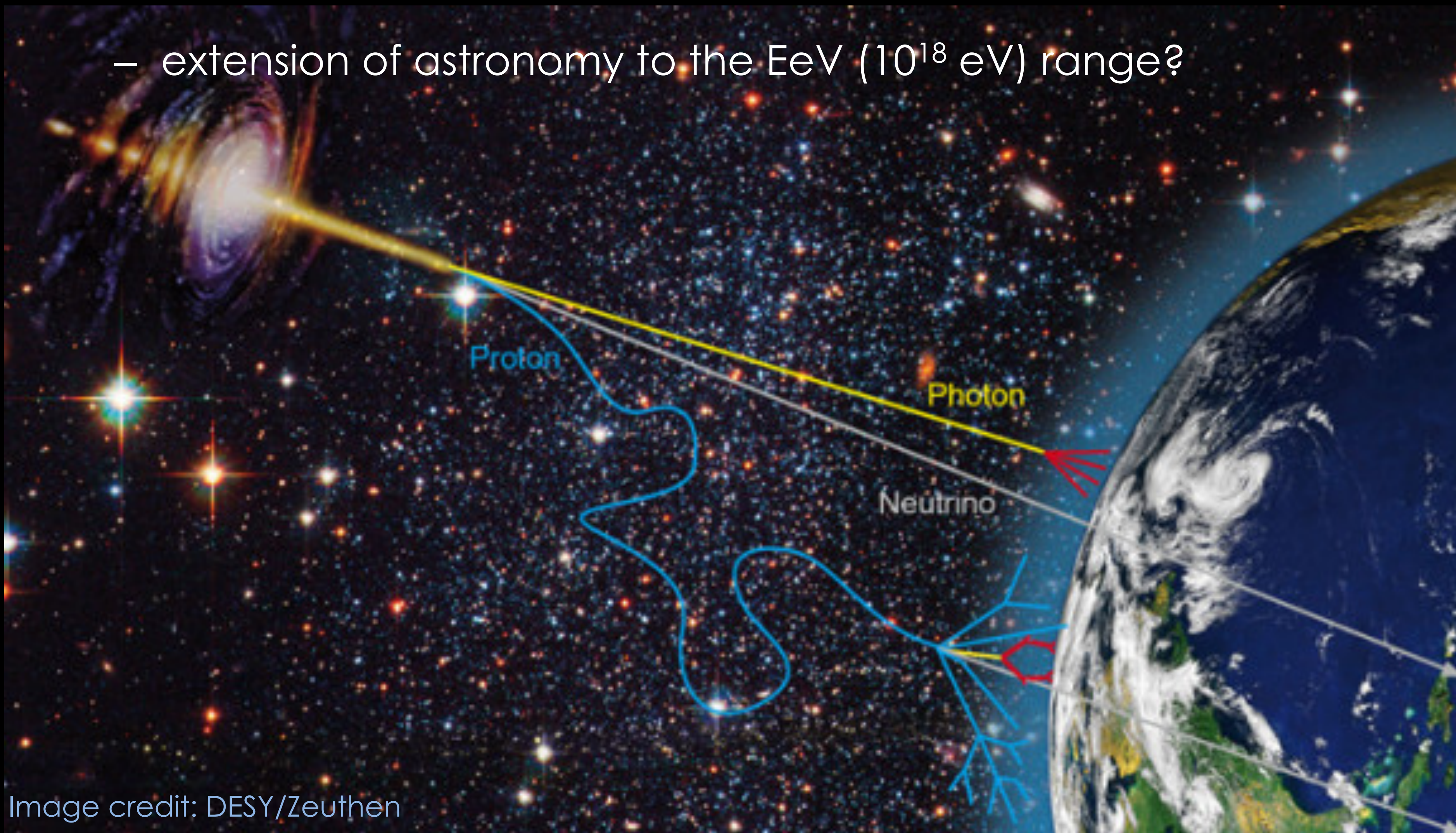


Image credit: DESY/Zeuthen

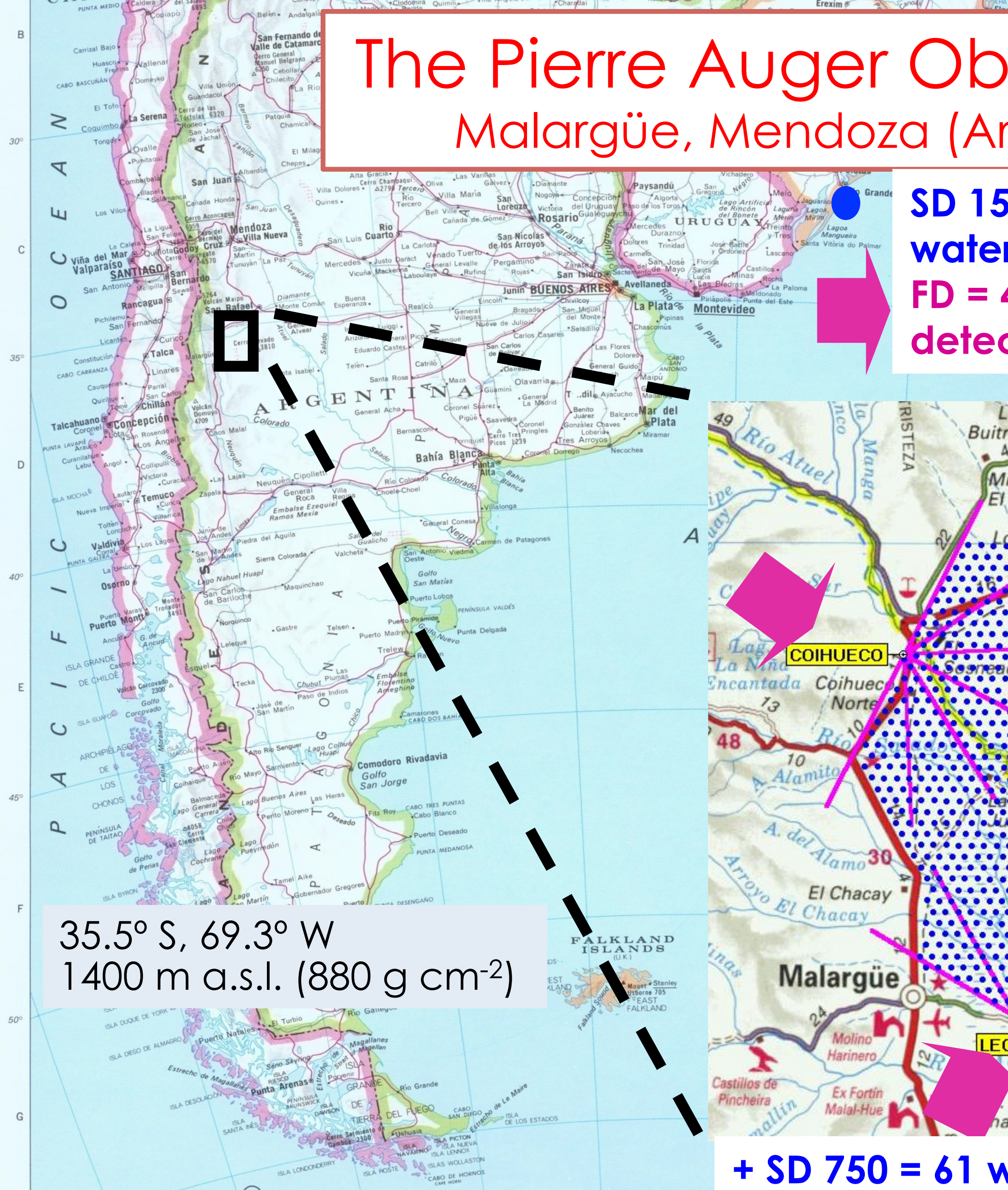
Search for neutrinos with the Pierre Auger Observatory

Pierre Auger Collaboration, Phys. Rev. D 9, 092008 (2015)

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

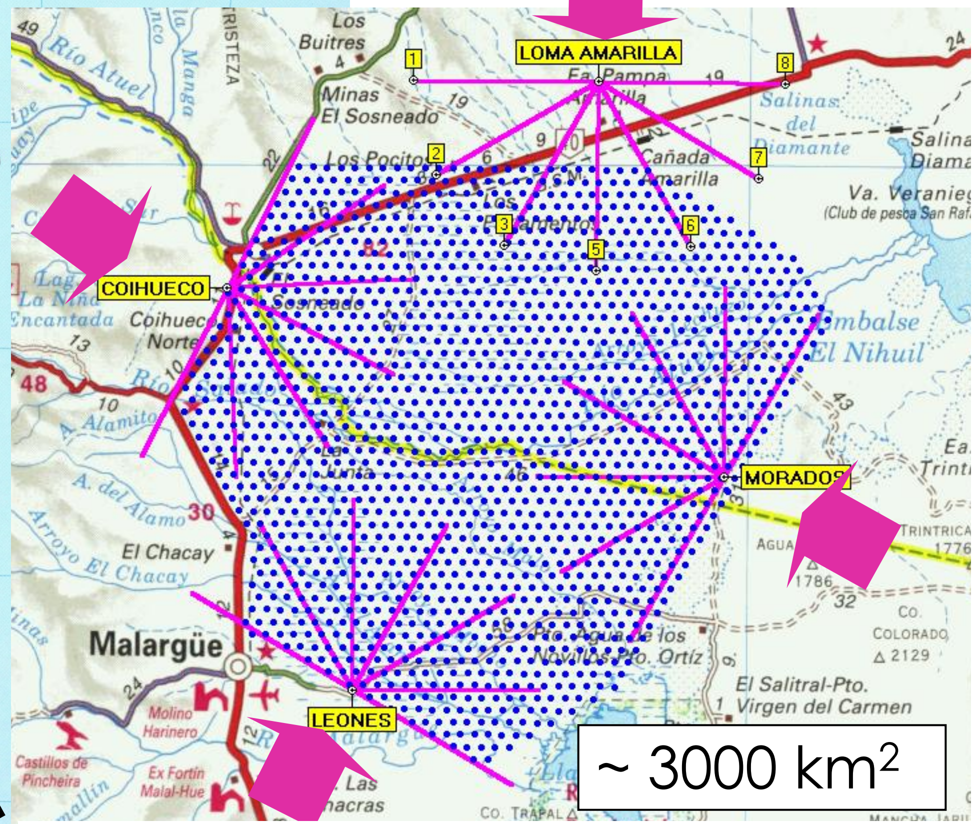
The Pierre Auger Observatory

Malargüe, Mendoza (Argentina)



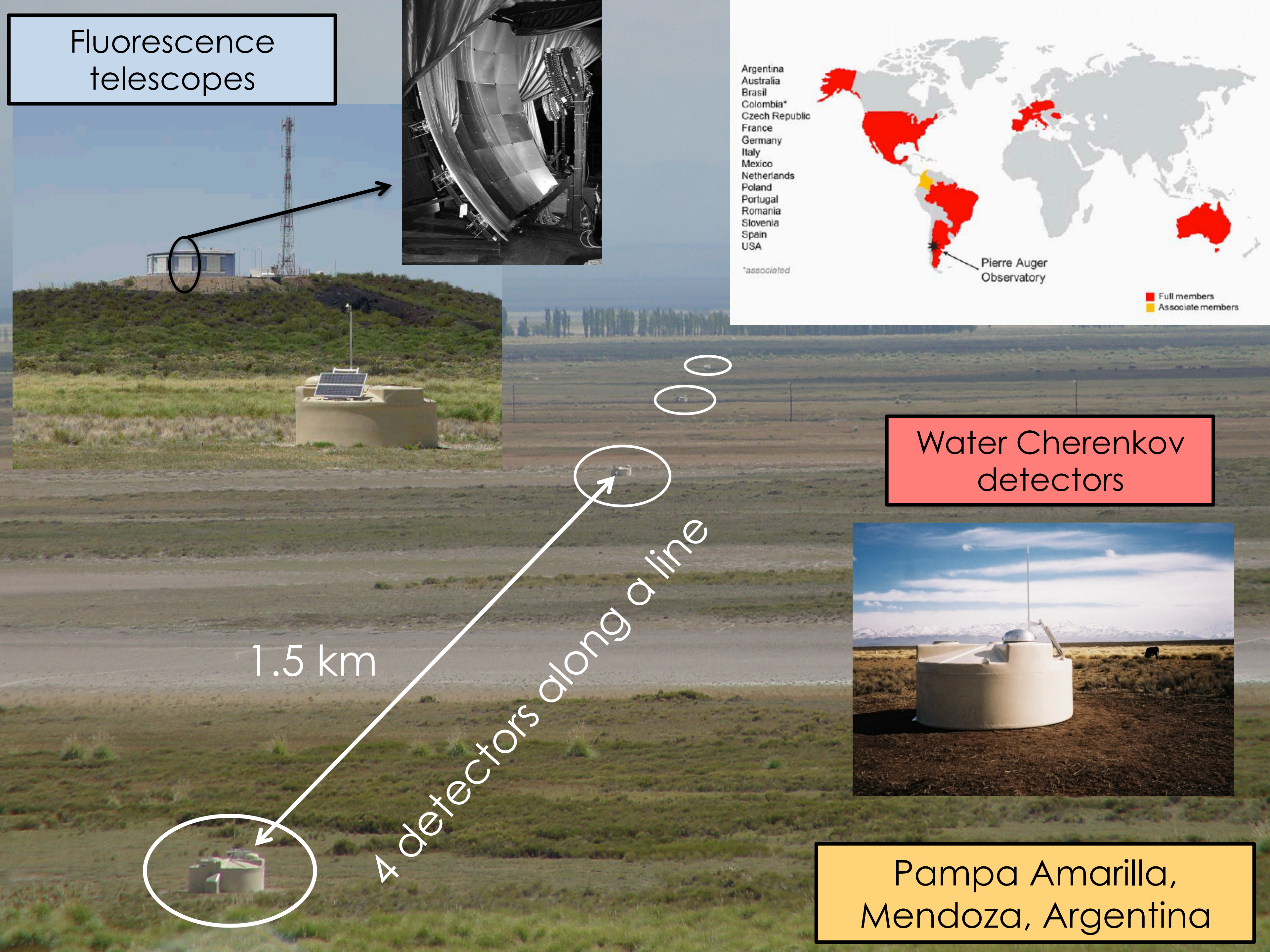
35.5° S, 69.3° W
1400 m a.s.l. (880 g cm^{-2})

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)
+ Array of 153 antennas (17 km^2)
+ Array of 7 buried muon detectors

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



Fluorescence telescopes
Argentina
Australia
Brasil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA
*associated
Pierre Auger Observatory
Full members
Associate members
Water Cherenkov detectors
1.5 km
4 detectors along a line
Pampa Amarilla, Mendoza, Argentina

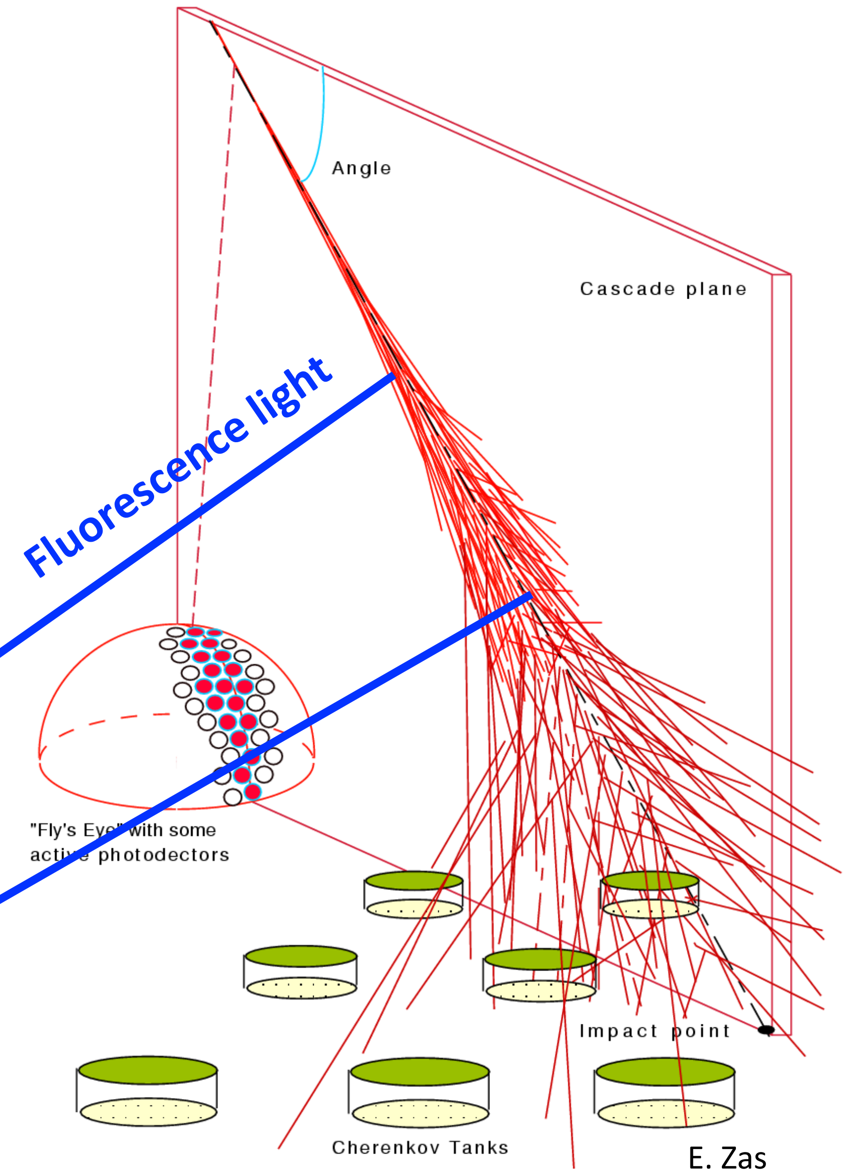
Detection technique

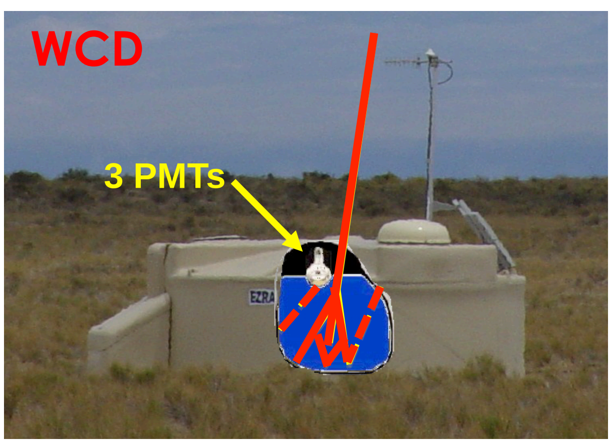
Auger combines 2 different techniques (hybrid mode):

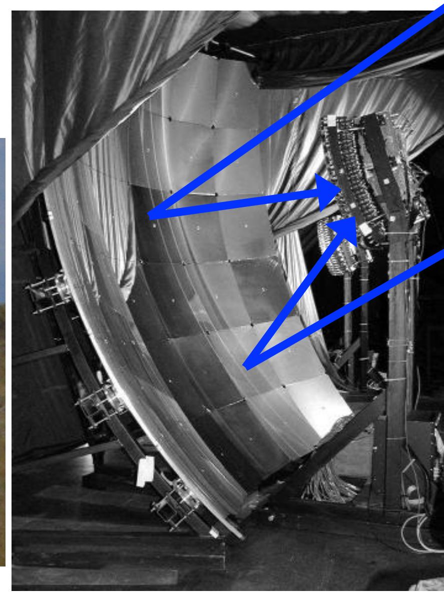
Fluorescence telescopes

Water-Cherenkov detectors

~ 10% of events are observed with both techniques: wealth of information about shower development.







Search for neutrinos with the Pierre Auger Observatory

- **Pierre Auger is not a dedicated neutrino observatory**

  (main aim is characterizing the properties UHECR) but …

- **UHE neutrinos** induce showers that **can be distinguished** from background charged CR showers:

Signature:

deeply penetrating showers that can start development very close to ground.

- With the **surface detector** (SD) we have a good sensitivity to UHE neutrinos at $\gtrsim$100 PeV energies.

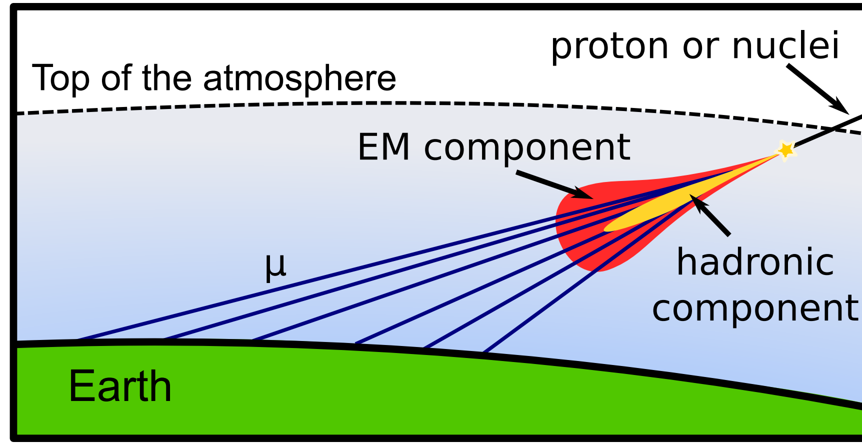
(details in next slides)

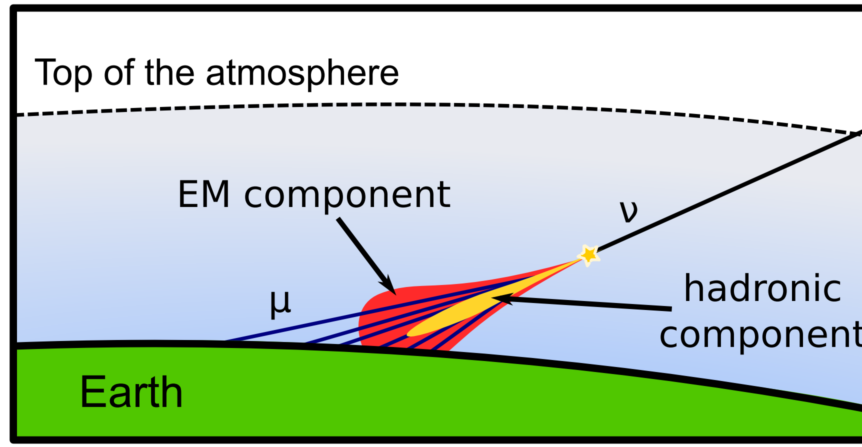
Inclined showers & UHE neutrinos

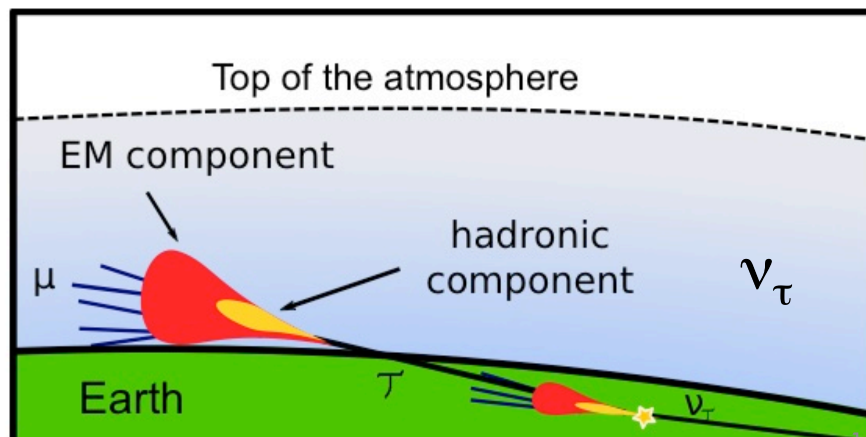
- Protons & nuclei initiate showers high in the atmosphere.
  ⇒ Shower front at ground:
  - mainly composed of muons
  - electromagnetic component absorbed in atmosphere

- Neutrinos can initiate "deep" showers close to ground.
  ⇒ Shower front at ground:
  - EM + muon component

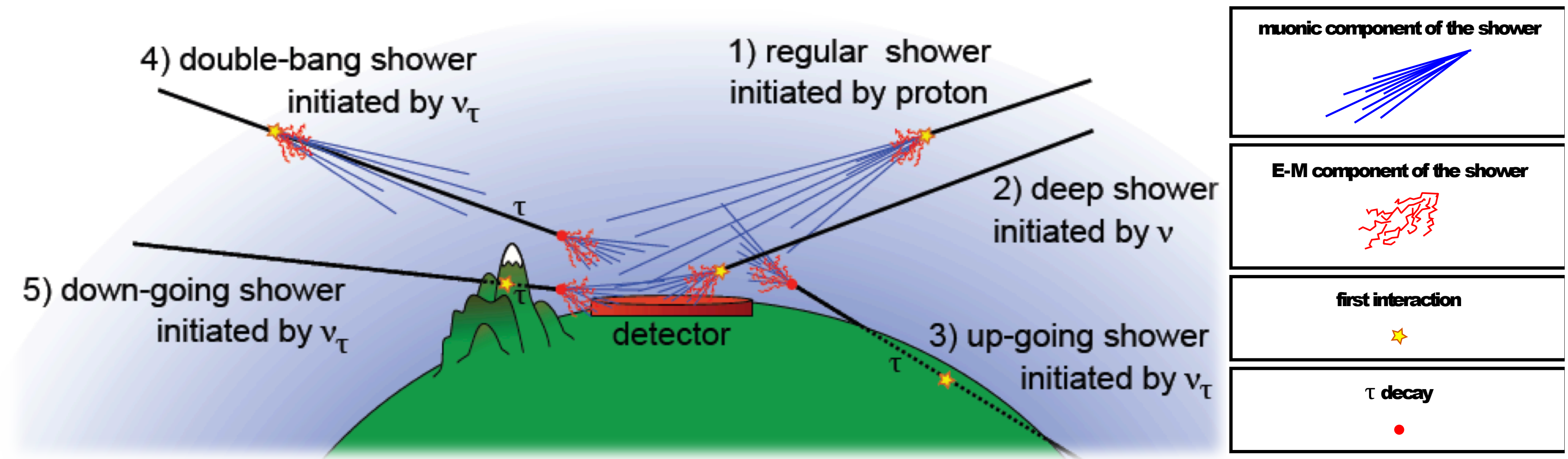
Searching for neutrinos ⇒
inclined showers
with electromagnetic component
("young showers")







Sensitivity to all flavours and channels



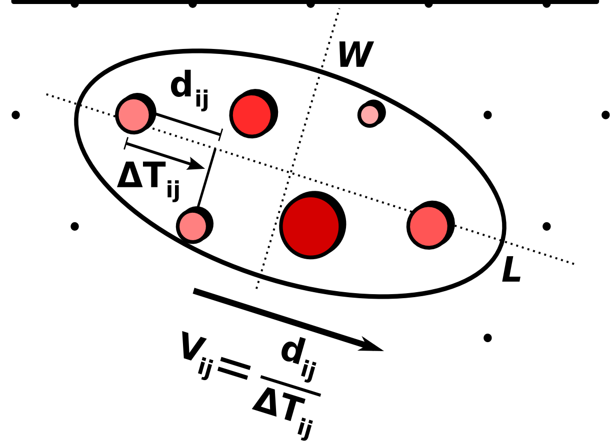
Three selection criteria

- Downward-going low angle (2 and 4) ⇒ DGL (60°-75°)
- Downward-going high angle (2, 4 and 5) ⇒ DGH (75°-90°)
- Earth-skimming (3) ⇒ ES (90°-95°)

The first two criteria (DGL and DGH) are bracketed together and apply to all flavours; Earth-skimming (ES) applies to ν_τ.

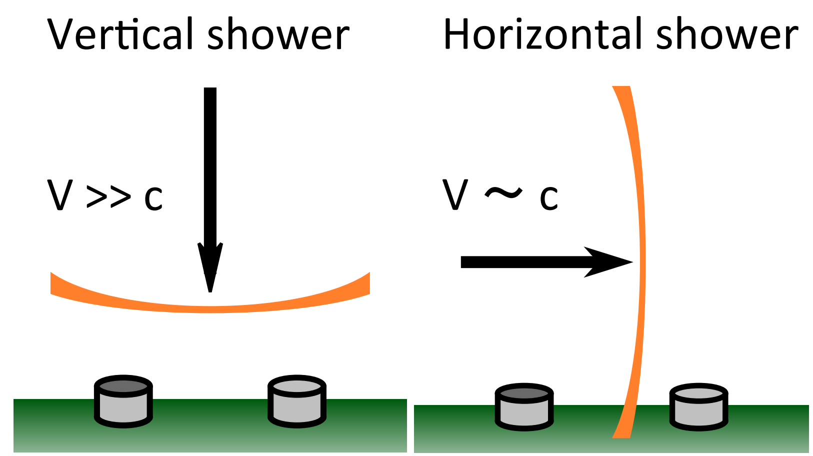
Selection of inclined showers collected at SD

(1) Elongated footprint



(3) Reconstructed θ

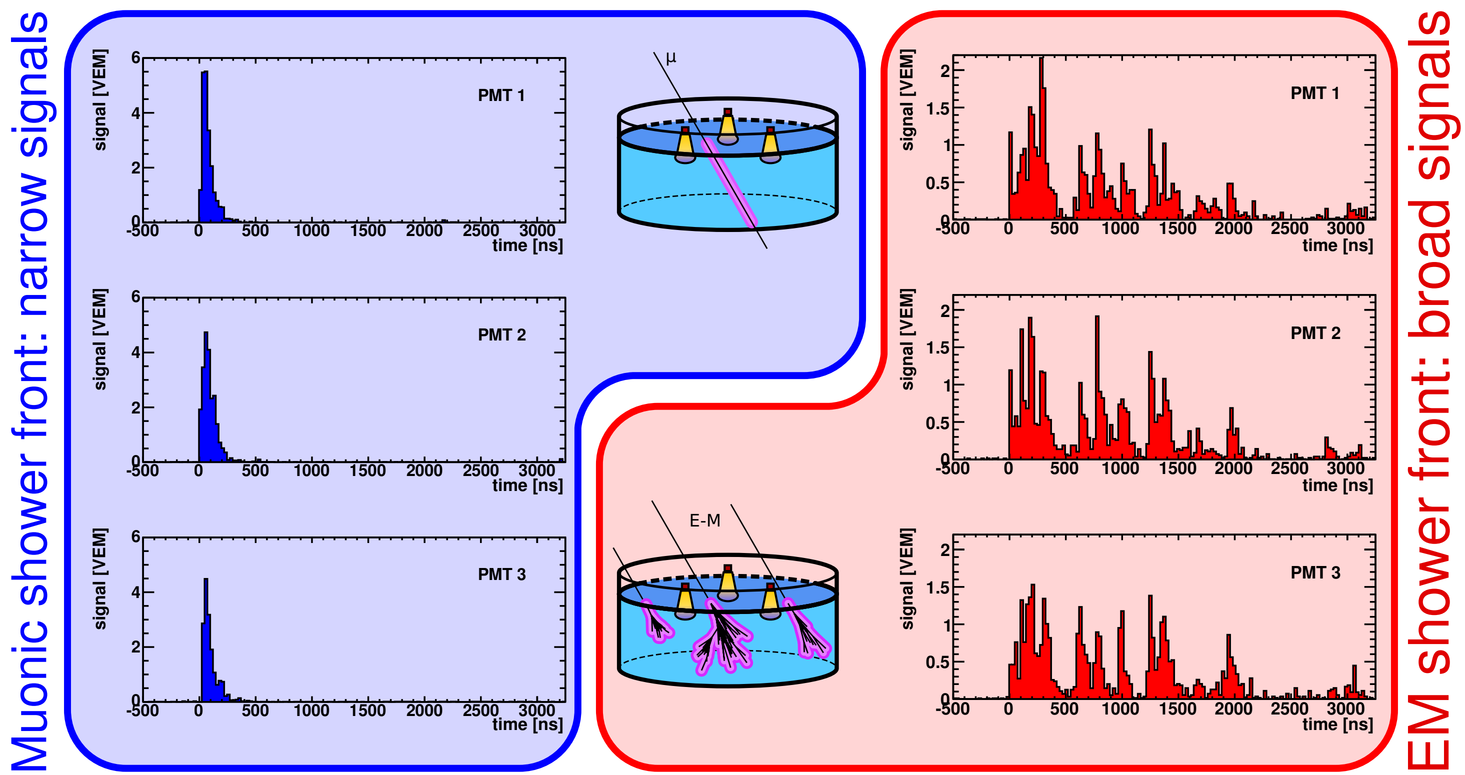
(2) Apparent velocity V of propagation of shower front at ground along major axis L



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

Identifying electromagnetic shower fronts

- Water Cherenkov detectors:
  - ✓ Sensitive to inclined showers
  - ✗ No directly sensitive to electromagnetic and muonic components
  - ✓ Can measure the time structure of signals induced by muons and EM



Identifying ν in data collected at SD

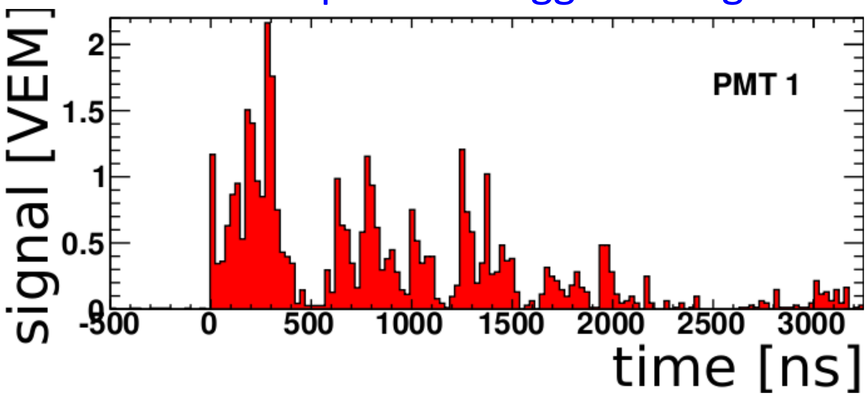
From the observational point of view, **signals extended in time**:

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

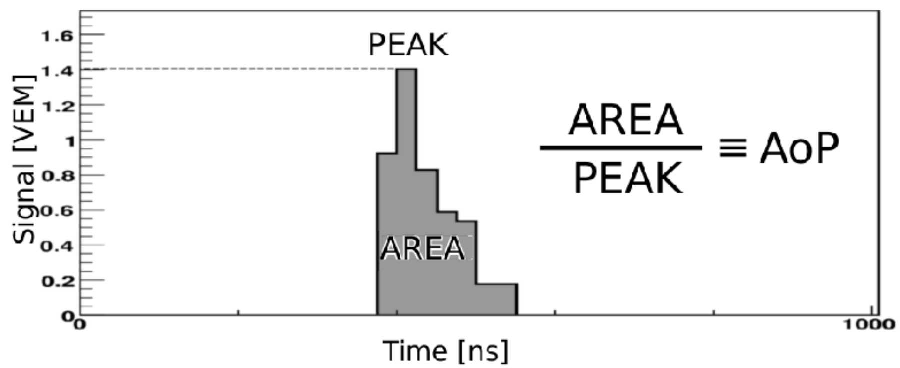
and/or

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

Trace example: ToT trigger & large AoP



Definition of Area-over-Peak (AoP)



$$\frac{\text{AREA}}{\text{PEAK}} \equiv \text{AoP}$$

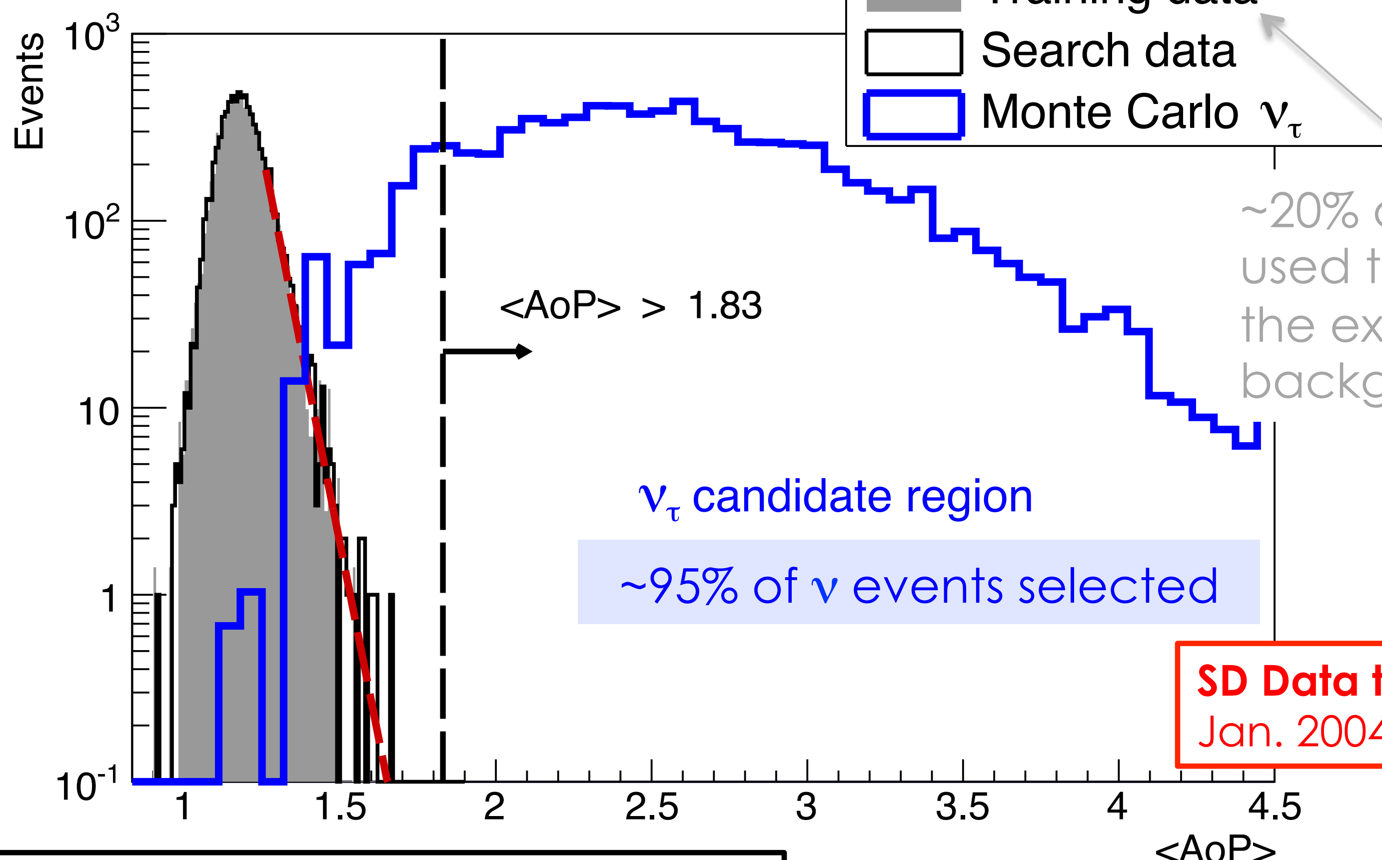
Searching for neutrinos ⇒
Searching for inclined showers with WCDs
with ToT triggers and/or large AoP

ν search results

Identification criteria applied "blindy" to the search data :

No ν candidate events found in any of the analyses

Example: Earth-skimming analysis



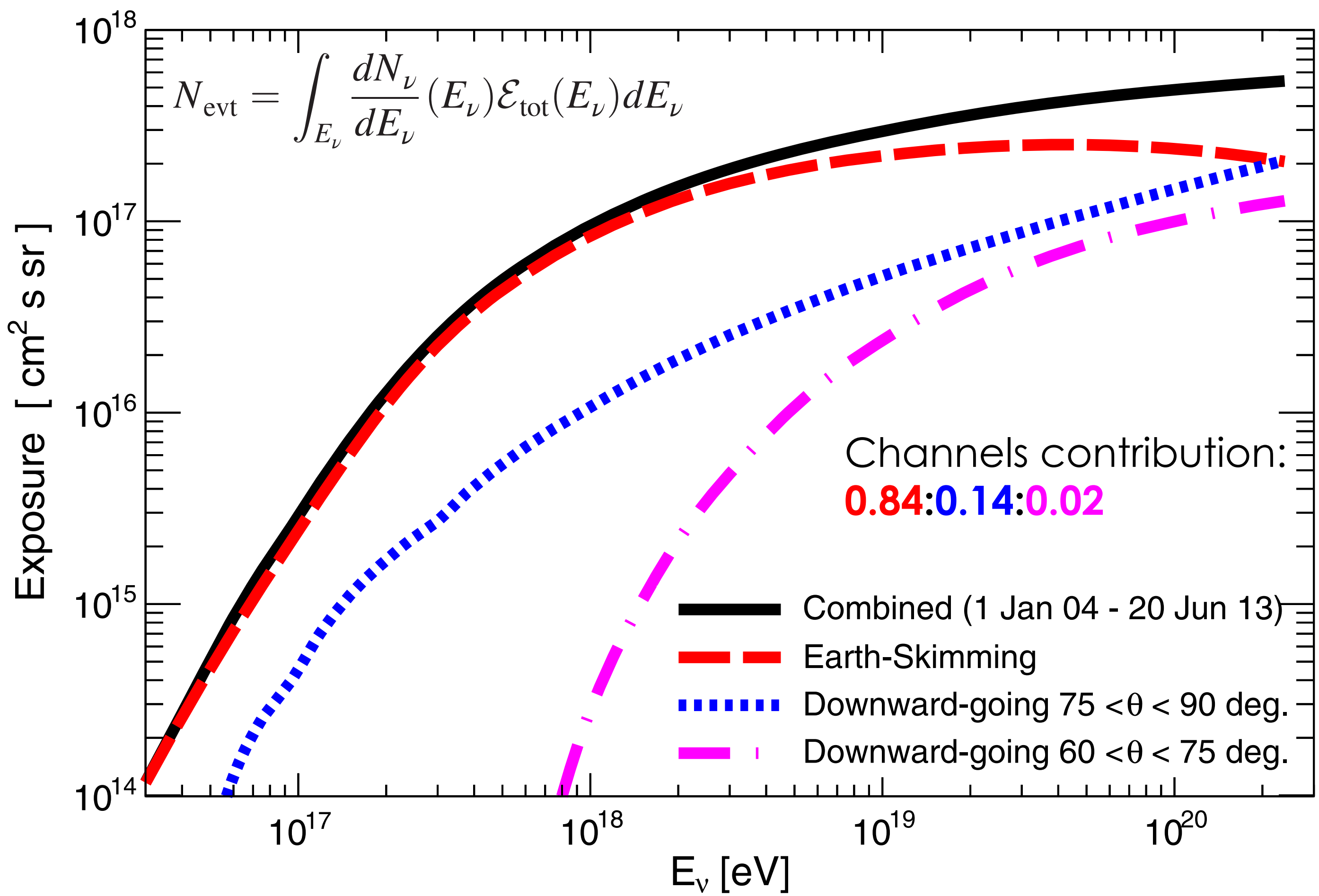
~20% of the data used to estimate the expected background

SD Data taking: Jan. 2004 – June 2013

<AoP> = mean value of Area-over-Peak in event

Neutrino exposure

Training data periods excluded



Systematic uncertainties

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

Upper limits on the neutrino flux

✓ combined exposure

✓ differential neutrino flux: $k E_\nu^{-2}$

✓ flavour ratio $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$

$$k = \frac{N_{\mathrm{up}}}{\int_{E_\nu} E_\nu^{-2} \mathcal{E}_{\mathrm{tot}}(E_\nu) dE_\nu}$$

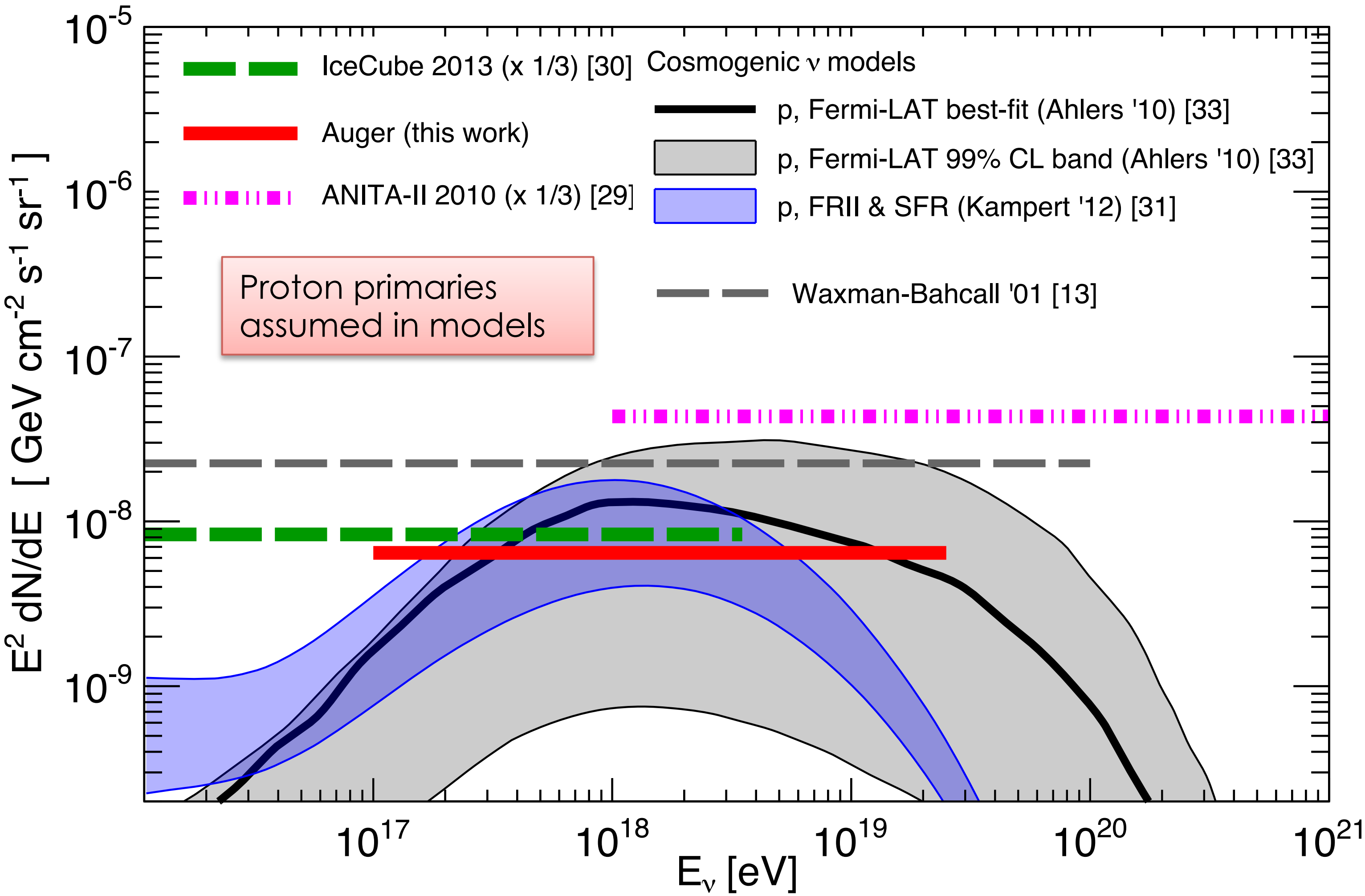
- 0 events observed
- 0 expected background events (conservative assumption)
- 90% C.L. required

} $N_{up} = 2.39$

Limits to the diffuse flux of UHEν

Single flavour, 90% C.L.

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



SD Data: Jan. 2004 – June 2013

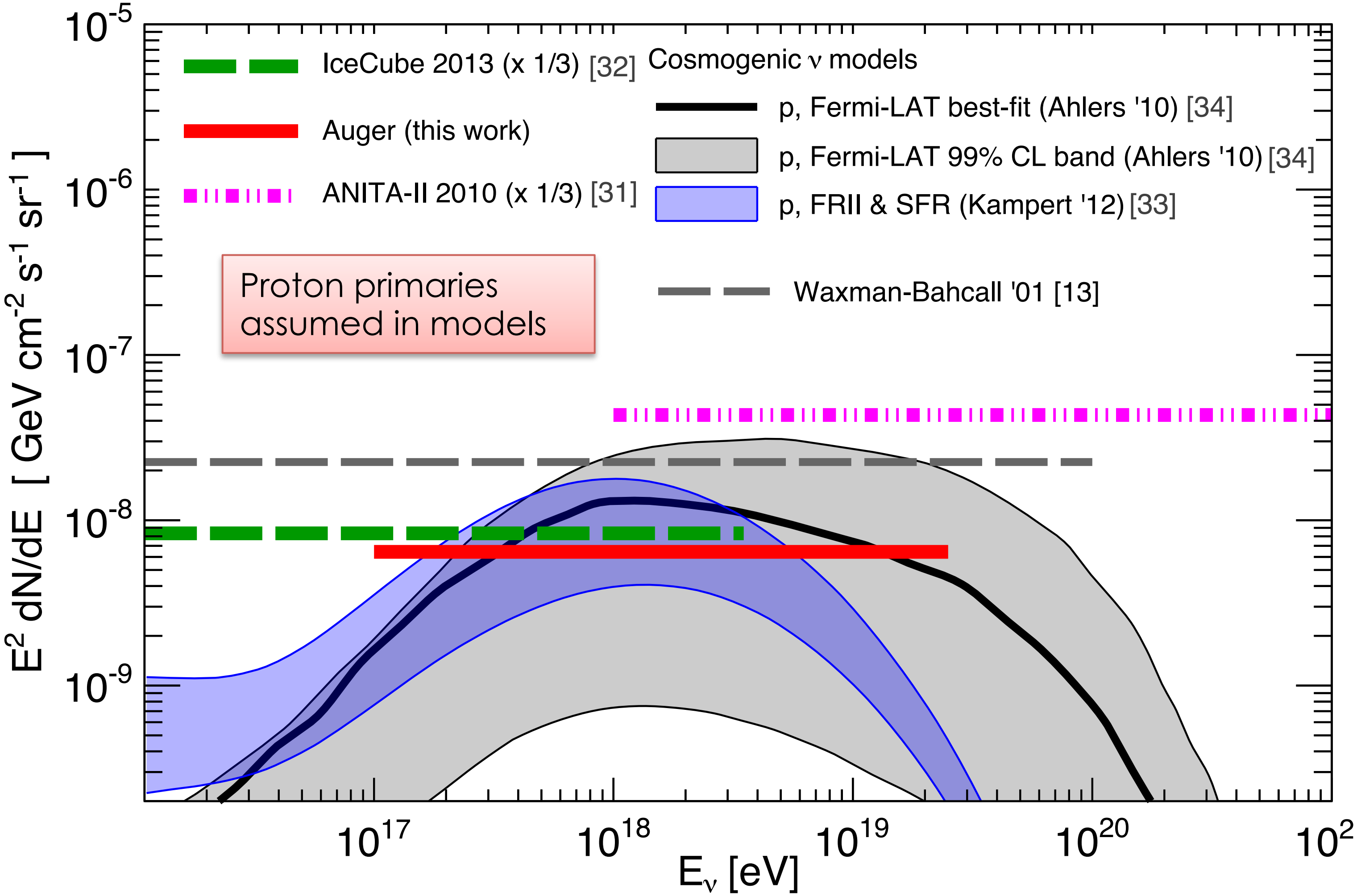
~ 6.4 yrs of full Auger SD

Auger LIMIT: $dN/dE = k\,E^{-2} \rightarrow k \sim 6.4 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}
@ 90% C.L. in 10^{17} eV < E_ν < 2.5×10^{19} eV

Limits to the diffuse flux of UHEν

Single flavour, 90% C.L.

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



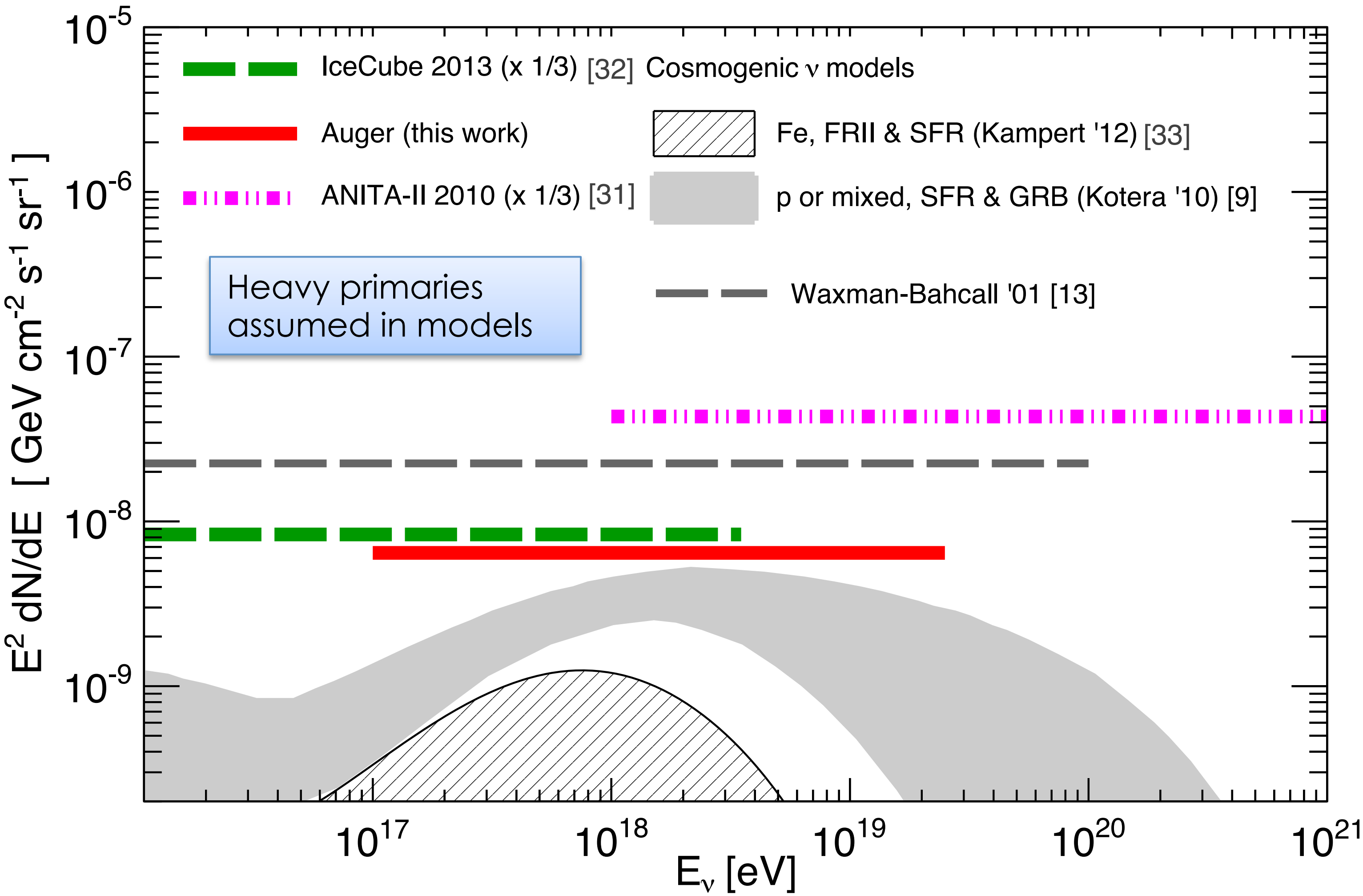
SD Data:
Jan. 2004 – June 2013

Auger limit constrains cosmogenic neutrino models with proton primaries & strong evolution of sources with redshift

Limits to the diffuse flux of UHEν

Single flavour, 90% C.L.

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



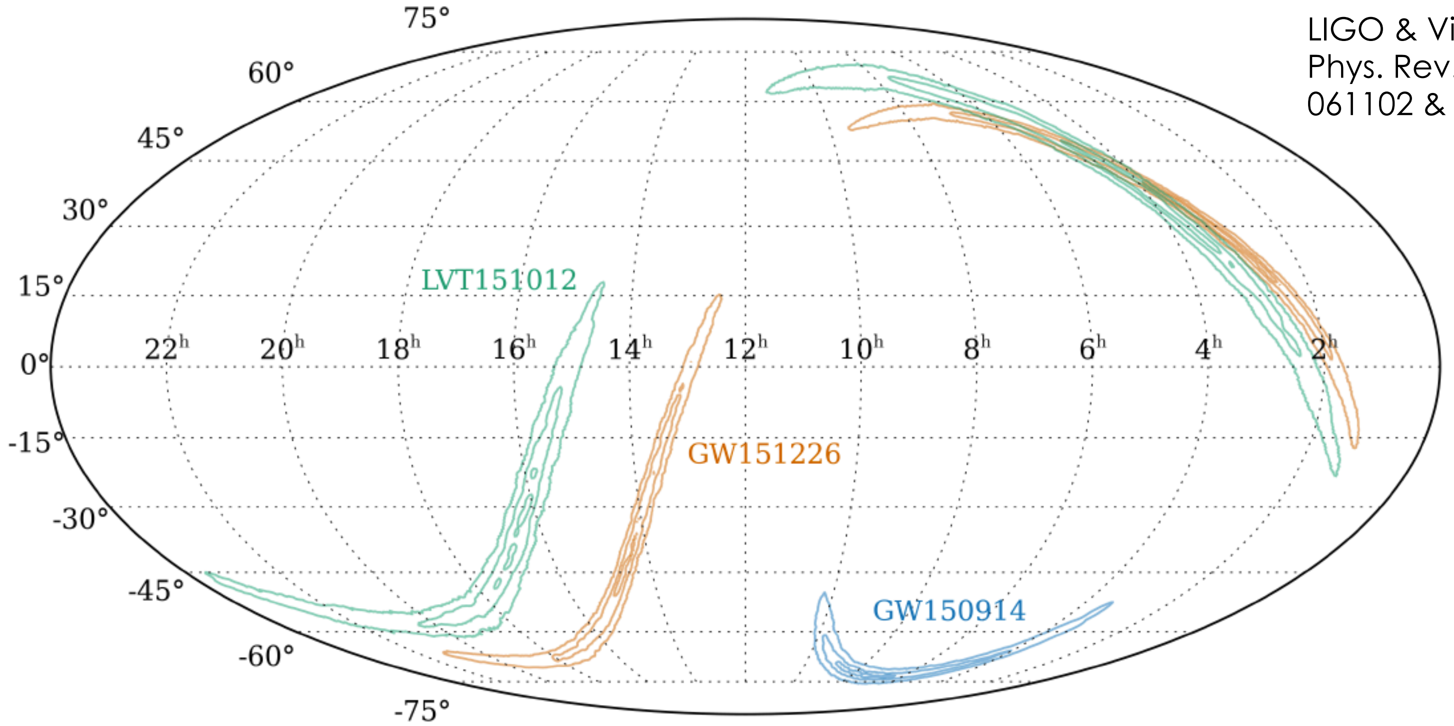
SD Data:
Jan. 2004 –
June 2013

Auger limit does not yet constrain models with heavier primaries

The 2015 LIGO gravitational waves events

Gravitational Wave events (GW150914 & GW151226) detected by Advanced-LIGO detectors (also LVT151012 candidate):

- Inferred source: **merger of binary black-hole** at D = 410 & 440 Mpc
- ~ 3 & 1 solar masses energy released in the form of GW
- Position in the sky uncertain: few 100 deg^2



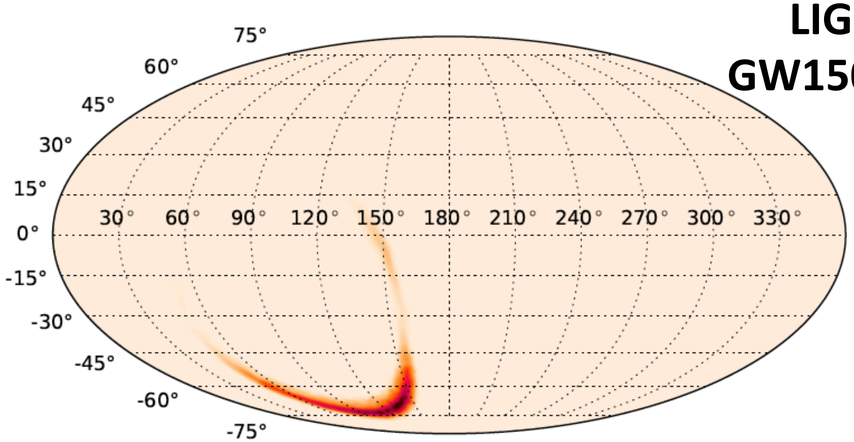
LIGO & Virgo Collab. Phys. Rev. Lett. **116**, 061102 & 241103 (2016)

UHE ν´s from binary-BH mergers?

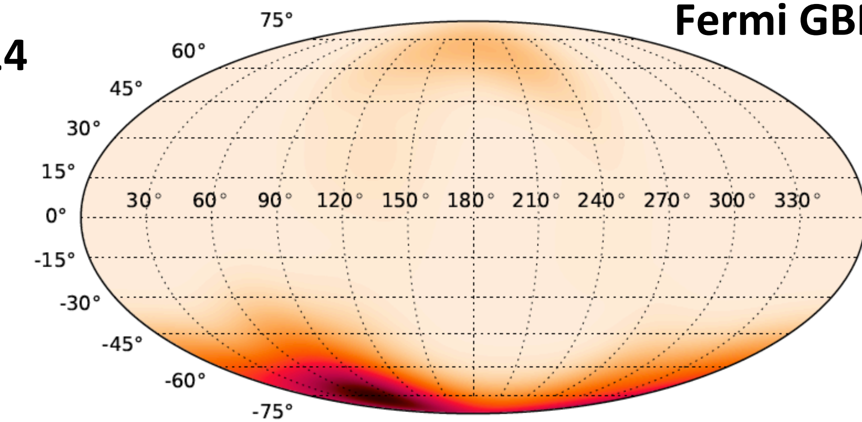
- **General consensus:** Binary BH merger does not produce electrom./neutrino counterpart, however:
  - **Signal reported by Fermi GBM**: transient source @ 50 keV, 0.4 s after GW150914 at consistent position

V. Connaughton et al, ApJL. **826**, L6 (2016)

LIGO GW150914



Fermi GBM



- There are indeed **models predicting UHE neutrinos:**
  - UHECR accelerated by Fermi mechamism if relic B-fields & debris from BH formation of BHs ⇒ emission of UHE ν´s & 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*

Searching for ν in coincidence with the GW events

- Energy range: E > 100 PeV – complementary to IceCube-Antares follow up *LIGO&VIRGO, Icecube, ANTARES coll. PRD 93, 122010 (2016)*

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

±500 s window around GW event time "coincidence" search

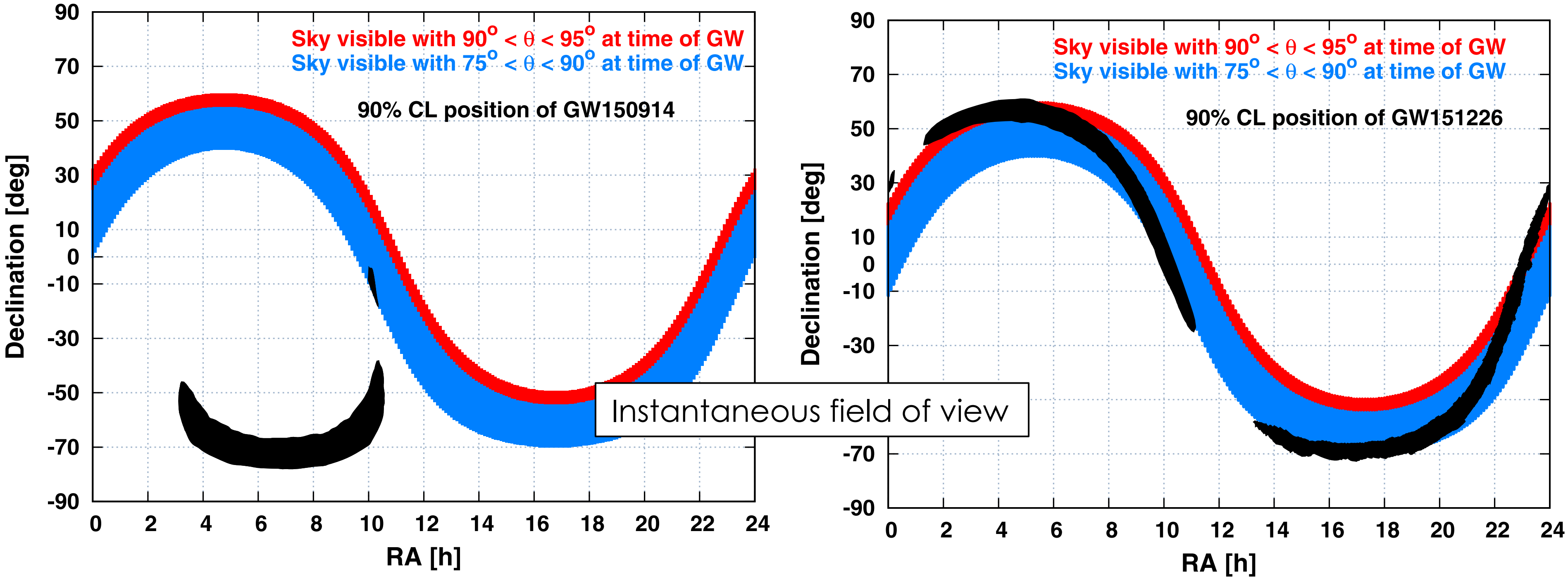
for each GW, data unblinded over an observations window T_{search} of 1d + 500s

Auger sensitivity to UHE ν´s from the GW events

- Auger sensitivity limited to large zenith angles : at each instant in time, neutrinos can be detected efficiently only from a specific portion of sky

Auger Latitude: $\lambda = -35.2°$

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



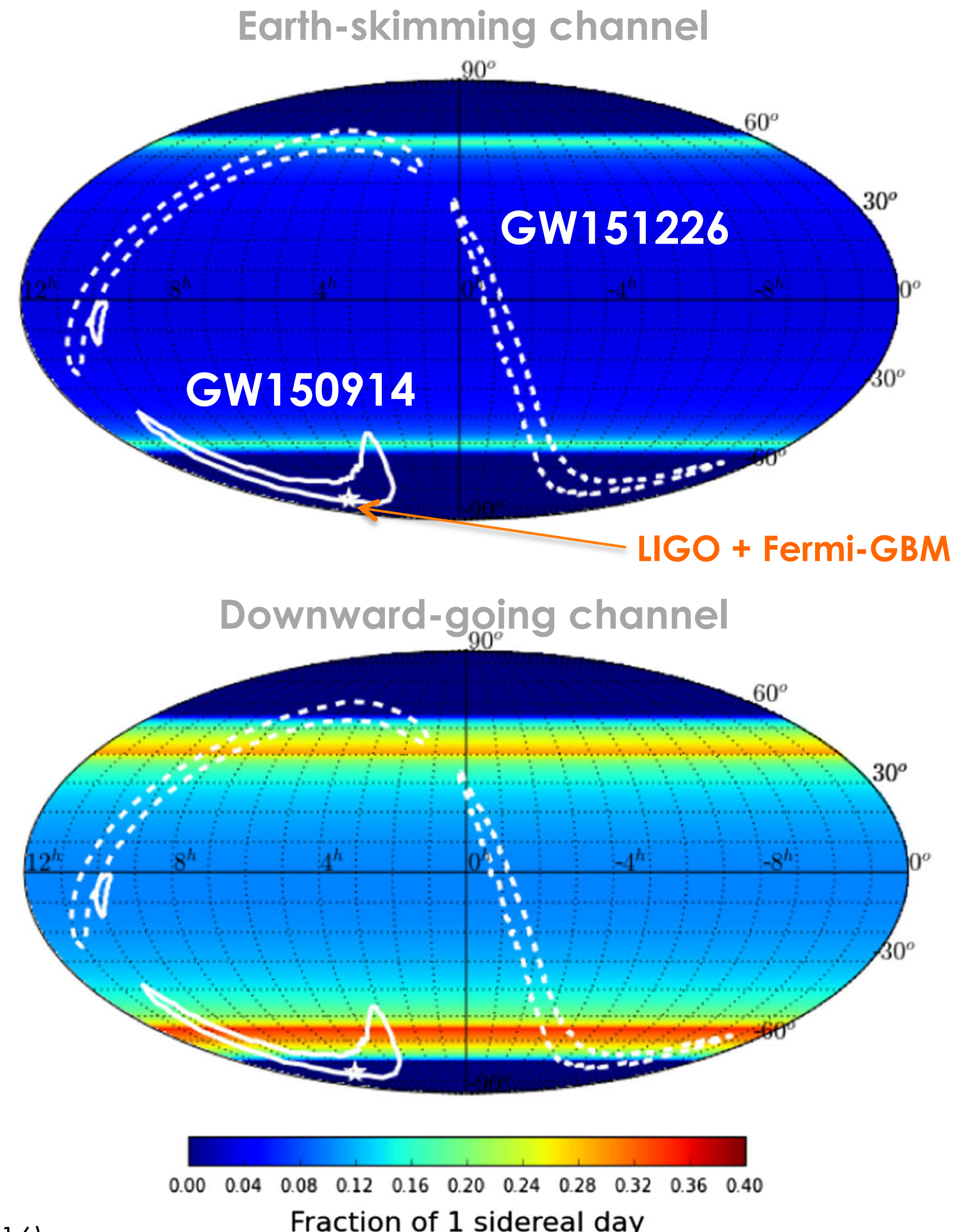
No ν candidate events found in the time window ± 500 s around the GW events

Sky map of visibility time fraction in 1 sidereal day

No ν candidate events found in 1 day after the GW events

Constraints are declination-dependent

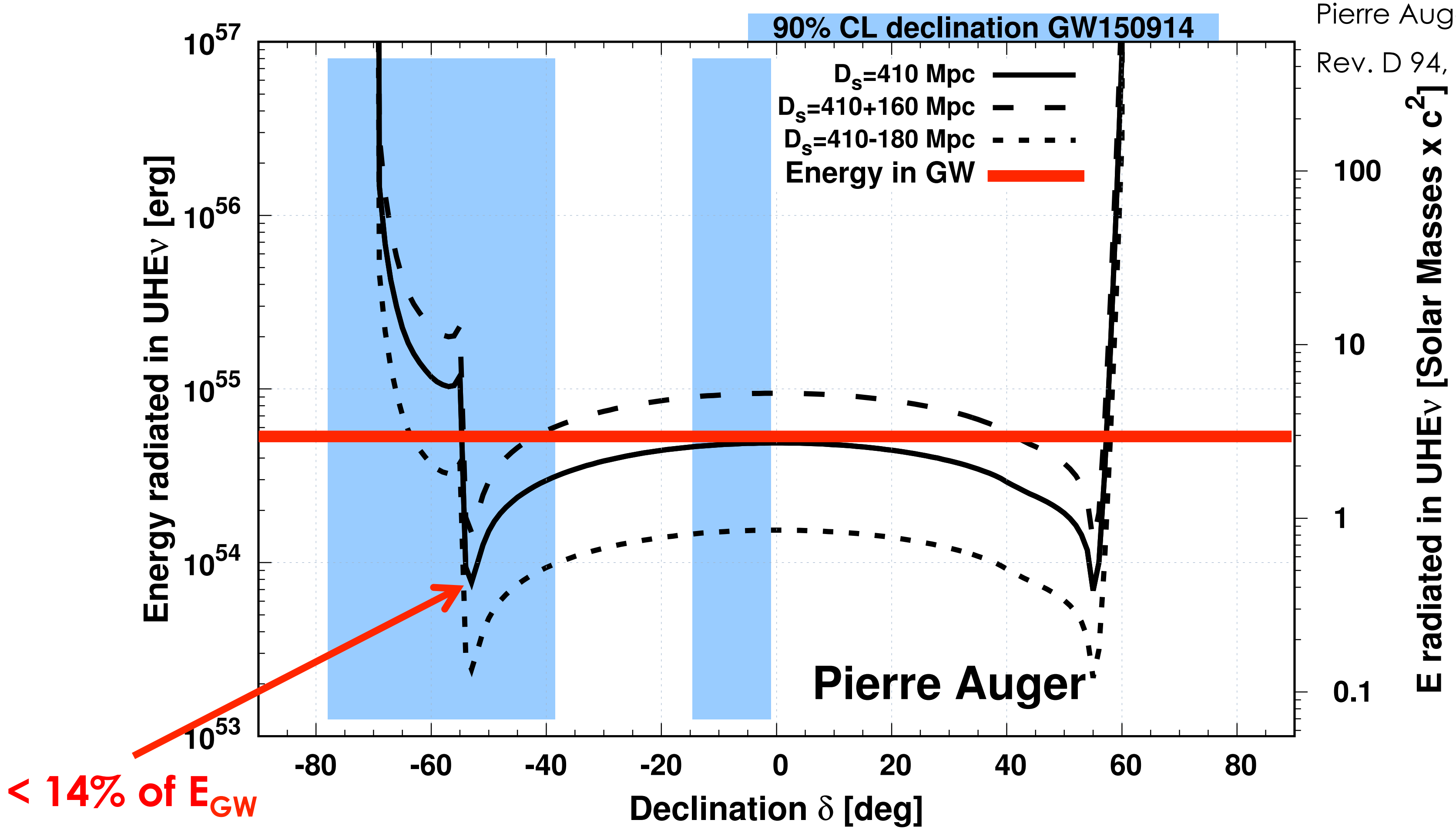
$$k^{\mathrm{GW}}(\delta) = \frac{2.39}{\int_{E_\nu} E_\nu^{-2} \mathcal{E}_{\mathrm{GW}}(E_\nu, \delta) dE_\nu}$$



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

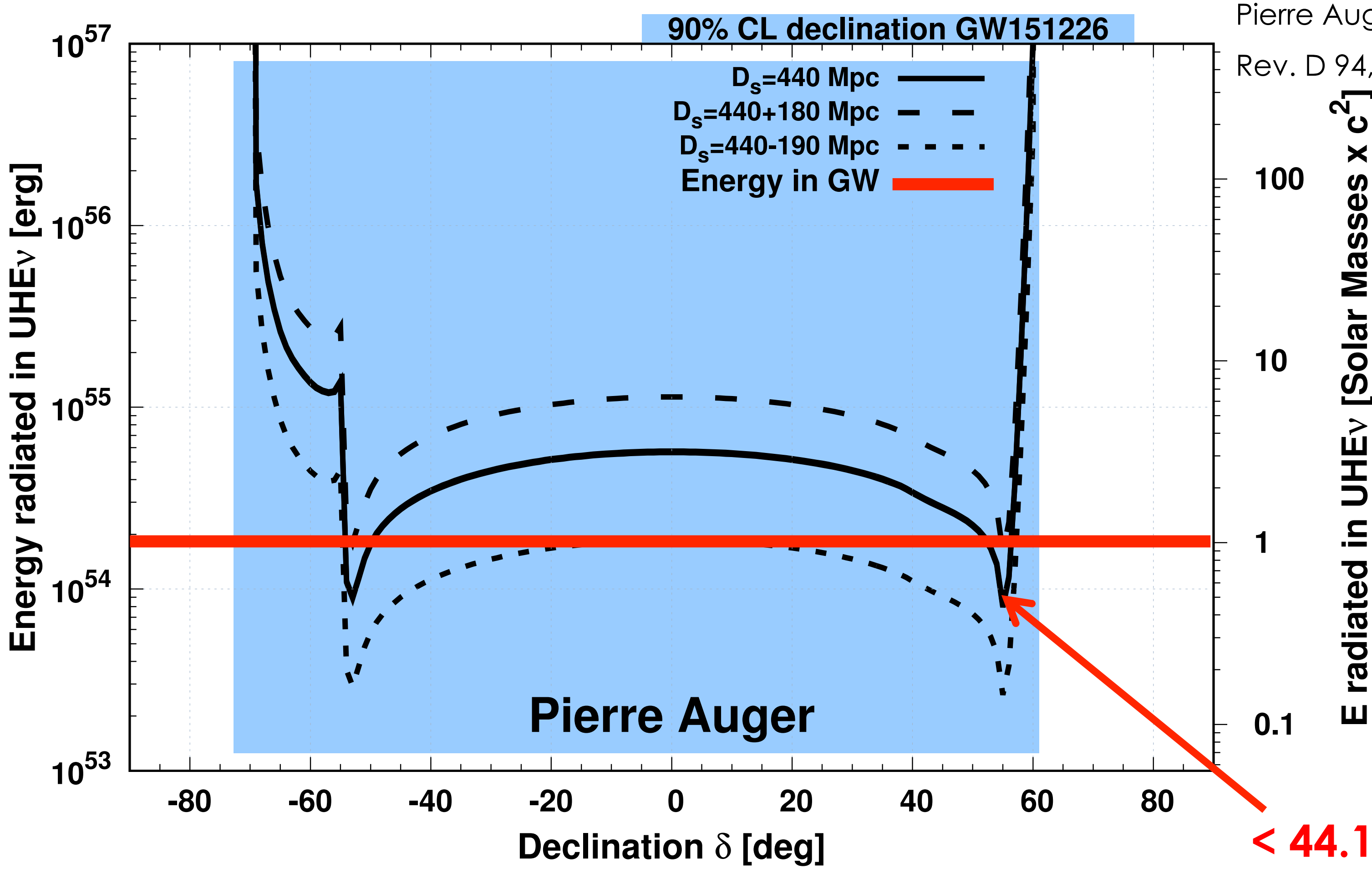
Constraints on energy radiated from GW150914 in UHEν ($E_\nu > 10^{17}$ eV)

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



less than (0.5, 3) solar masses depending on source declination

Constraints on energy radiated from GW151226 in UHEν ($E_\nu > 10^{17}$ eV)



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

< 44.1% of E_{GW}

less than (0.5, 3) solar masses depending on source declination

Conclusions I

- Surface Detector of the Auger Observatory sensitivity to 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)

- No ν candidates (1 Jan 2004 – 20 June 2013):
  - Stringent limit to diffuse flux:

    $dN/dE = k\, E^{-2} \longrightarrow k \sim 6.4 \times 10^{-9}$ GeV $cm^{-2}\, s^{-1}\, sr^{-1}$ @ 90% C.L.

    in 10^{17} eV $< E_n < 2 \times 10^{19}$ eV
  - Limit below the WB bound :
    - First shower array to achieve this benchmark
  - Top-down (exotic) models strongly constrained (many rule-out)
  - Cosmogenic model with pure proton composition at the source and strong FRII evolution disfavoured

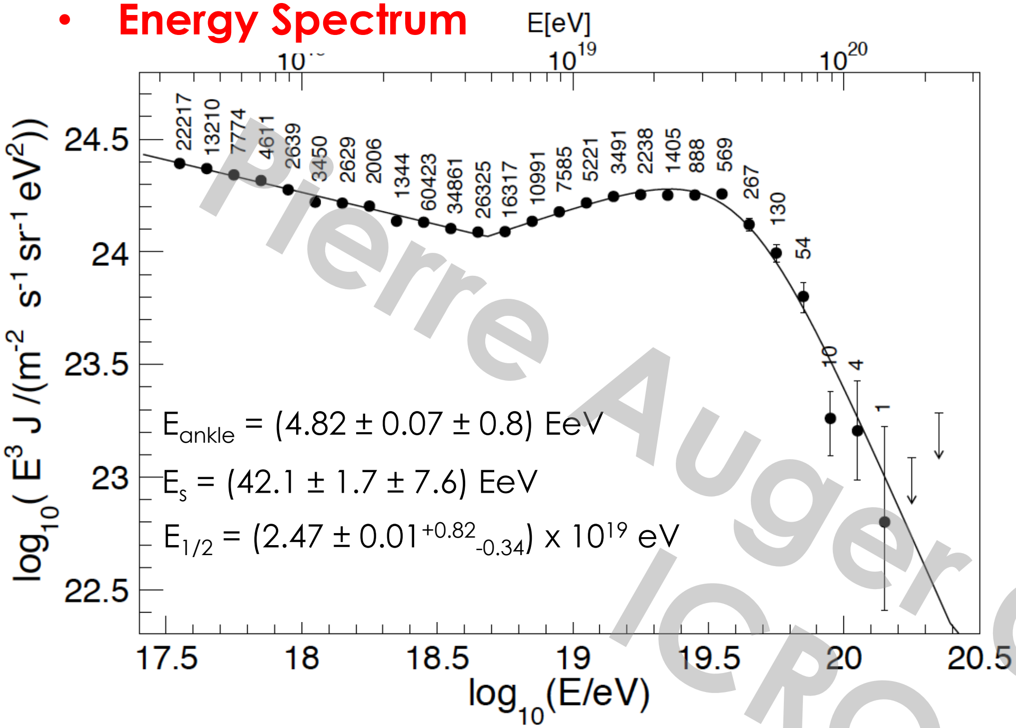
Conclusions II

- Follow-up of 2015 LIGO Gravitational-Wave events:
  - no neutrinos found
  - upper limits on UHE neutrinos in temporal & spatial correlation with LIGO GW events: first limits above 10^{17} eV (complementary to IceCube limits)

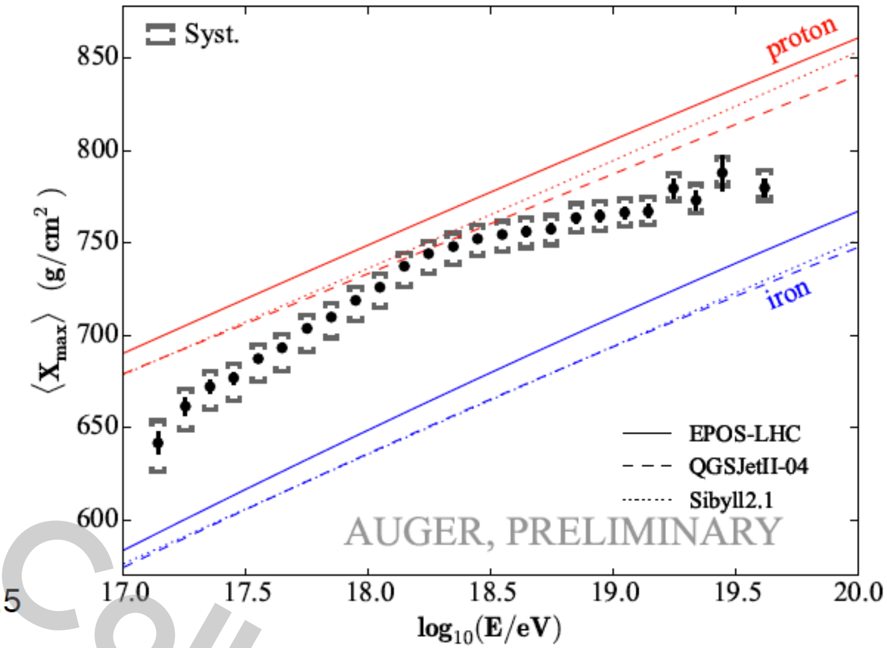
- More on neutrino searches with the Auger Observatory:
  - Search for point-like sources of UHE neutrinos
    Pierre Auger Collaboration, ApJL 755 (2012) L4
  - Correlation between IceCube neutrino events and UHECRs detected by Pierre Auger Observatory and Telescope Array
    *IceCube, Auger, Telescope Array, JCAP **01** (2016) 37*

Backup

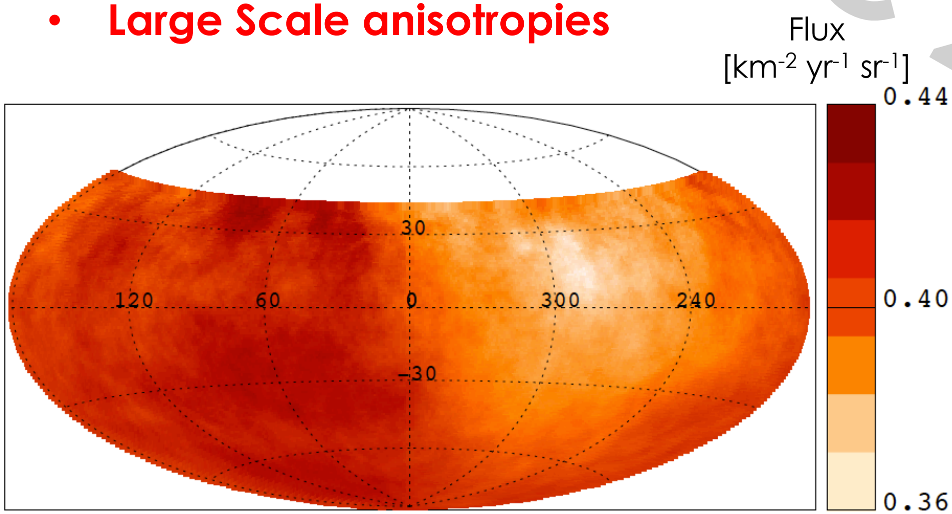
- **Energy Spectrum**



- **Mass composition**

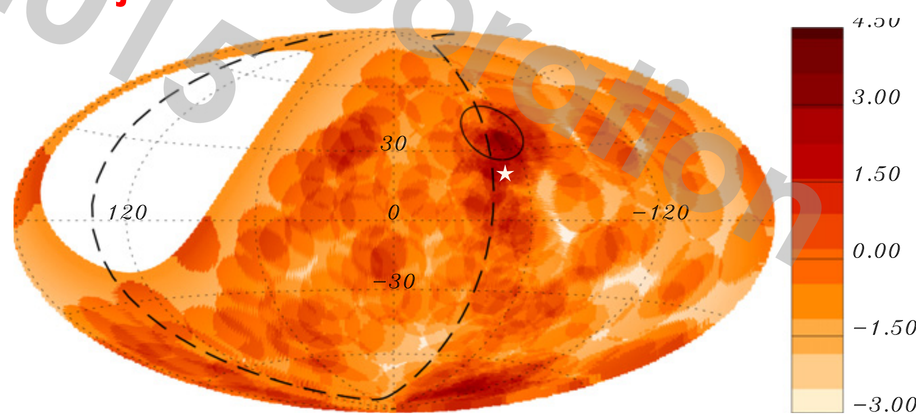


- **Large Scale anisotropies**



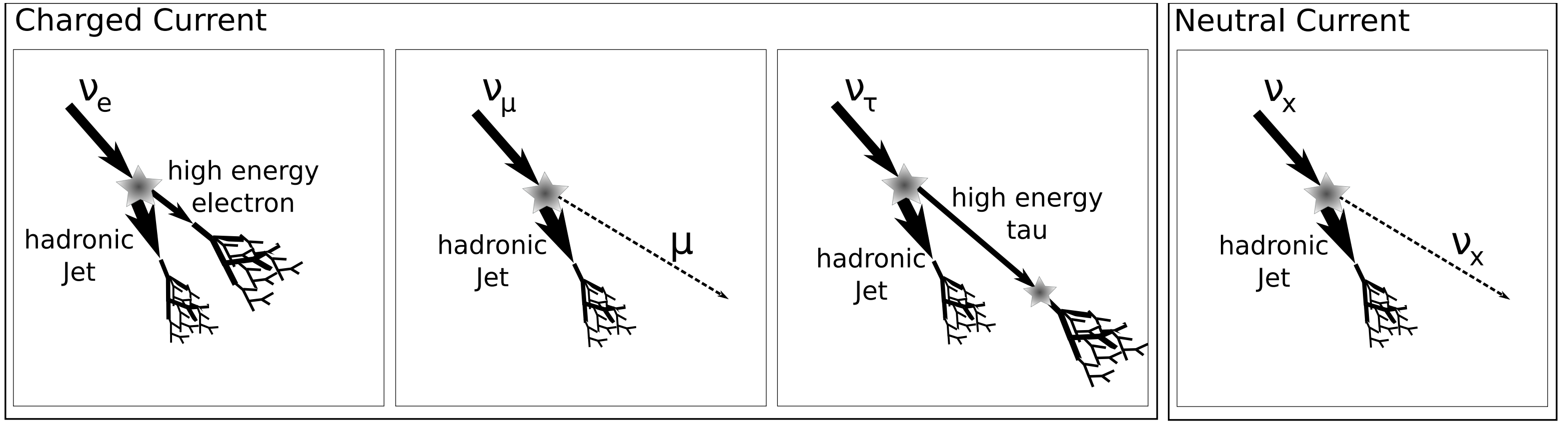
E > 8 EeV: Dipole of amplitude 7.3% ± 1.5%
Pointing to $(\alpha, \delta) = (95° \pm 13°, -39° \pm 13°)$

- **Correlation with nearby extra-galactic objects**



Events above 40 EeV in windows from 1° to 30°
No significant excess found

ν flavours and channels



Sets of selection criteria

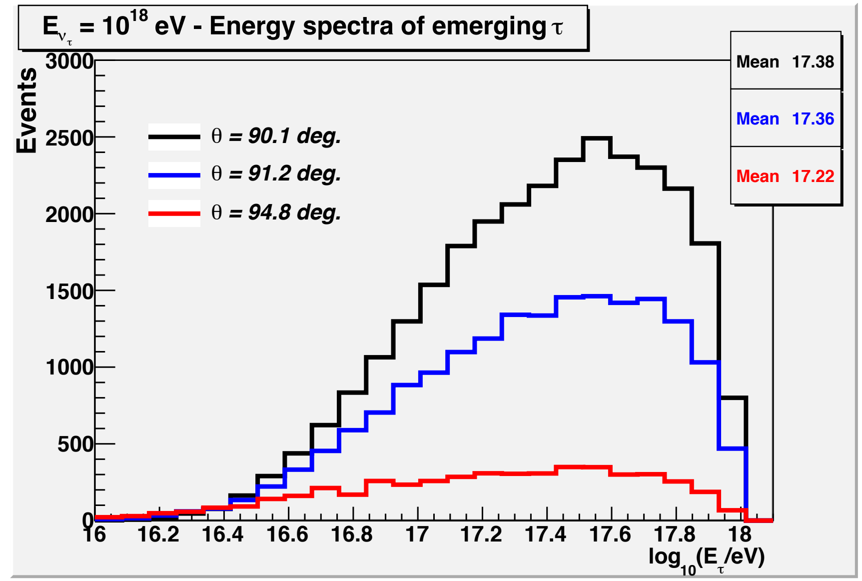
Auger Collaboration Phys. Rev. D 91, 092008 (2015)

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 ($N_{\rm st}$)	$N_{\rm st} \geq 3$	$N_{\rm st} \geq 4$	$N_{\rm st} \geq 4$
Inclined showers	$L/W > 5$ $\langle V \rangle \in (0.29, 0.31)$ m ns^{-1} rms$(V) < 0.08$ m ns^{-1}	$\theta_{\rm rec} > 75°$ $L/W > 3$ $\langle V \rangle < 0.313$ m ns^{-1} rms$(V)/\langle V \rangle < 0.08$	$\theta_{\rm rec} \in (58.5°, 76.5°)$
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 $\langle$AoP$\rangle > 1.83$ AoP$_{\rm min} > 1.4$ if $N_{\rm st} = 3$	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

Exposure: Earth-skimming ν_τ

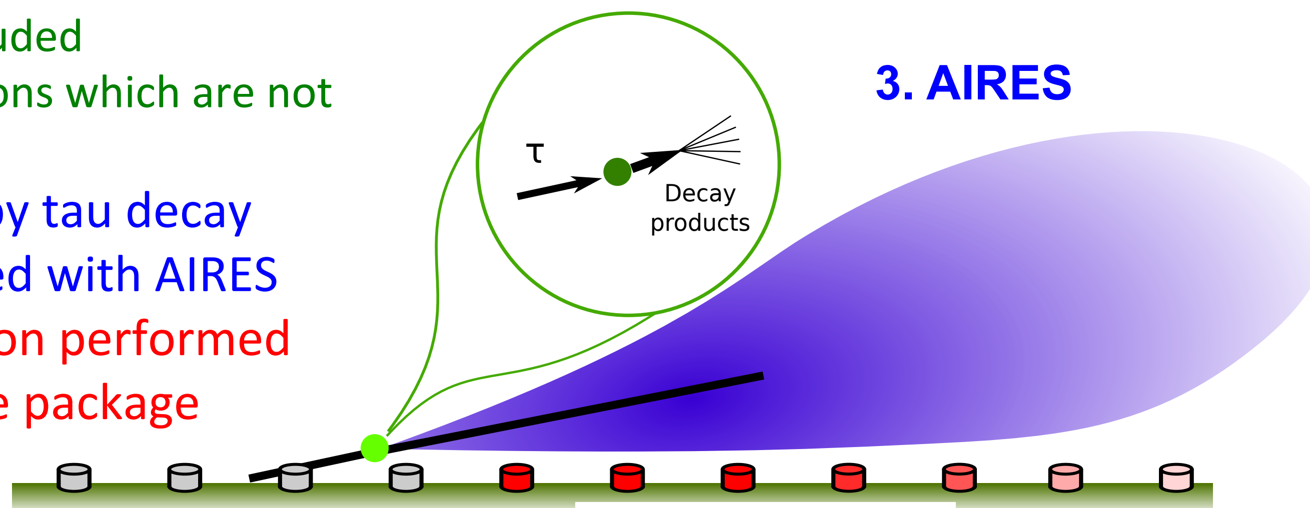
1. Tau neutrino propagation and tau production:
    - Dedicated MC for propagation of ν_τ through the Earth producing emerging tau leptons.
    - Convolute with probability of tau decay in the atmos. (exponential)
2. Tau decay products obtained with TAUOLA generator:
    - All decays included
    - 17% BR to muons which are not detected
3. Shower induced by tau decay products simulated with AIRES
4. Detector simulation performed with Auger Offline package

1. ν_τ PROPAGATION



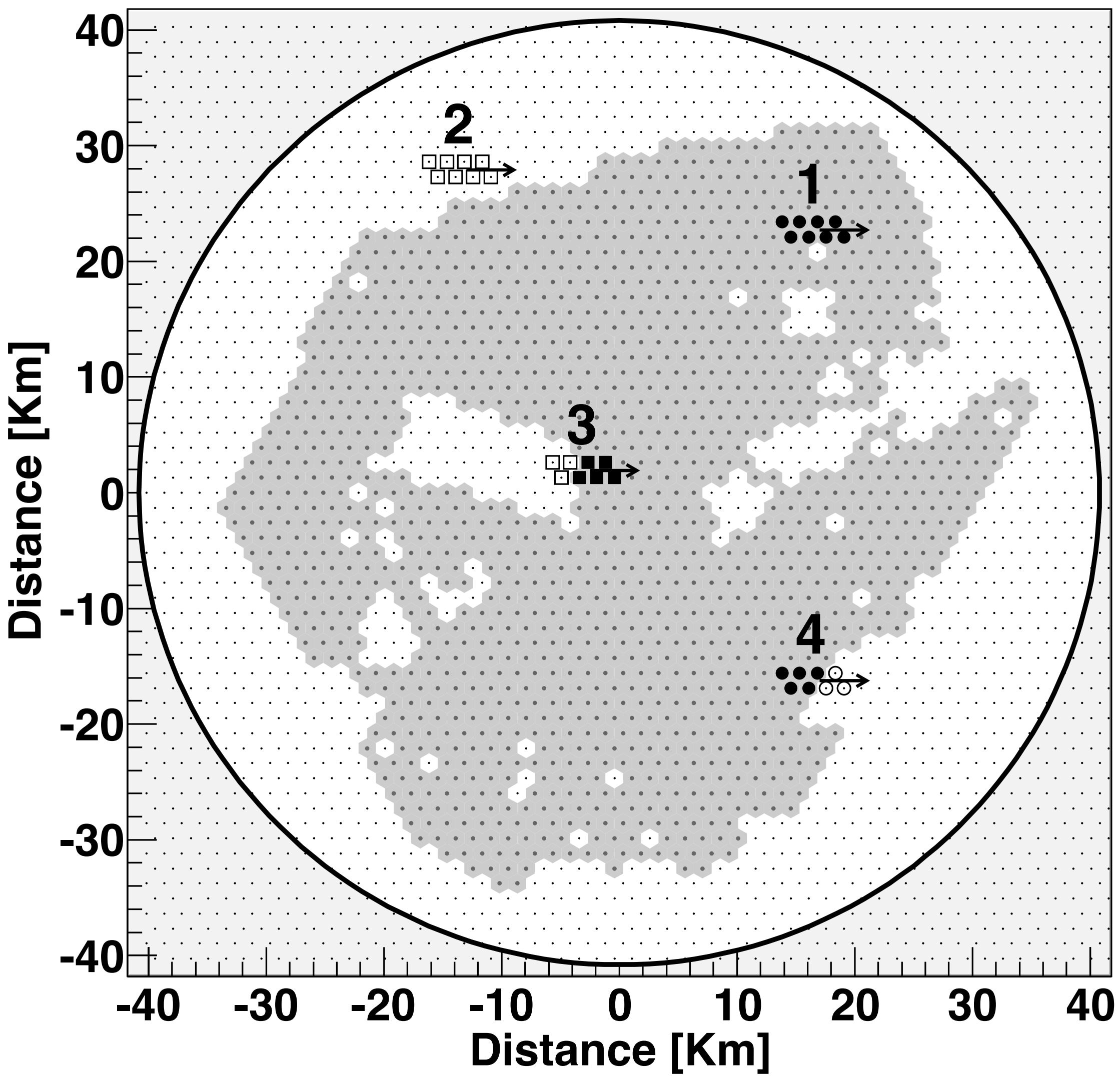
2. TAUOLA

3. AIRES



4. OFFLINE

Exposure calculation: accounting for a "dynamical" array



Array status in Nov. 2007 before construction ended (2008).

Neutrino simulated showers are "thrown" over a changing array

1. Shower fully contained, triggering and identified as a neutrino.
2. Shower outside array not triggering.
3. Shower not fully contained, triggering but not identified as a neutrino.
4. Shower not fully contained, but triggering and identified as a neutrino

Systematic uncertainties: ν limits

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)

Expected number of events

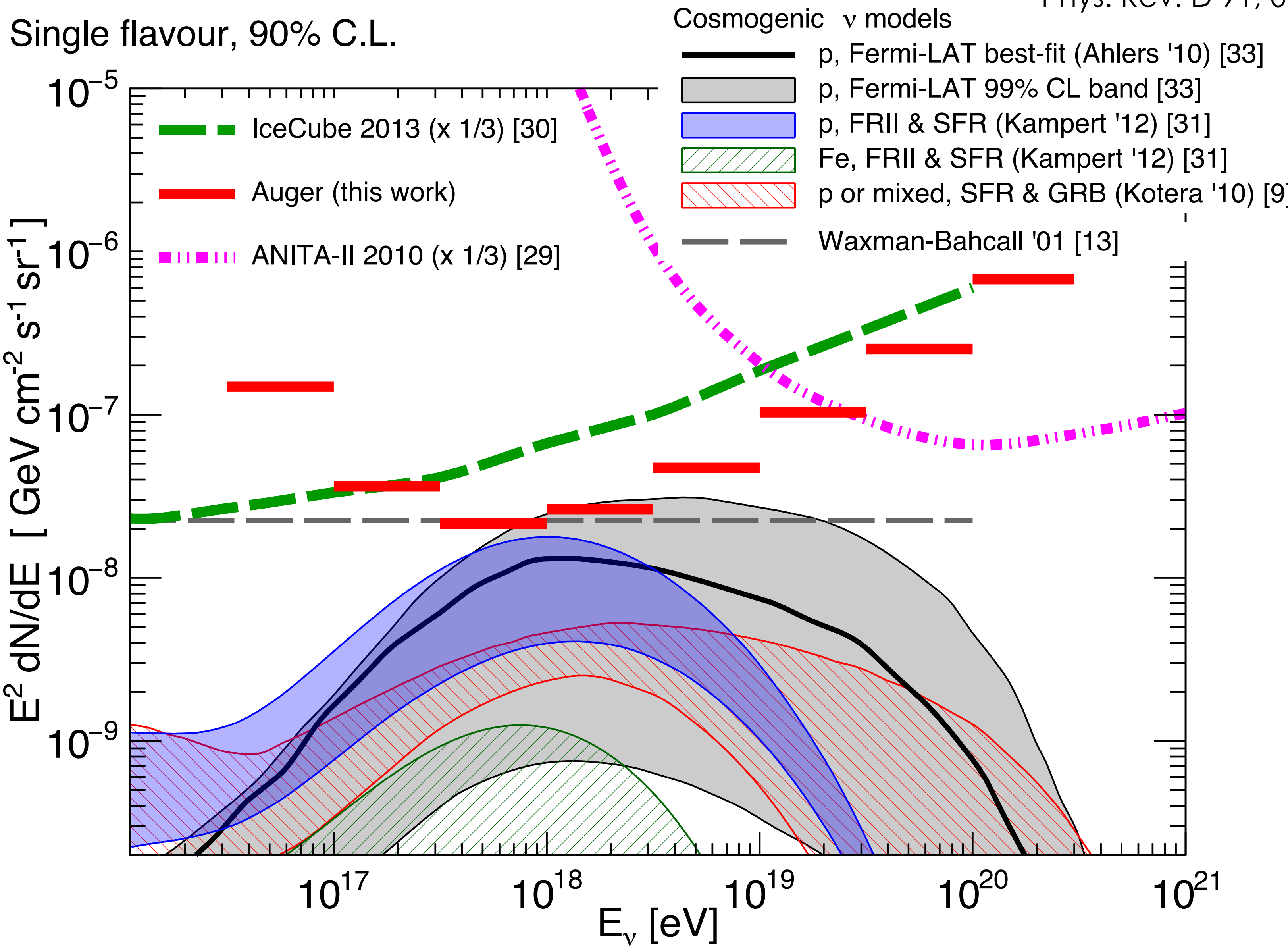
$$N_{\text{events}} = \int_{E_\nu} \Phi(E_\nu)\, \varepsilon_{\text{tot}}(E_\nu)\, \mathrm{d}E_\nu$$

Diffuse flux Neutrino model	Expected number of events (1 January 2004–20 June 2013)
Cosmogenic—proton, FRII [33]	~4.0
Cosmogenic—proton, SFR [33]	~0.9
Cosmogenic—proton, Fermi-LAT, $E_{\text{min}} = 10^{19}$ eV [34]	~3.2
Cosmogenic—proton, Fermi-LAT, $E_{\text{min}} = 10^{17.5}$ eV [34]	~1.6
Cosmogenic—proton or mixed, SFR & GRB [9]	~0.5–1.4
Cosmogenic—iron, FRII [33]	~0.3
Astrophysical ν (AGN) [35]	~7.2
Exotic [36]	~31.5

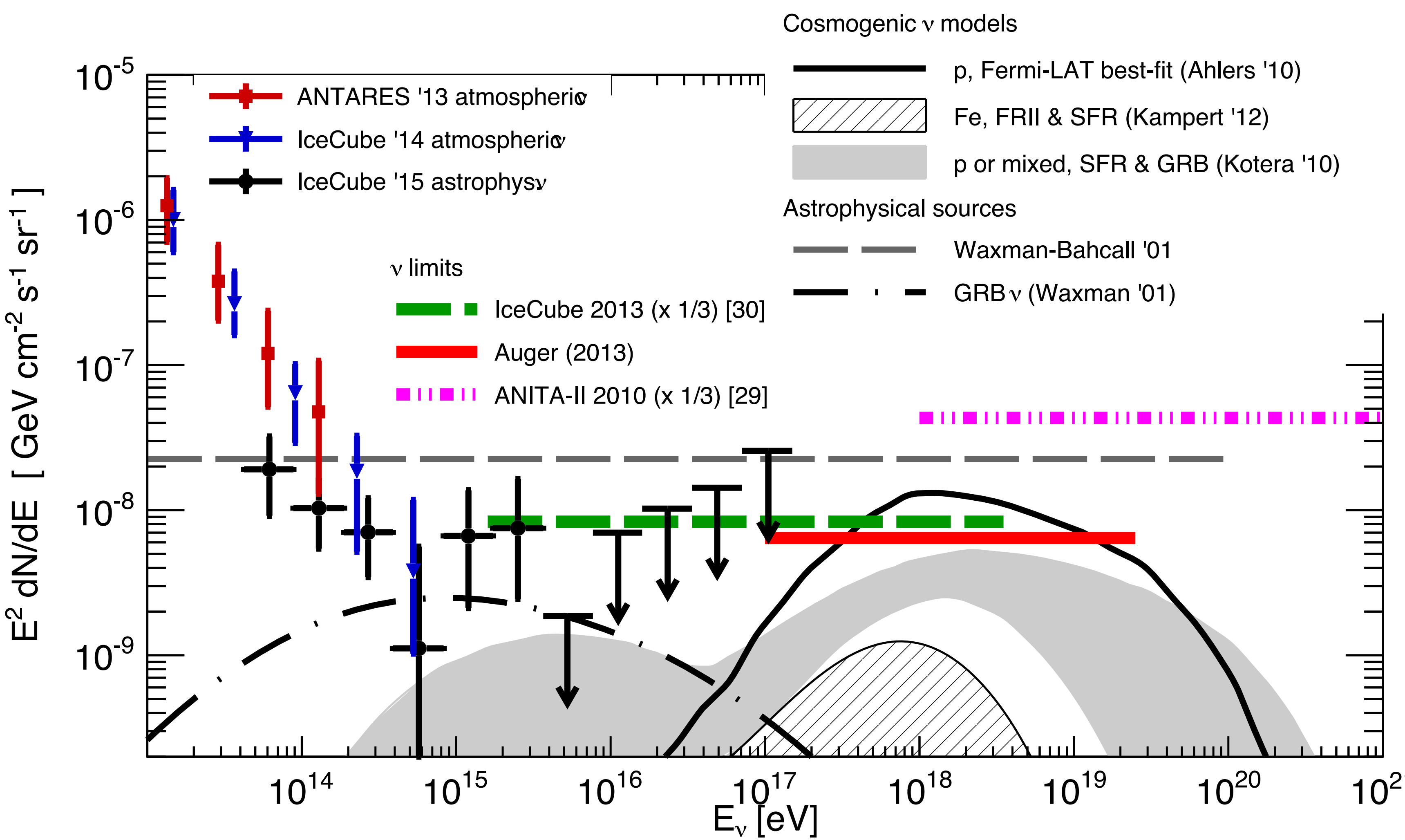
Auger Collaboration
Phys. Rev. D 91, 092008 (2015)

Differential limits to diffuse flux of UHEν

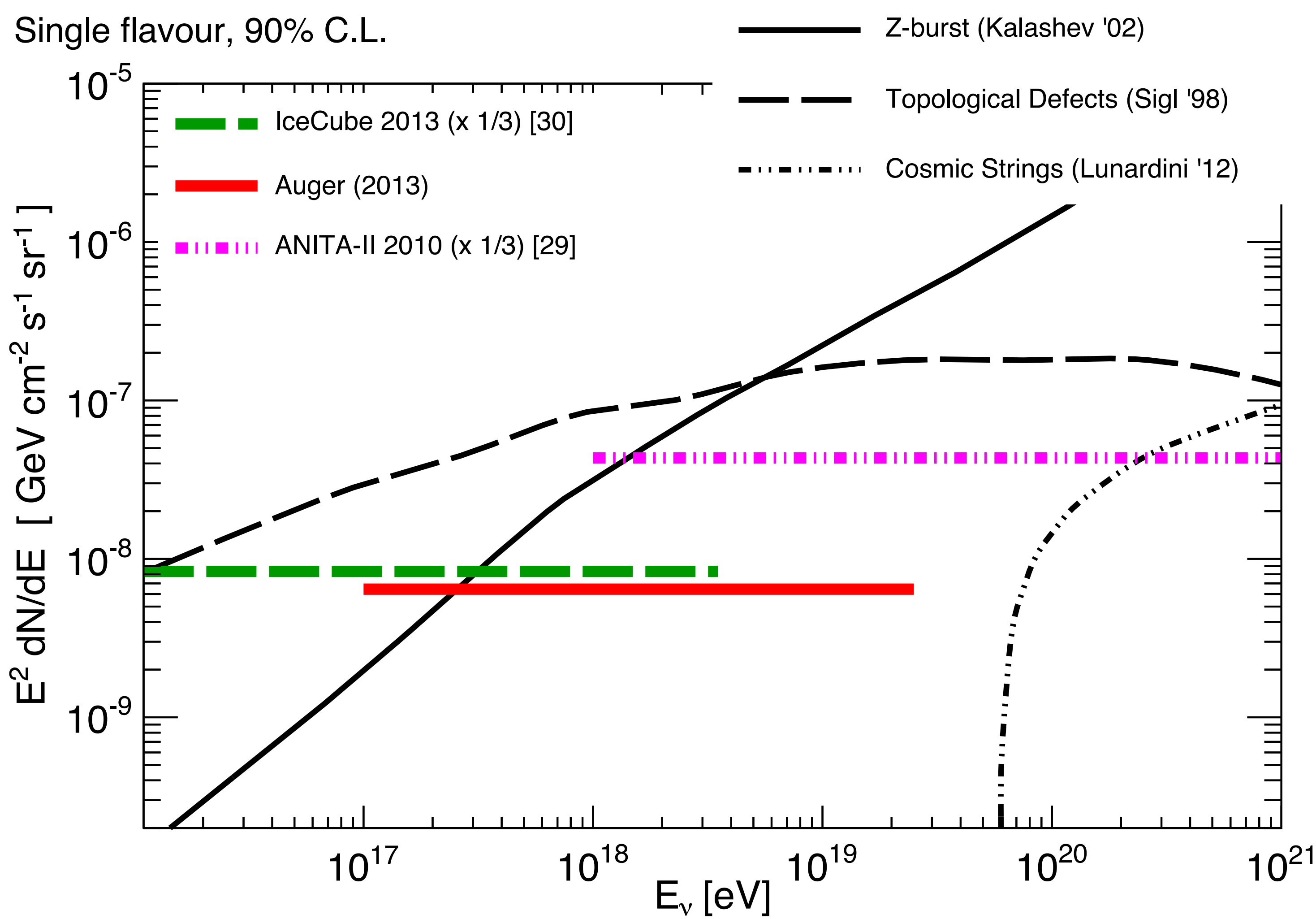
Auger Collaboration
Phys. Rev. D 91, 092008 (2015)



Status of neutrino searches

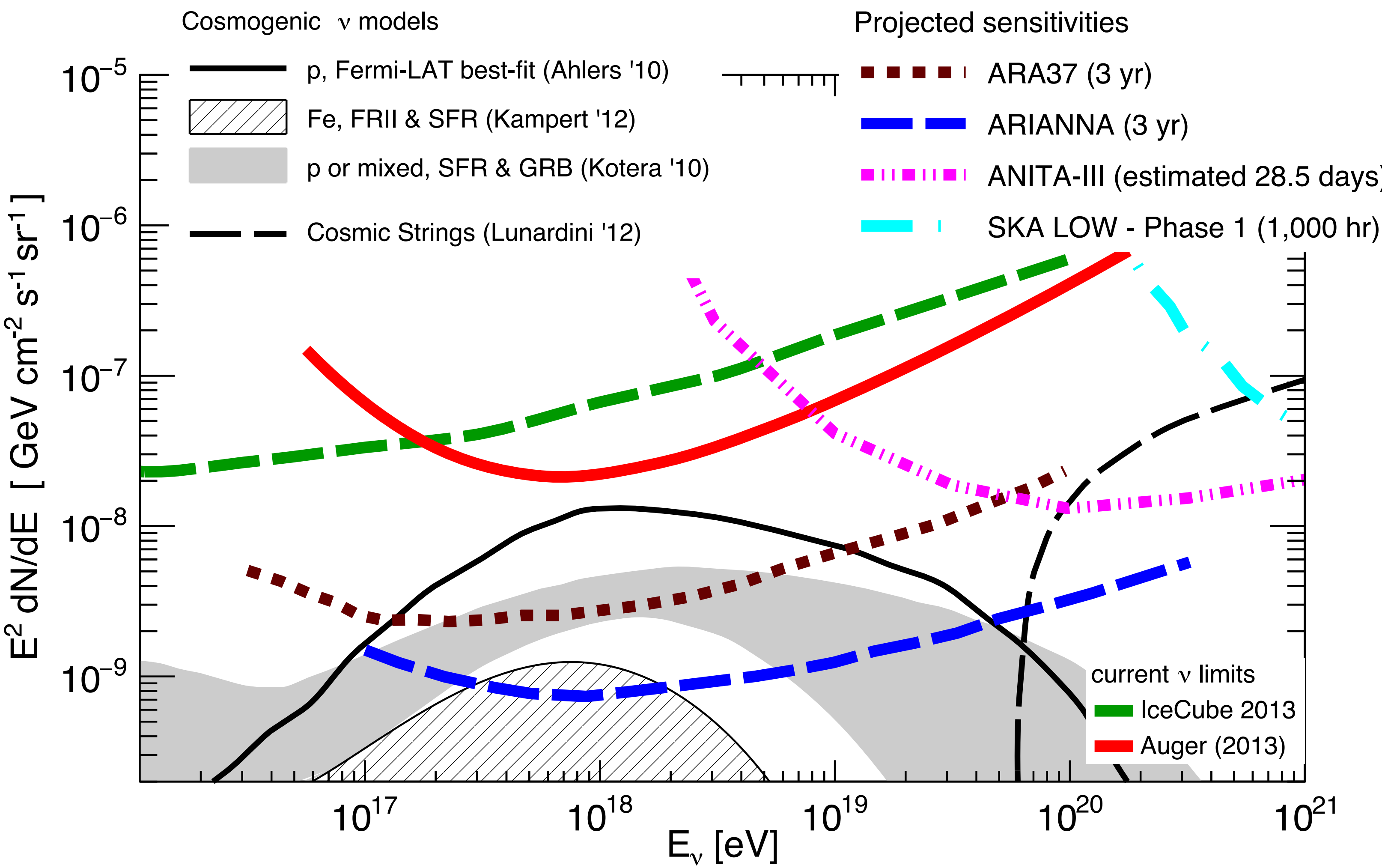


Limits to exotic models of ν production



Auger limit rules out many exotic models of UHEν production

UHE Neutrino Sensitivity with radio

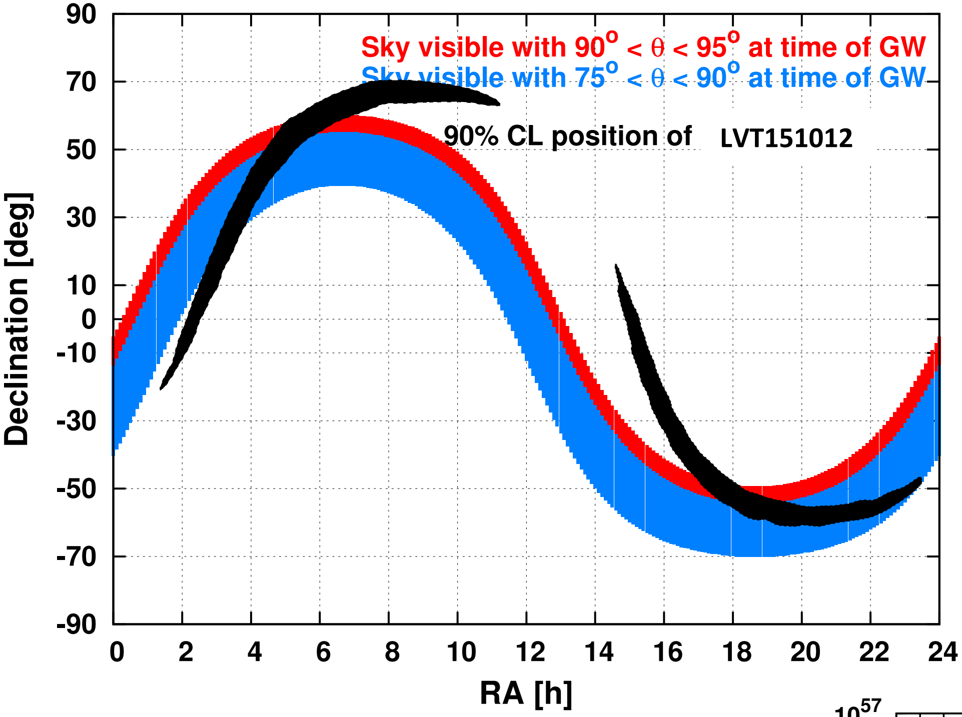


What if a ν candidate appears?

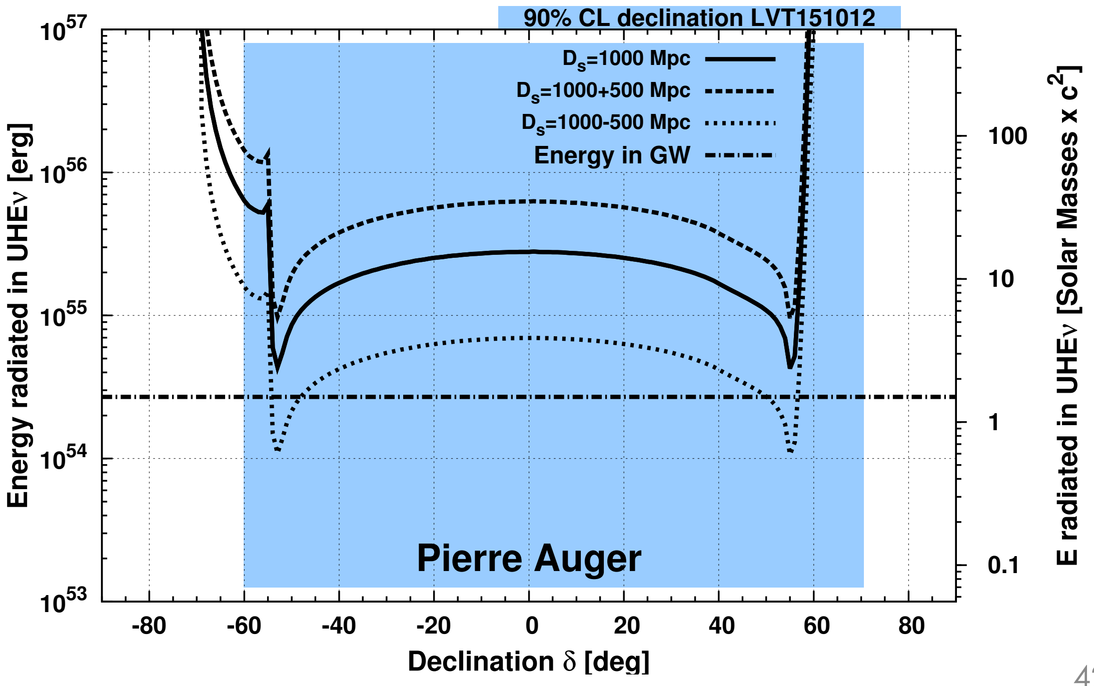
- **Energy estimate of a ν candidate** :
  - Only the energy of the ν-induced shower (E_{shower}) can be reconstructed
  - ν flavour cannot be determined & E_{shower} depends on flavour
  - At best a lower bound to Eν because $E\nu > E_{shower}$
  - ν can interact anywhere in atmosphere: E_{shower} estimation should include shower age – No algorithm including age exists so far.

- **Angular reconstruction of quasi-horizontal events** :
  - Not optimized for deeply penetrating & very inclined showers (> 80°) Angular resolution ~ 1- 2 °
  - Identification of upgoing shower would indicate ν_τ primary

- **Auger SD = discovery experiment (a "counter" of UHE neutrinos)**



The GW candidate event LVT151012



Auger constraints on models

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

- Kotera & Silk (ApJLett 823, L29, 2016): events such as GW1501914 can account for UHECR above 10^{19} eV
  - sufficient power to accelerate CR up to 10^{20} eV (if $B_{field} > 10^{11}$ G)
  - with < 3% of energy released in GW: UHECR energy budget achieved
- UHEν if BHs surrounded by debris where pγ interactions occur.

Upper limit to **diffuse** UHE neutrino flux from BH mergers:

$E^2 dN/dE \sim 1.5 - 6.9 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} (theory)

above Auger limit

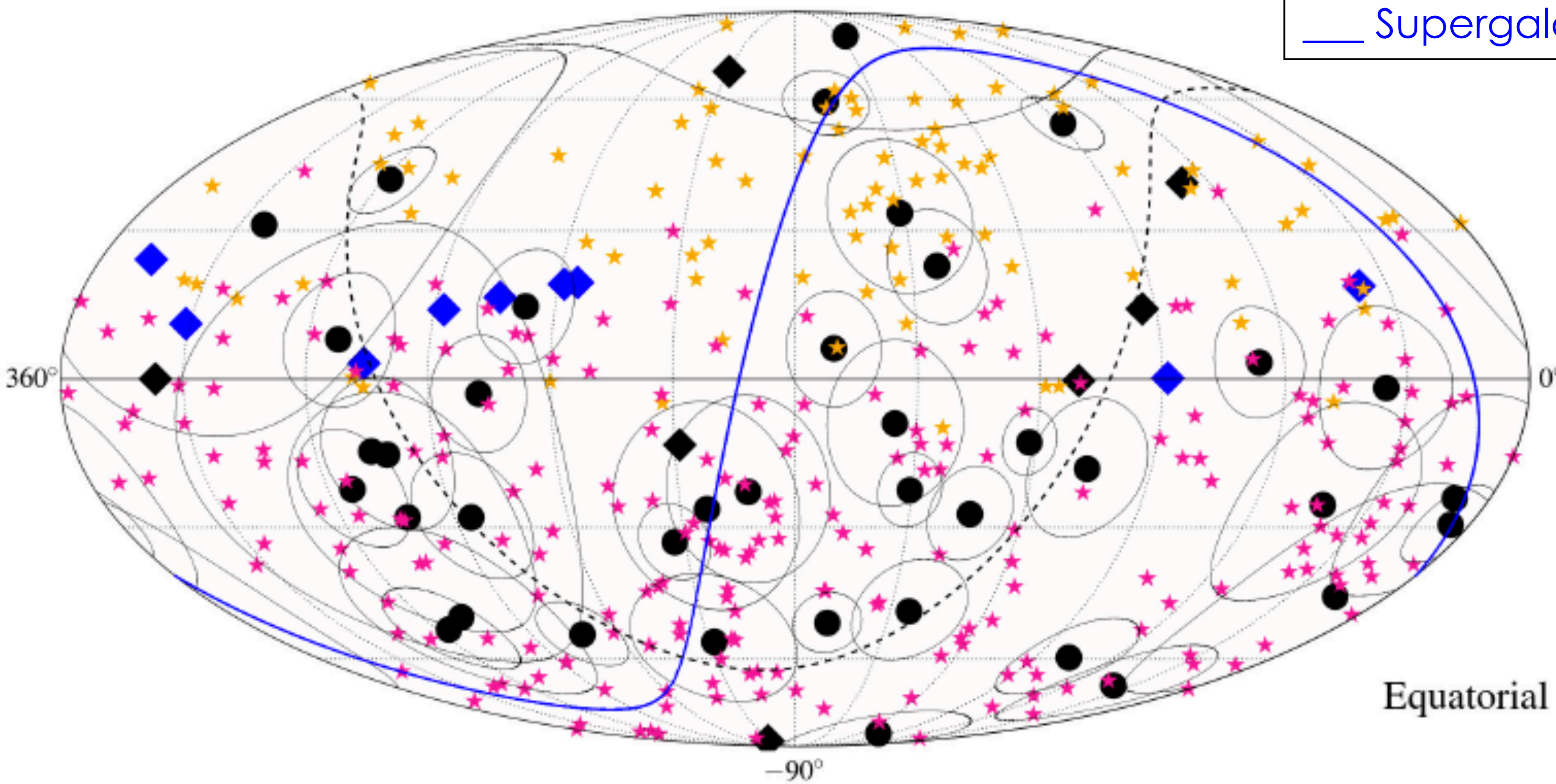
$E^2 dN/dE \sim 6.4 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1} (Auger)

- **Implications:**
  - optical depth to pγ SMALLER than 1
  - ONLY a fraction of energy in protons goes into charged pions -> neutrinos
  - ONLY a fraction of luminosity extracted from BH goes into UHECR acceleration

Correlation between Auger + Telescope Array UHECRs & IceCube ν

Three analyses to investigate correlations between 318 UHECRs in Auger + Telescope Array with samples of IceCube neutrino events.

- ★ Auger UHECRs
- ★ TA UHECRs
- ◆ IceCube HESE tracks
- ◆ IceCube tracks
- •IceCube cascades
- ---- Galactic plane
- ___ Supergalactic Plane



No indications of correlations above 3.3 σ

IceCube, Auger, Telescope Array
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