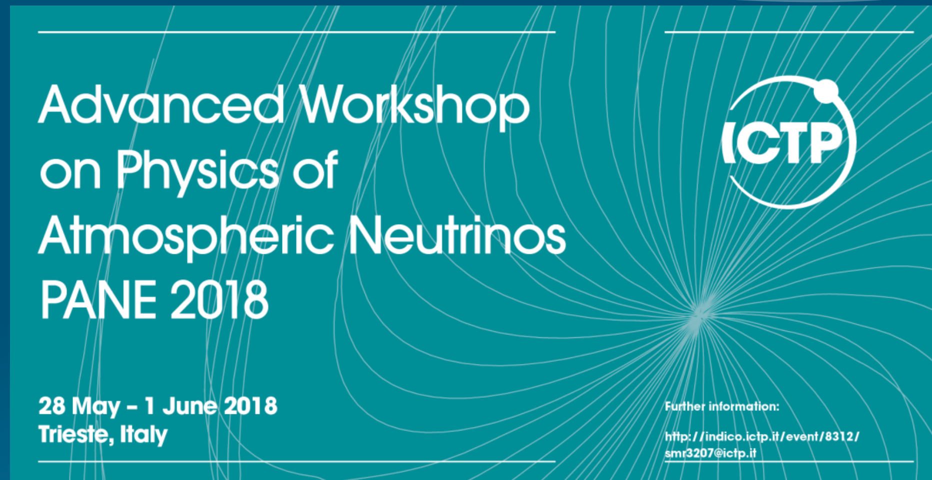


The Saga of Atmospheric Neutrinos

John Learned
University of Hawaii

With thanks to many friends and colleagues for slides and plots and general camaraderie over the years, and to the organizers for inviting me.

A Saga? Yes, a great scientific tale of persistence, dead ends, serendipitous discovery, redemption and glory

- Saga: "a long story of heroic achievement, especially a medieval prose narrative in Old Norse or Old Icelandic." (OED)
- Indeed the tale of atmospheric neutrino studies has much of this….

- Starts with fantastic dreams in Russia and US in 1950's
- Pioneer quests in gold fields in India and South Africa, 1960's
- Years of struggle by small groups of true believers on little support 1970's

- Saved by Magii who propose mystical quest for finding proton decay in late 1970's

- At last large underground instruments in 1980's in US, Europe, Japan and Russia
- Serious hints of muon neutrino anomaly in 1983 onwards, but much struggle to make sense of hints, and contrary results and even animosity amongst explorers

- SN 1987A yields Gold for Kamioka, IMB and Baksan
- Solar neutrinos seen by radiochamical experiments, but Kamiokande gives gold

- SuperK is built and brings redemption, fame and fortune in 1998 with the discovery of muon neutrino oscillations (and not electron neutrinos)
- SNO and KamLAND nail the lid on electron neutrino oscillations and neutrino mass

- Finally IceCube definitively finds cosmic HE neutrinos completing a 40 year quest to start neutrino astronomy.

Virtues of Atmospheric Neutrinos

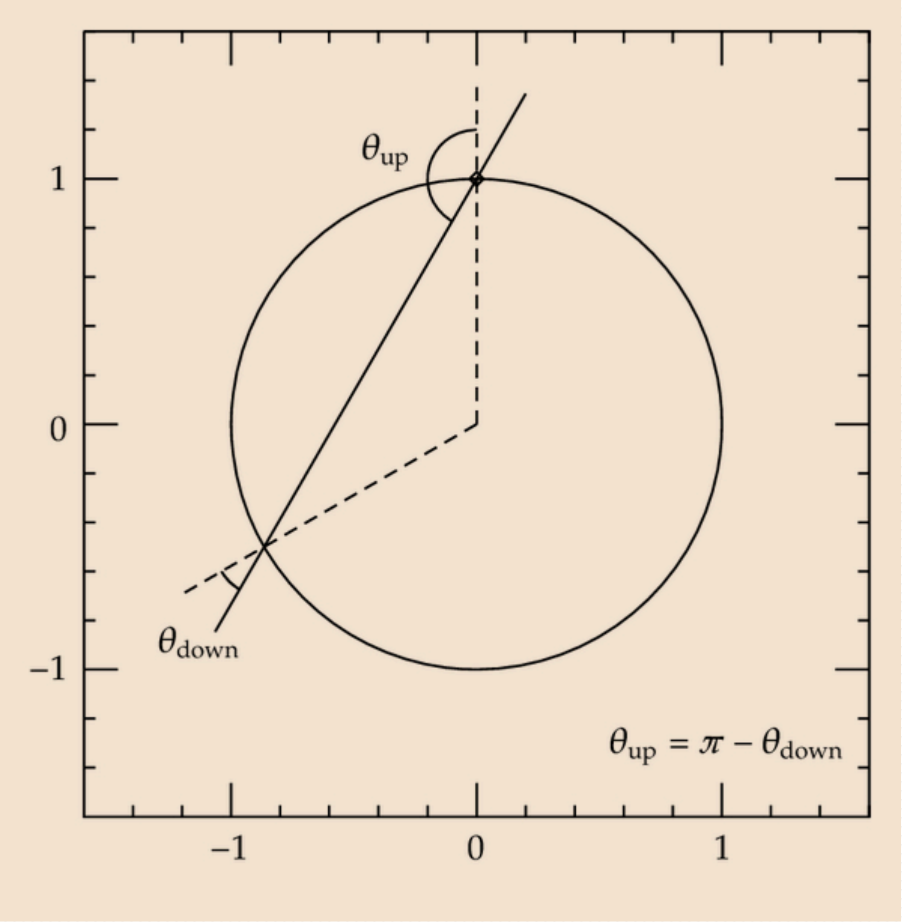
including contrast to manmade neutrinos

- **Free and beam always `on'**
- **Atm Neutrino Energy Range: ~10 MeV -> 100 TeV,**
  ~7 orders of mag + 5 orders more in astro
  accel: ~ 1-2 orders of mag for given beam, <10 TeV so far
- **Up/Down Going Symmetry, broken by oscillations**
- **Earth provides variable absorber, coded by zenith angle, ~0–10^{10} gm/cm^2**
- **mu/e at ~1 GeV: very reliable ratio**
- **Has small but useful tau content**
- **Venue for discovery of neutrino oscillations and mass**

- **Atm neutrino detectors can also detect accel beams**

The Up/Down Symmetry of the Atmospheric Neutrino Flux

Key to understanding Neutrino Oscillations:
<u>Up/Down errors cancel</u>



$\Phi(\theta) = \phi\ (\pi-\theta)$

To first order anyway

Takaaki Kajita, Advances in High Energy Physics Volume 2012, Article ID 504715, 24 pages http://dx.doi.org/10.1155/2012/504715

Fluxes <~3 GeV Depend Strongly on Location, & even Solar Activity

But these are the most abundant

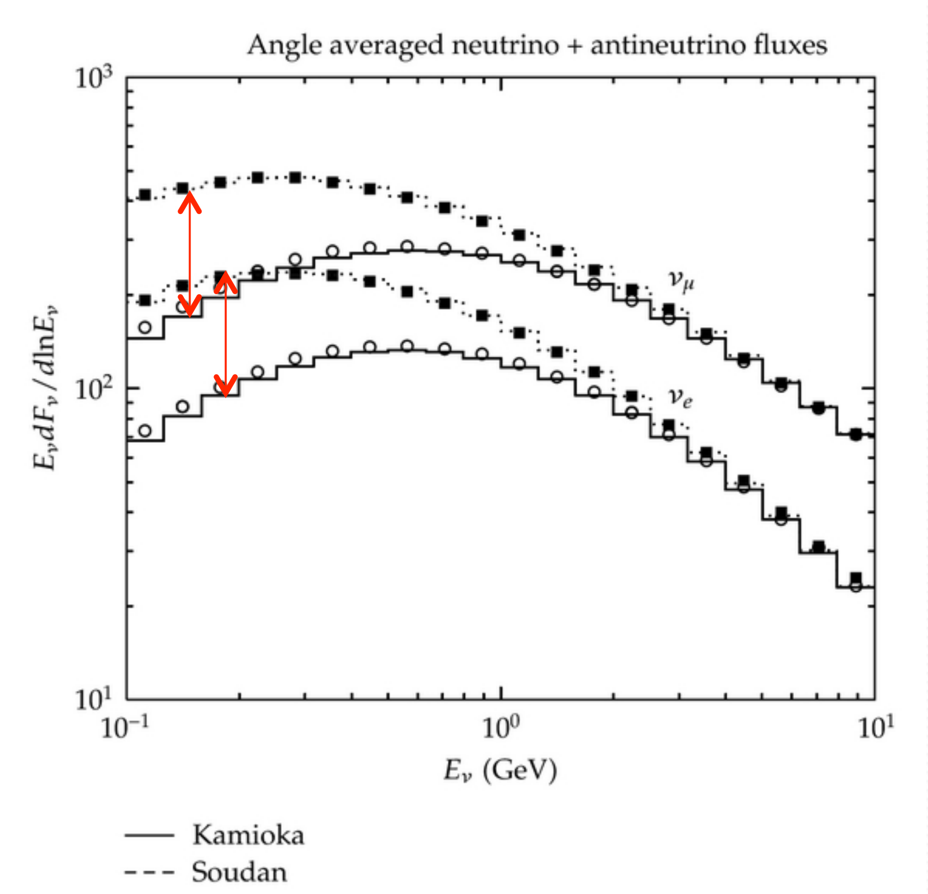


Figure 3: The atmospheric neutrino energy spectrum calculated for the Kamioka and Soudan-2 sites [6]. The electron and muon neutrino fluxes are plotted for the three-dimensional (points) and one-dimensional (histograms) calculations. The solid histograms are for the Kamioka site and the dashed histograms are for the Soudan-2 site.

Calculations varied at 10% Level

All agree

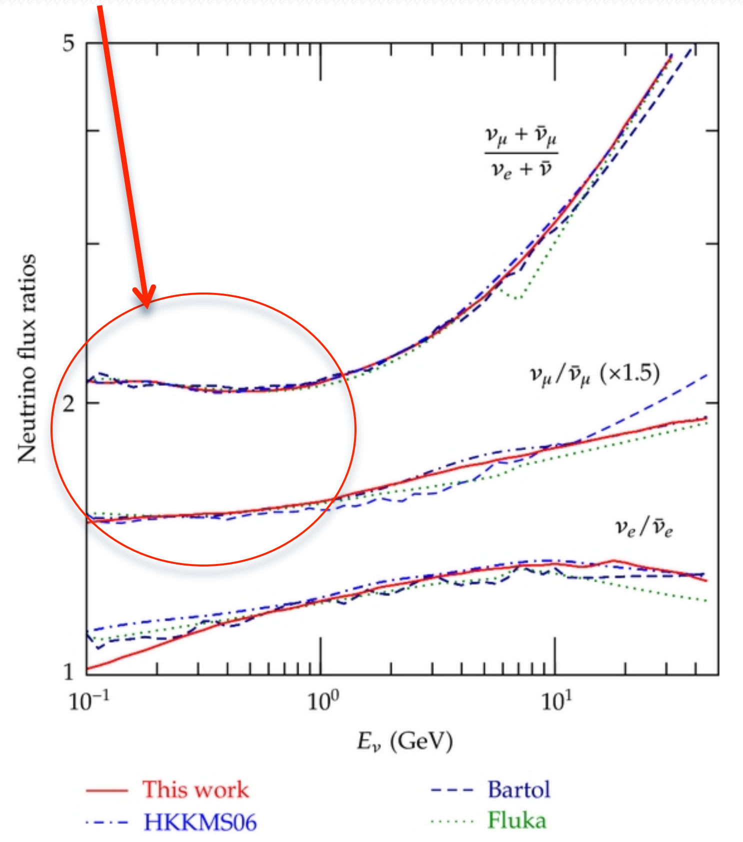


Figure 5: Comparison of the calculated flux ratios for Kamioka by the Bartol group [6], the Fluka group [10], HKKM06 [8] and HKKM11 ("This Work" in the figure) [7].

Uncertainty in Absolute Flux is Large Particularly at <1 GeV

Most data

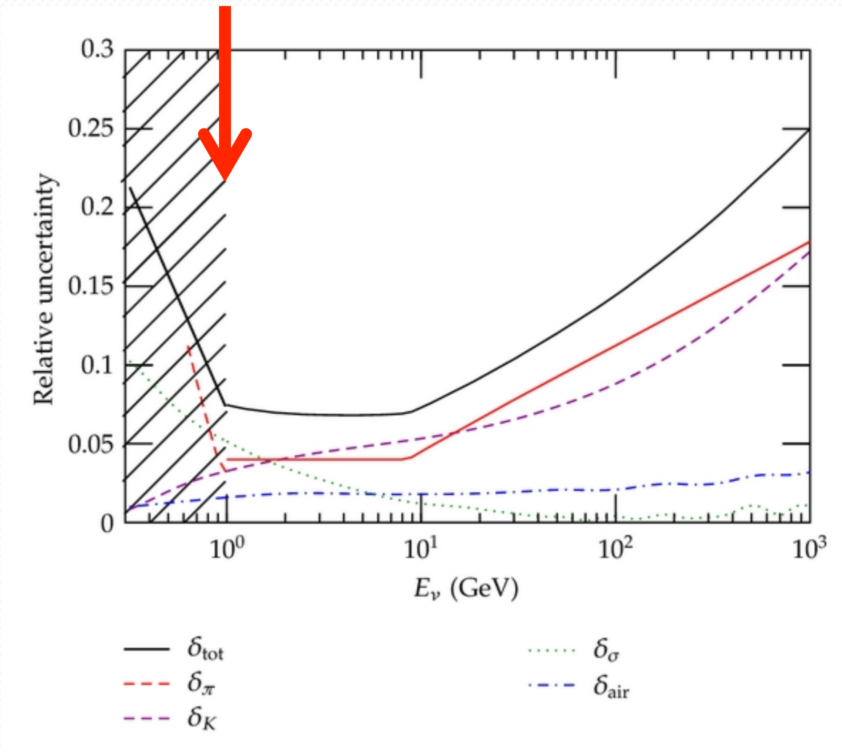


Figure 4: Estimated uncertainty of absolute atmospheric neutrino flux as a function of the neutrinos energy [8]. With the updated flux calculation, the uncertainty below 1 GeV is slightly improved to ~15% at 0.3 GeV [7].

Huge Range of Neutrino Energies in an Underground Experiment

Example, SuperK, largest underground neutrino detector

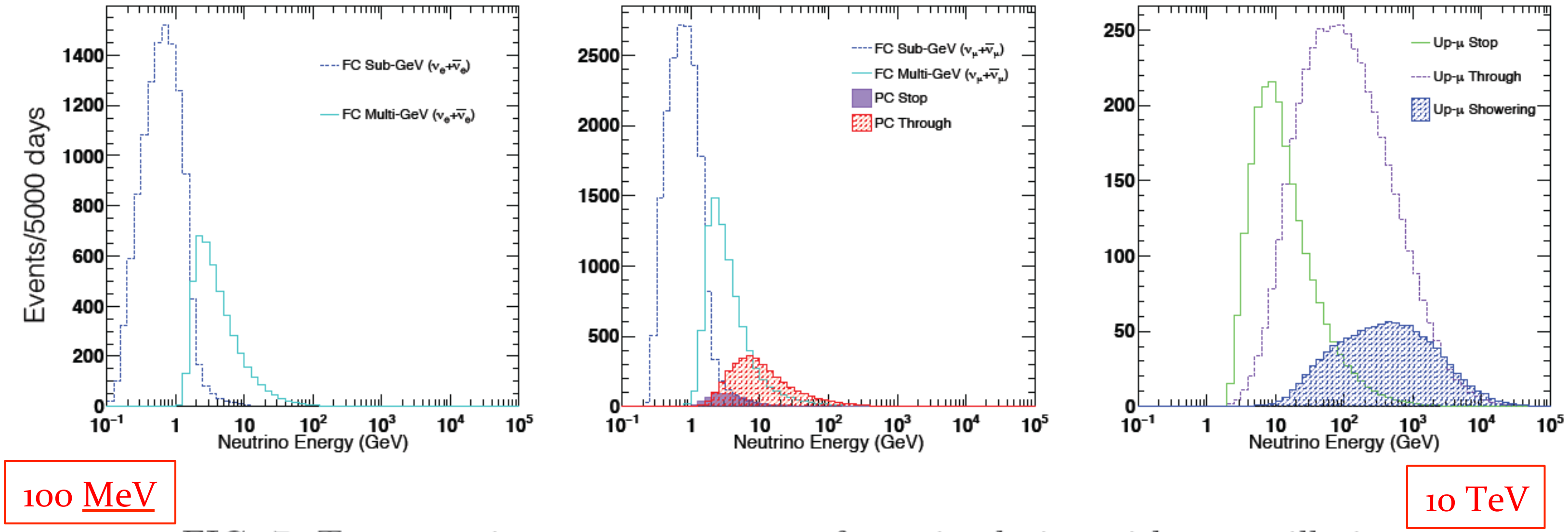


FIG. 7. True neutrino energy spectrum from simulation without oscillations.

"Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV"
Super-Kamiokande Collaboration (K. Abe, et al.) Phys.Rev. D97 (2018) no.7, 072001 (2018-04-03); arXiv:1710.09126

First Atmospheric Neutrino Detections in the Early 1960's

Built in world's deepest gold mines to see horizontal muons from neutrinos.

Kolar Gold Fields **South Africa**

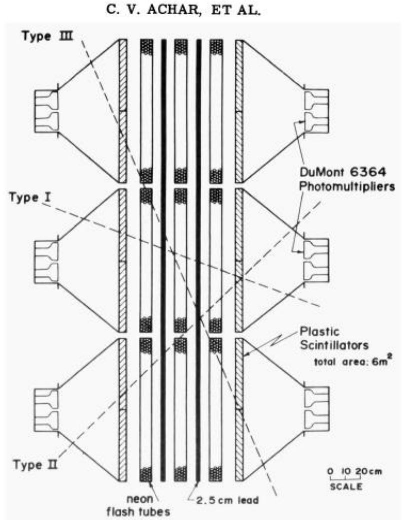


FIG. 1. Front view of one of the K. G. F. neutrino telescopes.

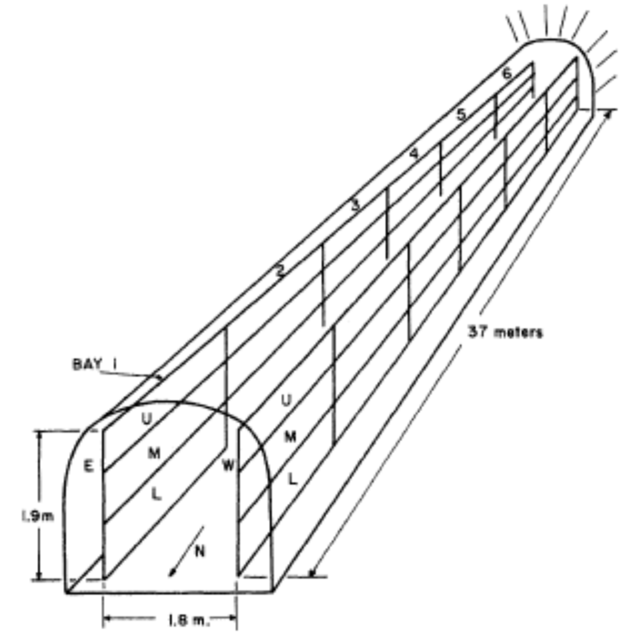


FIG. 1. Schematic of detector array.

Take note that muon neutrino was only discovered in 1962 at BNL

Some History of Atmospheric Neutrino Flux Calculations

- First calculations by M.A.Markov and Igor Zheleznykh, V.A.Kuzmin and George Zatsepin, and Ken Greisen all around 1960, and Cowsik ~'63.
- Other 1960's calculations by Osborne, Wolfendale, Pal, Budagov….
- First atmospheric neutrino observations at KGF (India) and CWI (Africa) 1963

- Not much happened for around 15 years….

- L. V. Volkova and G. Zatsepin did many early neutrino flux and rate calculations (see DUMAND '76 Proceedings).
- Calculational efforts picked up greatly after historic 1976 DUMAND conference

- Great increase in activity in early 1980's with rush to construct large nucleon decays search detectors
- Also greatly improved with computer calculational ability taking off

- Was somewhat of a trend for new measurements to be made, and then flux calculations validated them

[1]K. Greisen, Proceedings of the International Conference on Instrumentation for High-Energy Physics, Berkeley, California, September 1960 (Interscience Publishers, Inc., New York, 1961), p. 209; M. A. Markov and I. M. Zheleznykh, Nucl. Phys. 27, 385 (1961); G. T. Zatsepin and V. A. Kuzmin, Zh. Eksperim. i Teor. Fiz. 41, 1818 (1961) [translation: Soviet Phys.--JETP 14, 1294 (1962)]; R. Cowsik, Proceedings of the Eighth International Conference on Cosmic Rays, Jaipur, India, December 1963, edited by R. R. Daniels et al. (to be published).

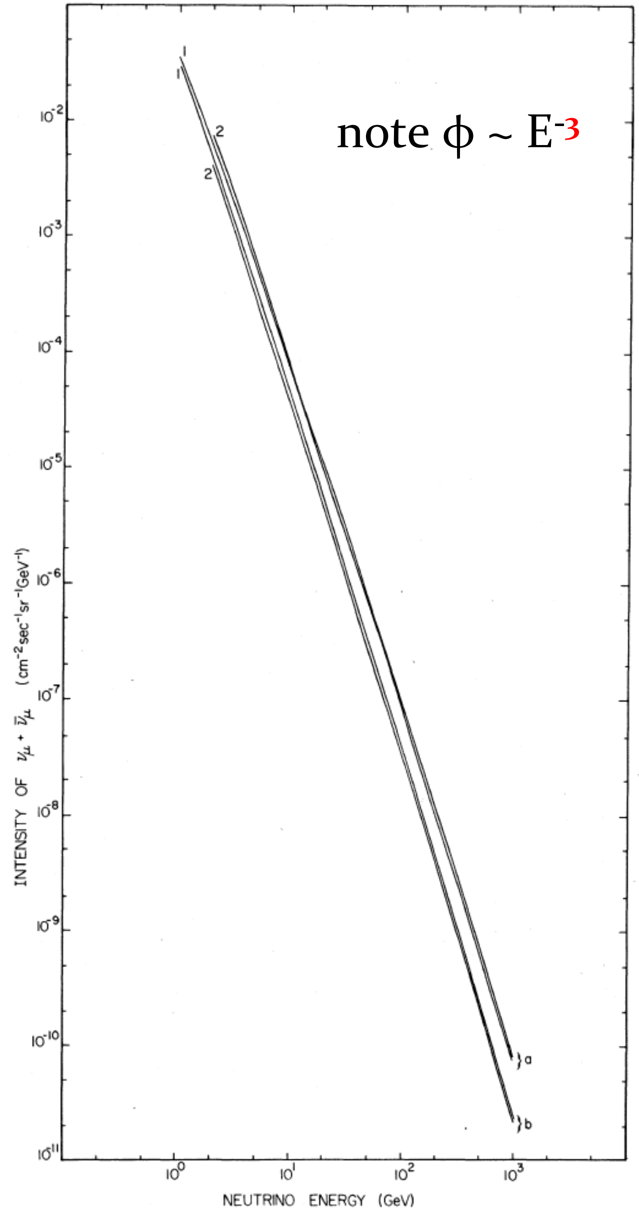


FIG. 1. Energy of atmospheric muon neutrinos plus antineutrinos in the horizontal (a) and vertical (b) directions as calculated by Osborne *et al.* (Ref. 11) (1) and Cowsik *et al.* (Ref. 6) (2).

Spectral calculations from the 1960's

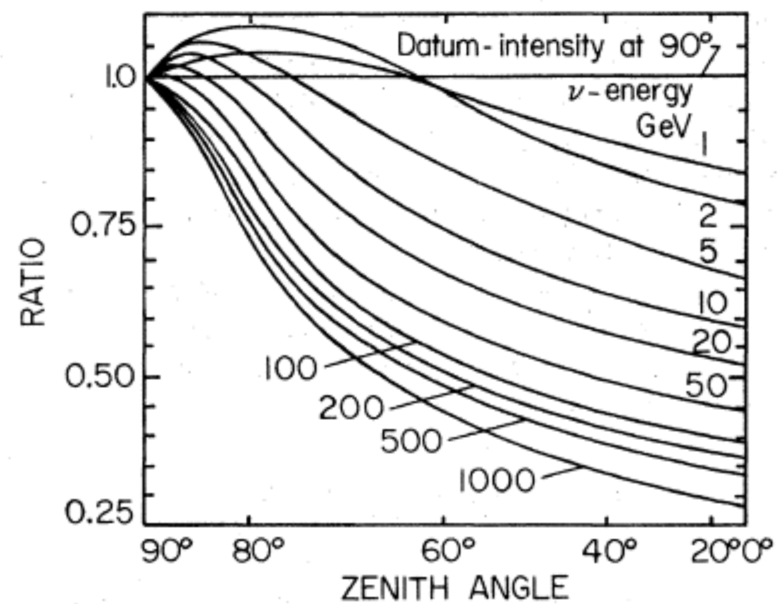
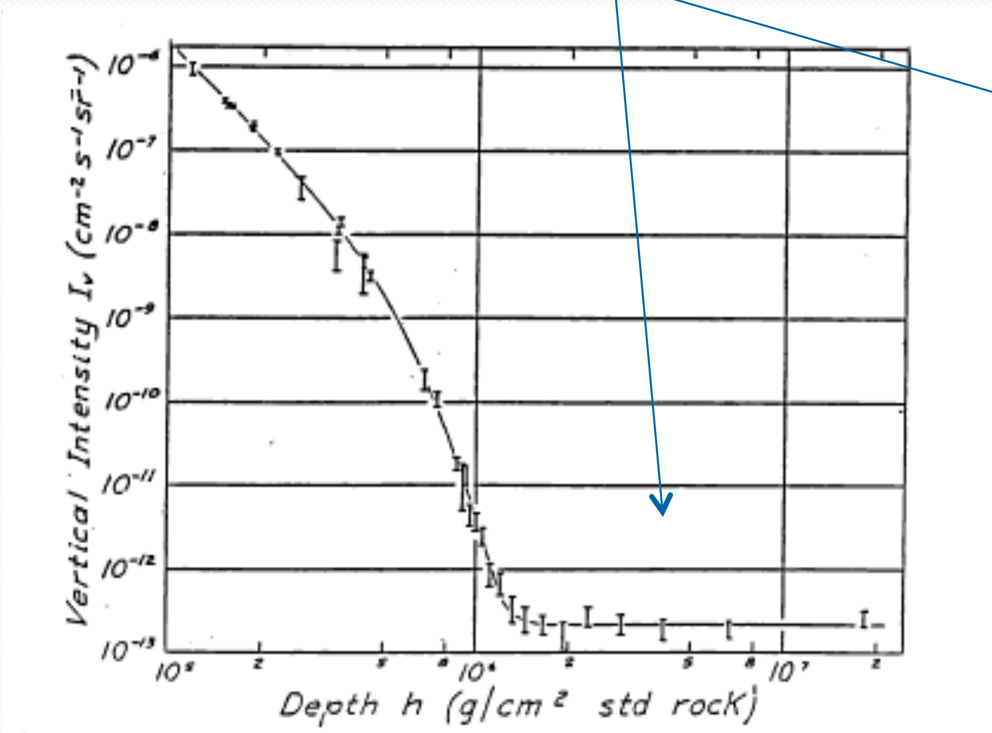


FIG. 2. Angular distribution of muon neutrinos plus antineutrinos for various energies and a K/π ratio of 20%. (Taken from Ref. 11.)

[11] J. L. Osborne, S. S. Said, and A. W. Wolfendale, Proc. Phys. Soc. (London) 86, 93 (1965).

H.H.Chen, W.R.Kropp. H.W.Sobel, and F.Reines, PRD4,1,July1971

Cos Ray Muon Depth-Intensity with Neutrino Tail



Marshall Crouch, Proc. 1987 ICRC, 6, 165

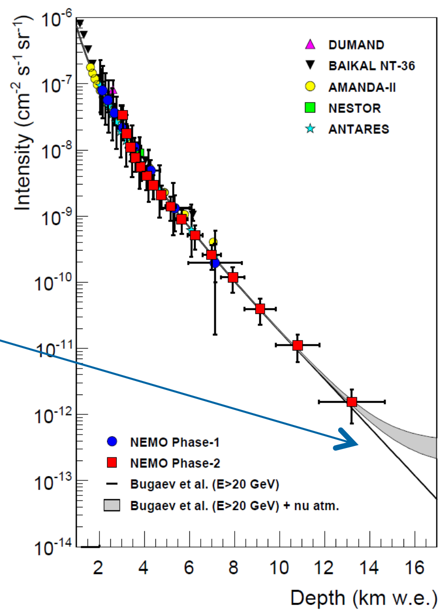


Figure 11: Vertical muon intensity, $I(\vartheta_Z = 0, h)$, versus depth measured using data acquired with the NEMO Phase-2 tower. For comparison, results from other experiments are quoted. The solid line is the prediction of Bugaev et al. [31]. The shaded area at large depths includes atmospheric neutrino-induced muons.

After 13 km water depth, it's all neutrinos!

- Measurement of the atmospheric muon depth intensity relation with the NEMO Phase-2 tower
- NEMO Collaboration (S. Aiello (INFN, Catania) et al.) *Astropart.Phys.* *66 (2015) 1-7*

Early Hints of Muon Neutrino Deficit

- CWI & KGF Rates a little low, but everything uncertain
- ν_μ/ν_e ratio low starting in IMB 1983
- Further evidence on mu/e being low via particle ID 1986 in IMB & Kamiokande
- None or ambiguous evidence from Frejus, Minnesota, Mont Blanc, and only later from others…..
- Christened “Neutrino anomaly”, and became rather heated debate (essentially US & Japan vs Europe)
- Kam claimed osc ~1990, but most dismissed them
- SuperK erased doubts in 1998 (except some in Europe)

Deficit of muon neutrino events long seen, *but not appreciated at first:*

	ν_μ events seen/expected	
• **CWI**	**66+/-14%**	**1965**
• **KGF**	**64+/-24%**	**1965**
• Frejus	75+/-27%	1988
• IMB mu-decays	76+/-10 %	1986
• Kamiokande	59+/-7%	1988

Note that the earlier experiments did not detect electron neutrino events, and this ratio is rather different than "R" in next slide

From A. W. Wolfendale in Neutrinos and Other Matters, p.179 Selected Works of Frederick Reines, 1989, World Scientific

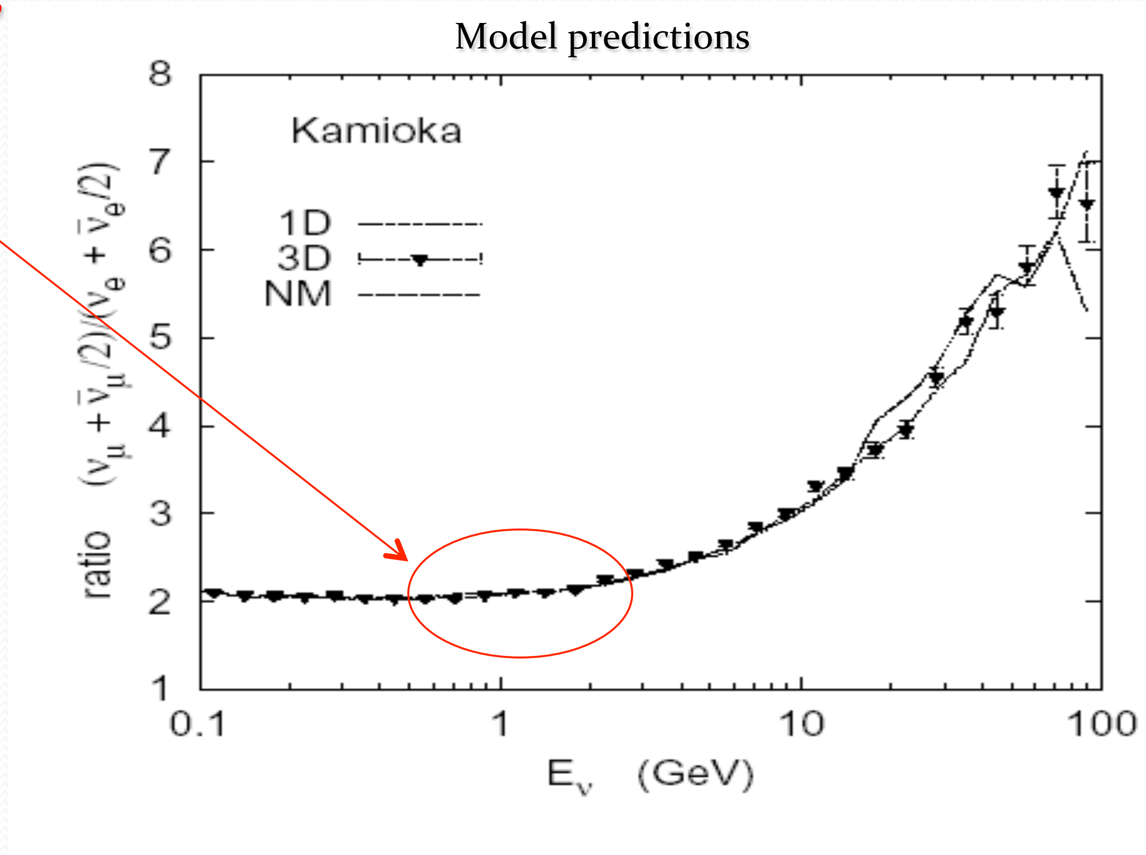
Expected e/μ Flavor Ratio Not in Doubt

At energies <2 GeV expected 2 μ : 1 e ratio determined by very well known decay kinematics:

$\Pi^- \to \mu^- + \bar{\nu}_\mu$, $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

$\Pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

Should have been 2 : 1,
But we saw ~ 1.5 : 1



The Muon Neutrino Anomaly

15 Years of confusion

- **First clearly seen in the IMB detector in 1983, and documented in theses of first PhD students (*Cortez, Foster, Shumard, Blewitt and Haines*).**
- **By the end of the IMB-1 run had 401 events 104 with a μ decay.**
- **Expected was 34+/-1%, seen 26+/-2%, a 3.5 σ problem**
- **Many possible causes recognized, including oscillations, but…**

- **NUSEX in the Mont Blanc Tunnel reported 28+/11%**
- **Kamiokande reported 36+/-8%(1986)**

- **By 1988 the anomaly was becoming more clear in IMB and Kam with the development of showering vs non-showering algorithms**

- **Due to underprediction of the electron neutrino flux there were too many electron events and too few muon events, and so early oscillation speculation was ν_μ <-> ν_e or somehow an excess of electrons**

John LoSecco, June 2016 arXiv:1606.00665v3

The Atmospheric Neutrino Anomaly

- State of the enigma in 1999 (just after SuperK)

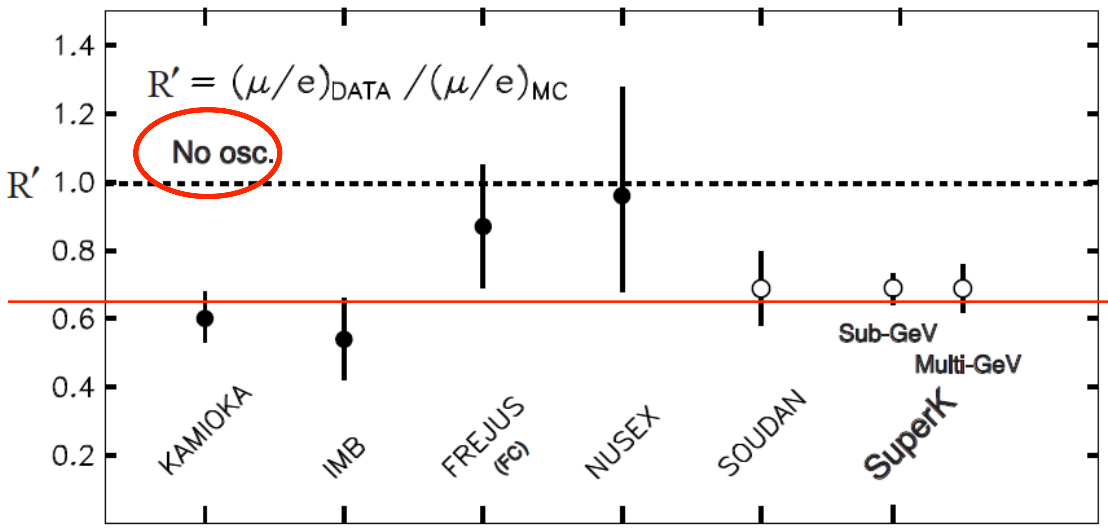


Fig. 1.3. The double ratio R of muon to electron neutrino events, data divided by expectations for various underground atmospheric neutrino detectors. From A. Mann[20]

This can be a bit misleading since the fluxes depend on energy, so if oscillations, all should <u>NOT</u> get the same R'

20. A. Mann, Plenary talk at *the XIX Int. Symposium on Lepton and Photon Interactions at High Energies, Stanford, Aug. 1999*, TUHEP-99-04/PDK-741, hep-ex/9912007.

Various Confusing Evidence

- Under-prediction of the electron neutrino flux:
  too many electron events + too few muon events,
  => early oscillation speculation was ν_μ <-> ν_e
- Tendency to be see anomaly in water detectors and not iron
- Cherenkov cone resolution in e vs μ, not yet demonstrated
- Cross sections and fluxes, could be wrong
- Possibility of Detector up/down or e/mu biases?
- Possibility of new source of electron neutrinos??
- Cosmic rays, not great reputation (+ claims of PDK observation by Miyake and even Koshiba)
- IMB paper on exiting events rejecting oscillations, incorrect
- Early osc claims from Kamiokande were not strong and got Δm^2 in nowadays disallowed region

Sociology/Science Comment:

Cosmic Ray studies, slow to modernize

- Starting in the 1950's particle physics progress began to shift to accelerators, and more precisely controlled experiments
- ICRC became somewhat of a backwater, and hot shots tended to go elsewhere
- CR studies and early neutrino work, not very attentive to error estimates (not easy)
- In any event many quantities like input CR fluxes, cross sections, etc. only good to 10-20%, or worse
- (W mass not known until 1983)
- And no fancy computer simulations to study acceptance, fluctuations, fitting … until ~ 1980's
- Precision era in CRs did not arrive until 1990's
- Since then non-accelerator experiments have ~led the way

OK LHC found Higgs, ho hum…

The Yellow Brick Road has many oft forgotten culs-de-sac

- On top of the whole muon neutrino puzzle:
- Early 90's also much confusion over solar neutrinos
- Theorists loved MSW solution with Cabbibo angles
- (JGL and Sandip loved vacuum oscillations)
- All were wrong as DM2 was large and s22theta small
- Atsuto Suzuki's gamble on KamLAND payed off, could have been a null experiment
- Solar oscillations made clear by SNO
- MSW in sun, not oscillations… (Smirnov
- Bottom line: we were fooled by neutrinos, again!

- In Teaching we tend to tell only the Yellow Brick Road
- But real time experience more complex and confusing

Evidence / Hypothesis	Pre 1998: R $E <$ 1 GeV	Pre 1998: μ dk Frac	Pre 1998: Vol Frac	From SK: R $E >$ 1 GeV	From SK: A_e ~0	From SK: A_μ > 0	From SK: R(L/E) ~0.5
Atm. Flux Calc.	xx			x		x	x
Cross Sections	xx			x		x	
Particle Ident.		xx	xx				
Entering Bkgrd.			xx			x	
Detector Asym.			xx				
X-Ter. ν_e						x	x
Proton Decay				x		x	
ν_μ Decay							x
ν_μ Abs.							x
ν_μ - ν_e osc					x		
Nonstandard Osc							x
$\nu_\mu - \nu_s$ osc							x
$\nu_\mu - \nu_\tau$ osc							

A=Down/Up

13 Neutrino Anomaly Alternative Hypotheses from ~1998

SuperK rules out all except μ <-> τ
But small violations ever allowed

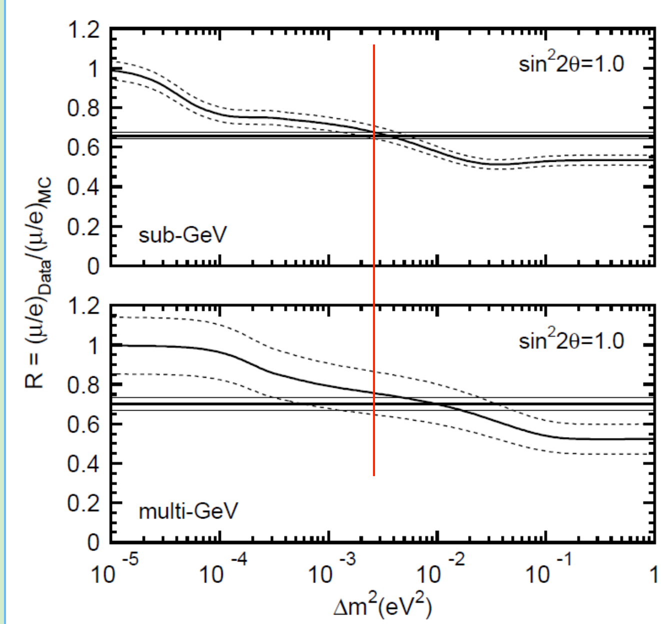


FIG. 30: Expected $(\mu/e)_{Data}/(\mu/e)_{MC}$ for singe-ring sub- and multi-GeV + PC samples as a function of Δm^2 for full $\nu_\mu \leftrightarrow \nu_\tau$ mixing. The values for the data together with $\pm 1\sigma$ statistical errors are shown by the horizontal lines. The systematic errors are shown by the band in the expectation.

Table 5.1. List of hypotheses invoked to explain the atmospheric neutrino anomaly. Columns 2–4 contain criteria available prior to SuperK, and the last four contain data available after the 1998 SuperK publication [5.30]. The hypotheses divide into five systematics issues and eight potential physics explanations. As indicated in the text, the only remaining likely hypothesis is oscillation between muon and tau neutrinos. A "×" schematically indicates which evidence rules out the hypothesis in that row

2005 SK

The Curious Luck in Neutrinos

(The gods like neutrino hunters?)

- **Distance ~1000 km between arrival direction hemispheres, between full oscillation up-coming and little for down-going for atm ν's ~1 GeV**
- **Mixing angle for ν_μ-ν_τ near max 45^o (if were tiny: unseen)**
- **4 MeV ν_e oscillation lengths ~2km and 150km, and mixing angle not tiny (very convenient)**
- **Wolfenstein Matter-Effect distance ~ radius of Earth**
- **Oscillation transitions actually not so important in sun*, adiabatic MSW dominates.**

We see what we can, but what are we not seeing?

**Smirnov arXiv:1609.02386v2*

Atm Nu Calculations are Hard

- **Two general methods: <u>Primaries on dow</u>n or start with <u>observed muon flux</u>**
- **- Top-down requires much knowledge of nasty hadronic physics as well as good incoming primary spectrum and composition**
- **- Using Muon & Kaon fluxes: problems with altitude, energy, K/π and observational accuracy**
- **Quark x distributions at x -> 1 not well known**
- **Plus geomagnetic field not ignorable <10 GeV or so**
- **And on top of all that the cross sections for nu observation are not perfect…**
- **You will hear much more from *Tom Gaisser and Anatoli Fedynitch, and Morihiro Honda***

Direct Production Not Yet Seen and Other Unsettled Issues

- **Neutrinos from short lived heavy states produced at high energies should have isotropic zenith angle distribution**
- **(Recall late '60's flap about false hint seen in Utah, Keuffel)**
- **Predicted cross over with normal π/k flux at ~100 TeV.**
- **Even with much IceCube data, Dir. Prod. <u>not found</u>**

Also (as we will here in detail…)

- **Mass order not yet settled but leaning towards "normal"**
- **CP violation, maybe** ***(but who really cares?)***
- Majorana or Dirac? *Theorists favor Majorana, but…*

SuperK Systematic Errors and Normalizations 2017

Systematic Error			Fit Value (%)	σ (%)
Flux normalization	$E_\nu < 1$ GeV[a]		14.3	25
	$E_\nu > 1$ GeV[b]		7.8	15
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$	$E_\nu < 1$ GeV		0.06	2
	$1 < E_\nu < 10$ GeV		−1.1	3
	$E_\nu > 10$ GeV[c]		1.6	5
$\bar{\nu}_e/\nu_e$	$E_\nu < 1$ GeV		1.7	5
	$1 < E_\nu < 10$ GeV		3.4	5
	$E_\nu > 10$ GeV[d]		−1.6	8
$\bar{\nu}_\mu/\nu_\mu$	$E_\nu < 1$ GeV		0.23	2
	$1 < E_\nu < 10$ GeV		2.9	6
	$E_\nu > 10$ GeV[e]		−2.9	15
Up/down ratio	$<$ 400 MeV	e-like	−0.026	0.1
		μ-like	−0.078	0.3
		0-decay μ-like	−0.286	1.1
	$>$ 400 MeV	e-like	−0.208	0.8
		μ-like	−0.13	0.5
		0-decay μ-like	−0.442	1.7
	Multi-GeV	e-like	−0.182	0.7
		μ-like	−0.052	0.2
	Multi-ring Sub-GeV	e-like	−0.104	0.4
		μ-like	−0.052	0.2
	Multi-ring Multi-GeV	e-like	−0.078	0.3
		μ-like	−0.052	0.2
	PC		−0.052	0.2
Horizontal/vertical ratio	$<$ 400 MeV	e-like	0.019	0.1
		μ-like	0.019	0.1
		0-decay μ-like	0.058	0.3
	$>$ 400 MeV	e-like	0.271	1.4

Flux Adjustment: Calculations continue to Underestimate. WHY?

Flux Uncertainty

K/π ratio in flux calculation[f]		−9.3	10
Neutrino path length		−2.17	10
Sample-by-sample	FC Multi-GeV	−6.5	5
	PC + Stopping UP-μ	0.19	5
Matter effects		0.52	6.8

[a] Uncertainty decreases linearly with $\log E_\nu$ from 25 %(0.1 GeV) to 7 %(1 GeV).
[b] Uncertainty is 7 % up to 10 GeV, linearly increases with $\log E_\nu$ from 7 %(10 GeV) to 12 %(100 GeV) and then to 20 %(1 TeV).
[c] Uncertainty linearly increases with $\log E_\nu$ from 5 %(30 GeV) to 30 %(1 TeV).
[d] Uncertainty linearly increases with $\log E_\nu$ from 8 %(100 GeV) to 20 %(1 TeV).
[e] Uncertainty linearly increases with $\log E_\nu$ from 6 %(30 GeV) to 40 %(1 TeV).
[f] Uncertainty increases linearly from 5% to 20% between 100GeV and 1TeV.

TABLE VII. Flux-related systematic errors that are common to all SK run periods. The second column shows the best fit value of the systematic error parameter, ϵ_j, in percent and the third column shows the estimated 1-σ error size in percent.

K/π Uncertainty

Still some oddities in Nu Flux Calcs

- **Over the years most flux calculations under-predicted the observed (μ & e) neutrino interaction rate. Typically ~20%**
- **(This contributed to consideration of ν_e <-> ν_μ early on… 90's)**
- **Strangely to me: also been true for accelerator neutrino flux predictions (going back to 70's)!?!**
  - Nowadays hidden by adjusting M_a, but… (see later talks)

- **Is there something going on which we have not recognized? Separate issues?**

And more, so much to do and understand….

- Still waiting for that next SN, and will there be early nus?
- And where are the BZ and Glashow Resonance events?
- And then there is the Reactor Neutrino Anomaly, including the "5 MeV Bump", still not gone away
- And the unexplained LSND and MiniBone anomalies
- And due to neutron lifetime enigma, speculations about
  n -> DM +?
- And nice suggestion about DM Balls~ 10^{23} m_n, which can explain solar corona heating, but which should make lots of (not seen) neutrinos
- And the ANITA observation of two ~30^o upcoming showers that appear to be neutrino showers ~500 PeV for which the earth is opaque

Some Conclusions on the Saga of Atmospheric Neutrino Studies

- Atmospheric neutrino studies have led to much surprising science and great scientific fun

- Definitive absolute flux calculations not yet, but getting better every year

- Neutrino Oscillations, the crowning achievement, keep on giving and presenting many open questions and mysteries.

- Not even a hint of PDK! (yet, payed the way for big detectors)

- Initial major motivation for starting atm nu studies, neutrino astronomy is finally underway thanks to Ice Cube! (And hopefully KM3 and Baykal soon).

- Many thanks to organizers, and looking forward to an interesting week here at ICTP!