Atmospheric Neutrino Flux Measurement

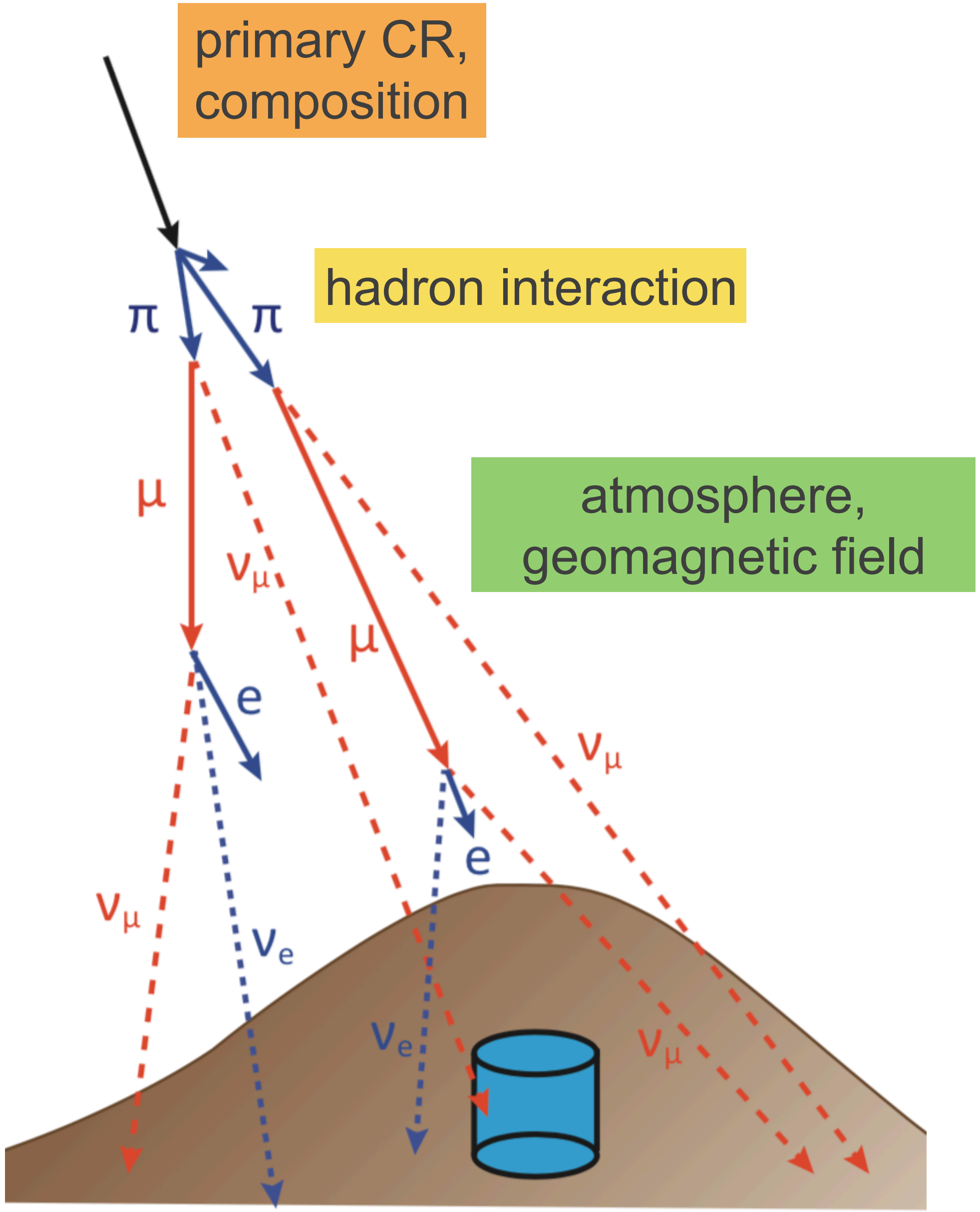
Kimihiro Okumura

okumura@icrr.u-tokyo.ac.jp

Institute for Cosmic Ray Research (ICRR), University of Tokyo

May 22th, 2018   ISVHECRI2018 @ Nagoya University

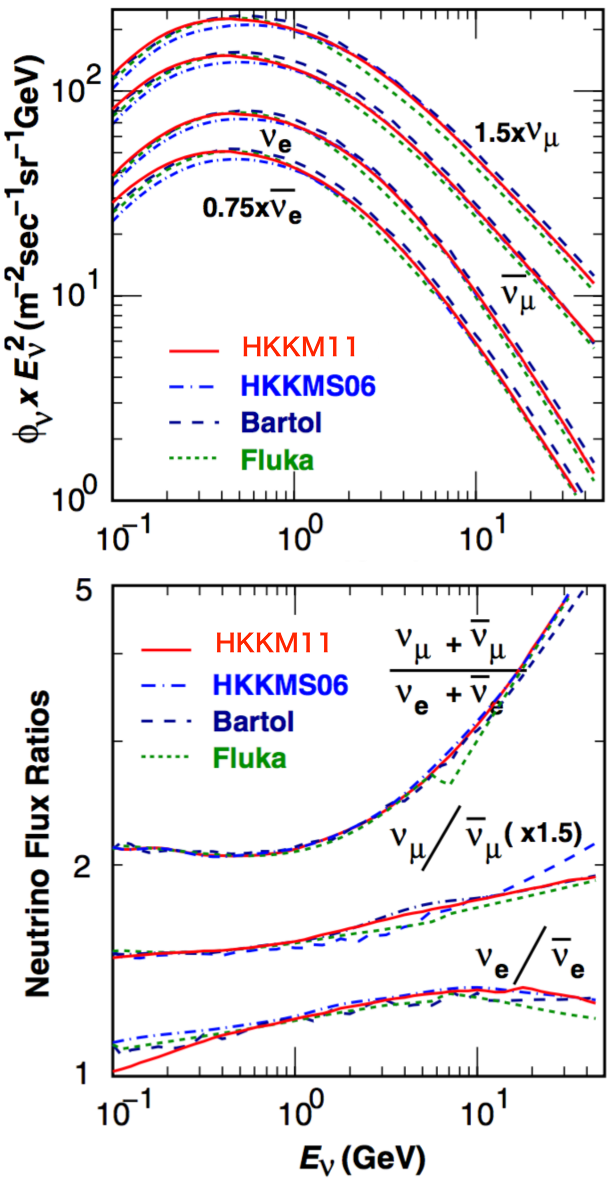
Introduction

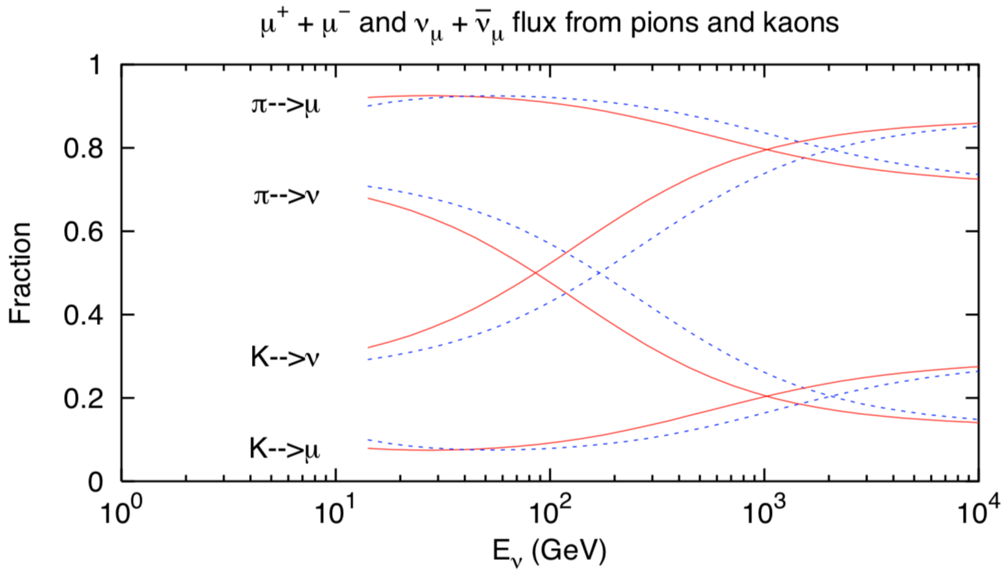


- Atmospheric neutrino: end particle of cosmic ray interactions with atmosphere
- Neutrino flux affected by several factors:
  - primary CR flux, composition
  - hadron interaction
  - atmosphere model, seasonal variation, geomagnetic effect
- These effects are introduced in flux simulations precisely
- Can test flux prediction directly by flux measurement

“Conventional” Atmospheric Neutrino

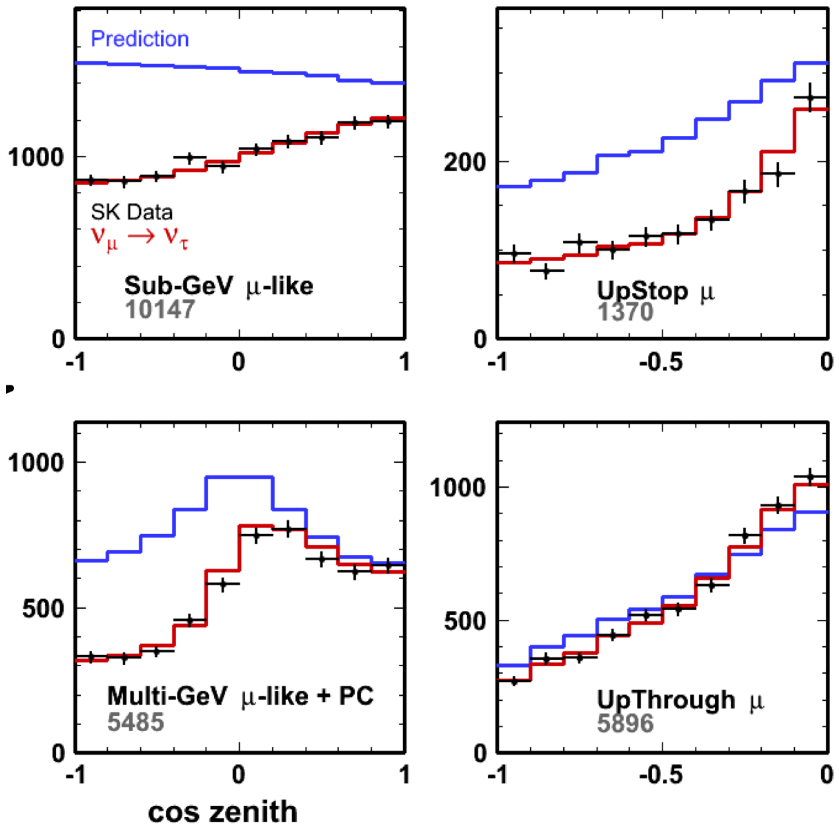
PRD 83, 123001 (2011)





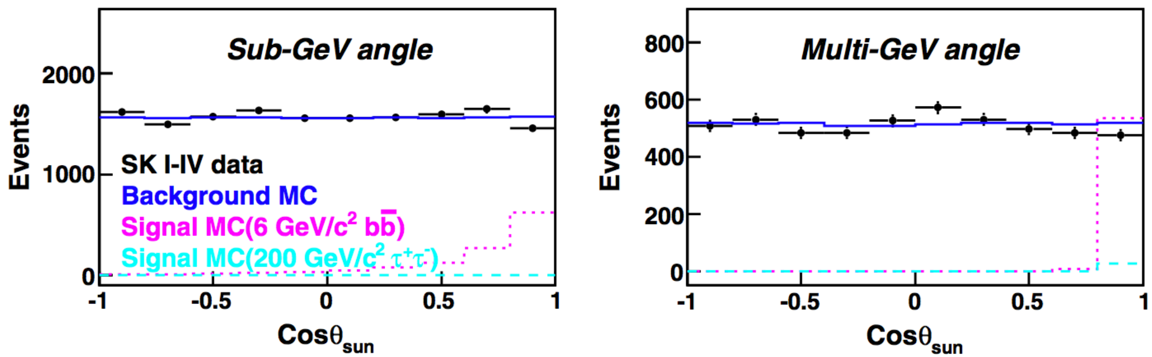
- Atmospheric neutrinos from π and K decays dominates below TeV energies
- Nominal spectrum: $dN/dE \propto E^{-3.7}$ steeper for ν_e
- ν_μ/ν_e ~2 at GeV determined from π decay
- Larger kaon fraction as higher energies
  - Uncertainties due to π/K ratio

Purpose of Flux Measurement



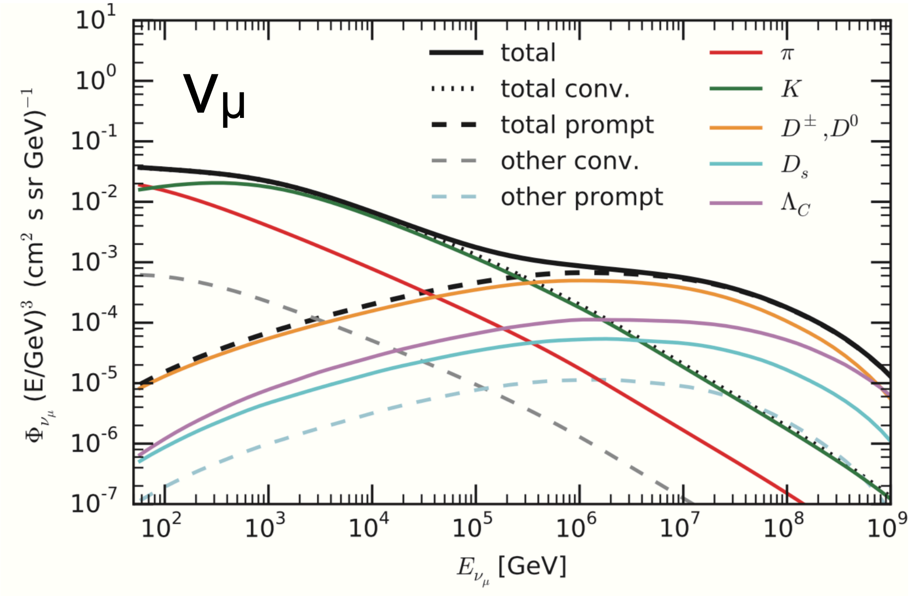
- Accurate flux prediction is necessary for
- as a signal:
  - neutrino oscillation measurement
- as a background:
  - proton decay (GeV)
  - dark matter (DM) search (GeV~TeV)
  - astrophysical neutrino (TeV~PeV)

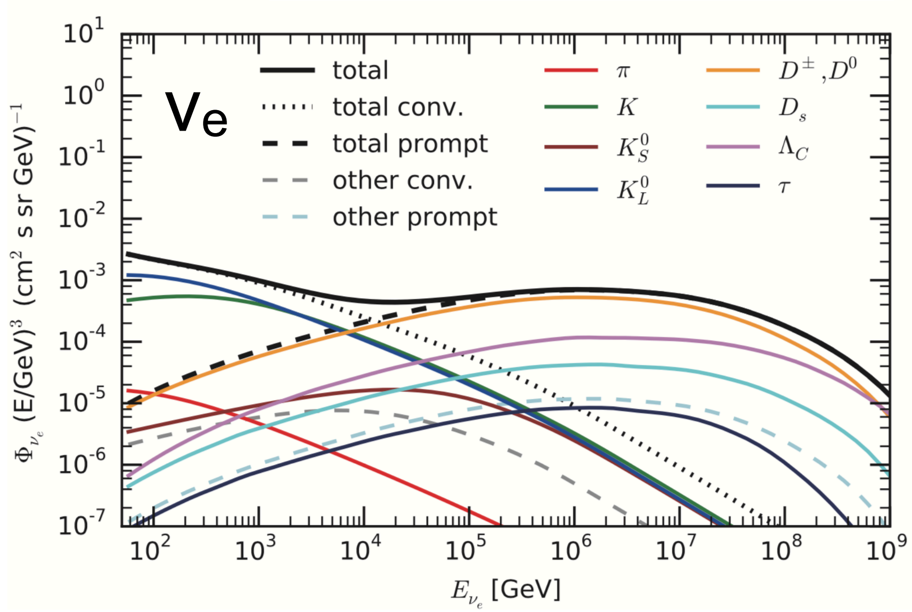
PRL **114,** 141301 (2015)



“Prompt” Flux

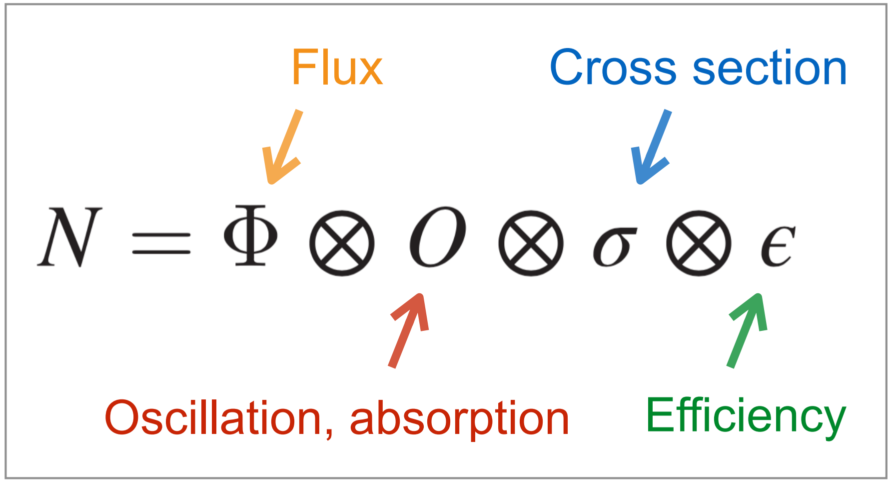
EPJ Web of Conferences **99**, 08001 (2015)

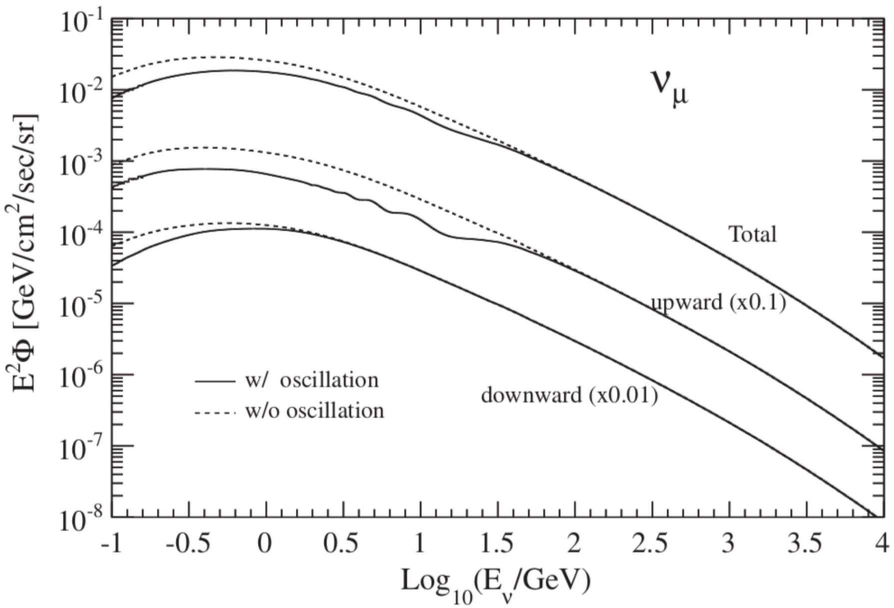




- “Conventional” flux from π/K decay is suppressed at high energies as they reach ground before decay
- Instead “prompt” flux from D meson decay begins to dominate
- Could be background of astrophysical neutrino
- Has not yet been successfully detected

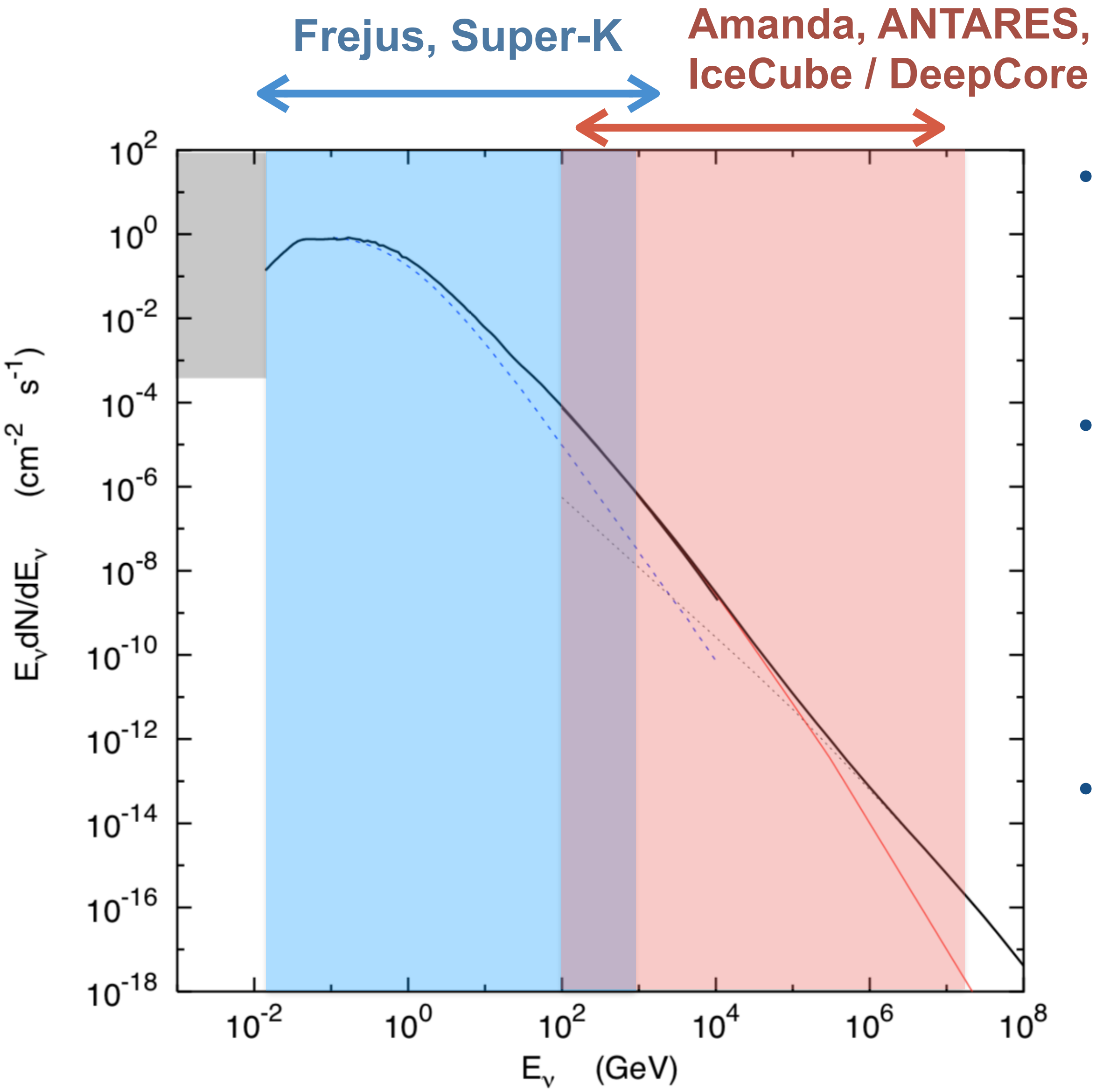
Flux Measurement Method





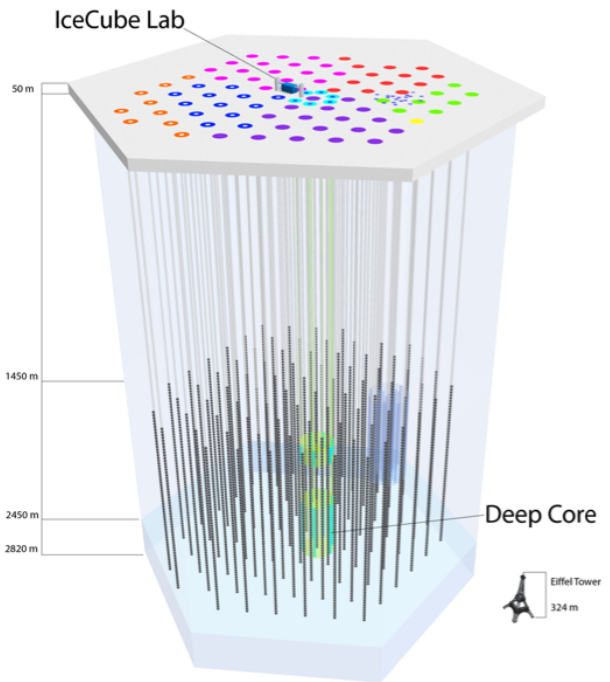
- Basic method: event counting with large FV mass
- Require particle ID capability:
  - ν_e, ν_μ event separation
  - neutral-current (NC) rejection
- Neutrino interaction uncertainty is important
- Additional Effect:
  - Neutrino oscillation below 100 GeV by atmospheric mass parameter ($|\Delta m_{32}^2|$~2.5×10^{-3}eV^2)
  - Earth absorption at O(10) TeV and higher

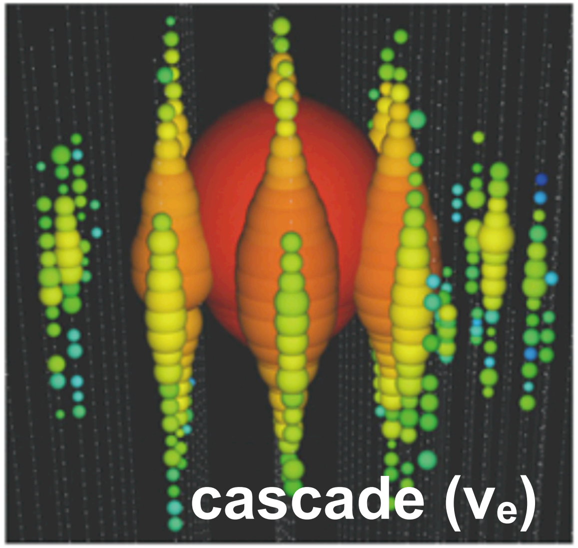
Neutrino Detectors

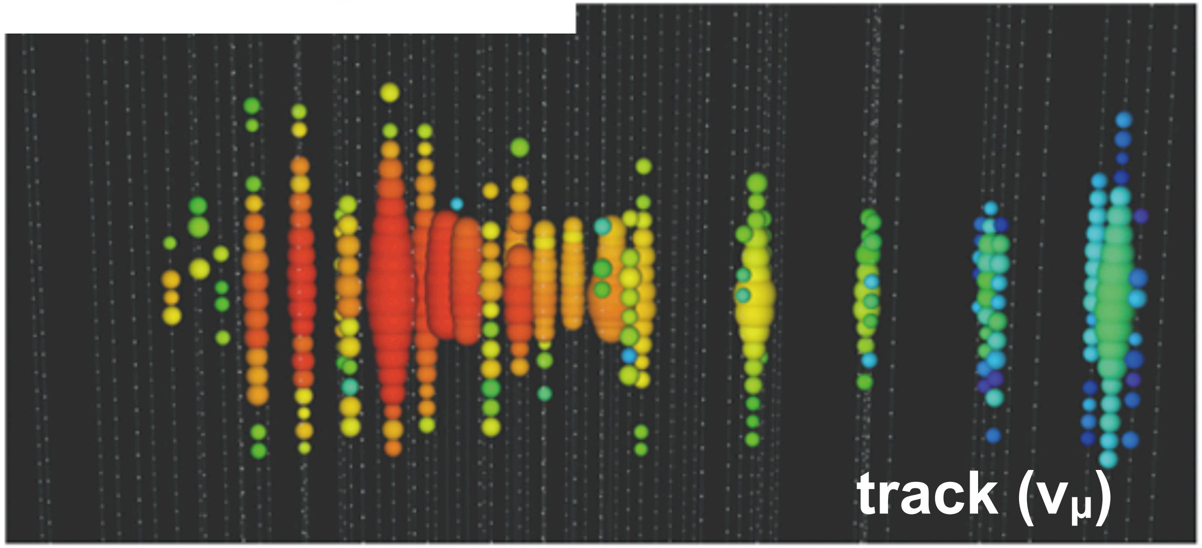


- Roughly two mass scales of detectors covering wider energy range
- Lower energy (sub-GeV ~ O(1)TeV)
  - Frejus, Super-K
  - O(1) ~ O(10) kiloton mass
- Higher energy (>100GeV)
  - Amanda, ANTARES, IceCube / DeepCore
  - ~ km^3 scale detectors

Measurement by IceCube

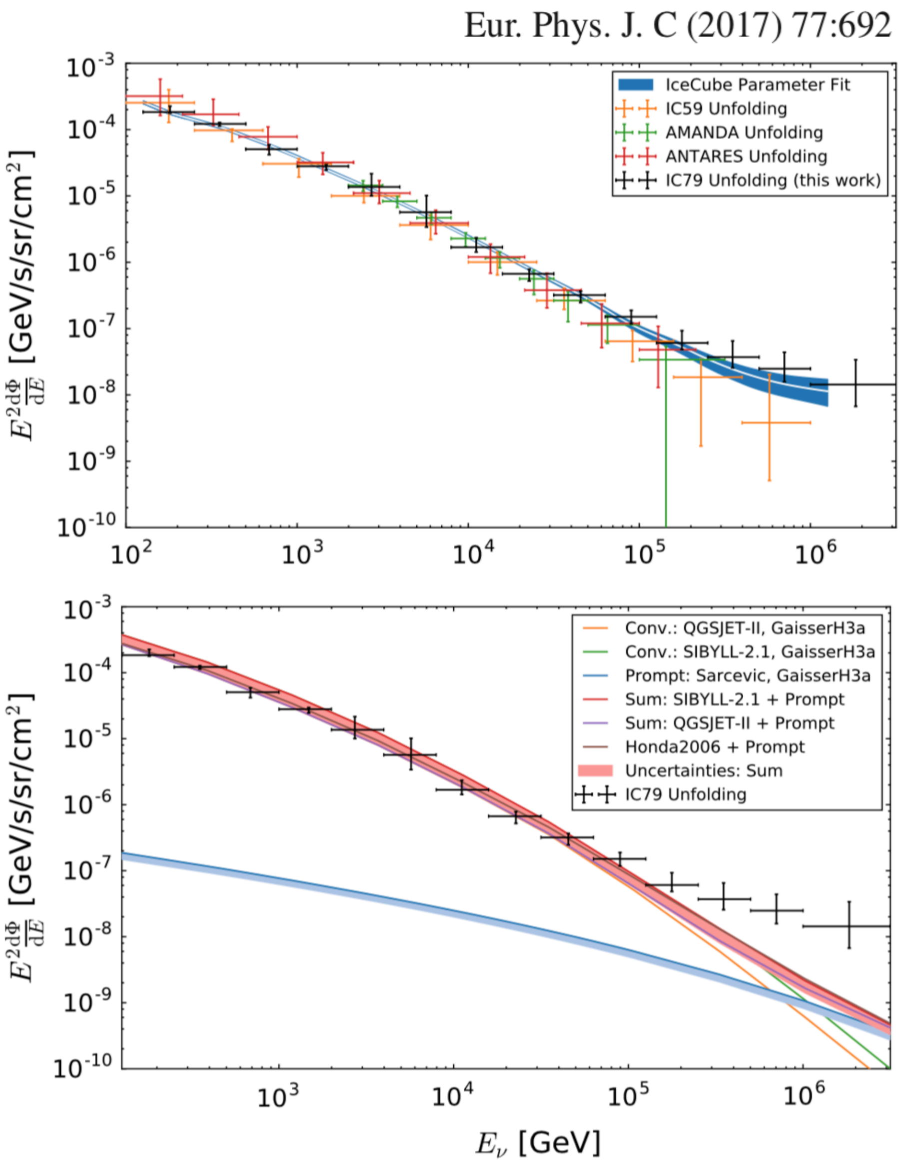






- Events categorized by track type for ν_μ and cascade type for ν_e
- Providing good quality data for ν_μ while NC background contamination for ν_e

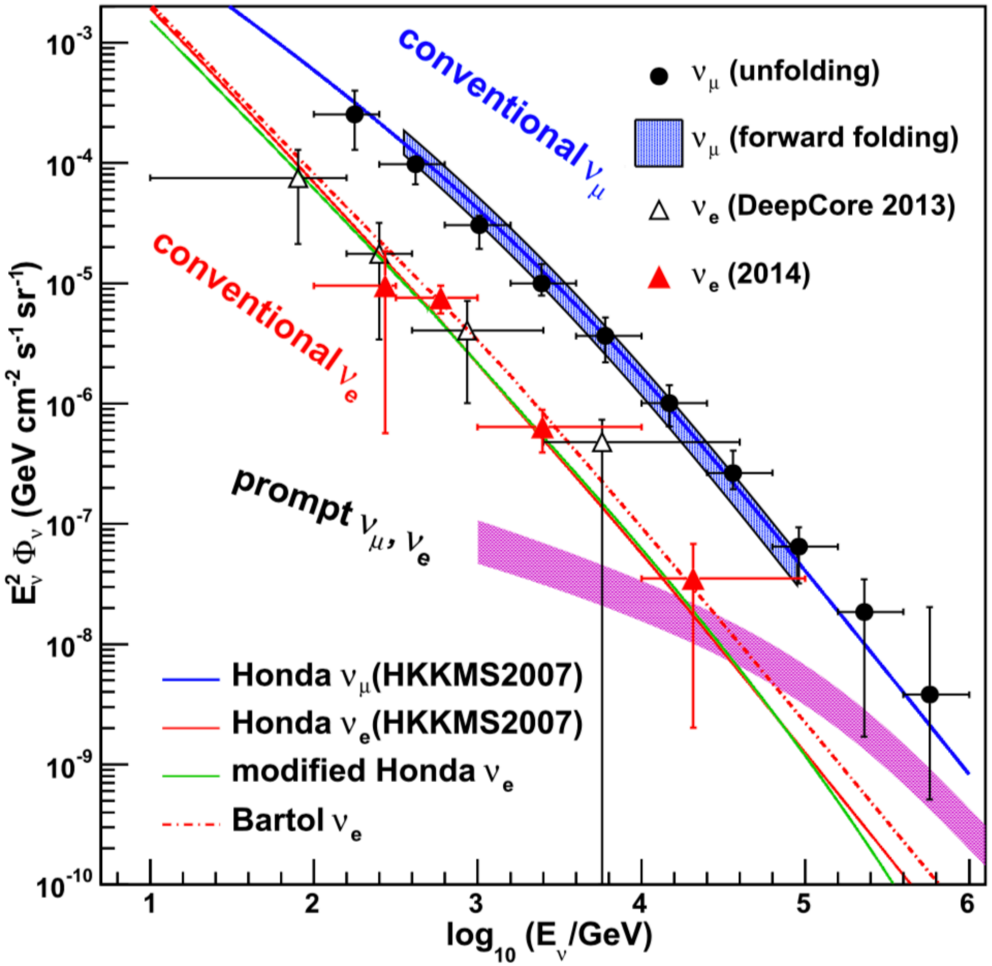
ν_μ Flux Measurement



- Basically upward-going ν_μ sample are utilized to reduce cosmic muon background
- Well studied by several experiments: AMANDA, ANTARES, and IceCube
- Spectrum measured from ~100GeV up to several PeV
- Observed spectra are consistent among experiments
- Recent IceCube result shows clear excess beyond 100 TeV
  - consistent with IceCube's astrophysical neutrino results

ν_e Flux Measurement

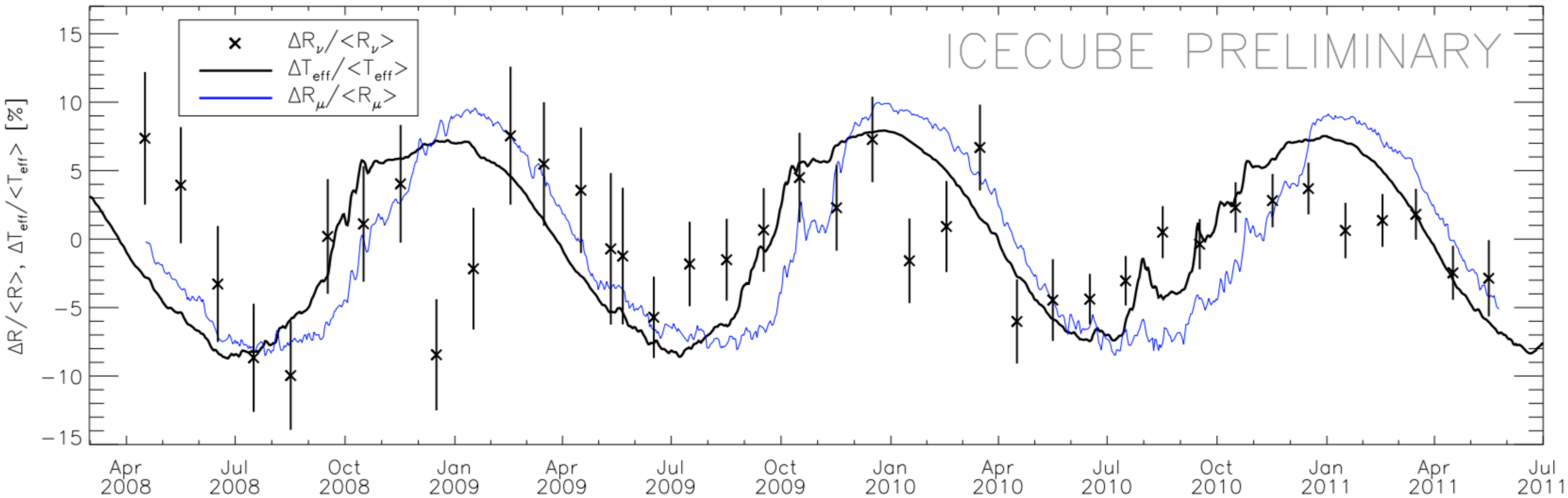
PHYSICAL REVIEW D **91,** 122004 (2015)



- Dominant contribution from Kaon decay at high energies
- Prompt flux starts to dominate from several 10 TeV
- Difficult to measure because:
  - smaller flux due to steeper spectrum
  - neutral-current backgrounds
- Observed higher flux (~30%) than prediction, indicating larger kaon component
- No evidence for prompt neutrino

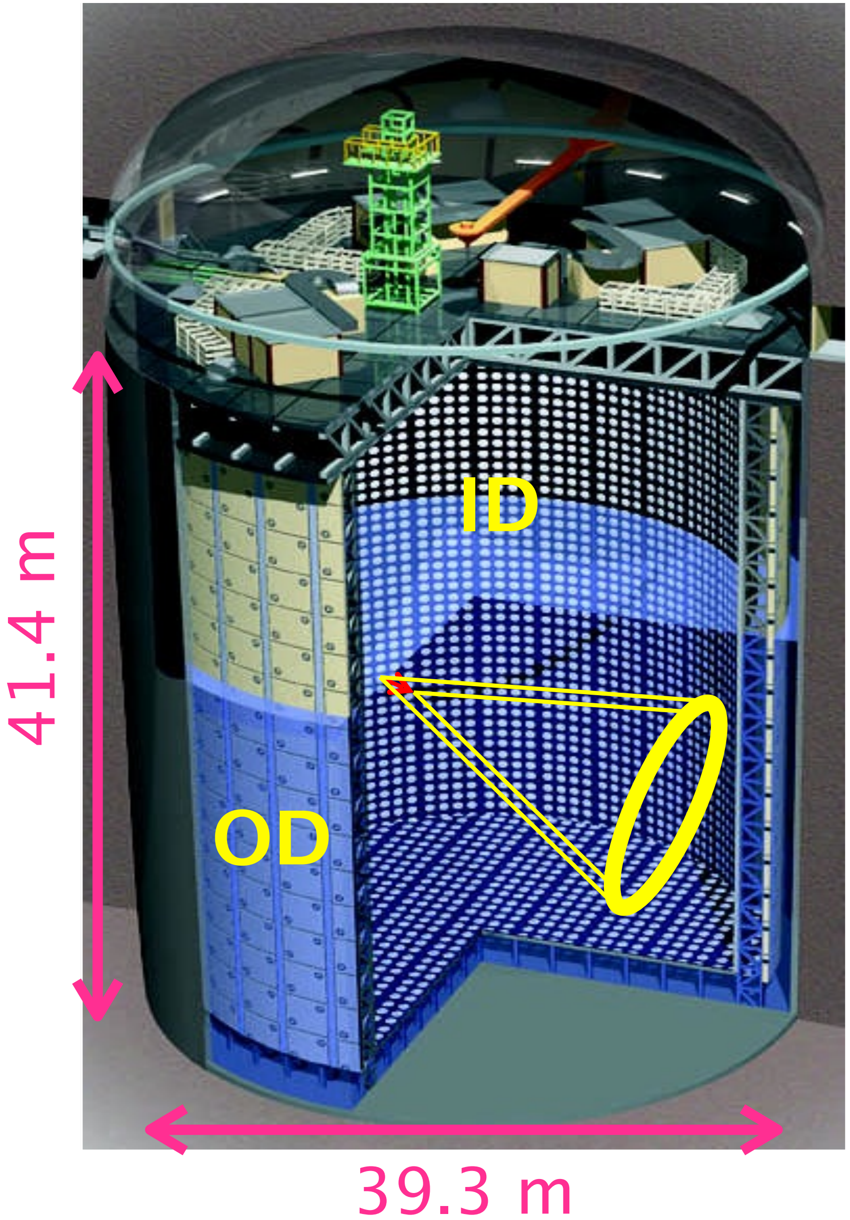
Seasonal Variation

(ICRC 2013)



- Correlations between atmosphere temperature and neutrino flux are investigated
  - atmosphere expansion by temp. rise increases probability of meson decay
- Seasonal variation analyzed using upward moving neutrino ($90^\circ<\theta<120^\circ$)
- Clear correlation seen with T_{eff} rejecting constant rate hypothesis with 3.4σ

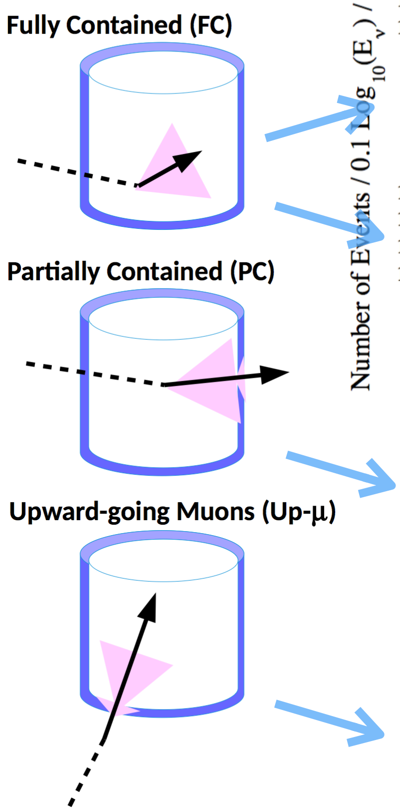
Measurement by Super-K

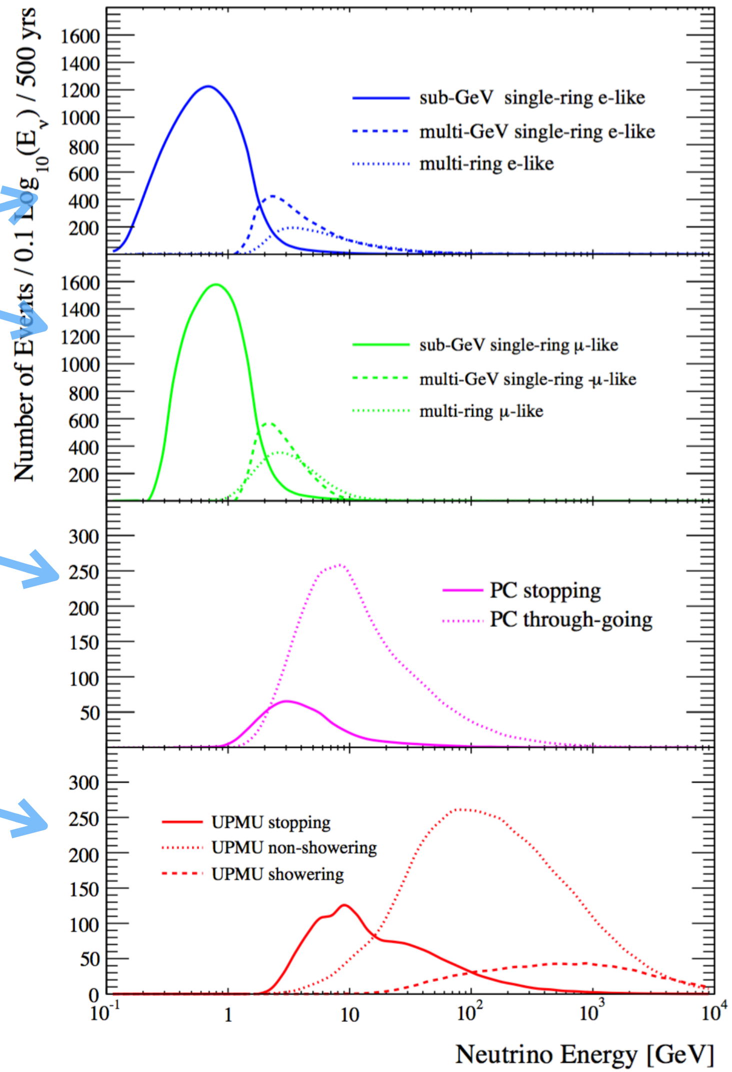


- Water Cherenkov imaging detector
- 1000 m underground in Kamioka mine
- 50 kton volume (fiducial 22.5 kton)
- 11129 20” PMTs in inner detector (ID)
- 1885 8” PMTs for outer detector (OD)

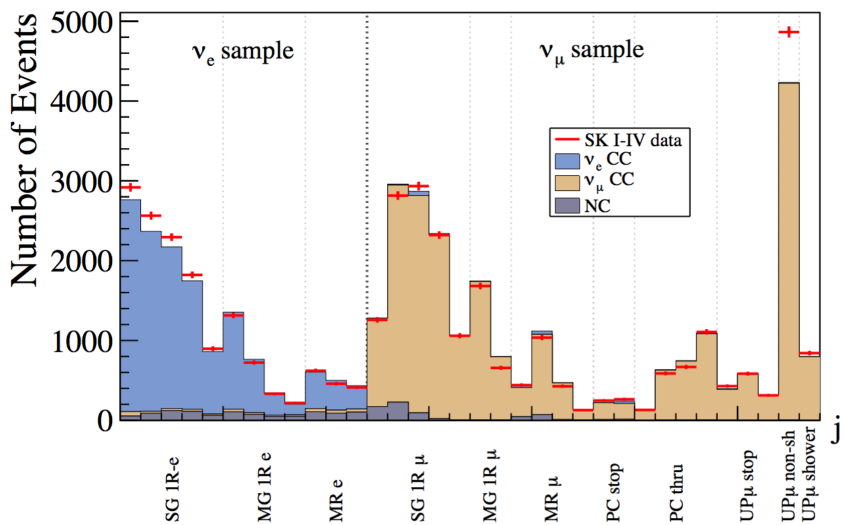
Phase	Period	# of PMTs
SK-I	1996.4 ~ 2001.7	11146 (40%)
SK-II	2002.10 ~ 2005.10	5182 (20%)
SK-III	2006.7 ~ 2008.8	11129 (40%)
SK-IV	2008.9 ~	

Data Sample, Neutrino Energy

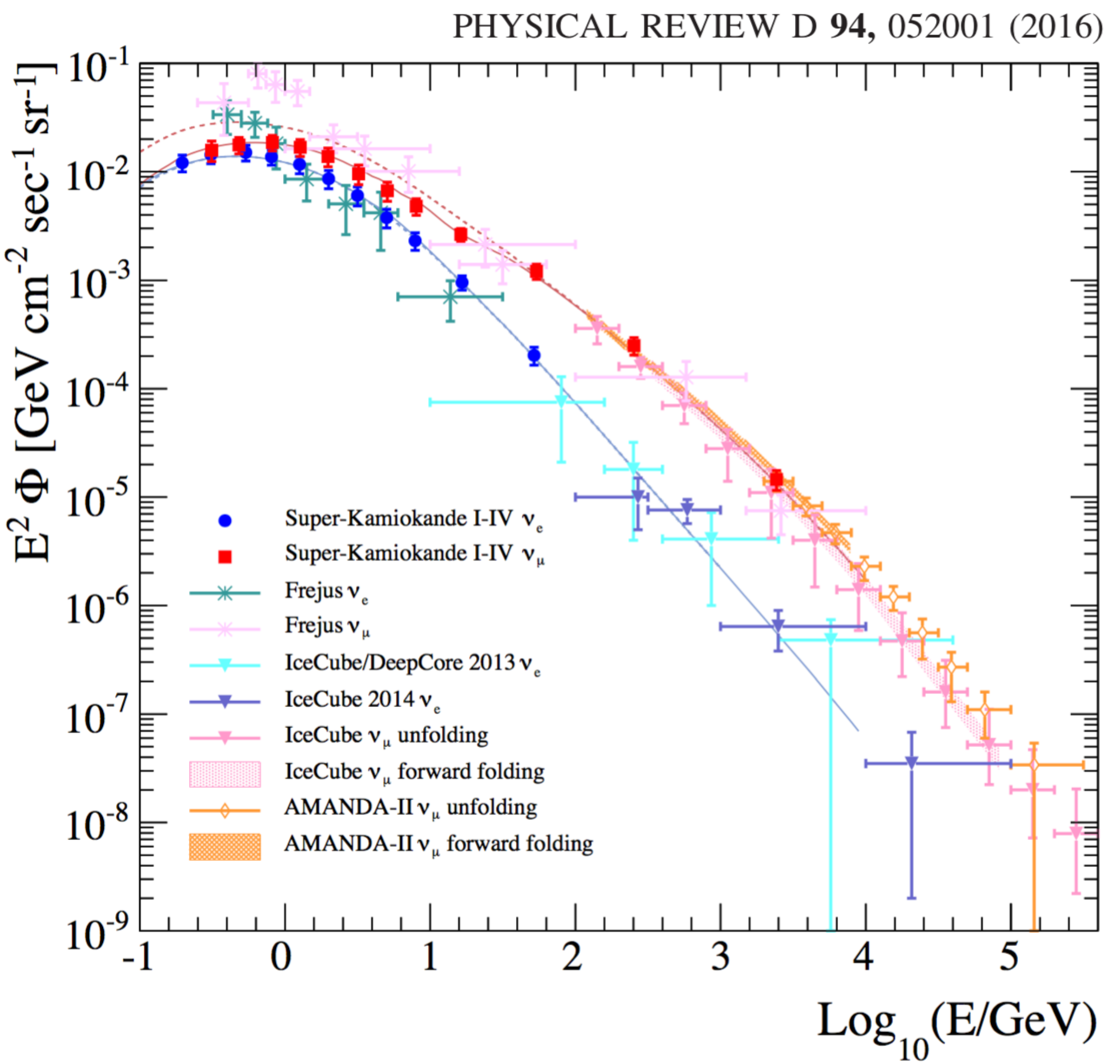




- Three event topologies: FC, PC, UPμ
- Covers from sub-GeV up to 100 GeV (10 TeV) for ν_e (ν_μ)
- Provide high purity ν_e and ν_μ sample thanks to excellent particle identification and NC background abilities

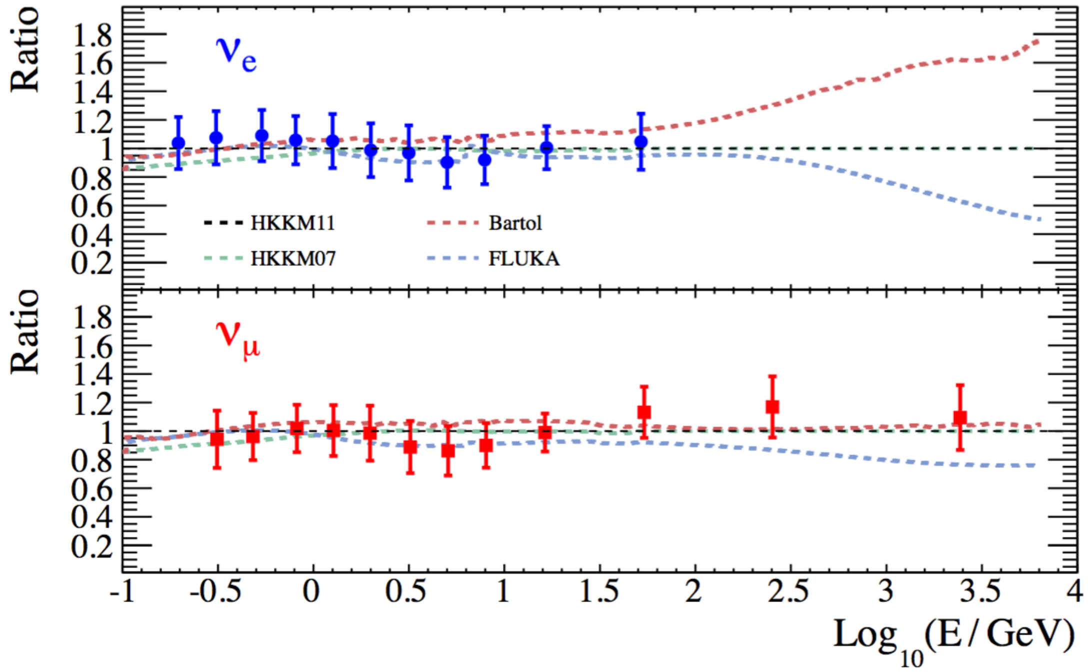


Super-K Flux Measurement

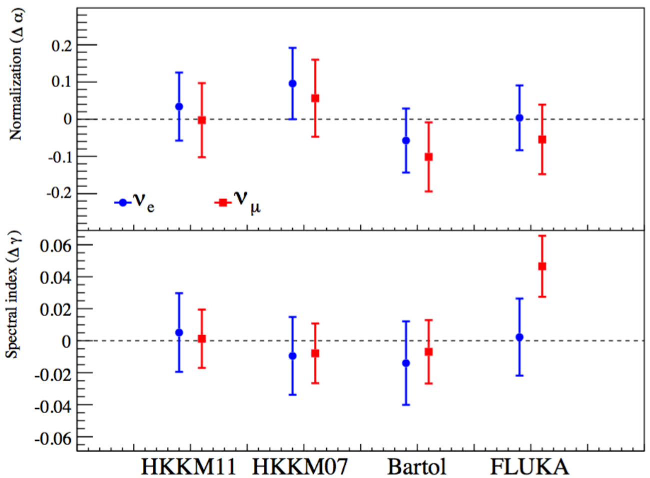


- Precedent result by Frejus in 1995
  - caveat: larger flux expected at Frejus site due to lower rigidity cutoff
- Super-K improved accuracy and extend to lower and higher energies
- Well agree with flux prediction with consideration of oscillation effect
- Overlap with AMANDA, ANTARES, IceCube regions

Comparison with Flux Predictions



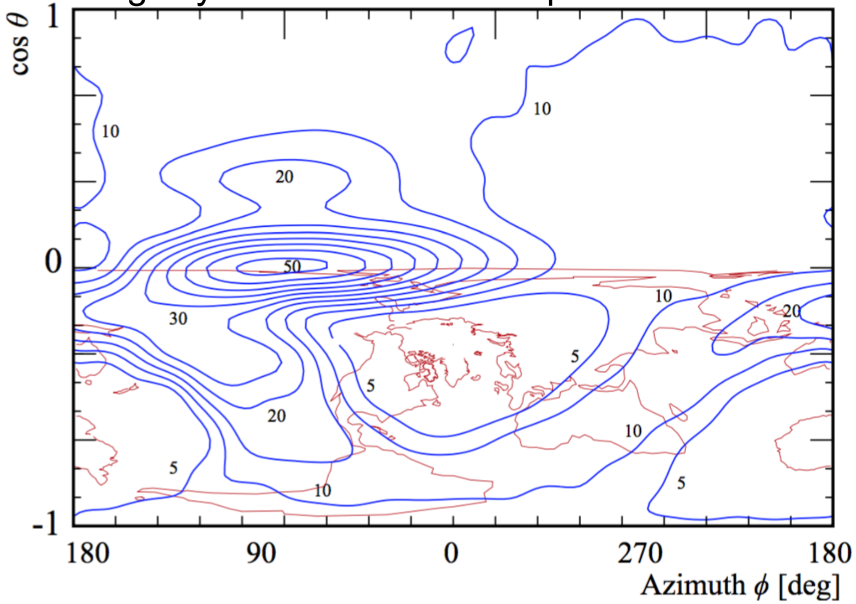
- Test agreement with flux predictions by χ^2 test
  - HKKM, Bartol, Fluka
- Also tested by changing normalization and spectral index
- Agree with data within estimated uncertainties



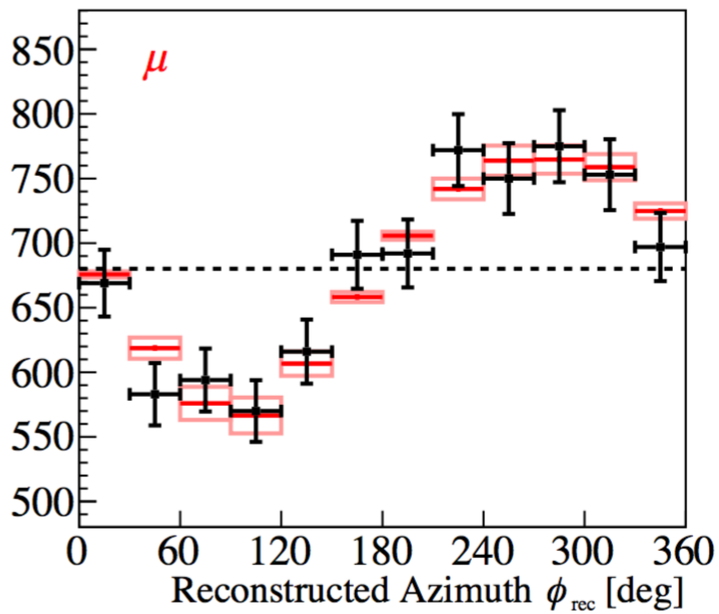
	χ^2		
Flux model	ν_e and ν_μ	ν_e only	ν_μ only
HKKM11 [21]	21.8	4.9	10.3
HKKM07 [20]	22.2	6.2	10.0
Bartol [23]	30.7	7.1	14.7
FLUKA [22]	25.6	5.4	11.4
(DOF	23	11	12)

Geomagnetic Effect

Rigidity cutoff seen from Super-K

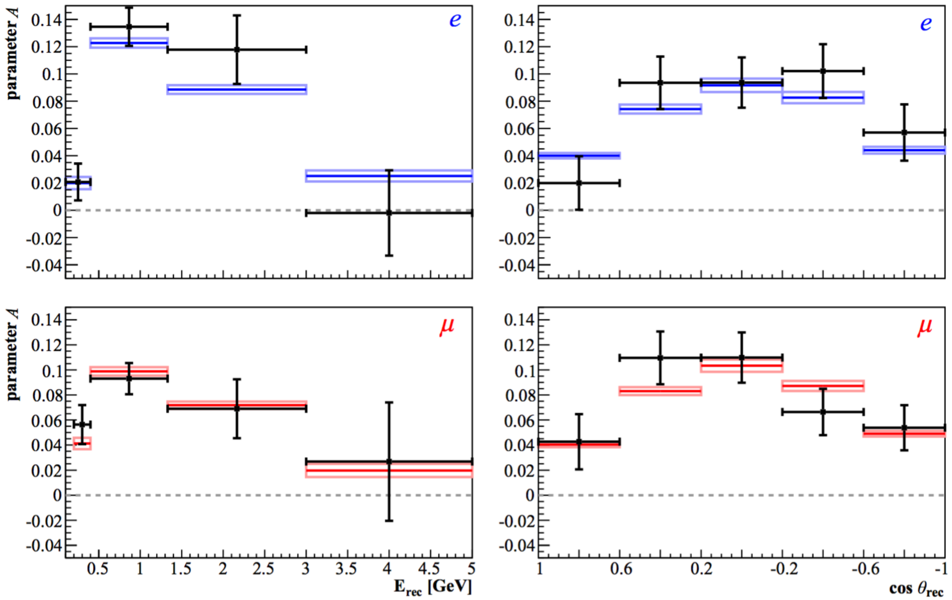


- "East-west effect" due to geomagnetic field is well-known in CR
- Geomagnetic field effect is implemented in detail in flux simulation: rigidity cutoff depends on position and direction at Earth's surface



- Observed clear east-west asymmetry for 6.0σ (8.0σ) for ν_μ (ν_e)
- Study on geo-magnetic effect in detail

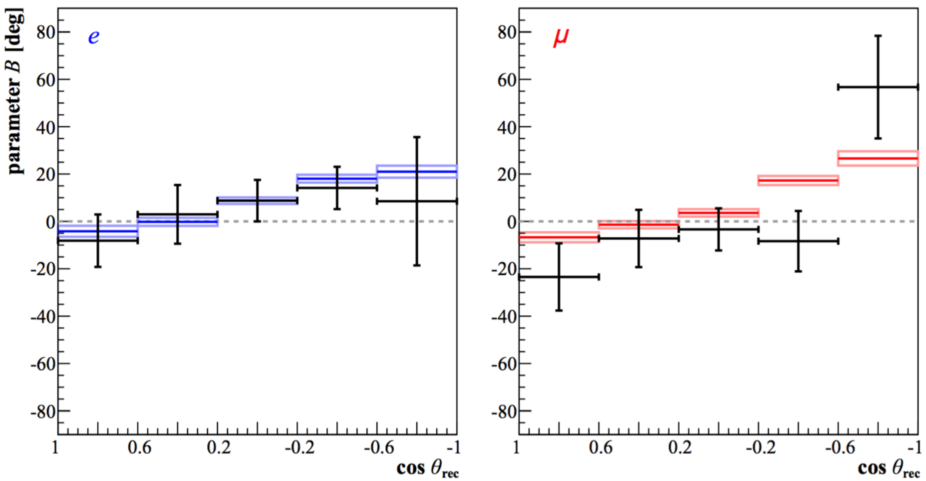
Energy and Zenith Dependence



- Introduce "east-west" asymmetry parameter:

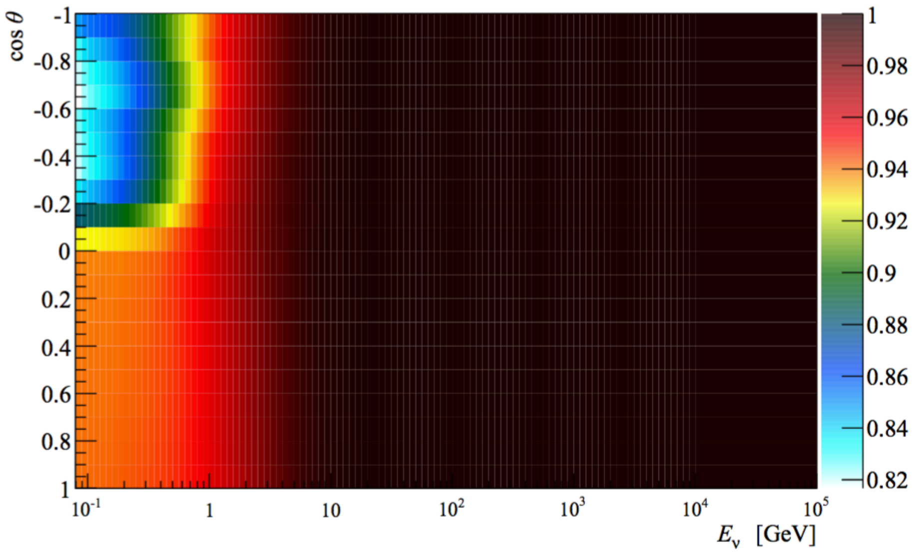
$$A = \frac{n_{\mathrm{east}} - n_{\mathrm{west}}}{n_{\mathrm{east}} + n_{\mathrm{west}}}$$

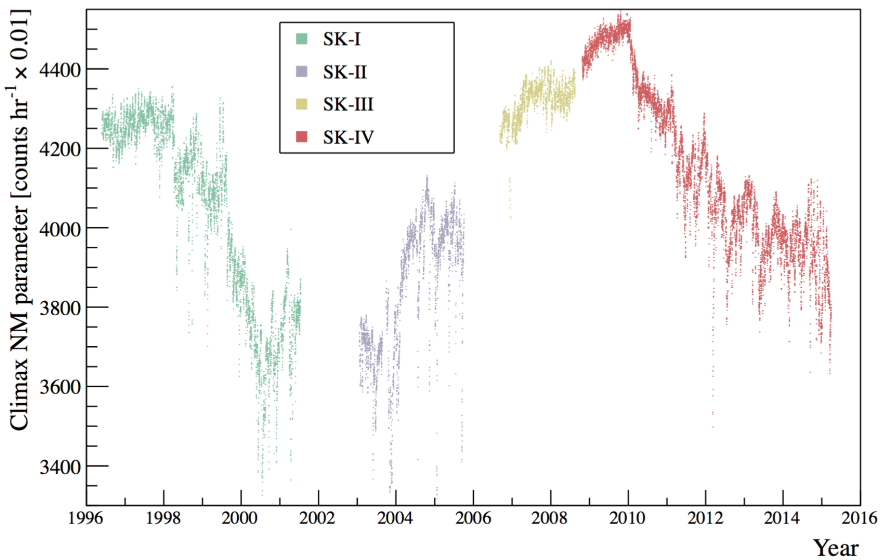
- Larger asymmetries in horizontal direction around 1 GeV
- Agrees with prediction



- Phase shift in dipole structure of magnetic field:
  $k_2 \times \sin(\phi + B) + k_1$
  - Zenith dependence is seen with 2.2σ
  - Consistent

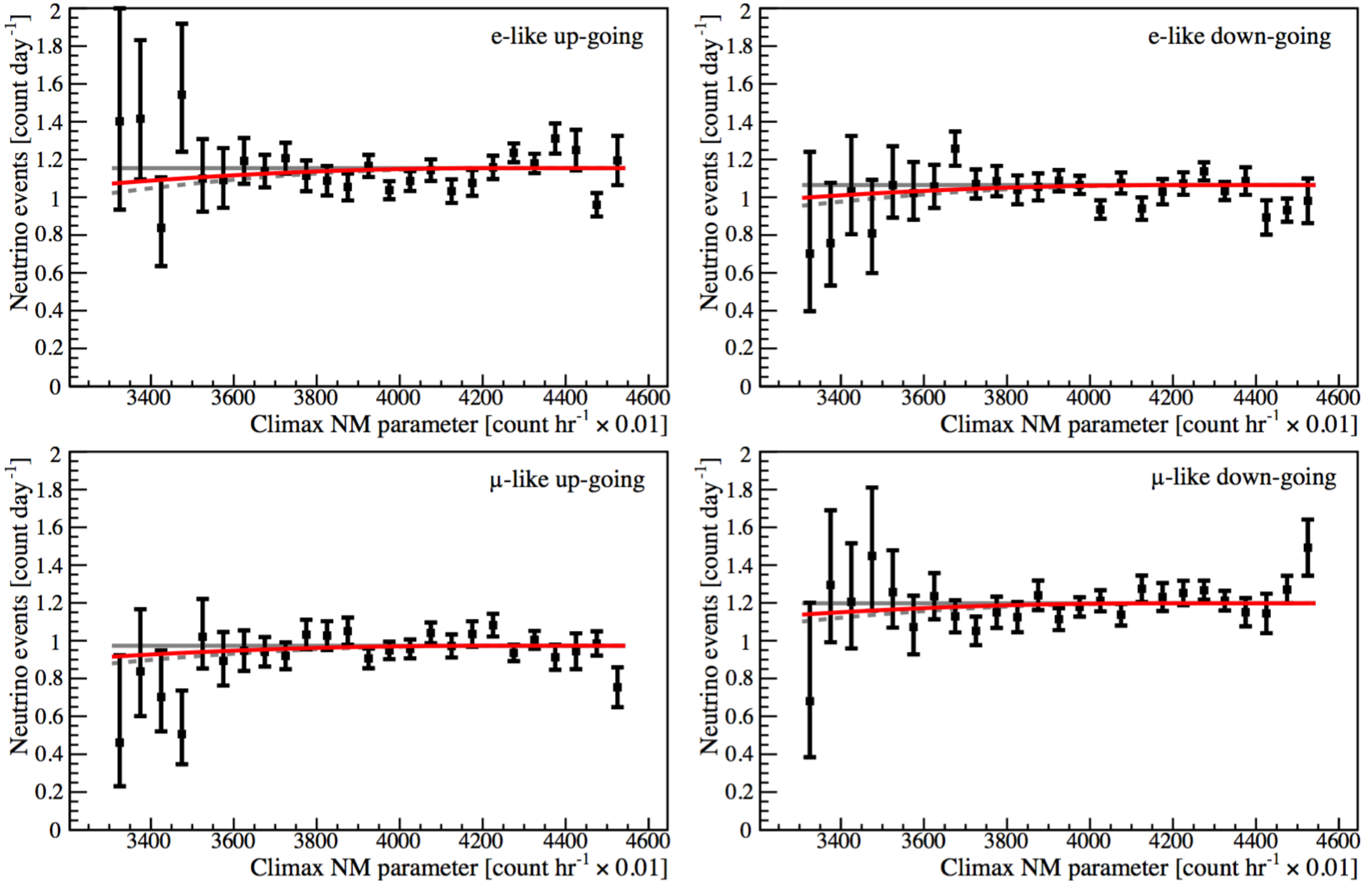
Modulation Effect of Solar Activity





- Atmospheric neutrino flux will be affected by solar activity below 1 GeV
    - Solar wind scatter off CR
- Larger effect for upward direction coming from polar regions, where solar effect is larger
- SuperK data covers more than one and half solar cycles
- Test correlation with solar modulation by detection rate change

Correlation with Solar Modulation



Best fit
Prediction (α=1)
No correlation (α=0)

- Correlations between sub-GeV event rate vs neutron monitor are investigated
- Effect is small and difficult to see:
    - directional information is lost by neutrino scattering
- Estimate correlation by one parameter fitting (α)
- Best fit :
  α = 0.62 ± 0.58 (1.06 σ)

Summary

- Review atmospheric neutrino flux measurements
- Wide range of neutrino energies (0.1GeV~PeV) covered by several experiments :
  - Frejus, Super-K, AMANDA, ANTARES, IceCube/DeepCore
- Tested flux prediction in a various aspect:
  - energy spectrum (ν_e and ν_μ)
  - geomagnetic field effect
  - seasonal variation
- So far no significant difference seen between flux measurements and predictions within current estimated uncertainties

Prospect and Discussion

- Accurate flux prediction will be available with improved CR flux input and hadron interaction model
- Reduce systematic error by better understanding of neutrino cross section
  - Input from neutrino beam measurement
- Individual neutrino and anti-neutrino flux measurements
  - possible ν / $\bar{\nu}$ separation in Super-K Gd by recoil neutron tagging below O(1) GeV
- Demand from other communities for flux below sub-GeV (E<0.1GeV)
  - future direct DM sensitivity reaches to “atmospheric floor”
  - supernova relic neutrino
- Detection of “prompt” flux component is open question
- Future detectors will bring better flux understanding
  - Hyper-Kamiokande, DUNE, IceCube-Gen2, PINGU, KM3Net, …

Thank you