

The background is a dark blue gradient with a starry texture. On the left side, there are several overlapping circular elements. A prominent one is a large circle with a scale around its perimeter, ranging from 140 to 260 in increments of 10. Other circles are smaller and some have dashed lines or arrows, suggesting motion or cycles. The overall aesthetic is scientific and technical.

DISCOVERY OF NEUTRINO OSCILLATIONS

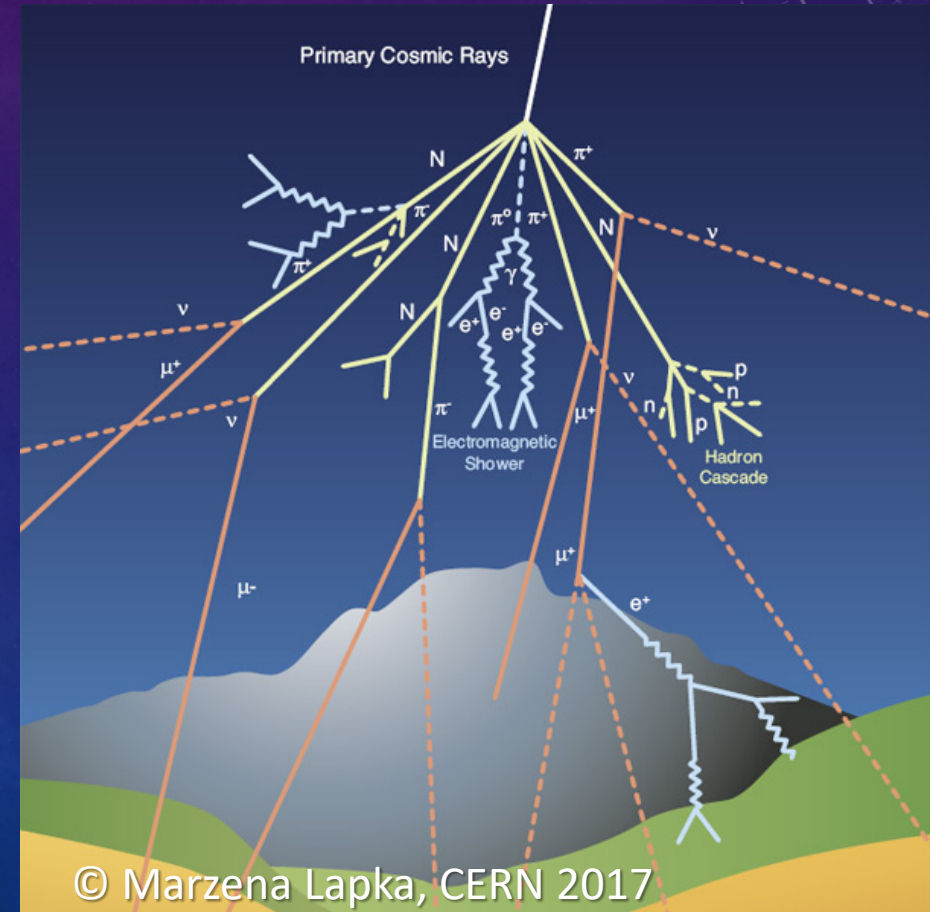
FRANKLIN ADAMS

KAMIOKANDE

- Kamioka Nucleon Decay Experiment
 - 3000 tons of water
 - 1000 50cm PMTs
 - 1000m underground
- Built in 1983 to detect proton decay
- Cherenkov radiation detector
- By 1986, no evidence of proton decay
- Suspected that software was not good enough
- New software was tested on single Cherenkov-ring events
- Unexpected result
 - Much fewer ν_{μ} than expected
 - Audit of software showed it was right

COSMIC RAY DECAY

- Cosmic Ray enters the atmosphere
- Produces a $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Should expect $\sim 2 \nu_\mu$ per ν_e



RESULTS OF KAMIOKANDE

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 :

$$\begin{aligned} \begin{pmatrix} \nu_1(\vec{x}, t) \\ \nu_2(\vec{x}, t) \end{pmatrix} &= e^{i\vec{p}\cdot\vec{x}} \begin{pmatrix} e^{-iE_1 t} |\nu_1(0)\rangle \\ e^{-iE_2 t} |\nu_2(0)\rangle \end{pmatrix} \\ &= e^{i\vec{p}\cdot\vec{x}} \begin{pmatrix} e^{-iE_1 t} & 0 \\ 0 & e^{-iE_2 t} \end{pmatrix} \begin{pmatrix} |\nu_1(0)\rangle \\ |\nu_2(0)\rangle \end{pmatrix} \end{aligned}$$

Using the relation between mass and flavor eigenstates :

$$\begin{pmatrix} |\nu_\mu(\vec{x}, t)\rangle \\ |\nu_\tau(\vec{x}, t)\rangle \end{pmatrix} = e^{i\vec{p}\cdot\vec{x}} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} e^{-iE_1 t} & 0 \\ 0 & e^{-iE_2 t} \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_\mu(0)\rangle \\ |\nu_\tau(0)\rangle \end{pmatrix}$$

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

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

WHY DOES NEUTRINO OSCILLATION IMPLY MASS

If $E_1, E_2 \gg m_1, m_2$:

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

and

$$\begin{aligned} t &\approx |\vec{x}| \equiv L, \\ p &\approx E \end{aligned}$$

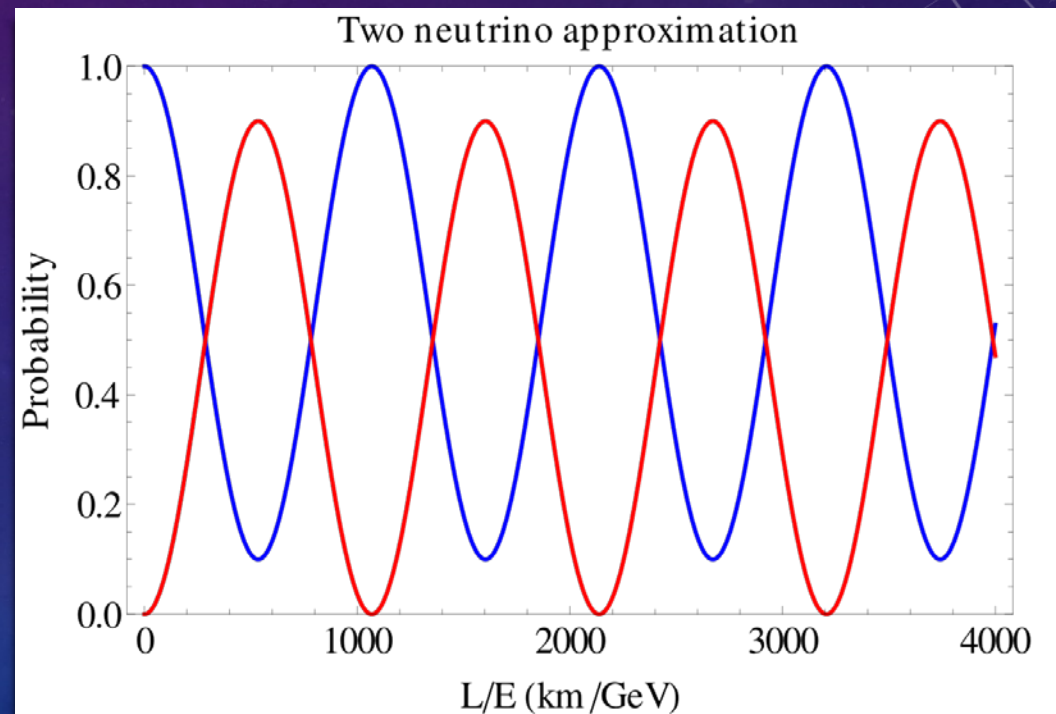
Therefore:

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

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

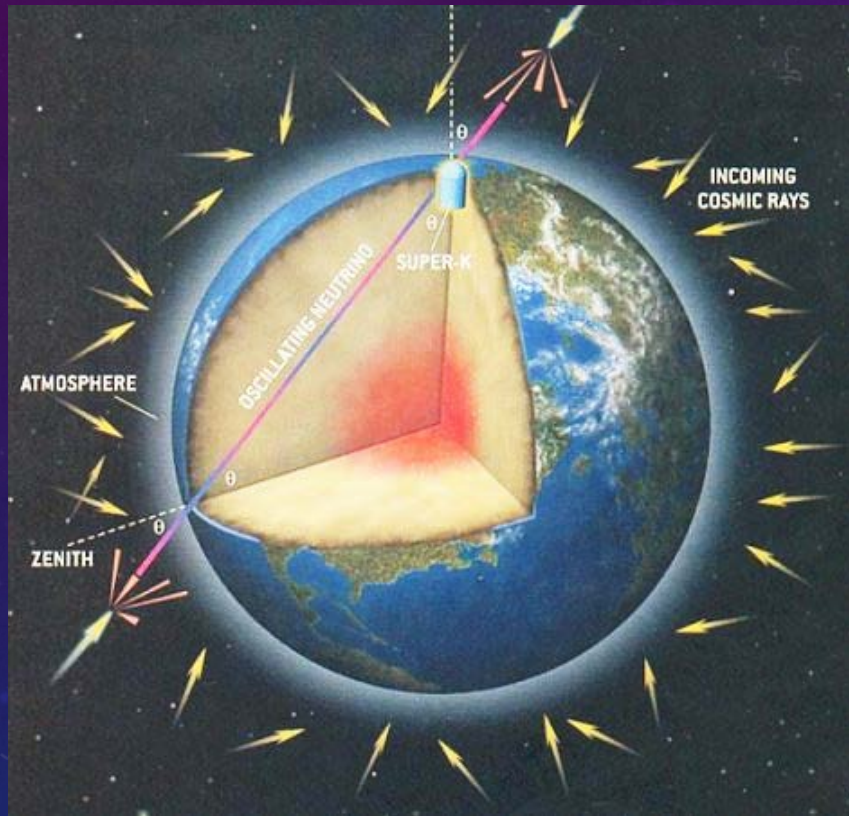
NEUTRINO OSCILLATION CONDITIONS

- In the case of $\nu_\mu \rightarrow \nu_\tau$ 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



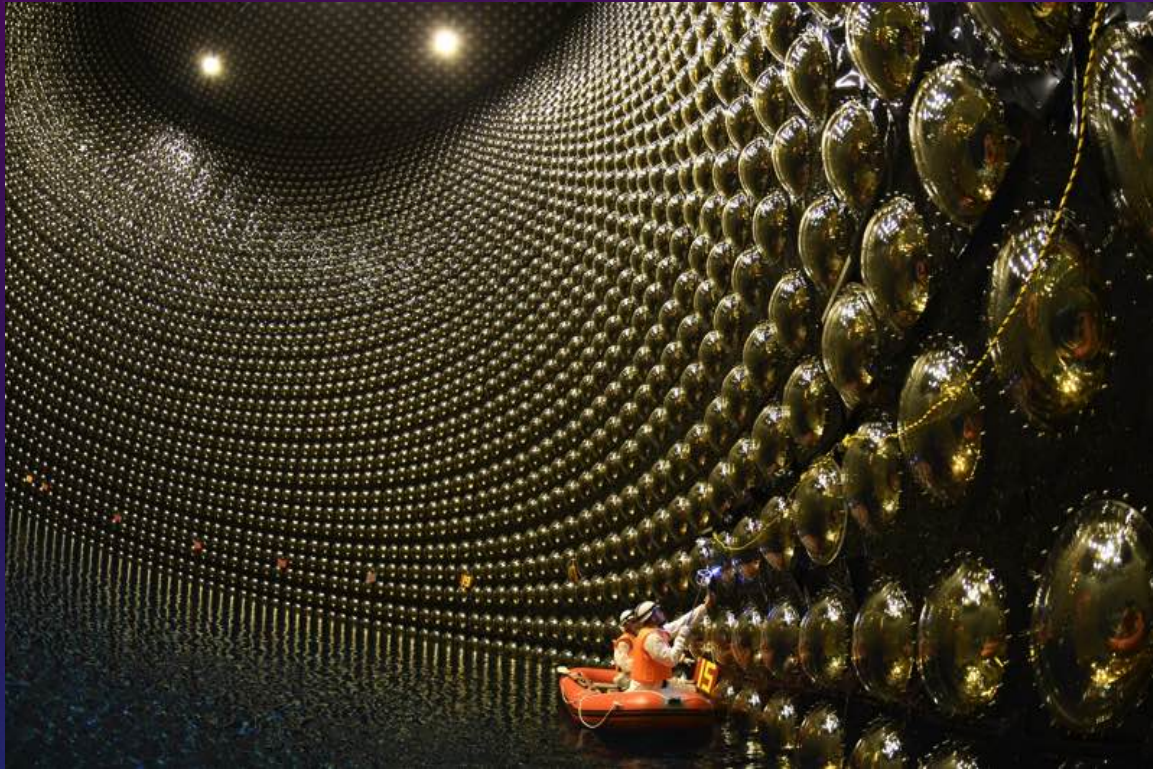
© Wikipedia, Neutrino oscillation 2011

NEUTRINO OSCILLATION CONDITIONS



- 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

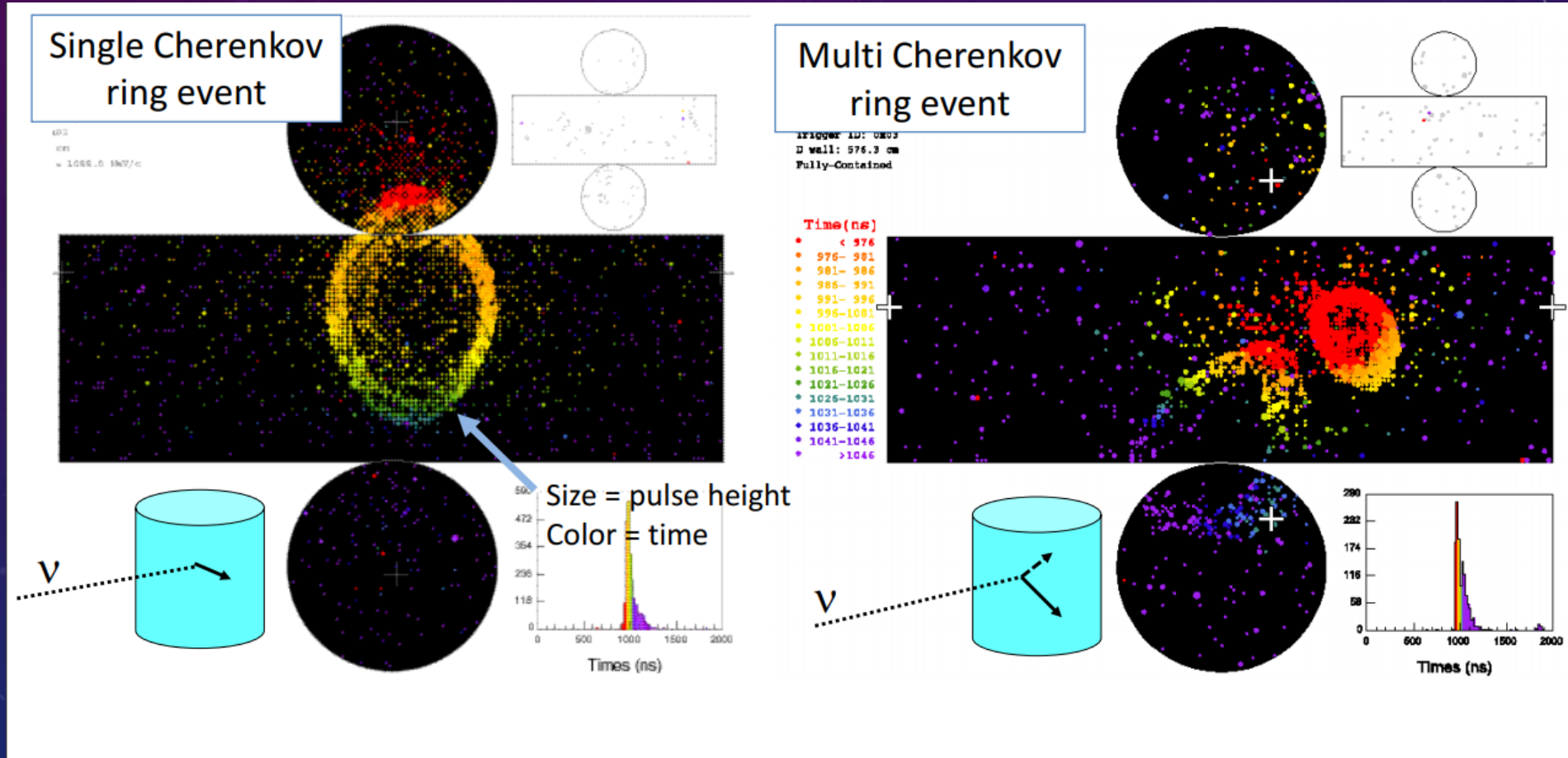
SUPER-KAMIOKANDE



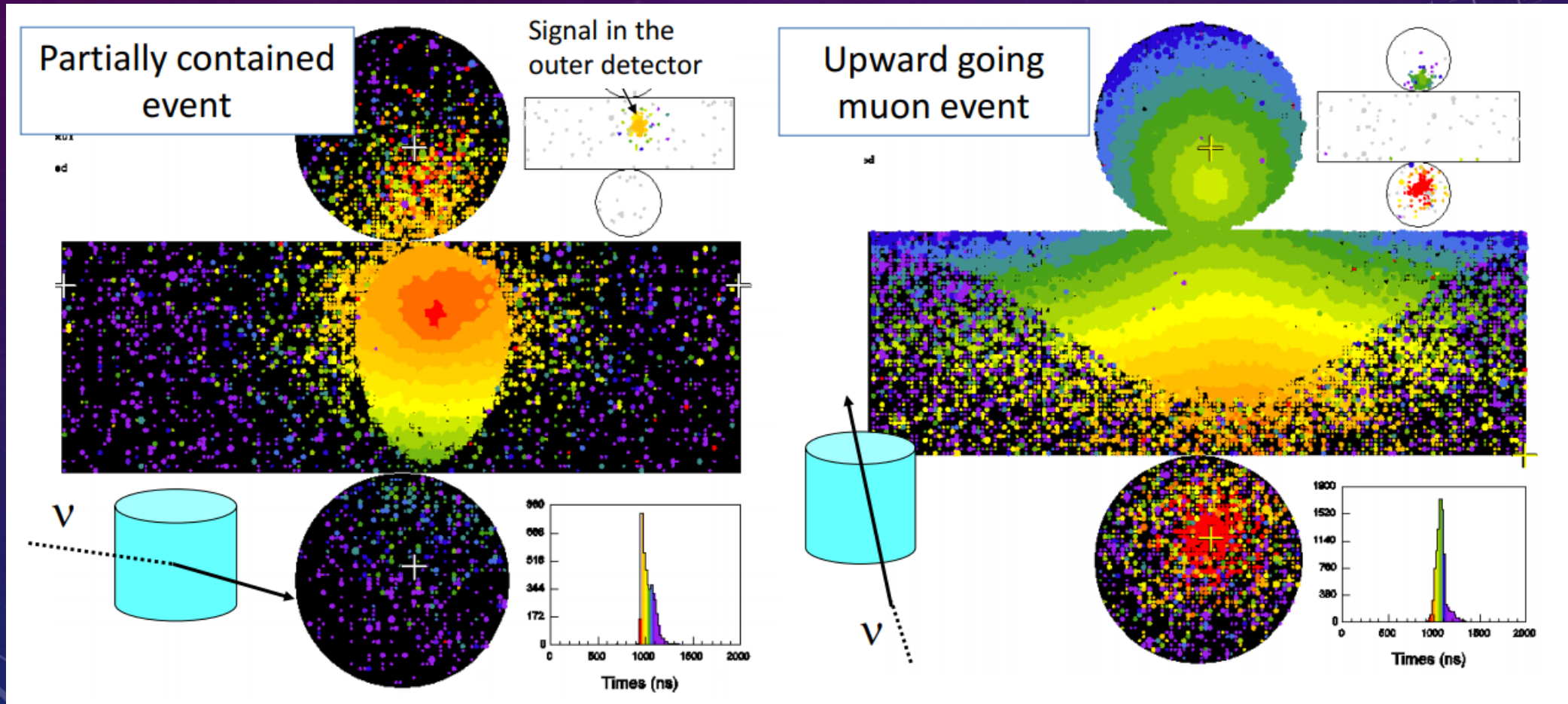
© Kamioka Observatory 2018

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

POSSIBLE NEUTRINO EVENTS



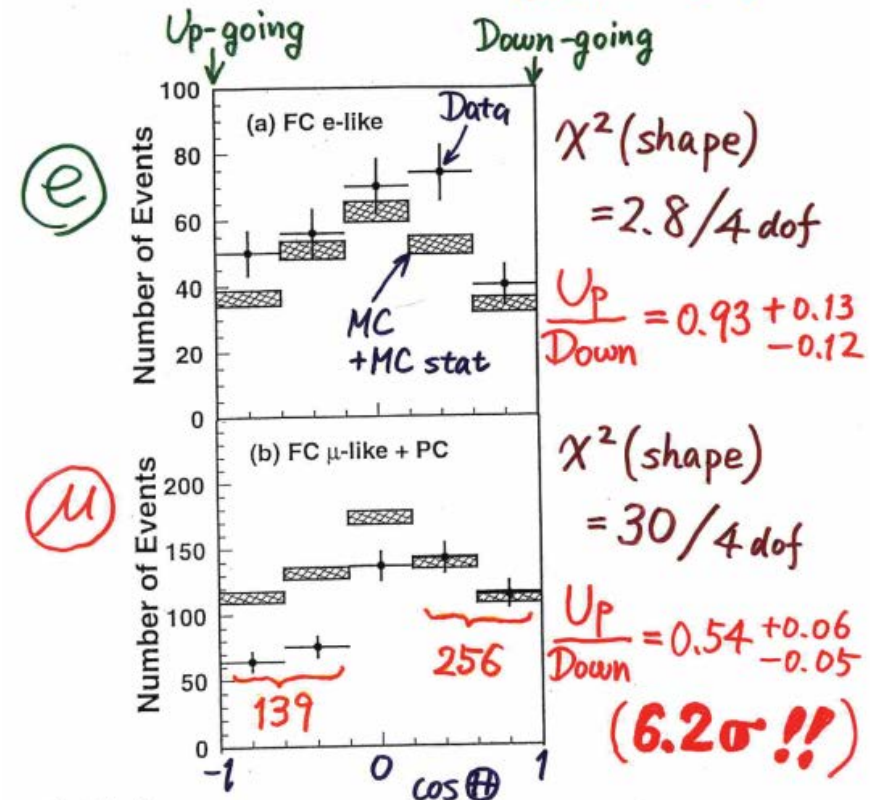
POSSIBLE NEUTRINO EVENTS



RESULTS

- $\cos\theta = 1$ 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)



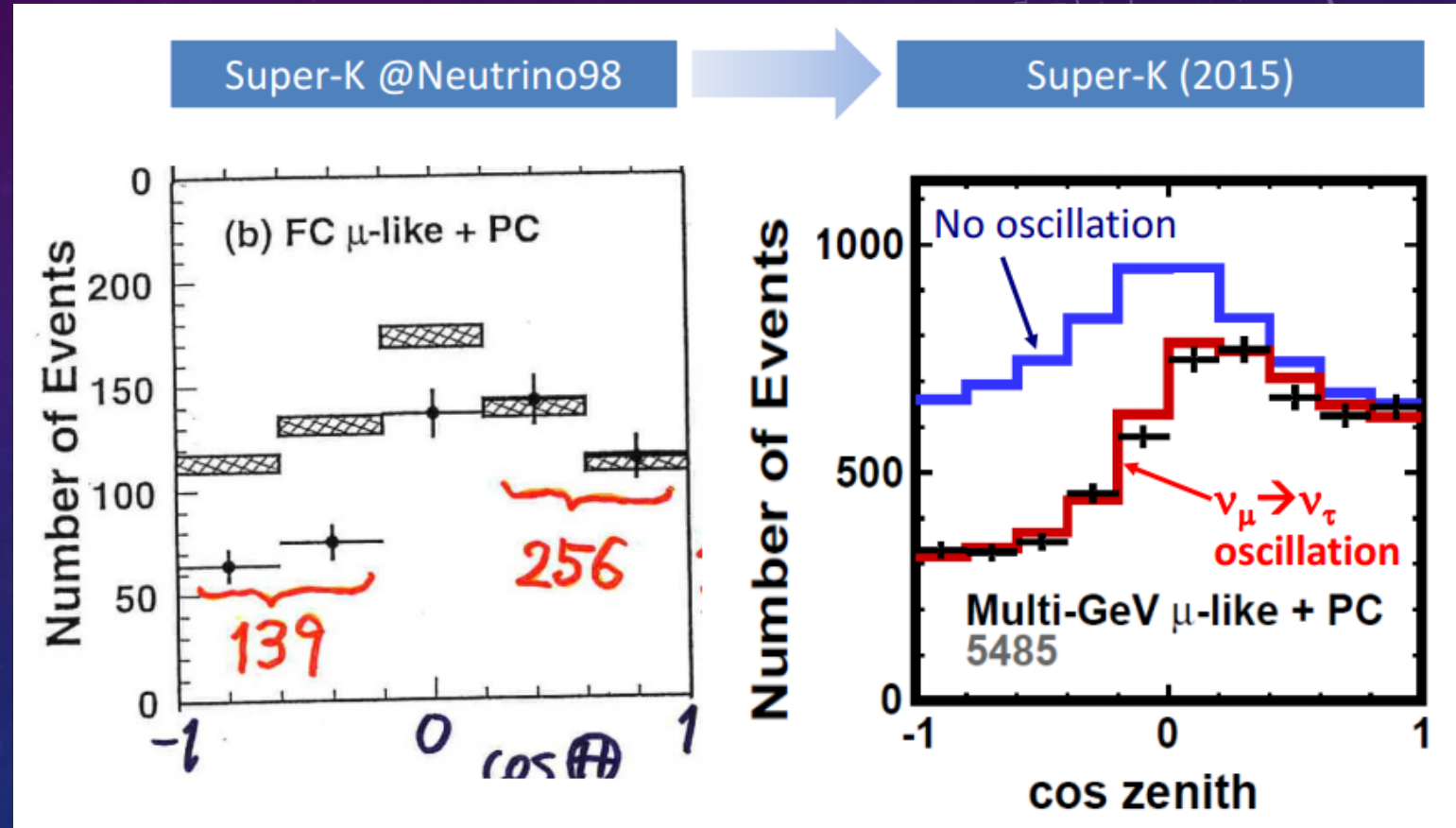
* Up/Down syst. error for μ -like

Prediction (flux calculation $\dots \lesssim 1\%$
1km rock above SK $\dots 1.5\%$) 1.8%

Data (Energy calib. for $\uparrow\downarrow \dots 0.7\%$
Non ν Background $\dots < 2\%$) 2.1%

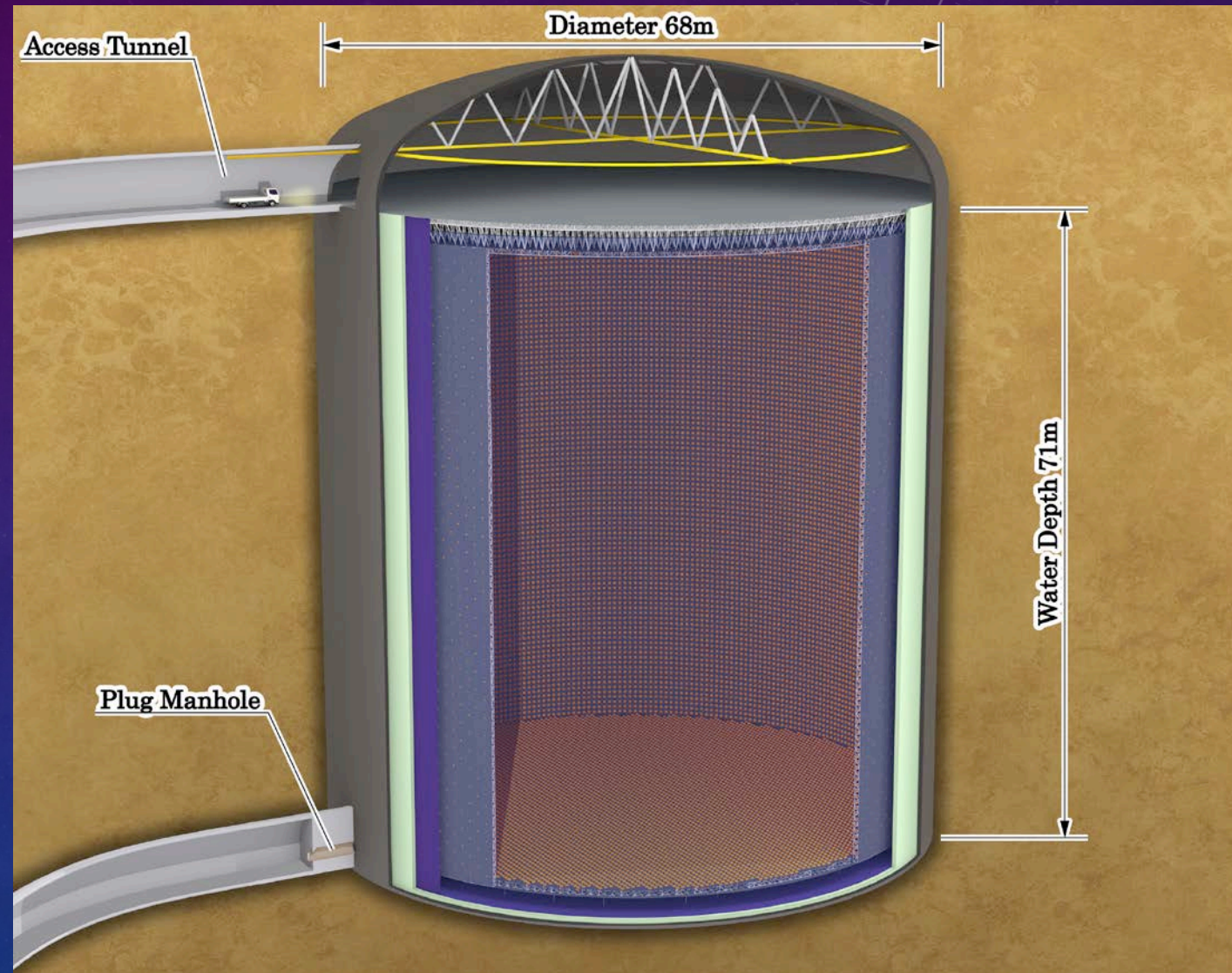
MORE DATA

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



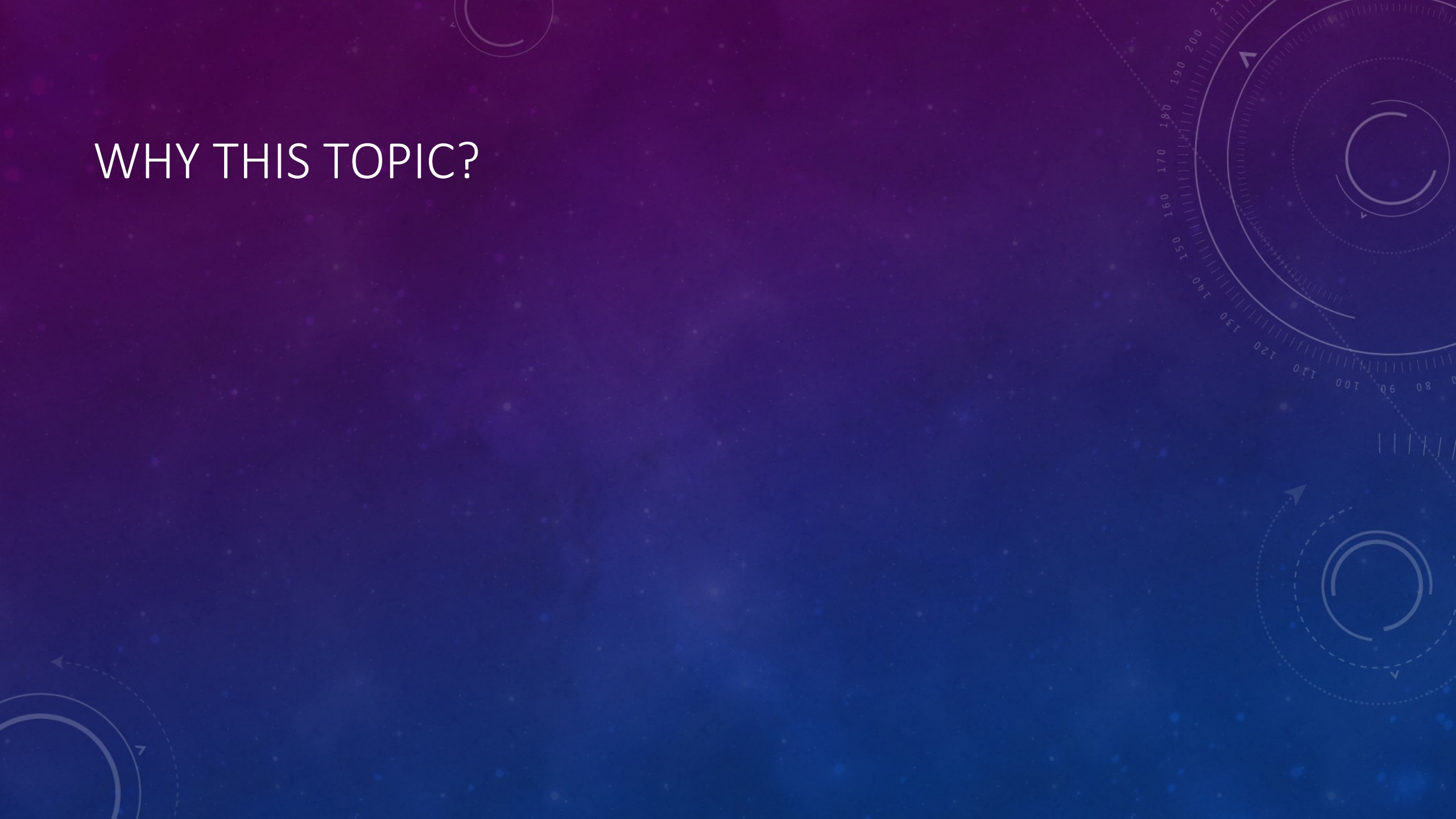
WHAT NEXT

- 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
 - Intends to order neutrino masses



© Hyper-Kamiokande Collaboration, hyper-k.org 2019

WHY THIS TOPIC?



QUESTIONS?

