DISCOVERY OF NEUTRINO OSCILLATIONS

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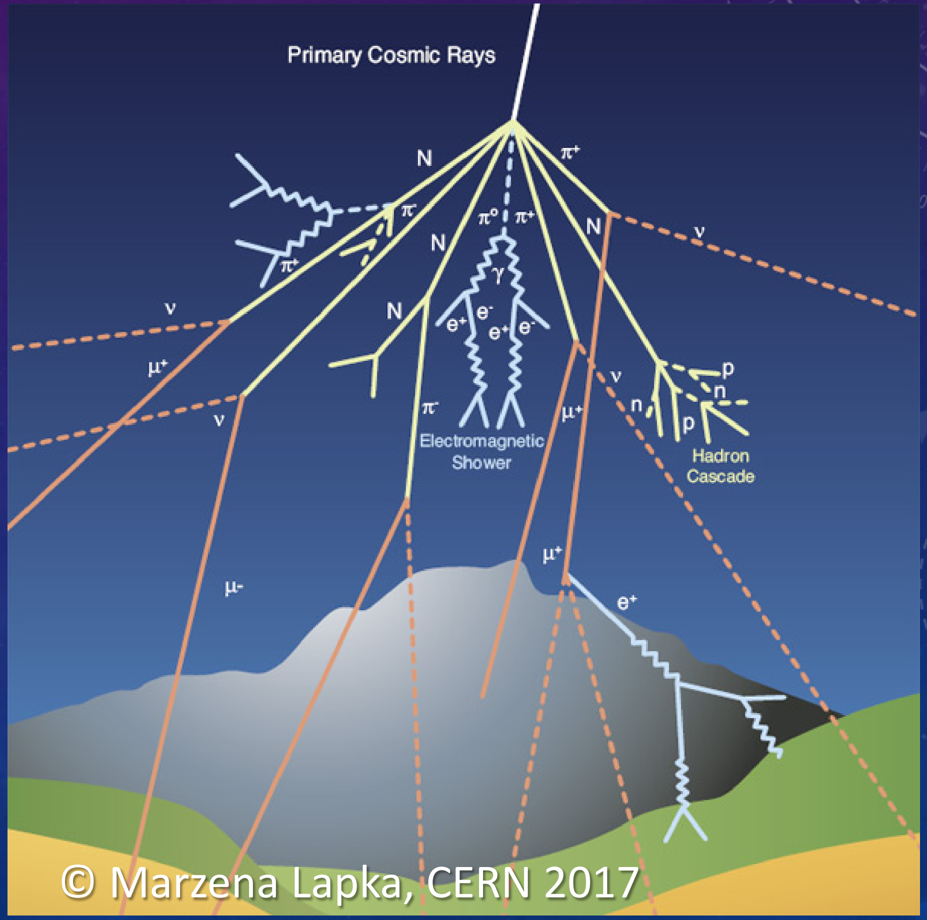
KAMIOKANDE

- 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 $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$
- Should expect ~2 ν_μ 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:

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

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

Using the relation between mass and flavor eigenstates:

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

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

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

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

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

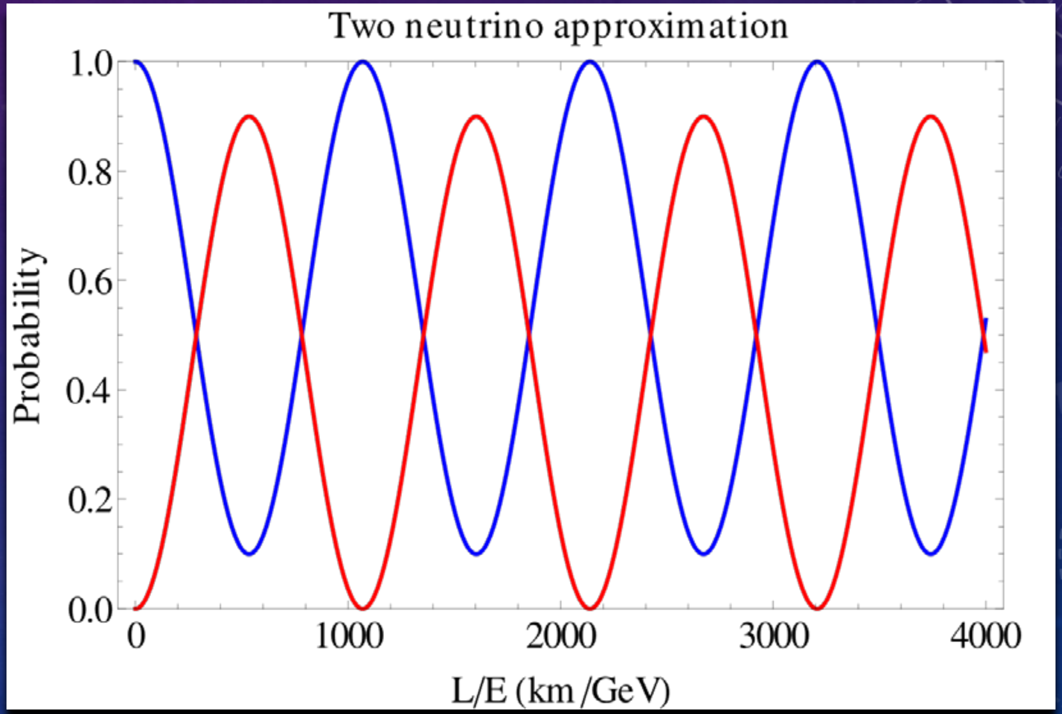
Therefore :

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

- 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

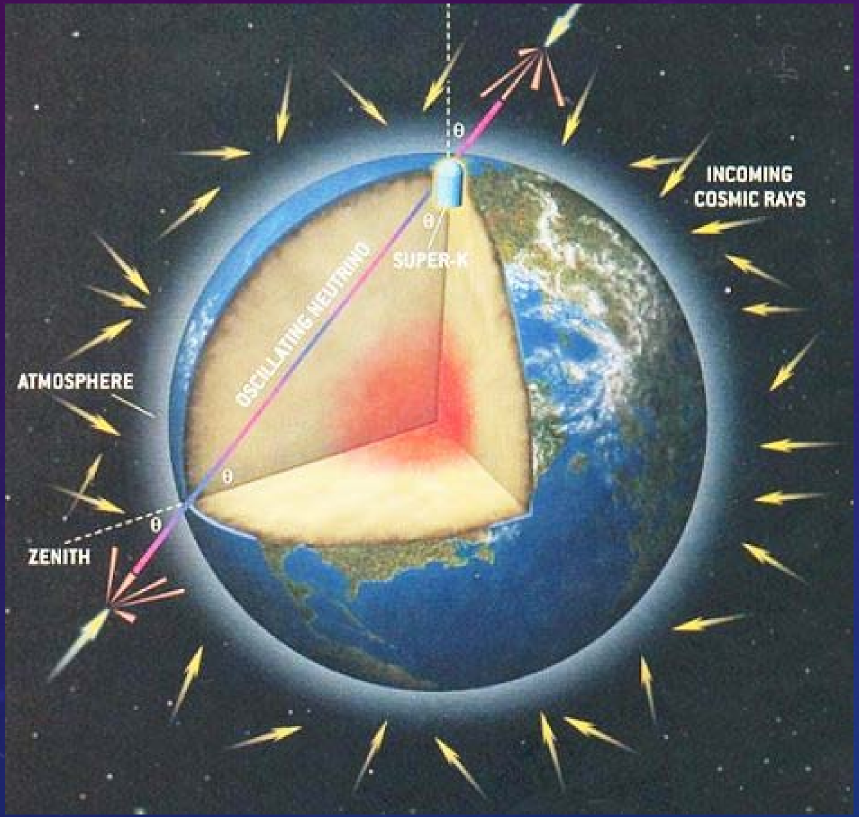
NEUTRINO OSCILLATION CONDITIONS

- 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



© Wikipedia, Neutrino oscillation 2011

NEUTRINO OSCILLATION CONDITIONS



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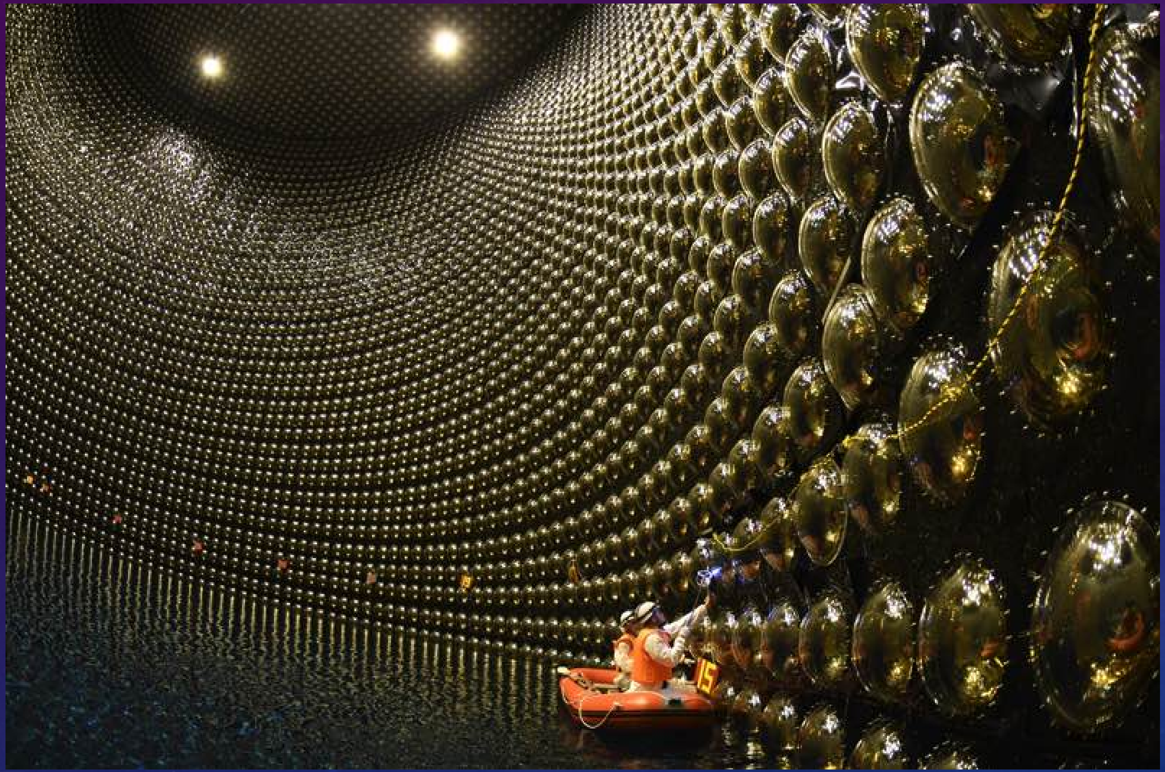
- Should observe a deficit in ν_μ that pass through the earth
  - Upward going ν_μ
- Want to create conditions to observe oscillations
- Kamiokande was not enough to be conclusive
- Need a much larger detector

SUPER-KAMIOKANDE



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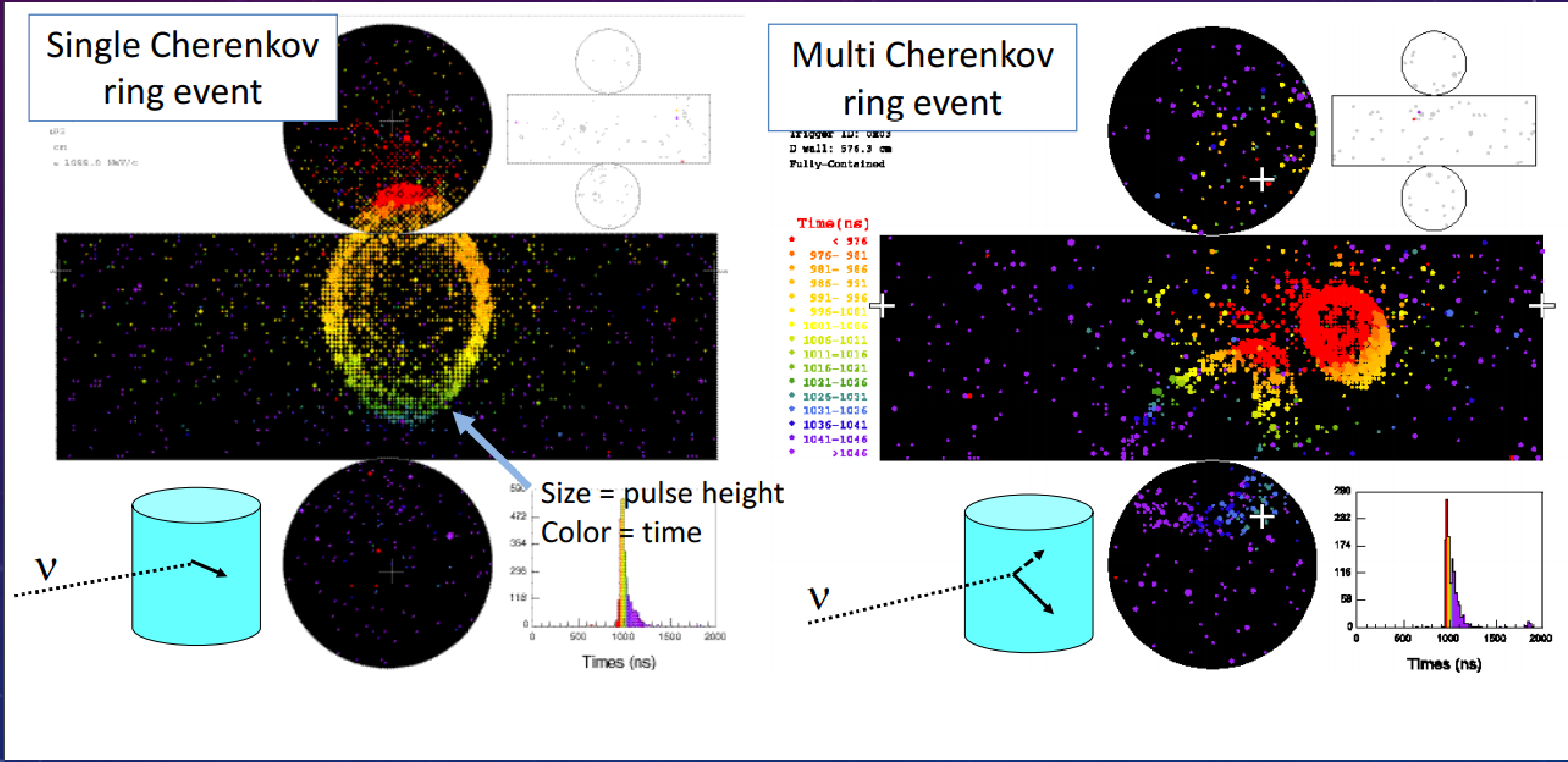
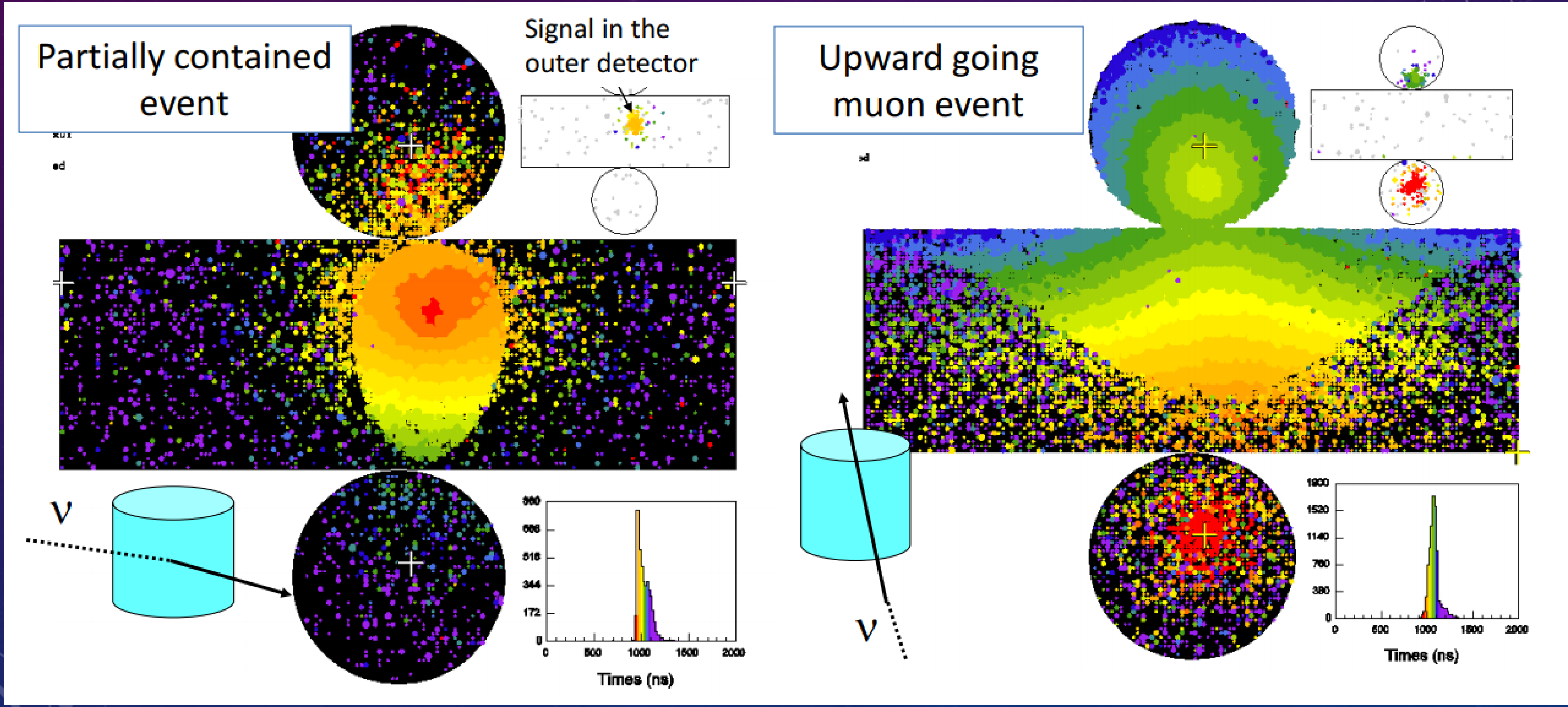
- 3000 -> 50,000 ton water Cherenkov Detector
- 1000 -> 13,000 PMT
- 1000m underground

POSSIBLE NEUTRINO EVENTS

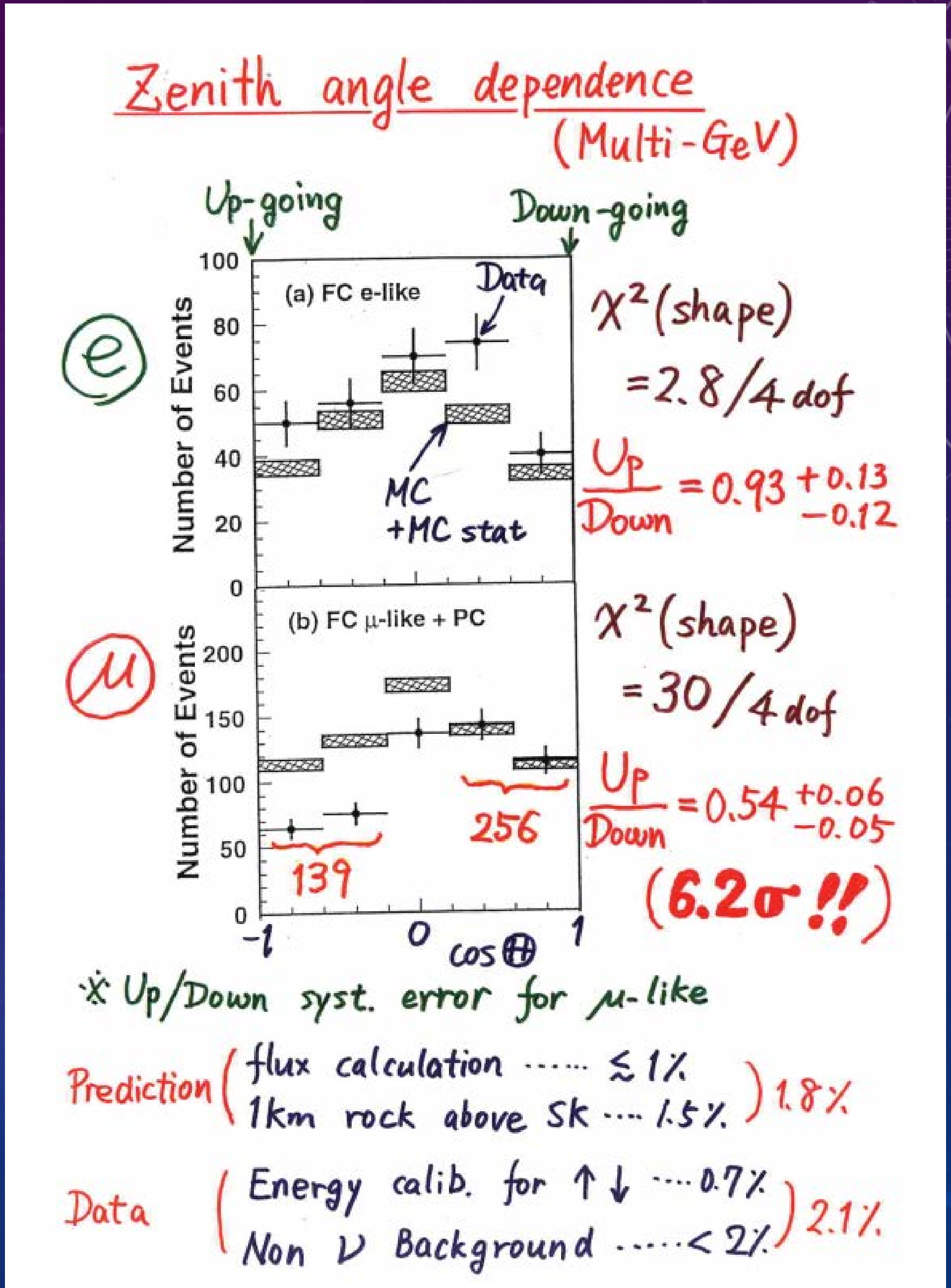


POSSIBLE NEUTRINO EVENTS



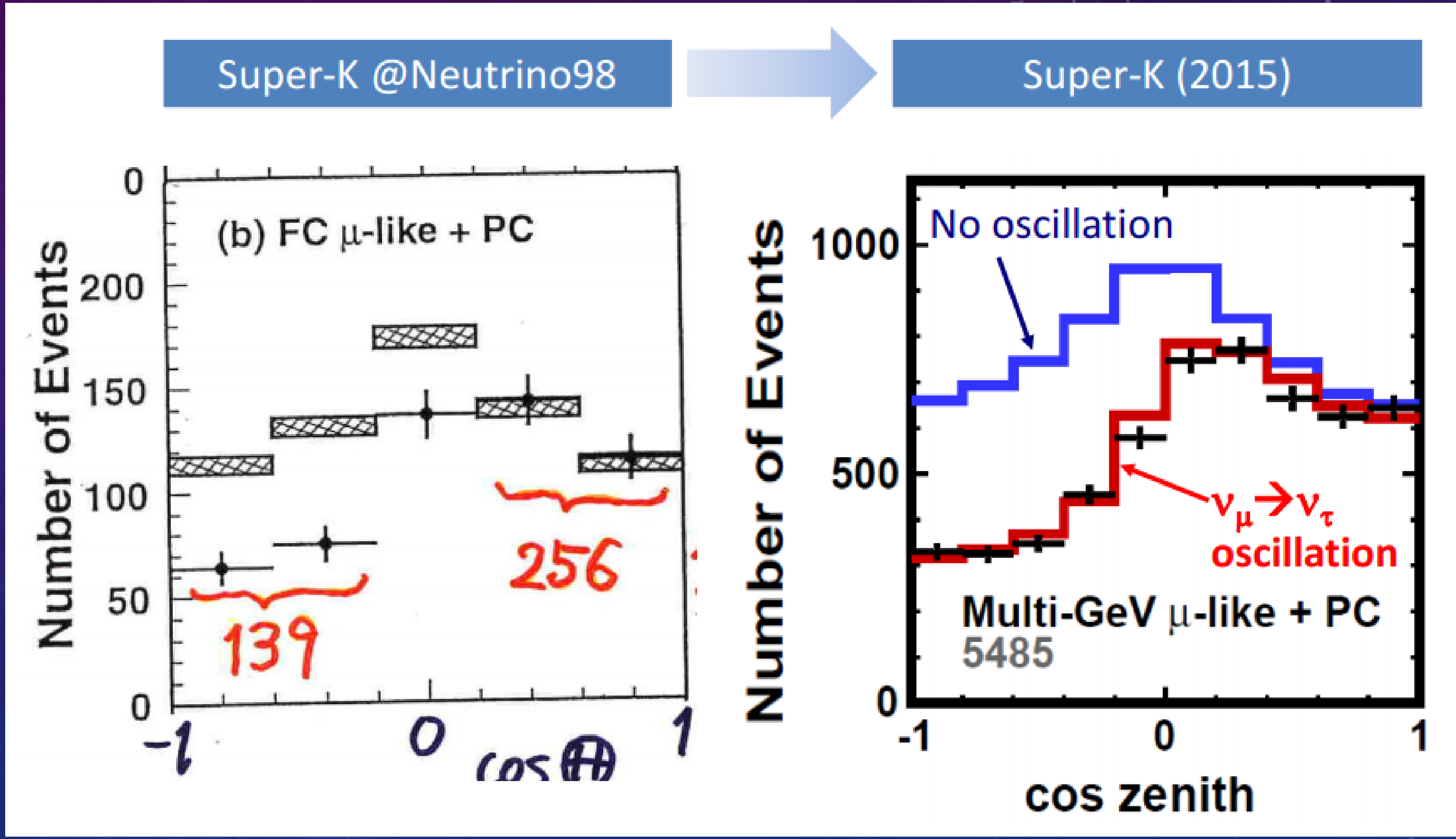
RESULTS

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



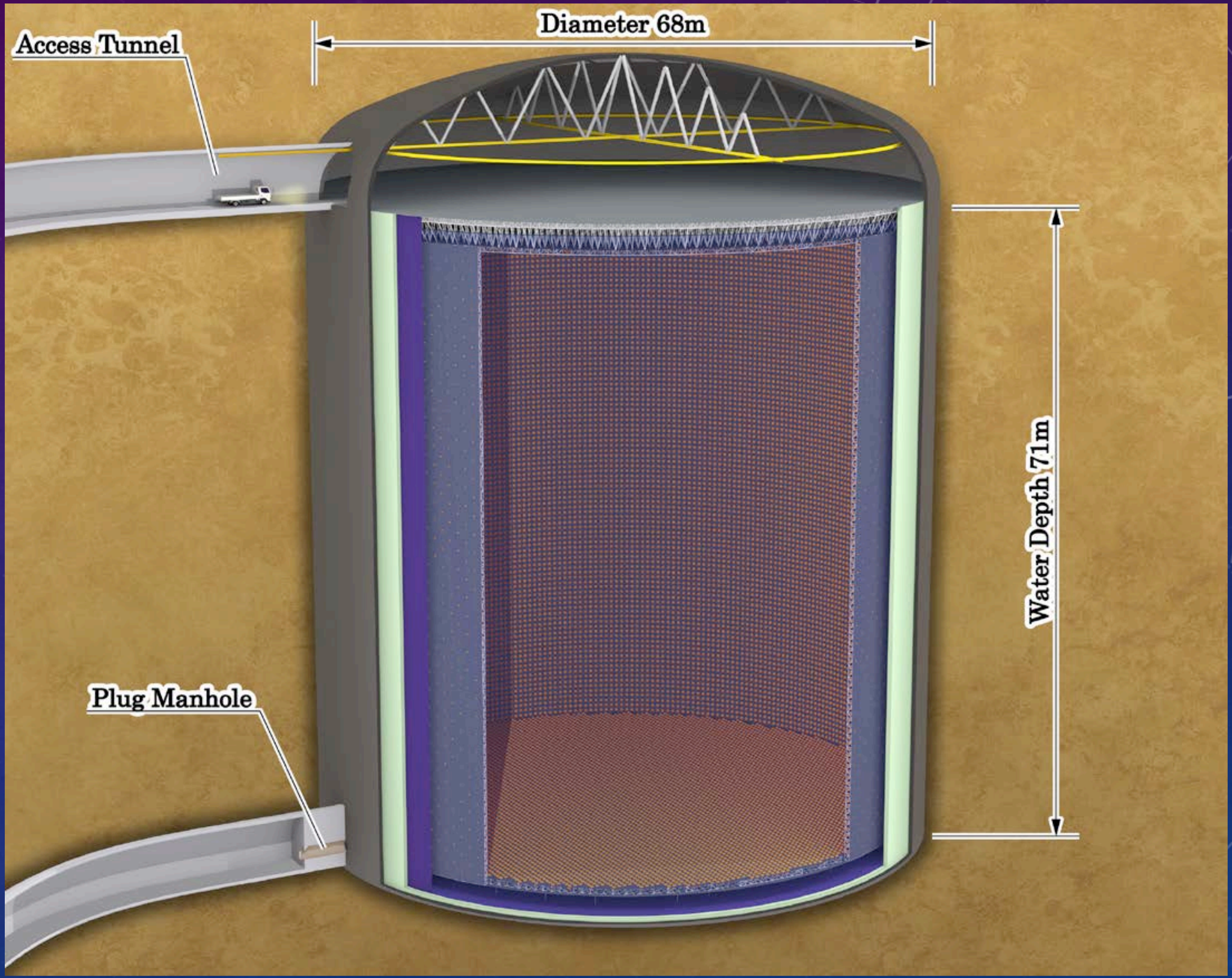
MORE DATA

- 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



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



WHY THIS TOPIC?

QUESTIONS?