

# Atmospheric Neutrinos for Non-Specialists



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Boston University

**Multi-messenger Tomography of Earth Workshop  
MMTE22, part of NUFACt 2022**

July 30, 2022

# Quarks

<i>u</i>	<i>c</i>	<i>t</i>
up	charm	top

<i>d</i>	<i>s</i>	<i>b</i>
down	strange	bottom

<i>e</i>	$\mu$	$\tau$
electron	muon	tau

$\nu_e$	$\nu_\mu$	$\nu_\tau$
electron neutrino	muon neutrino	tau neutrino

# Leptons

# Forces

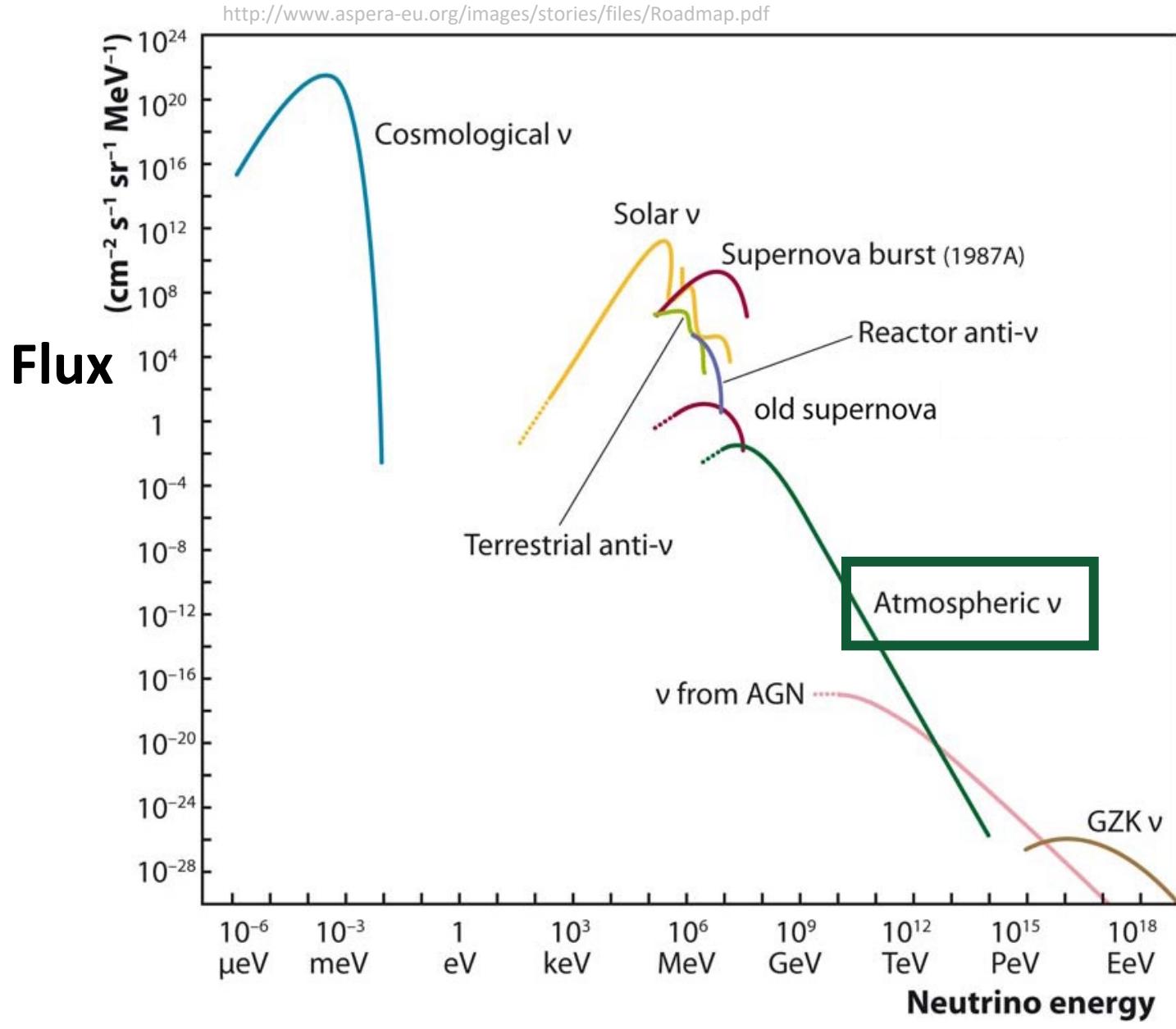
$Z$	$\gamma$
Z boson	photon

$W$	$g$
W boson	gluon

H  
Higgs  
boson

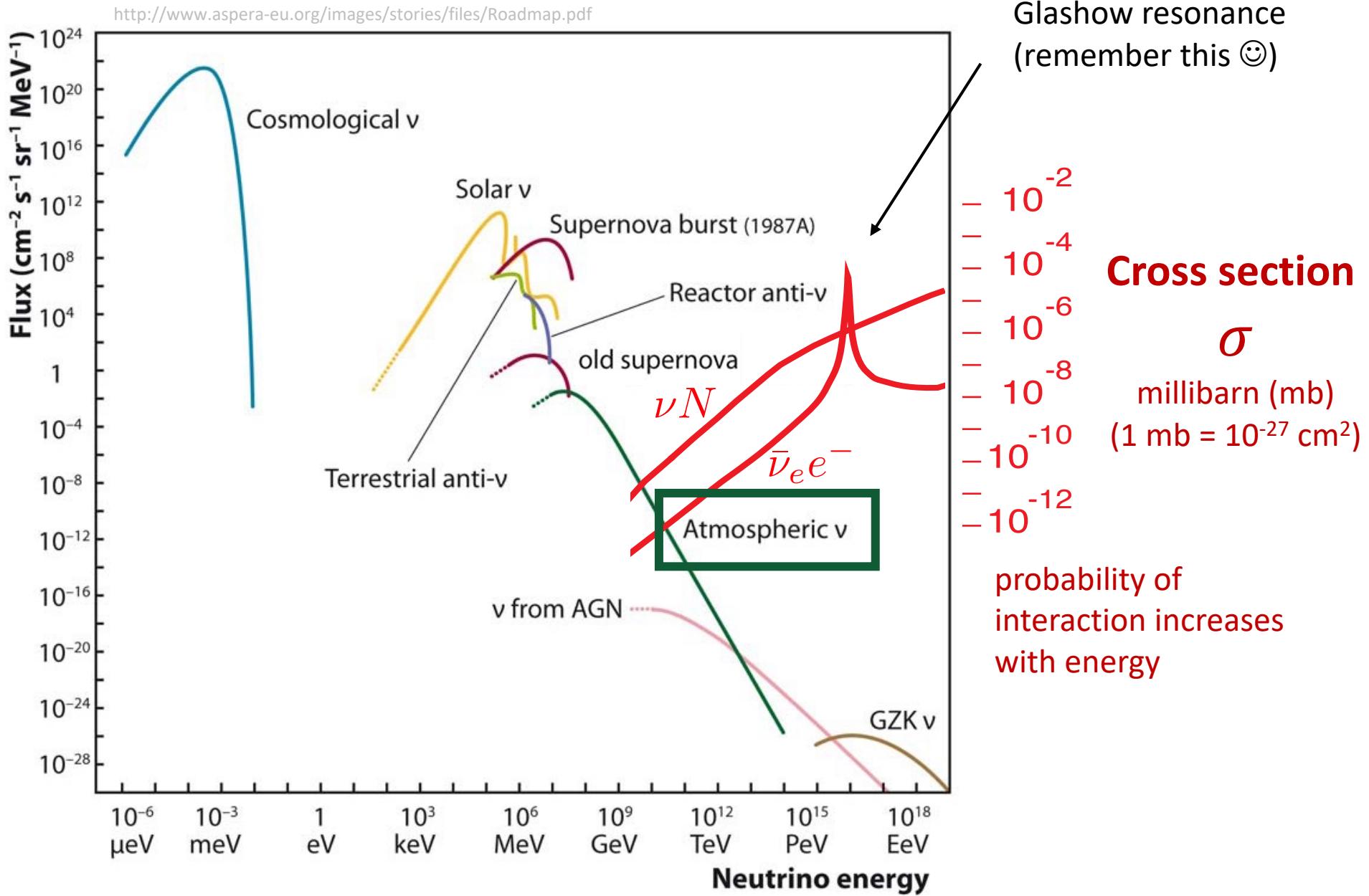
# Sources of neutrinos



100 MeV and above – steeply falling spectrum



# Neutrino interaction



# Neutrino interaction and detection: $\nu_l + N \rightarrow l + X$

(Mostly) turning the neutrino into the lepton ( $l$ ) of the **same flavor** ( $e$  or  $\mu$  or  $\tau$ ) --- “charged current”

When interacting with a nucleon ( $N$ ), the nucleon recoils, often accompanied by more particles ( $X$ )



Unless we have a neutrino beam or know the location of the source,  
we infer the neutrino direction from the final state particles using conservation of momentum.

Below a few GeV the **pointing resolution** between the lepton and  $\nu$  direction is poor: 10's of degrees.  
At the highest energies, 10 GeV and above, the neutrino direction is well determined.

At the highest energies, **more hadronic particles** are in accompaniment.

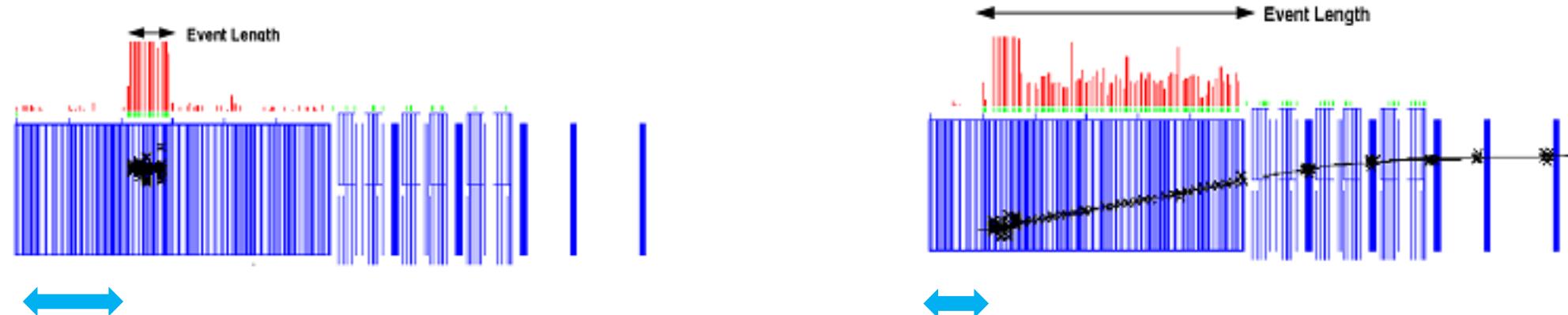
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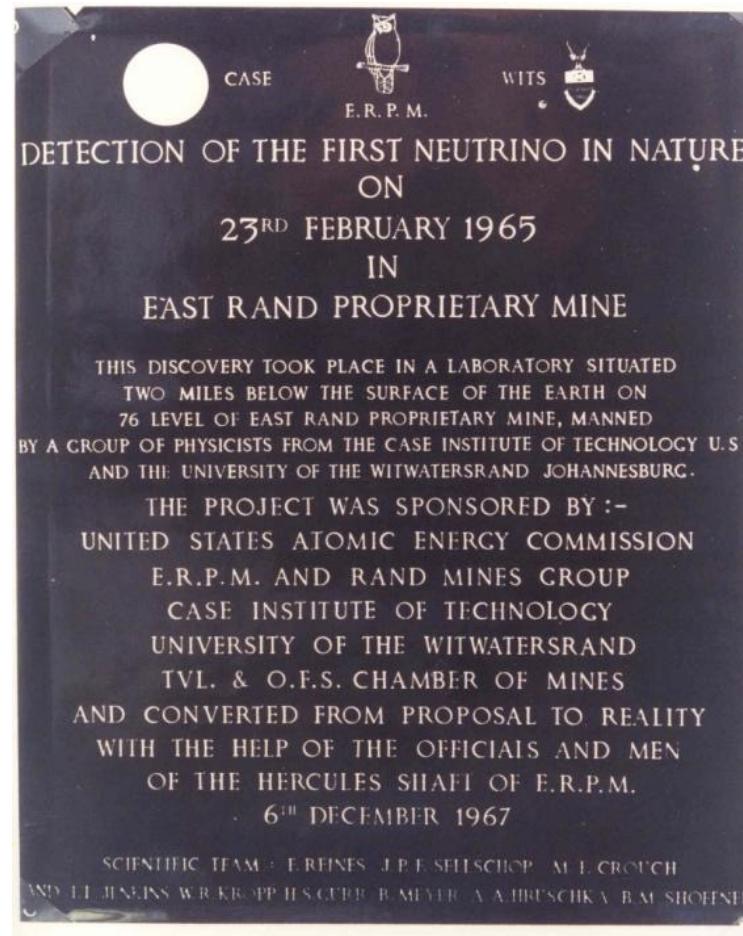
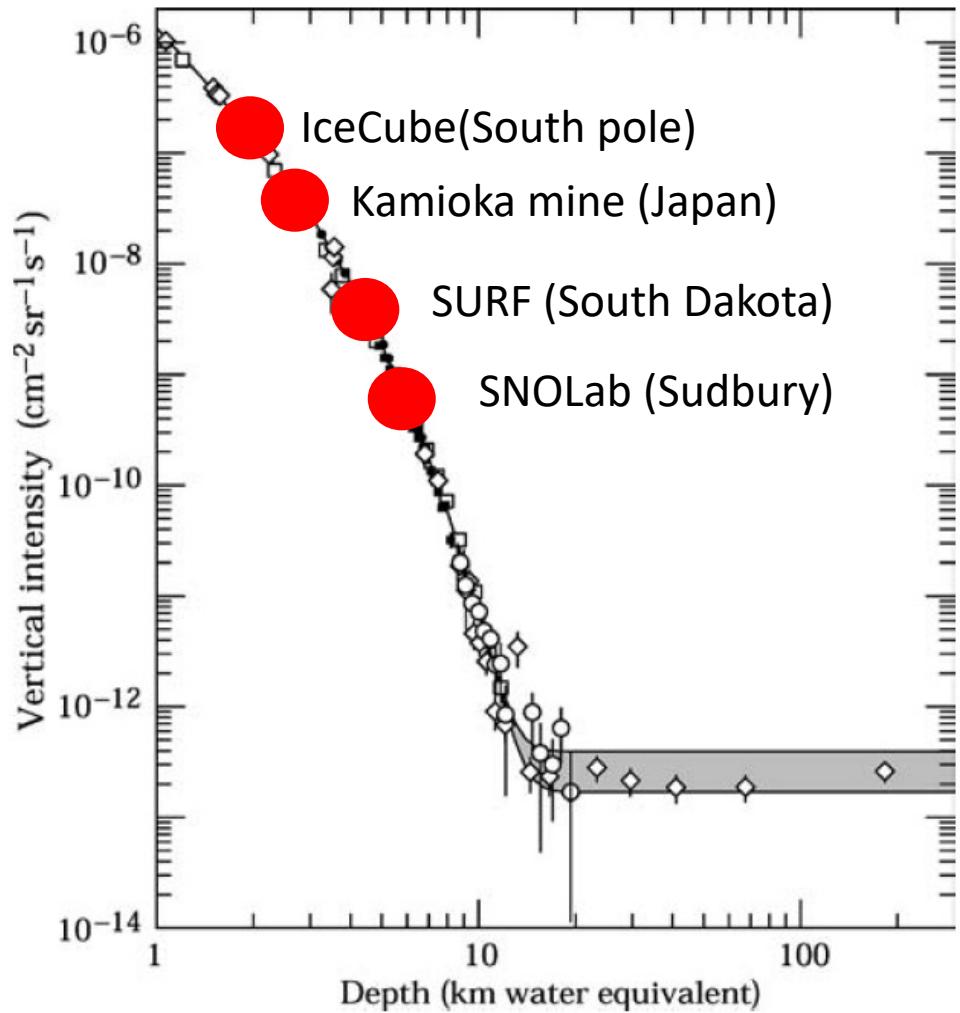


Example event displays from a beam neutrino experiment (NuTeV at Fermilab)



The key point is **here** --- no record of a particle entering, the neutrino appears in the middle of the detector

# Cosmic ray muon intensity



## Neutrino interaction and detection:

core of Earth

$$\rho = 13 \text{ g/cm}^3$$

$$A_{nucleon} = 1 \text{ g/mol}$$

$$n = N_A \times \rho = 8 \times 10^{24} \text{ nucleon/cm}^3$$

$$\sigma(1 \text{ GeV}) \sim 10^{-11} \text{ mb} = 10^{-38} \text{ cm}^2$$

mean free path

$$\lambda = \frac{1}{n\sigma} \sim 100 \times 10^9 \text{ m}$$

neutrinos pass readily  
through matter!

atmospheric  $\nu$  flux

$$\Phi \sim 1 \text{ cm}^{-2}\text{s}^{-1}$$

$$N(1 \text{ kton}) = 6 \times 10^{32} \text{ nucleons}$$

$$\text{rate} = \Phi \sigma N \sim 1 \text{ interaction/day}$$

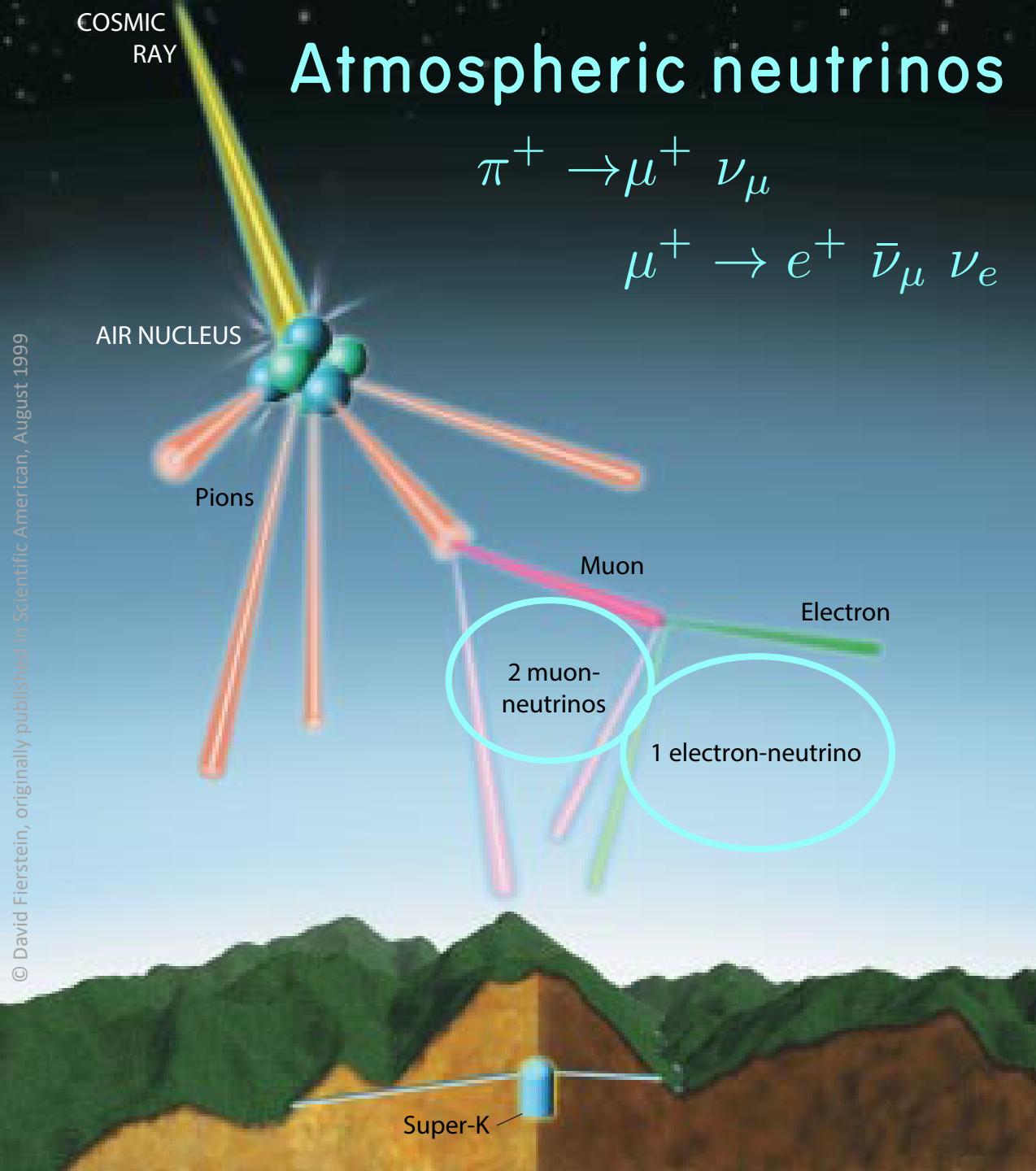
kiloton scale detector mass  
(or larger) is needed

# Neutrino Oscillation

Difficult!

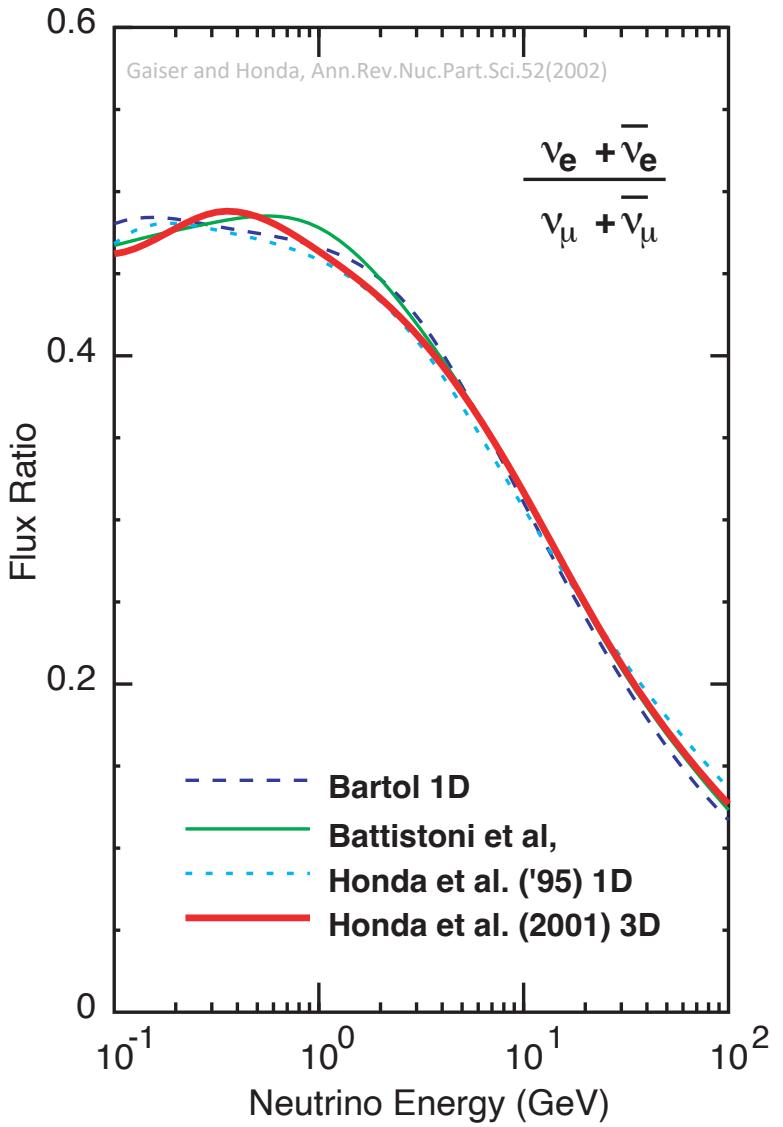
# Neutrino Absorption

Has been demonstrated!

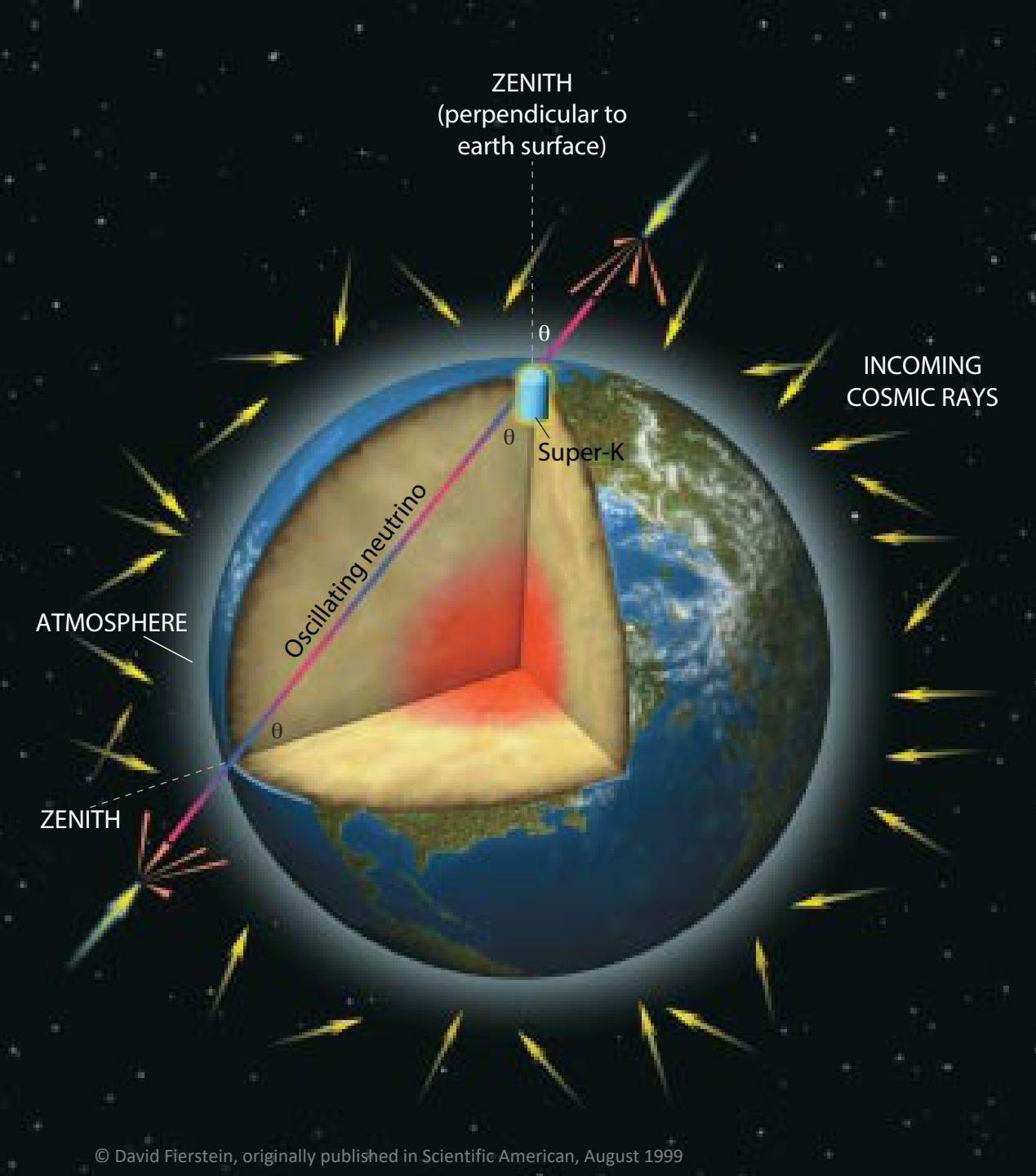


$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

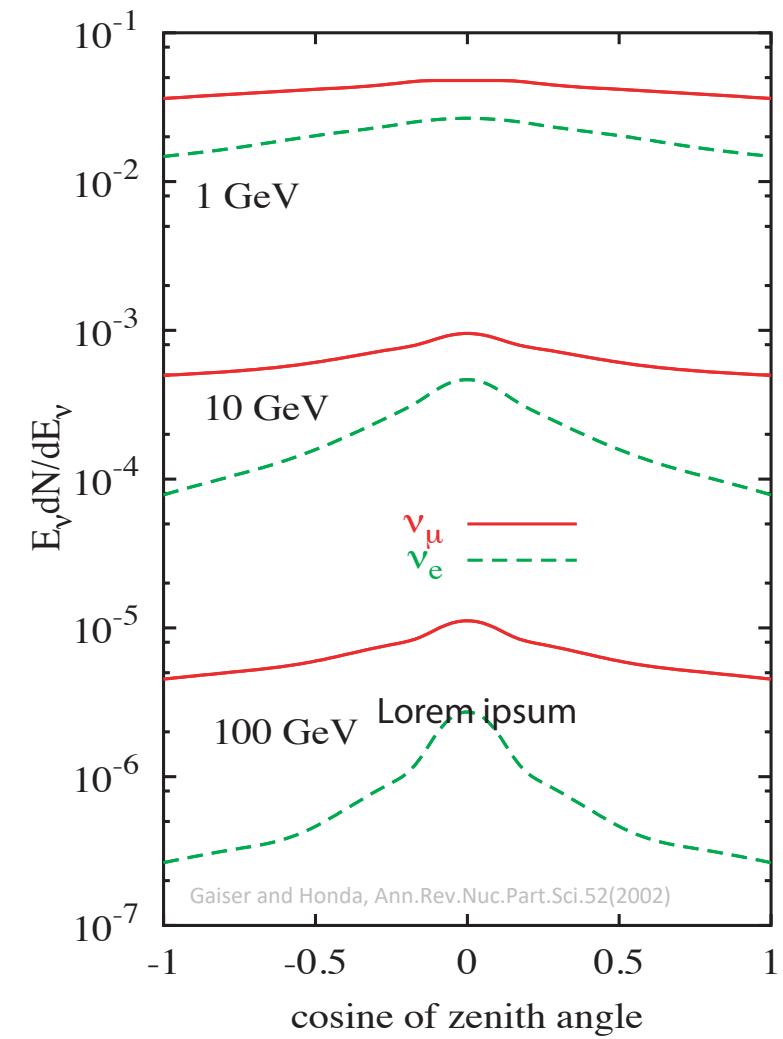
$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

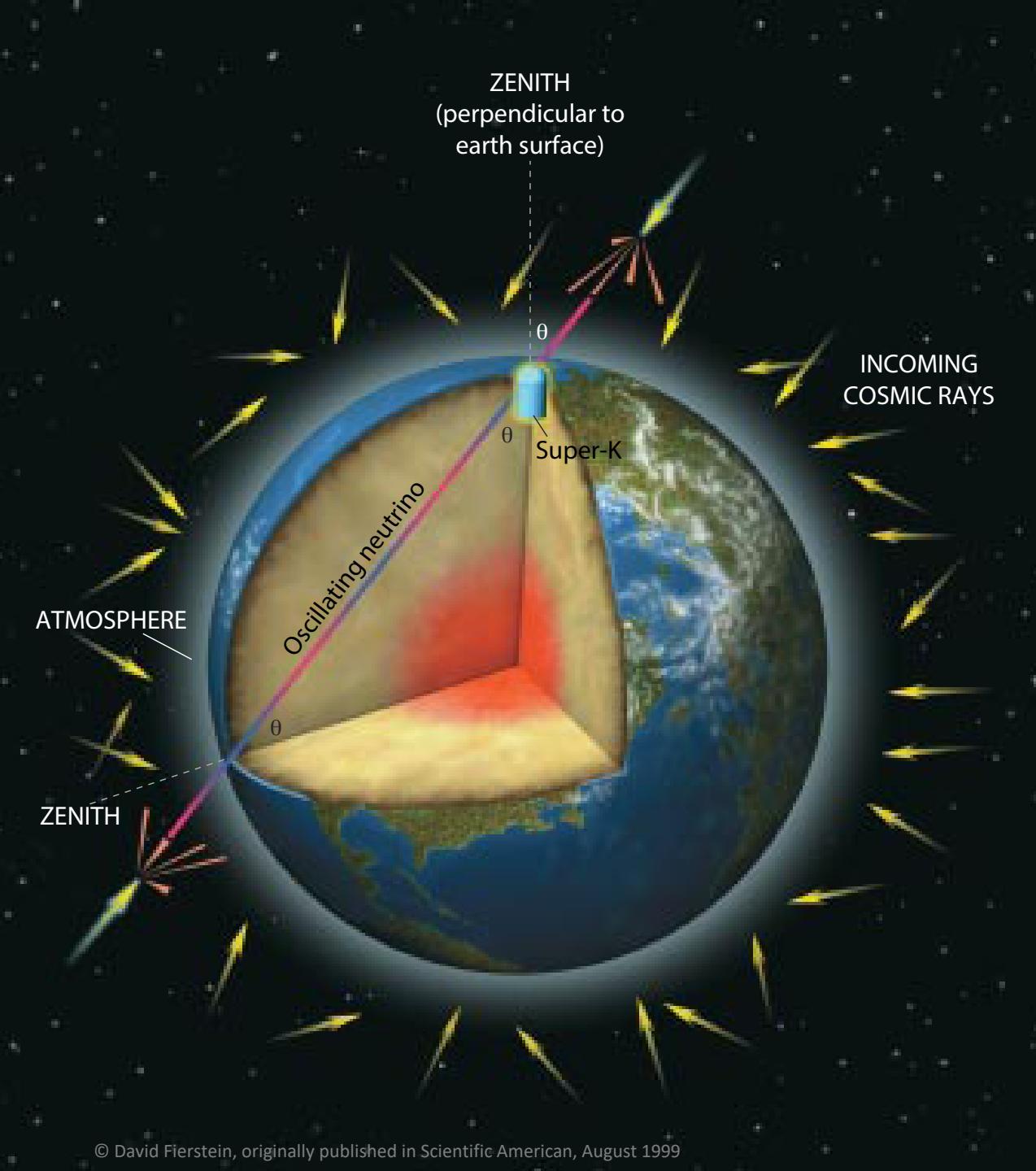


Relative flux of muon/electron neutrinos is well predicted. Expect 2:1 at low energy.

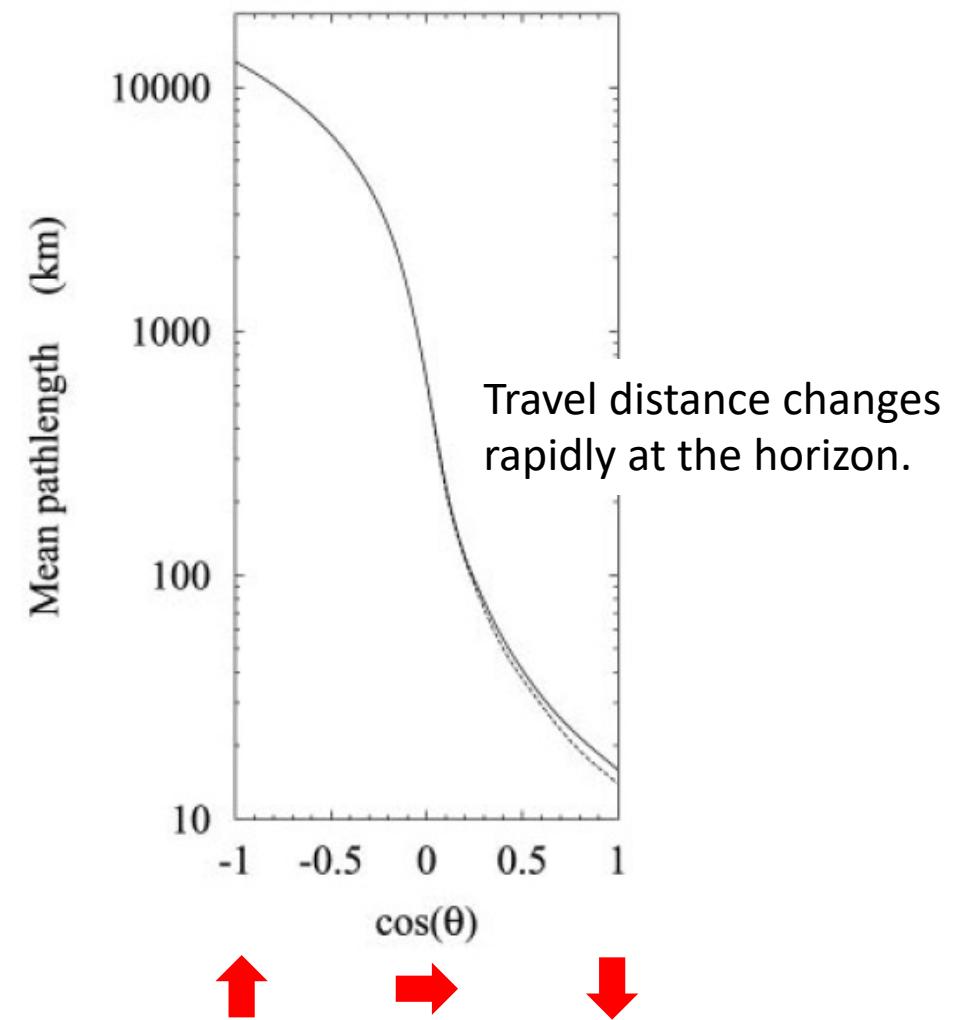


Flux of atmospheric neutrinos is  
up-down symmetric



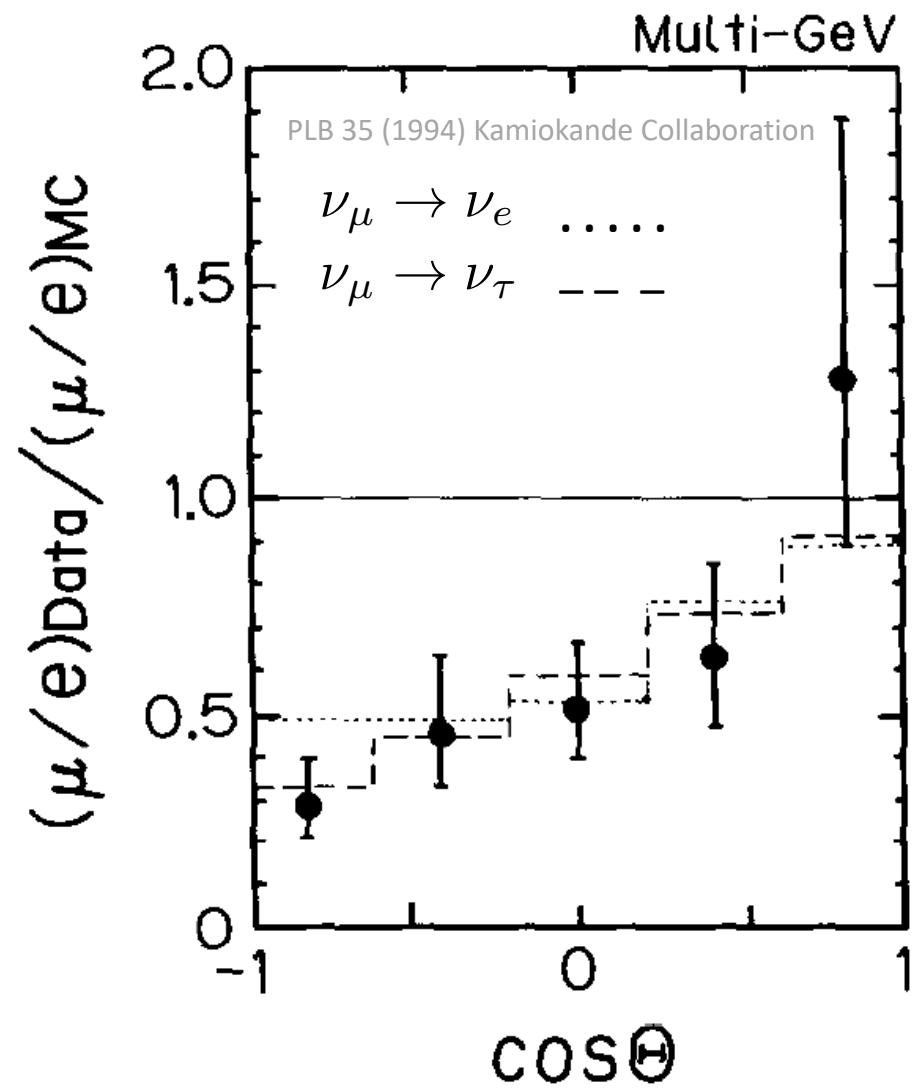
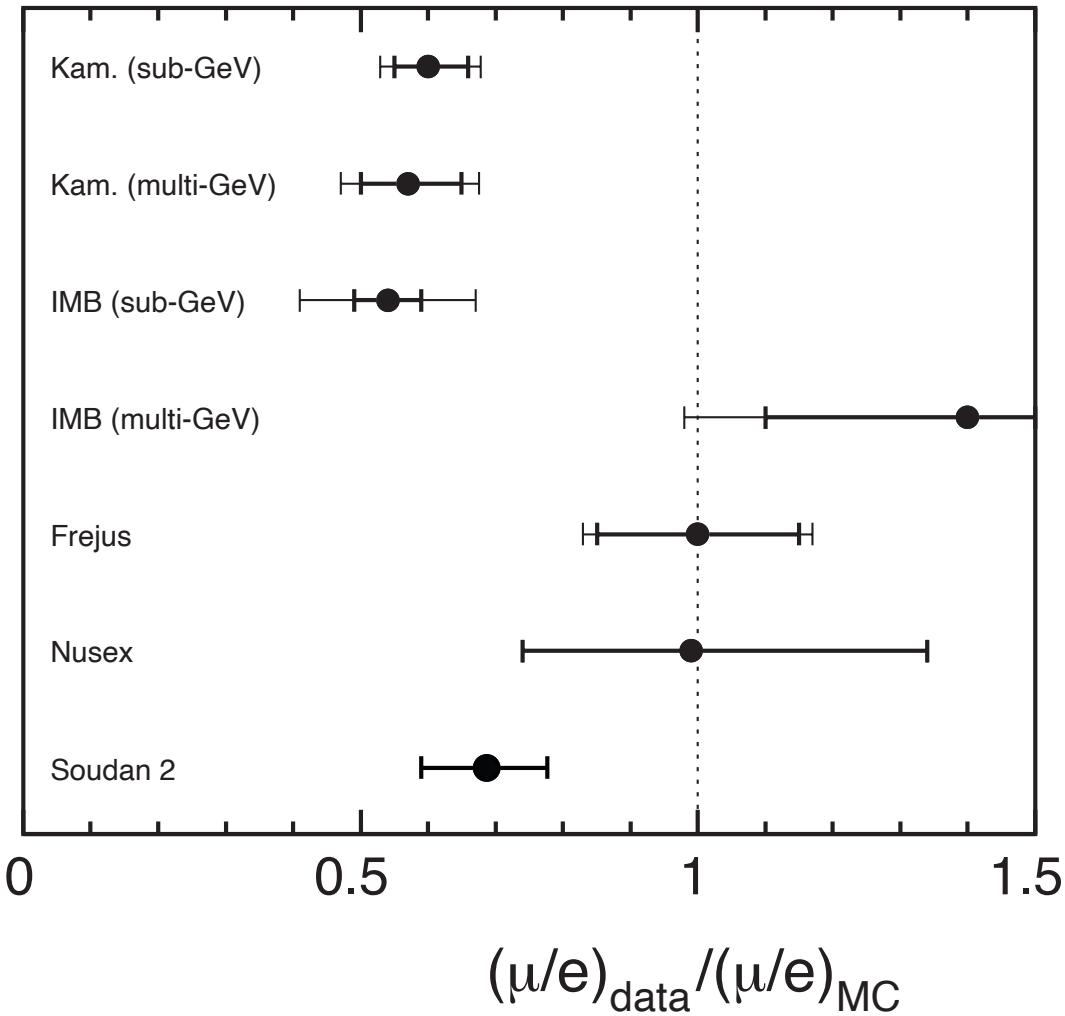


Atmospheric neutrinos travel  
15 km to 13000 km.

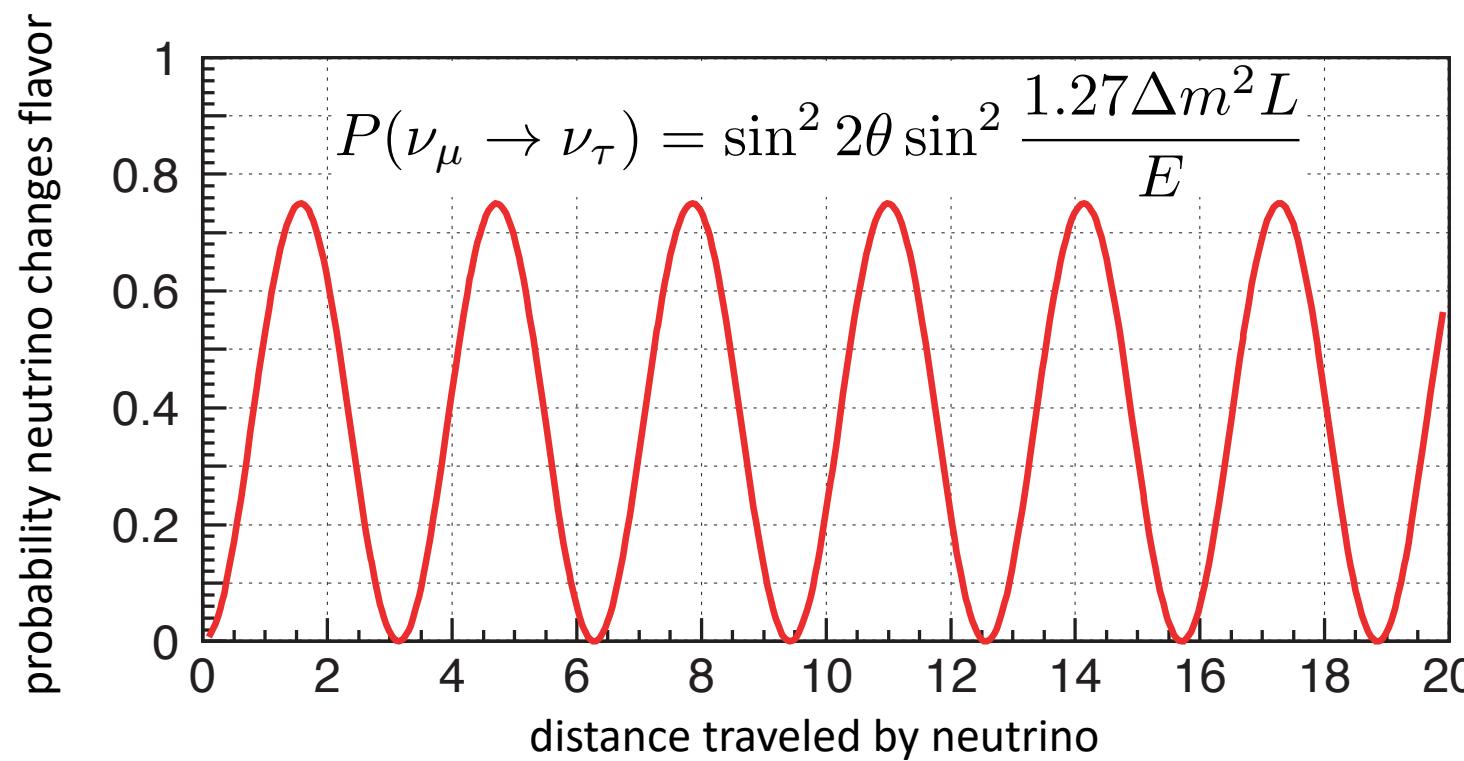
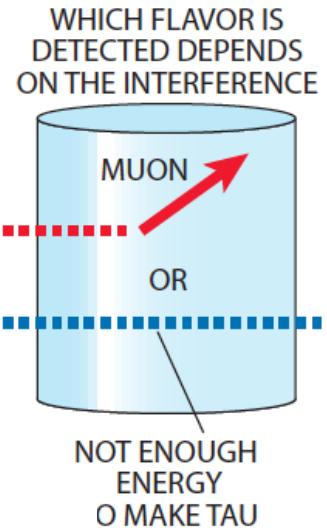
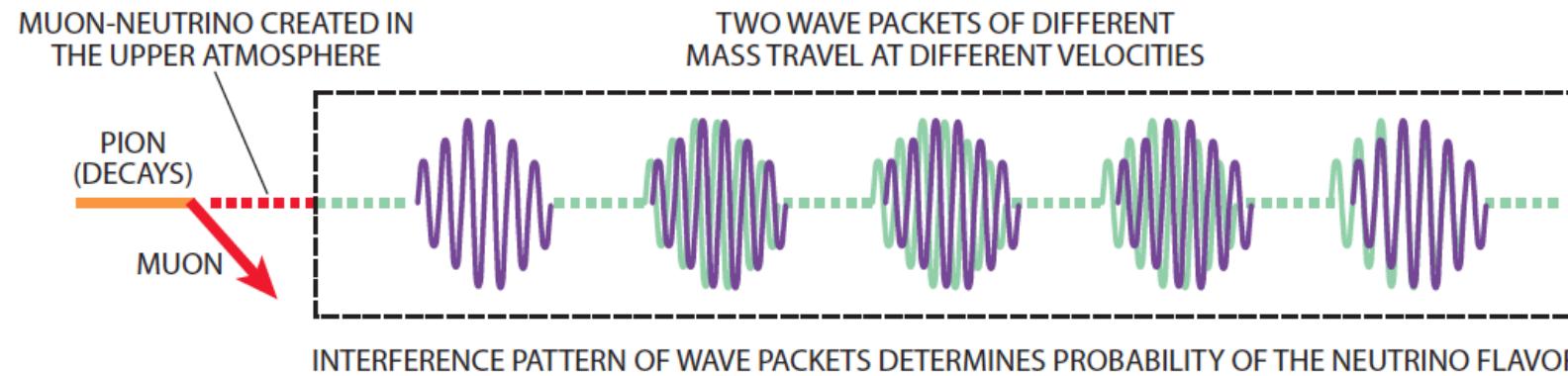


note definition of zenith angle

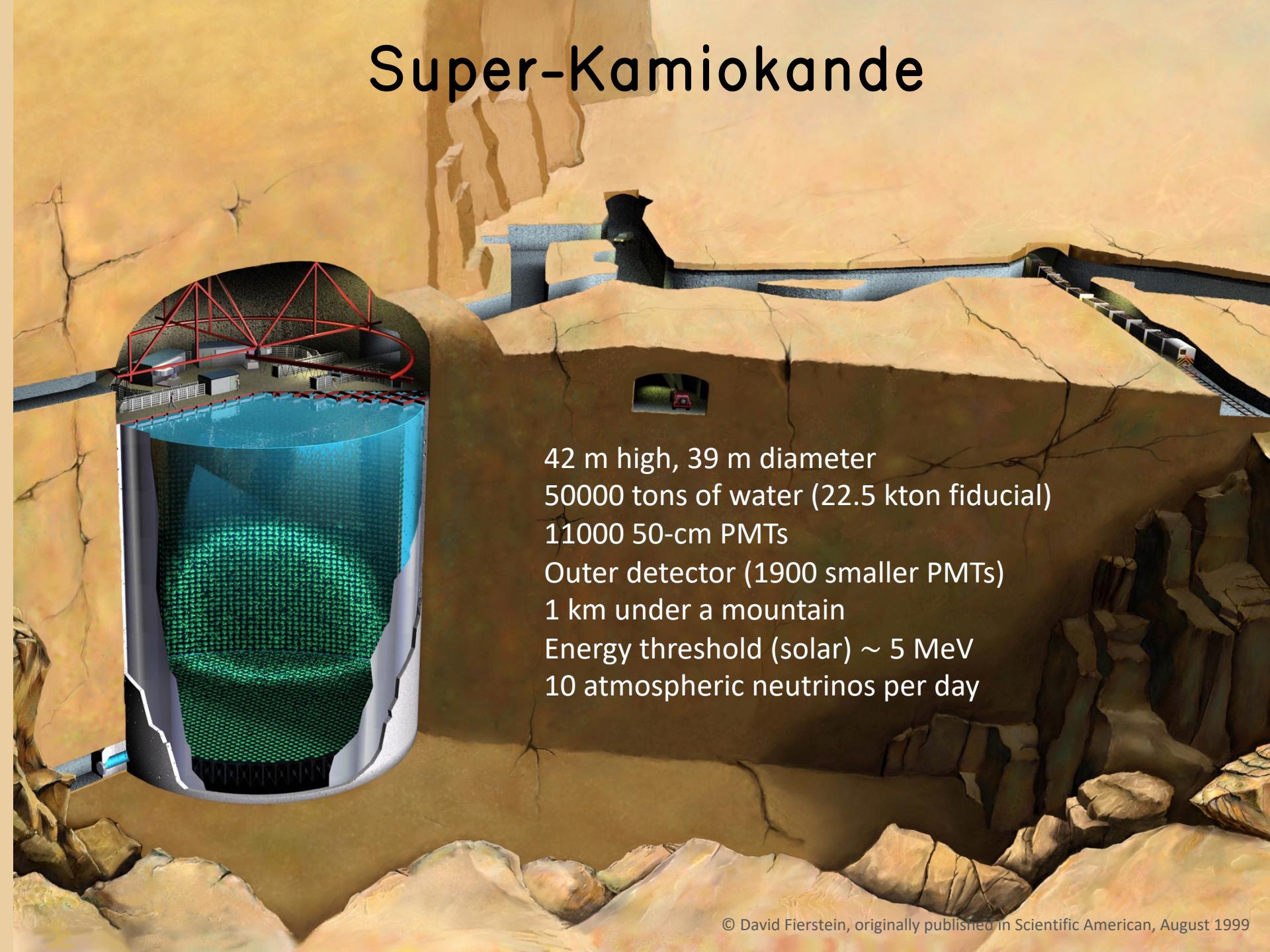
# Atmospheric neutrino anomaly (circa 1996)



# Neutrino Oscillation



# Super-Kamiokande



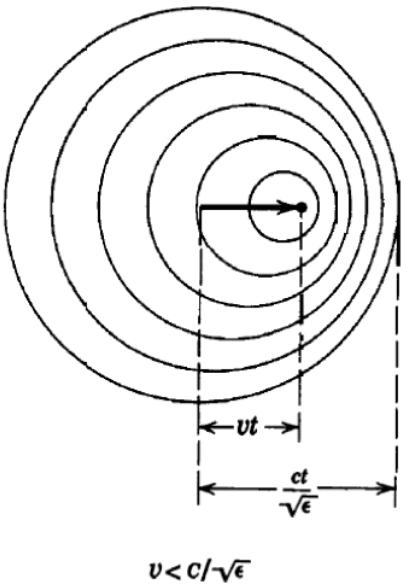
42 m high, 39 m diameter  
50000 tons of water (22.5 kton fiducial)  
11000 50-cm PMTs  
Outer detector (1900 smaller PMTs)  
1 km under a mountain  
Energy threshold (solar)  $\sim$  5 MeV  
10 atmospheric neutrinos per day

© David Fierstein, originally published in Scientific American, August 1999

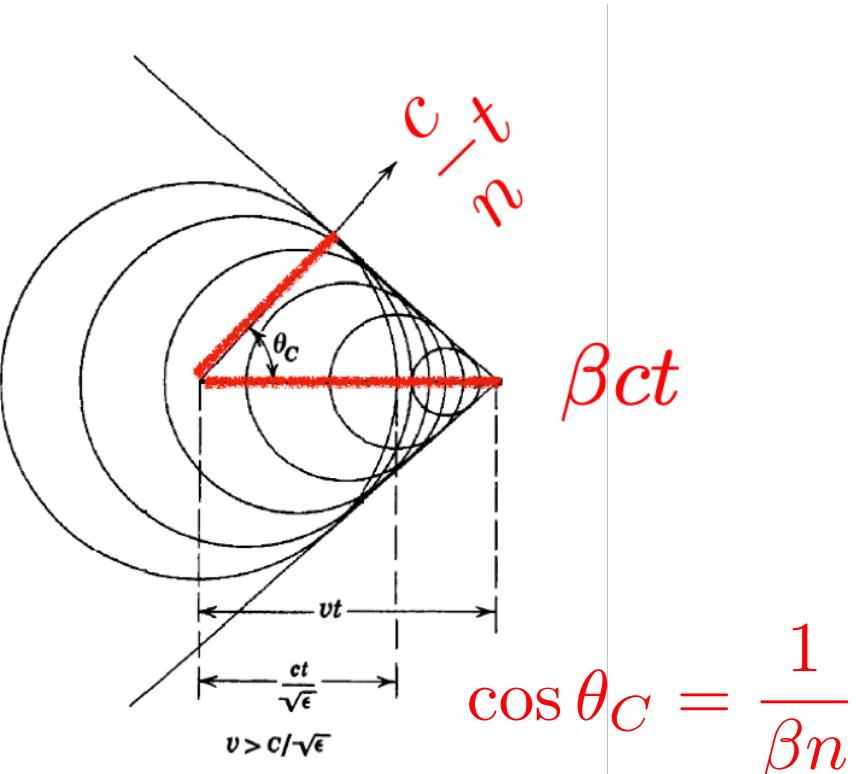


2015 Nobel Prize in Physics  
Super-Kamiokande (atm. nu)  
SNO (solar neutrinos)  
T. Kajita, A. McDonald

# Cherenkov Radiation



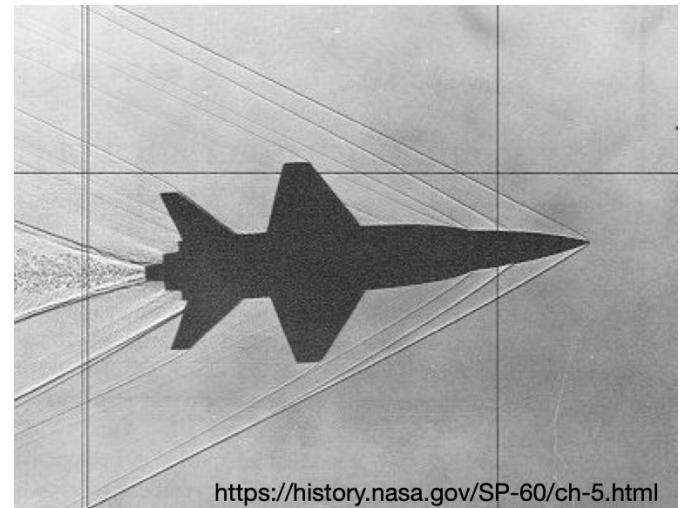
$$v < c/\sqrt{\epsilon}$$



$$\cos \theta_C = \frac{1}{\beta n}$$

**Figure 13.5** Cherenkov radiation. Spherical wavelets of fields of a particle traveling less than and greater than the velocity of light in the medium. For  $v > c/\sqrt{\epsilon}$ , an electromagnetic “shock” wave appears, moving in the direction given by the Cherenkov angle  $\theta_C$ .

J.D. Jackson, Classical Electrodynamics 3e

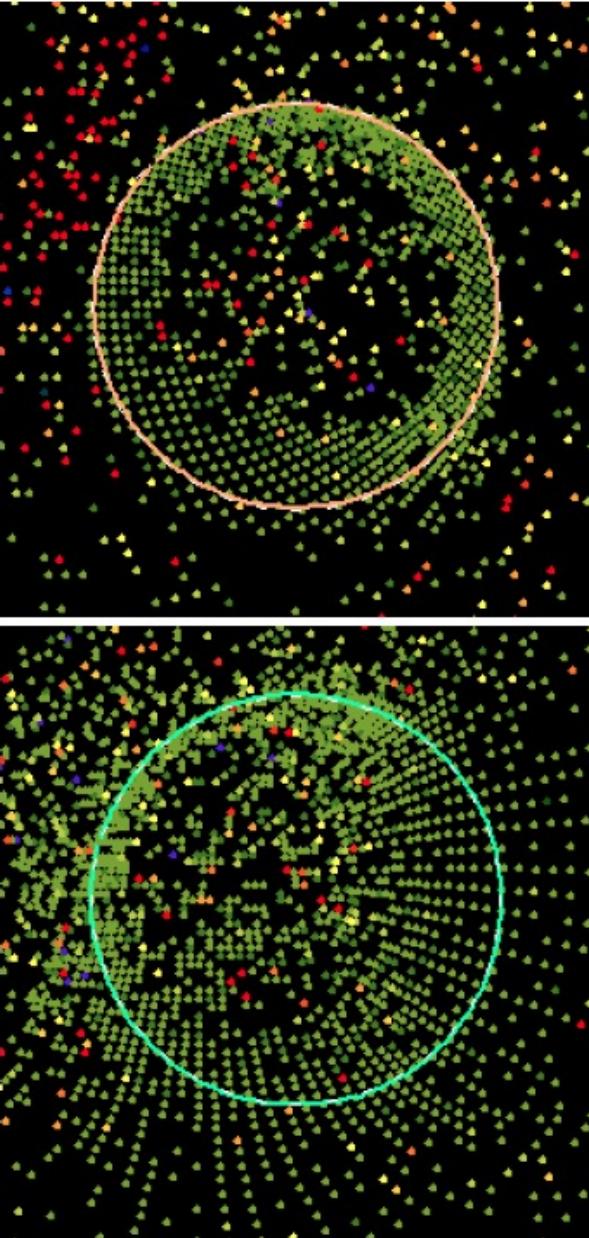
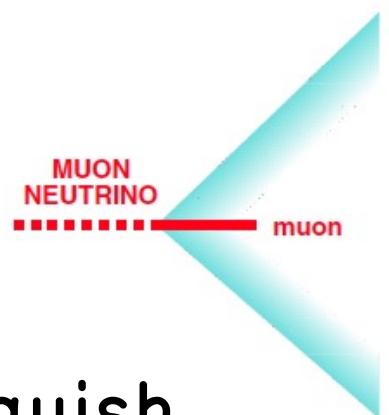


<https://history.nasa.gov/SP-60/ch-5.html>



<http://www.erbe.hu/products-and-services/>

# How to distinguish muon neutrinos from electron neutrinos



Time(ns)

• < 958

● 958- 963

○ 963- 968

○ 968- 973

○ 973- 978

○ 978- 983

○ 983- 988

○ 988- 993

○ 993- 998

○ 998-1003

● 1003-1008

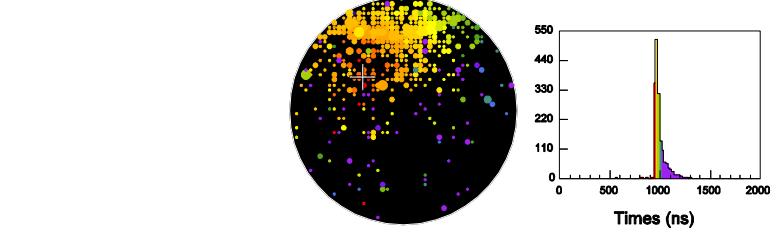
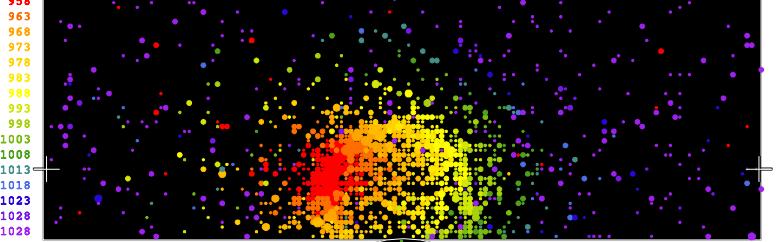
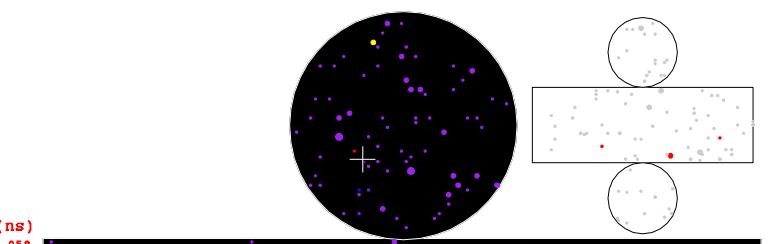
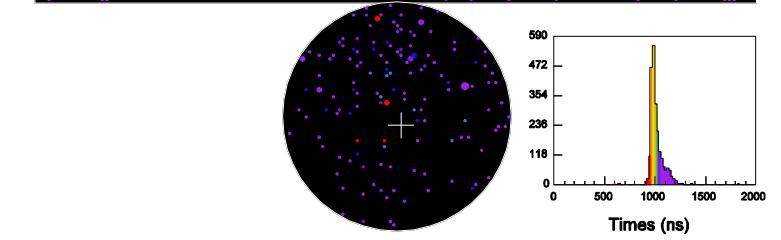
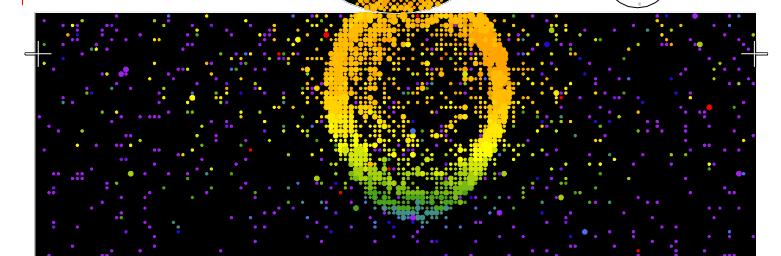
● 1008-1013

● 1013-1018

● 1018-1023

● 1023-1028

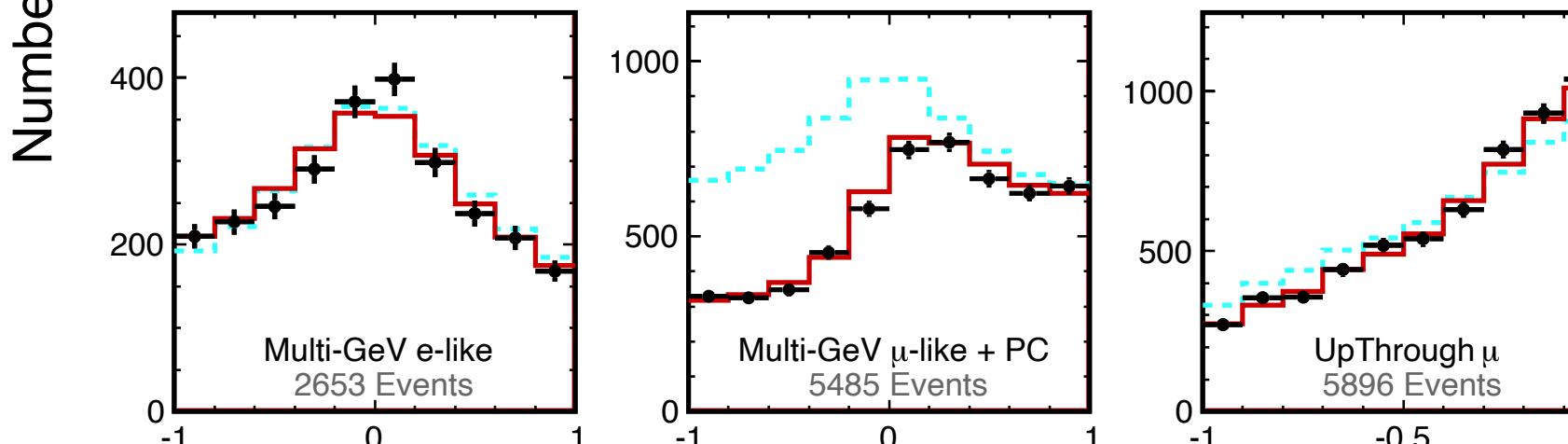
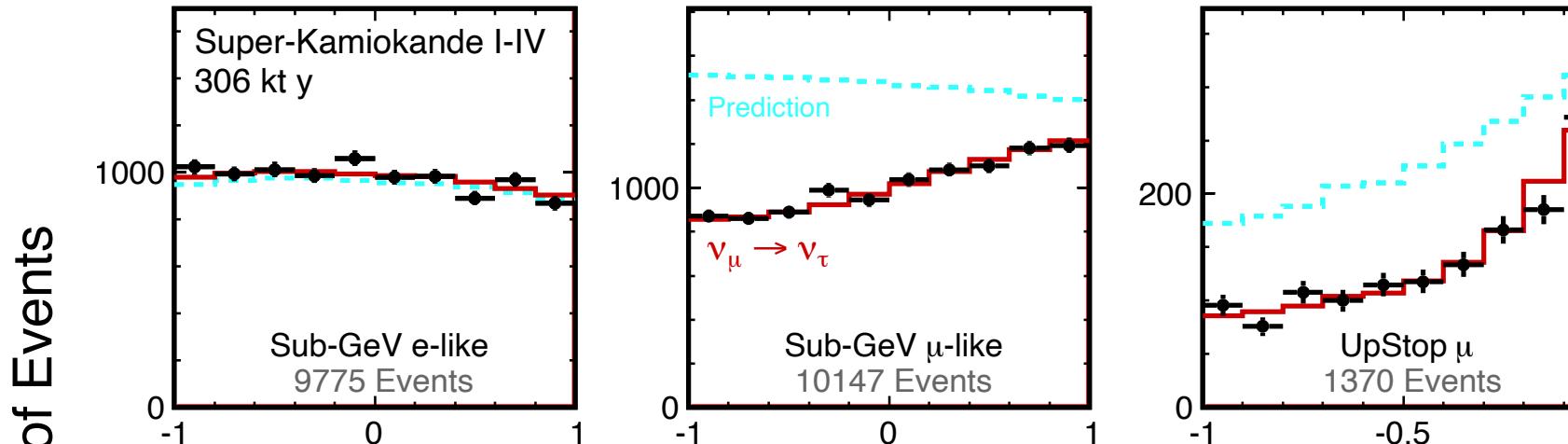
● >1028



# Contemporary Super-Kamiokande Atmospheric Neutrino Data

$E_\nu \sim 1 \text{ GeV}$

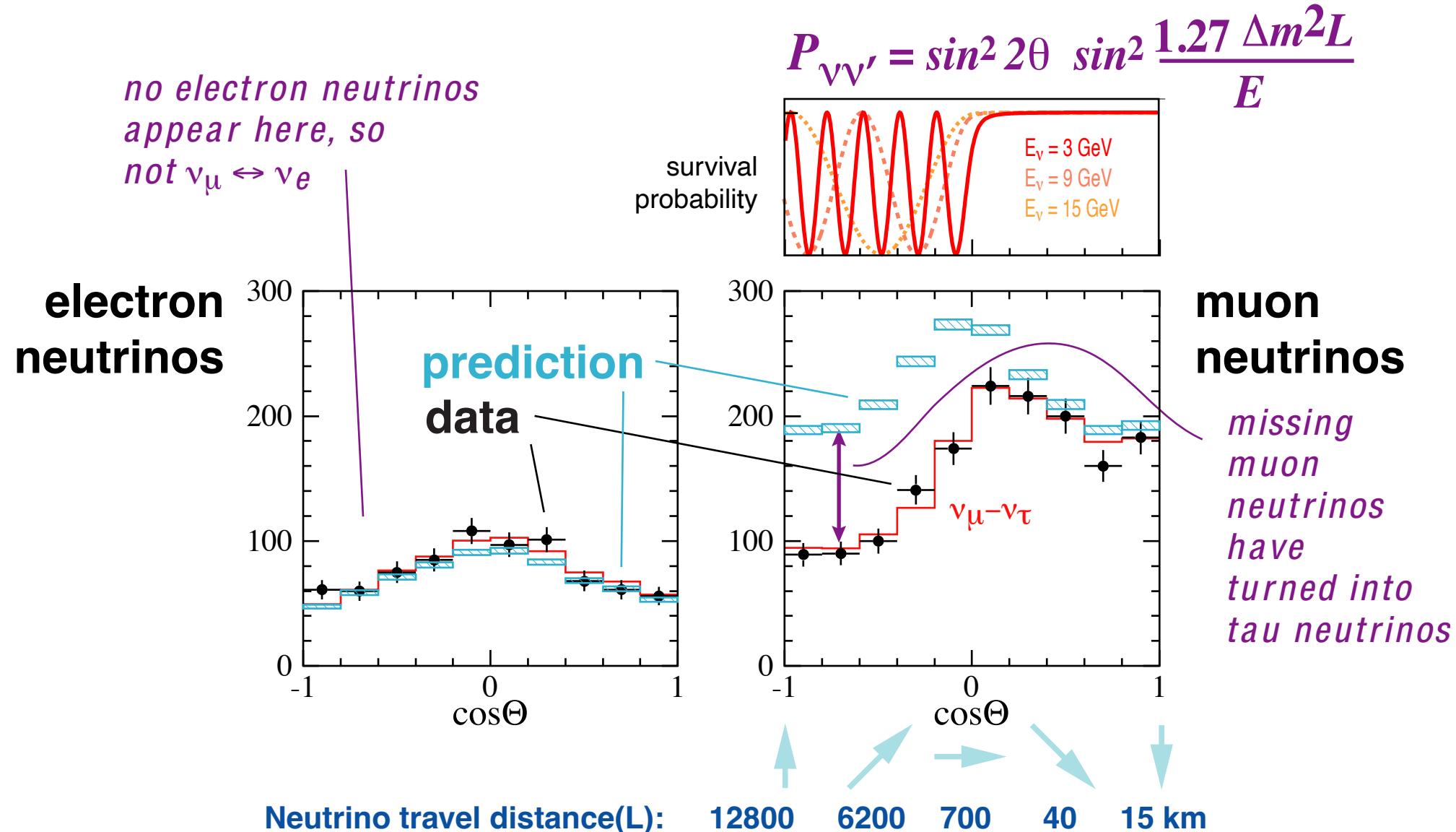
$E_\nu \sim 10 \text{ GeV}$



$E_\nu \sim 10 \text{ GeV}^{\cos \text{ zenith}}$

$E_\nu \sim 100 \text{ GeV}$

# How is this Neutrino Oscillation?



# The Neutrino Matrix

Pontecorvo-Maki-Nakagawa-Sakata Matrix (PMNS or MNS)

*PMNS matrix*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor

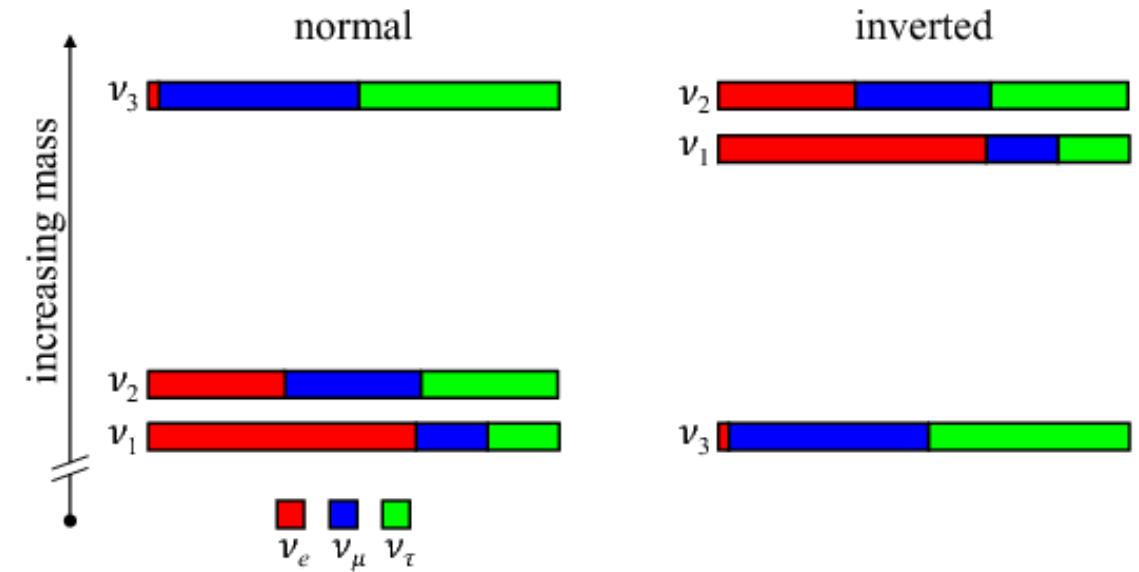
mass

$$\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} e^{-i\delta} \\ & 1 & \\ -s_{13} e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

*atmospheric*

*interference*

*solar*



# Three Flavor Neutrino Oscillation in Matter

$$P(\nu_\mu \rightarrow \nu_e) \cong T_1 \sin^2 2\theta_{13} - T_2 \alpha \sin 2\theta_{13} + T_3 \alpha \sin 2\theta_{13} + T_4 \alpha^2$$

$$\begin{aligned} \text{atmospheric} \quad T_1 &= \sin^2 \theta_{23} \frac{\sin^2 [(1-x)\Delta]}{(1-x)^2} & \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \\ \text{interference} \quad \left\{ \begin{array}{l} T_2 = \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ T_3 = \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \end{array} \right. \\ \text{solar} \quad T_4 &= \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} \end{aligned}$$

$$\boxed{\Delta = \Delta m_{31}^2 L / 4E \quad x = 2\sqrt{2}G_F N_e E / \Delta m_{31}^2 \cong E/12 \text{ GeV}}$$

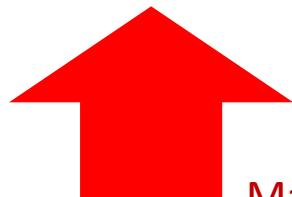
**matter effects:** for anti-neutrinos, sign of  $x$  and  $\sin \delta_{CP}$  is changed  
hierarchy inversion also exchanges role of anti-neutrinos and neutrinos

# Primary Goals of Neutrino Physics: understand the parameters of nature

“Mass Ordering” a.k.a.  
“Mass Hierarchy”  
or sign of  $\Delta m^2$ ?

“Octant”: is  $\theta_{23}$   
different from 45°?

CP violation?

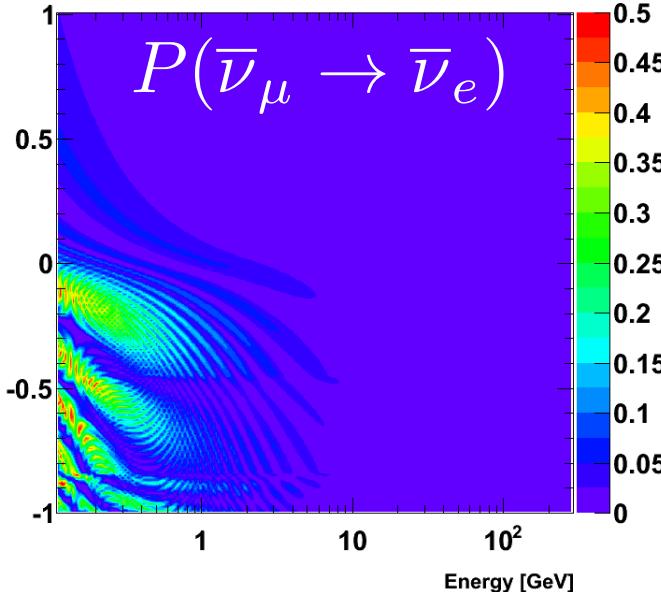
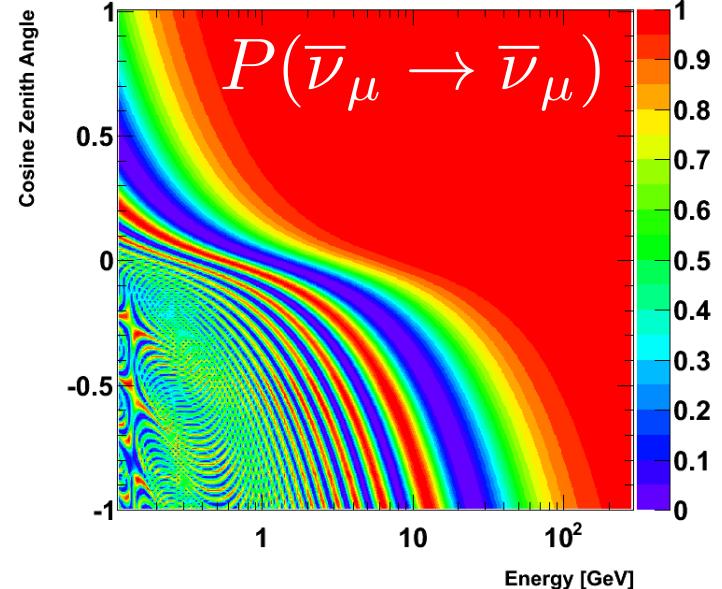
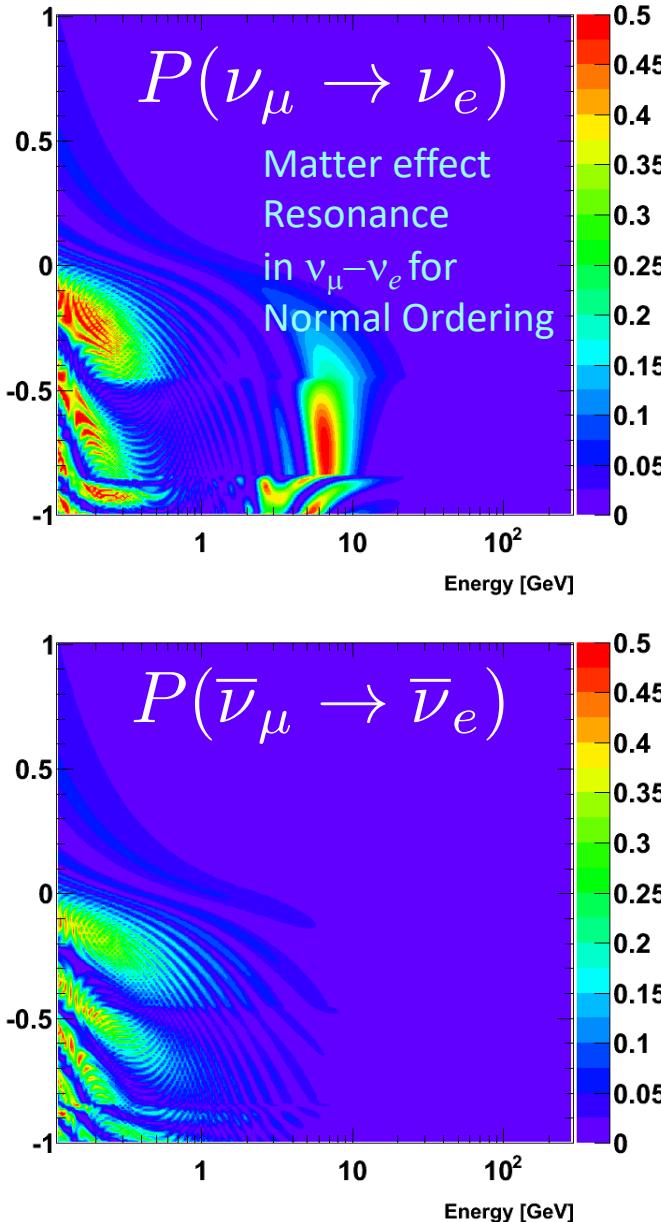
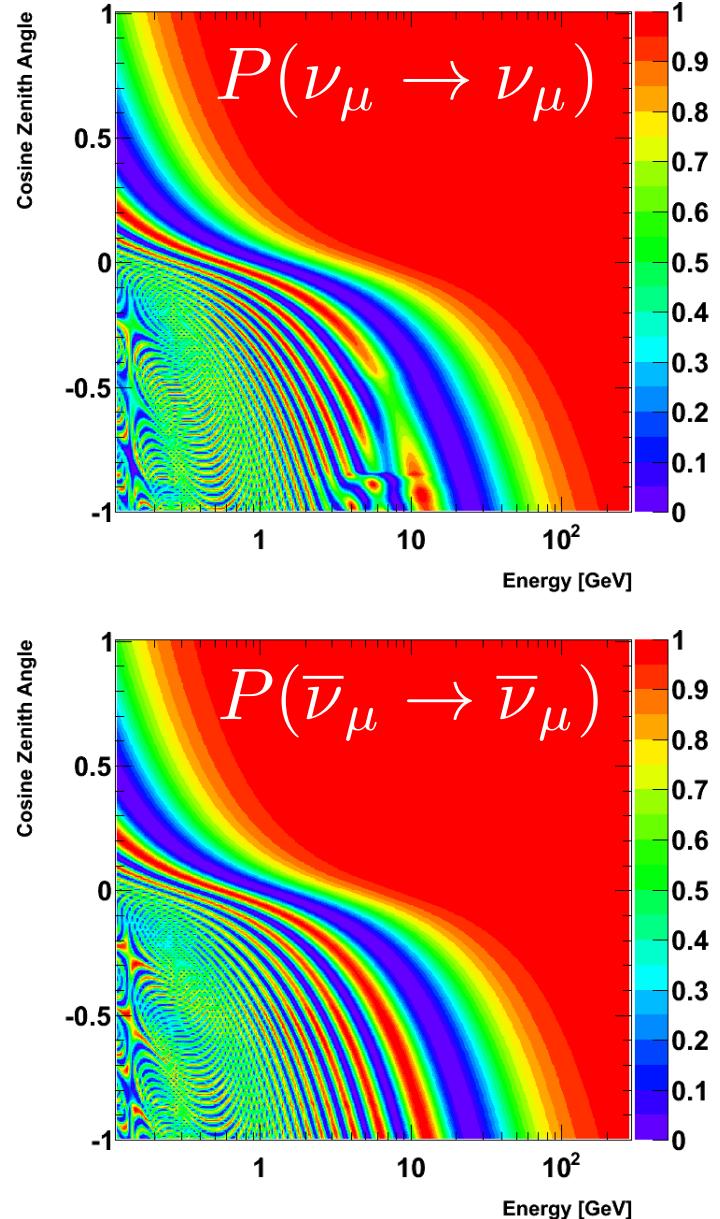


Parameter	best-fit	rough 1 $\sigma$ uncertainty
$\Delta m_{21}^2$ [10 <sup>-5</sup> eV <sup>2</sup> ]	7.37	$\pm 0.17$ (2.3%)
$ \Delta m^2 $ [10 <sup>-3</sup> eV <sup>2</sup> ]	2.50 (2.46)	$\pm 0.06$ (2.4%)
$\sin^2 \theta_{12}$	0.297	$\pm 0.017$ (5.7%)
$\sin^2 \theta_{23}, \Delta m^2 > 0$	0.437	+8%
$\sin^2 \theta_{23}, \Delta m^2 < 0$	0.569	-5%
$\sin^2 \theta_{13}, \Delta m^2 > 0$	0.0214	+5%
$\sin^2 \theta_{13}, \Delta m^2 < 0$	0.0218	-9%
$\delta/\pi$	1.35 (1.32)	$\} \pm 0.0012$ (5.5%)
		0 $\leftrightarrow$ 2 $\pi$ at 1 $\sigma$

From 2016 RPP by PDG, based on 1601.07777 (Bari group)

Many next generation experiments using beam, reactor, natural neutrinos: see Snowmass 2022 Seattle

# Oscillograms: Graphical representations of neutrino mixing probability



You will be seeing a lot of these during this workshop 😊

**Important theorem:**

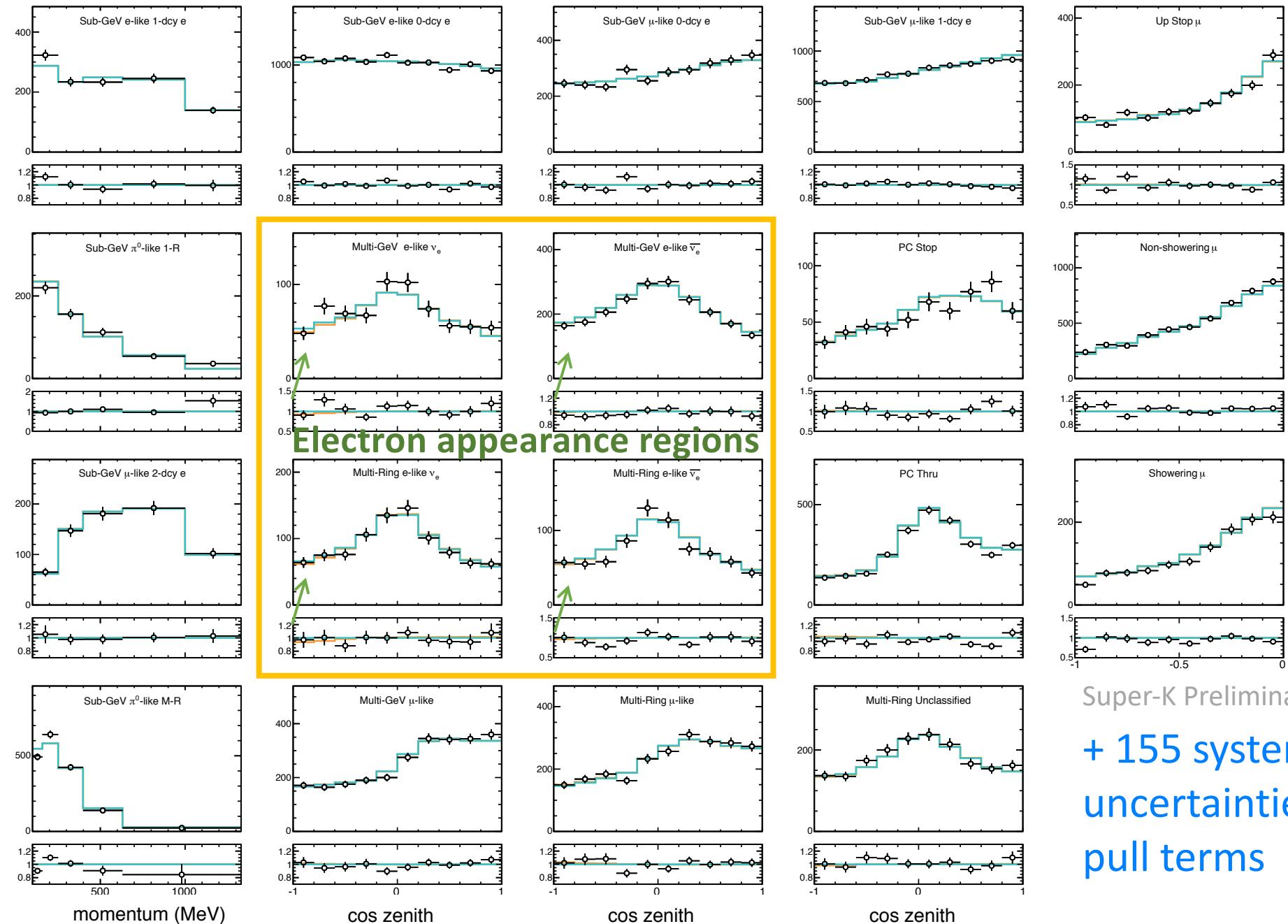
Oscillogram switch pattern between neutrino and antineutrino if the mass ordering changes between “normal ordering” and “inverted ordering”

**Remember:**

Statistics is lower at high energy

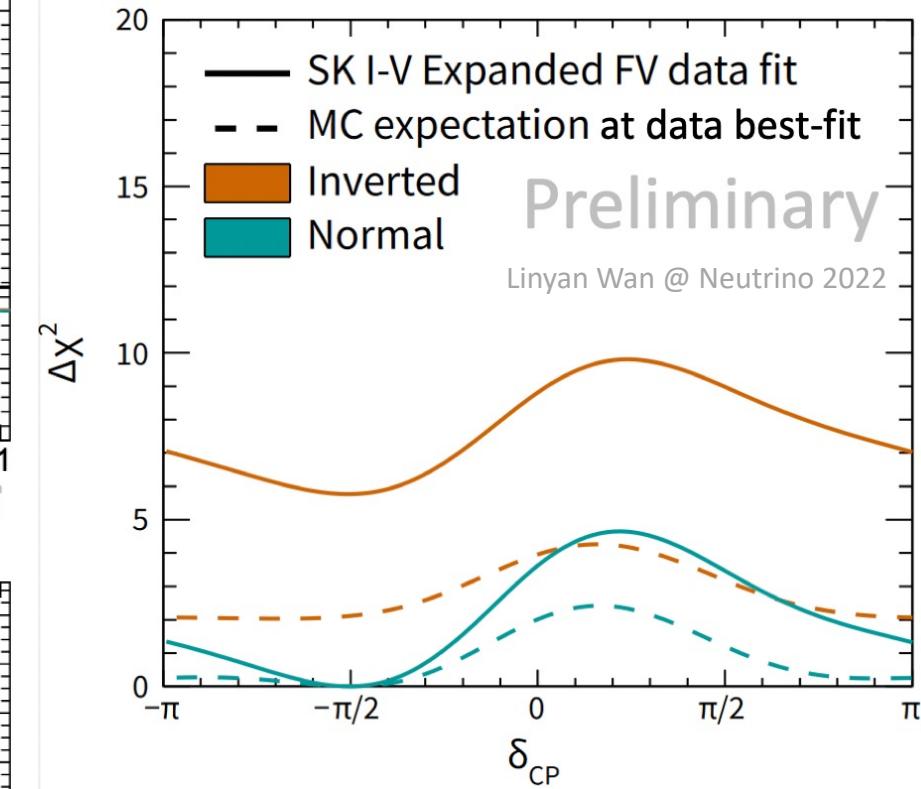
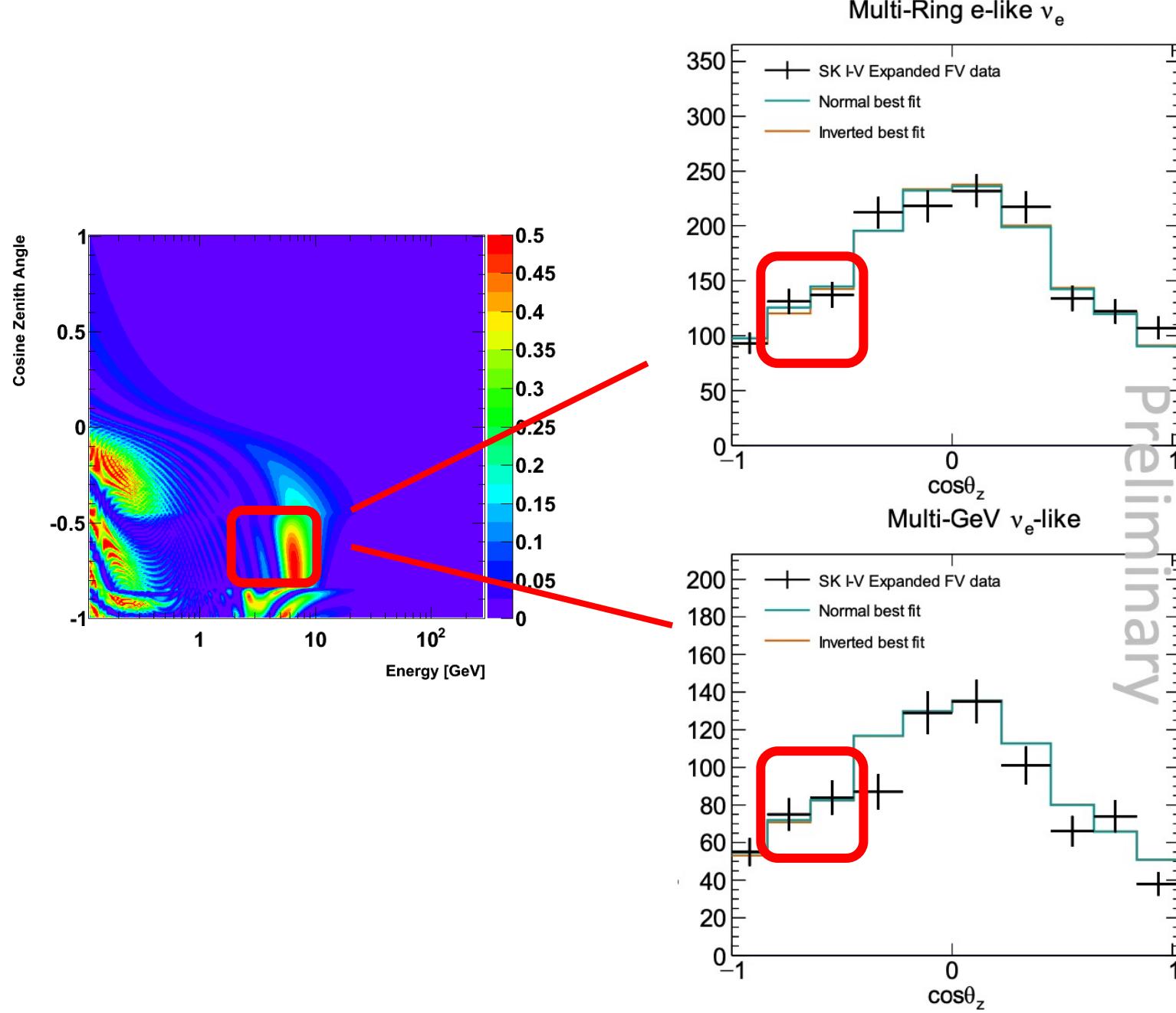
Pointing is better at high energy

# State-of-the-art Super-K Analysis



Super-K Preliminary  
+ 155 systematic  
uncertainties as  
pull terms

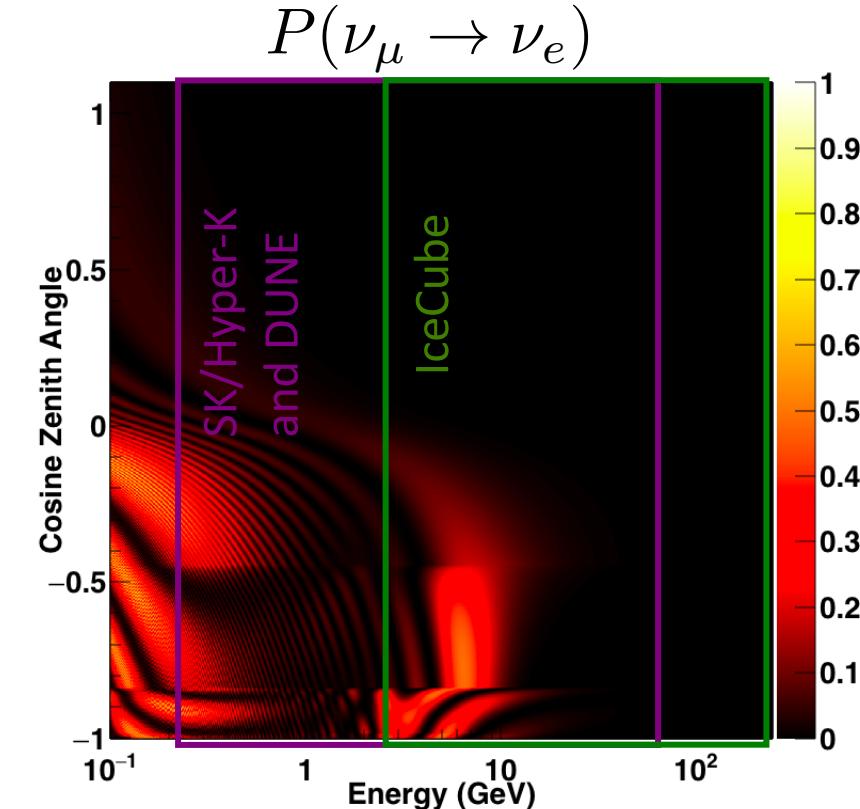
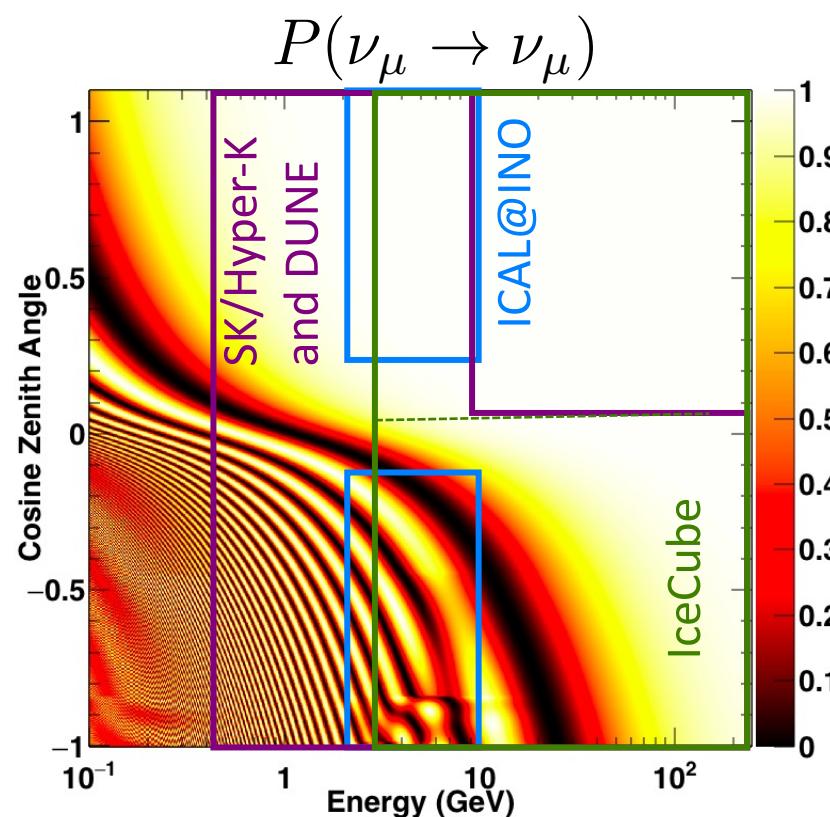
# Super-K 2022



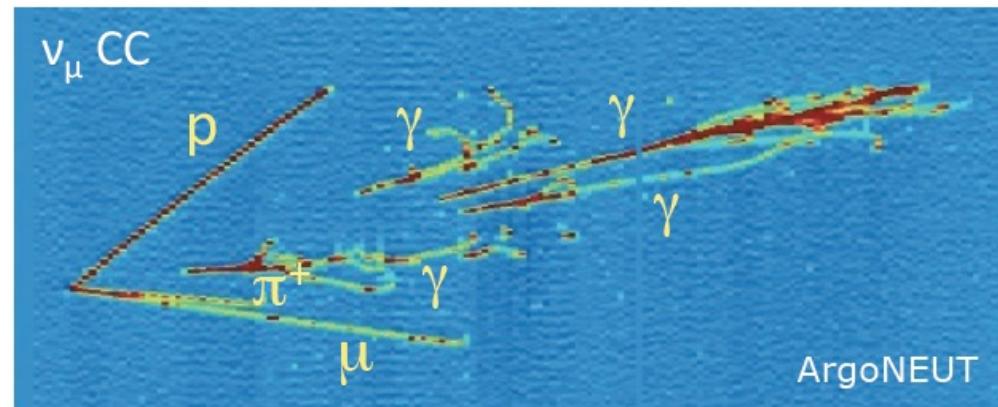
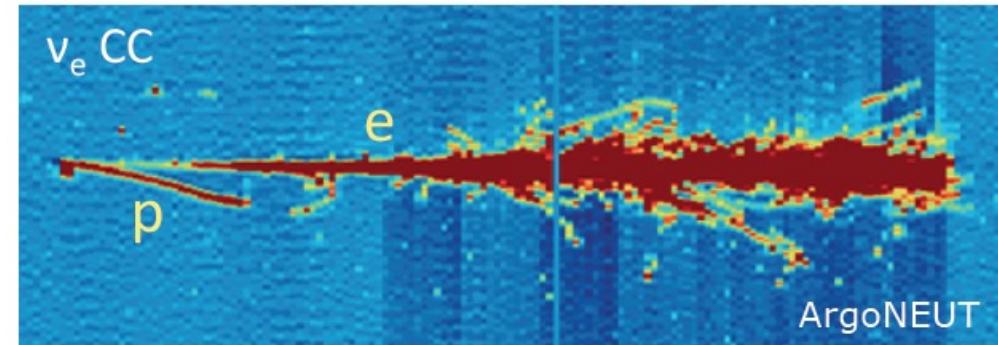
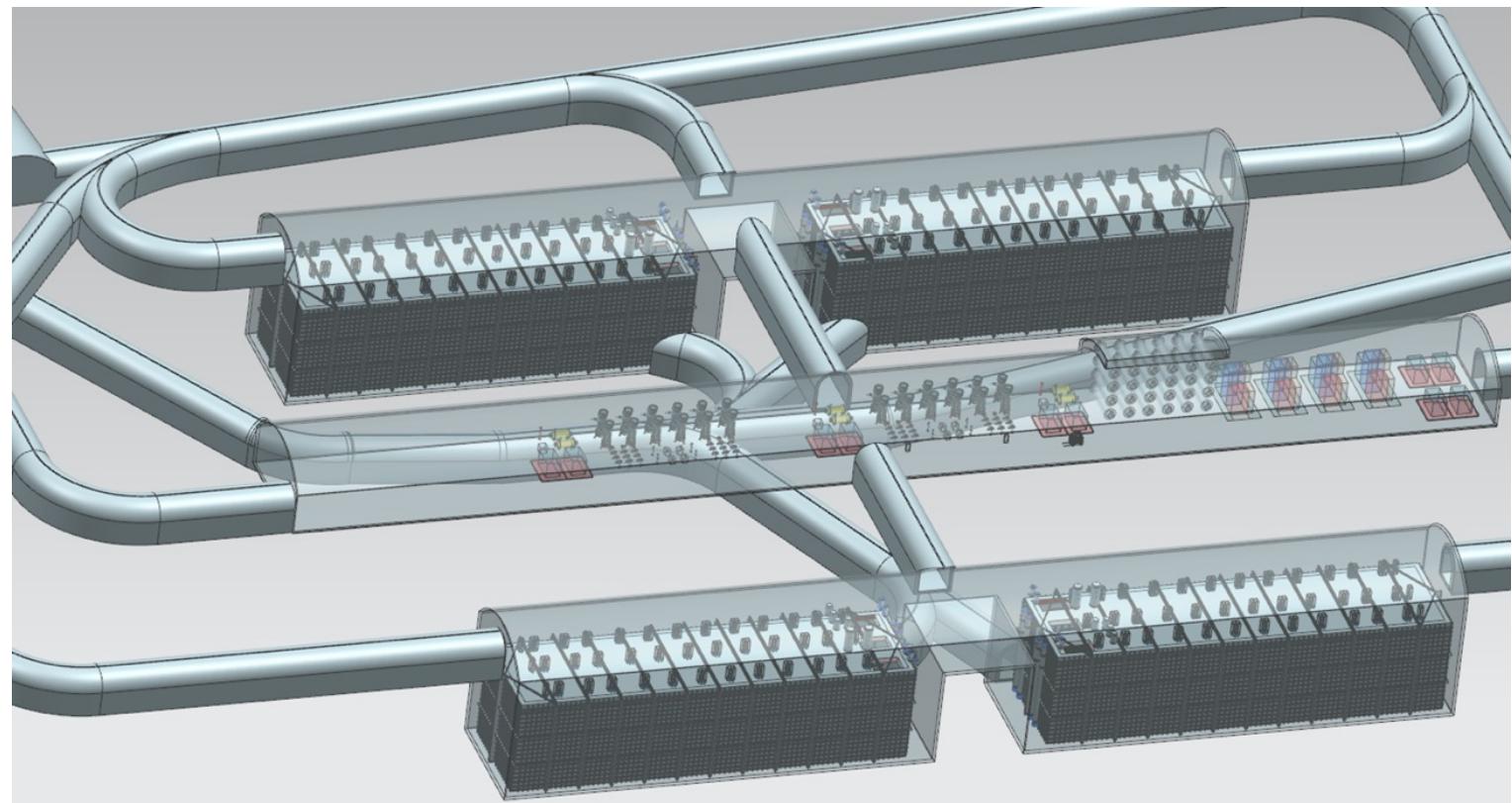
**Message:** we are barely sensitive to the highest priority unknown parameters of nature: CP-violation and mass ordering, using our best techniques and 20+ years of data. This relies on our treatment of matter effects (i.e. tomography).

# More Atmospheric Neutrino Experiments

Category	Examples	$\nu_\mu - \nu_e$	$\nu_\mu - \nu_\tau$	$\nu/\text{anti-}\nu$	Mass
Water Cherenkov	Super-K Hyper-K	**	*	*	* 27 kton ** 189 kton
Magnetized Iron	ICAL@INO			*** ( $\mu$ )	** 50 kton
Neutrino Telescope	IceCube/KM3Net (w high density)	*	***	*	*** Mton
Liquid Argon TPC	DUNE	***	**	**	** 20-40 kton



# DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

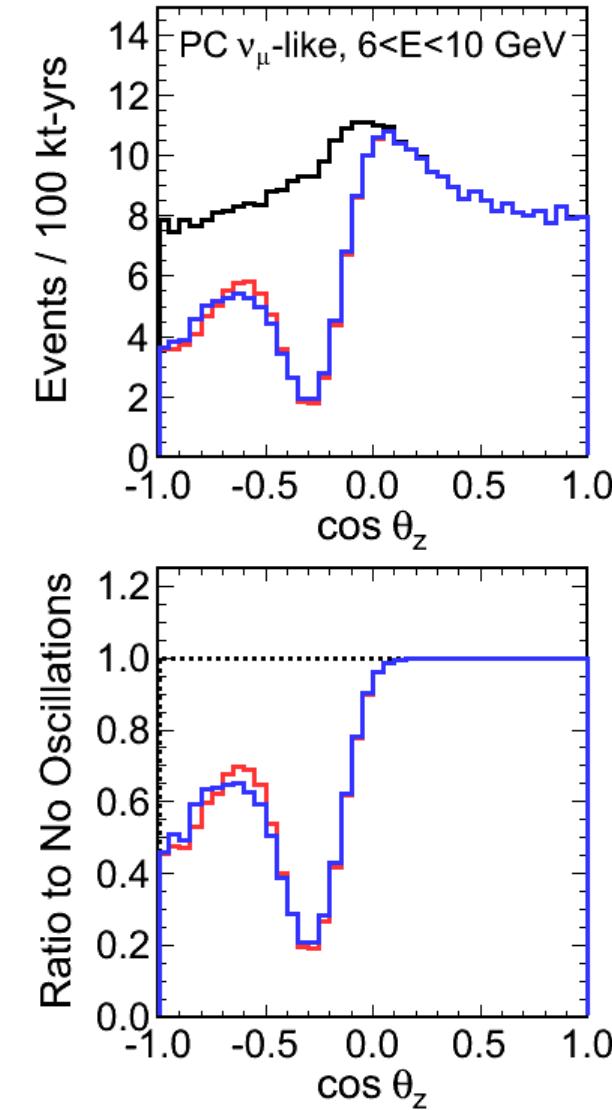
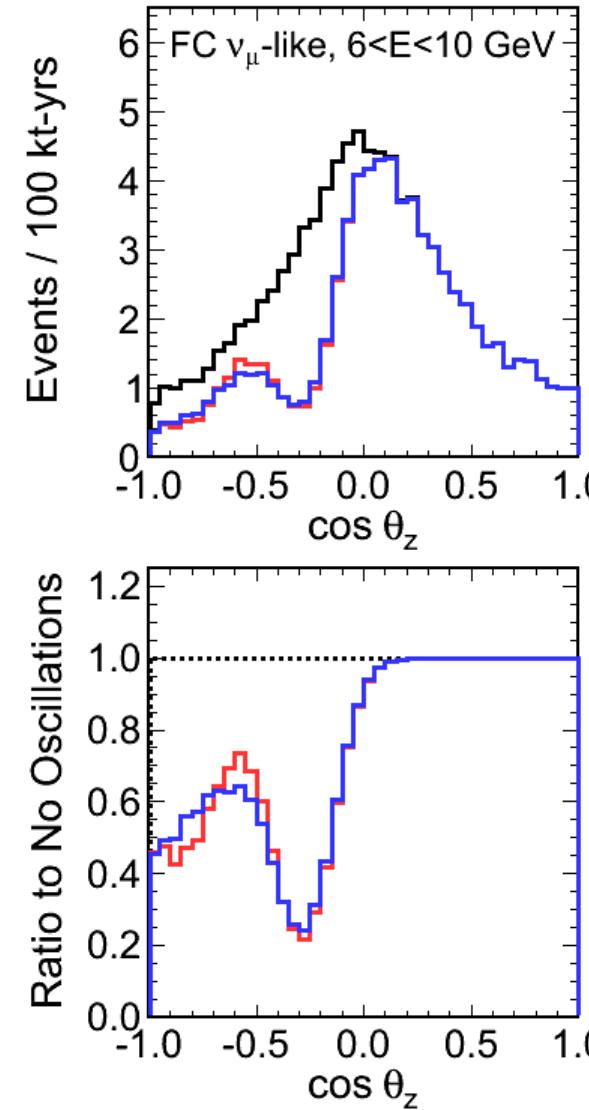
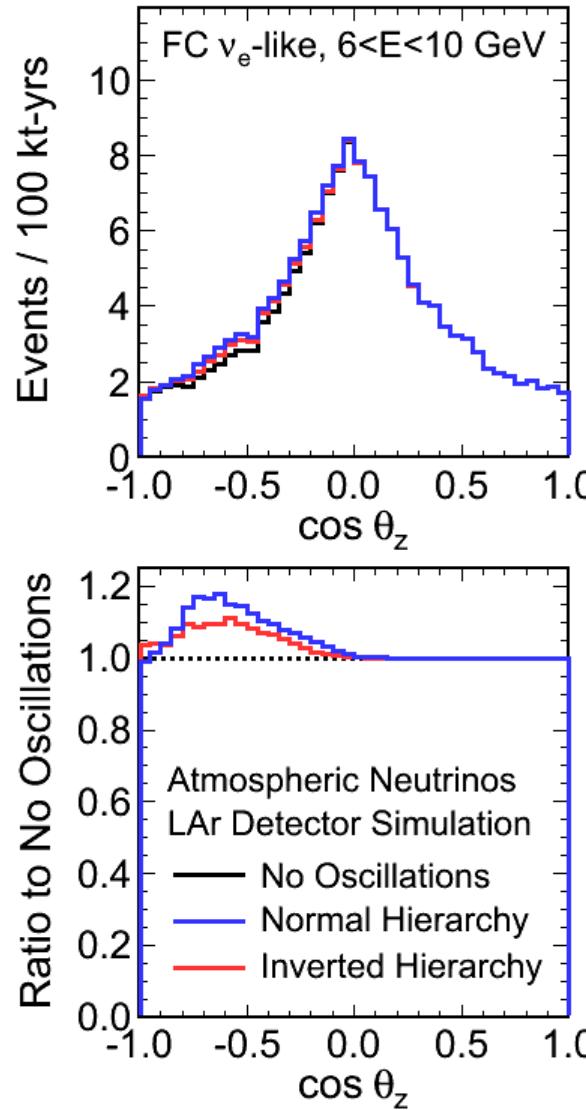


Visible proton:  $\nu/\bar{\nu}$  tagging

Final state hadrons: excellent  $\nu$  direction determination

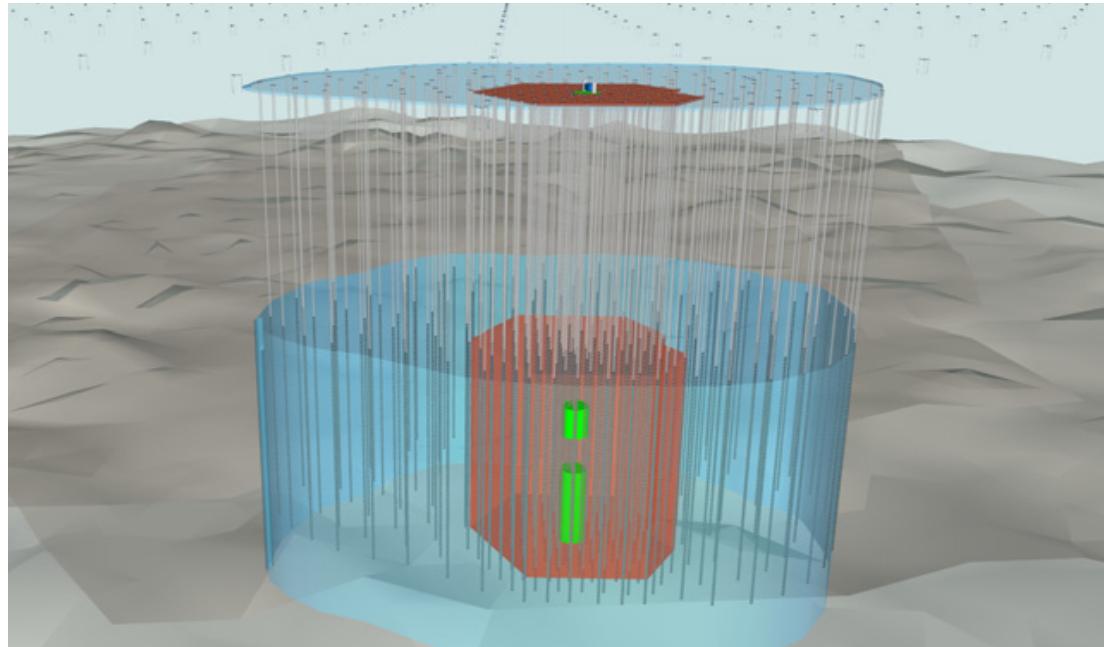
Visible gap for EM shower: NC rejection

# DUNE: Better Resolution of Oscillation Pattern

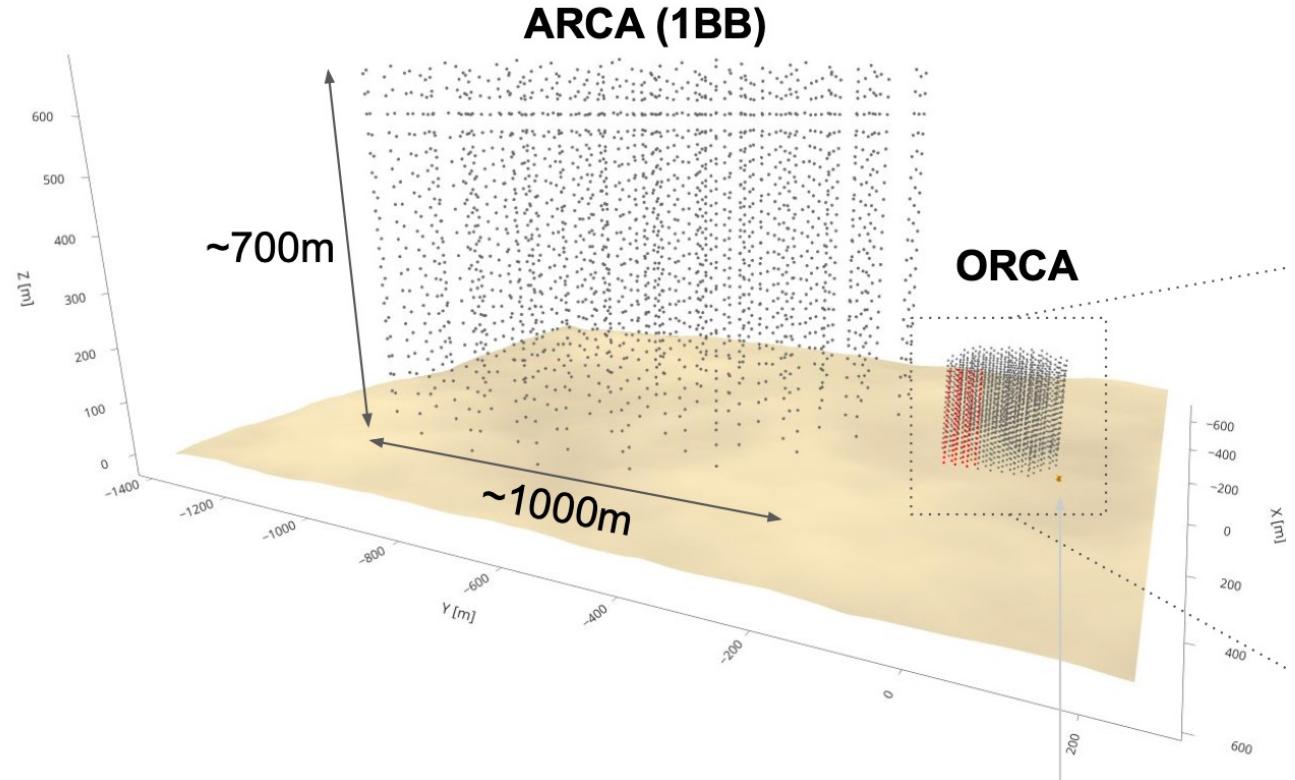


# Kilometer-scale arrays

**IceCube**



**KM3Net**



kilometer-scale ice/water Cherenkov detectors

Huge statistics, specializing in **highest energy neutrinos**

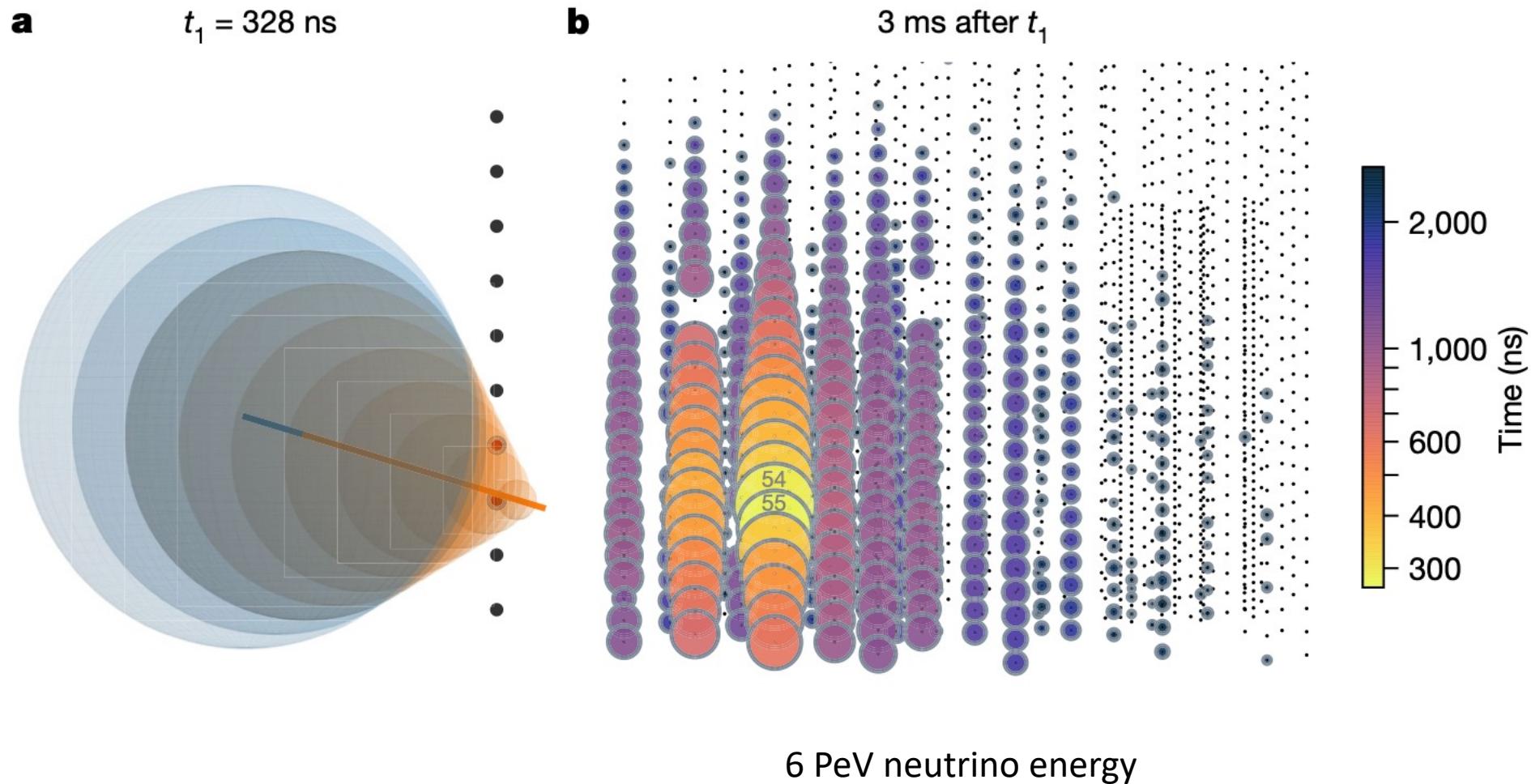
High density infill to achieve lower energy thresholds (below 10 GeV is the challenge)

Will be covered in more expert detail by others in the workshop.

# Detection of a particle shower at the Glashow resonance with IceCube

<https://doi.org/10.1038/s41586-021-03256-1> The IceCube Collaboration\*

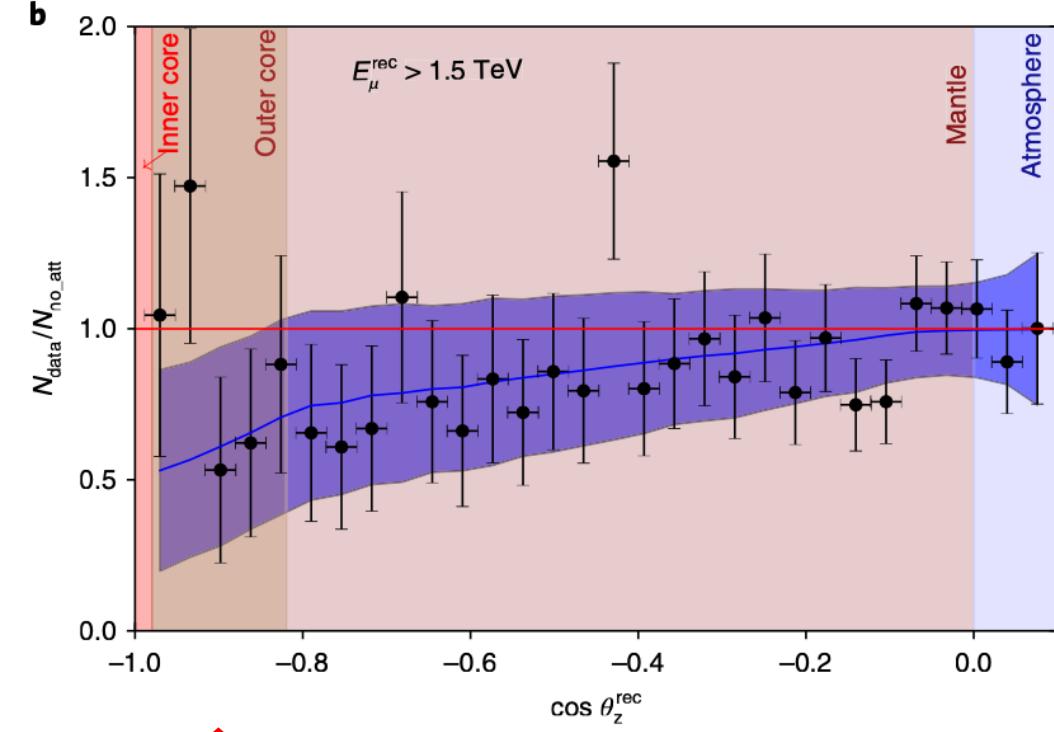
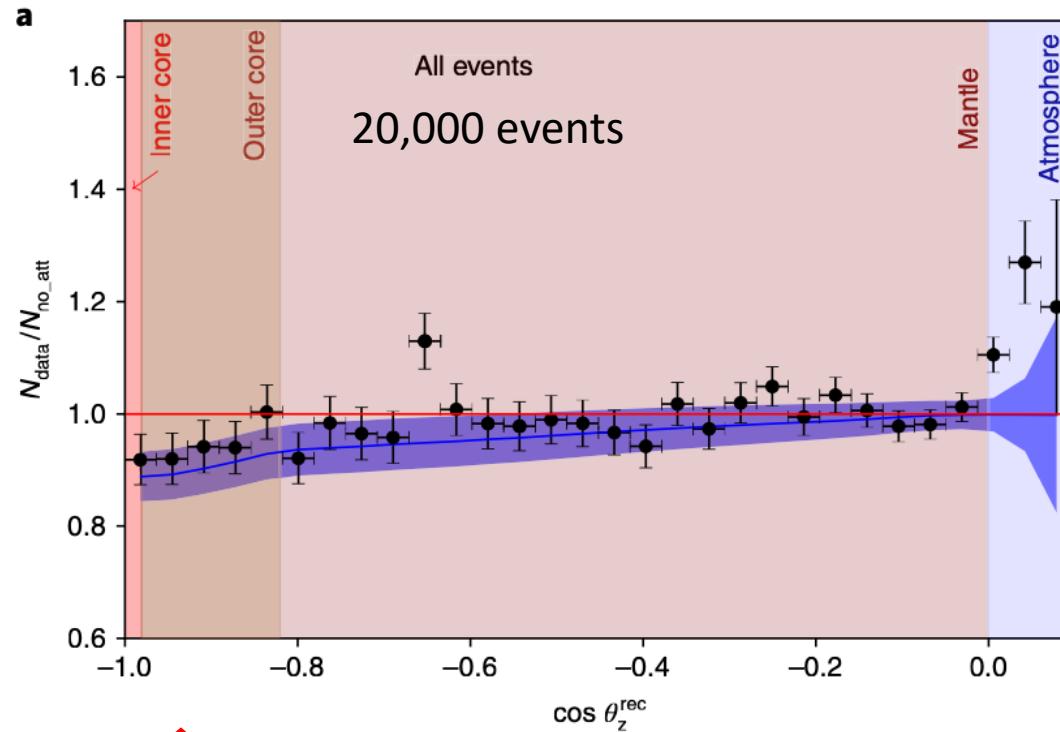
## Relevant highlight I



# Relevant highlight 2

**Neutrino tomography of Earth**, Donini, Palomares-Ruiz, and Salvado

NATURE Physics | VOL 15 | JANUARY 2019 | 37–40 | [www.nature.com/naturephysics](http://www.nature.com/naturephysics)



Congratulations are in order, for these expected signatures of neutrino interactions plus rich high energy neutrino astrophysics including multi-messenger astronomy

# Concluding thoughts

Atmospheric neutrinos are freely given by nature.

They are background for some physics (proton decay, dark matter).

They provide signatures for some physics (oscillation, BSM physics).

Statistically, atmospheric neutrino oscillation yields a few- $\sigma$ -level window into the unknown parameters of nature (CP-violation, mass ordering).

This requires sensitivity to matter effects.

With sufficient statistics and flavor identification, matter effects may allow neutrino oscillation to play a role in tomography.

Kilometer-scale arrays have demonstrated that absorption tomography is in reach.