Search for neutrinos at the Pierre Auger Observatory

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Multi-messenger Astronomy

GeV-TeV-PeV γ-rays

Fermi LAT/Magic/HESS/CTA/...

UHECRs

Auger/TA/...

Optic/x-rays/IR/Radio UV/Sub-mm

VLT/Hubble/E-ELT/Alma/VLA/...

HE Neutrinos

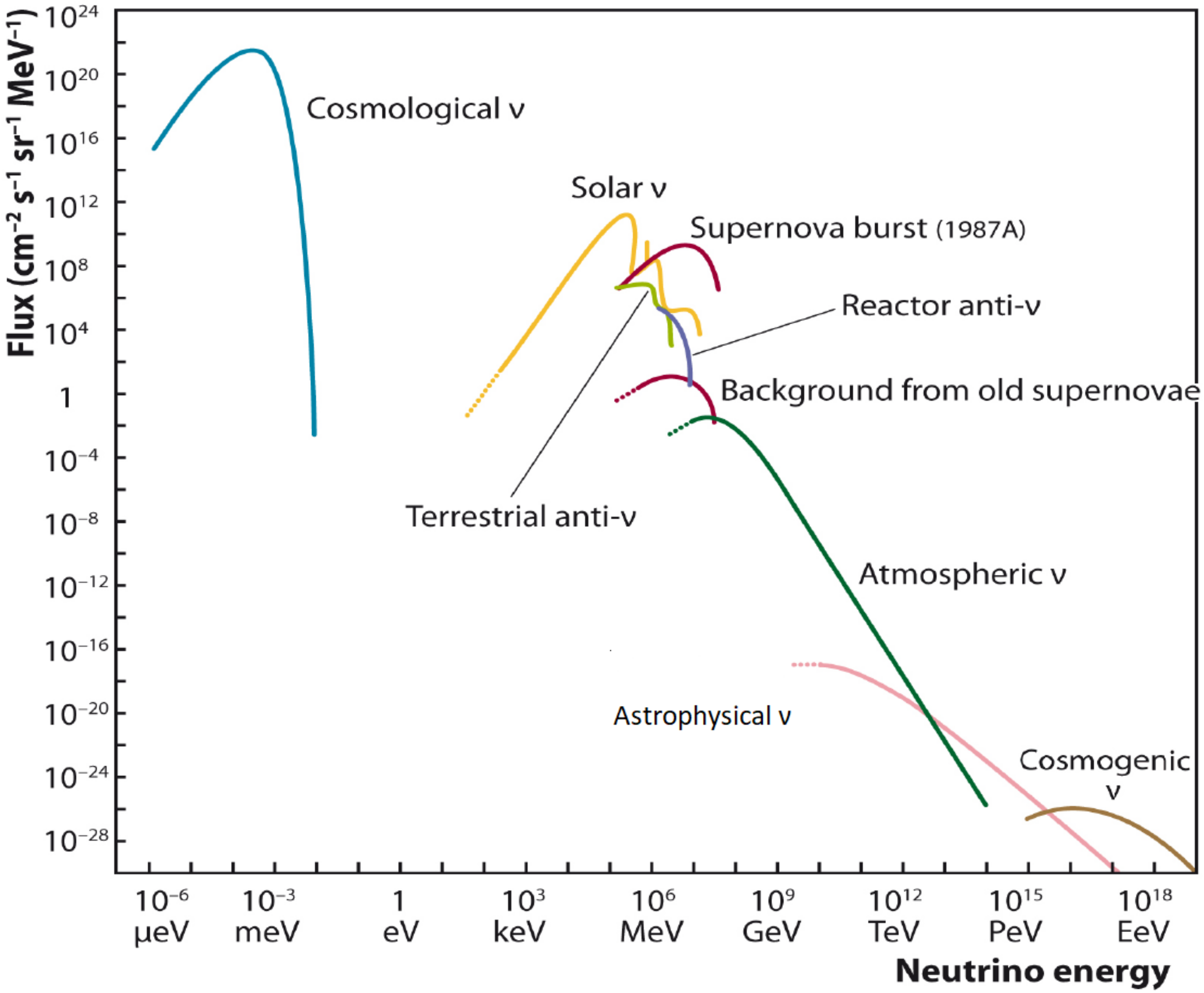
IceCube/Baskan/KM3NeT/...

Gravitational Waves

Ligo/Virgo/...

→GRBs/Blazars flares/Crab/SN Ib,c/Follow-up GW events/UHECRs and ν correlations

Neutrinos



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
Astrophysical ν
Cosmogenic ν
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

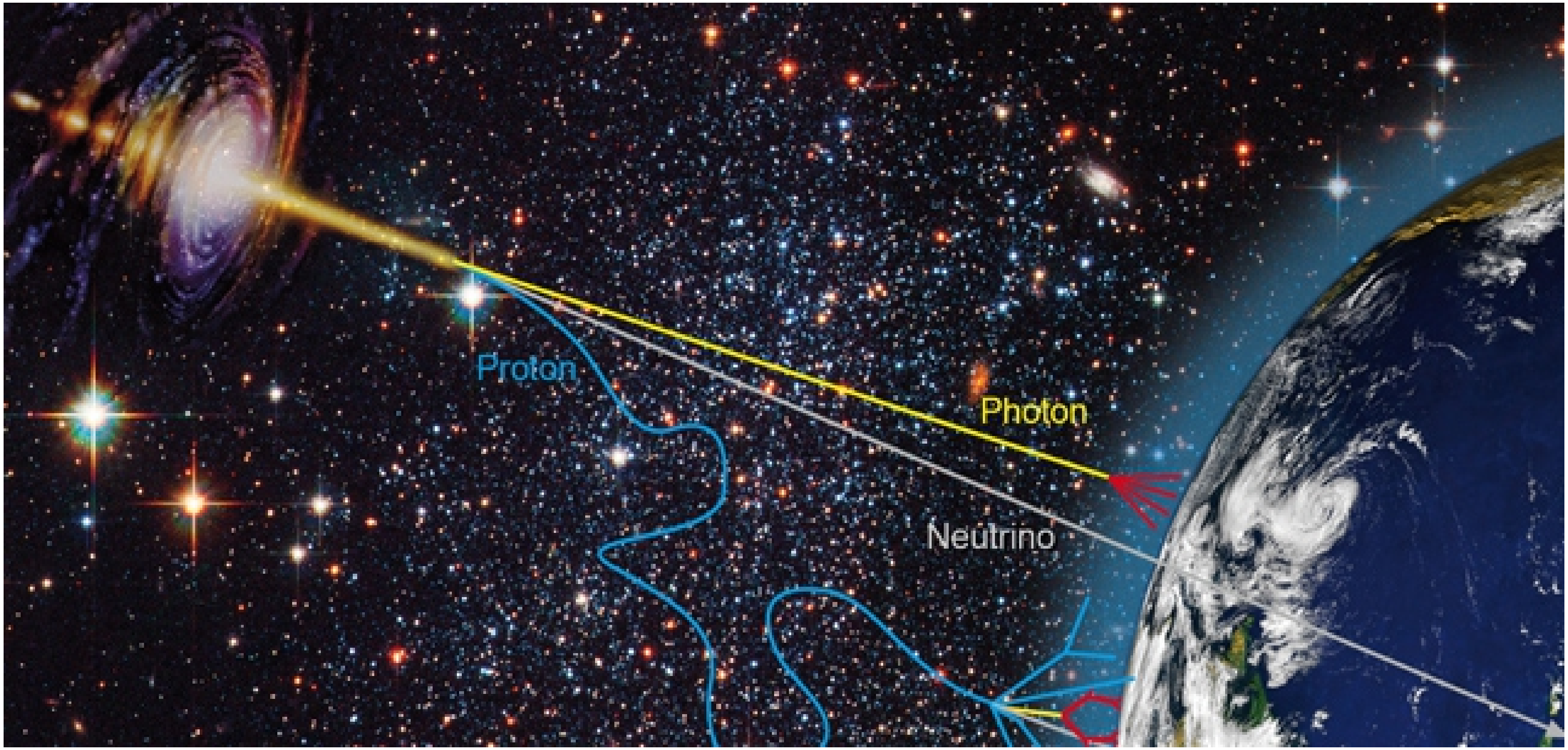
High Energy Neutrinos as Astrophysical Messengers

- From nonthermal high-energy phenomena in the Universe (like core-collapse supernovae, accretion disks around black holes, pulsars, GRBs, UHCRs …)
- Related to hadronic interactions of protons and nuclei (as gamma rays)
- Neutral: not deflected by electromagnetic fields

BUT

- Weak interaction: able to escape even from very dense production regions and traverse large distances without being absorbed → **difficult** to detect

- **Protons** trajectories are bent in galactic and extragalactic magnetic fields, UHE cutoff
- **γ-rays** horizon is only 500 Mpc at 1 TeV and 8.5 kpc at 1 PeV



Cosmic Rays and Cosmogenic neutrinos

- Ultra-high energy ($E > 10^{18}$ eV) protons and nuclei travelling through intergalactic space can interact with CMB photons production new particles, e.g.

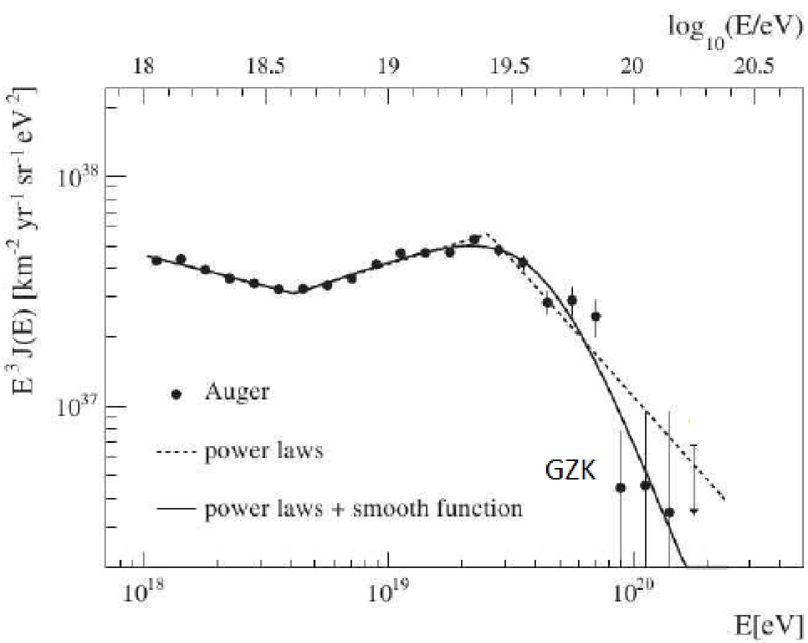
Pair production: $p + \gamma \to p + e^+ + e^-;$

Pion production: $p + \gamma \to p + \pi^0$ or $p + \gamma \to n + \pi^+$

- These processes (especially pion production) cause protons to lose part of their energy, modifying their energy spectrum. In particular, no proton originating more than 50 Mpc away should reach Earth with $E > 10^{19.5}$ eV. This is known as the **Greisen–Zatsepin–Kuzmin** (GZK) limit.

- Ultra-high energy nuclei can also undergo photodisintegration (both on CMB and on IR/opt/UV intergalactic background light):

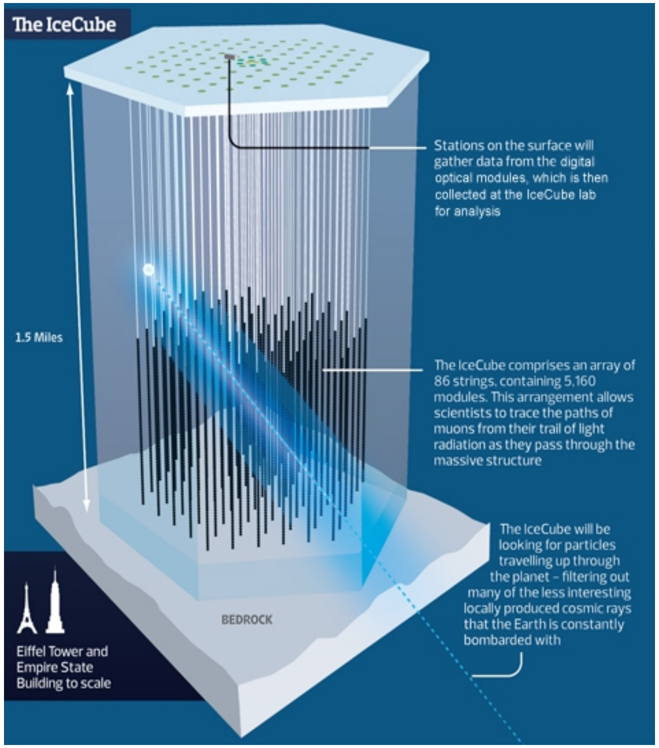
$$(A,Z)+\gamma \to (A-1,Z-1)+\mathrm{p}$$
$$(A,Z)+\gamma \to (A-1,Z)+\mathrm{n}$$
$$(A,Z)+\gamma \to (A-2,Z-1)+\mathrm{p}+\mathrm{n},\ \text{etc.}$$



- NOTE: Measurements of the cut-off are nowadays not conclusive ...source exhaustion?

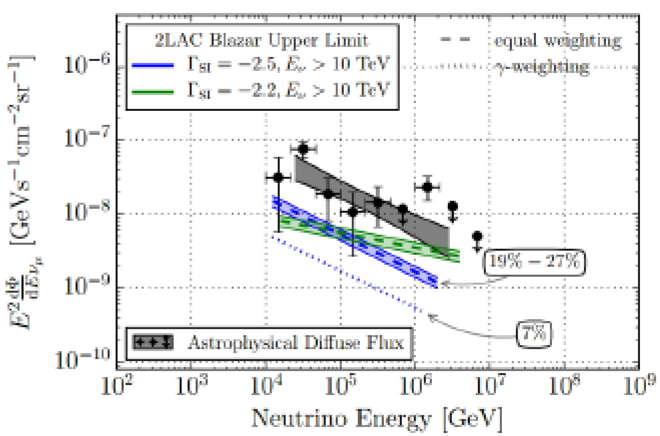
High Energy Neutrino Astronomy

- Huge particles detector needed
- Big volumes of water or ice → Cherenkov light of secondary muons and electrons from neutrino interaction
- TeV to PeV energies
- The largest neutrino detector yet is IceCube at the South Pole (updated IceCube-Gen2, with the tenfold volume).

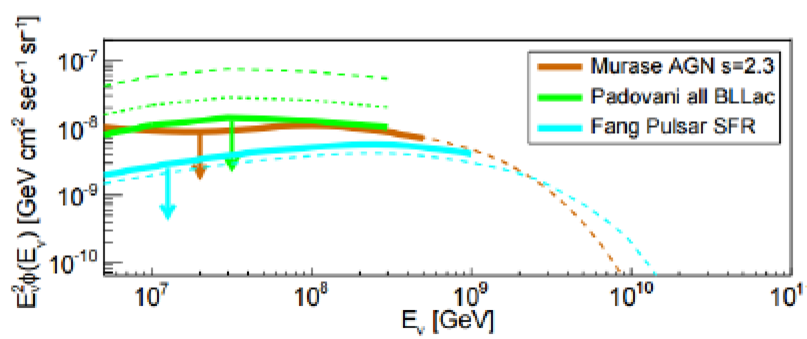


Ice Cube Results

- The diffuse astrophysical cosmic neutrino flux is extending up to few PeV (*arXiv:1611.03874v1*) - the energy of these neutrinos does not match the expectation for a cosmogenic neutrino flux
- Soft spectrum (spectral index -2/-2.5) between 10 TeV and 2 PeV with equal flavor composition at Earth (*Aartsen et al. 2015b*)



90% C.L. flux upper limits for all 2LAC blazars in comparison to the observed astrophysical neutrino flux

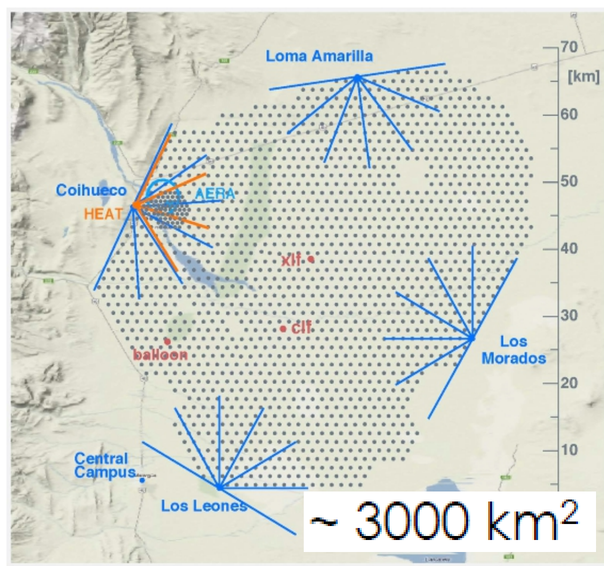


Model-dependent 90% C.L. limits (solid lines) for astrophysical neutrino fluxes from AGN (BLR) models of Murase, Padovani and Fang

The Pierre Auger Observatory

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

- **SD 1500** Surface Detector array of 1600 water Cherenkov stations
- **FD** 4 Fluorescence buildings detectors
- **SD 750** 61 water Cherenkov stations (25 km^2)
- **AERA** Array of 153 antennas (17 km^2)
- **AMIGA** Array of 7 buried muon detectors



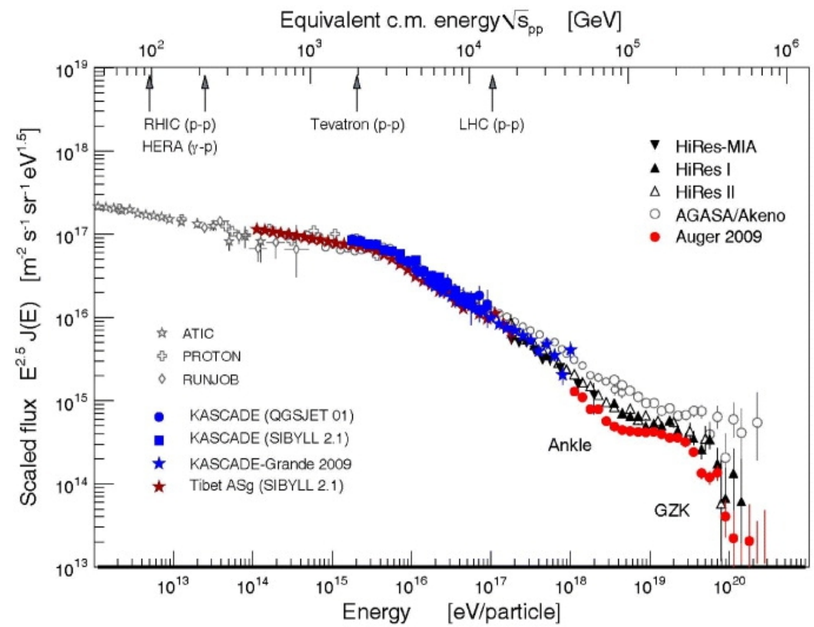
Scientific goals

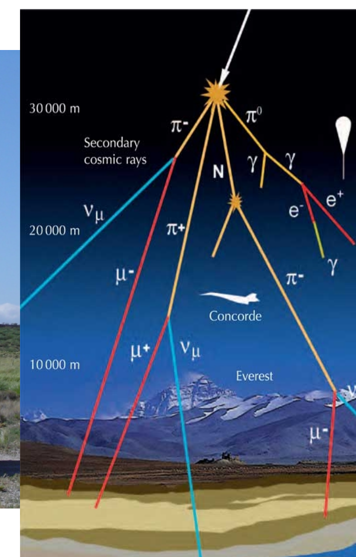
- Detection of **Extensive Particle Air Showers** induced by Ultra High Energy Cosmic Rays (E > 10^{18} eV) with high statistics, a good understanding of the systematics and a full sky coverage
  → ***hybrid technique***

- Determine **energy**, incoming **direction** and **type** of primary particle → acceleration mechanisms and sources

- Search for gamma photon point sources (EeV, PeV)

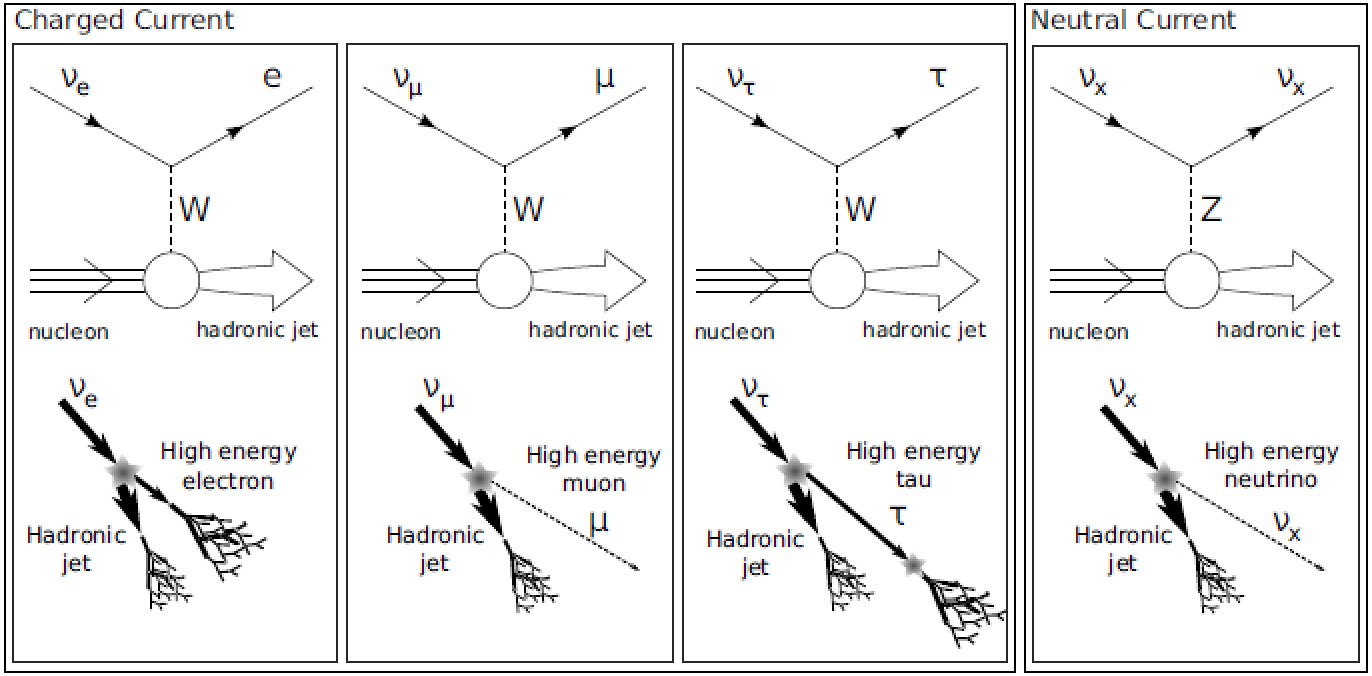
- Neutrino search at Ultra High Energies





UHEvs induced showers

Neutrino interaction (with atmospheric nucleon) channels according to the Standard Model

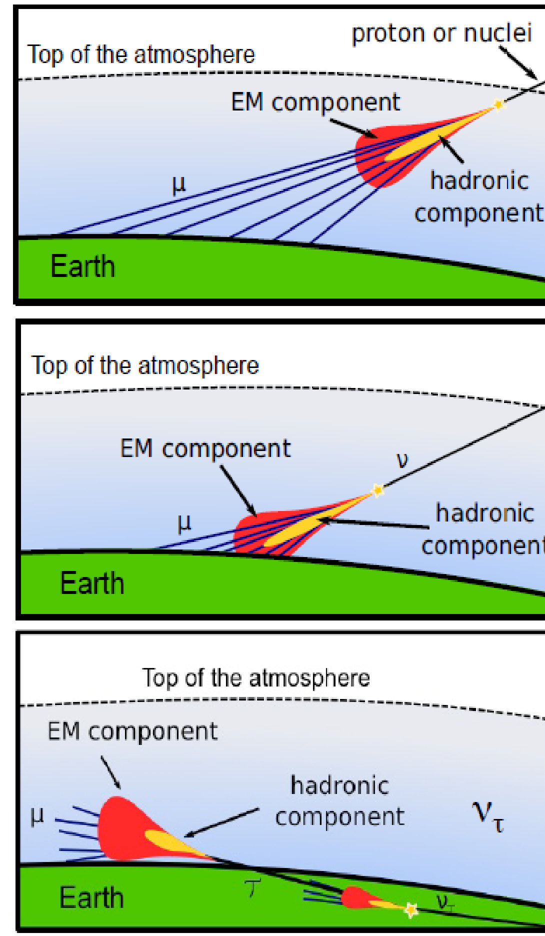


- The primary interaction of the neutrino is DIS
- 20% of the energy of the primary neutrino is transferred to the hadronic jet. The remaining 80% is contained in a ultra-energetic lepton. Neutral current interactions produce a secondary neutrino instead of a lepton

Identification of EeV ν induced showers with SD array

Discrimination power enhanced looking at <u>very inclined</u> showers!

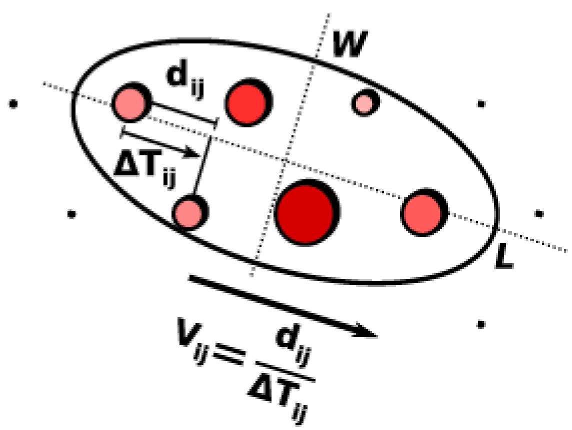
• Protons & nuclei initiate showers high in the atmosphere.
– Shower front at ground mainly composed of muons
(electromagnetic component
absorbed in atmosphere)
• Neutrinos can initiate "deep" showers close to ground.
– Shower front at ground:
electromagnetic + muonic components
• Tau neutrinos can initiate "up-going" showers close to ground.

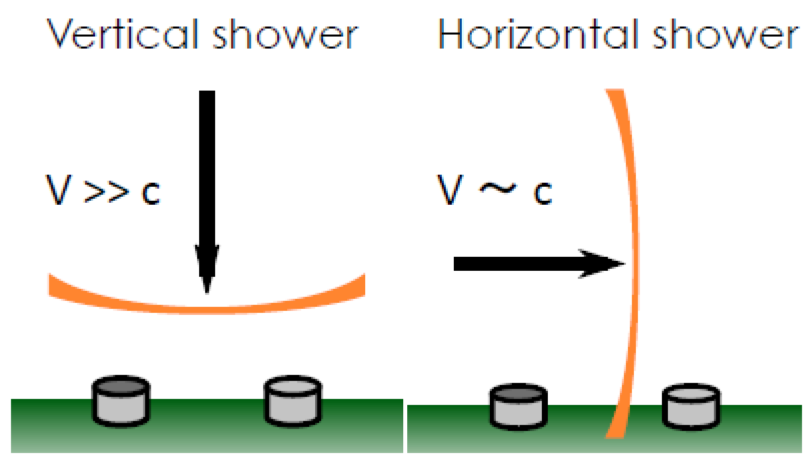


<u>→deep (young) inclined shower</u>

Inclined showers selection

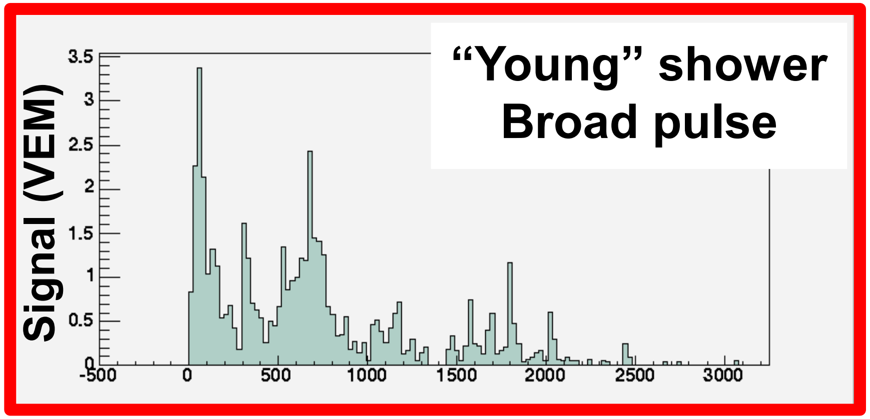
- Reconstructed arrival zenith angle from 85° to 89° (and from 90° to 95°)
- Observables: **length/width footprint**, **ground speed of the shower front** in-depended from reconstruction algorithms
- Phy. Rev. 2015 observables cuts for down going showers SD1500:
  - *length/width* **>5**
  - $<\Delta t_{ij}/d_{ij}>$ **<3.313 m/ns**
  - RMS($\Delta t_{ij}/d_{ij}$)/ $<\Delta t_{ij}/d_{ij}>$ **< 0.08**
  - number of candidate stations: at least **4**

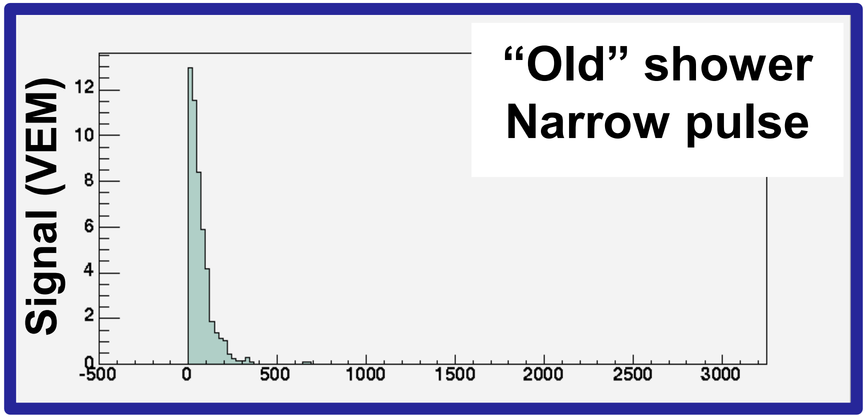


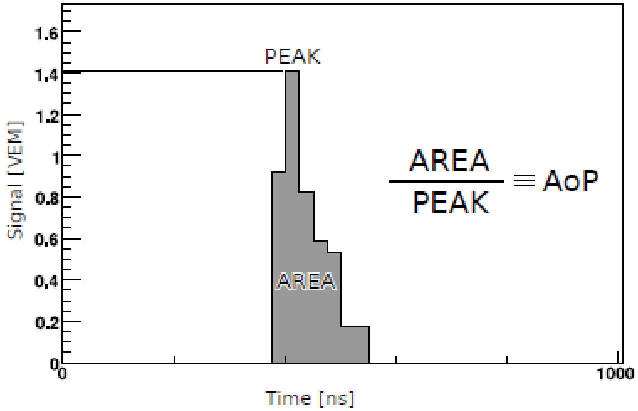


Young showers selection

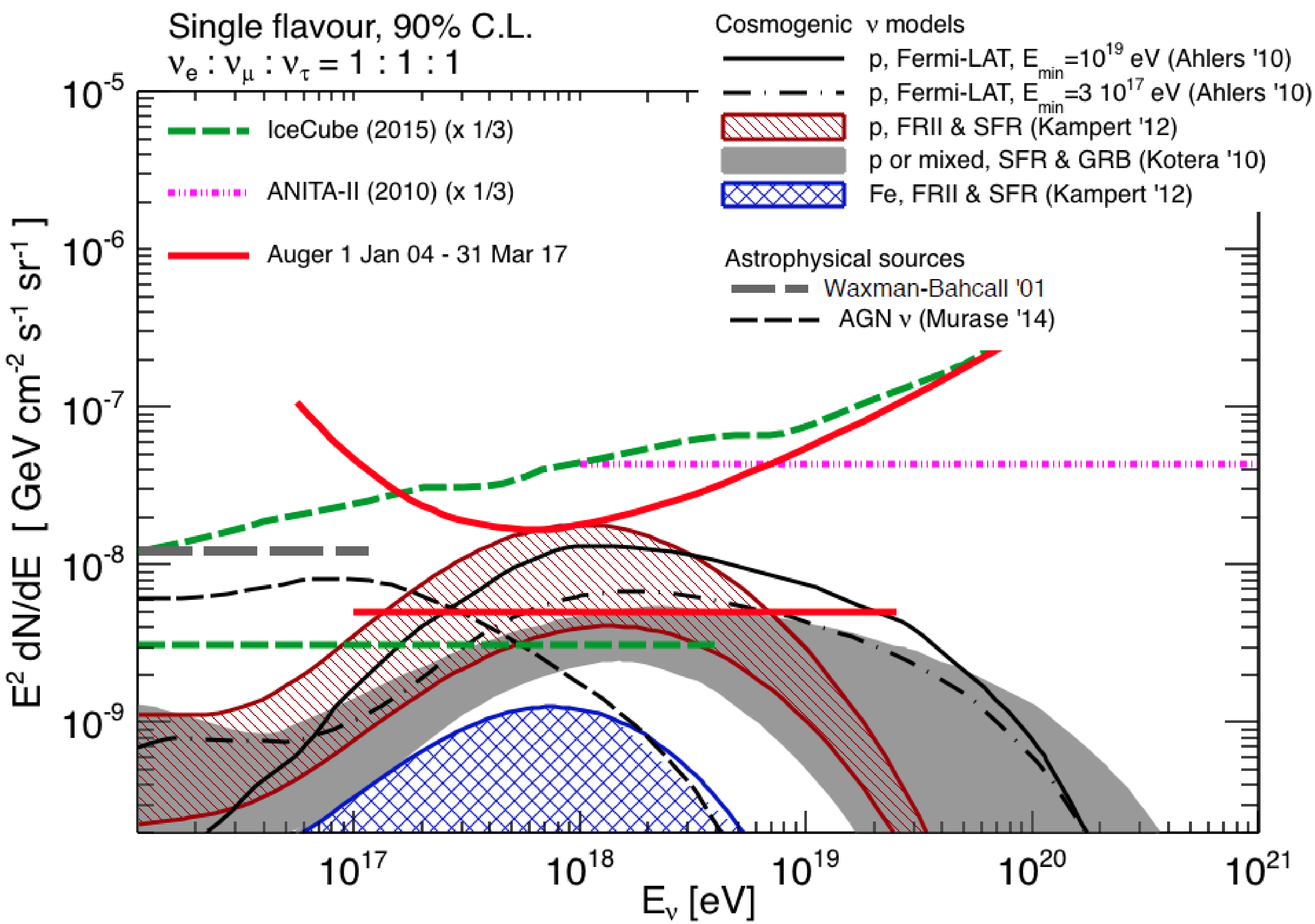
- **Area over Peak**: ratio of the integrated signal of the **3 PMTs** of each station over the biggest value of the signal
- Broad EM signals have values of AoP >> 1







Limit to diffuse flux: 1 Jan 04 – 31 Mar 17

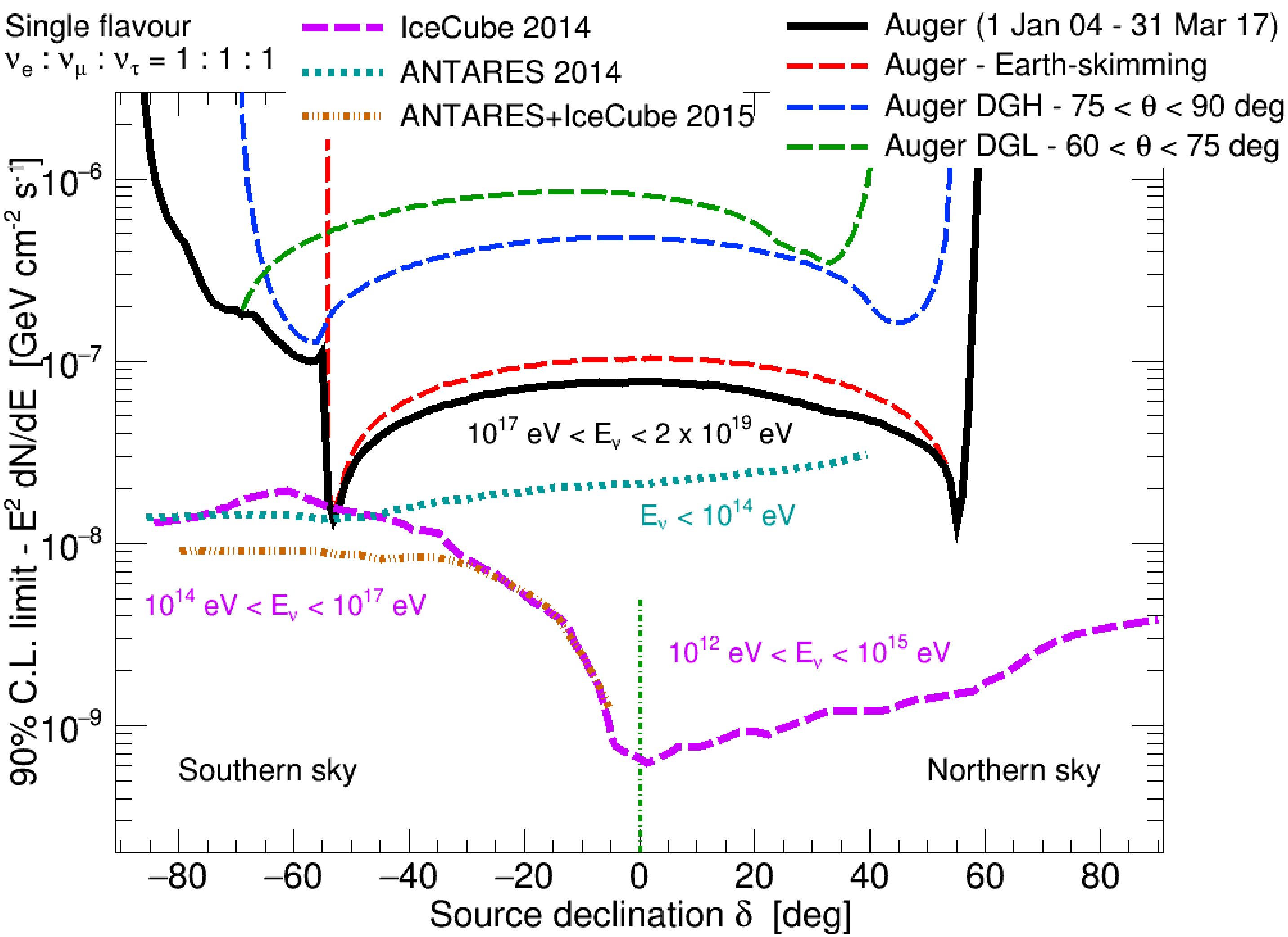


Auger LIMIT to normalization of **dN/dE = k E^{-2}**

1 Jan 04 – 31 Mar 17 → **$k \leq 5.0 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}**

Limits to point-like sources of UHEν:

1 Jan 04 – 31 Mar 17



Expected events: 1 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, $E_{\rm max} = 10^{21}$ 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, $E_{\rm min} = 10^{19}$ eV (Ahlers 2010)	~ 4.0
Cosmogenic - proton, Fermi-LAT, $E_{\rm min} = 10^{17.5}$ 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**

- **Cosmogenic neutrinos:**

– Protons & Strong source evolution (FRII – like): **excluded.**

– Protons & Source evolution comparable to GRB & SFR: **beginning to be constrained.**

– Protons & models normalized to observed diffuse GeV γ-rays (Fermi-LAT): **excluded**

– Mixed or pure Fe composition: **unreacheable with current Auger**

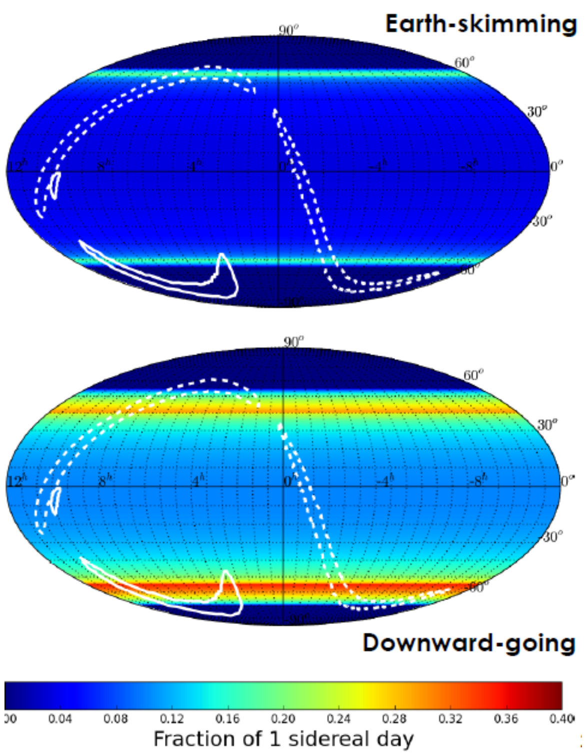
- **Astrophysical sources:**

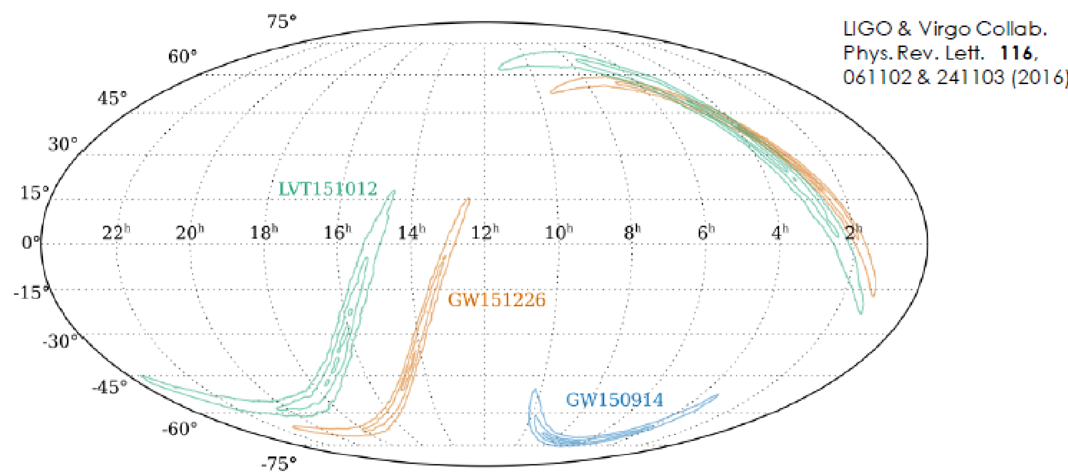
– Weak constraints on models that peak below 10^{17} eV.

– Radio-loud AGNs with large UHECR luminosity : **disfavored/excluded**.

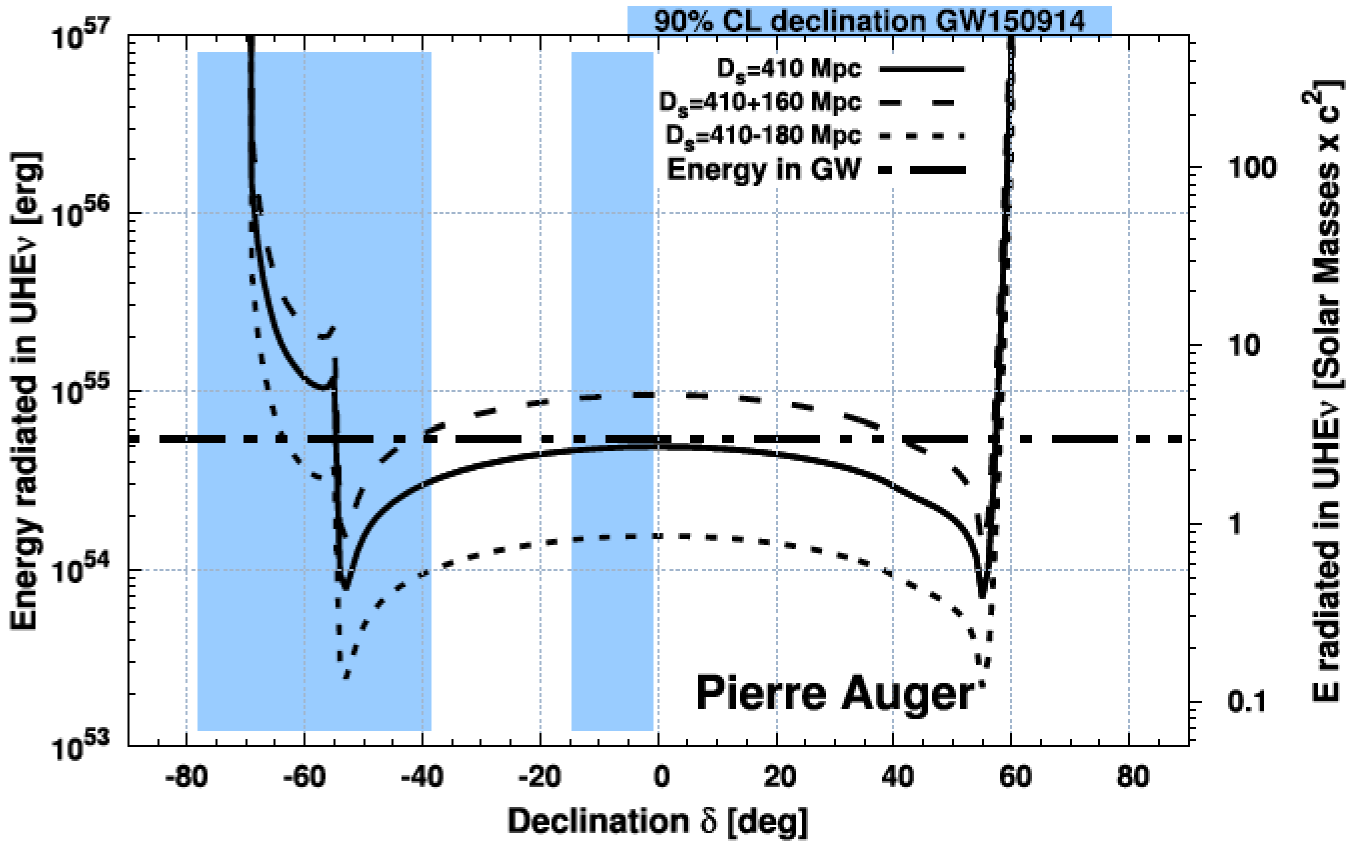
Search for UHEν in coincidence with Gravitational Wave events

- Merger of binary black-hole at D = 410 & 440 Mpc
- ~ 3 & 1 solar masses released in the form of GW





Constraints on energy radiated in the form of UHEν (Eν> 10^{17}eV)

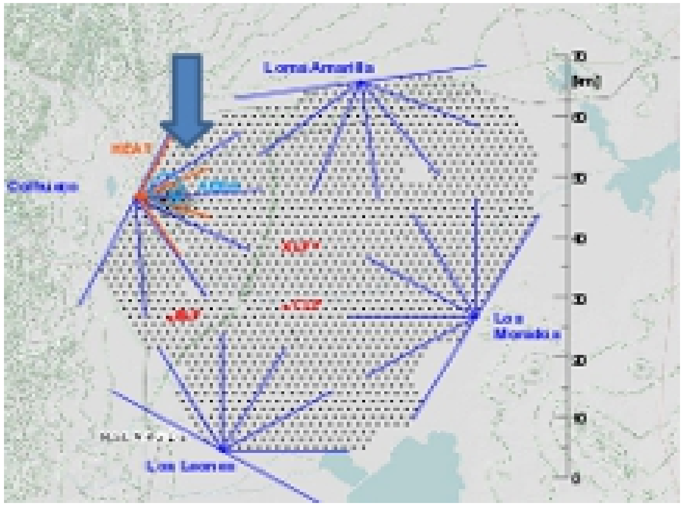


Pierre Auger, arXiv:1608.07378

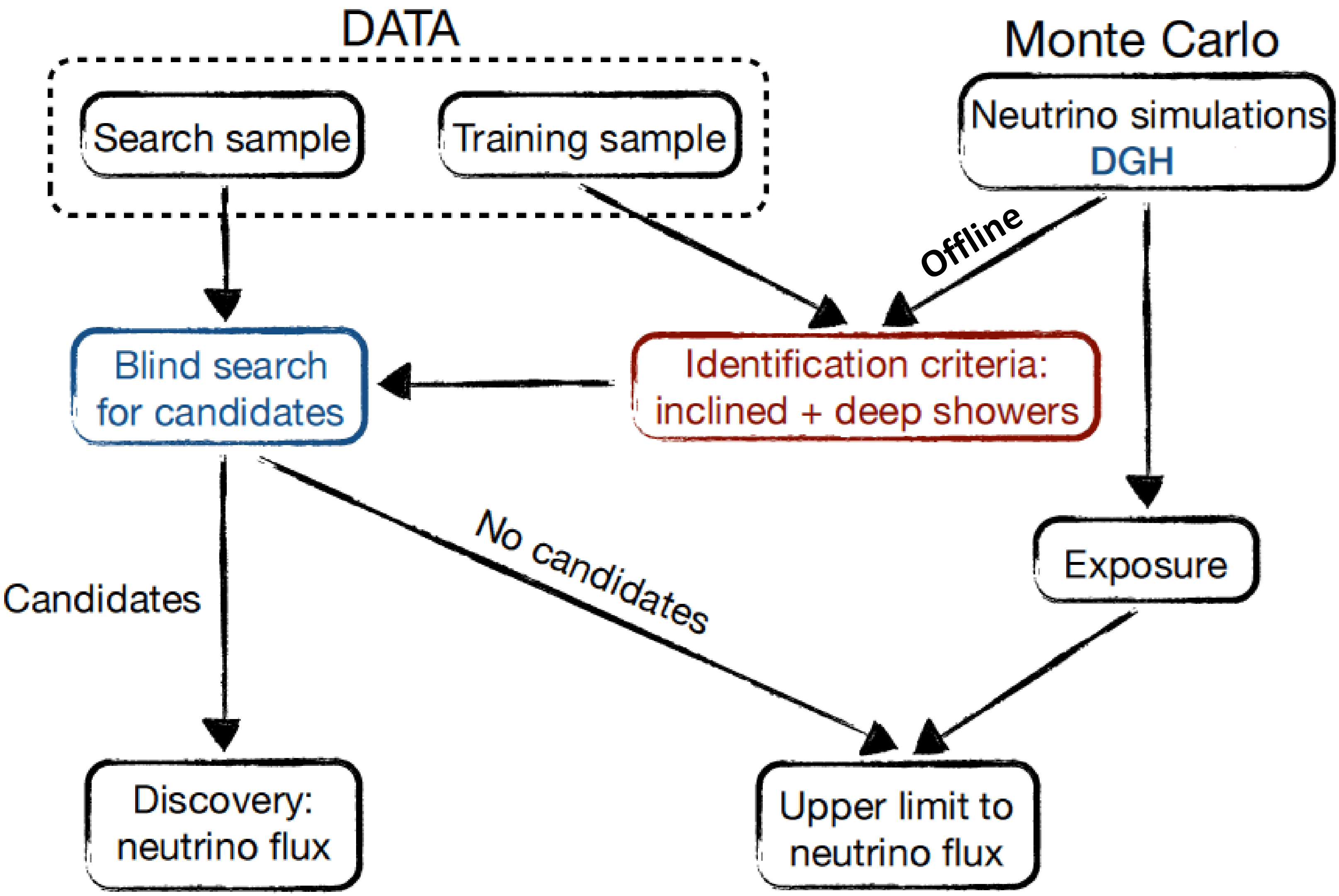
Constraints on energy radiated from **GW150914** in UHEν: less than (0.5, 3) solar masses depending on source declination

Neutrinos at the Infilled Array

- Smaller space grid ⇨ optimal neutrino detection efficiency at lower energies than SD1500 (10s PeV-EeV)
- Infilled array area about 100 times smaller than the standard array ⇨ small exposure (10yrs data)
- The PeV-EeV energy range is particularly interesting:
- for neutrino astrophysics
- energy range of transition between galactic and extragalactic cosmic rays



General strategy



Conclusions

- The Pierre Auger Observatory has complementary properties to other ν telescopes
- Largest exposure at **EeV** energies (cosmogenic)
- Different flavour response to underwater/ice telescopes (very sensitive to $\nu\tau$ in a small δ range, lowest sensitive to $\nu\mu$
- The current Auger limit is a factor $\sim$4 below the Waxman-Bahcall bound on neutrino production in optically thin sources $\rightarrow$ not optimistic scenario.

Thank you!