Searching for neutrino induced showers in the Pierre Auger Observatory

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- General facts (cosmic ray spectrum, sources of neutrinos, neutrino tau induced showers ...)
- Discrimination criteria to identify neutrino induced showers (footprint analysis, study of asymmetry of the rise and fall time)
- MC computations (FD event rate)

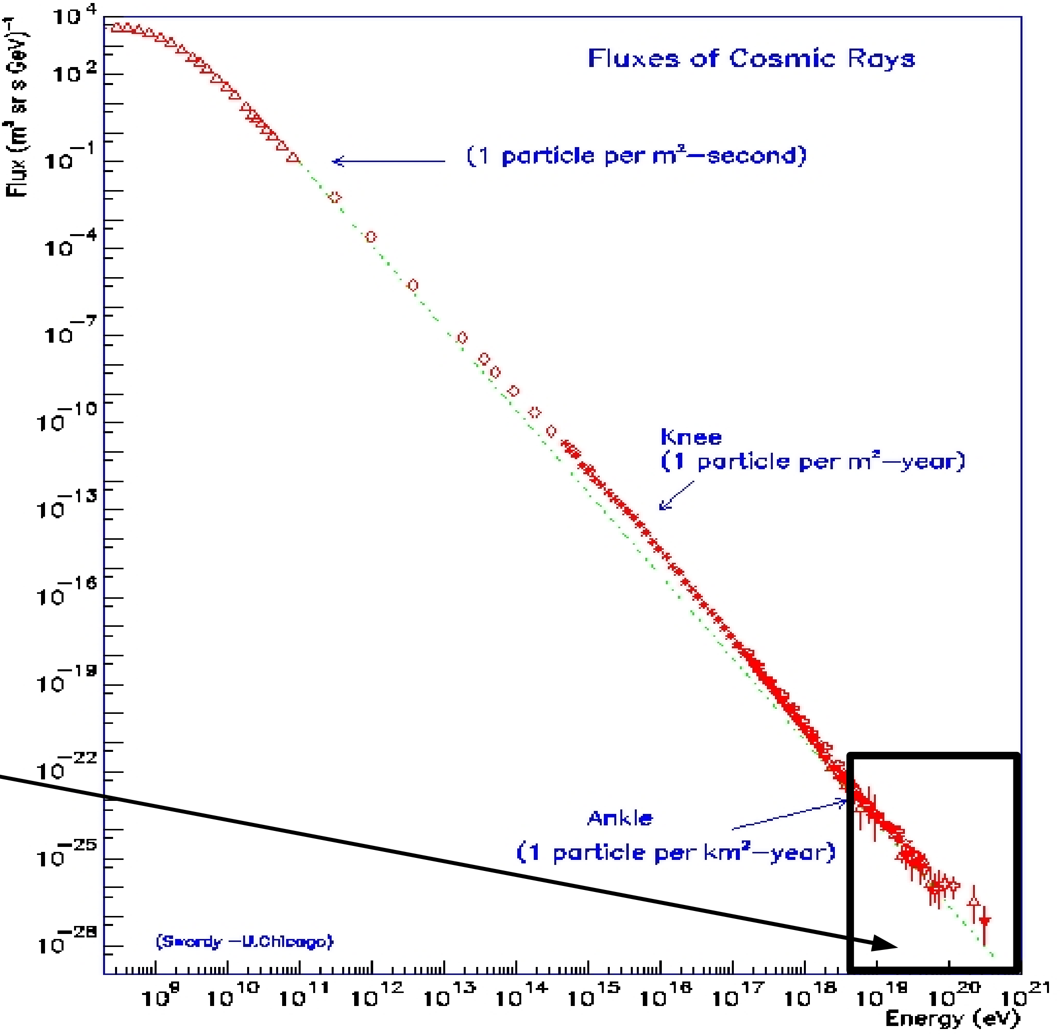
Ultra High Energy Cosmic Rays (UHECR)

- **Cosmic ray** are defined as charged particles that reach from interstellar space

What are UHE Cosmic rays ???

Where do UHECR originate ???

How are UHECR accelerated ???



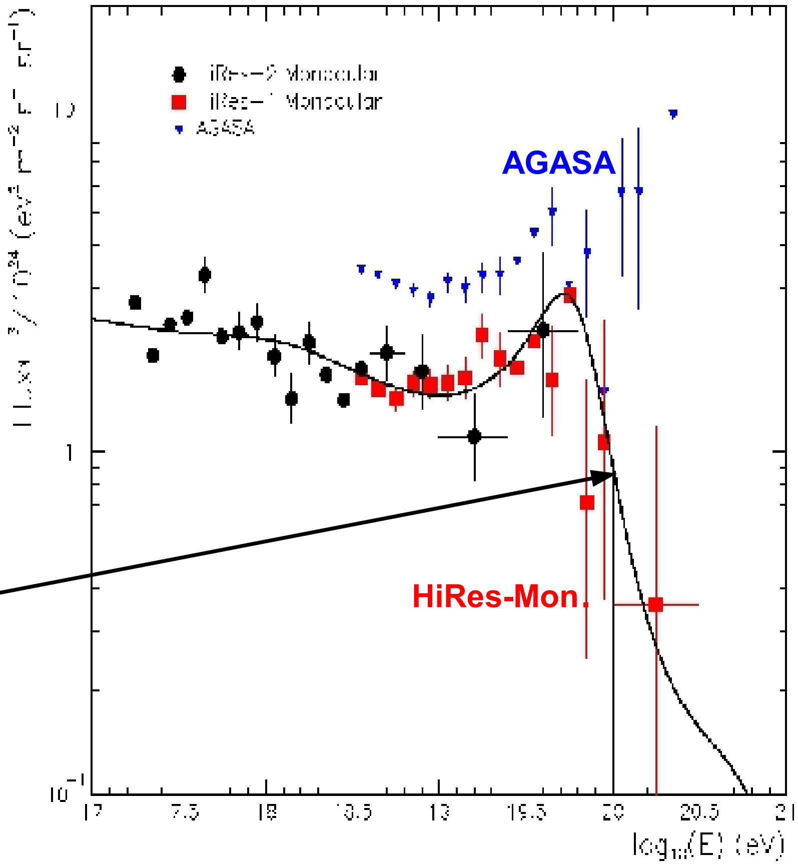
The Highest Energy Cosmic Rays
(GZK cut off)

- Cosmic ray (protons) interact with the Cosmic Microwave Background (CMB) producing pions via the Δ-resonace.

- The attenuation length of protons of $E=2x10^{11}$GeV is 30 Mpc.
  Therefore, cosmic rays emitted from sources located at larger distances do not reach the Earth without substantial energy loss.

- Should see no extragalactic UHECR above ~50 EeV (GZK cut off)

Is there the GZK cut off in the spectrum ?



Neutrinos

- Sources of Neutrinos (bottom-up scenario)

- Active Galactic Nuclei (AGN)

- Supernovae followed by Shock Acceleration

- Gamma Ray Bursters (GRB)

These *conventional* sources produce E^{-2} spectrum

- Exotic Sources (top - down scenario)

Cosmic rays result from decay of super-heavy particles ($M_X >> 10^{21}$ eV)

- Primordial Topological Defects (TD)

- Z-bursts from UHE neutrino (RNB collisions)

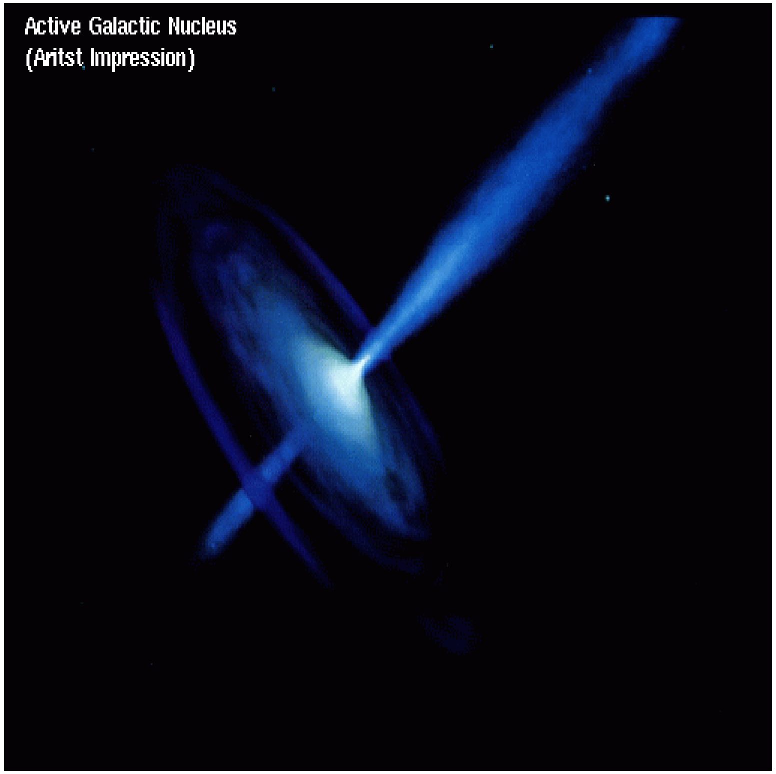
These models predict harder neutrino spectrum.

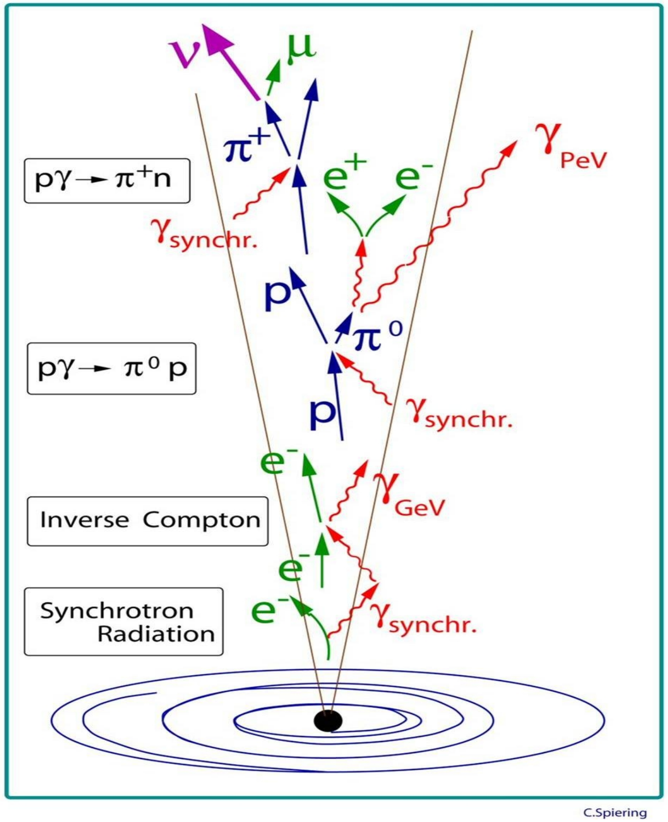
- Acceleration:

Relativistic Fermi Shock Front Acceleration in galactic/extragalatic magnetic fields

Neutrino production

(AGN production)





hadronic production

leptonic production

$$p + p\ (\gamma) \longrightarrow \pi^{\pm} + X$$

$$\hookrightarrow \mu^{\pm} + \nu_{\mu}\,(\overline{\nu}_{\mu})$$

$$\hookrightarrow e^{\pm} + \nu_e\,(\overline{\nu}_e) + \overline{\nu}_{\mu}\,(\nu_{\mu})$$

$$\hookrightarrow \pi^{o} + X$$

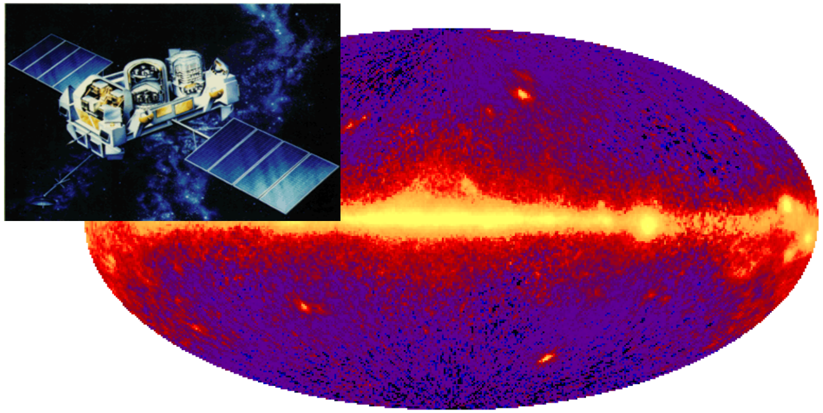
$$\hookrightarrow 2\gamma$$

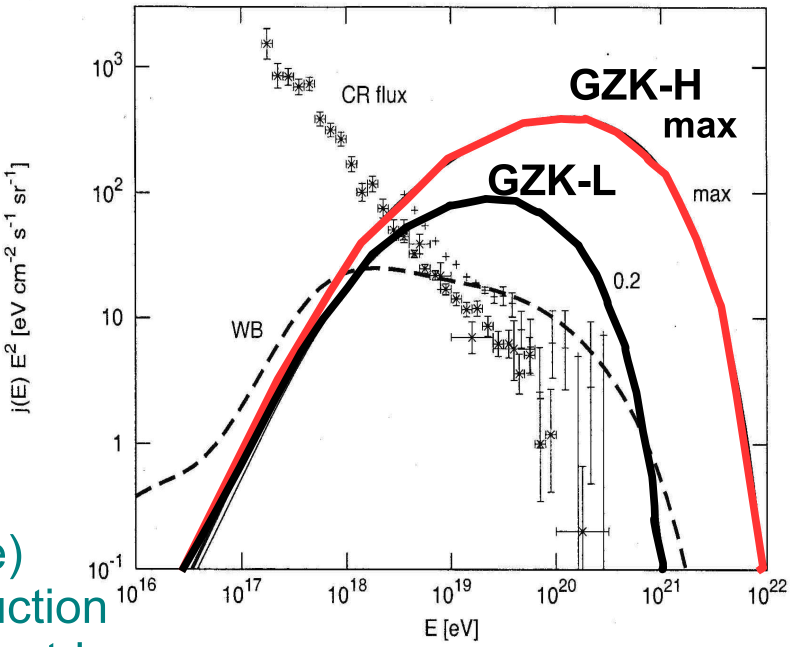
- Photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other

Diffuse Neutrinos

- **Diffuse flux of neutrinos**
  (if the directions of the sources generating the flux are not resolvable)

Photon flux at E>100 MeV as measured by EGRET till 1995





- GZK events are diffuse (scattering-based), so EGRET γ flux sets upper limit ('max' curve) assuming pion production in CMB photoproduction accounts for all UHE photons and all UHE neutrinos

- Waxman-Bahcall ν flux limit assumes UHECR sources are optically thin due to pγ and pp interactions and ν production occurs via CMB photoproduction

$$E^2 \Phi(E_\nu) = 1 \times 10^{-8} (GeV\, cm^{-2} s^{-1} sr^{-1})$$

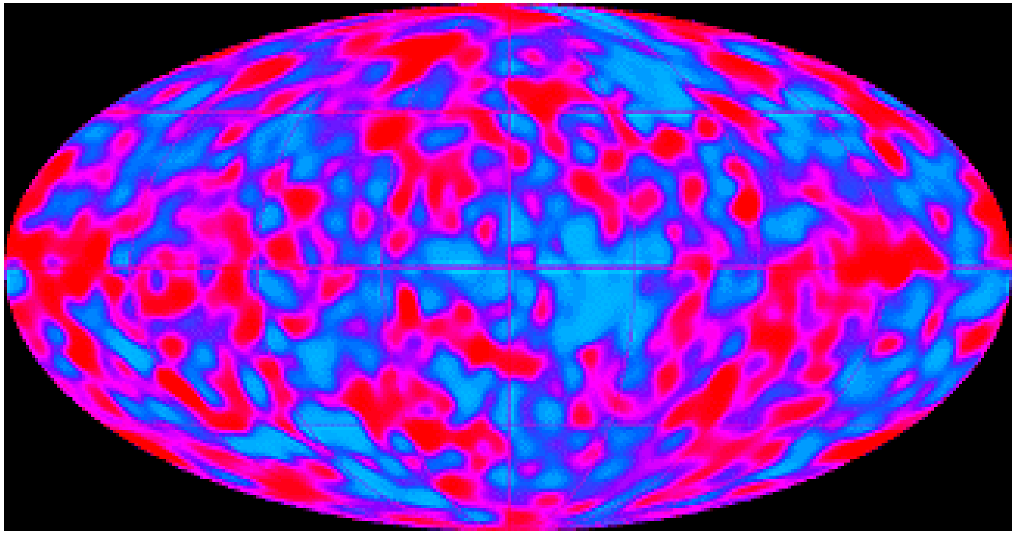
J.N. Bahcall, E. Waxman, Phys. Rev. D 64 (2001) 023003

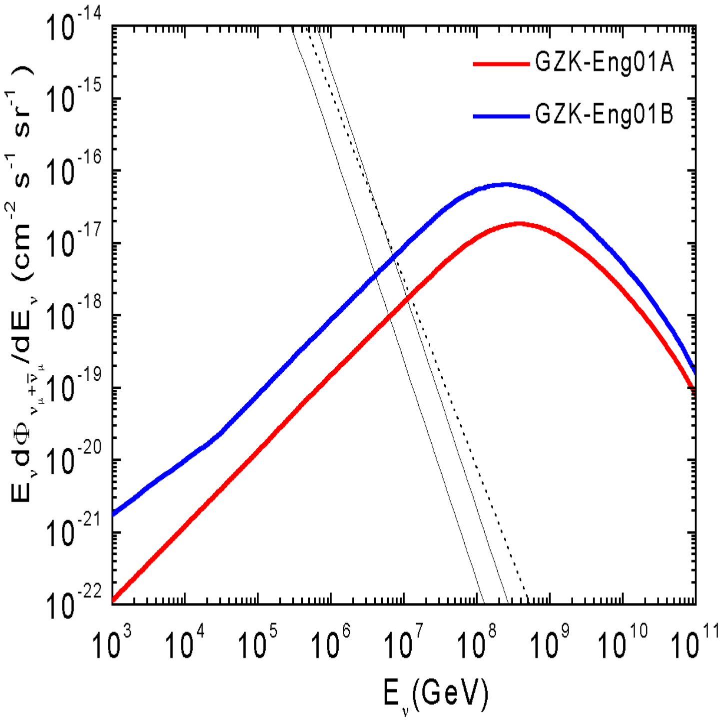
GZK UHE Neutrinos

- **GZK neutrinos** (cosmogenic neutrinos) come from inverse photoproduction of the Δ^+ resonance on CMB photons throughout space and time back to the Big Bang

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

attenuates proton flux above threshold and limits UHECR energy to < 40 EeV for sources > 50 MPc away.





UHE neutrino Flux Models

1 pp core AGN (Nellen)

2 pγ core AGN
(Stecker Salomon)

3 pγ „maximum model“
(Mannheim et al.)

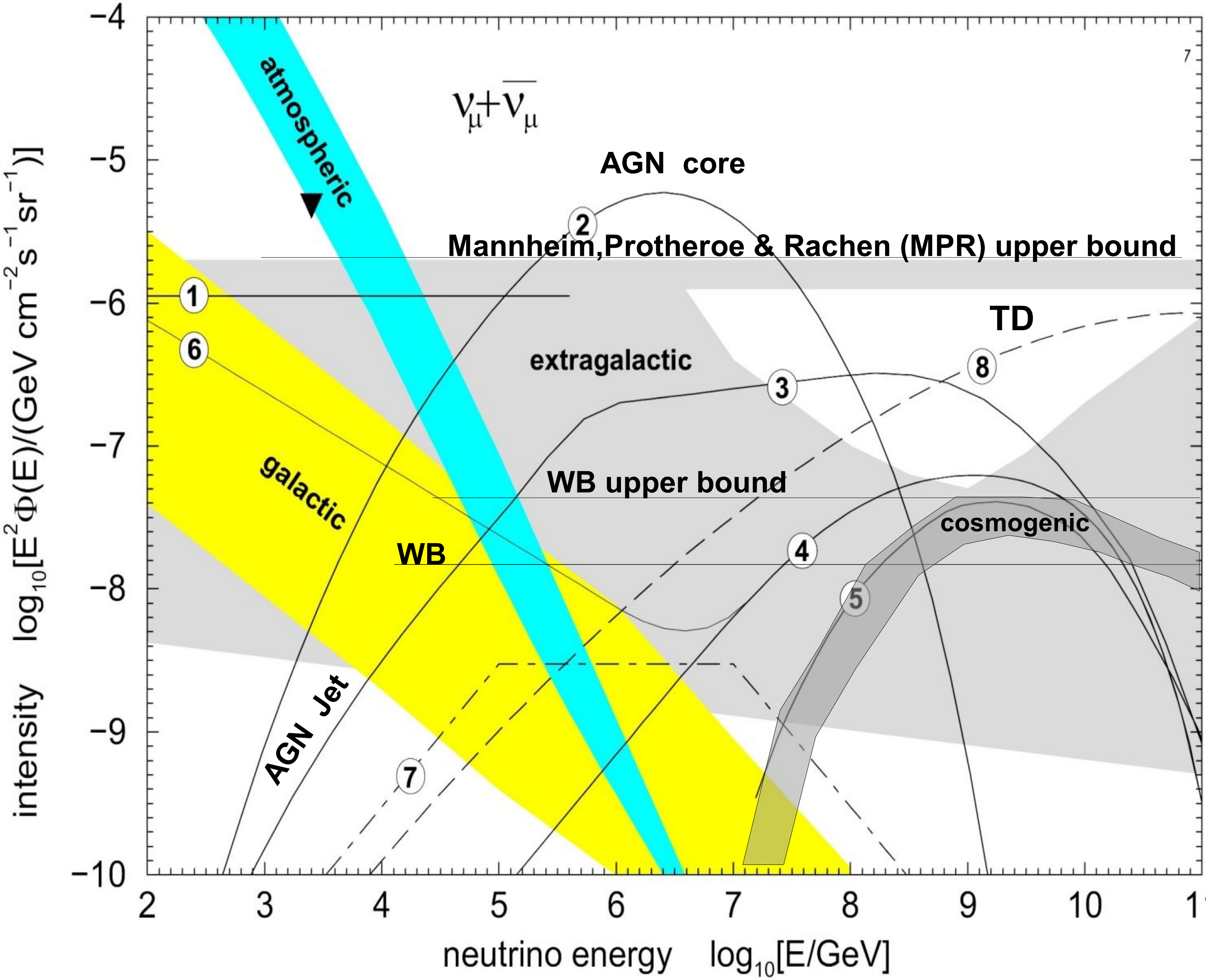
4 pγ blazar jets (Mannh)

5 pγ AGN
(Rachen & Biermann)

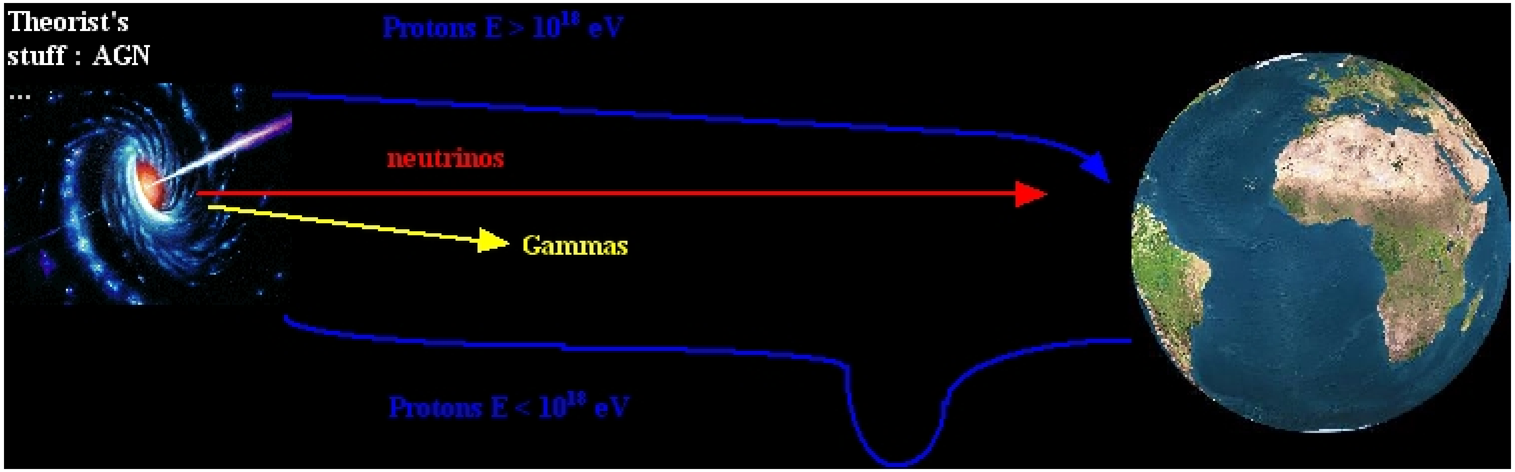
6 pp AGN (Mannheim)

7 GRB
(Waxman & Bahcall)

8 TD (Sigl)



Neutrino Propagation Effects



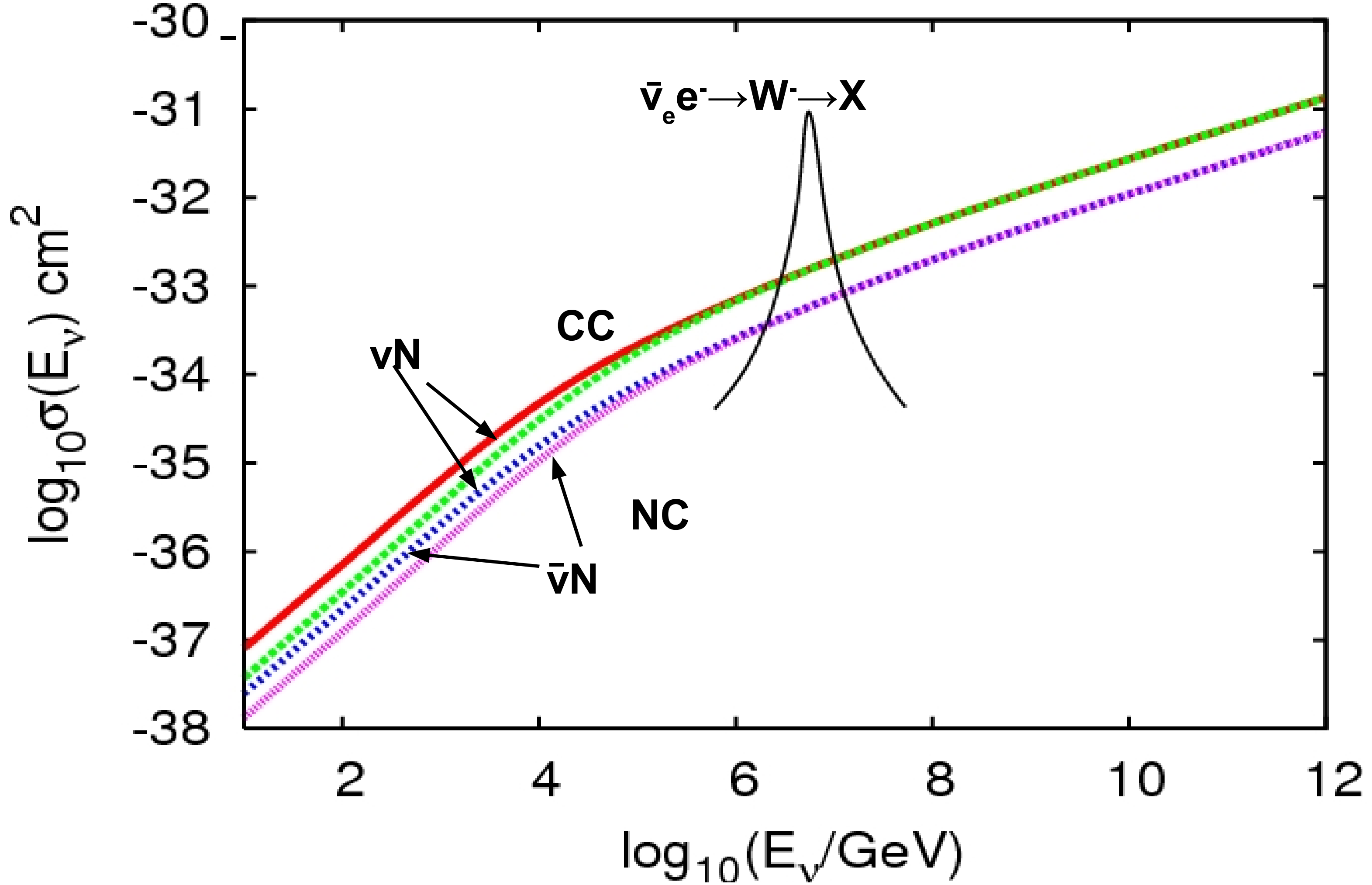
- Galactic and intergalactic magnetic fields smear UHECR trajectories over Mpc distance scales, destroying source information for charged cosmic rays.

- **Pointing capability of neutrinos offers unique chance to identify discrete sources.**

- **Highest energy neutrinos are born as ν_μ ,ν_e**

  Neutrino **mixing** of ν_μ produces ν_e ,ν_μ and ν_τ fluxes in ratio of 1:1:1
  after propagating astronomical distances $\Rightarrow$
  can use special decay characteristics of τ neutrinos to enhance detection
  (Beacom, Bell, Hooper, Pakvasa, and Weiler, Phys. Rev. D 68 (2003) 093005).

Neutrino cross-section at very high energy



- **Due to small interaction cross-section large detectors are needed for detection of ν**

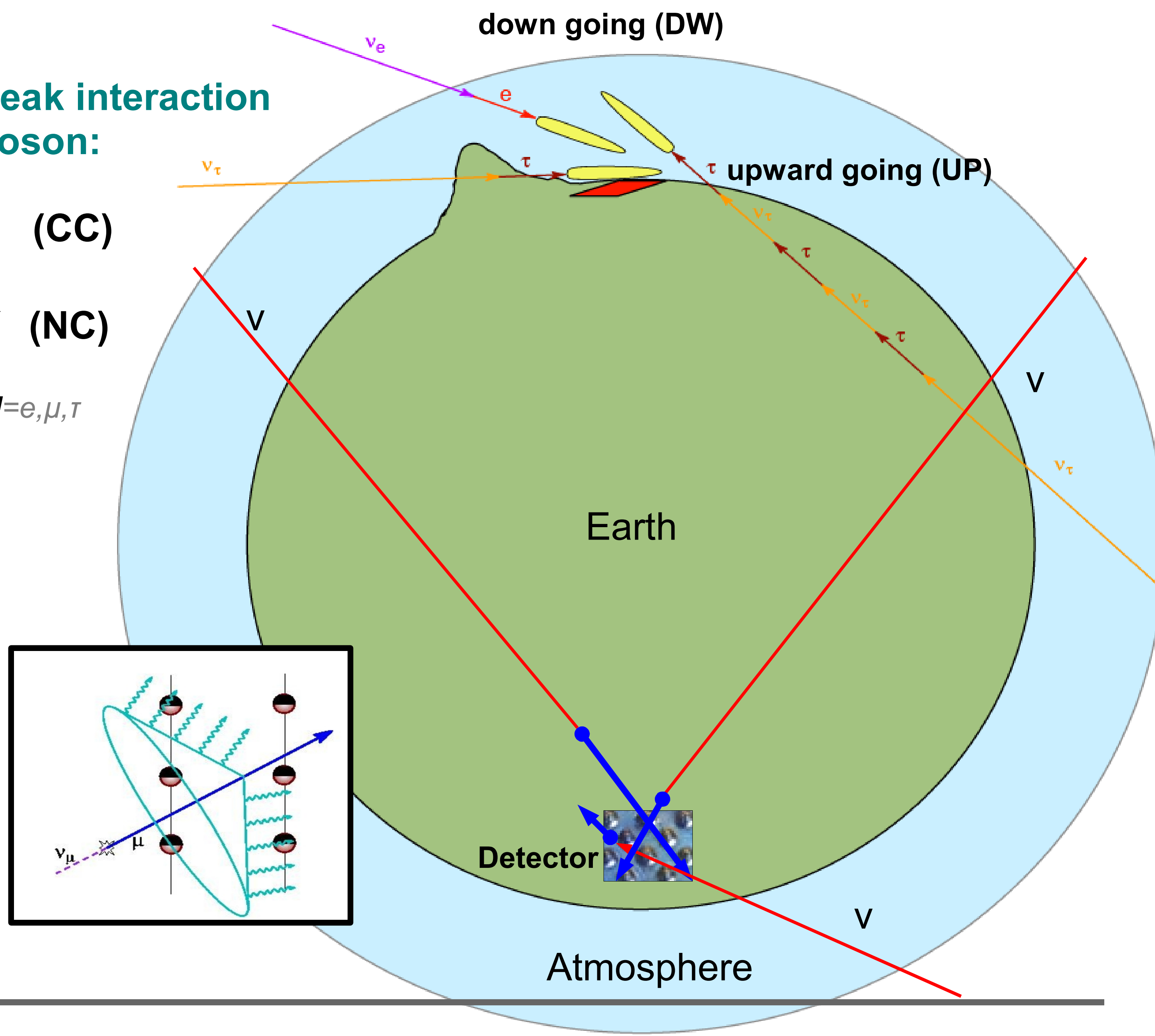
Neutrino interaction

- **In Standard Model by weak interaction via Z^0 and $W^{+/-}$ boson:**

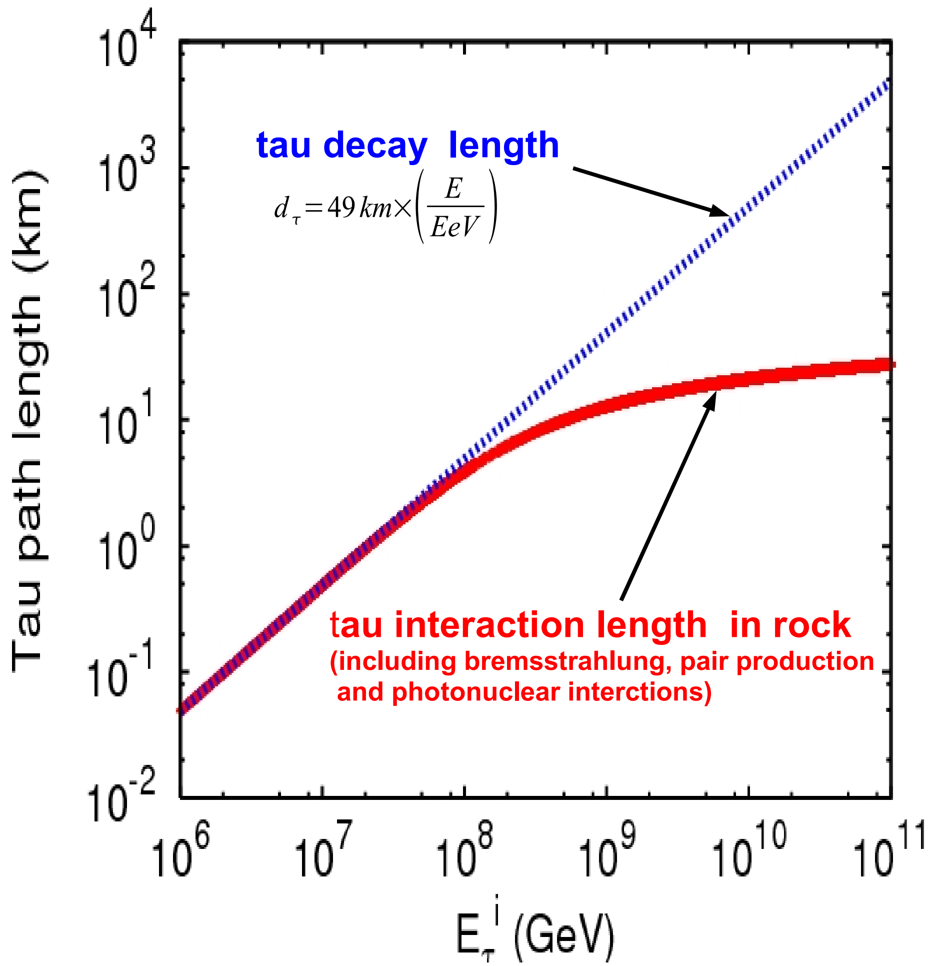
$$\nu_l + N \rightarrow W^{\pm} \rightarrow l + X \quad \text{(CC)}$$

$$\nu_l + N \rightarrow Z^0 \rightarrow \nu_l + X \quad \text{(NC)}$$

l represents the lepton flavour $l = e, \mu, \tau$
and *X* the final hadronic state



Tau neutrino propagation and decay



- **tau decay channels**

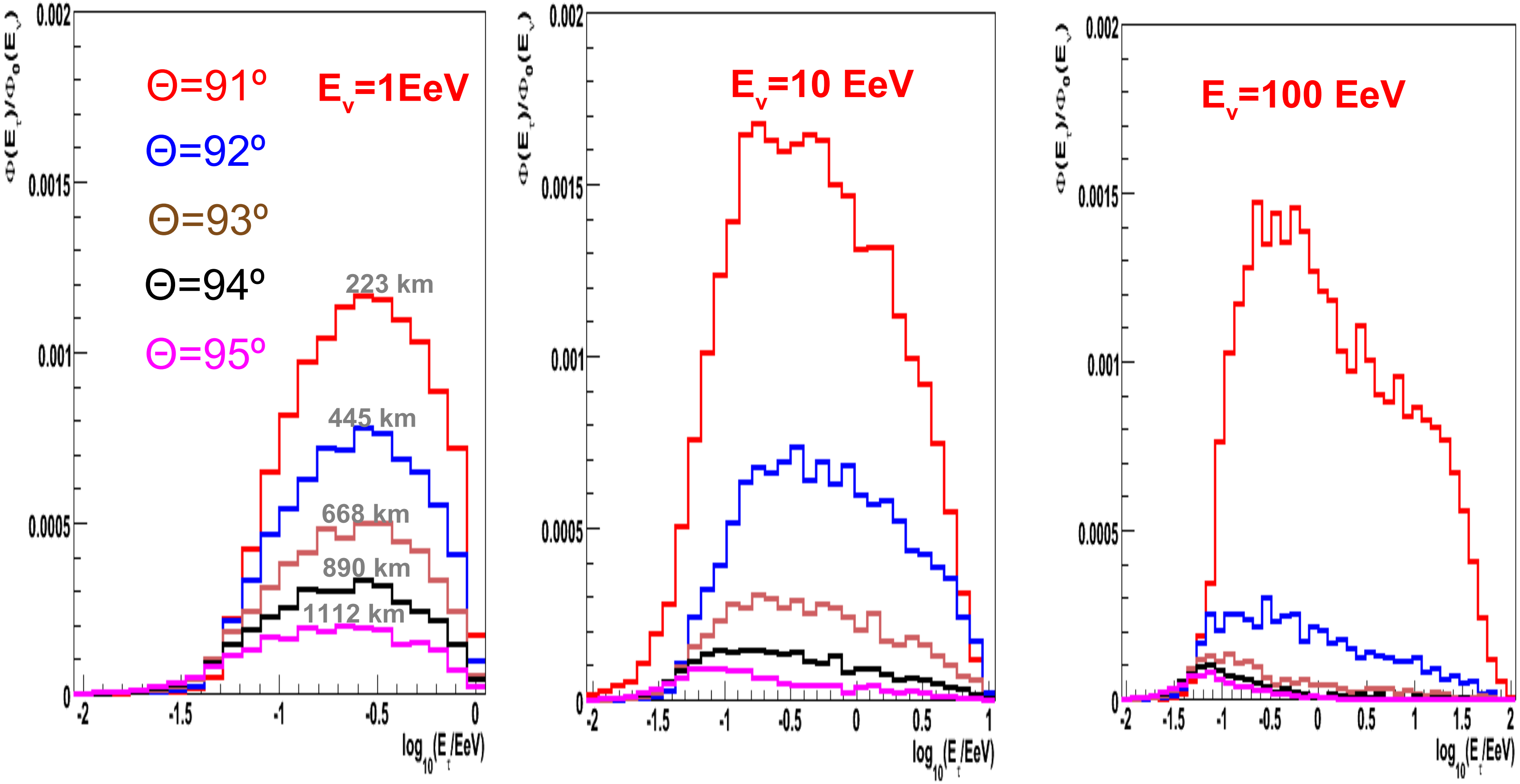
Decay	Secondaries	Probability	Air-shower
$\tau \to \mu^- \bar{\nu}_\mu \nu_\tau$	μ^-	17.4%	Unobservable
$\tau \to e^- \bar{\nu}_e \nu_\tau$	e^-	17.8%	1 Electromagnetic
$\tau \to \pi^- \nu_\tau$	π^-	11.8%	1 Hadronic
$\tau \to \pi^- \pi^0 \nu_\tau$	$\pi^-,\ \pi^0 \to 2\gamma$	25.8%	1 Hadronic, 2 Electromagnetic
$\tau \to \pi^- 2\pi^0 \nu_\tau$	$\pi^-,\ 2\pi^0 \to 4\gamma$	10.79%	1 Hadronic, 4 Electromagnetic
$\tau \to \pi^- 3\pi^0 \nu_\tau$	$\pi^-,\ 3\pi^0 \to 6\gamma$	1.23%	1 Hadronic, 6 Electromagnetic
$\tau \to \pi^- \pi^- \pi^+ \nu_\tau$	$2\pi^-, \pi^+$	10%	3 Hadronic
$\tau \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	$2\pi^-, \pi^+, \pi^0 \to 2\gamma$	5.18%	3 Hadronic, 2 Electromagnetic

adopted from Fargion

- **Tau interaction length about a few km at 1 EeV, so produced lepton τ close to the Earth surface can emerge and produce potentially detectable ν showers**

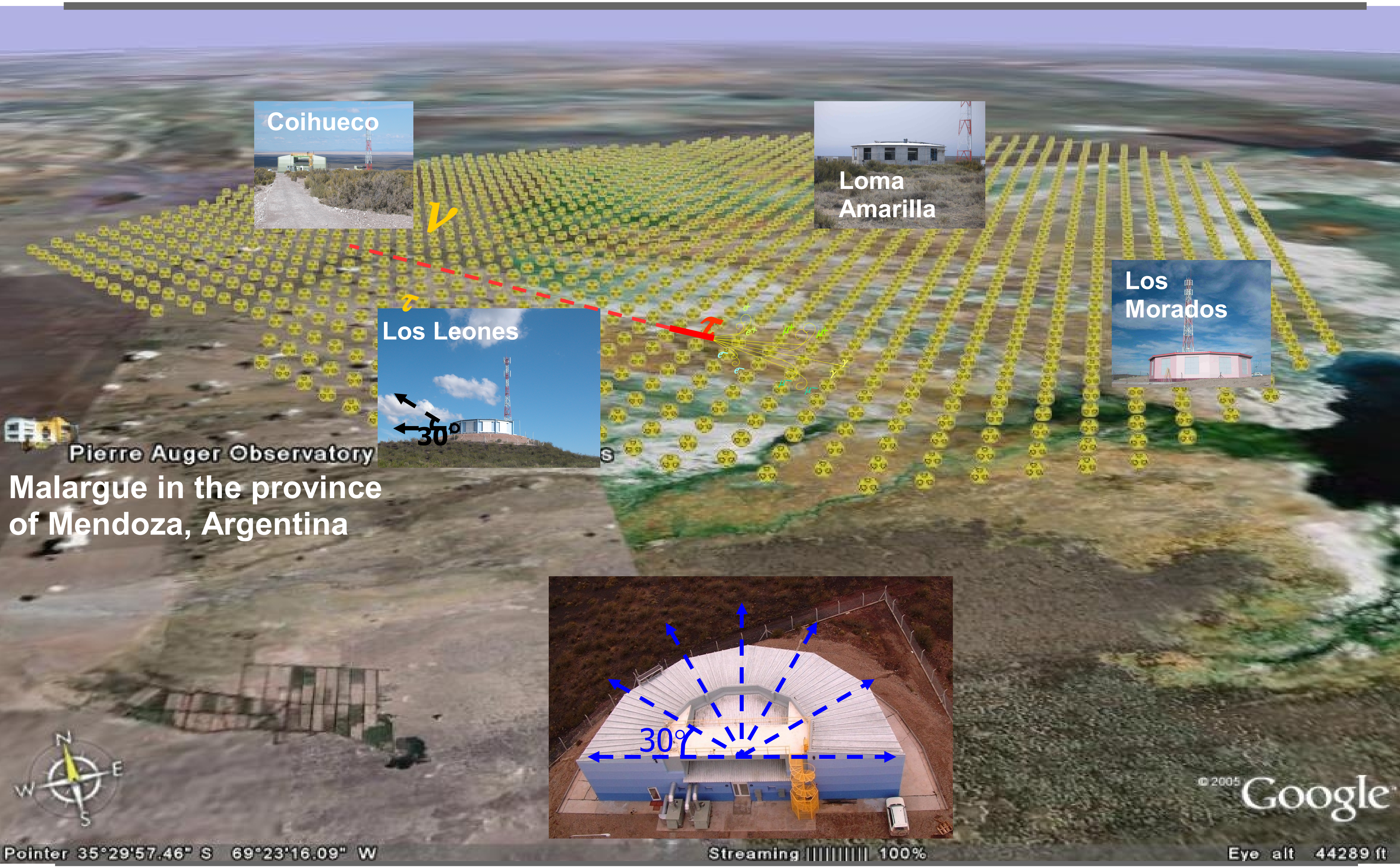
Emerging Tau neutrino flux

- Neutrino monoenergetic beam, computations with the simple spherical model of the Earth (6371 km)



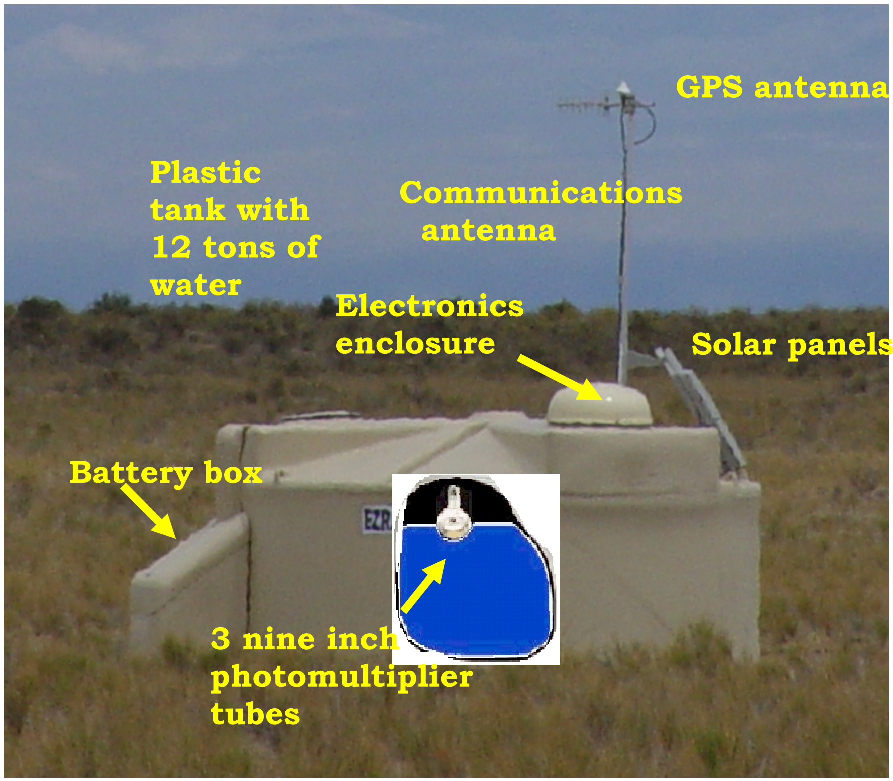
- τ **emerging within a few degrees from horizon**
- **largest efficiency for tau induced showers at about 10 EeV**

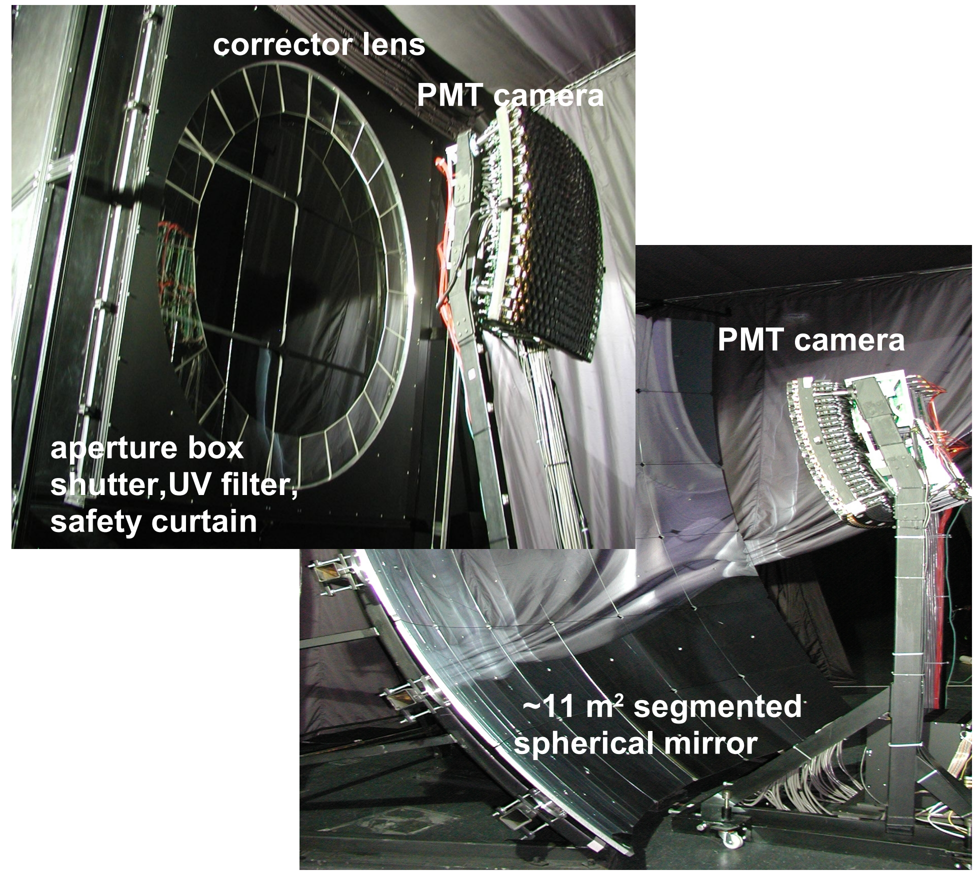
Pierre Auger Observatory as neutrino detector



Pierre Auger Observatory

- The Surface Array Detector (SD)
- Fluorescence Detector (FD)





- PMT signals

  shape in 25 ns intervals ⇒

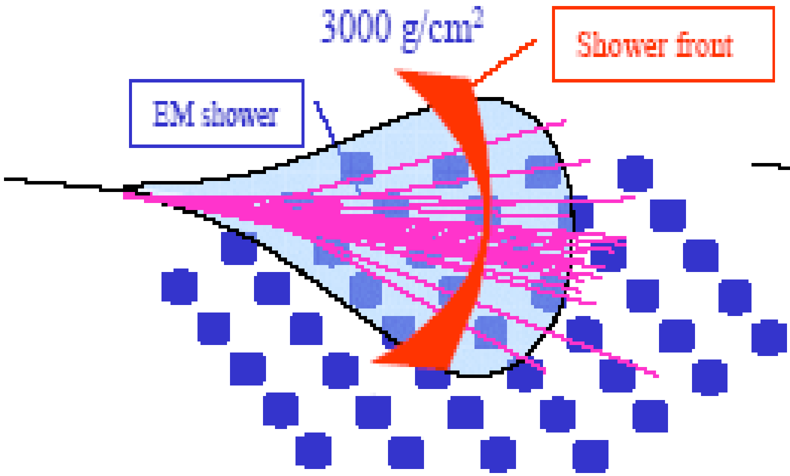
  Information on muonic and EM component

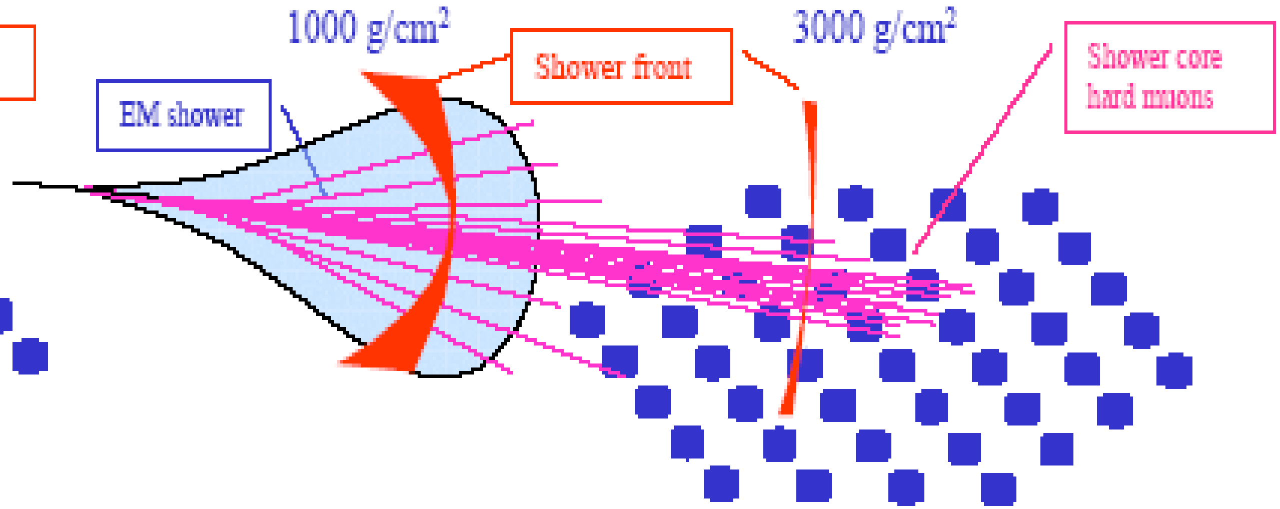
- 440 PMT per camera, each 1.5°

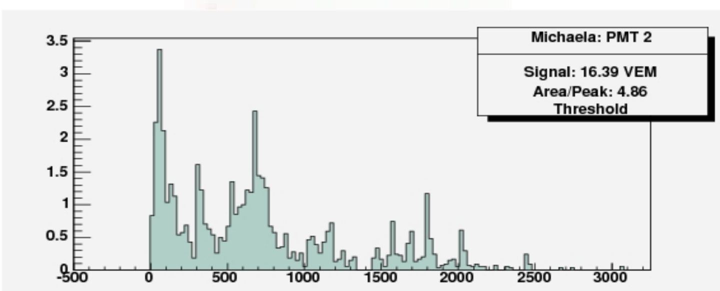
  15% duty cycle, 100 ns sampling intervals

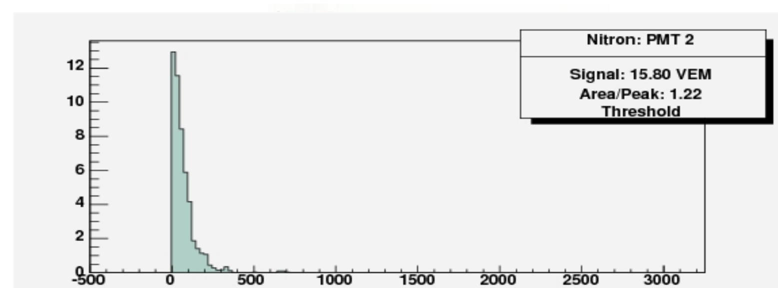
Identification of neutrinos

Neutrino showers	Nucleonic showers





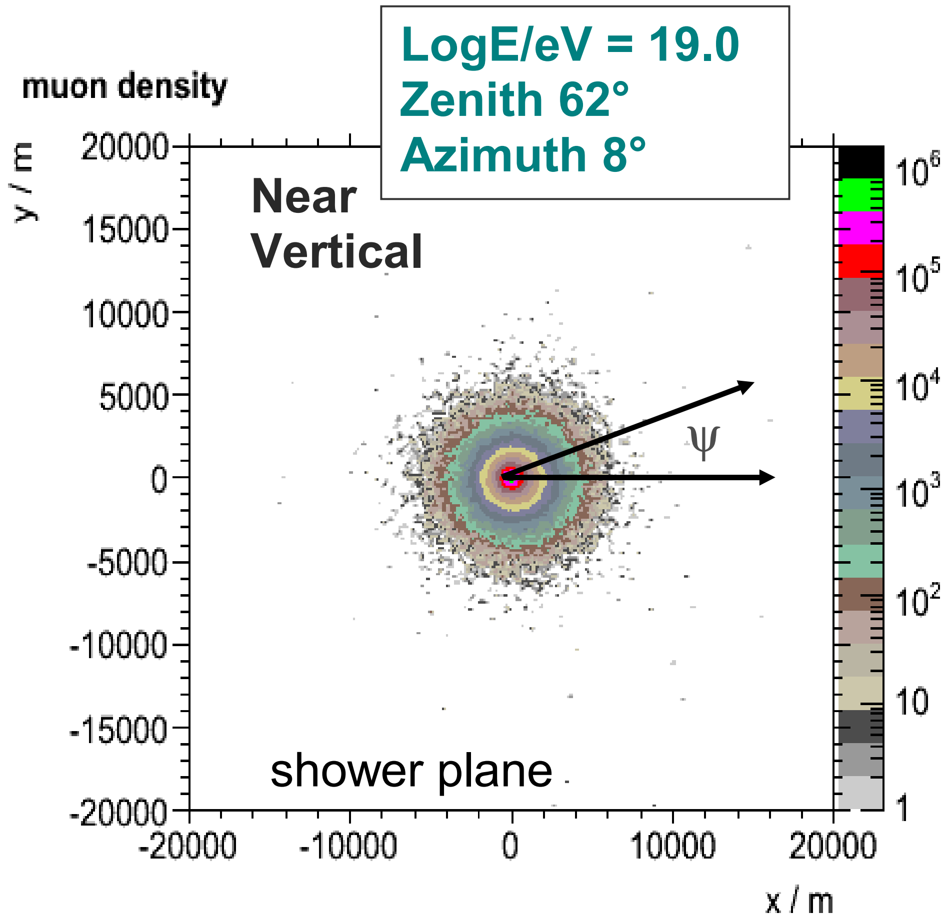




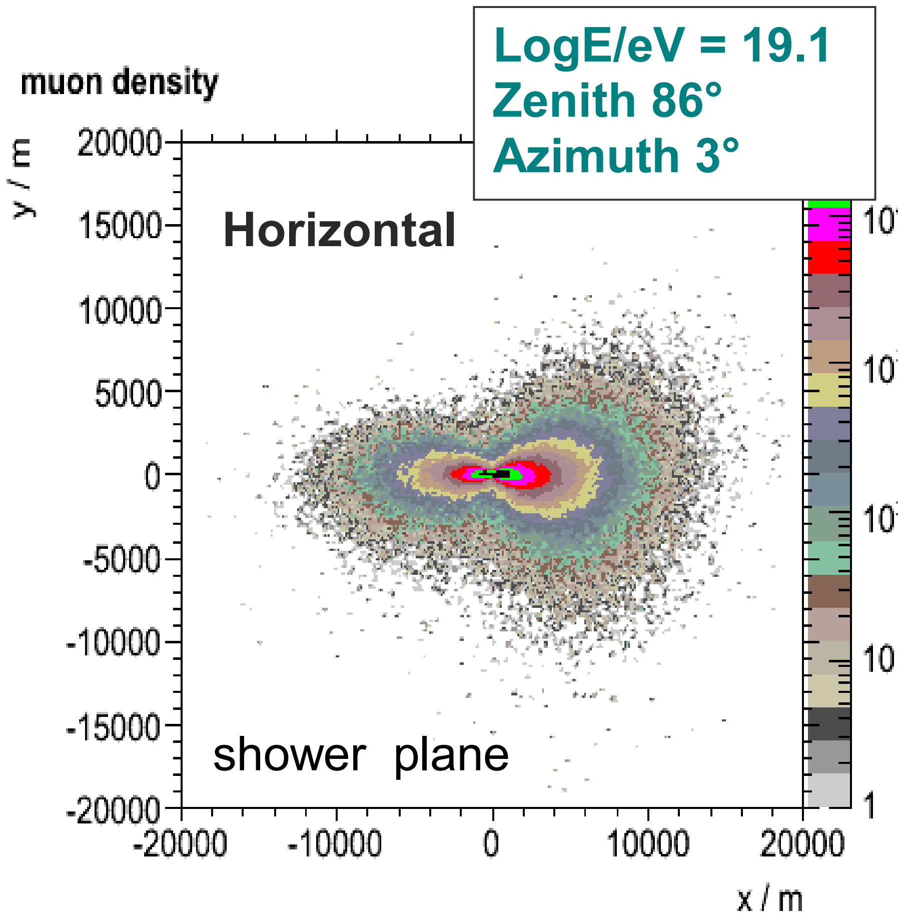
- **Signal is:**
  Few events per year
  EM rich, curved and thick front
  Broad signal

- **Background is:**
  Thousands events per year
  EM poor, muon rich, flat and thin front
  Prompt signal

Footprint in case of proton induced showers



$$\mathrm{LDF} = \mathrm{LDF}(\, r\, ;\, \theta\,)$$

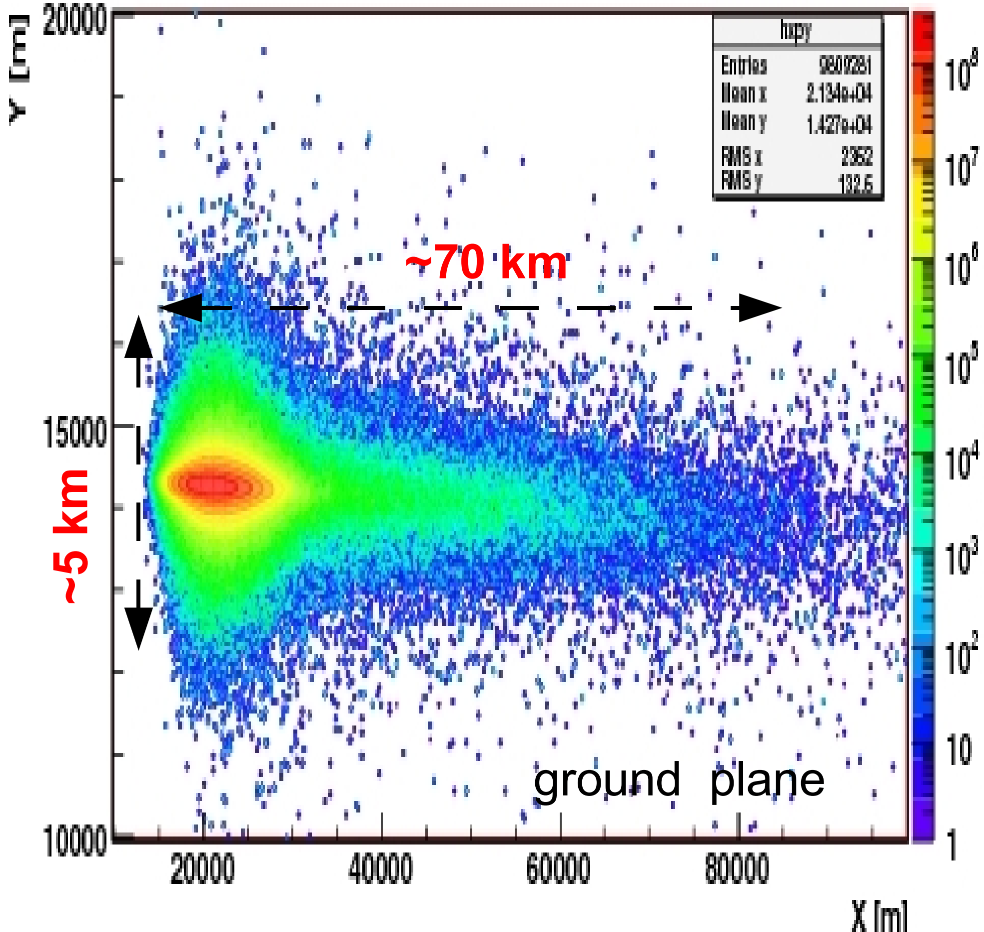


$$\mathrm{LDF} = \mathrm{LDF}(\, r, \psi\, ;\, \theta, \phi\,)$$

Footprint in case of up-going tau neutrino induced shower

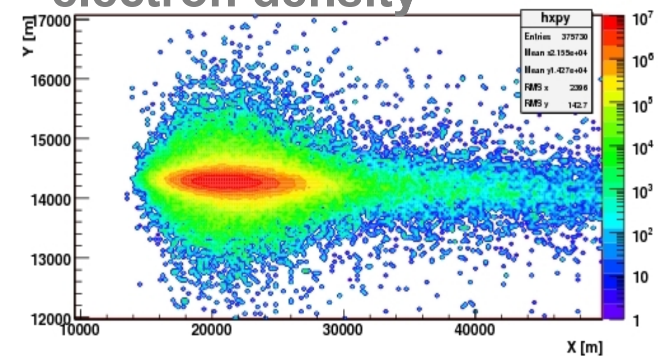
electron+muon+photon density

$\tau^- \rightarrow \pi^+ 2\pi^0 \nu_\tau$

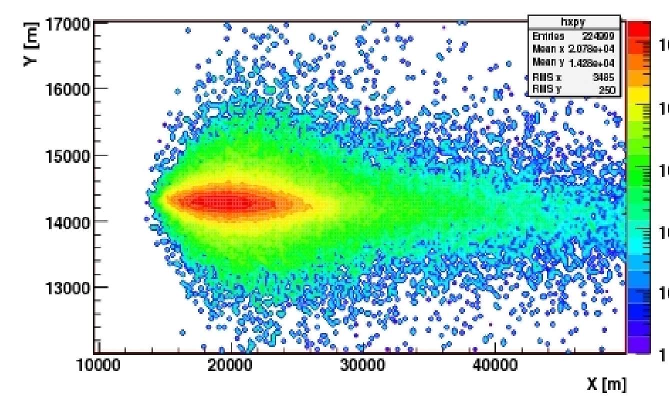


LogE/eV = 20.69
Zenith 90.5°
Azimuth 0°, h_{decay}=700 m

electron density



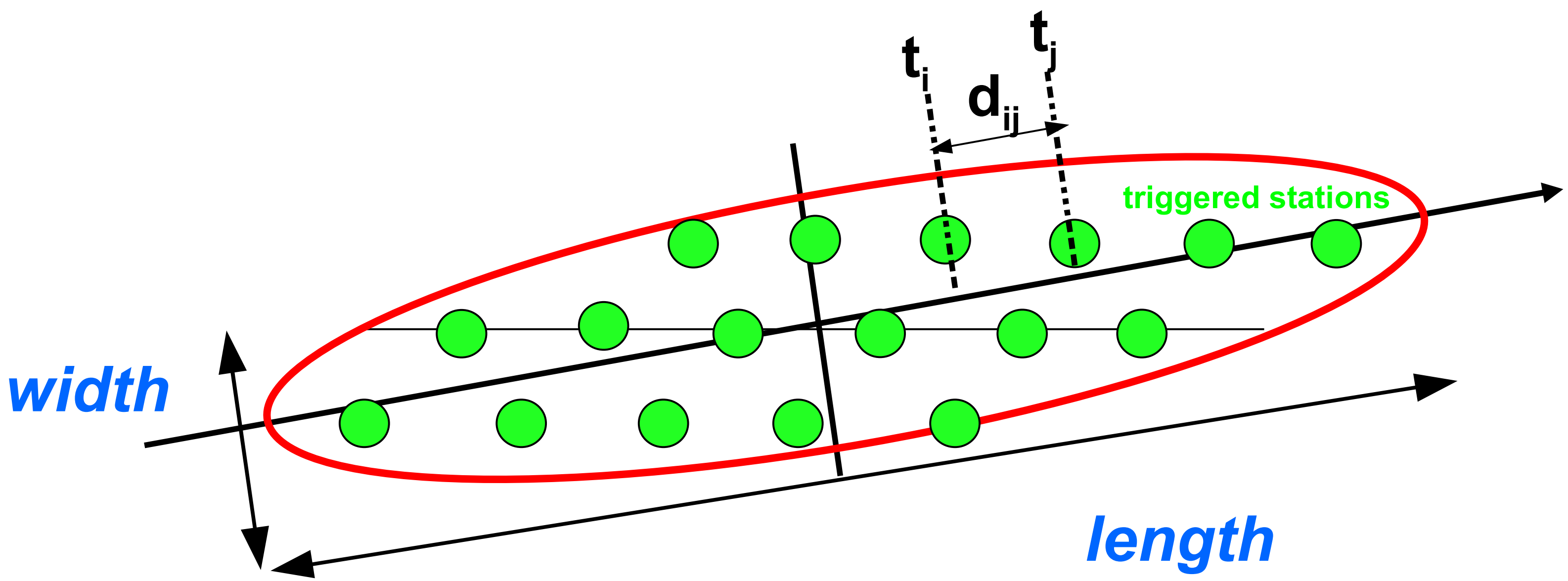
muon density



EAS simulation Aires code, S. Sciutto, www.fisica.unlp.edu.ar/auger/aires/

- **Elongated footprint on the ground with large EM component**

Selection criteria based on footprint analysis



- **Variables defined from the footprint (in any configuration, even aligned)**

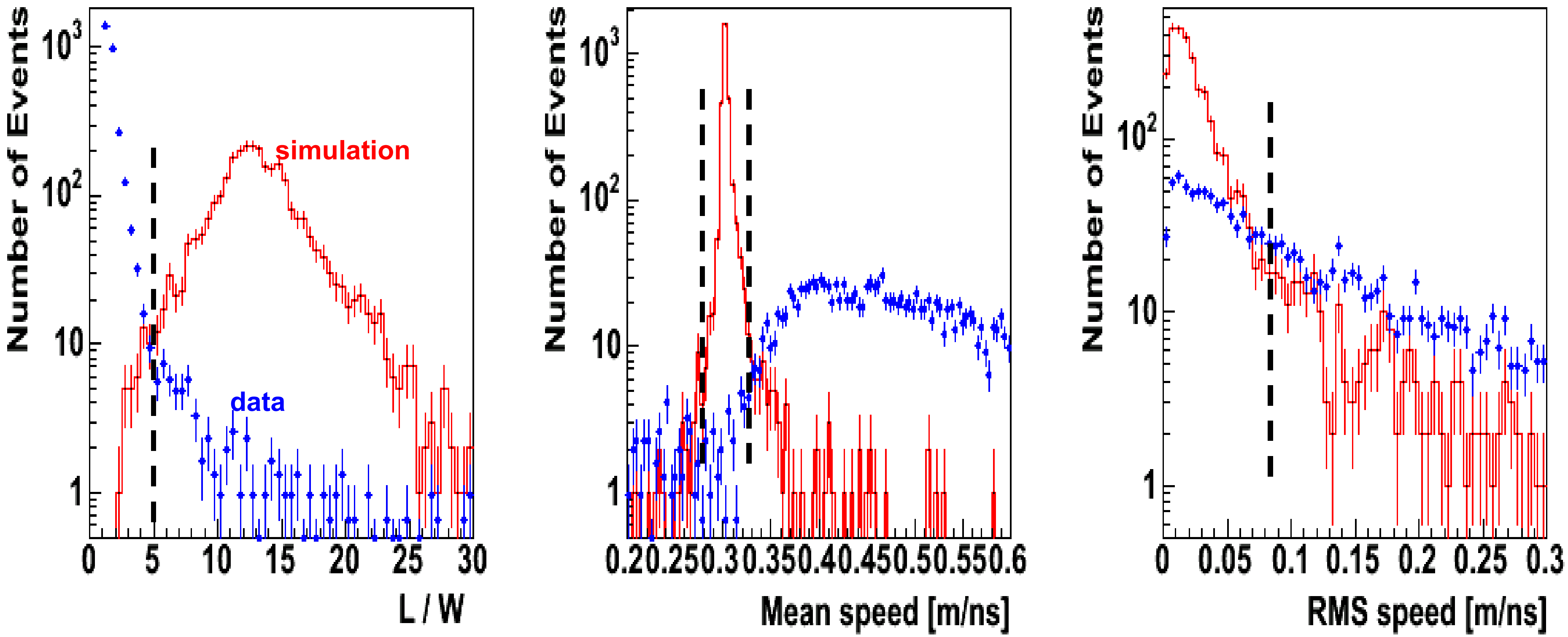
length **L** and *width* **W** - major and minor axis of the ellipsoid of inertia weighted by the station signals

"speed" - for each pair of stations (distance projected onto main axis/difference between the start time)

Selection criteria

(up-going tau neutrino induced showers)

cuts: L/W > 5 0.29 < av. Speed < 0.31 r.m.s. < 0.08

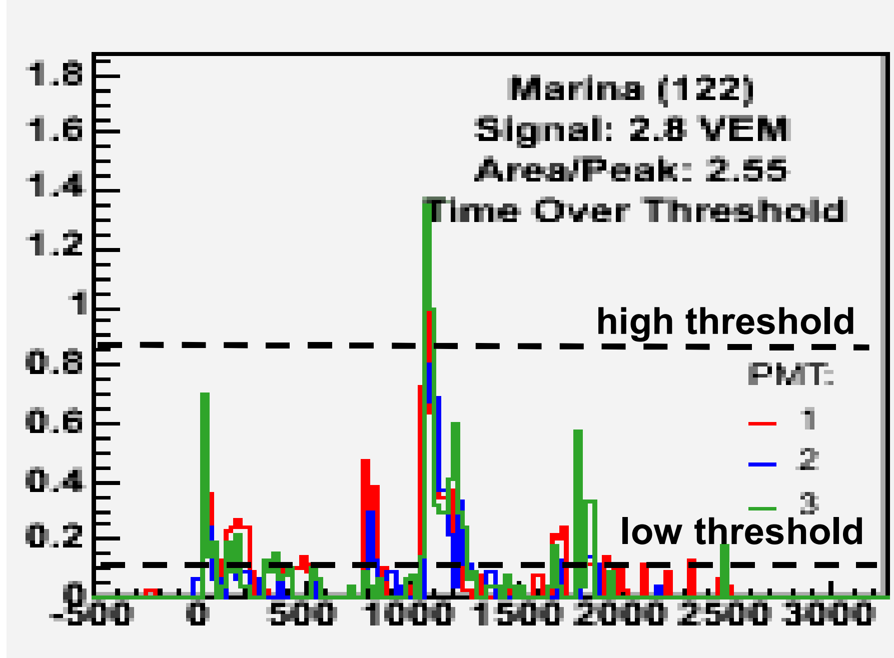


- **Search for long shaped configurations, compatible with a front moving horizontally at speed c, well contained inside the array**

P. Billoir Nove III international Workshop “Neutrino Oscillation in Venice”

Identification of neutrinos

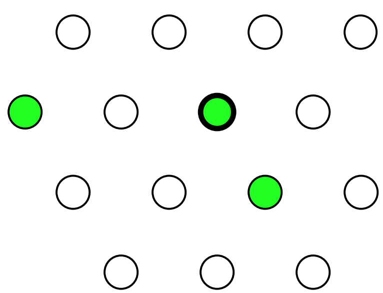
(trigger conditions)



- The **local trigger**
  (at level of the one tank)
  is the logical *or* of two conditions:

  - either a high threshold is passed at least one slot of the FADC trace

  - low threshold is passed at least N times in a given time interval, so called ***ToT*** ("time over threshold") designed to select broad signal.



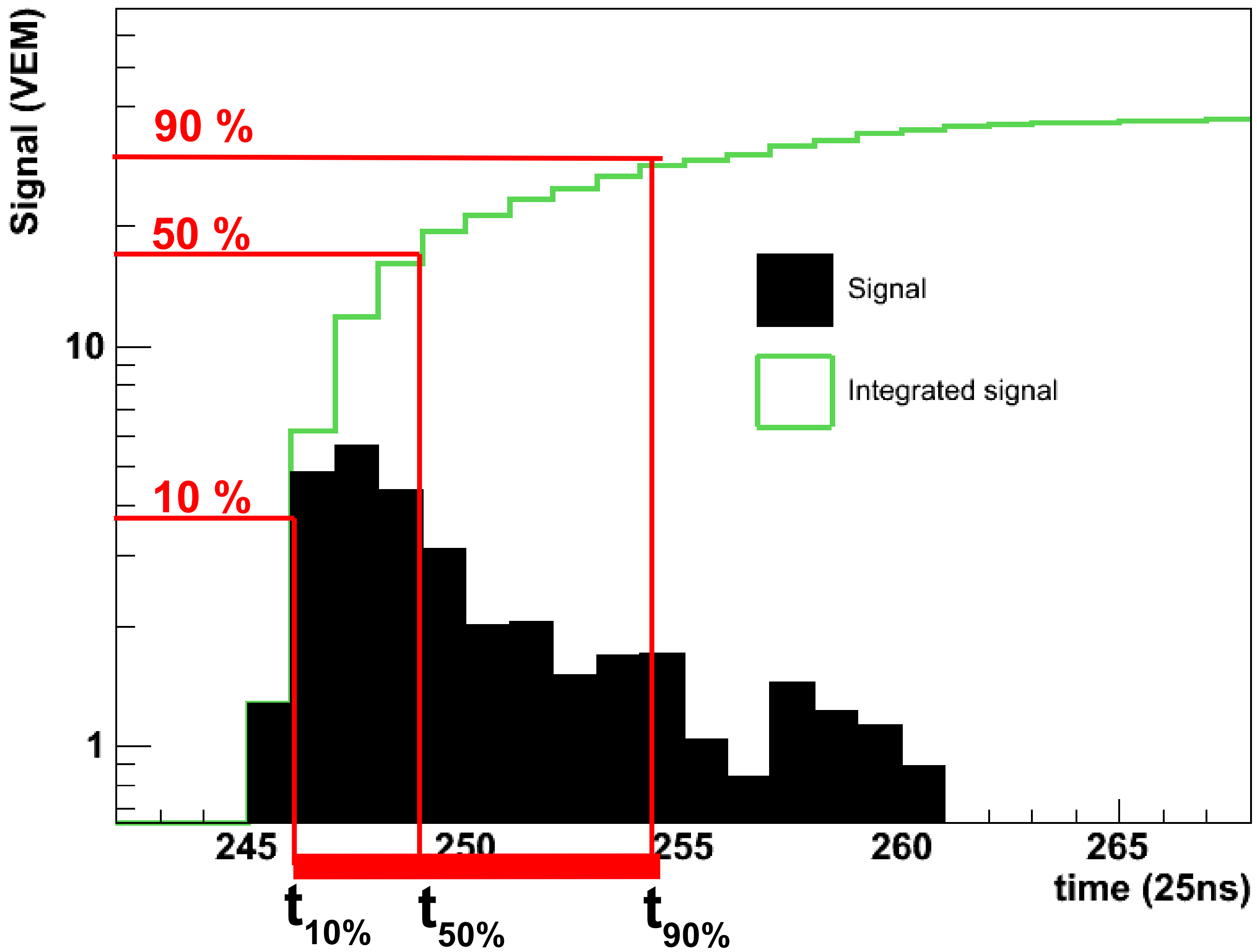
- The **global condition**:
  - compact configuration is required (3 local station satisfying the ***ToT***, one "central" + one within 1500 m + one within 3000m)

  - to get rid of coincidences of large signal the ratio area/peak >1.4

- **Neutrino event is required to have more than 80% of tagged as *ToT*.**

Identification of neutrinos

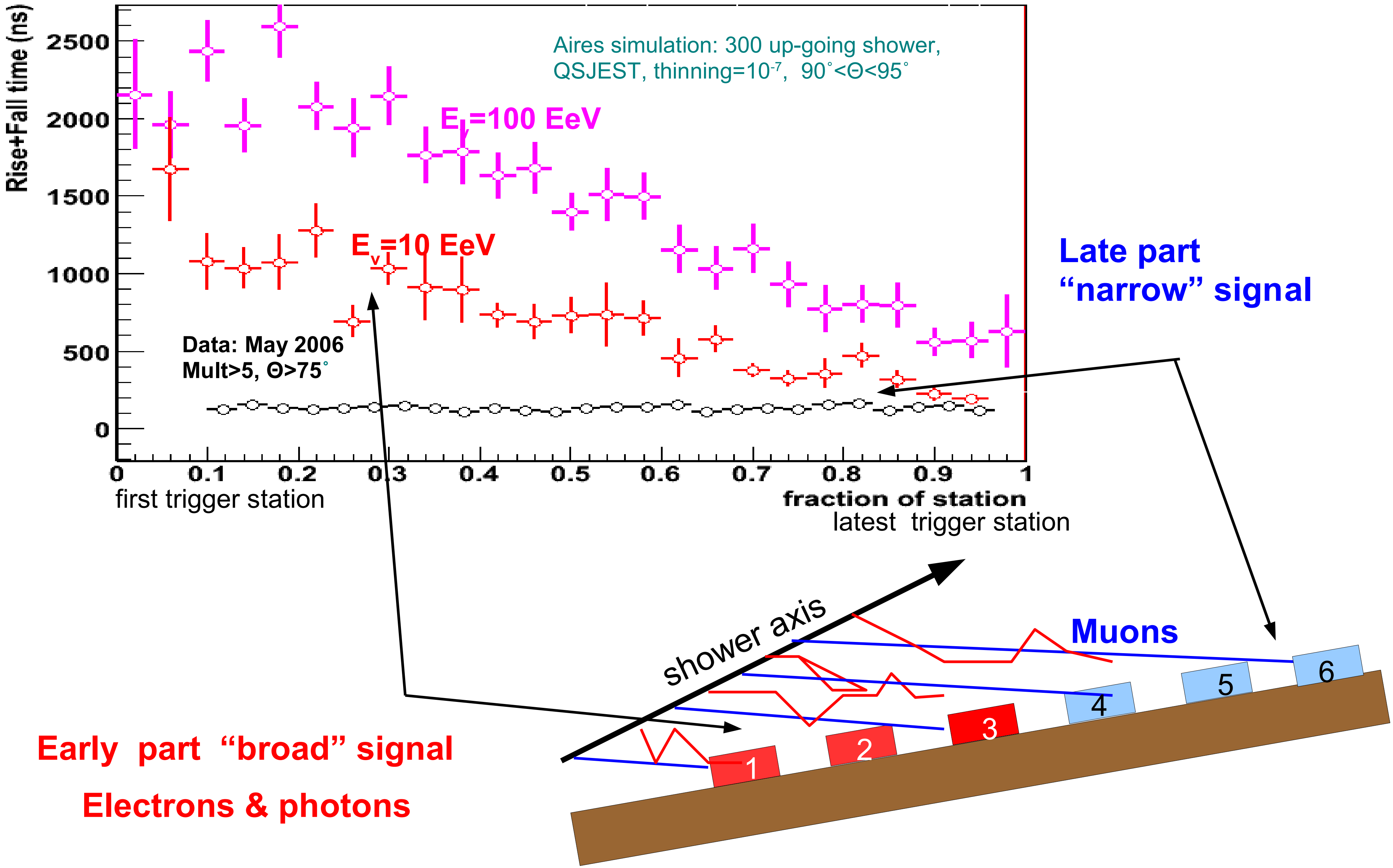
(rise time & fall time)



rise time= $t_{50\%}$-$t_{10\%}$ **fall time= $t_{90\%}$-$t_{50\%}$**

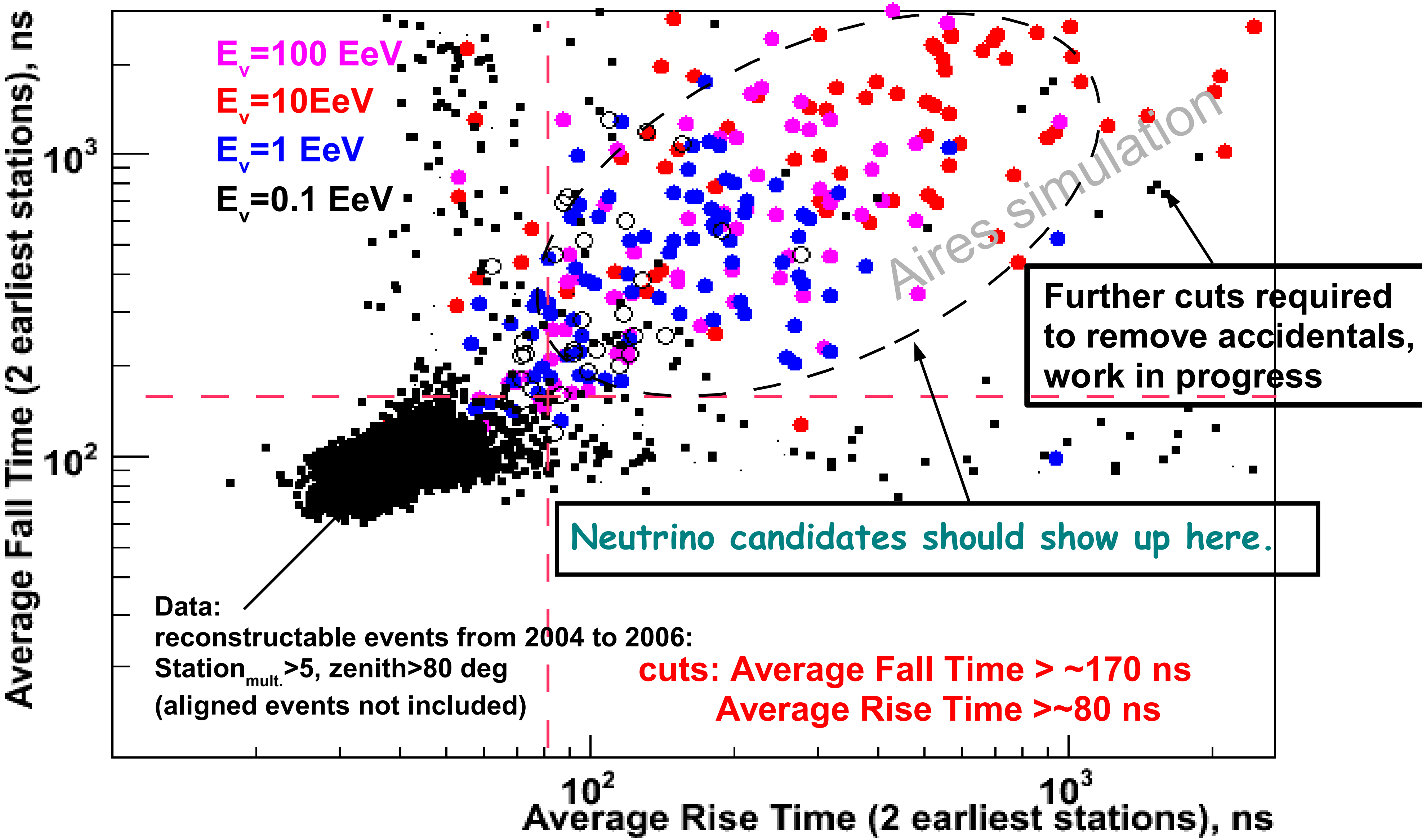
Asymmetric time structure

(up-going tau neutrino induced showers)



Identification of neutrinos

(asymmetric time structure – up going tau induced neutrino showers)

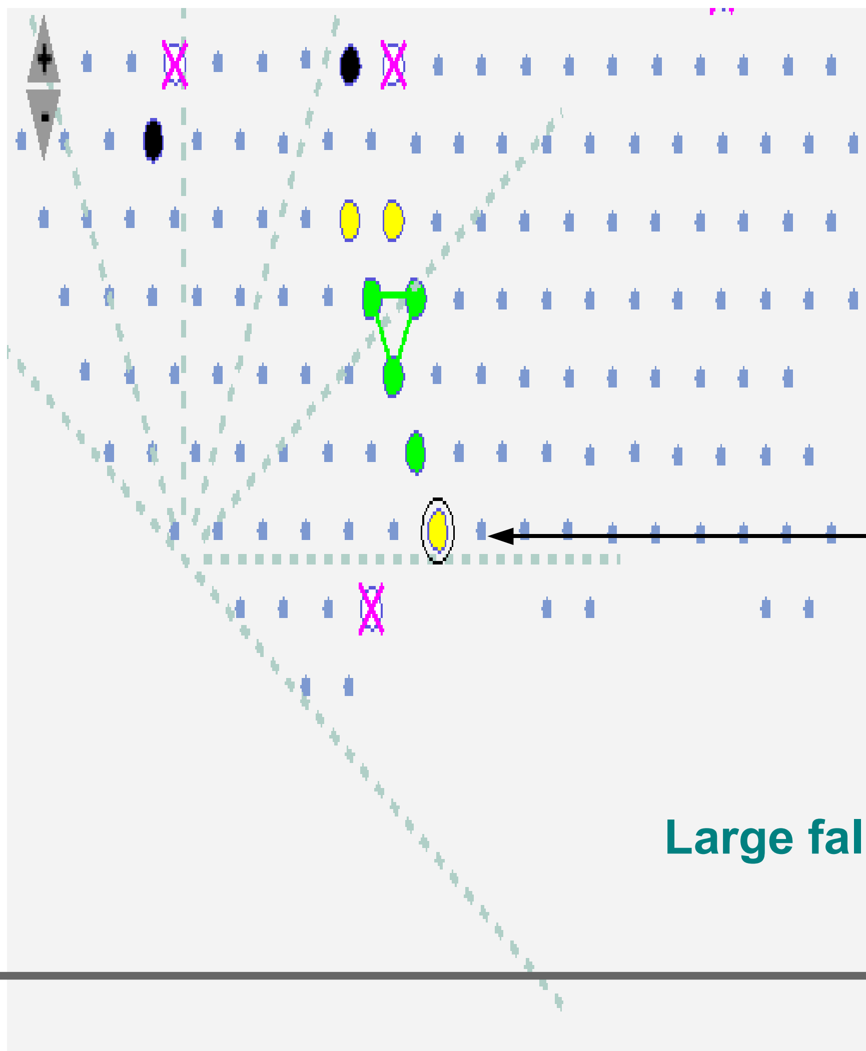


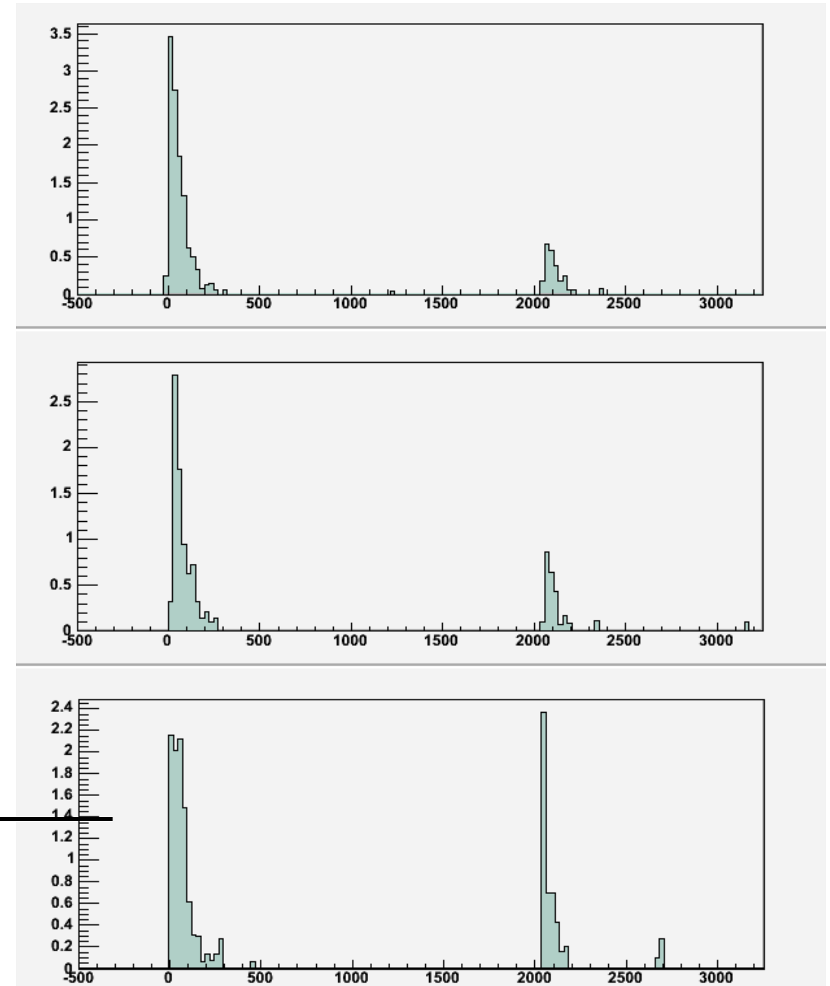
Identification of neutrinos

(a real event)

- **Background due to accidental muons can produce large rise time or fall time**

Event 2361558, theta=81deg



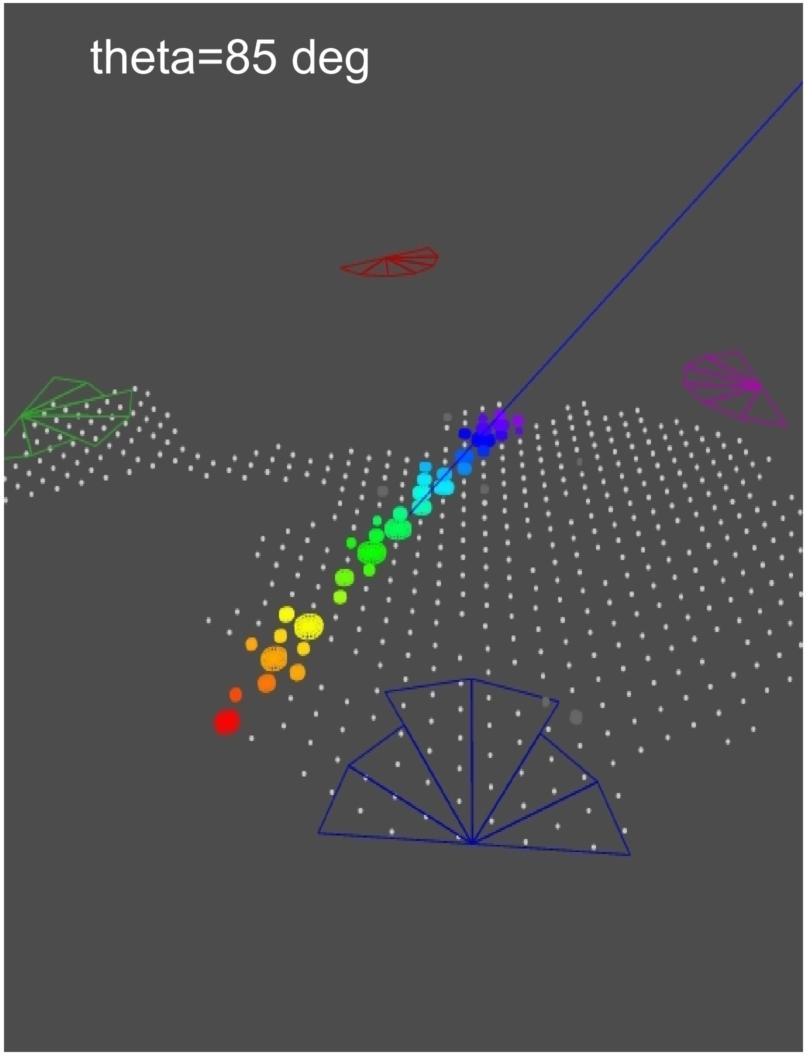


Large fall time (2034 ns) & small rise time (60 ns)

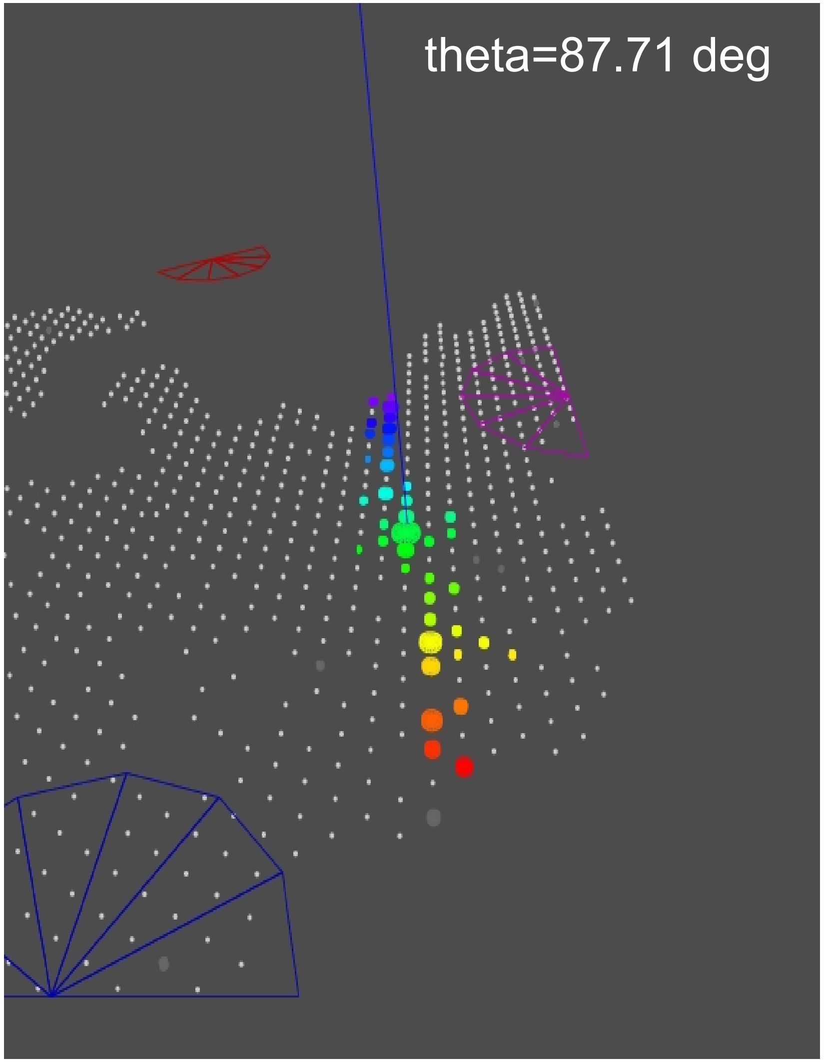
Identification of neutrinos
(Example of the real elongated events)

- **Elongated footprints are observed:**

event 1101015 Dec 2005

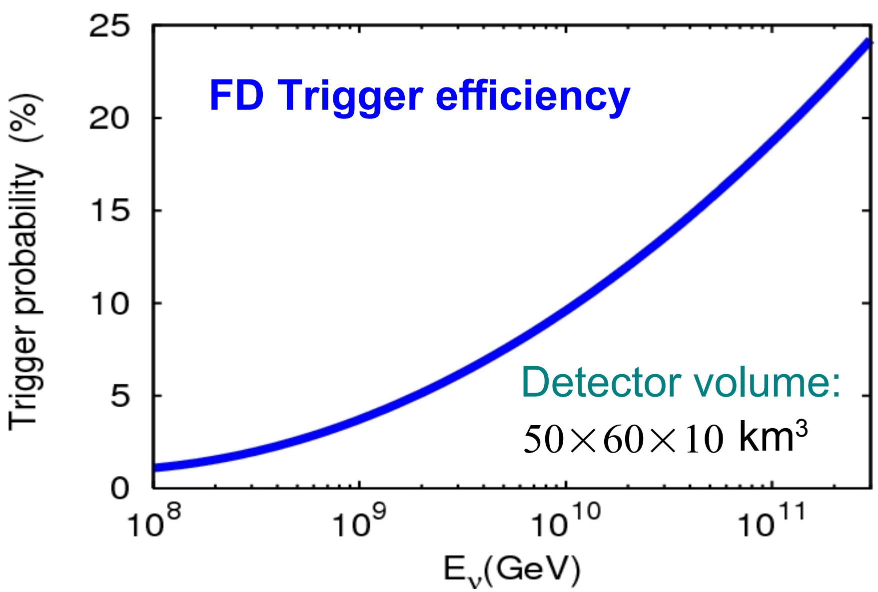


event 2924050 Dec 2006



FD acceptance

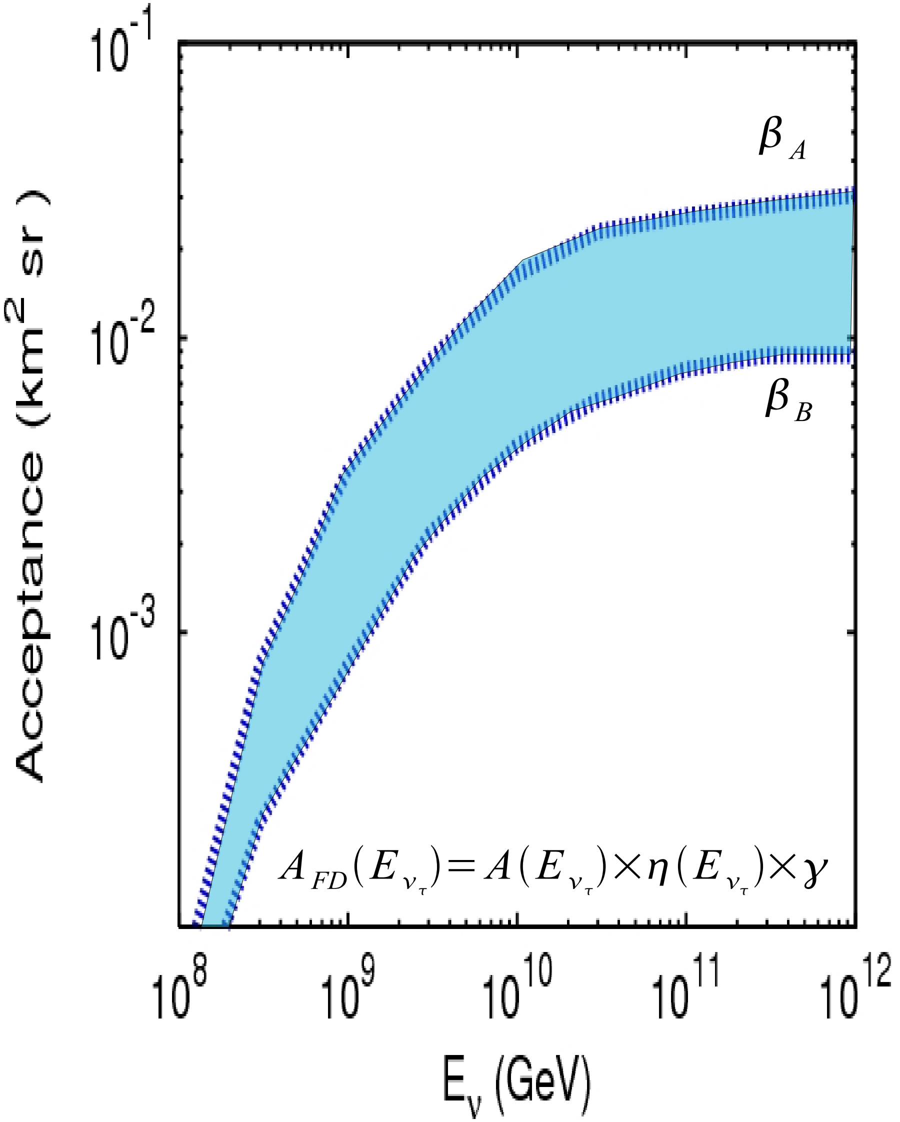
(up going tau neutrino showers as seen by FD)



- **Simulation chain:**

Neutrino simulation (ANIS) => EAS simulation (AIRES) => FD-simulation (Offline)

Offline code, **P. Auger Collaboration, T. Paul et al., Proc. 29th ICRC, 2005**



Continuous energy loss approach:

$$dE_\tau/dX = -\alpha - \beta(E_\tau)\times E_\tau$$

$\beta_A = 10^{-7}\,cm^2 g^{-1}$ (extreme case)

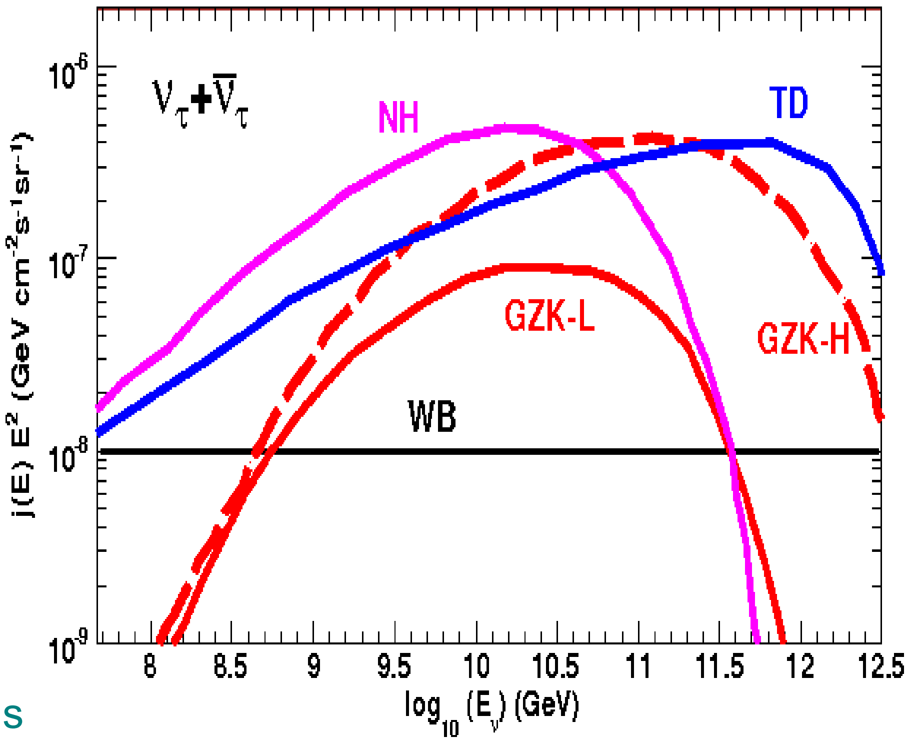
$\beta_B = (1.508 + 6.3(E_\tau/10^9)^{-0.2})\times 10^{-7}\,cm^2 g^{-1}$ (original ANIS parametrization)

with CTEQ5 cross-section

Yearly event rate
(up going tau neutrino showers as seen by FD)

- Tau neutrino and anti-neutrino fluxes from various models, taken from

Aramo et al., Astropart. Physc. 23,65 ,2005



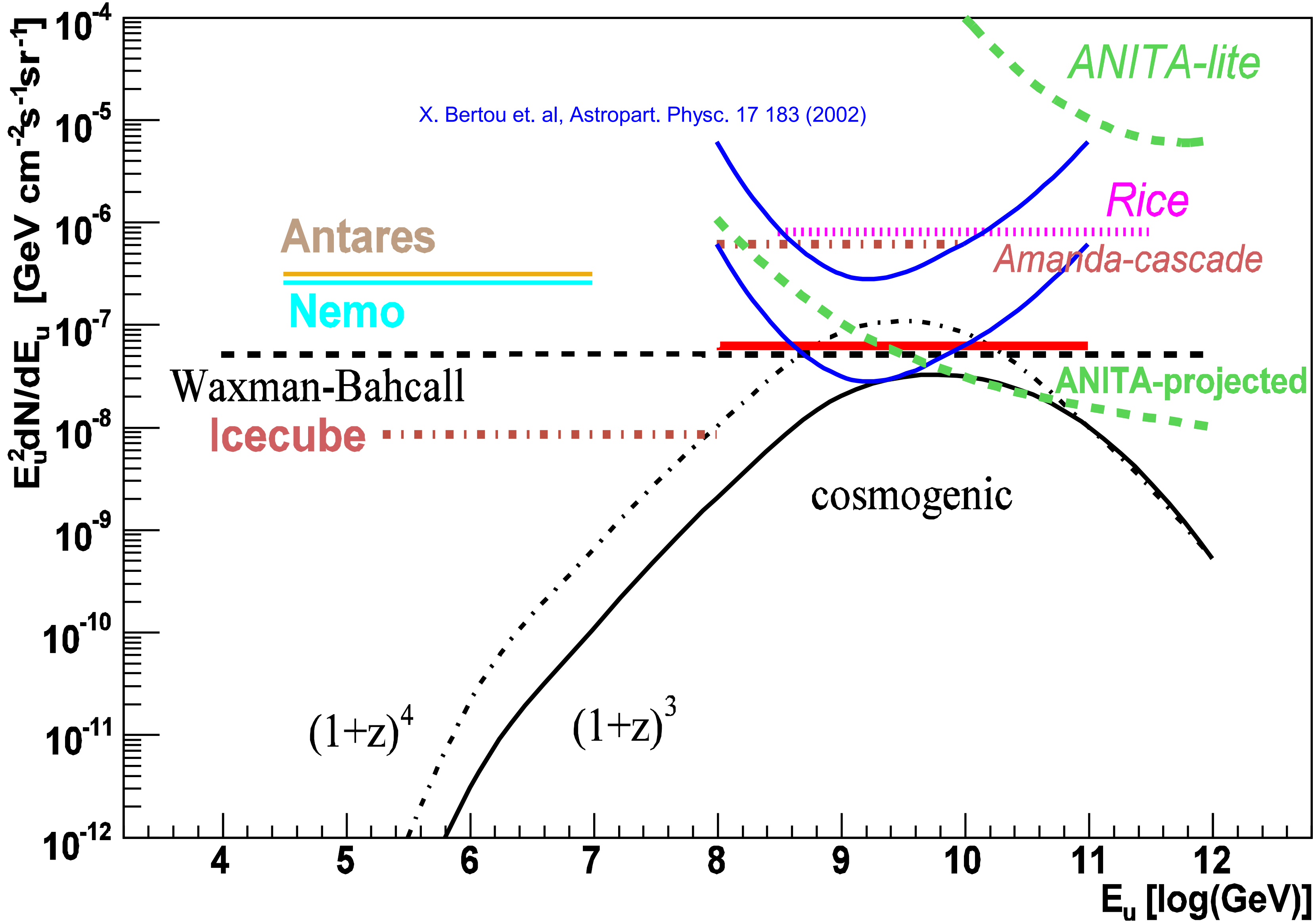
- Including 10% duty cycle for FD computations

Gora et. al. Astropart. Phys. 26 402 2007

E_τ>0.1 EeV	WB	GZK-L	GZK-H	TD	NH
N^{Acc}_{SD}	0.21	0.62	1.02	0.77	1.85
N^{Acc}_{FD}	0.01	0.08	0.14	0.11	0.28

- **about one event per 10 years in case of GZK neutrinos**

Sensitivity for Cosmogenic ν



Summary and Outlook

- The Pierre Auger Observatory is sensitive to UHE neutrinos (most promising scenario: tau lepton induced showers)

- Criteria like footprint analysis and study of rise/fall time allow to distinguish neutrino induced events from large background of the "normal" nucleonic showers

- The possible detection with fluorescence telescope

  event rate is smaller than for ground detector but ..

  - direct evaluation of altitude and energy
  - possibility to distinguish up-going induced showers from down going showers