Daya Bay II

Resolving Neutrino Mass Hierarchy
with a 60km Baseline Reactor Experiment

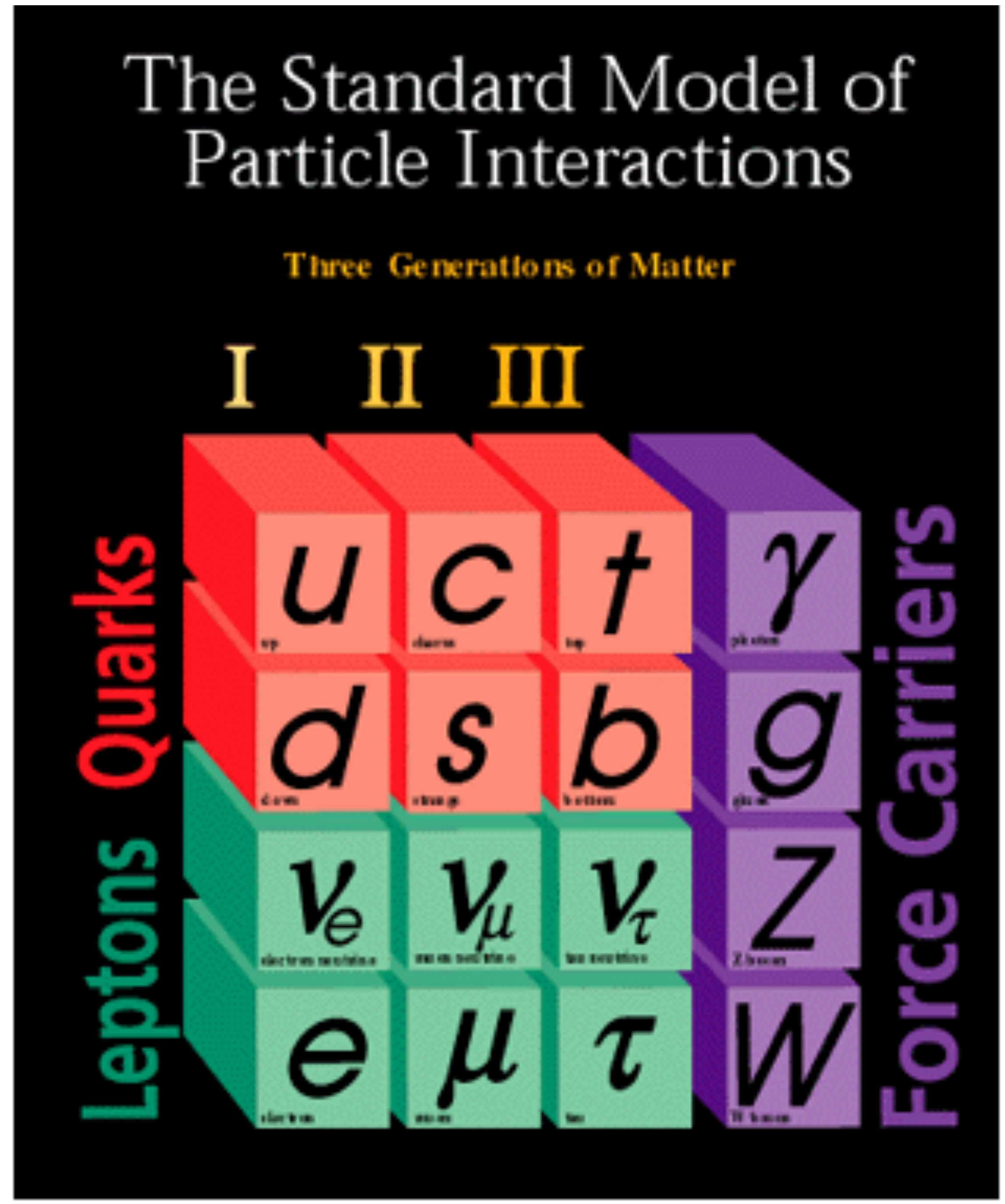
Chao Zhang
BNL

Outline

- Introduction to the neutrino oscillation physics, in particular the mass hierarchy problem and how to solve it.
  - Accelerator vs. Reactor
- Introduction to some basics of the reactor neutrino experiments.
- Daya Bay II and its technical challenges.

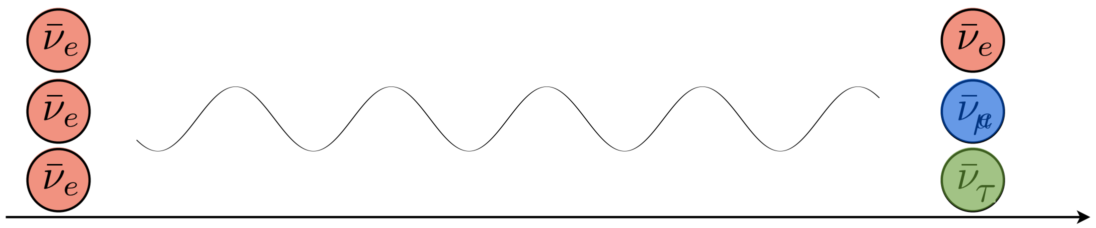
What is A Neutrino

- Neutrino is a fundamental particle in standard model
  - 3 flavors
  - spin 1/2
  - zero charge
  - weak interactions
  - only left-handed observed
  - non-zero mass
  - may be a Majorana fermion
    - particle == anti-particle



Neutrino Oscillation

neutrino flavor eigenstate ≠ mass eigenstate



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1/2} & 0 \\ 0 & 0 & e^{-i\alpha_2/2} \end{pmatrix}$$

Solar / KamLAND	Short baseline reactor / Long baseline accelerator	Atmospheric / Long baseline accelerator	Neutrinoless double beta decay

Neutrinos are produced and detected by weak interaction
but propagate in vacuum as mass eigenstates

Two neutrino model $|\nu_\alpha(t)\rangle = \cos\theta e^{-iE_it}|\nu_1\rangle + \sin\theta e^{-iE_it}|\nu_2\rangle$

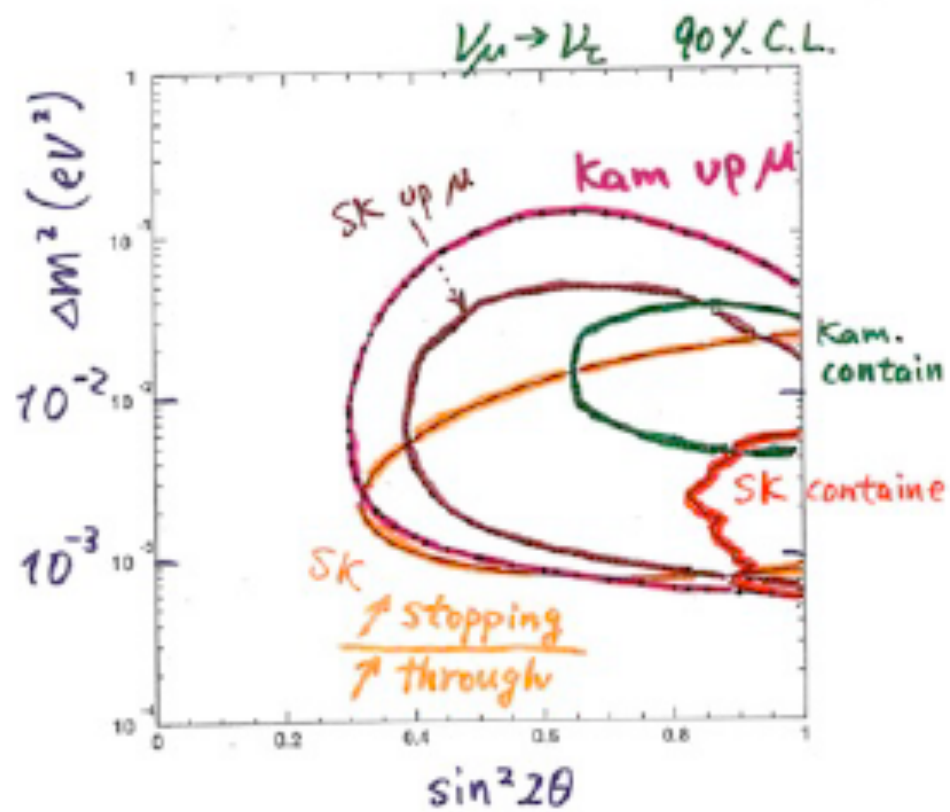
Appearance $P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2[\text{eV}^2]\dfrac{L\,[\text{km}]}{E\,[\text{GeV}]}\right)$

Disappearance $P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2[\text{eV}^2]\dfrac{L\,[\text{km}]}{E\,[\text{GeV}]}\right)$

Neutrino Oscillation

Summary Neutrino1998

Evidence for ν_μ oscillations



- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

Neutrino Oscillation

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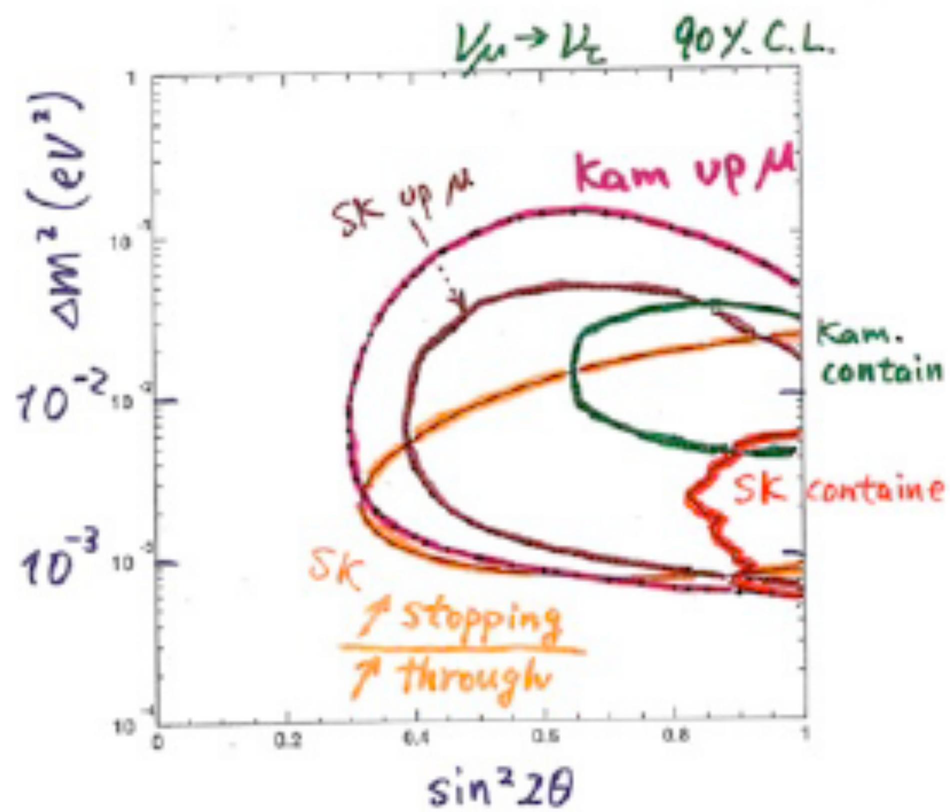

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(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

~25 years later

2012 Status

(from Lisi's 3ν fit)

$\Delta m^2_{23} = (2.43^{+0.06}_{-0.10}) \times 10^{-3}\ eV^2$

$\Delta m^2_{12} = (7.54^{+0.26}_{-0.22}) \times 10^{-5}\ eV^2$

$\sin^2\theta_{13} = 0.0242^{+0.0025}_{-0.0025}$

$\sin^2\theta_{12} = 0.307^{+0.18}_{-0.16}$

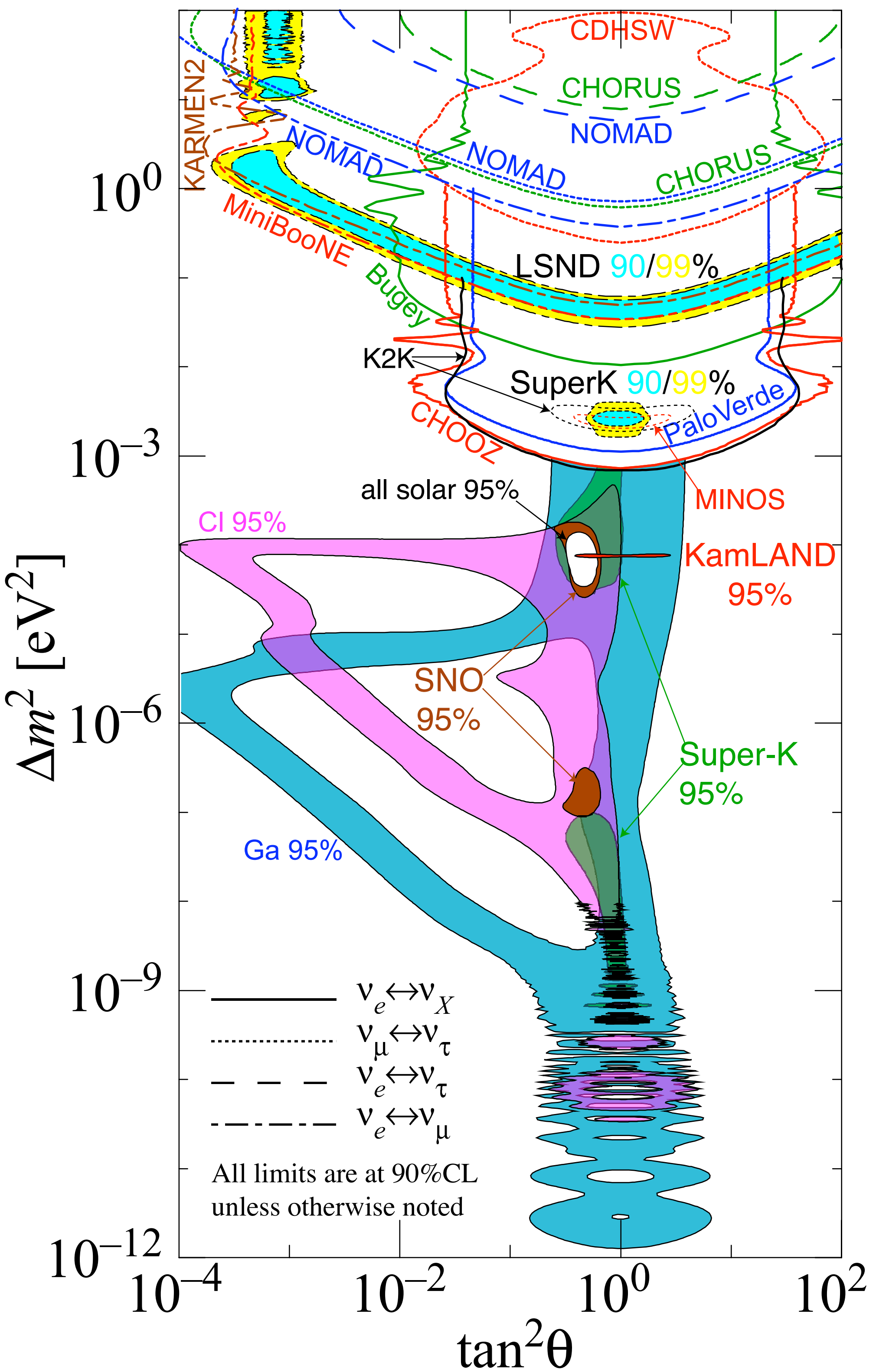
$\sin^2\theta_{23} = 0.389^{+0.24}_{-0.21}$

Fractional 1σ accuracy [defined as 1/6 of ±3σ range]

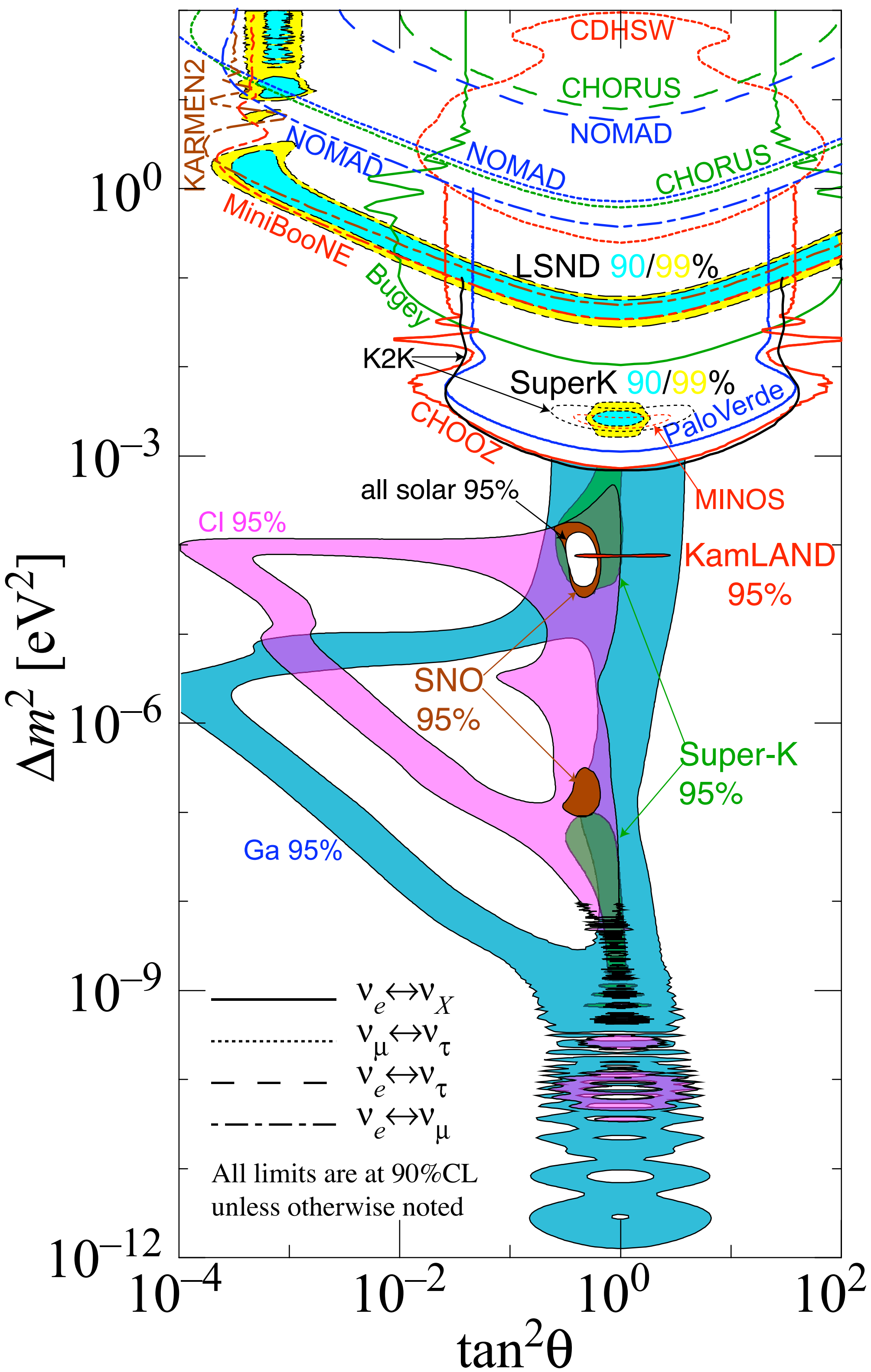
δm^2	Δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
2.6%	3.0%	5.4%	10%	14%

Fogli et al. arXiv: 1205.5254

‘Many Many’ Oscillation Experiments



Combining Together



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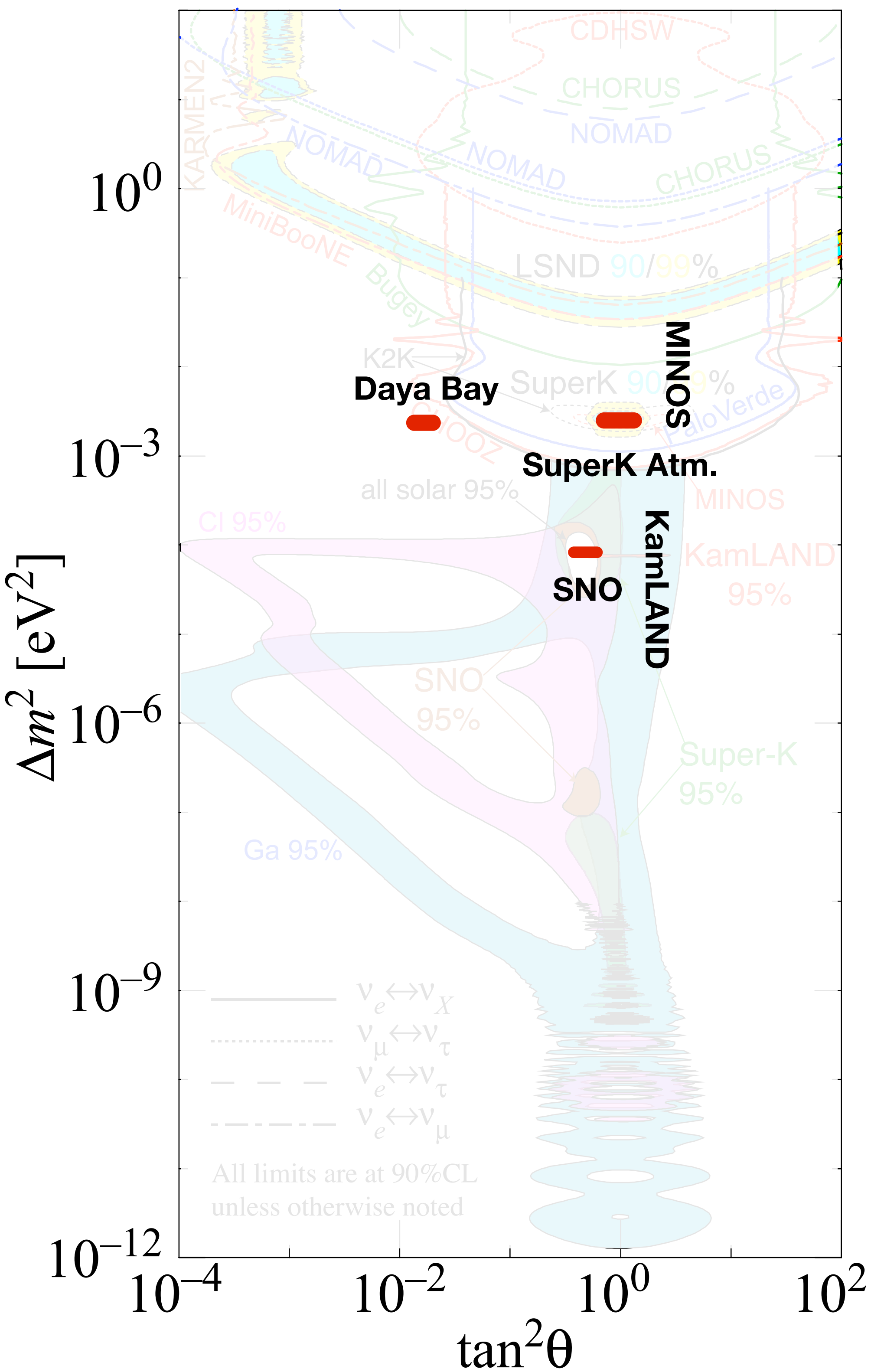
Great success of the neutrino oscillation experiments!

Combining Together



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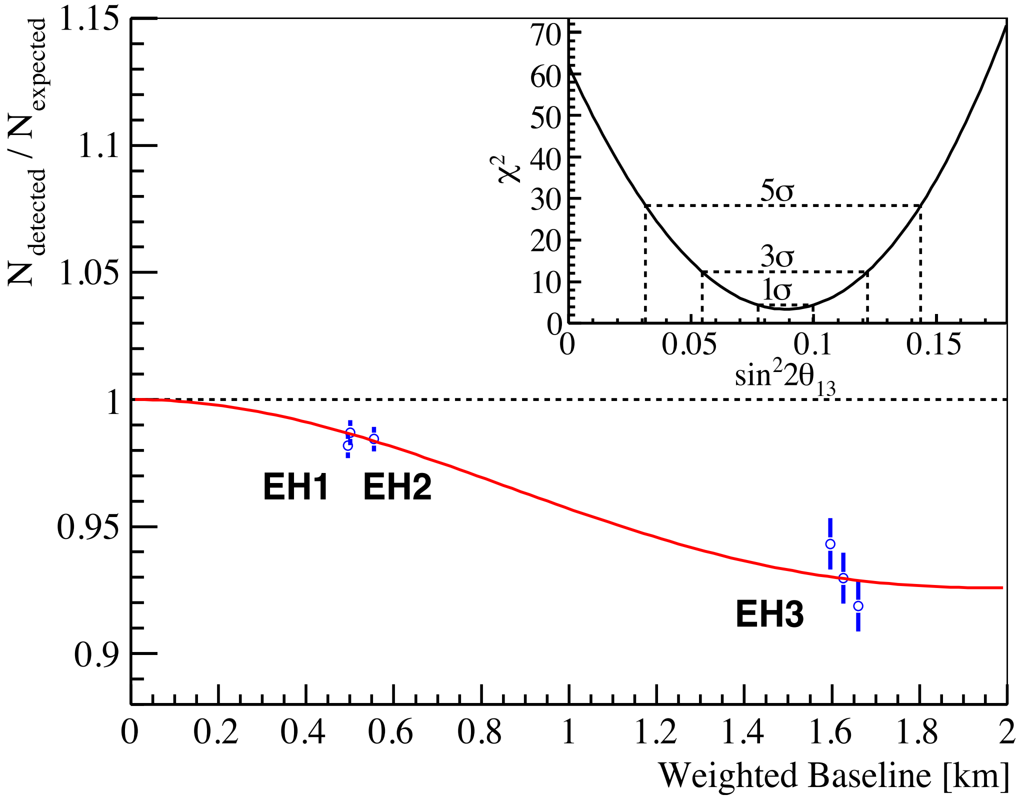
Great success of the neutrino oscillation experiments!

θ_{13} is Large!

The Daya Bay Group at BNL



$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\mathrm{stat}) \pm 0.005\ (\mathrm{syst})$

Neutrino 2012

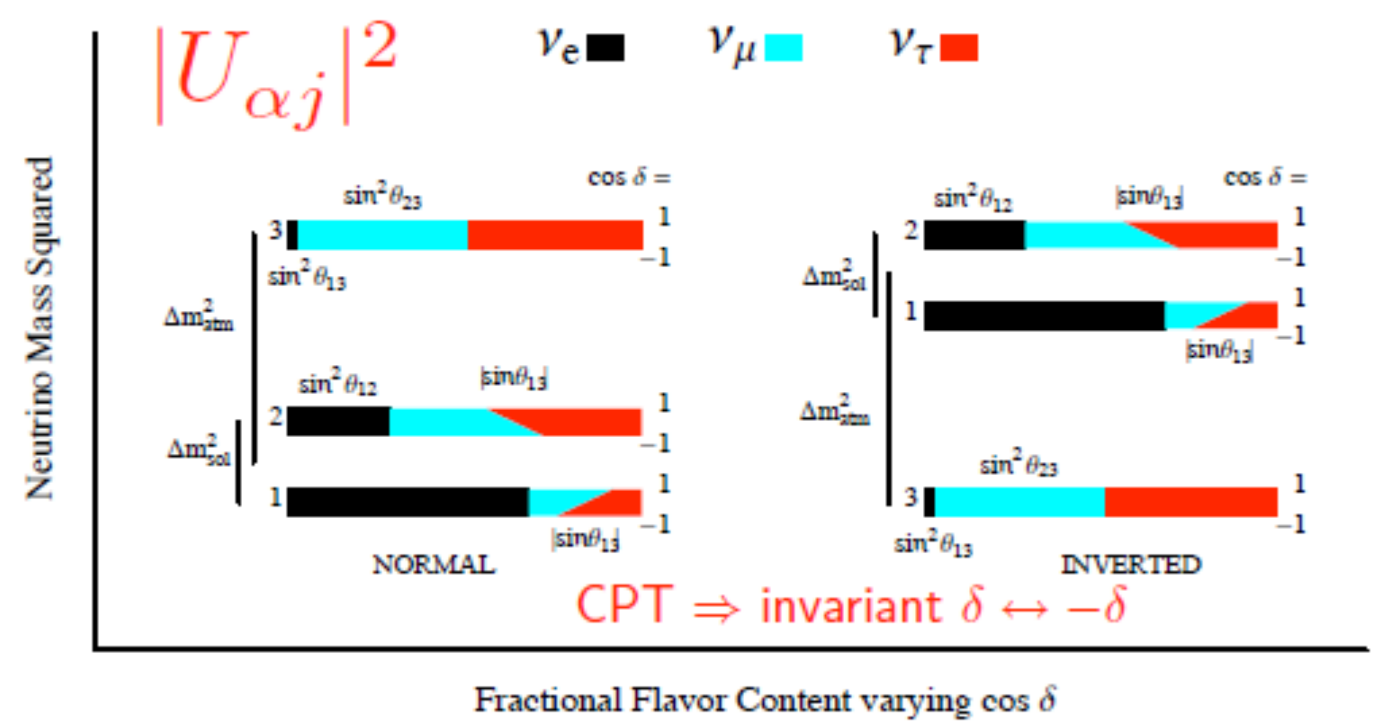
http://www.bnl.gov/video/index.php?v=265

Remaining Unknown

Atm. dom. | Atm. subdom. | Solar | Majorana

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\times\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\times\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\times\begin{pmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}$$

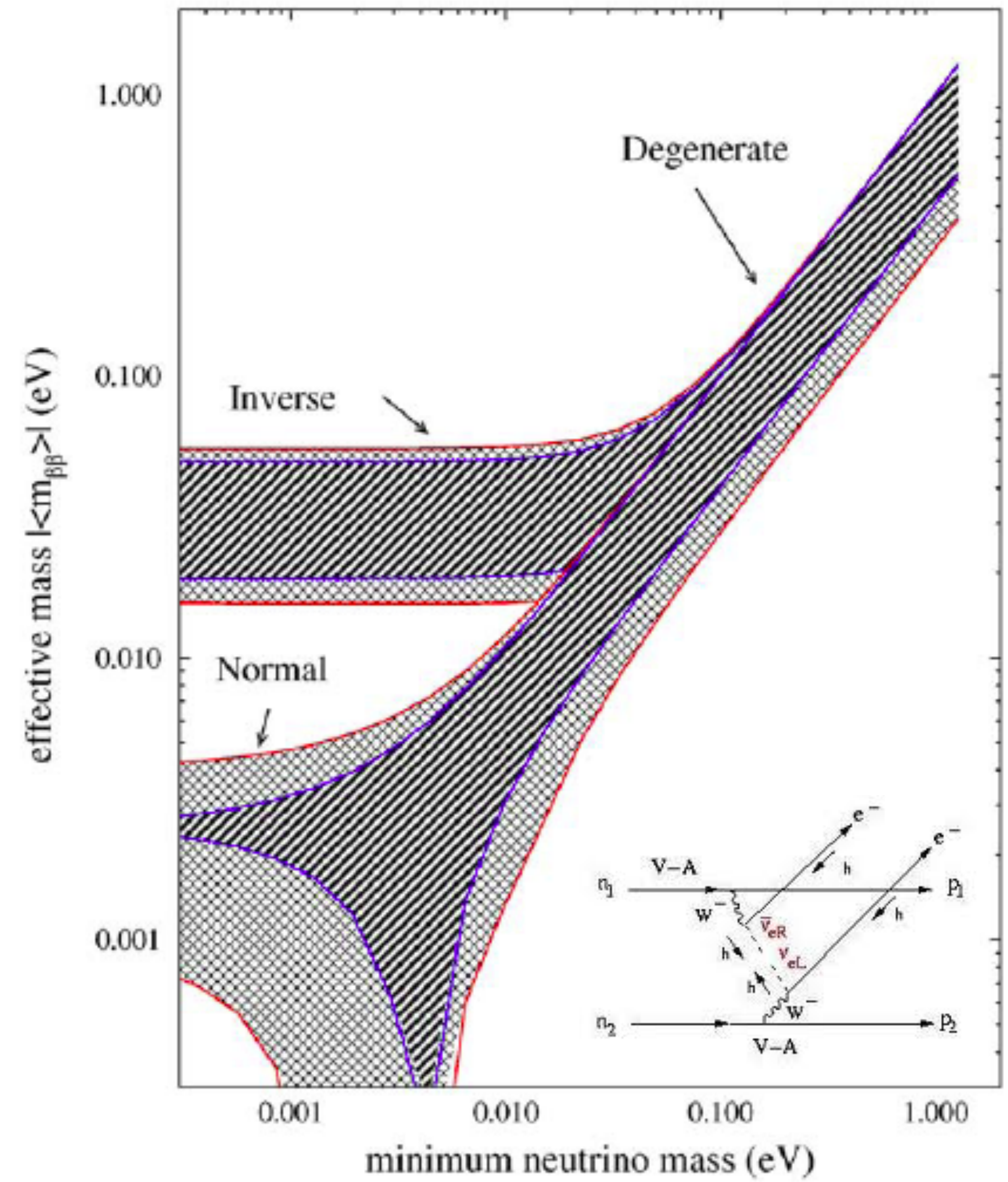
- **How large is the CP phase?**
- **Is neutrino a Majorana particle?**
- **Is neutrino mass hierarchy normal or inverted?**



The known, large θ_{13} allows us to define future program

Why Is Mass Hierarchy Important

- One example impact on Neutrino-less Double Beta Decay Search
  - If MH is **Inverse**, the potential for detecting neutrino as a **Majorana Particle** is greatly enhanced



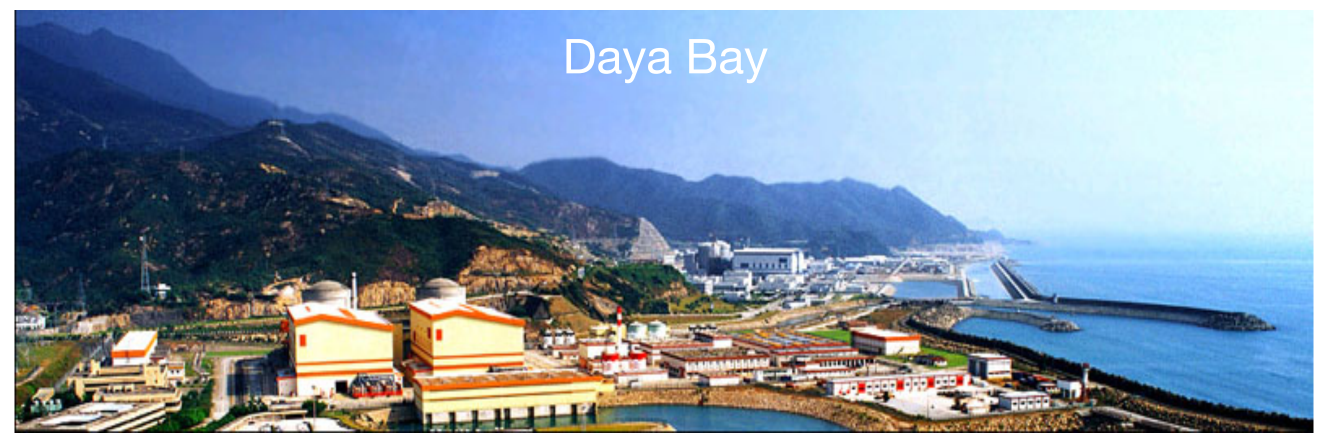
Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yrs]	Status	Start of data-taking	Sensitivity $\langle m_\nu \rangle$ [eV]
GERDA	^{76}Ge	18	3×10^{25}	running	~ 2011	0.17-0.42
		40	2×10^{26}	in progress	~ 2012	0.06-0.16
		1000	6×10^{27}	R&D	~ 2015	0.012-0.030
CUORE	^{130}Te	200	$6.5 \times 10^{26*}$	in progress	~ 2013	0.018-0.037
			$2.1 \times 10^{26**}$			0.03-0.066
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	in progress	~ 2013	0.06-0.16
		1000	6×10^{27}	R&D	~ 2015	0.012-0.030
EXO	^{136}Xe	200	6.4×10^{25}	running	~ 2011	0.073-0.18
		1000	8×10^{26}	R&D	~ 2015	0.02-0.05
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	~ 2013-15	0.04-0.096
KamLAND-Zen	^{136}Xe	400	4×10^{26}	running	~ 2011	0.03-0.07
		1000	10^{27}	R&D	~ 2013-15	0.02-0.046
SNO+	^{150}Nd	132	1.8×10^{25}	in progress	~ 2014	0.09-0.18

from Rodejohann

Two 'Conventional' Approaches

Accelerator

V.S.



Reactor

Accelerator Experiments

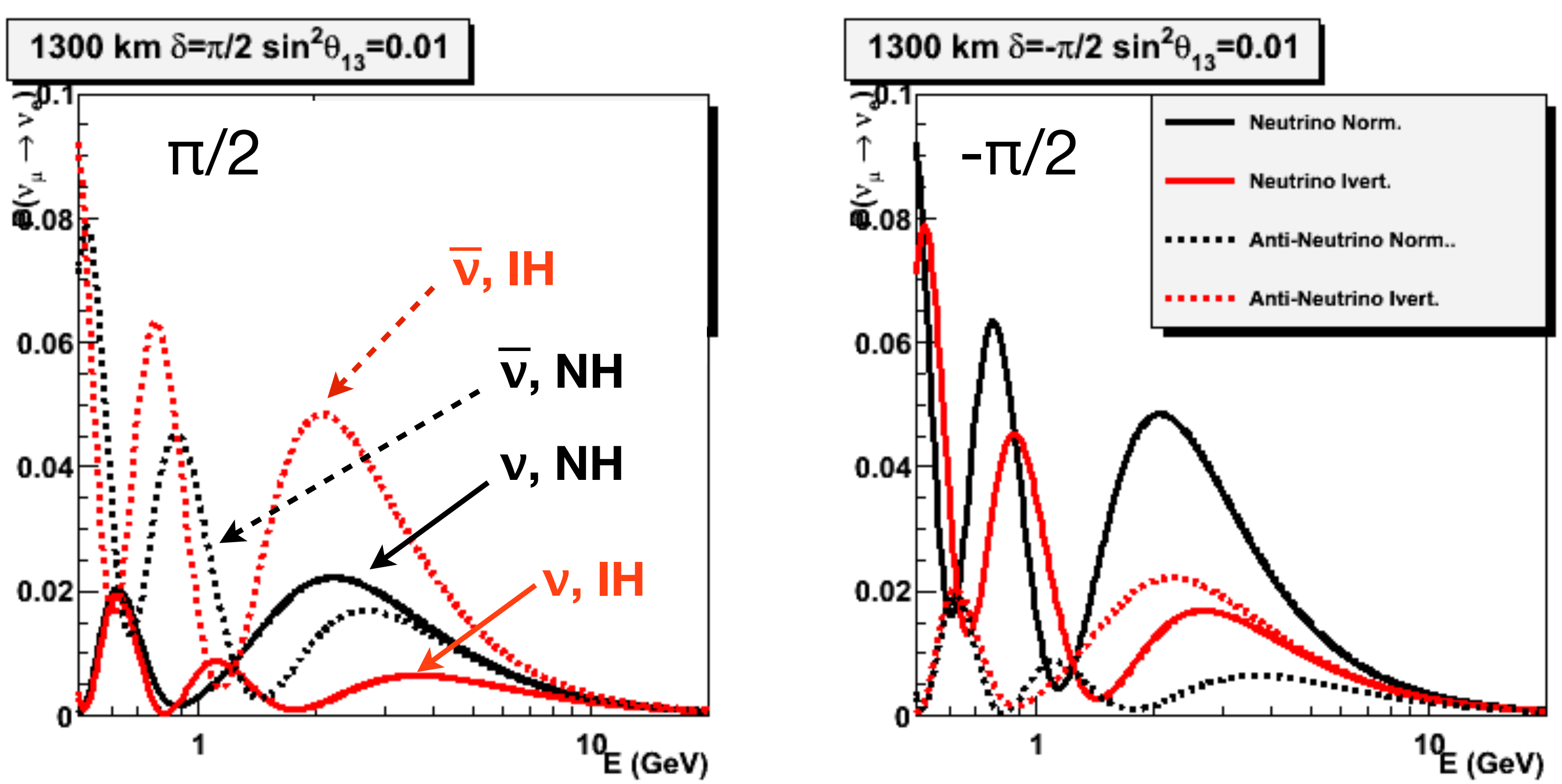
$$P(\nu_\mu \to \nu_e) = x^2 f^2 + 2xyfg(\cos\delta\cos\Delta - \sin\delta\sin\Delta) + y^2 g^2$$
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = x^2 \overline{f}^2 + 2xy\overline{f}g(\cos\delta\cos\Delta + \sin\delta\sin\Delta) + y^2 g^2$$
$$\Bigg\} \Delta m^2_{31} > 0$$

$$P(\nu_\mu \to \nu_e) = x^2 \overline{f}^2 - 2xy\overline{f}g(\cos\delta\cos\Delta + \sin\delta\sin\Delta) + y^2 g^2$$
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = x^2 f^2 - 2xyfg(\cos\delta\cos\Delta - \sin\delta\sin\Delta) + y^2 g^2$$
$$\Bigg\} \Delta m^2_{31} < 0$$

$$\Delta = 1.27\,|\Delta m^2_{31}|\frac{L}{E} \qquad x = 2s_{23}s_{13}c_{13} \qquad f, \overline{f} = \frac{\sin\left[(1 \mp \hat{A})\Delta\right]}{(1 \mp \hat{A})}$$

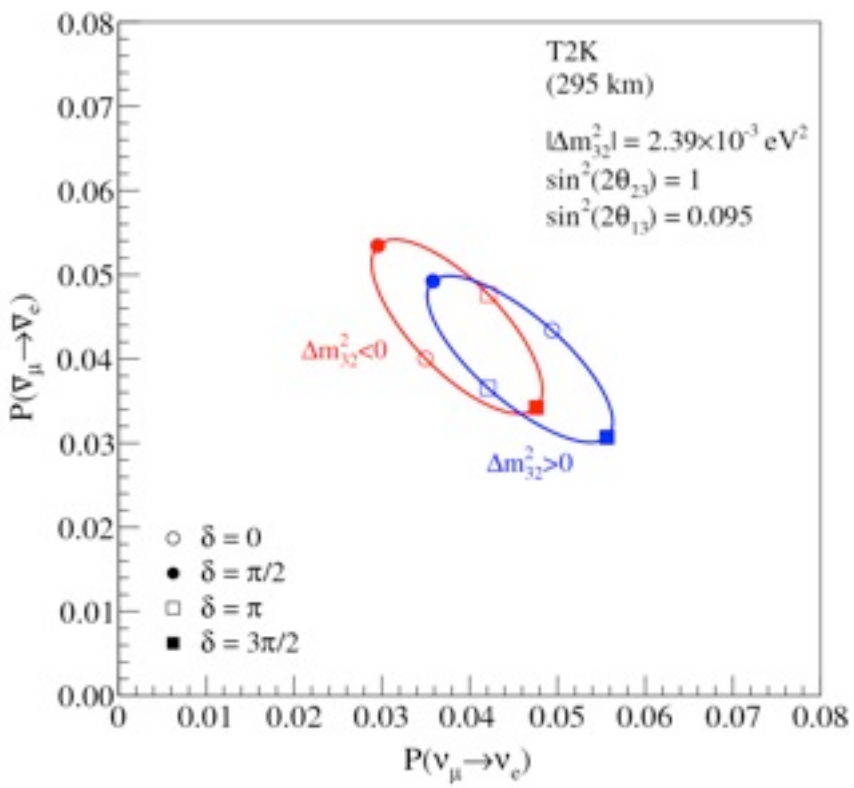
$$\hat{A} = \left|A / \Delta m^2_{31}\right| \qquad y = 2\alpha \cdot c_{23}s_{12}c_{12} \qquad g = \frac{\sin(\hat{A}\Delta)}{\hat{A}} = \Delta(\hat{A} \equiv 0)$$

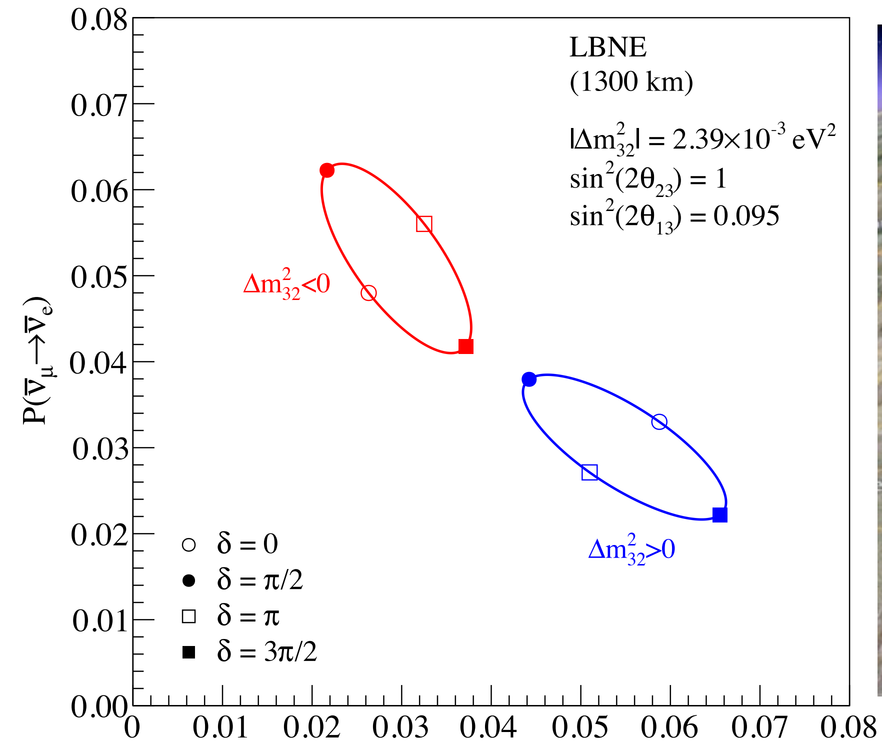
$$\alpha = |\Delta m^2_{21} / \Delta m^2_{31}|$$

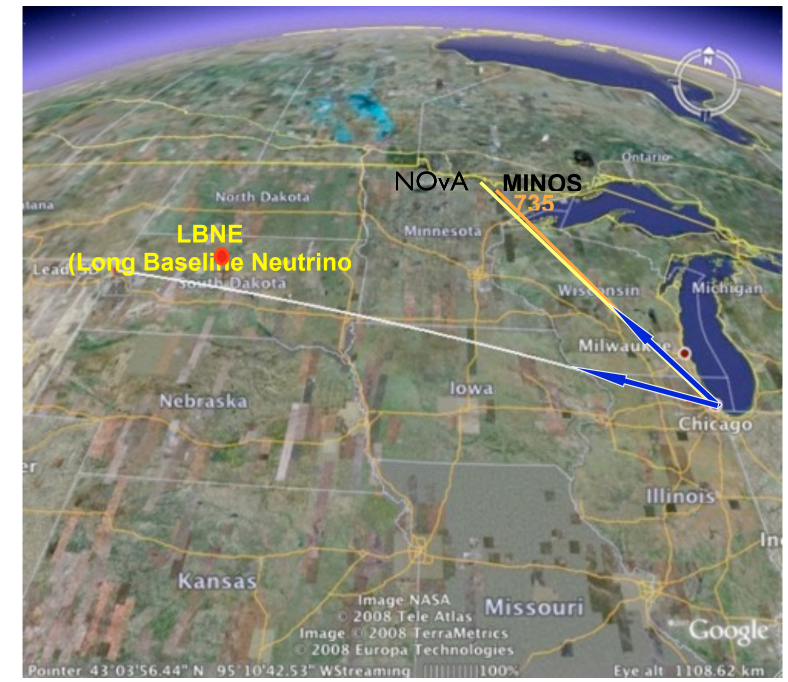


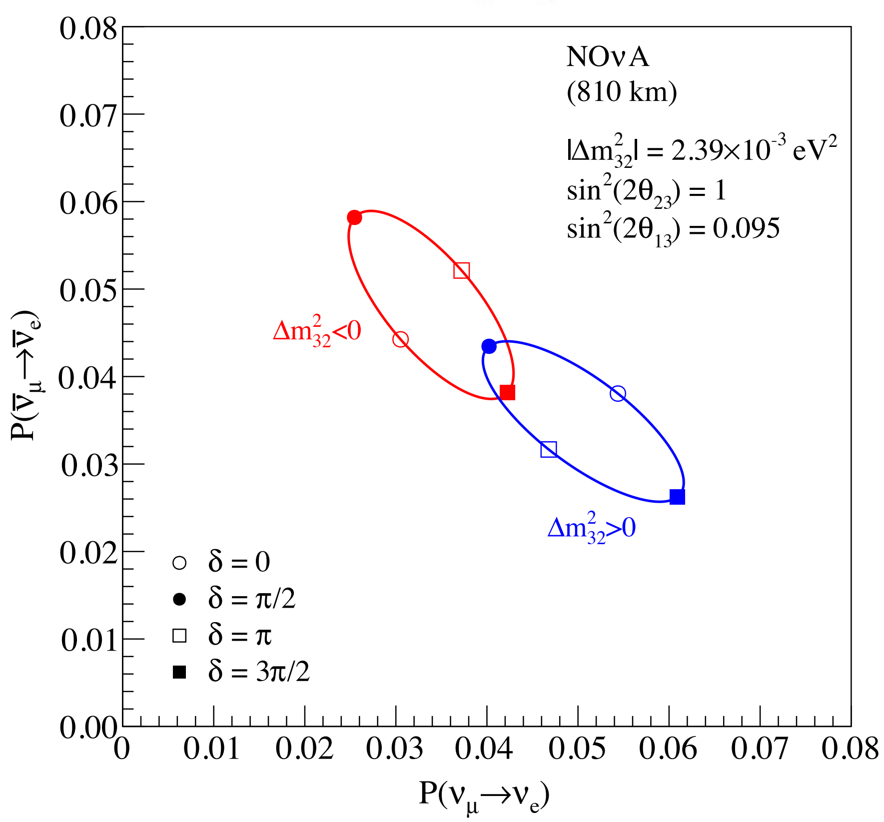
- Complicated Formula
  - Interference of all oscillation parameters, in particular CP.
  - Resolve the CP degeneracy by comparing appearance probability between neutrinos and antineutrinos
- Clear signal with the optimized energy and distance
  - large MH dependence through matter effect.

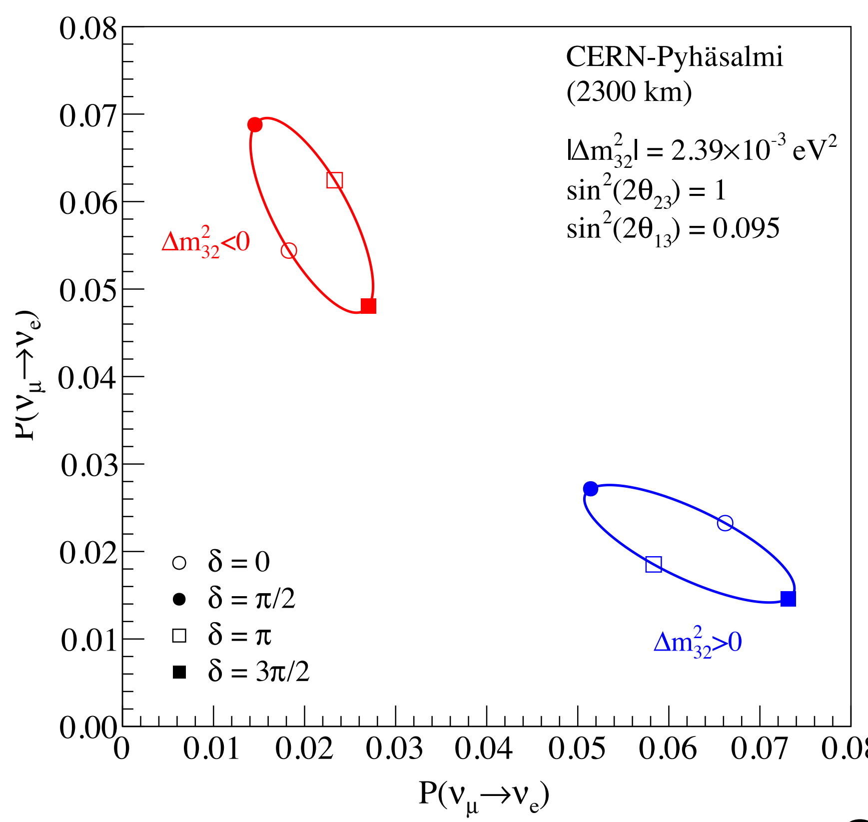
How to Resolve Degeneracy









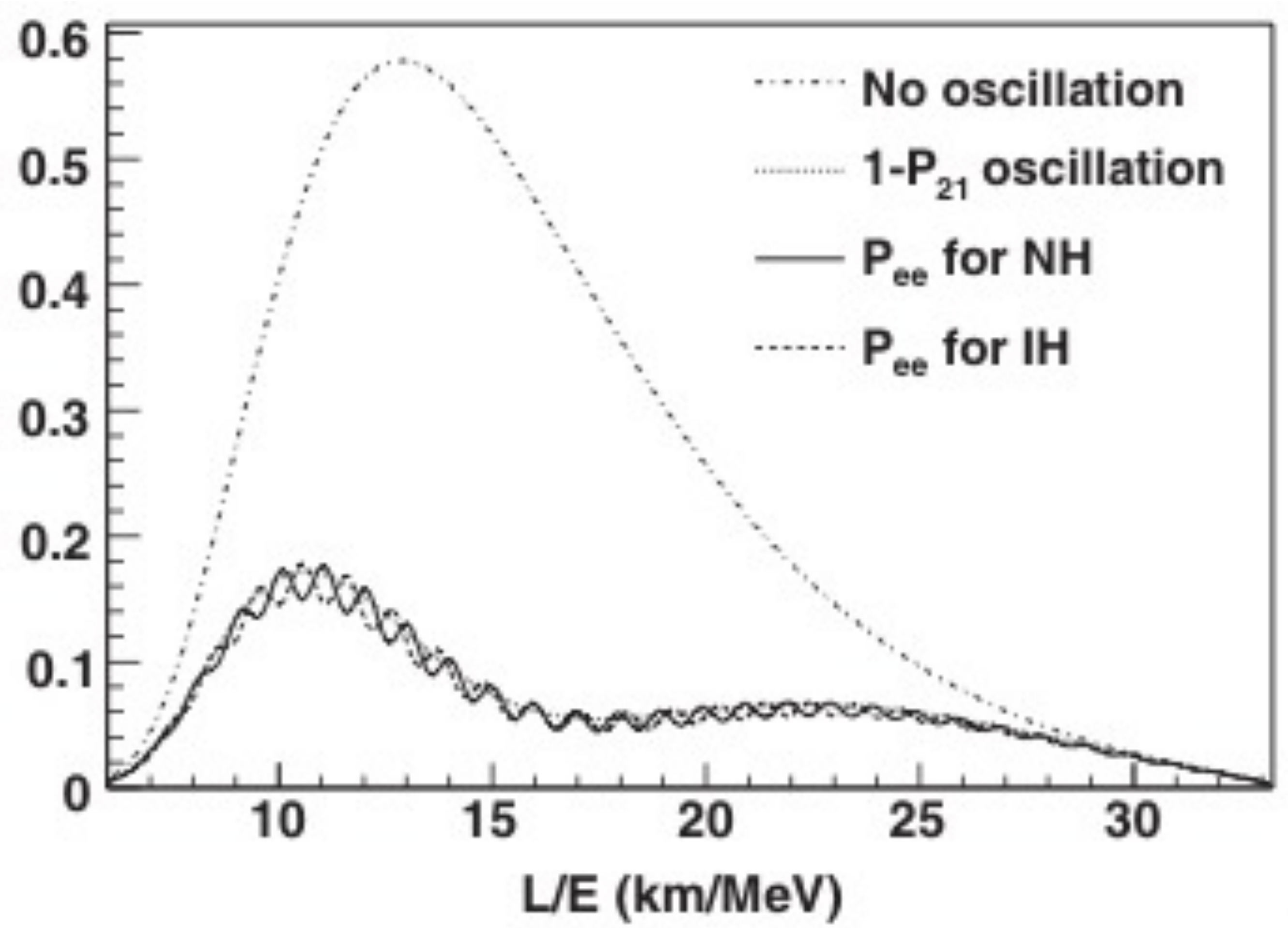


S. Wojcicki, NPB2012

Reactor Experiments

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - 4s_{13}^2 c_{13}^2 \left(c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32}\right) - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}$$

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij} \qquad \Delta_{ij} : \delta m_{ij}^2 \cdot \frac{L}{E}$$

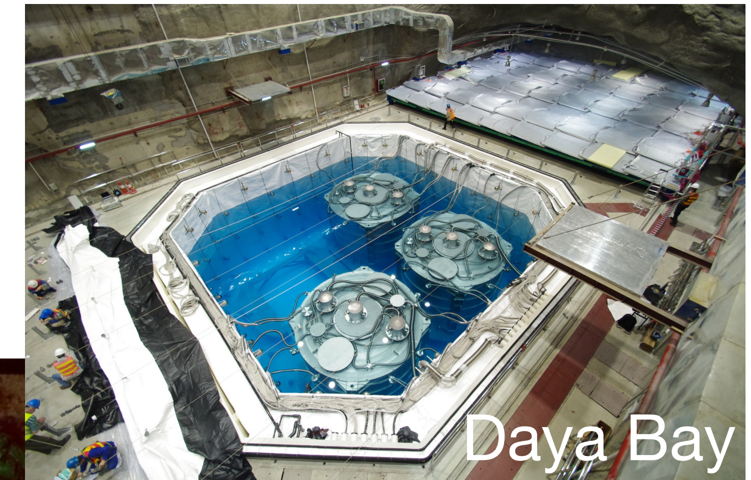


- Simple Formula
  - Disappearance
  - No CP dependence
- Small MH dependence
  - Two different oscillation frequencies, but the difference is small
  - need large statistics
  - need good control of systematics

History of Reactor Experiments

From Karsten Heeger

2012 - Observation of short baseline reactor electron neutrino disappearance



2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos

Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
KamLAND, Japan
Double Chooz, France
Reno, Korea
Daya Bay, China

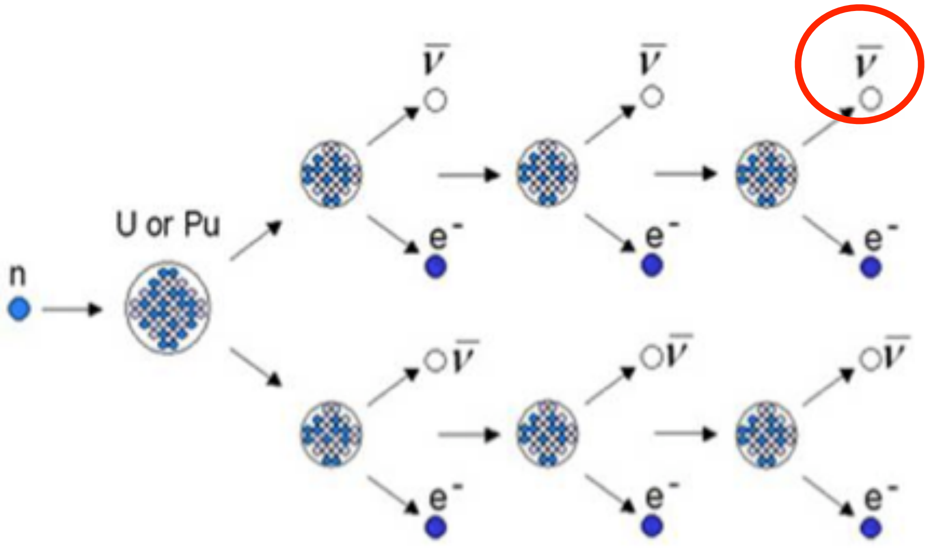
Reactor Neutrinos

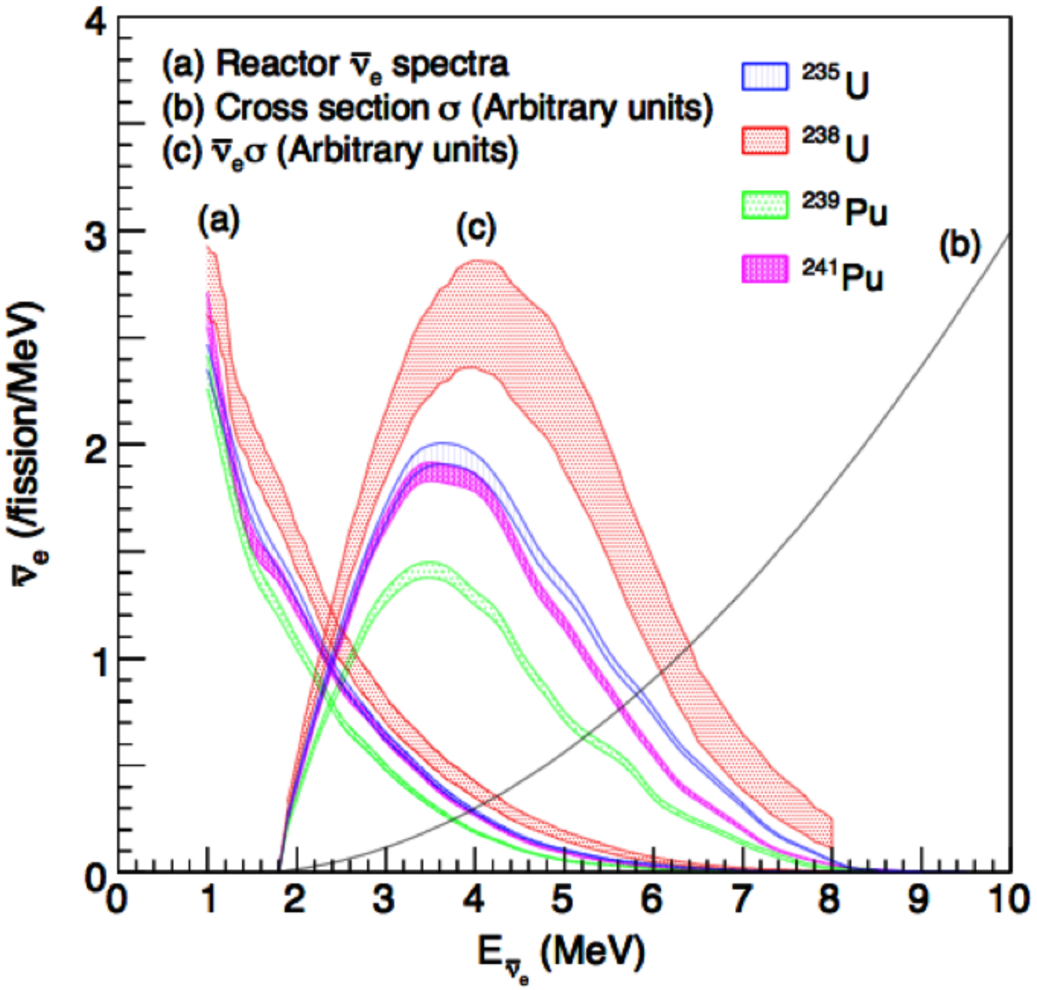
Nuclear Reactor

- pure $\bar{\nu}_e$ source
- 6 $\bar{\nu}_e$ / fission
- 6 x 10^{20} $\bar{\nu}_e$ / sec / $3GW_{th}$

Free neutrinos!

β[-] decay of neutron rich fission fragments





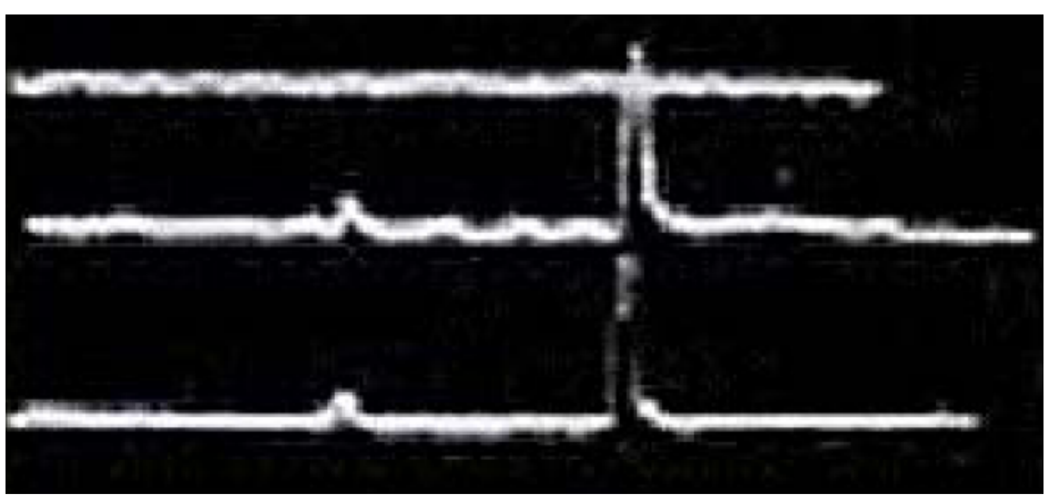
Detection of Reactor Antineutrinos

Inverse Beta Decay (IBD)

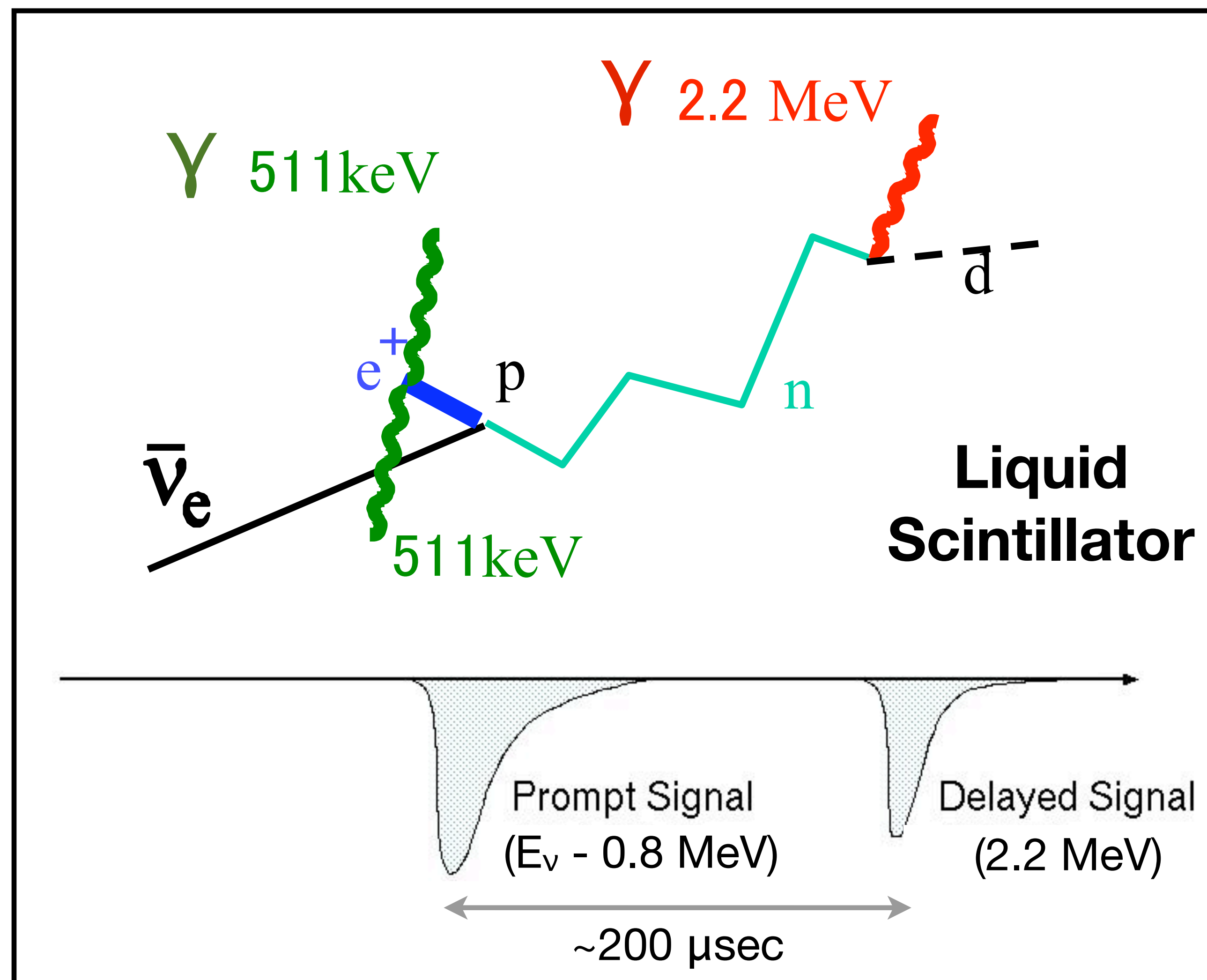
- $E_{threshold}$ = 1.8 MeV
- 'Large' cross section $\sigma \sim 10^{-42}$ cm^2
- Distinctive coincidence signature in a large liquid scintillator detector

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

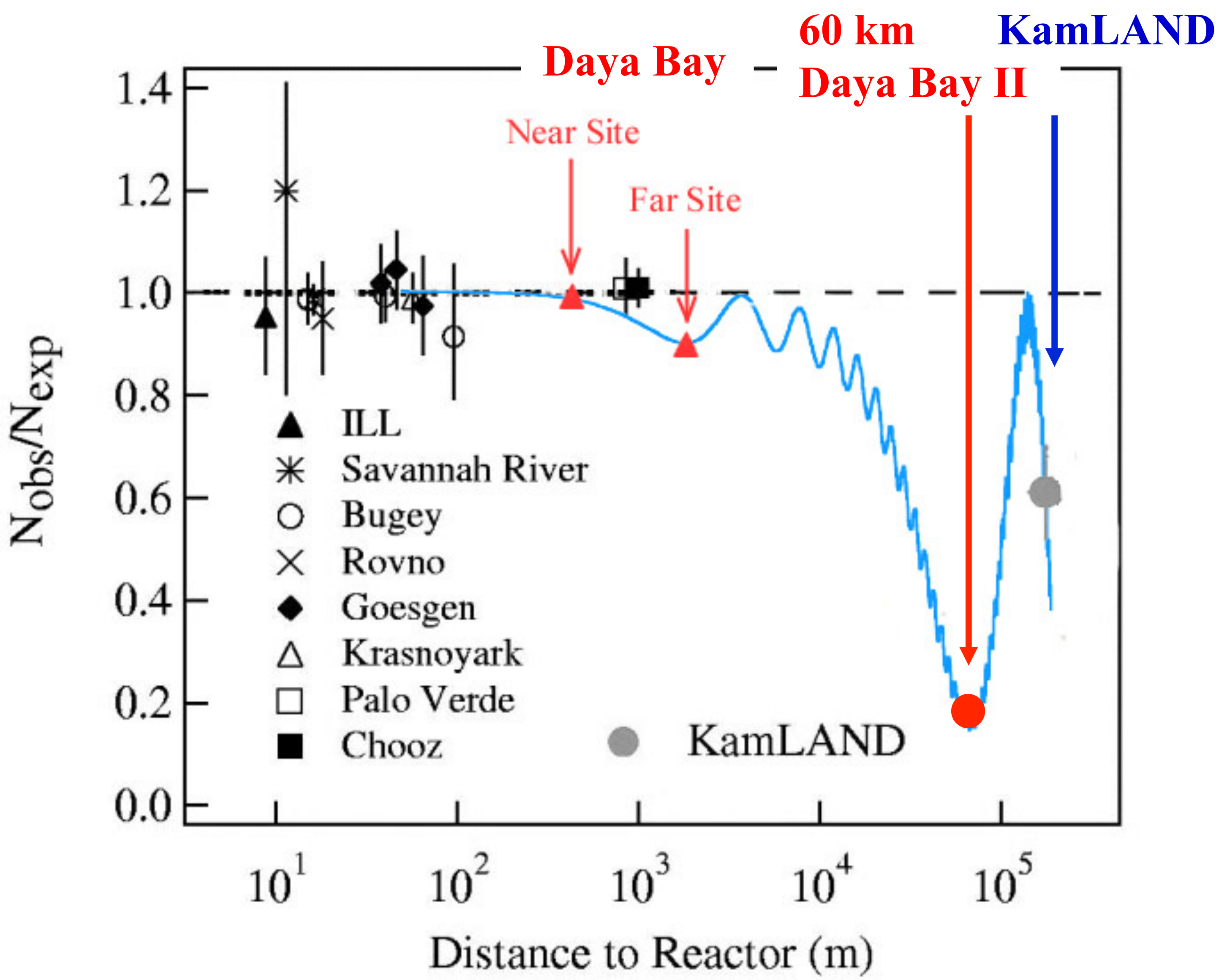
$$n + p \rightarrow d + \gamma$$



Cowan & Reines, Savannah River 1956



Daya Bay II

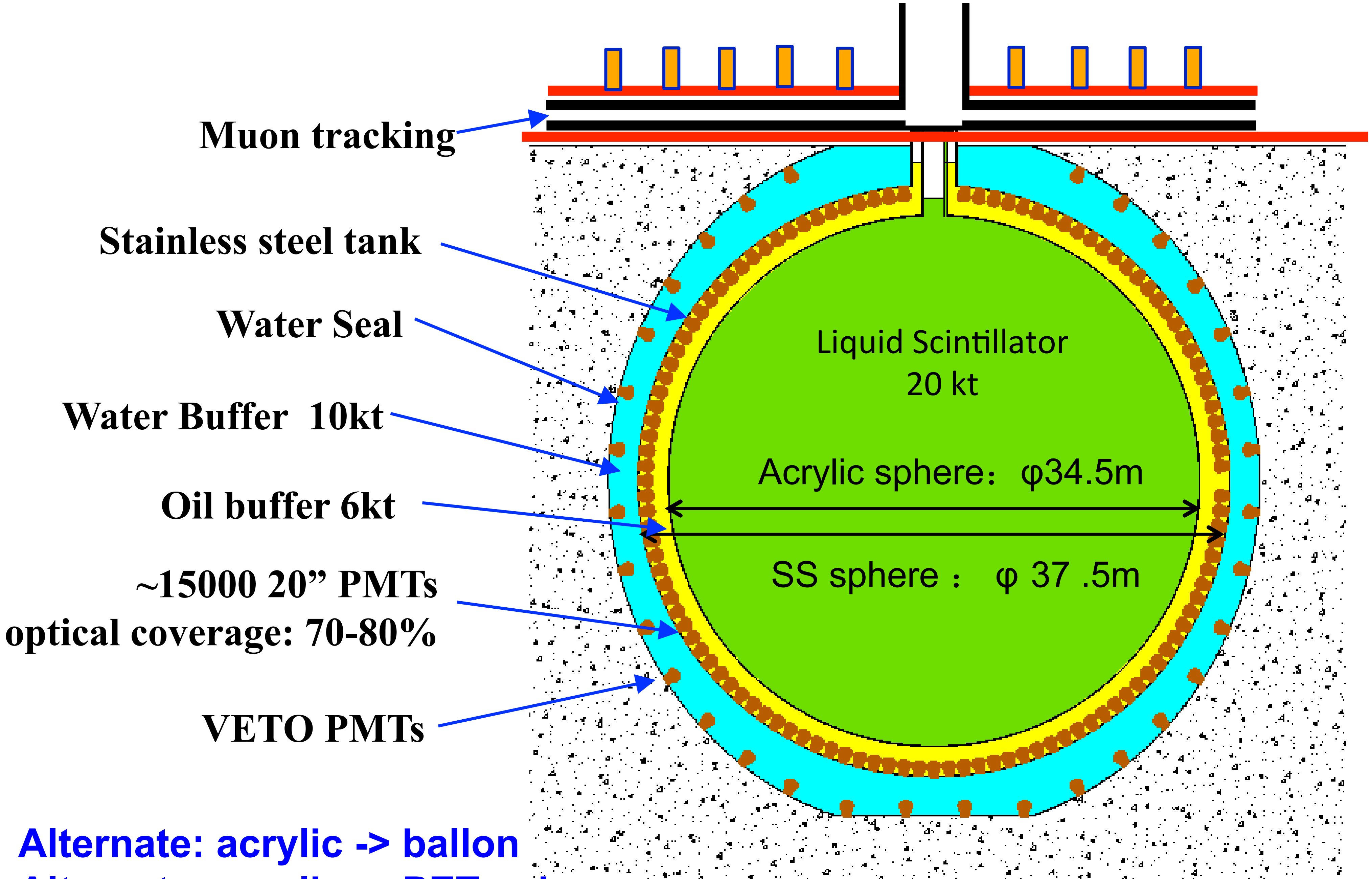


- **20-50 kton LS detector**
- **2-3 % energy resolution**
- Rich physics possibilities
  - **Mass hierarchy**
  - **Precision measurement of 4 mixing parameters**
  - **Supernovae neutrino**
  - **Geoneutrino**
  - **Sterile neutrino**
  - **Atmospheric neutrinos**
  - **Exotic searches**

- Possible time schedule:
  - Proposal to government: 2015
  - Construction: 2016 - 2020

Yifang Wang, Nufact 2012

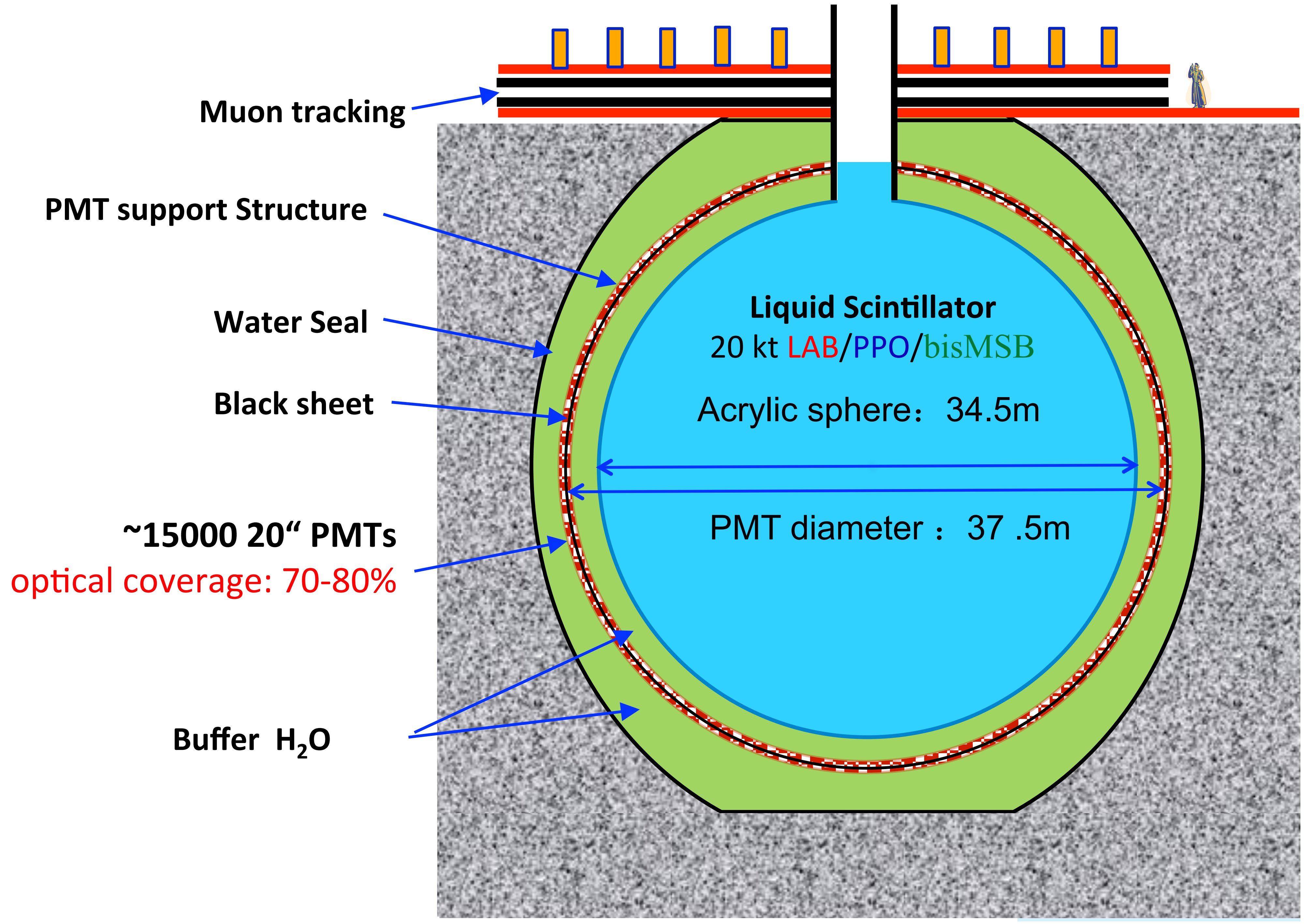
Detector Concept (Traditional)



Alternate: acrylic -> ballon
Alternate: acrylic -> PET sphere

J. Cao, NPB2012

Alternative One: Water



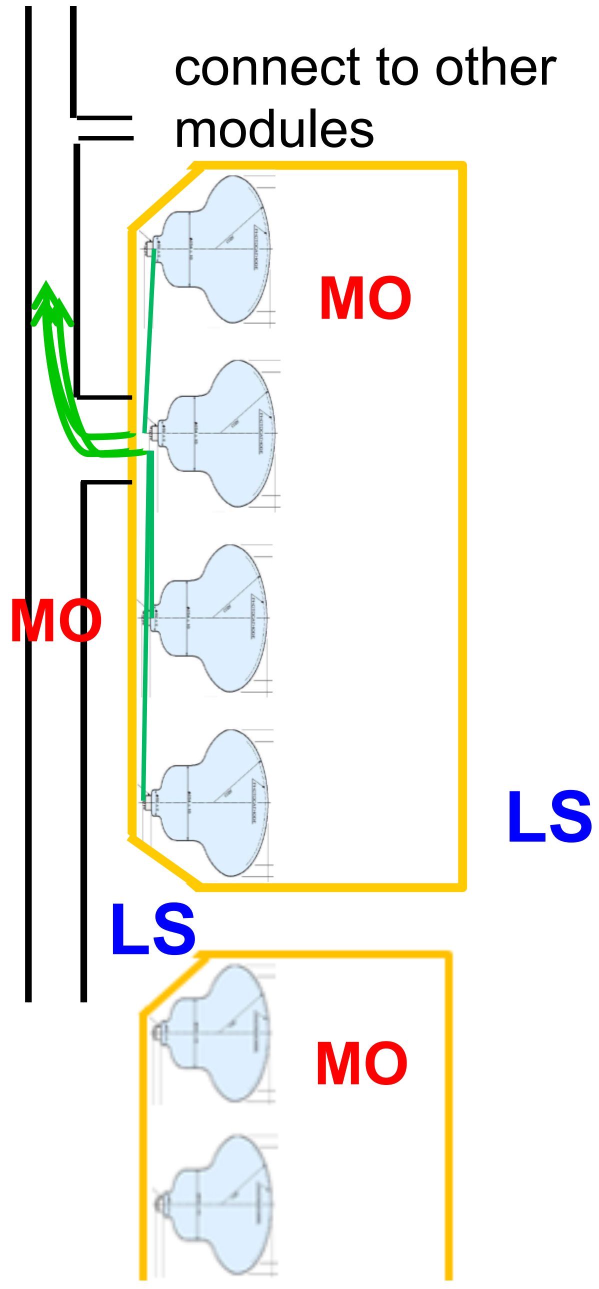
J. Cao, NPB2012

Alternative Two: MO Module

- **Seal the Mineral Oil in the optical modules.**
- **LS contact with SS vessel**
- **pipe for filling MO and cabling**

- **Detector can be cylindric or spheric**

- **Disadvange:**
  - **Radioactivity: LS in the gap produce light**
  - **Contamination to LS from complex structure**



J. Cao, NPB2012

Technical Challenges

- Parameter Degeneracy
- Energy Resolution
- Energy Non-linearity

Challenge: Degeneracy From $|\Delta m^2_{32}|$

$$\begin{aligned} P(\bar{\nu}_e \to \bar{\nu}_e) &= 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &= 1 - 2s^2_{13}c^2_{13} - 4c^2_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21} + 2s^2_{13}c^2_{13}\sqrt{1 - 4s^2_{12}c^2_{12}\sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi) \end{aligned}$$

$$\sin\phi = \frac{c^2_{12}\sin 2\Delta_{21}}{\sqrt{1 - 4s^2_{12}c^2_{12}\sin^2\Delta_{21}}} \qquad \Delta_{ij} \equiv |\Delta_{ij}| = 1.27|\Delta m^2_{ij}|\frac{L(m)}{E(MeV)}$$

$$\cos\phi = \frac{c^2_{12}\cos 2\Delta_{21} + s^2_{12}}{\sqrt{1 - 4s^2_{12}c^2_{12}\sin^2\Delta_{21}}}.$$

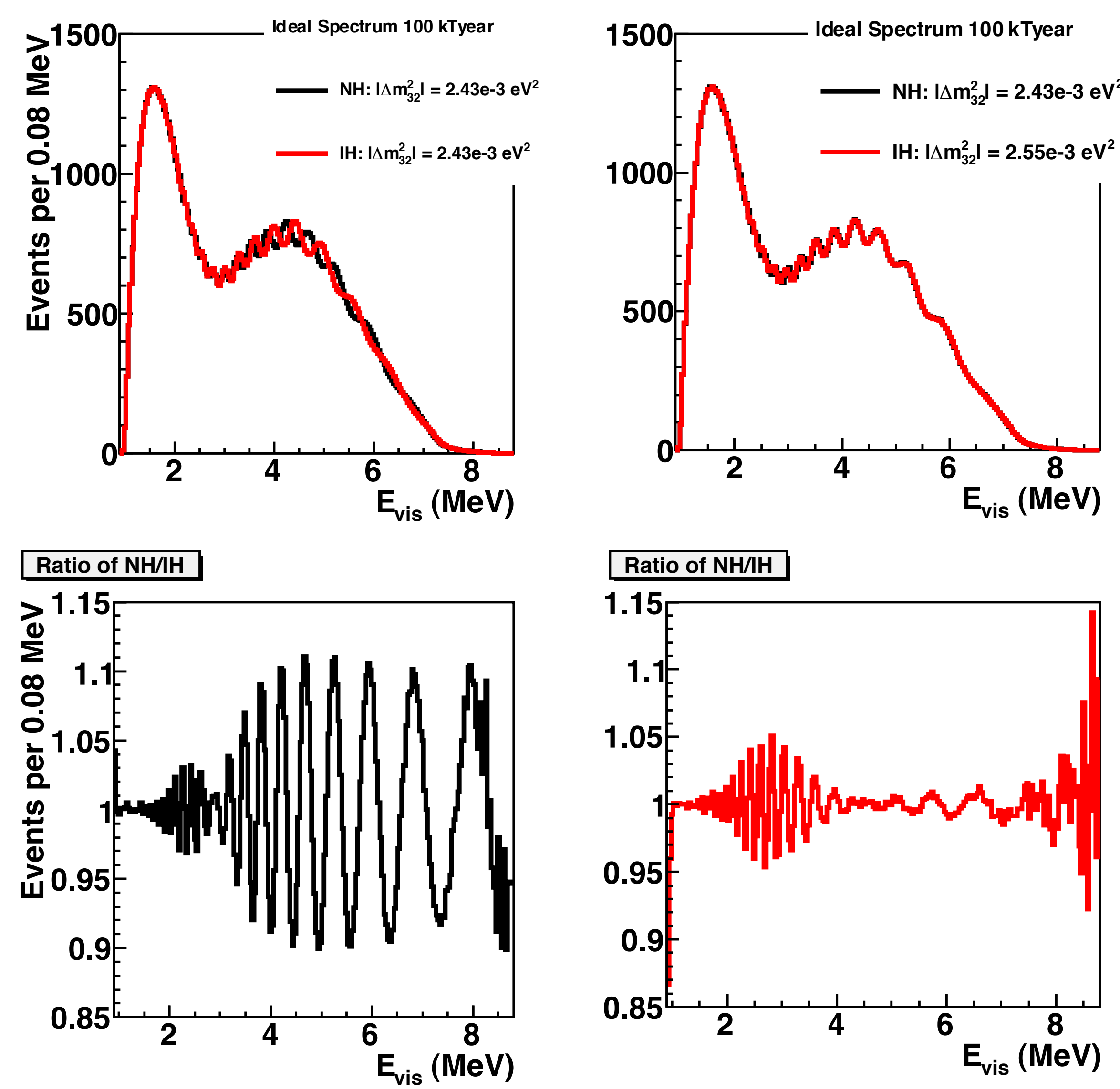
- There is a degenerate solution due to the uncertainties in Δm^2_{32} measurement.

$$\left|\Delta m^2_{32}\right| = 2.43^{+0.12}_{-0.09} \times 10^{-3}\,eV^2$$

NH: $2\Delta_{32} + \Phi$

IH: $2\Delta'_{32} - \Phi$

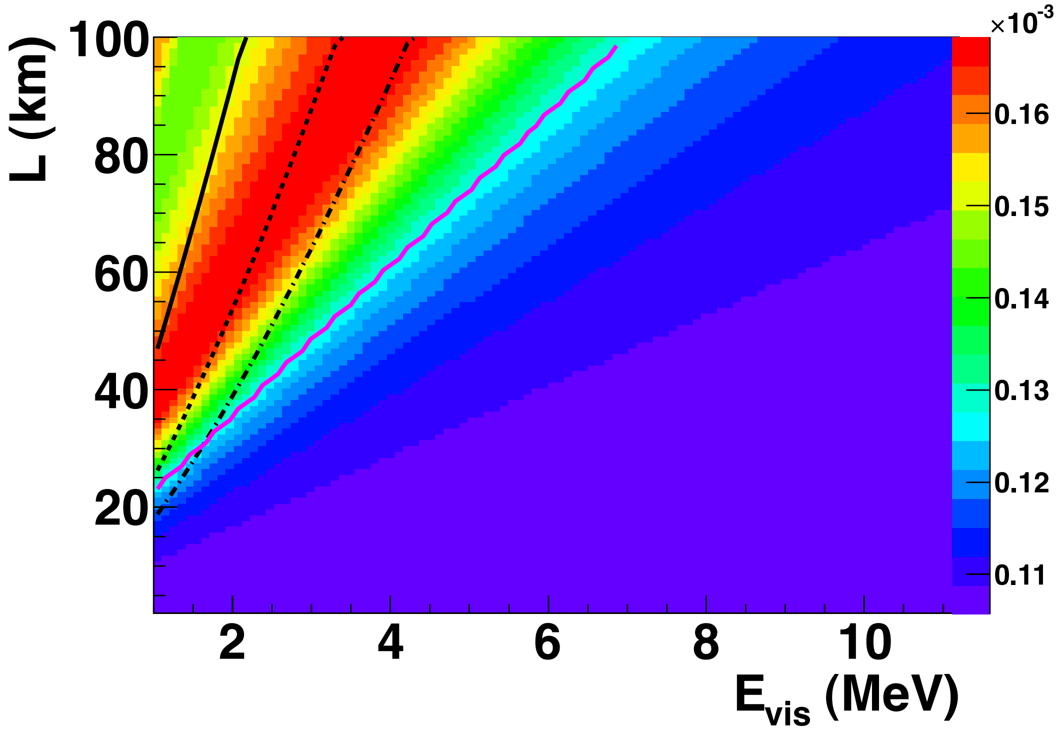
X. Qian et.al. arXiv: 1208.1551



Degeneracy From $|\Delta m^2_{32}|$

- Given the current precision on Δm^2_{32} precision, need Δm^2_{Φ} bigger than ~0.12 x 10^{-3} eV^2 need to resolve MH
  - below 20 km, almost no sensitivity to MH
  - around 60 km, most sensitivity comes from 1.5 - 4 MeV region
- Reactor Experiments will benefit from future precision measurements on Δm^2_{32} on from ν_u channel

$$\Delta m^2_{\phi}(L,E) = \frac{\phi}{1.27} \cdot \frac{E}{L}$$

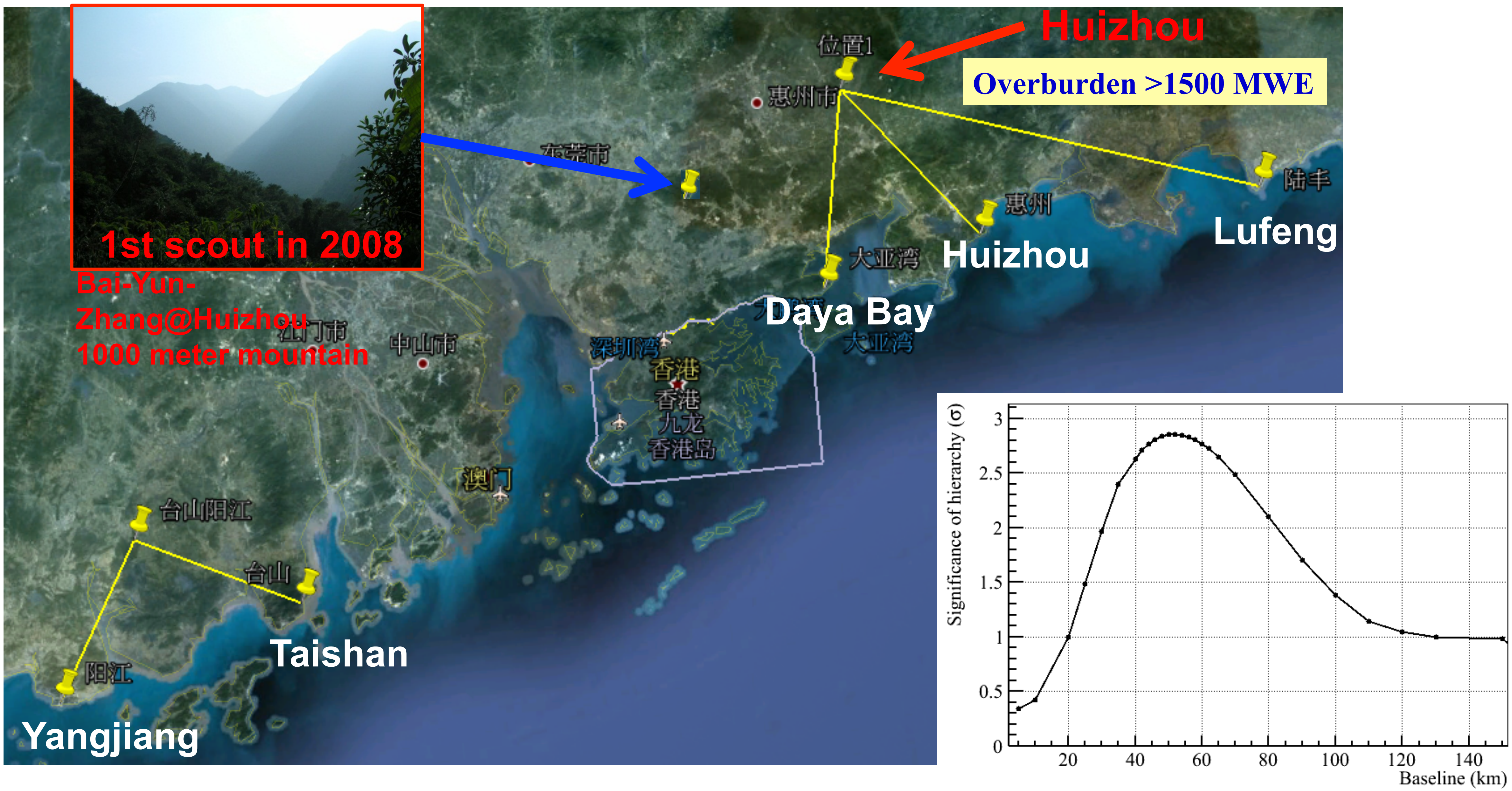


(Color indicates the size of Δm^2_{Φ})

X. Qian et.al. arXiv: 1208.1551

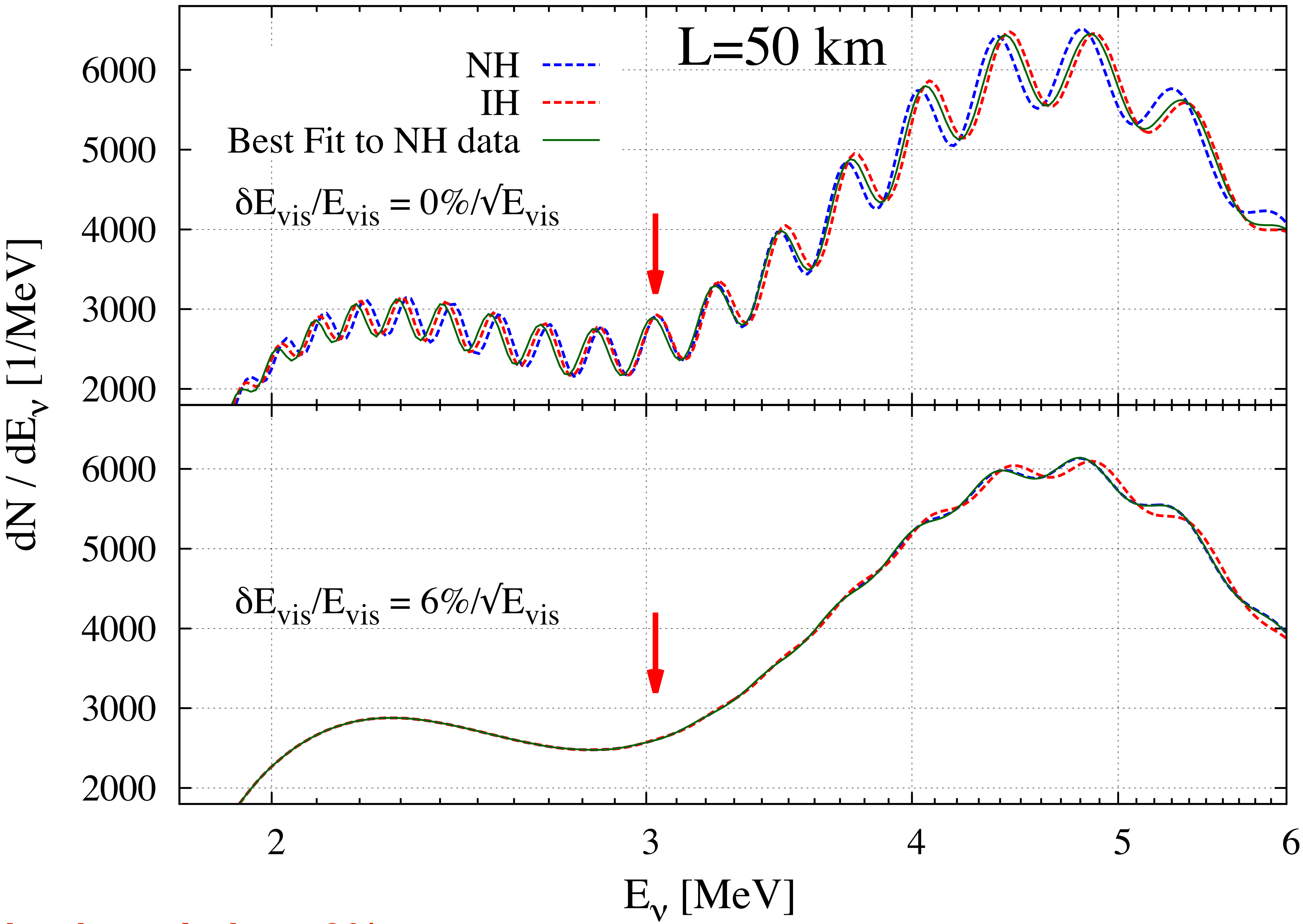
How to Resolve Degeneracy

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Find the optimum baseline

Challenge: Energy Resolution



- **Need resolution <3%**

K. Hagiwara, NPB2012

How To Reach 3% Resolution

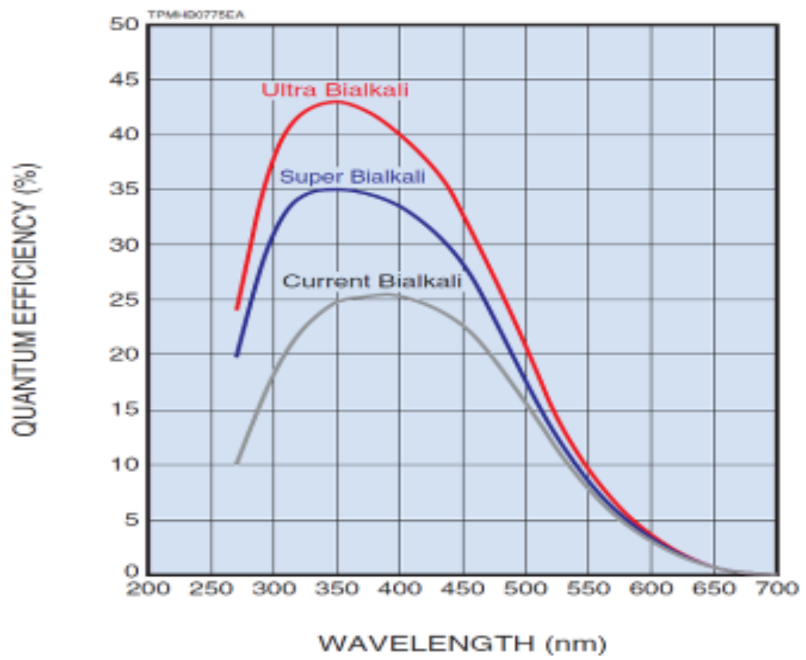
More Photo-electrons!

	KamLAND	Daya Bay II
Mass	**1kt**	**20kt**
Resolution	**6%**	**3%**

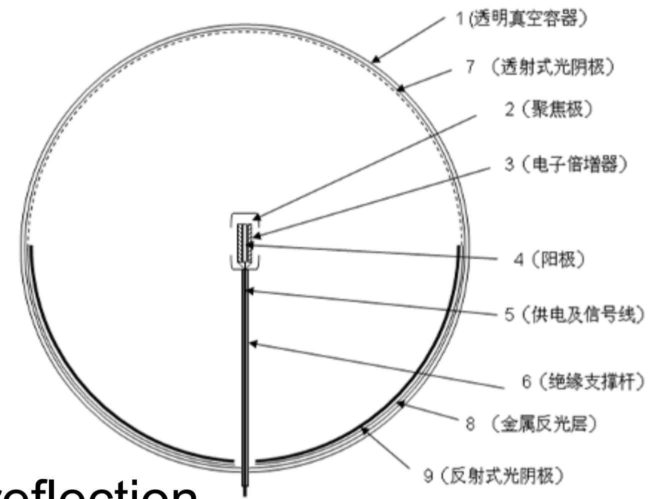
- Photocathode coverage
  KamLAND: 34% -> 80% x 2.3
- High QE PMT
  KamLAND: 20% -> 35% x 1.7
- Highly transparent LS
  Attenuation length: 15m -> 30m x 0.9
- High light yield LS
  KamLAND: 30% -> 45% x 1.5
- Light Collector

total: x ~5.3 -> ~2.7% / √E

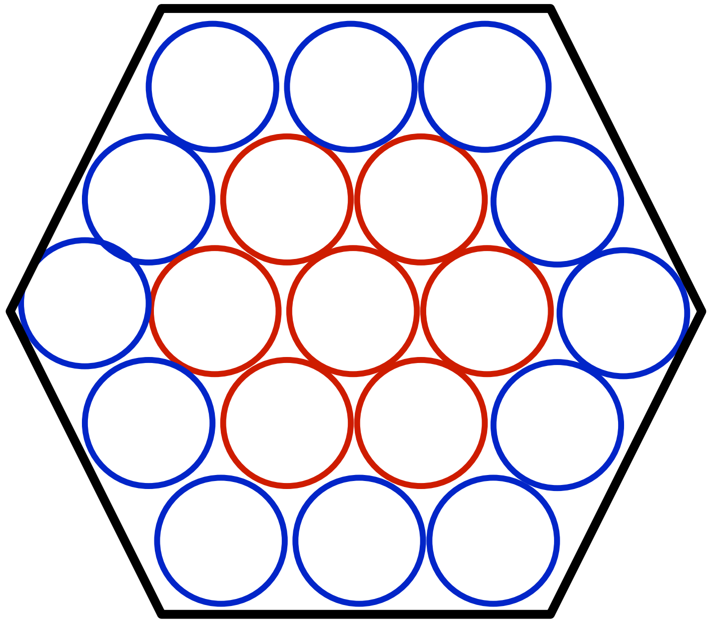
More Photo-electrons: PMT

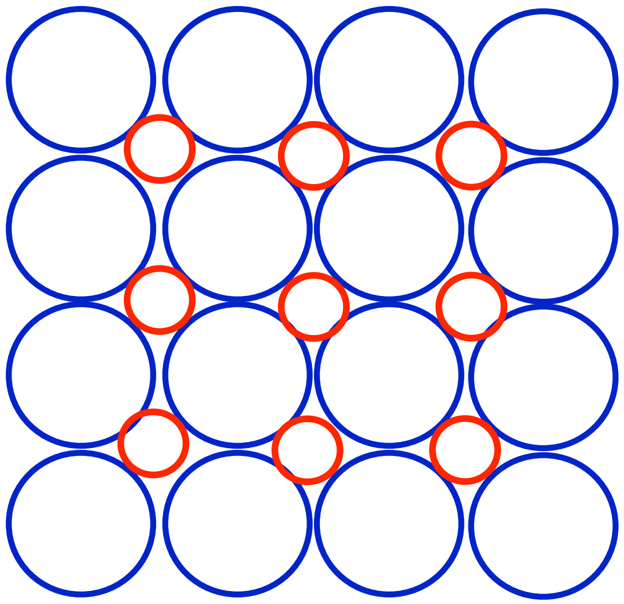


SBA
photocatode



MCP PMT with reflection
photocathode at bottom





20" + 8" PMT
8" PMT better timing

No clearance: coverage 86.5%

1cm clearance: coverage: 83% $*(d/D)^2$= 73%

J. Cao, NPB2012

MCP-PMT Development at IHEP

2009~2010 — IHEP Beginning 5” MCP-PMT

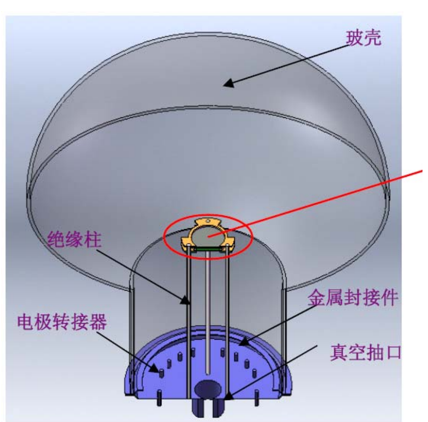
2011 Prototype
8” Dynode PMT QE=20%
Collaboration 8” MCP-PMT QE=20% Trans--photocathode

2012 Prototype
8” Dynode PMT QE=20%
Collaboration 8” MCP-PMT QE=20% Trans—photocathode Ref--Photocathode

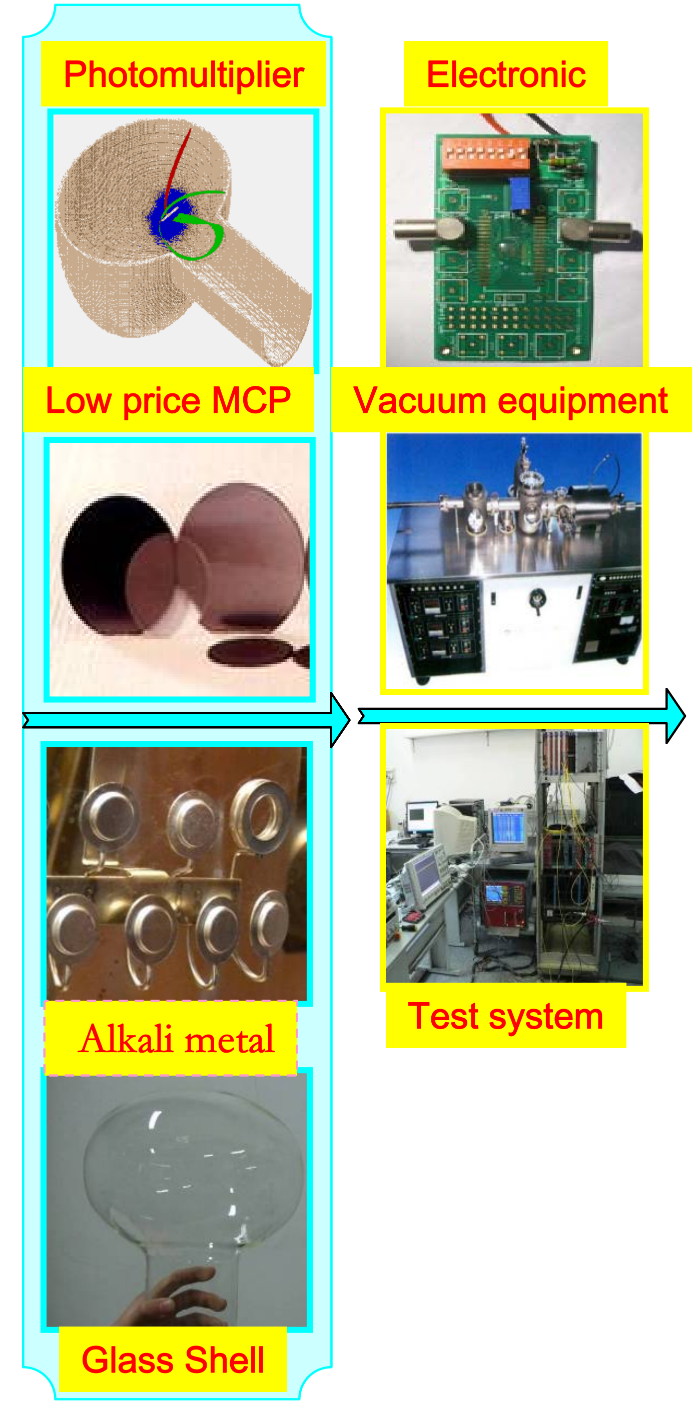
2013 Prototype
12” Dynode PMT QE=SBA
Collaboration 20” MCP-PMT QE=20% Trans—photocathode Ref--Photocathode

2014 Prototype
20” Dynode PMT QE=SBA
Collaboration 20” MCP-PMT QE=SBA Trans—photocathode Ref--Photocathode

5” **8”** **6”**



8” ellipse **8” spherical**

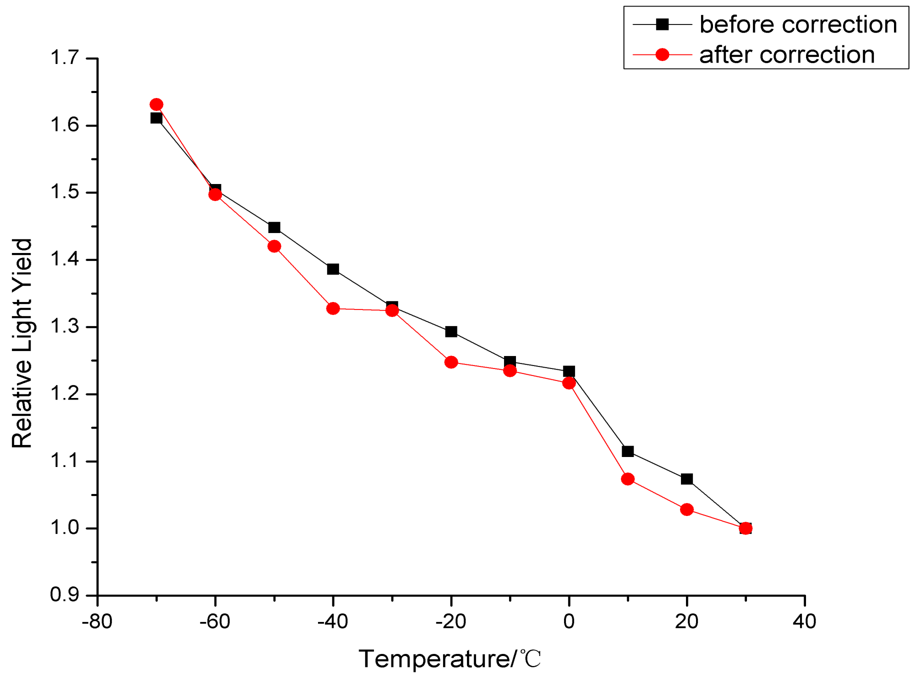


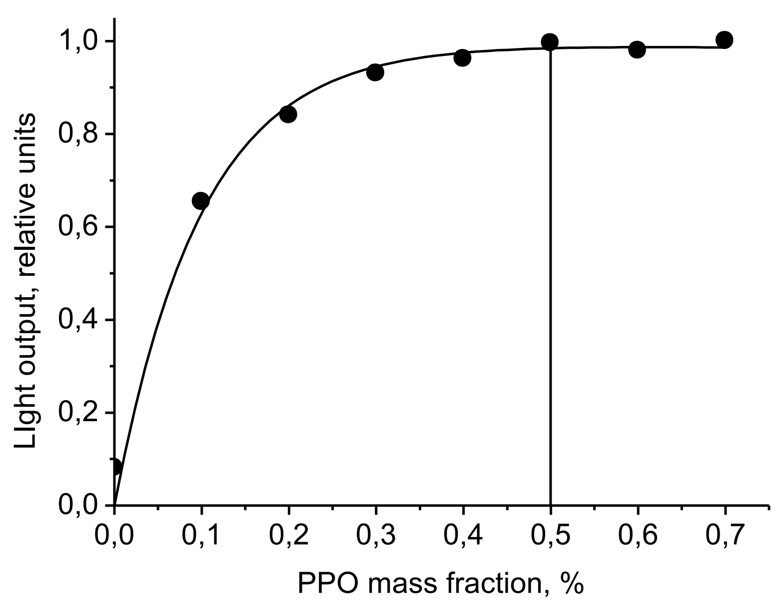
S. Qian, NPB2012

More Photo-electrons: LS

- **Attenuation length.**
- **Low temperature (4 degree)**
- **fluor concentration optimization (especially at**

Linear Alky Benzene	Atte. Length @ 430 nm
RAW	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	22.3 m





J. Cao, NPB2012

Challenge: Energy Non-linearity

- Experimentally measured is essentially the reconstructed energy based on the light collection, which may not be linear to the real energy of the particle
  - Quenching of the scintillator
  - Cherenkov contribution
  - Position dependence
  - Electronics
- With certain non-linearity, the IH could behave like the NH, and vice versa

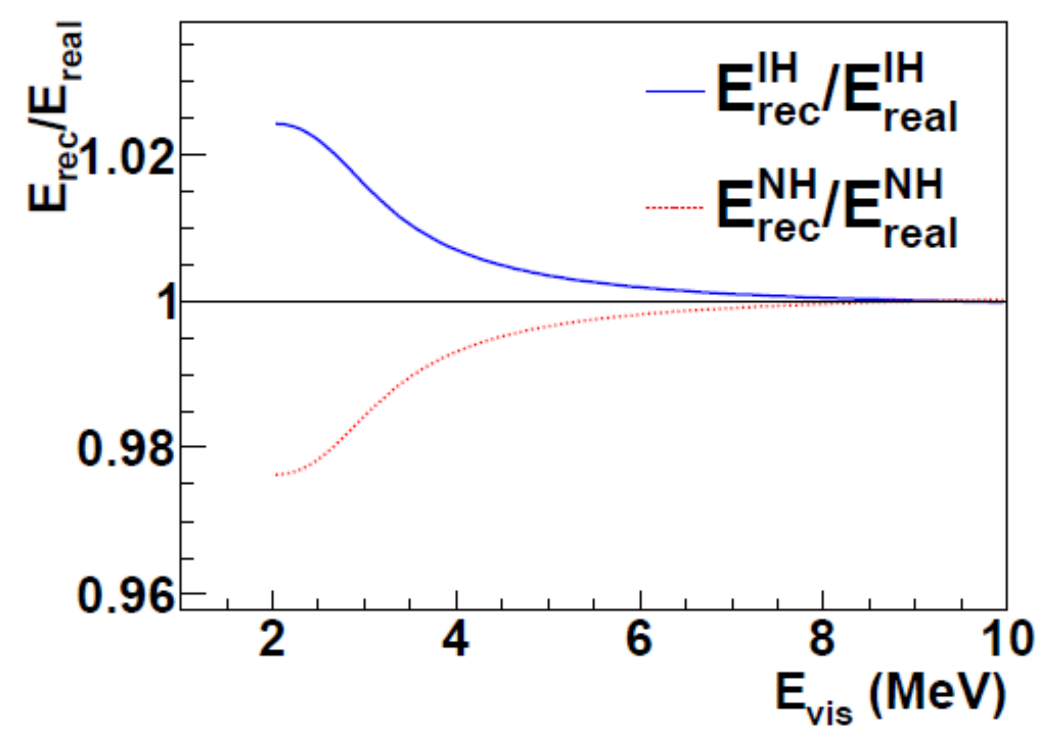
IH: $$\cos\left((2|\Delta m^2_{32}| - \Delta m^2_{\phi}(E_{\bar{\nu}}, L))\frac{L}{E_{real}}\right)$$

=

NH: $$\cos\left((2|\Delta' m^2_{32}| + \Delta m^2_{\phi}(E_{\bar{\nu}}, L))\frac{L}{E_{rec}}\right)$$

Assuming a non-linearity function

$$E_{rec} = \frac{2|\Delta' m^2_{32}| + \Delta m^2_{\phi}(E_{\bar{\nu}}, L)}{2|\Delta m^2_{32}| - \Delta m^2_{\phi}(E_{\bar{\nu}}, L)} E_{real} \ .$$



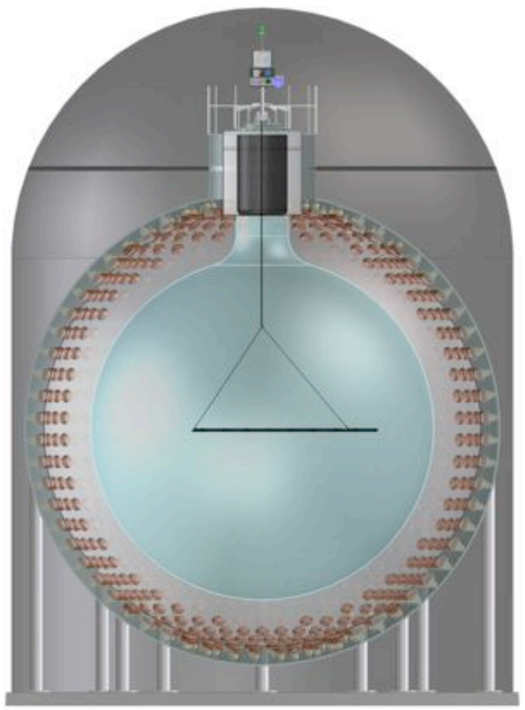
Need to know the non-linearity to <1%

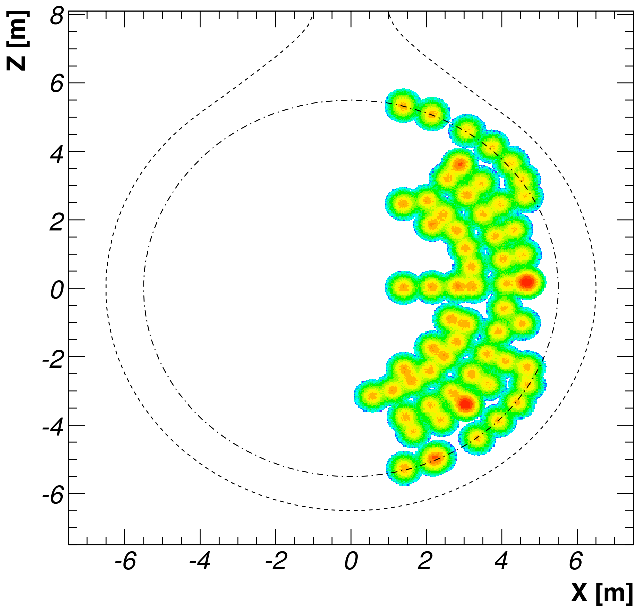
X. Qian et.al. arXiv: 1208.1551

How to Resolve Non-linearity

- Extensive energy calibration
  - Multiple sources at various energy
  - full-volume calibration at various positions
  - A positron source
- Two "identical" detectors?
  - one at 55km, one at 30km

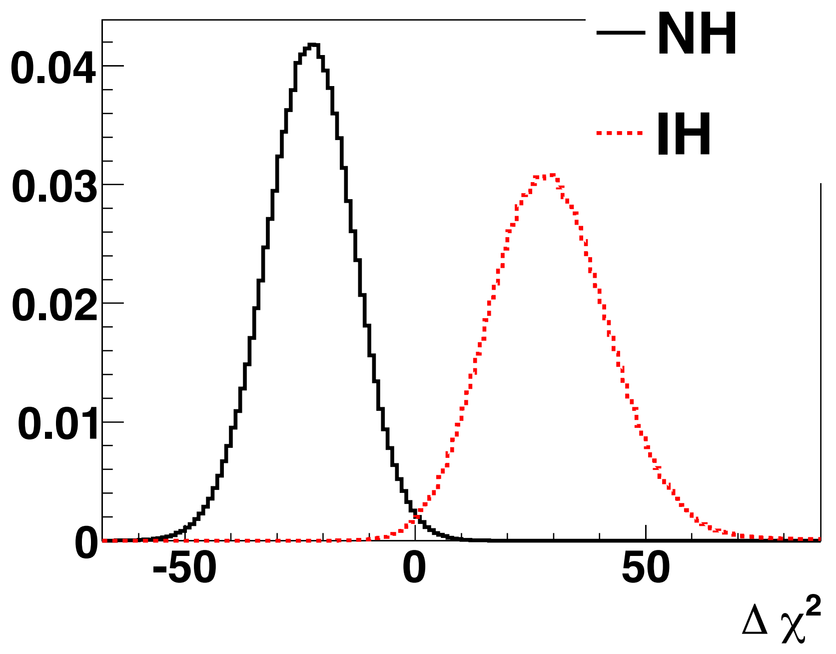
KamLAND, 4π Calibration





Sensitivity: χ^2 Method

- Traditional chi-square analysis
  - Assuming the truth is NH/IH, calculate the theoretical spectra
  - Fit the data to the NH/IH, calculate the χ^2_{min} difference ($\Delta\chi^2_{min}$)
  - Run many Monte Carlo experiments to get the $\Delta\chi^2_{min}$ distribution



- 100 kt.year
- 40 GW_{th}
- 60 km baseline
- 2.6% energy resolution
- Only statistical fluctuation

Average probability to determine MH: 98.9%

X. Qian et.al. arXiv: 1208.1551

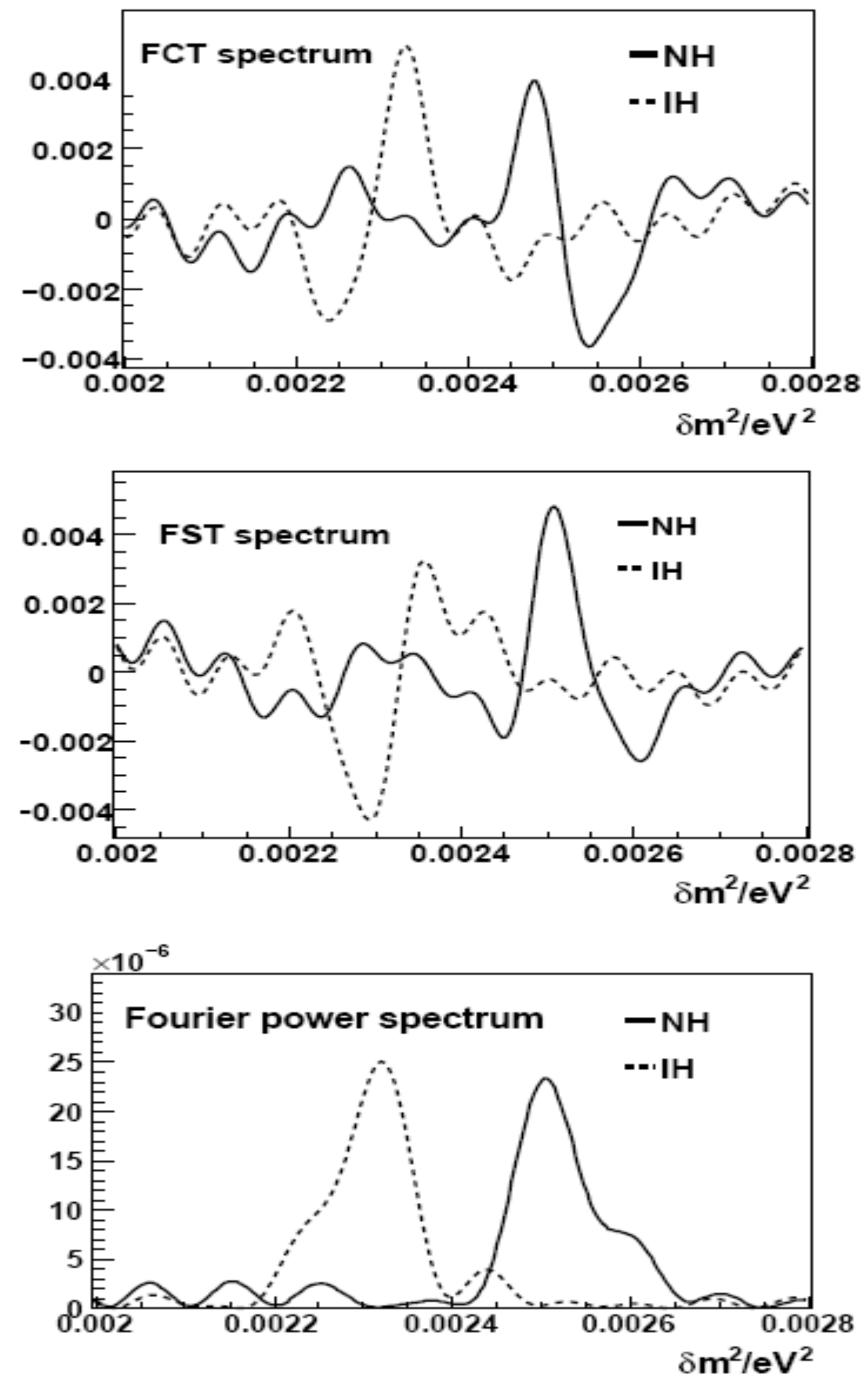
Alternative Analysis Method: Fourier Transform

- **Frequency regime is in fact the ΔM^2 regime ➔ enhance the visible features in ΔM^2 regime**
- **Take ΔM^2_{32} as reference**
  - ⇨ **NH: $\Delta M^2_{31} > \Delta M^2_{32}$, ΔM^2_{31} peak at the right of ΔM^2_{32}**
  - ⇨ **IH: $\Delta M^2_{31} < \Delta M^2_{32}$, ΔM^2_{31} peak at the left of ΔM^2_{32}**
- **The Fourier formalism:**

$$FST(\omega) = \int_{t_{min}}^{t_{max}} F(t)\sin(\omega t)\mathrm{d}t$$

$$FCT(\omega) = \int_{t_{min}}^{t_{max}} F(t)\cos(\omega t)\mathrm{d}t$$

- **Distinctive features**
- **No pre-condition of Δm^2_{23}**

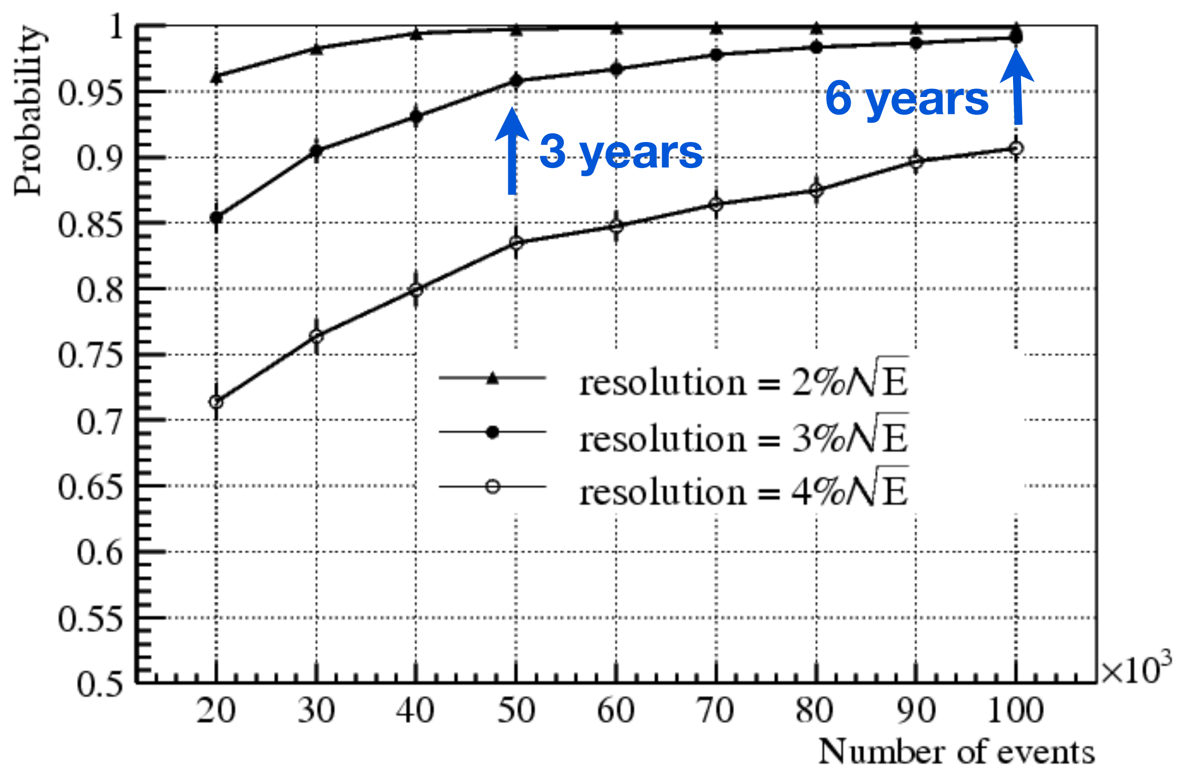


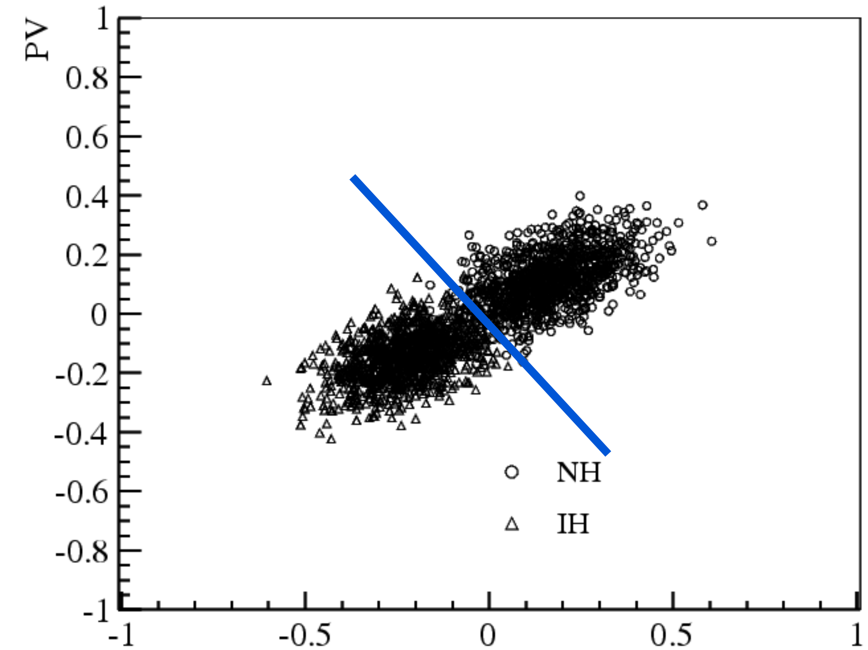
Yifang Wang, Nufact 2012

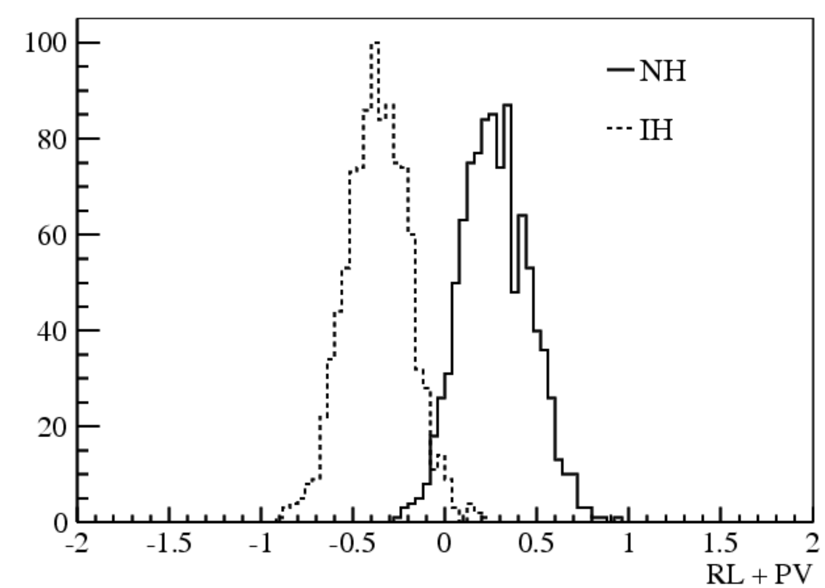
Choubey, Petcov, and Piai PRD68,113006 (2003)
Learned et al. PRD78, 071302R, (2008)
Zhan, PRD78, 111103R (2008)
Zhan, PRD79, 073007 (2009)

Alternative Analysis Method: Fourier Transform

- **New default parameters:**
  - **Detector size: 20kt**
  - **Energy resolution: 3%**
  - **Thermal power: 36 GW**
  - **Baseline 58 km**







Yifang Wang, Nufact 2012

Background Estimation

Signal rate: ~ 40 IBD/day/20kt, (KamLAND: ~0.5 IBD/day/1kt)

- **Based on a very rough back-on-the-envelope calculation, 500 m (1350 m.w.e.) is the minimum overburden**

DYBII		
Accidentals (B/S)	~ **2.5%**	Accurate subtraction
Fast neutrons (B/S)	~ **1%**	Roughly flat
$^{8}He/^{9}Li$ (B/S)	~ **4%**	Known spectrum

- **Used track and distance between vertices.**
- **Since we are looking at the small oscillations, slow varying in energy spectrum backgrounds are not serious.**

J. Cao, NPB2012

Other Physics Reach

- **Fundamental to the Standard Model and beyond**
- **Probing the unitarity of U_{PMNS} to ~1% level !**

	Current	Daya Bay II
Δm^2_{12}	3%	< 1%
Δm^2_{23}	5%	< 1%
$\sin^2\theta_{12}$	6%	< 1%
$\mathrm{Sin}^2\theta_{23}$	20%	-
$\sin^2\theta_{13}$	14% → 4%	-

To be elaborated

Others

1. **Exotics searches**
   1. **Sterile neutrinos**
   2. **Monopoles, Fractional charged particles, ….**
2. **Target for neutrino beams**
3. **Atmospheric neutrinos**
4. **Solar neutrinos**
5. **High energy cosmic-rays & neutrinos**
   1. **Point source: GRB, AGN, BH, …**
   2. **Diffused neutrinos**
   3. **Dark matter**

Supernova neutrinos

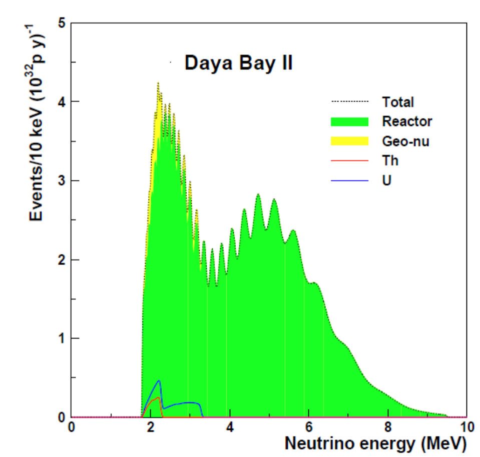
- **Less than 20 events observed so far**
- **Assumptions:**
  - **Distance: 10 kpc (our Galaxy center)**
  - **Energy: 3×10^{53} erg**
  - **L_ν the same for all types**
  - **Tem. & energy** $T(\nu_e) = 3.5$ MeV, $\langle E(\nu_e)\rangle = 11$ MeV; $T(\bar{\nu}_e) = 5$ MeV, $\langle E(\bar{\nu}_e)\rangle = 16$ MeV; $T(\nu_x) = 8$ MeV, $\langle E(\nu_x)\rangle = 25$ MeV
- **Many types of events:**
  - $\bar{\nu}_e + p \rightarrow n + e^+$, ~ 3000 correlated events
  - $\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B^* + e^+$, ~ 10-100 correlated events
  - $\nu_e + {}^{12}C \rightarrow {}^{12}N^* + e^-$, ~ 10-100 correlated events
  - $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$, ~ 600 correlated events
  - $\nu_x + p \rightarrow \nu_x + p$, single events
  - $\nu_e + e^- \rightarrow \nu_e + e^-$, single events
  - $\nu_x + e^- \rightarrow \nu_x + e^-$, single events

Water Cerenkov detectors can not see these correlated events

Energy spectra & fluxes of all types of neutrinos

Geoneutrinos

- **Current results:**
  - **KamLAND: 40.0±10.5±11.5 TNU**
  - **Borexino: 64±25±2 TNU**
- **Desire to reach an error of 3 TNU: statistically dominant**
- **Daya Bay II: >×10 statistics, but difficult on systematics**
- **Background to reactor neutrinos**



Stephen Dye

Summary

- Reactor experiment with ~60km baseline has the potential to determine neutrino mass hierarchy
- Daya Bay II was proposed a few years ago, now boosted by the large θ_{13}
- The scientific case is strong with significant technical challenges
- The funding situation is promising
- Possible time schedule:
  - Proposal to government: 2015
  - Construction: 2016 - 2020
  - Competitive and complementary to the long baseline accelerator neutrino experiments.