

## Relation of our notaion ( $\nu_+$ , $\nu_-$ ) and regular notation ( $\nu_1$ , $\nu_2$ )

### Regular notation

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$\nu_1$  ≡ mass eigenstate whose  $\nu_e$  component is larger than  $\nu_\mu$

$\nu_2$  ≡ mass eigenstate whose  $\nu_\mu$  component is larger than  $\nu_e$

→ by definition,  $\cos^2 \varphi > \sin^2 \varphi$ .  
Can be  $m_1 > m_2$ .

$m_1 < m_2$  → Normal Hierarchy  
 $m_1 > m_2$  → Inverted Hierarchy

### Our notation

$$\begin{pmatrix} \nu_- \\ \nu_+ \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$\nu_-$  ≡ mass eigenstate whose mass is smaller

$\nu_+$  ≡ mass eigenstate whose mass is larger

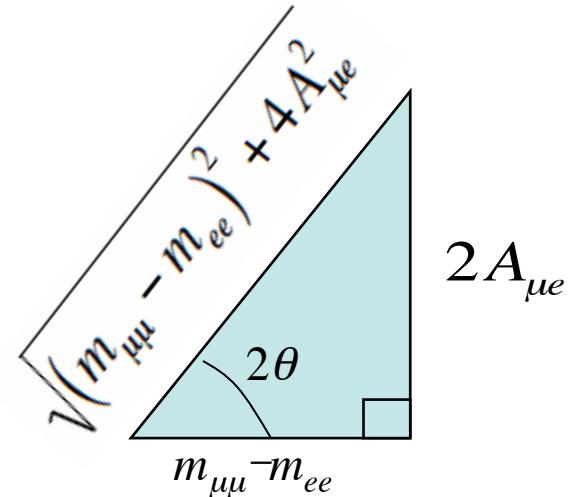
→ by definition,  $m_+ > m_-$   
Can be  $\cos^2 \theta < \sin^2 \theta$

$\cos^2 \theta > \sin^2 \theta$  → Normal Hierarchy  
 $\cos^2 \theta < \sin^2 \theta$  → Inverted Hierarchy

# What Mass Hierarchy Physically Means

Relation between  $\nu_{\pm}$  and  $\nu_{1,2}$

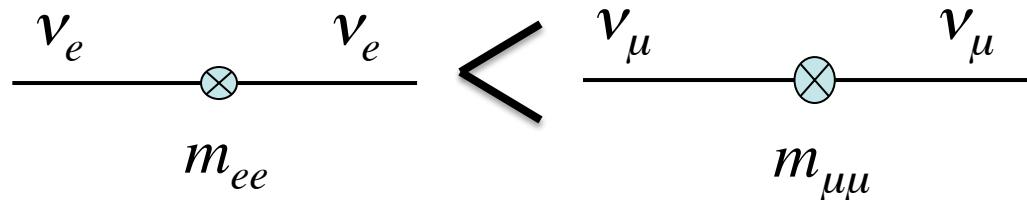
$$\begin{cases} \cos^2 \theta > \sin^2 \theta \Rightarrow \begin{cases} \nu_1 = \nu_- \\ \nu_2 = \nu_+ \end{cases} \\ \cos^2 \theta < \sin^2 \theta \Rightarrow \begin{cases} \nu_1 = \nu_+ \\ \nu_2 = \nu_- \end{cases} \end{cases}$$



$$\text{NH} \Leftrightarrow m_2 > m_1 \Leftrightarrow \cos^2 \theta > \sin^2 \theta \Leftrightarrow \cos 2\theta > 0 \Leftrightarrow m_{\mu\mu} > m_{ee} \Leftrightarrow \langle m_{\nu_u} \rangle > \langle m_{\nu_e} \rangle$$

$$\text{IH} \Leftrightarrow m_2 < m_1 \Leftrightarrow \cos^2 \theta < \sin^2 \theta \Leftrightarrow \cos 2\theta < 0 \Leftrightarrow m_{\mu\mu} < m_{ee} \Leftrightarrow \langle m_{\nu_u} \rangle < \langle m_{\nu_e} \rangle$$

M.H. corresponds to the hierarchy of  $m_{\mu\mu}, m_{ee}$



## Transition amplitudes in the sun

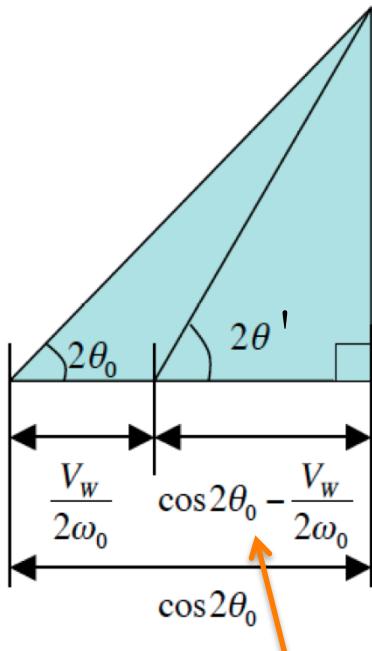
$\nu_e$	$\otimes$	$\nu_e$	$\nu_\mu$	$\otimes$	$\nu_\mu$	$\nu_\mu$	$\otimes$	$\nu_e$
$E_0 - \omega_0 \cos 2\theta_0 + V_Z + V_W$			$E_0 + \omega_0 \sin 2\theta_0 + V_Z$			$\omega_0 \sin 2\theta_0$		

As always, mass eigenstates and their energy are,

$$\begin{pmatrix} \nu'_- \\ \nu'_+ \end{pmatrix} = \begin{pmatrix} \cos \theta' & \sin \theta' \\ -\sin \theta' & \cos \theta' \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$$\sin^2 \theta' = \frac{1}{2} \left( 1 - \frac{(\cos 2\theta_0 - (V_W/2\omega_0))^2}{\sqrt{(\cos 2\theta_0 - (V_W/2\omega_0))^2 + \sin^2 2\theta_0}} \right)$$

$$\begin{cases} E'_+ = E_0 + 2\omega_0 \sqrt{(\cos 2\theta_0 - (V_W/2\omega_0))^2 + \sin^2 2\theta_0} \\ E'_- = E_0 - 2\omega_0 \sqrt{(\cos 2\theta_0 - (V_W/2\omega_0))^2 + \sin^2 2\theta_0} \end{cases}$$



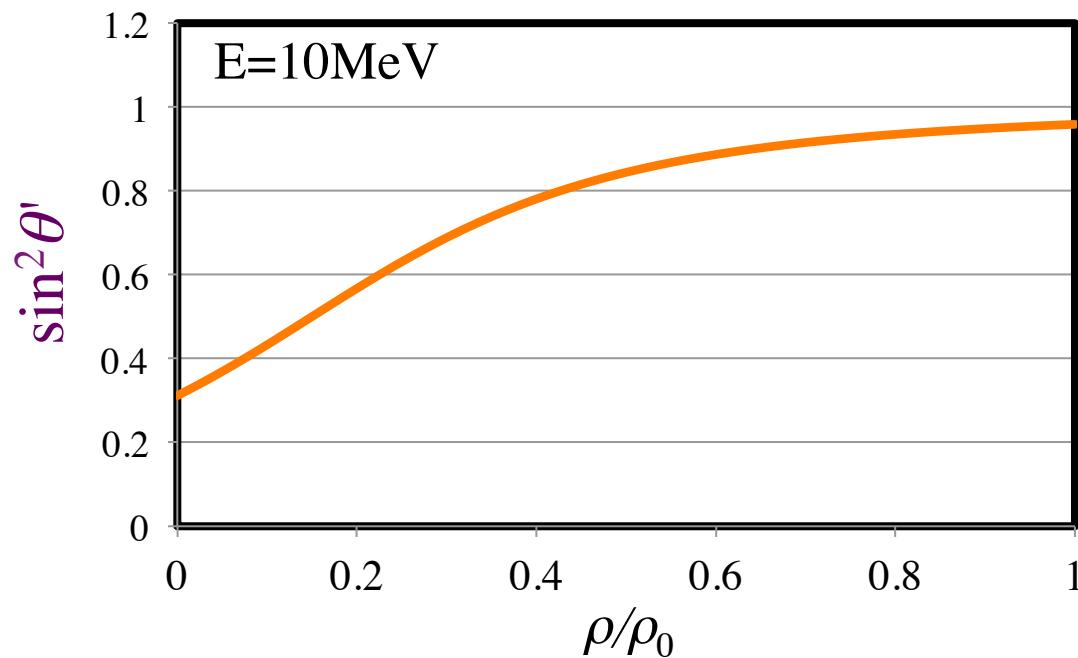
Notice  $V_Z$  cancels out.

We know

$$\begin{cases} \theta_0 \sim 34^\circ \\ \Delta m^2 \sim 7.7 \times 10^{-5} [eV^2] \\ \rho_0 \sim 150 [g/cm^3] \end{cases}$$

Heavy neutrino component ( $\nu_+$ ) of  $\nu_e$

$$\rightarrow \sin^2 \theta' = \frac{1}{2} \left( 1 - \frac{(1.5 - (\rho/\rho_0)E[MeV])}{\sqrt{(1.5 - (\rho/\rho_0)E[MeV])^2 + 13.8}} \right)$$



If  $\nu_e$  (E=10MeV) is generated near the center of the sun, it corresponds to the heavier neutrino state.

$$\nu_e \sim \nu'_+$$

## $\nu$ oscillation in the sun

$$\begin{cases} \nu_e(t) = \cos\theta' \nu'_- e^{-iE'_- t} - \sin\theta' \nu'_+ e^{-iE'_+ t} \\ \nu_\mu(t) = \sin\theta' \nu'_- e^{-iE'_- t} + \cos\theta' \nu'_+ e^{-iE'_+ t} \end{cases}$$

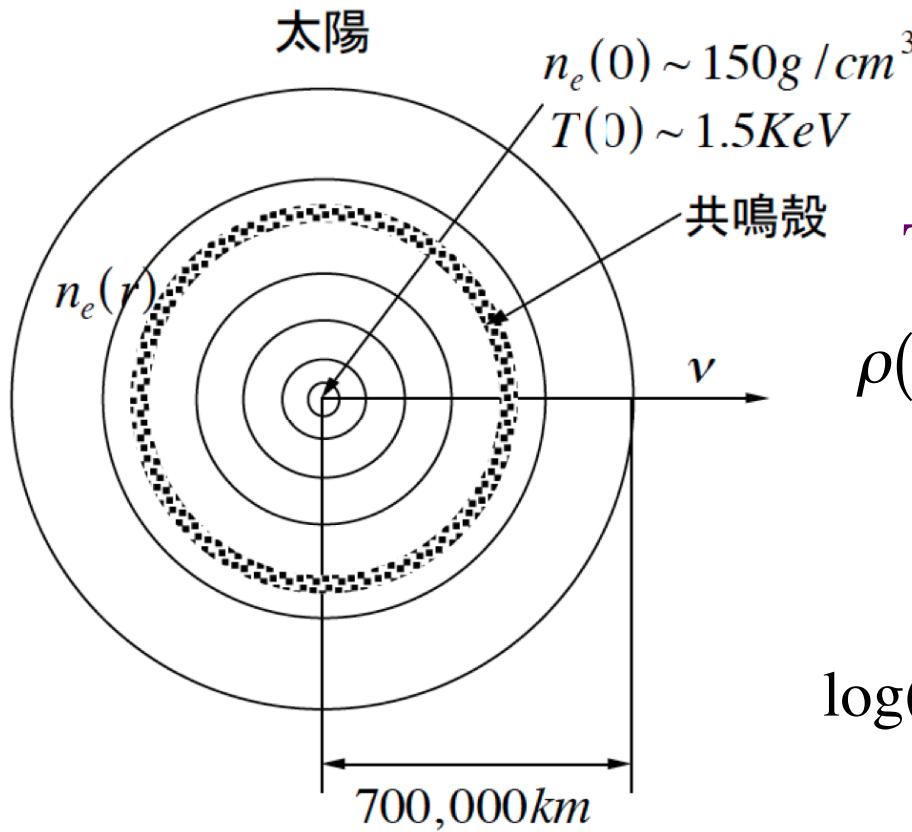
Then as always,

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

Oscillation length in the sun

$$\lambda' = \frac{4\pi}{\Delta E'} = \frac{\pi}{\omega_0 \sqrt{(\cos 2\theta_0 - (V_w/2\omega_0))^2 + \sin^2 2\theta_0}} < 2 \times 10^3 \text{ km} \ll R_{SUN}$$

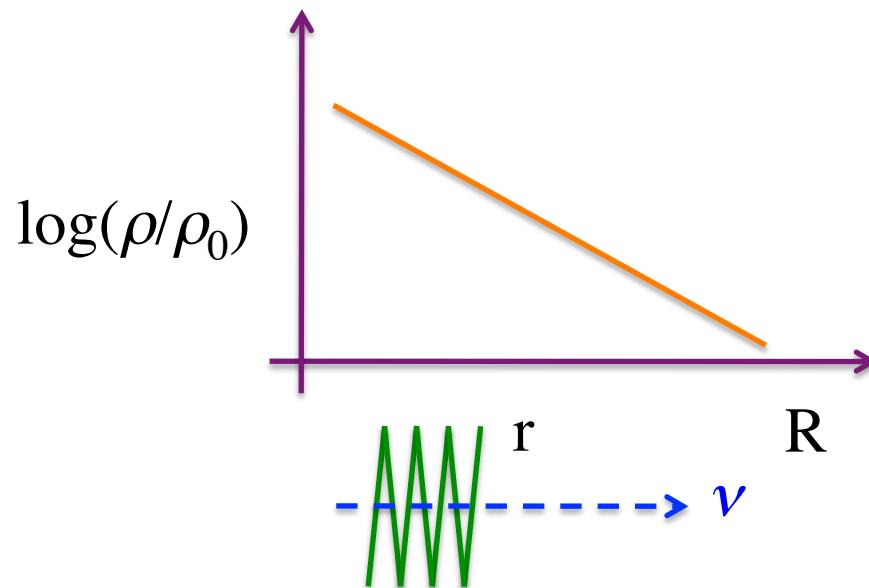
$\nu$  oscillates many times before escaping from the sun



While traveling in the sun,  
 $\nu$  experiences density change

The density distribution in the sun is

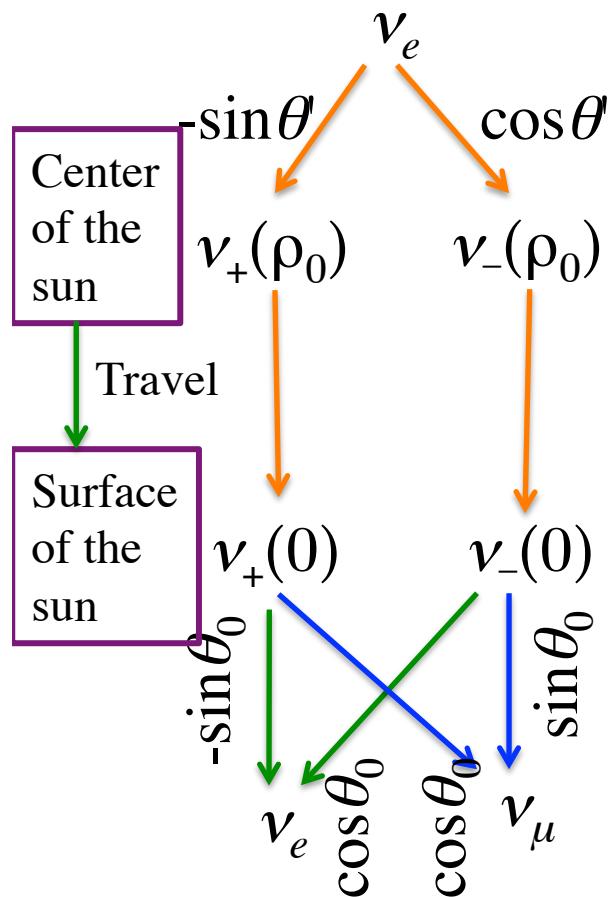
$$\rho(r) \sim \rho_0 \exp\left[-10.5 \frac{r}{R}\right]; \quad (0.2 < r/R < 1)$$



For 1 turn of the oscillation,  
the density change rate is small.

=> adiabatic condition

When produced in the sun, the neutrino is pure  $\nu_e$  state, which is a superposition of  $\nu_{\pm}$



$$\psi_{\nu}(0) = \nu_e = \cos \theta' \nu_-(\rho_0) e^{-iE'_- t} - \sin \theta' \nu_+(\rho_0) e^{-iE'_+ t}$$

While traveling,  $\nu_{\pm}$  stays  $\nu_{\pm}$  state, respectively  
(Adiabatic)

At  $t=T$ , the neutrino reaches the sun surface.

$$\psi_{\nu}(T) = \cos \theta' \nu_-(0) e^{-i\phi_-(T)} - \sin \theta' \nu_+(0) e^{-i\phi_+(T)}$$

$\phi$  is the phase rotation during the travel

$$\phi_{\pm}(T) = \int_0^T E_{\pm}(\rho(r)) dt$$

is mass eigenstate in the vacuum

$$\begin{pmatrix} \nu_-(0) \\ \nu_+(0) \end{pmatrix} = \begin{pmatrix} \cos \theta_0 & \sin \theta_0 \\ -\sin \theta_0 & \cos \theta_0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

At the surface of the sun ( $t=T$ ), the neutrino state is

$$\begin{aligned}\psi_\nu(T) &= \cos\theta' \nu_-(0) e^{-i\phi_-(T)} - \sin\theta' \nu_+(0) e^{-i\phi_+(T)} \\ &= (\cos\theta' \cos\theta_0 e^{-i\phi_-(T)} + \sin\theta' \sin\theta_0 e^{-i\phi_+(T)}) \nu_e \\ &\quad + (\cos\theta' \sin\theta_0 e^{-i\phi_-(T)} - \sin\theta' \cos\theta_0 e^{-i\phi_+(T)}) \nu_\mu\end{aligned}$$

The probability that  $\nu_e$  remains  $\nu_e$  is

$$\begin{aligned}P(\nu_e \rightarrow \nu_e) &= |\cos\theta' \cos\theta_0 e^{-i\phi_-(T)} + \sin\theta' \sin\theta_0 e^{-i\phi_+(T)}|^2 \\ &= \frac{\cos^2\theta' \cos^2\theta_0 + \sin^2\theta' \sin^2\theta_0 + \frac{1}{2} \sin 2\theta' \sin 2\theta_0 \cos \Delta\phi(T)}{2}\end{aligned}$$

Since neutrinos are generated at various positions, T has some variation and  $\cos\Delta\phi$  term is averaged to 0

$$P(\nu_e \rightarrow \nu_e) = \frac{1}{2}(1 + \cos 2\theta_0 \cos 2\theta')$$

(If there is no MSW effect,  $P(\nu_e \rightarrow \nu_e) = \frac{1}{2}(1 + \cos^2 2\theta_0)$  )

$$P_{NH}(\nu_e \rightarrow \nu_e) \sim \frac{1}{2} \left( 1 + 0.38(1.5 - E_\nu [MeV]) / \sqrt{(1.5 - E_\nu [MeV])^2 + 13.8} \right)$$

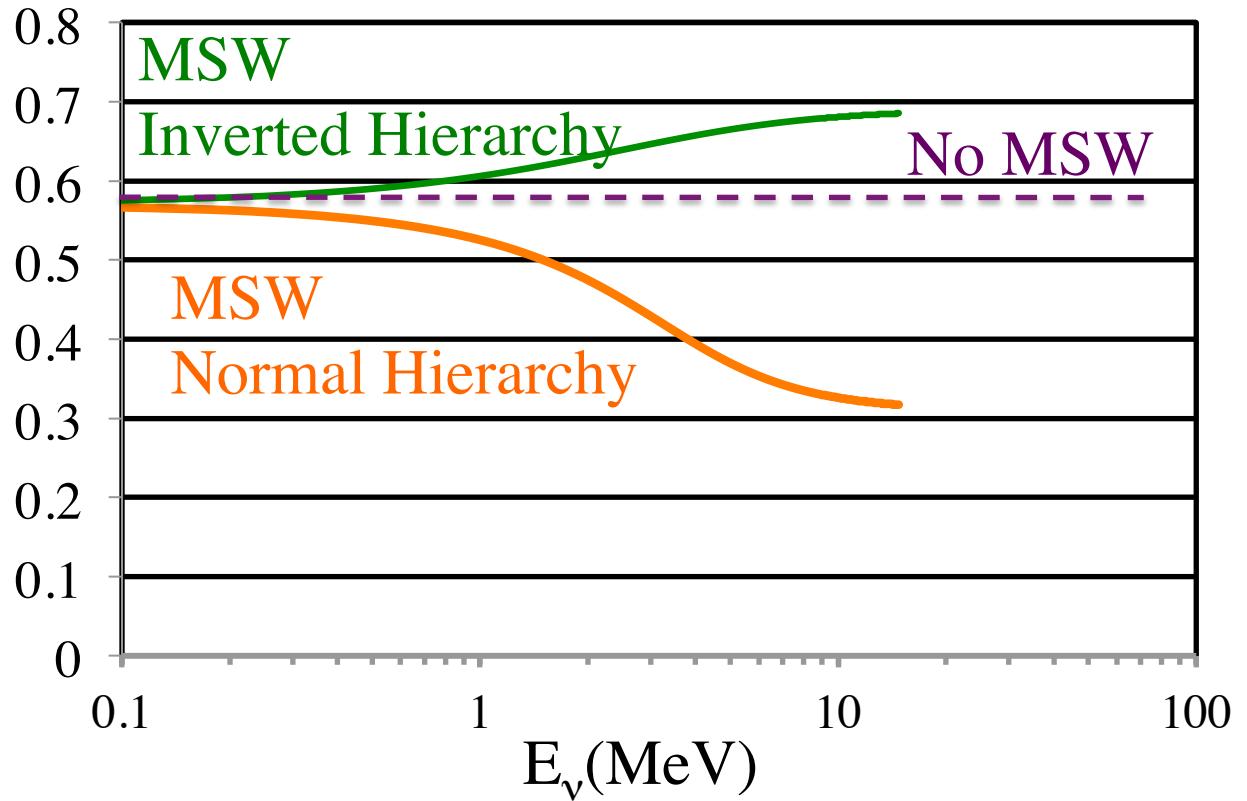
If  $IH$  ( $\cos 2\theta_0 < 0$ ), the relative sign of the potential is reversed and probability becomes;

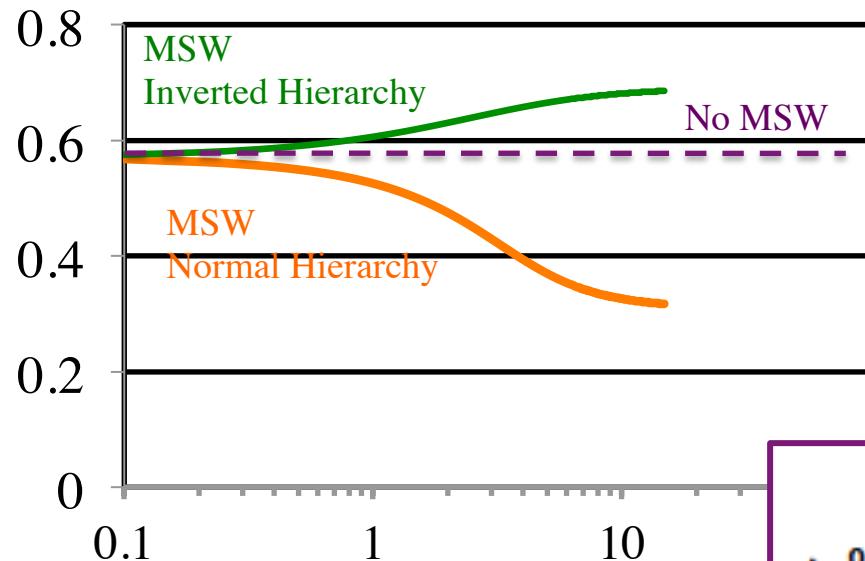
$$P_{IH}(\nu_e \rightarrow \nu_e) \sim \frac{1}{2} \left( 1 + 0.38(1.5 + E_\nu [MeV]) / \sqrt{(1.5 + E_\nu [MeV])^2 + 13.8} \right)$$

$$P(\nu_e \rightarrow \nu_e)$$

There is energy dependence.

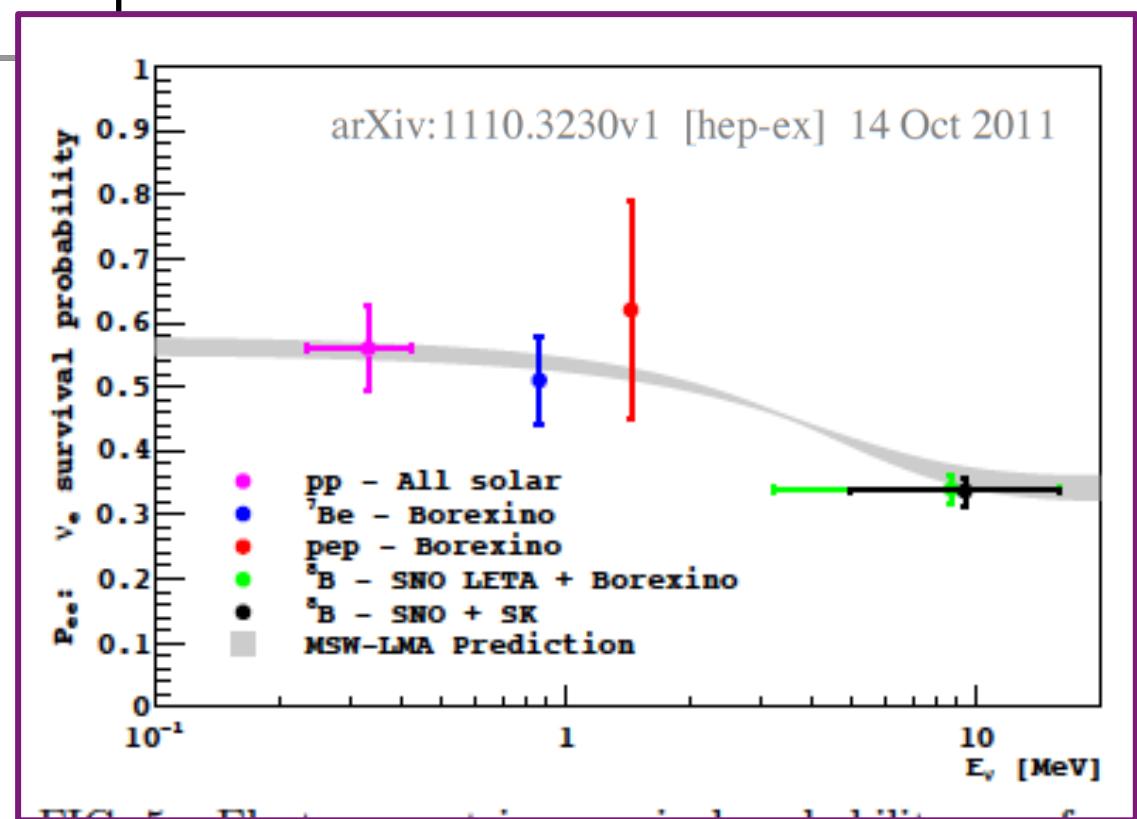
This dependence depends on the mass hierarchy





NH is confirmed  
by matter effect  
 $m_2 > m_1$

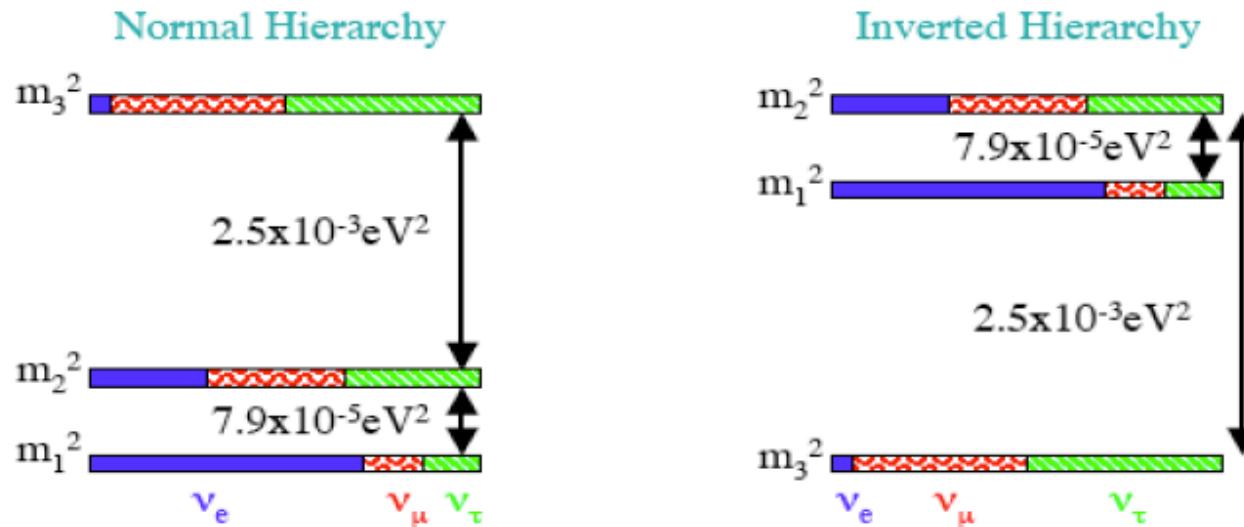
## Observation of $\nu$ flux



# More Mass Hierarchy

$$\Delta m_{12}^2 \sim 8 \times 10^{-5} eV^2, \quad |\Delta m_{23}^2| \sim 2.5 \times 10^{-3} eV^2$$

There are still 2 possibilities.



Mass Hierarchy is important for detectability of  $\nu_e$  mass.

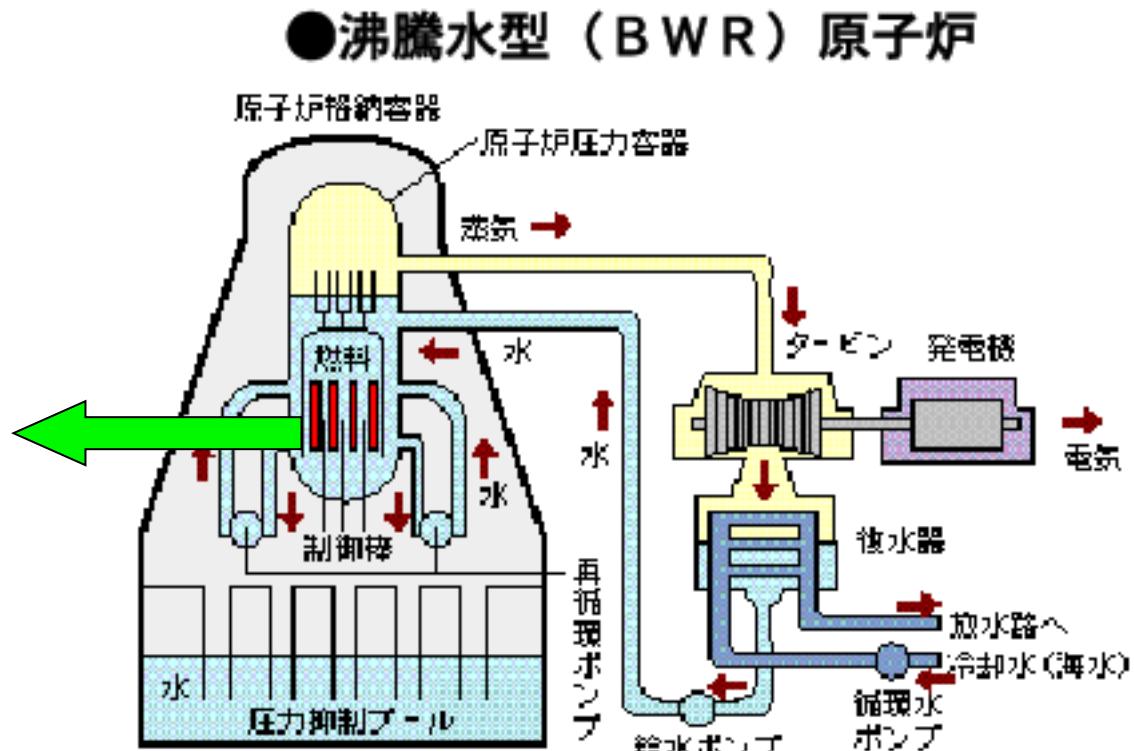
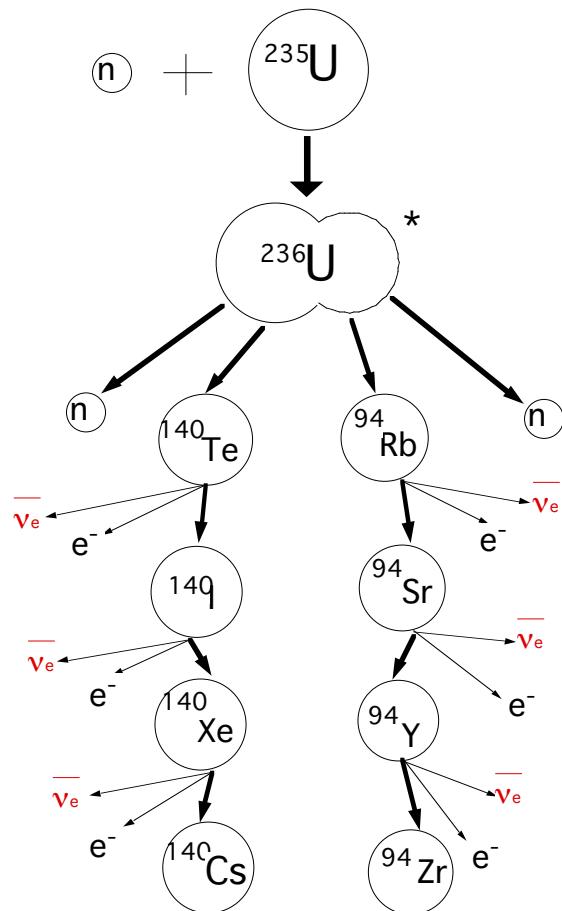
If it is IH,  $\langle m_{\nu_e} \rangle > 50 meV$  and there is a chance to measure it.

So I hope it is IH.

# Reactor Neutrino Experiments so far



# Reactor Neutrino



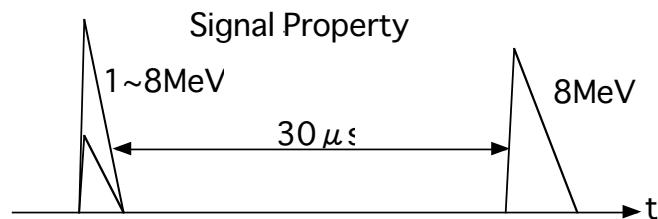
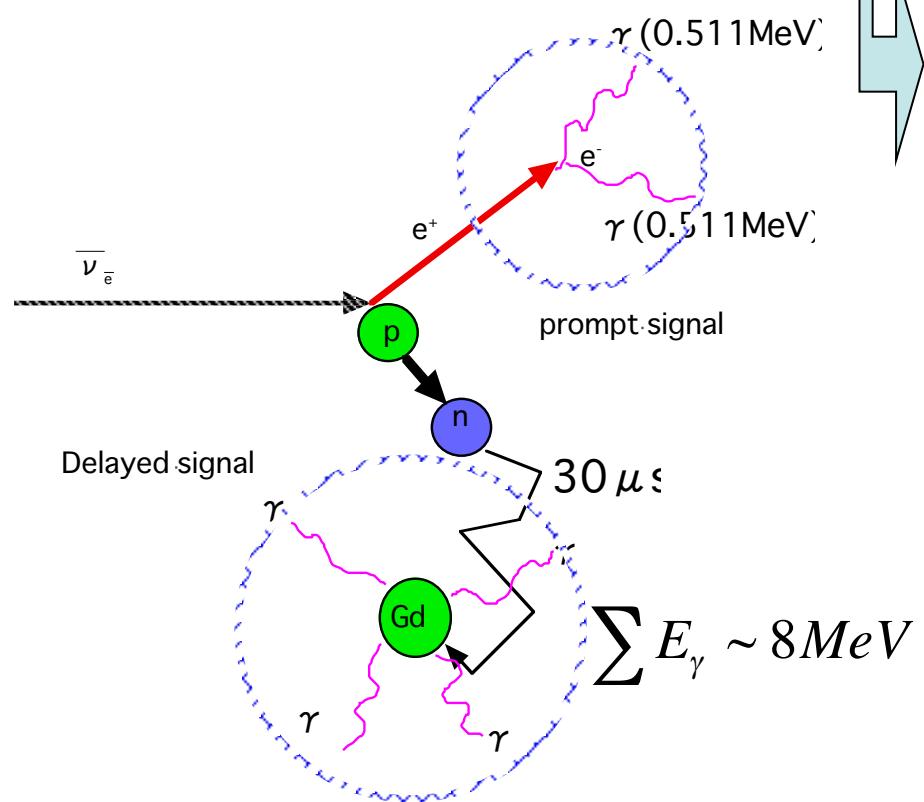
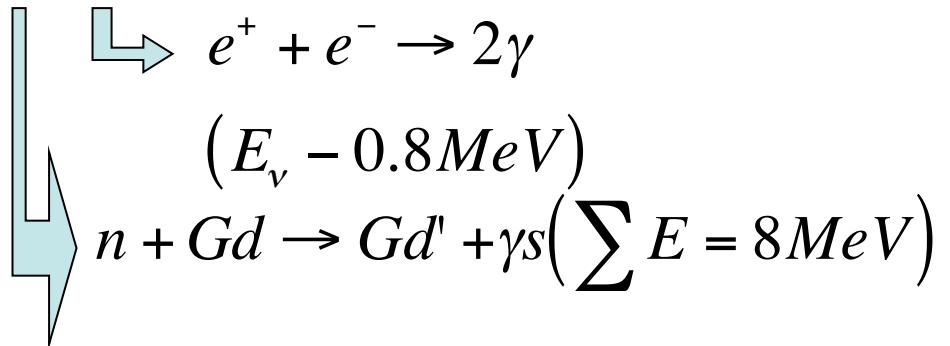
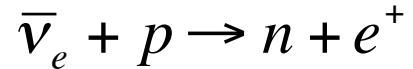
$\sim 6\bar{\nu}/\text{fission} \& \sim 200\text{MeV/fission}$



$$\sim 6 \times 10^{20} \bar{\nu} / \text{s/reactor} \quad (1\text{GWe})$$

suekane@FAPPS

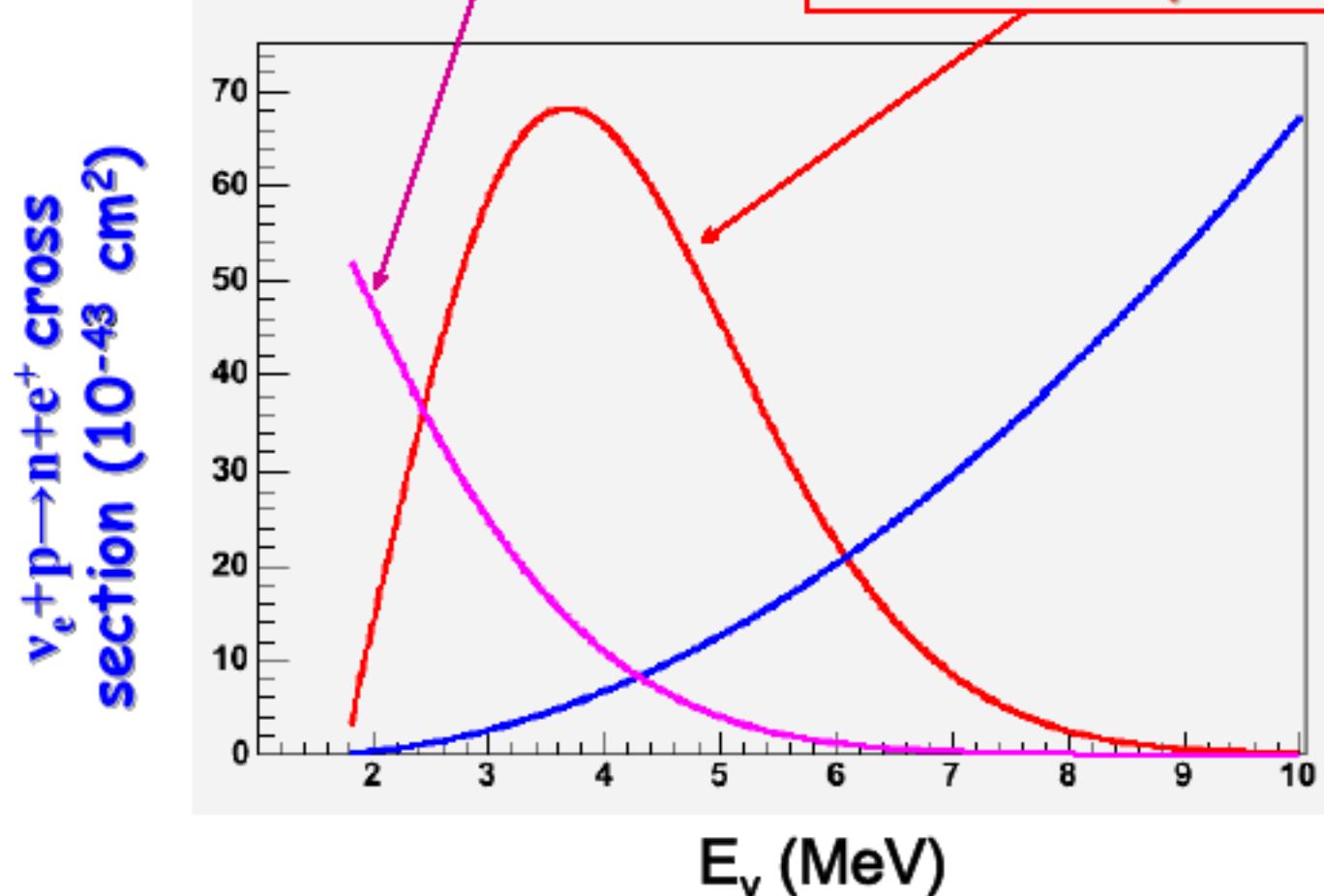
# $\bar{\nu}_e$ Detection (Chooz)



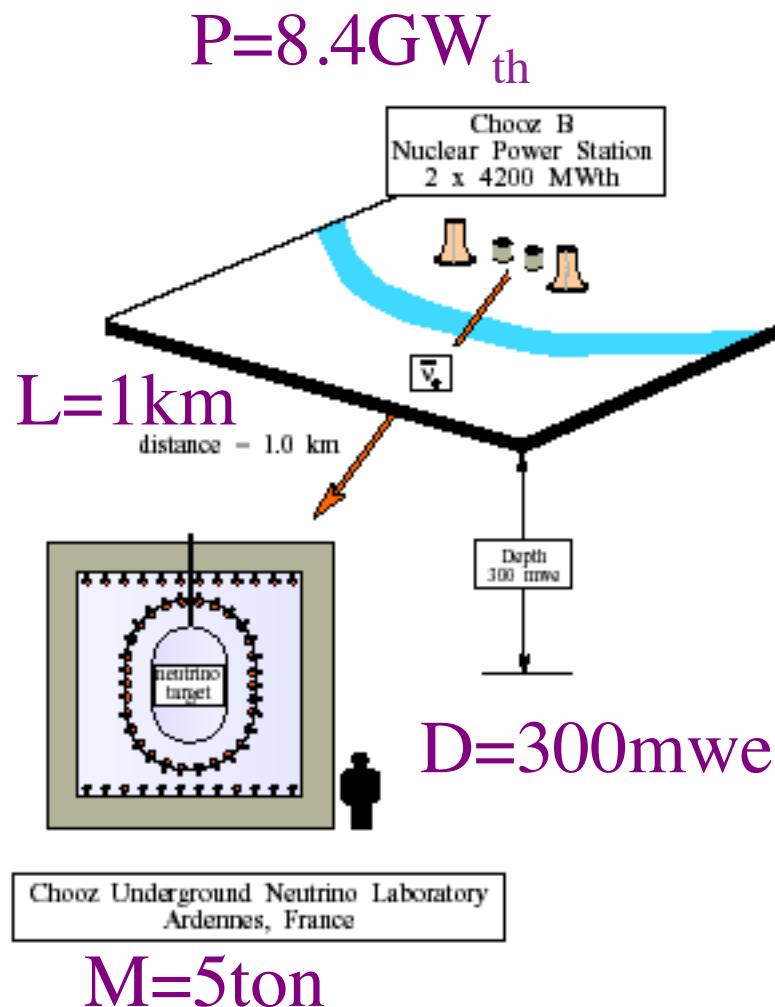
## The $\bar{\nu}_e$ energy spectrum

Reactor  $\nu_e$  spectrum (a.u.)

Observed spectrum (a.u.)



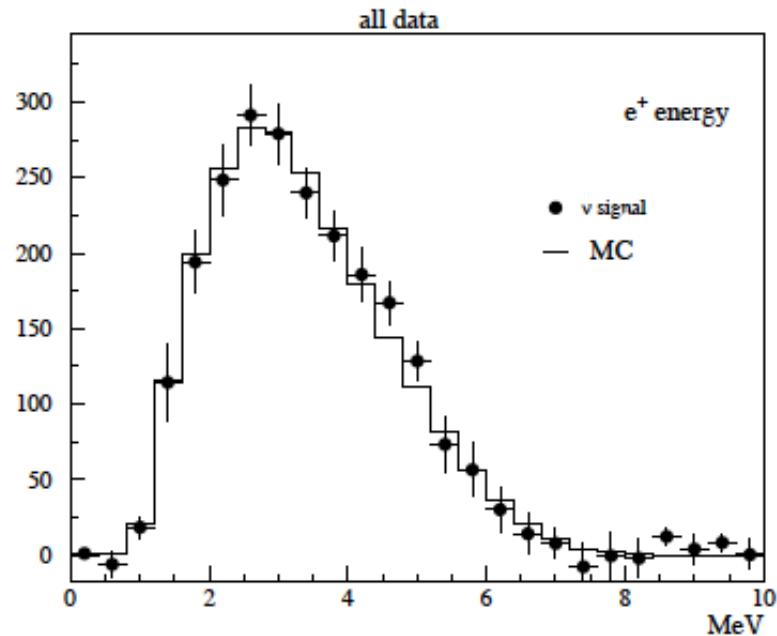
# CHOOZ experiment



From atmospheric  $\nu$  oscillation,  
 $\Delta m^2 \sim 10^{-2}\text{eV}^2$ (in those days)

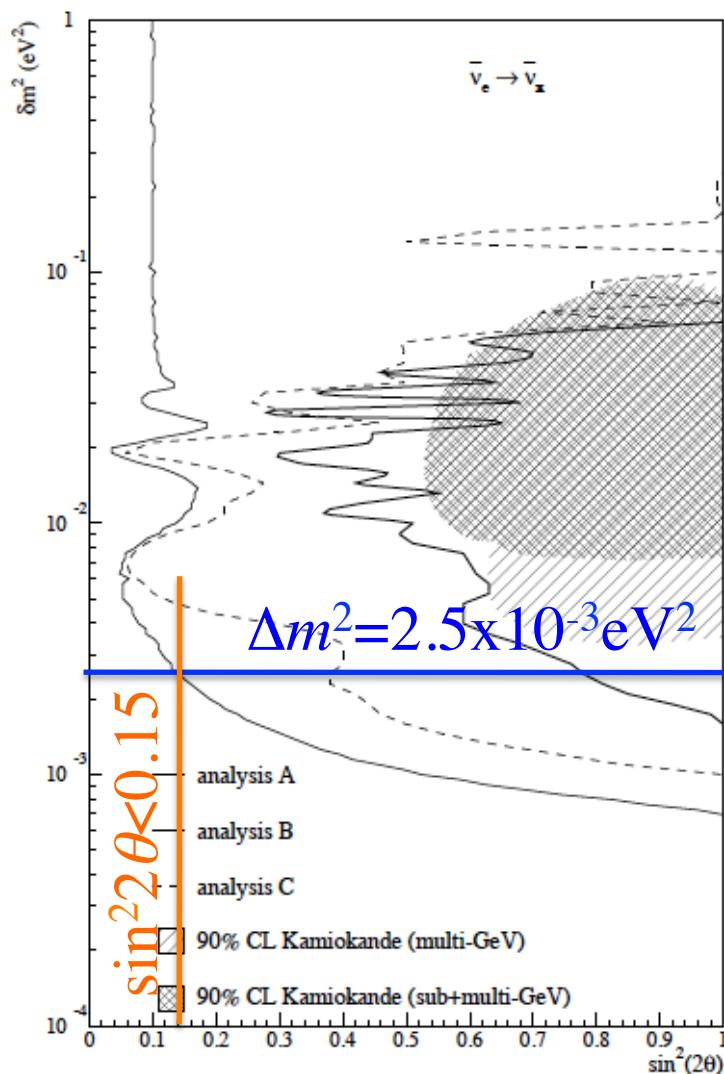
Then for  $E_\nu \sim 4\text{MeV}$ ,  
same oscillation may take place at  $L \sim 1\text{km}$

## Chooz energy spectrum



Deficit was not observed.

## Chooz result

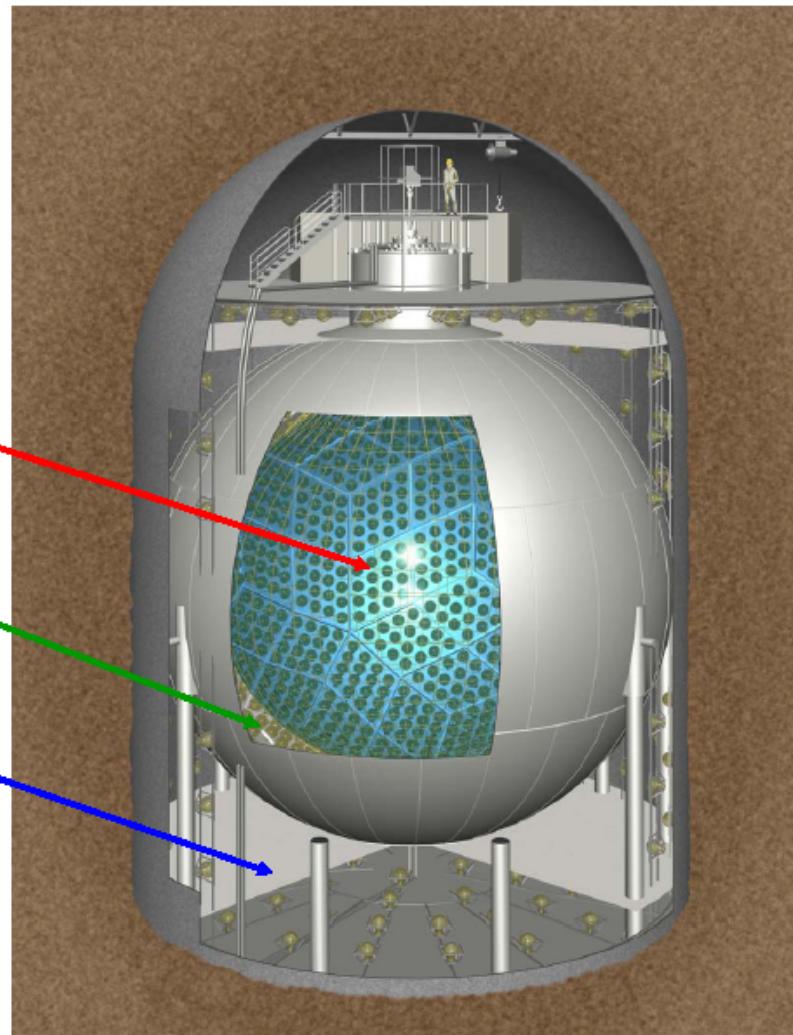


This is the current most strong upper limit of  $\theta_{13}$

# KamLAND

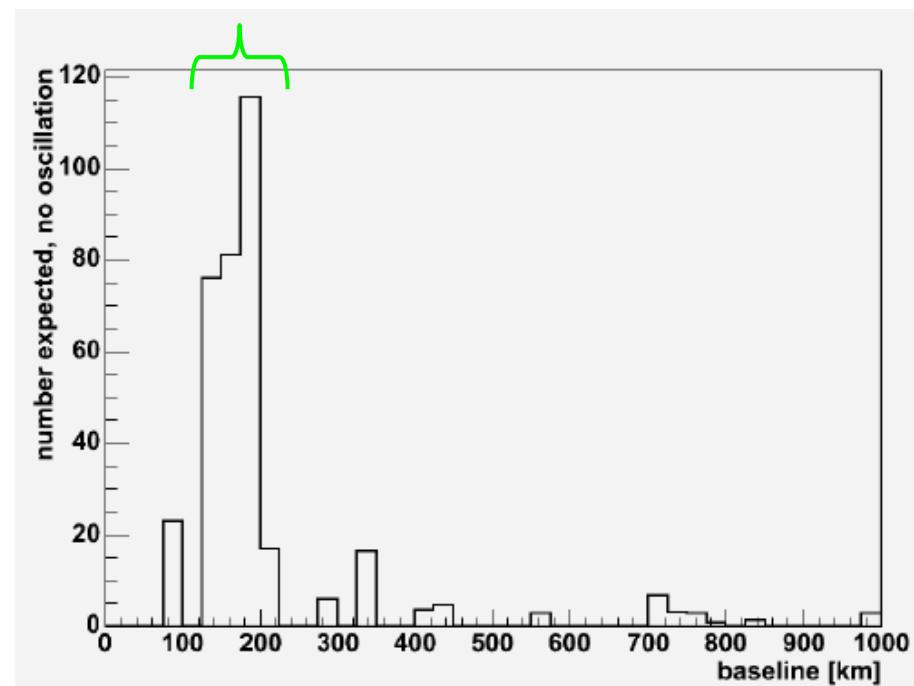
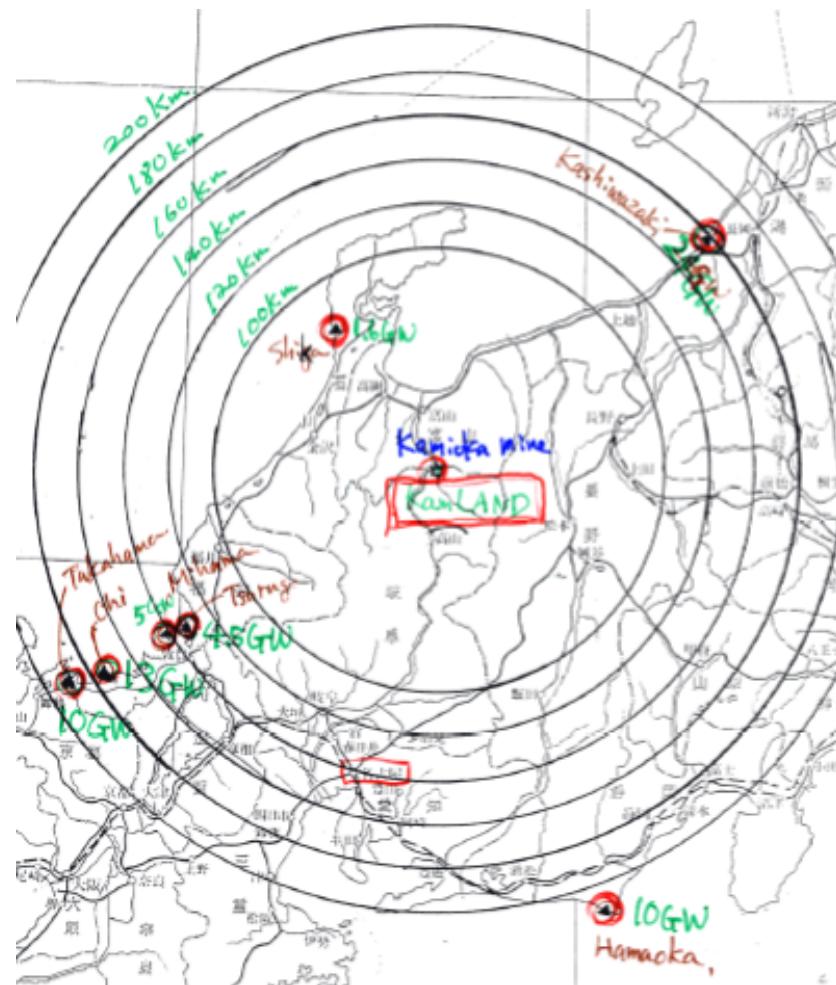
**KamLAND:**  
**Kamioka Liquid scintillator**  
**AntiNeutrino Detector**

- 1 kton liq. Scint. Detector  
in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- $\text{H}_2\text{O}$  Cerenkov veto counter



# KamLAND and Reactors

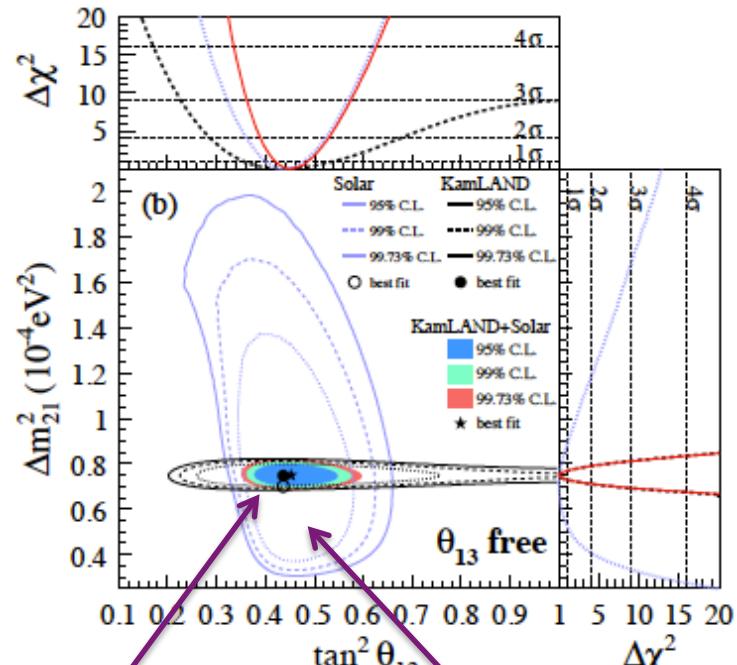
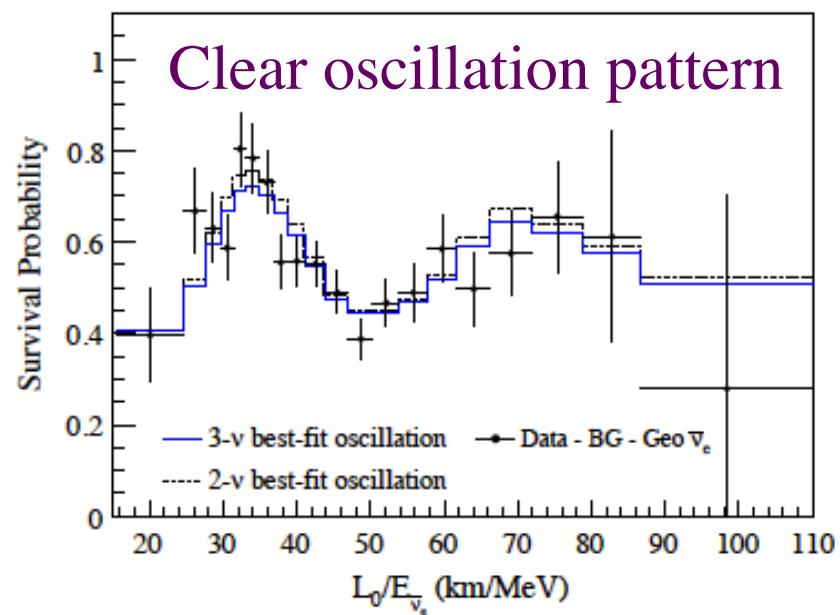
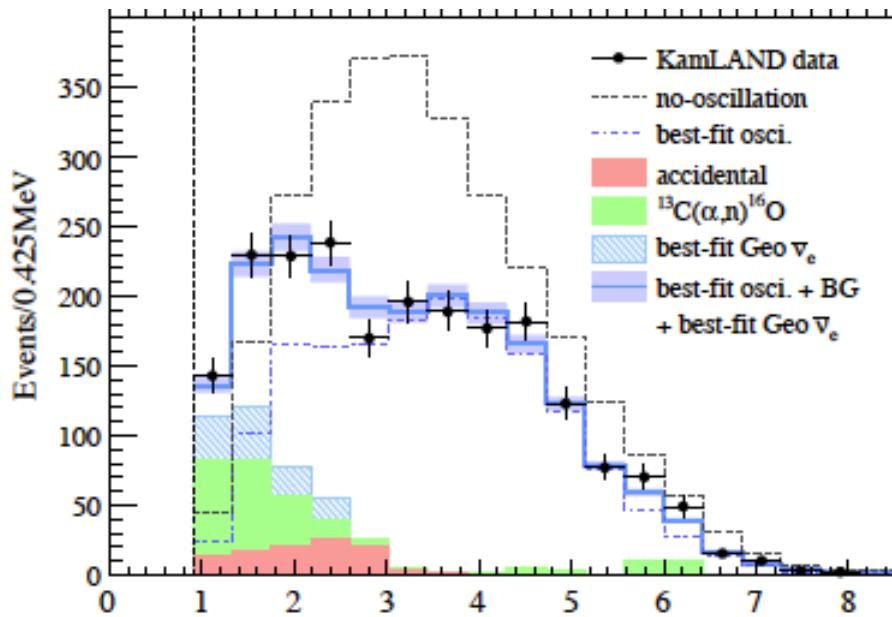
68GWth



$\langle \text{Baseline} \rangle \sim 180\text{km}$

Although there are many reactors,  
the baseline is almost unique.  
 $\sim 1$  Gigantic Reactor @  $L \sim 180\text{km}$

# Results

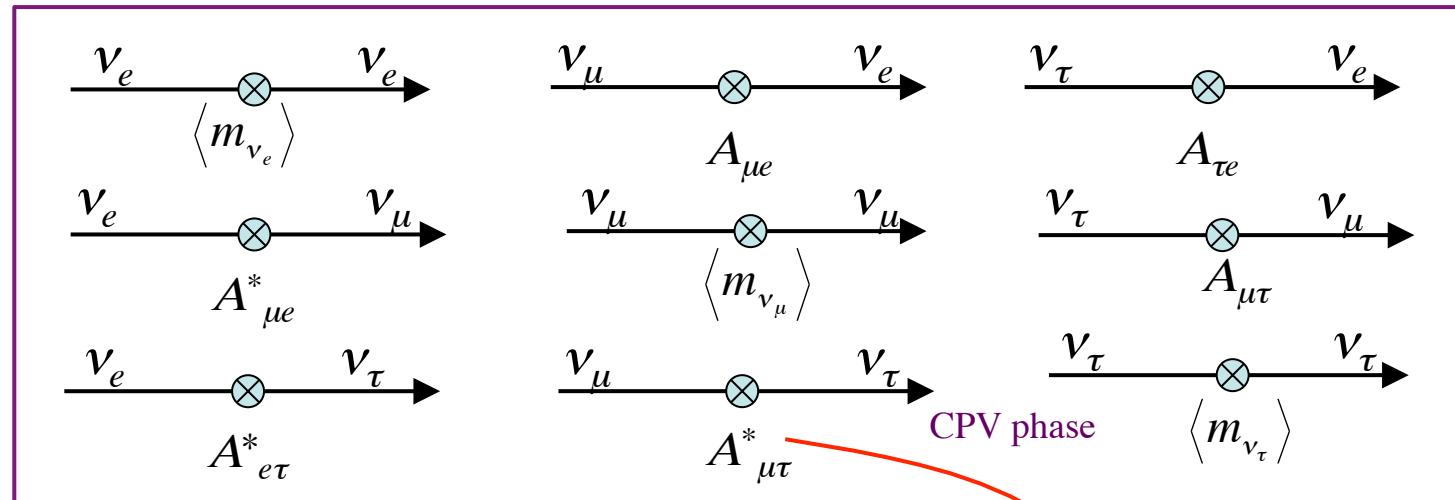


Since KL ( $\bar{\nu}$  disappearance)  
& Solar ( $\nu$  disappearance)  
agrees, CPT is OK.

$$\tan^2 \theta \sim 0.44, \quad \Delta m^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$$

## 3 Flavor ( $\nu_e$ , $\nu_\mu$ , $\nu_\tau$ ) case

Transition amplitudes



3 mixing angles + 1 phase (+ 3 masses)

Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

This parametrisation happens to be very useful because angles can be independently related to the experimental results.

(not always so. Wolfenstein parametrization is not useful here.)

## 3 flavor $\nu$ oscillation

Probability of  $\nu$  oscillations (after some boring calculations)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \operatorname{Re}[\Omega_{ij}^{\alpha\beta}] \sin^2 \Phi_{ij} - 2 \sum_{i>j} \operatorname{Im}[\Omega_{ij}^{\alpha\beta}] \sin 2\Phi_{ij}$$

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \operatorname{Re}[\Omega_{ij}^{\alpha\beta}] \sin^2 \Phi_{ij} + 2 \sum_{i>j} \operatorname{Im}[\Omega_{ij}^{\alpha\beta}] \sin 2\Phi_{ij}$$

Assuming

CPT

$$\Omega_{ij}^{\alpha\beta} \equiv U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \quad \Phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad \Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

Especially for disappearance probability

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - 4 \sum_{i>j} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin^2 \Phi_{ij} = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha)$$

# Where CP violation may comes from

CP violation in neutrino oscillation

$$P(\nu_{\alpha L} \rightarrow \nu_{\beta L}) \xrightarrow{C} P(\bar{\nu}_{\alpha L} \rightarrow \bar{\nu}_{\beta L}) \xrightarrow{P} P(\bar{\nu}_{\alpha R} \rightarrow \bar{\nu}_{\beta R})$$

If  $P(\nu_{\alpha L} \rightarrow \nu_{\beta L}) \neq P(\bar{\nu}_{\alpha R} \rightarrow \bar{\nu}_{\beta R})$ , CP symmetry violates.

Since  $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) - P(\nu_\alpha \rightarrow \nu_\beta) = 4 \sum_{i>j} \text{Im}(\Omega_{ij}^{\alpha\beta}) \sin 2\Phi_{ij}$ ,

→ CPV <= imaginary part of mixing matrix

For  $\beta=\alpha$ ,  $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha) - P(\nu_\alpha \rightarrow \nu_\alpha) = 4 \sum_{i>j} \text{Im}(\Omega_{ij}^{\alpha\alpha}) \sin 2\Phi_{ij}$   
 $= 4 \sum_{i>j} \text{Im}(|U_{\alpha i}|^2 |U_{\alpha j}|^2) \sin 2\Phi_{ij} = 0$

→ CPV does not appear in disappearance.

## What about CPT?

CPT violation in neutrino oscillation

$$P(\nu_{\alpha L} \rightarrow \nu_{\beta L}) \xrightarrow{CP} P(\bar{\nu}_{\alpha R} \rightarrow \bar{\nu}_{\beta R}) \xrightarrow{T} P(\bar{\nu}_{\beta R} \rightarrow \bar{\nu}_{\alpha R})$$

$$P(\nu_{\alpha L} \rightarrow \nu_{\alpha L}) \xrightarrow{CPT} P(\bar{\nu}_{\alpha R} \rightarrow \bar{\nu}_{\alpha R})$$

Especially when  $\beta=\alpha$

$$P(\nu_{\alpha L} \rightarrow \nu_{\alpha L}) \xrightarrow{CPT} P(\bar{\nu}_{\alpha R} \rightarrow \bar{\nu}_{\alpha R})$$

If disappearance of  $\nu$  and  $\bar{\nu}$  is different,  $\rightarrow \cancel{CPT}$

In the  $\nu$  oscillation formalism so far, CPT symmetry is assumed.

- ➔ If CPTV is found, we have to change our theory.
- => Comparison of  $\nu$  disappearance and  $\bar{\nu}$  disappearance is important

# Correspondence between experimental results and 3 flavor mixing angles; $\theta_{12}$ , $\theta_{23}$ , $\theta_{13}$

What have observed:

$$\begin{cases} @ |\Delta m^2| = 2.5 \times 10^{-3} eV^2, & \begin{cases} \sin^2 2\theta_{\mu\tau} \sim 1 (\text{Atmos, K2K, MINOS}) \\ \sin^2 2\theta_{ee} < 0.15 (\text{CHOOZ}) \end{cases} \\ @ \Delta m^2 = 8.0 \times 10^{-5} eV^2, & \sin^2 2\theta_{ee} \sim 0.8 (\text{Solar, KamLAND}) \end{cases}$$

What is the relation with  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{31}$ ,  $\delta$ ?

We define  $\Delta m_{12}^2 \equiv 8.0 \times 10^{-5} eV^2$ ,  $|\Delta m_{23}^2| \equiv 2.5 \times 10^{-3} eV^2$

Then  $|\Delta m_{31}^2| = |\Delta m_{12}^2 + \Delta m_{23}^2| \sim |\Delta m_{23}^2| = 2.5 \times 10^{-3} eV^2$

Since  $|\Delta m_{31}^2| \ll |\Delta m_{23}^2|$  oscillations at two L/Es are well separated  
=> It makes things simpler.

# Correspondence between experimental results and 3 flavor mixing angles

For Chooz limit

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - 4 \left( |U_{e2}|^2 |U_{e1}|^2 \sin^2 \Phi_{21} + |U_{e3}|^2 |U_{e1}|^2 \sin^2 \Phi_{31} + |U_{e3}|^2 |U_{e2}|^2 \sin^2 \Phi_{32} \right)$$

For Chooz E/L  $\sin^2 \Phi_{23} \sim \sin^2 \Phi_{31} \sim O(1)$  and,  $\Phi_{12} \sim 0$

Then,

$$P_{@23}(\nu_e \rightarrow \nu_e) \sim 1 - 4 |U_{e3}|^2 (|U_{e1}|^2 + |U_{e2}|^2) \sin^2 \Phi_{31} = 1 - \sin^2 2\theta_{13} \sin^2 \Phi_{31}$$

From experimental result,

$$\boxed{\sin^2 2\theta_{13} < 0.15}$$

## Relation between experimental results and 3 flavor mixing angles

Similarly, for accelerator and atmospheric results,

$$P_{@23}(\nu_\mu \rightarrow \nu_\mu) \sim 1 - 4|U_{\mu 3}|^2 \left( |U_{\mu 1}|^2 + |U_{\mu 2}|^2 \right) \sin^2 \Phi_{32} = 1 - 4c_{13}^2 s_{23}^2 (c_{23}^2 + s_{13}^2 s_{23}^2) \sin^2 \Phi_{32}$$

Because  $s_{13}^2 < 0.04$  we ignore it:

$$P_{@23}(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2 \Phi_{32}$$

From accelerator and atmospheric experiment,

$$\sin^2 2\theta_{23} \sim 1$$

## Relation between experimental results and 3 flavor mixing angles

For solar and KamLAND experiment,

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - 4 \left( |U_{e2}|^2 |U_{e1}|^2 \sin^2 \Phi_{21} + |U_{e3}|^2 |U_{e1}|^2 \sin^2 \Phi_{31} + |U_{e3}|^2 |U_{e2}|^2 \sin^2 \Phi_{32} \right)$$

at  $\Phi_{12} \sim O(1)$ ,  $\Phi_{13}$  and  $\Phi_{23}$  quickly oscillate and averaged to 1/2

$$P_{12}(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2 2\theta_{12} \sin^2 \Phi_{21} + O(s_{13}^2)$$

from data,

$$\boxed{\sin^2 2\theta_{12} \sim 0.8}$$

## Our current knowledge

Global analysis before  $\theta_{13}$

(T. Schwetz, et al., New J. Phys. **10** (2008) 113011 [arXiv:0808.2016])

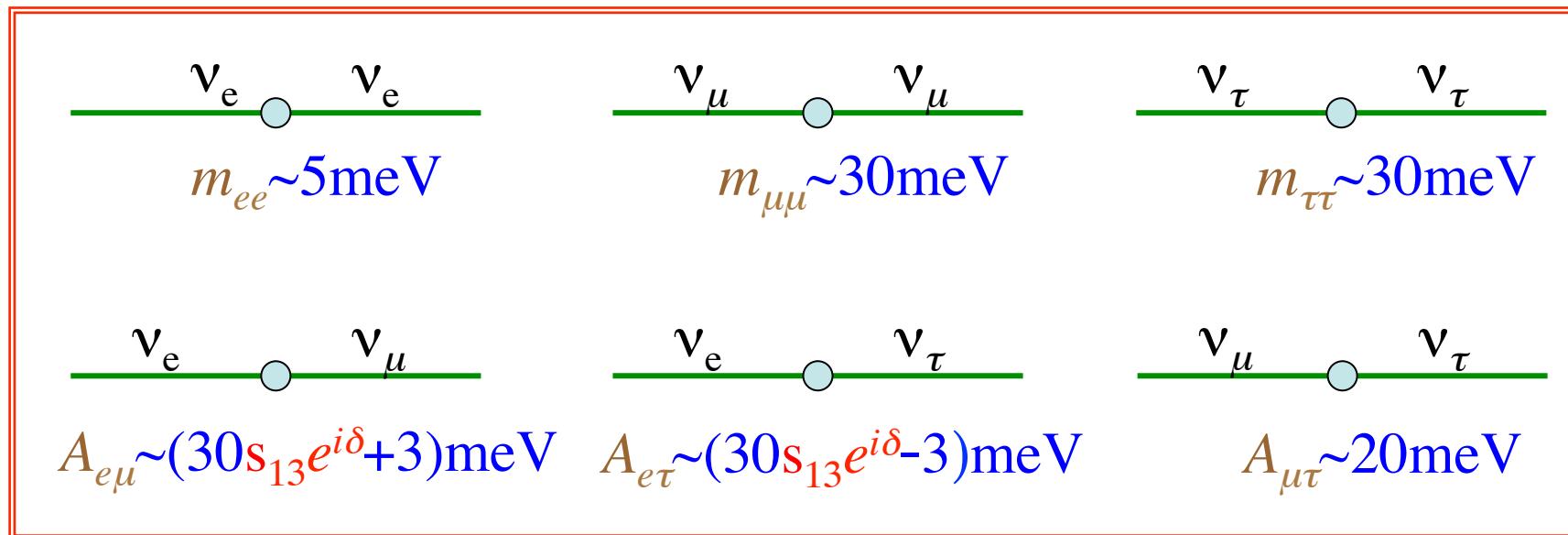
$$\begin{cases} \sin^2 2\theta_{23} > 0.88(3\sigma), \quad |\Delta m_{23}^2| \sim 2.40_{-0.11}^{+0.12} \times 10^{-3} \text{ eV}^2 \\ \sin^2 2\theta_{12} = 0.846_{-0.026}^{+0.033}, \quad \Delta m_{12}^2 \sim 7.65_{-0.20}^{+0.23} \times 10^{-5} \text{ eV}^2 \\ \sin^2 2\theta_{13} < 0.21(3\sigma), \text{ (or } = 0.17 \text{ if T2K most probable value is correct)} \end{cases}$$

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & s_{13}e^{i\delta} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix}$$

## Our current knowledge

Unfortunately transition amplitudes can not be determined because we do not know absolute mass.

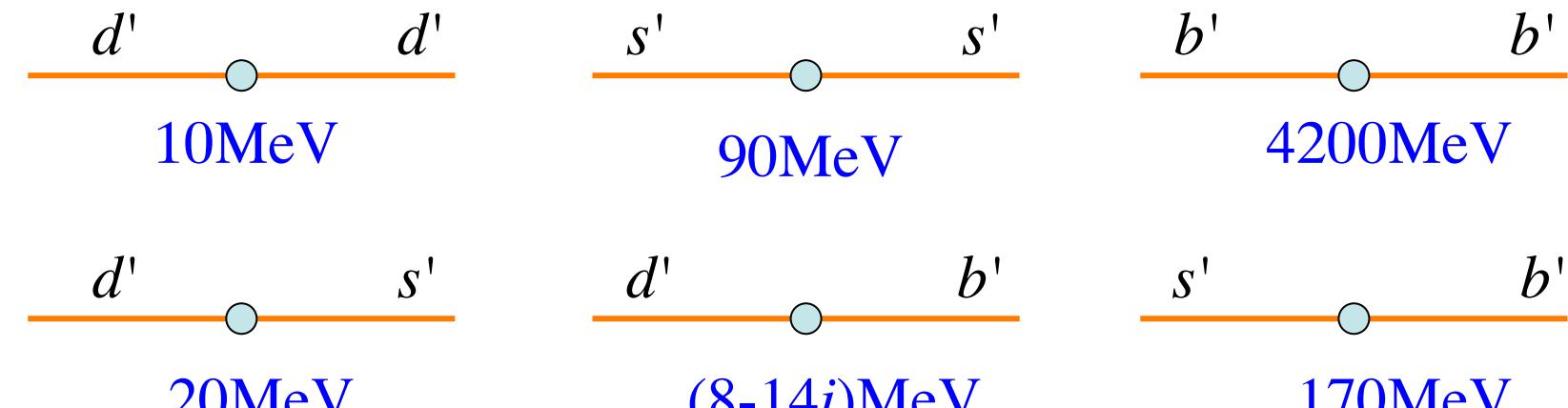
If we assume  $m_3 > m_2 > m_1 \sim 0$



## Our current knowledge for quarks (Sometimes it is instructive to look aside)

Exactly same discussions can be applied to quarks.  
For quarks we can determine T.A. since we know quark masses.

Quark transition amplitudes from CKM &  $m_q$

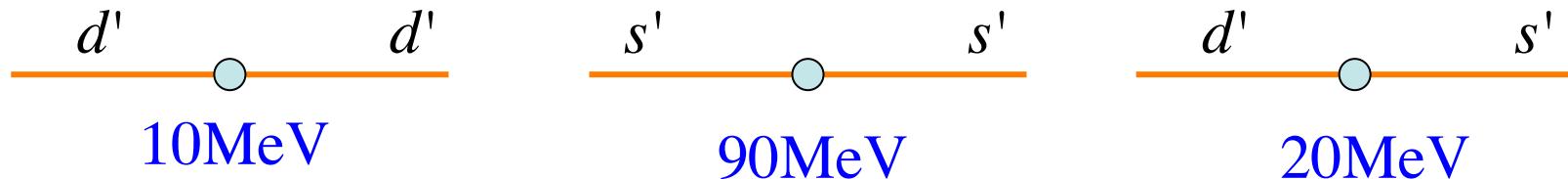


For this case these amplitudes are understood to be caused by the Higgs potential.

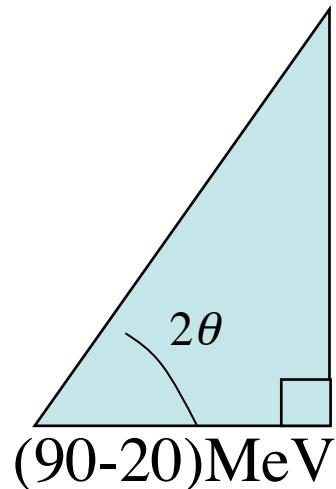
## Quark oscillation

Quarks are oscillating. You just don't notice it.

Let's take light quarks only for simplicity



as always  $d' \leftrightarrow s'$  oscillation takes place.



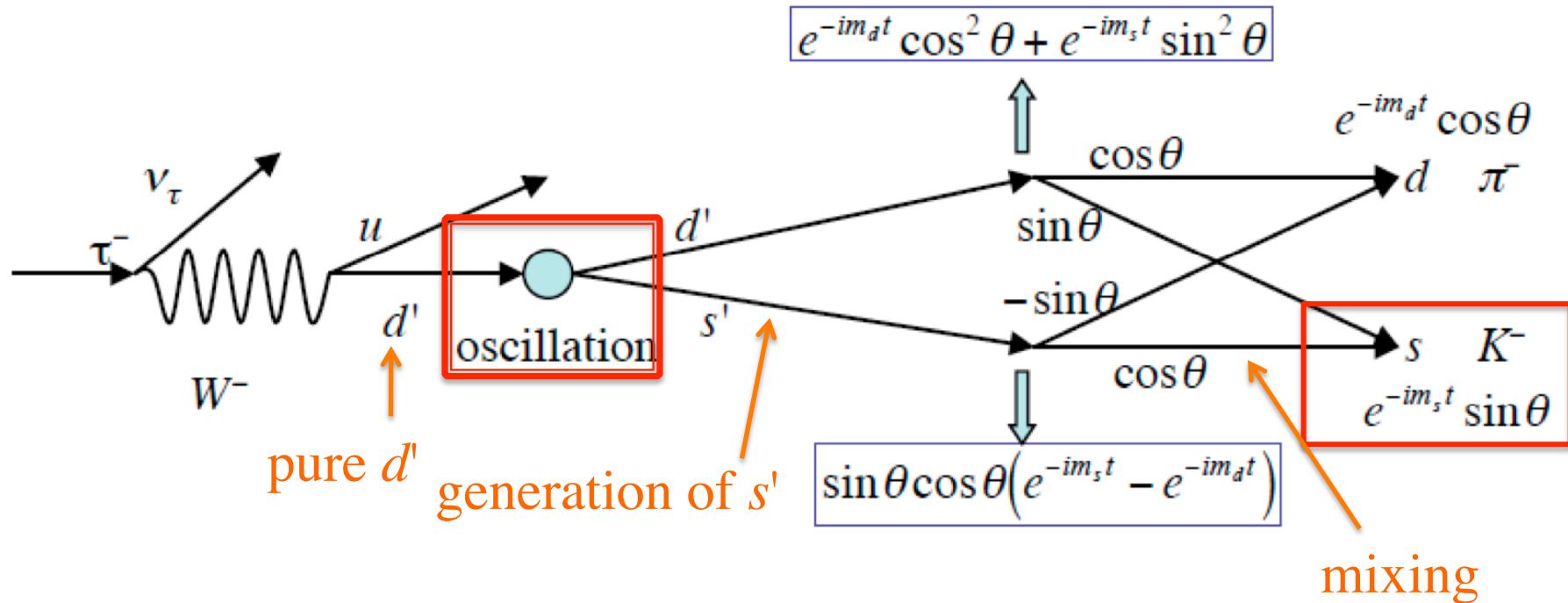
$$\begin{cases} \tan 2\theta = \frac{40 \text{ MeV}}{80 \text{ MeV}} = 0.5 \Rightarrow \theta = 13^\circ \\ m_d = 5 \text{ MeV}, \quad m_s = 95 \text{ MeV} \end{cases}$$

$$\frac{1}{\omega} = \frac{1}{\Delta m} = \frac{1}{45 \text{ MeV}} \sim 10^{-23} \text{ s}$$

Too quick to observe. You can only see the averaged results.  
This is essential difference from  $\nu$ -oscillations.

## Quark oscillation: an example

How  $\tau^- \rightarrow K^- + \nu$  decay takes place from this view.



$$\frac{\Gamma(\tau \rightarrow K\nu)}{\Gamma(\tau \rightarrow \pi\nu)} = \tan^2 \theta \sim 0.05$$

We call this  $\theta$  as Cabibbo angle;  $\theta_C$ .

This is the physics behind the Cabibbo angle.

# Near Future & Beyond

**4 still  
unknowns**

- (1)  $\sin^2 2\theta_{13}$
- (2) Mass Hierarchy ( $m_3 > m_1$  or  $m_1 > m_3$ ?)
- (3)  $\theta_{23}$  degeneracy ( $\theta_{23} > \pi/2$  or  $\theta_{23} < \pi/2$ ?)
- (4) CP violating  $\delta$

**Available  
information**

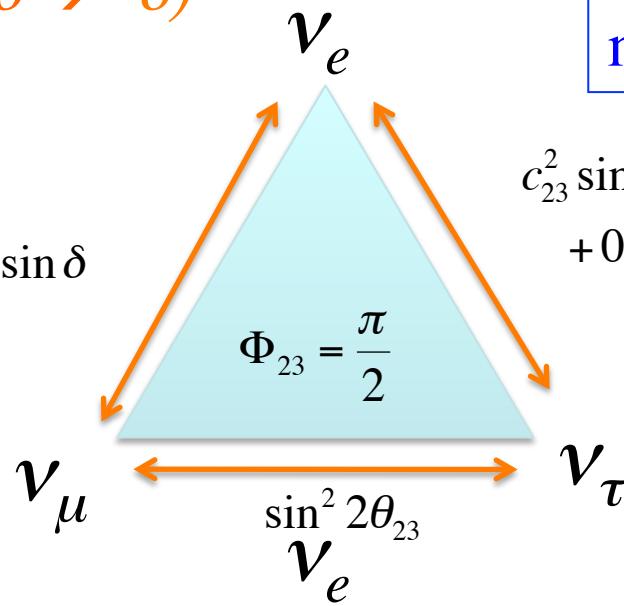
- (1)  $\nu_\mu \Rightarrow \nu_e$  (accelerator)
- (2)  $\bar{\nu}_\mu \Rightarrow \bar{\nu}_e$  (accelerator)
- (3) Matter effect (accelerator)
- (4)  $\nu_\mu \Rightarrow \nu_\mu$  (accelerator)
- (5)  $\bar{\nu}_e \Rightarrow \bar{\nu}_e$  (reactor)
- (6) Solar, Atmospheric

## Complete set of neutrino oscillation formulas (For anti neutrinos $\delta \rightarrow -\delta$ )

You can calculate any oscillations @ oscillation maximums by this set.

$$s_{23}^2 \sin^2 2\theta_{13}$$

$$- 0.05 \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{31} \sin \delta$$

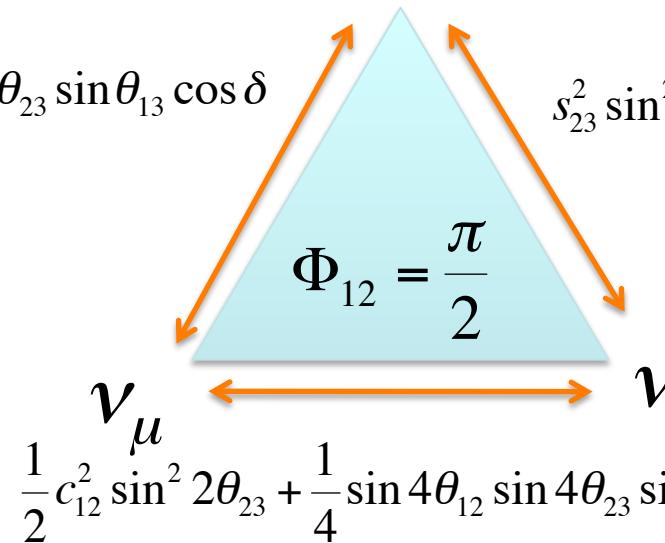


$$c_{23}^2 \sin^2 2\theta_{13}$$

$$+ 0.05 \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{31} \sin \delta$$

$$c_{23}^2 \sin^2 2\theta_{12} + \frac{1}{2} \sin 4\theta_{12} \sin 2\theta_{23} \sin \theta_{13} \cos \delta$$

$$s_{23}^2 \sin^2 2\theta_{12} - \frac{1}{2} \sin 4\theta_{12} \sin 2\theta_{23} \sin \theta_{13} \cos \delta$$



$$\frac{1}{2} c_{12}^2 \sin^2 2\theta_{23} + \frac{1}{4} \sin 4\theta_{12} \sin 4\theta_{23} \sin \theta_{13} \cos \delta$$

$$\theta_{13}$$

## Importance of $\theta_{13}$ measurement

Future ν experiments strongly depends on  $\theta_{13}$

→ Precise measurement of  $\theta_{13}$  is very important.

<b>Parameter</b>	<b>Measurement Method</b>
$\delta_{CP}$	$\left[ P_A(\nu_\mu \rightarrow \nu_e) - P_A(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \right]_{@\Delta_{23}} \sim 0.1 \sin 2\theta_{13} \sin \delta$
$\theta_{23}$ degeneracy	$\left[ P_A(\nu_\mu \rightarrow \nu_e) + P_A(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \right]_{@\Delta_{23}} \sim 2 \sin^2 \theta_{23} \sin^2 2\theta_{13}$
Mass Hierarchy	$\left[ P_A(\nu_\mu \rightarrow \nu_e; L) + P_A(\nu_\mu \rightarrow \nu_e; L') \right]_{@\Delta_{23}} \sim \text{sgn}(\Delta m_{23}^2) (L' - L) \sin^2 2\theta_{13}$ $P_R(\bar{\nu}_e \rightarrow \bar{\nu}_e)_{@\Delta_{12}} \sim 1 - 0.5 \sin^2 2\theta_{13} (\sin^2 \Delta_{31} + \tan^2 \theta_{12} \sin^2 \Delta_{32})$

# Reactor & Accelerator $\theta_{13}$ measurement

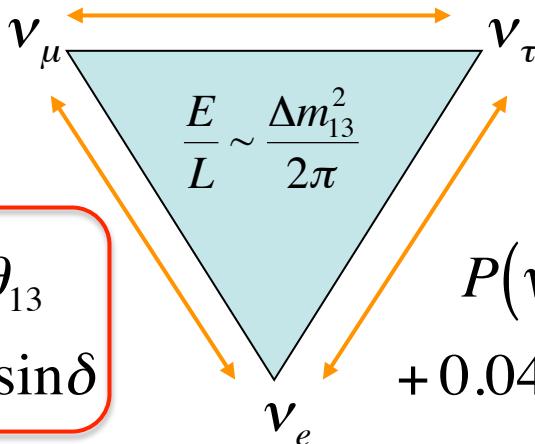
$$@ \frac{\Delta m_{13}^2 L}{4E} \sim \frac{\pi}{2} \left\{ \begin{array}{l} E \sim \text{MeV}, L \sim 1\text{km} \\ E \sim \text{GeV}, L = 100 \sim 1000\text{km}; \text{ Accelerator experiments} \end{array} \right.$$

Reactor Experiments

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} - 0.045 \cdot \sin 2\theta_{13} \sin \delta$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^2 \theta_{23} \sin^2 2\theta_{13} + 0.045 \cdot \sin 2\theta_{13} \sin \delta$$

Accelerator  
Measurements  
T2K, NOvA



$$\underline{P_{\nu_e \leftrightarrow \nu_\mu} + P_{\nu_e \leftrightarrow \nu_\tau} = \sin^2 2\theta_{13}}$$

Reactor measurements  
DoubleChooz, RENO, Dayabay



H.A.Tanaka (2011LP conference)

Super Kamiokande  
“far” detector (FD)



J-PARC



~500 collaborators from  
58 institutions, 12 nations

Intense ~600 MeV  $\nu_\mu$  beam for  
neutrino oscillation studies

- High sensitivity search for  $\theta_{13}$
- Precision measurement of  $\theta_{23}$ ,  $\Delta m^2_{23}$

see “T2K Experiment”  
arXiv:1106.1238 submitted to NIM A



The XXV<sup>th</sup> International Symposium on Lepton Photon Interactions at High Energies

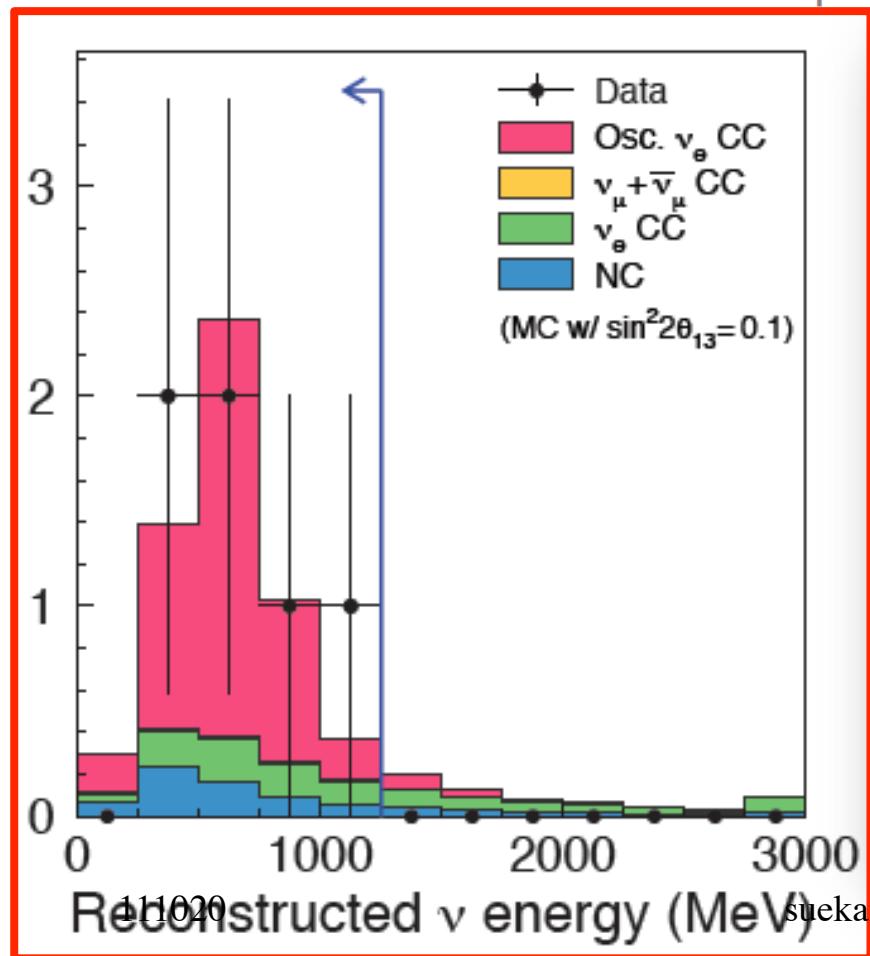
39

2

# T2K Indication of $\nu_\mu \rightarrow \nu_e$ appearance

Signals : Single-electron events by osc.  $\nu_e$  CCQE

2011.7



6  $\nu_\mu \rightarrow \nu_e$  appearance were observed.  
BKG=1.5 ± 0.3 events.

$\delta=0, \theta_{23}=\pi/4$   
For Normal Hierarchy  
 $\sin^2 2\theta_{13}=0.11$ (best fit),  
 $=0.03-0.28$ (90%CL)

For Inverted Hierarchy  
 $\sin^2 2\theta_{13}=0.14$ (best fit),  
 $=0.04-0.34$ (90%CL)

## An issue of accelerator $\theta_{13}$ measurement; $\theta_{23}$ degeneracy

$$P(\nu_\mu \rightarrow \nu_e) = \underline{\sin^2 \theta_{23}} \sin^2 2\theta_{13} - 0.045 \cdot \sin 2\theta_{13} \sin \delta$$

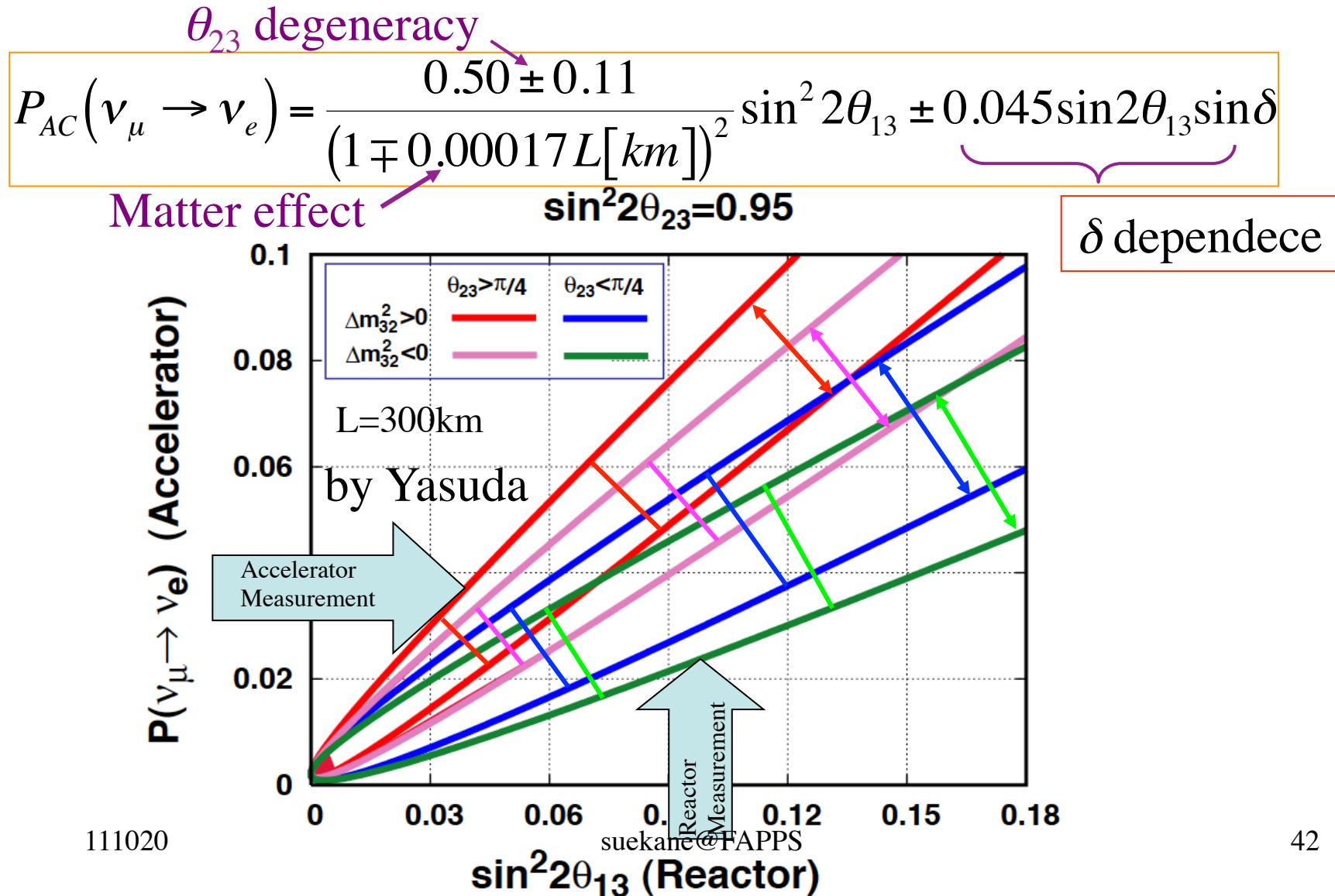
$\sin^2 2\theta_{23}$  is measured by  $\nu_\mu \rightarrow \nu_\mu$  disappearance by accelerator, but there are 2 possibilities of  $\sin^2 \theta_{23}$  if  $\sin^2 2\theta_{23}$  is not 1 or 0.

$$\sin^2 \theta_{23} = \frac{1 \pm \sqrt{1 - \sin^2 2\theta_{23}}}{2}$$

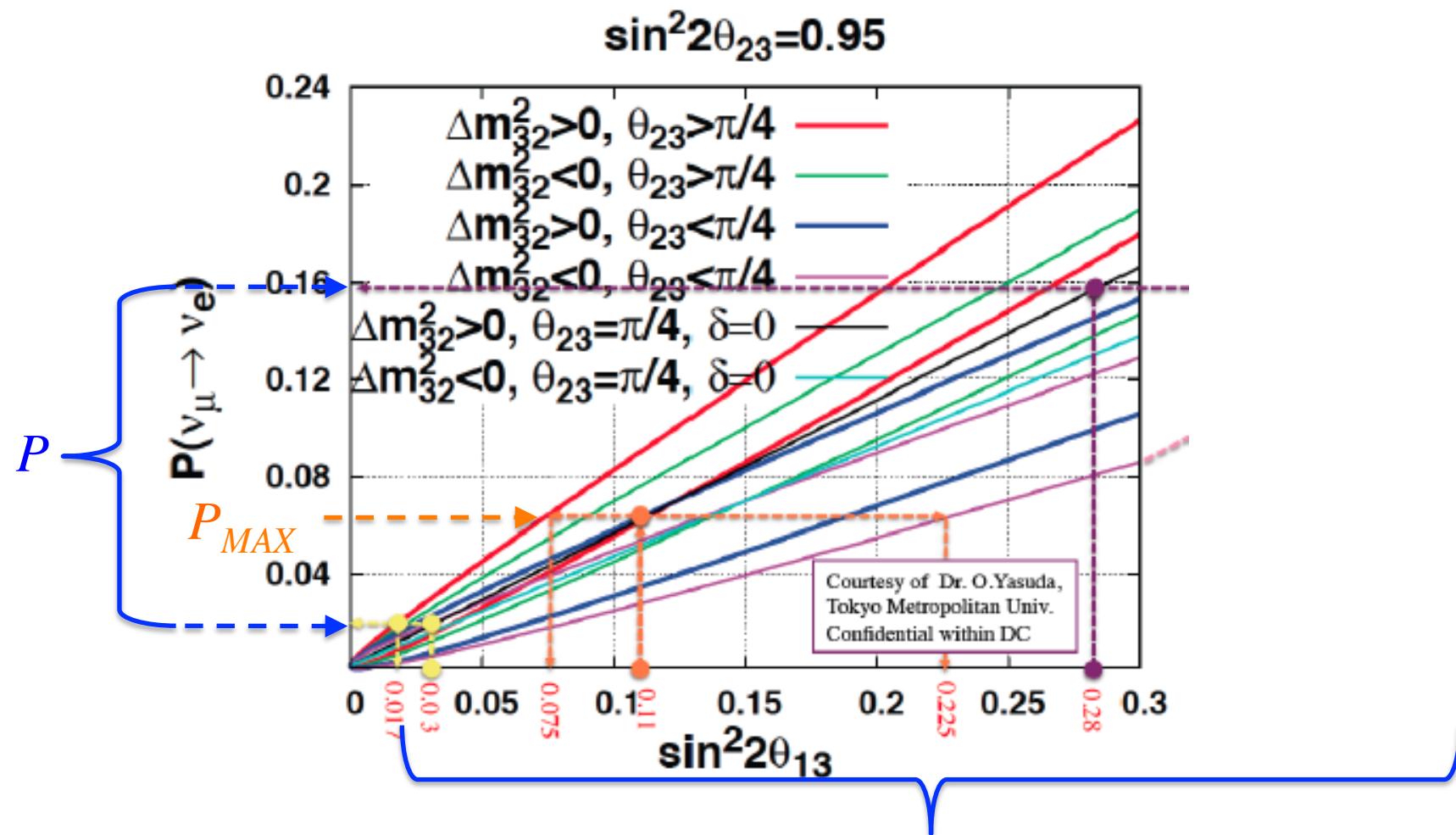
For example, for  $\sin^2 2\theta_{23} > 0.95 \rightarrow 0.49 < \sin^2 \theta_{23} < 0.61$ .

This is called  $\theta_{23}$  degeneracy and it will become problematic when measuring the mass hierarchy by accelerator experiments.

# Complementarity of Reactor-Accelerator $\theta_{13}$ measurement

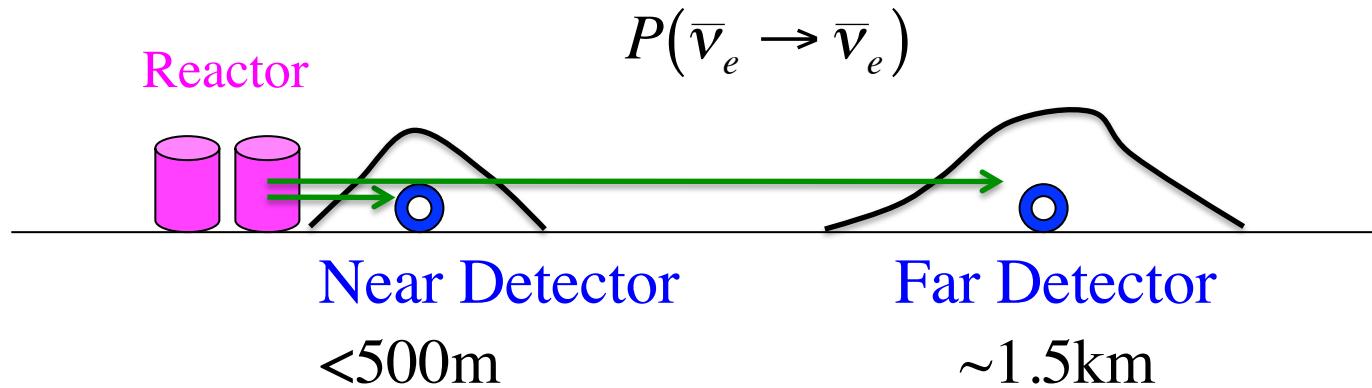


## Recent T2K indication



T2K result ( $0.03 < \sin^2 2\theta_{13} < 0.28$ ) is obtained by fixing  $\delta=0$  and  $\theta_{23}=\pi/4$ .  
 If all parameters are set free, it corresponds to  $0.017 < \sin^2 2\theta_{13} < \sim 0.5$

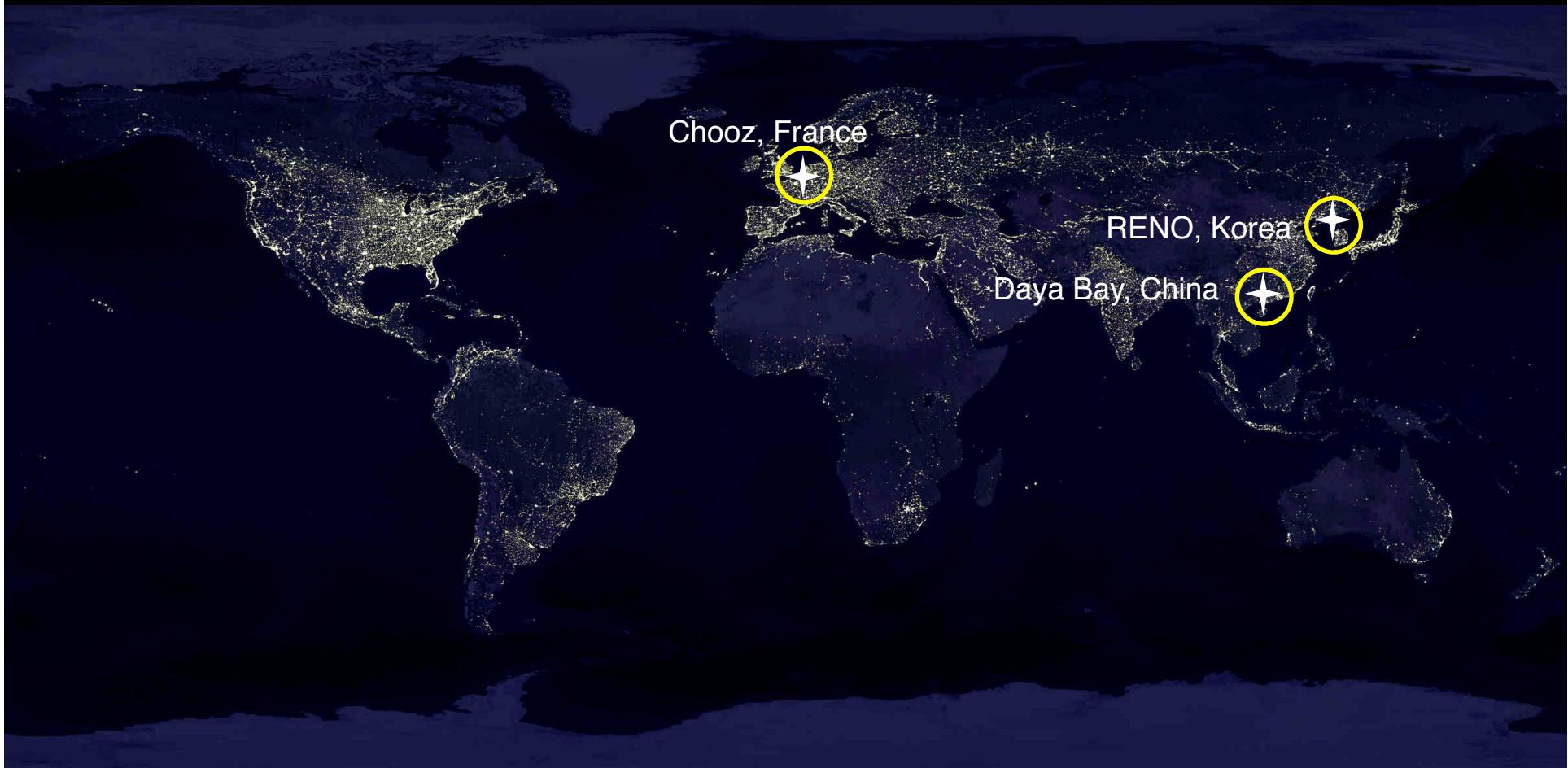
# Reactor- $\theta_{13}$



Cancel uncertainty of neutrino flux and detection efficiency by comparing near & far detector

Sensitivity(1st generation)  $\sin^2 2\theta_{13} = 0.01 \sim 0.03$

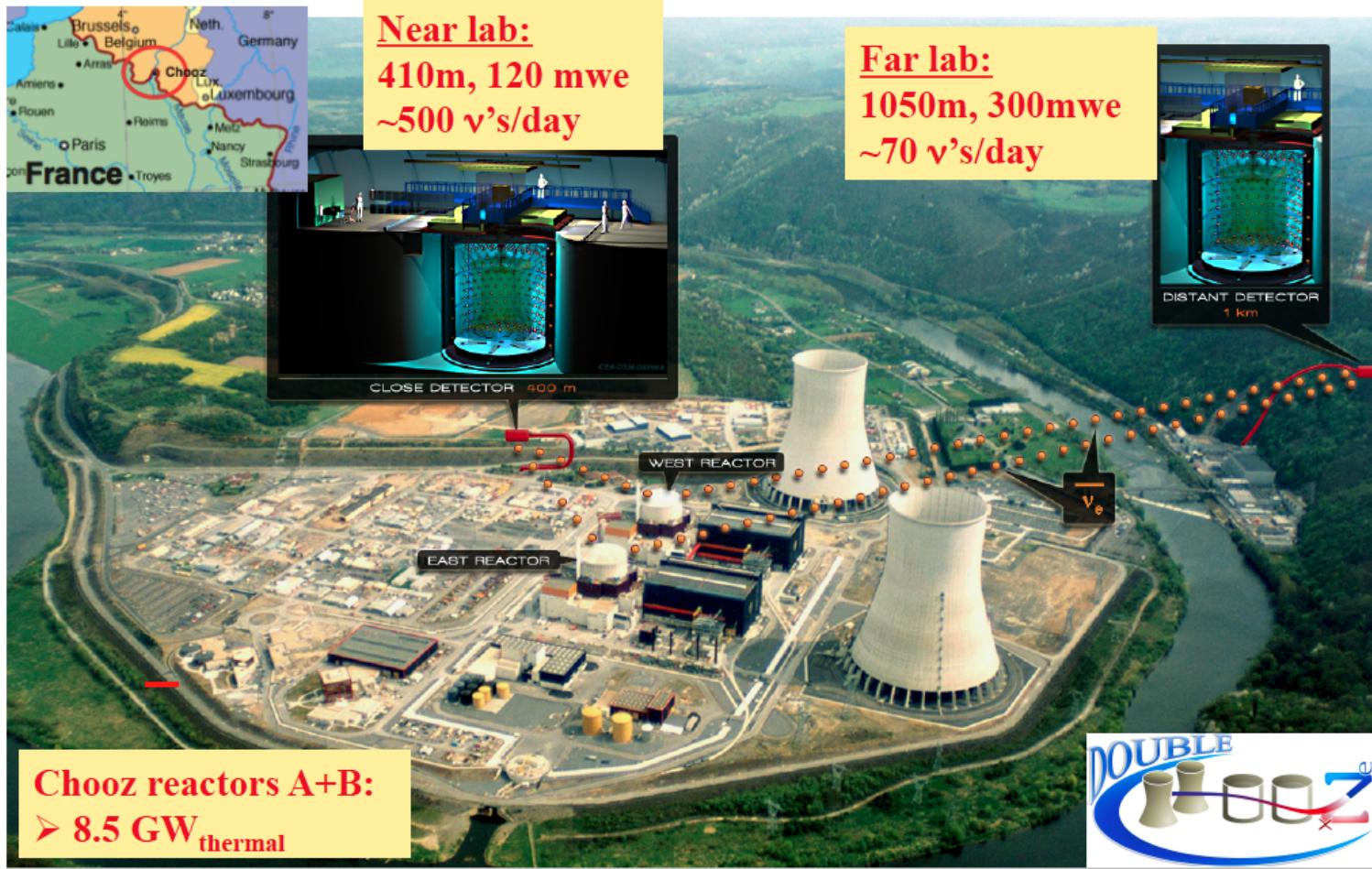
# Reactor $\theta_{13}$ Neutrino Experiments



data taking started

# Double Chooz

Thanks to T. Lasserre; see also talks  
@parallel by P. Pfahler





# Daya Bay

Thanks to Y. Wang; see also talks  
@parallel by K. Heeger and Z. Wang



- Near-far relative meas. to cancel correlated syst. errors: 2 near + 1 far
- Multiple neutrino detector modules at each site → cross check and reduce un-correlated syst. errors
  - Gd-loaded liquid scintillator
  - Stainless steel tank+ 2 nested acrylic vessel + reflectors
- Multiple muon-veto to reduce bkgd-related syst. errors
  - 4-layer RPC +2-layer water Cerenkov

## Civil construction

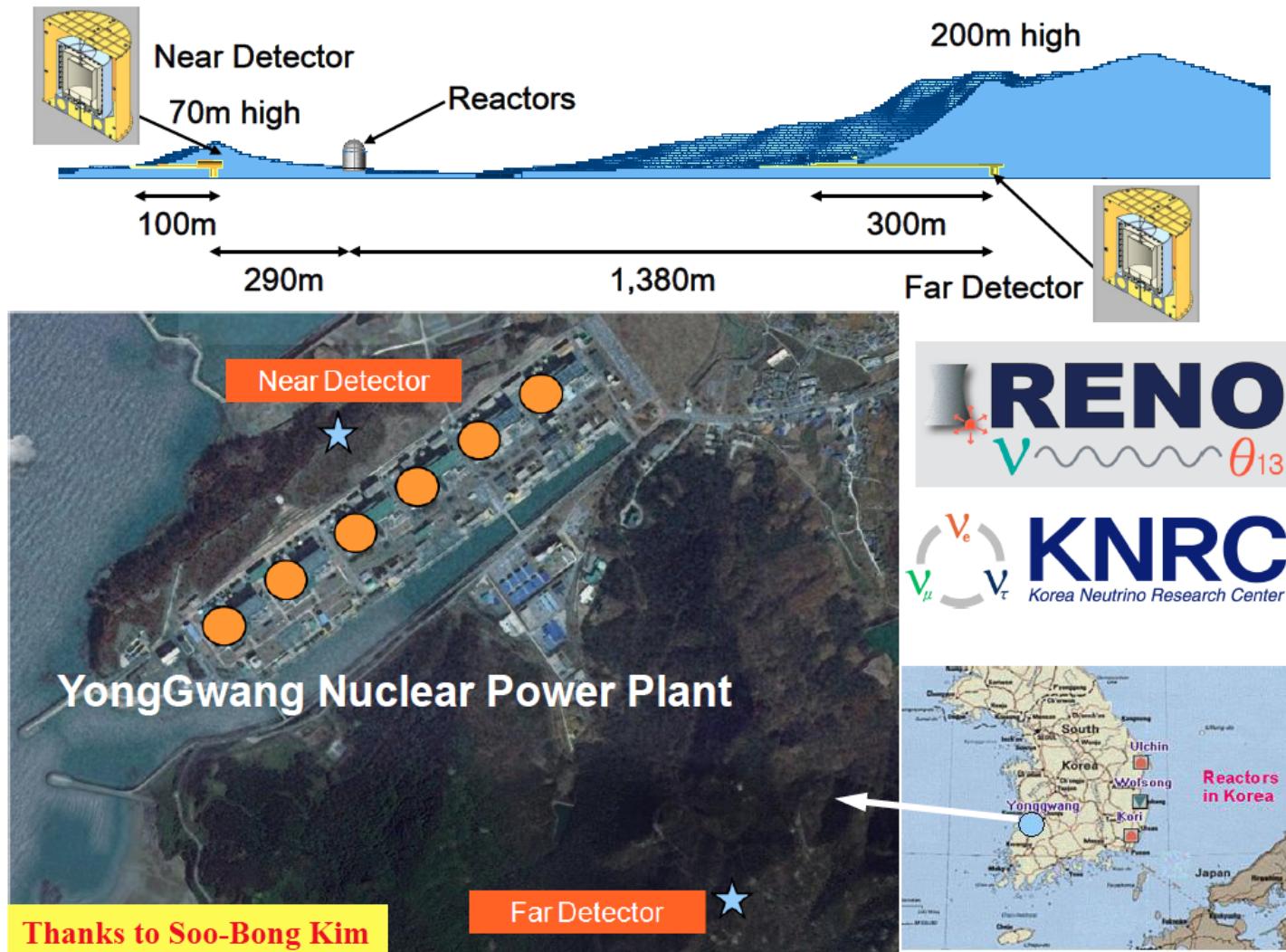
- Tunnel length: ~ 3100m
- Three experimental halls
- One assembly hall
- Water purification hall



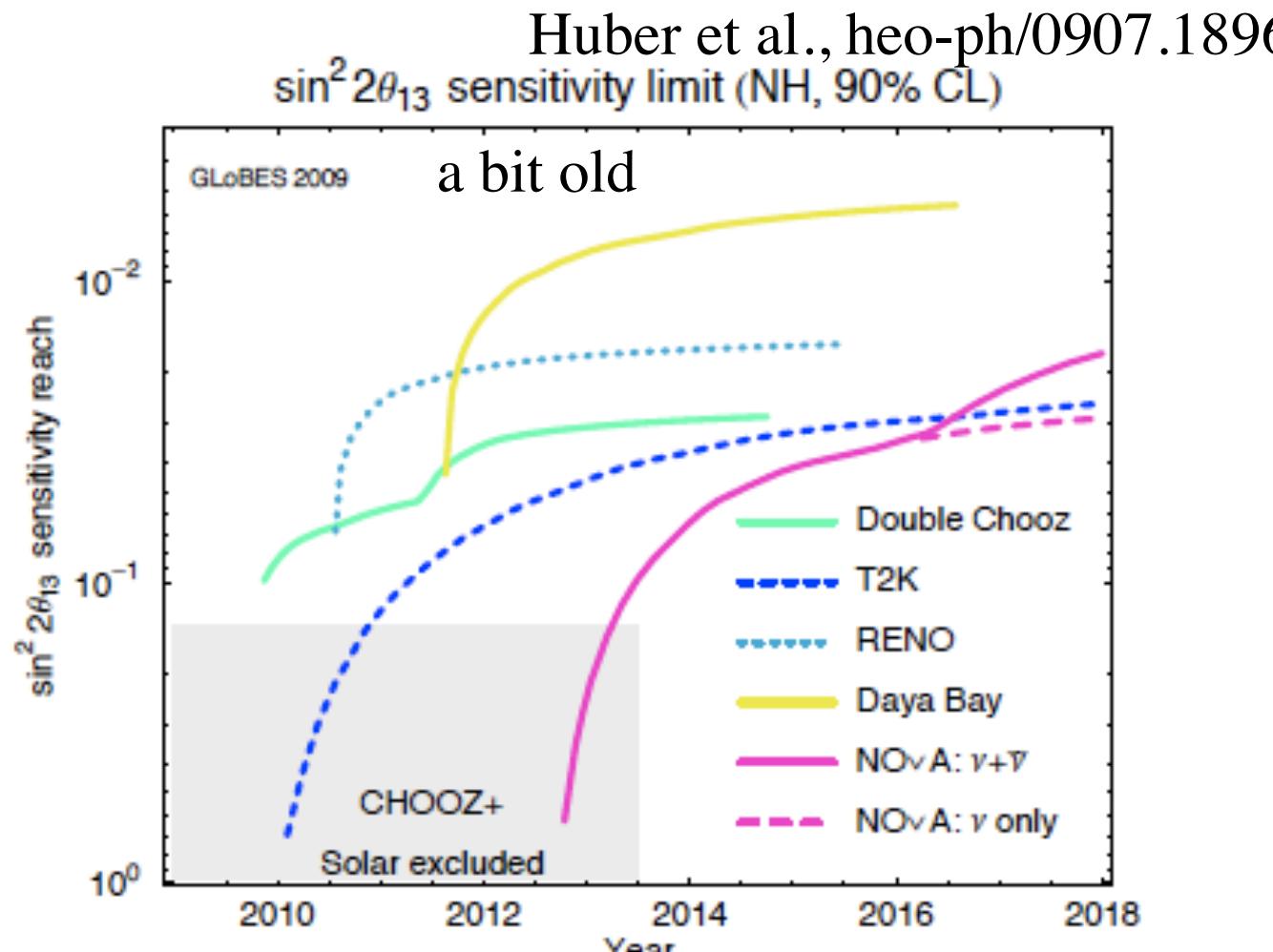
M. Lindner, MPIK

TAUP 2011

12



# An exciting time is just around the corner ....



Results: within a few years

# CPV- $\delta$

$\delta$

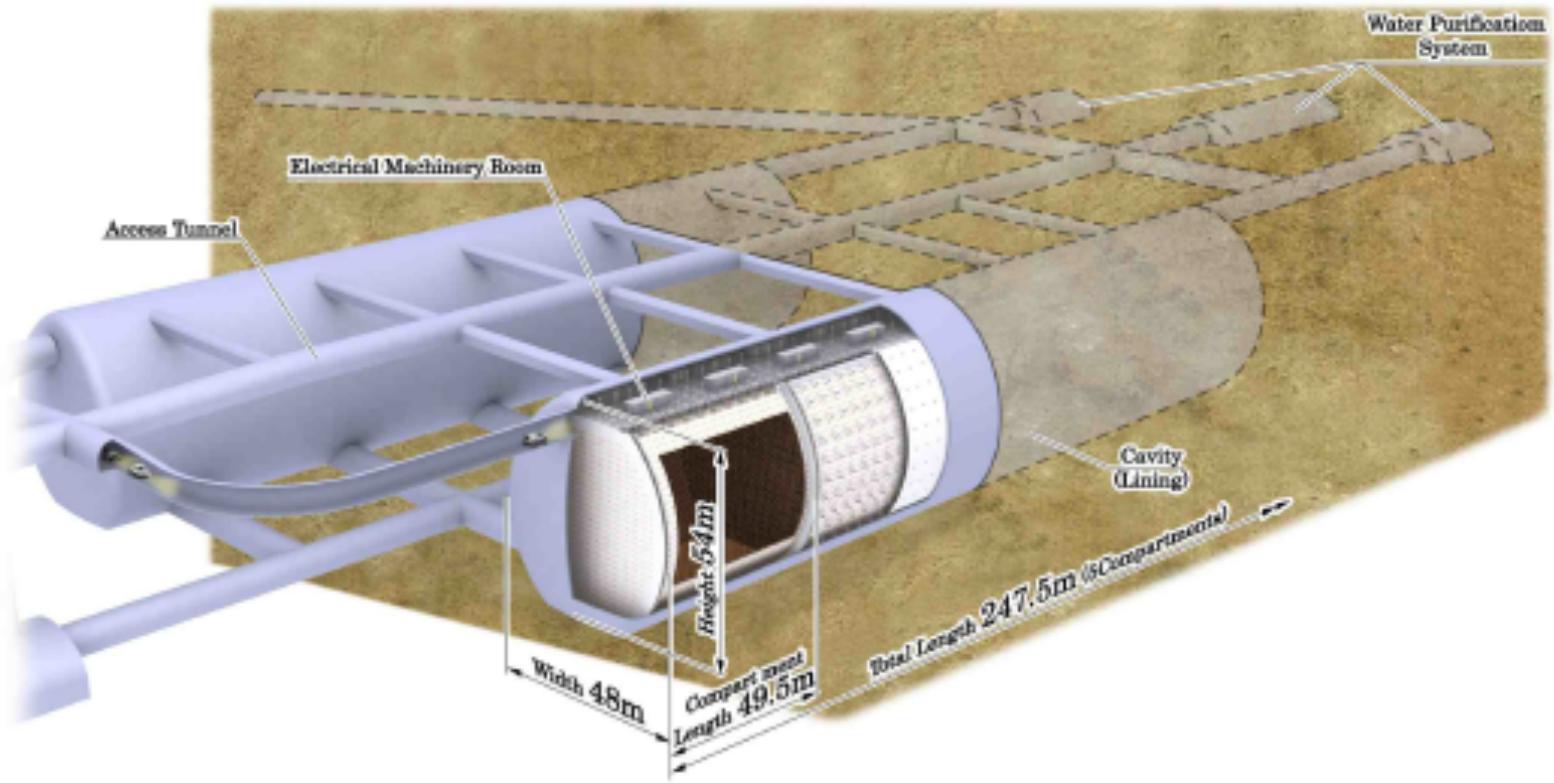
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} - 0.45 \sin 2\theta_{13} \sin \delta$$

Change sign

$$\bar{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} + 0.45 \sin 2\theta_{13} \sin \delta$$

$$A = \frac{P - \bar{P}}{P + \bar{P}} = \frac{0.045}{\sin^2 \theta_{23} \sin 2\theta_{13}} \sin \delta$$

$\bar{P}$  needs 3x more luminosity to obtain same statistics as  $P$ , since cross section of  $\bar{\nu} + A$  is smaller than  $\nu + A$  and  $\bar{\nu}$  is produced fewer than  $\nu$ .



**FIG. 1.** Schematic view of the Hyper-Kamiokande detector.

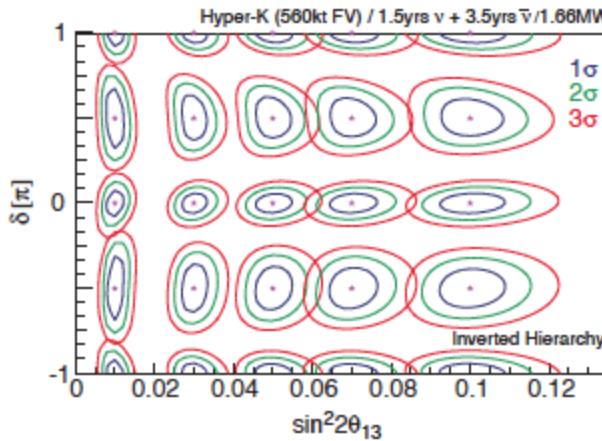


FIG. 22. Allowed regions for inverted hierarchy. See caption of Fig. 21

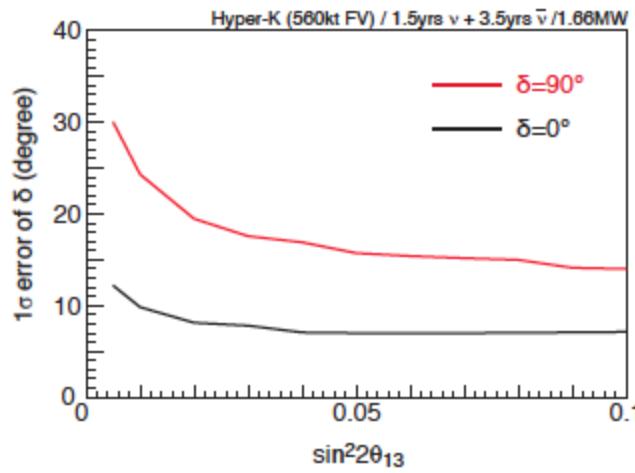


FIG. 23.  $1\sigma$  error of  $\delta$  as a function of  $\sin^2 2\theta_{13}$  for the normal hierarchy case.

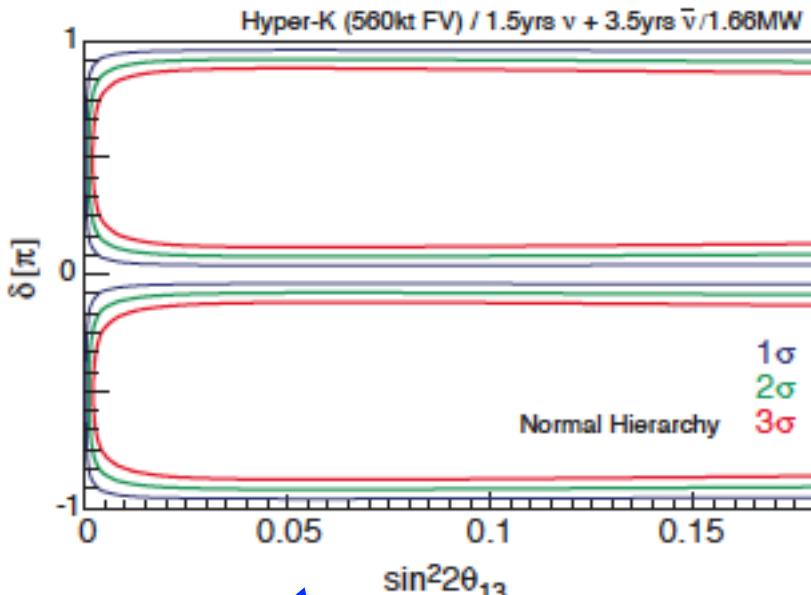


FIG. 24. Sensitivity to CP violation. Blue, green, and red lines correspond to 1, 2, and 3  $\sigma$  exclusion of  $\sin \delta = 0$ , respectively.

# *Mass Hierarchy*

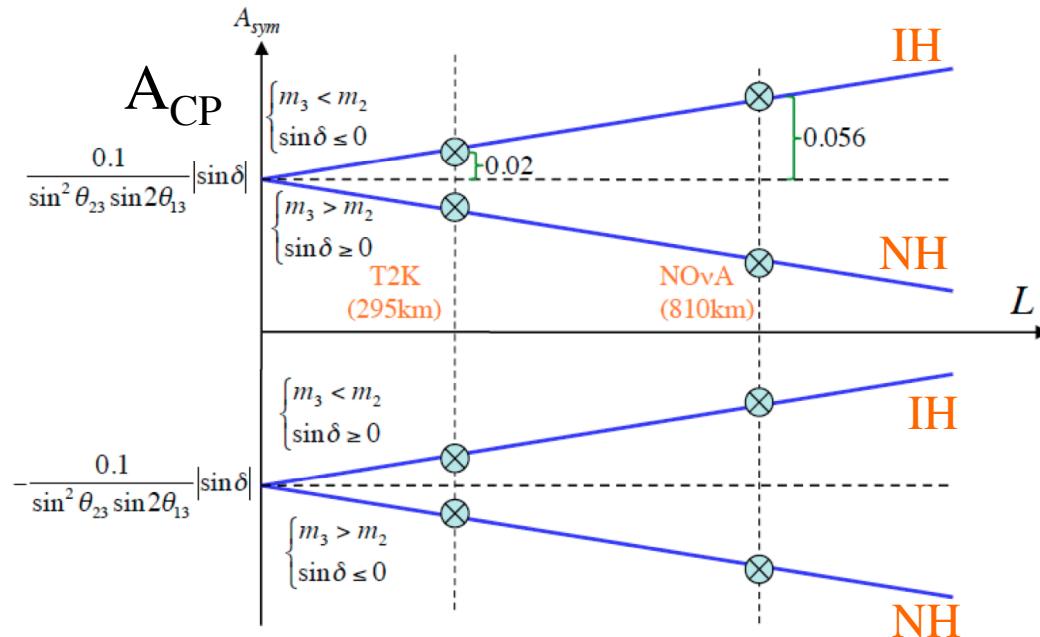
$(m_3 > m_1 \text{ or } m_1 > m_3?)$

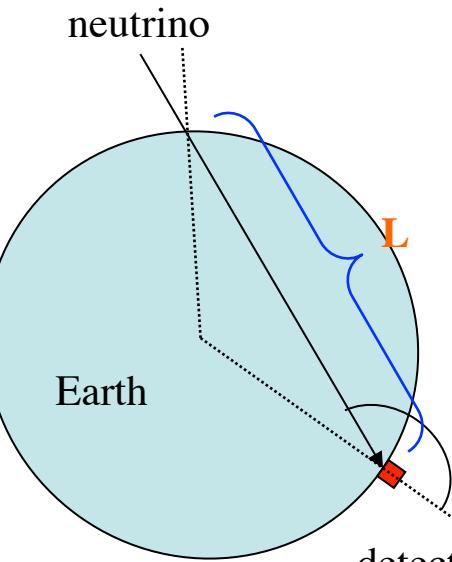
With High energy  $\nu_\mu$ ,

$$P_{AC}(\nu_\mu \rightarrow \nu_e) = \frac{\sin^2 \theta_{23} \sin^2 2\theta_{13}}{(1 \mp 0.00017L[km])^2} \pm 0.045 \sin 2\theta_{13} \sin \delta$$

↑ **Matter effect**

Mass Hierarchy (like solar neutrino case)  
 L dependence → Mass Hierarchy





## Cosmic-ray measurement at HK

$\theta$  dependence =  $L$  dependence

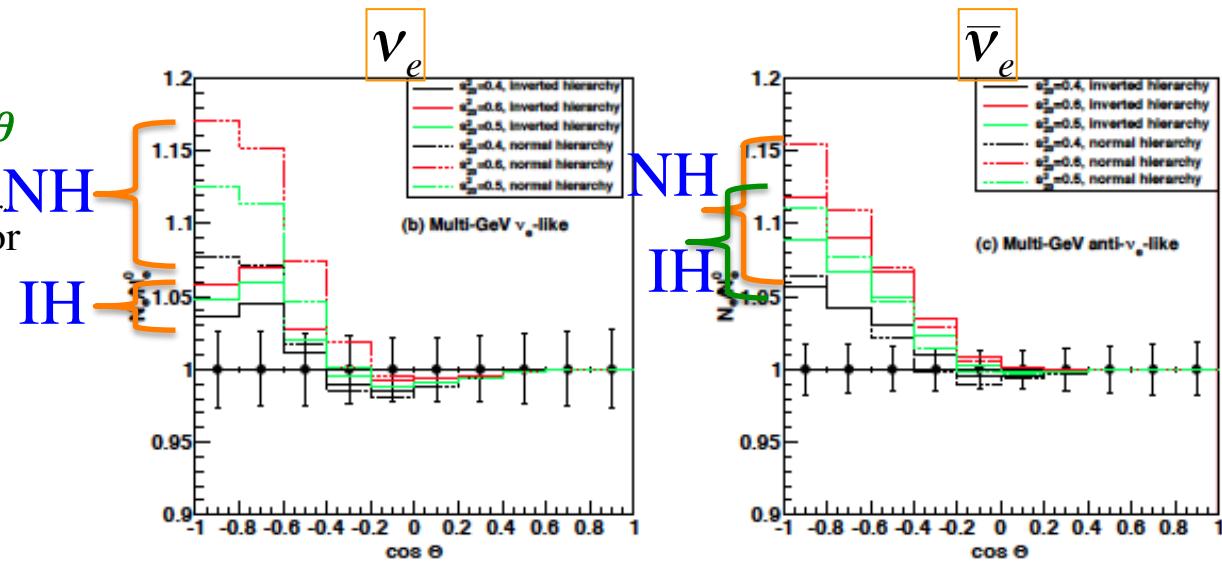


FIG. 35. Expected event rate changes in (a) sub-GeV single-ring  $e$ -like, (b) multi-GeV  $\nu_e$ -like, and (c) multi-GeV  $\bar{\nu}_e$ -like event samples. The vertical axis shows the ratio of oscillated  $e$ -like event rate to the non-oscillated one. Mass hierarchy is normal for dashed lines and inverted for solid lines. Colors show  $\sin^2 \theta_{23}$  values as 0.4 (black), 0.5 (green), and 0.6 (red). Points with error bars represent null oscillation expectations with expected statistical errors for 5.6 Megaton-years exposure or 10 years of Hyper-K.

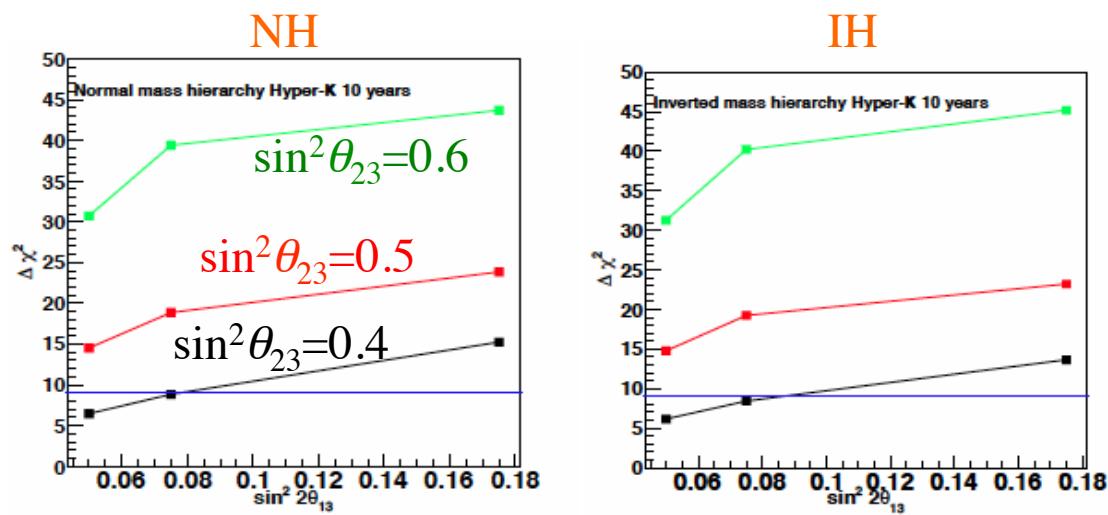
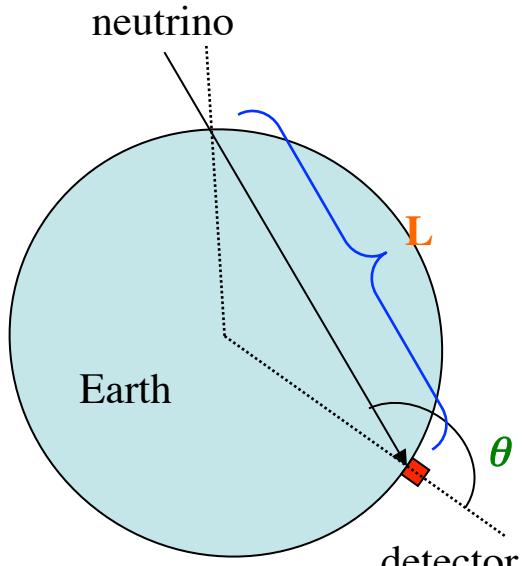
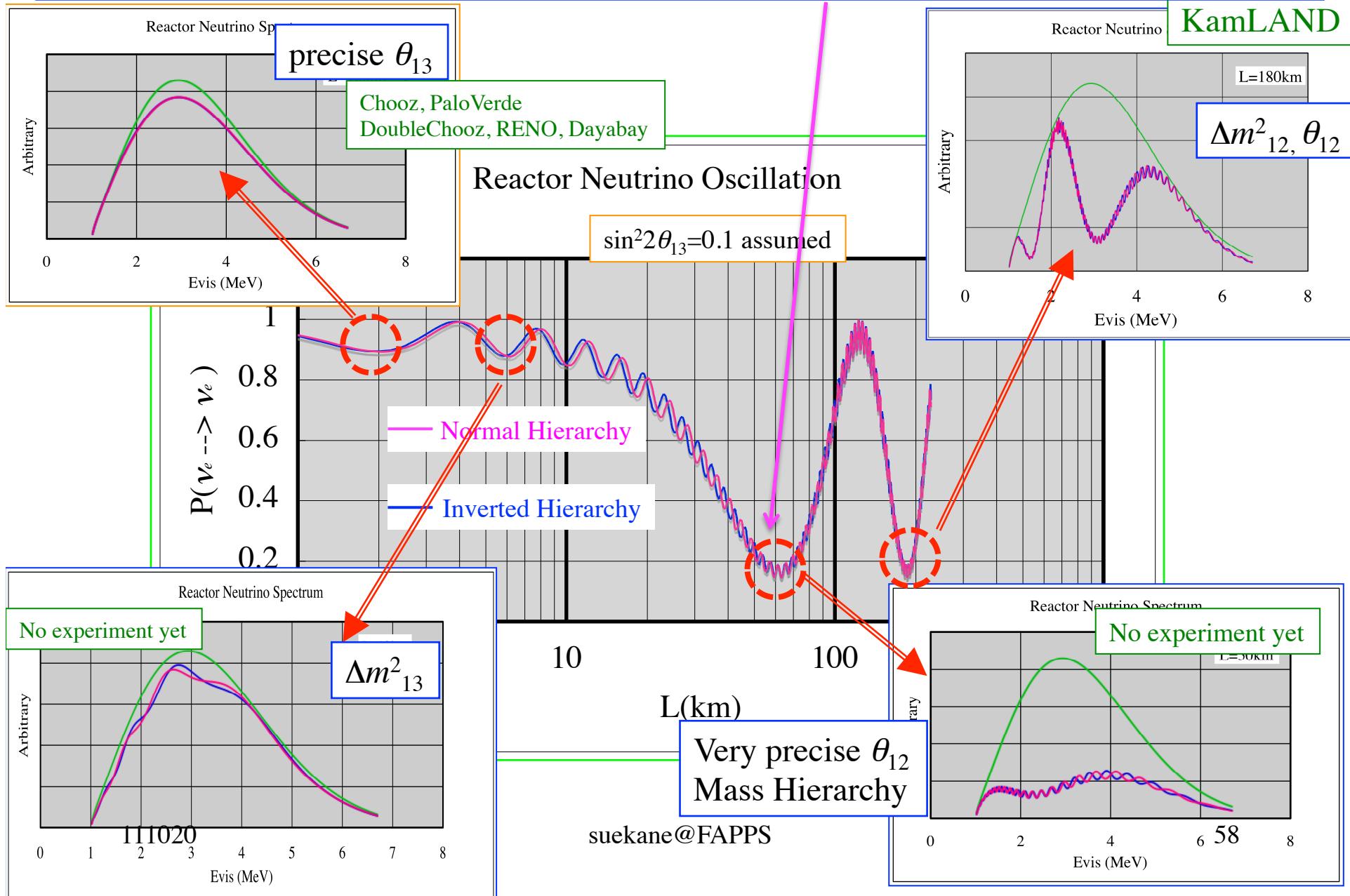


FIG. 38. Expected significance for the mass hierarchy determination. In the left panel, normal mass hierarchy is the case and  $\chi^2$  for the wrong assumption;  $\Delta\chi^2 \equiv \chi^2_{\min}(\text{inverted}) - \chi^2_{\min}(\text{normal})$  is shown for various true values of  $\sin^2 2\theta_{13}$ . The right panel is for the inverted hierarchy case. Each colors show the case of  $\sin^2 \theta_{23} = 0.4$  (black), 0.5 (red), and 0.6 (green), and the blue horizontal lines show  $3\sigma$  ( $\Delta\chi^2 = 9.2$ ).

Sensitivity very much depend on  $\theta_{23}$  degeneracy

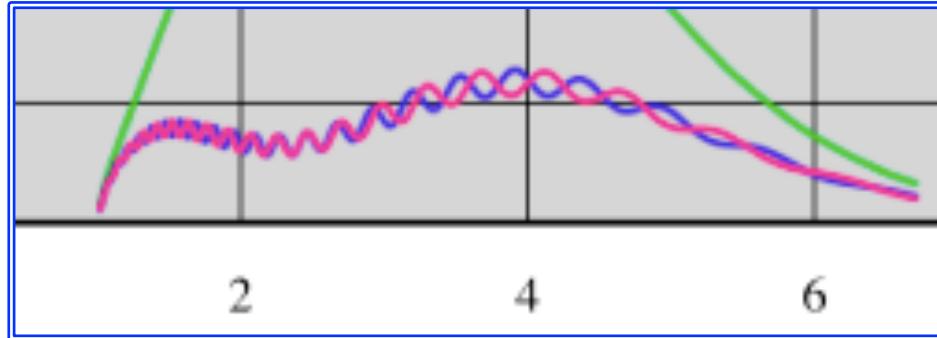
# Mass Hierarchy Determination by Reactor



# Mass Hierarchy by Reactor 50km

## Principle

Petcov et al., Phys. Lett. B 533, 94 (2002)  
 S.Choubey et al., Phys. Rev. D 68,113006 (2003)  
 J. Learned et al., hep-ex/062022  
 L.Zhan et al., hep-ex/0807.3203  
 M.Batygov et al., hep-ex/0810.2508

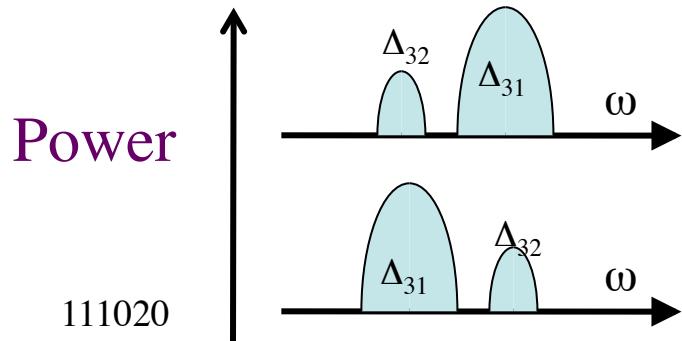


$$\text{Ripple} \propto \sin^2 2\theta_{13} (\sin^2 \Delta_{31} + \tan^2 \theta_{12} \sin^2 \Delta_{32})$$

↓  
 It is essential that  $\theta_{12}$  is not maximum ( $\tan^2 \theta_{12} \sim 0.4$ )

Fourier Analysis  $\Rightarrow$  Power Spectrum Peaks at  $\omega = |\Delta m_{31}^2|, |\Delta m_{32}^2|$

The smaller peak is  $|\Delta m_{32}^2|$  and larger peak is  $|\Delta m_{31}^2|$ ,



: Normal Hierarchy

: Inverted Hierarchy

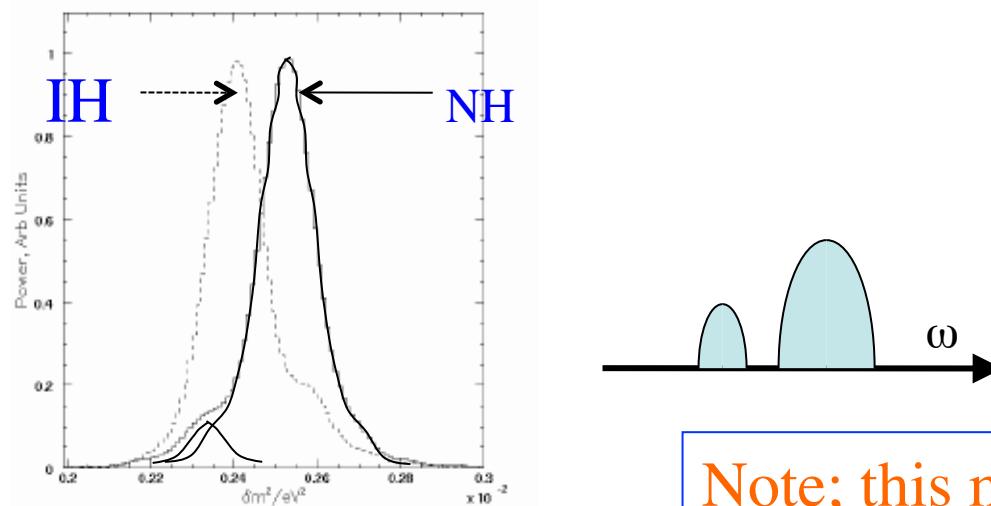


FIG. 3: Neutrino mass hierarchy (normal=solid; inverted=dashed) is determined by the position of the small shoulder on the main peak.

Note; this method does  
not use the matter effect.

## Simulation of power spectrum

If  $\sin^2 2\theta_{13} = 0.05$ , 3kton x24GW x5yr ,

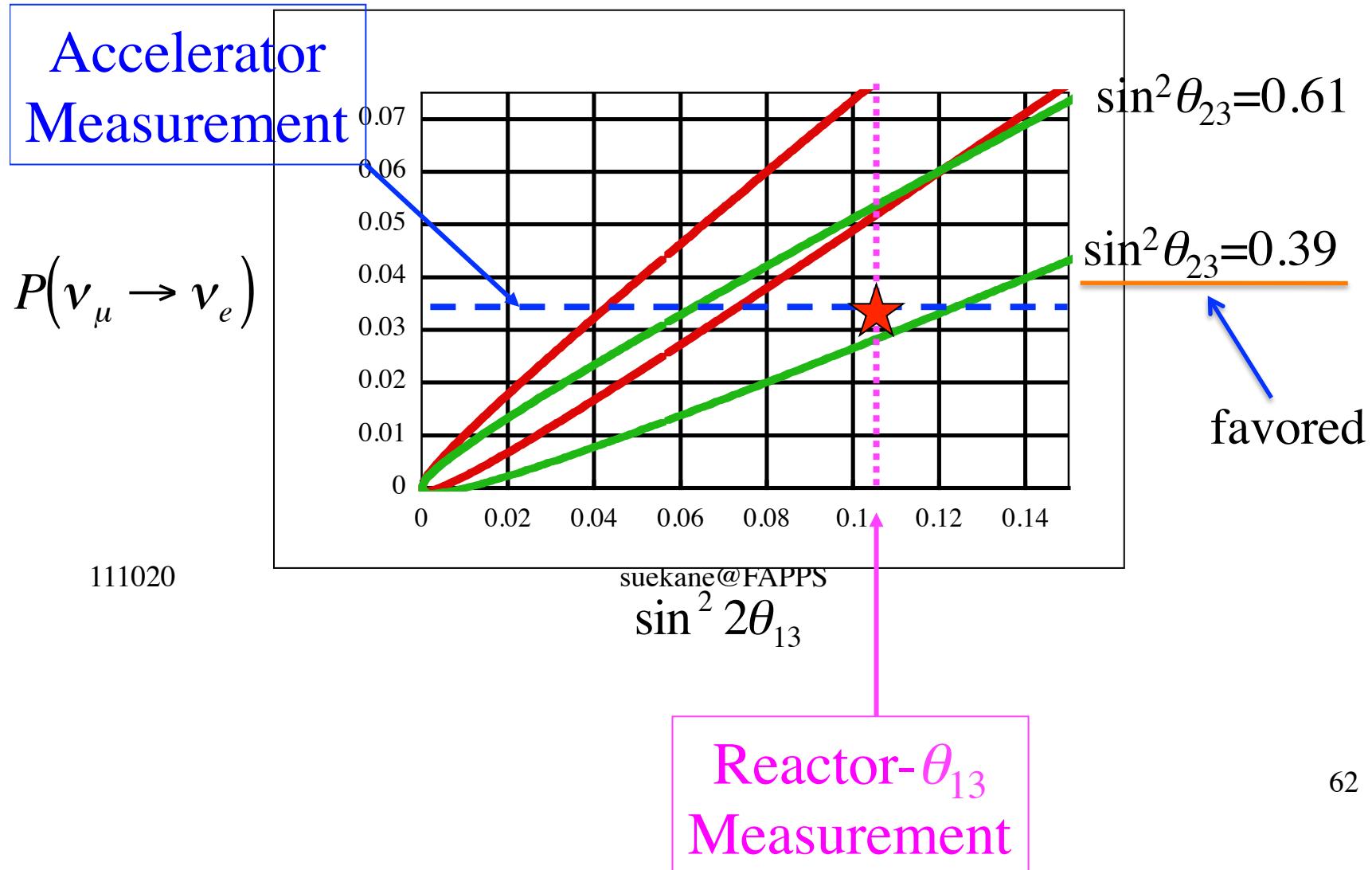
Mass Hierarchy can be determined with  $1\sigma$  significance.

(L.Zhan et al.=> Mass Hierarchy could be determined if  $\sin^2 2\theta_{13} > 0.005$ .)

More studies are necessary to estimate actual sensitivity

# $\theta_{23}$ degeneracy

# Combination Reactor-Accelerator Meas.



# $0\nu2\beta$ decays

(Is  $\nu = \bar{\nu}$ ?)

The quark structure of the  $\pi^0$ -meson (mass eigenstate) is

$$\pi^0 = u\bar{u} + d\bar{d}$$

Anti-particle state of the  $\pi^0$ -meson is,

$$\overline{\pi^0} = \bar{u}u + \bar{d}d$$

Because quark structure is the same,

$$\overline{\pi^0} = \pi^0$$

If superposition of neutrino and antineutrino is mass eigenstate

$$\psi_\nu = \nu + \bar{\nu}$$

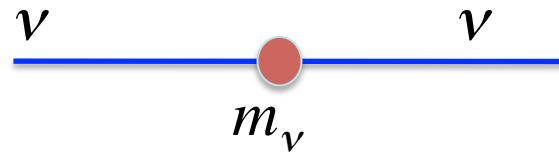
The anti-particle state of  $\psi_\nu$  is,

$$\overline{\psi_\nu} = \bar{\nu} + \nu = \psi_\nu$$

The particle and antiparticle state can be interpreted as same particle.

## Majorana neutrino and neutrino-less double beta decays

Now we know that neutrinos have small but finite masses.



$$\dot{\psi}_\nu = -im_\nu\psi_\nu$$

If this transition amplitude come from Higgs coupling, like quarks and charged leptons, the coupling is unnaturally small compared with other fermion masses

$$\frac{\sqrt{\Delta m_{12}^2}}{m_e} \sim 1.8 \times 10^{-8}$$

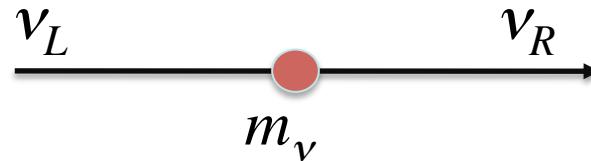
Theorists do not like it.

## Majorana neutrino and neutrino-less double beta decays

Dirac equation can be re-written as

$$\dot{\psi} = -im\gamma_0\psi \Rightarrow \begin{cases} \dot{\psi}_L = -im\gamma_0\psi_R \\ \dot{\psi}_R = -im\gamma_0\psi_L \end{cases}$$

This means there is  $L \Leftrightarrow R$  transition



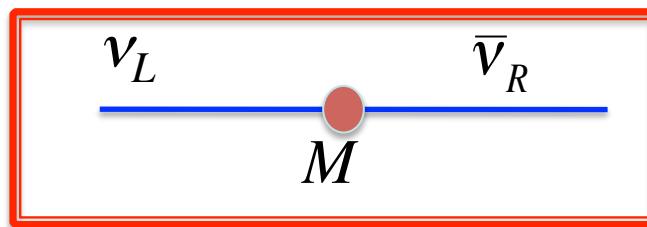
However,  $\nu_R$  does not exist in the standard model.

Theorists do not like it, either.

## Majorana neutrino and neutrino-less double beta decays

In the standard model, only the  $\nu_L$  &  $\bar{\nu}_R$  exist and both perform weak interaction.

If the following transition amplitude exists for some reason,



The equation of motion is

$$\begin{cases} \dot{\nu}_L = -iM\bar{\nu}_R \\ \dot{\bar{\nu}}_R = -iM\nu_L \end{cases}$$

# Majorana neutrino and neutrino-less double beta decays

Dirac equation

$$\begin{cases} \dot{e}_L = -im\gamma_0 e_R \\ \dot{e}_R = -im\gamma_0 e_L \end{cases}$$

Majorana equation

$$\begin{cases} \dot{\nu}_L = -iM\gamma_0 \bar{\nu}_R \\ \dot{\bar{\nu}}_R = -iM\gamma_0 \nu_L \end{cases}$$

We know this

Then the mass eigenstates are,

$$\psi_e = (|e_L\rangle + |e_R\rangle) e^{-im_e t} = |e\rangle e^{-im_e t}$$

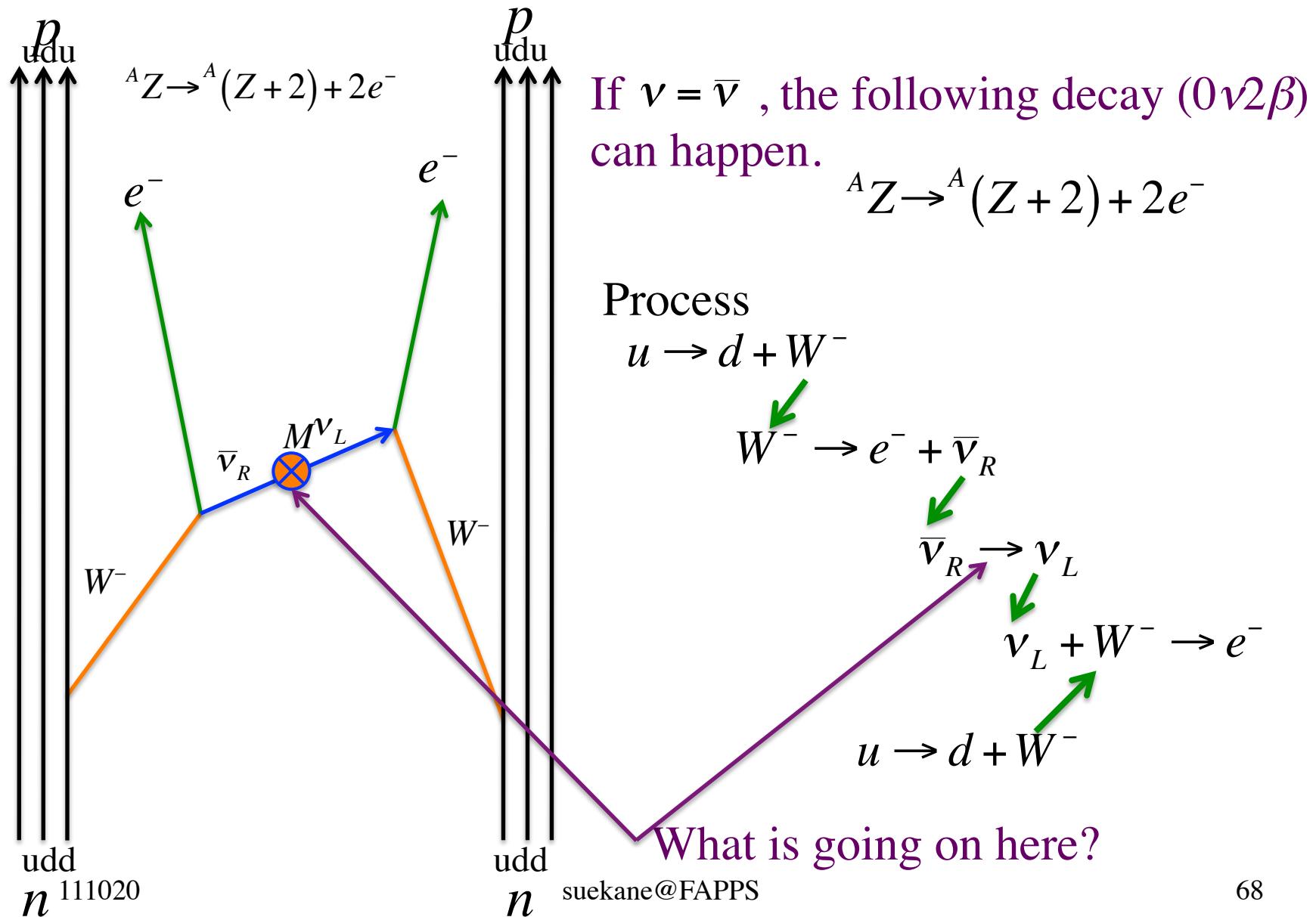
$$\psi_\nu = (|\nu_L\rangle + |\bar{\nu}_R\rangle) e^{-iMt} \equiv |w\rangle e^{-iMt}$$

Analogy from  
Dirac equation

This  $\psi_\nu$  may be our neutrino.

This case does not require  $\nu_R$  and theorists like it.

## Neutrinoless double beta decays to check Majorana or Dirac



# Chirality Oscillation

Majorana Eq.



The transition amplitude changes  $\bar{\nu}_R$  state to  $\nu_L$ , but how much?

Try to think of the case of Dirac equation for analogy



General solution is,

$$\psi(x) = \sqrt{\frac{1+\gamma}{2}} \left[ \begin{pmatrix} \hat{u} \\ \vec{\eta} \cdot \vec{\sigma} \hat{u} \end{pmatrix} e^{i(\vec{p}\vec{x}-Et)} + \begin{pmatrix} -\vec{\eta} \cdot \vec{\sigma} \hat{v} \\ \hat{v} \end{pmatrix} e^{i(\vec{p}\vec{x}+Et)} \right]$$

$$|\hat{u}|^2 + |\hat{v}|^2 = 1 \quad \vec{\eta} \equiv \frac{\vec{p}}{E+m}$$

## Chirality Oscillation

If the state is P.C. at  $x=0$ , the N.C. component of the wave function is 0

$$\gamma_L \psi(0) \propto \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} \hat{u} - \vec{\eta} \cdot \vec{\sigma} \hat{v} \\ \vec{\eta} \cdot \vec{\sigma} \hat{u} + \hat{v} \end{pmatrix} = 0$$

Which is satisfied if there is a relation;

$$\hat{v} = \gamma(1 - \vec{\beta} \cdot \vec{\sigma})\hat{u}$$

And from the normalization condition, there  $\hat{u}$  has to satisfy

$$[\hat{u}^\dagger (1 - \vec{\beta} \cdot \vec{\sigma}) \hat{u}] = \frac{1}{2\gamma^2}$$

## Chirality Oscillation

The wave function at  $x$  is,

$$\psi(x) = \sqrt{\frac{1+\gamma}{2}} \left[ -2i \begin{pmatrix} \hat{u} \\ \vec{\eta} \cdot \vec{\sigma} \hat{u} \end{pmatrix} \sin Et + \gamma (1 - \vec{\eta} \cdot \vec{\sigma}) \begin{pmatrix} \hat{u} \\ \hat{u} \end{pmatrix} e^{iEt} \right] e^{i\vec{p}\vec{x}}$$

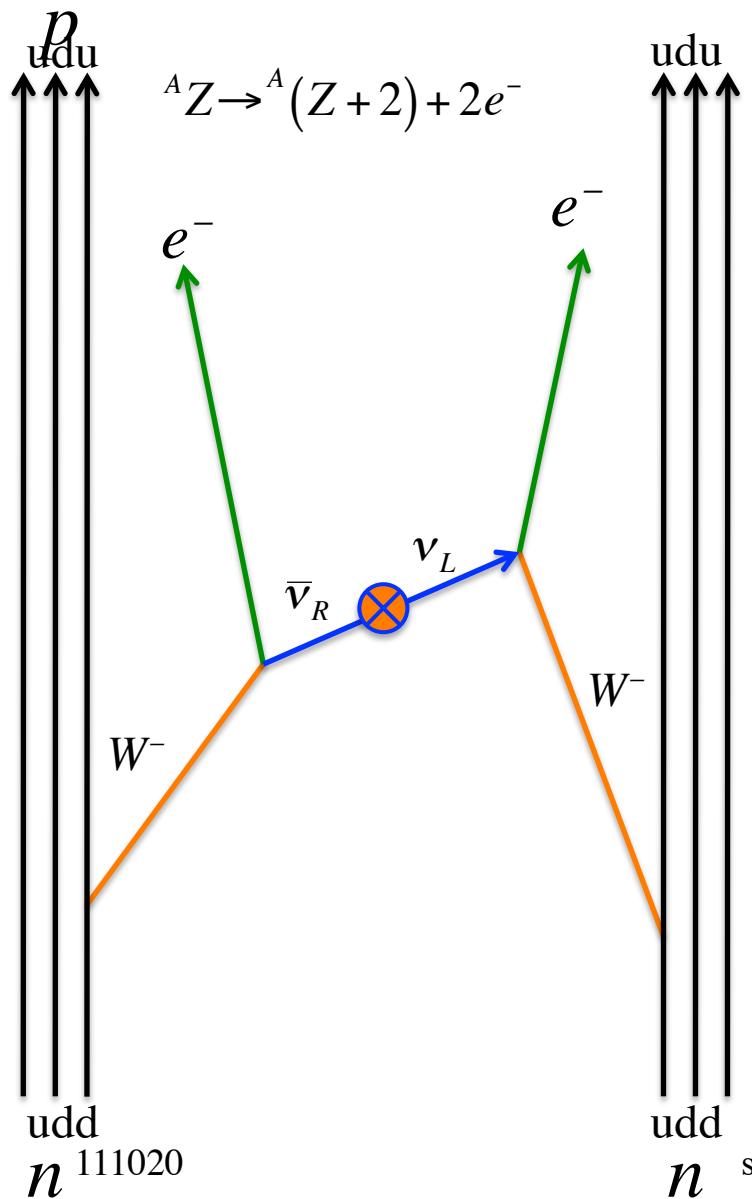
Then N.C. component at  $x$  is,

$$\psi_L(x) = \gamma_L \psi(x) = -i \sqrt{\frac{1+\gamma}{2}} (1 - \vec{\eta} \cdot \vec{\sigma}) \begin{pmatrix} \hat{u} \\ -\hat{u} \end{pmatrix} e^{i\vec{p}\vec{x}} \sin Et$$

The probability to be N.C. state is

$$P_L(x) = \frac{|\psi_L(x)|^2}{|\psi(x)|^2} = 2 \left[ \hat{u}^\dagger (1 - \vec{\beta} \cdot \vec{\sigma}) \hat{u} \right] \sin^2 Et = \frac{1}{\gamma^2} \sin^2 Et$$

=> The chirality oscillates with amplitude  $1/\gamma^2$  and angular speed  $2E$



Exactly same formalism can be applied to  $\bar{\nu}_R \rightarrow \nu_L$  transition

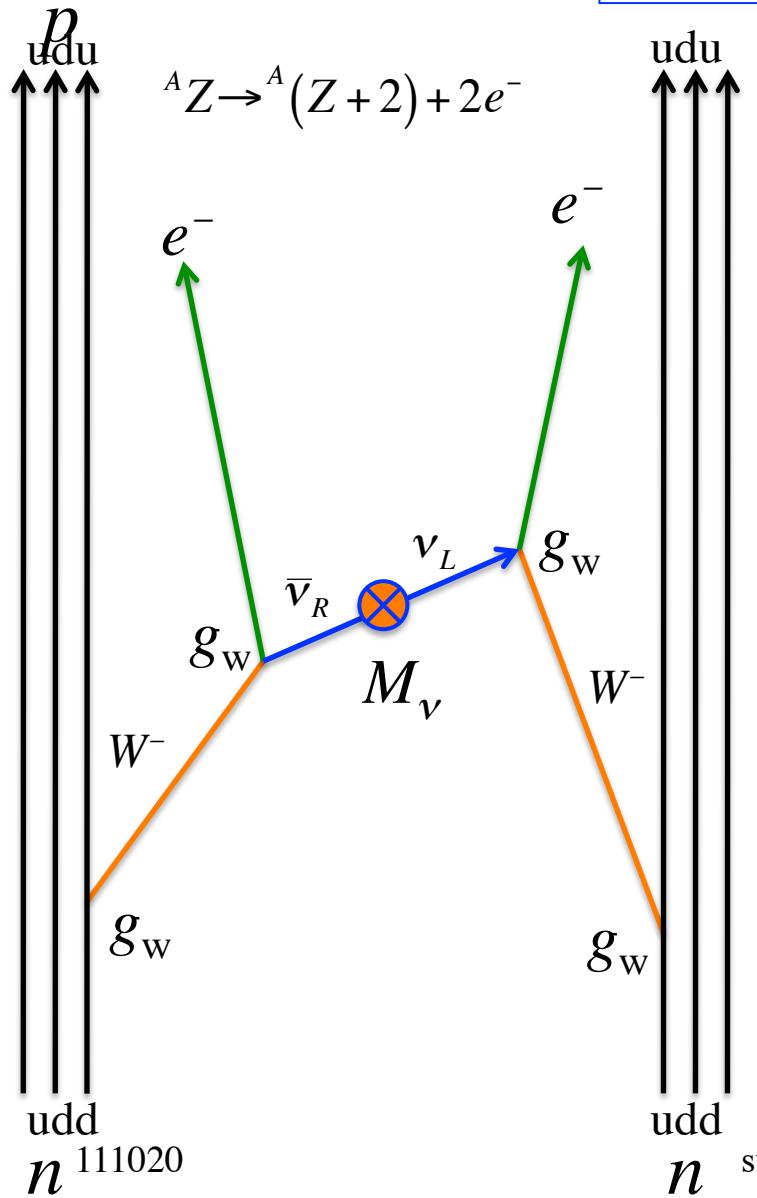
$$P_{\bar{\nu}_R \rightarrow \nu_L}(x) = \frac{M^2}{E^2} \sin^2 Et$$

For  $0\nu\beta\beta$  decays of nuclei,  
 $E \sim \text{MeV}$ ,  $t \sim 1 \text{ fm}/c$   
 $\rightarrow Et \sim 10^{-2}$

$$P_{\bar{\nu}_R \rightarrow \nu_L} \rightarrow \frac{M^2}{E^2} (Et)^2 \sim M^2 L^2$$

The probability is proportional to  $M^2$

## 0νββ probability



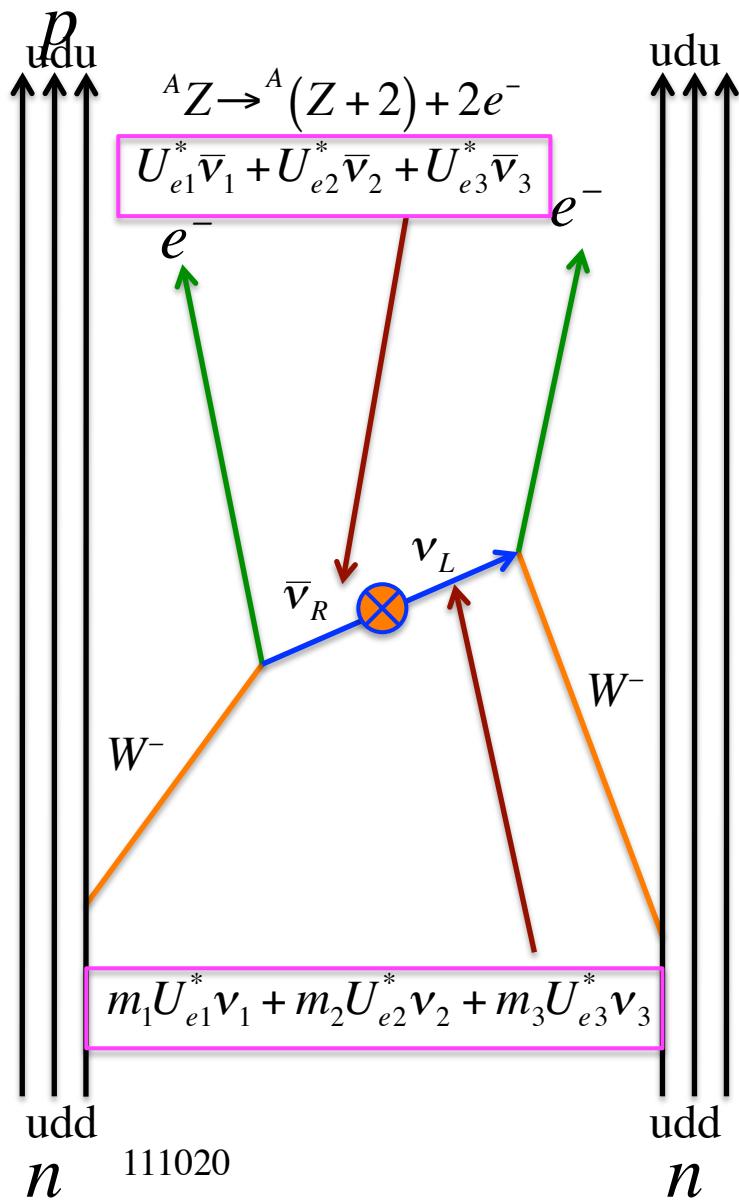
$$\Gamma = \frac{1}{\tau} = G |M_A|^2 M_\nu^2$$

$M_A$ =nuclear matrix element  
This is complicate and beyond the scope of this lecture. But in principle calculable by nuclear theory.

$G \sim G_F^2$ ; known

→ Neutrino mass can be measured from lifetime

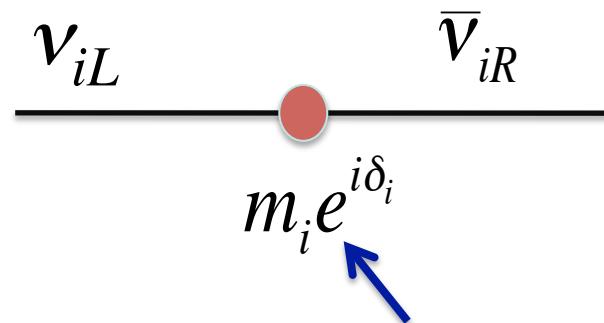
$$m_\nu^2 = \frac{1}{\tau G |M_A|^2}$$



In case there is flavor mixing,

Initial state is

$$\psi(0) = \bar{\nu}_e = U_{e1}^* \bar{\nu}_1 + U_{e2}^* \bar{\nu}_2 + U_{e3}^* \bar{\nu}_3$$



can be complex

$$\psi(x) \sim$$

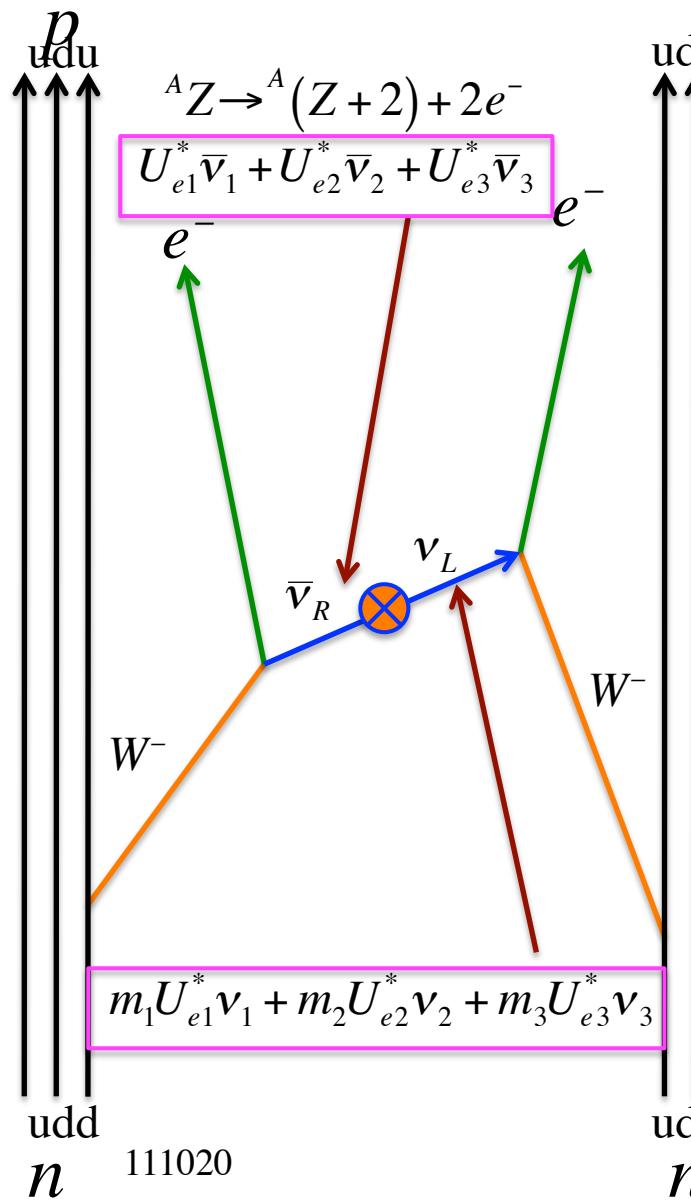
$$m_1 e^{i\delta_1} U_{e1}^* \nu_1 + m_2 e^{i\delta_2} U_{e2}^* \nu_2 + m_3 e^{i\delta_3} U_{e3}^* \nu_3$$

## Neutrino mixing matrix will be modified

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

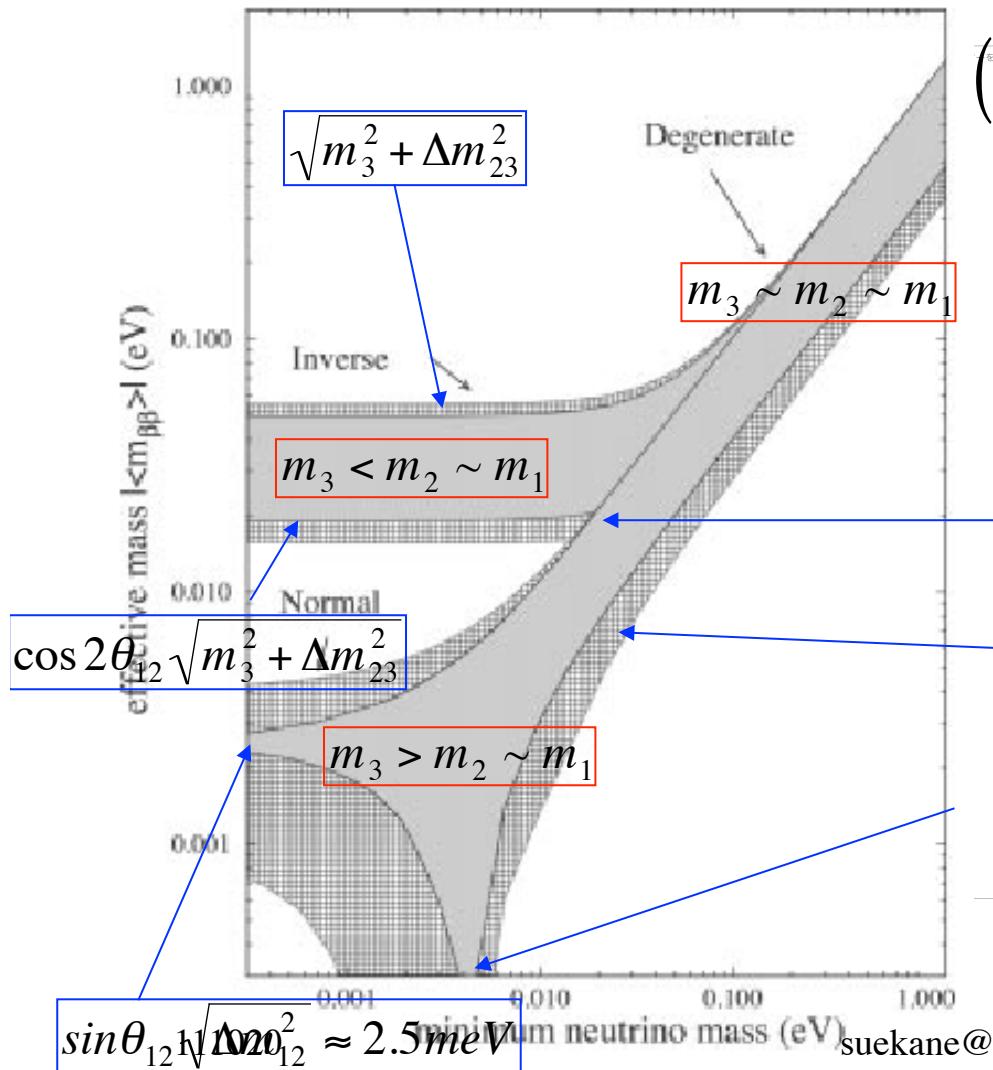


$$\begin{aligned}
|M|^2 &\propto \left| \langle \nu_e | m_1 U_{e1}^* \nu_1 + m_2 e^{i\alpha} U_{e2}^* \nu_2 + m_3 e^{i\beta} U_{e3}^* \nu_3 \rangle \right|^2 \\
&= \left| \langle U_{e1} \nu_1 + U_{e2} \nu_2 + U_{e3} \nu_3 | \right. \\
&\quad \times \left. | m_1 U_{e1}^* \nu_1 + m_2 e^{i\alpha} U_{e2}^* \nu_2 + m_3 e^{i\beta} U_{e3}^* \nu_3 \rangle \right|^2 \\
&= \left| (U_{e1}^*)^2 m_1 + (U_{e2}^*)^2 e^{i\alpha} m_2 + (U_{e3}^*)^2 e^{i\beta} m_3 \right|^2
\end{aligned}$$

$$\alpha = \delta_2 - \delta_1, \beta = \delta_3 - \delta_1$$

$$\langle m_{\beta\beta} \rangle \equiv (U_{e1}^*)^2 m_1 + (U_{e2}^*)^2 e^{i\alpha} m_2 + (U_{e3}^*)^2 e^{i\beta} m_3$$

# effective mass of $0\nu\beta\beta$ -decay



$$\langle m_{\beta\beta} \rangle =$$

$$(U_{e1}^*)^2 m_1 + (U_{e2}^*)^2 e^{i\alpha} m_2 + (U_{e3}^*)^2 e^{i\beta} m_3$$

+known oscillation parameters.

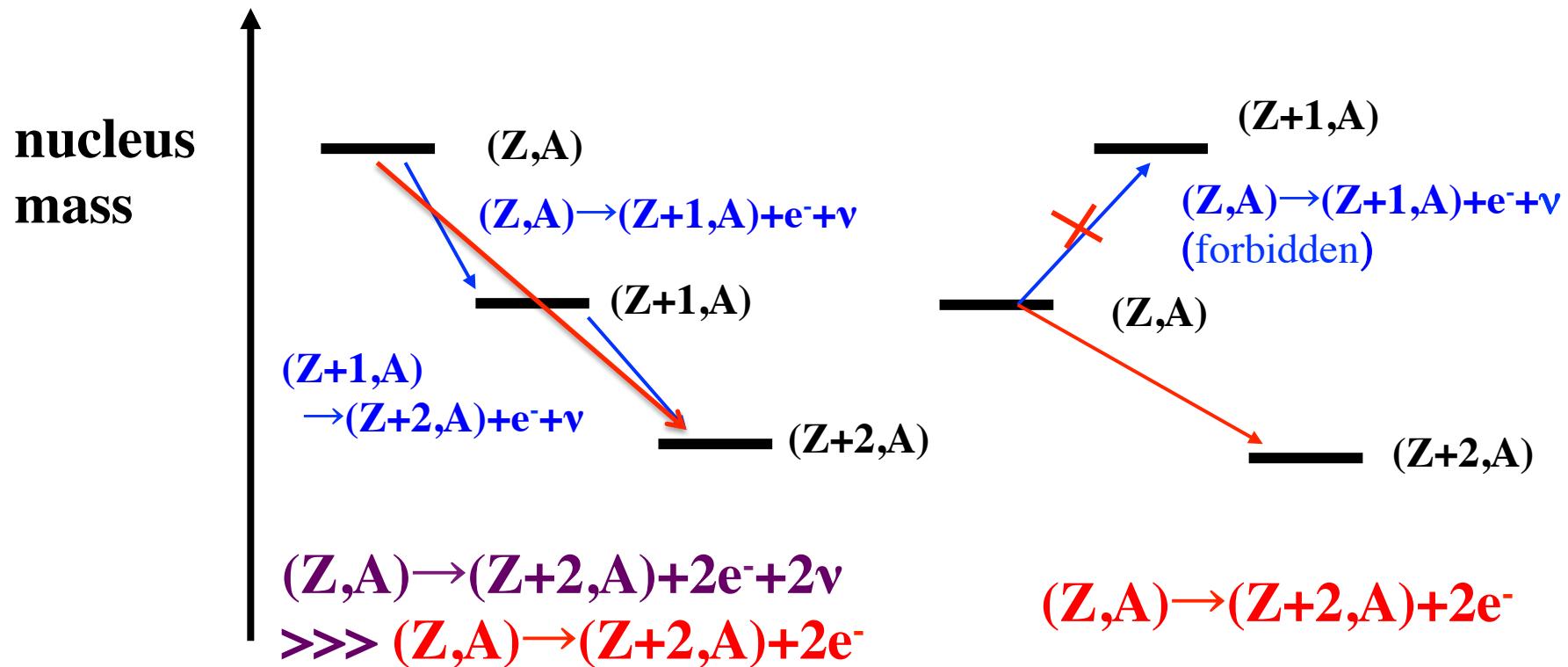
If IH, there is a lower limit  
of  $\langle m_{\beta\beta} \rangle > 20 \text{ meV}$

$$\cos^2 \theta_{12} m_1 + \sin^2 \theta_{12} \sqrt{m_1^2 + \Delta m_{12}^2}$$

$$\cos^2 \theta_{12} m_1 - \sin^2 \theta_{12} \sqrt{m_1^2 + \Delta m_{12}^2}$$

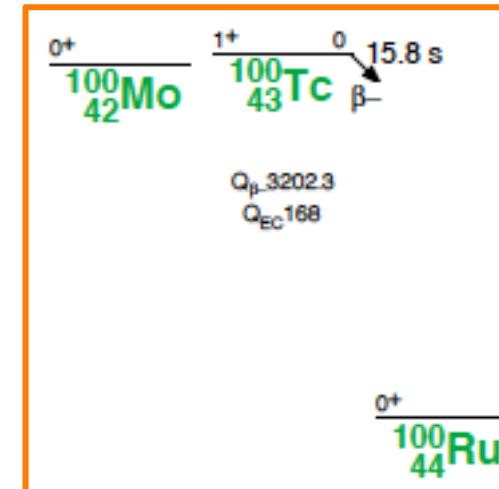
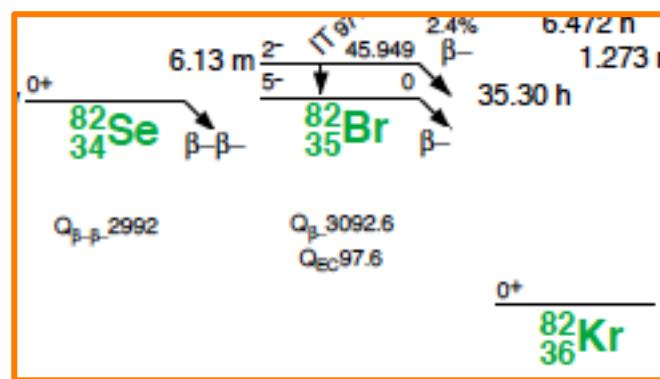
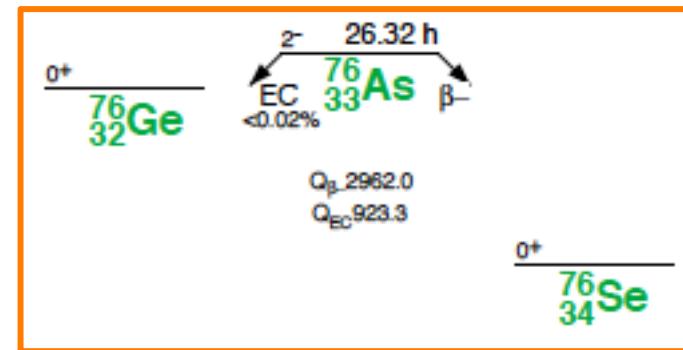
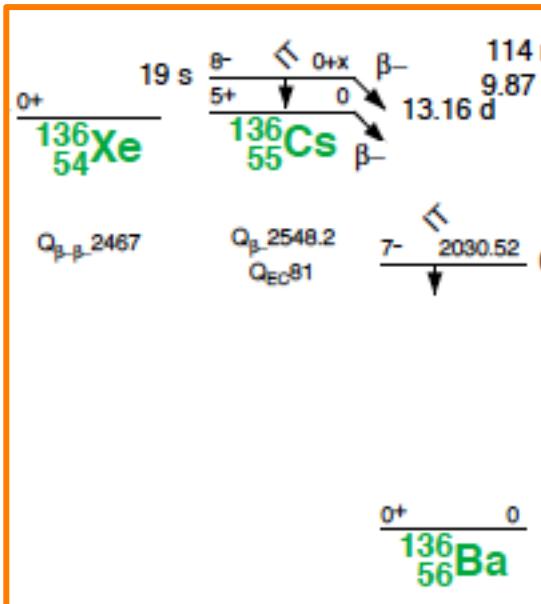
$$\frac{\sin^2 \theta_{12}}{\sqrt{\cos 2\theta_{12}}} \sqrt{\Delta m_{12}^2} \approx 4.0 \text{ meV}$$

## double $\beta$ -decay nuclei

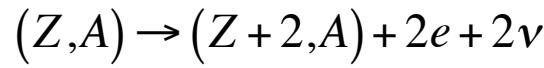


$^{48}\text{Ca}, ^{82}\text{Se}, ^{100}\text{Mo}, ^{116}\text{Cd}, ^{130}\text{Te}, ^{136}\text{Xe}, ^{150}\text{Nd}, \dots$

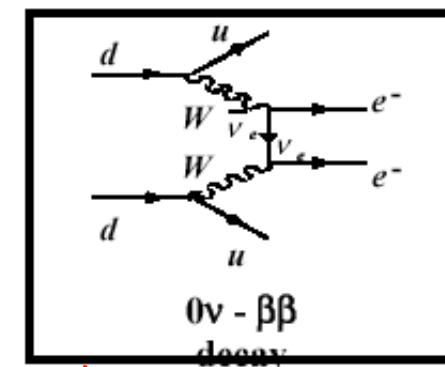
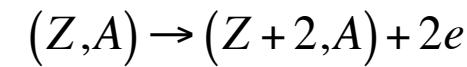
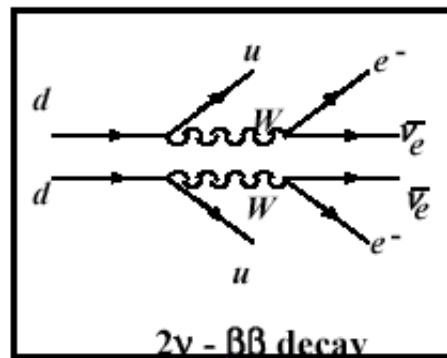
# Examples of level schemes for $\beta\beta$ decay nuclei



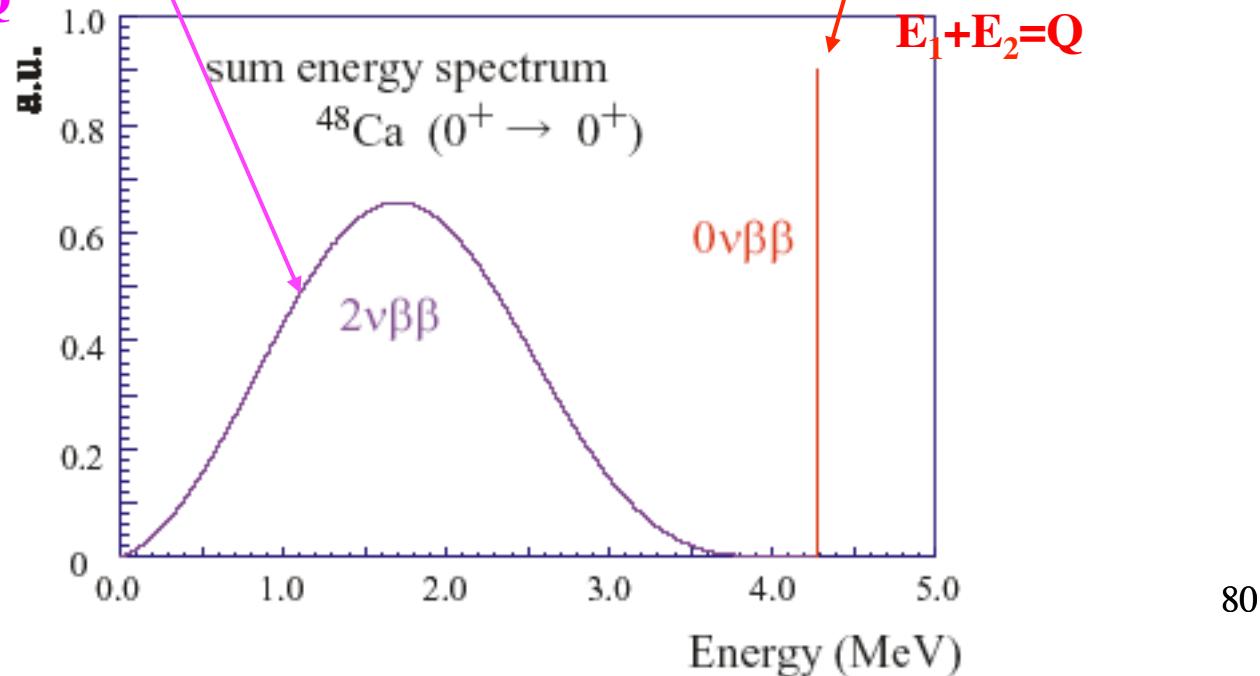
# $2\nu\beta\beta$ & $0\nu\beta\beta$



$$\Delta t < \frac{\hbar}{E}$$

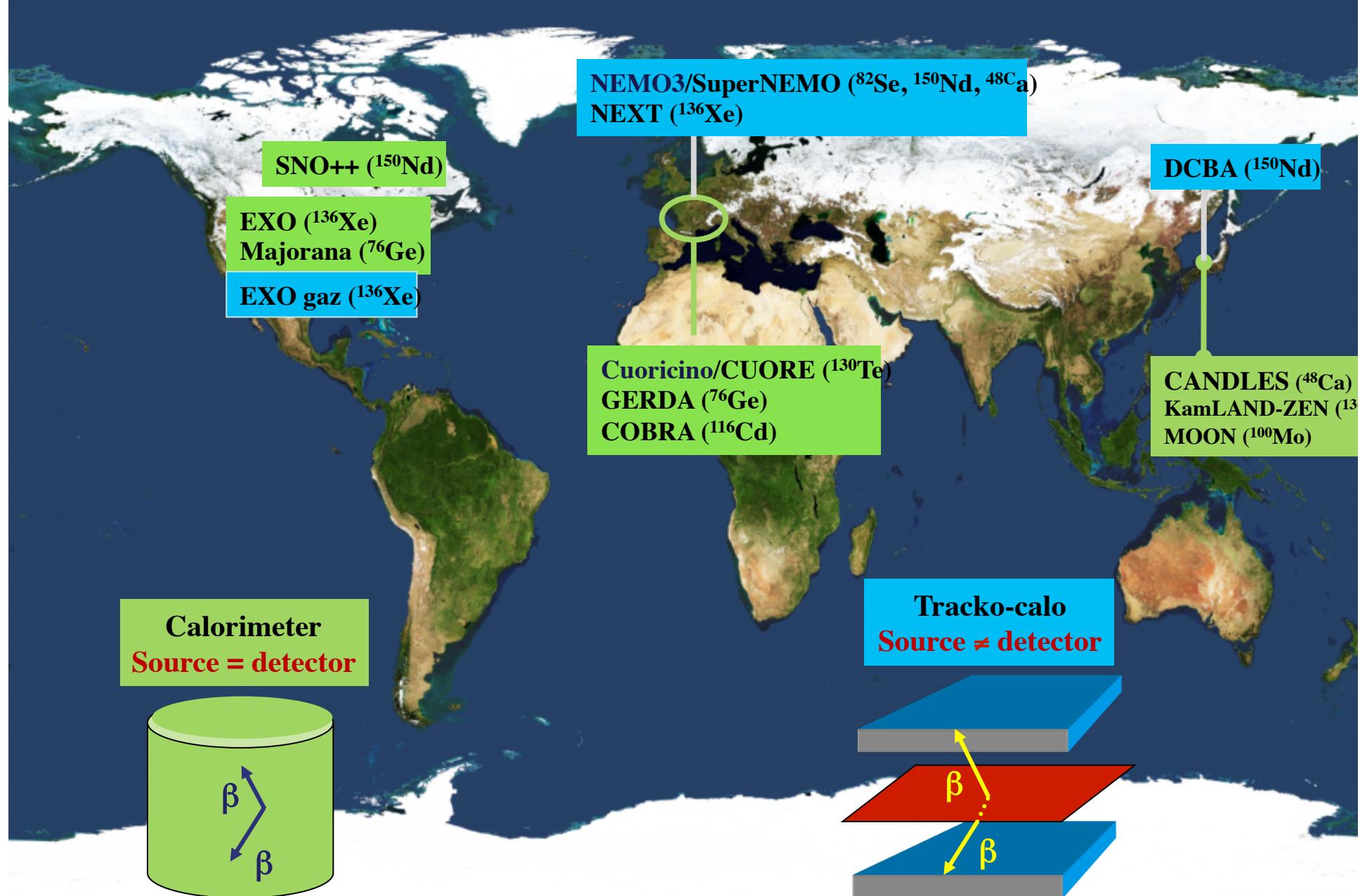


$$E_1 + E_2 < Q$$





# $\beta\beta(0\nu)$ : experiments and projects



# Overview experiments

Name	Nucleus	Mass	Method	Location	Time
Past/Recent experiments					
Heidelberg-Moscow	$^{76}\text{Ge}$	11	ionization	LNGS	-2003
IGEX	$^{76}\text{Ge}$	6	ionization	Canfranc	-2000
Cuoricino	$^{130}\text{Te}$	11	bolometer	LNGS	-2008
NEMO-3	$^{100}\text{Mo}/^{82}\text{Se}$	7/1	track./calor.	Modane	-2011
Current experiments (funded, under construction or running)					
GERDA I/II	$^{76}\text{Ge}$	15/35	ionization	LNGS	2011/13
Majorana	$^{76}\text{Ge}$	30	ionization	SUSEL	2013
EXO200	$^{136}\text{Xe}$	200	liquid TPC	WIPP	2011
Cuore0/Cuore	$^{130}\text{Te}$	10/200	bolometer	LNGS	2011/14
Kamland-Zen	$^{136}\text{Xe}$	400	LS	Kamioka	2011
SNO+	$^{150}\text{Nd}$	44	LS	Sudbury	2014
(substantial) R&D funding, proto-typing					
NEXT	$^{136}\text{Xe}$	100	gas TPC	Canfranc	2013+
CandlesIII	$^{48}\text{Ca}$	0.35	scint crystal	Oto Cosmo	2011
MOON	$^{82}\text{Se}, ^{150}\text{Nd}$				
DCBA	$^{150}\text{Nd}$	32	tracking		
Cobra	$^{116}\text{Cd}$		solid TPC	LNGS	
SuperNEMO	$^{82}\text{Se}$	7/100-200	track./calor.	Modane	2014/-
XMASS	$^{136}\text{Xe}$		liquid SC	Kamioka	
Lucifer	$^{82}\text{Se}$		bolom+scint		

# Experimental approach

## Geochemical experiments

$^{82}\text{Se} = > ^{82}\text{Kr}$ ,  $^{96}\text{Zr} = > ^{96}\text{Mo}$  (?),  $^{128}\text{Te} = > ^{128}\text{Xe}$  (non confirmed),  $^{130}\text{Te} = > ^{130}\text{Te}$

## Radiochemical experiments

$^{238}\text{U} = > ^{238}\text{Pu}$  (non confirmed)

## Direct experiments

Source = detector  
(calorimetric)



Source  $\neq$  detector



Source  $\neq$   
Detector

# $0\nu\beta\beta$ searches

Summary of the most sensitive neutrinoless  $\beta\beta$  experiments

Experim	Isotope	$\tau_{1/2}^{0\nu} (\nu)$	$m_{ee}^* (\text{eV})$	Range $m_{ee}$
Heidelberg – Moscow 2001	$^{76}\text{Ge}$	$> 1.9 \times 10^{25}$	$< 0.35$	$< 0.3 - 2.5$
IGEX 2002		$> 1.57 \times 10^{25}$	$< 0.38$	$< 0.3 - 2.5$
Mi DBD – v 2002	$^{130}\text{Te}$	$> 2.1 \times 10^{23}$	$< 1.5$	$< 0.9 - 2.1$
Bernatowicz et al. 1993 (GEO)	$^{128}\text{Te}^{geo}$	$> 7.7 \times 10^{24}$	$< 1.0$	$< 1.0 - 4.4$
Belli et al. 2003	$^{136}\text{Xe}$	$> 1.2 \times 10^{24}$	$< 1.0$	$< 0.8 - 2.4$
Bizzeti et al. 2003	$^{116}\text{Cd}$	$> 1.7 \times 10^{23}$	$< 1.7$	$< 1.6 - 5.5$
Ejiri et al. 2001	$^{100}\text{Mo}$	$> 5.5 \times 10^{22}$	$< 4.8$	$< 1.4 - 256$
Osawa I. et al. 2002	$^{48}\text{Ca}$	$> 1.8 \times 10^{22}$	$< 6.0$	

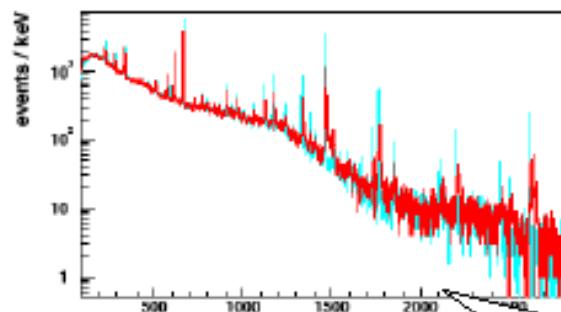
\* Staudt, Muto, Klapdor-Kleingrothaus Europh. Lett 13 (1990)

The “Klapdor effect” =>  $T = 1.2 \times 10^{25} \text{ a} \Rightarrow \langle m_\nu \rangle \sim 0.44 \text{ eV}$

# Positive Result? (Hidelberg-Moscow Experiment)

## $0\nu\beta\beta$ in $^{76}\text{Ge}$

5 detectors of overall 10.96 kg enriched to 86-88% in the  $\beta\beta$ -emitter  $^{76}\text{Ge}$



hep-ph/0403018

$$T = (0.69 - 4.18) \times 10^{25} \text{ years } (3\sigma)$$

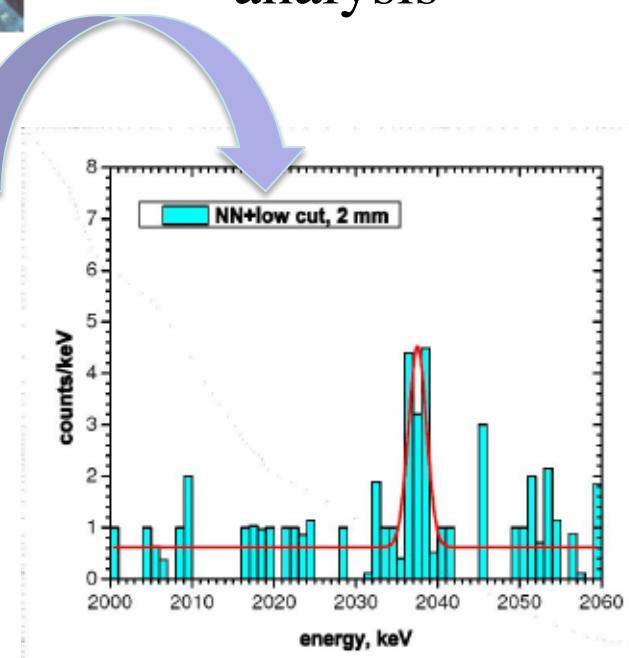
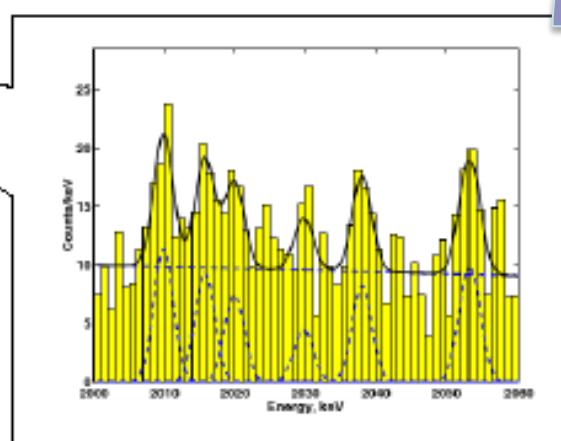
Majorana  $\nu$  Mass

$$m_\nu = (0.24 - 0.58) \text{ eV } (3\sigma)$$

$$m_{\nu \text{ best}} = 0.44 \text{ eV}$$



Pulse Shape  
analysis



111020

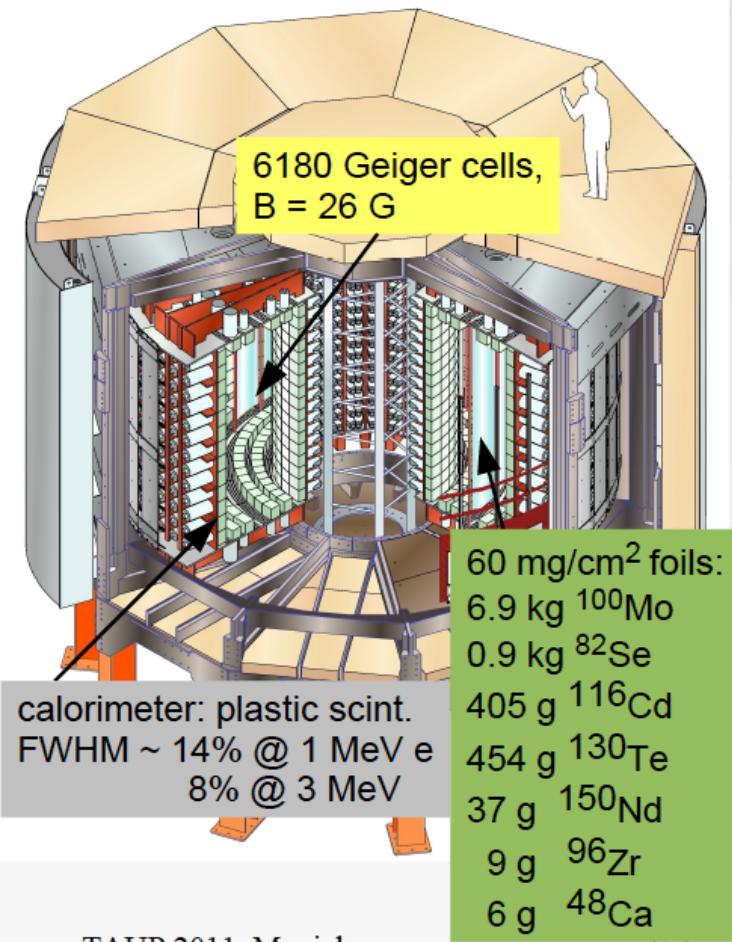
suekane@FAPPS

$$T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \times 10^{25} \text{ y}$$

From here, I borrowed many slides from Dr. Bernhard Schwingenheuer's very nice review talk @ TAUP2011

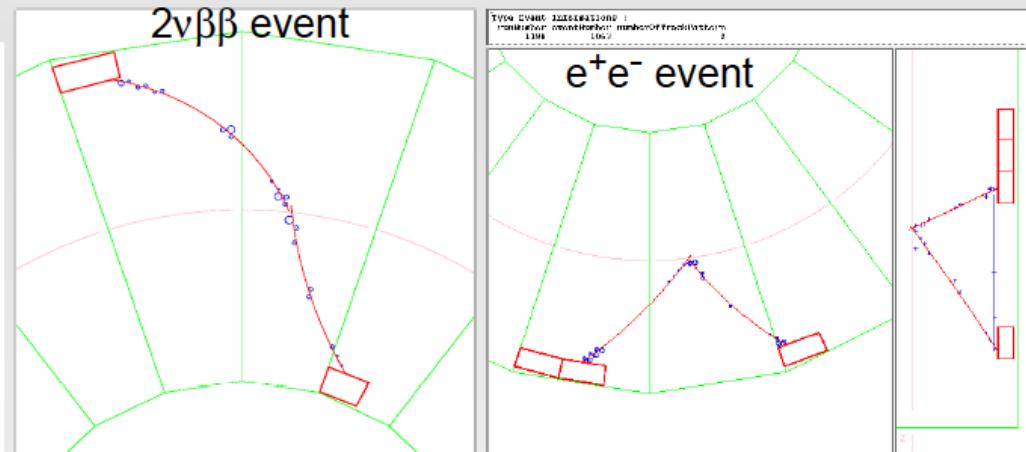
# NEMO-3

tracking – calorimeter detector



TAUP 2011, Munich

111020



full event topology to identify backgrounds  
different target materials can be used,  
many results on  $2\nu\beta\beta$  decays  
BUT: poor energy resolution & low efficiency

data taking stopped Jan 2011

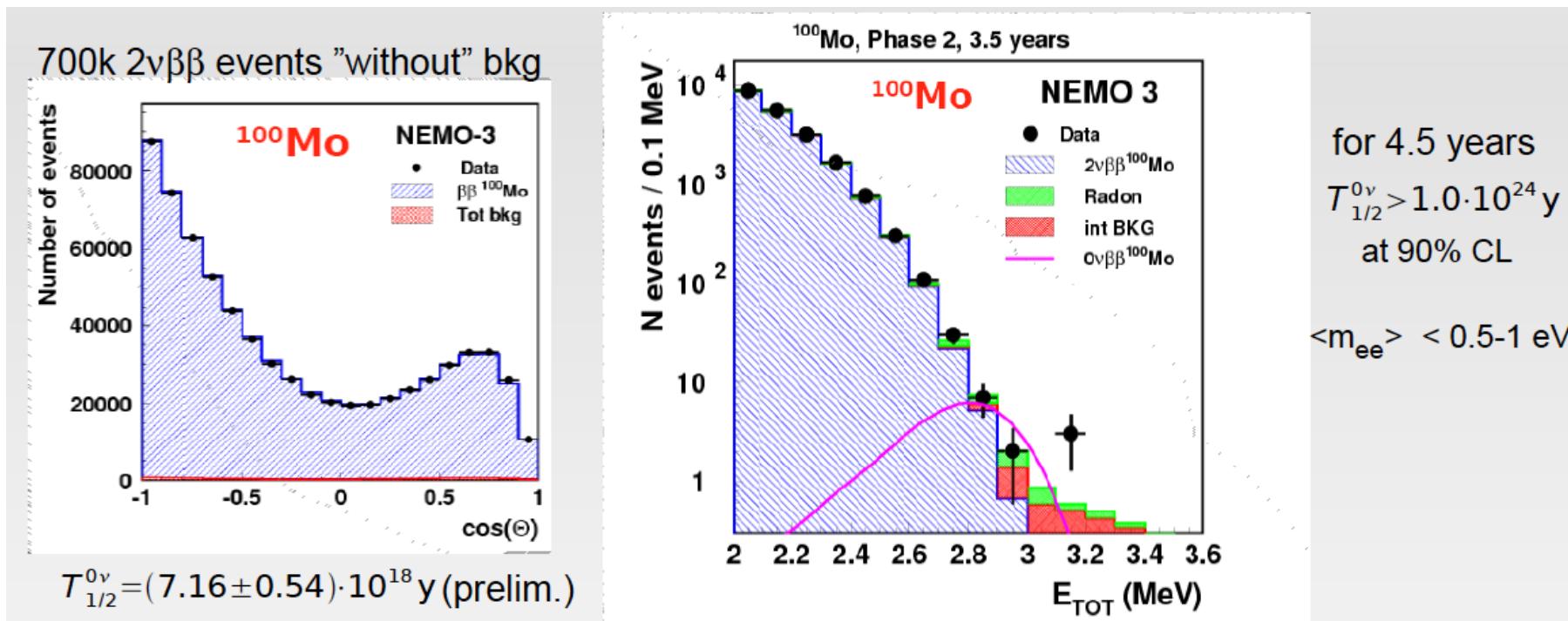
Schwingenheuer, Double Beta Decay

suekane@FAPPS

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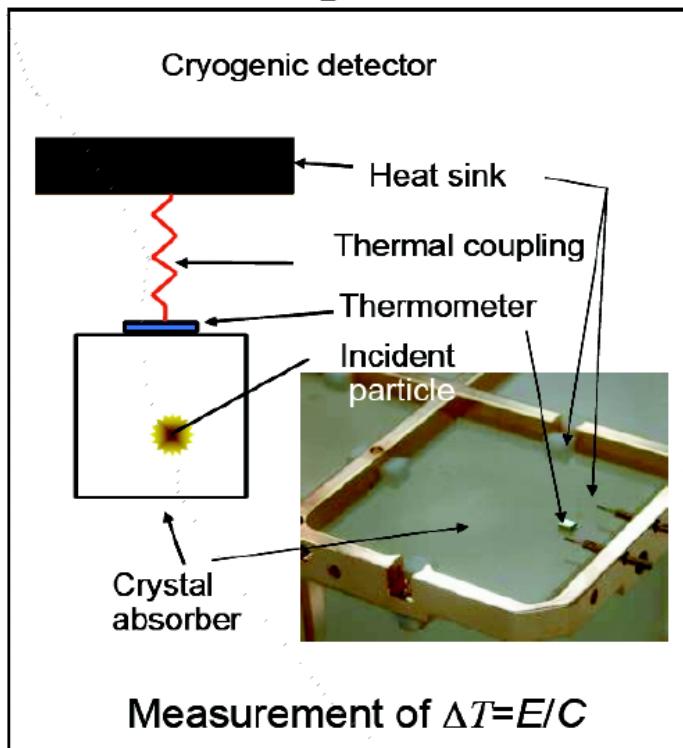
87

# NEMO-3



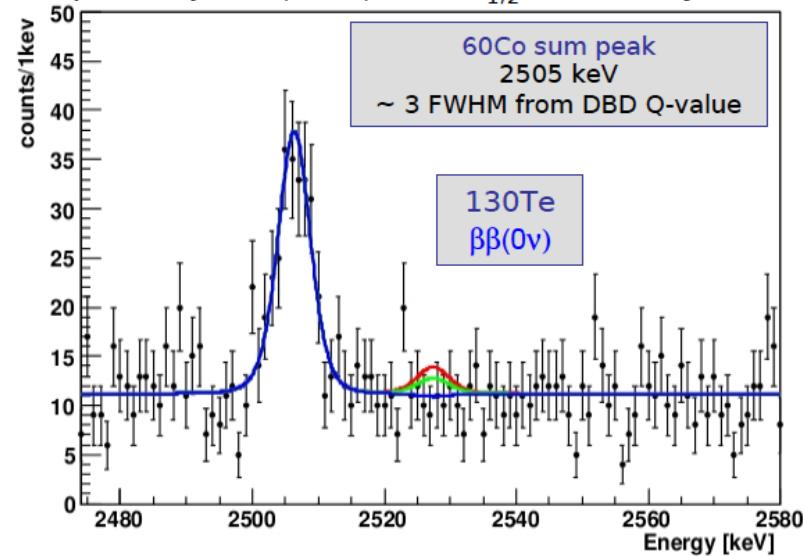
# Cuoricino

bolometer TeO<sub>2</sub> crystals @ 10 mK



- 41 kg TeO<sub>2</sub>, active mass ~ 11 kg,
- avg FWHM = 7.5 keV at 2527 keV
- stopped June 2008
- total statistics 19.75 kg y

Astropart. Phys 34 (2011) 822  $T_{1/2}^{0\nu} > 2.8 \cdot 10^{24}$  y (90% CL)



$$\langle m_{ee} \rangle < 0.3-0.7 \text{ eV}$$

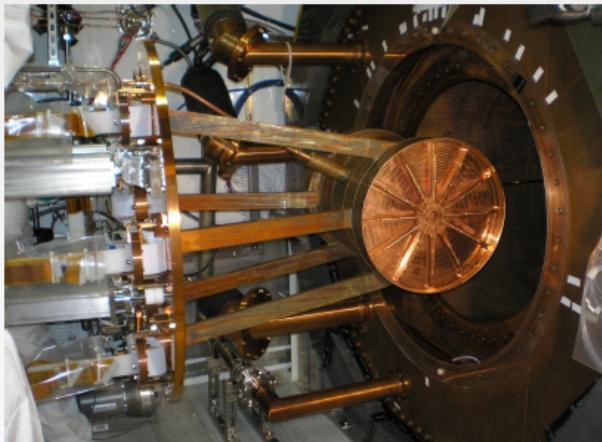
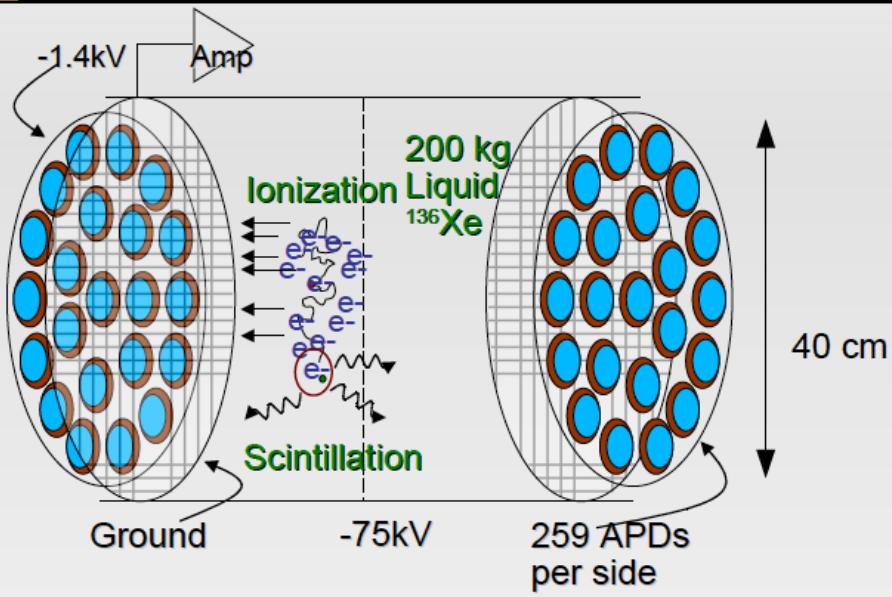
not sensitive enough to check Heidelberg-Moscow claim

TAUP 2011, Munich

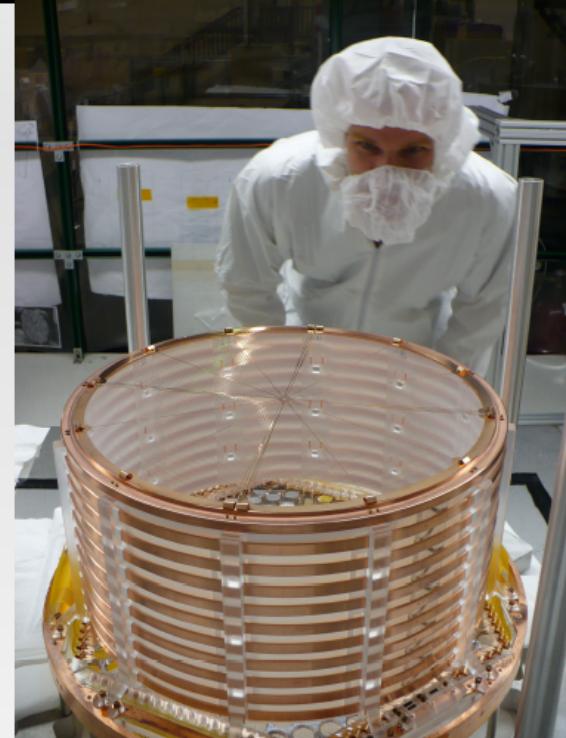
Schwingenheuer, Double Beta Decay

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# Exo 200



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engineering run Dec 2010, 140 kg  $^{136}\text{Xe}$  filled in spring,  
cathode at -8 kV,  $\sigma = 4.5\%$  at 2.6 MeV using ionization,

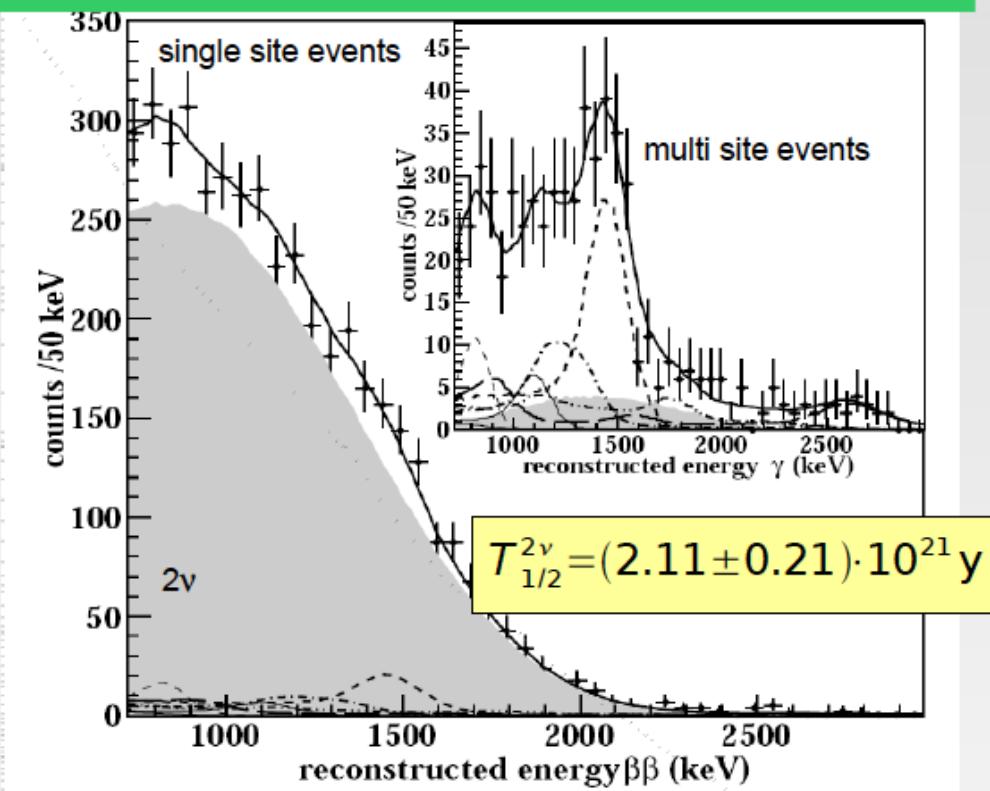
design:  $\sigma=1.6\%$  using ionization+scintillation  
 $0\nu\beta\beta T_{1/2}$  sensitivity  $6.4 \times 10^{25} \text{ y}$  (90% CL), testing Hd-Ms

Schwingenheuer, Double Beta Decay

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# Exo 200

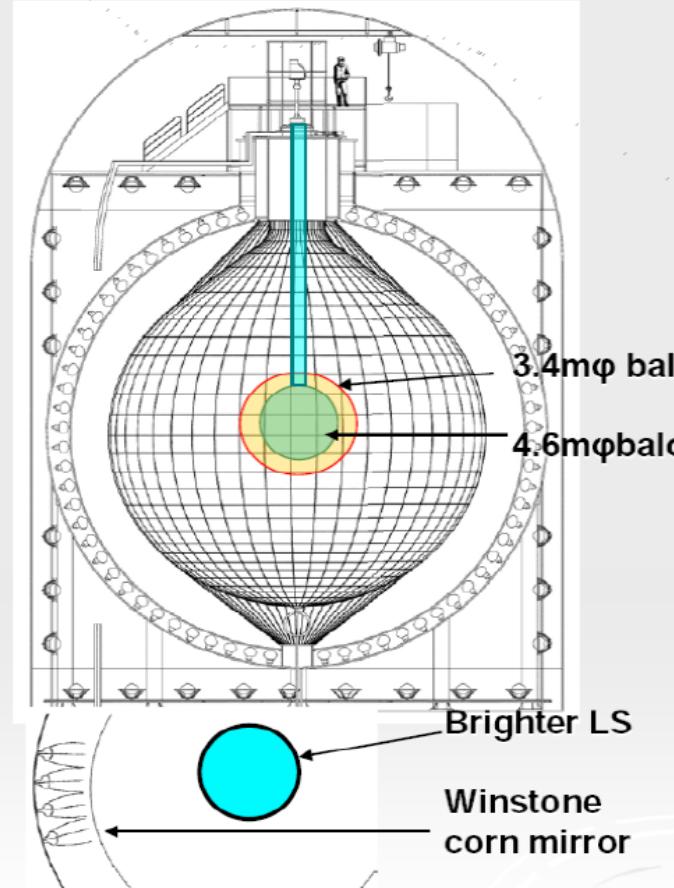
first  $T^{2\nu}$  for  $^{136}\text{Xe}$  EXO200: arXiv:1108.4193



The 1<sup>st</sup> observation of  $2\nu 2\beta$  decay of  $^{136}\text{Xe}$   
111020 suekane@FAPPS

# Kamland-Zen

## KamLAND-Zen project



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Schwingenheuer, Double Beta Decay

suekane@FAPPS

### 1st phase enriched Xe 400kg

R=1.7m balloon

V=20.5m<sup>3</sup>, S=36.3m<sup>2</sup>

LS : C10H22(81.8%)+PC(18%)  
+PPO+Xe(~2.5wt%)

ρLS : 0.78kg/ℓ

high sensitivity with low cost



tank opening (2013 or 2015)

### 2nd phase enriched Xe 1000kg

R=2.3m balloon

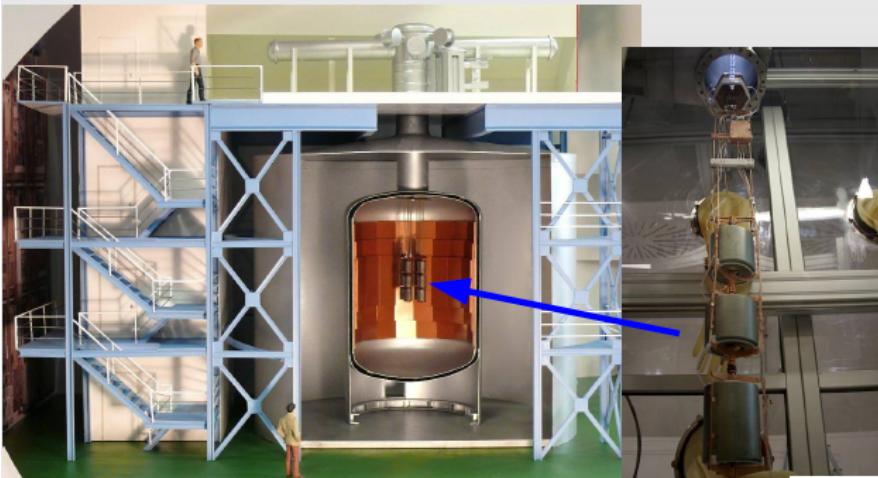
V=51.3m<sup>3</sup>, S=66.7m<sup>2</sup>

improvement of energy resolution  
(brighter LS, higher light concentrator )

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# Gerda

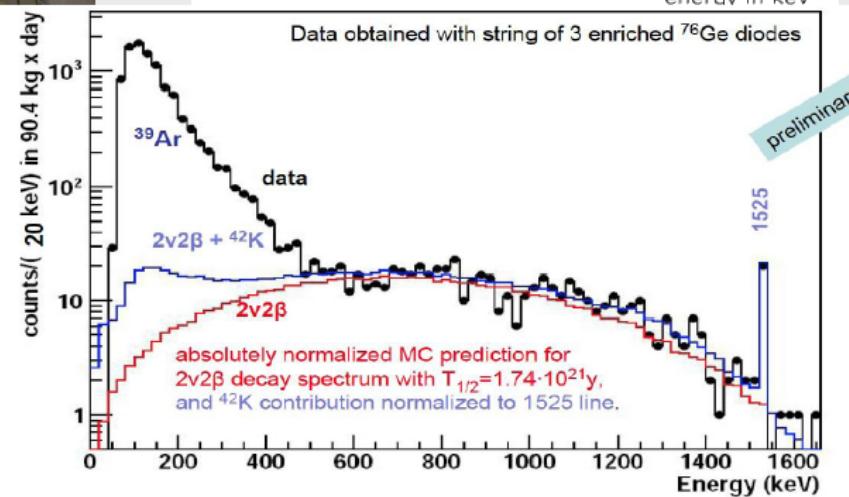
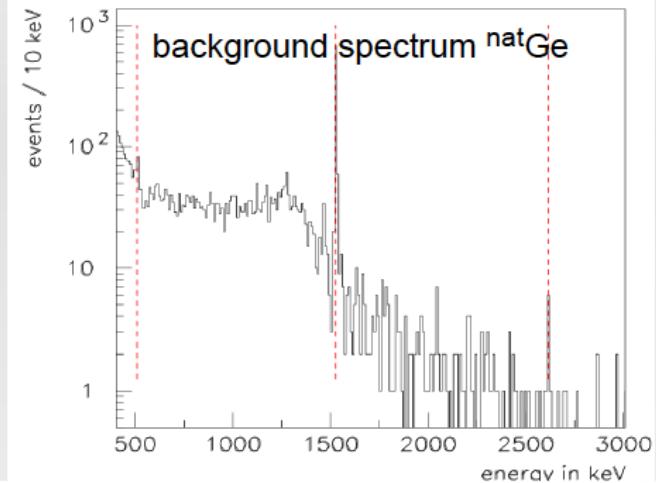


$^{76}\text{Ge}$  diodes in LAr cryostat in water tank

data taking started June 2010

- peak at 1525 keV from  $^{42}\text{K}$  decay ( $^{42}\text{Ar}$  progeny)
- other peaks weak
- background at  $Q_{\beta\beta} \sim 0.06 \text{ cnt/(keV kg y)}$ , lower than for Hd-Ms, IGEX, Cuoricino but still factor ~6 higher than anticipated
- some background sources identified
- start operation of Phase I this fall

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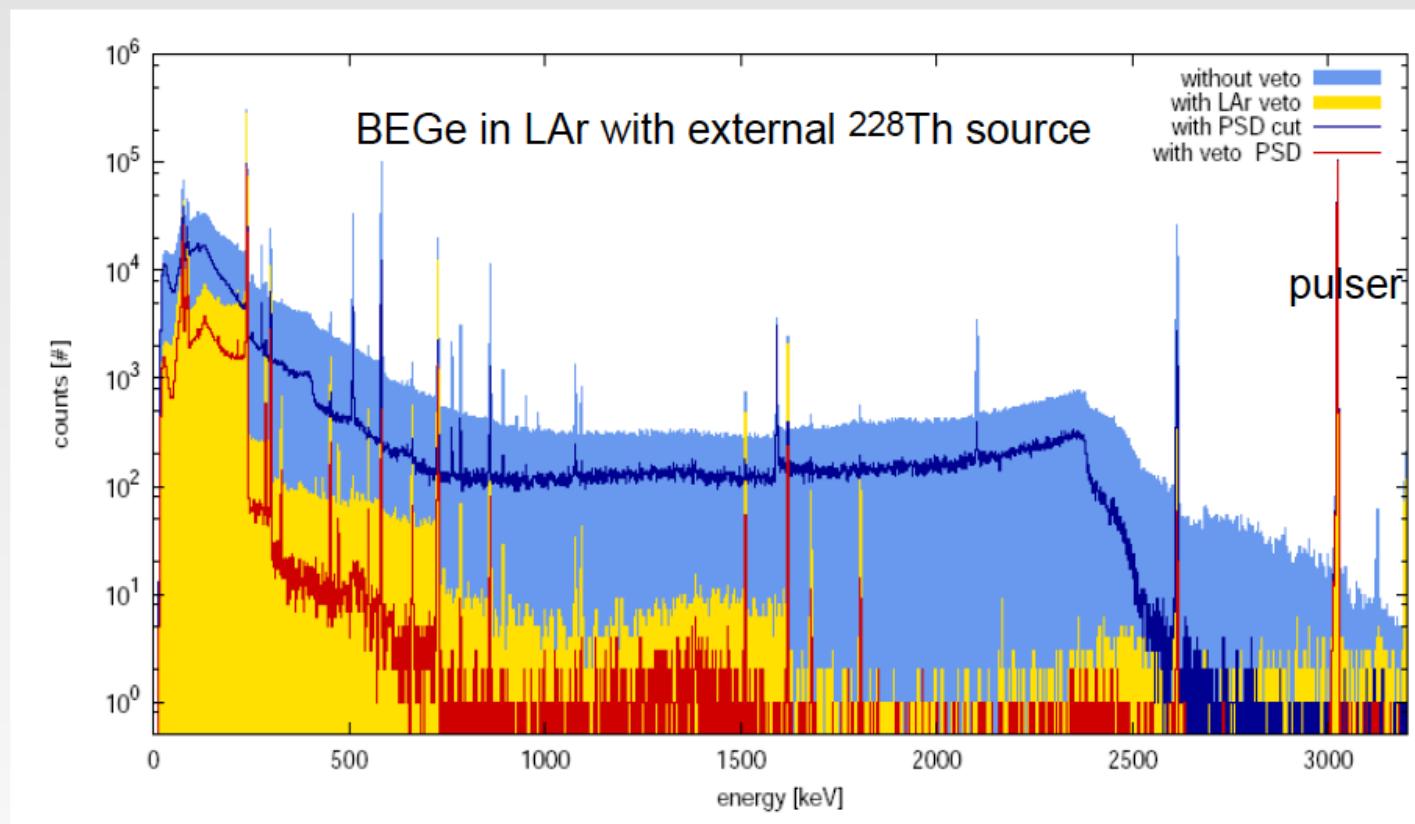
Schwingenheuer, Double Beta Decay

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# Gerda: Phase II

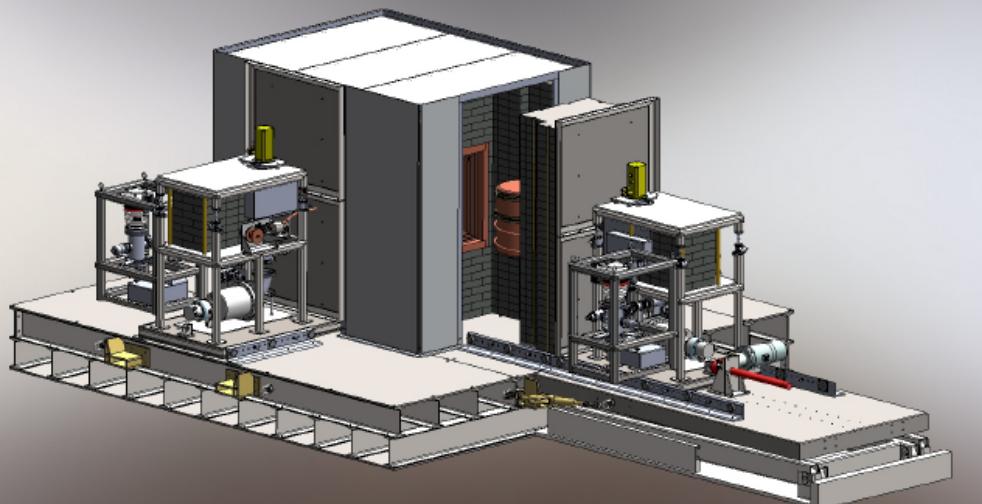
+20 kg in diodes and background 0.001 cnt/(keV kg y)

Method: BEGe detector design (superior pulse shape discrimination) & LAr instrumentation  
start 2013,  $T_{1/2}$  sensitivity for 100 kg y about  $1.4 \times 10^{26}$  y (90% CL)



# Majorana Demonstrator

BEGe detectors in conventional cryostat



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III020

19  $^{nat}$ Ge diodes in hand working in string



20 kg enriched Ge on its way!

Next steps:

- 2012 first cryostat above ground with  $^{nat}$ Ge detectors
  - 2013 below ground with  $^{nat}$ Ge and  $^{enr}$ Ge diodes
  - 2014 full experiment
  - background level 0.004 cnt/(ROI kg y), ROI  $\sim$  4 keV
- background level would be good enough for ton scale exp.**

# SNO+



0.1% of  $^{nat}Nd$   
--> 44 kg  $^{150}Nd$

6.8% FWHM  
@ 3MeV

3y sensitivity  
 $5.5 \times 10^{24}$  y (90%CL)

start filling 2013,  
Nd later

# Cuore



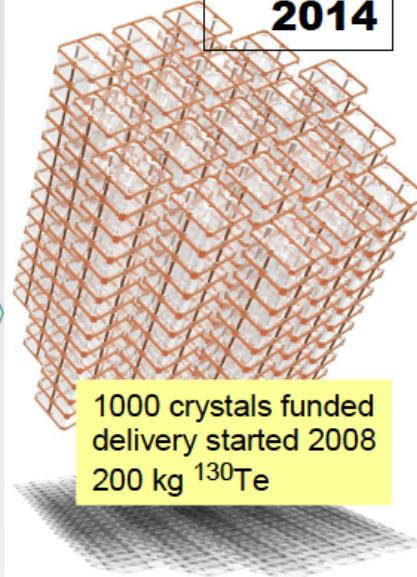
## CUORICINO



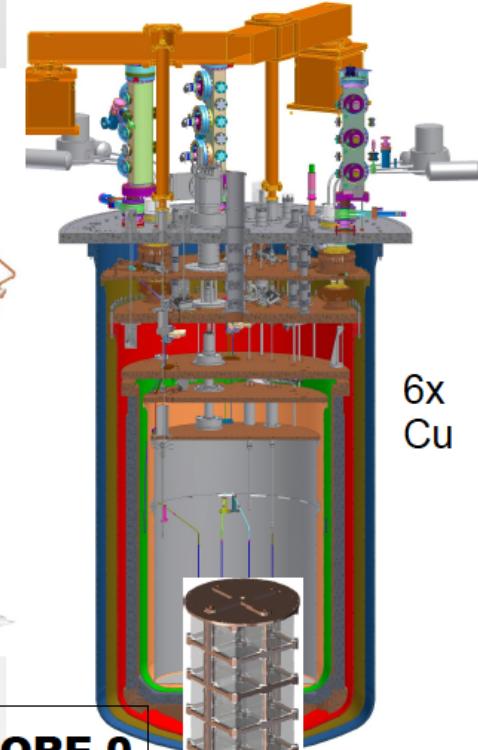
study of background,  
--> careful screening,  
new surface cleaning

- Careful design and construction
- Hut and infrastructures
  - Detector
    - Crystals
    - Structure
    - Assembly
  - Cryostat and shields
  - Calibration system
  - Electronics

CUORE  
2014



1000 crystals funded  
delivery started 2008  
200 kg  $^{130}\text{Te}$



6x Cu

CUORE-0  
2011

in Cuoricino cryostat,  
system test for Cuore,  
also physics output

Cuore:  $B \sim 0.01 \text{ cnt}/(\text{keV kg y})$ , FWHM=5 keV  
sensitivity on  $T_{1/2} \sim 6 \times 10^{25}$  (90% CL) in 1 year  
bkg  $\sim 30 \text{ evt/year}$

TAUP 2011, Munich

111020

Schwingenheuer, Double Beta Decay

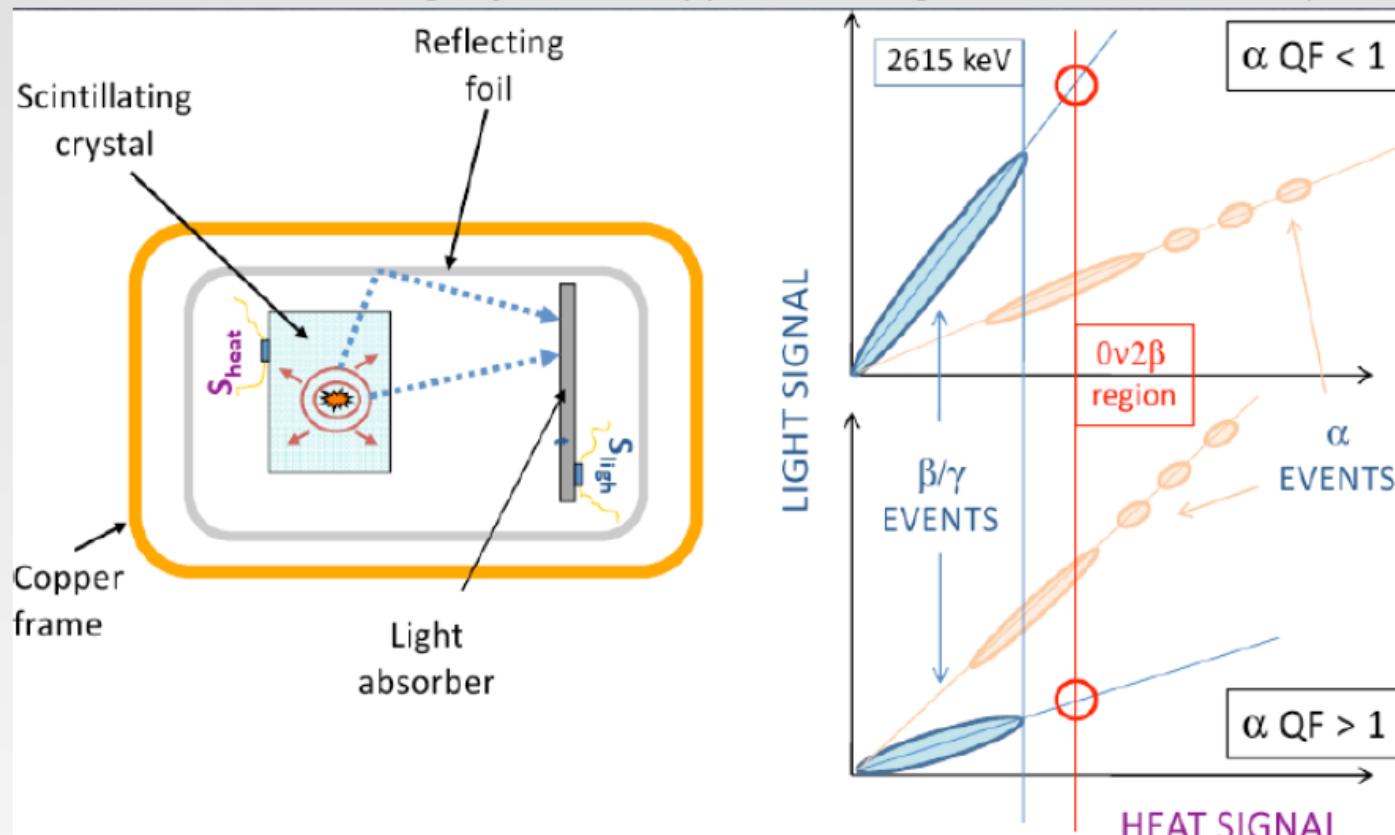
suekane@FAPPS

28

97

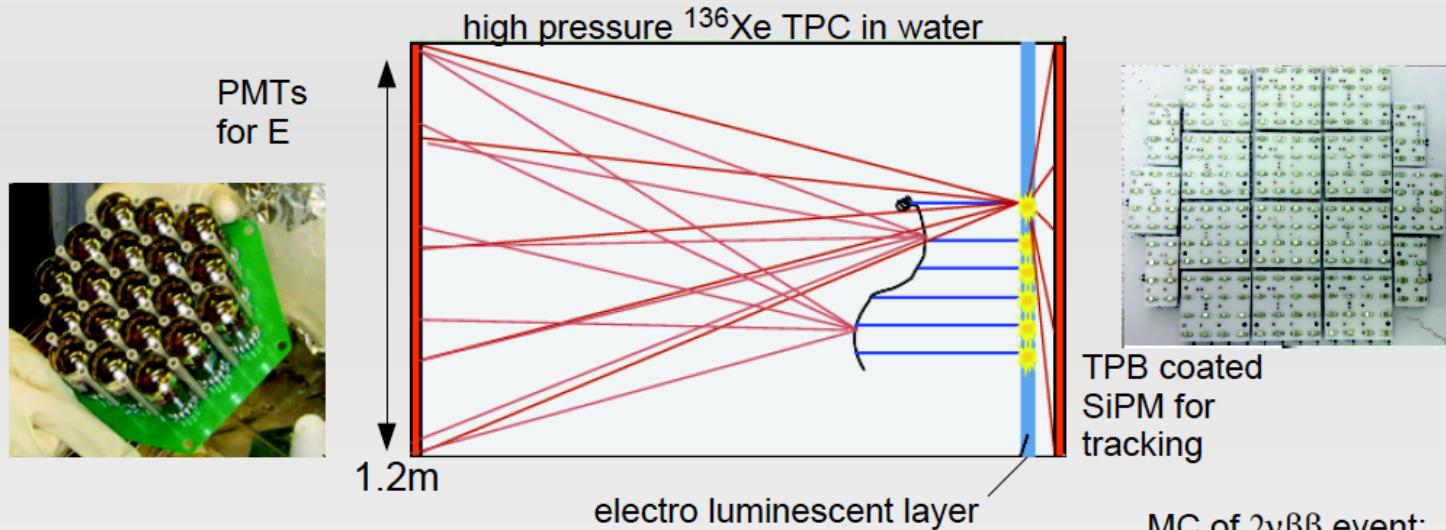
# Lucifer

"CUORE" with scintillating crystal to suppress backgrounds  $< 0.001 \text{ cnt}/(\text{keV kg y})$



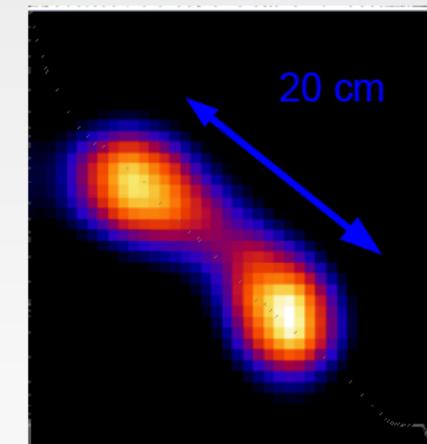
best candidate ZnSe, plan to use Cuoricino cryostat

# NEXT



TPB coated  
SiPM for  
tracking

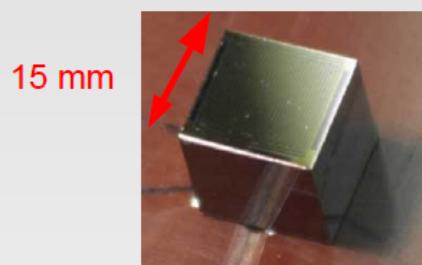
MC of  $2\nu\beta\beta$  event:  
topological bkg suppression



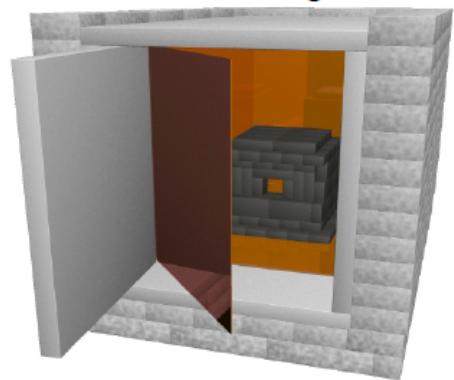
Conceptual Design Report: arXiv:1106.3630  
- 100 kg  $^{136}\text{Xe}$  already in hand  
- extremely low bkg  $B \sim 0.0002 \text{ cnt/(keV kg y)}$   
- extremely good FWHM 0.8% at 2.5 MeV  
- "easy" to build  
- "little" R&D needed, several proto-types exist  
can be ready in 2013

# COBRA

Use large amount of CdZnTe Semiconductor Detectors  
with 55  $\mu\text{m}$  pixel readout: as solid state TPC



new shielding

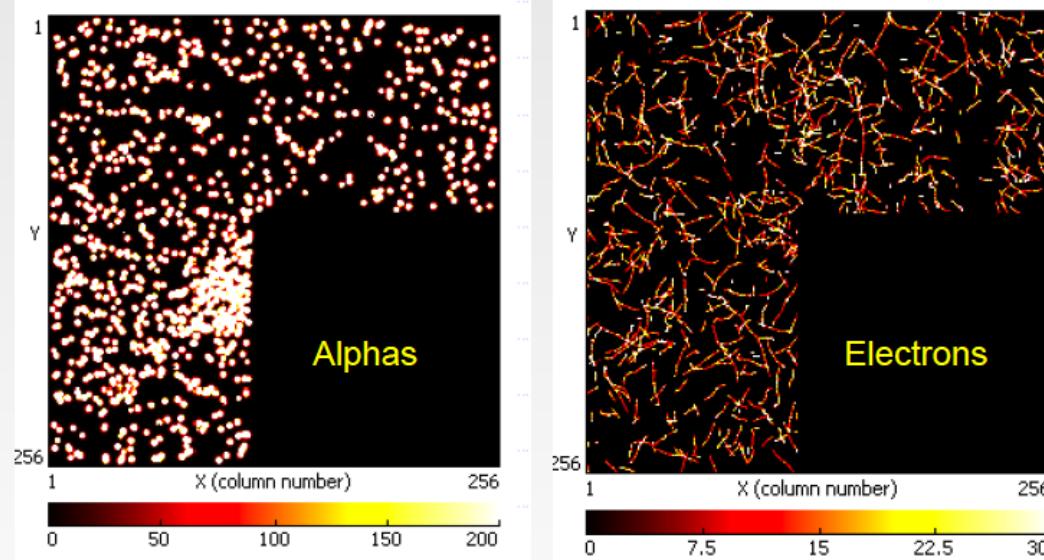


TAUP 2011, Munich

111020

currently upgrade to 64 detector setup with new DAQ + shielding

simulation of detector response

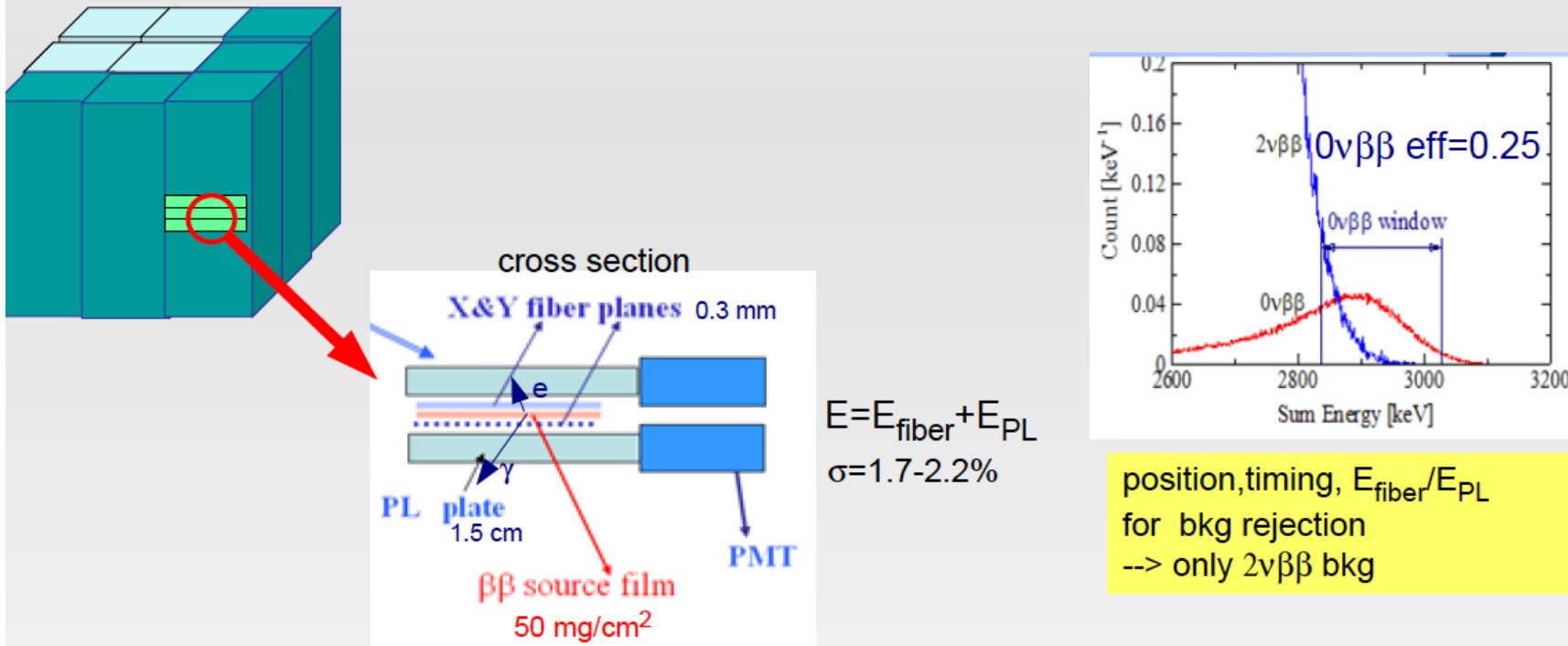


Schwingenheuer, Double Beta Decay

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# MOON

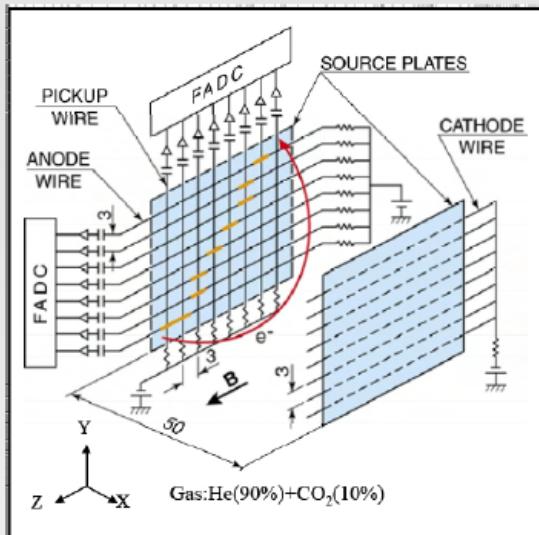


MOON-1 R&D: 6 layers pf PL + 5 Mo films (94.5% <sup>100</sup>Mo) of 40 mg/cm<sup>2</sup>, 56 PMTs inside active+passive shield of ELEGANT V,  $\sigma = 2.9\%$  at 3 MeV

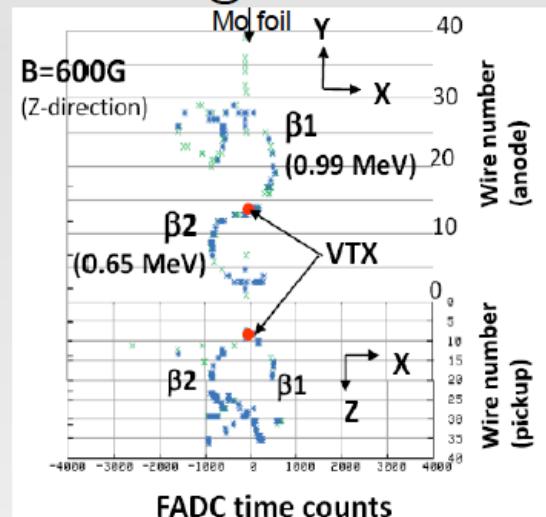
Phase I,II,III with 30, 120, 480 kg foreseen with 1.5, 4.1,  $20 \times 10^{25}$  y (90 % CL) sensitivity for <sup>100</sup>Mo or 3.2, 11.2,  $59 \times 10^{25}$  y (90% CL) sensitivity for <sup>82</sup>Se

# DCBA

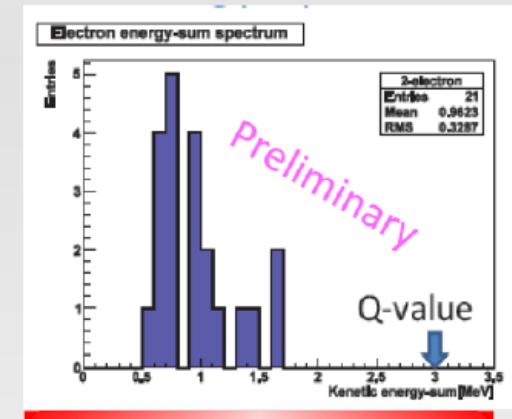
foil in drift chamber with uniform B



DCBA T2 9 cm x 26 cm x 26 cm  
FWHM @ 3 MeV = 6.2%



21 2νββ candidates



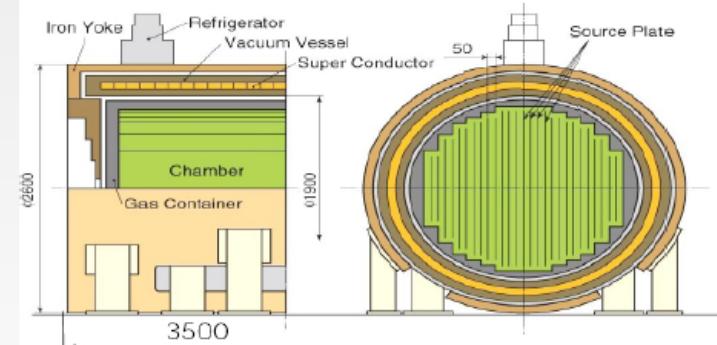
measured at KEK !!  
powerful bkg rejection !!

T2 chamber in T3 magnet (>2 kG)



next step:  
FWHM<5%?

## Magnetic Tracking Detector (temporary name)

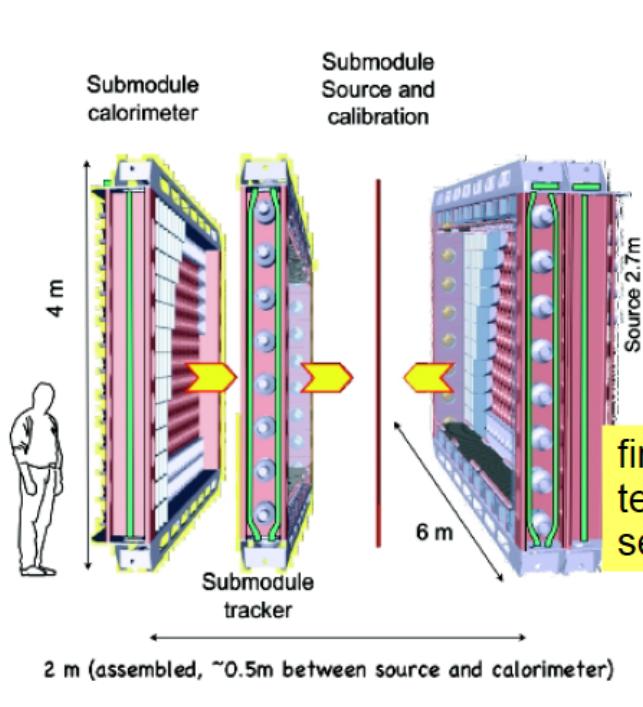


Schwingenheuer, Double Beta Decay  
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the future

# SuperNEMO

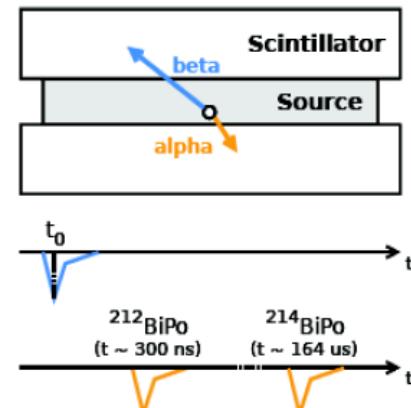
tracking + calorimeter, 20 modules



target material:  $^{82}\text{Se}$  40 mg/cm<sup>2</sup>

	NEMO3	SuperNEMO
mass	8 kg	100-200 kg
resolution	8%	4%
efficiency	8%	30%
foil bkg	<20 <300	<2 $\mu\text{Bq/kg}$ ( $^{208}\text{Tl}$ ) <10 $\mu\text{Bq/kg}$ ( $^{214}\text{Bi}$ )
sensitivity	$1.4 \times 10^{24}$	$1 \times 10^{26}$ $T_{1/2}$ 90% CL

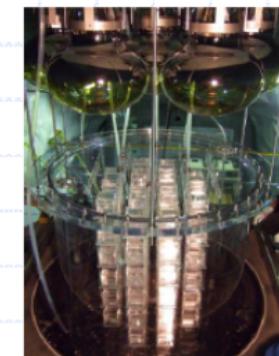
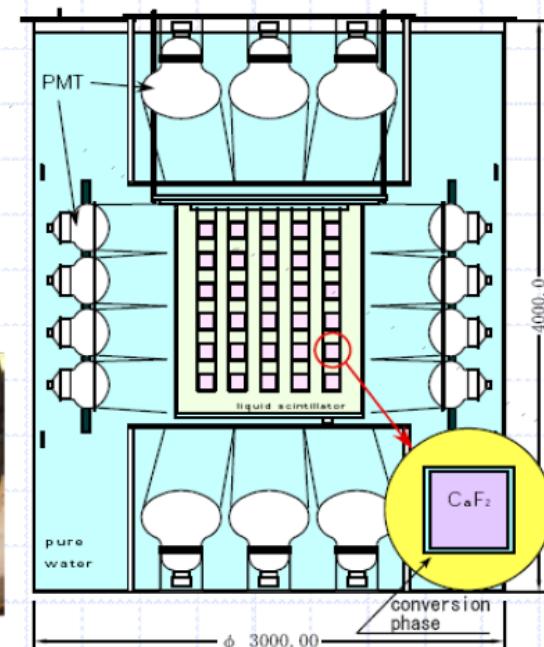
BiPo detector (3 m<sup>2</sup>) in 2012  
for foil measurement



# Candles

## CANDLES III(U.G.)

- ◆  $\text{CaF}_2$ (pure)
  - $10^3 \text{ cm}^3 \times 96$  crystals; 305 kg ( $^{48}\text{Ca}$ ;350 g)
- ◆ Liquid scintillator
  - two phase system
  - Purification system
- ◆  $\text{H}_2\text{O}$  Buffer
  - passive shield
- ◆ PMTs
  - 17" PMT ( $\times 14$ ) : R7250
  - 13" PMT ( $\times 48$ ) : R8055

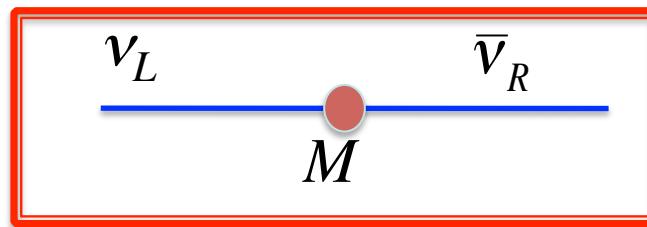


- ◆ Run will start at autumn 2011

R&D enrichment of  $^{48}\text{Ca}$  with Crown Ether chromatography



If  $0\nu2\beta$  is observed, it is important to understand what is the "magnetic field" which causes the transition

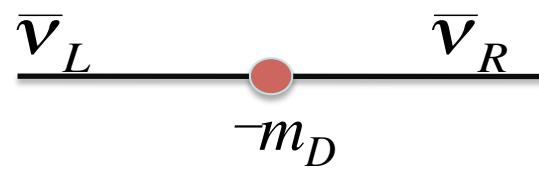
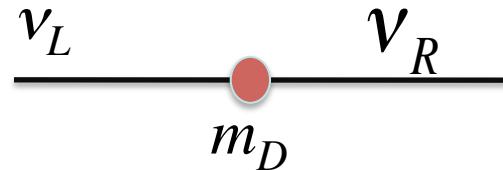


=> Theorist's job.

# Seesaw mechanism

The Majorana mass still does not explain the smallness of neutrino mass

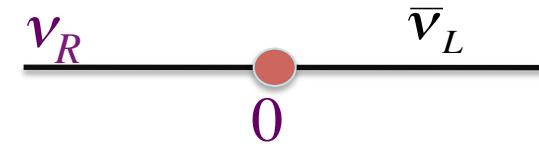
Assume  $\nu_R$  exists after all and the following 2 transition amplitude exist.



Where  $m_D$  is a typical Dirac mass  $\sim \text{GeV}$



exists but



does not exists.

And  $M$  is very large;  $\gg m_D$

## Seesaw mechanism to explain smallness of neutrino mass

In this case, the general neutrino wave function is expressed as,

$$\psi_\nu(t) = \nu_L(t)|\nu_L\rangle + \nu_R(t)|\nu_R\rangle + \bar{\nu}_L(t)|\bar{\nu}_L\rangle + \bar{\nu}_R(t)|\bar{\nu}_R\rangle$$

The equation of motion is,

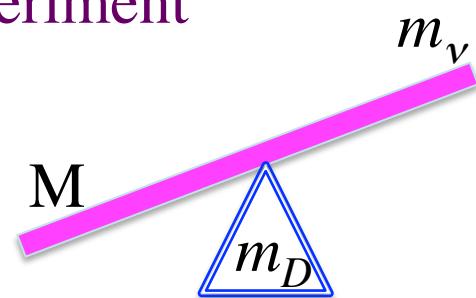
$$\frac{d}{dt} \begin{pmatrix} \nu_L \\ \nu_R \\ \bar{\nu}_L \\ \bar{\nu}_R \end{pmatrix} = -i \begin{pmatrix} 0 & m_D & 0 & M \\ m_D & 0 & 0 & 0 \\ 0 & 0 & 0 & -m_D \\ M & 0 & -m_D & 0 \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \\ \bar{\nu}_L \\ \bar{\nu}_R \end{pmatrix}$$

Assumeing  $M \gg m_D$ , the energy eigenstates ( $E > 0$ ) are,

$$\psi_\nu(t) \rightarrow \begin{cases} (|\bar{\nu}_R\rangle + |\nu_L\rangle) \exp(-i(m_D^2/M)t) & \leftarrow \text{This is our neutrino} \\ (|\nu_R\rangle + |\bar{\nu}_L\rangle) \exp(-iMt) & \leftarrow \text{This is heavy neutrino..} \\ & \text{too heavy to be produced} \\ & \text{by experiment} \end{cases}$$

If this is true, our neutrino mass is,

$$m_\nu = \frac{m_D^2}{M} = m_D \left( \frac{m_D}{M} \right)$$

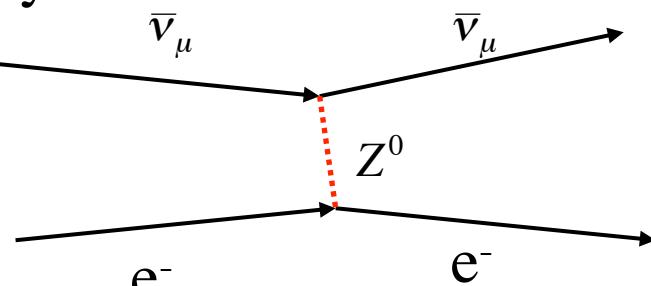


and is suppressed by factor  $m_D/M$  and lightness of neutrino mass can be naturally explained.

If we assume;  $m_\nu = m_{\nu 3} \sim 50 \text{ meV}$  &  $m_D = m_\tau = 1.7 \text{ GeV}$ ,  
 $M \sim 10^{11} \text{ GeV}$

# Roles of Neutrino Studies

## What we have learned from neutrino related observations

- \* Solved the anomaly of beta decays. 1930 Pauli
- \* Energy spectrum of beta decays  
→ Fermi theory of interaction (1934) Fermi
- \* Parity violation of  $\beta$  decays, Helicity of neutrinos → V-A theory
- \* Discovery of neutral current ( $Z^0$ )
- \* Determination of # of generations=3 from  $\nu$  flavor counting

→  $\nu$  has contributed to establish the standard model

- \* neutrino oscillation → beyond the standard model
- \* Mixing pattern different from quark's

== What comes next? ==

- \* Mass hierarchy ? absolute mass ?
- \* CP Violation?
- \* Majorana?



Will contribute to GUT

# **Now, it's your turn.**

I would like to thank to the FAPPS organizers  
for giving this very good opportunity to me.