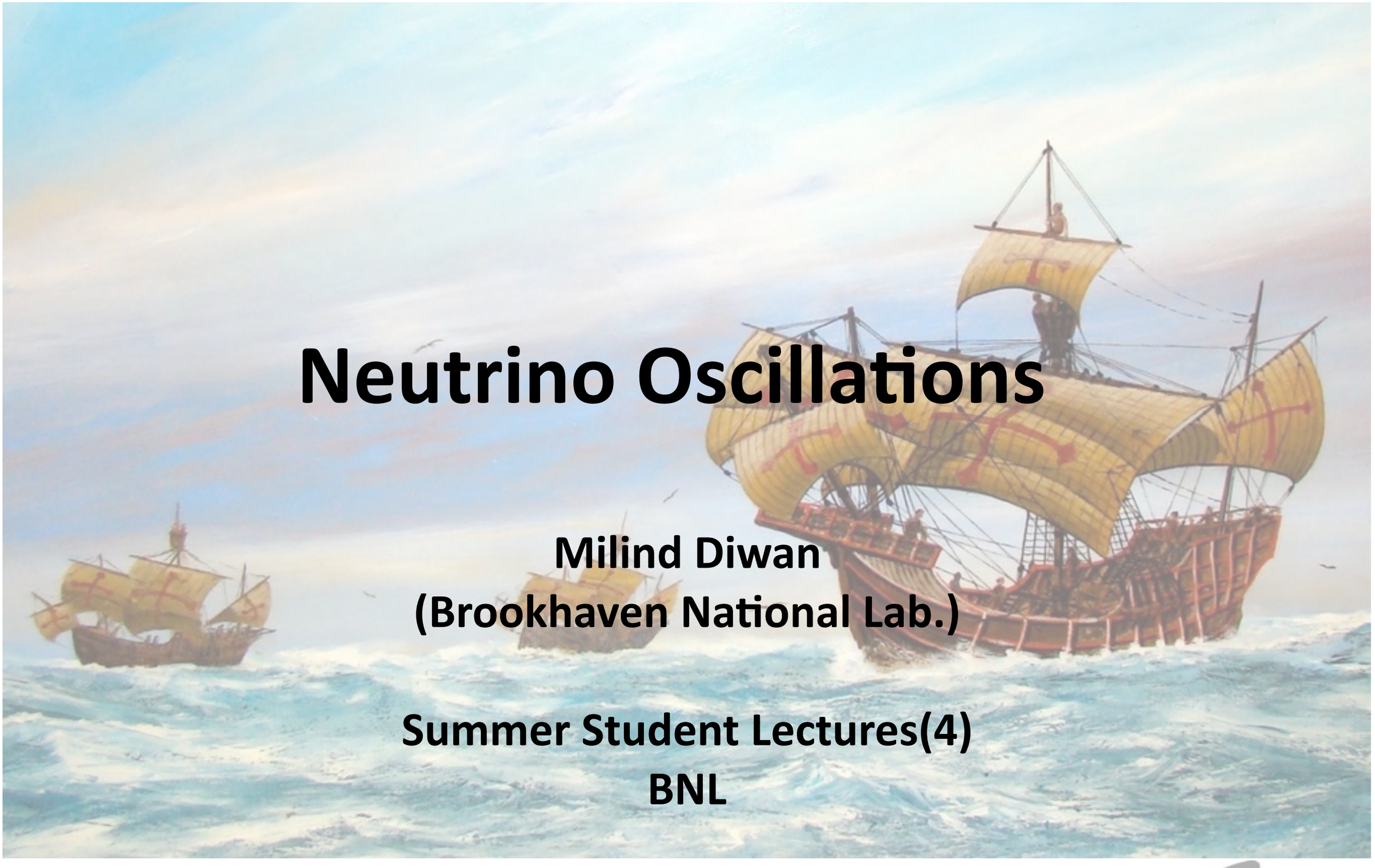


# Neutrino Oscillations


Milind Diwan
(Brookhaven National Lab.)


Summer Student Lectures(4)
BNL

BROOKHAVEN NATIONAL LABORATORY

# Outline

- **Brief review of natural and manmade sources and detectors.**
- **Current status of data from oscillations with emphasis on the recent measurement of $\theta_{13}$**
- **Benefits of $\theta_{13}$ and the scientific case for a new accelerator experiment.**
- **Reference: The recent review of Long-Baseline for annual reviews (2016) by Diwan, Galymov, Qian, Rubbia**

**http://www.phy.bnl.gov/~diwan/talks/Brazil**

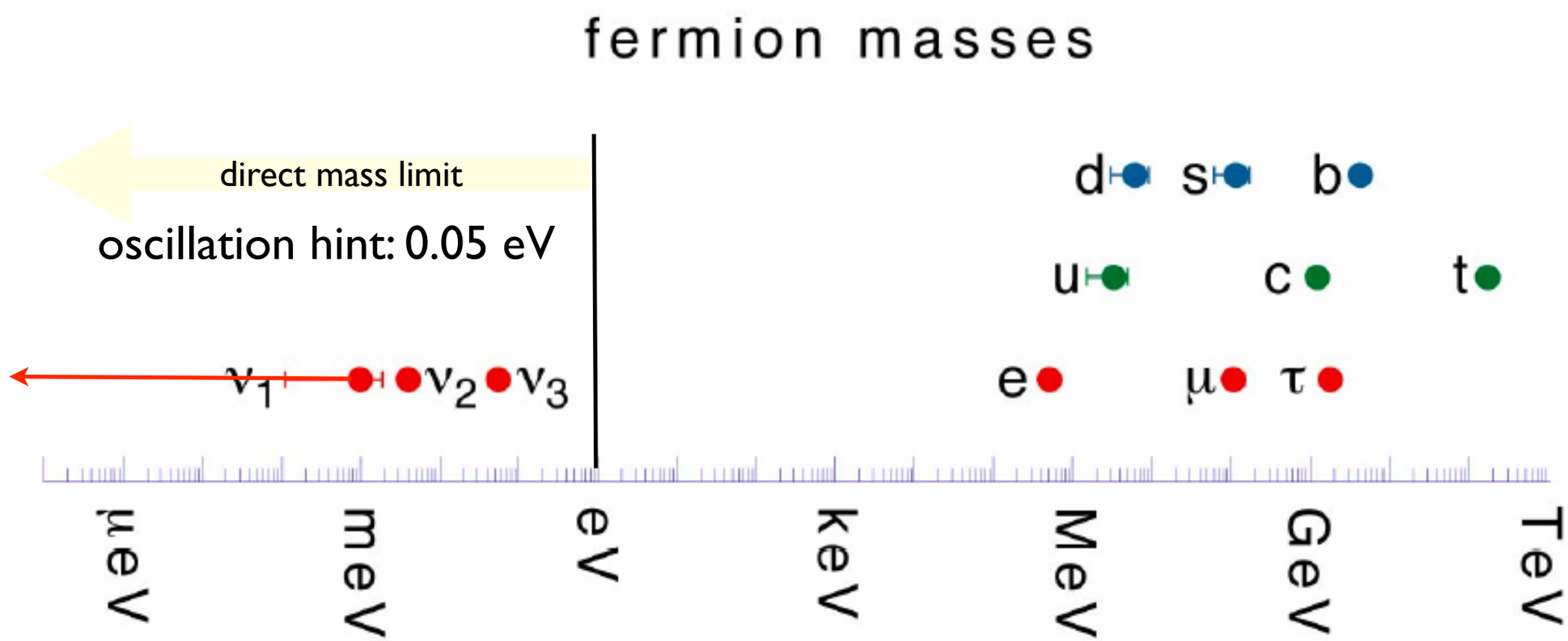
I will move from basic to technical explanation in the talk.

# What do we know and how do we know it ?

- **Neutrinos are definitely massive with extremely small mass - from the existence of oscillations.**

- **Neutrino is the most abundant particle of matter with probably only 3 active types - cosmology and precision EW.**

- **Neutrino mass and mixing is completely different compared to quarks. I will review backwards for simplicity.**



# What is the scientific interest in neutrinos ?

**FERMIONS** matter constituents spin = 1/2, 3/2, 5/2, ...

**Leptons** spin =1/2

| Flavor | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| $\nu_L$ lightest neutrino* | $(0-0.13)\times10^{-9}$ | 0 |
| e electron | 0.000511 | –1 |
| $\nu_M$ middle neutrino* | $(0.009-0.13)\times10^{-9}$ | 0 |
| $\mu$ muon | 0.106 | –1 |
| $\nu_H$ heaviest neutrino* | $(0.04-0.14)\times10^{-9}$ | 0 |
| $\tau$ tau | 1.777 | –1 |

**Quarks** spin =1/2

| Flavor | Approx. Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| u up | 0.002 | 2/3 |
| d down | 0.005 | –1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | –1/3 |
| t top | 173 | 2/3 |
| b bottom | 4.2 | –1/3 |

- ~20 yrs ago all neutrino masses were thought to be 0 and all neutrino flavors distinct.
- With new discoveries a distinct, unexpected pattern appears to be emerging.

- Science of neutrinos is has deep connections to understanding of matter, cosmology, and astrophysics.
- Existence of neutrino mass itself is physics beyond the standard model because in the standard model there is no interaction with right handed neutrinos. And so by definition the mass is zero.
- A new mechanism for mass generation may be needed in which neutrinos are their own anti-particles.

**If neutrinos have mass; the massive states need not be the same as the Weak interaction states. A neutrino could be in a classic superposition of states.**

This will lead to interference effects

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Massive Neutrinos

Flavored neutrinos

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

Sufficient to understand most of the physics:

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$ .

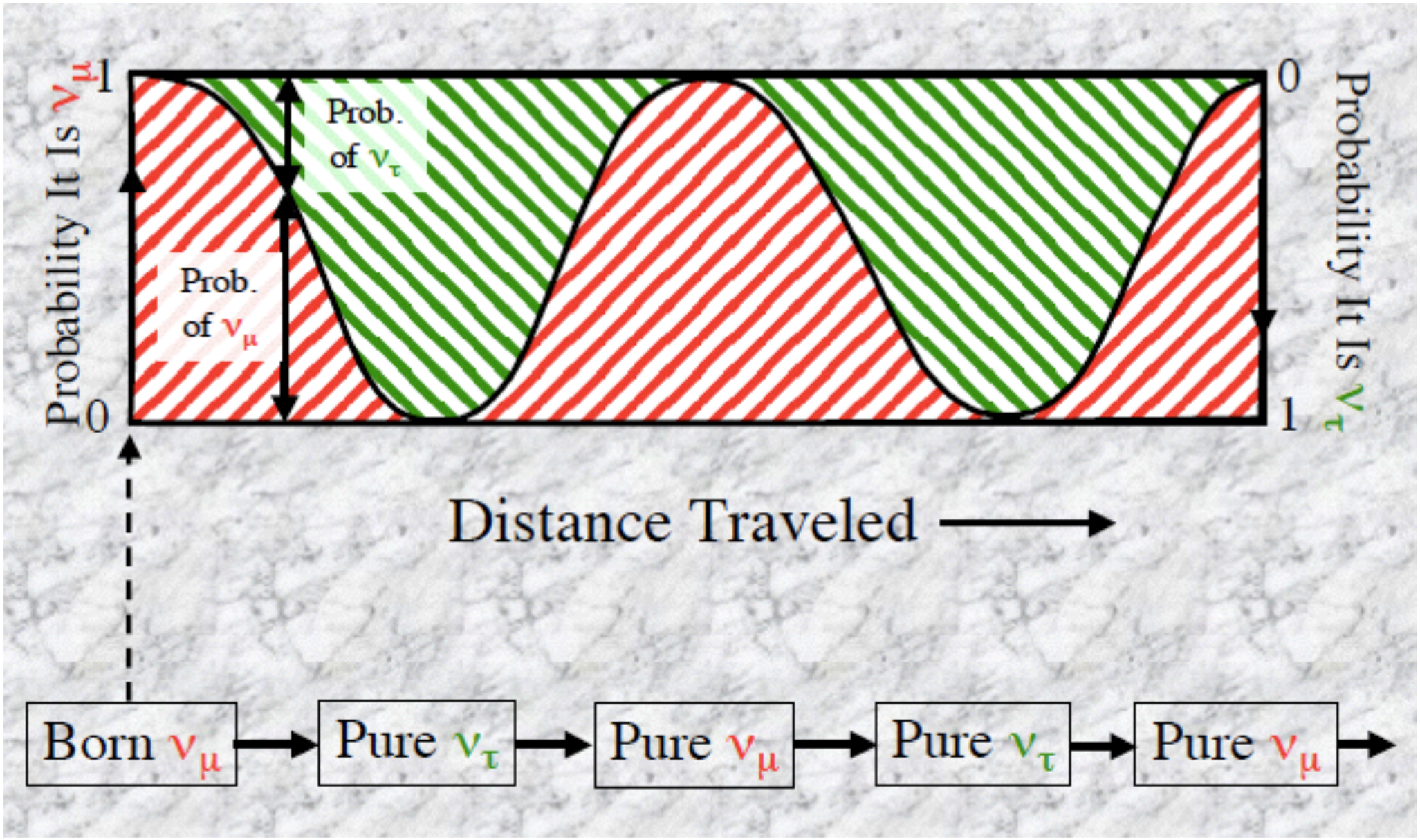
# Definition

$Appearance : \nu_a \rightarrow \nu_b \quad \Rightarrow$ Make beam type (a) and Detect (b) after some distance to see if neutrino (a) tranformed to (b).

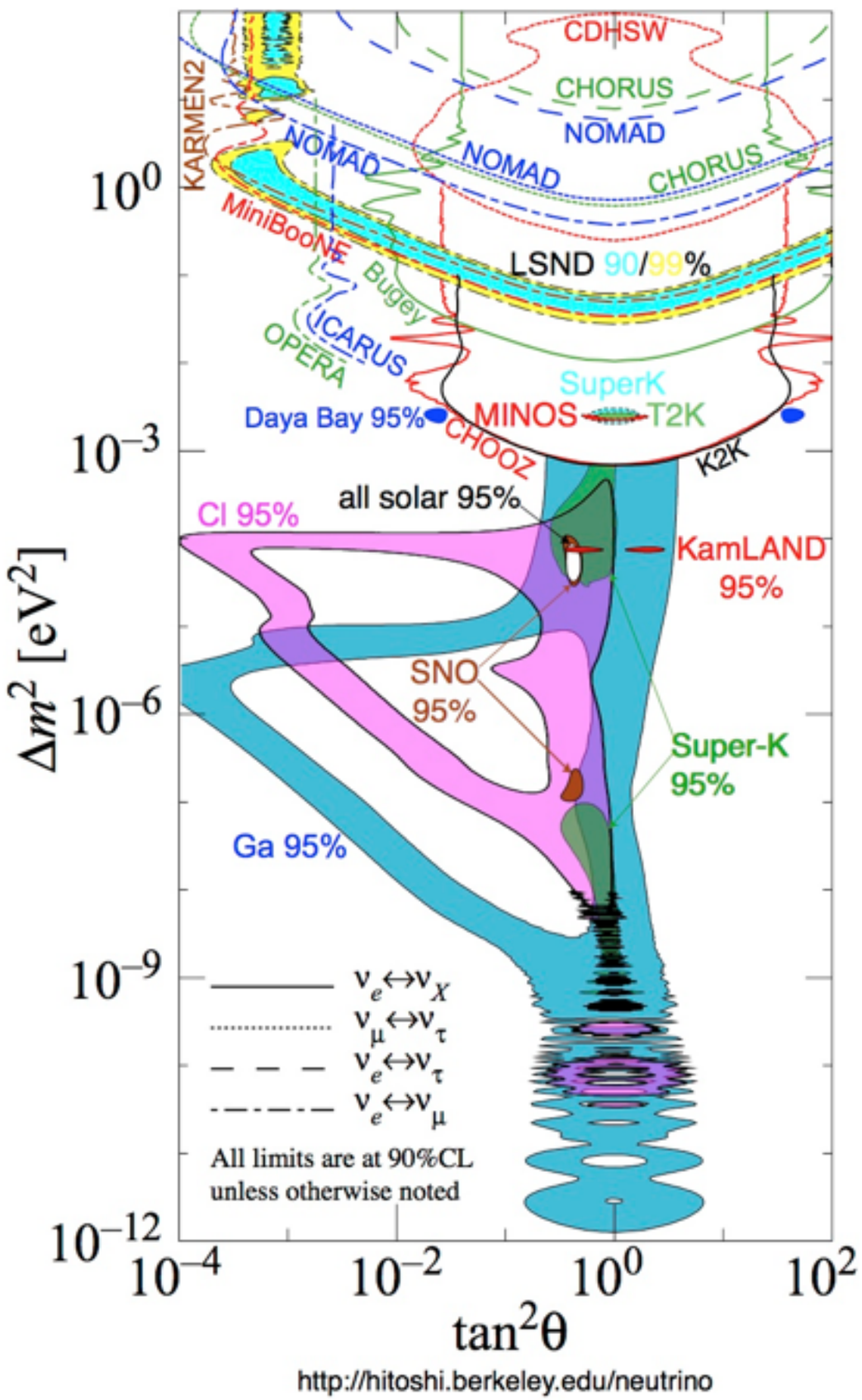
$Dis-appearance : \nu_a \rightarrow \nu_a \quad \Rightarrow$ Make beam type (a) and Detect (a) to see how many are left after traveling some distance

- **In both cases we must know how many (a) type were created and sent to the far detector. A precise prediction in the far detector is needed.**
- **In the first case, we must know if any events will fake the signature of (b) (these are called backgrounds.**
- **In the second we must know how many (a) to expect.**

# Picture with θ = 45 deg




Everything we know about neutrino properties comes from this astonishing effect.




All oscillations data from PDG in two parameter plot

$$P(\nu_a \rightarrow \nu_b) = \mathrm{Sin}^2 2\theta \, \mathrm{Sin}^2 (1.27 \Delta m^2 \frac{L}{E})$$

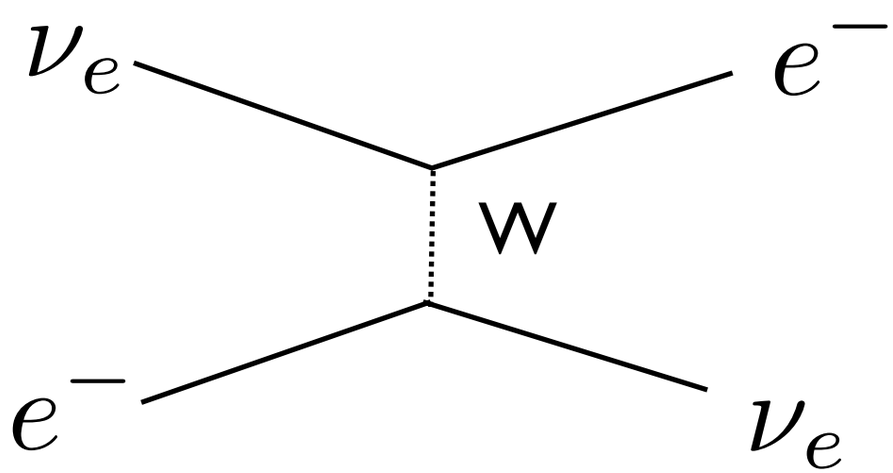
$\Delta m^2$ *in* $eV^2$

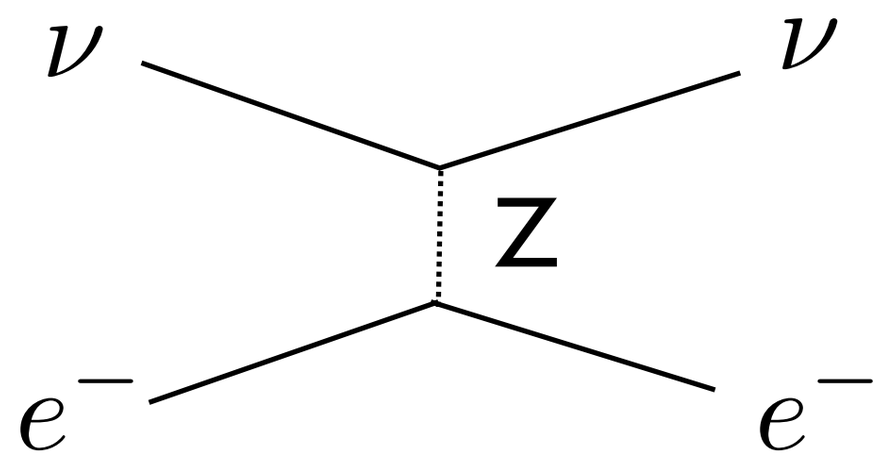
*L in km*

*E in GeV*

$$i\frac{d}{dx}\nu_f = HR_\theta\nu_m$$

L. Wolfenstein: Oscillations need to be modified in presence of matter.




Charged Current
for electron type only

Neutral Current
for all neutrino types

Additional potential for $\nu_e$ ($\bar{\nu}_e$): $\pm\sqrt{2}G_F N_e$ =Q/2E

$N_e$ is electron number density.

**The matter effect is an example of how additional phases can affect interferometry.**

# Oscillations in presence of matter

$$i\frac{d}{dx}\nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\left(R_\theta\begin{pmatrix}m_2^2-m_1^2 & 0\\ 0 & m_1^2-m_2^2\end{pmatrix}R_\theta^T + 2E\begin{pmatrix}\sqrt{2}G_F N_e & 0\\ 0 & -\sqrt{2}G_F N_e\end{pmatrix}\right)\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \quad (3)$$

Looking at conversions of muon to electron neutrinos.

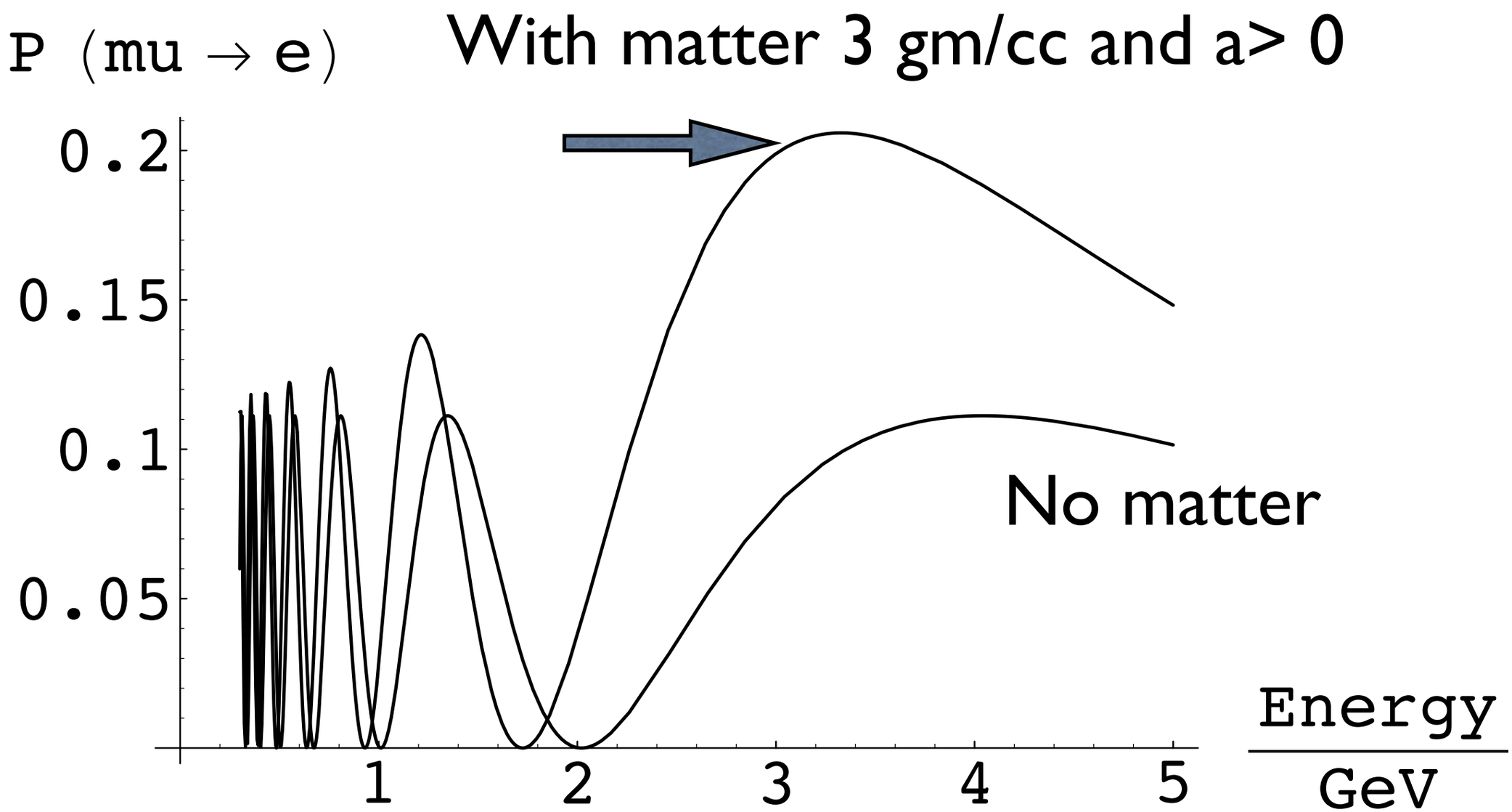
$$P_{\mu\to e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta}\times\sin^2\frac{L\Delta m^2}{4E}\sqrt{(a-\cos 2\theta)^2+\sin^2 2\theta}$$

This is a signed quantity

$$\begin{aligned} a &= 2\sqrt{2}EG_F N_e/\Delta m^2 \\ &\approx 7.6\times 10^{-5}\times D/(gm/cc)\times E_\nu/GeV/(\Delta m^2/eV^2) \end{aligned} \quad (4)$$

This effect present if electron neutrinos in the mix

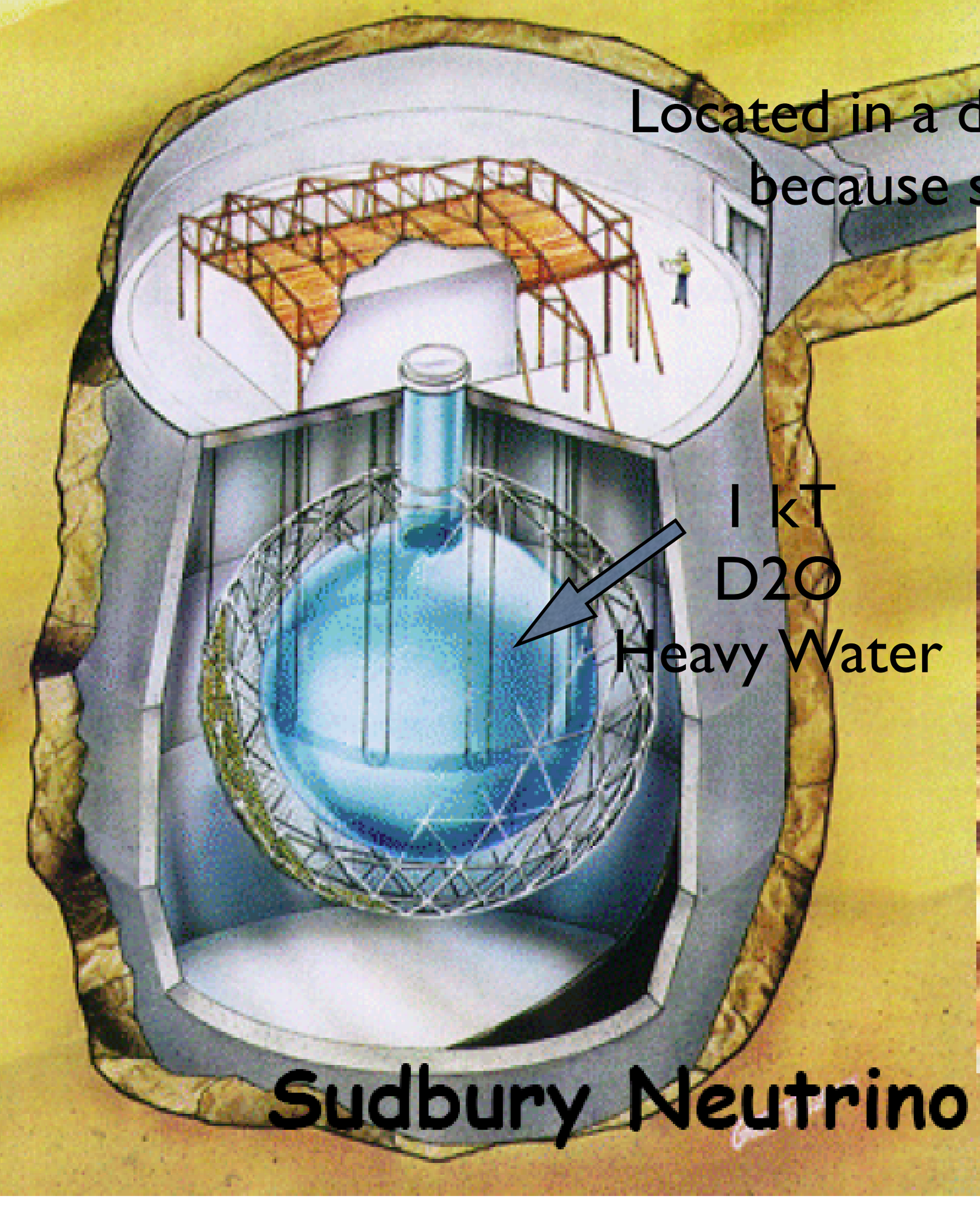
# 2 neutrinos with matter effect.

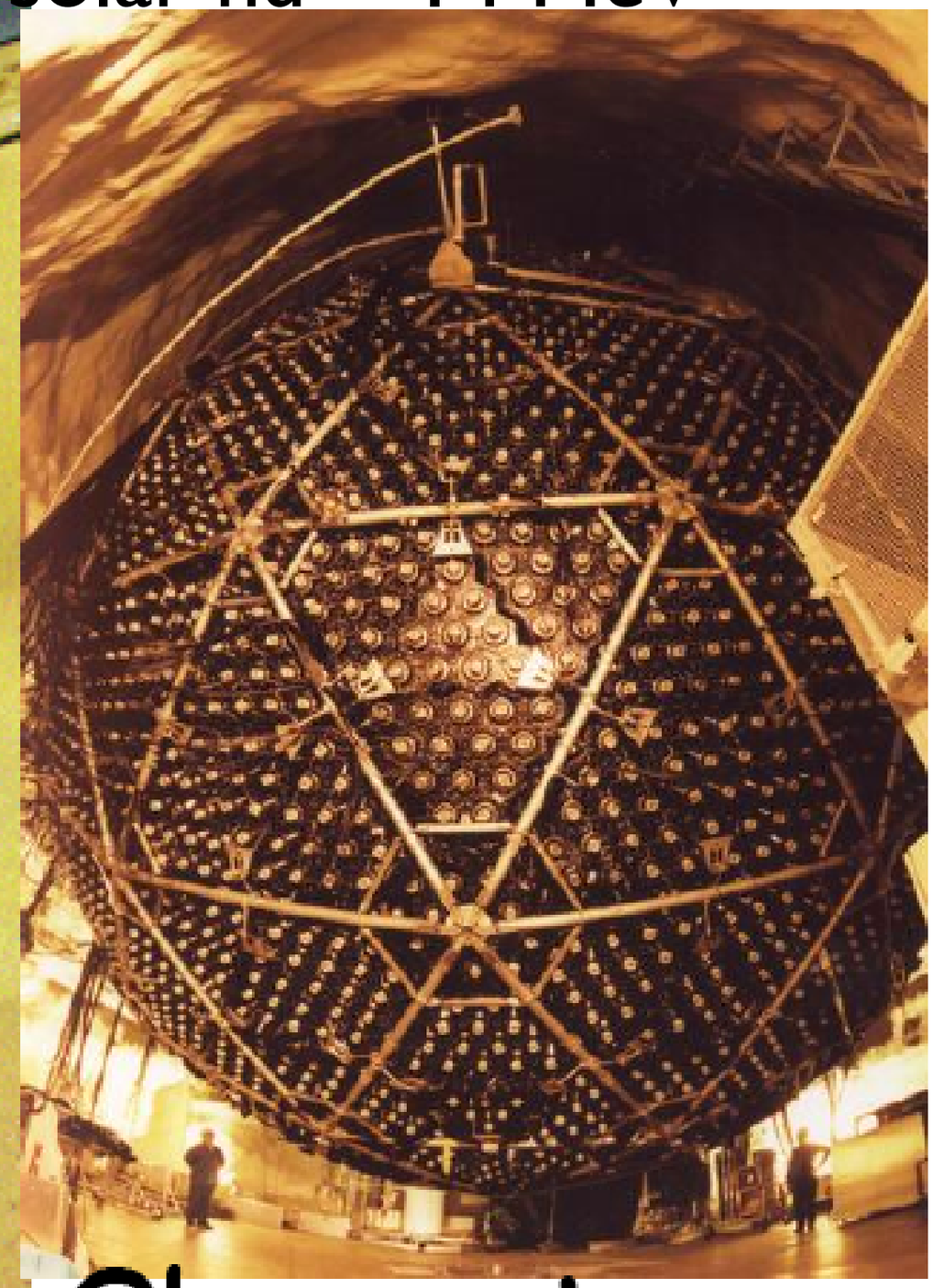



Osc. probability: 0.0025 eV^2, L= 2000 km, Theta=10deg

# So Far….

- 3 types of neutrinos
- Still many unknowns about these particles, but they play an important role in the early universe as well as current astrophysical processes.
- If they have mass there are fundamental consequences.
- Oscillation phenomenology
- In next slides I will review the complete picture of the 3 neutrinos: masses and mixing.

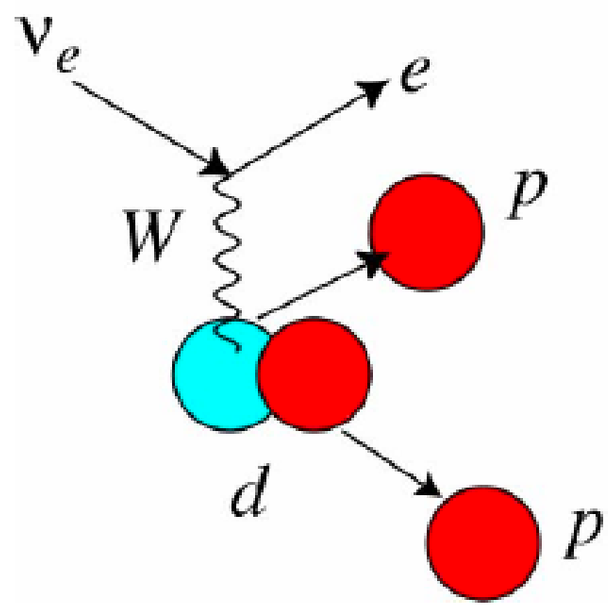

Located in a deep mine ~ 6000 mwe
because solar nu < 14 MeV
1 kT
D2O
Heavy Water
Sudbury Neutrino Observatory



# Why does SNO use $300M worth of heavy water?

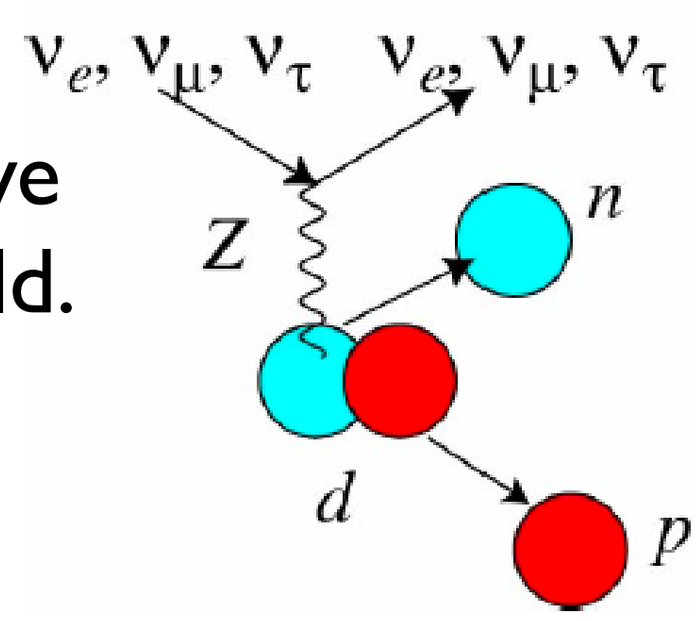
The Sun is known to emit electron neutrinos.

About $10^{11}$ /cm$^2$/sec,



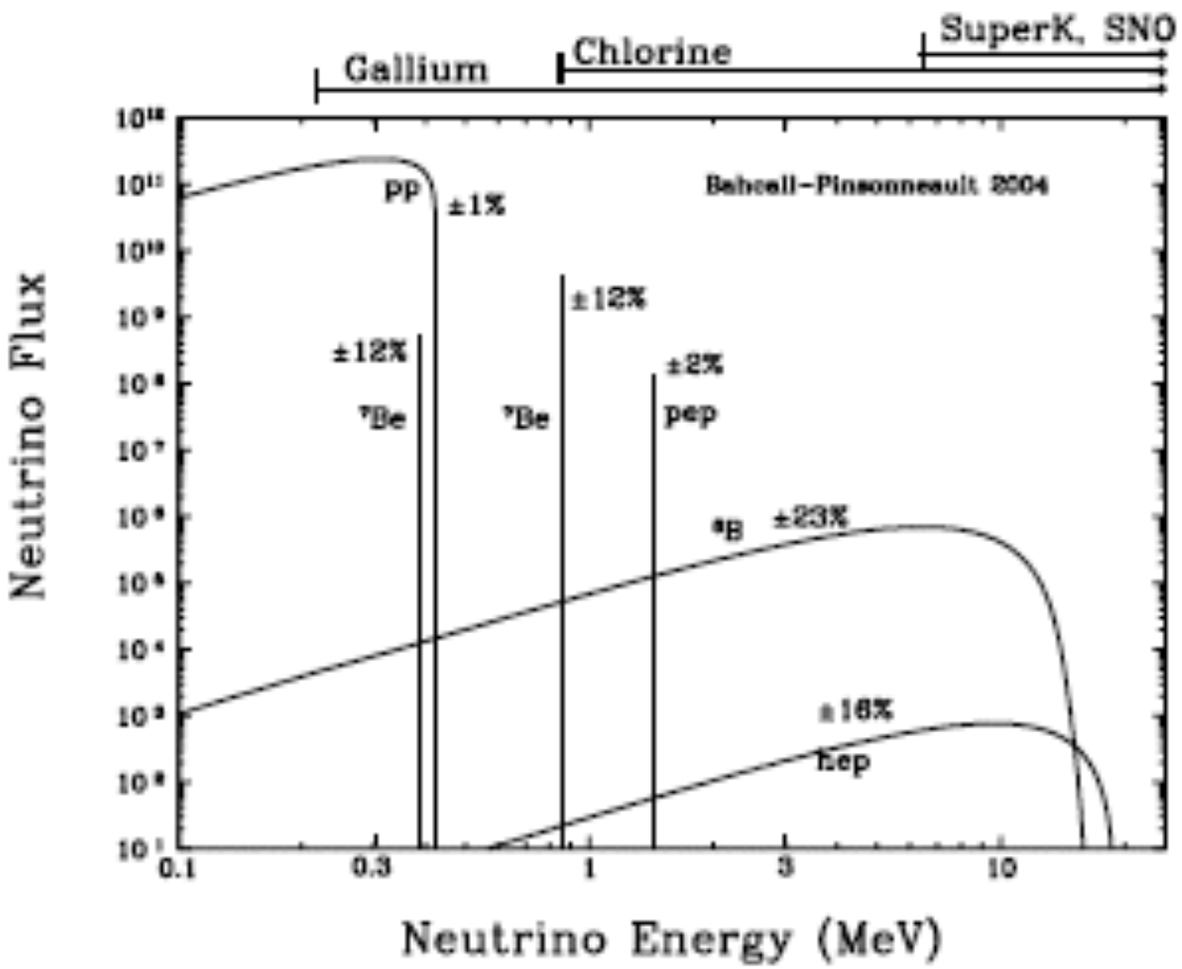

Charged Current

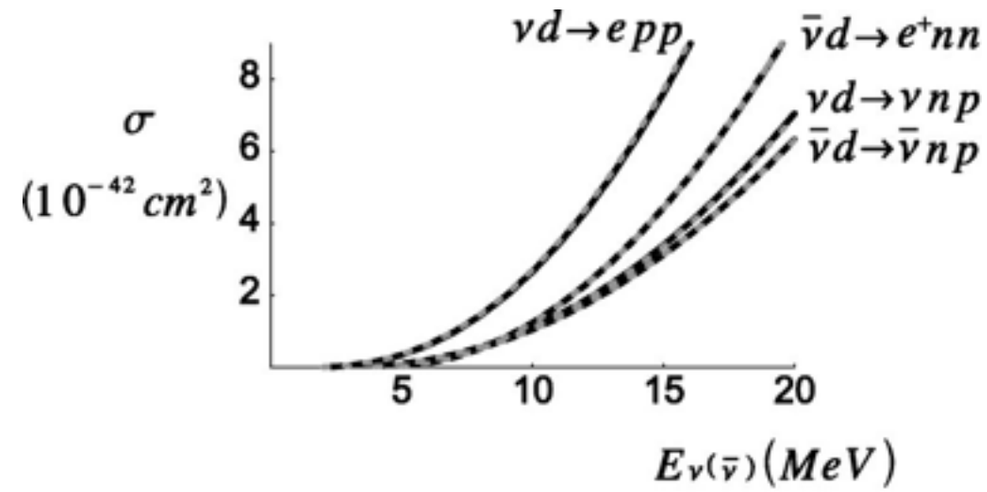
But only a fraction are above practical detection threshold.

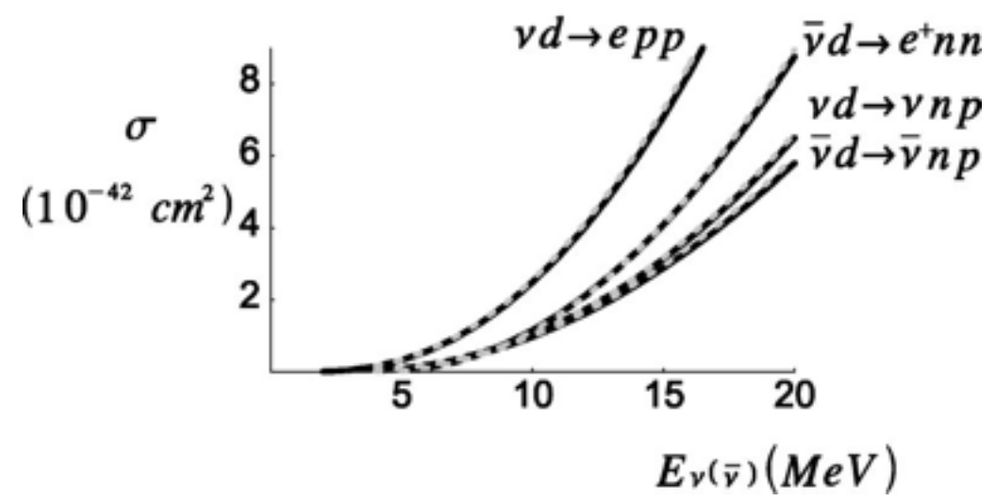



Neutral Current

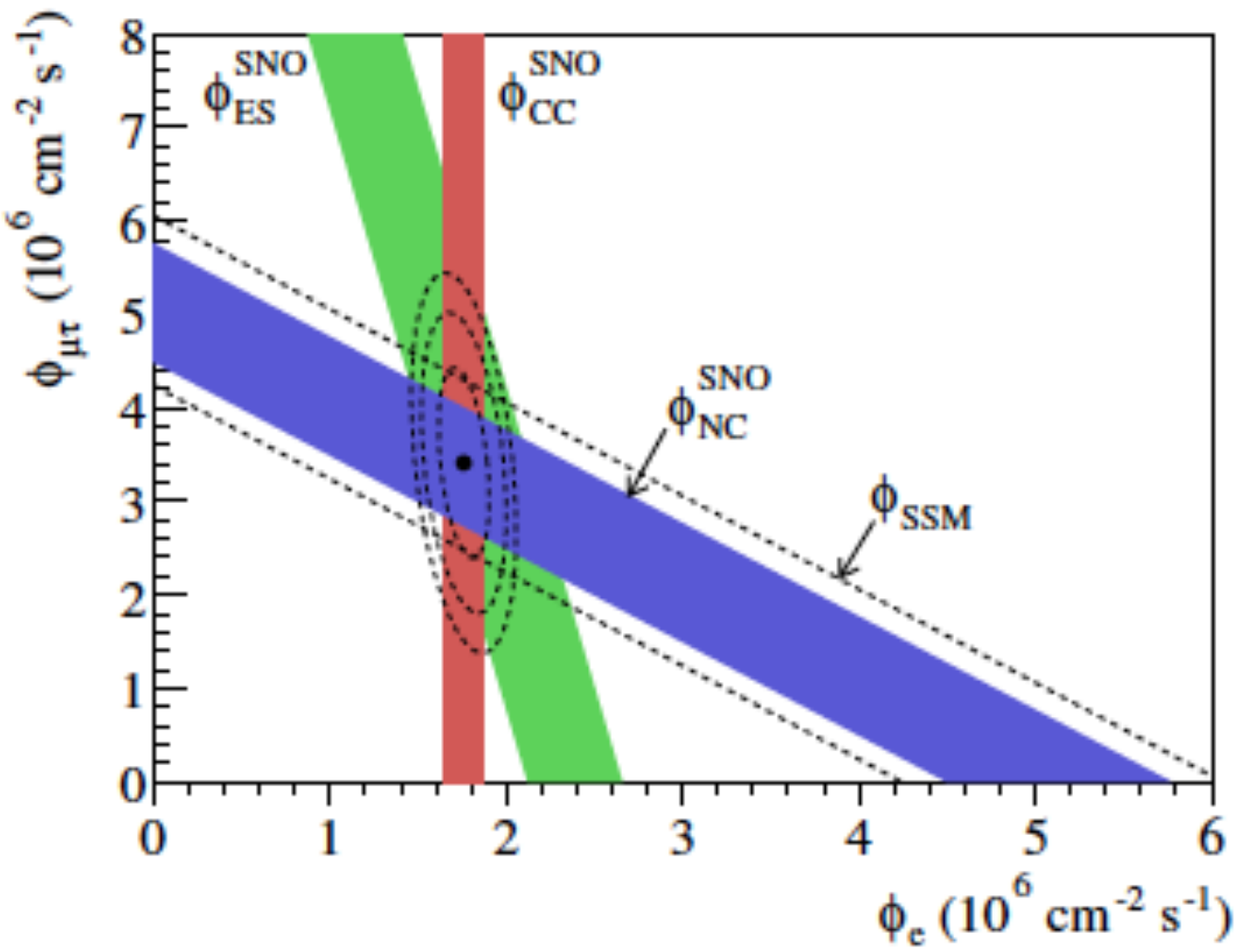
# Sno event rate



# SNO data

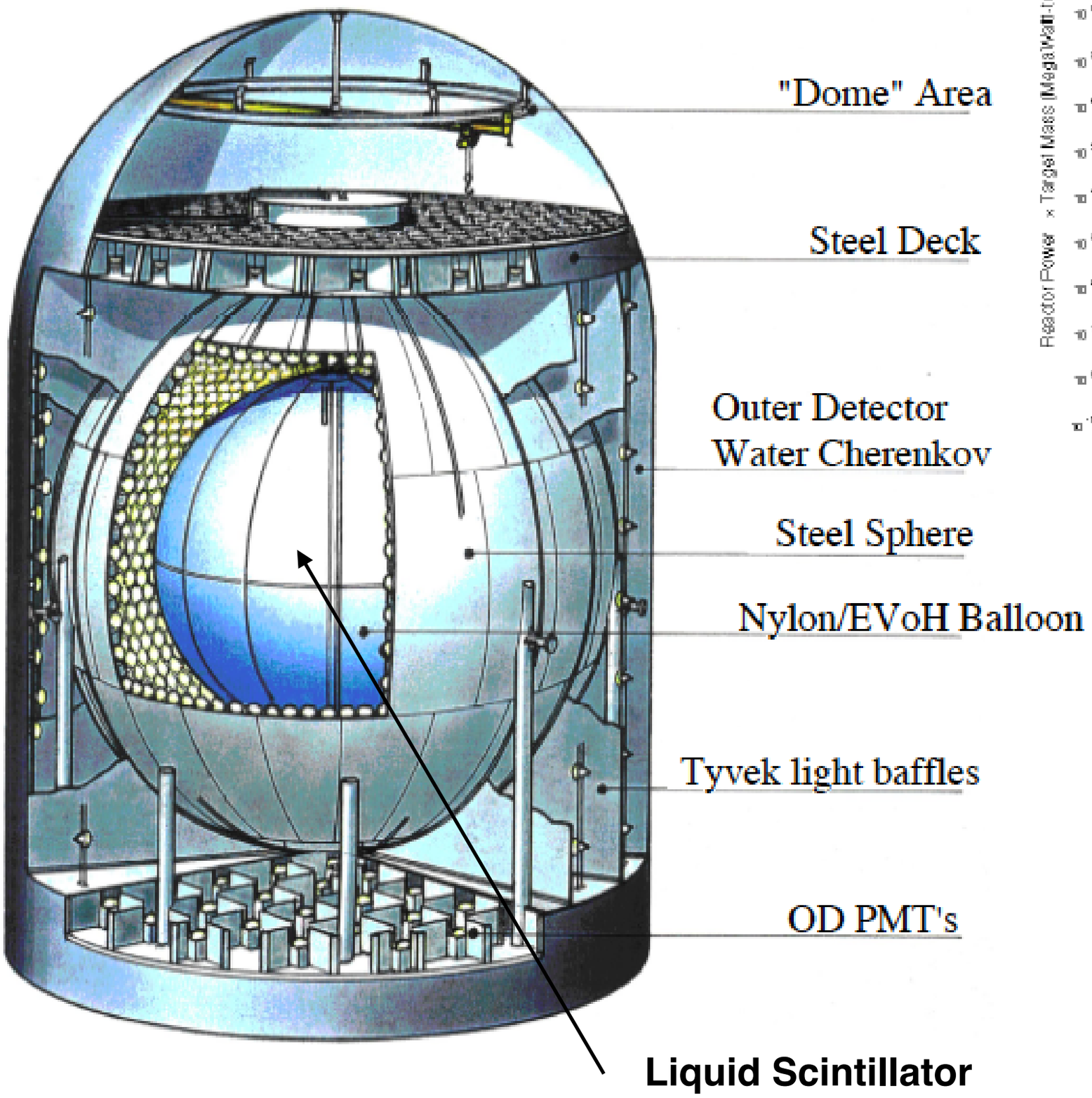


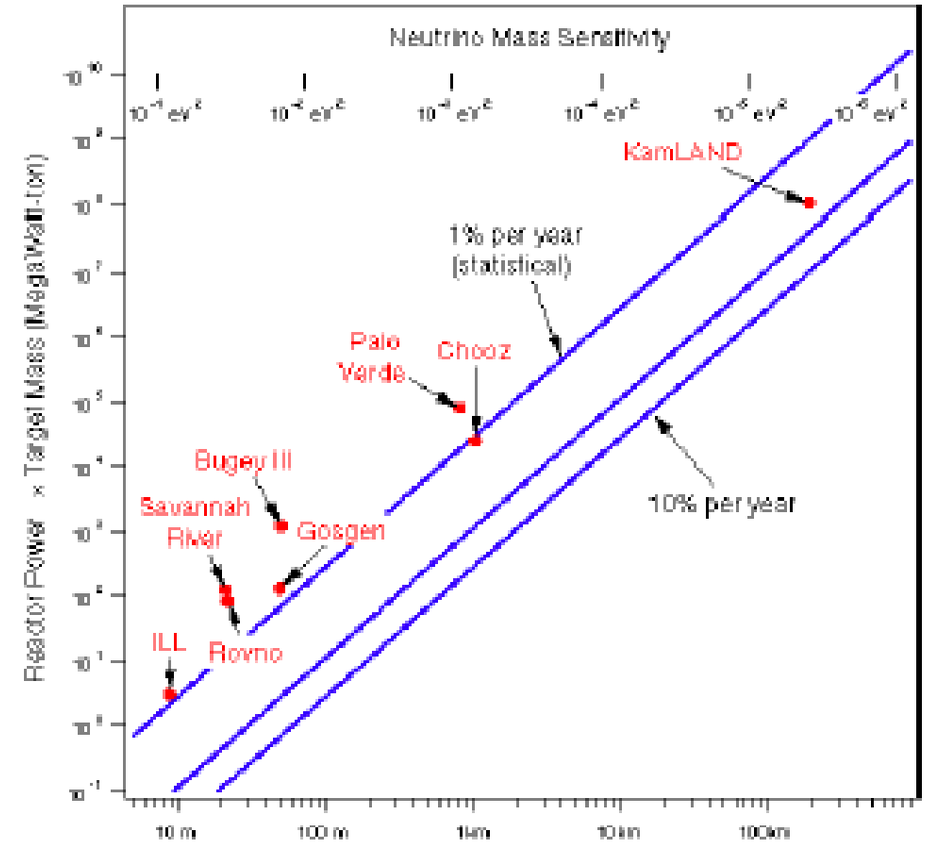

$\phi_{SSM} = 5.82 \pm 1.34 \times 10^6 \, cm^{-2} \sec^{-1}$

For Boron8 Neutrinos.

~2/3 of the electron neutrinos turned into other types.

# KamLAND


"Dome" Area
Steel Deck
Outer Detector
Water Cherenkov
Steel Sphere
Nylon/EVoH Balloon
Tyvek light baffles
OD PMT's
Liquid Scintillator

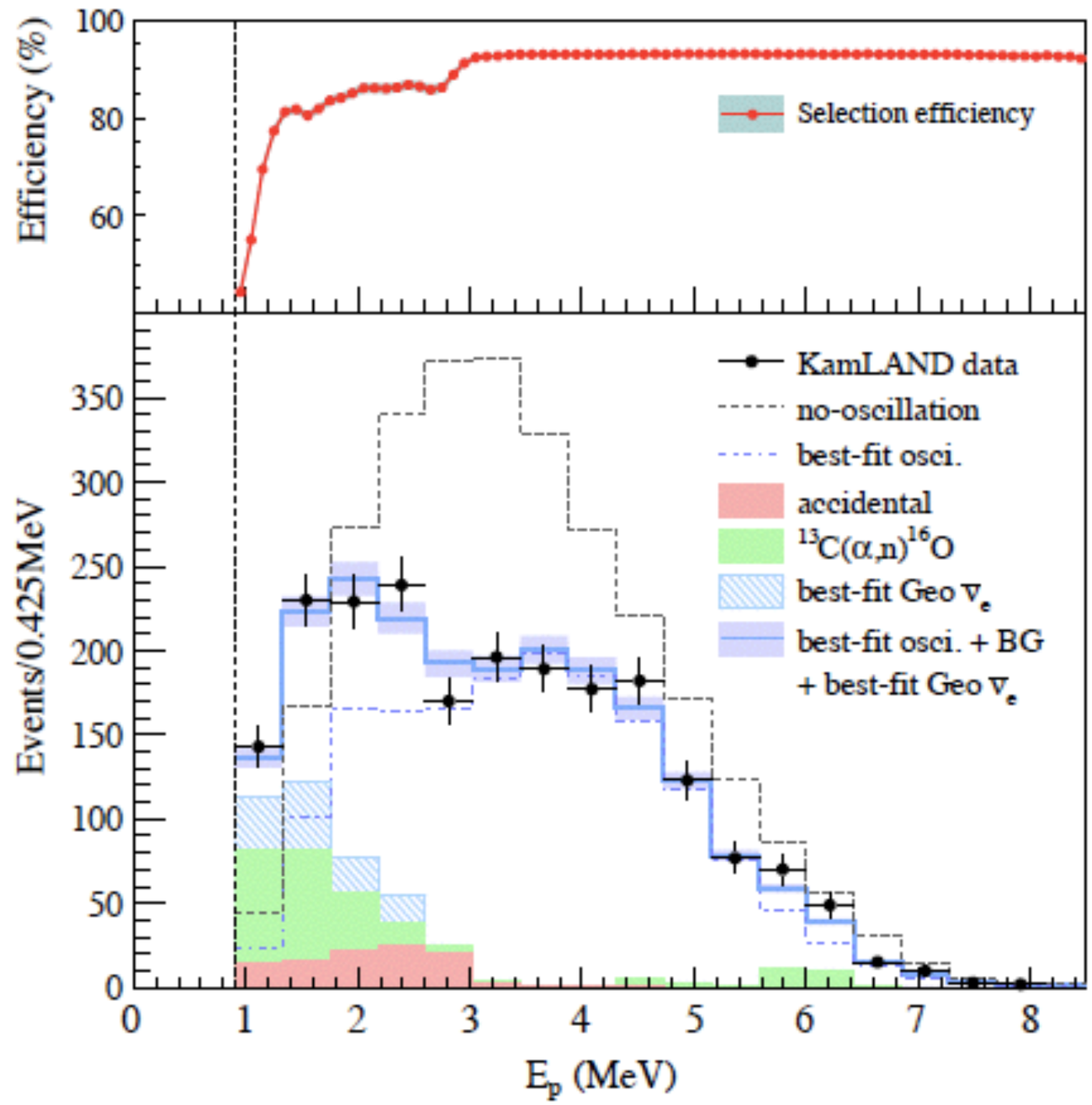

Neutrino Mass Sensitivity
KamLAND
1% per year
(statistical)
Palo
Verde
Chooz
Bugey III
Savannah
River
Gosgen
ILL
Rovno
10% per year
Reactor Power × Target Mass (MegaWatt-ton)
Baseline
10 m
100 m
1km
10km
100km

Primorskaya
Russia
China
West Asia
South Korea
KamLAND

Reactors are prolific sources of anti-neutrinos ~$10^{20}$/$GW_{th}$/sec

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

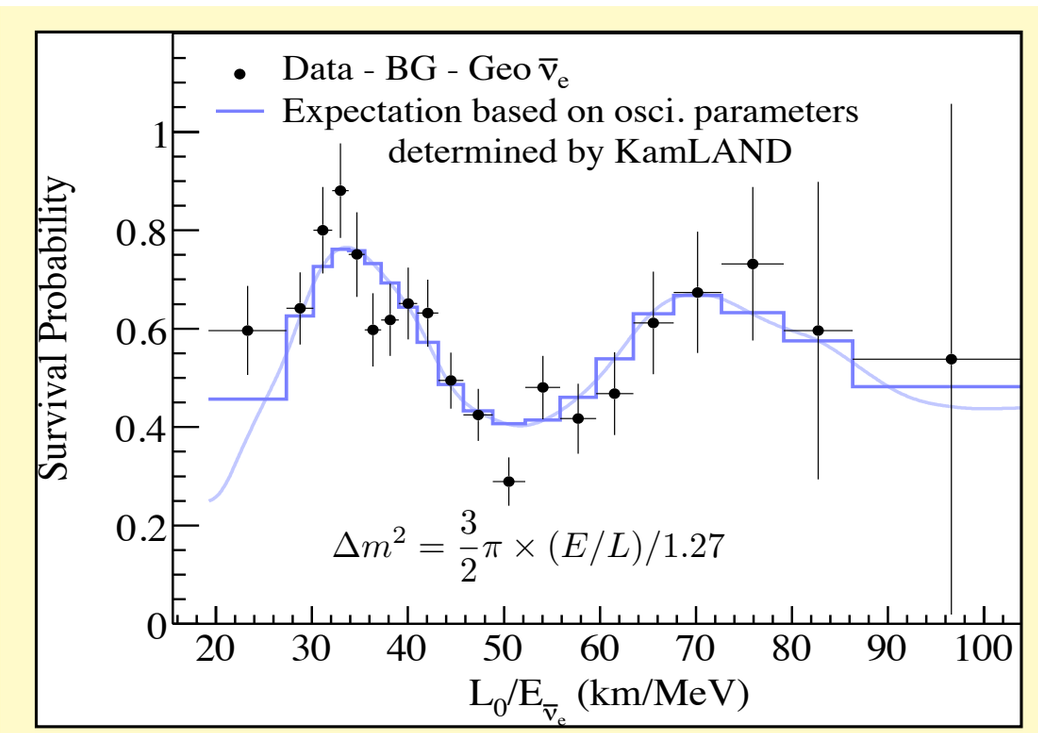
The detection reaction is inverse beta decay. The final state neutron is also detected thru absorption on hydrogen.

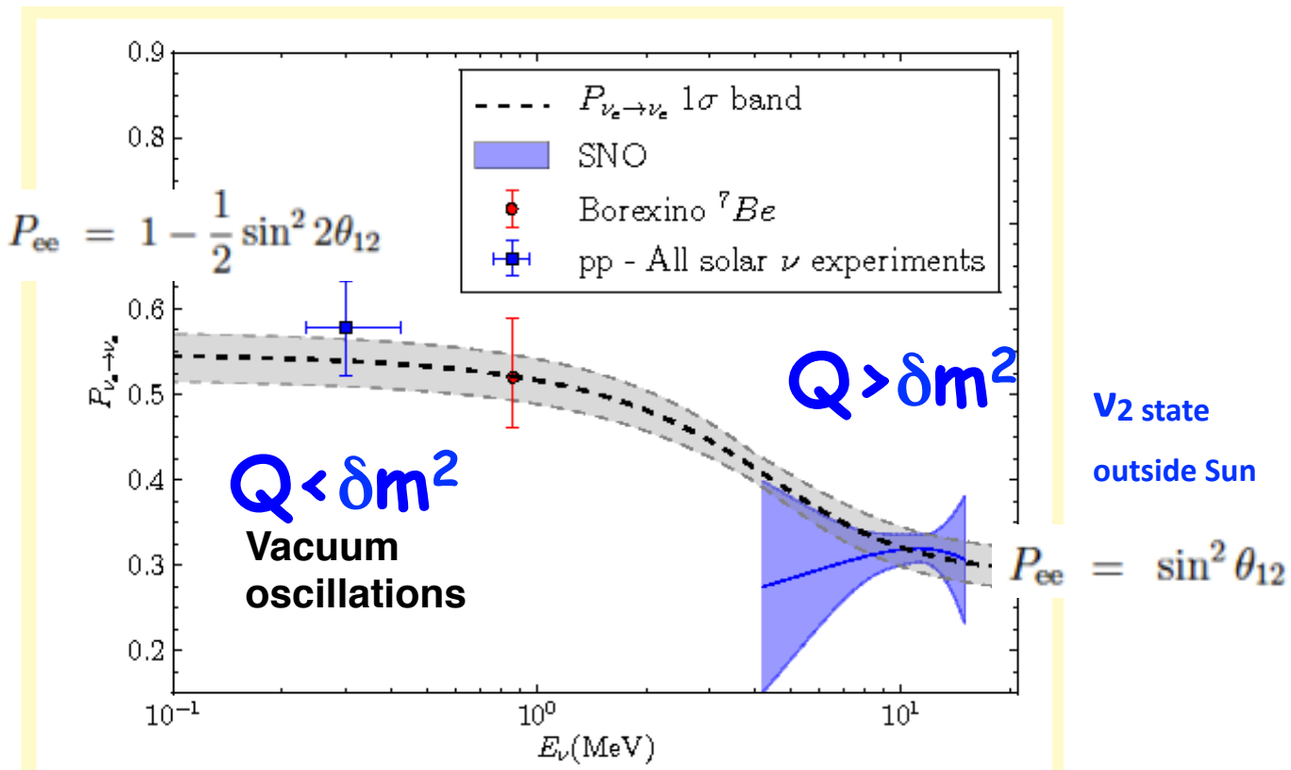



1009:4771

# The $\nu_e$ state

- $\nu_e \sim 0.82\ \nu_1 + 0.55\ \nu_2 + e^{-i\delta}\ 0.16\ \nu_3$

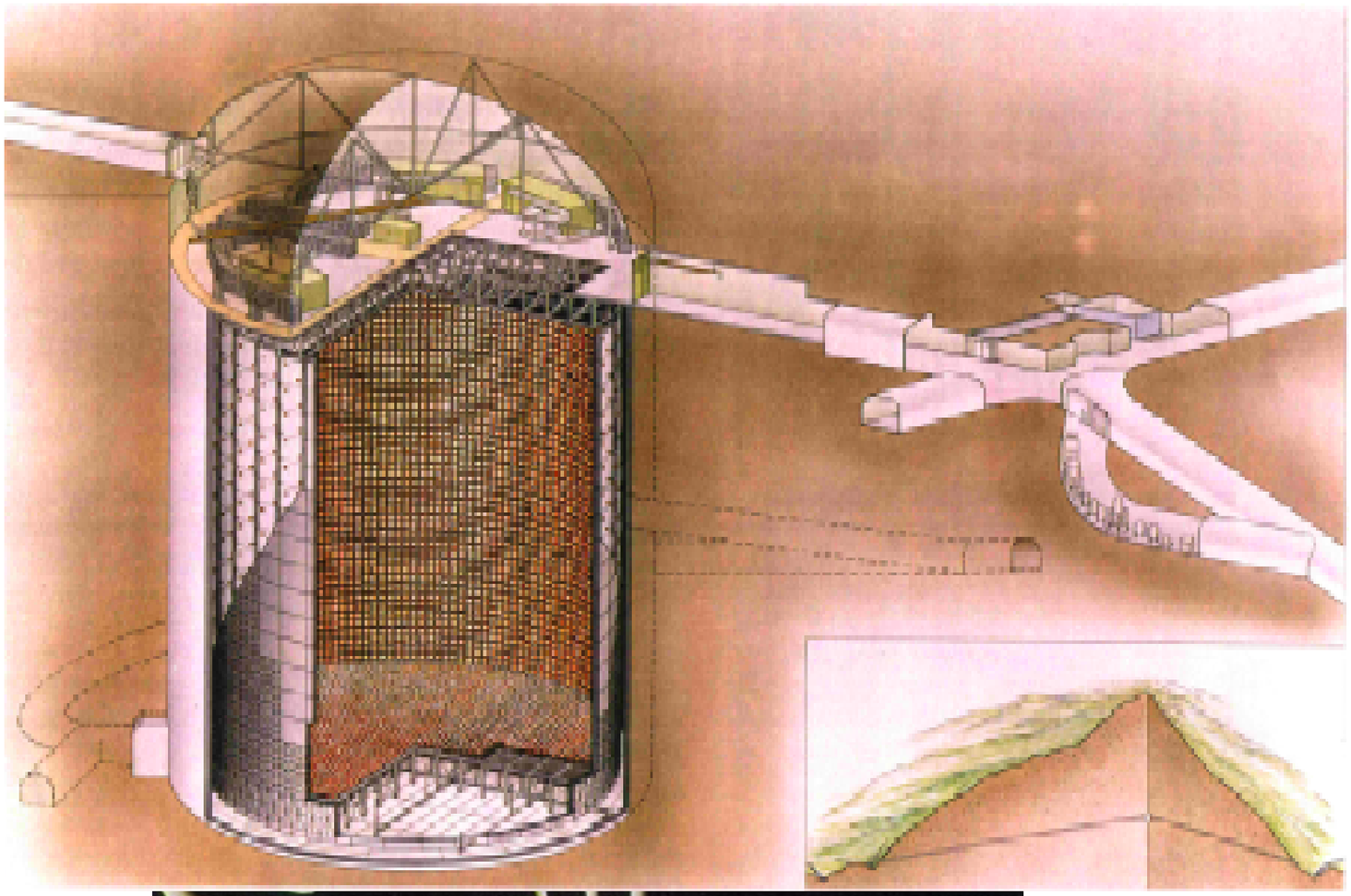


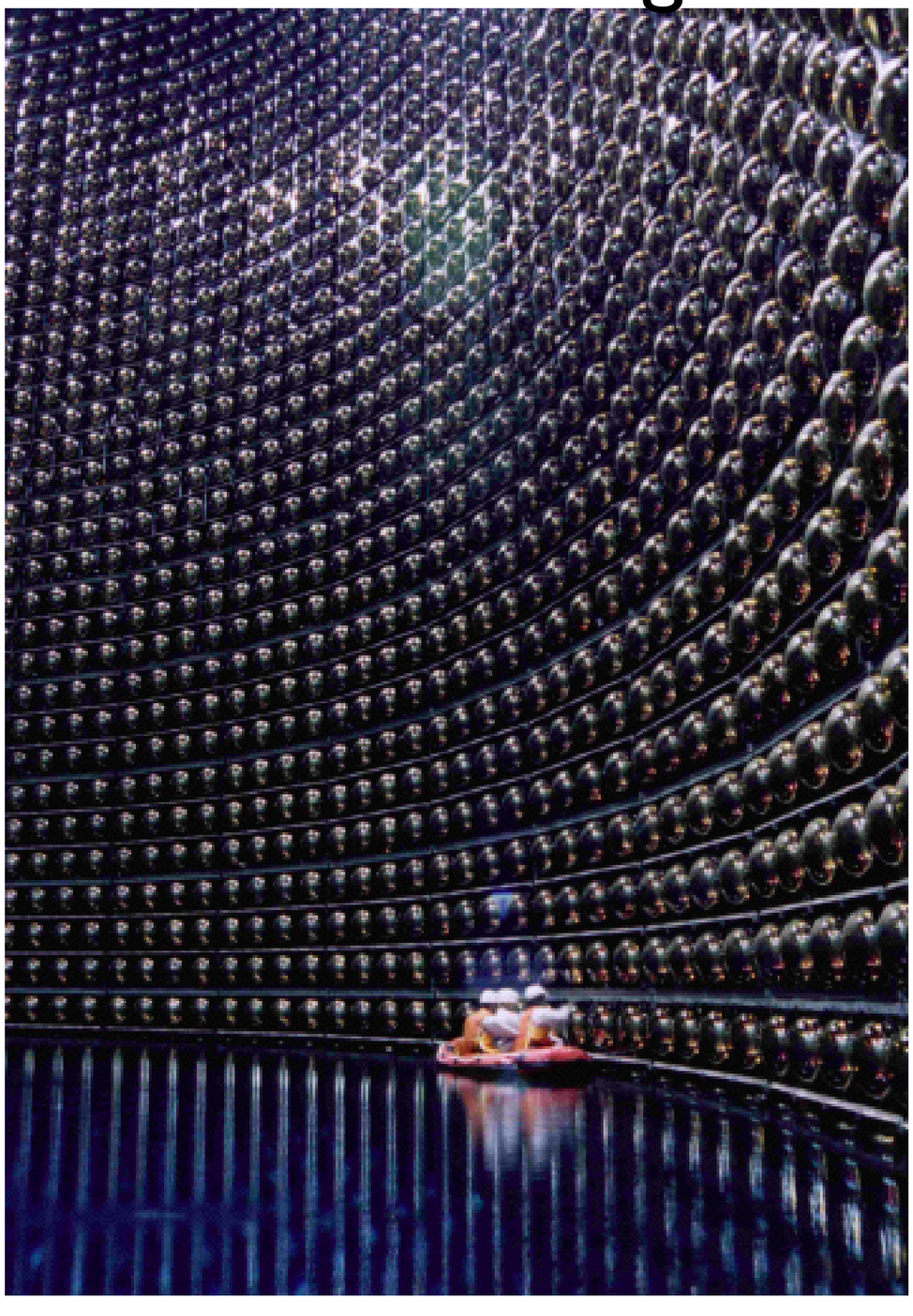

$\nu_2$ state outside Sun

**Kamland Reactor data determines the first two elements of this mixing with a well-defined frequency or mass splitting. Data from the Sun (SNO, Borexino, Gallium) is needed to determine which one is heavier !**

$\delta m^2 = m^2_2 - m^2_1 \sim 7.5 \times 10^{-5} eV^2$ $\qquad \theta_{12} \approx 35^o$

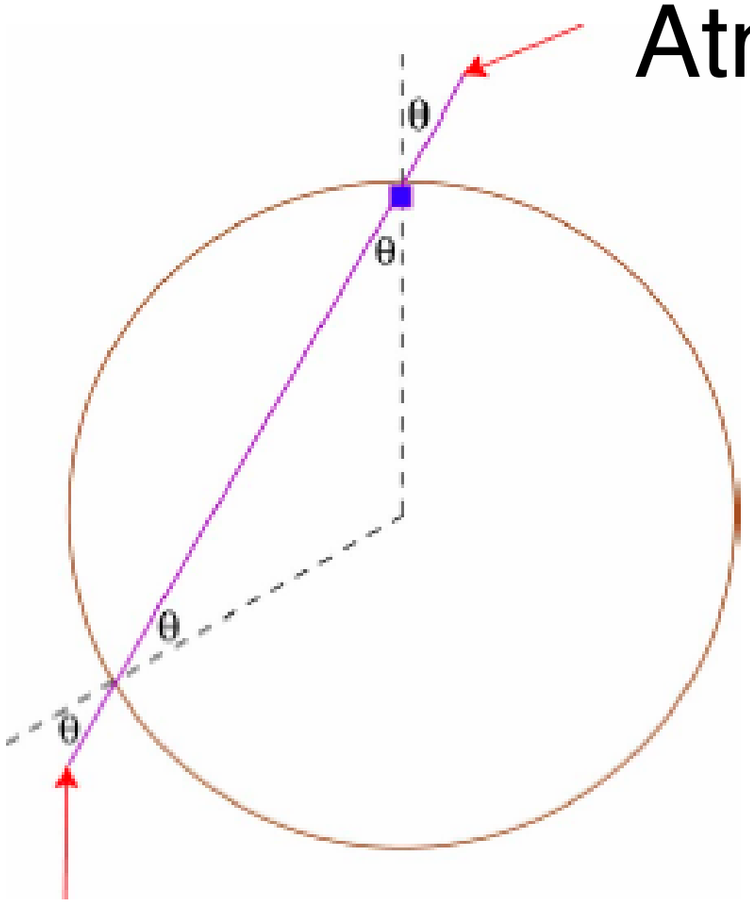


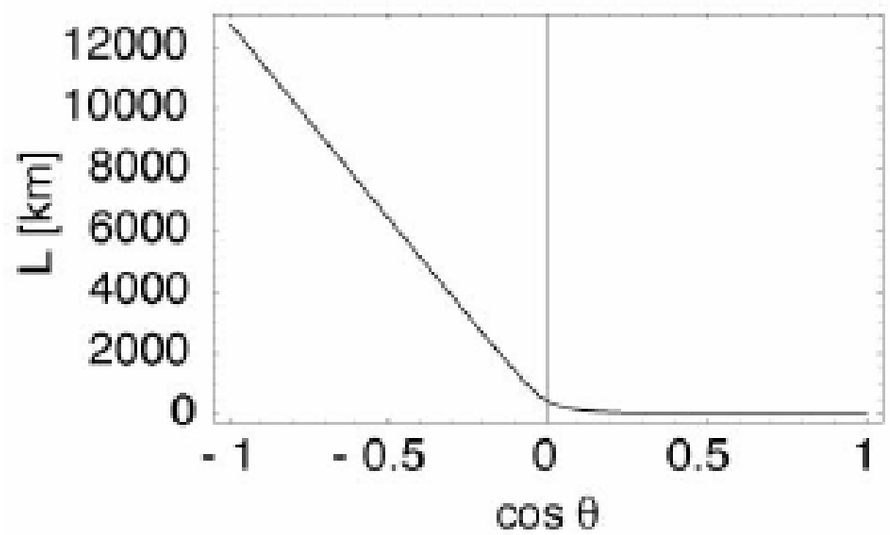
# SuperKamiokaNDE
# 50,000 tons of water
# 11000 photomultipliers
# Cherenkov light

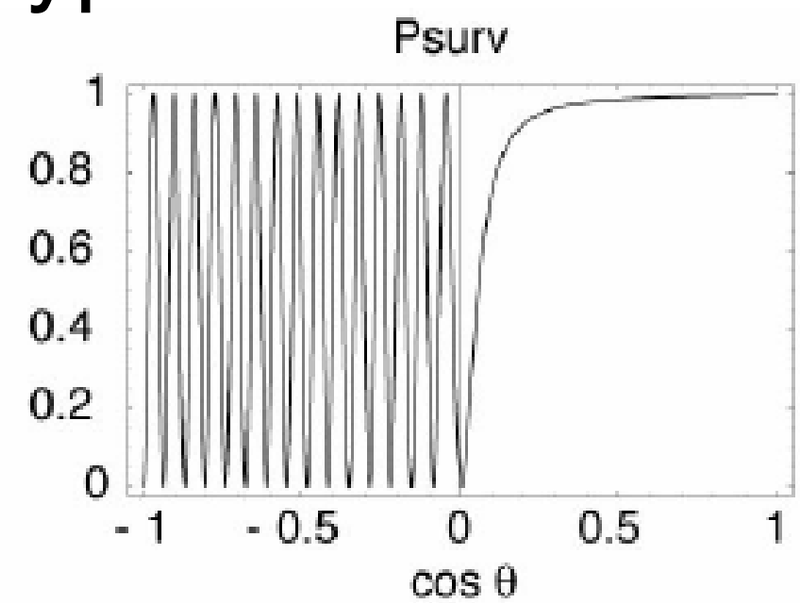


# Atmospheric neutrinos as a source for oscillation experiments

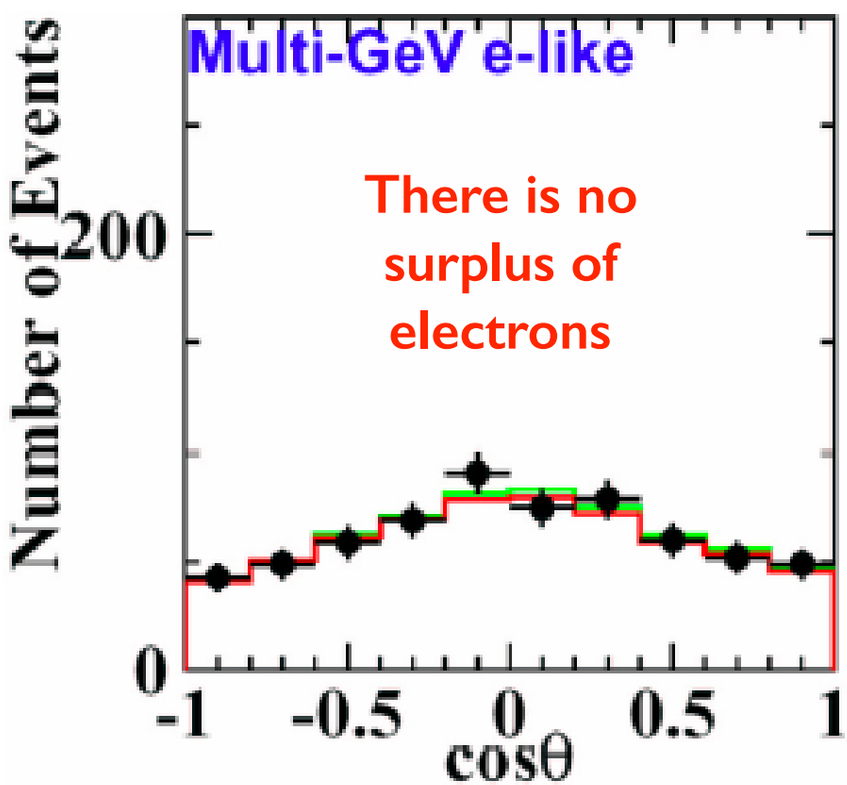
## Atm. neutrinos 2:1 mu:e type

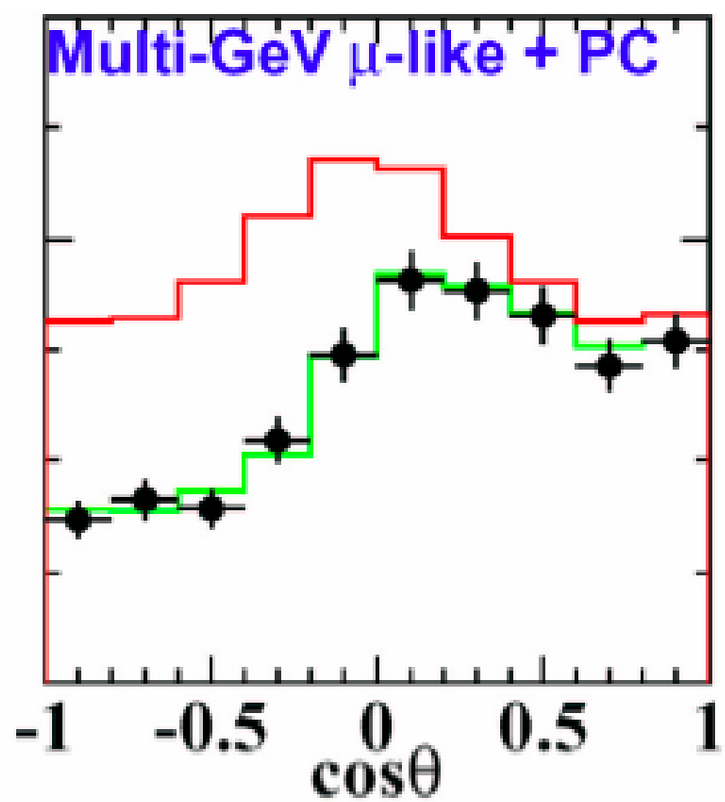



Flux inside uniformly illuminated spherical shell is constant and isotropic everywhere in the volume



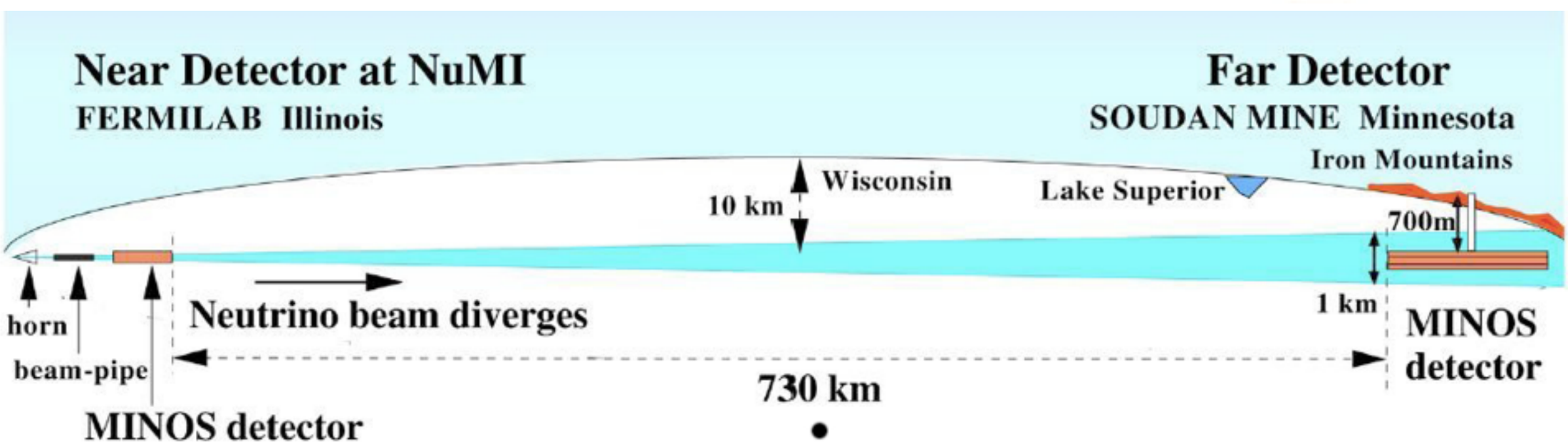



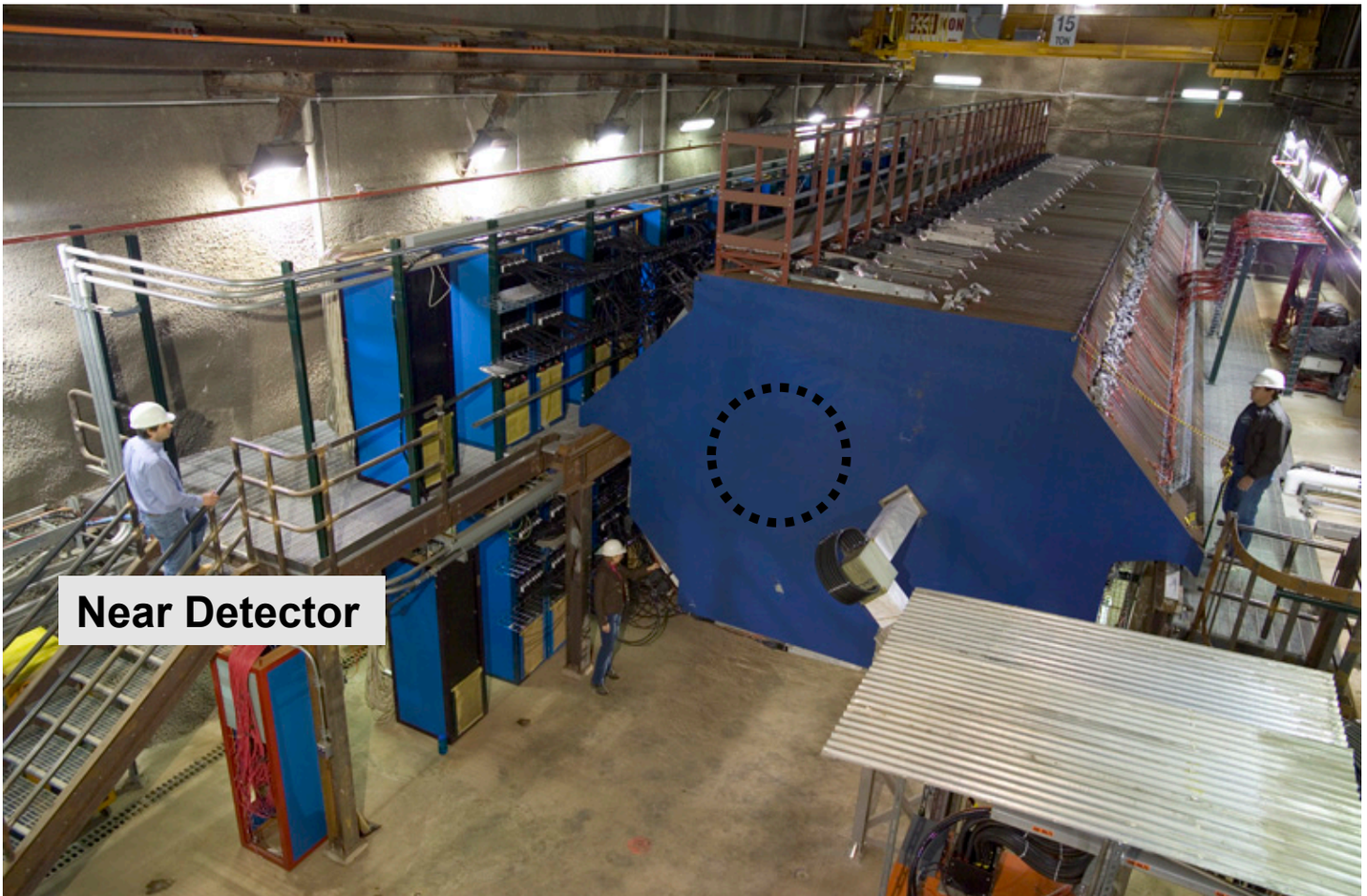

**Muon neutrinos coming from below disappear**

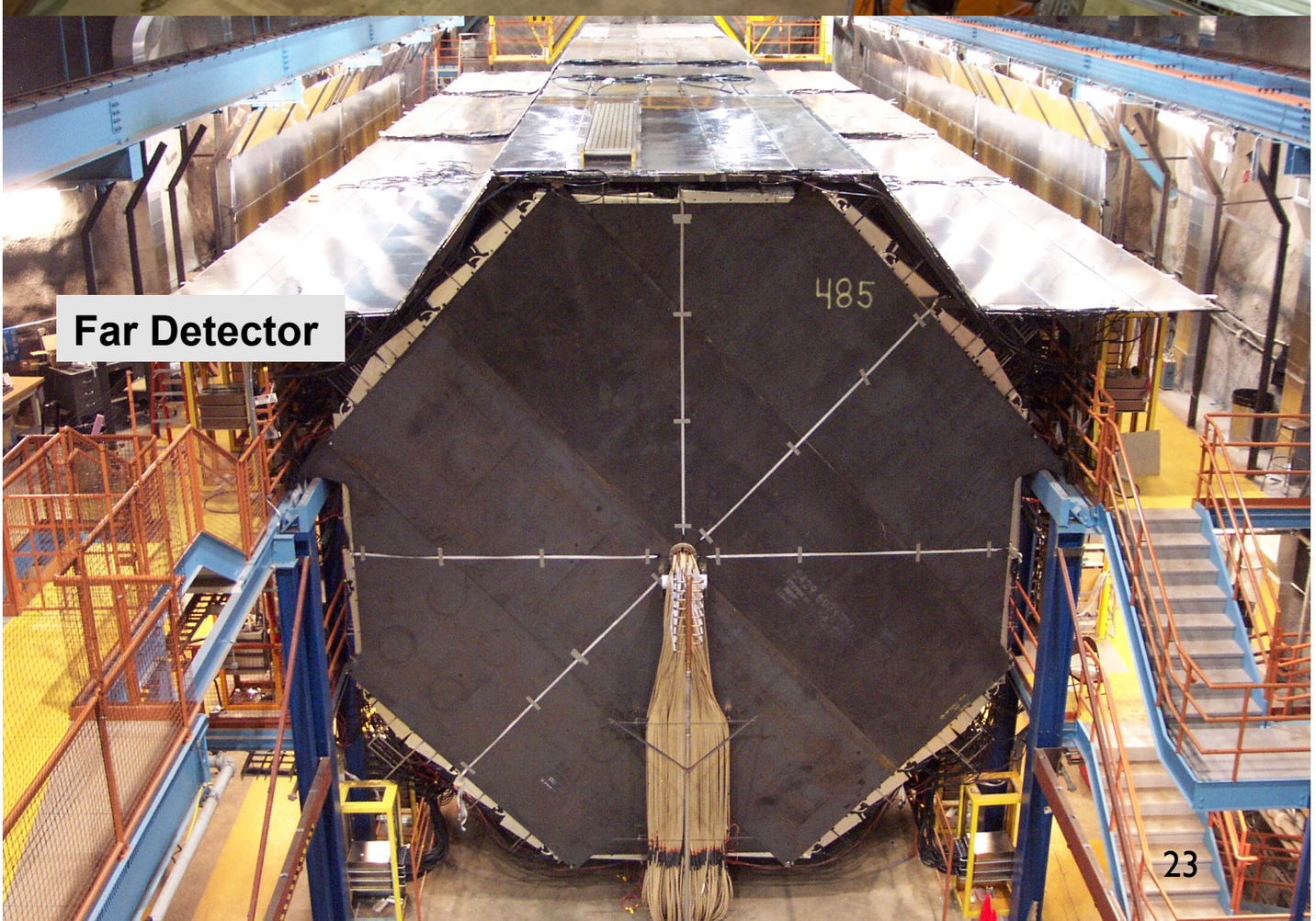
Evidence for neutrino oscillations from SuperK

# MINOS

- Prepare a pure beam of muon neutrino beam.
- Aim it towards a large muon detector.
- Observe spectrum of muon neutrinos to see oscillations in energy.





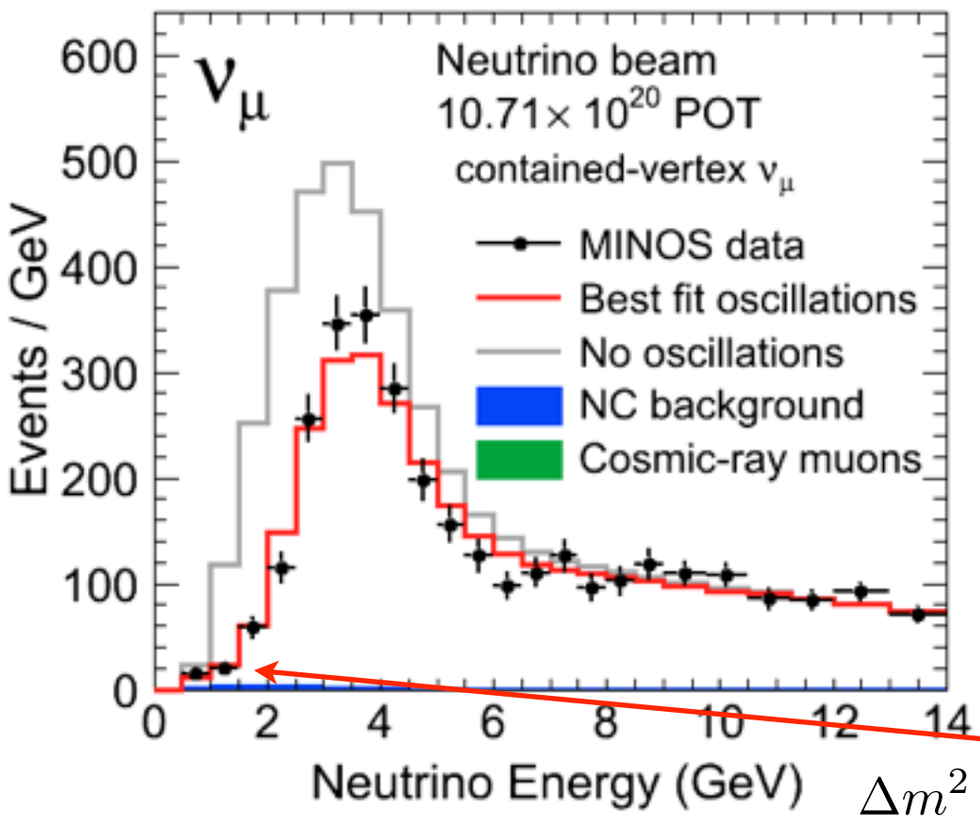

# MINOS Detectors

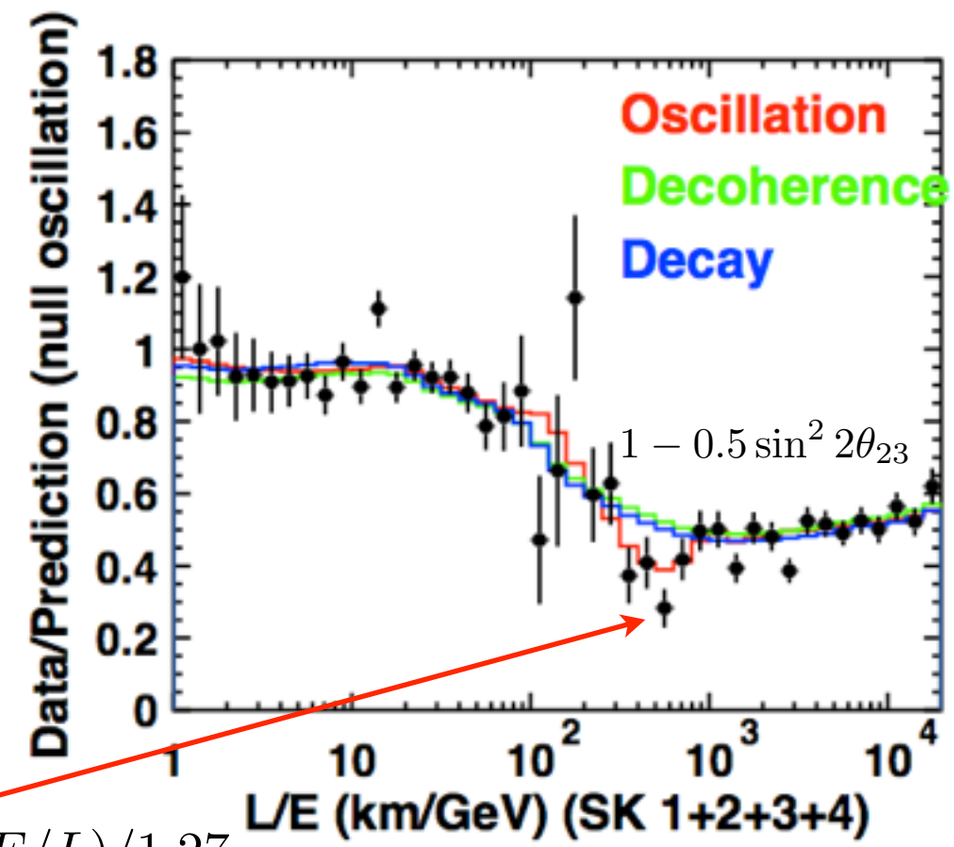
- Massive
  - 1 kt Near detector (small fiducial)
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
    - 1 Muon ~ 27 planes
    - 1.4 radiation lengths
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
    - Molier radius ~3.7 cm
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

# The $\nu_\mu$ state

- $\mathbf{v}_\mu \sim -(p)0.4\ \mathbf{v}_1 + (p')0.5\ \mathbf{v}_2 - 0.7\ \mathbf{v}_3$

**In addition - Important confirmation of tau neutrino mixing came from OPERA**




SK2012

$\Delta m^2 = (\pi/2)(E/L)/1.27$

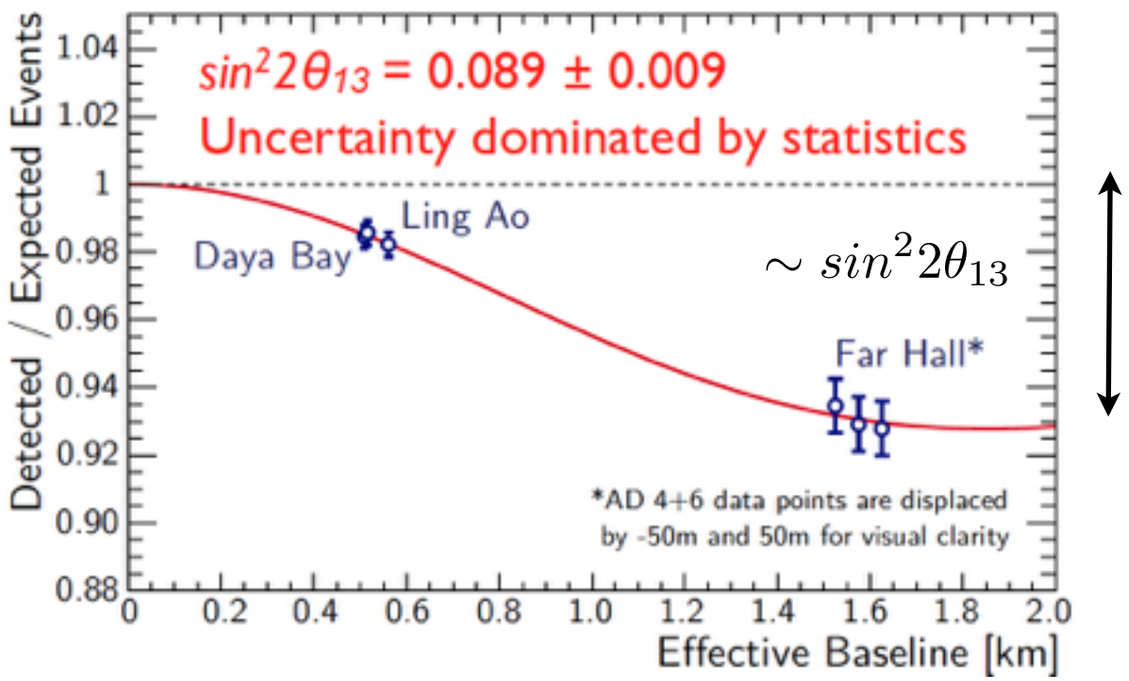
**Accelerator MINOS data provides precise difference of mass for the third element, and atmospheric SuperK data shows the mixing to be maximal, but we do not know which is heavier.**

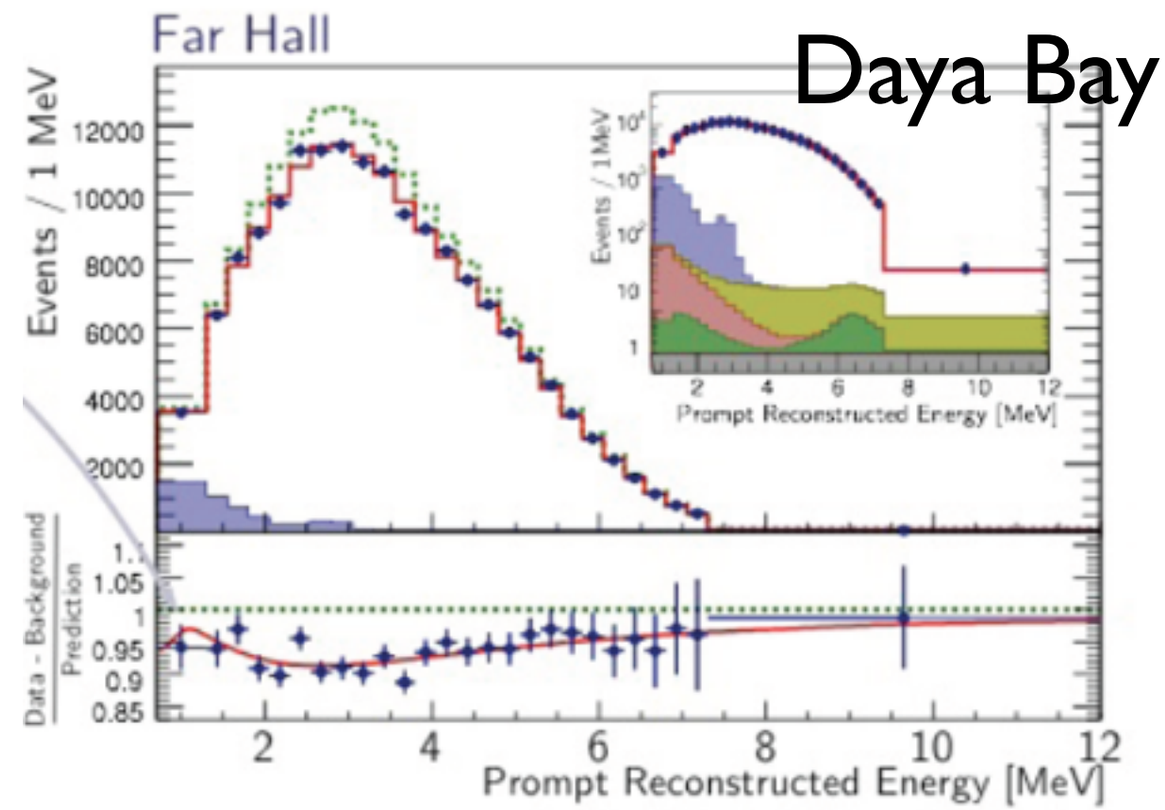
**$\Delta m^2 = |m_3^2 - m_{1,2}^2| \sim 2.4 \times 10^{-3}\ eV^2$** $\theta_{23} \approx 45^o$

p, p' represent phases. Cannot determine sign of mass diff.

# The $\nu_e$ state again !

- $\nu_e \sim 0.82\ \nu_1 + 0.55\ \nu_2 + e^{-i\delta}\ 0.16\ \nu_3$




**Daya Bay/DC/Reno Reactor data determines that the last element (with an unknown phase) is indeed non-zero and that the mass difference is the SAME as the one measured in the case of the $\nu_\mu$.**

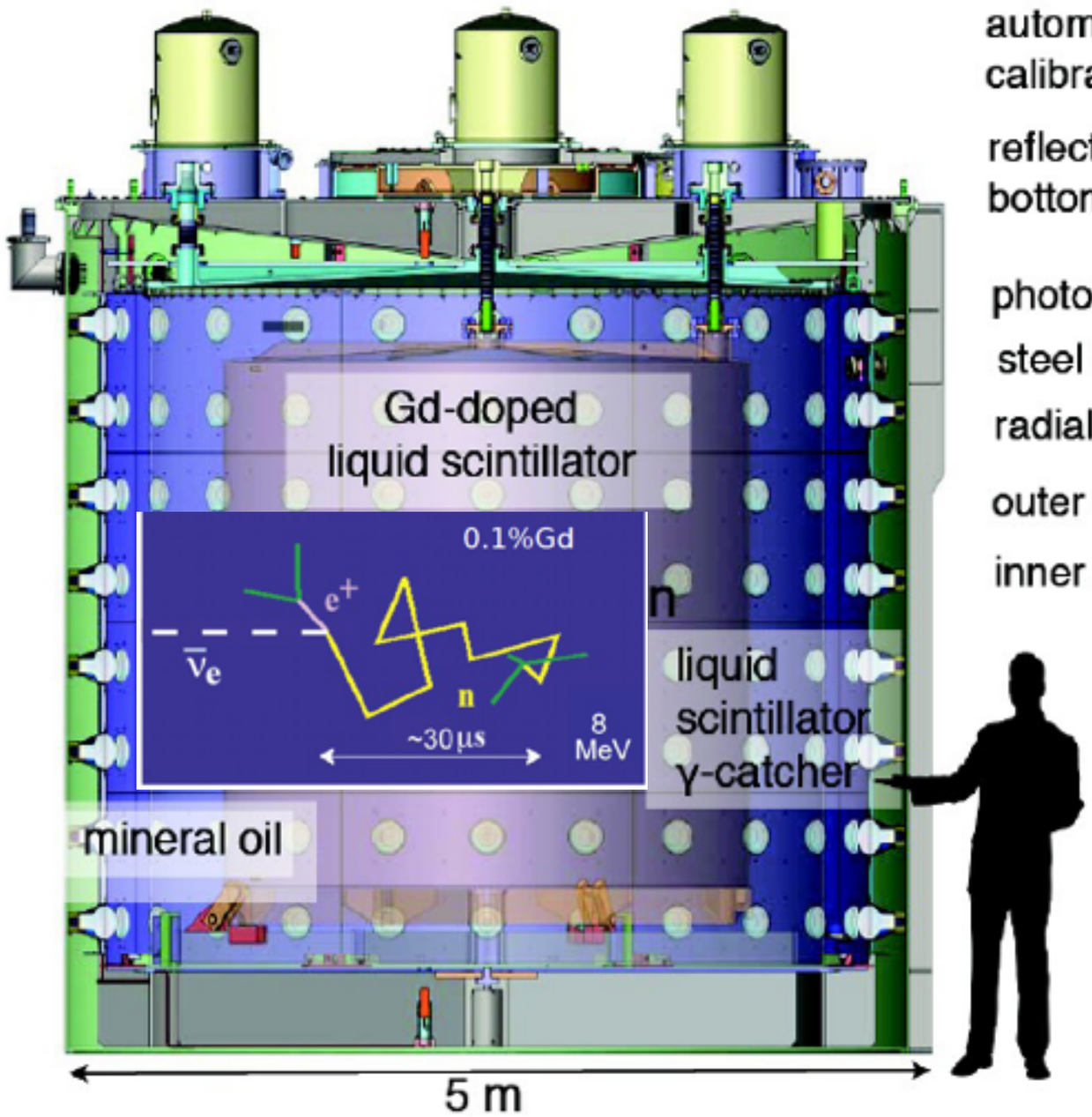
$$\Delta m^2 = |m_3^2 - m_{1,2}^2| \sim 2.4 \times 10^{-3}\ eV^2 \quad \sim \pi/2(3.5MeV/1800m)/1.27$$

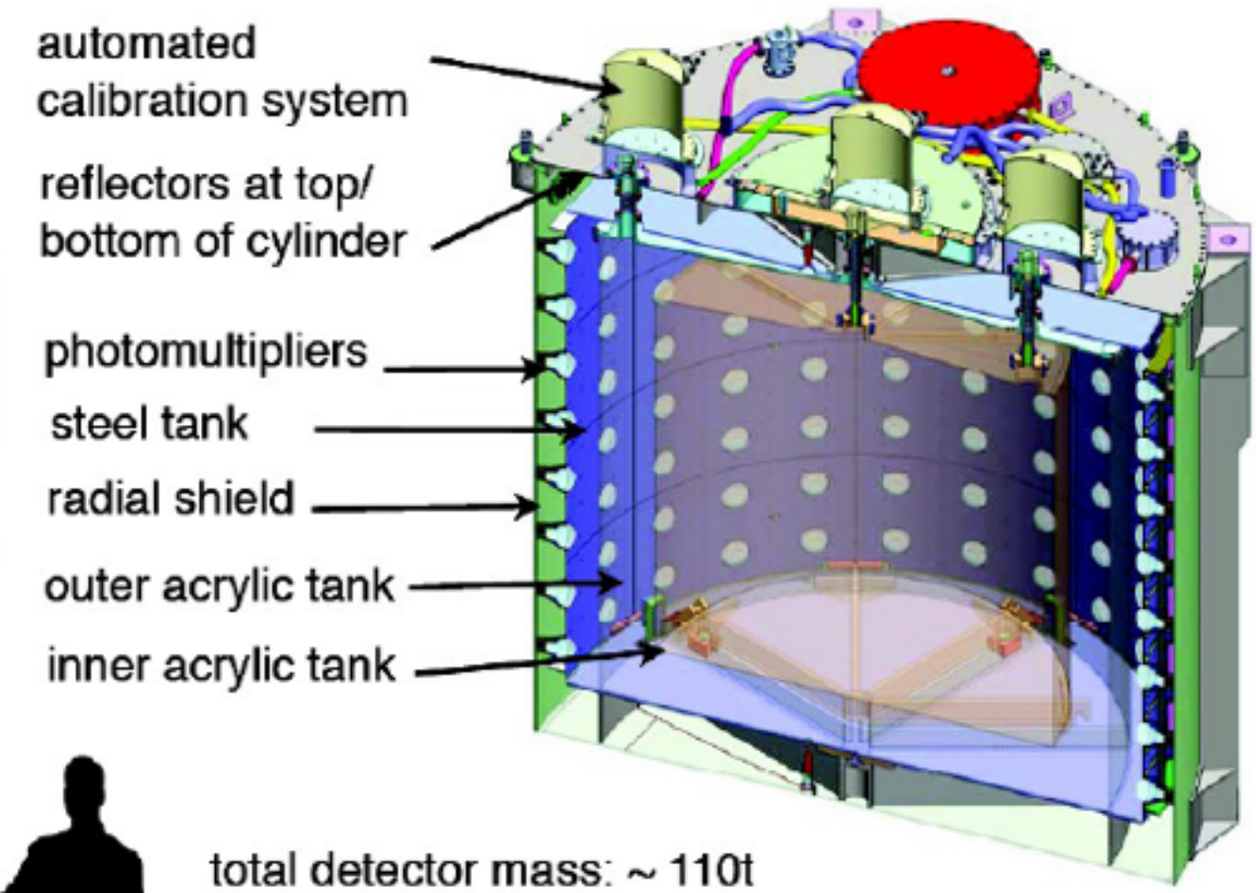
$$\delta m^2 = m^2_2 - m^2_1 \sim 7.5 \times 10^{-5} eV^2$$

# Daya Bay Experimental Method

- **Reactors make lots of anti-electron neutrinos which are easy to detect. $2x10^{20}$/sec for 1 GW**
- **Daya Bay has 6 cores each 2.9 GW ➜ 17.4 GW total**
- **The geography is ideal with hills rising away from the bay.**
- **We have placed several detectors close to the reactors and several far away to see how many anti-electron neutrinos disappear (after accounting for the $1/r^2$ reduction. )**
- **Location is northeast of Hong Kong**

# Daya Bay Antineutrino Detectors (AD)




total detector mass: ~ 110t
- inner: 20 tons Gd-doped LS (d=3m)
- mid: : 22 tons LS (d=4m)
- outer: 40 tons mineral oil buffer (d=5m)

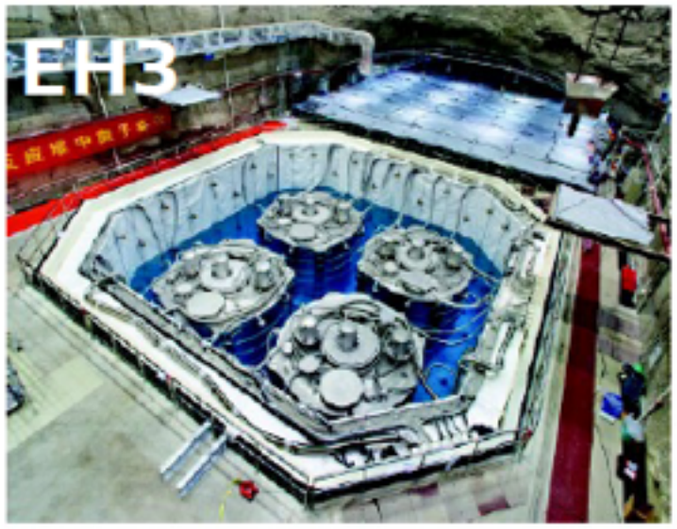
photosensors: 192 8"-PMTs

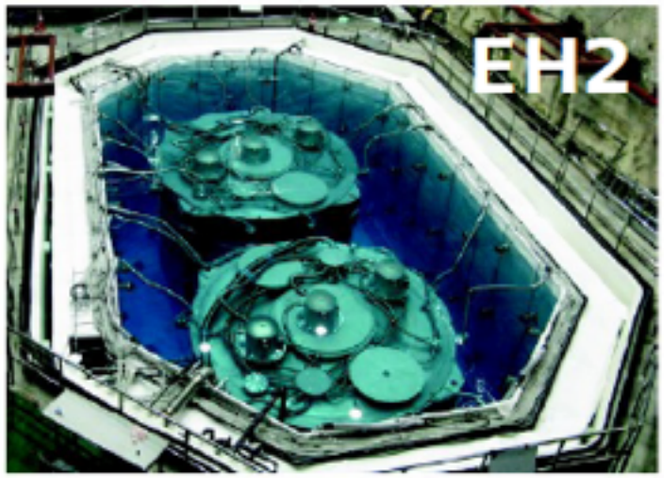
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

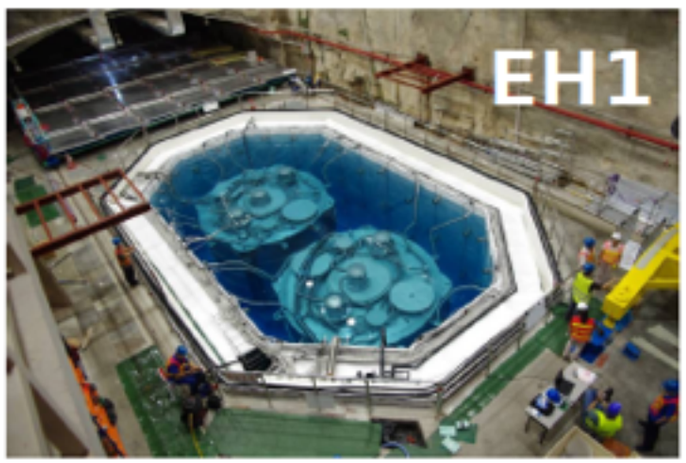
**8 "functionally identical", 3-zone detectors reduce systematic uncertainties.**

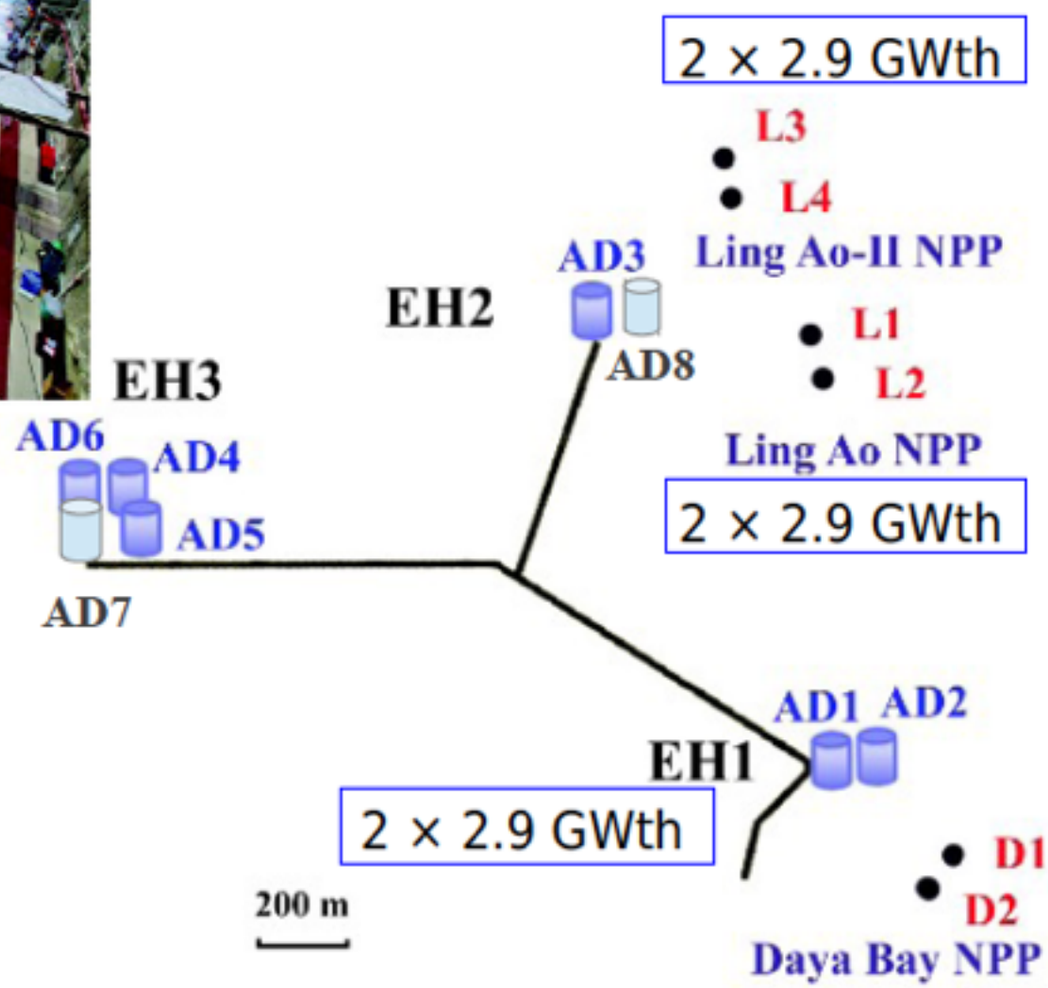
*Very well defined target region*

# Completion of 8-AD Installation



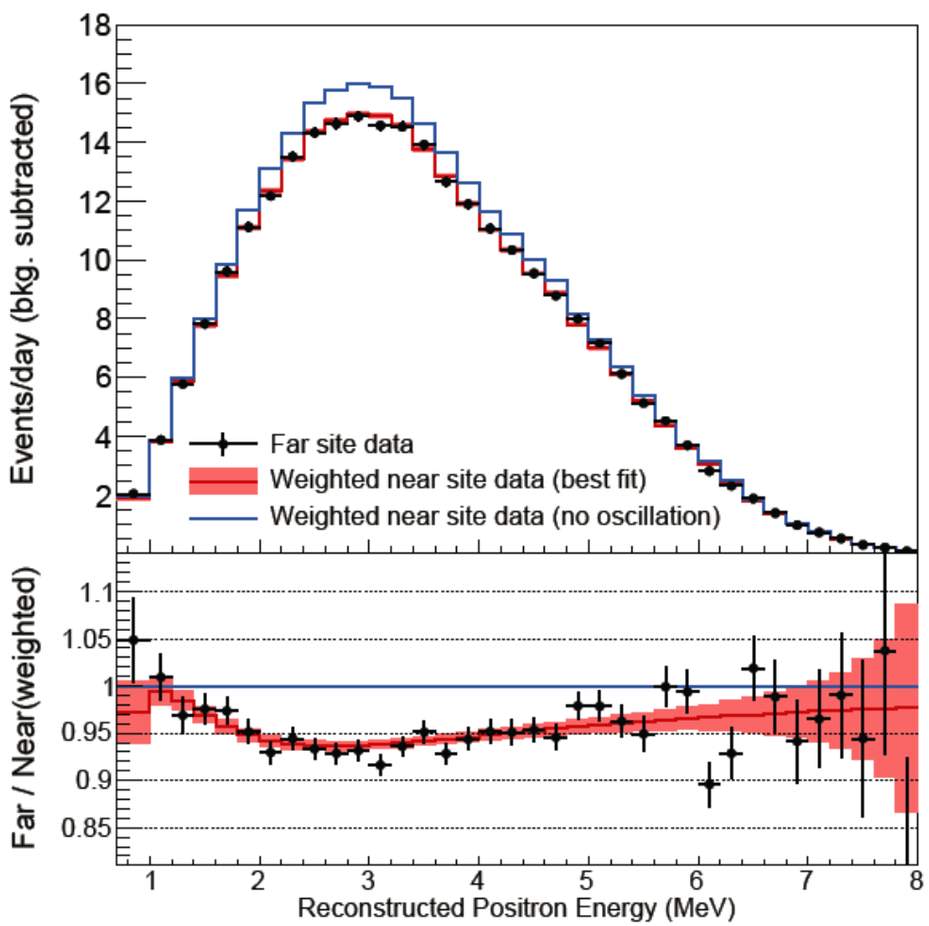



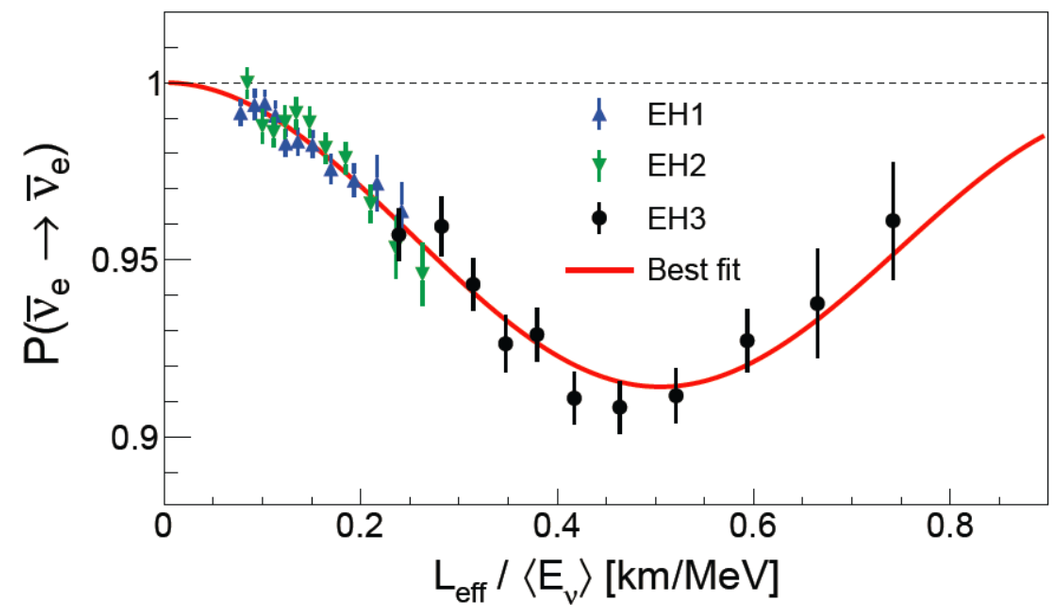




*Two more ADs are installed in in EH2 and EH3 in the fall of 2012.*

# Latest Result From Daya Bay with data up to Nov 2013.




$\sin^2 2\theta_{13} = 0.084 \pm 0.005$

$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \mathrm{eV}^2$

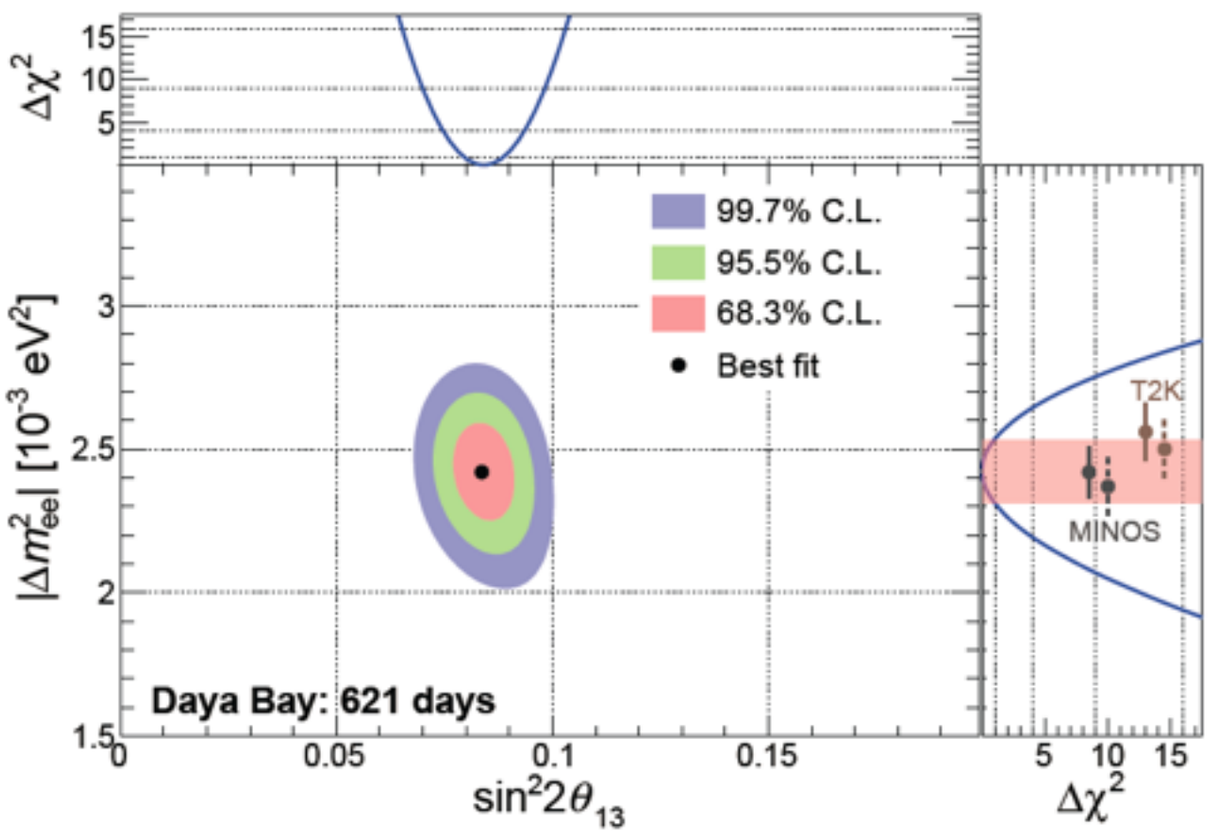
- Using 217 days of 6 AD data and 404 days of 8 AD data.
- Total of 1.2 M events
- Improved modeling of the energy response.

# nGd Spectral Analysis Result

- Most presise measurement of $\sin^2 2\theta_{13}$ (6%)
- Measurement of effective mass splitting $|\Delta m^2_{ee}|$ reaches 4%
  - Consistent with muon neutrino disappearance experiments
  - Comparable precision

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$$

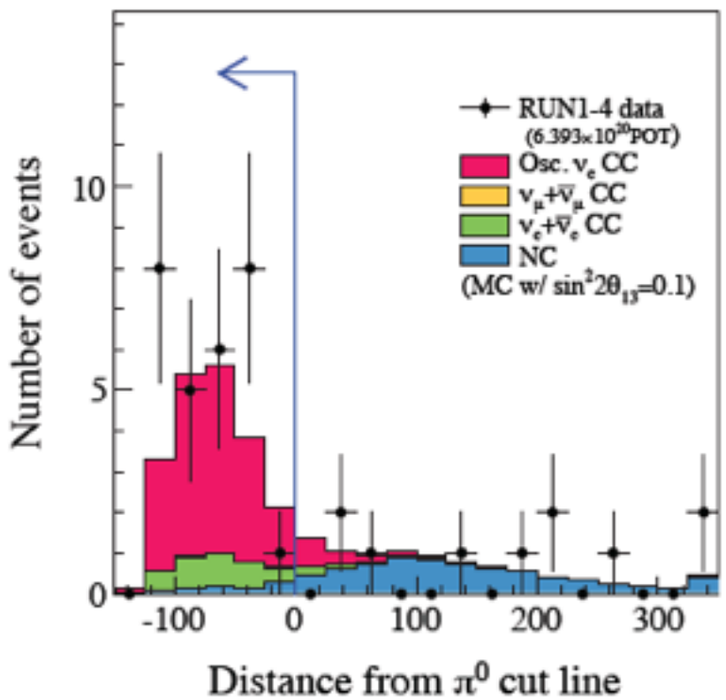


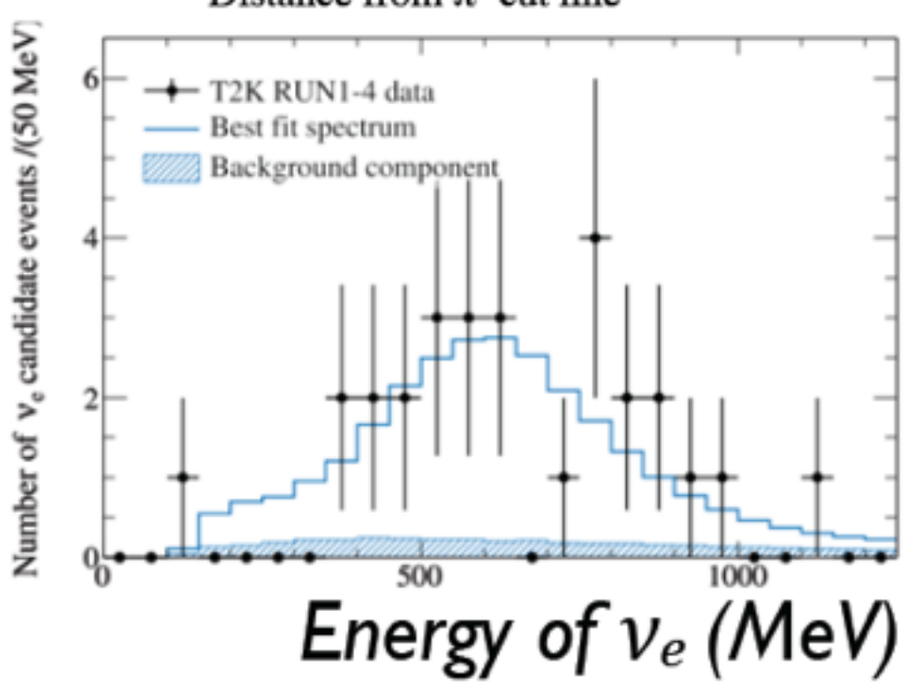

arXiv:1505.03456 [hep-ex]

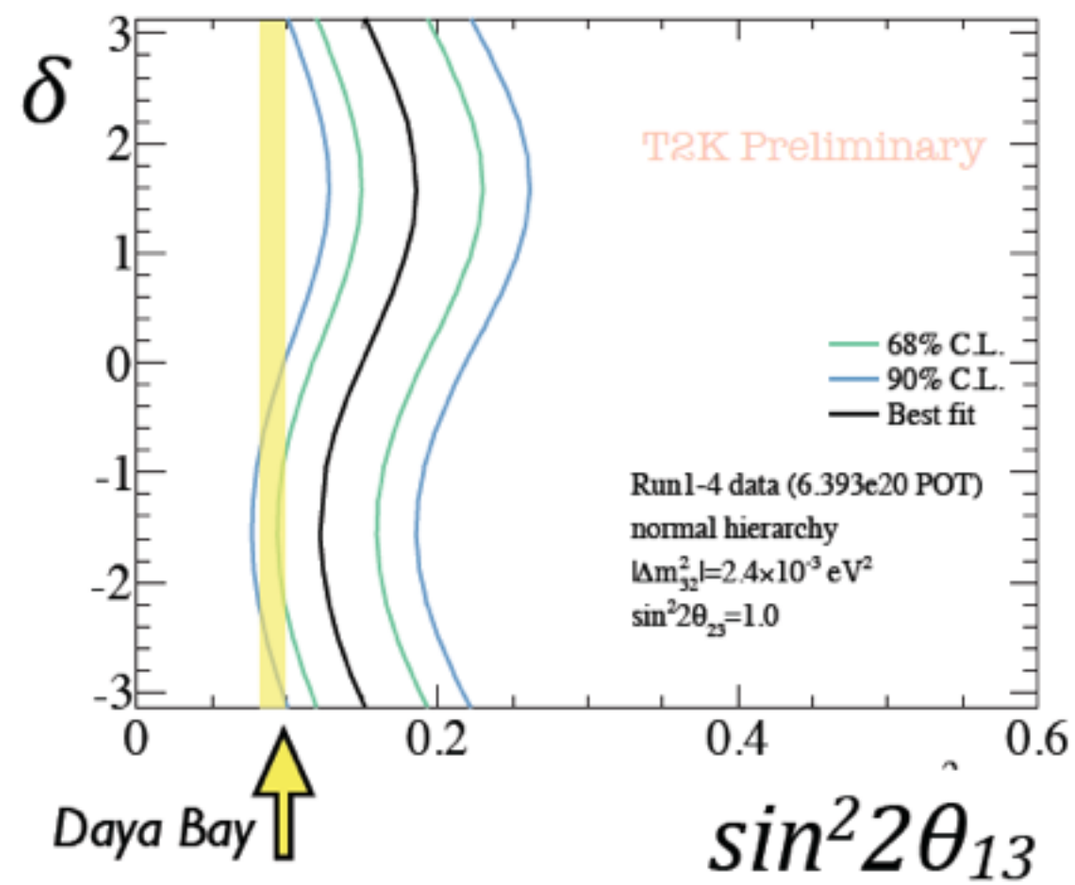
**Accepted by Phys. Rev. Lett.**

# T2K: $\nu_\mu \rightarrow \nu_e$ Appearance

M. Wilking, EPS 2013, Stokholm
Phys. Rev. D 88, 032002 (2013)




*Hints of $\delta \neq 0$ ?*

As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

For 3 Active neutrinos.

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

**Pontecorvo-Maki-Nakagawa-Sakata matrix**

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

| Atmospheric, Accel. | CP Violating Phase | Reactor, Accel. | Solar,Reactor | Majorana CP Phases |
|---|---|---|---|---|

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

Range defined for $\Delta m_{12}$, $\Delta m_{23}$

For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

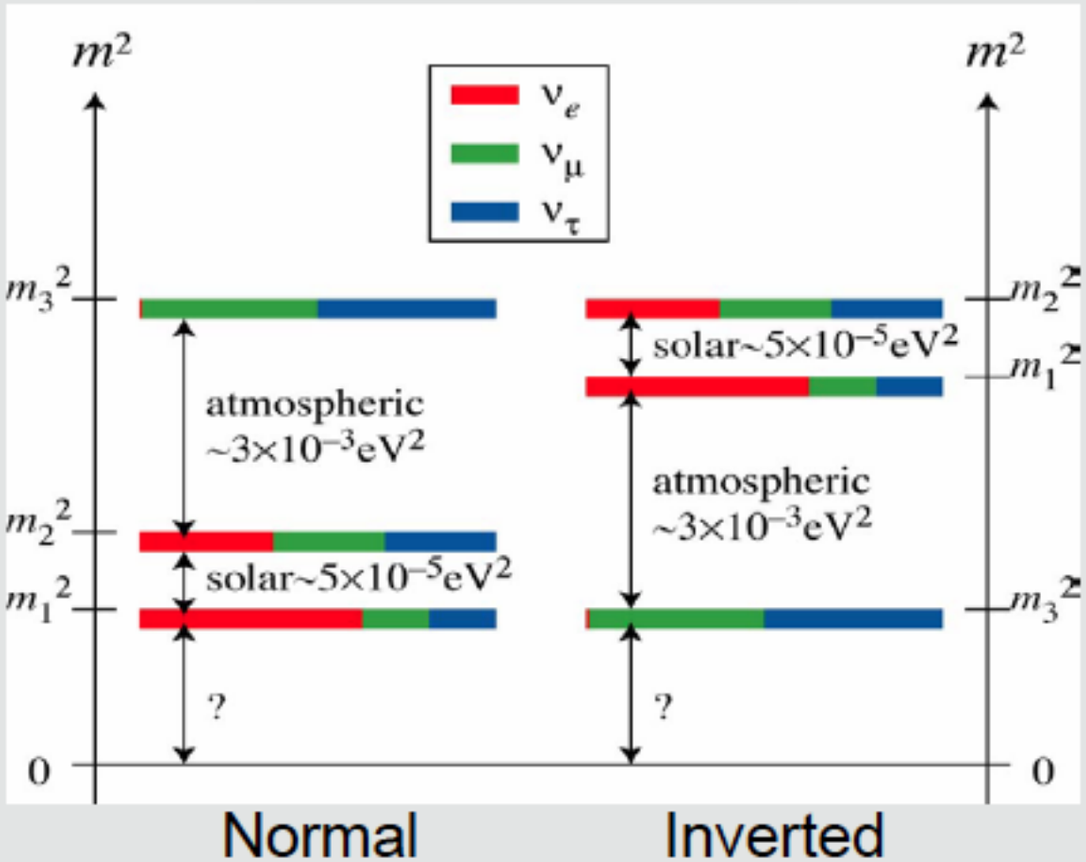
CP Violating Phases: implication for Antimatter/Matter asymmetry via Leptogenesis?

# SUMMARY OF RESULTS FOR THREE ACTIVE ν TYPES

**Δm~0.05 eV**

| Parameter | best-fit ($\pm 1\sigma$) |
|---|---|
| $\Delta m^2_{\odot}$ [$10^{-5}$ eV $^2$] | $7.58^{+0.22}_{-0.26}$ |
| $\lvert\Delta m^2_A\rvert$ [$10^{-3}$ eV $^2$] | $2.35^{+0.12}_{-0.09}$ |
| $\sin^2\theta_{12}$ | $0.306\ (0.312)^{+0.018}_{-0.015}$ |
| $\sin^2\theta_{23}$ | $0.42^{+0.08}_{-0.03}$ |
| $\sin^2\theta_{13}$ [140] | $0.021\ (0.025)^{+0.007}_{-0.008}$ |
| $\sin^2\theta_{13}$ [142] | $0.0251 \pm 0.0034$ |

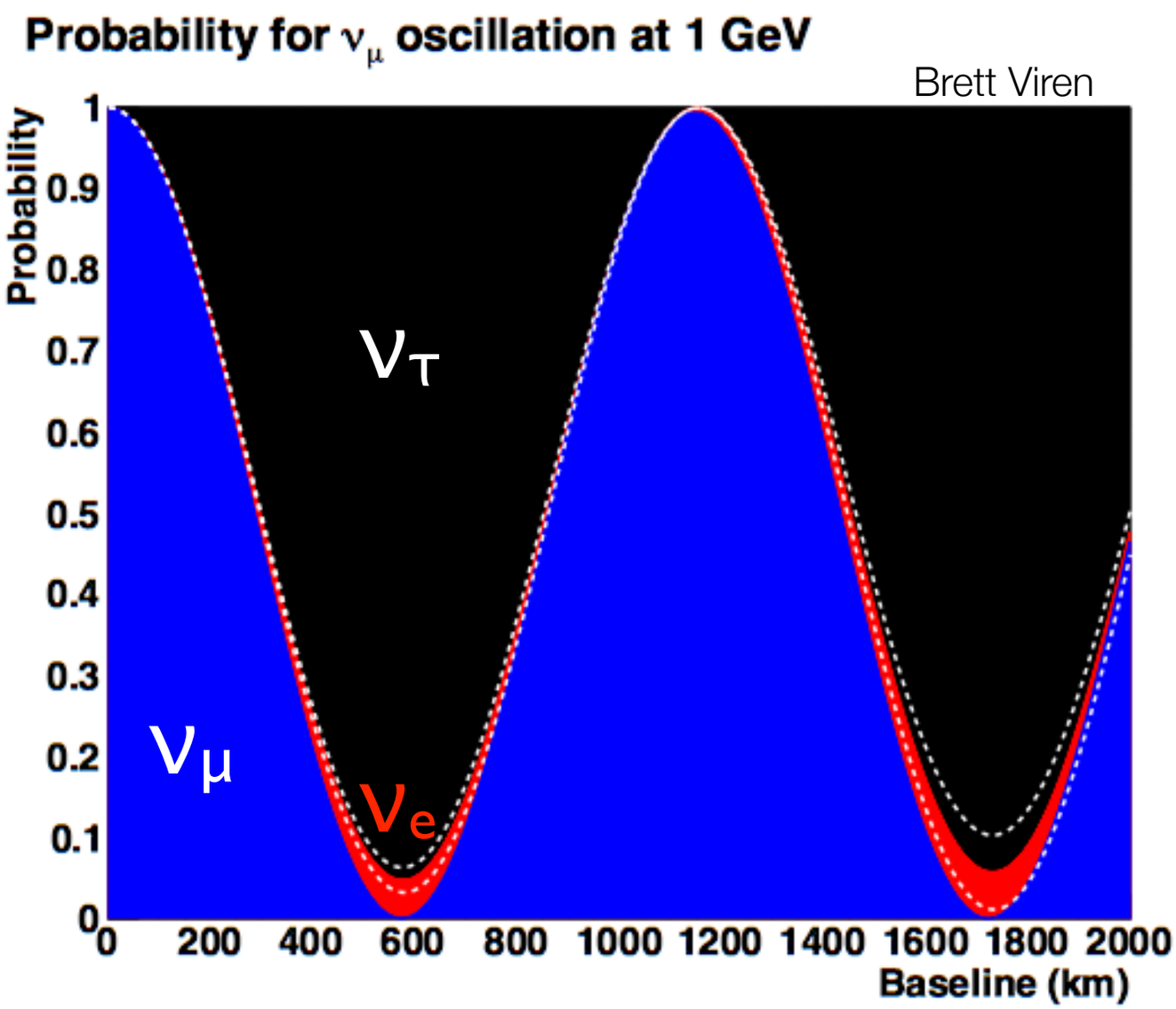
Mass Hierarchies




**No strong theoretical motivation for choosing between these hierarchies**

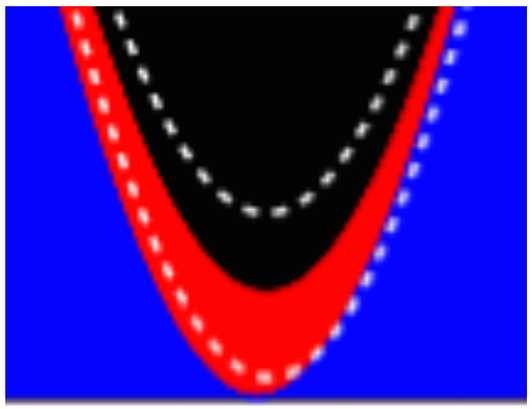
**Hierarchy, CP phase, and precise values of mixings could be very important to gain understanding of underlying symmetries. See talk by Smirnov from recent meeting.**

# The full picture of the oscillation effect starting with pure muon type neutrino.



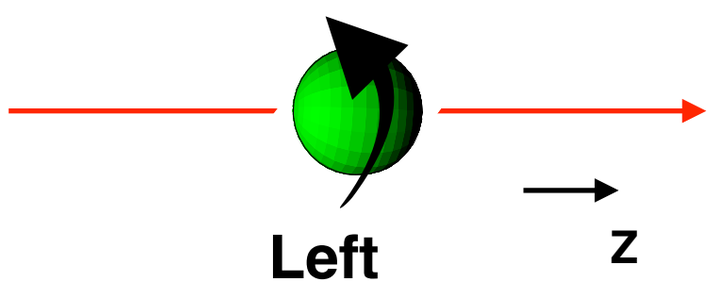

**Dashed white lines correspond to CP violation or the unknown phase.**

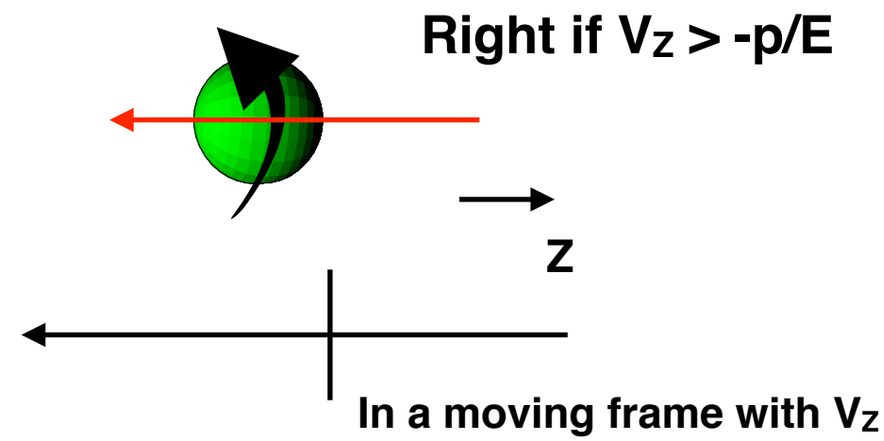
**Notice that for sizable effects one needs long distances and large energies.**



- **There are precise predictions:**
  - **Large Matter Effects (not yet seen in a laboratory experiment)**
  - **Potentially large CP violation (not yet seen)**
  - **We should measure this picture with a detailed spectrum. We need to measure electron and muon type of neutrinos at high energies.**

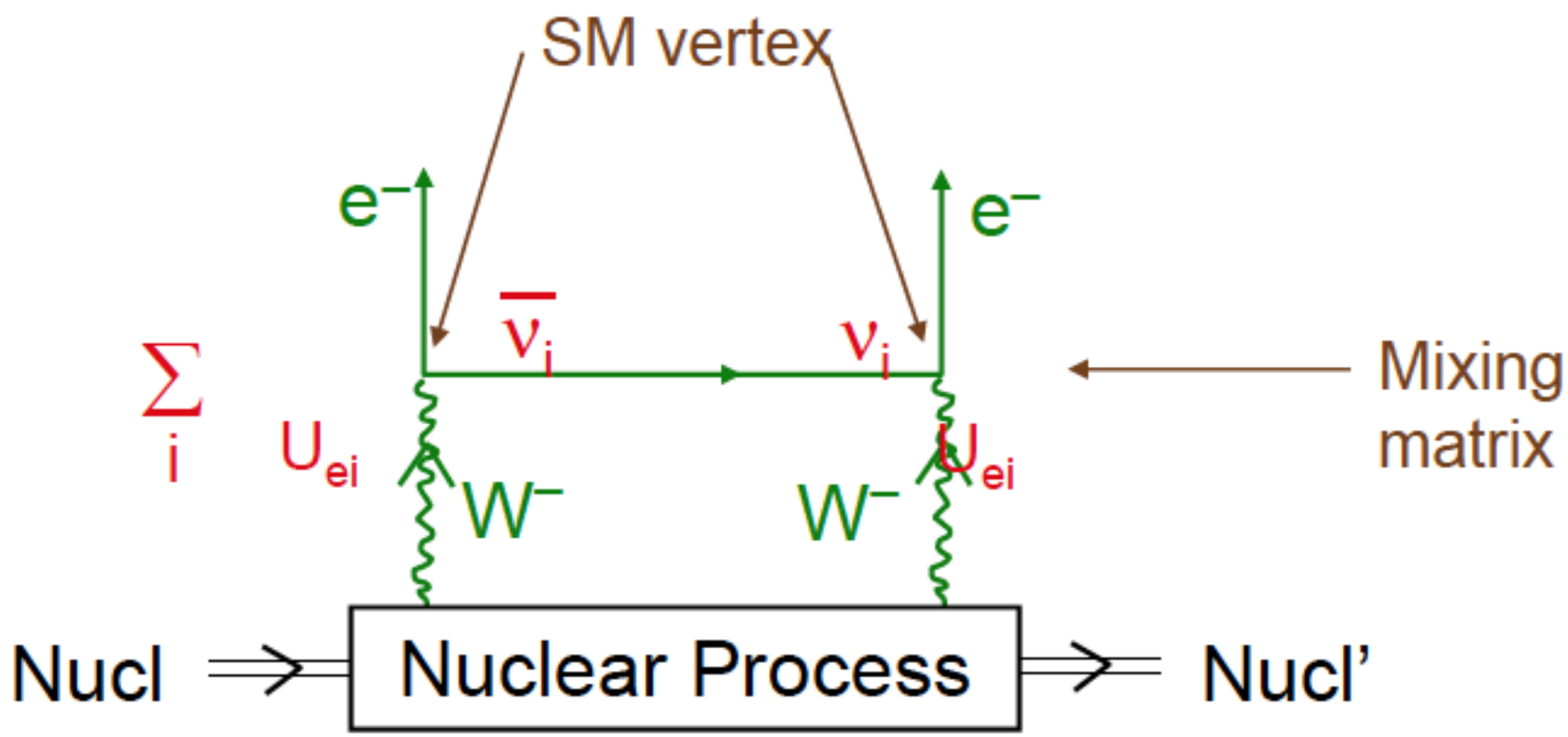
# Importance of neutrino mass



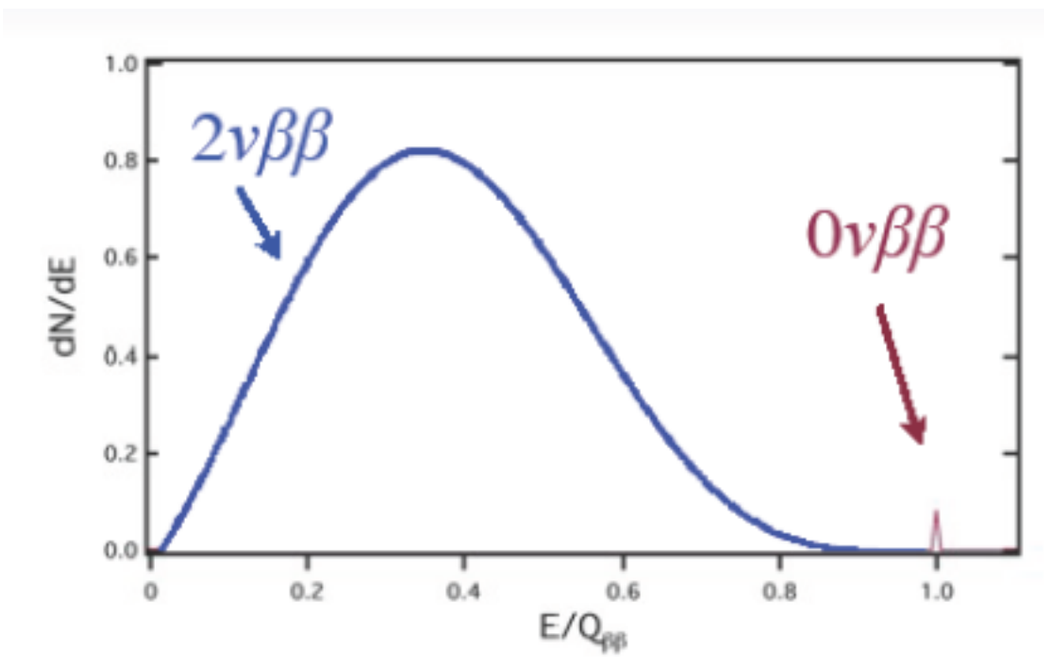

- In the standard model only $\nu_L$ interacts with matter, $\nu_R$ does not interact. Since neutrinos are produced in weak interactions only, $\nu_R$ do not exist.
- Handedness and Helicity are identical if particles are massless.
- Particles with mass can be transformed to opposite helicity by a Lorentz transformation.
- **Since massive neutrinos have no charge, is anti-$\nu_L$ == $\nu_R$ ?** This would simplify our understanding and also lead to Lepton-Number violation.

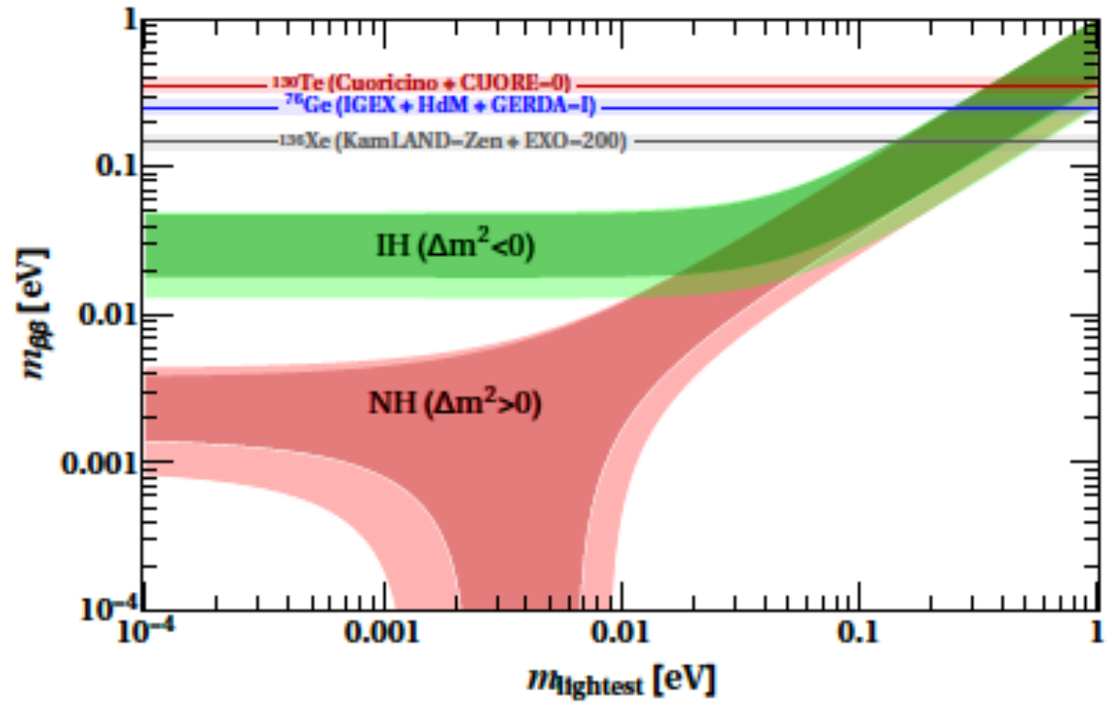
# 0-neutrino double beta decay




- Only practical way to test for Majorana (are neutrinos their own anti-particles ?) nature.
- Amplitude must be $\propto (G_F)^2$ therefore rate will be very small compared to ordinary beta decay which has amplitude of $G_F$.
- In the decay a right-handed antineutrino is emitted and then a left-handed neutrino is absorbed. The RH neutrino has a LH projection only if it has a small mass ⇒ Amplitude must be $\propto m_\nu/E$
- Therefore 0nuDBB is sensitive to Majorana neutrino mass.

# Experimental double beta decay



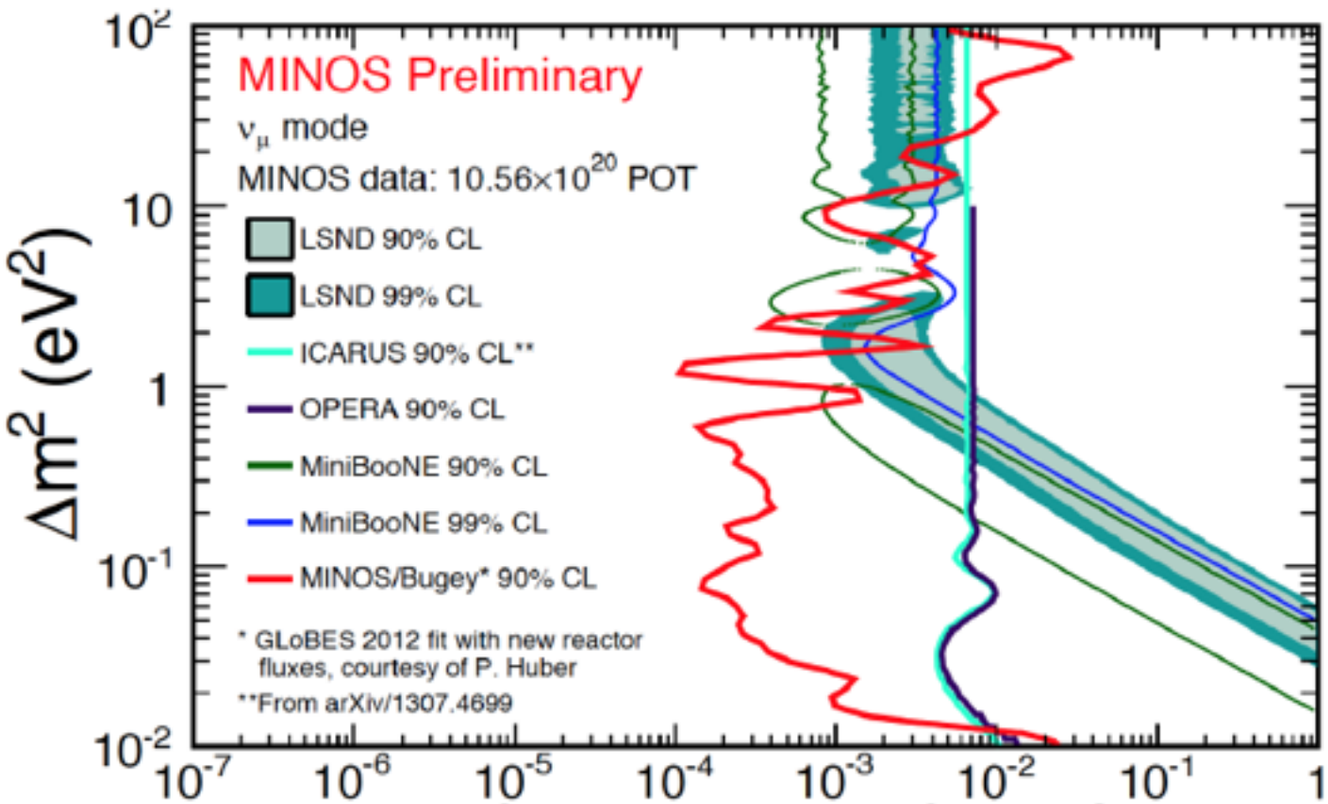



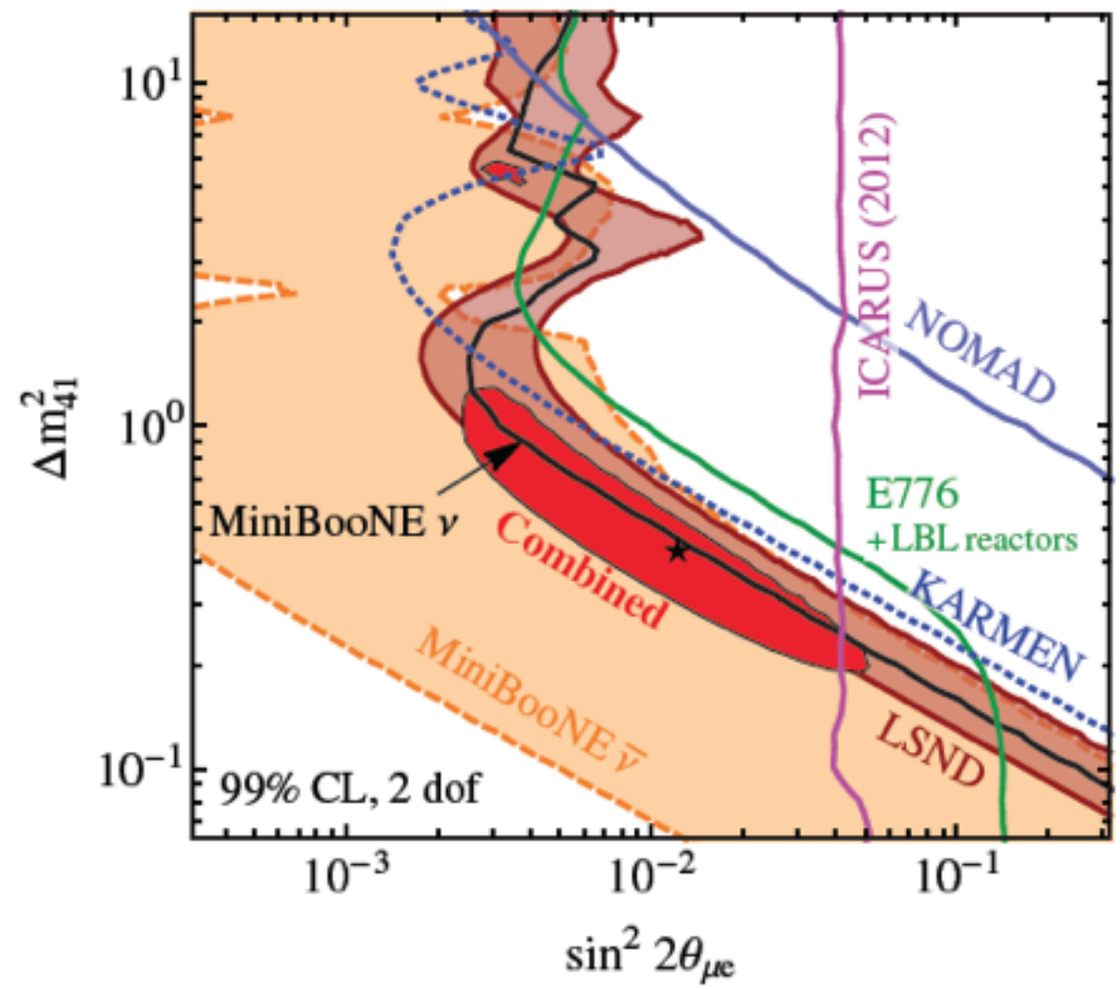

$$\left\langle m_{\beta\beta} \right\rangle = \sum_{i=1,2,3} U_{ei}^2 m_i$$

$$\Gamma^{0\nu} = 1/T_{1/2}^{0\nu} \propto G_F^4 \frac{|m_{\beta\beta}|^2}{m_e^2} \times (factors)$$

- Must test in nuclei where single beta decay not allowed.
- (A,Z) → (A,Z+2) + 2 $e^-$ + 2 (anti-nu) $\Delta L = 0$
- (A,Z) → (A,Z+2) + 2 $e^-$ $\Delta L = 2$
- Lifetimes of $>10^{26}$ years must be measured (with >tons of nuclei) to reach sensitivity indicated by oscillation physics.

# Anomalies




$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14}\sin^2\theta_{24}$$

- There are indications of anomalies around ~1 eV.
- These are getting severely limited by disappearance results.

# Implications of the large $\theta_{13}$

- It should be possible to see effects of matter enhancement with atmospheric neutrinos and determine the mass hierarchy => INO (India)
- It should be possible to see oscillatory signal in reactor neutrinos and determine the mass hierarchy => JUNO (China), RENO50 (Korea), etc.
- Best possibility: An accelerator based program to get enough statistics to perform a comprehensive experiment with $\nu_\mu \to \nu_e$

# Conclusion

- There is an exciting new scientific opportunity due to the discovery that the neutrino is a superposition of 3 mass states. We do not know all the implications of this.
- We can now measure if neutrinos violate the CP symmetry. This is an extremely important measurement that is guaranteed !
- The NOVA experiment and the T2K experiment in Japan are slowly accumulating data.
- Both in the US (LBNF/DUNE) and Japan (HyperK) there are plans to perform experiments to collect much more data with good spectral resolution.