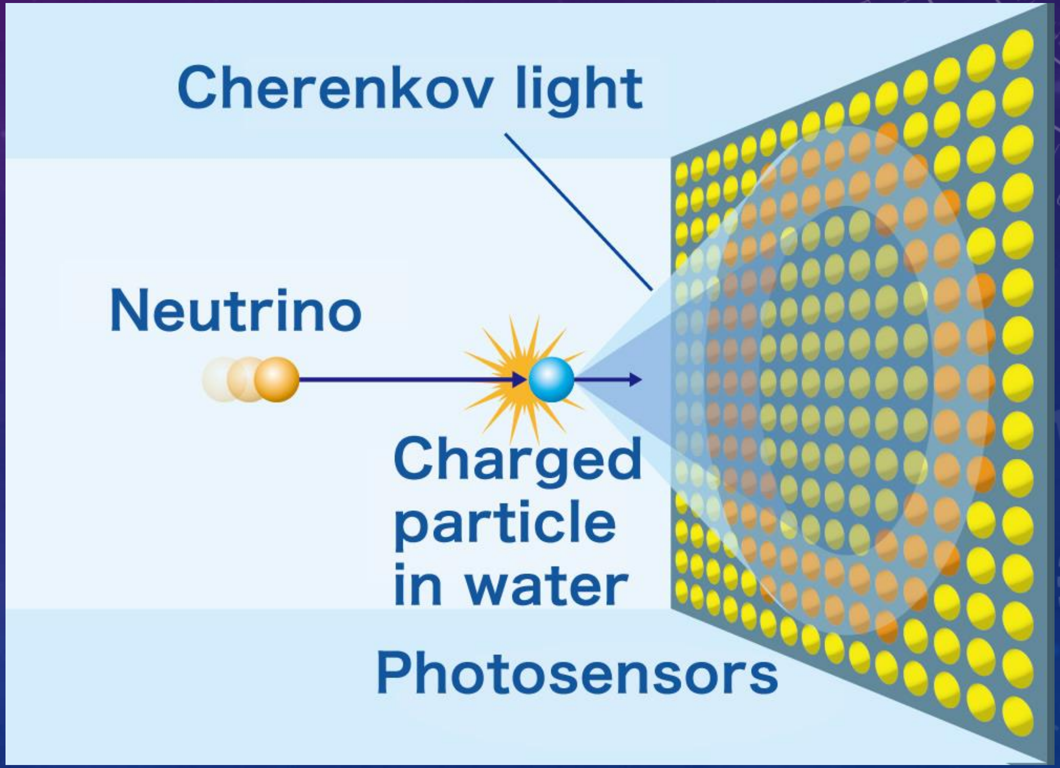
DISCOVERY OF NEUTRINO OSCILLATIONS

FRANKLIN ADAMS

UNIVERSITY OF SOUTH CAROLINA – DEPARTMENT OF PHYSICS AND ASTRONOMY

KAMIOKANDE

- Kamioka Nucleon Decay Experiment
  - 3000 tons of water
  - 1000 50cm PMTs
  - 1000m underground
- Built in 1983 to detect proton decay, no evidence after 3 years
- Suspected that software was not good enough
- New software was tested on single Cherenkov-ring events
- Unexpected result
  - Much fewer ν_μ than expected



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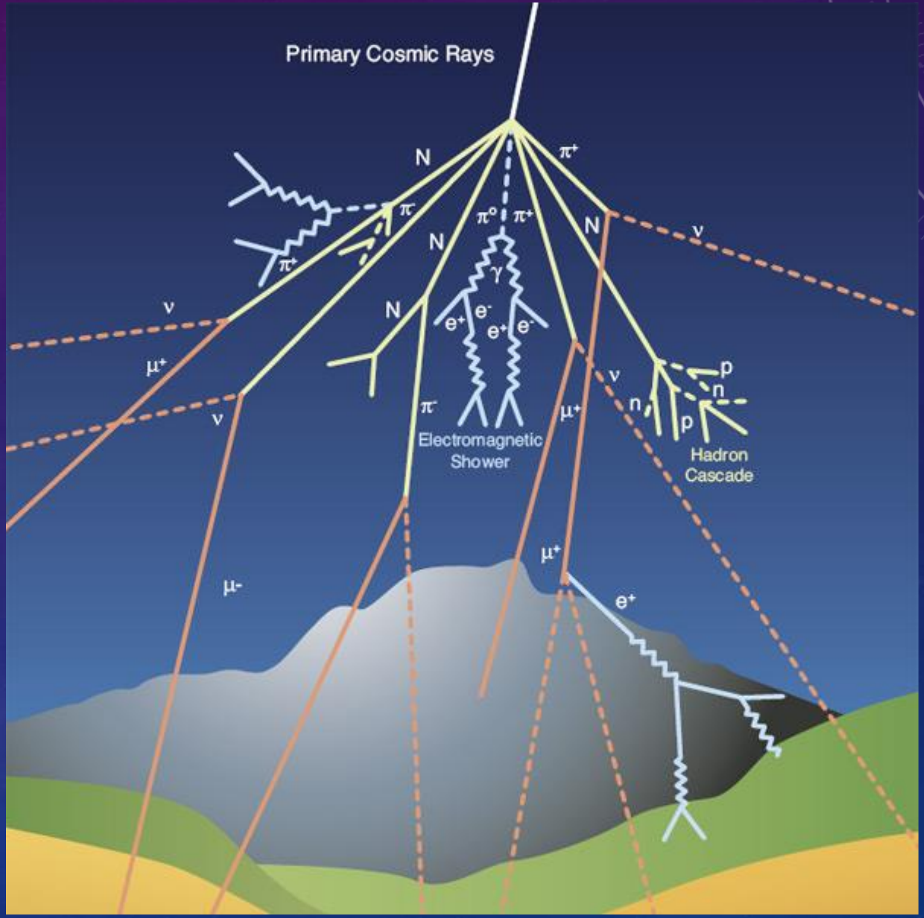
COSMIC RAY DECAY

- Cosmic Ray enters the atmosphere
- Produces a π -> $\mu + \nu_\mu$
- μ -> $e + \nu_e + \nu_\mu$
- Should expect ~2 ν_μ per ν_e for atmospheric neutrinos



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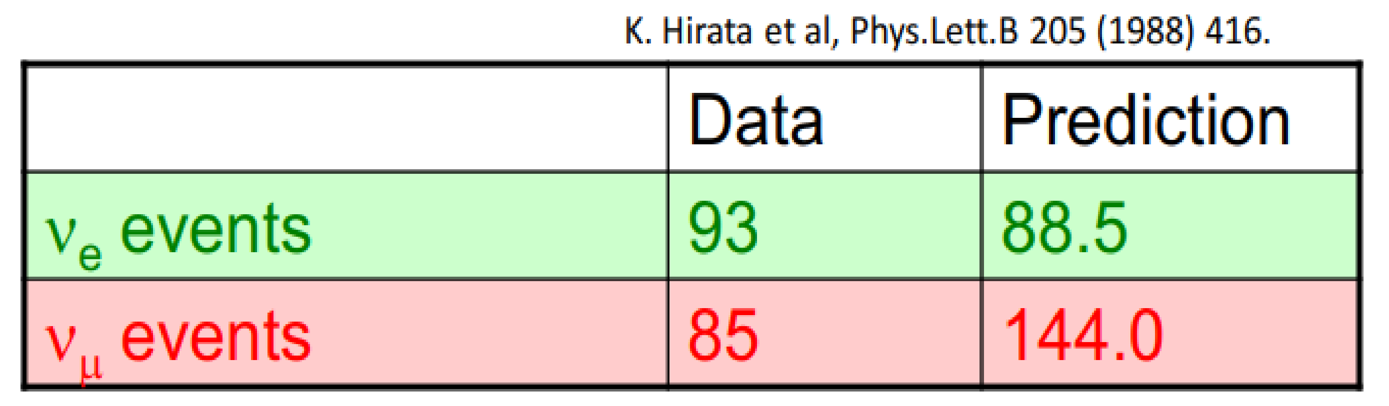
RESULTS OF KAMIOKANDE

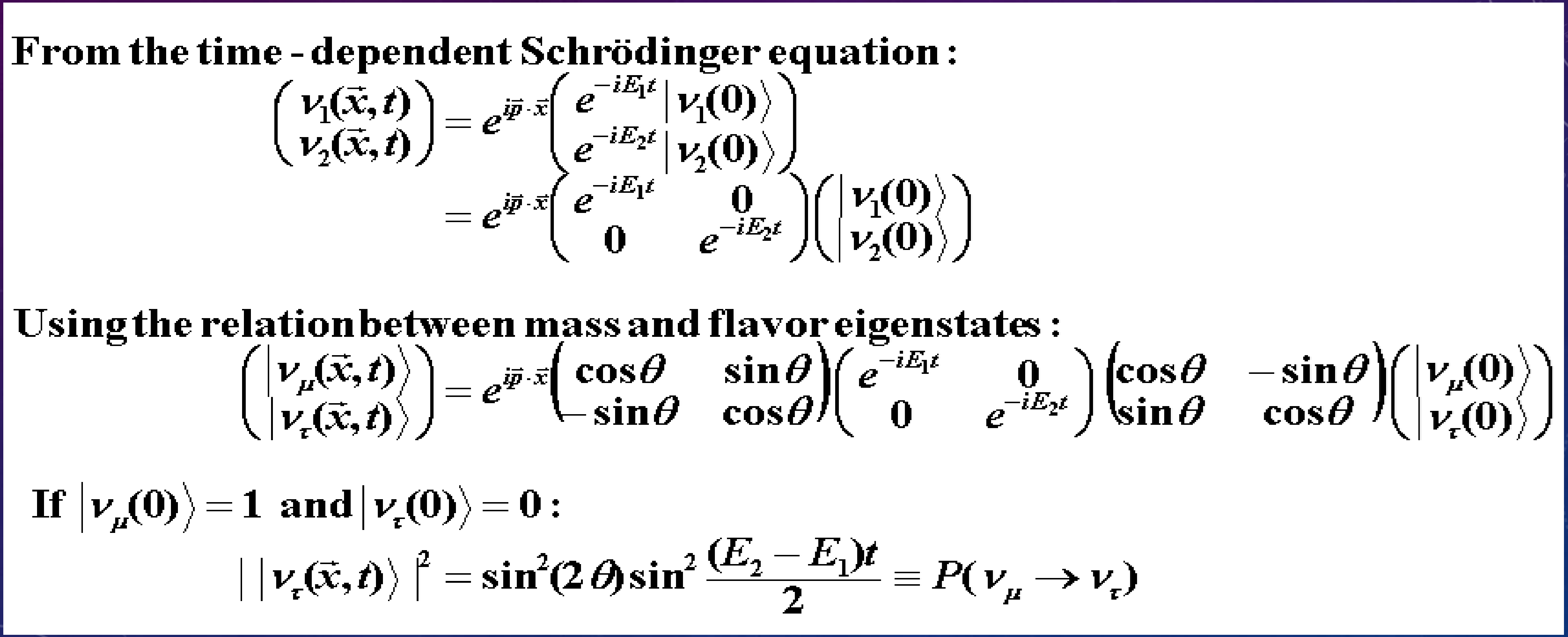
- Monte Carlo simulation 21.8 kiloton*year
- Data from 2.86 kiloton*year exposure
- Not at 2:1 ratio due to detection efficiency of μ detection
- ν_e ratio 1.05±0.11
- ν_μ ratio 0.59±0.07



K. Hirata et al, Phys.Lett.B 205 (1988) 416.

	Data	Prediction
ν_e events	93	88.5
ν_μ events	85	144.0

WHY DOES NEUTRINO OSCILLATION IMPLY MASS



From the time-dependent Schrödinger equation:

$$\begin{pmatrix} \nu_1(\vec{x},t) \\ \nu_2(\vec{x},t) \end{pmatrix} = e^{i\vec{p}\cdot\vec{x}} \begin{pmatrix} e^{-iE_1t}|\nu_1(0)\rangle \\ e^{-iE_2t}|\nu_2(0)\rangle \end{pmatrix}$$

$$= e^{i\vec{p}\cdot\vec{x}} \begin{pmatrix} e^{-iE_1t} & 0 \\ 0 & e^{-iE_2t} \end{pmatrix} \begin{pmatrix} |\nu_1(0)\rangle \\ |\nu_2(0)\rangle \end{pmatrix}$$

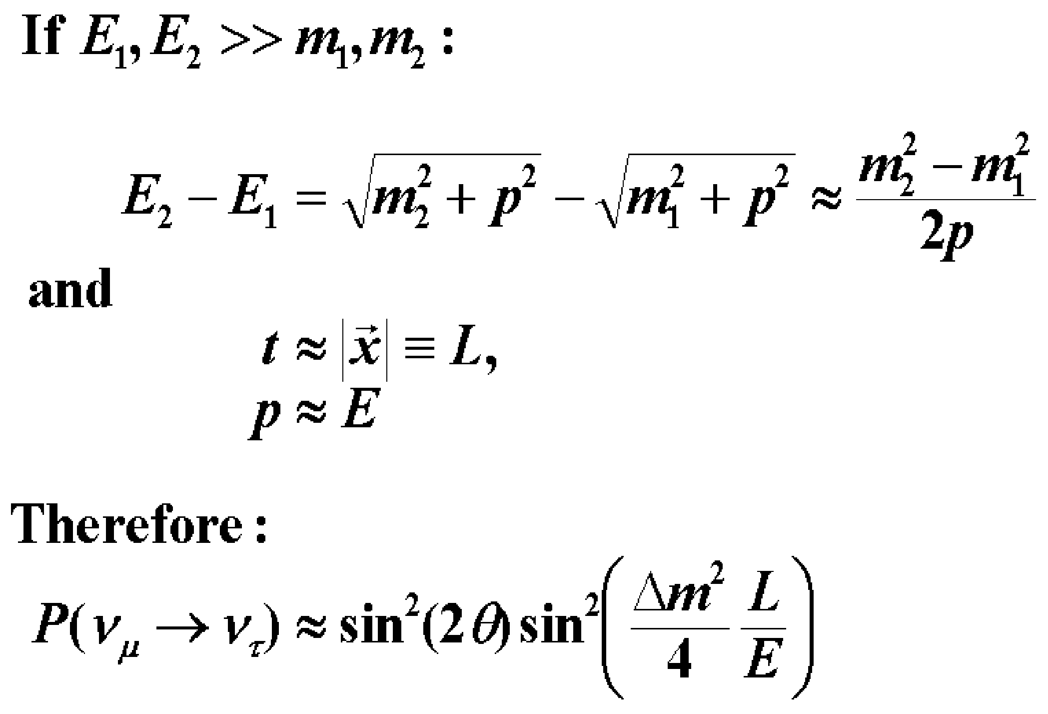
Using the relation between mass and flavor eigenstates:

$$\begin{pmatrix} |\nu_\mu(\vec{x},t)\rangle \\ |\nu_\tau(\vec{x},t)\rangle \end{pmatrix} = e^{i\vec{p}\cdot\vec{x}} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} e^{-iE_1t} & 0 \\ 0 & e^{-iE_2t} \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_\mu(0)\rangle \\ |\nu_\tau(0)\rangle \end{pmatrix}$$

If $|\nu_\mu(0)\rangle = 1$ and $|\nu_\tau(0)\rangle = 0$:

$$\left|\,|\nu_\tau(\vec{x},t)\rangle\,\right|^2 = \sin^2(2\theta)\sin^2\frac{(E_2-E_1)t}{2} \equiv P(\nu_\mu \rightarrow \nu_\tau)$$

WHY DOES NEUTRINO OSCILLATION IMPLY MASS



If $E_1, E_2 >> m_1, m_2$ **:**

$$E_2 - E_1 = \sqrt{m_2^2 + p^2} - \sqrt{m_1^2 + p^2} \approx \frac{m_2^2 - m_1^2}{2p}$$

and

$$t \approx |\vec{x}| \equiv L,$$
$$p \approx E$$

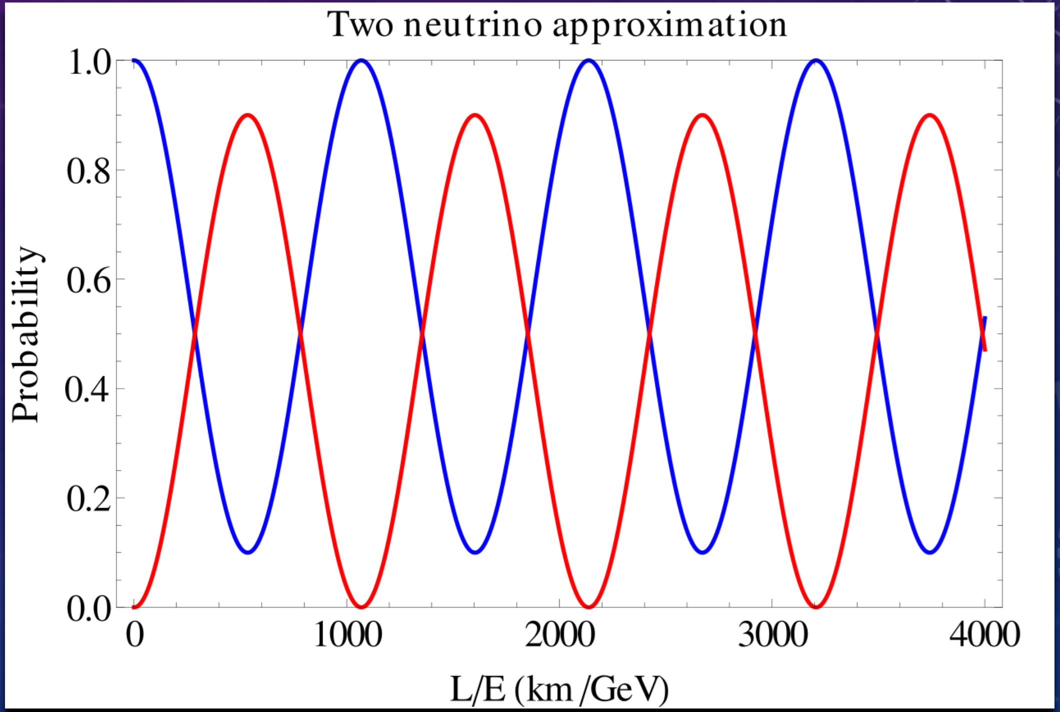
Therefore :

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E}\right)$$

- So, the probability of a neutrino oscillating is a function of: θ, L, E, and Δm
- If Δm = 0 neutrinos will have a zero probability to oscillate

NEUTRINO OSCILLATION CONDITIONS

- In the case of ν_μ -> ν_τ oscillation
    - Blue curve represents probability to remain ν_μ
    - Red curve represents probability to become ν_τ
- At short distances L, neutrinos will have a very low probability to oscillate



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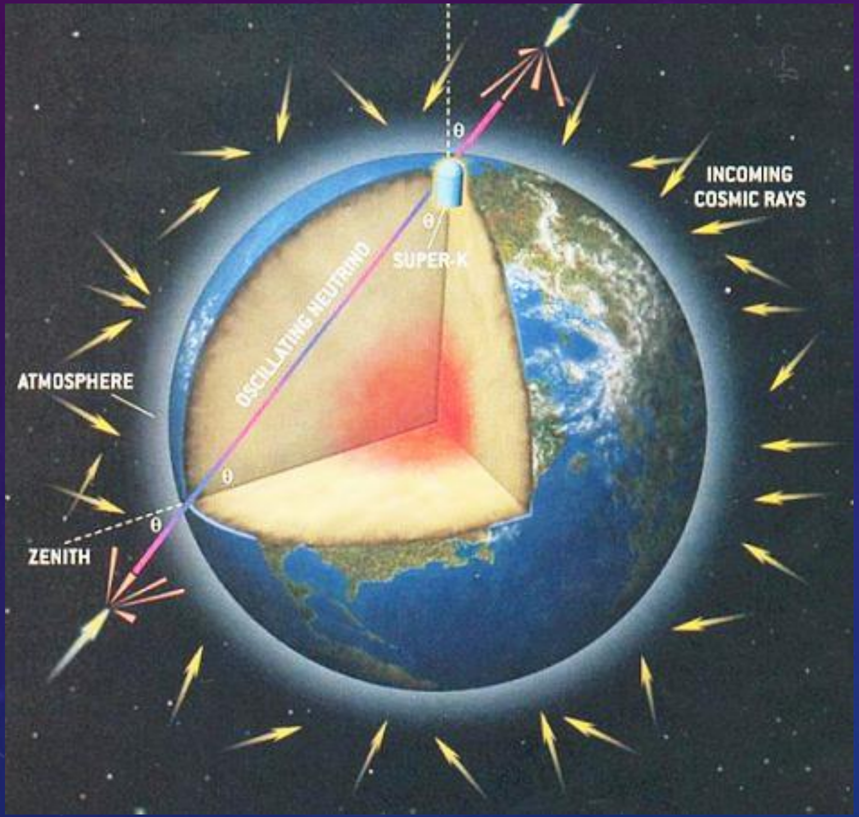
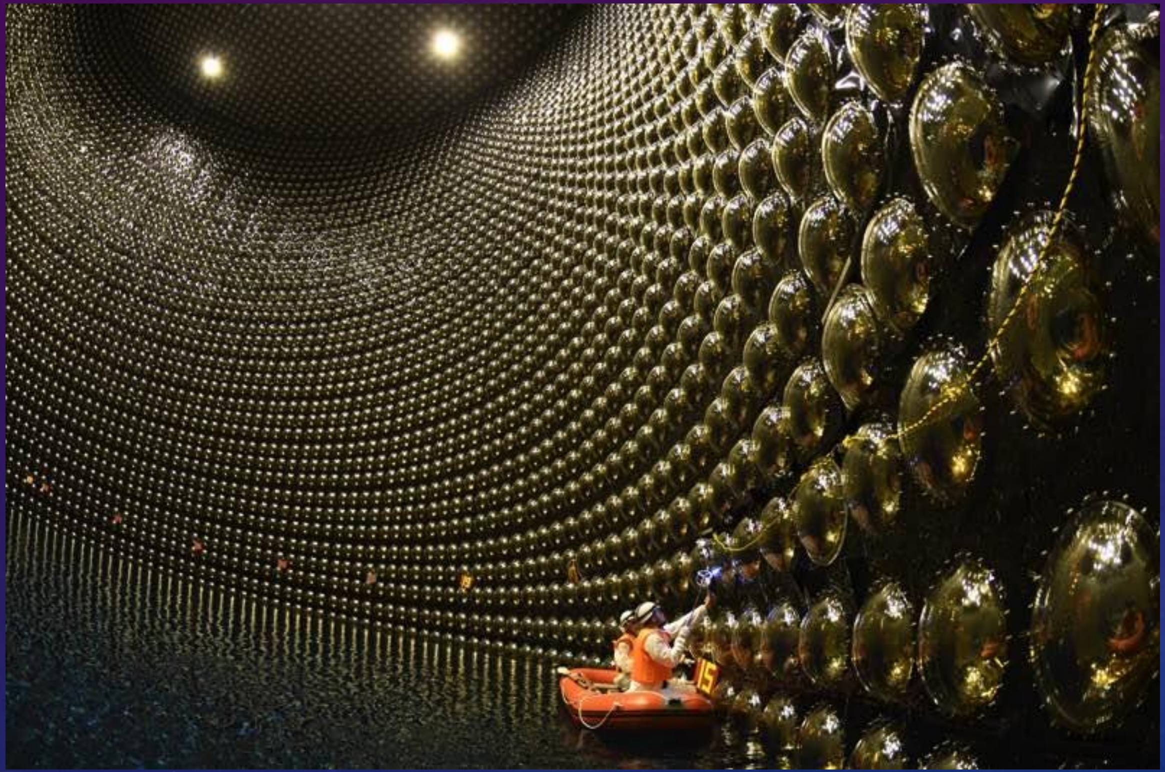
NEUTRINO OSCILLATION CONDITIONS



© Review of the Universe

- Should observe a deficit in ν_μ that pass through the earth
  - Upward going ν_μ
- Want to create conditions to observe oscillations
- Kamiokande was not enough to be conclusive
- Need a much larger detector

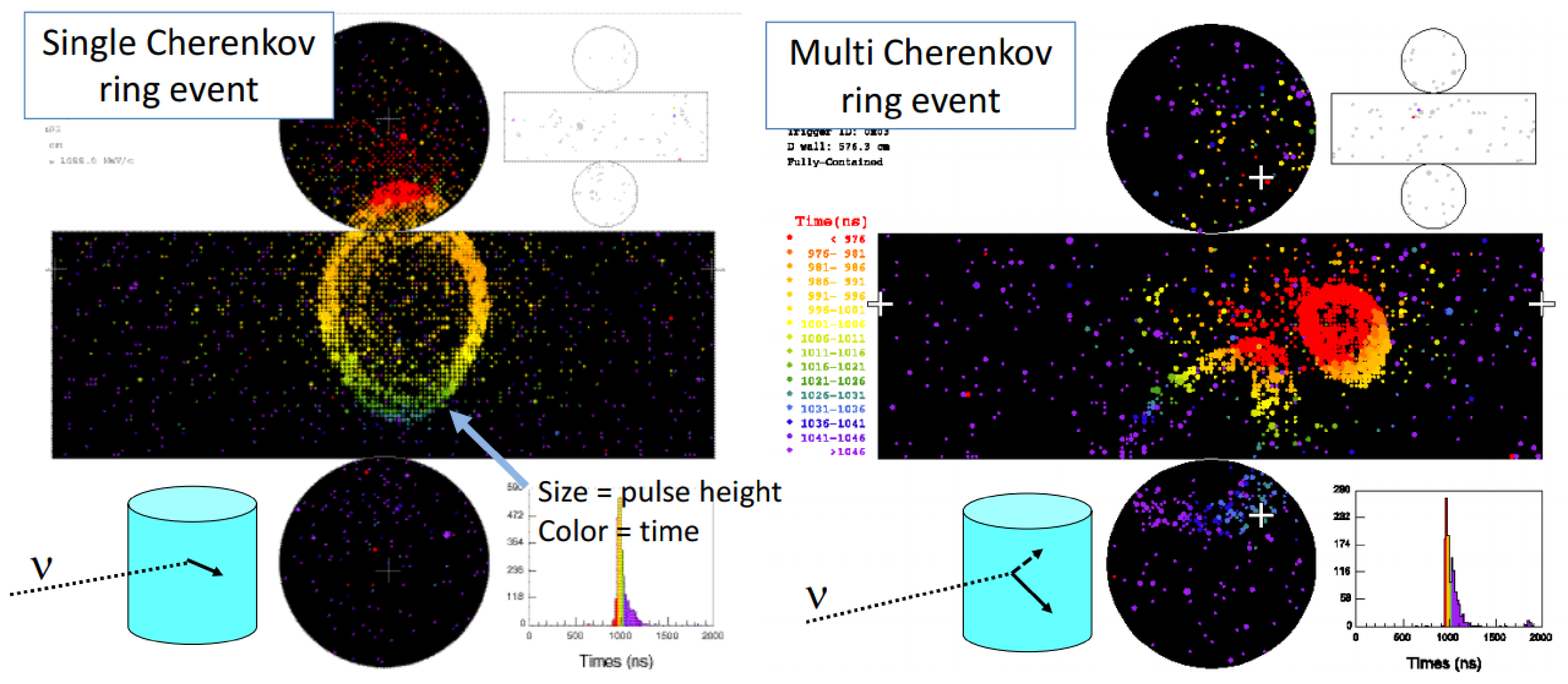
SUPER-KAMIOKANDE



© Kamioka Observatory 2018

- 3000 -> 50,000 ton water Cherenkov Detector
- 1000 -> 13,000 PMT
- 1000m underground

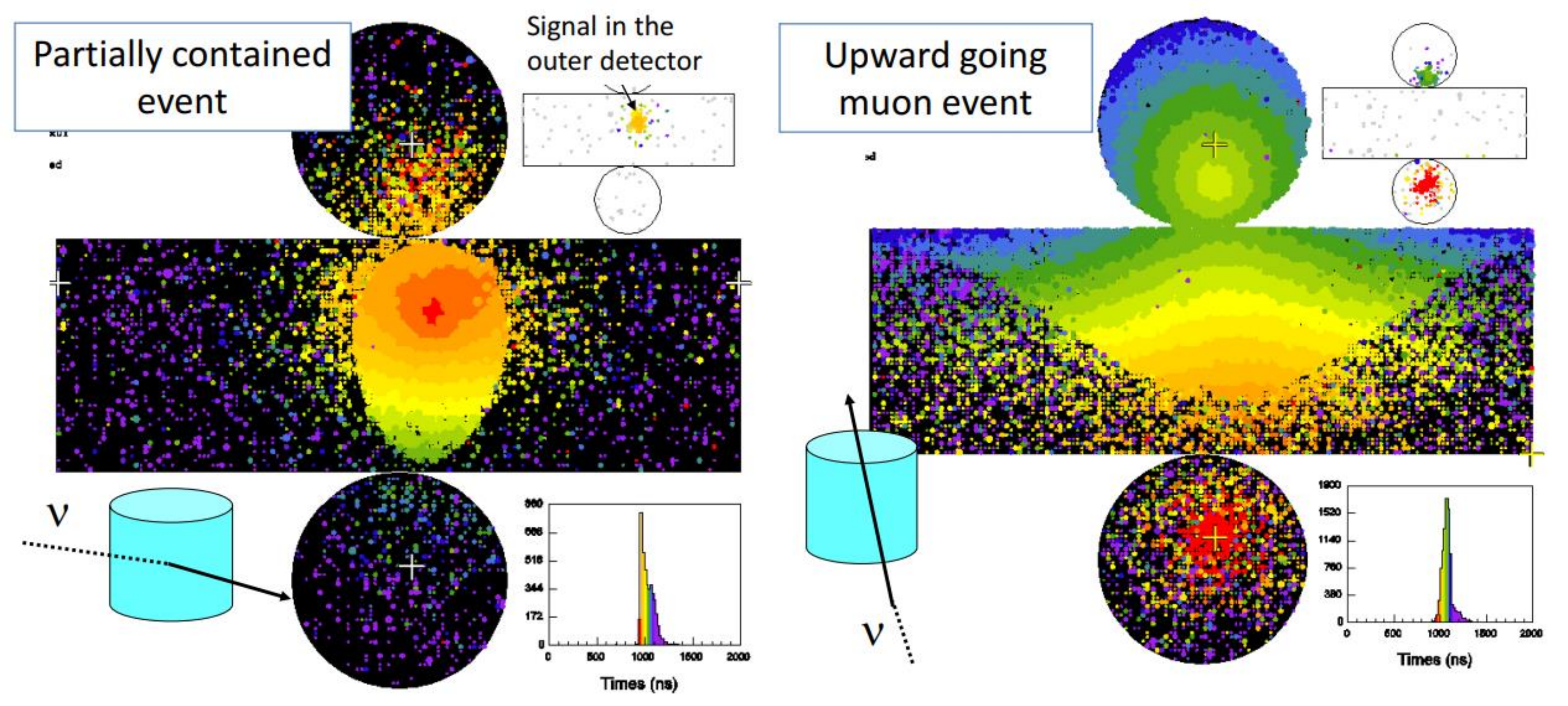
POSSIBLE NEUTRINO EVENTS


Single Cherenkov ring event

Multi Cherenkov ring event

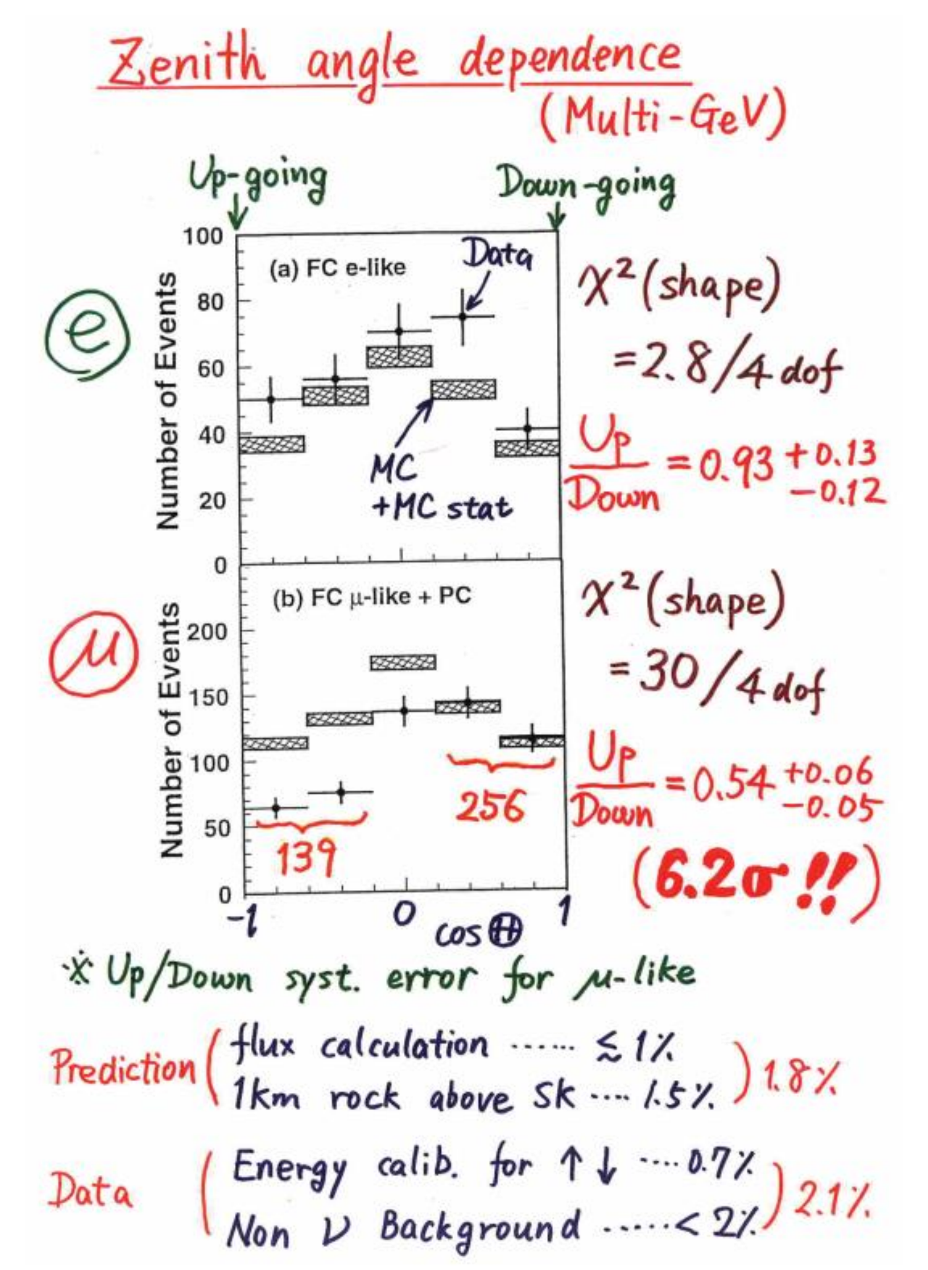
Size = pulse height
Color = time

POSSIBLE NEUTRINO EVENTS



RESULTS

- cosθ = 1 down-going neutrino
- Shaded boxes are predictions
- Crosses are observations
- All things considered 6.2σ
  - ~1 in 1.8 billion



Zenith angle dependence
(Multi-GeV)

χ^2(shape) = 2.8/4 dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) = 30/4 dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ!!)

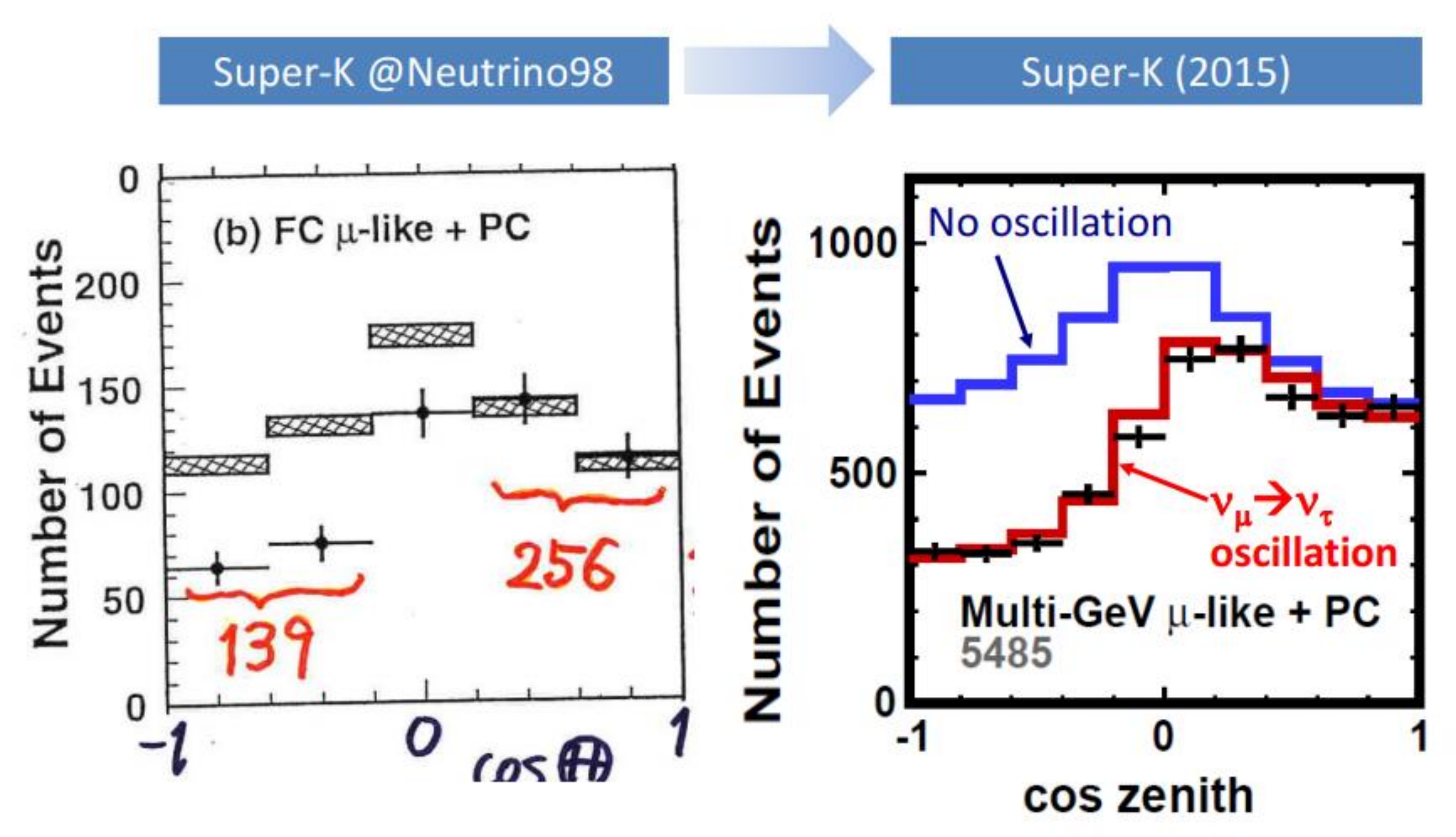
※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1%, 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7%, Non ν Background …. < 2%) 2.1%

MORE DATA

- 1998 data contains 531 events
- 2015 data contains 5485 events
- Heaviest neutrino ~10,000,000 times smaller than electron
- ν_μ oscillate maximally to ν_τ



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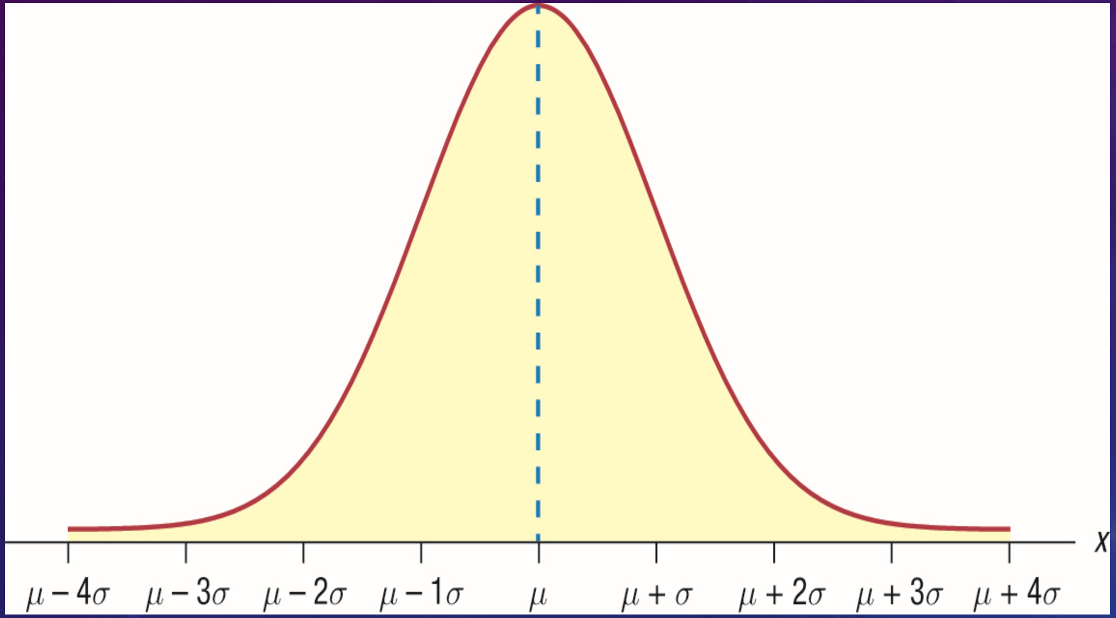
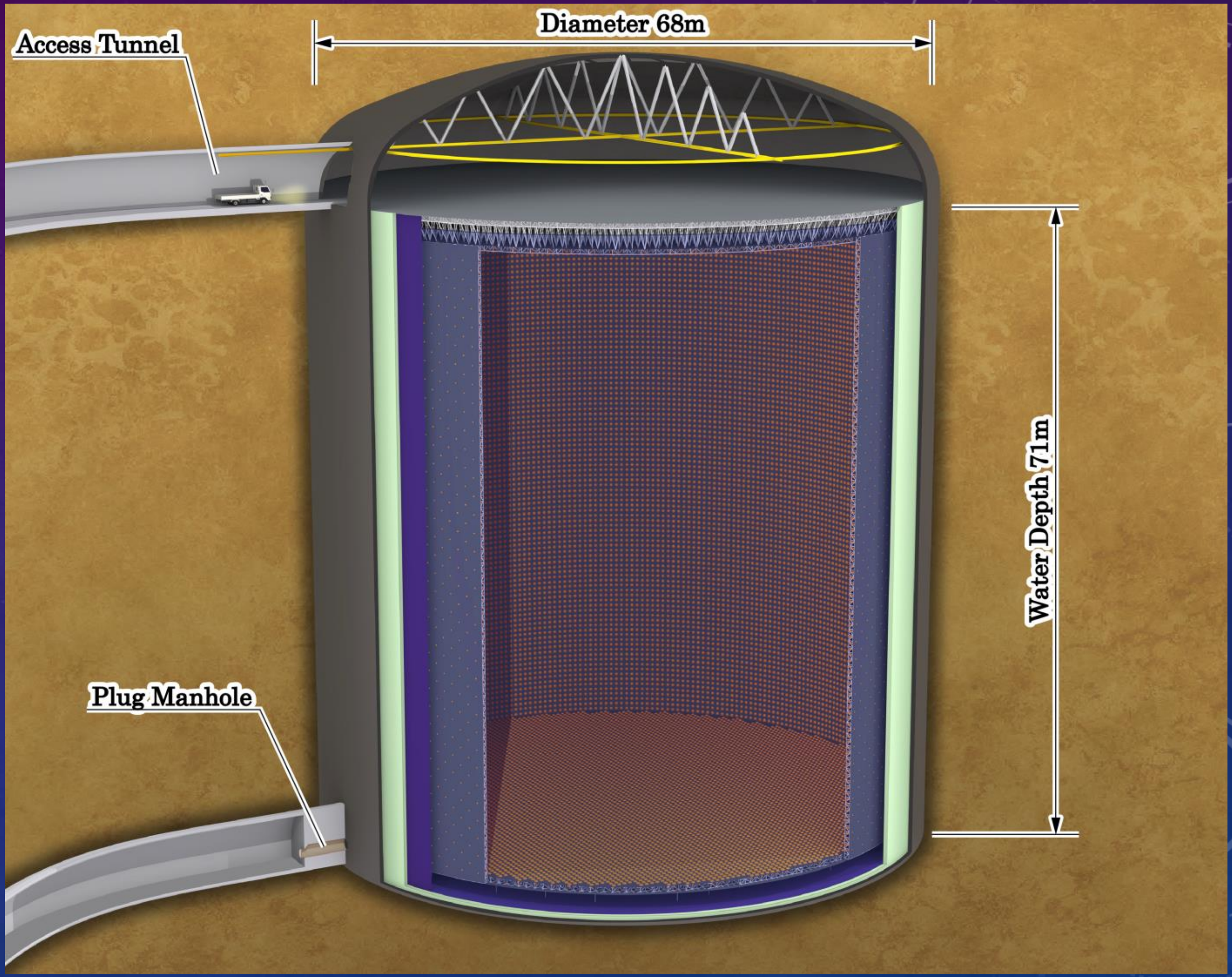
GAUSSIAN DISTRIBUTION



μ ± Nσ	% within range	Daily Frequency
1	68.26894921%	Twice a week
2	95.44997361%	Every three weeks
3	99.73002039%	Yearly
4	99.99366575%	Every 43 years
5	99.99994267%	Every 4776 years
6	99.99999980%	Every 1.38 M years

WHAT NEXT

- Even bigger detector, Hyper-Kamiokande
  - To start taking data in second half of 2020’s
  - 50,000 -> 260,000 tons of water
  - 11,000 -> 40,000 PMT
- Goals are to
  - Order neutrino masses
  - CP violation measurement
  - Proton decay



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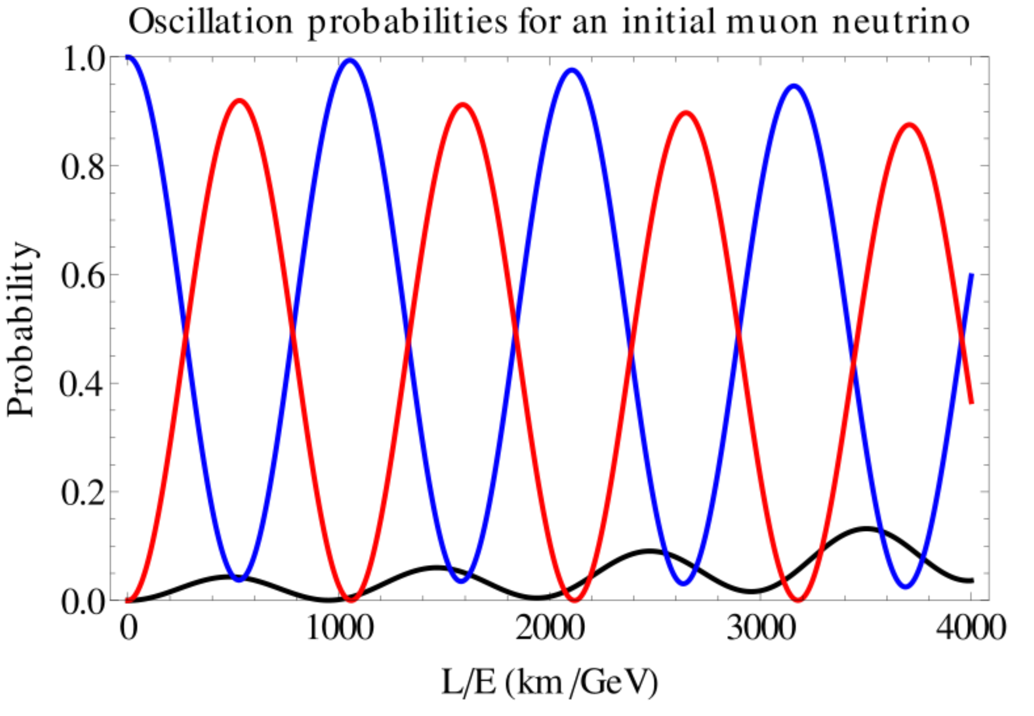
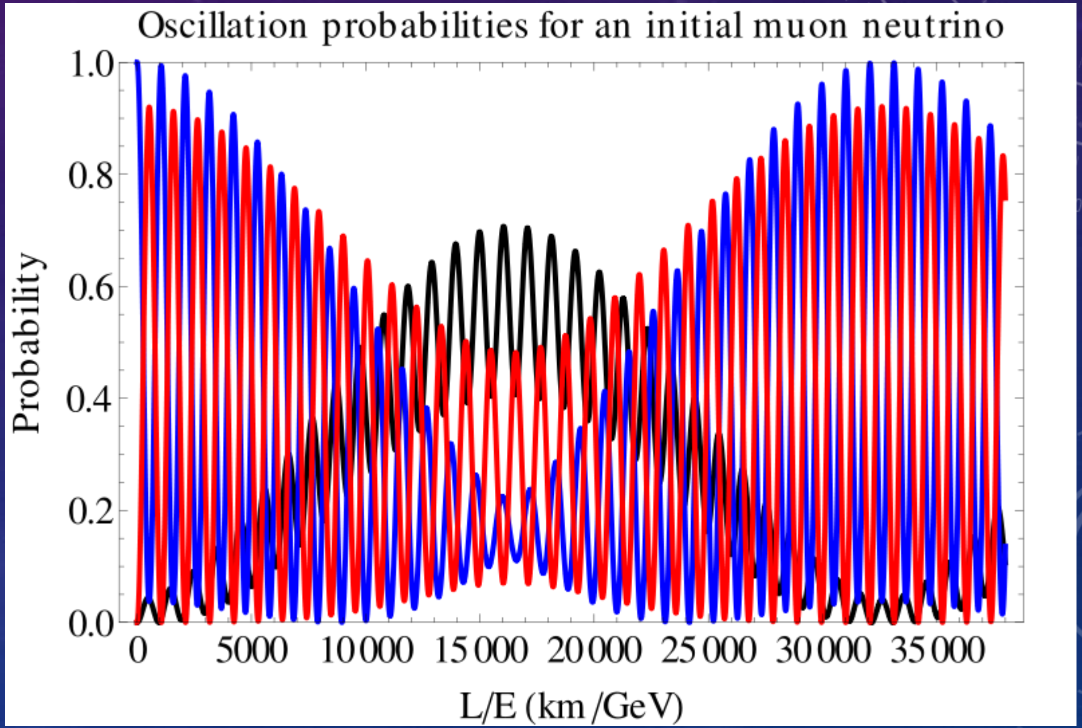
ACKNOWLEDGEMENTS

- Takaaki Kajita – Nobel Lecture. NobelPrize.org. Nobel Media AB 2021. Thu. 4 Mar 2021. https://www.nobelprize.org/prizes/physics/2015/kajita/lecture/
- Hyper Kamiokande Goals – http://www.hyper-k.org/en/physics.html
- Neutrino Oscillation Calculations – http://www.ps.uci.edu/~superk/oscmath2.html
- Kamiokande Expectations – K. Hirata et al, Phys.Lett.B 205 (1988) 416

THREE NEUTRINO OSCILLATIONS





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