Atmospheric neutrino experiments

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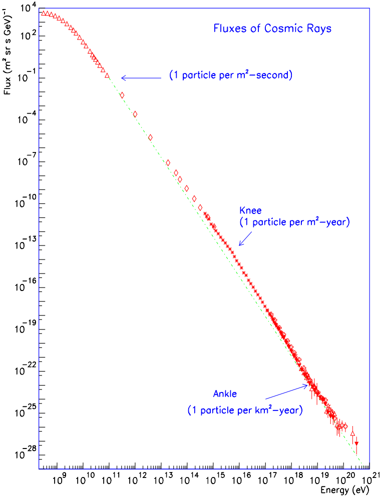
Atmospheric neutrinos

- Atmospheric neutrinos are created by the interactions of primary cosmic rays with the nuclei of the atmosphere
- Primary cosmic rays are mainly composed of protons, with a small component of heavier nuclei
- Interactions of these primary cosmic rays with the nuclei of the atmosphere generate secondary cosmic rays, which include all hadrons and their decay products
- Energy spectrum peaked in the GeV range and extends to higher energy with an approximated power law



L. Anchordoqui *et al.*, Int. J. Mod. Phys. A18, 2229 (2003)

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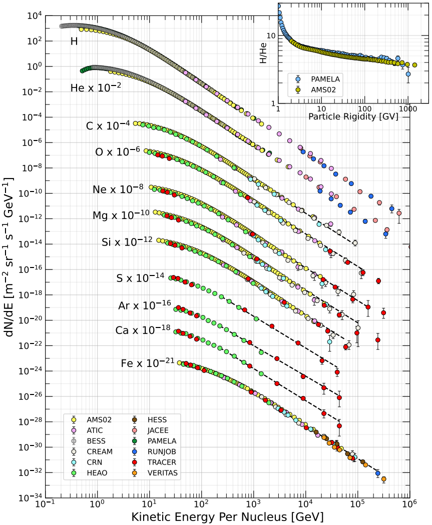

R.L. Workman *et al.* (PDG), Prog. Theor. Exp. Phys., 083C01 (2022)

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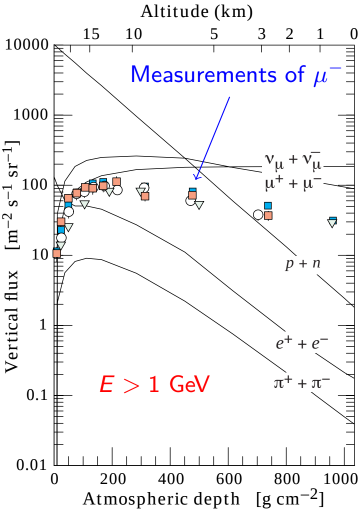


R.L. Workman *et al.* (PDG), Prog. Theor. Exp. Phys., 083C01 (2022)

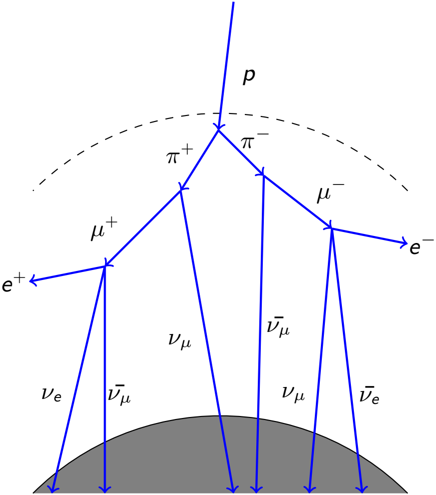
- Among hadrons, many secondary pions are produced and decay through:

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

- At high energies, kaons also contribute to the production of μs and νs
- Some muons can decay before hitting the ground through:

$$\mu^{\pm} \longrightarrow e^{\pm} + \overset{(-)}{\nu}_{\mu} + \overset{(-)}{\nu}_{e}$$

- Neutrinos generated in these reactions are called atmopheric neutrinos
- If 100 MeV $\lesssim E_{\nu} \lesssim$ 100 GeV, they can be detected in underground experiments (in order to be shielded from the flux of secondary muons)



The atmospheric neutrino anomaly

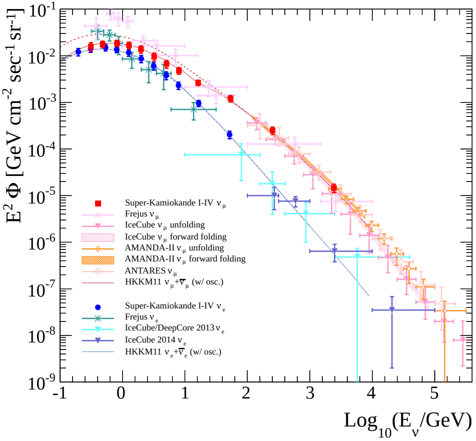
- At low energies $E \leq 1$ GeV for which most muons decay before hitting the ground, the neutrino fluxes satisfy the following ratios

$$\frac{\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}}{\phi_{\nu_e} + \phi_{\bar{\nu}_e}} \sim 2 \qquad \frac{\phi_{\nu_\mu}}{\phi_{\bar{\nu}_\mu}} \sim 1 \qquad \frac{\phi_{\nu_e}}{\phi_{\bar{\nu}_e}} \sim \frac{\phi_{\mu^+}}{\phi_{\mu^-}}$$

- At higher energies, the fraction of muons which hit the ground before decaying increases, leading to an increase of the flavor ratio $\left(\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}\right)/\left(\phi_{\nu_e} + \phi_{\bar{\nu}_e}\right)$
- First observation of atmospheric neutrinos in 1965 by detectors located in gold mines (South Africa & India) $\Rightarrow$ detection of horizontal μ produced by neutrino interaction with scintillators w/ 8000 mwe overburden
- In the second half of the 1980s, atmopheric neutrinos began to be observed by the large underground Kamiokande and IMB water Cerenkov experiments (initially build to observe nucleon decay)
- Both experiments observed a number of atmospheric muons neutrino interactions significantly smaller than the predicted one $\Rightarrow$ *atmospheric neutrino anomaly*

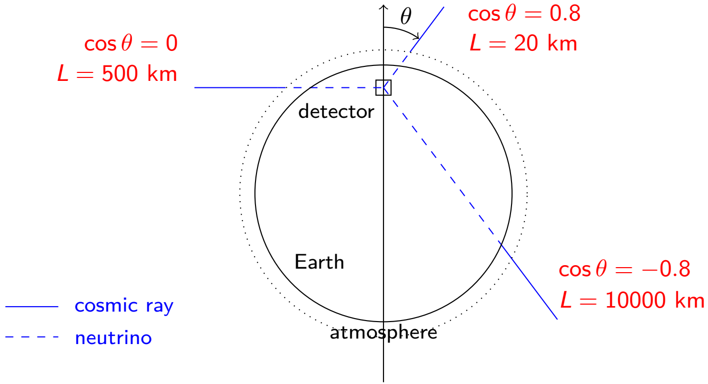
- Detailed simulations are required to compute the neutrino flux taking into account cosmic ray flux, complex hadron interactions, geomagnetic field, solar activity, etc...
- Dominant uncertainties: cosmic ray flux (20% below 100 GeV, 30% above) and hadronic interactions (20-25%)
- Spoiler alert: on top of that, oscillations! Appearance of ν_τ and complicated matter effect of neutrinos travelling through Earth

E. Richard *et al.* (SK collab.) Phys. Rev. D 94, 052001 (2016)



$\Rightarrow$ 5 orders of magnitude of neutrino energy in atmospheric experiments

What about the baseline?



Range of pathlength of atmospheric neutrinos is very wide from about 15 km for vertical downward-going neutrinos to 1.3×10^4 km for upward-going neutrinos

L/E ratio allows to investigate $10^{-4} < \Delta m^2 < 10$ eV^2 (assuming pathlength $\gtrsim 100$ km)

[Remember that oscillations are observables if $\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \sim \pi/2$]

Water Cherenkov detectors

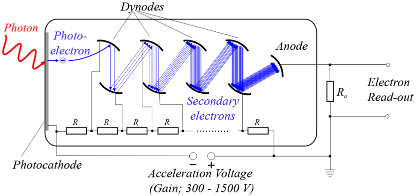
- Detection of neutrinos in real-time by observing the tracks of the ultrarelativistic charged leptons produced by neutrino interactions
- When a charge particle passes with velocity $v > 1/n$ through a medium with index of refraction n, it emits Cherenkov light in a cone around direction of the motion
- Half-opening angle $\cos\theta = 1/nv$ (water, $n = 1.33$, $\theta \sim 42^\circ$) and spectrum:

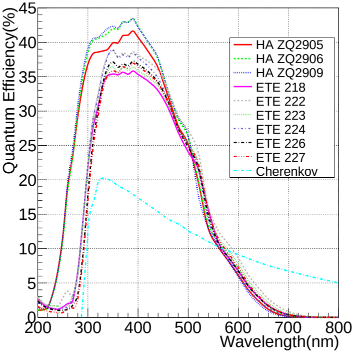
$$\frac{dN}{d\lambda dx} = 2\pi\alpha\left[1 - \left(\frac{1}{nv}\right)^2\right]\lambda^{-2},$$

  where N is the number of photons, λ the wavelength, and x the coordinate along the track
- $\lambda = 300$-600 nm, appropriate for detection using photomultiplier tube (PMT) $\Rightarrow$ through observation of photons with a precise determination of arrival time at each PMT, one can determine vertex, direction and energy of charged lepton
- Large mass of water surrounded by PMTs (need substantial coverage $\gtrsim 20\%$)

PhotoMultiplier Tubes (PMTs)

Courtesy of SK collaboration

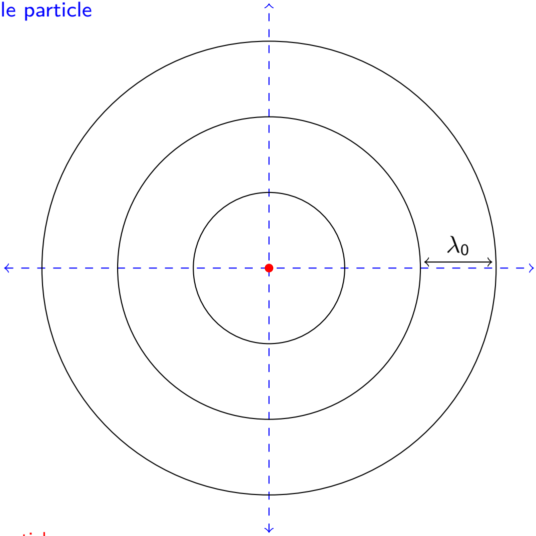




T. Toyama *et al.* (CTA consort.) arXiv:1307.5463 [astro-ph.IM] (2013)

Cherenkov effect

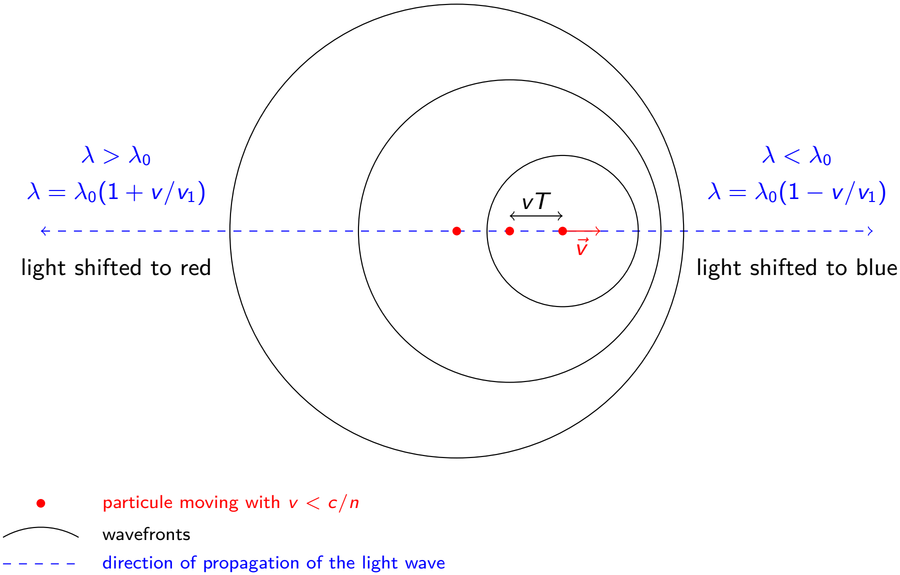
Case of an immobile particle



$$v_1 = c/n$$
$$T = \lambda_0 / v_1$$

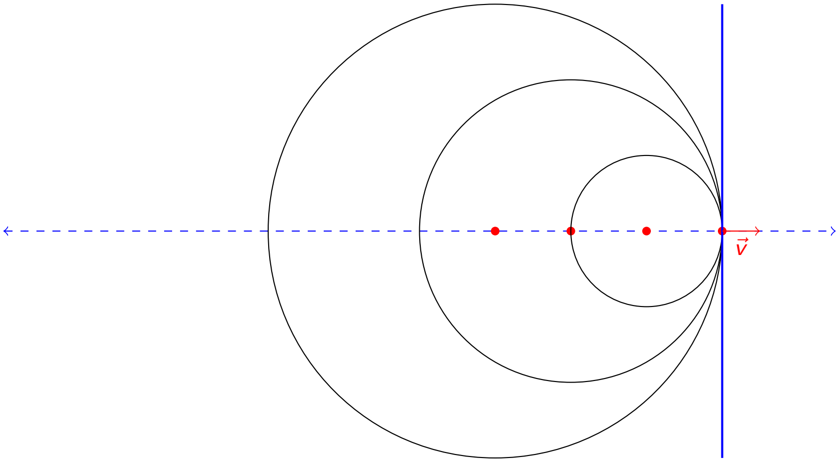
- immobile particle
- wavefronts
- direction of propagation of the light wave

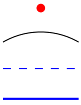
Case particle moving with $v < c/n$ (Doppler effect)



Cherenkov effect

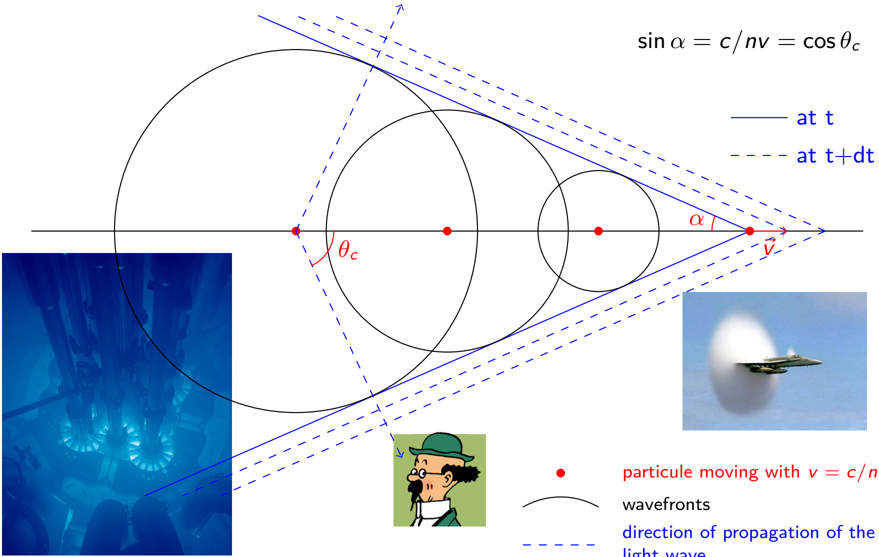
Case particle moving with $v = c/n$





Case particle moving with $v > c/n$

$$\sin\alpha = c/nv = \cos\theta_c$$

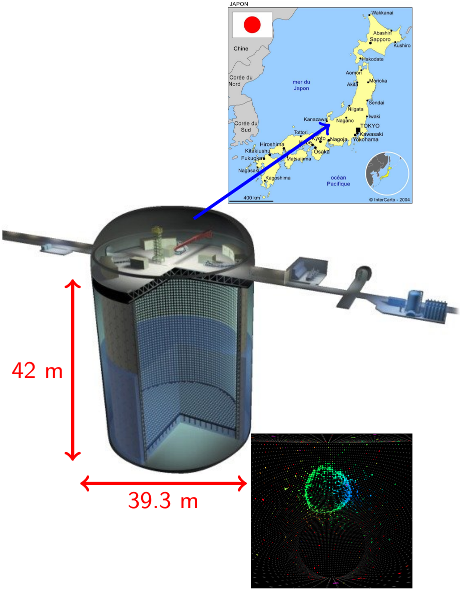


particule moving with $v = c/n$

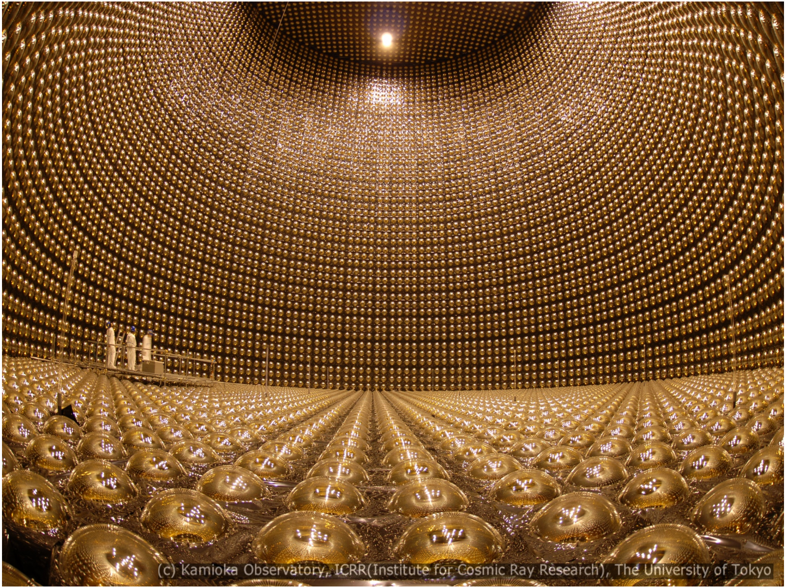
wavefronts

direction of propagation of the light wave

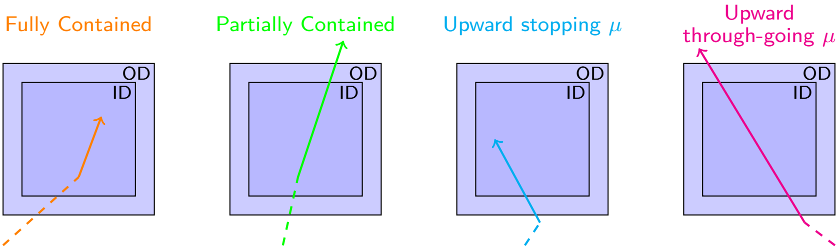
- 50 kton water Cherenkov detector
- Located in Kamioka, Japan, under Mt. Ikenoyama : 1 km rock overburden (2.7 km water equivalent)
- Optically divided into an inner detector (ID) with a fiducial volume of 22.5 kton and an outer detector (OD), instrumented with:
  - ID : 11146 inward facing large 20"-PMTs, 40% photo-coverage
  - OD : 1885 8"-PMTs primarily used as veto



An example: the Super-Kamiokande detector (cont'd)

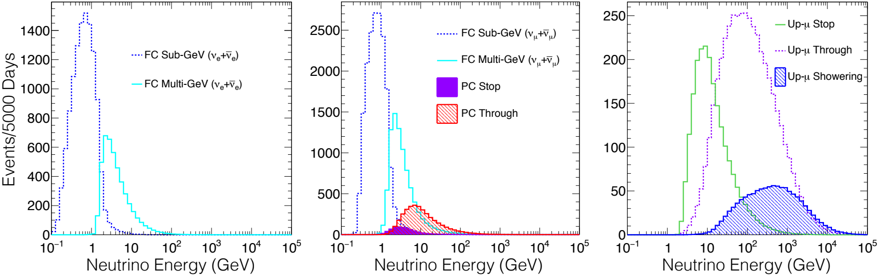


Depending on the topology and ID and OD activities

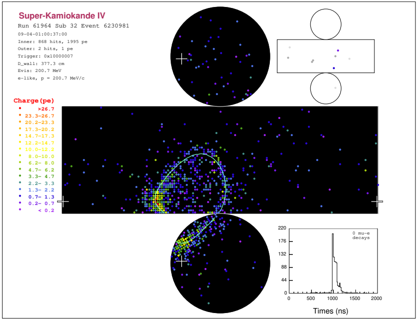


MC simulations

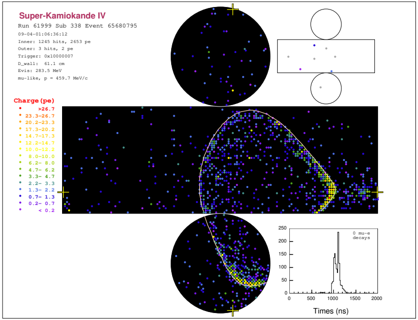
Phys. Rev. D97, 072001 (2018)



e-like ring



μ-like ring



Courtesy of SK collaboration

- Excellent particle identification (PID) obtained from the sharpness of the edge of the Cherenkov ring
- The multiple scattering of electrons is large, so electromagnetic showers produce fuzzy rings. Highly relativistic muons, in contrast, travel almost straight through the detector and produce rings with sharp edges.

Measured flavor *ratio-of-ratios* by atmospheric experiments

- Detection of the produced charged lepton in CC interactions

$$\nu_l + N \rightarrow l^- + X \qquad \bar{\nu}_l + N \rightarrow l^+ + X \qquad l = (e, \mu, \tau)$$

- No magnetization = no sensitivity to lepton charge = no difference between neutrino and antineutrinos

- τ leptons decay immediately = no track can be seen

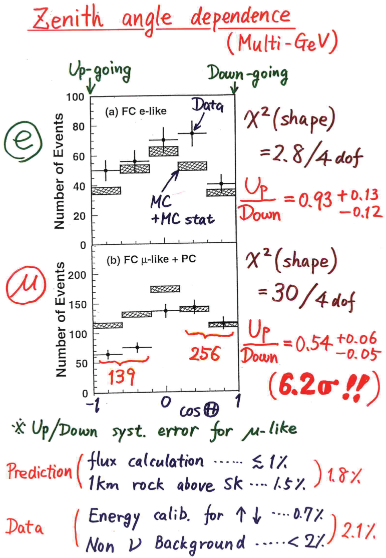
- Ratio-of-ratios:

$$R_{\mu/e} = \frac{(N_{\mu-\text{like}}/N_{e-\text{like}})_{\text{data}}}{(N_{\mu-\text{like}}/N_{e-\text{like}})_{\text{MC}}}$$

Experiments	Kamiokande	IMB	Soudan2	Super-Kamiokande
$R_{\mu/e}^{\text{sub-GeV}}$	0.60 ± 0.09	-	0.69 ± 0.12	0.658 ± 0.038
$R_{\mu/e}^{\text{multi-GeV}}$	0.57 ± 0.11	0.54 ± 0.12	-	0.702 ± 0.106

*Soudan2 is not a water Cherenkov detector but an iron tracking calorimeter

$\Rightarrow$ ratio significantly lower than unity (more than 8σ for SK) $\equiv \nu_\mu$ disappearance

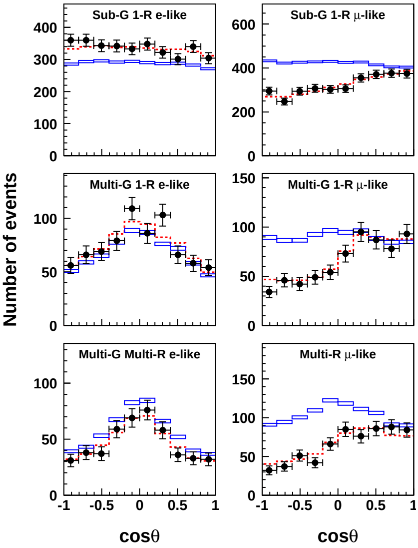


- In order to test the hypothesis of neutrino oscillation, one can vary the pathlength travelled by neutrinos
- If no oscillation :

$$N_l(\cos\theta) = N_l(-\cos\theta)$$
$$(l = e, \mu)$$

- Equation is verified for electron events but not the case for muons events
- On the plots, blue boxes are MC predictions and red dashed lines the best-fit expectations for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\sin^2 2\theta = 1$ and $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2
- Nobel prize 2015 awarded to T. Kajita

Y. Ashie et al. *Phys. Rev.* D71, 2005



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Oscillation of atmospheric neutrinos in the 2ν framework

- $(L/E)_{\rm atm}$ observed ratios cover $10^{-4} < \Delta m^2 < 10$ eV^2 squared-mass region

$$\Rightarrow \Delta m^2_{21} (\frac{L}{E})_{\rm atm} \ll 1$$

  in most of the cases and we can neglect the Δm^2_{21} contribution

- Reactor experiments (Double Chooz, Daya Bay & RENO) and accelerator long-baseline experiments (T2K, NOνA) have measured θ_{13} to be small

- Atmopheric neutrinos disappearance comes from $\nu_\mu \leftrightarrow \nu_\tau$ oscillations

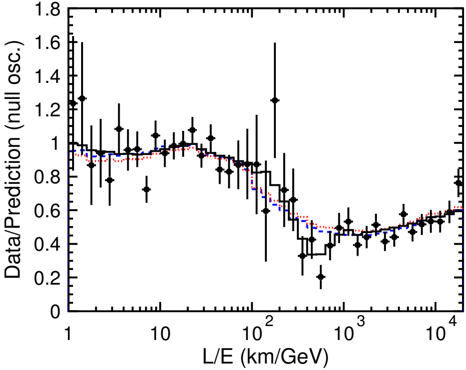
$$P^{\rm atm}_{ee} \sim 1 - \mathcal{O}(\theta_{13}, \Delta m^2_{21})$$

$$P^{\rm atm}_{\mu\mu} \sim 1 - P^{\rm atm}_{\mu\tau} \sim 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E}\right)$$

  with $\sin^2 2\theta_{23} \sim 1$ and $|\Delta m^2_{31}| \sim 0.0021$ eV^2

Oscillatory signal in atmospheric neutrinos

Y. Ashie et al. *Phys. Rev. Lett.* 93, 101801 (2004)



black solid histogram shows the best fit expectation for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\sin^2 2\theta = 1$ and $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2 in the 2ν oscillation framework

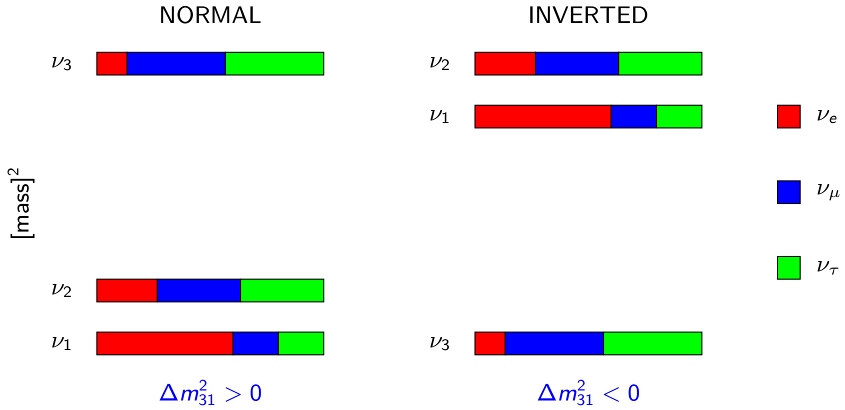
*please don't consider the red dashed and blue dotted lines which correspond to best-fit expectation for ruled out scenarios (neutrino decay / neutrino decoherence)

Modern atmospheric neutrinos results

- Nowadays, always perform analysis in the 3ν-framework
- Assuming $m_1 \simeq m_2$, atmospheric ν's probe $\Delta m^2 = \Delta m^2_{32} \sim \Delta m^2_{31}$ and all mixing matrix elements $U_{\alpha 3}$
- $U_{e3} = -\sin\theta_{13} e^{-i\delta_{\mathrm{CP}}}$, $U_{\mu 3} = \sin\theta_{23}\cos\theta_{13}$, $U_{\tau 3} = \cos\theta_{23}\cos\theta_{13}$
  [please notice that $U^2_{e3} + U^2_{\mu 3} + U^2_{\tau 3} = 1$ for unitarity]
- Sensitivity to θ_{13} and to δ_{CP}
- Take matter effects into account $\Rightarrow$ sensitivity to the mass hierarchy

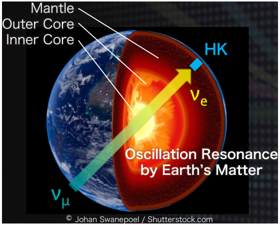
What is the mass hierarchy?

two possibilities for the neutrino mass spectrum

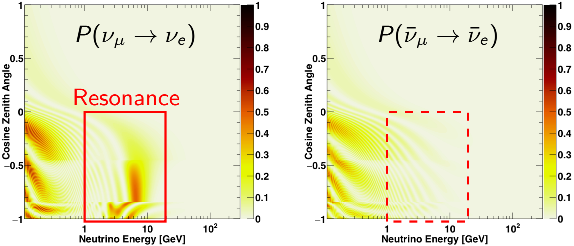


NB: we know that the mass state containing most ν_e is the lighter of the two "solar mass" states $\Delta m^2_{21} \equiv m^2_2 - m^2_1 > 0$ and $\theta_{12} < 45^\circ$ thanks to the observation of the matter effect in the Sun

- Mass-hierarchy can be accessed through matter effects in the 3ν-oscillation framework, the longer the baseline, the higher the effects



Normal Hierarchy



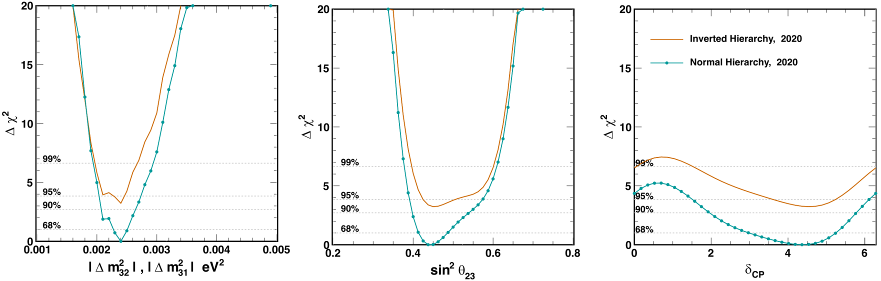
Phys. Rev. D97, 072001 (2018)

- Mass-hierarchy determined with upward-going multi-GeV ν_e sample
  - Normal hierarchy : enhancement of $P(\nu_\mu \to \nu_e)$
  - Inverted hierarchy : enhancement of $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

- Sensitivity enhanced if $\nu/\bar{\nu}$ separation

SK atmospheric neutrinos results (2020)

PMNS official, SK collaboration, june 2020

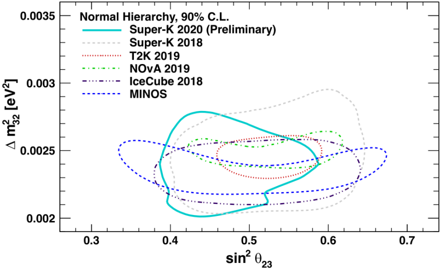


Data favors first octant for θ_{23}

Data favors NH at 1.7σ
$\Delta\chi^2(\text{IH}) - \Delta\chi^2(\text{NH}) = 2.8$

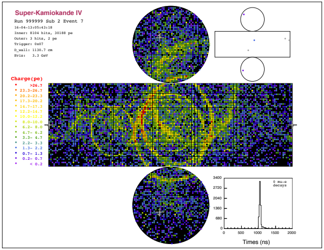
δ_{CP} best fit agrees with that of T2K

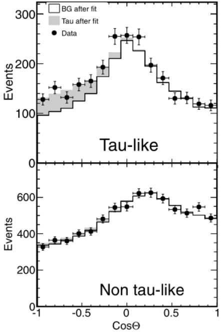
Some constraining power over θ_{13}
consistent with LBL results



Results shown here are with θ_{13} constrained by reactor experiments

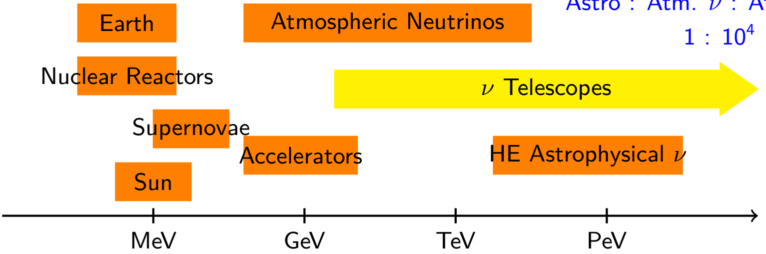
- Results taken from Phys.Rev.D 98 (2018) 5, 052006
- τ leptons produced in CC ν_τ interactions decay quickly to secondary particles $\Rightarrow$ not possible to directly detect τ in SK
- Leptonic τ decay look quite similar to atmospheric CC ν_e or ν_μ
- Hadronic decays are dominant and produce one or more pions $\Rightarrow$ allows separation of CC ν_τ signal from CC ν_μ, CC ν_e and NC background
- Results excludes no-tau appearance at 4.6σ





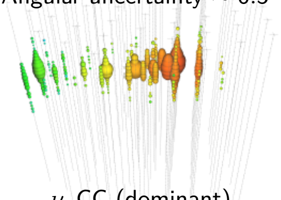
Neutrino telescopes - Event energies and topologies

Astro : Atm. ν : Atm. μ
1 : 10^4 : 10^{10}



Tracks

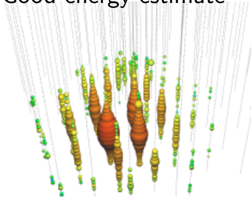
Traditional ν astro channel
Angular uncertainty $\sim 0.5^\circ$



ν_μCC (dominant)
ν_τCC w/ τ decaying into μ (minor)

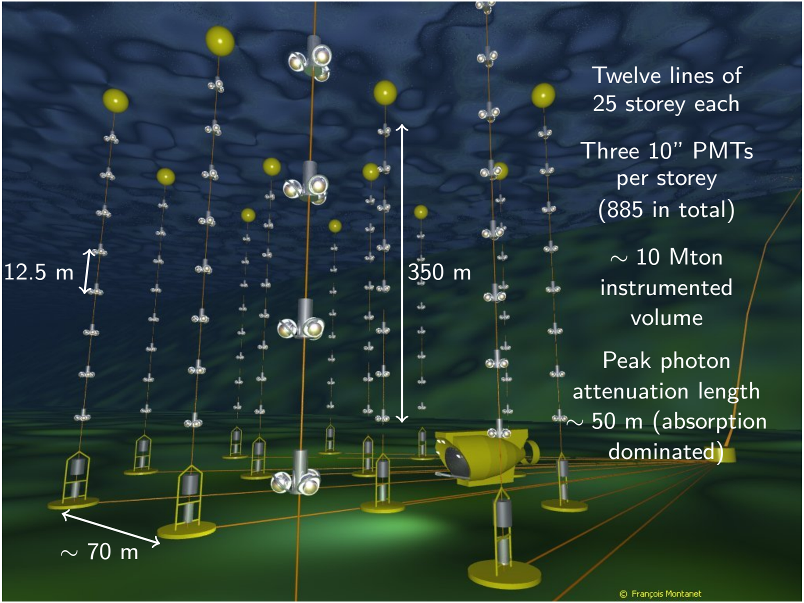
Cascades / showers

Angular uncertainty $\sim 3 - 10^\circ$
Good energy estimate



everything else (including ν_μCC)

ANTARES (Mediterranean Sea)



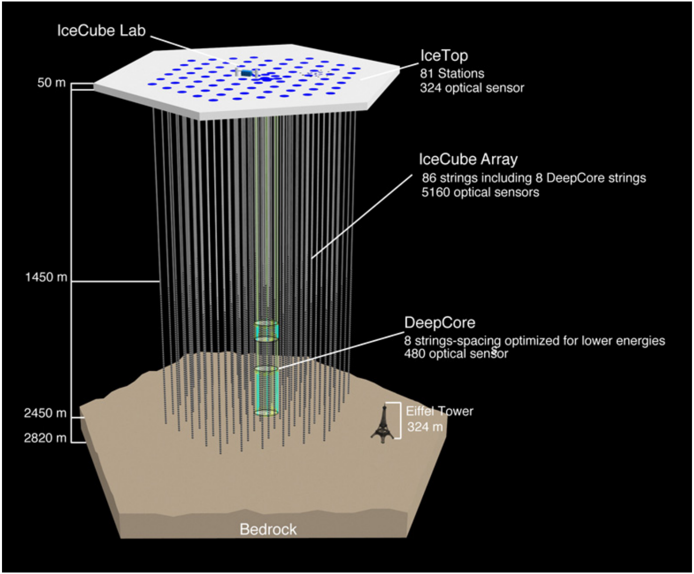
Twelve lines of 25 storey each

Three 10" PMTs per storey (885 in total)

$\sim$ 10 Mton instrumented volume

Peak photon attenuation length $\sim$ 50 m (absorption dominated)

IceCube (South Pole)



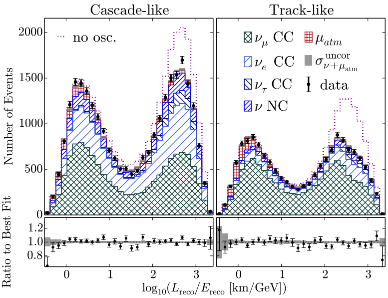
$\sim$ 600 Mt

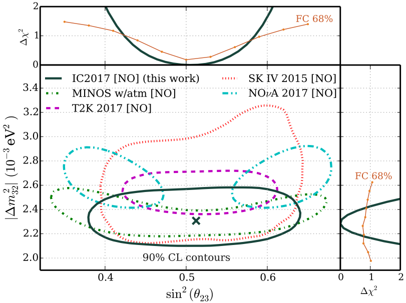
$\sim$ 15 Mt for DeepCore

One 10" PMT per optical sensor

Peak photon attenuation length $\sim$ 45 m (scattering dominated)

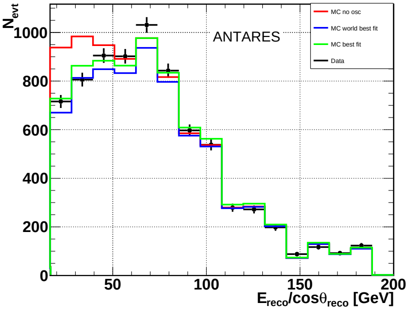
- Resuts taken from Phys.Rev.Lett. 120 (2018) 071801
- 1022 days livetime (2012-14)
- 41599 events (full-sky)
- Best fit $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$, $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}$ eV^2

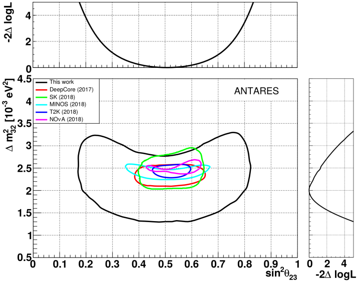




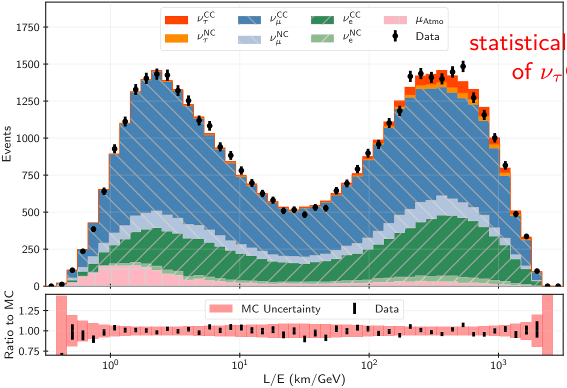
ν_μ disappearance at ANTARES

- Results taken from JHEP 06, 113 (2019)
- 2830 days livetime (2007-16)
- 7710 events
- Best fit $\theta_{23} = 45^\circ \pm 12^\circ$, $\Delta m^2_{32} = (2.0 \pm 0.3) \times 10^{-3}$ eV^2





- Results taken from Phys. Rev. D 99 (2019) 3, 032007
- Search for a statistical excess of cascade-like ν events which are the signature of ν_τ interactions
- Absence of ν_τ appearance excluded at 3.2σ



Future of atmospheric neutrino experiments

- Competition with long baseline accelerator experiments (T2K, NOνA, Hyper-Kamiokande, DUNE) on "atmospheric parameters" ($\theta_{23}, \Delta m^2_{32}$)
- Atmospheric neutrinos have still a major role to play for the determination of the θ_{23} octant and the mass hierarchy, which are required for the subsequent study of CP violation in the leptonic sector
- The possibility to study many oscillation channels within a single experiment will allow to test PMNS unitarity
- Future experiments:
  - Hyper-Kamiokande $\rightarrow$ 8$\times$ SK fiducial volume
  - PINGU $\rightarrow$ IceCube upgrade to lower threshold below 5 GeV
  - ORCA $\rightarrow$ KM3Net detector optimised for atmospheric neutrino oscillation studies at energies of a few GeV