Atmospheric Neutrinos

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IPHC, Strasbourg

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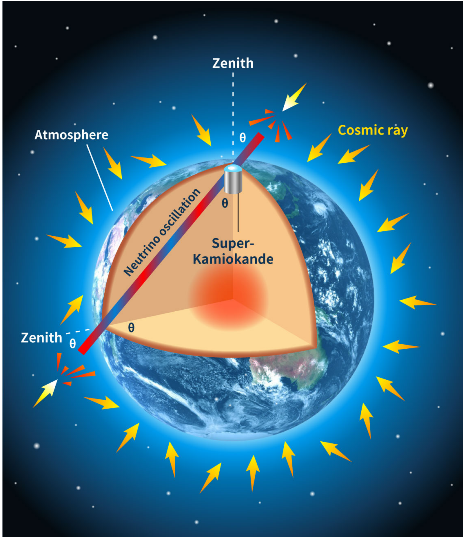
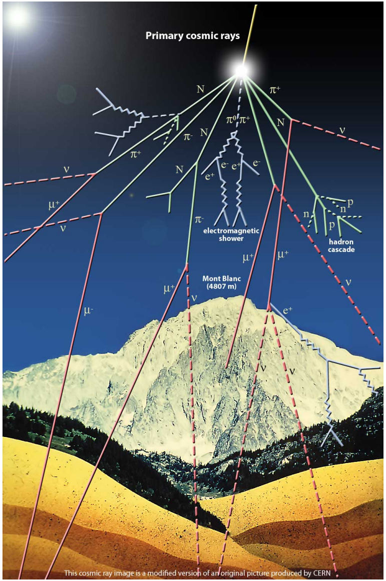
What are Atmospheric Neutrinos?



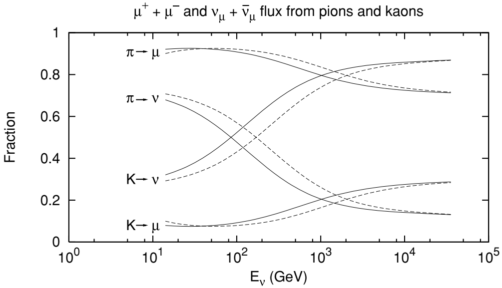
https://www-sk.icrr.u-tokyo.ac.jp/en/sk/about/research/#tab2

- Cosmic Ray's interaction with Earth Atmosphere $\rightarrow$ particle shower
- In particle shower you have $\pi^{\pm}$, $K^{\pm}$, ... produced that decay producing ν
- Those ν are called "atmospheric neutrinos"
- Due to low ν cross-section, detectors have a "4π view" of the neutrino flux

The Atmospheric Neutrino flux



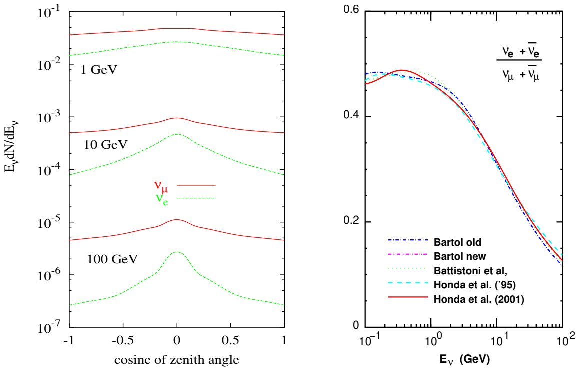
- Principal decays producing ν:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$ + cc
  - $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ + cc
  - $K^+ \rightarrow \mu^+ + \nu_\mu$ + cc
- Note: K decays have larger chance to produce ν_e than π decays (5.0% vs 0.012%)



T Gaisser, Earth Planets Space 62 (2010) 195-199

The Atmospheric Neutrino flux

- Assuming all particles decay
  - $\phi(\nu_\mu) + \phi(\bar{\nu}_\mu) : \phi(\nu_e) + \phi(\bar{\nu}_e) \sim 2:1$
  - $\phi(\nu_\mu) \sim \phi(\bar{\nu}_\mu)$
  - $\phi(\nu_e)/\phi(\bar{\nu}_e) \sim \phi(\mu^+)/\phi(\bar{\mu}^-)$
- At several GeV, μ reach ground and no longer decay
  - $\frac{\phi(\nu_\mu)+\phi(\bar{\nu}_\mu)}{\phi(\nu_e)+\phi(\bar{\nu}_e)}$ increases
  - Atmosphere 'depth' depends on zenith (θ) angle
- $\phi(\nu_i) = \sum_A \phi(A) \otimes R_A \otimes Y_{A\to\nu_i}$
  - A: cosmic ray particle (p or heavier nuclei)
  - Y: yield of CR transforming into ν_i
  - R_A: filtering effect of geomagnetic field



T. Gaisser and M. Honda, Ann.Rev.Nucl.Part.Sci. 52 (2002) 153-199

The Atmospheric Neutrino flux

of $\nu_\mu + \bar{\nu}_\mu$ from decay of pions and kaons is

$$\frac{dN_\nu}{dE_\nu} = \frac{\phi_N(E_\nu)}{(1-Z_{NN})(\gamma+1)} \left\{ \left[\frac{Z_{N\pi}(1-r_\pi)^\gamma}{1+B_{\pi\nu}\cos\theta E_\nu/\epsilon_\pi} \right] + 0.635 \left[\frac{Z_{NK}(1-r_K)^\gamma}{1+B_{K\nu}\cos\theta E_\nu/\epsilon_K} \right] \right\}, \quad (6)$$

where

$$\phi(E_0) = \frac{dN}{dE_0} = A \times E_0^{-(\gamma+1)} \quad (7)$$

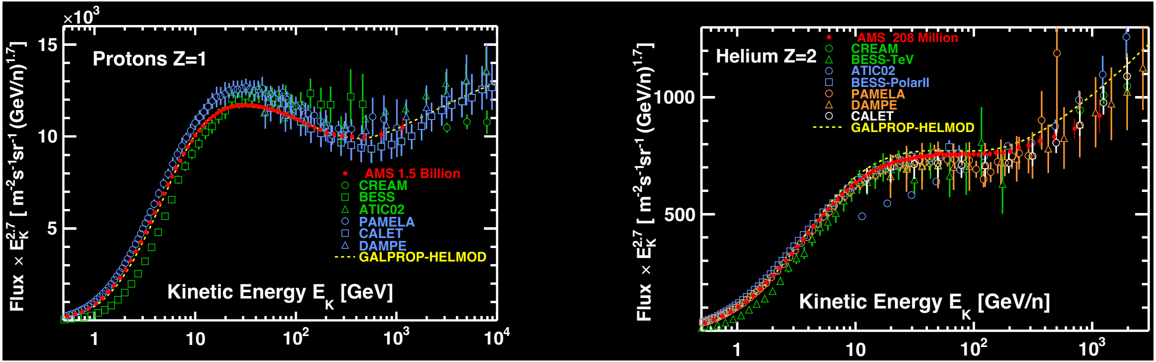
- $r_i = m_\mu^2/m_i^2$
- B: depends on hadron attenuation & decay kinematics
- $Z_{N\to i}$: production function for $i = \pi, K$
- Doesn't include ν from μ decay...
- At very high E: add charm component

Table 1: Parameters for atmospheric $\nu_\mu + \bar{\nu}_\mu$ from π,K-decay

Mass-square ratios	r_π	r_K	B_π	B_K
& B-factors:	0.573	.046	2.77	1.18
Characteristic E_{decay}:	ϵ_π	ϵ_K	ϵ_{charm}	
	115 GeV	850 GeV	$\sim 5\times10^7$ GeV	
Z-factors:	Z_N	Z_π	Z_K	
	0.30	0.079	0.0118	

T. Gaisser and M. Honda, Ann.Rev.Nucl.Part.Sci. 52 (2002) 153-199

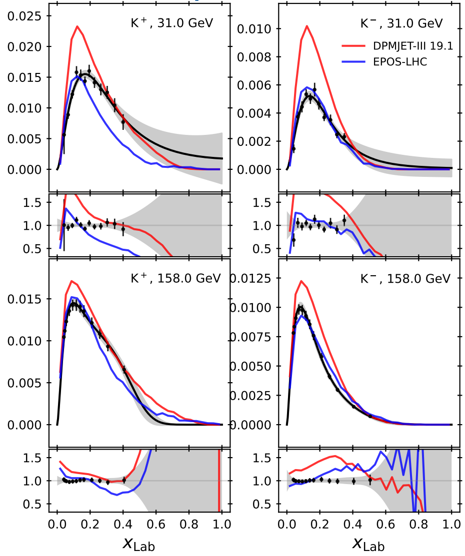
The Atmospheric Neutrino flux: primary CR flux



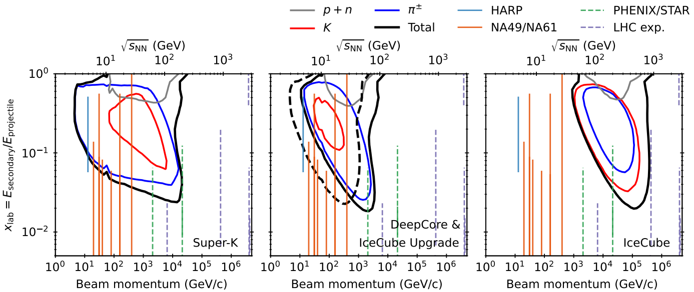
Z. Wang talk at TAUP 2023

- Typical spectral shape roughly $\phi(E) \propto E^{-2.7}$
- Solar activity can change CR flux (solar modulation)
- Neutrino flux typically follow same power law, but can get steeper at high energies

The Atmospheric Neutrino flux: interaction

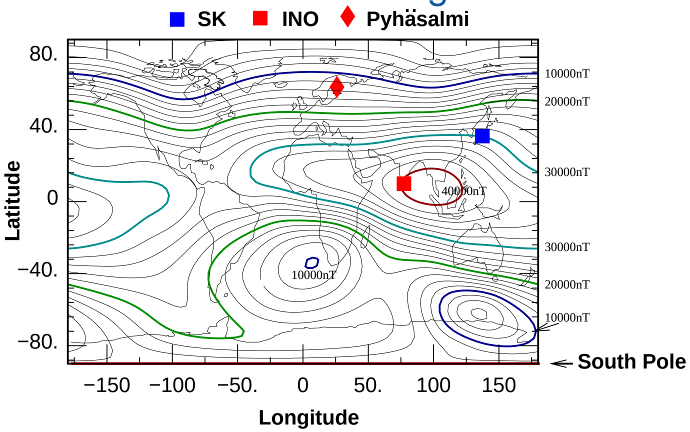


- Data/models tuned from accelerators
- Doesn't fully match requirements for ν flux calculation



A Fedynitch et al, Phys.Rev.D 106 (2022) 8, 083018

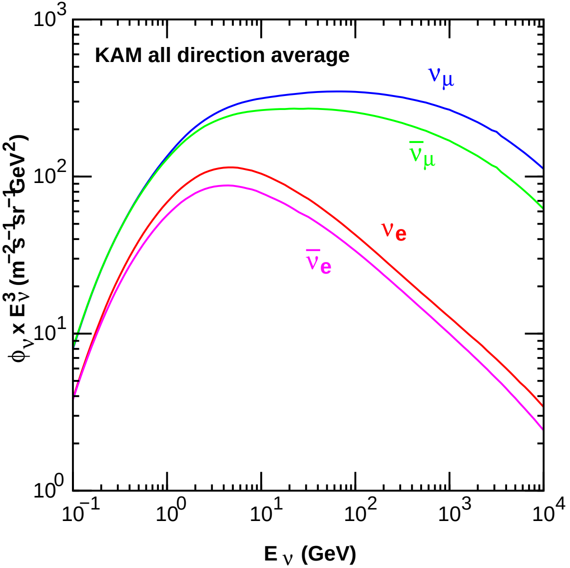
The Atmospheric Neutrino flux: Geomagnetic effect



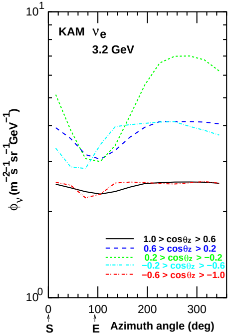
M. Honda et al, Phys.Rev.D 92 (2015) 2, 023004

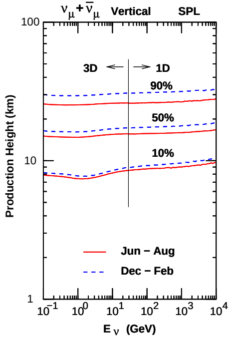
- Cut-off in primary CR
- Deviation of charge particles during propagation
  - East-West asymmetry, 3D calculations needed at low-energy

The Atmospheric Neutrino flux: Honda calculation



- Fluxes computed and provided (tabulated) for several sites
  - `http://www-rccn.icrr.u-tokyo.ac.jp/mhonda/public/`
- Account for local effects (geomagnetic field, average weather)





M. Honda et al, Phys.Rev.D 92 (2015) 2, 023004

The Atmospheric Neutrino flux uncertainties: prescription from Barr

TABLE I: Summary of primary flux parameter variation

Parameter	Proton fluxes	Nuclear fluxes
a (normalization)	1.49 ± 0.10	0.060 ± 0.004
b	2.15 ± 0.025	1.25 ± 0.03
c	-2.21 ± 0.02	-0.14 ± 0.02
d (index) $< 200\mathrm{GeV/n}$	2.74 ± 0.01	2.64 ± 0.02
$> 200\mathrm{GeV/n}$	2.74 ± 0.03	2.64 ± 0.04

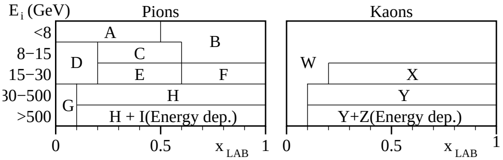
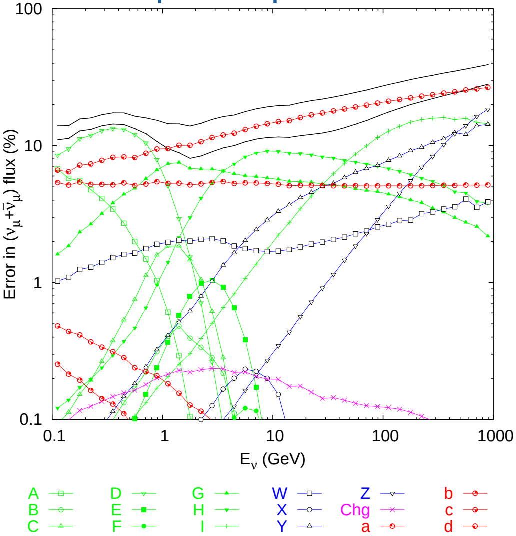


FIG. 3: Uncertainty sources for hadron production. The uncertainties which are applied are fully correlated within each region shown and completely uncorrelated between regions. The letters used to label each region are used on subsequent figures. The levels of uncertainties applied are shown in figure 2.



Barr et al. Phys.Rev.D 74 (2006) 094009

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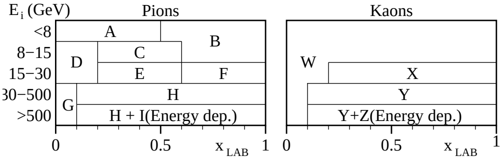

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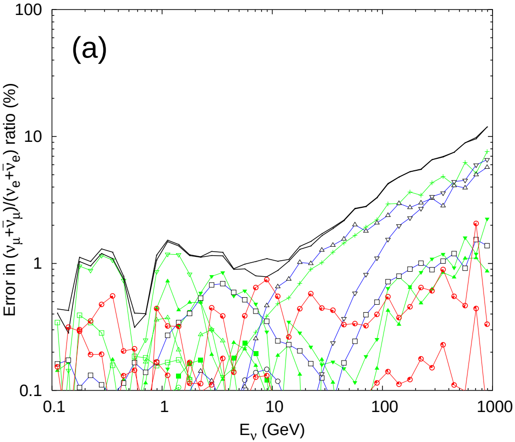
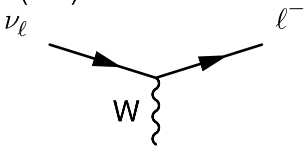


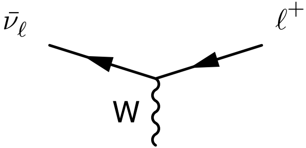
Barr et al, Phys.Rev.D 74 (2006) 094009

Neutrino Interaction with matter

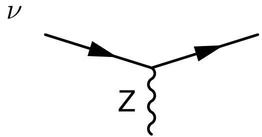
Looking on the ν side of the interaction

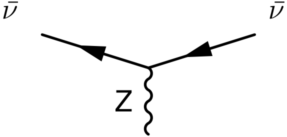
Charged Current (CC) interaction :





Neutral Current (NC) interaction :

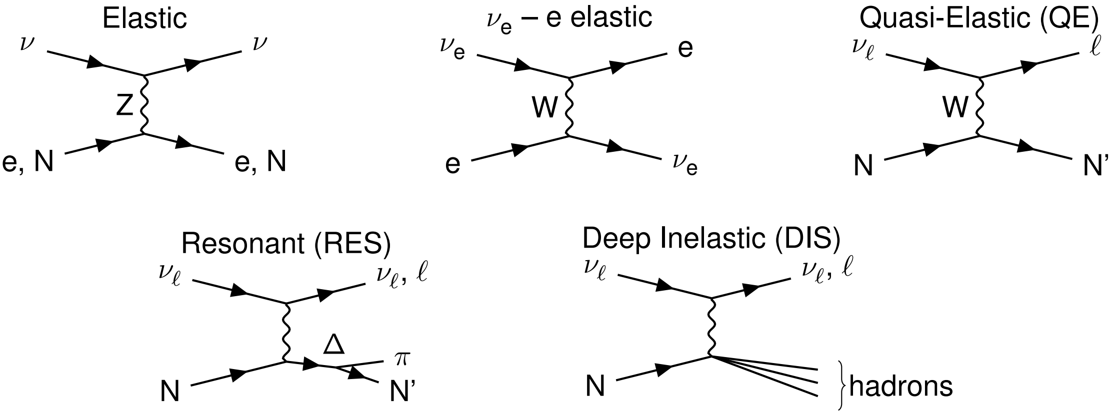




- Measure of produced lepton (ℓ) $\rightarrow$ define ν flavor
- May measure recoil of nucleus or hadronization

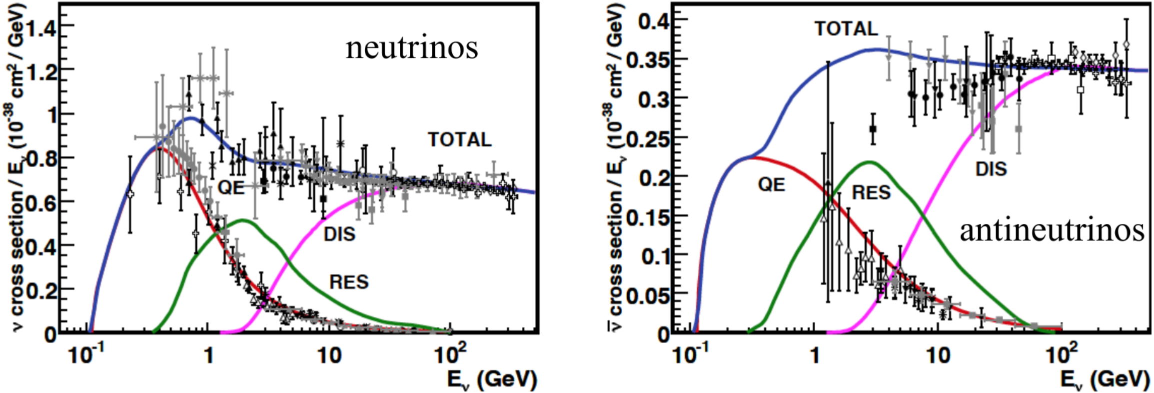
Neutrino Interaction with matter

Classifications regarding what happens on nuclei



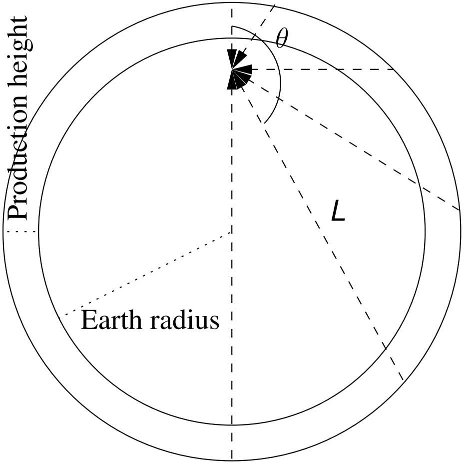
- For detection purposes, need to consider nuclear effects at low energy

Neutrino Interaction with matter: cross section



- You'll have a full lecture on this topic later today!

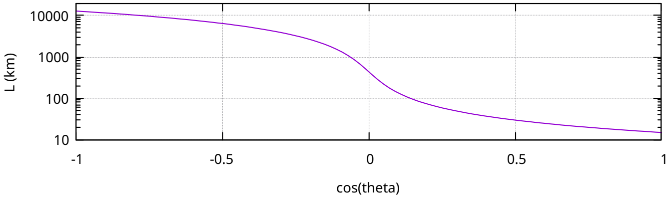
Using Atmospheric Neutrinos to study Neutrino oscillations



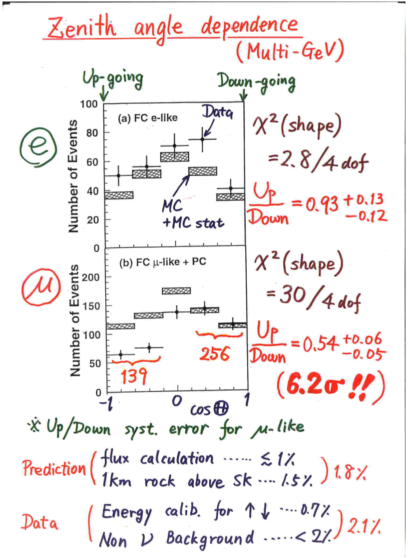
- Many baselines available from production height of neutrinos ($h \sim 15$ km) to over the diameter of the Earth ($d_{\text{Earth}} \sim 12756$ km)
- L known from ν direction θ:

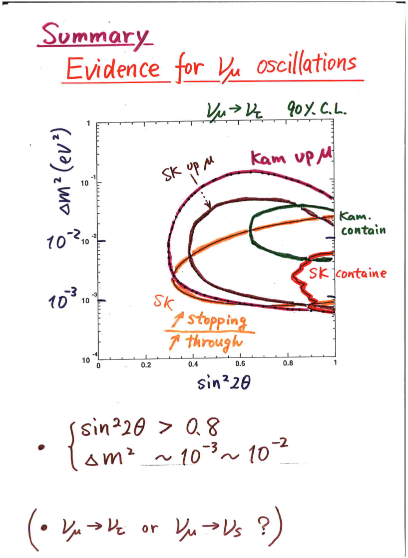
$$L = \frac{\sqrt{d_{\text{Earth}}^2 \cos^2\theta + 4(h^2 + d_{\text{Earth}} h)} - d_{\text{Earth}} \cos\theta}{2}$$

  - neglecting detector depth...



Discovery of Neutrino Oscillations: Super-Kamiokande 2015





Neutrino oscillation through matter

- In vaccum Hamiltonian H_0 is

$$H_0 = \frac{1}{2E} U \, \mathrm{diag}(m_1^2, m_2^2, m_3^2) \, U^\dagger$$

  - NB: $H = H' + \alpha\mathbb{1}$, α term is global phase $\rightarrow$ H and H' same for oscillations
- In matter, Hamiltonian $H_m = H_0 + H_{int}$, with H_{int} describing interaction ν – matter
  - Of interest here is the elastic scattering where coherence of ν preserved
  - ν – u and ν – d not interesting as $H_{int}^{\mathrm{u}} \propto \mathbb{1}$ and $H_{int}^{\mathrm{d}} \propto \mathbb{1}$
  - ν – e interesting: $H_{int}^{\mathrm{e}} = \mathrm{diag}(V^W, 0, 0) + V^Z\mathbb{1}$, with $V^W = \pm\sqrt{2} G_F N_e$
    - ★ N_e: electron density in medium
    - ★ $+$ sign for ν and $-$ sign for $\bar{\nu}$
- For 2-flavor osc.: $\theta \rightarrow \theta_m$ matter mixing angle related to matter-eigenstates $|\nu_i^m\rangle$

$$\tan 2\theta_m = \frac{\tan 2\theta}{1 \mp N_e/N_e^r} \, ; \; \Delta m_m^2 = \Delta m^2 \cos 2\theta \sqrt{\left(1 \mp \frac{N_e}{N_e^r}\right)^2 + \tan^2 2\theta} \, ; \; N_e^r = \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2} G_F}$$

- Resonance condition for specific densities if ν and $\Delta m^2 > 0$ (or $\bar{\nu}$ and $\Delta m^2 < 0$)
- As δ_{CP}, produce $\nu - \bar{\nu}$ asymmetry observable in experiments

Measuring structures within the Earth

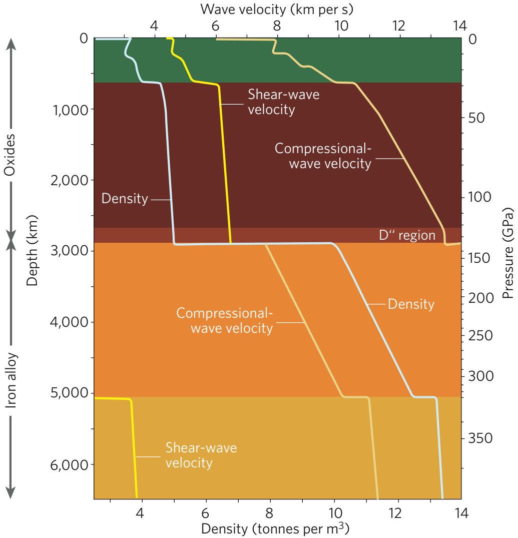
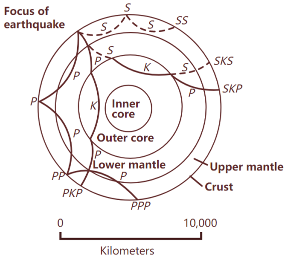
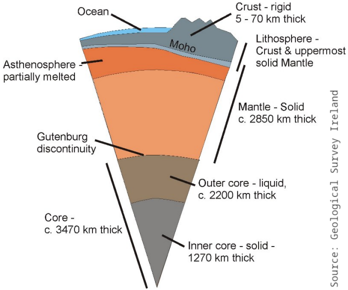


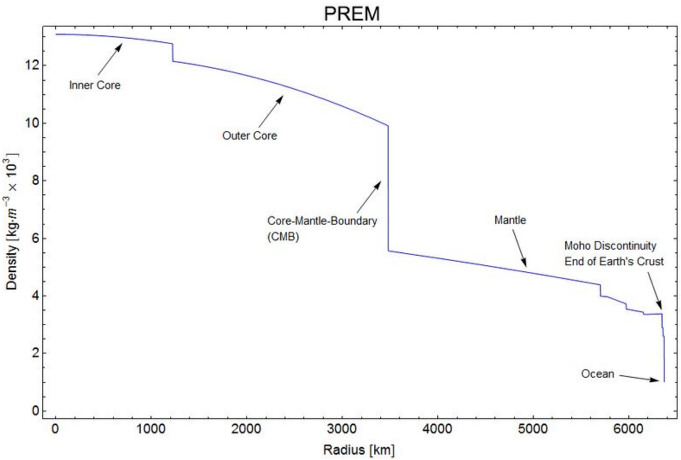
Figure 1 | Radial structure of Earth. The first-order structural units of Earth — its suite of concentric shells and their approximate composition — were established over the first half of the twentieth century from measurements of the travel times of seismic waves refracted and reflected inside Earth, whereas proof of the solidity of the inner core had to await the capability to record and digitize long time series and measure the frequencies of free oscillations. The '660 km' discontinuity is a phase change, and possibly a compositional change, in the silicate mantle. This illustration is of the preliminary reference Earth model[14].





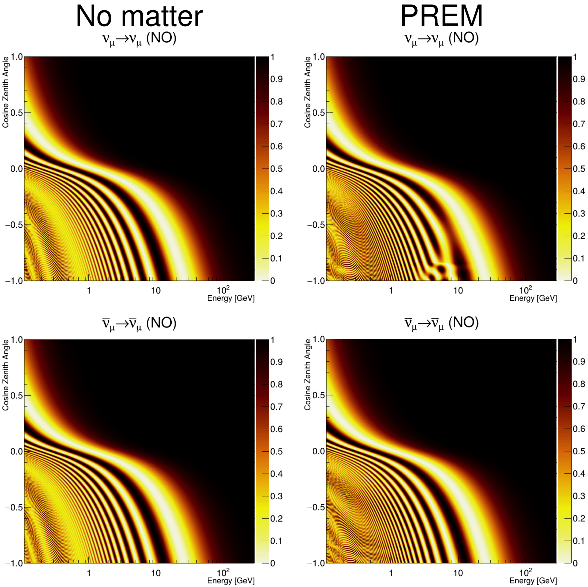
B. Romanowicz, Nature 451, p266–268 (2008)

Preliminary Reference Earth Model (PREM)



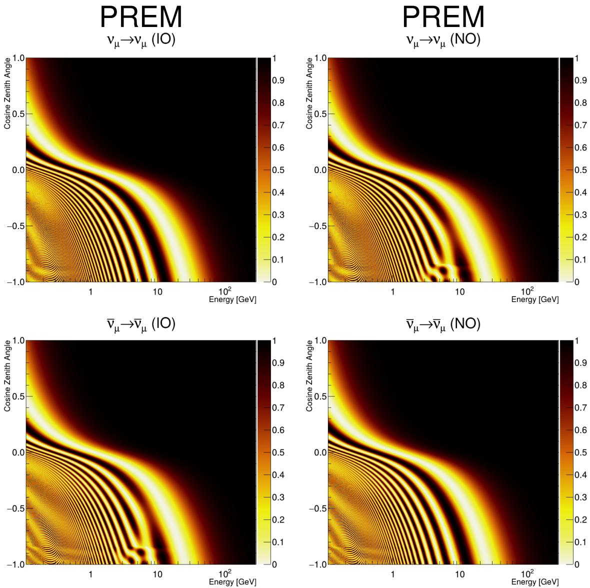
- PREM is a 1D model containing global structure
- Several 'unrealistic' assumption:
  - No mountains
  - 3 km thick ocean around the globe
  - Same crust thickness (varies from 7 km oceanic to 39 km continental)
- However it still captures all needed details
  - In fact we usually used 'simplified' versions of the PREM

Atmospheric Neutrino Oscillations: matter effects



- Most visible oscillation: $\nu_\mu \to \nu_\mu$
- Plots made using Prob3++ to calculate oscillation probability
- Matter effects leave clear signature in oscillation probability
- Core/Mantle boundary: $\cos\theta \approx -0.84$
  - Smaller boudaries @ core (-0.98) and mantle (-0.45)
- Effect on $\bar{\nu}$ and ν different in presence of matter (depends on ordering)
- However keep in mind ‘fast‘ oscillations will get ‘averaged out’

Atmospheric Neutrino Oscillations: matter effects



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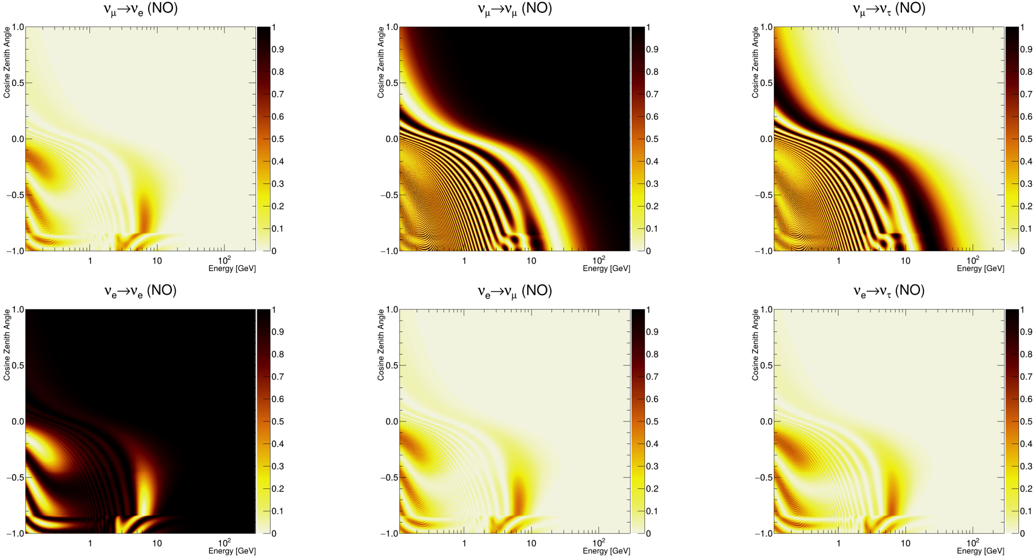
Atmospheric Neutrino Oscillations



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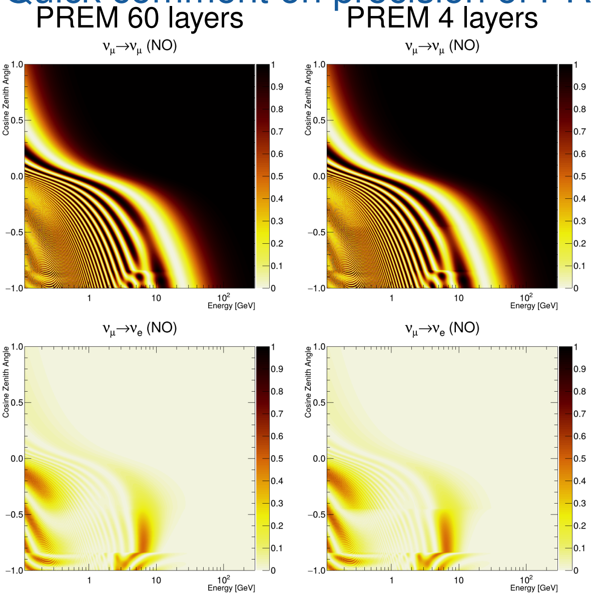
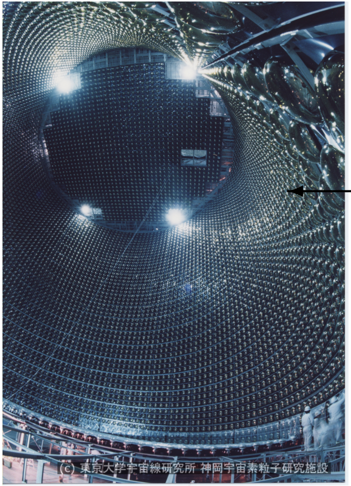
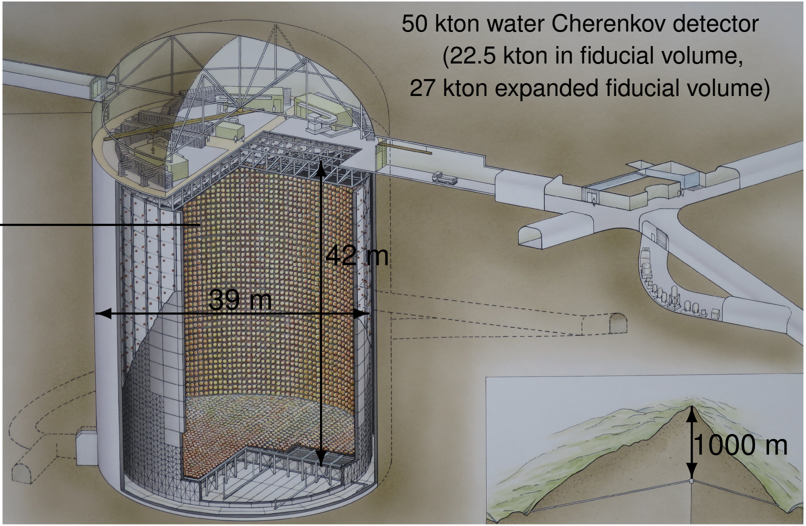
Quick comment on precision of PREM. . .



- Plots made using Prob3++ to calculate oscillation probability
- In previous plots I was using 60 layers to approximate PREM
- But most critical is match the main transitions, so 4 layers usually enough
- Less layers $\to$ less computing time

The Super-Kamiokande Detector



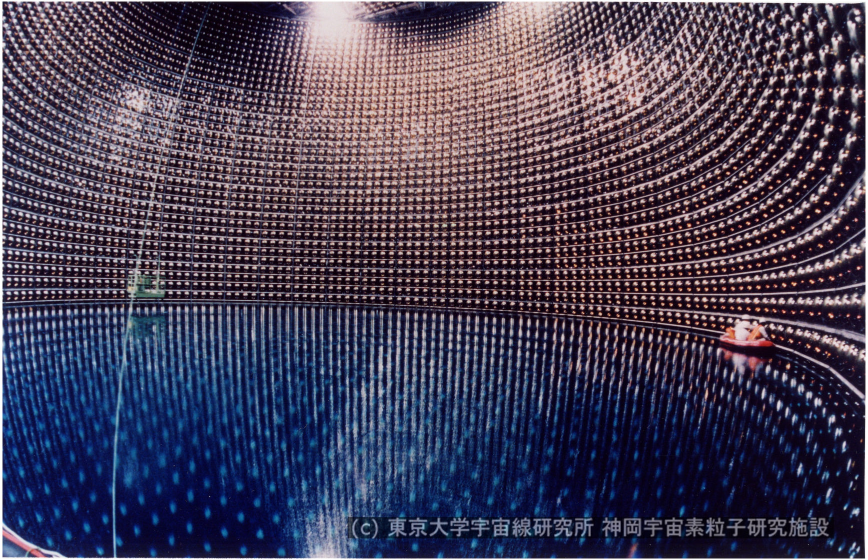


SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

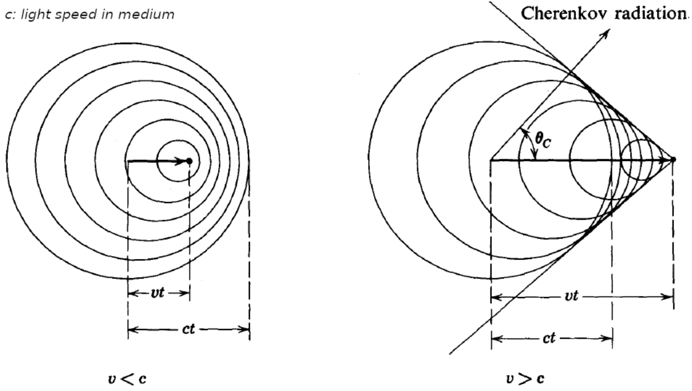
(C) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

NIKKEN SEKKEI

The Super-Kamiokande Detector



Cherenkov effect



- Speed of light in medium: c/n
- $\cos\theta_C = \frac{1}{\beta n}$; $\beta = \frac{v}{c}$
- Energy threshold: $\frac{m}{\sqrt{1 - \frac{1}{n^2}}}$
- $n \approx 1.33$ for water:
  - $\theta_C \approx 41^\circ$ for $\beta = 1$
  - $E_{\text{thresh}} \approx 0.78$ MeV for e
  - $E_{\text{thresh}} \approx 160$ MeV for μ
  - $E_{\text{thresh}} \approx 212$ MeV for π
  - $E_{\text{thresh}} \approx 1.4$ GeV for p

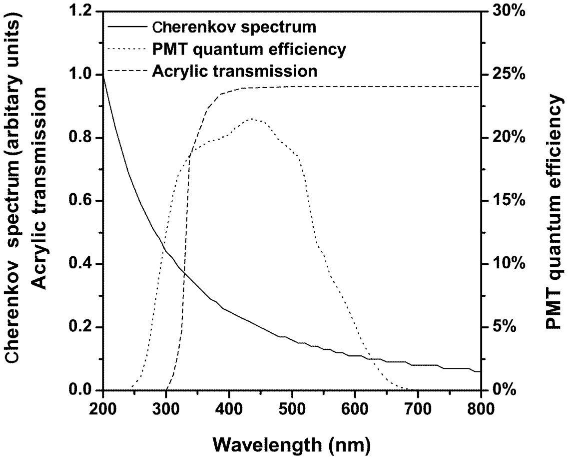
Cherenkov effect: wavelength dependency

- Spectra given by (see PDG, ch 34):

$$\frac{d^2E}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

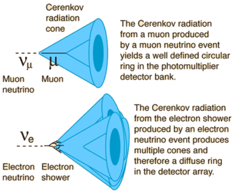
  - λ: wavelength
  - z: charge of particle

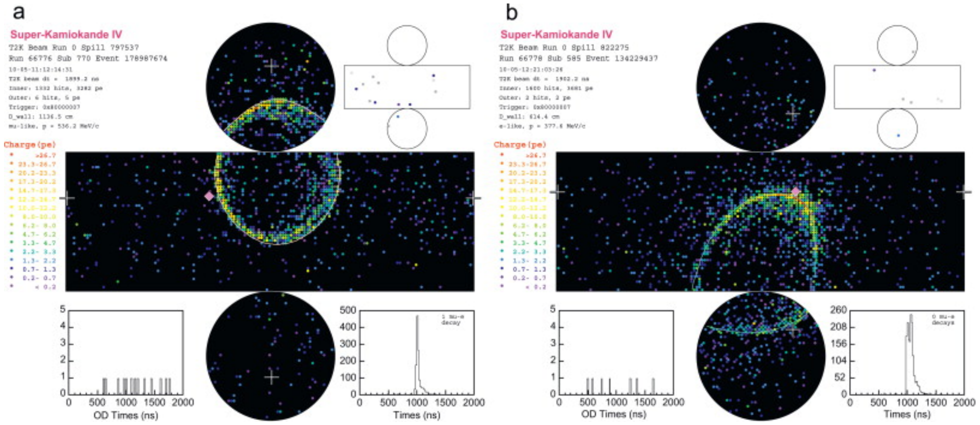
- For $\beta \approx 1$, amount of cherenkov light proportional to track length



X. Dai, Nucl.Instrum.Meth.A 589 (2008) 290-295

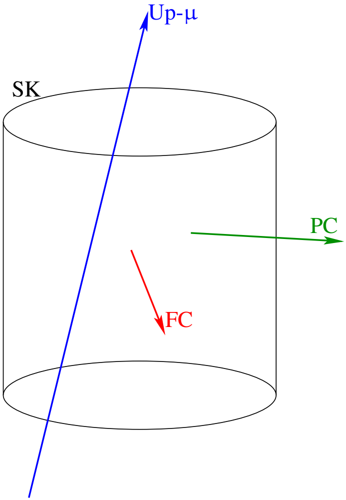
Detecting ν at Super-Kamiokande: ν_e vs ν_μ



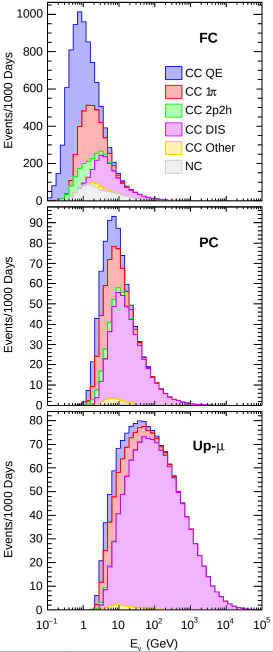


Event Samples for Atmospheric Neutrinos @ SK

- Fully Contained (FC)
  - Mostly CCQE interactions: $\nu_l + N \to l + N'$
    - ★ N' below Cherenkov threshold: 1-ring only
  - Can measure both energy & direction of outgoing lepton
  - Typically divided in Sub-GeV and Multi-GeV
- Particially Contained (PC)
  - Can measure direction, only lower bound for energy
- Up-going μ
  - Non-contained event $\to$ must be upgoing to be ν_μ



Plot from T. Wester et al., Phys. Rev. D 109, 072014 (2024)



Event Samples for Atmospheric Neutrinos @ SK: details

TABLE III. Monte Carlo CC and NC purities by sample and data event counts used in this analysis. Purities and MC counts are shown with oscillation probabilities applied and without the effects of systematic pulls. The "ν_τ CC" column shows the purity of both ν_τ and $\bar{\nu}_\tau$ CC events. The Up-μ data counts are shown after background subtraction.

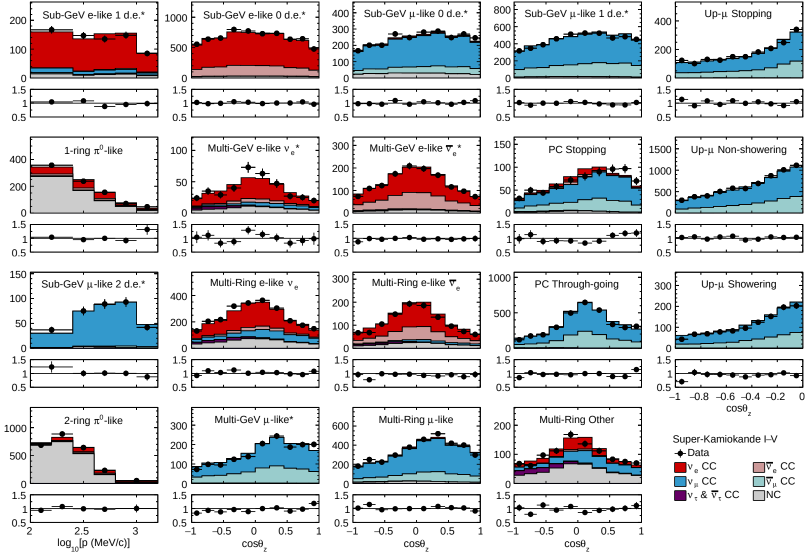
Sample	Energy bins	$\cos\theta_z$ bins	MC purity						Events	
			ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_τ CC	NC	MC	Data
Fully contained (FC), single ring, Sub-GeV										
SK I-III										
e-like										
0 decay-e	5 $e^\pm$ momentum	10 in $[-1,1]$	0.733	0.226	0.003	0.001	0.000	0.036	6409.1	6647
1 decay-e	5 $e^\pm$ momentum	single bin	0.796	0.016	0.086	0.020	0.001	0.081	612.0	682
μ-like										
0 decay-e	5 $\mu^\pm$ momentum	10 in $[-1,1]$	0.027	0.008	0.704	0.149	0.001	0.112	2153.9	2419
1 decay-e	5 $\mu^\pm$ momentum	10 in $[-1,1]$	0.001	0.000	0.677	0.291	0.000	0.030	4241.4	4476
2 decay-e	5 $\mu^\pm$ momentum	single bin	0.001	0.000	0.948	0.029	0.001	0.022	330.7	336
SK IV-V										
ν_e-like	5 $e^\pm$ momentum	10 in $[-1,1]$	0.794	0.016	0.090	0.024	0.001	0.074	943.7	1093
$\bar{\nu}_e$-like 0 n	5 $e^\pm$ momentum	10 in $[-1,1]$	0.789	0.175	0.003	0.001	0.000	0.031	5961.8	6669
$\bar{\nu}_e$-like 1 n	5 $e^\pm$ momentum	10 in $[-1,1]$	0.582	0.367	0.003	0.002	0.001	0.044	2266.6	1668
ν_μ-like	5 $\mu^\pm$ momentum	10 in $[-1,1]$	0.011	0.003	0.755	0.173	0.000	0.057	6596.0	7879
$\bar{\nu}_\mu$-like	5 $\mu^\pm$ momentum	10 in $[-1,1]$	0.001	0.000	0.533	0.417	0.001	0.049	2150.4	1793
Fully contained (FC), single ring, Multi-GeV										
SK I-III										
ν_e-like	4 $e^\pm$ momentum	10 in $[-1,1]$	0.568	0.086	0.102	0.014	0.039	0.190	359.6	383
$\bar{\nu}_e$-like	4 $e^\pm$ momentum	10 in $[-1,1]$	0.556	0.341	0.013	0.002	0.012	0.075	1359.8	1339
ν_μ-like	2 $\mu^\pm$ momentum	10 in $[-1,1]$	0.002	0.001	0.621	0.371	0.003	0.002	1588.5	1564
SK IV-V										
ν_e-like	4 $e^\pm$ momentum	10 in $[-1,1]$	0.607	0.087	0.098	0.015	0.033	0.159	584.1	643
$\bar{\nu}_e$-like 0 n	4 $e^\pm$ momentum	10 in $[-1,1]$	0.637	0.287	0.008	0.002	0.007	0.058	866.4	986
$\bar{\nu}_e$-like 1 n	4 $e^\pm$ momentum	10 in $[-1,1]$	0.435	0.460	0.009	0.002	0.015	0.079	736.1	616
ν_μ-like	2 $\mu^\pm$ momentum	10 in $[-1,1]$	0.002	0.001	0.695	0.297	0.003	0.001	1464.0	1619
$\bar{\nu}_\mu$-like	2 $\mu^\pm$ momentum	10 in $[-1,1]$	0.001	0.000	0.446	0.549	0.004	0.002	593.1	503
SK I-V common samples										
Fully contained (FC) Sub-GeV NC π^0-like										
Single-ring	5 $e^\pm$ momentum	single bin	0.219	0.064	0.018	0.002	0.001	0.696	748.0	868
Two-ring	5 π^0 momentum	single bin	0.096	0.028	0.015	0.001	0.000	0.860	2095.3	2494
Fully contained (FC) Multi-GeV, multi-ring										
ν_e-like	3 visible energy	10 in $[-1,1]$	0.495	0.066	0.175	0.014	0.035	0.215	2149.7	2411
$\bar{\nu}_e$-like	3 visible energy	10 in $[-1,1]$	0.519	0.260	0.052	0.007	0.025	0.138	1210.0	1131
μ-like	4 visible energy	10 in $[-1,1]$	0.028	0.003	0.713	0.200	0.006	0.050	3257.7	3427
Other	4 visible energy	10 in $[-1,1]$	0.203	0.023	0.257	0.014	0.074	0.429	837.9	982
Partially-contained (PC)										
Stopping	2 visible energy	10 in $[-1,1]$	0.089	0.034	0.559	0.262	0.011	0.045	641.6	689
Through-going	4 visible energy	10 in $[-1,1]$	0.006	0.002	0.638	0.341	0.007	0.006	3310.2	3397
Upward-going muons (Up-μ)										
Stopping	3 visible energy	10 in $[-1,0]$	0.008	0.003	0.646	0.340	0.000	0.003	1574.3	1753.8
Non-showering	single bin	10 in $[-1,0]$	0.002	0.001	0.662	0.334	0.000	0.001	5315.8	6423.9
Showering	single bin	10 in $[-1,0]$	0.001	0.000	0.671	0.327	0.000	0.001	1051.4	1110.6

Phase	Dates	Livetime (Days)	Photo-coverage (%)	Neutron tagging
SK I	1996–2001	1489.2	40	–
SK II	2002–2005	798.6	19	–
SK III	2006–2008	518.1	40	–
SK IV	2008–2018	3244.4	40	H
SK V	2019–2020	461.0	40	H
SK Gd	2020–Present	–	40	H+Gd

- Different class. between SK I–III and IV-V
  - neutron tagging helps separate ν and $\bar{\nu}$
- Decay e help tag ν_μ from ν_e beyond PID
- Number of rings separate between CCQE-like, RES-like, . . .

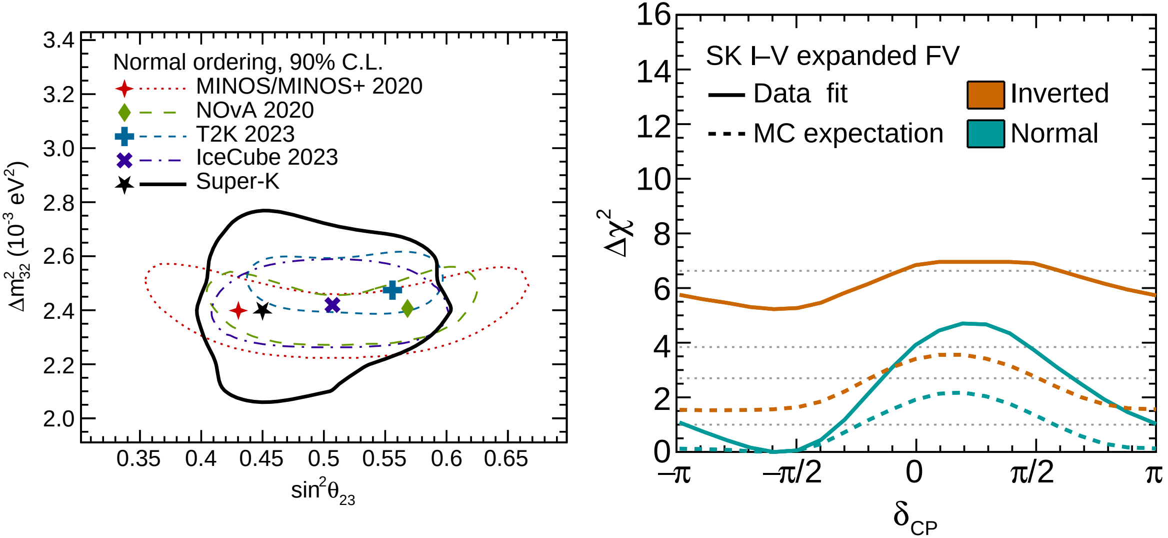
From T. Wester et al., Phys. Rev. D 109, 072014 (2024)

SK Event Samples for Atmospheric Neutrinos



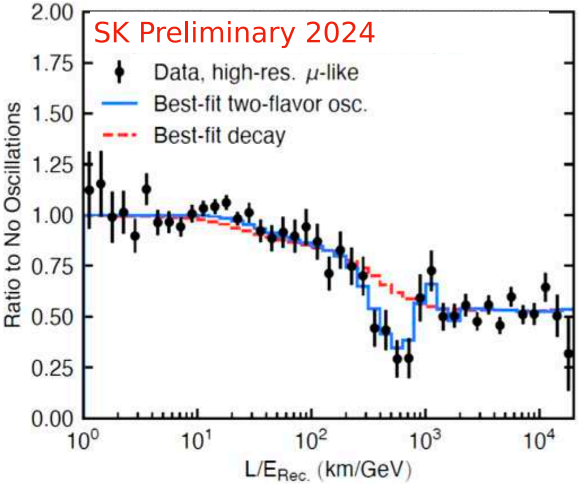
From T. Wester et al., Phys. Rev. D 109, 072014 (2024)

Latest results from Super-Kamiokande: oscillation



From T. Wester et al., Phys. Rev. D 109, 072014 (2024)

Latest results from Super-Kamiokande: oscillation

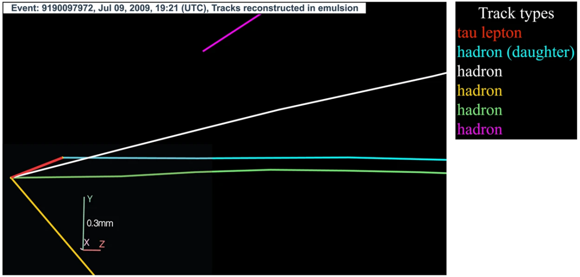


- Dividing data in L/E rather than just 2 energy and 10 $\cos\theta$ bins
  - NB: different analysis with same data
- Need to re-evaluate uncertainties due to finer binning
- Clear oscillation pattern shown
- As far as I saw, not yet published, just shown in conferences

M Mandal talk at ICHEP 2024

ν_τ appearance: motivation

- $\nu_\mu \to \nu_\tau$ main oscillation for atmospheric neutrinos
- $m_\tau = 1.78$ GeV $\Rightarrow$ need high-energy ν_τ for CC interaction
- At lower energies $\nu_\mu \to \nu_s$ and $\nu_\mu \to \nu_\tau$ indistinguishable

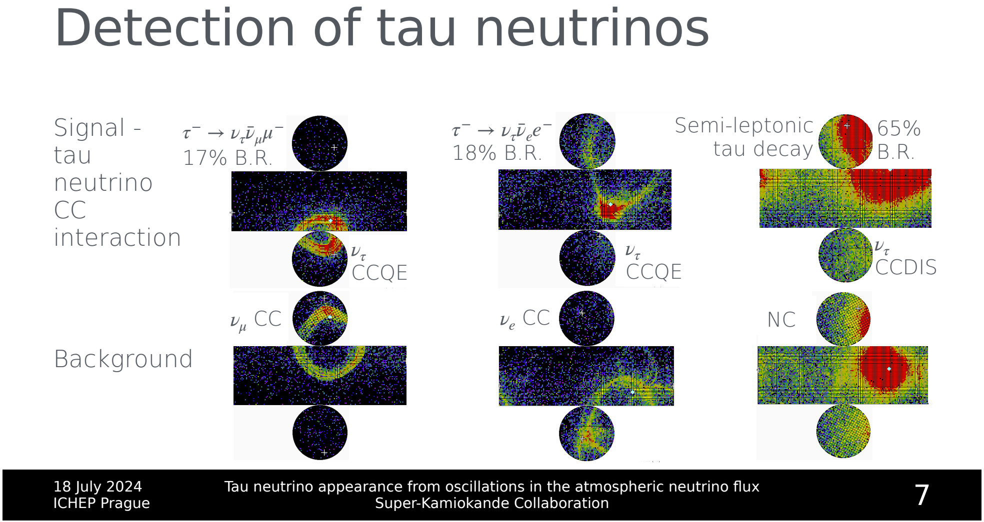


τ length: 822 μm

`https://www.nature.com/articles/s41597-021-00991-y`

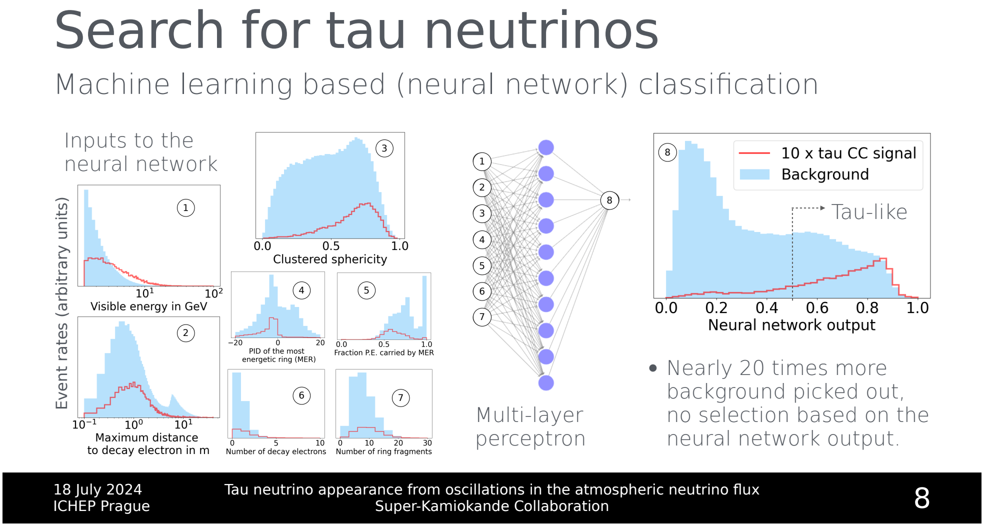
- ν_τ measurement in ν beams:
  - DONUT: produced ν_τ beam, 9 ν_τ identified
  - OPERA: $\nu_\mu \to \nu_\tau$ from CERN to LNGS, 10 ν_τ candidates
- Expected production in SK: 20 ν_τ/year
  - However, no capability to do ‘tracking’ as well as DONUT/OPERA

ν_τ appearance @ SK: event types



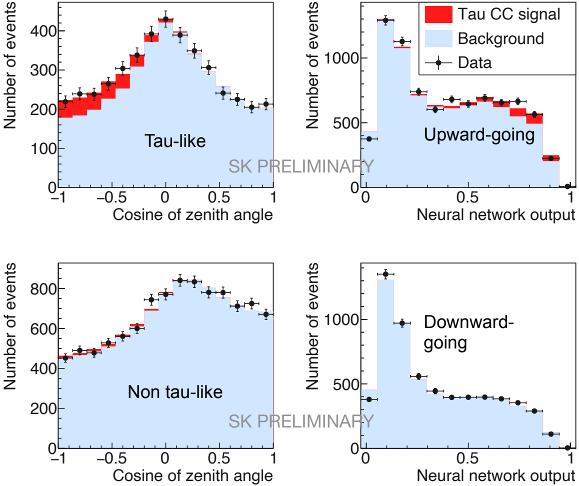
M Mandal talk at ICHEP 2024

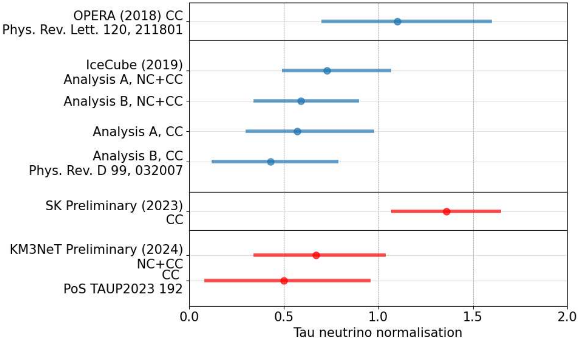
ν_τ appearance @ SK: background separation



M Mandal talk at ICHEP 2024

ν_τ appearance @ SK: results

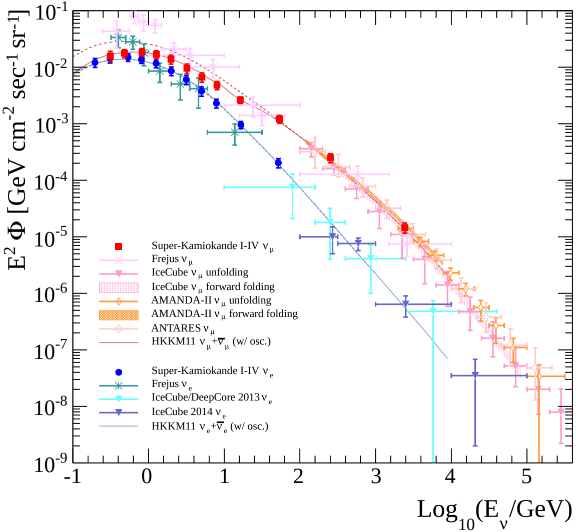


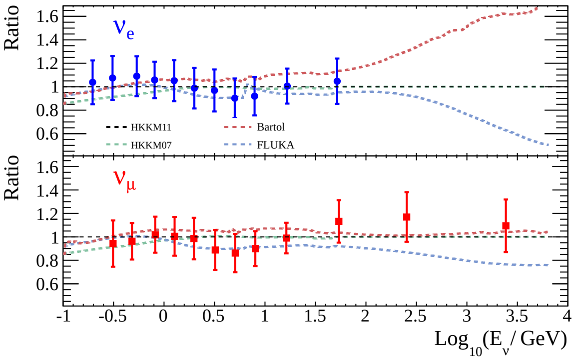


428 ± 92 ν_τ CC events

M Mandal talk at ICHEP 2024

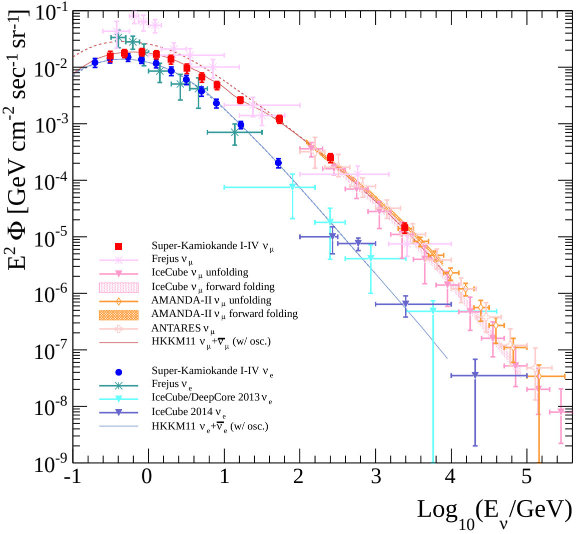
Measurements of the atmospheric neutrino flux with SK

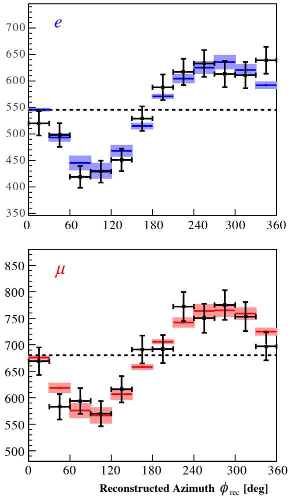




Super-Kamiokande, Phys.Rev.D 94 (2016) 5, 052001

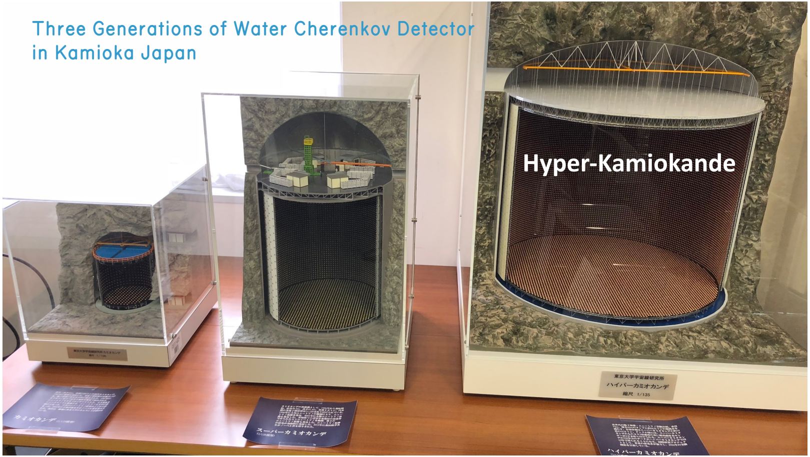
Measurements of the atmospheric neutrino flux with SK





Super-Kamiokande, Phys.Rev.D 94 (2016) 5, 052001

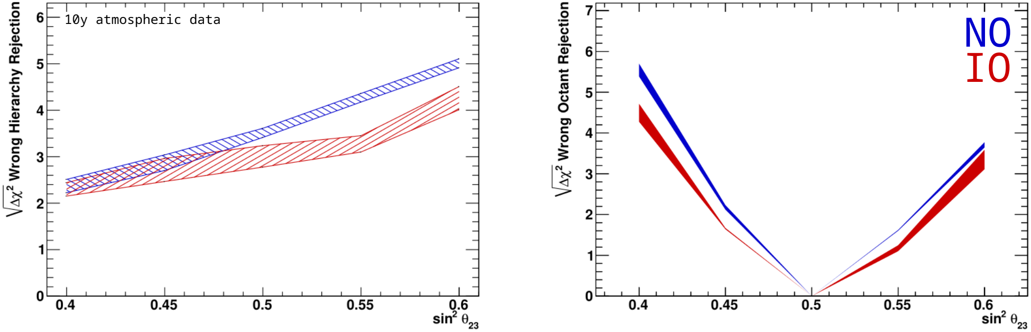
Hyper-Kamiokande



From Ed Kearns talk @ INSS 2023

- Larger version of SK
- 186.5 kton FV
  (258 kton total)
  - 7–8 $\times$ larger FV
- Data taking foreseen in 2027

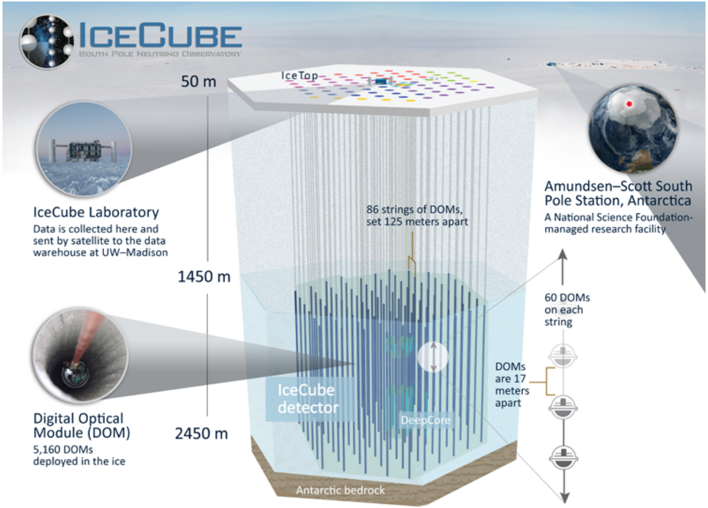
Hyper-Kamiokande: performance

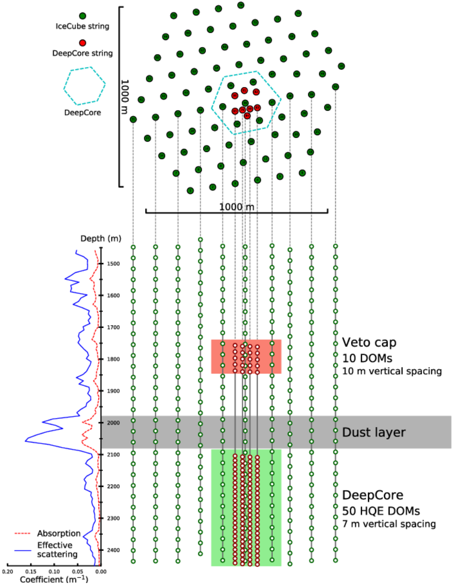


Hyper-Kamiokande [1805.04163]

- HK detector also use in T2HK
- Complementarity about beam & atmospheric

The IceCube detector & IceCube/DeepCore

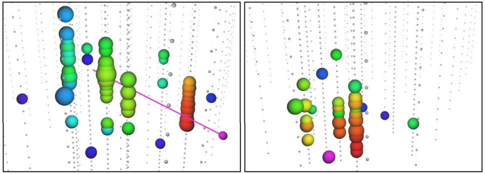




Analysis considerations by **energy**

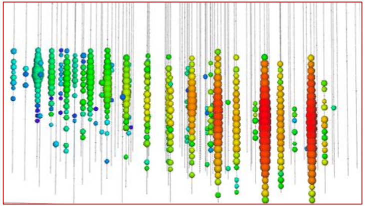
DeepCore (GeV-scale)

- Use events starting in the DeepCore region
  - Strong atm. μ background suppression
  - Mostly contained, good E estimation
  - All flavor, with possibility to tag the presence of a muon (ν_μ-CC)



IceCube (TeV scale)

- Use tracks going through the detector
  - No containment, only lower limit on E
  - Sample is ν_μ-CC only
- Excellent pointing
  - Atm. μ bkg suppressed by Earth



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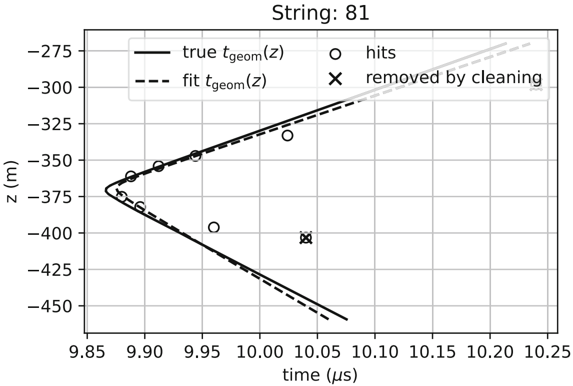
J P Yanez talk @ Neutrino 2024

Reconstructing low-energy events in IceCube/DeepCore

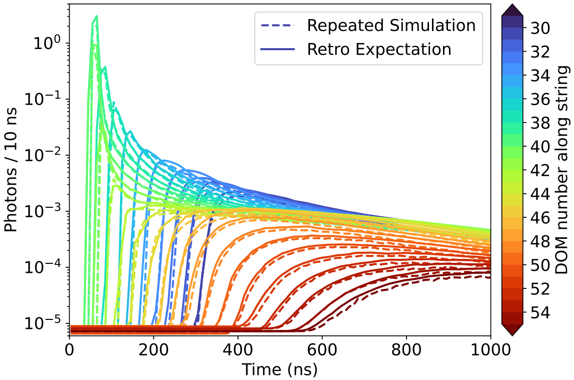
"Golden" sample

- 'Clean' events with low scattering
  - ν_μ CC only
- Uses μ Cherenkov cone light pattern



"Inclusive" sample

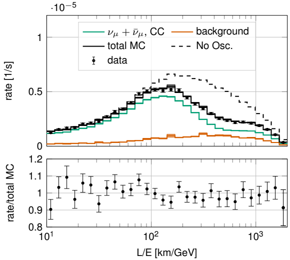
- Tries to reconstruct all events
- Needs to model scattering in ice
- Order of magnitude more events



IceCube, Eur.Phys.J.C 82 (2022) 9, 807

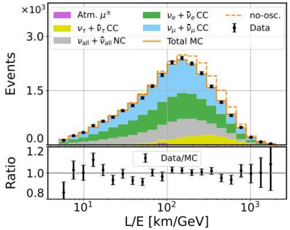
IceCube/Deepcore: samples for oscillation measurements

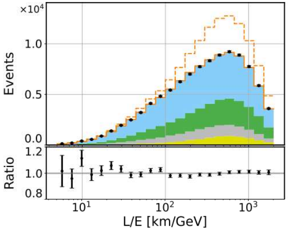
“Golden” sample

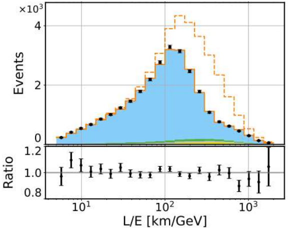


IceCube, Phys.Rev.D 108 (2023) 1, 012014

“Inclusive” sample



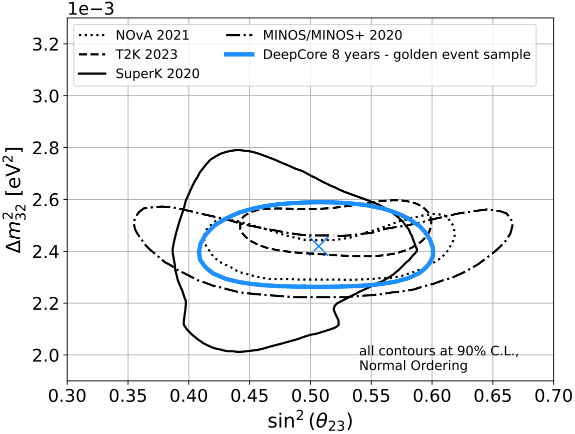




From Cascade-like to track-like samples. IceCube, Phys.Rev.Lett. 134 (2025) 9, 091801

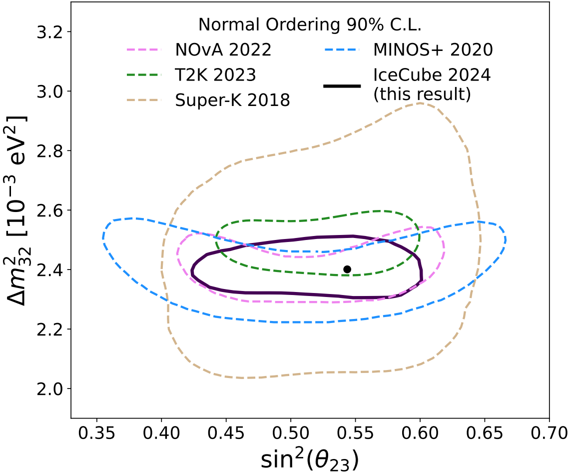
IceCube: Searches for 3-flavor neutrino oscillation

"Golden" sample



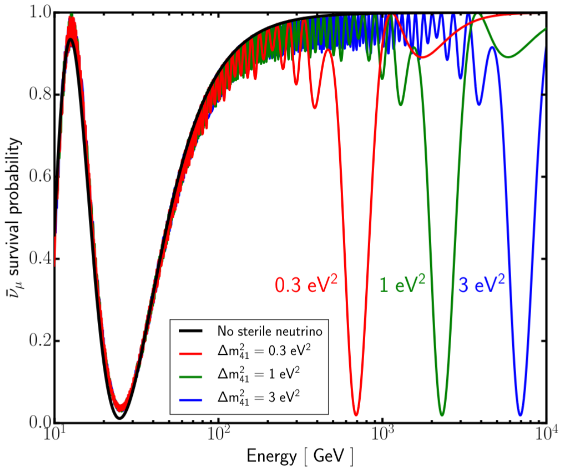
IceCube, Phys.Rev.D 108 (2023) 1, 012014

"Inclusive" sample



IceCube, Phys.Rev.Lett. 134 (2025) 9, 091801

IceCube: Searches for sterile neutrinos



J P Yanez talk @ Neutrino 2024

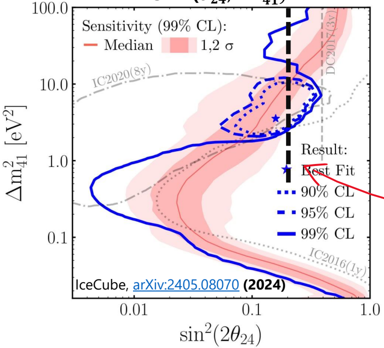
- 2 main signatures visible:
  - Low En: “small” changes to oscillation
  - High En: Matter-effect resonance driven oscillation
    - $H_{int}^{u,d}$ and $H_{int}^{e\text{-}Z}$ no longer $\propto \mathbb{1}$ in 4-flavor oscillations!
- Sensitive to different parameters
- High energy signature only in reach of ν telescopes!

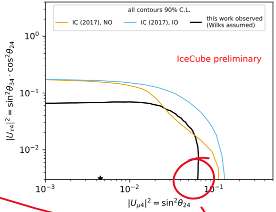
IceCube: Searches for sterile neutrinos – results

Comparison of **E regimes**

- Improved sample
  - 370k events
  - Split starting events
  - Updated flux systematics
- Results
  - No sterile hypothesis p-value = 3%
  - Non-zero fit significance: 2σ
  - Decay scenario disfavored

3+1 $(\theta_{24}, \Delta m^2_{41})$





DeepCore sample
All-flavor
3+1 $(U_{\mu4}, U_{\tau4})$

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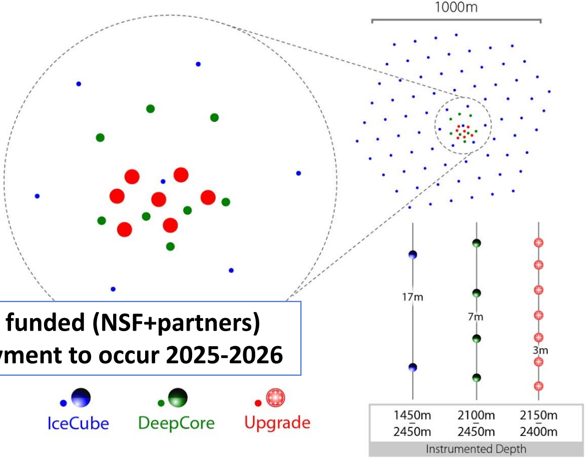
J P Yanez talk @ Neutrino 2024

The IceCube **Upgrade**

- New devices in the ice
  - Recalibration of all data
  - Lower E threshold for DC



Fully funded (NSF+partners)
Deployment to occur 2025-2026

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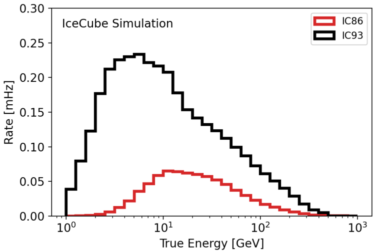
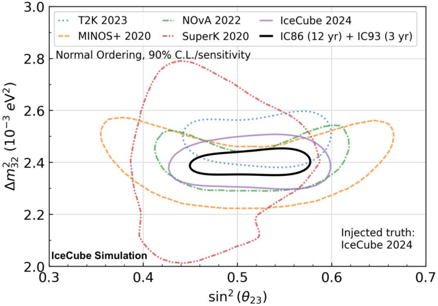
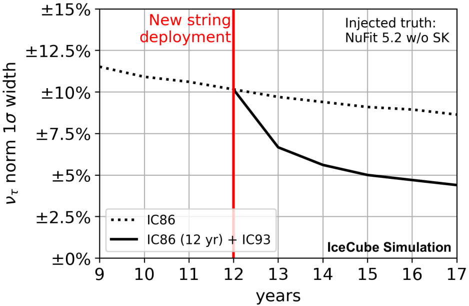
J P Yanez talk @ Neutrino 2024

IceCube Upgrade **potential**

- Significant increase of events at 10 GeV
- Projecting precision on std. oscillations
  - Includes selection, reconstruction and current uncertainties







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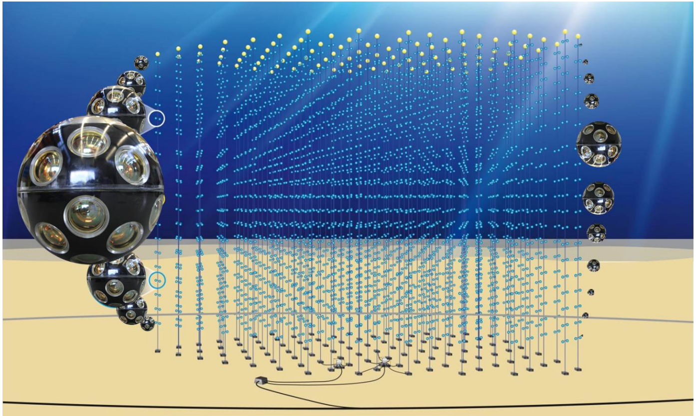
J P Yanez talk @ Neutrino 2024

The KM3Net/ORCA detector



- Same principle as IceCube. . .
- . . . but in sea water
  - less light scattering
  - more uniform medium
  - ⇒ easier reconstruction
  - PMTs might move with current
  - ⇒ harder reconstruction
- mDOMs give additional photon-direction information
- distance between
  - lines: 20 m (vs 42 m DC)
  - mDOMs: 9 m (vs 7 m DC)

ORCA current status

The KM3NeT experiment

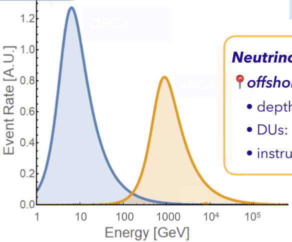
- **Water Cherenkov neutrino telescope**
- two detection sites for a **complementary physics program**

Neutrino oscillations in ORCA

📍***offshore Toulon (France)***

- depth: 2450 m
- Detection Units (DUs): 115
- instrumented vol. ~ 23%

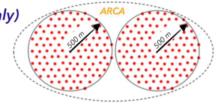
- **atmospheric neutrinos**:
  - ❍ wide energy range (1-100 GeV)
  - ❍ different baselines (L), from ~10 to ~13000 km



Neutrino astronomy in ARCA

📍***offshore CapoPassero (Italy)***

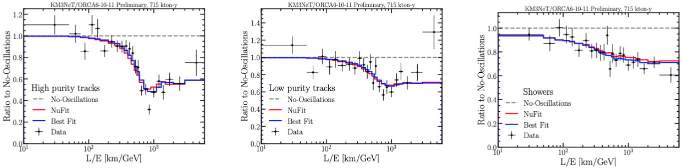
- depth: 3560 m
- DUs: 230
- instrumented vol. ~ 12%

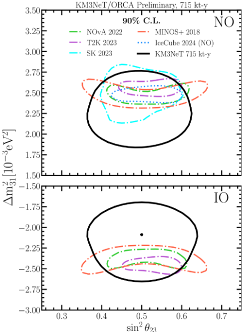


13.06.2025 - IRN Lyon - C. Lastoria 5

C Lastoria talk @ IRN-ν meeting in Lyon 2025

Oscillation results with ORCA6-11





$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3} eV^2, & IO \\ [2.10, 2.37] \times 10^{-3} eV^2, & NO \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$

$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$

Slight preference for IO, but not significant

A. Lazo Pedrajas   Atmospheric neutrino oscillations

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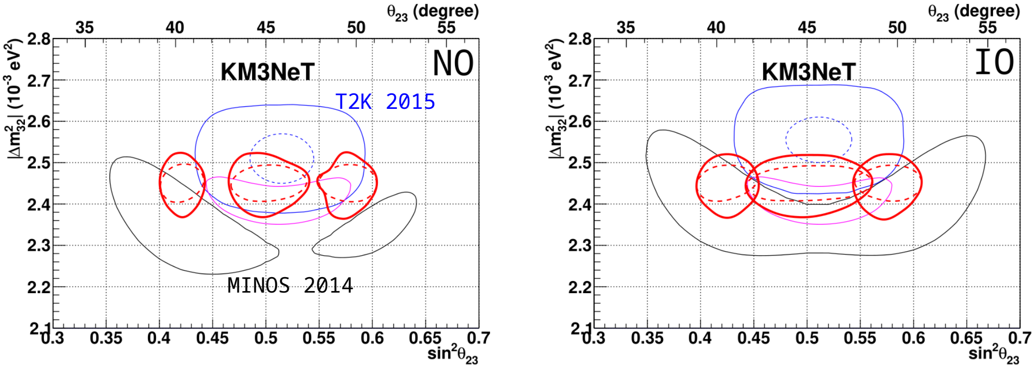
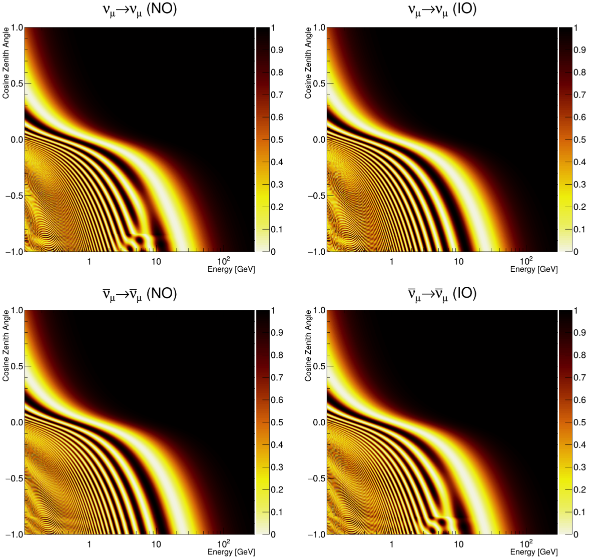
P Coyle talk @ ICHEP 2024

ORCA expected sensitivity



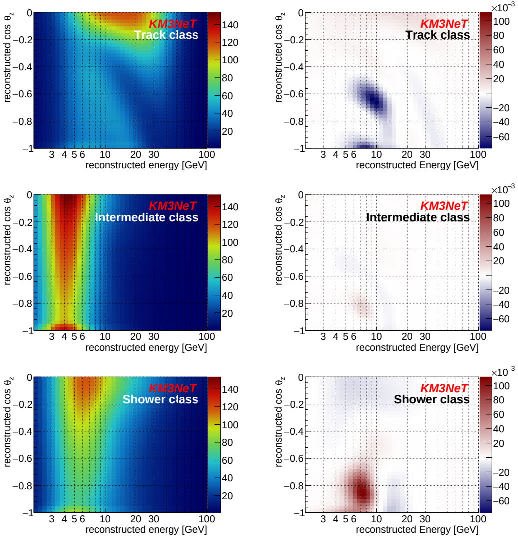
ORCA, J. Phys. G 43 (2016) no.8, 084001

Determining the neutrino mass ordering with atmospheric neutrinos

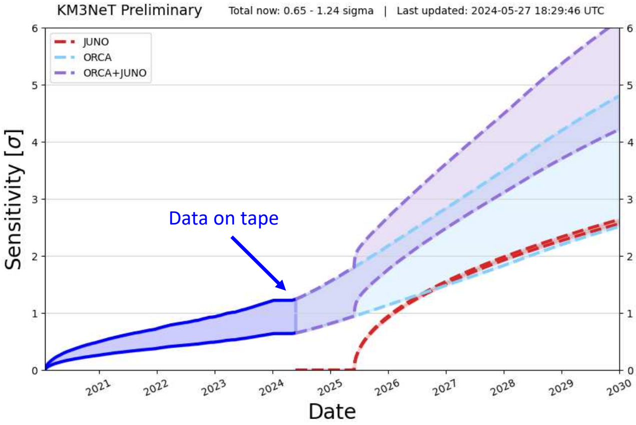


- As discussed before: oscillation pattern depends on ordering, but
  - $P(\nu_\mu \to \nu_l, NO) = P(\bar{\nu}_\mu \to \bar{\nu}_l, IO)$
  - $P(\nu_\mu \to \nu_l, IO) = P(\bar{\nu}_\mu \to \bar{\nu}_l, NO)$
- IceCube/DeepCore & ORCA: (very) low ability to distinguish ν from $\bar{\nu}$
  - Can we still distinguish NO and IO?
- Yes! Flux & xsec not same for ν from $\bar{\nu}$
  - $\phi_{\nu_\mu} > \phi_{\bar{\nu}_\mu}$
  - $\sigma_{\nu_\mu} \approx 2\sigma_{\bar{\nu}_\mu}$

Determining the neutrino mass ordering with ORCA

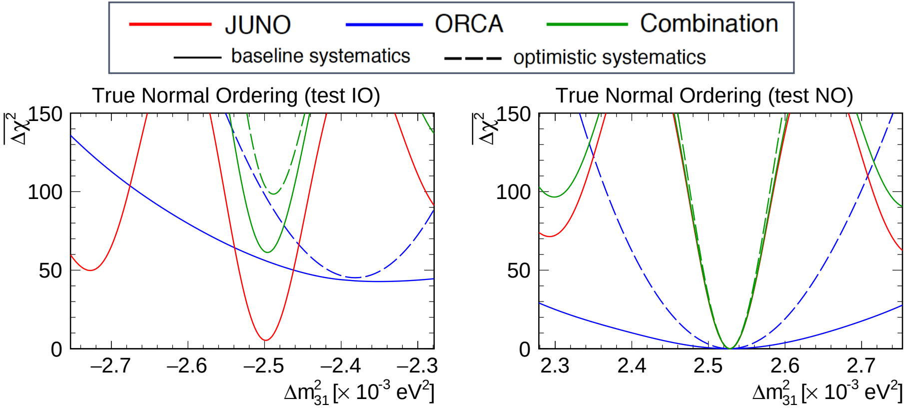


KM3Net, Eur.Phys.J.C 82 (2022) 1, 26



P Coyle talk @ ICHEP 2024

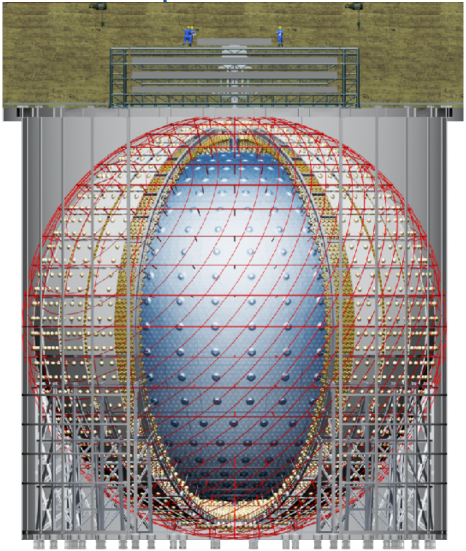
Complementarity between reactor & atmospheric neutrinos



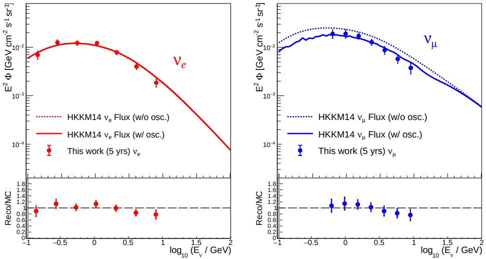
KM3NeT + some JUNO members, JHEP 03 (2022) 055

- Δm^2 from reactors ($\nu_e \to \nu_e$) and accelerators or atmospherics ($\nu_\mu \to \nu_\mu$) misaligned in wrong ordering but same in correct ordering
- Joint measurement boosts sensitivity beyond simply adding both sensitivities!
- Separate studies done also for JUNO+IceCube, JUNO+Accelerators, . . .

JUNO capabilities as an Atmospheric Neutrino detector



- Slightly smaller FV (20 kt) than SK (ext: 27 kt)
- LS detector $\rightarrow$ much more light/event
  - Better energy measurement
  - Harder to measure direction of lepton
  - Might have access to information from particle below Cherenkov threshold
- Sensitivity to ν oscillation still under study. . .

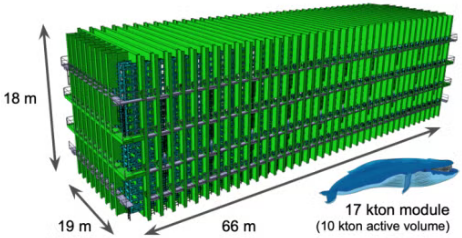


JUNO, Eur.Phys.J.C 81 (2021) 10

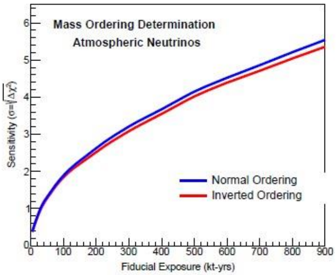
Reminder: JUNO starting to take data in 2025!

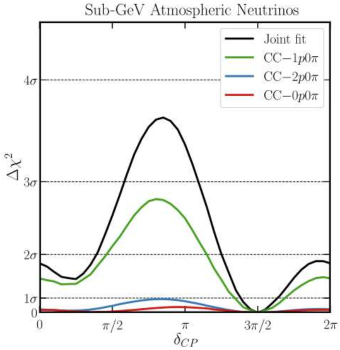
DUNE capabilities as an Atmospheric Neutrino detector

- 4×10 kton in active volume
- LAr TPC $\rightarrow$ exquisite detail
  - Detailed event topology
  - Potential for good ν_τ PID?



https://web.slac.stanford.edu/neutrino/experiments/dune

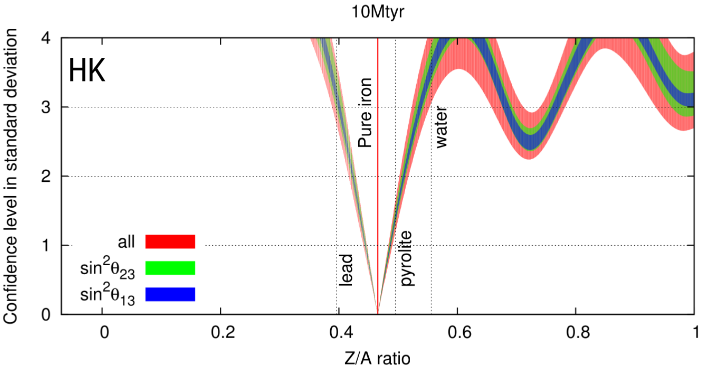




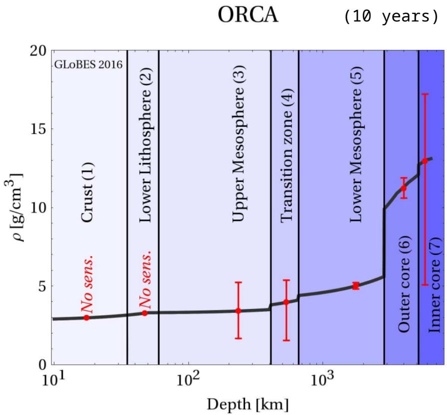
T Thakore talk @ MMTE 2023

Earth Tomography

- As we understand better ν oscillations can invert the problem to probe Earth interior
- Deeper (complementary) probe of Earth than with geo-neutrinos
- For now not competitive with 'traditional' methods, but independent information



Hyper-Kamiokande [1805.04163]



W Winter, Nucl.Phys.B 908 (2016)

Summary

- While atmospheric neutrino fluxes are complicated
  - Flux ratios are much better modeled
  - Fairly good data/MC agreement with current model & data
- Atmospheric neutrinos have played a crucial role in discovery of ν oscillations
- Atmospheric neutrinos continue to provide precise oscillation measurements!
  - SK is almost 30 years old, but still with comparable precision to newer experiments
  - IceCube/DeepCore has been providing good results for the past several years
  - SK and IceCube/DeepCore focus on somewhat different energy ranges, so complementary results
  - KM3Net/ORCA turning on gradually
- Thanks to higher energy of E_ν & longer L, sensitive to
  - ν_τ appearance, high energy effect of ν_s in atmospheric ν
- Potentially first claims of discovery of neutrino mass ordering soon?
  - Good sensitivity by itself, good complementarity with JUNO
  - Sensitivity depends on what are the real oscillation parameters
- Potential still to be fully explored for some experiments not focused on atm.ν...