

# Neutrino Oscillation Experiments

(Necessarily) Selected topics  
(i.e., an abbreviated story)

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*The University of Texas at Austin*



**GraSPA 2014**

Summer School in **Particle and Astroparticle physics**  
of Annecy-le-Vieux

21-25 July 2014

**Partners:**

- IAPP**
- LAPTh**
- CNRS**
- IN2P3**  
Les deux Infinis
- EnigmaSS**
- PTIGA**  
Centre de Physique Théorique Grenoble-Alpes
- ICPASC**

## OUTLINE:

- ◆ Neutrino puzzles resolved
  - ⇒ Solar neutrino deficit
  - ⇒ Atmospheric neutrino anomaly
- ◆ Some neutrino oscillations QM
  - ⇒ A little formalism
  - ⇒ Approximations and
- ◆ 2-v disappearance
  - ⇒ Reactor experiments
  - ⇒ Accelerator experiments
- ◆ Precision experiments
- ◆ Appearance experiments
- ◆ What remains: loooong baselines

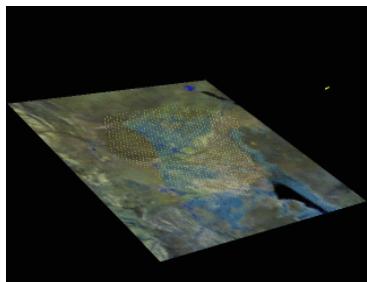
# Remarkable “Neutrino Years”

(painted with a broad brush)

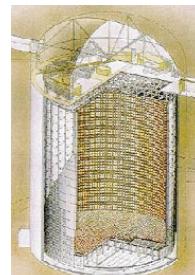
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< 1998

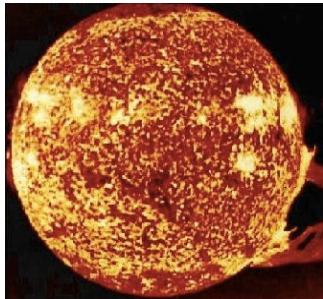
- $m_\nu = 0$ ,  $\nu = e, \mu, \tau$
- atmospheric neutrinos *anomaly*



$$\frac{N(\nu_\mu)}{N(\nu_e)} \neq 2$$

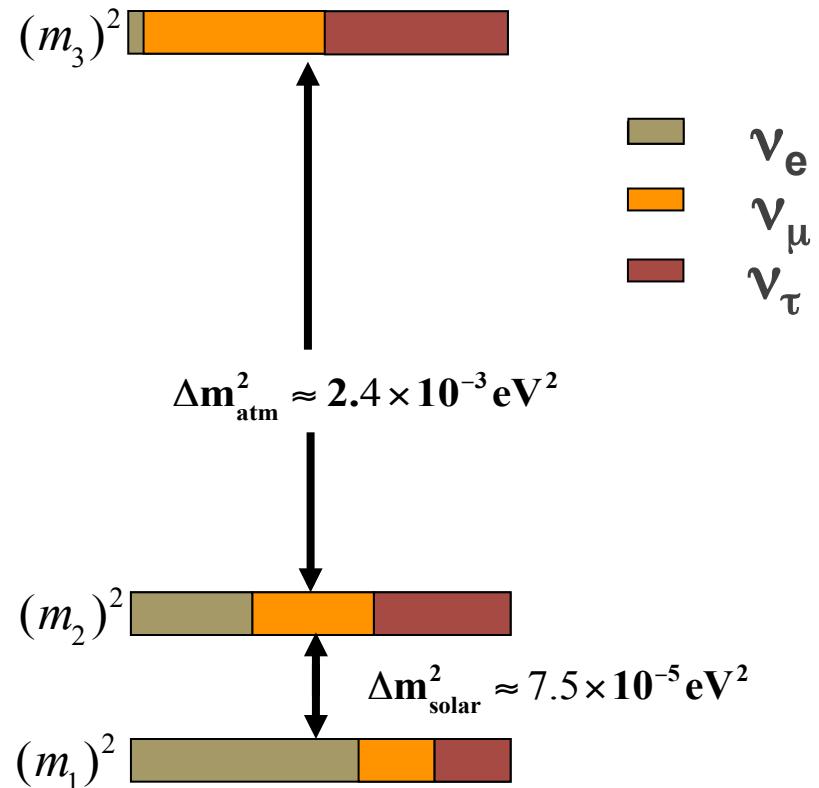


- solar neutrinos *deficit*



1998 - 2014

- neutrino oscillations  $\rightarrow m_\nu \neq 0$
- measured  $\Delta m_{sol}^2$  and  $\Delta m_{atm}^2$
- measured 3 out of 4 angles



# Remarkable “Neutrino Years”

(painted with a broad brush)

< 1998

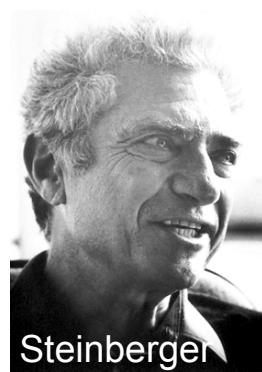
- $m_\nu = 0$ ,       $\nu = e, \mu, \tau$



Lederman

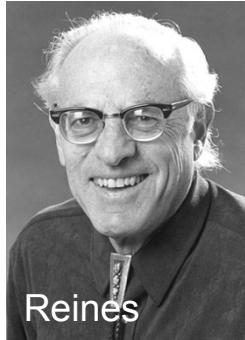


Schwartz



Steinberger

Nobel 1988



Reines



Pearl

Nobel 1995

1998 - 2014

- neutrino oscillations  $\rightarrow m_\nu \neq 0$
- measured  $\Delta m_{sol}^2$  and  $\Delta m_{atm}^2$
- measured 3 out of 4 angles



Davis



Koshiba

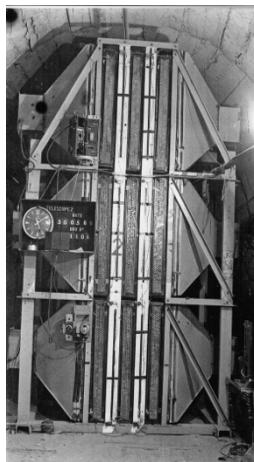
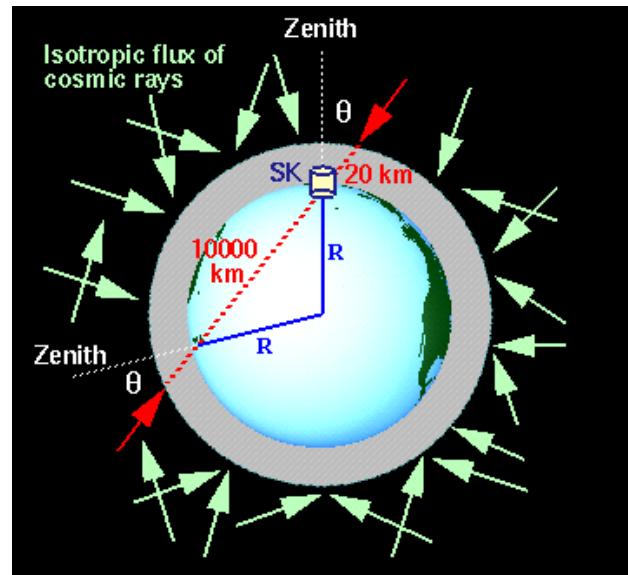
Nobel 2002

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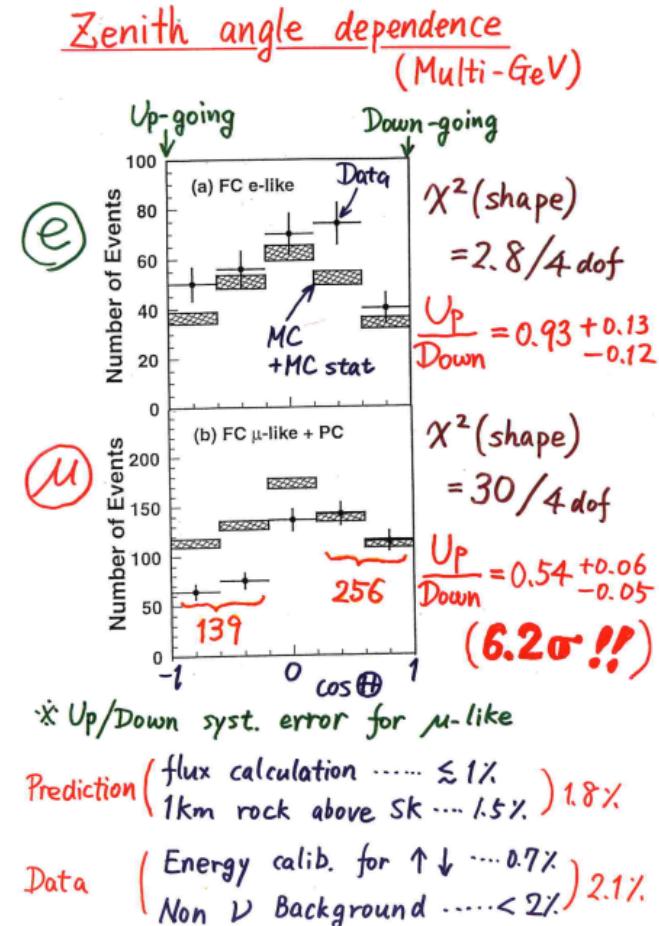
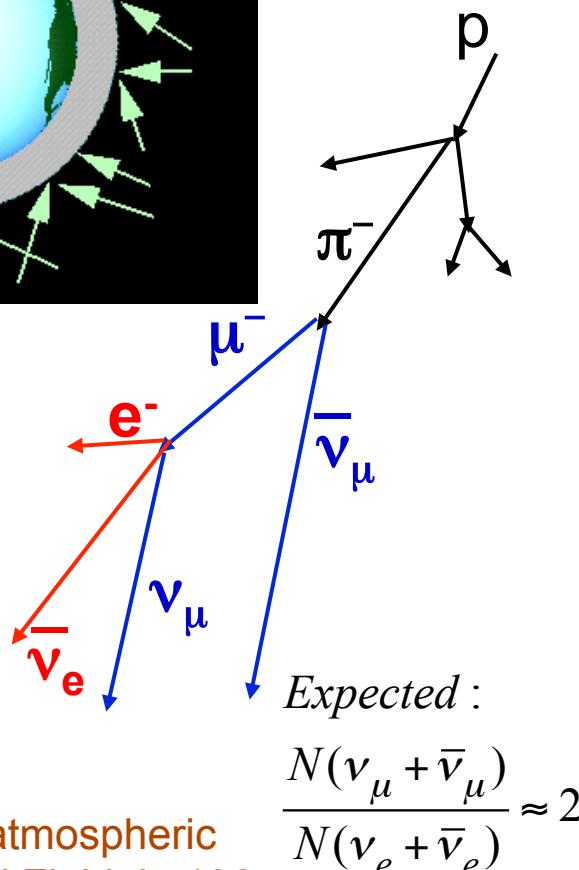
# **ATMOSPHERIC NEUTRINOS ANOMALY RESOLVED**

# Atmospheric neutrinos *anomaly* resolved

## The advent of LARGE detectors

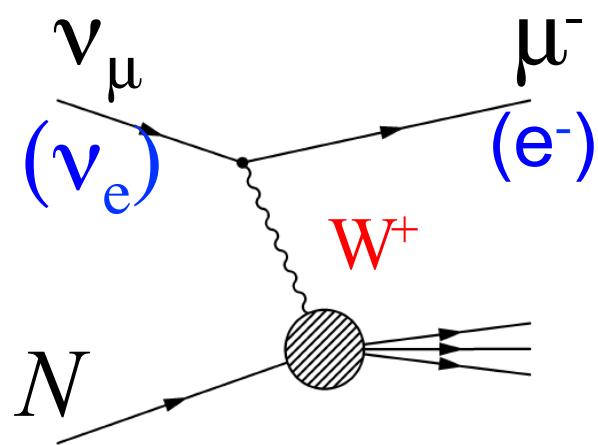


First detection of atmospheric neutrino at Kolar Gold Field in 1965

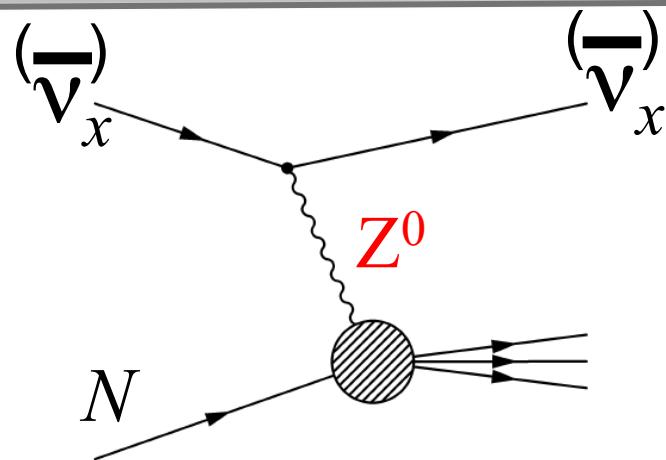


The announcement of the discovery  
of neutrino oscillation at Neutrino 98  
by T. Kajita

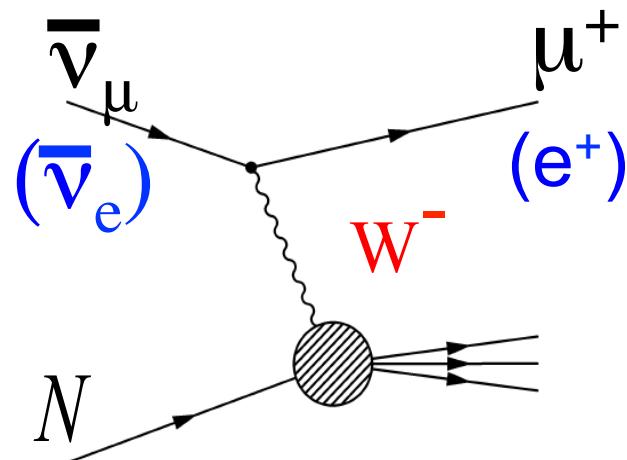
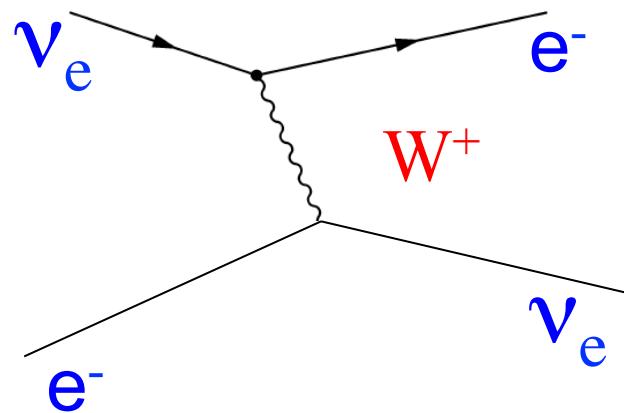
# Neutrino Interactions



**Charged Current**

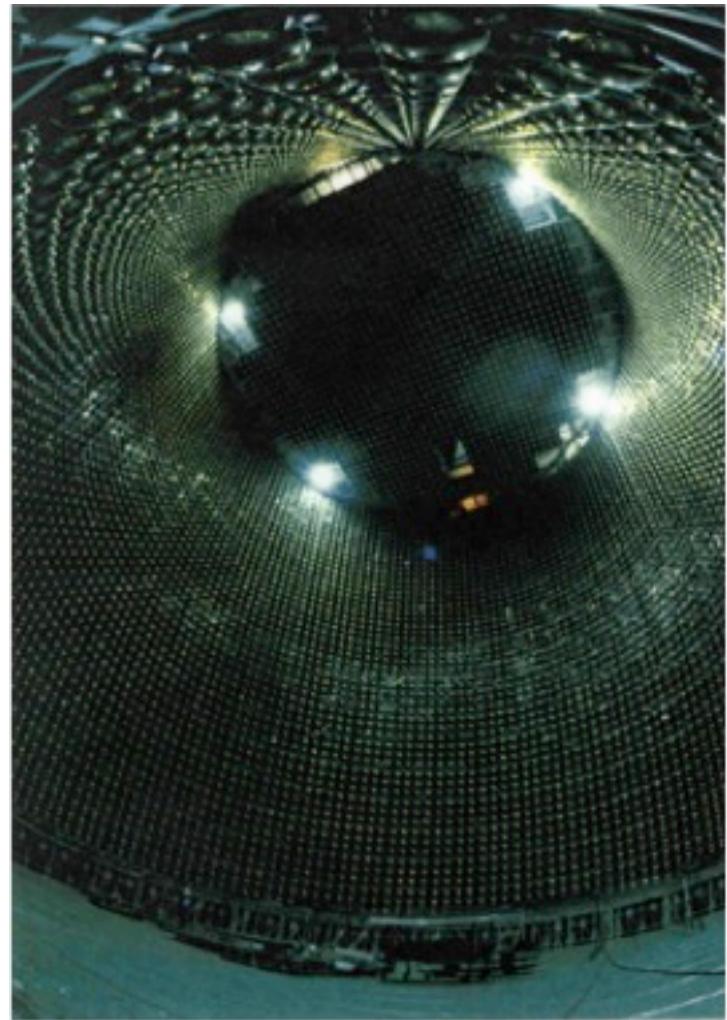
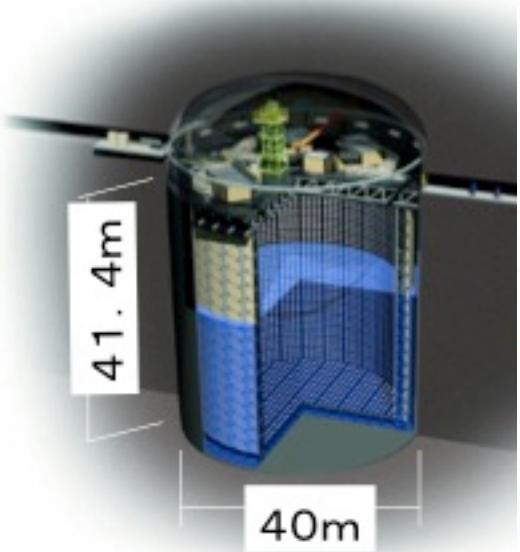
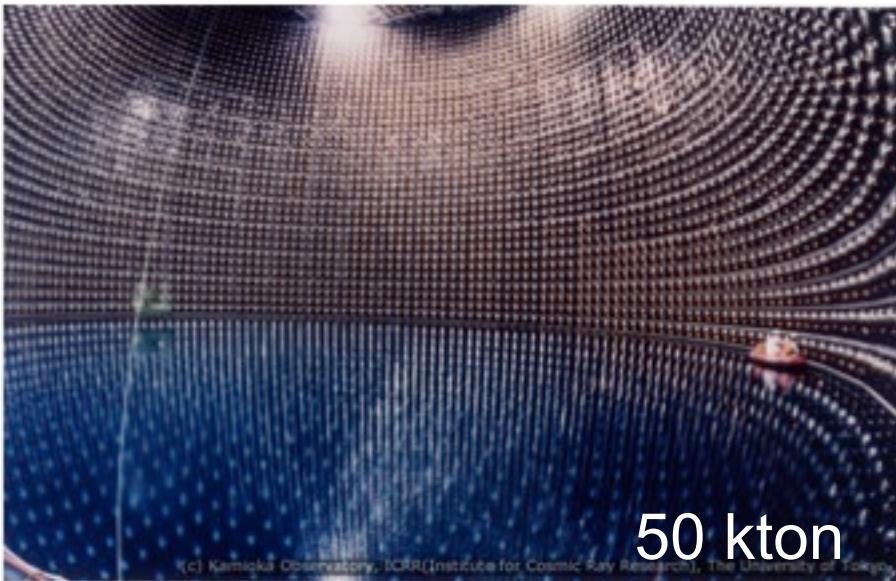


**Neutral Current**



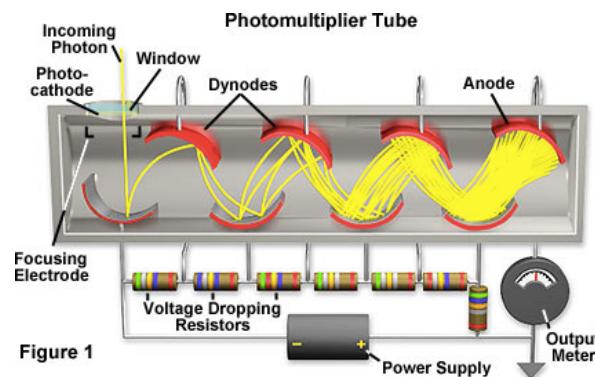
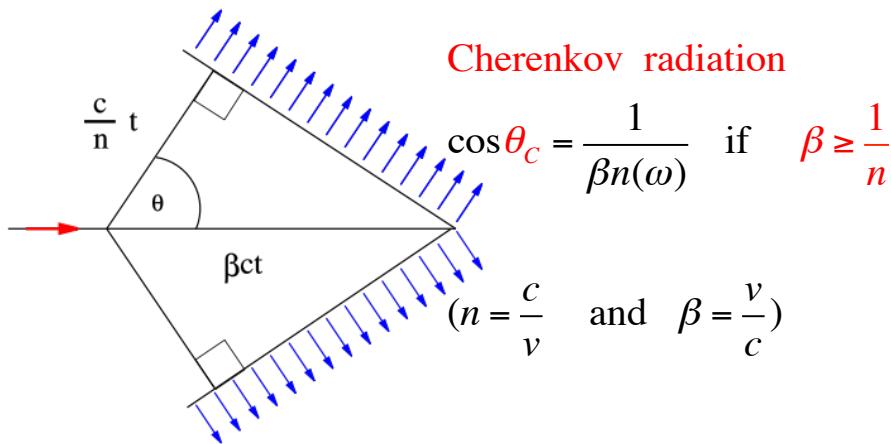
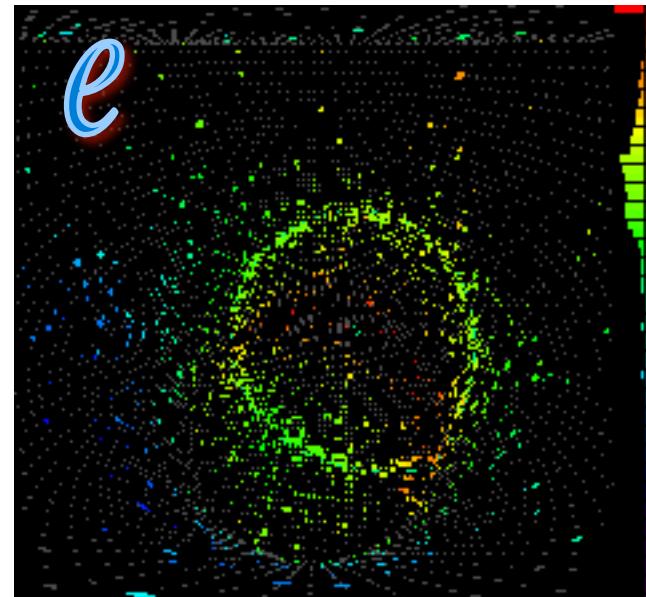
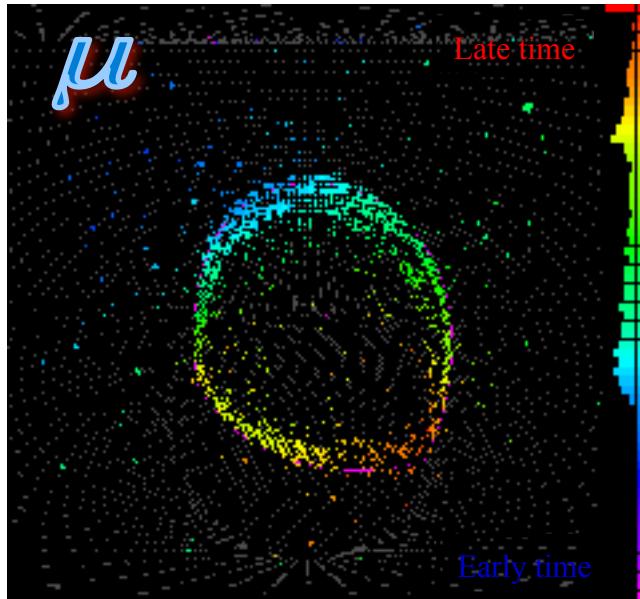
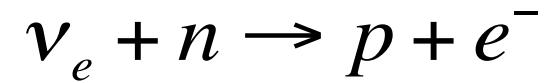
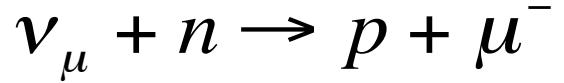
**Antineutrino Charged Current**

## Detecting atmospheric neutrinos: (Underground) SuperKamiokande Experiment



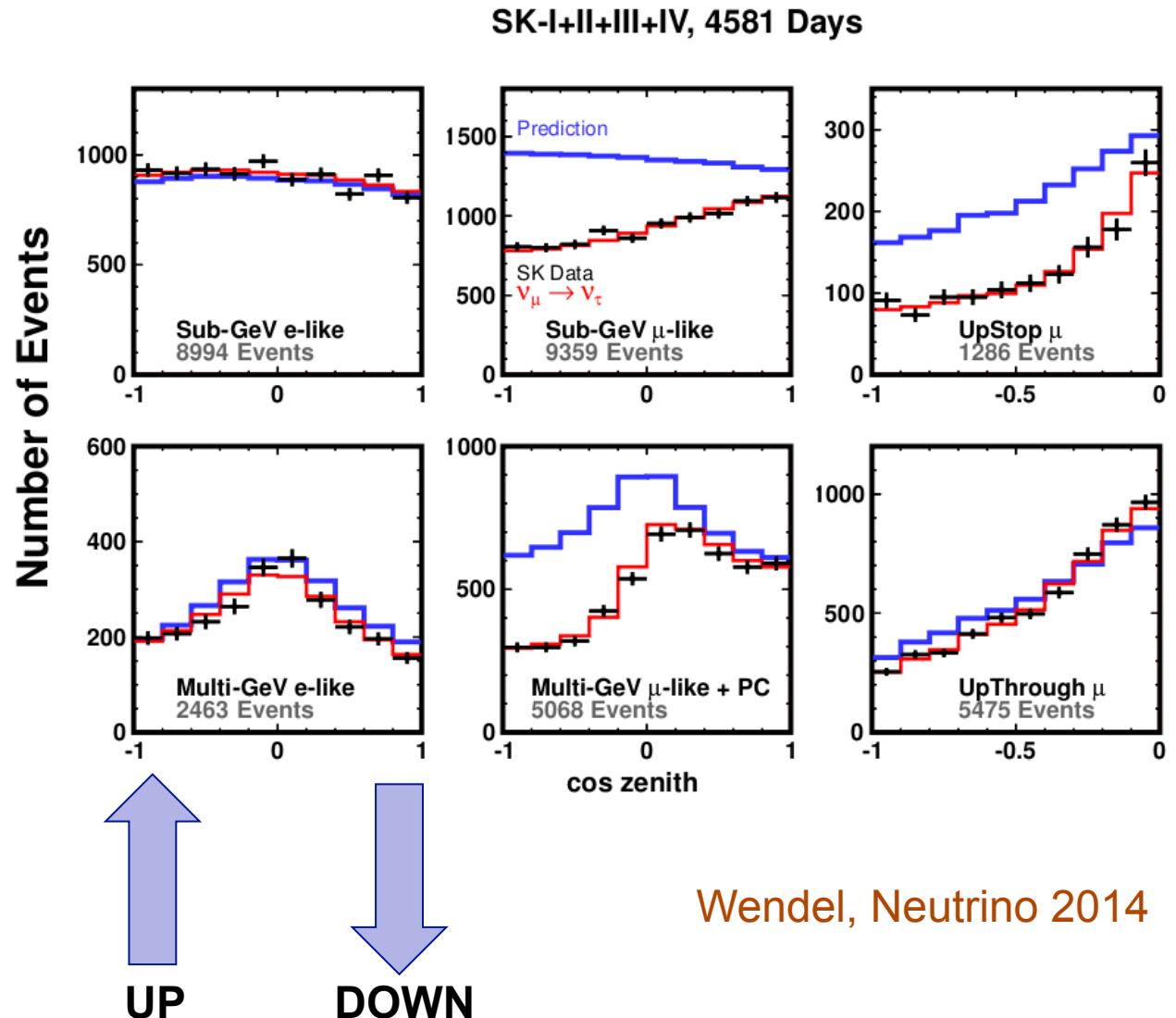
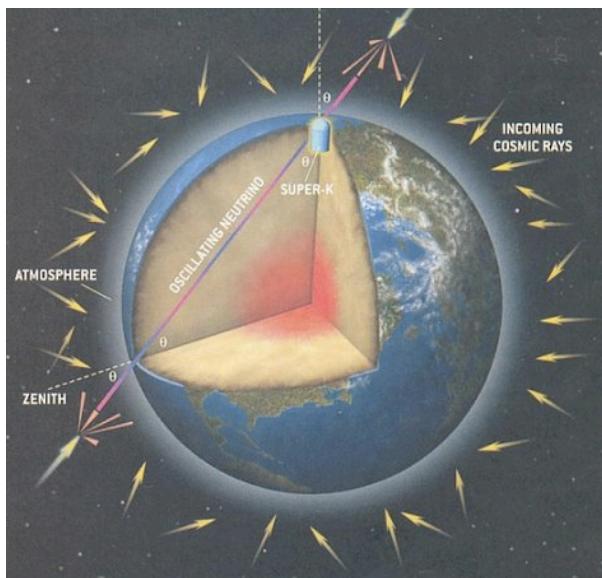
- ◆ 50 kton water (22.5 kton fid.vol.)
- ◆ 11,146 PMTs + 1,885 PMTs
- ◆ overburden 2,700 m.w.e.

# SuperKamiokande Cherenkov rings



# 16 years later ... (lots of statistics)

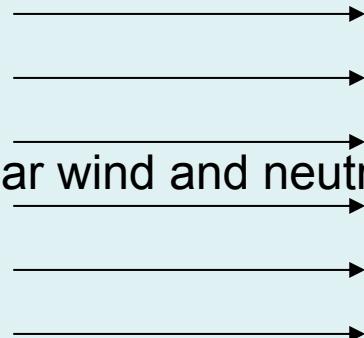
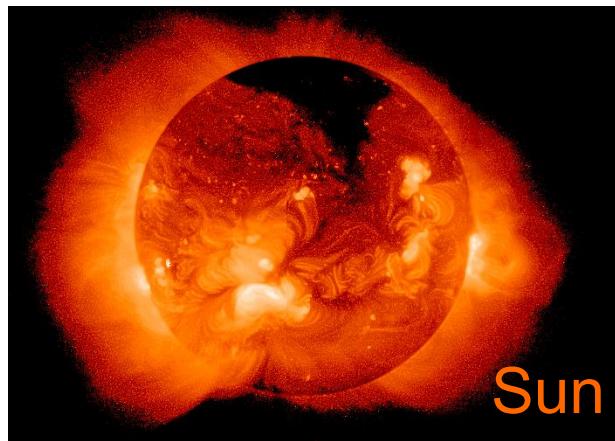
## SK Detector



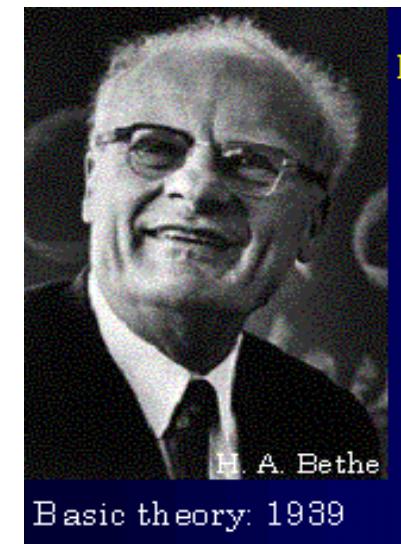
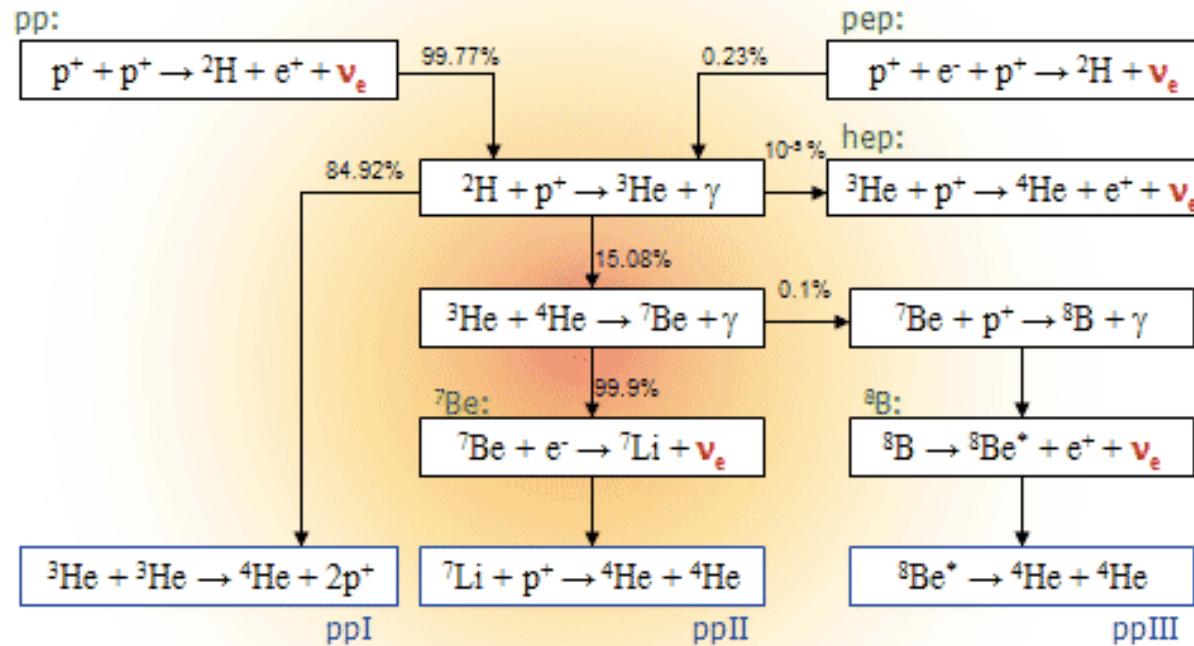
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# **SOLAR NEUTRINOS DEFICIT RESOLVED**

# Solar neutrinos



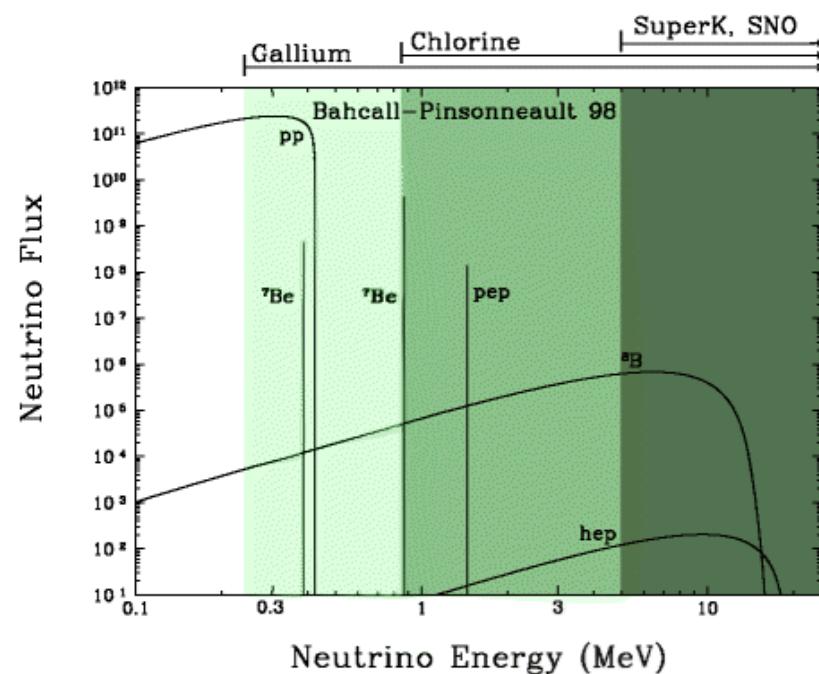
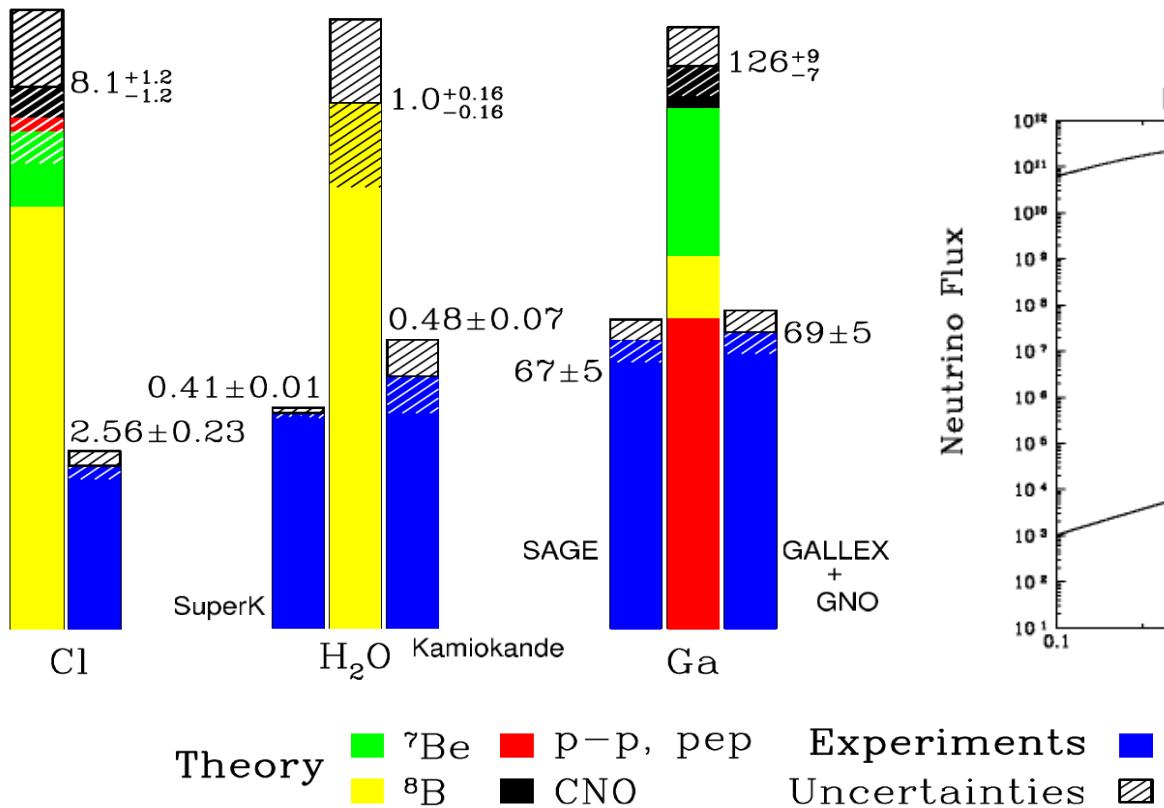
Solar wind and neutrinos



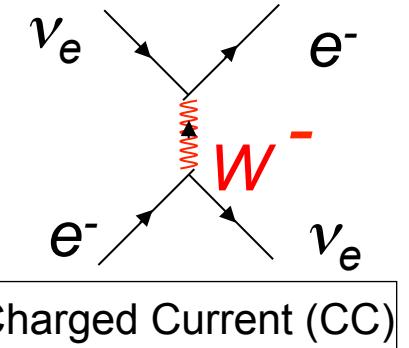
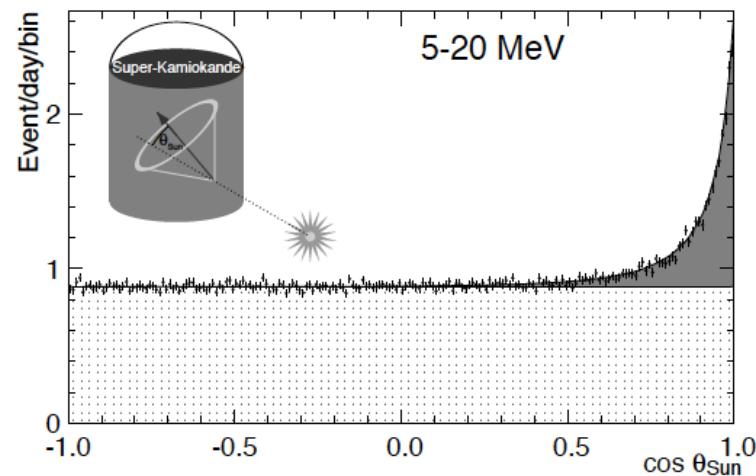
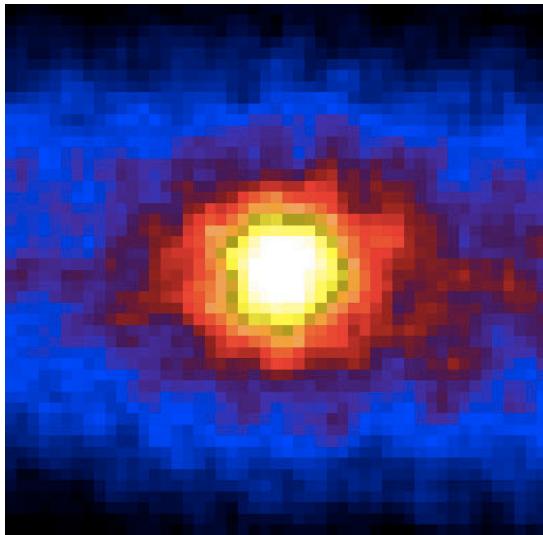
Nobel 1967

# Deficit of solar neutrinos

Total Rates: Standard Model vs. Experiment  
Bahcall–Serenelli 2005 [BS05(OP)]

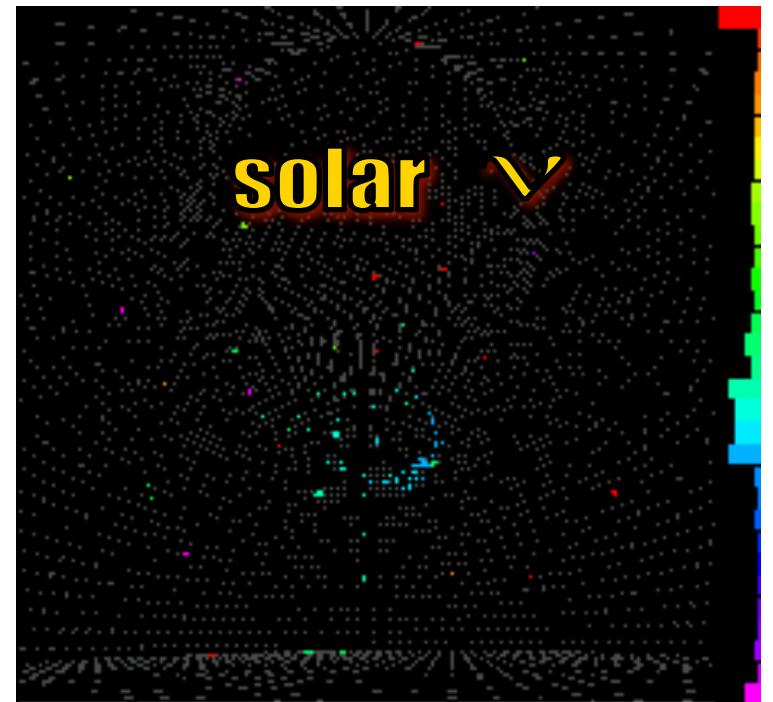


# SuperK – solar events

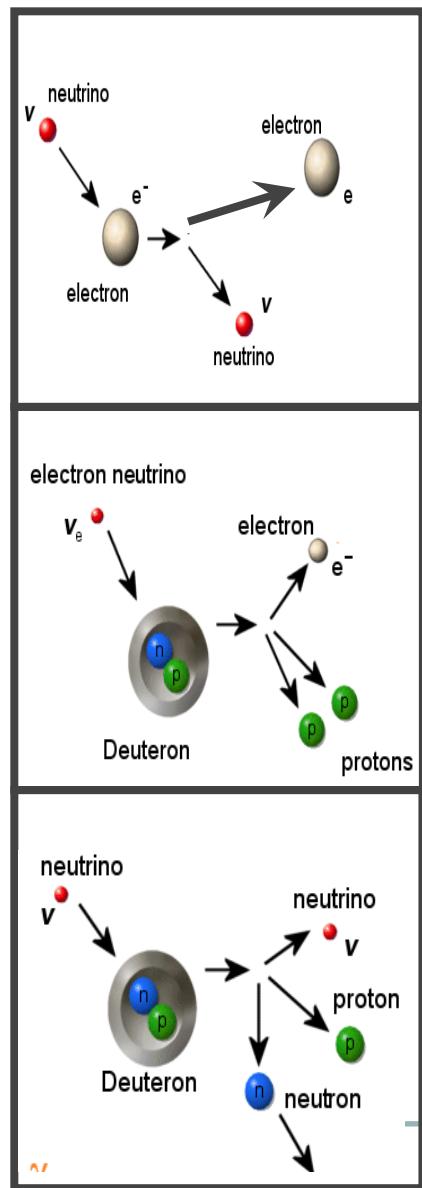


$$\frac{\text{measured}}{\text{expected}} = 0.465 \pm 0.005(\text{stat})^{+0.015}_{-0.013}(\text{syst})$$

measured << expected



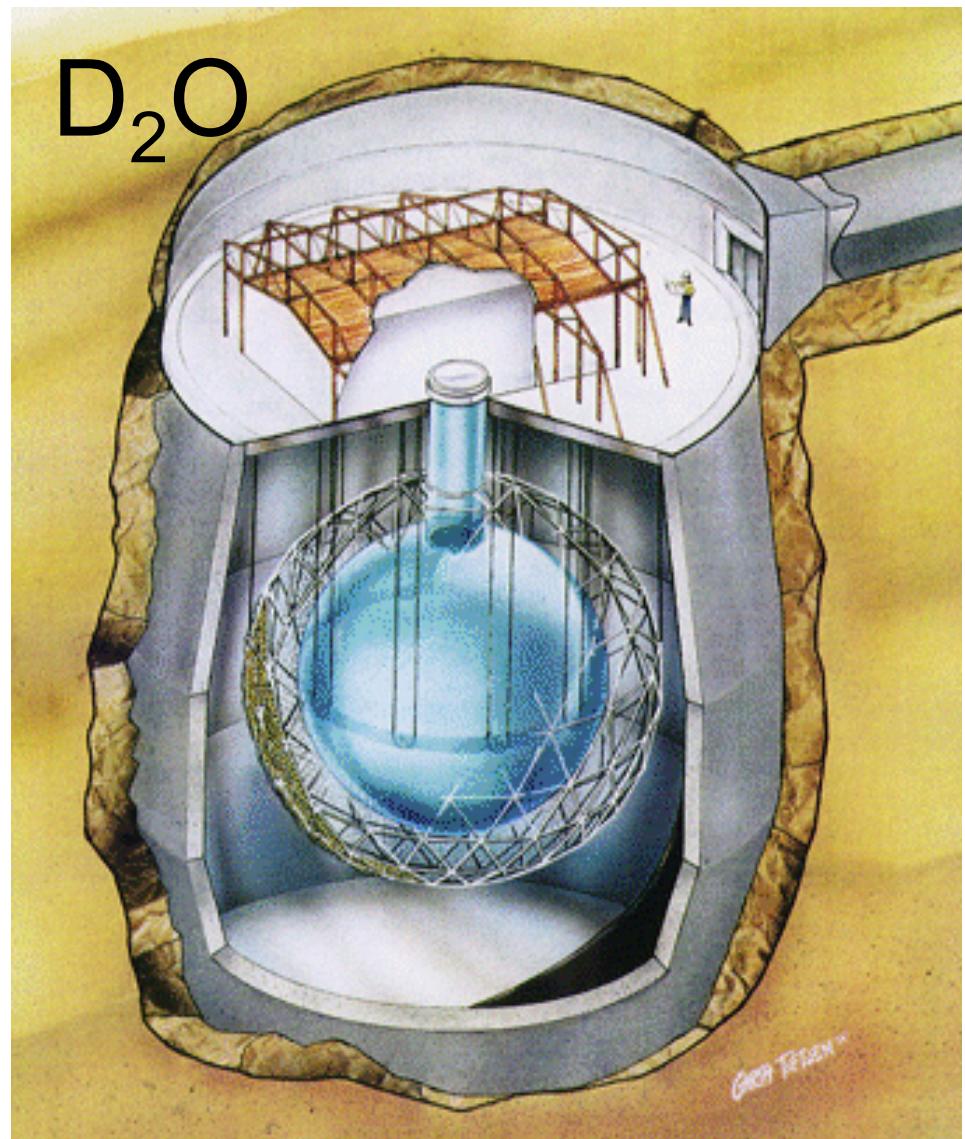
# Sudbury Neutrino Observatory (SNO)



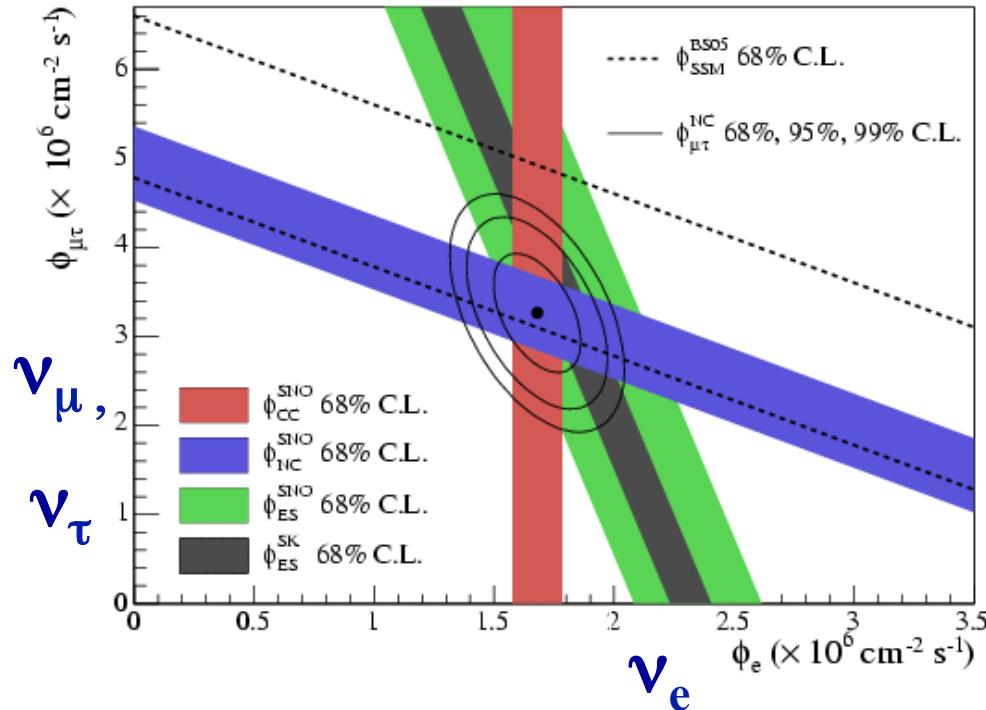
Neutrino-Electron  
Scattering (ES)

Charged Current (CC)

Neutral Current  
(NC)



# SNO measurements (total solar flux)



The total flux of active neutrinos is measured independently (NC) and agrees well with solar model.

Calculations:

$5.82 \pm 1.3$  (Bahcall *et al.*),

$5.31 \pm 0.6$  (Turck-Chieze *et al.*)

$$\begin{aligned}\phi_{CC} &= 1.68 \quad {}^{+0.06}_{-0.06} (\text{stat.}) \, {}^{+0.08}_{-0.09} (\text{syst.}) \\ \phi_{NC} &= 4.94 \quad {}^{+0.21}_{-0.21} (\text{stat.}) \, {}^{+0.38}_{-0.34} (\text{syst.}) \\ \phi_{ES} &= 2.35 \quad {}^{+0.22}_{-0.22} (\text{stat.}) \, {}^{+0.15}_{-0.15} (\text{syst.})\end{aligned}$$

(In units of  $10^6 \text{cm}^{-2} \text{s}^{-1}$ )

$$\frac{\varphi_{CC}}{\varphi_{NC}} = 0.34 \pm 0.023 (\text{stat.}) \, {}^{+0.029}_{-0.031}$$

Electron neutrinos are  
Only about 1/3 of total!

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# **NEUTRINO OSCILLATIONS**

## **SOME QM**

# Neutrino mixing

## The PMNS matrix

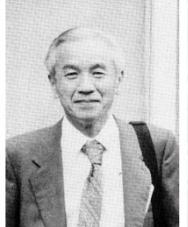


Бруно Понтецорво

Bruno Pontecorvo  
1913 — 1993



Ziro Maki  
1929 — 2005



Masami Nakagawa  
1932 — 2001



Shoichi Sakata  
1911 — 1970

### Pontecorvo – Maki – Nakagawa - Sakata

$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

Flavor eigenstates

Mass eigenstates

so, e.g., :  $v_e = U_{e1}v_1 + U_{e2}v_2 + U_{e3}v_3$

$$|v_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |v_i\rangle$$

$$|v_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i} |v_\alpha\rangle$$

$$|U_{\alpha i}|^2 = \text{flavor-}\alpha \text{ fraction of } |v_i\rangle$$

# Neutrino propagation

The state function at birth:  $|\nu(0,0)\rangle = |\nu_\alpha^{flavor}\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_\alpha^{mass}\rangle$

Propagation (plane wave):  $|\nu(t, \vec{x})\rangle = |\nu_\alpha^{flavor}\rangle = \sum_{i=1}^3 U_{\alpha i}^* e^{-ip_i x} |\nu_\alpha^{mass}\rangle$

$$\phi_i \equiv p_i x = E_i t - \vec{p}_i \vec{x}$$

Probability of evolution:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta^{flavor} | \nu(t, \vec{x}) \rangle \right|^2$$

This is heuristic.  
Not rigorous!  
Should do either  
Wave packets or QFT

For ultra-relativistic neutrinos:

$$p_i = \sqrt{E^2 - m_i^2} \approx E - \frac{m_i^2}{2E}$$

$$-\Delta p \equiv p_1 - p_2 = -\frac{\Delta m^2}{2E}$$



$$P(\nu_\alpha \rightarrow \nu_\beta; L) = \left| \sum_i U_{\beta i} e^{-i \frac{m_i}{2p} L} U_{\alpha i}^* \right|^2$$

## Two neutrino case

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Transition probability :  $P(\nu_\alpha \rightarrow \nu_\beta) = \left| \left\langle \nu_\beta^f \middle| \nu(t, x) \right\rangle \right|^2$

Now more explicitly:

$$P(\nu_\alpha \rightarrow \nu_\beta; L) = \left| \sum_i U_{\beta i} e^{-i \frac{m_i}{2p} L} U_{\alpha i}^* \right|^2$$

Consider a two component theory:  $U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

So

$$|\nu_\alpha\rangle = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle$$

$$|\nu_\beta\rangle = -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle$$

$$P(\nu_\alpha \rightarrow \nu_\beta; L) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

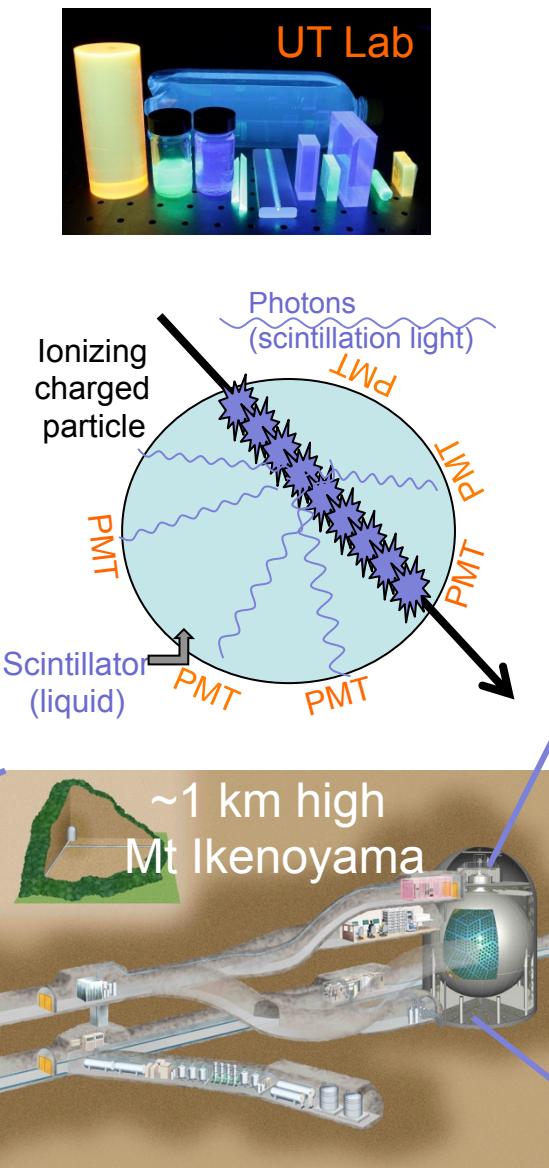
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# **NEUTRINO OSCILLATIONS**

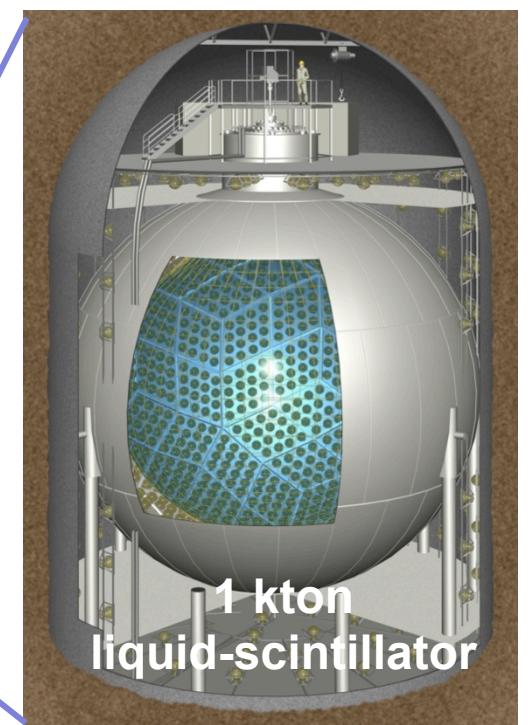
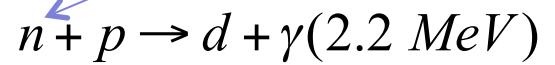
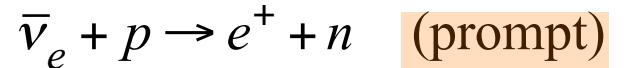
## **EXPERIMENTAL OBSERVATIONS USING NUCLEAR REACTORS**

# KamLAND

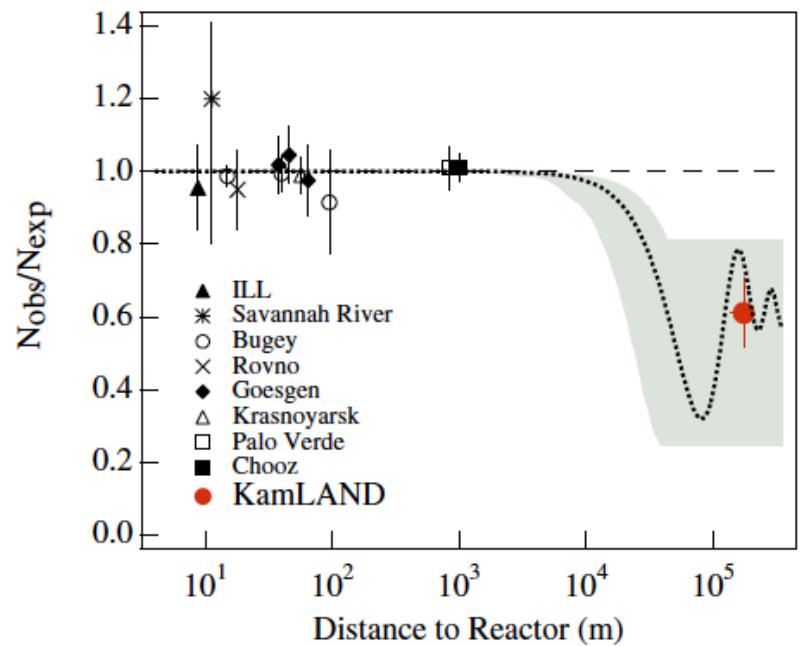
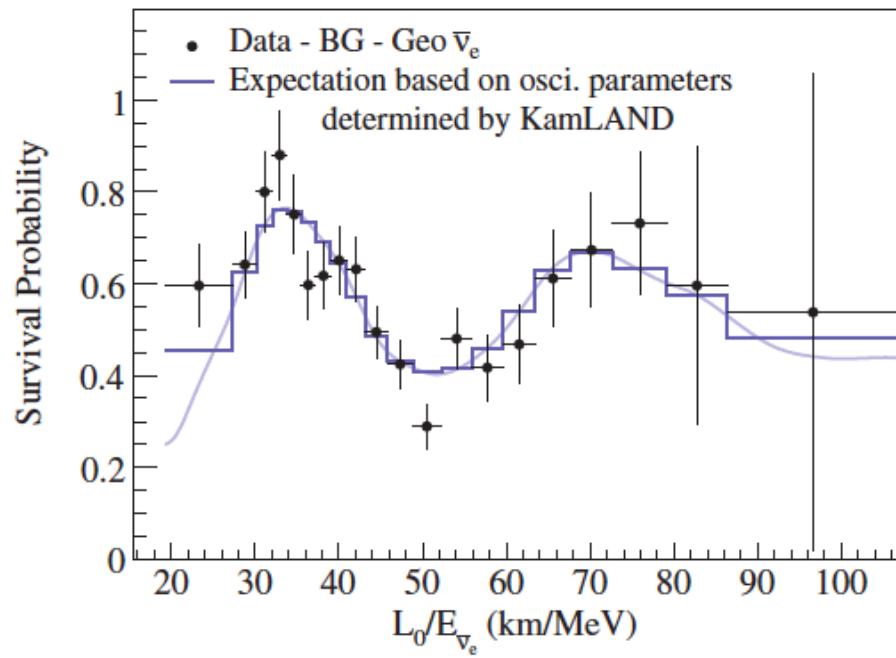
- ◆ KamLAND is surrounded by nuclear power plants which produce electron anti-neutrinos.
- ◆ 180 km away on average



Detecting anti-neutrinos



# KamLAND results



$$\Delta m_{21}^2 = \left( 7.58^{+0.14}_{-0.13} (\text{stat}) \pm 0.015 (\text{syst}) \right) \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \theta_{12} = 0.56^{+0.10}_{-0.07} (\text{stat})^{+0.10}_{-0.06} (\text{syst})$$

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# **NEUTRINO OSCILLATIONS**

## **EXPERIMENTAL OBSERVATIONS USING ACCELERATORS**

# Two Neutrinos Case

## A disappearance experiment

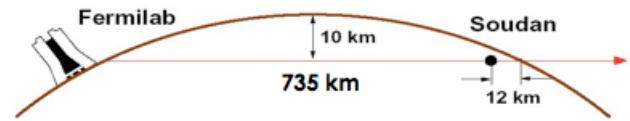
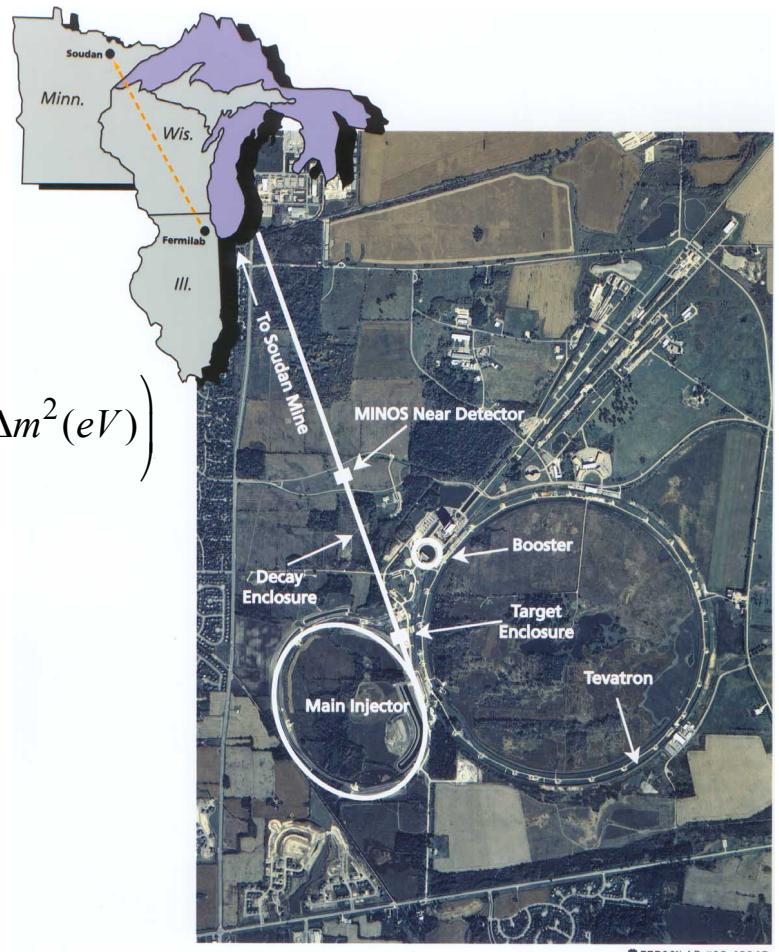
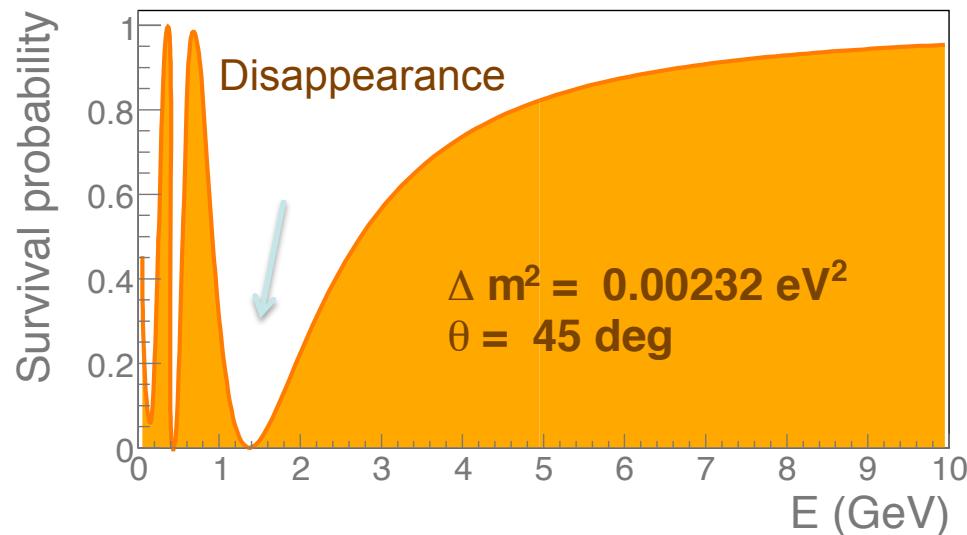
$$P(\nu_\alpha \rightarrow \nu_\beta; L) = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2}{4E} L \right)$$

$$P(\nu_\alpha \rightarrow \nu_\beta; L) = \sin^2(2\theta) \sin^2 \left( 1.267 \frac{L(km)}{E(GeV)} \Delta m^2(eV) \right)$$

Survival probability:

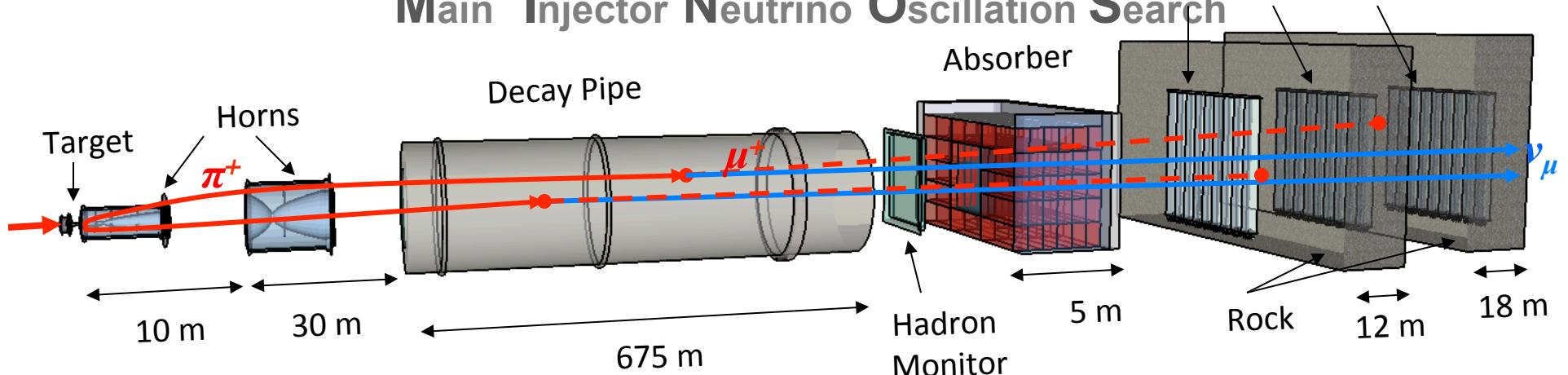
$$P(\nu_\alpha \rightarrow \nu_\alpha; L) = 1 - P(\nu_\alpha \rightarrow \nu_\beta; L) = 1 - \sin^2(2\theta) \sin^2 \left( 1.267 \frac{L(km)}{E(GeV)} \Delta m^2(eV) \right)$$

For  $L = 734$  km and  $\theta = 45^\circ$  (MINOS at Fermilab)



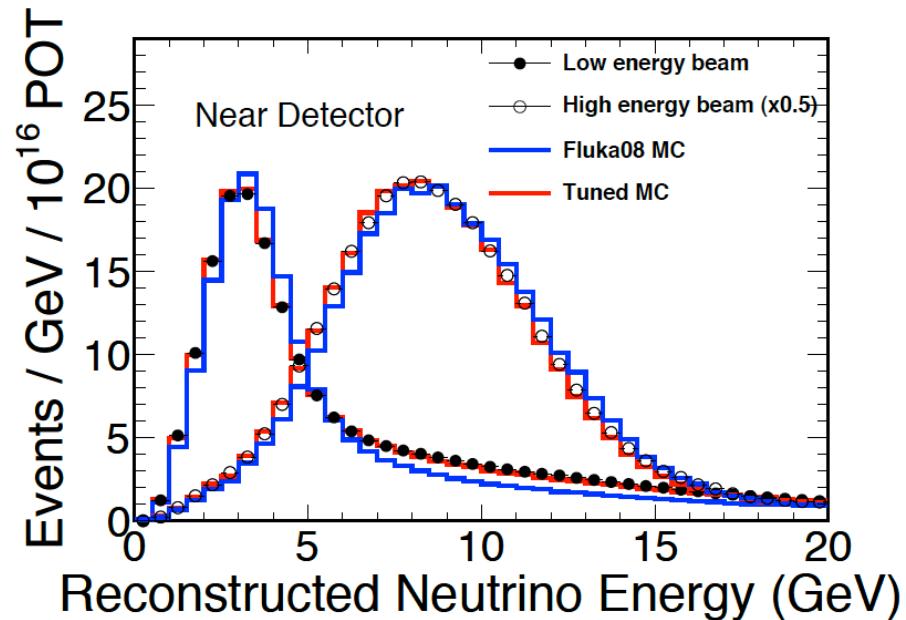
# MINOS

## Main Injector Neutrino Oscillation Search

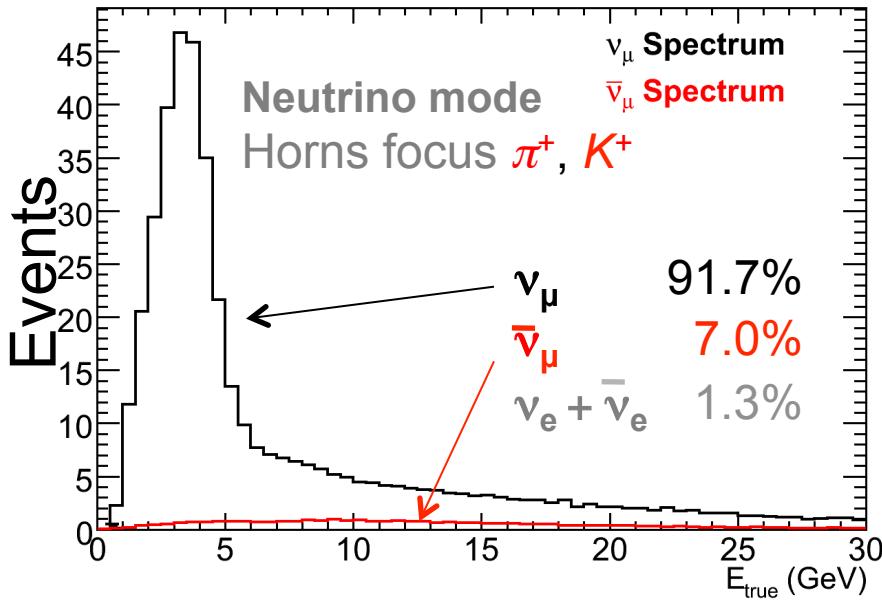


## Strategy

- ◆ Two functionally similar magnetized detectors
- ◆ High intensity, flexible beam
  - ⇒  $3.5 \times 10^{13}$  protons/pulse  
(320 kW beam)
  - ⇒ two magnetic horns
  - ⇒ movable target  
(→ adjustable energy spectrum)

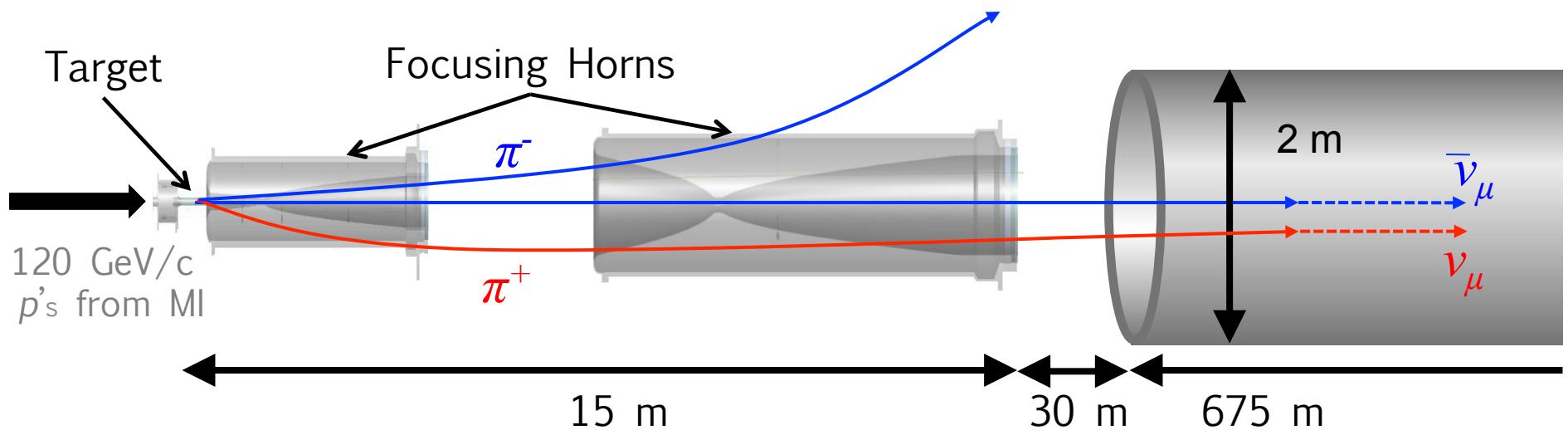


# Making a neutrino beam

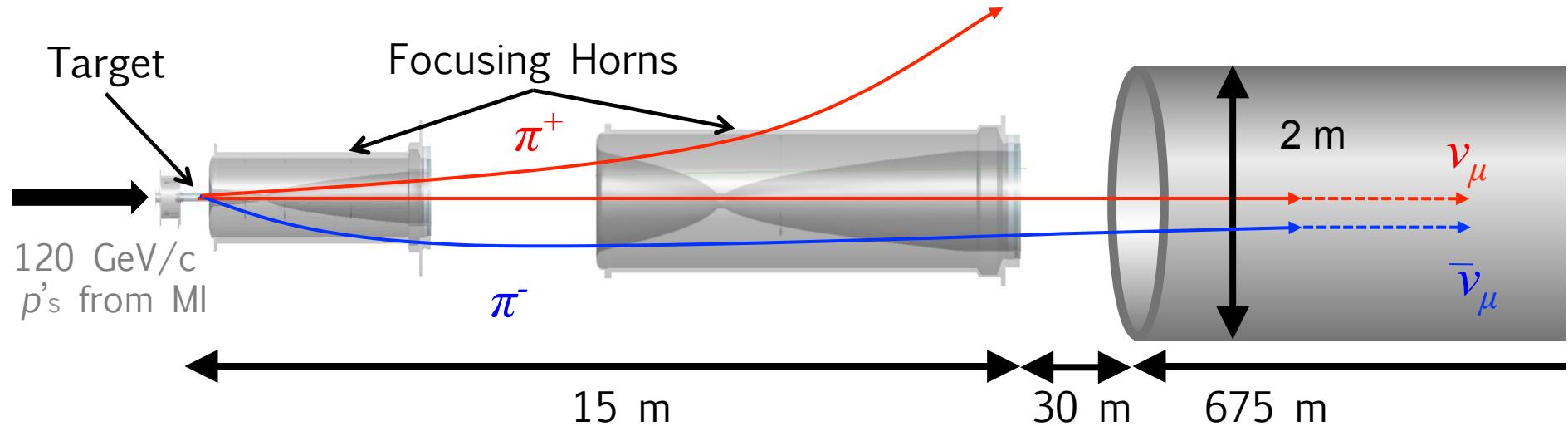
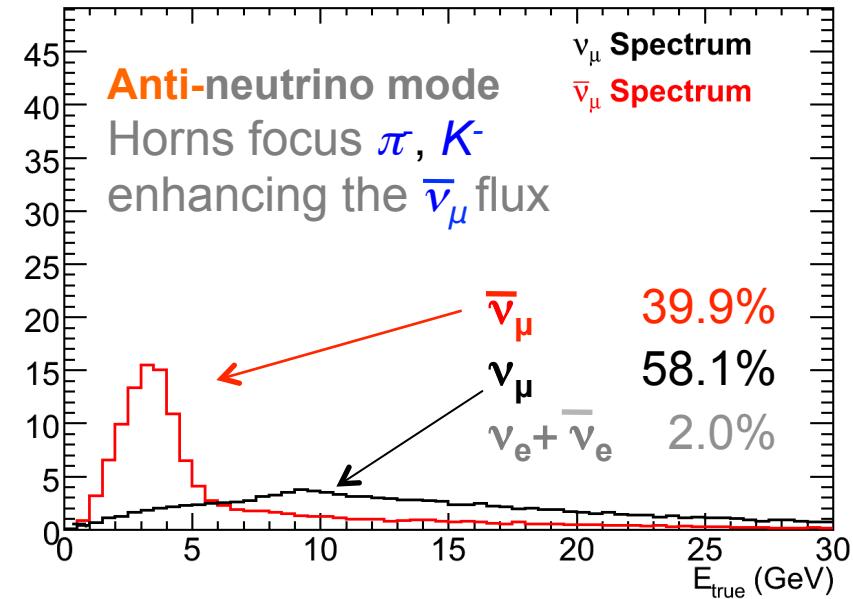
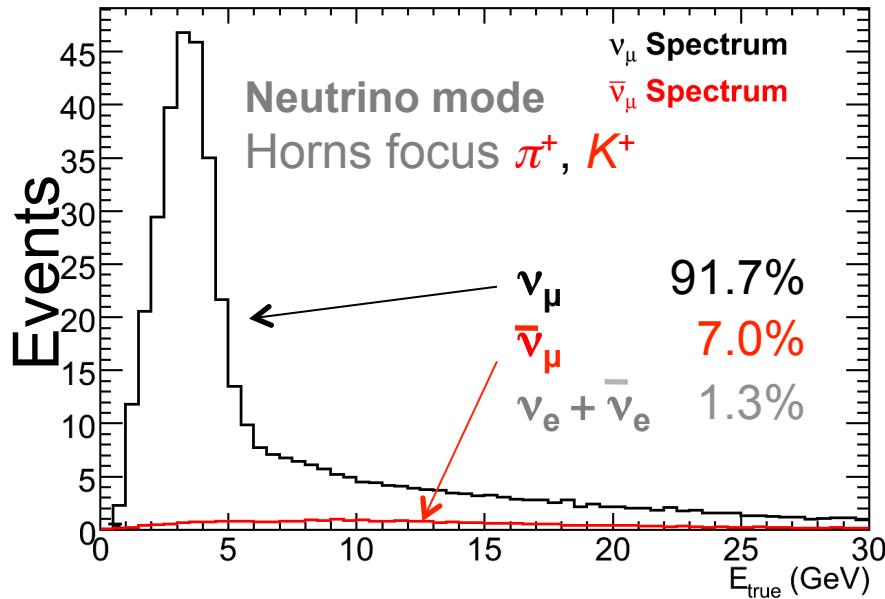


$$E_\nu \approx E_\pi \frac{1 - m_\mu^2 / m_\pi^2}{1 + \gamma^2 \theta^2} \approx \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

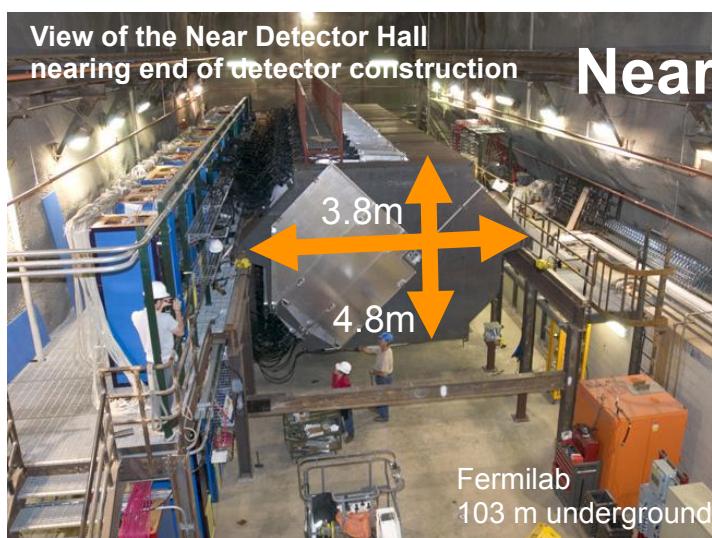
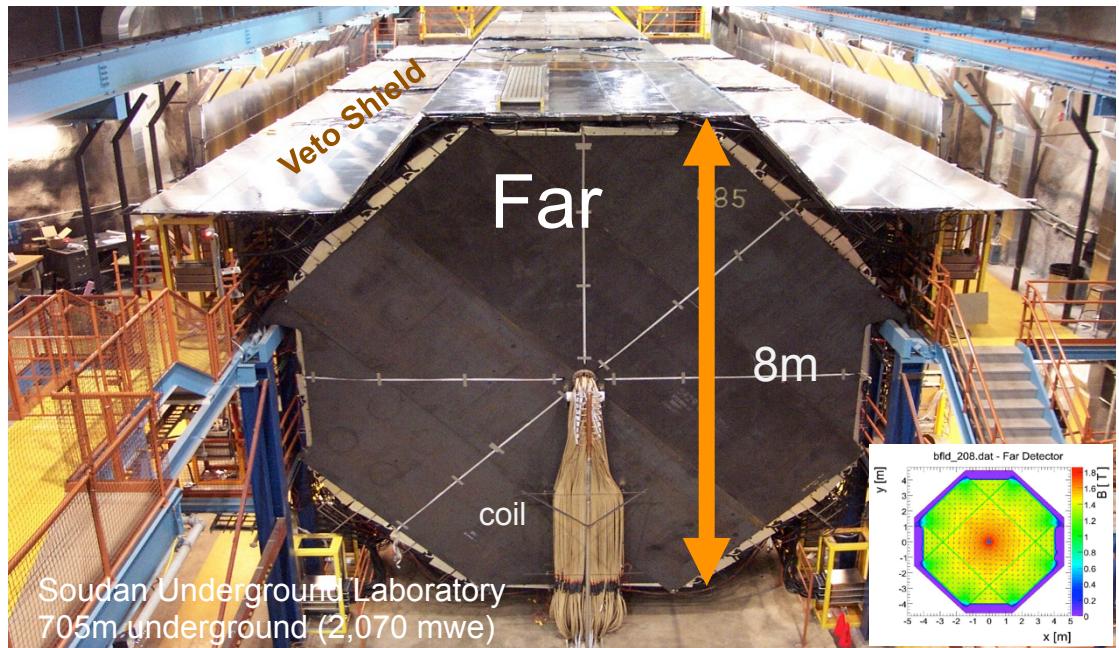
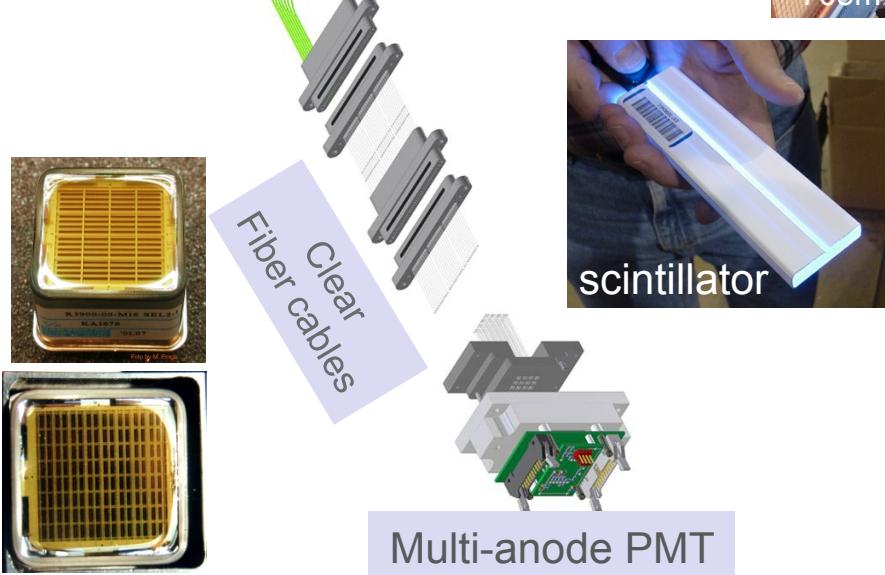
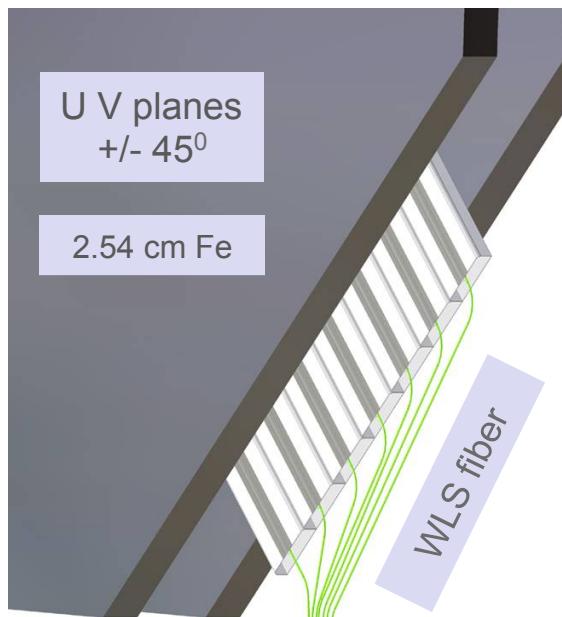
$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi} \left( \frac{2\gamma}{1 + \gamma^2 \theta^2} \right)^2$$



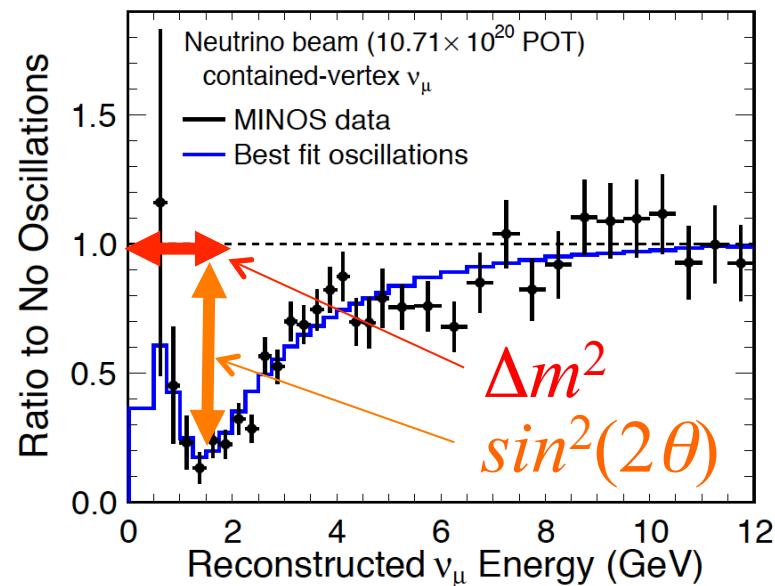
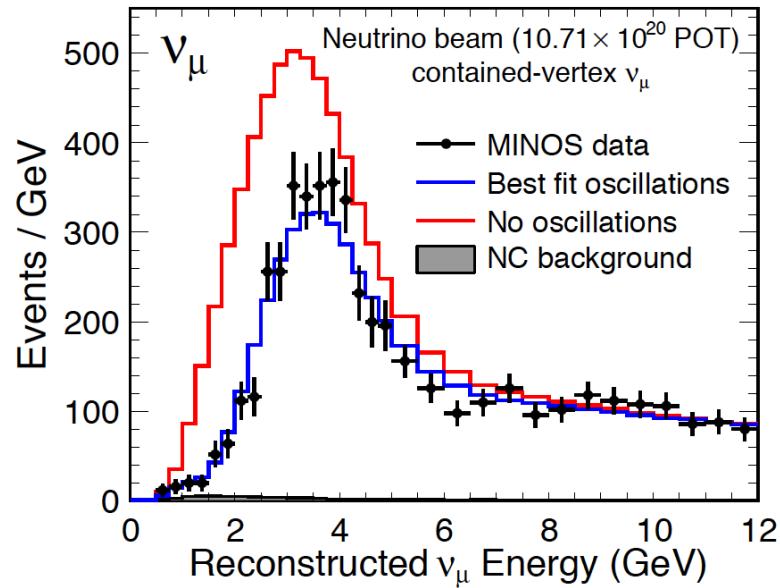
# Making an anti-neutrino beam



# MINOS: Near and Far Detectors



# MINOS disappearance results



Survival probability:

$$P(\nu_\mu \rightarrow \nu_\mu; L) = 1 - \sin^2(2\theta) \sin^2 \left( 1.267 \frac{L(km)}{E(GeV)} \Delta m^2(eV) \right)$$

For  $L = 734$  km and  $E = 1-50$  GeV (MINOS at Fermilab)

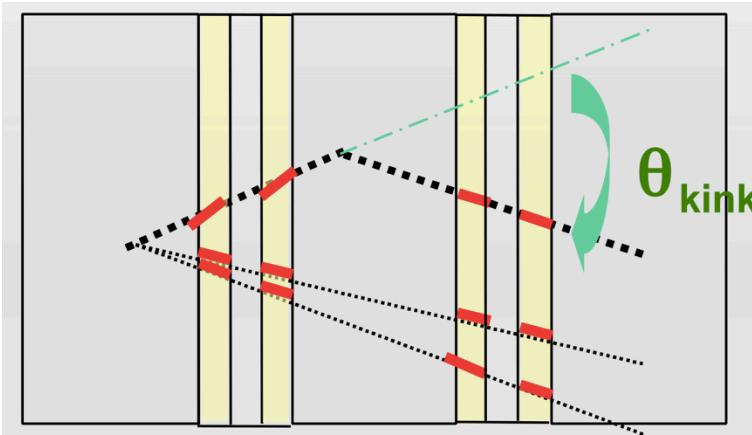
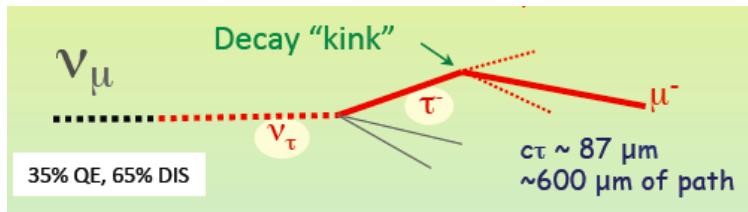
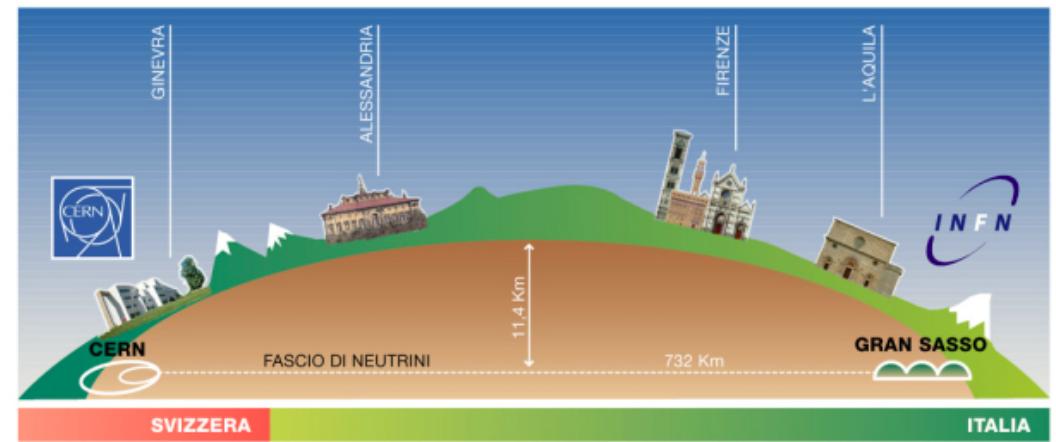
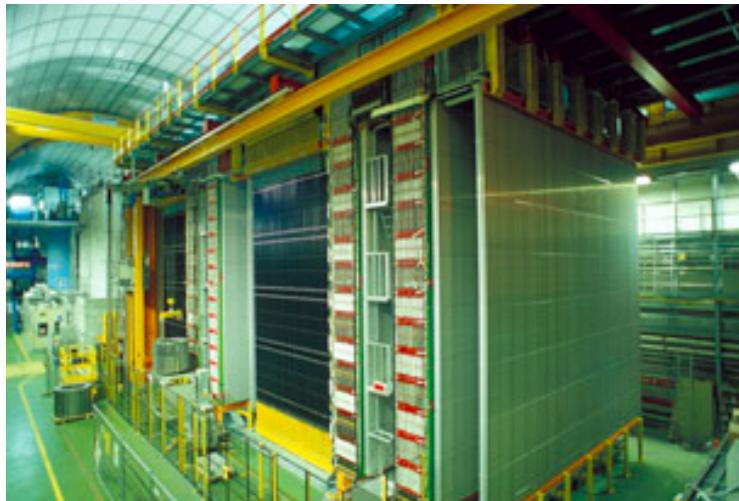
$$|\Delta m^2| = 2.41_{-0.10}^{+0.09} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) = 0.950_{-0.036}^{+0.035}$$

$$\left[ \sin^2(2\theta) > 0.890 \text{ (90% C.L.)} \right]$$

K. Lang, Venice NeuTel'2013

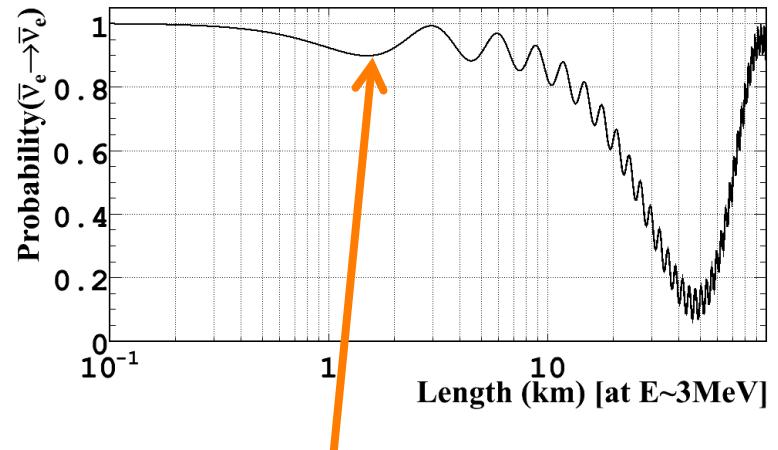
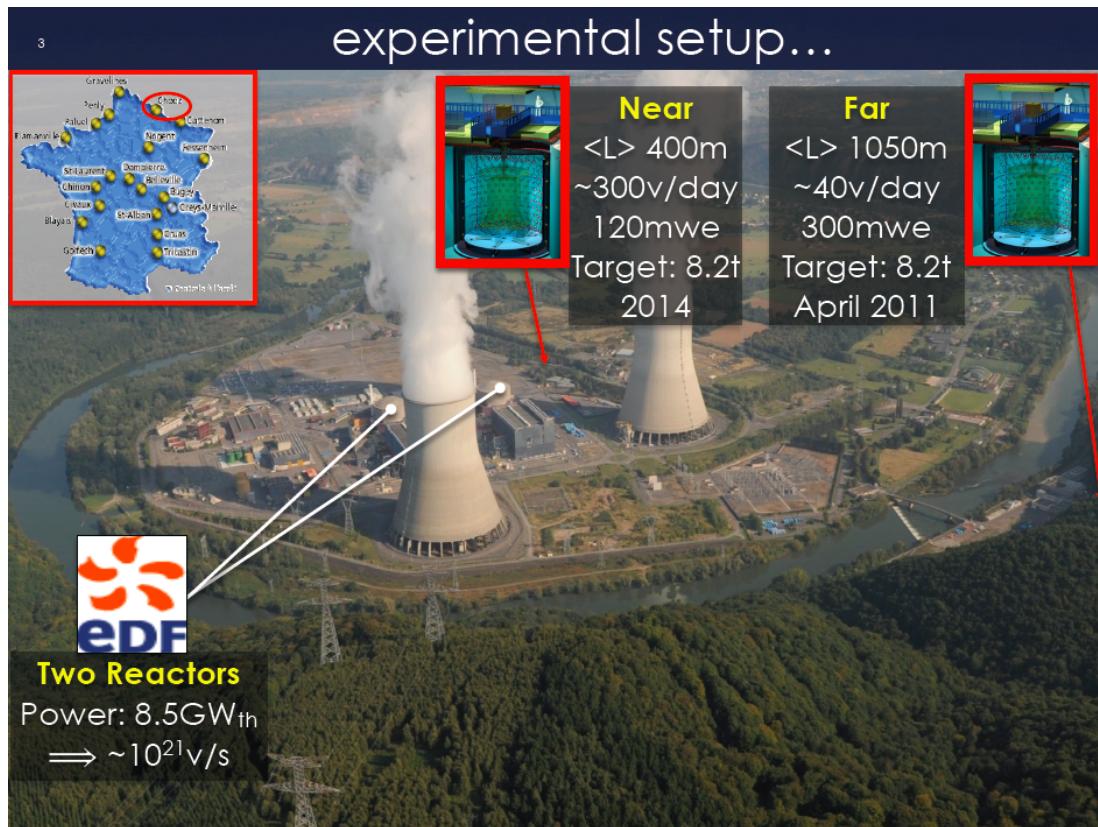
# OPERA → appearance experiment



- 4  $\nu_\tau$  candidates (so far) (0.23 background)
- $4.2\sigma$  exclusion of no  $\nu_\mu \rightarrow \nu_\tau$  oscillation
- $\Delta m^2 = [1.8 - 5.0] \times 10^{-3} \text{ eV}^2$

(Neutrino 2014)

# From CHOOZ to Double CHOOZ

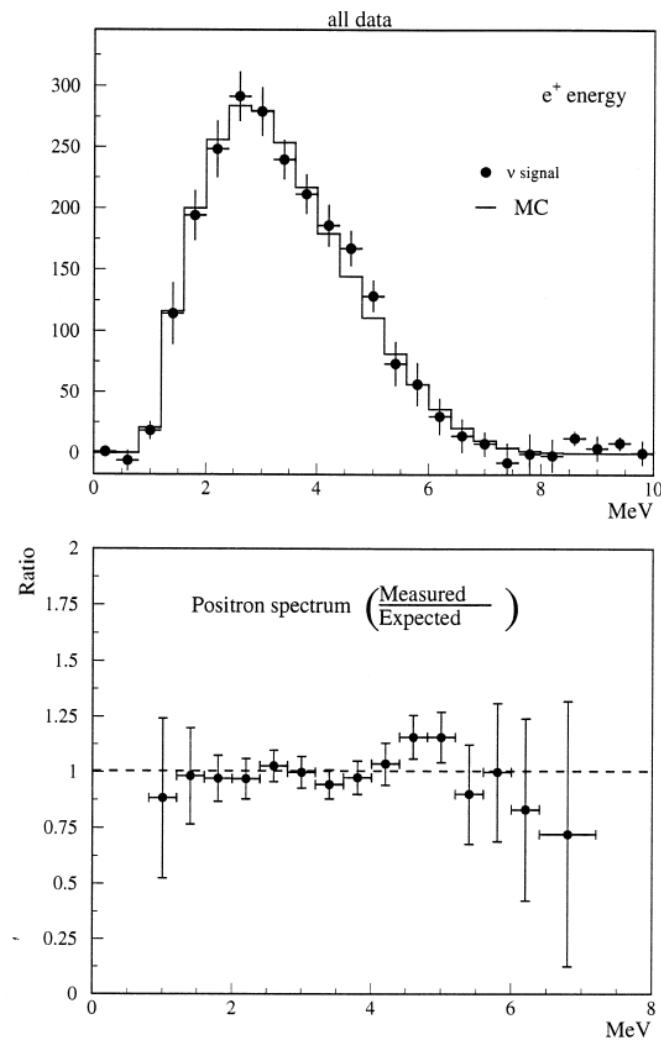


- ◆ Simple 2-flavor oscillation formula is good for  $L \sim 1$  km:
  - ✓ No matter effects
  - ✓ No parameter degeneracy

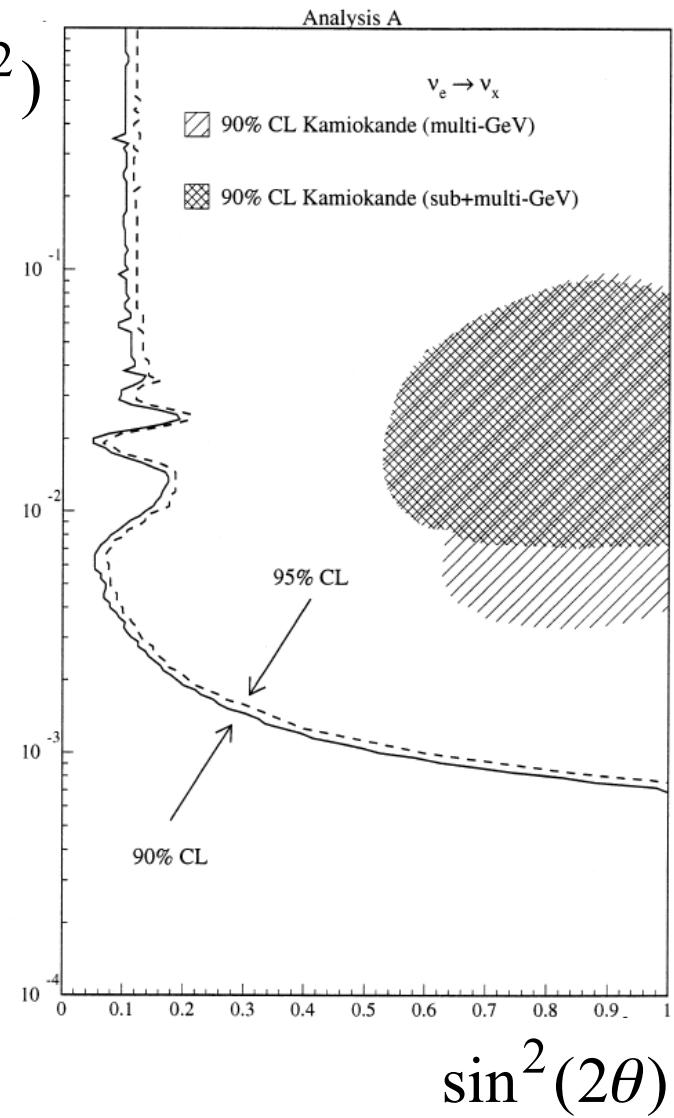
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

# CHOOZ (5 ton detector)

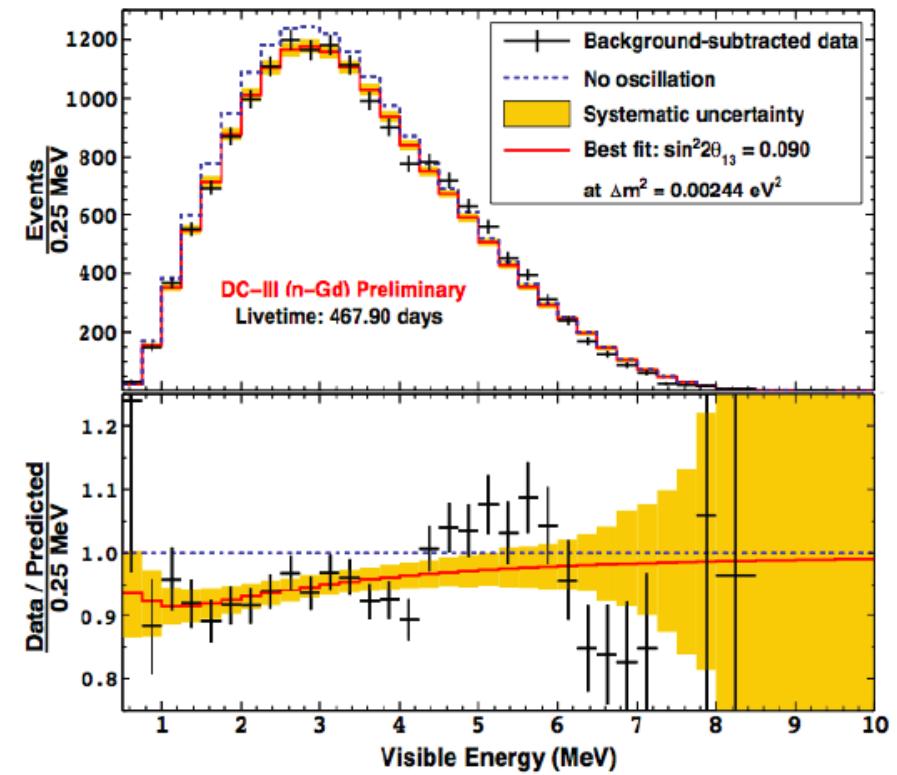
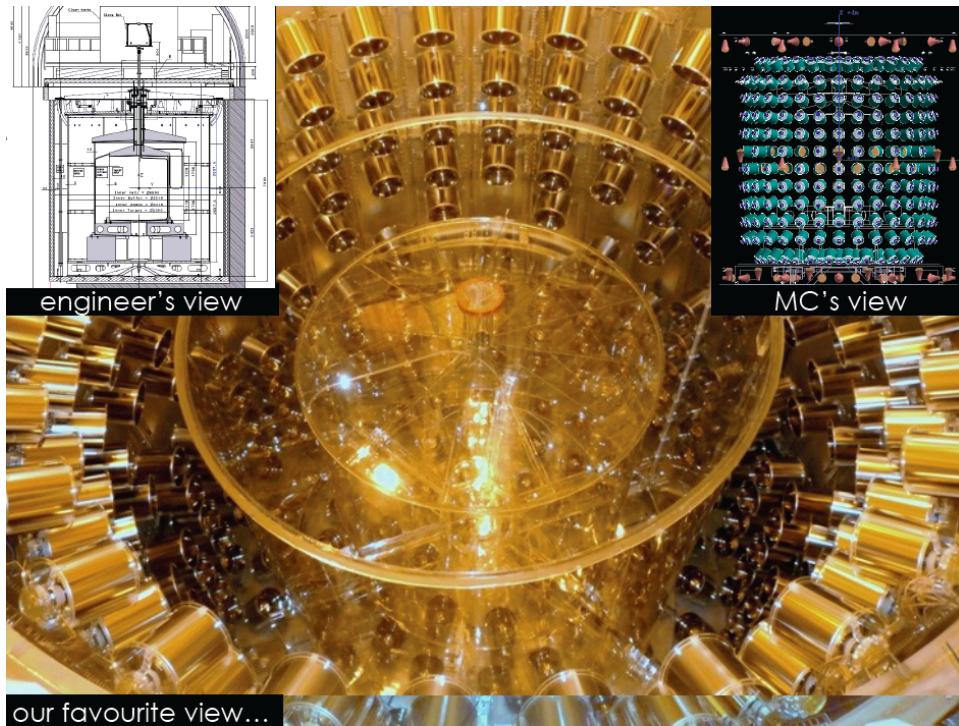
M. Apollonio et al. / Physics Letters B 466 (1999) 415–430



$$\Delta m^2(eV^2)$$



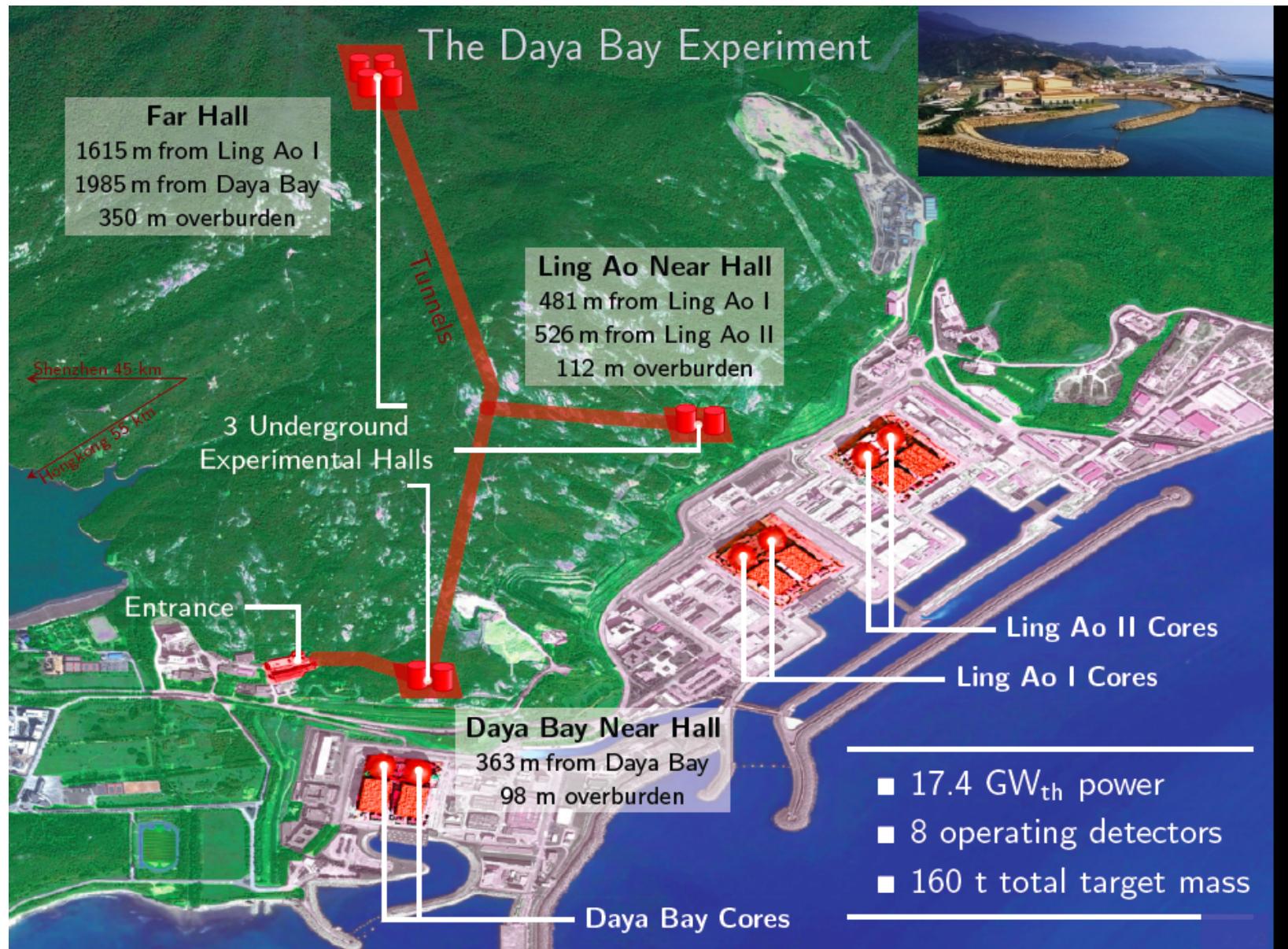
# Double CHOOZ 8.2 ton



$$\sin^2(2\theta_{13}) = (0.09 \pm 0.03)$$

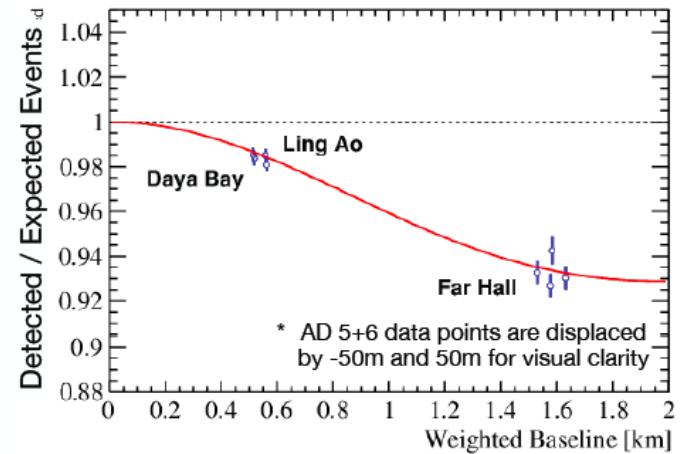
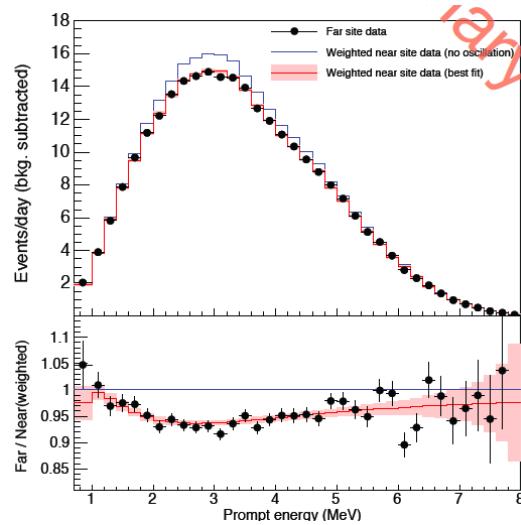
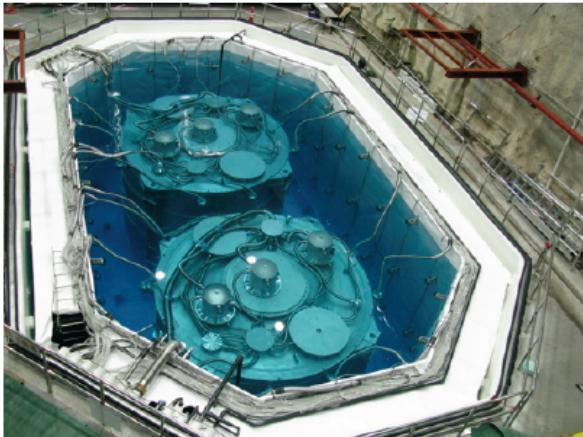
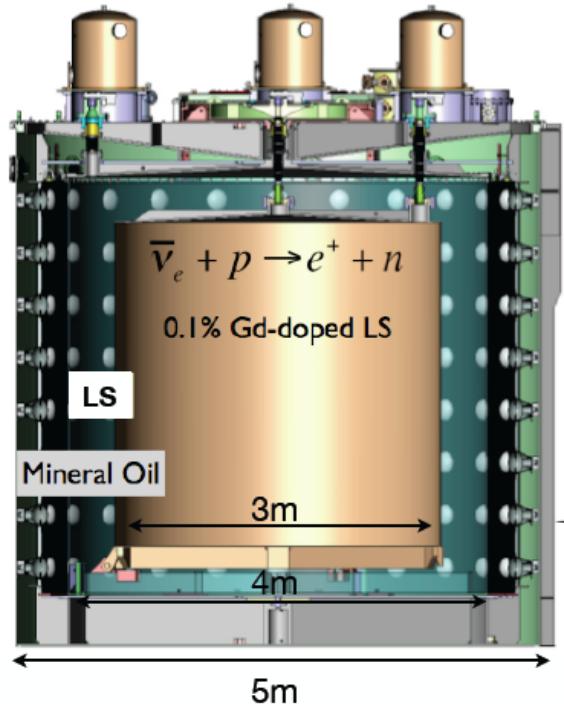
Neutrino 2014

# Daya Bay Experiment



# Daya Bay: 8 detectors

2x20ton + 2x20ton + 4x20ton



$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m_{ee}^2| = 2.44^{+0.10}_{-0.11} \times 10^{-3} \text{ eV}^2$$

$$\chi^2/NDF = 134.7/146$$

- [1] Mixing angle  $\theta_{13}$  governs overall size of  $\bar{\nu}_e$  deficit
- [2] Effective mass squared difference  $|\Delta m_{ee}^2|$  determines deficit dependence on  $L/E$

|   |               |
|---|---------------|
| Short Baseline  | Long Baseline |
| $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( \Delta m_{ee}^2 \frac{L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2 \left( \Delta m_{21}^2 \frac{L}{4E} \right)$ |               |
| $\rightarrow \sin^2(\Delta m_{ee}^2 \frac{L}{4E}) \equiv \cos^2 \theta_{12} \sin^2(\Delta m_{31}^2 \frac{L}{4E}) + \sin^2 \theta_{12} \sin^2(\Delta m_{32}^2 \frac{L}{4E})$   |               |

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# **NEUTRINOS OSCILLATIONS PRECISION ERA**

**(NEED 3-NEUTRINO FORMALISM  
AND MATTER EFFECTS)**

## More on the PMNS matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}$$

$$c_{ij} = \cos \theta_{ij}$$

$$s_{ij} = \sin \theta_{ij}$$

Decomposition:

$$U = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & s_{13}e^{-i\delta_{CP}} & \\ & 1 & \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ c_{23} & s_{23} & \\ -s_{23} & c_{23} & \end{pmatrix} \times M$$

Solar,  
LB reactor

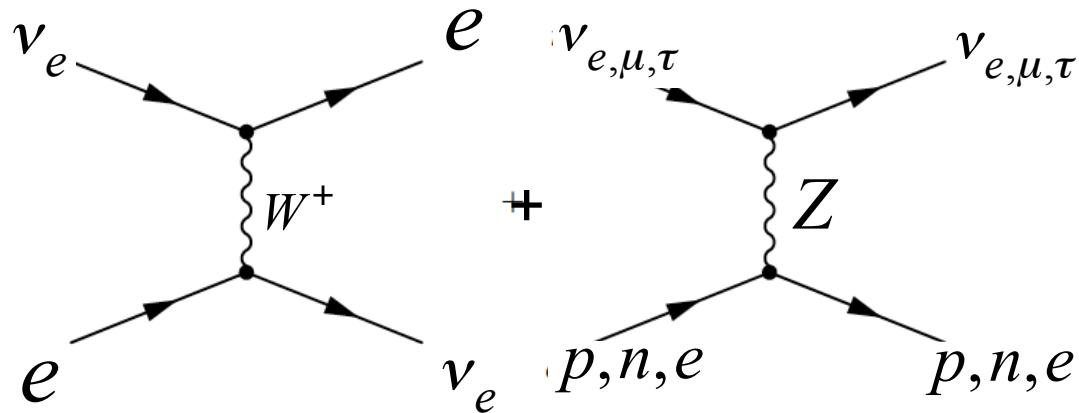
Reactor,  
LB accelerators

Reactor,  
LB accelerators

Majorana

$$M = \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

# Neutrinos in matter



Neutrino interactions  
in matter

This gives an effective potential  
of electron neutrinos:  $V = \sqrt{2}G_F N_e$

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + V & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$\theta_m$  diagonalizes the Hamiltonian in matter:

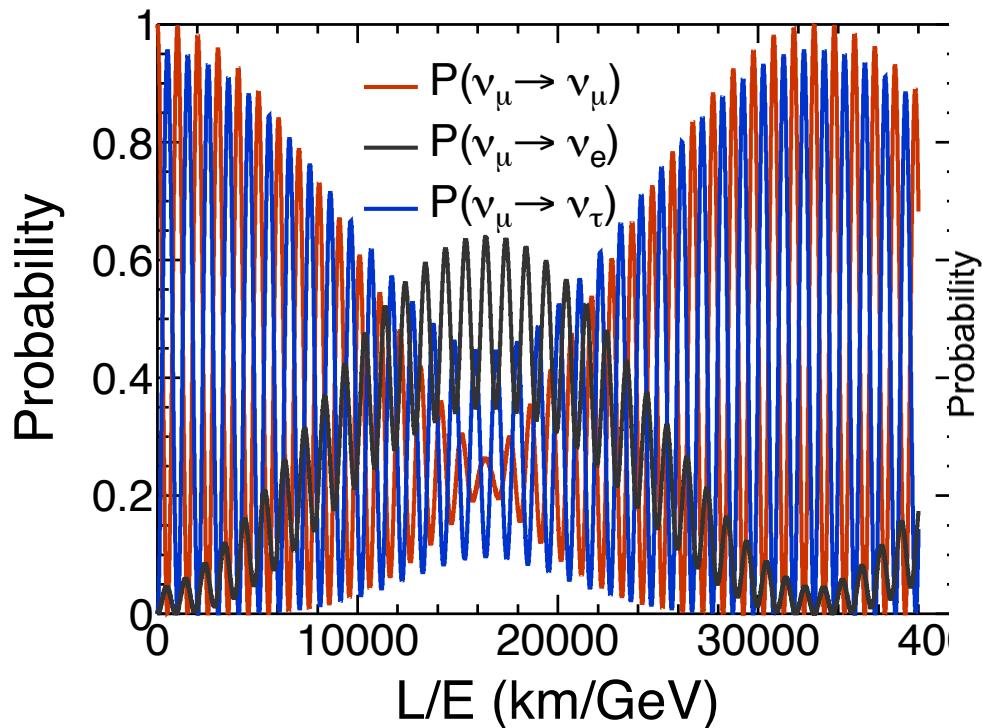
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta \cdot \left( \frac{\Delta m^2}{2E} \right)^2}{\left[ \frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}G_F N_e \right]^2 + \left( \frac{\Delta m^2}{2E} \right)^2 \sin^2 2\theta}$$

The flavor eigenstates are (in  $2\nu$  approx.):

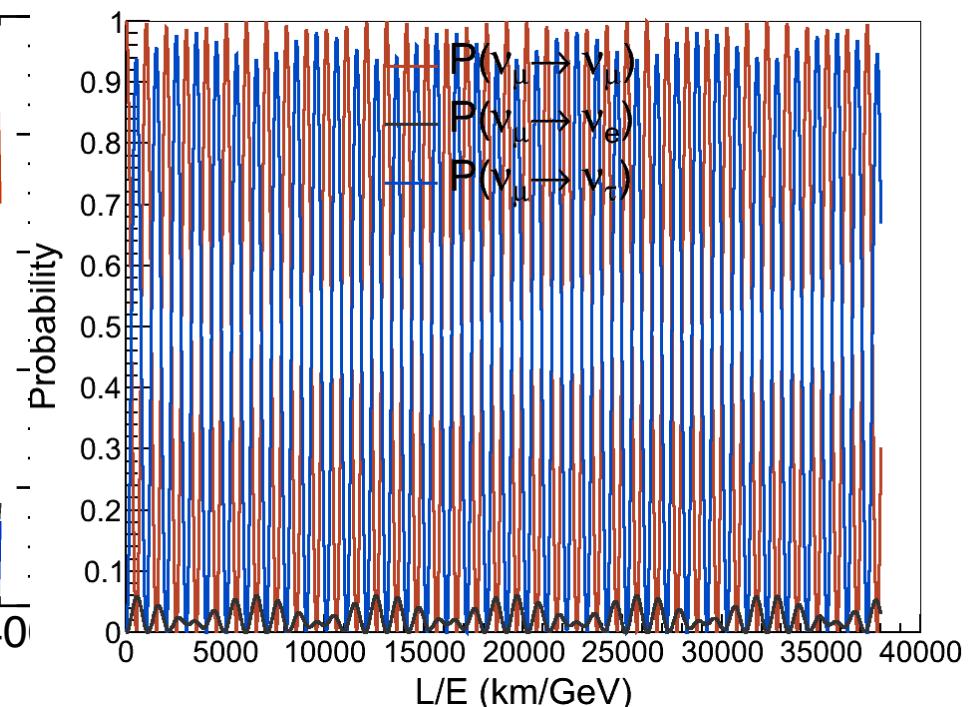
$$\begin{aligned} |\nu_e\rangle &= \cos \theta_m |\nu_{1m}\rangle + \sin \theta_m |\nu_{2m}\rangle \\ |\nu_\mu\rangle &= -\sin \theta_m |\nu_{1m}\rangle + \cos \theta_m |\nu_{2m}\rangle \end{aligned}$$

# Matter does matter

No matter



With matter



Hypothetical example for illustration purposes only!

# MINOS disappearance + appearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4 \sin^2 \theta_{23} \cos^2 \theta_{13} (1 - \sin^2 \theta_{23} \cos^2 \theta_{13}) \sin^2 \left( \frac{\Delta m_{32}^2 L_\nu}{4E_\nu} \right)$$

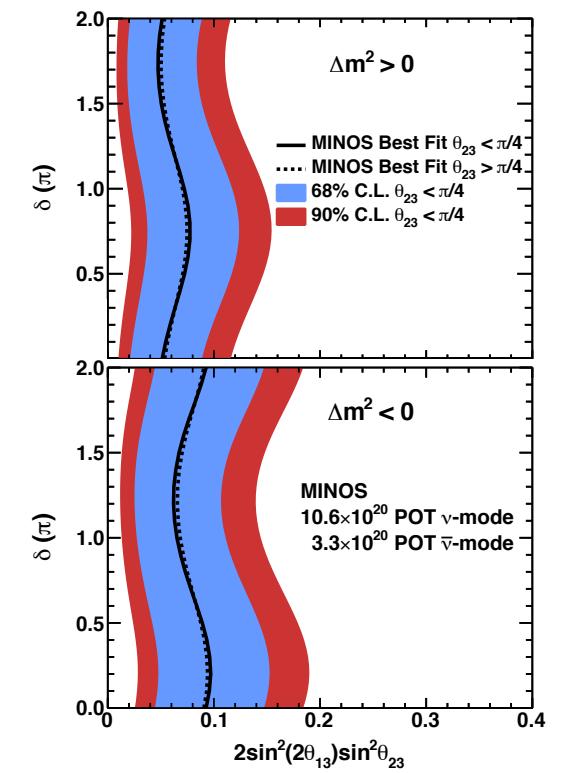
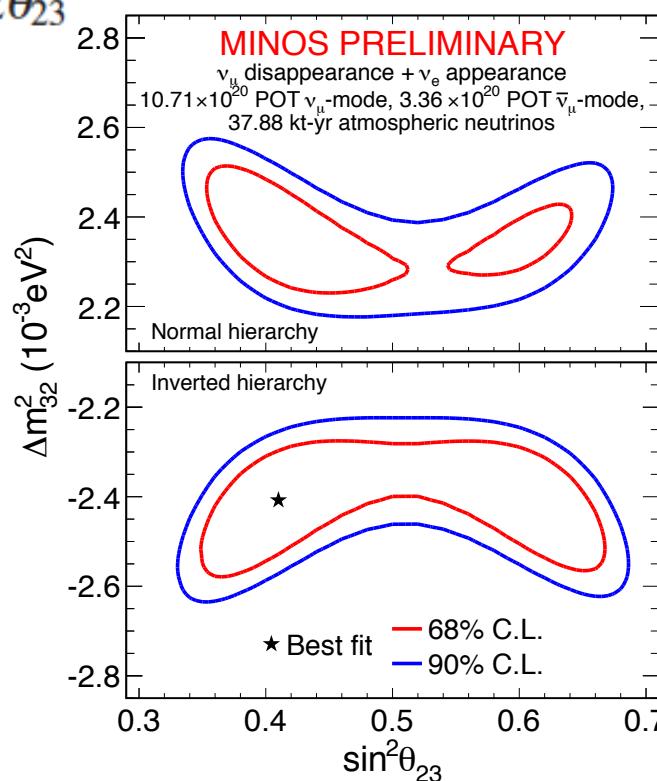
$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) = & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 \Delta(1-A)}{(1-A)^2} + \alpha J \cos(\Delta \pm \delta_{CP}) \frac{\sin \Delta A}{A} \frac{\sin^2 \Delta(1-A)}{(1-A)} \\ & + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 \Delta A}{A^2} \end{aligned}$$

$$J = \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

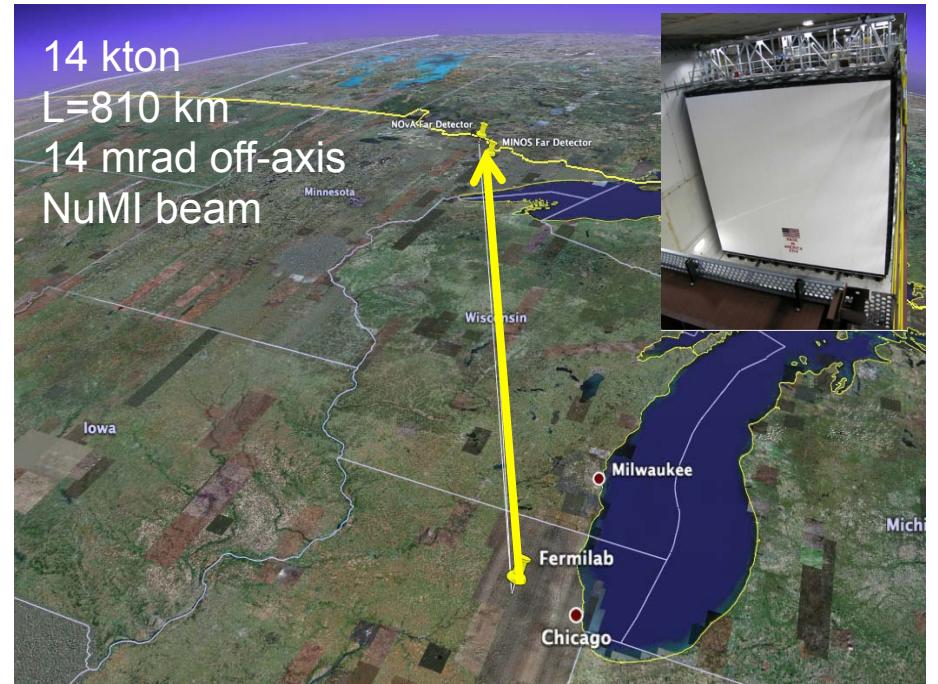
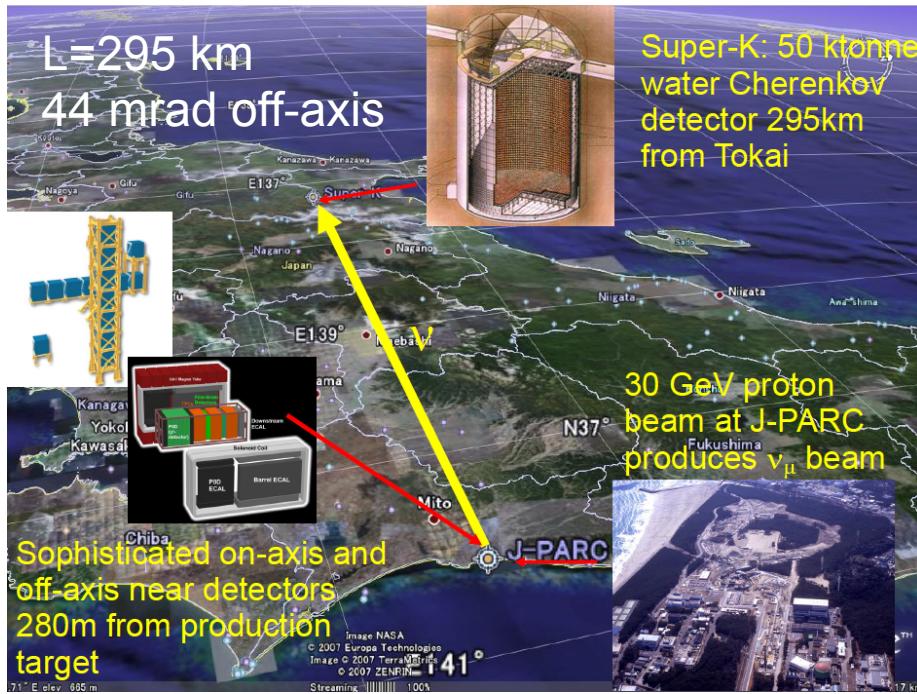
$$A = \pm 2\sqrt{2} G_F n_e E_\nu / \Delta m_{31}^2$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{32}^2 \approx 1/32$$

$$\begin{aligned} |\Delta m_{32}^2| &= [2.28 - 2.46] \times 10^{-3} \text{ eV}^2 \quad (68\% \text{ C.L.}) \\ \sin^2 \theta_{23} &= 0.35 - 0.65 \quad (90\% \text{ C.L.}) \\ |\Delta m_{32}^2| &= [2.32 - 2.53] \times 10^{-3} \text{ eV}^2 \quad (68\% \text{ C.L.}) \\ \sin^2 \theta_{23} &= 0.34 - 0.67 \quad (90\% \text{ C.L.}) \end{aligned}$$



# T2K vs NOvA

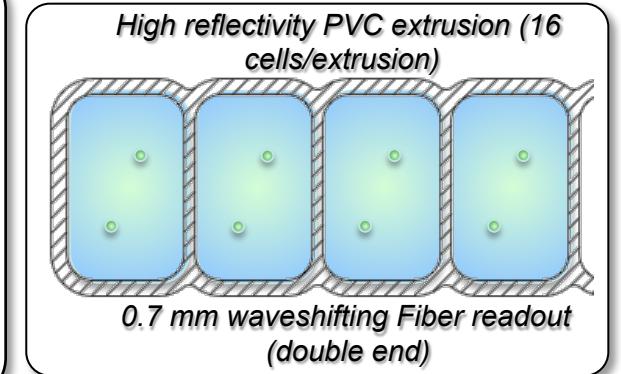


$$P\left(\begin{array}{c}(-) \\ \bar{\nu}_\mu \rightarrow \bar{\nu}_e\end{array}\right) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

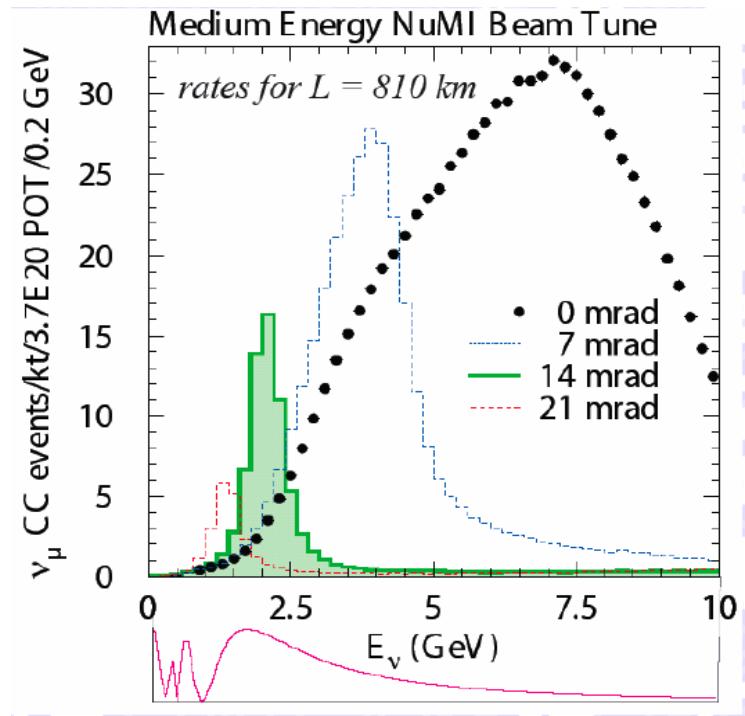
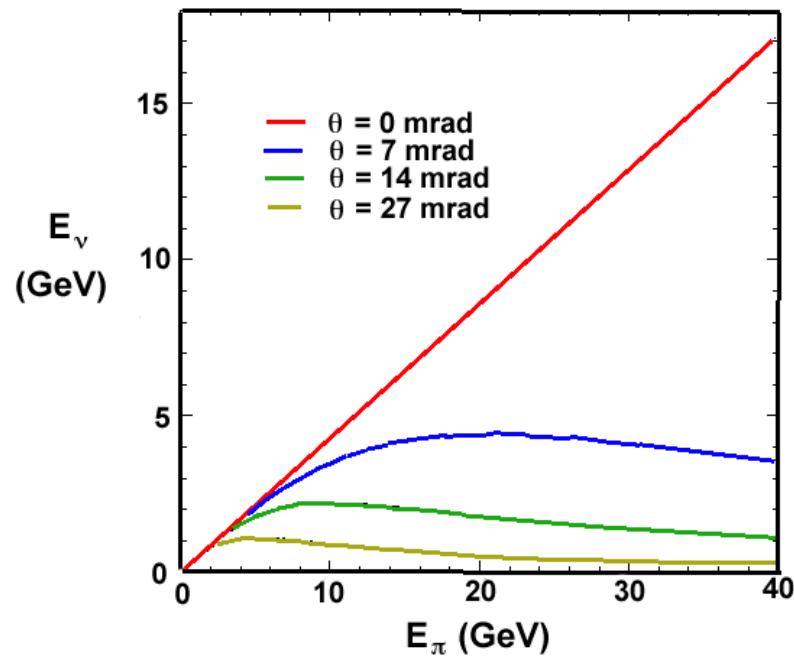
$$- 2\alpha \sin \theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin \Delta$$

$$+ 2\alpha \sin \theta_{13} \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos \Delta$$

Where:  $\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$     $\Delta = \Delta m_{31}^2 \frac{L}{4E}$     $A = + G_f N_e \frac{L}{\sqrt{2}\Delta}$



# The strategy: off-axis NuMI beam



$$E_\nu = E_\pi \frac{1 - \frac{m_\mu^2}{m_\pi^2}}{1 + \gamma^2 \theta^2}$$

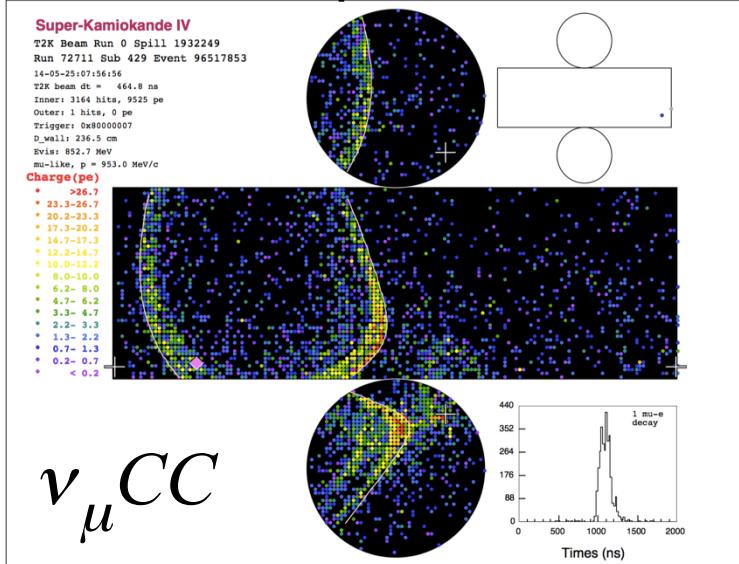
or

$$E_\nu = \frac{0.43 \gamma m_\pi}{1 + \gamma^2 \theta^2} = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

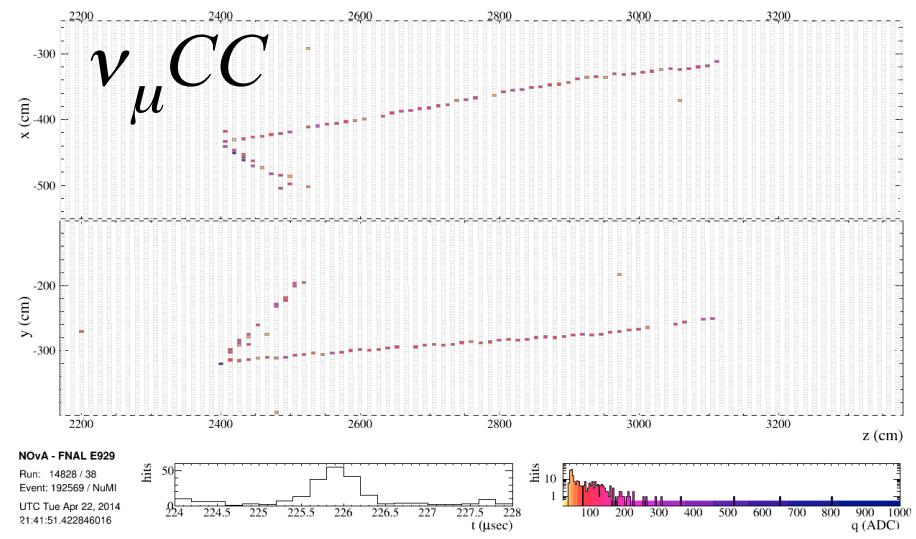
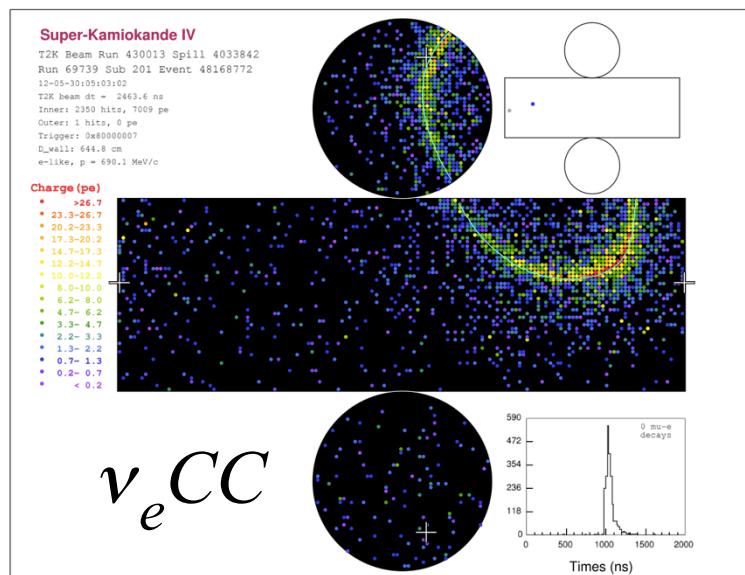
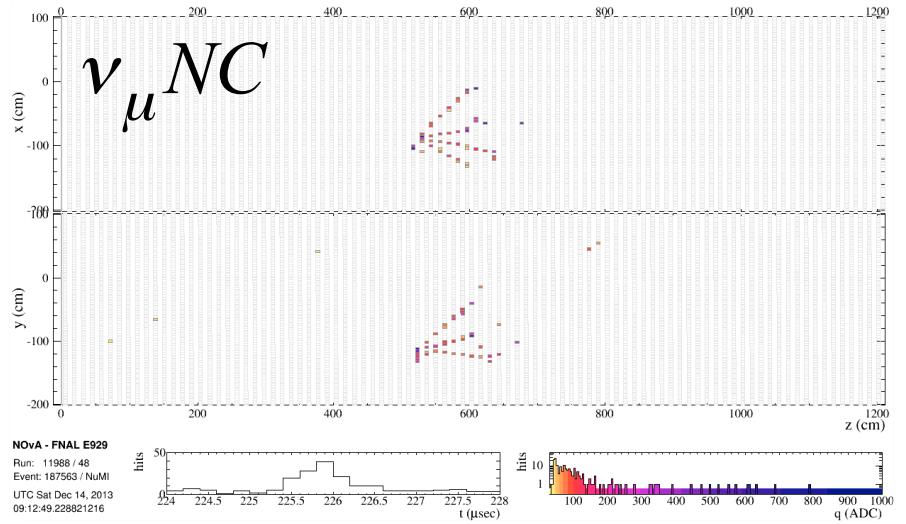
$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi} \left( \frac{2\gamma}{1 + \gamma^2 \theta^2} \right)^2$$

# Event displays

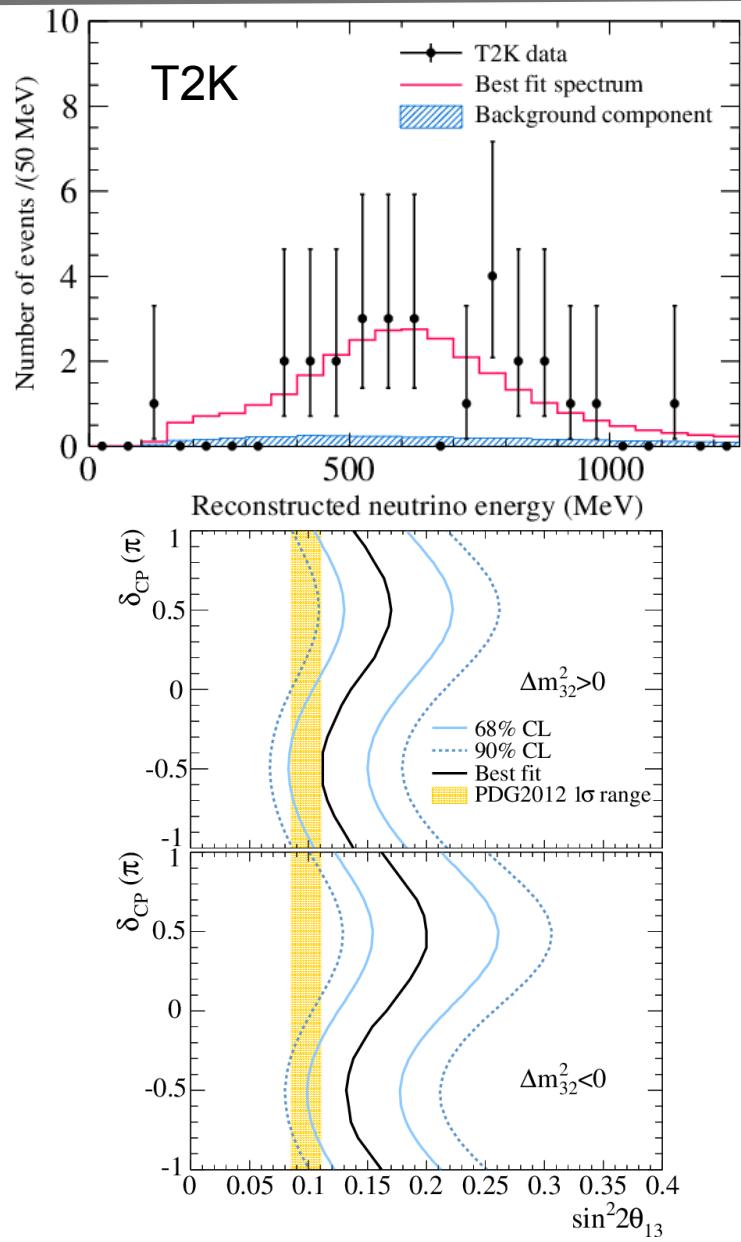
## T2K experiment



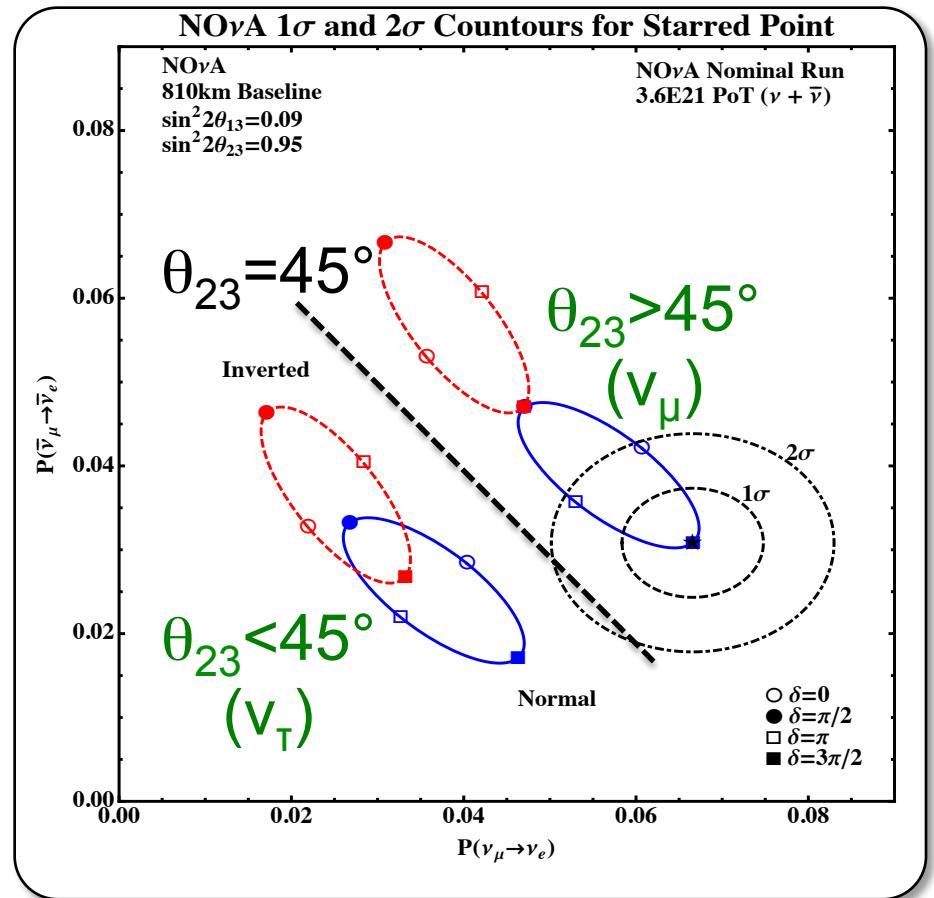
## NOvA experiment



# T2K measurements & NOvA starting up



NOvA (results soon)



T2K and NOvA @ Neutrino 2014

---

*It's tough to make predictions,  
especially about the future.*

*Yogi Berra  
(baseball player)*



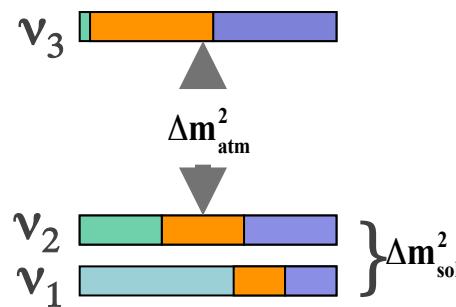
# NEUTRINOS OSCILLATIONS FUTURE ERA

# Future

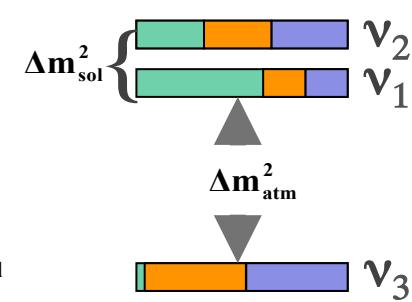
## ◆ What is left:

- ⇒ Mass hierarchy
- ⇒  $\theta_{23}$  octant
- ⇒  $\delta_{CP}$

Normal hierarchy



Inverted hierarchy



## ◆ If $\theta_{CP} \neq 0$ (CP violation)

- ⇒ Major consequences in particle physics and cosmology
- ⇒ The “holy grail” of neutrino physics (and beyond)

## ◆ What is the nature of neutrinos

- ⇒ Majorana
- ⇒ Dirac

## ◆ Are there sterile neutrinos [LSND and miniBooNE puzzles (“anomalies”)]

*Not covered  
but important*

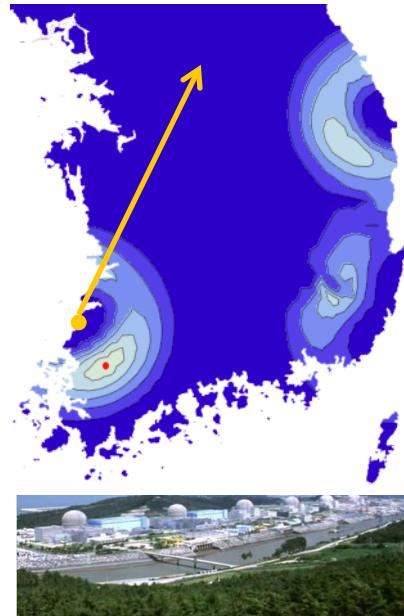
# Future MH & CPV experiments

(mass hierarchy and CP violation)

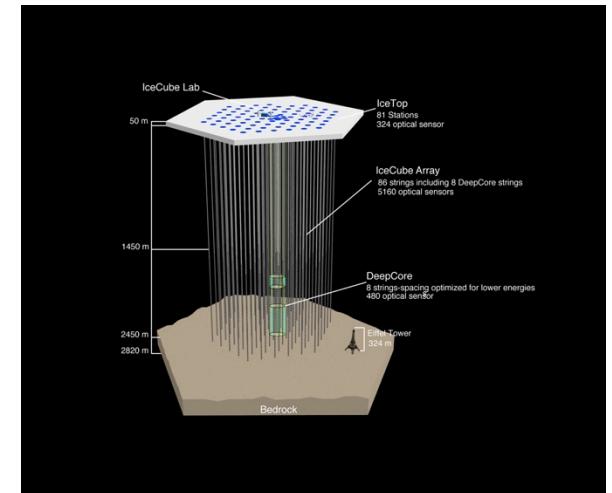
**JUNO (L=60 km) - China**



**RENO (L=60 km) - Korea**



**PINGU – South Pole**



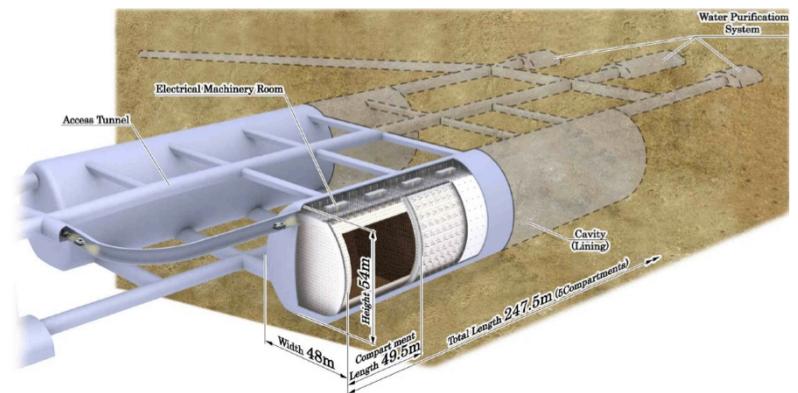
**?? LBNO (L=2,300 km) - Eu**



**?? LBNF (L=1,300 km) - US**

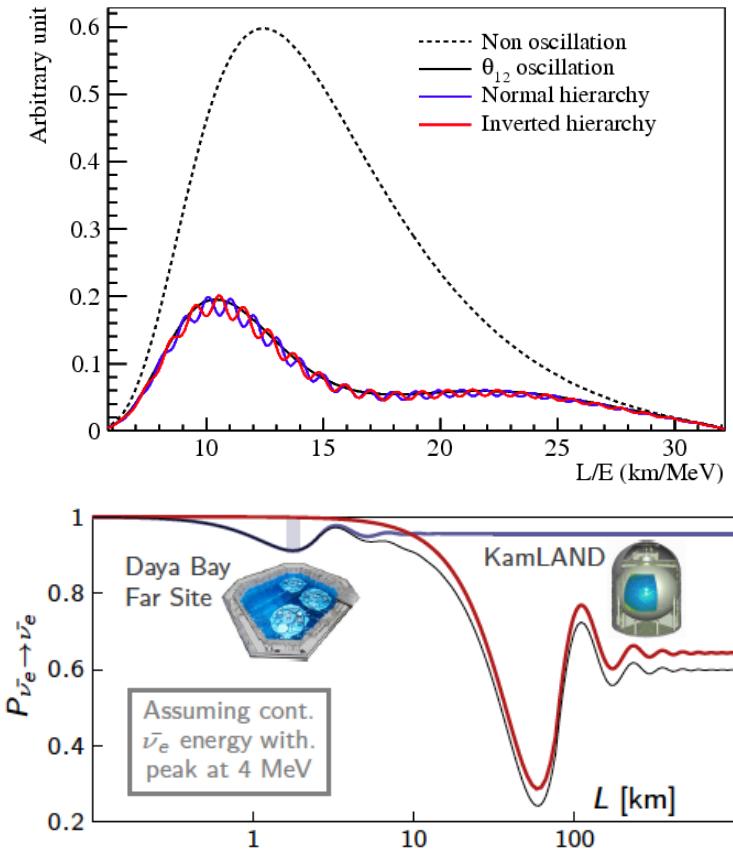


**? HyperK (L=295 km) - Japan**



# Future LBL experiments: MH and CPV

## Reactor long baseline



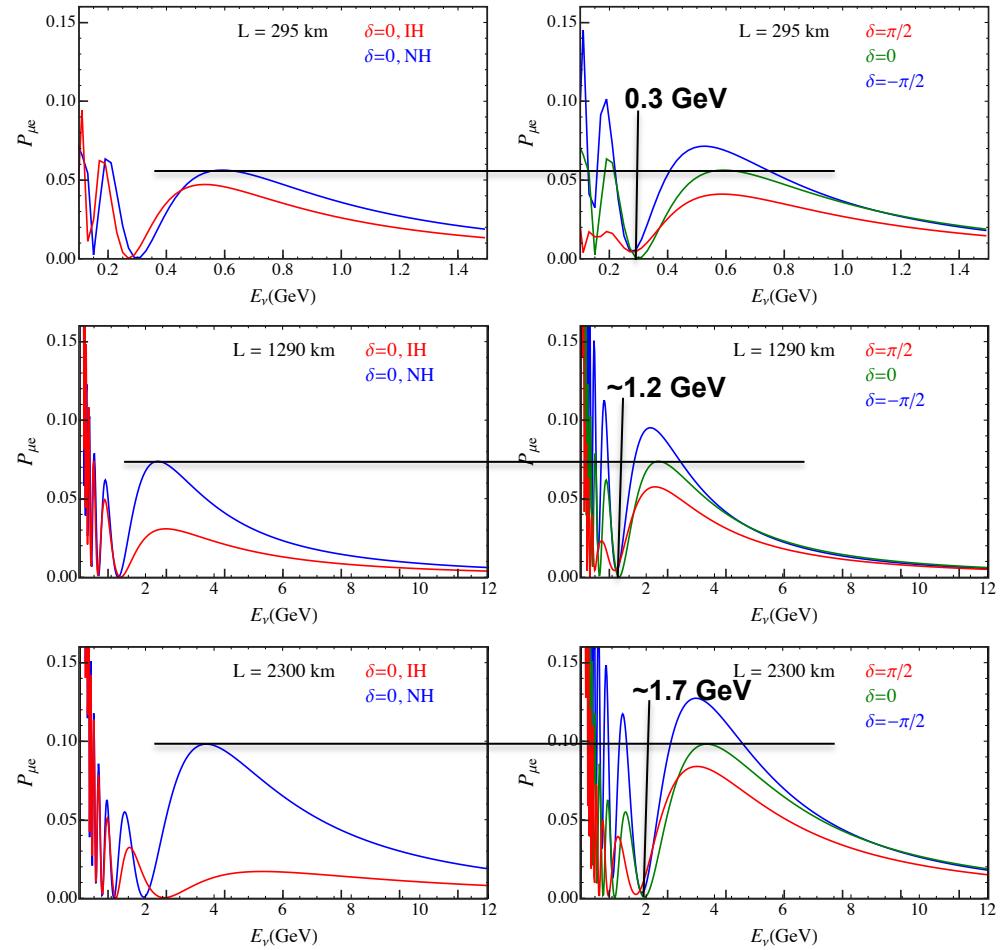
$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$

$$P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$$

$$P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})$$

## Accelerator long baseline



- ◆ Mass hierarchy and CP modulate oscillation probability:  
⇒ Need to measure as a function of  $L/E$  [measure  $E$  spectrum]
- ◆ MH sensitivity grows with  $L$  [matter effect]
- ◆ CP modulation grows with  $L/E$  [but, measure  $E$  spectrum]

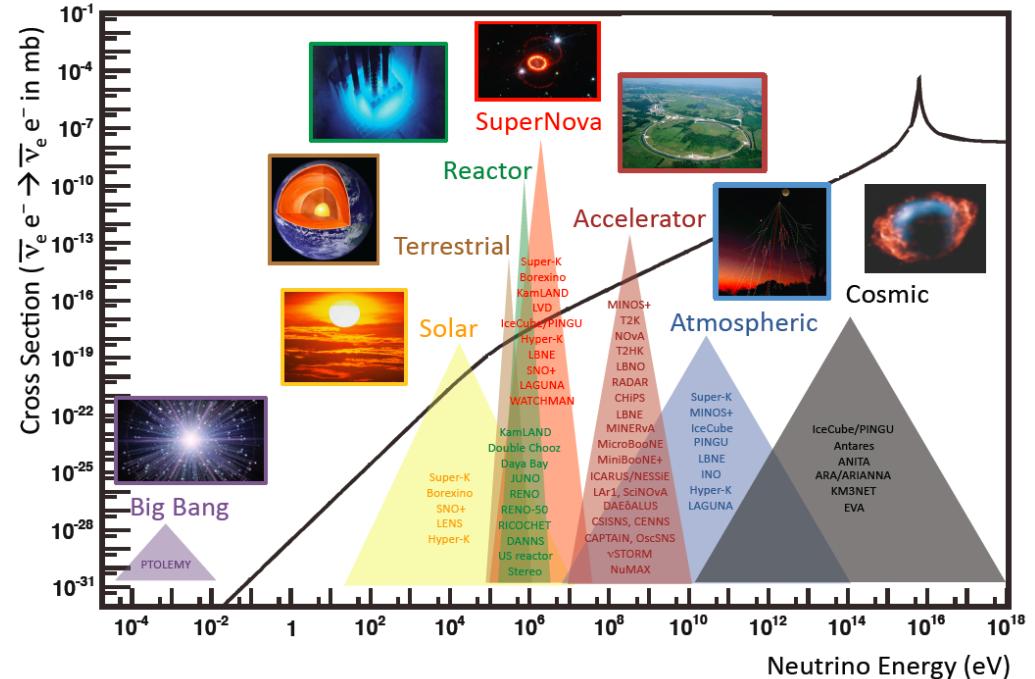
# Closing remarks (lessons learned ?)

## ◆ In neutrino physics

- ⇒ Build a large detector or two
- ⇒ Build an intense neutrino source
- ⇒ Much to do!

## ◆ Be first!

- ⇒ No one argues with success!
- ⇒ Winners take it all!
- ⇒ Be decisive!



*When you come to a fork in the road,  
take it!*

*Yogi Berra  
(baseball player)*

*Don't work on it!  
Do it!*

*Dick Tracy  
(fictional character)*