# EeV Neutrinos in UHECR Surface Detector Arrays:

## Challenges & Opportunities

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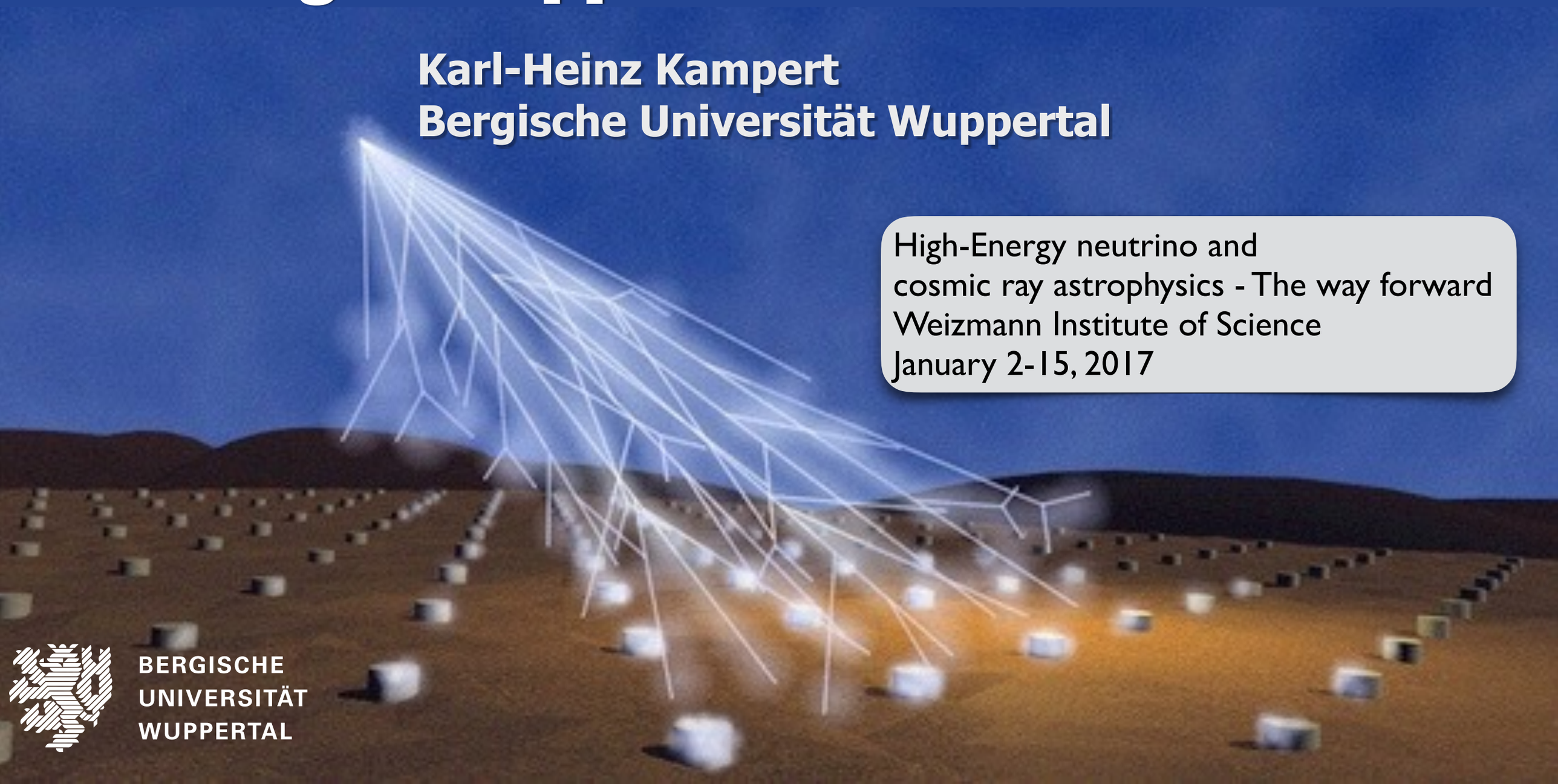


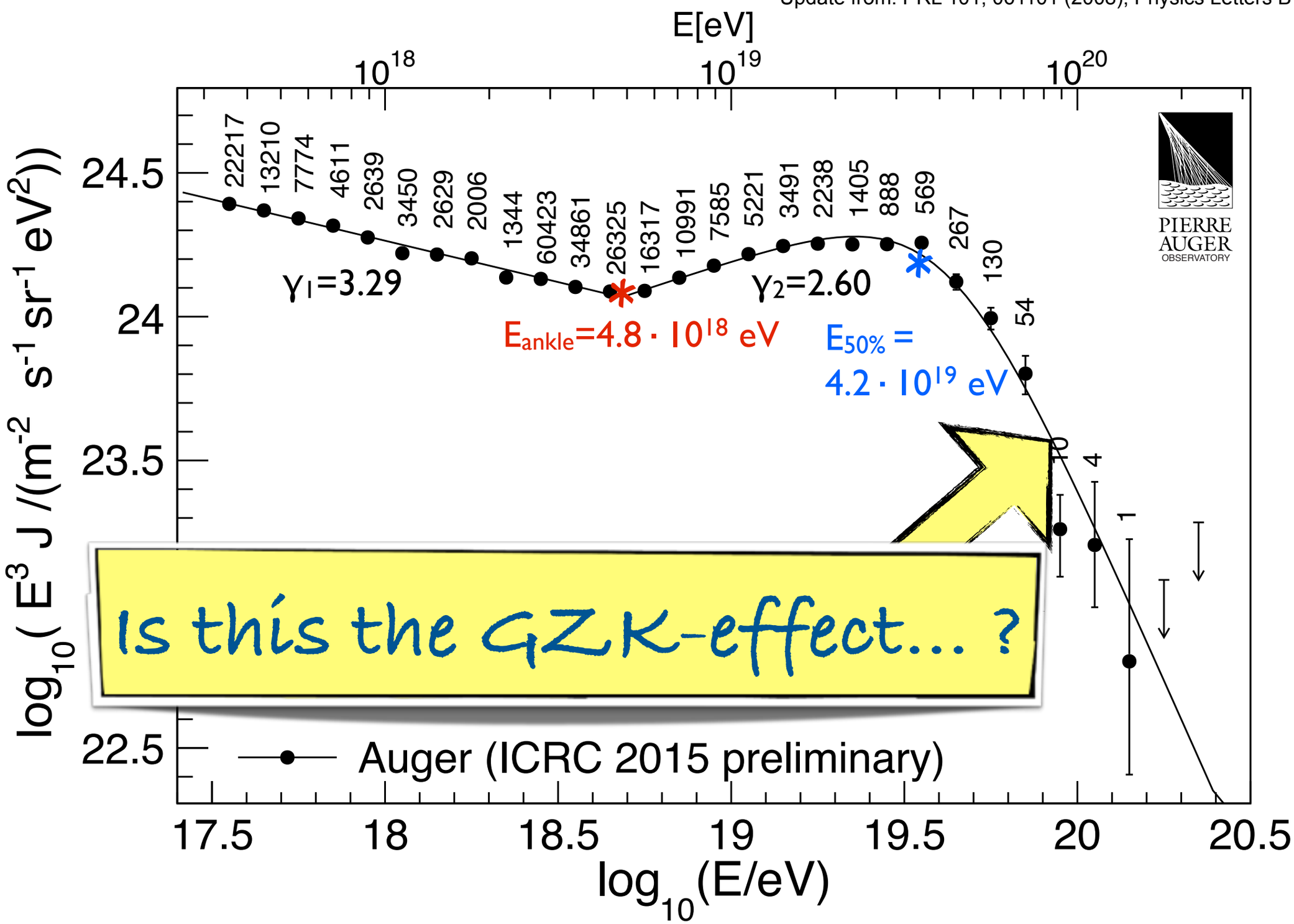
High-Energy neutrino and
cosmic ray astrophysics - The way forward
Weizmann Institute of Science
January 2-15, 2017

PIERRE AUGER OBSERVATORY

BERGISCHE UNIVERSITÄT WUPPERTAL

# The Search for GZK Suppression

arXiv:1509.03732
Update from: PRL 101, 061101 (2008), Physics Letters B 685 (2010) 239




combined from: infill+hybrid+vertical+inclined events

# Cosmogenic Neutrinos

Recall:

- If flux suppression above $5.10^{19}$ eV is due to GZK-effect: expect cosmogenic neutrinos & photons as „smoking gun"
- Additional benefit: UHE neutrino physics

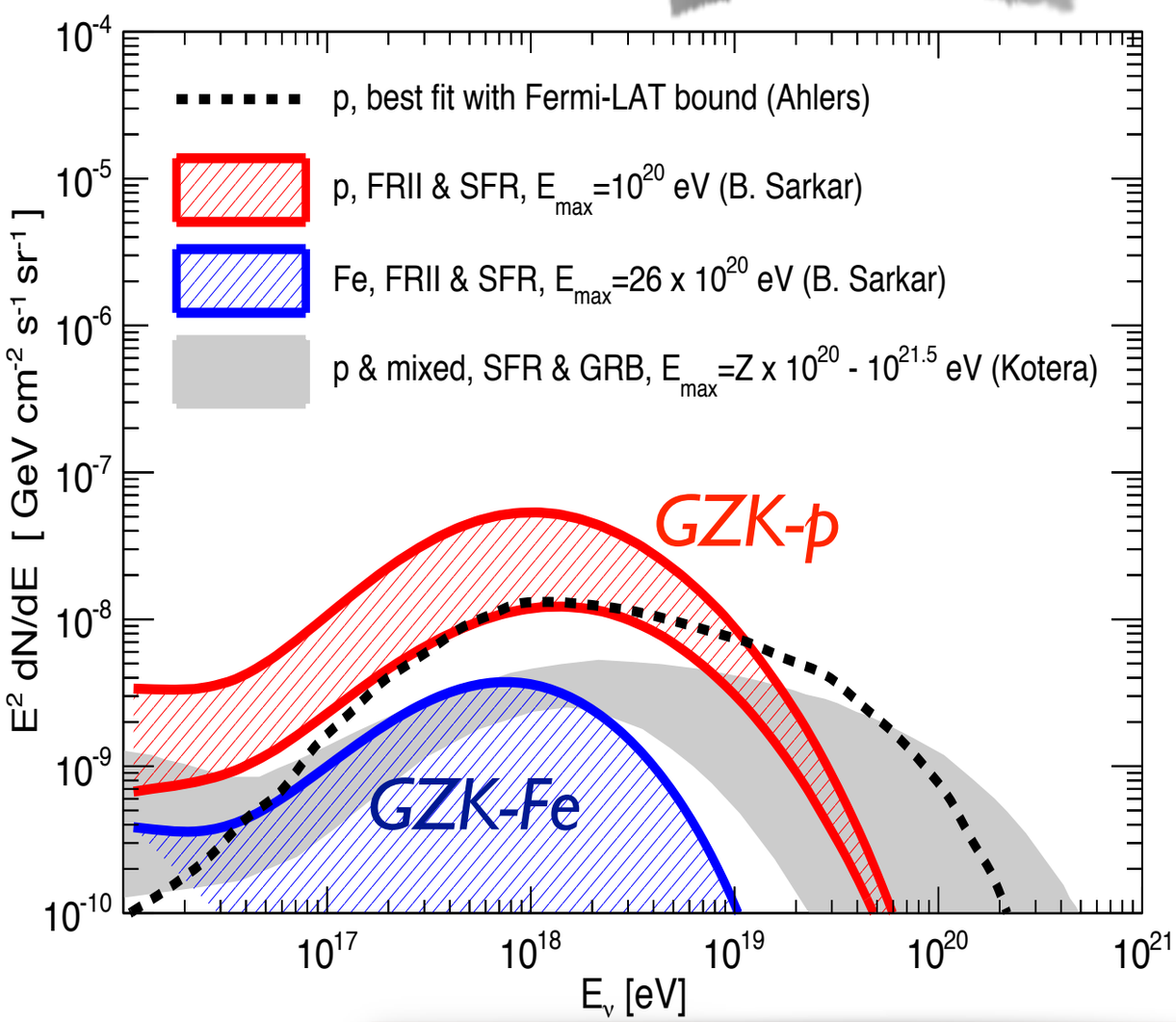
- If due to source exhaustion: neutrinos & photons strongly suppressed

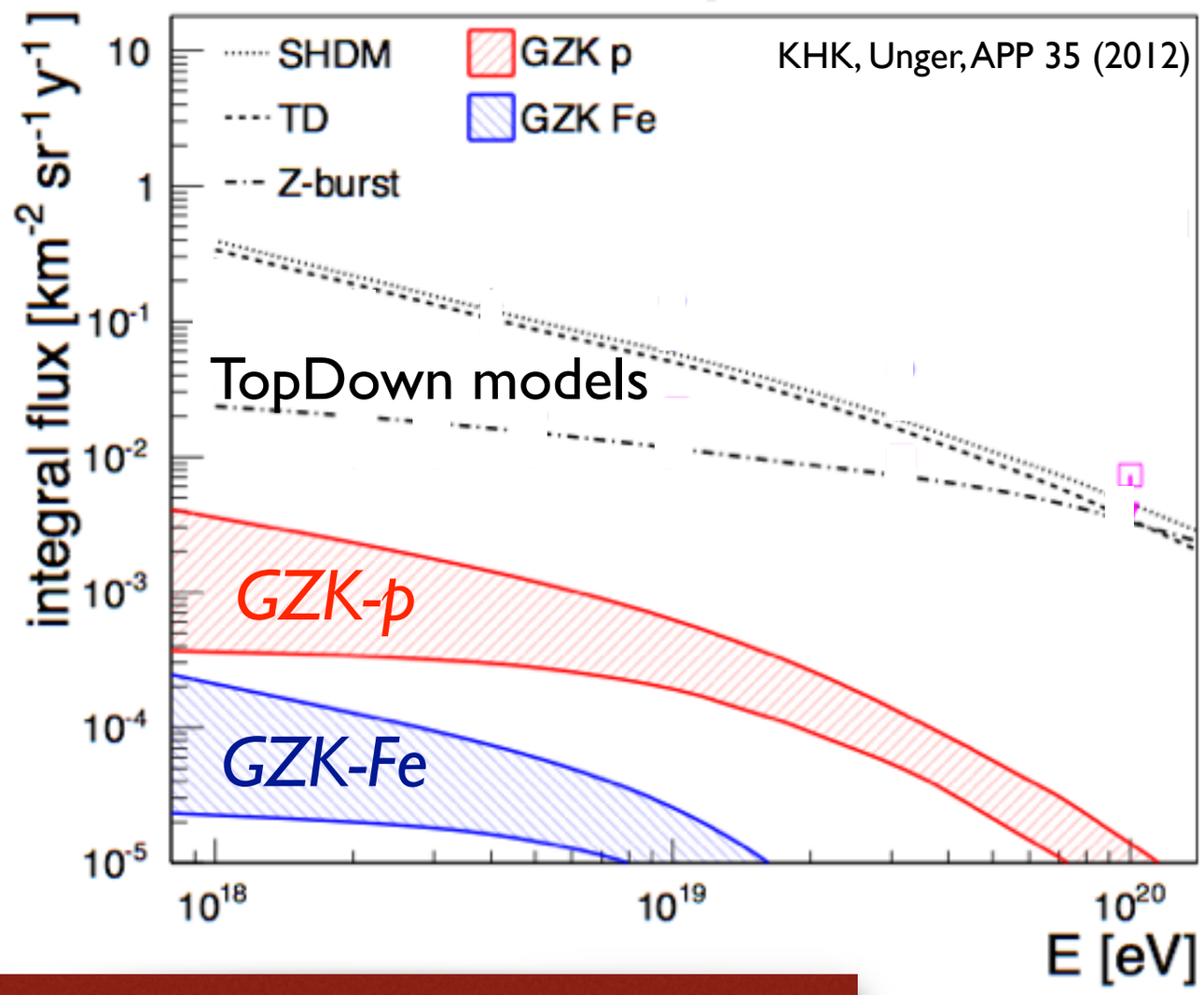
# EeV ν's and γ's : Smoking gun of GZK-effect

$$p + \gamma_{\rm CMB} \to \Delta \to$$

$$\to n + \pi^+ \to \nu_{\rm EeV}$$

$$\to p + \pi^0 \to \gamma_{\rm EeV}$$

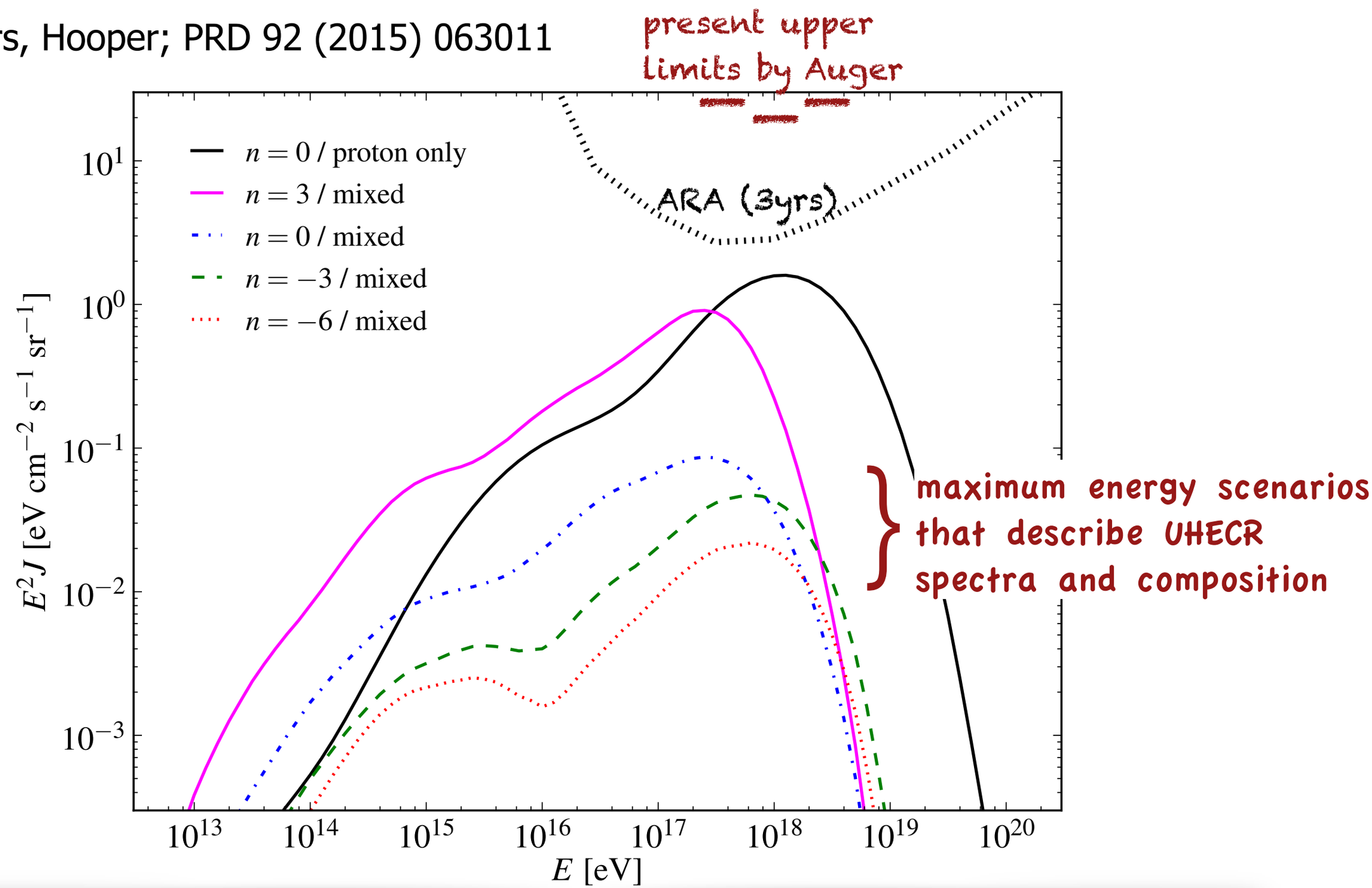



Note, these calculations assume that the flux suppression is caused solely by the GZK-effect

# Exhausted UHECR Sources

Taylor, Ahlers, Hooper; PRD 92 (2015) 063011

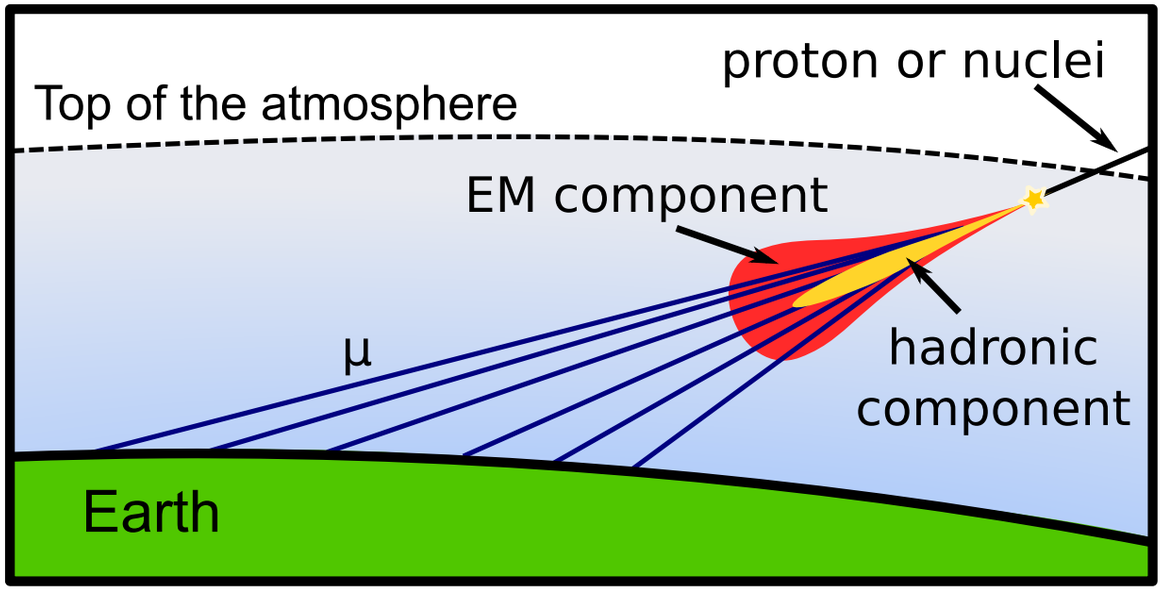


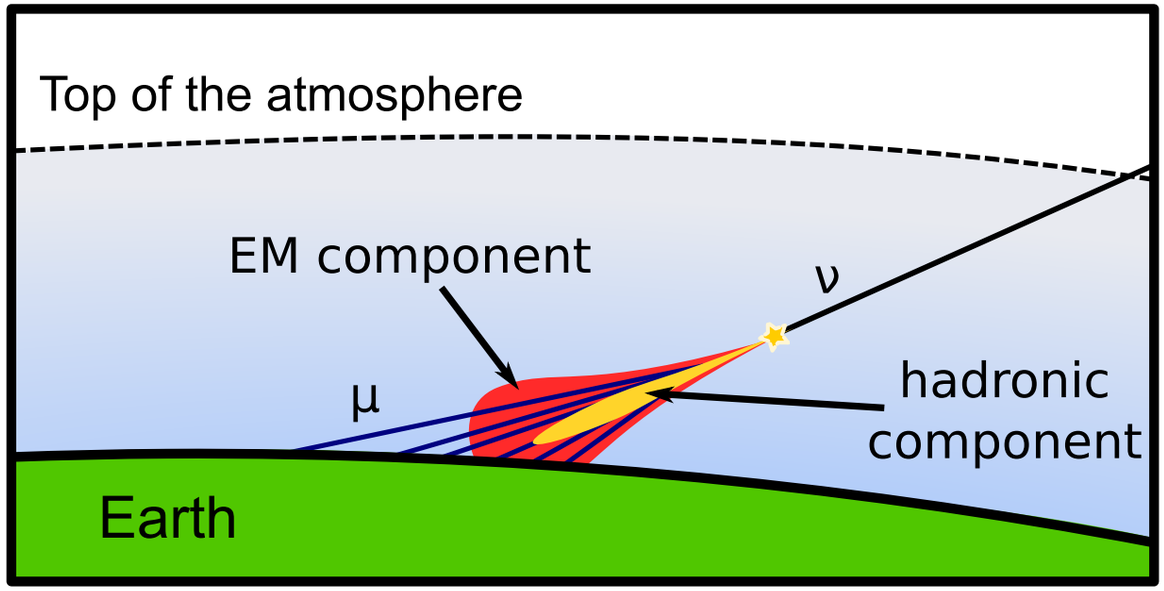

**Cosmogenic neutrino fluxes may be down by ~2 orders of magnitudes for exhausted sources !!**

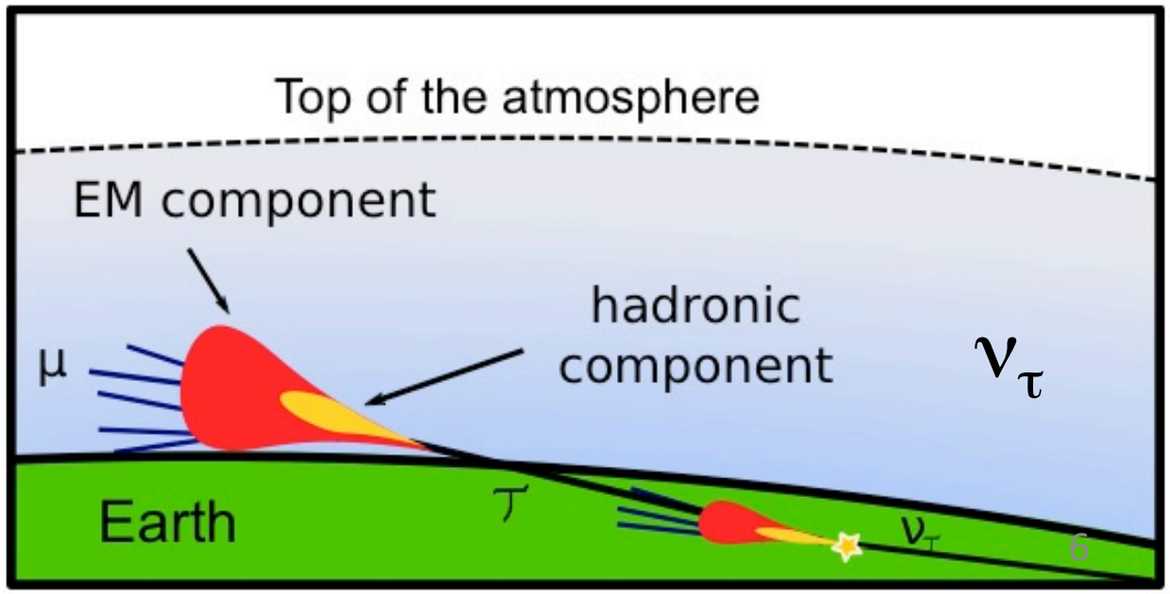
# Search for EeV Neutrinos in inclined showers

- 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

Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component



# Particle Detectors and Radio Antennas

**This talk:**

Particle Detectors at the surface: Auger and beyond
Optical detection by Fluorescence Telescopes not covered
(lower exposure because of duty cycle)

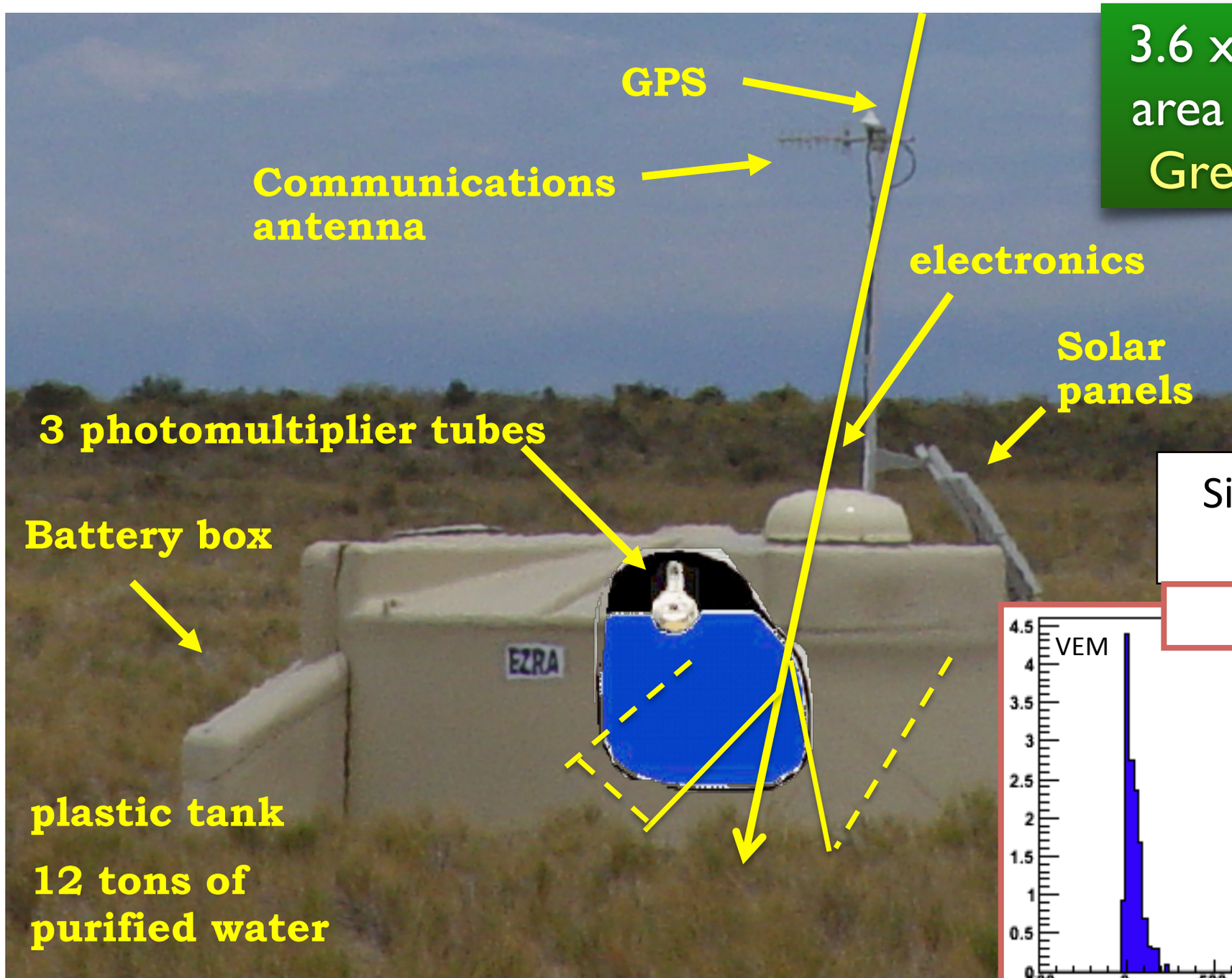
**Next Talk by Jörg Hörandel:**

Potential of radio detection at the surface

# Surface Detector Station

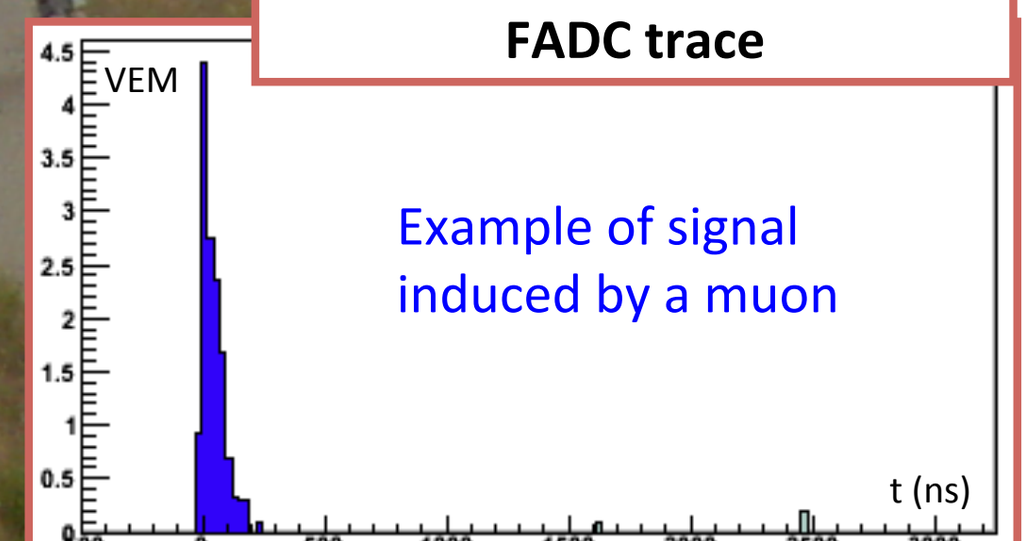
- ✓ Sensitive to inclined showers.
- x Not directly sensitive to electromagnetic and muonic components.
- ✓ Can measure the time structure of the signals induced by electrons and muons

3.6 x 1.2 = 4.3 $m^2$ detector area in horizontal direction. Great advantage of WCD!




Signals are digitized with 25 ns time resolution

**FADC trace**



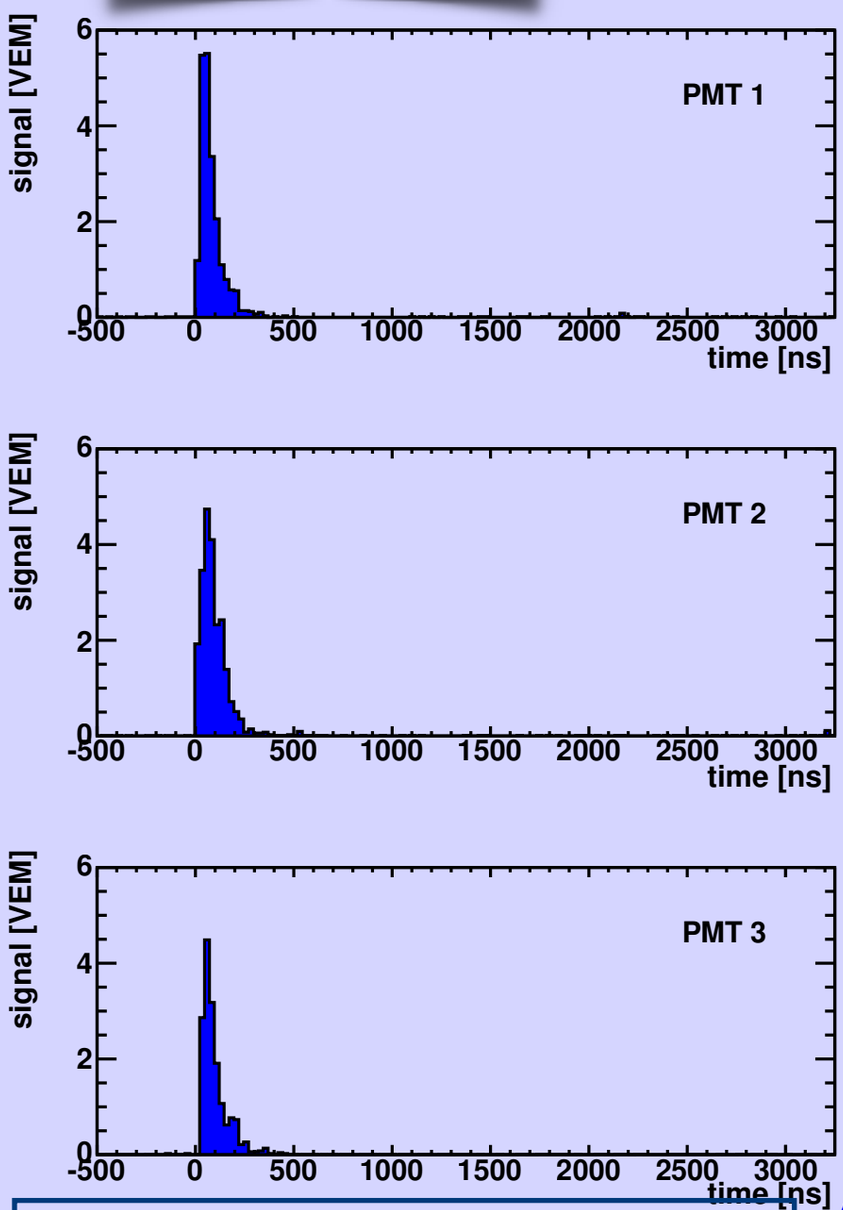

Example of signal induced by a muon

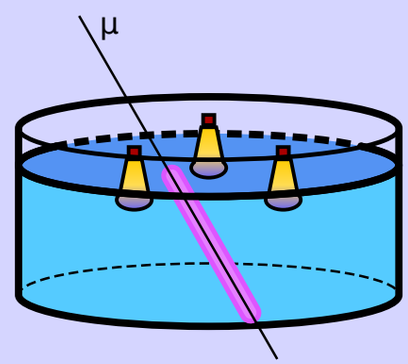
# Identifying νs in surface detector data

With the SD, we can distinguish muonic from electromagnetic shower fronts (using the time structure of the signals in the water Cherenkov stations).

Muonic shower front: narrow signals

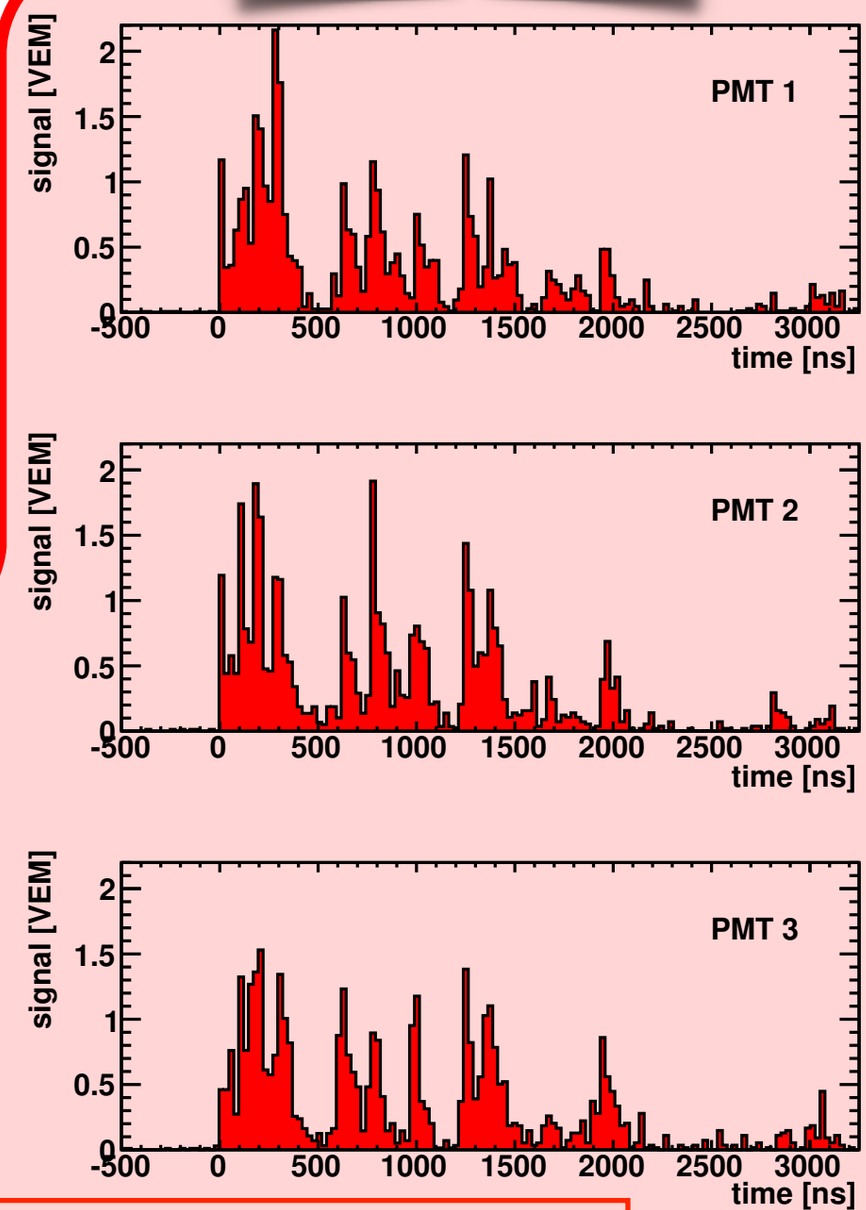
„old“ shower

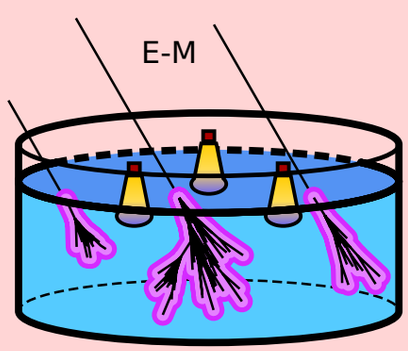



5 EeV, distance to shower axis ~1km
zenith angle ~80°

„new“ shower




*5 EeV, distance to shower axis ~1km*
*zenith angle ~22°*

EM shower front: broad signals

# Identifying νs in surface detector data

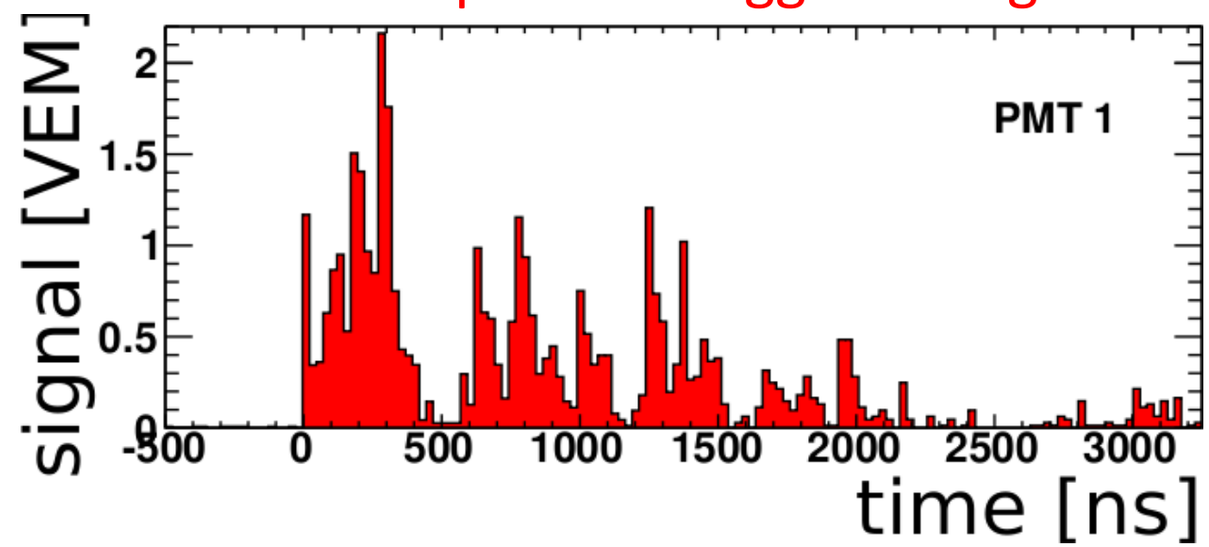
From the observational point of view, signals extended in time:

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

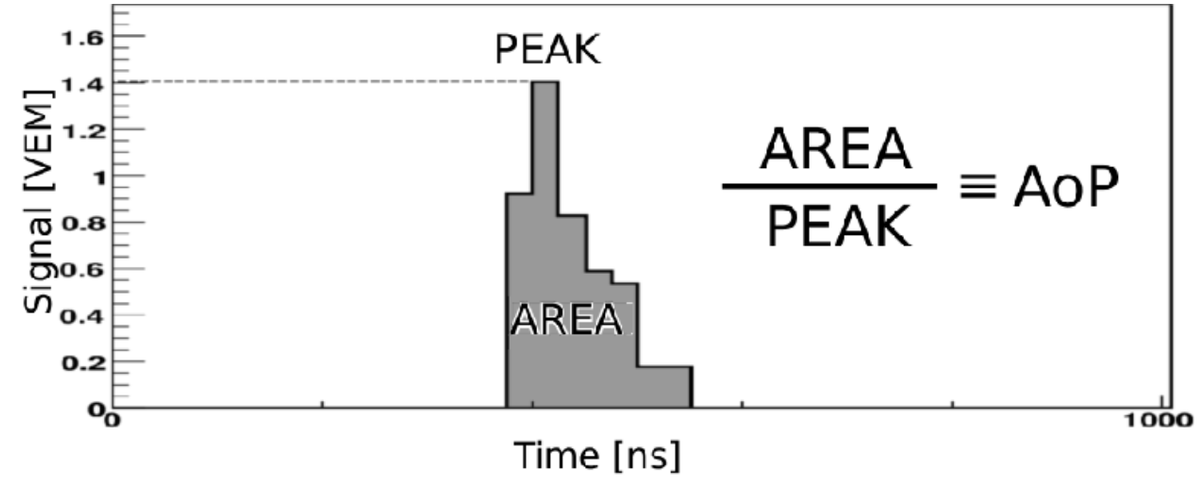
and/or

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

Trace example: ToT trigger & large AoP

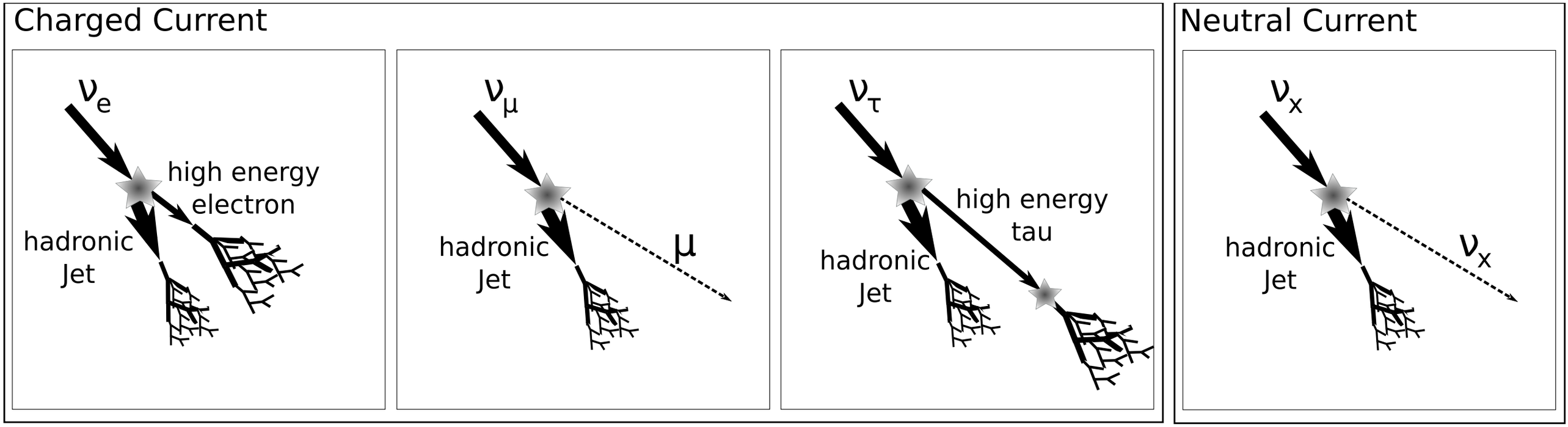


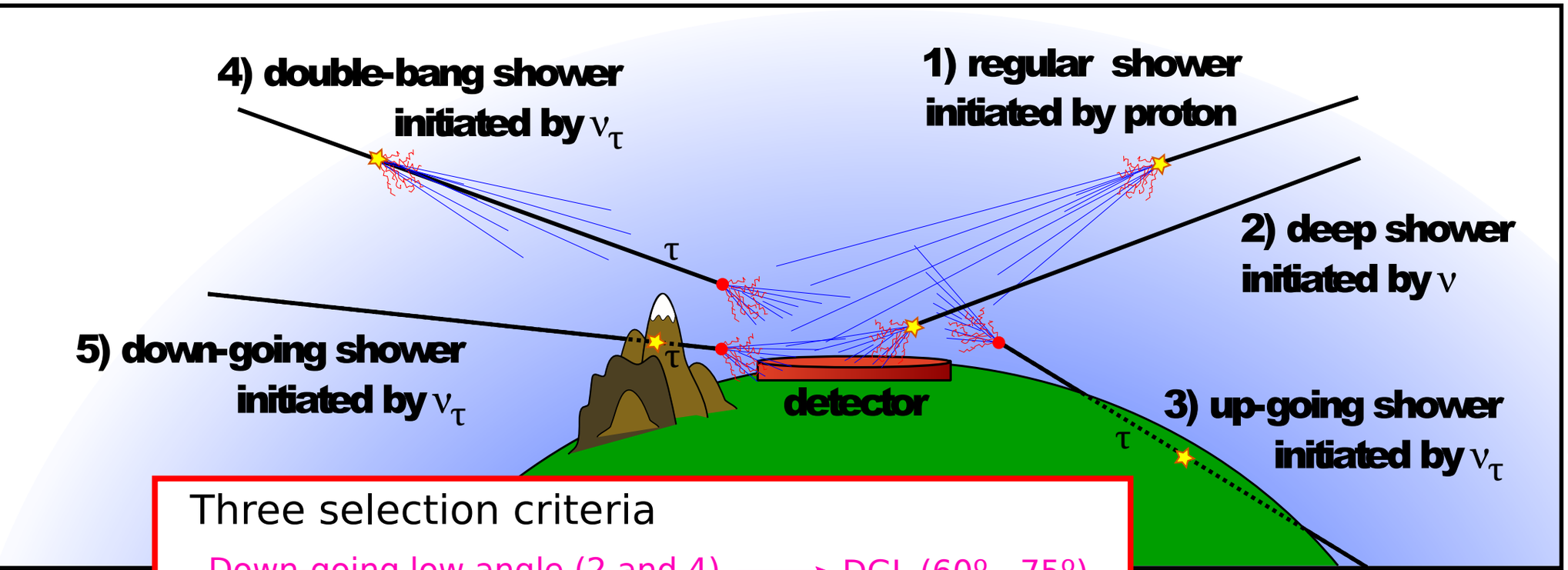

Definition of Area-over-Peak (AoP)

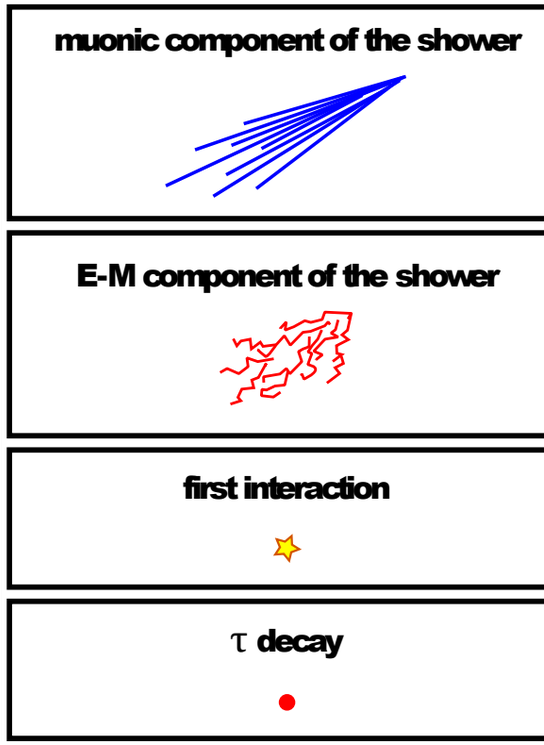



Searching for neutrinos ⇒
Searching for inclined showers with stations with ToT triggers and/or large AoP

# EAS are sensitive to all ν flavors and channels



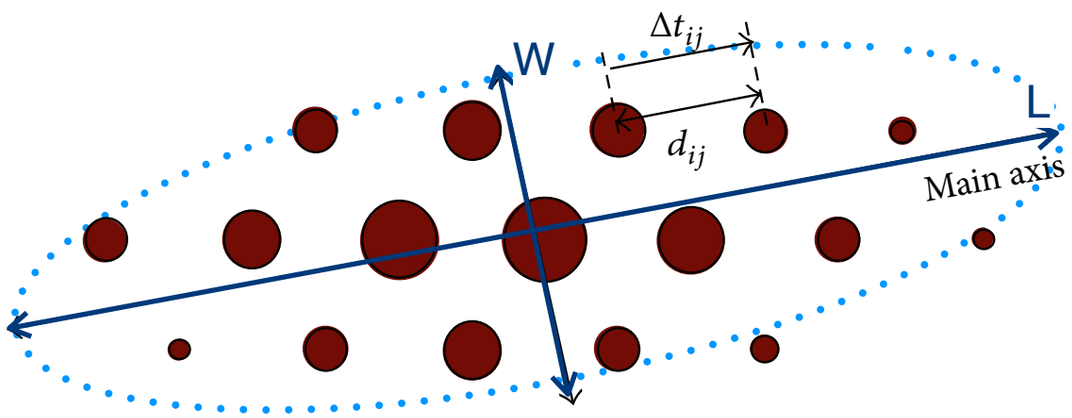




Three selection criteria

Down-going low angle (2 and 4) → DGL (60º - 75º)
Down-going high angle (2, 4 and 5) → DGH (75º - 90º)
Earth-skimming (3) → ES (90º - 95º)

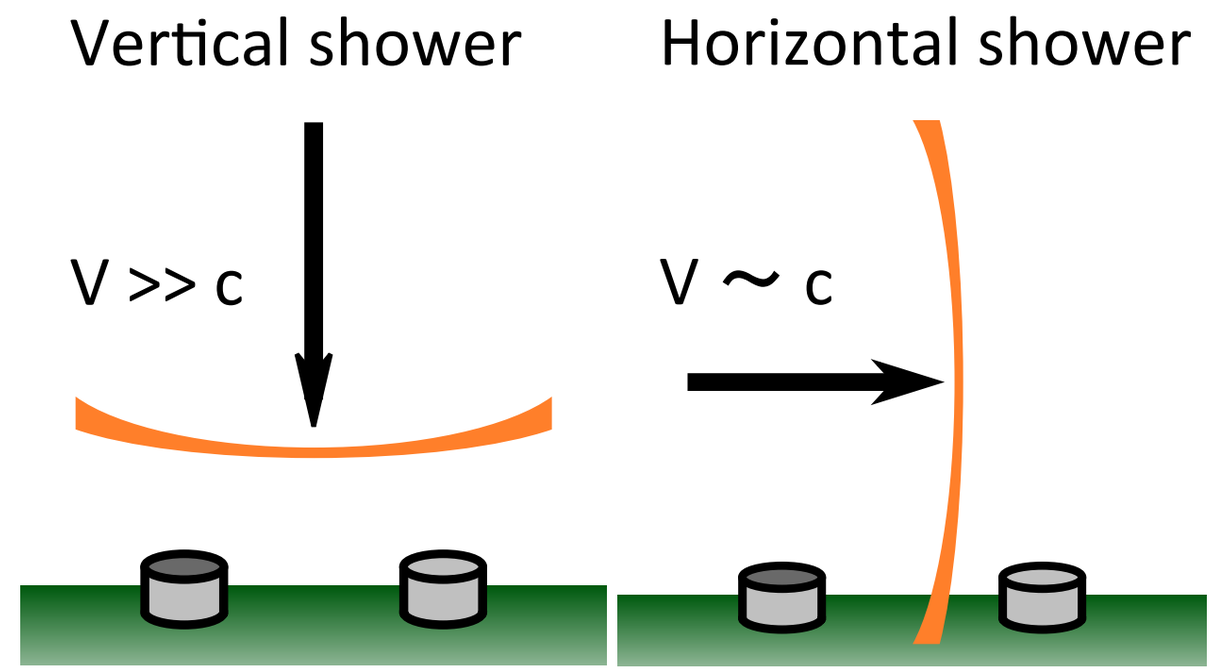
# Selection of inclined showers: 3 Observables

(1) Elongated footprint




Parameters: L/W, <v>, RMS(v)

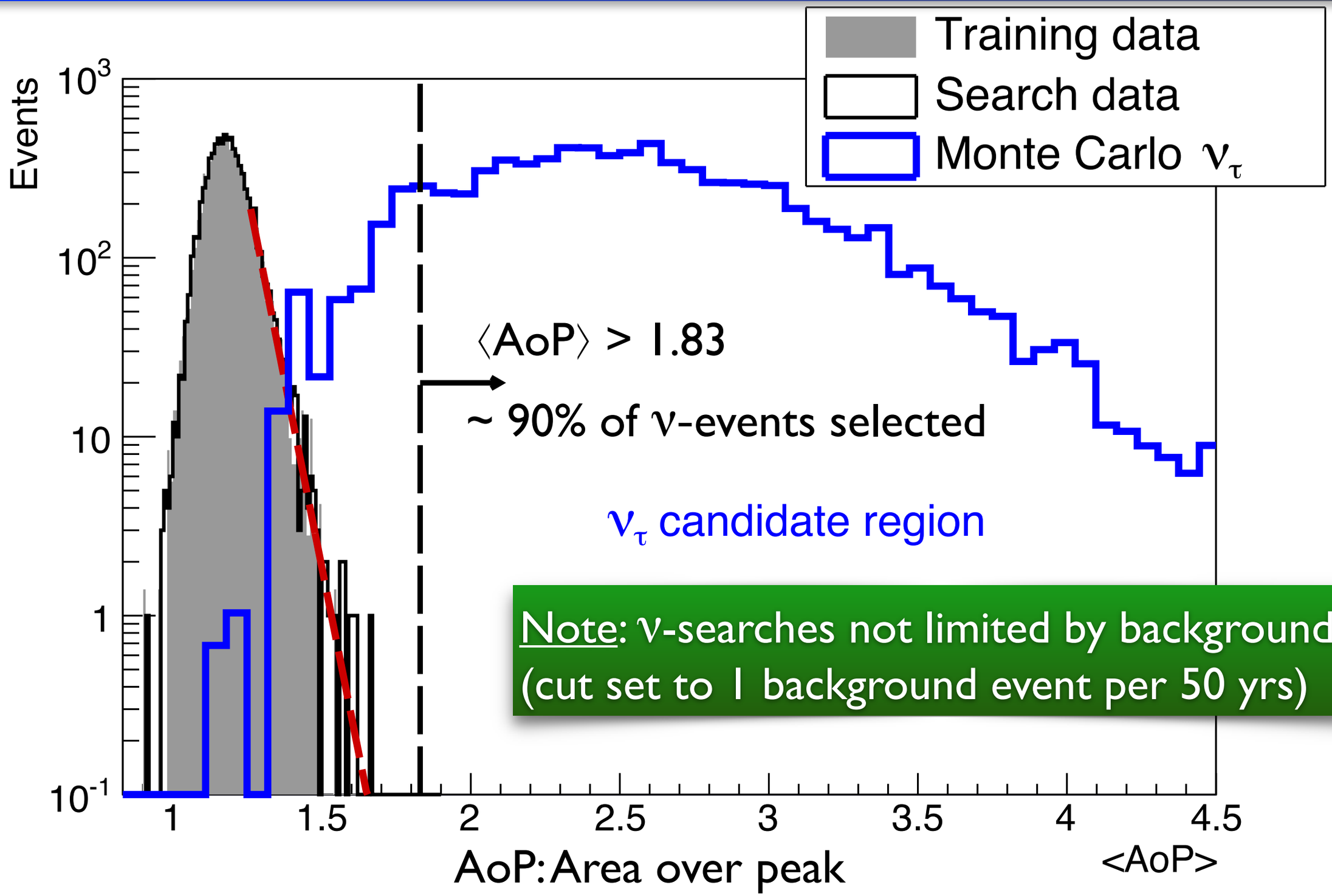
(2) Apparent velocity V of propagation of shower front at ground along major axis L




(3) Reconstructed θ

| Selection | Earth-skimming (ES) | Downward-going *high* angle (DGH) | Downward-going *low* angle (DGL) |
|---|---|---|---|
| Flavours and interactions | $\nu_\tau$ CC | $\nu_e, \nu_\mu, \nu_\tau$ CC & NC | $\nu_e, \nu_\mu, \nu_\tau$ CC & NC |
| Angular range | $\theta > 90°$ | $\theta \in (75°, 90°)$ | $\theta \in (60°, 75°)$ |
| N° of stations ($N_{\rm st}$) | $N_{\rm st} \geq 3$ | $N_{\rm st} \geq 4$ | $N_{\rm st} \geq 4$ |
| | | $\theta_{\rm rec} > 75°$ | $\theta_{\rm rec} \in (58.5°, 76.5°)$ |
| Inclined showers | $L/W > 5$<br>$\langle V \rangle \in (0.29, 0.31)$ m ns$^{-1}$<br>rms$(V) < 0.08$ m ns$^{-1}$ | $L/W > 3$<br>$\langle V \rangle < 0.313$ m ns$^{-1}$<br>rms$(V)/\langle V \rangle < 0.08$ | |

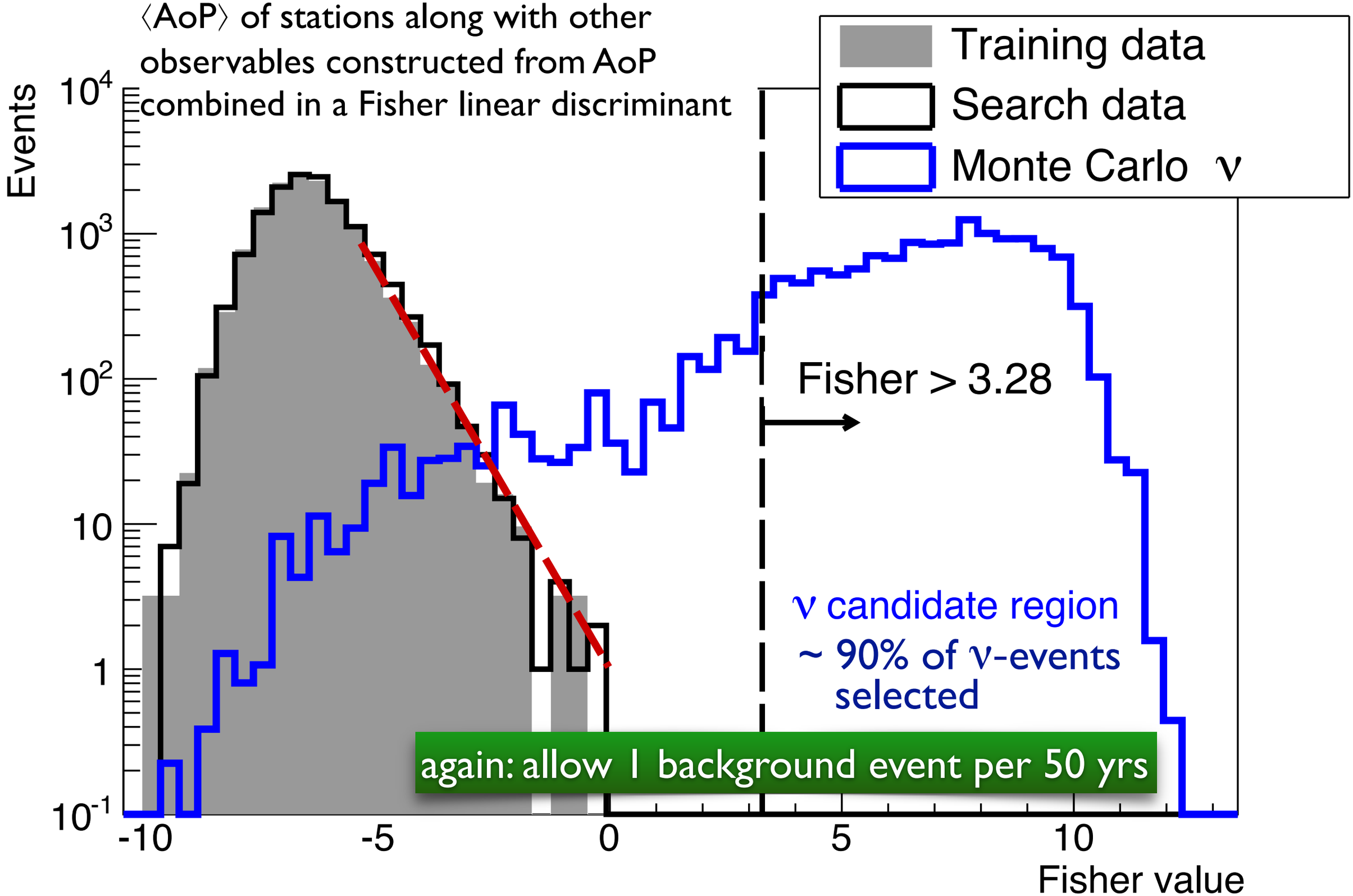
# ν Identification: Earth Skimming




Note: ν-searches not limited by background!
(cut set to 1 background event per 50 yrs)

# ν Identification: Down Going (75°-90°)

⟨AoP⟩ of stations along with other observables constructed from AoP combined in a Fisher linear discriminant

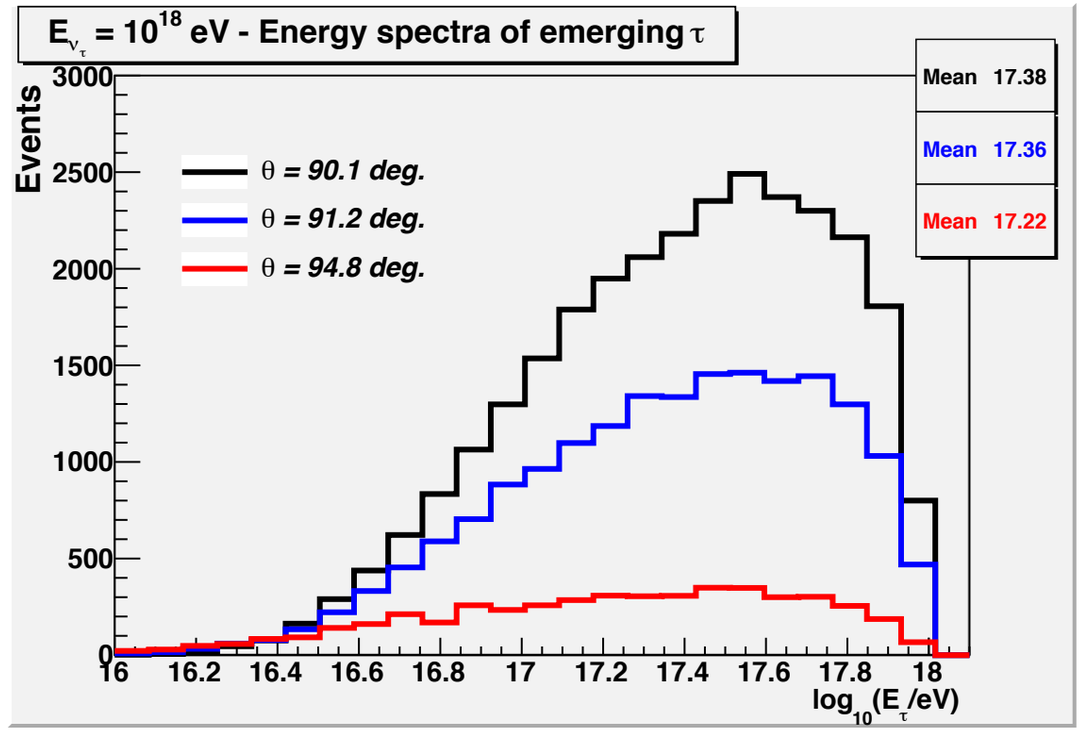



again: allow 1 background event per 50 yrs

# Exposure: Earth Skimming $\nu_\tau$

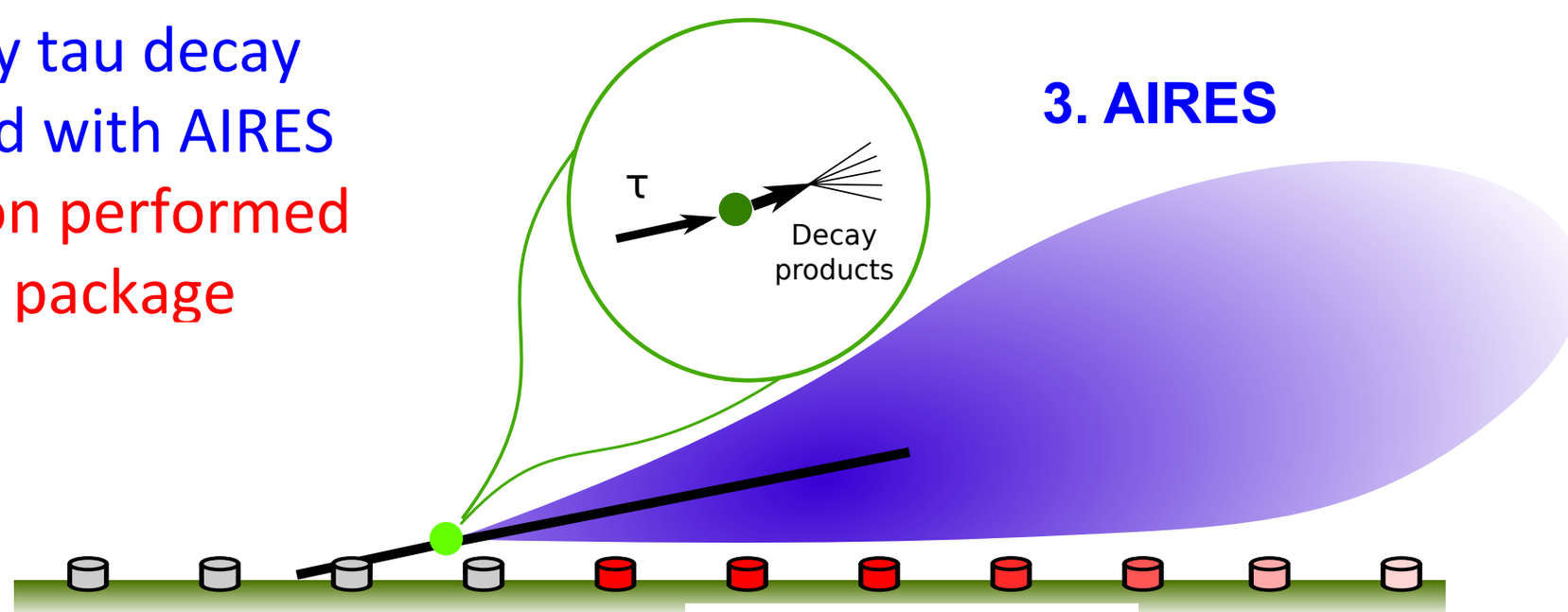
1. Tau neutrino propagation and tau production:
   - Dedicated MC for propagation of $\nu_\tau$ through the Earth producing emerging tau leptons.
   - Convolute with probability of tau decay in the atmos. (exponential)
2. Tau decay products obtained with TAUOLA generator:
   - All decays included
   - 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. $\nu_\tau$ PROPAGATION**



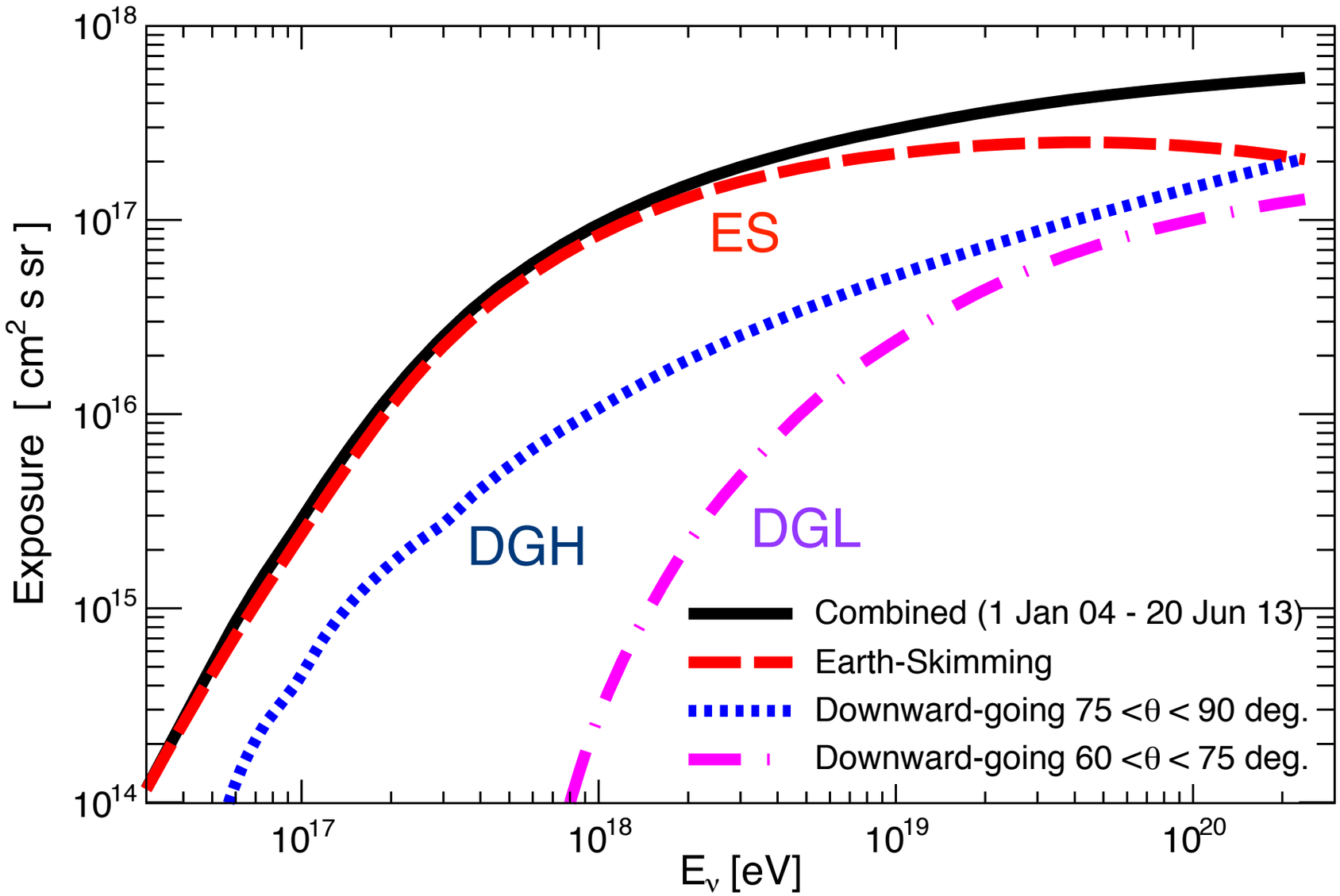

**2. TAUOLA**

**3. AIRES**




**4. OFFLINE**

# Acceptance and Uncertainties




Earth-Skimming $\nu_\tau$ dominates exposure

(loss at higher energies due to $\tau$ decays high in the atmosphere)

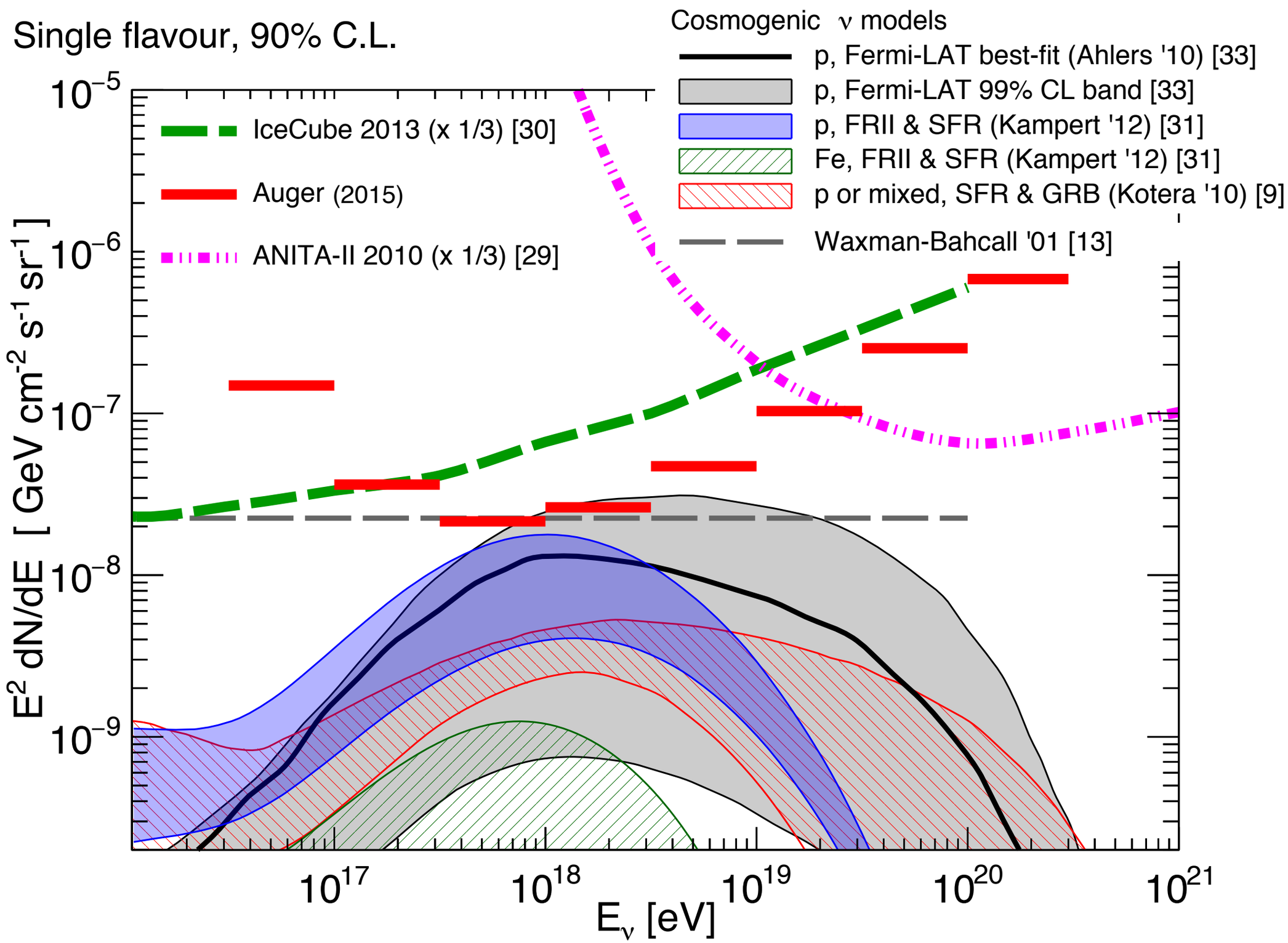
Relative contribution to expected event rate:

Earth Skimming: ~84%
Down Going (75°-90°): ~ 14%
Down Going (60°-75°): ~ 2%

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

# EeV Neutrino Limits

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



# EeV Neutrino Limits

Single flavour, 90% C.L.

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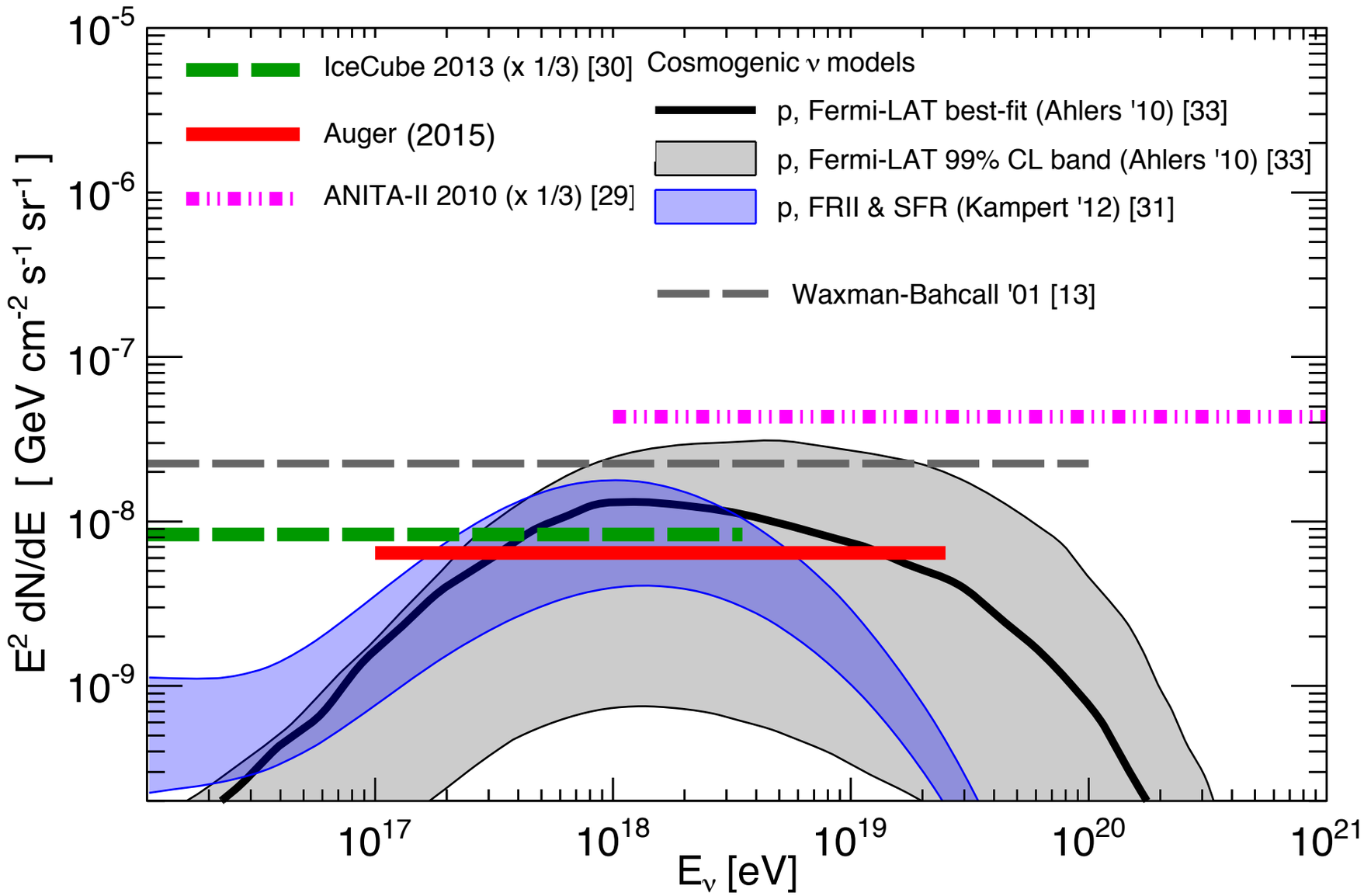


**Would have expected to see 1-7 GZK neutrinos (for different models), have seen none**

Neutrino upper limits start to constrain cosmogenic neutrino fluxes of p-sources

# EeV Neutrino Limits

Single flavour, 90% C.L.

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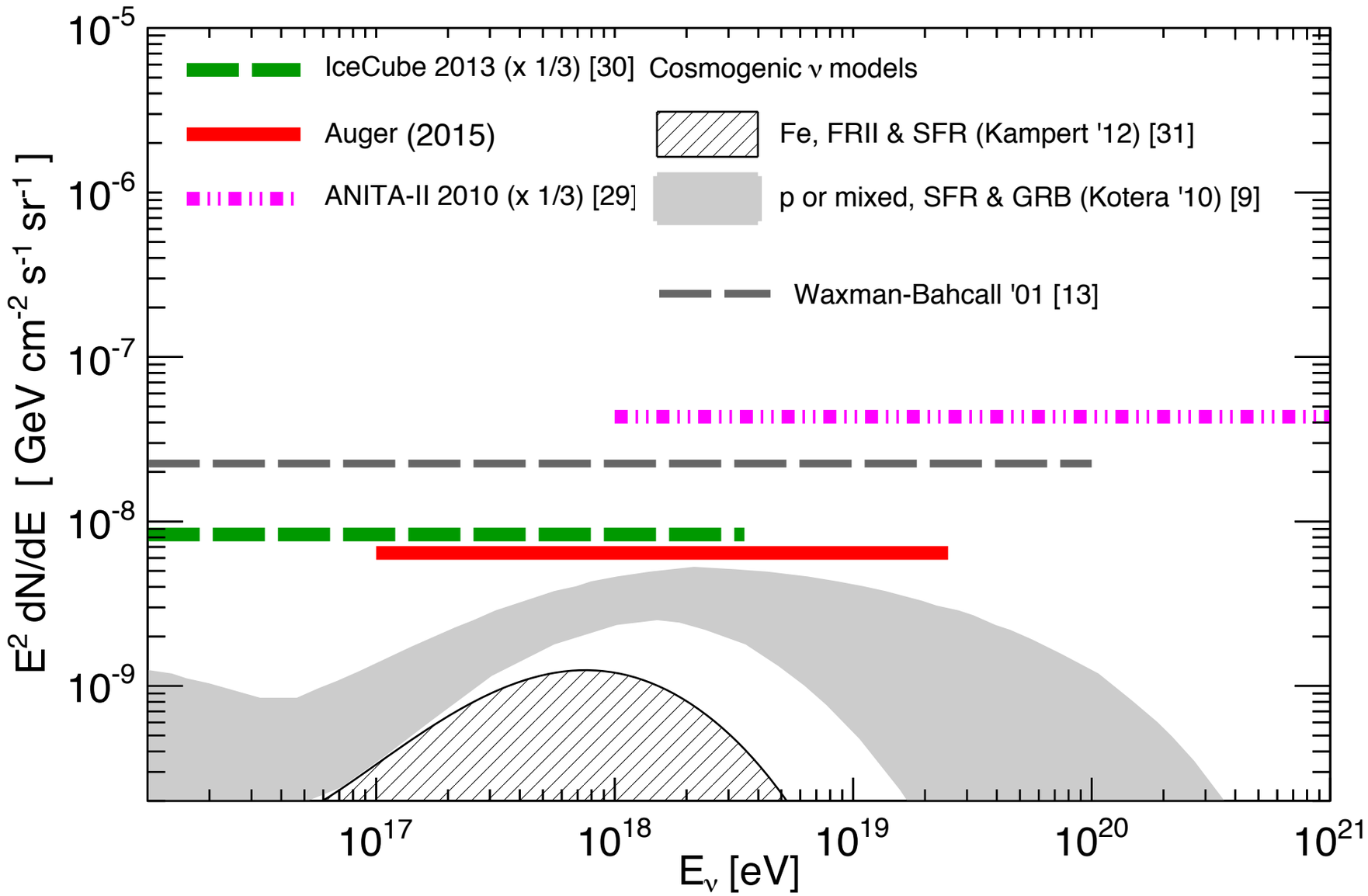
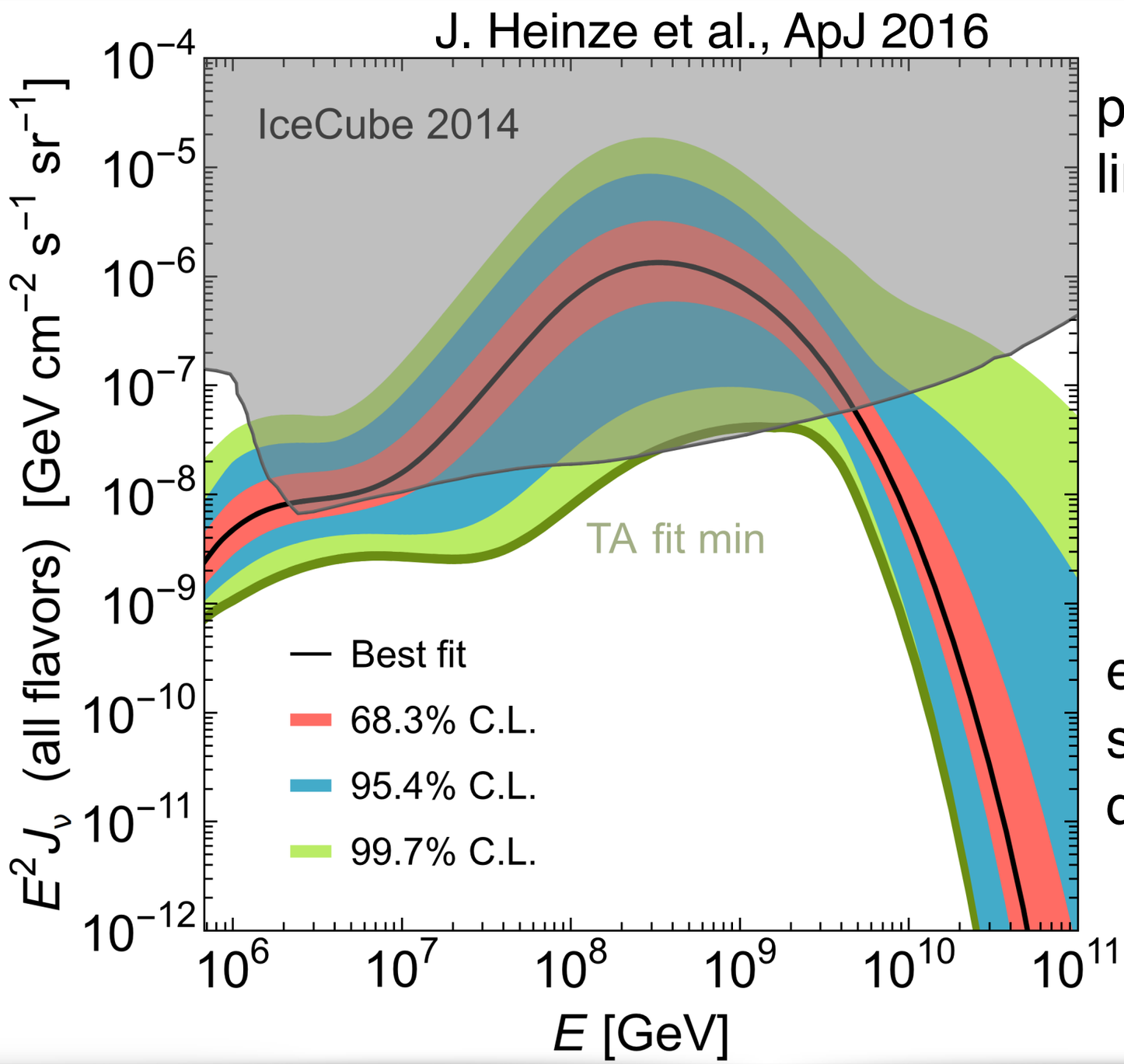



**Cosmogenic Neutrino Models with mixed/heavy primaries still below present upper limits**

# EeV Neutrino Limits Challenge GZK




preliminary exclusion limits from IceCube

expected ν-fluxes if flux suppression of TA is due to GZK-effect

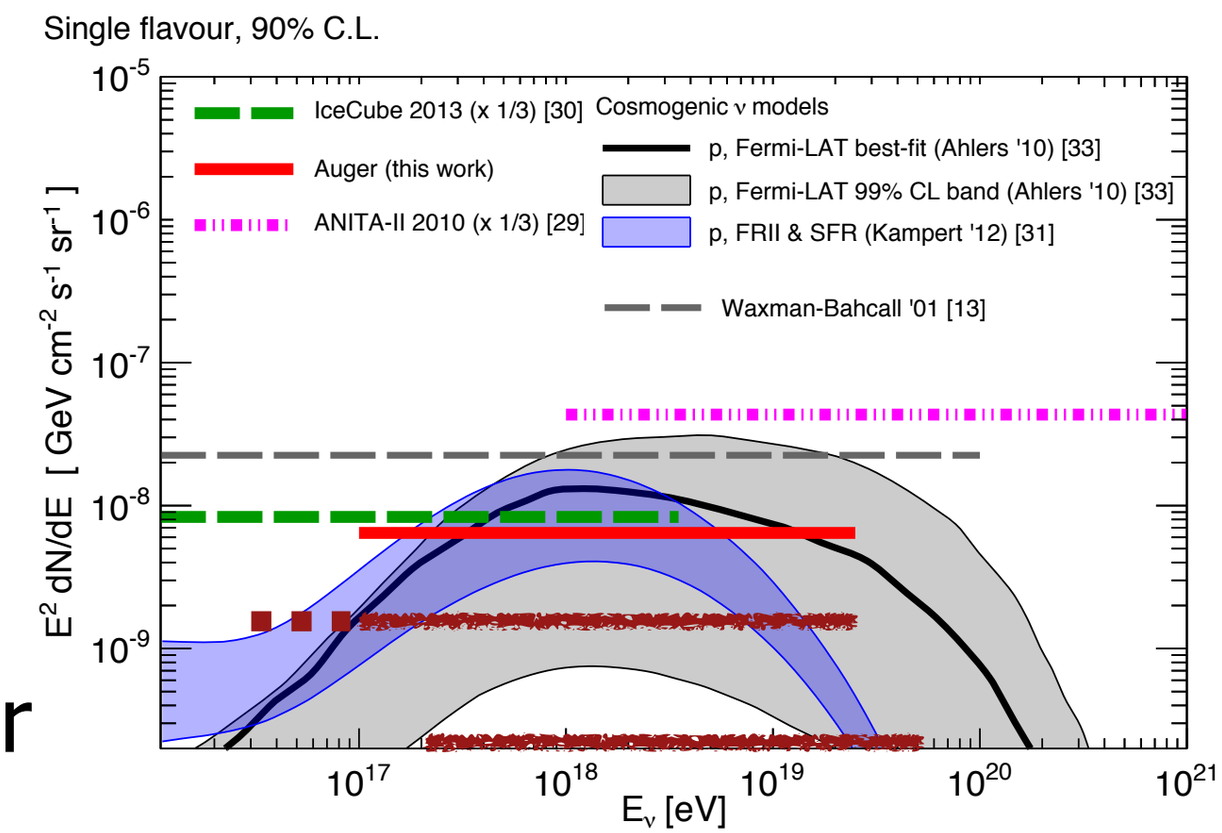
**Pure proton with GZK suppression challenged by upper limits to neutrino fluxes**

# Where could we get with Auger and beyond?

Present data represent 3 yrs (4.5 yrs) of full SD array and run into 2013

⇒ if no ν are observed, limits will go down by factor ~ 2.5-3.5

⇒ rule out high flux models




Moreover: exploit new trigger for better sensitivity at lower energies

… and use data of infill array (low exposure, however)

… a next generation CR-Observatory would reach down to Fe/mixed composition scenarios

# What, if we observe a Neutrino?

## 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 $E_\nu$, because $E_\nu > E_{shower}$
- ν can interact anywhere in atmosphere:
  $E_{shower}$ determination should include shower age
- No algorithm including age exists so far

## Angular reconstruction of quasi-horizontal events:

- Not optimised for deeply penetrating & very inclined showers (> 80°)
  Angular resolution ~ 1-2°
- Identification of up-going shower would indicate tau neutrino primary

## Conservative statement:

## Auger = discovery experiment (a "counter" of UHE neutrinos)