Waxman and Bahcall meet Auger @ a single energy bin

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Table of Contents

Cosmic ray $\leftrightharpoons$ neutrino connection

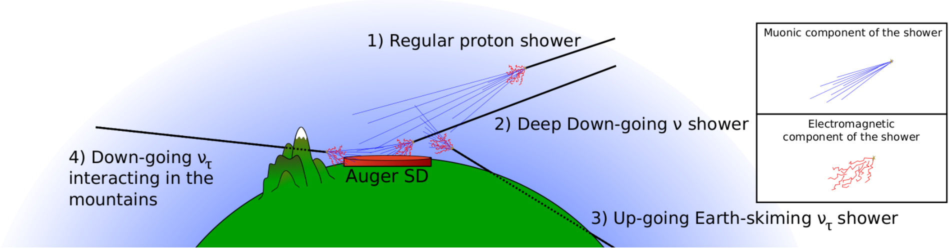
1. UHEν's are expected to be produced through decay of $\pi^{\pm}$'s which originate in CR interactions with matter and or radiation
2. CRs could scatter off ambient gas and thermal photons while undergoing acceleration at sources or *en route* to Earth
3. Observation of UHEν's can provide clues on:
   - Dominant mechanism for CR production
   - Cosmological evolution of CR sources
   - CR nuclear composition (constraint on proton fraction)

   `(Ahlers-LAA-Sarkar,2009)`
4. PeV neutrino detection @ IceCube ☞ major breakthough in field

   `(IceCube Collaboration,2013-2014)`
5. EeV ν's have so far escaped detection by existing experiments
6. Waxman-Bahcall energetics sets upper bound on these ν's

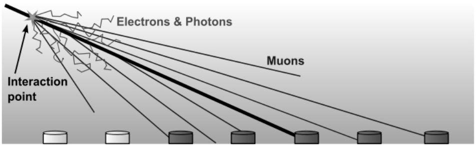
   `(Waxman-Bahcall,1999)`

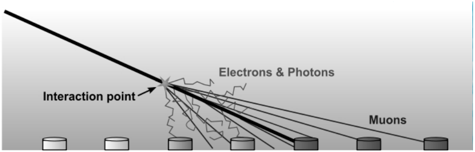
1,600 water-Cherenkov stations overlooked by 4 fluorescence detectors



Baryonic background

- Quasi-horizontal showers traverse several vertical atmospheres
- Beyond two vertical atm most EM component is extinguished
- Hadron shower front is relatively flat only very high μ's survive

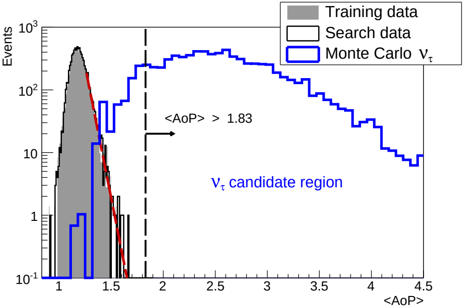


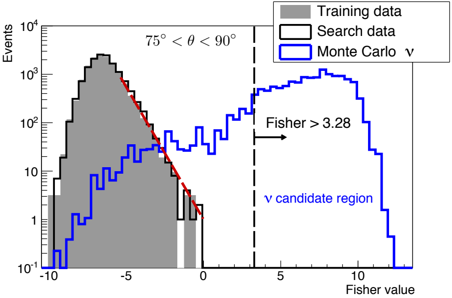


AoP

- Auger is not directly sensitive to μ and EM components separately nor to depth at which shower is initiated
- Signals produced by passage of shower particles are digitized by flash analog to digital converters (FADC) with 25 ns resolution
- FADC traces allow discrimination of narrow signals in time from broad signals expected in showers initiated close to ground
- Area-over-Peak ☞ ratio of integral of FADC trace to its peak value normalized to average signal produced by single muon
- AoP provides estimate of spread time of traces
  ☞ observable to discriminate broad from narrow shower fronts
- Optimization of signal-to-noise separation via Fisher discriminant: projection of the distributions of discriminating variables onto a line

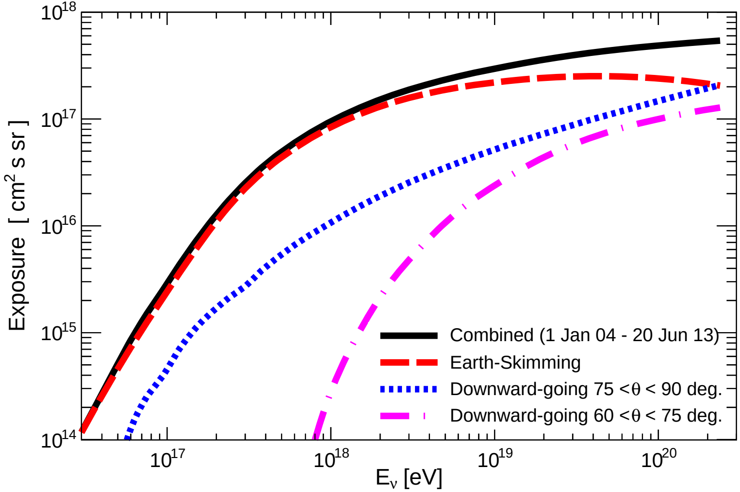
Distributions of ⟨AoP⟩ and Fisher variable





- $90^\circ < \theta < 95^\circ$ ☞ $\langle \mathrm{AoP} \rangle$ over all triggered stations
- $75^\circ < \theta < 90^\circ$ ☞ linear combination of:
  1. AoP and $(\mathrm{AoP})^2$ of four stations that trigger first in each event
  2. product of four AoP
  3. global parameter measuring asymmetry between average AoP of early stations and those triggered last on event
- $60^\circ < \theta < 75^\circ$ ☞ individual AoP of four or five stations closest to core

$\mathcal{E}$



Exposure [cm^2 s sr]
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{17}
10^{18}
10^{19}
10^{20}
E_ν [eV]
Combined (1 Jan 04 - 20 Jun 13)
Earth-Skimming
Downward-going 75 <θ < 90 deg.
Downward-going 60 <θ < 75 deg.

(01/01/04 – 06/20/13) data unblinding ☞ no events survive selection criteria

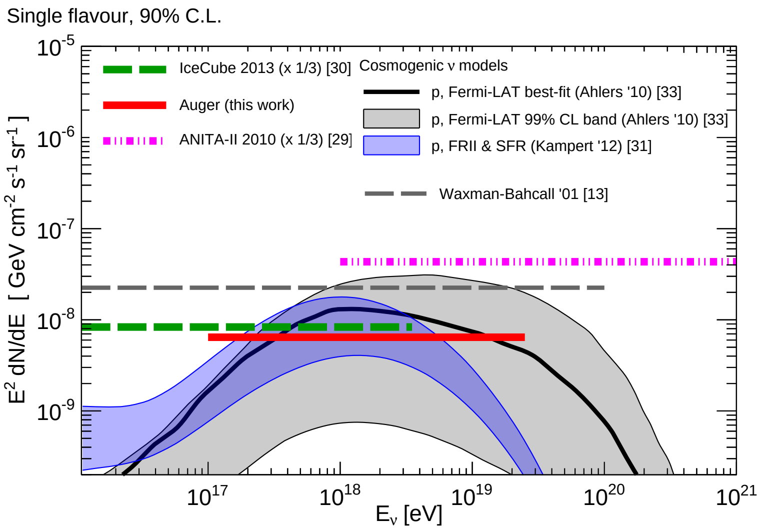
90% CL upper limit on ν-flux normalization for Fermi engines

- Assume differential ν flux ☞ $\frac{dN}{dE_\nu} = N_0\, E^{-2}$
- Assume flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$
- Assume zero background events ☞ $N_0 = \frac{2.4}{\int_{E_{\nu,min}} E_\nu^{-2}\, \mathcal{E}_{\rm tot}(E_\nu)\, dE_\nu}$

Systematic uncertainties

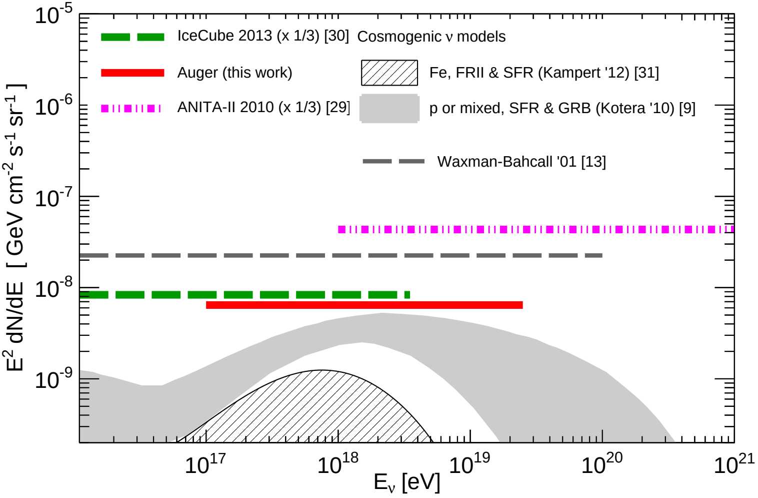
Source of systematic	Combined uncertainty band
Simulations	$\sim$ +4%, -3%
ν cross section & τ E-loss	$\sim$ +34%, -28%
Topography	$\sim$ +15%, 0%
Total	$\sim$ +37%, -28%

90% CL upper limit on N_0

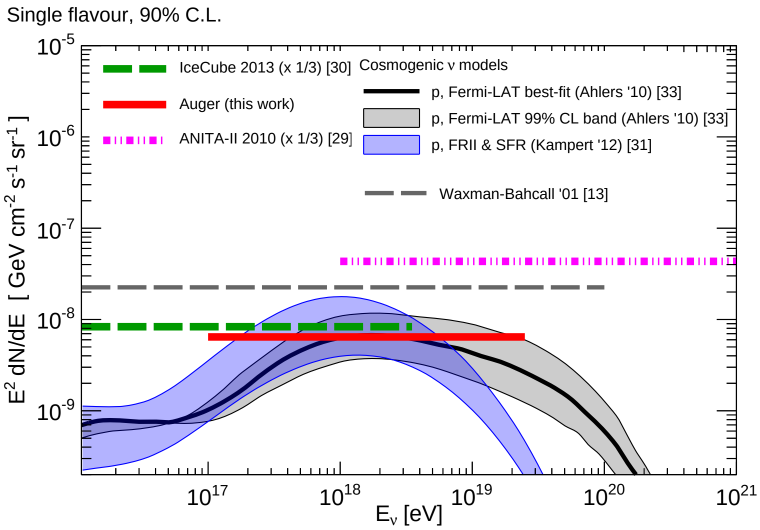


90% CL upper limit on N_0

Single flavour, 90% C.L.



90% CL upper limit on N_0



Model-independent 90%CL upper limit on ν flux

- If number of events integrated over energy is bounded by 2.4 it is also certainly true bin by bin in energy

- At 90% CL for some interval Δ ☞ $\int_\Delta dE_\nu \, \frac{dN}{dE_\nu} \, \mathcal{E}_{\rm tot}(E_\nu) \; < 2.4$
- In logarithmic interval Δ ☞ take $\frac{dN}{dE_\nu} \; \mathcal{E}_{\rm tot}(E_\nu) \sim E_\nu^\alpha$ to obtain

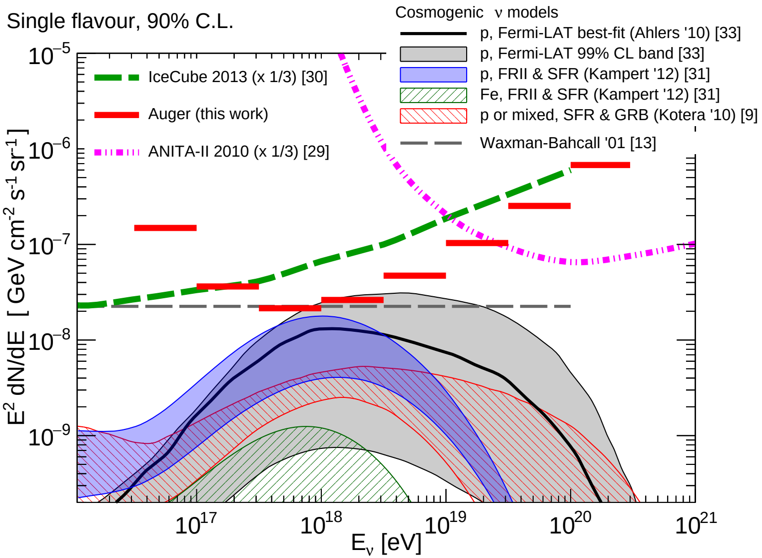
$$\int_{\langle E_\nu \rangle e^{-\Delta/2}}^{\langle E_\nu \rangle e^{\Delta/2}} \frac{dE_\nu}{E_\nu} \, E_\nu \, \frac{dN}{dE_\nu} \, \mathcal{E}_{\rm tot}(E_\nu) = \langle \mathcal{E}_{\rm tot}(E_\nu) \, E_\nu \, dN/dE_\nu \rangle \, \frac{\sinh \delta}{\delta} \, \Delta$$

  with $\delta = (\alpha + 1)\Delta/2$
- Since $\sinh \delta / \delta > 1$ ☞ $\langle \mathcal{E}_{\rm tot}(E_\nu) \rangle \, \langle E_\nu dN/dE_\nu \rangle < 2.4/\Delta$

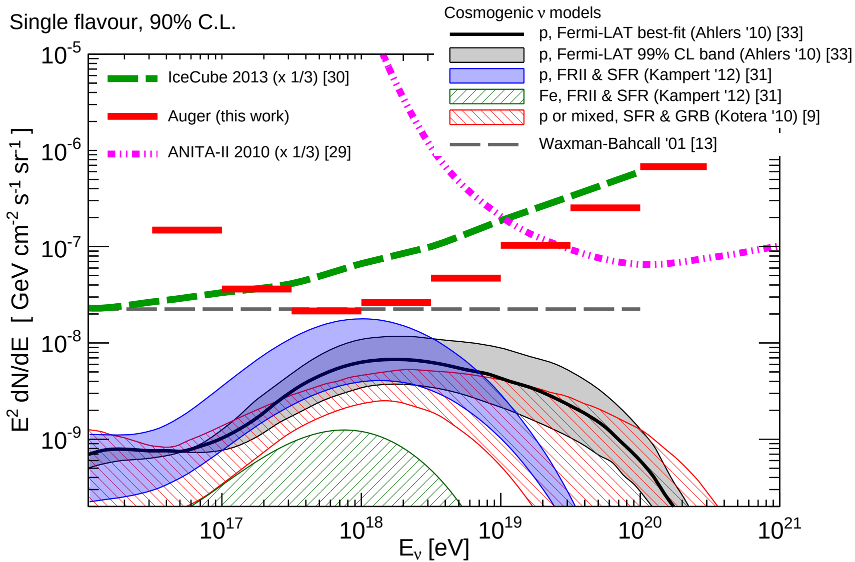
(LAA-Feng-Goldberg-Shapere,2002)

Hereafter ☞ $\Delta = 0.5$ in $\log_{10} E_\nu$

90% CL upper limit on ν flux



90% CL upper limit on ν flux



Take home message

1. No ν candidates were found
2. Flux upper limit challenges predictions near WB bound
3. Maximum sensitivity of Auger is achieved in EeV bins
4. Energy weighted cosmogenic ν-flux also peaks around EeV
5. Extrapolation of IceCube flux

$$\frac{dN}{dE_\nu} = 2.06 \times 10^{-18} \left(\frac{E_\nu}{10^5 \mathrm{GeV}}\right)^{2.46} (\mathrm{GeV\,cm^2\,s\,sr})^{-1}$$

up to 10^{11} GeV ☛ would produce ~ 0.1 events @ Auger