# Daya Bay Neutrino Oscillation Experiment

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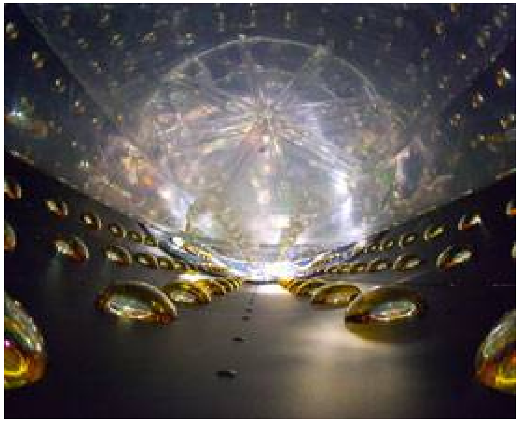
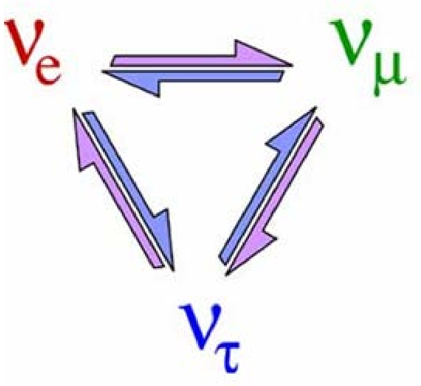
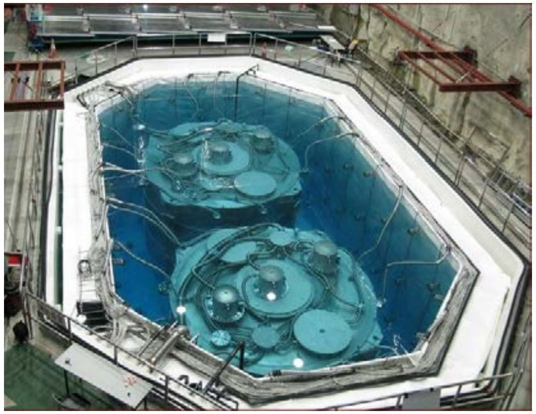




NPP Seminar, LANL
October 28, 2011

# Outline

- Brief history of reactor neutrino physics
- Physics case for a precise $\theta_{13}$ measurement
- Status and plan for the Daya Bay neutrinos oscillation experiment
- Relic neutrino with radioactive nuclei? (time permitting)

# Neutrino News - OPERA Experiment

**Researchers Claim Particles Can Travel Faster than Light**

Tiny Neutrinos May Have Broken Cosmic Speed Limit

By DENNIS OVERBYE
Published: September 22, 2011

Roll over, Einstein?

**Challenging Einstein usually a losing venture**

Updated 9/23/2011 10:18 PM

By Seth Borenstein, Associated Press

Comment 251 Recommend 8K Tweet 331

GENEVA – Betting against Einstein and his theory of relativity is a way to go broke.

Friday, 23 September 2011

The Phantom of OPERA

October 4, 2011

**THE FAT LADY SINGS**

# A great puzzle in the 1920's

Why is the β-decay energy spectrum not a sharp peak?

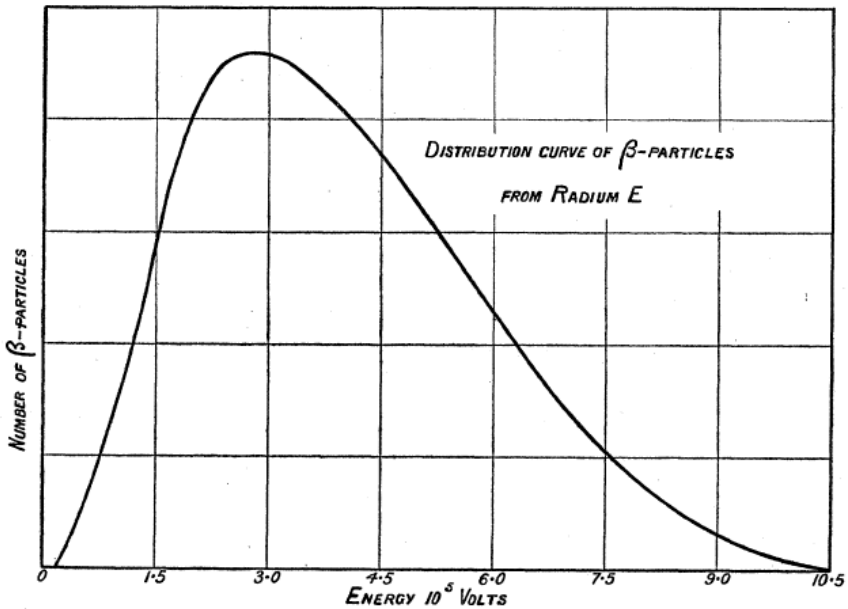



FIG. 1.

$$ {}^{210}_{83}Bi \rightarrow {}^{210}_{84}Po + e^- + X $$

C.D. Ellis and W.A. Wooster,
Proc. R. Soc. (London) A117, 109 (1927)

Bohr suggested that energy conservation is only valid "on average"

# Postulate of the Neutrino

1930

Photo: AIP, Emilio Segrè Visual Archives

Wolfgang Pauli

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

›schrift

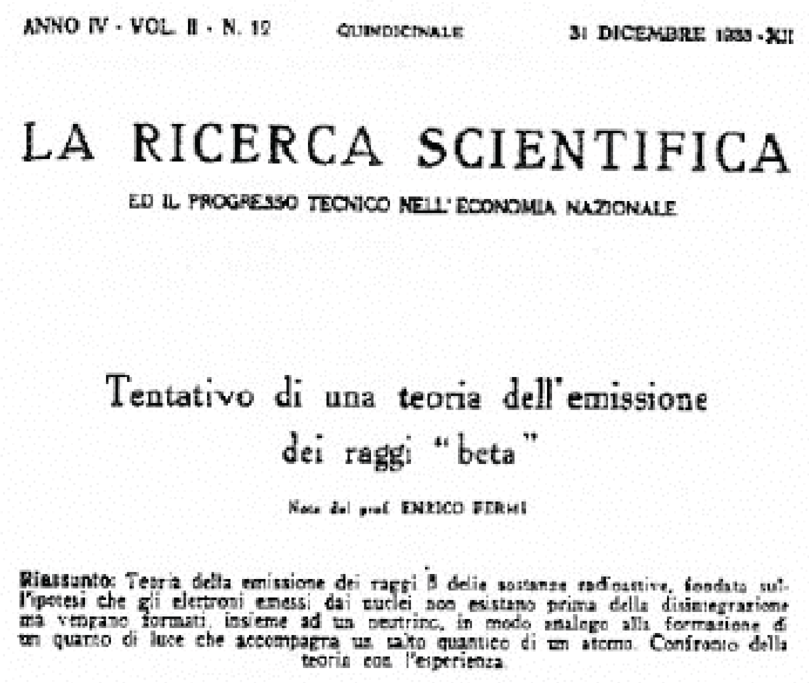
ysikalisches Institut
ır Eidg. Technischen Hochschule
ırich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst
ızuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
ıgesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
ıs kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg
ırfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz
ı retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,
welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und
sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen
müsste von derselben Grossenordnung wie die Elektronenmasse sein und
jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche
beta- Spektrum wäre dann verständlich unter der Annahme, dass beim
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert
wird, derart, dass die Summe der Energien von Neutron und Elektron
konstant ist.

# Fermi wrote down the theory of β-decay in 1933 (after including neutrino)


ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

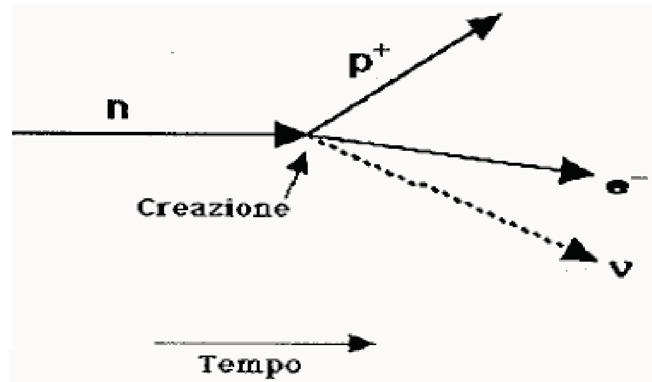
LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.




Fermi's theory agreed perfectly with experiment

However, neutrinos were not detected until 23 years later!

Bethe

Peierls

# The "Neutrino"

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

(Inverse beta decay)

For an energy of $2{\cdot}3 \times 10^6$ volts, $t$ is 3 minutes and therefore $\sigma < 10^{-44}$ cm.$^2$ (corresponding to a penetrating power of $10^{16}$ km. in solid matter). It is

of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

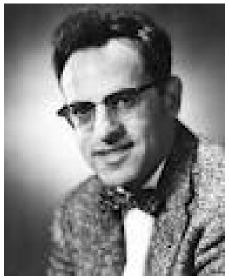
H. Bethe.
R. Peierls.

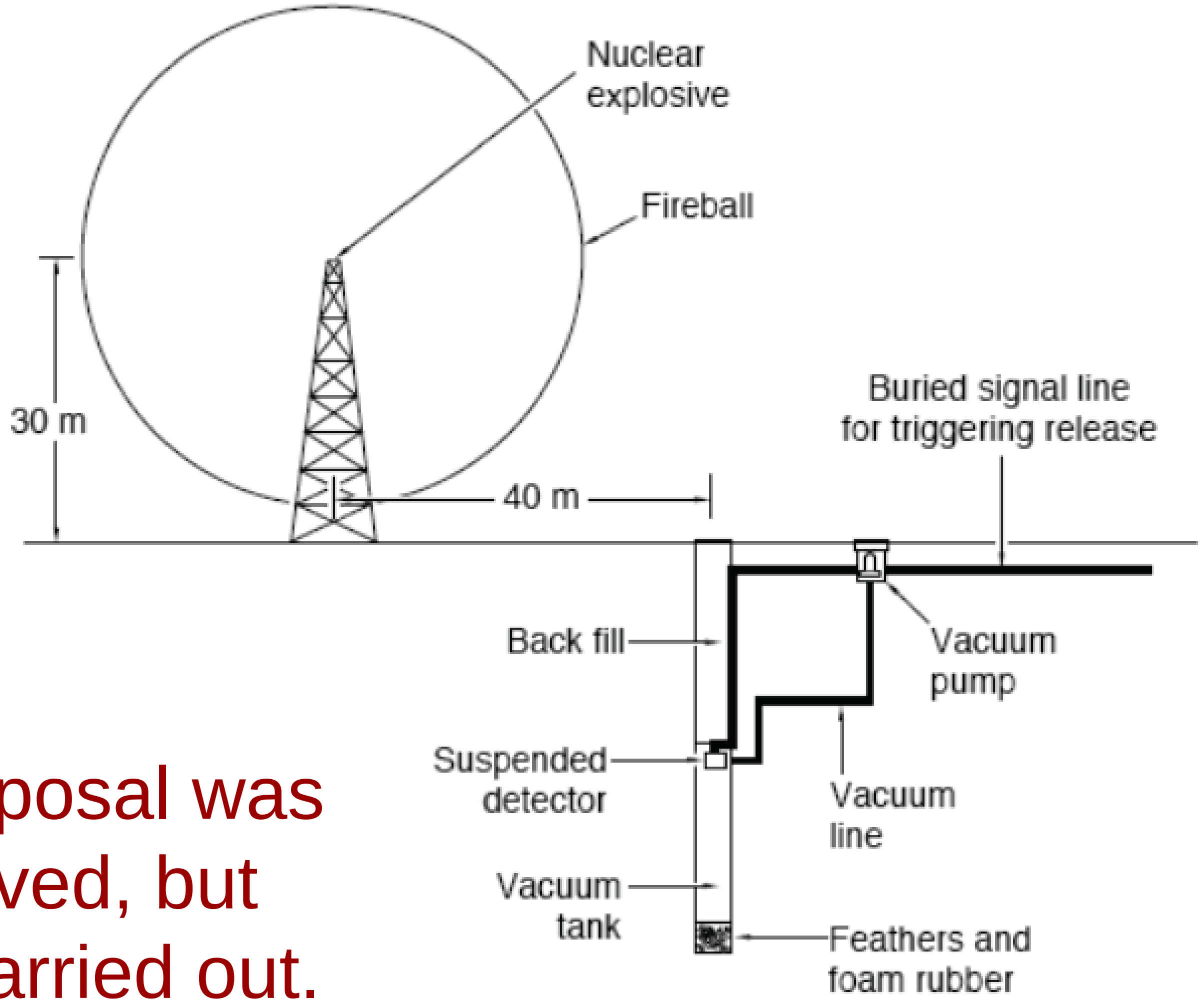
*“I have done something very bad by proposing a particle that cannot be detected; it is something no theorist should ever do.”*

*- Wolfgang Pauli*

# An explosive idea to detect neutrinos

Reines



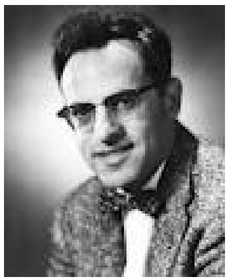


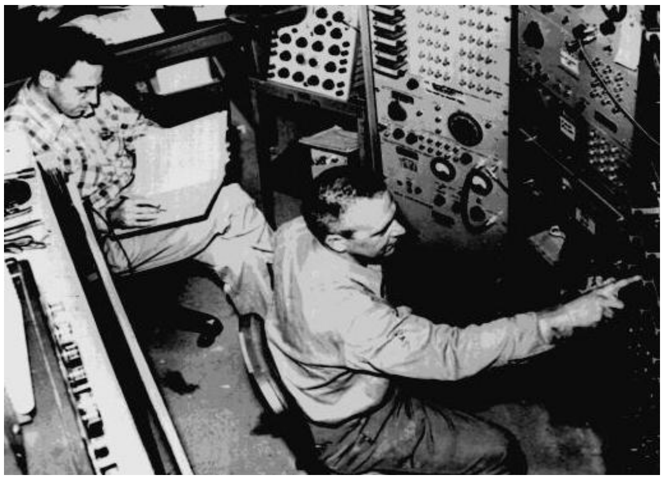

The proposal was approved, but never carried out.

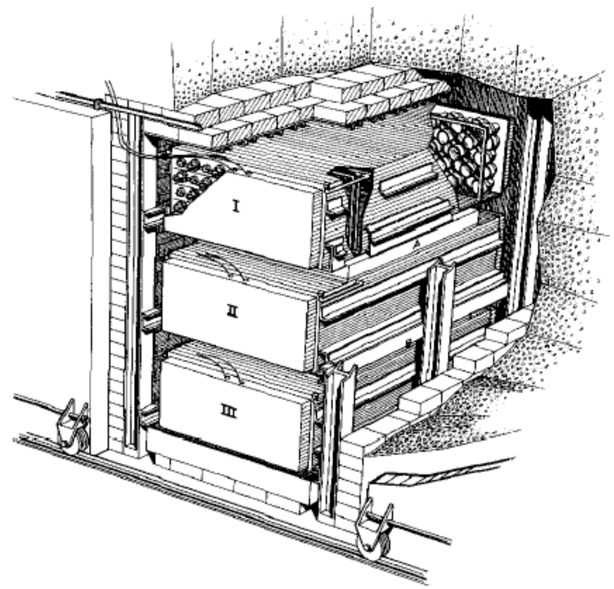
# A Better Idea

Nuclear reactor generates a lot of neutrinos continuously ~$10^{20}$/second

Reines



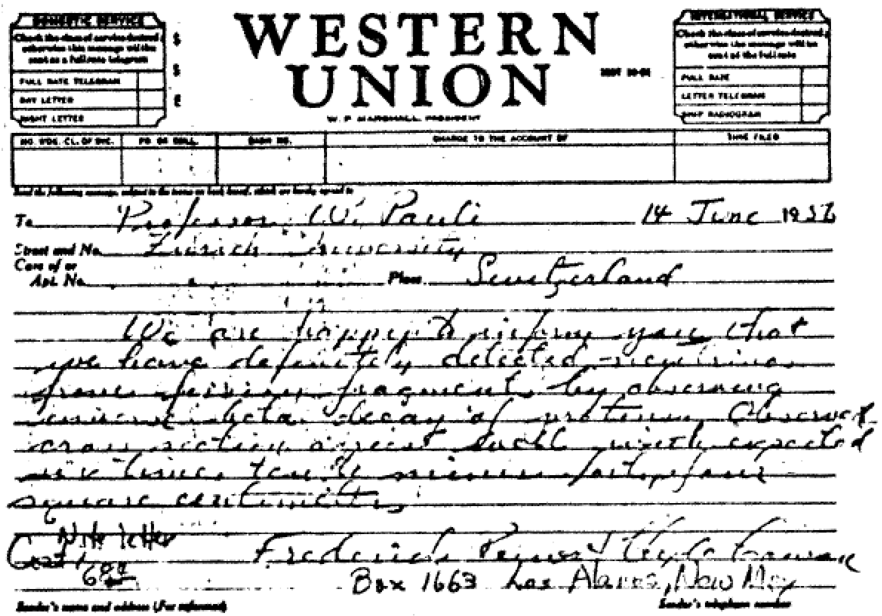





Cowan

Reines and Cowan successfully detected neutrinos from nuclear reactors using the “inverse neutron beta decay”

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


WESTERN UNION

To: Professor W. Pauli — 14 June 1956
Street and No.: Zurich University
Place: Switzerland

We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.

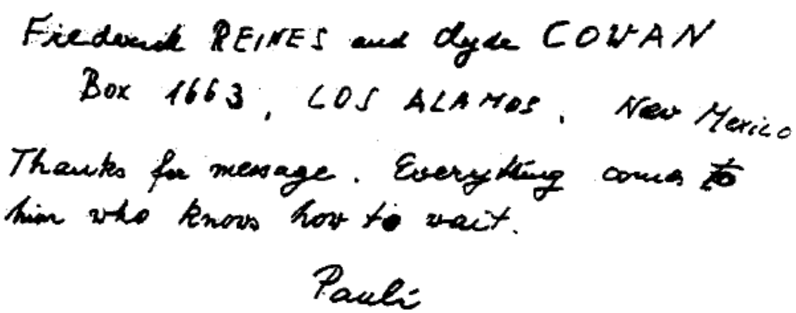
Frederick Reines Clyde Cowan
Box 1663 Las Alamos, New Mex

## Telegram to Pauli

14 June, 1956

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay."

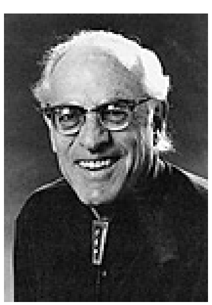
Reines and Cowan


Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli

## Reply from Pauli

"Thanks for message. Everything comes to him who knows how to wait."

Pauli



Nobel prize

1995

# What we have learned from neutrino oscillation experiments

1) Neutrinos are massive

$$\Delta m_{21}^2 = m_2^2 - m_1^2 = (7.9 \pm 0.7) \times 10^{-5}\,\mathrm{ev}^2 \quad (90\%\,\mathrm{c.l.})$$

$$|\Delta m_{32}^2| = |m_3^2 - m_2^2| = (2.4 \pm 0.6) \times 10^{-3}\,\mathrm{ev}^2 \quad (90\%\ \mathrm{c.l.})$$

2) Neutrinos do mix with each other

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

$$(c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij})$$

$\theta_{12} \approx 34^\circ$, $\theta_{23} \approx 45^\circ$, $\theta_{13} \le 13^\circ$ for the lepton MNSP Matrix

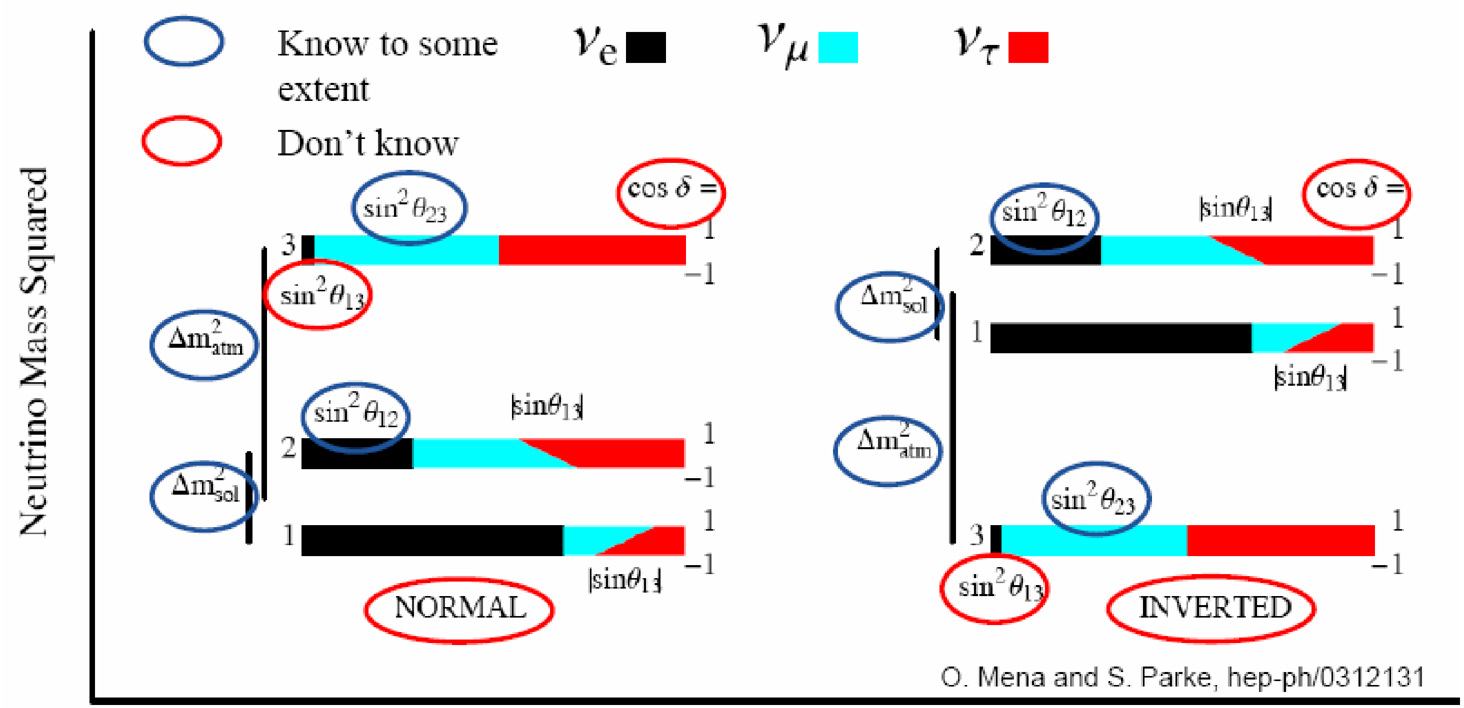
$\theta_{12} \approx 13^\circ$, $\theta_{23} \approx 2.2^\circ$, $\theta_{13} \approx 0.22^\circ$ for the quark CKM Matrix

3) Neutrino masses and mixings have provided clear evidence for physics beyond the Standard Model

# What we do not know about the neutrinos

- Are neutrinos their own antiparticles?
- The exact values of their masses?
- Existence of other types of neutrinos?
- Value of the $\theta_{13}$ mixing parameter?
- Do neutrinos violate fundamental symmetries (CP, CPT)?
- Why are they so light?
- Do neutrinos travel faster than light?
- Other unknown neutrino mysteries…..

# What we know and do not know about the neutrinos



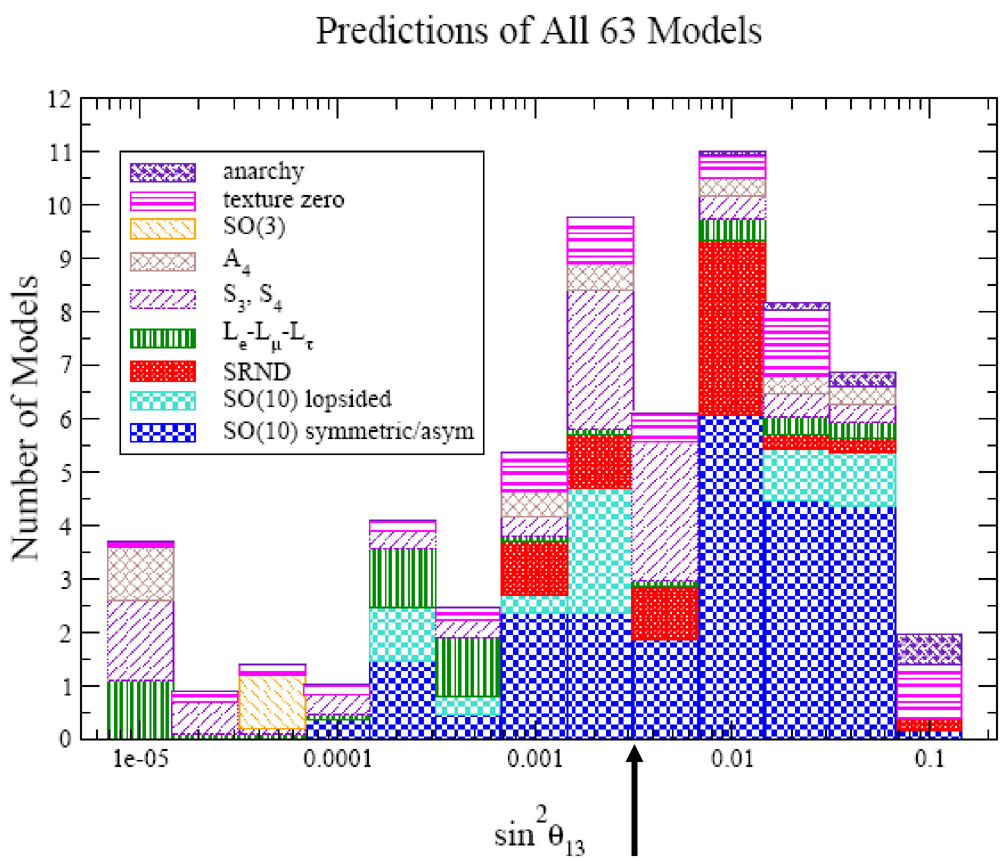

- What is the $\nu_e$ fraction of $\nu_3$? (proportional to $\sin^2\theta_{13}$)
- Contributions from the CP-phase $\delta$ to the flavor compositions of neutrino mass eigenstates depend on $\sin^2\theta_{13}$)

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

# Why measuring $\theta_{13}$?

A tabulation of predictions of 63 neutrino mass models on $\sin^2\theta_{13}$

(hep-ph/0608137)




- Models based on the Grand Unified Theories in general give relatively large $\theta_{13}$
- Models based on leptonic symmetries predict small $\theta_{13}$

A measurement of $\sin^2 2\theta_{13}$ at the sensitivity level of 0.01 can rule out at least half of the models!

# Modeling the Neutrino Mass Matrix

$$U_l^\dagger M_l U_l = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}; \quad U_\nu^\dagger M_\nu U_\nu = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

$$U_{PMNS} = U_l^\dagger U_\nu$$

Examples of neutrino mass matrix:

$a)$ $\nu_\mu - \nu_\tau$ symmetry

$$M_\nu = \begin{pmatrix} A & B & B \\ B & C & D \\ B & D & C \end{pmatrix};$$

Symmetric with respect to

$\nu_\mu - \nu_\tau$ permutation

(diagonal $M_l$ mass matrix)

After diagonalization, one can determine the mass hierarchy and the mixing parameters

- Normal mass hierachy $(m_1 < m_2 < m_3)$
- $\theta_{13} = 0,\ \theta_{23} = \pi / 4$

Two ways to get $\theta_{13} \neq 0$:

$a)$ explicit symmetry breaking at the model scale

b) Radiative correction (RGE) from high scale to low scale

# Modeling the Neutrino Mass Matrix

Examples of neutrino mass matrix:

*b*) $\nu$ mass matrices with texture zeros

(Frampton, Glashow, Marfatia)

$$M_\nu = \begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}; \qquad X : \text{non-zero entries}$$

$$\sin^2\theta_{13} \simeq \frac{R_\nu \tan^2\theta_{12}}{\tan^2\theta_{23}\,|1-\tan^4\theta_{12}|} \;;\quad R_\nu = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

$$M_\nu = \begin{pmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}; \qquad X : \text{non-zero entries}$$

$$\sin^2\theta_{13} \simeq \frac{R_\nu \tan^2\theta_{12}\tan^2\theta_{23}}{|1-\tan^4\theta_{12}|}$$

# Why measuring $\theta_{13}$?

## Leptonic CP violation

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \times$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

If $\sin^2 2\theta_{13}$>0.02-0.03, then LBNE+T2K will have good coverage on $\delta_{CP}$.

Reactor experiments set the scale for future leptonic CP-violation studies

# Caution: value of $\theta_{13}$ depends on parametrization of mixing matrix

***Define***

$$R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}, \quad R_{13} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

$$R_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

and

$$W_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23}e^{-i\delta_{cp}} \\ 0 & -s_{23}e^{i\delta_{cp}} & c_{23} \end{pmatrix},$$

$$W_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix},$$

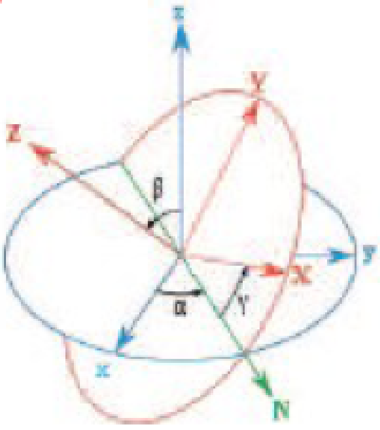
$$W_{12} = \begin{pmatrix} c_{12} & s_{12}e^{-i\delta_{cp}} & 0 \\ -s_{12}e^{i\delta_{cp}} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

***$R_{23}\, W_{13}\, R_{12}$ is conventional Rep.***

# Various possible mixing matrix parametrizations

***Other possible parametrizations:***

♣♣ ***(1)*** $R_{23}\, W_{13}\, R_{12}$, $R_{23}\, W_{12}\, R_{13}$, $R_{13}\, W_{23}\, R_{12}$
$R_{13}\, W_{12}\, R_{23}$, $R_{12}\, W_{23}\, R_{13}$, $R_{12}\, W_{13}\, R_{23}$
***rotation around 3 distinct axes***
► $R_{23}\, W_{13}\, R_{12}$ ***: conventional rep.***




***(2)*** $R_{12}\, W_{23}\, R_{12}$, $R_{12}\, W_{13}\, R_{12}$, $R_{13}\, W_{23}\, R_{13}$,
$R_{13}\, W_{12}\, R_{13}$, $R_{23}\, W_{13}\, R_{23}$, $R_{23}\, W_{12}\, R_{23}$
***rotation around 2 distinct axes***
► $R_{12}\, W_{23}\, R_{12}$ ***: using definition of Euler angles***

# In certain parametrizations $\theta_{13}$ can be rather large

*CP-phase $\delta = 0$*

*(23)(12) order*: cases A, B, C

*(12)(23) order*: cases D, E, F

| Case | $U$ Mixing Matrix | $\theta_{23}$ | $\theta_{13}$ | $\theta_{12}$ |
|---|---|---|---|---|
| A | $XYZ \equiv (23)(13)(12)$ | 45.00 | 0.00 | 33.91 |
| B | $XZY \equiv (23)(12)(13)$ | 45.00 | 0.00 | 33.91 |
| C | $YXZ \equiv (13)(23)(12)$ | 45.00 | 0.00 | 33.91 |
| D | $YZX \equiv (13)(12)(23)$ | 50.31 | -25.43 | 23.24 |
| E | $ZXY \equiv (12)(23)(13)$ | 35.93 | -29.16 | 43.55 |
| F | $ZYX \equiv (12)(13)(23)$ | 39.69 | -23.24 | 25.43 |

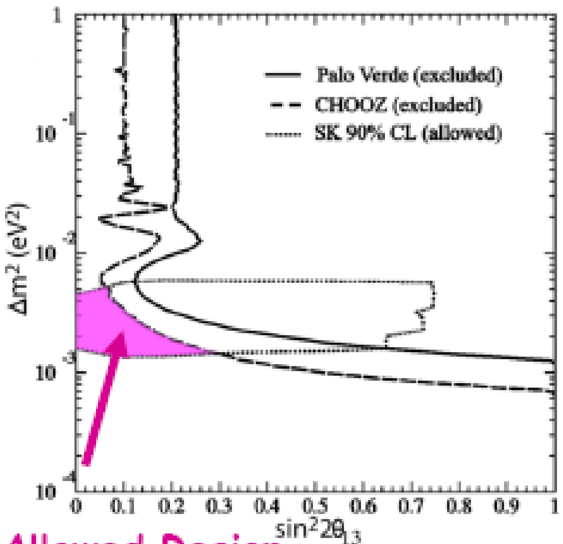
*Most recent Results PRD83, 071301 (2011)*

| Case | $U$ Mixing Matrix | $\theta_{23}$ | $\theta_{13}$ | $\theta_{12}$ |
|---|---|---|---|---|
| A | $XYZ \equiv (23)(13)(12)$ | 45.00 | 5.44 | 33.91 |
| B | $XZY \equiv (23)(12)(13)$ | 48.65 | 6.55 | 33.74 |
| C | $YXZ \equiv (13)(23)(12)$ | 44.74 | 7.68 | 39.33 |
| D | $YZX \equiv (13)(12)(23)$ | 52.03 | -22.30 | 26.76 |
| E | $ZXY \equiv (12)(23)(13)$ | 38.63 | -25.71 | 45.31 |
| F | $ZYX \equiv (12)(13)(23)$ | 41.57 | -19.81 | 28.59 |

(See Huang, Liu, JCP, Reitner, arXiV:11908.3906)

# Current knowledge on $\theta_{13}$

## Upper limit from reactors

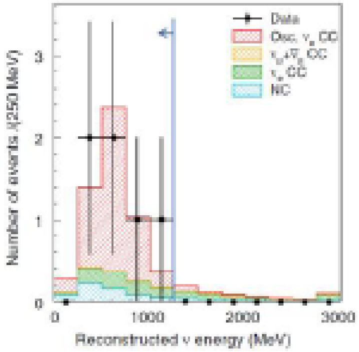



Allowed Region

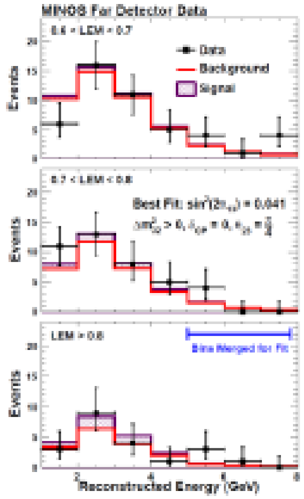
$\sin^2 2\theta_{13} < 0.17$ (90% c.l.)

Chooz collaboration, *Eur. Phys. J. C.* 27 (331-374), 2003.

## Evidence from accelerators

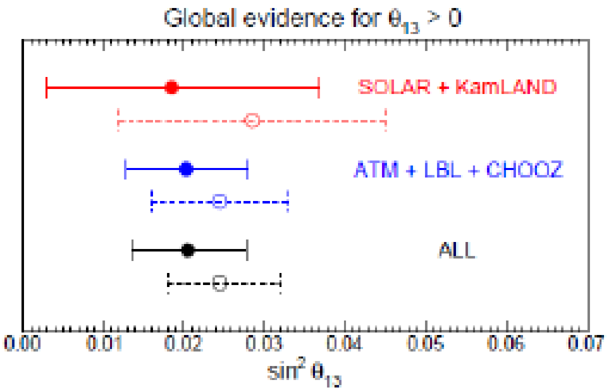



T2K collaboration 2011 *Phys. Rev. Lett.* 107 041801.




MINOS collaboration 2011 arXiv:1108.0015v1

## "3σ" non-zero from global analysis

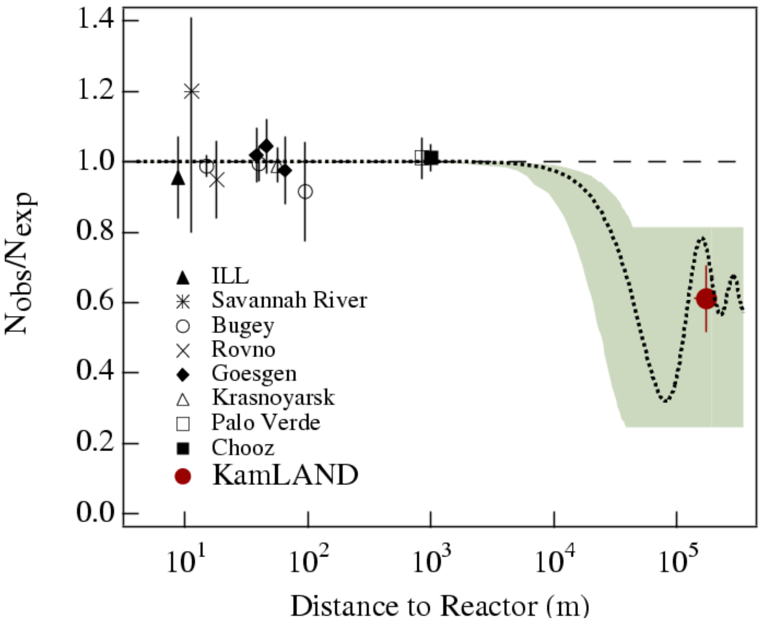


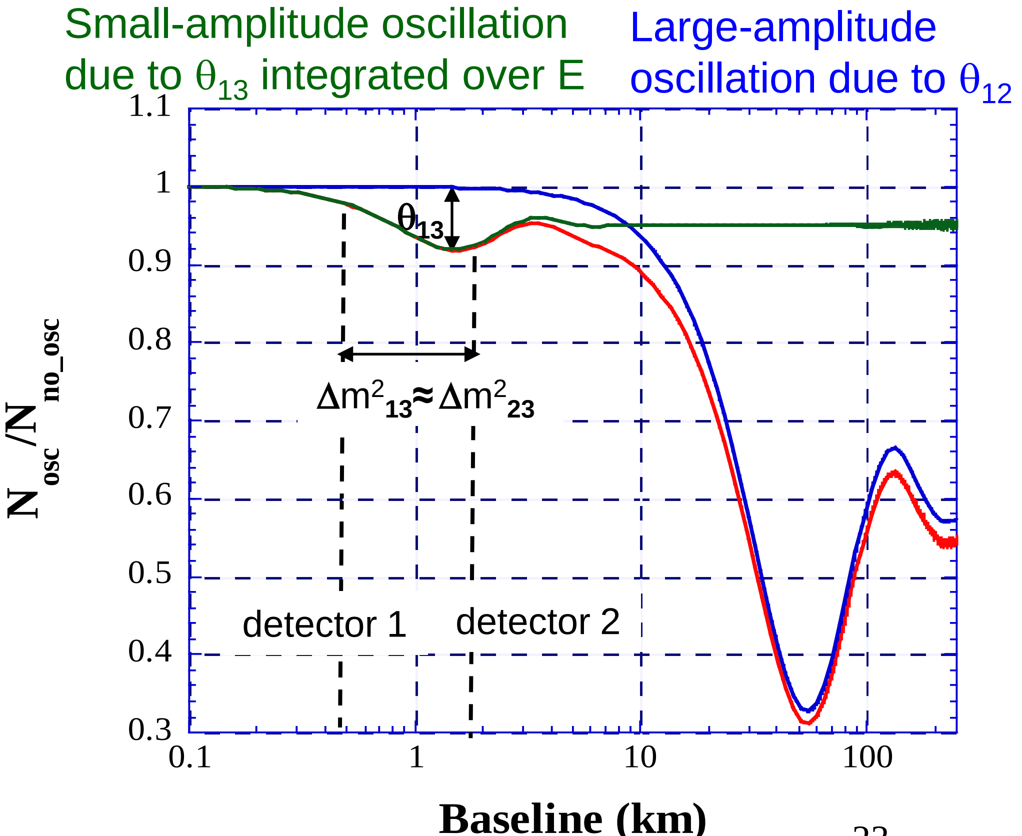

Fogli et al., arXiv:1106.6028

# Measuring $\theta_{13}$ with Reactor Neutrinos

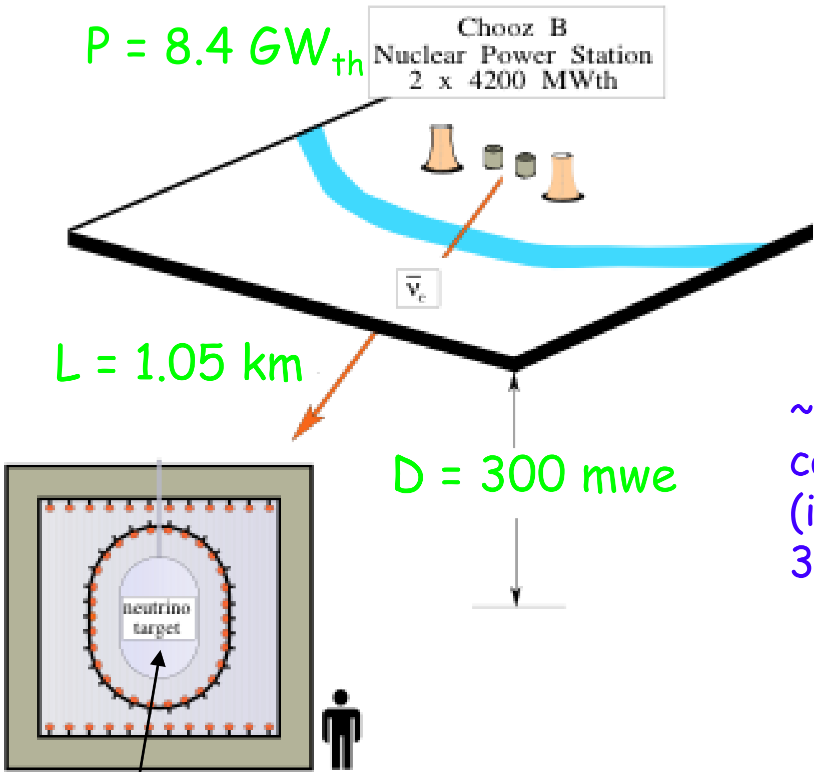
Search for $\theta_{13}$ in new oscillation experiment

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

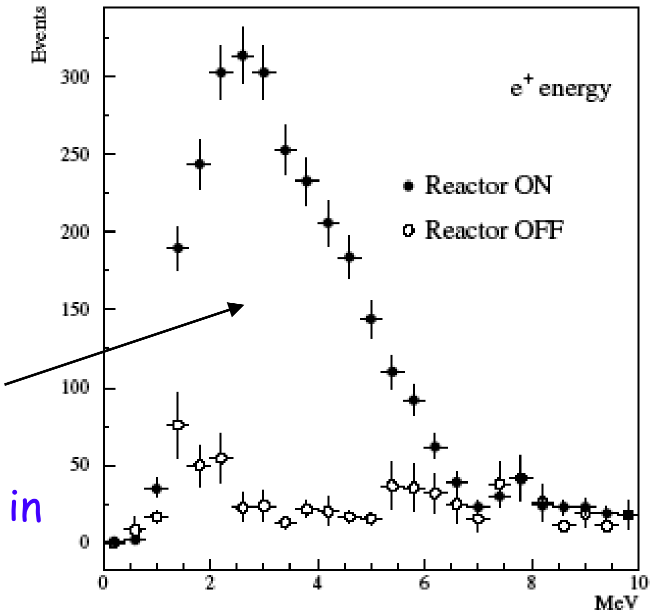


# Results from Chooz




~3000 $\bar{\nu}_e$ candidates (included 10% bkg) in 335 days




5-ton 0.1% Gd-loaded liquid scintillator to detect $\bar{\nu}_e + p \rightarrow e^+ + n$

Rate:

~5 evts/day/ton (full power)

including 0.2-0.4 bkg/day/ton

## Systematic uncertainties

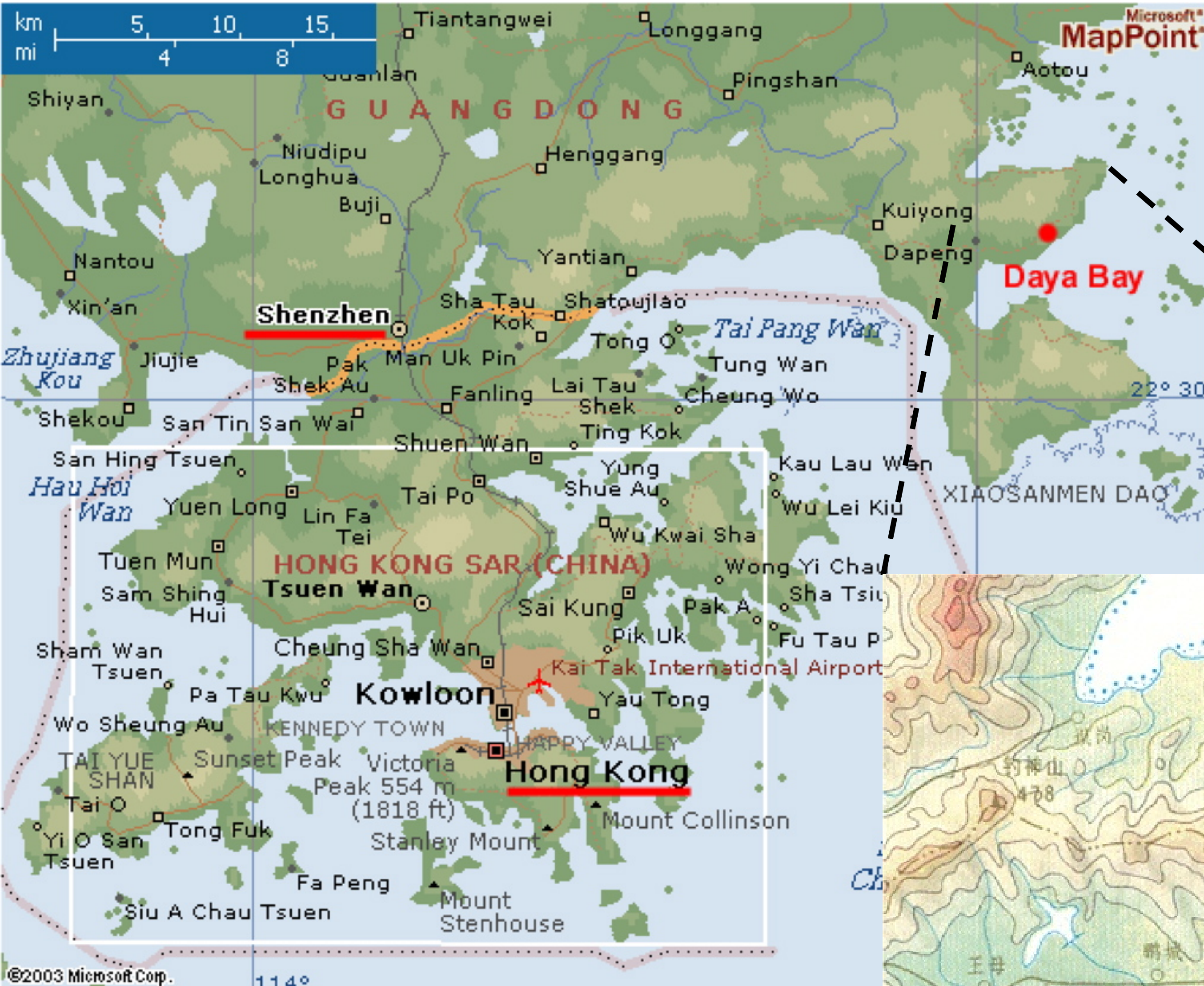
| parameter | relative uncertainty (%) |
|---|---|
| reaction cross section | 1.9 |
| number of protons | 0.8 |
| detection efficiency | 1.5 |
| reactor power | 0.7 |
| energy released per fission | 0.6 |
| combined | 2.7 |

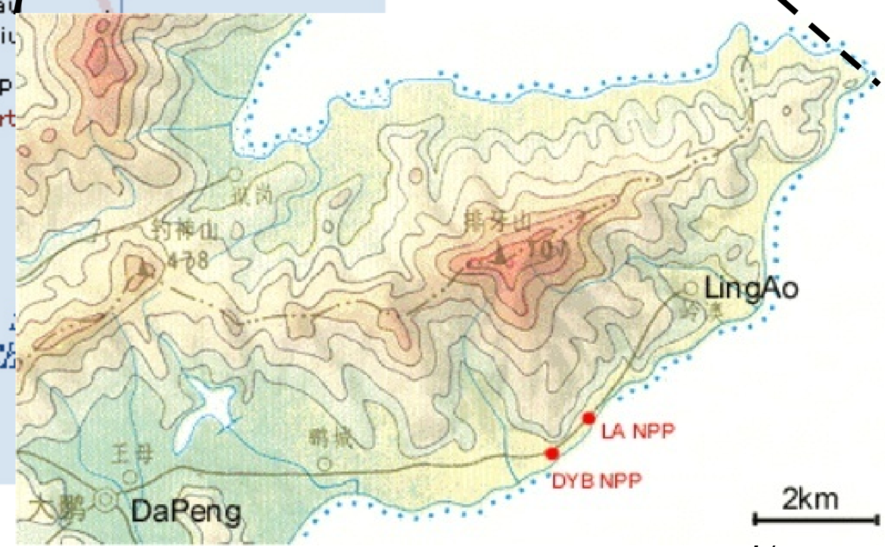
# How to Reach a Precision of 0.01 in $\sin^2 2\theta_{13}$?

- **Increase statistics:**
  - Use more powerful nuclear reactors
  - Utilize larger target mass, hence larger detectors
- **Suppress background:**
  - Go deeper underground to gain overburden for reducing cosmogenic background
- **Reduce systematic uncertainties:**
  - Reactor-related:
    - Optimize baseline for best sensitivity and smaller reactor-related errors
    - Near and far detectors to minimize reactor-related errors
  - Detector-related:
    - Use “Identical” pairs of detectors to do *relative* measurement
    - Comprehensive program in calibration/monitoring of detectors
    - Interchange near and far detectors (optional)

# World of Proposed Reactor Neutrino Experiments

# Location of Daya Bay




- 45 km from Shenzhen
- 55 km from Hong Kong

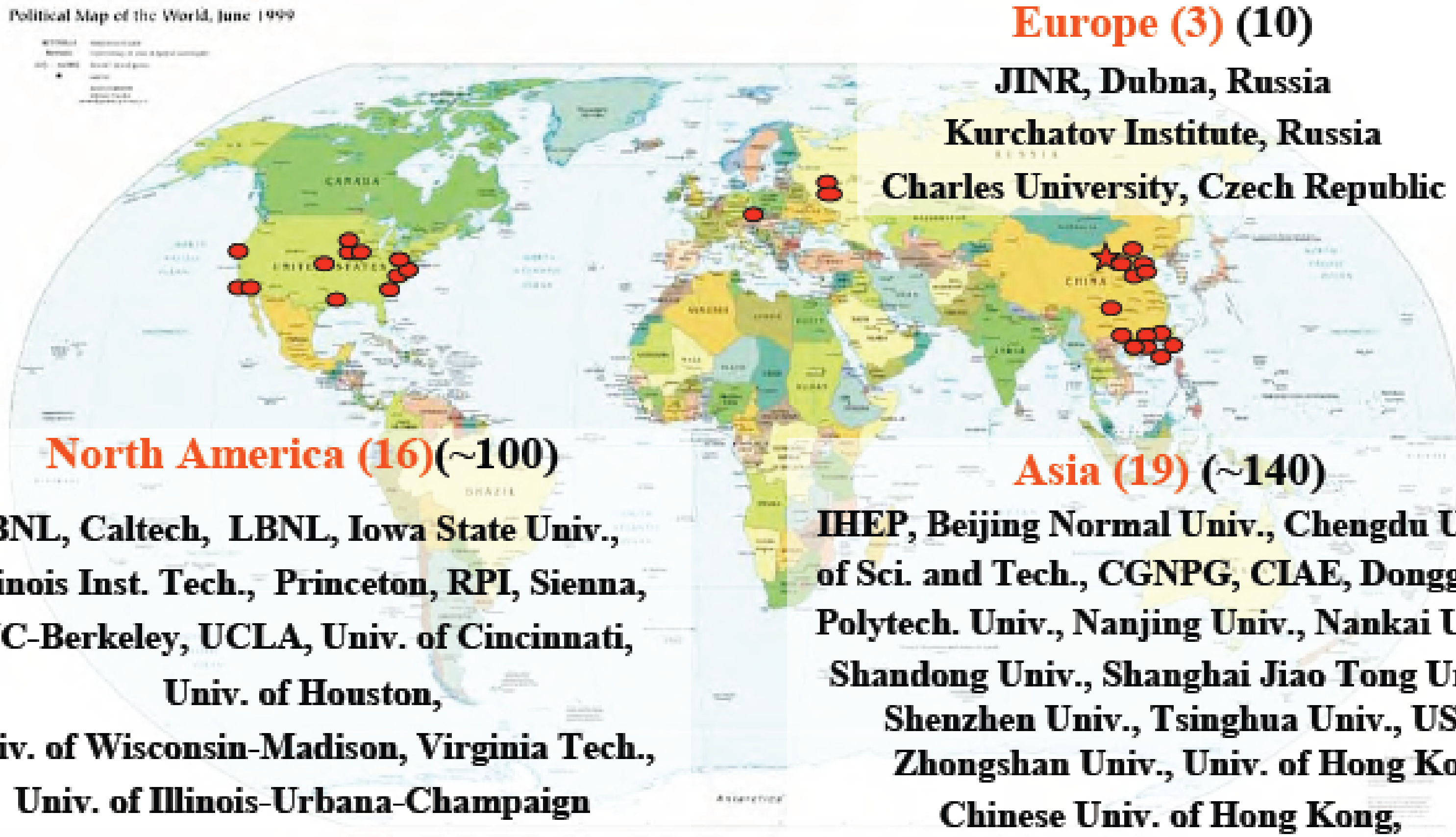
# Daya Bay Nuclear Power Complex

- ~55 km from Hong Kong central
- All 6 reactors are in commercial operation
- one of top 5 most powerful nuclear power plants in the world


$6 \times 2.95\ GW_{th} = 17.7\ GW_{th}$


Daya Bay Collaboration Meeting
IHEP,Beijing,Feb.13-15,2006

# The Daya Bay Collaboration




**Europe (3) (10)**

**JINR, Dubna, Russia**
**Kurchatov Institute, Russia**
**Charles University, Czech Republic**

**North America (16)(~100)**

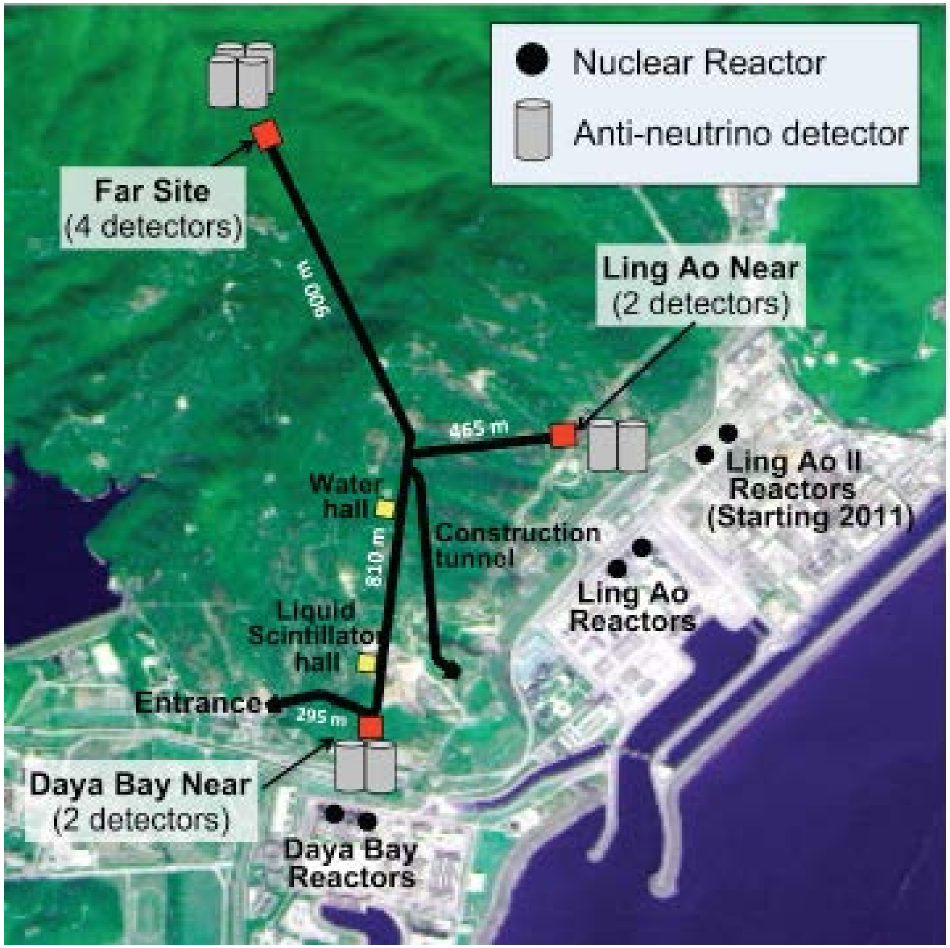
**BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, Sienna, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Virginia Tech., Univ. of Illinois-Urbana-Champaign**

**Asia (19) (~140)**

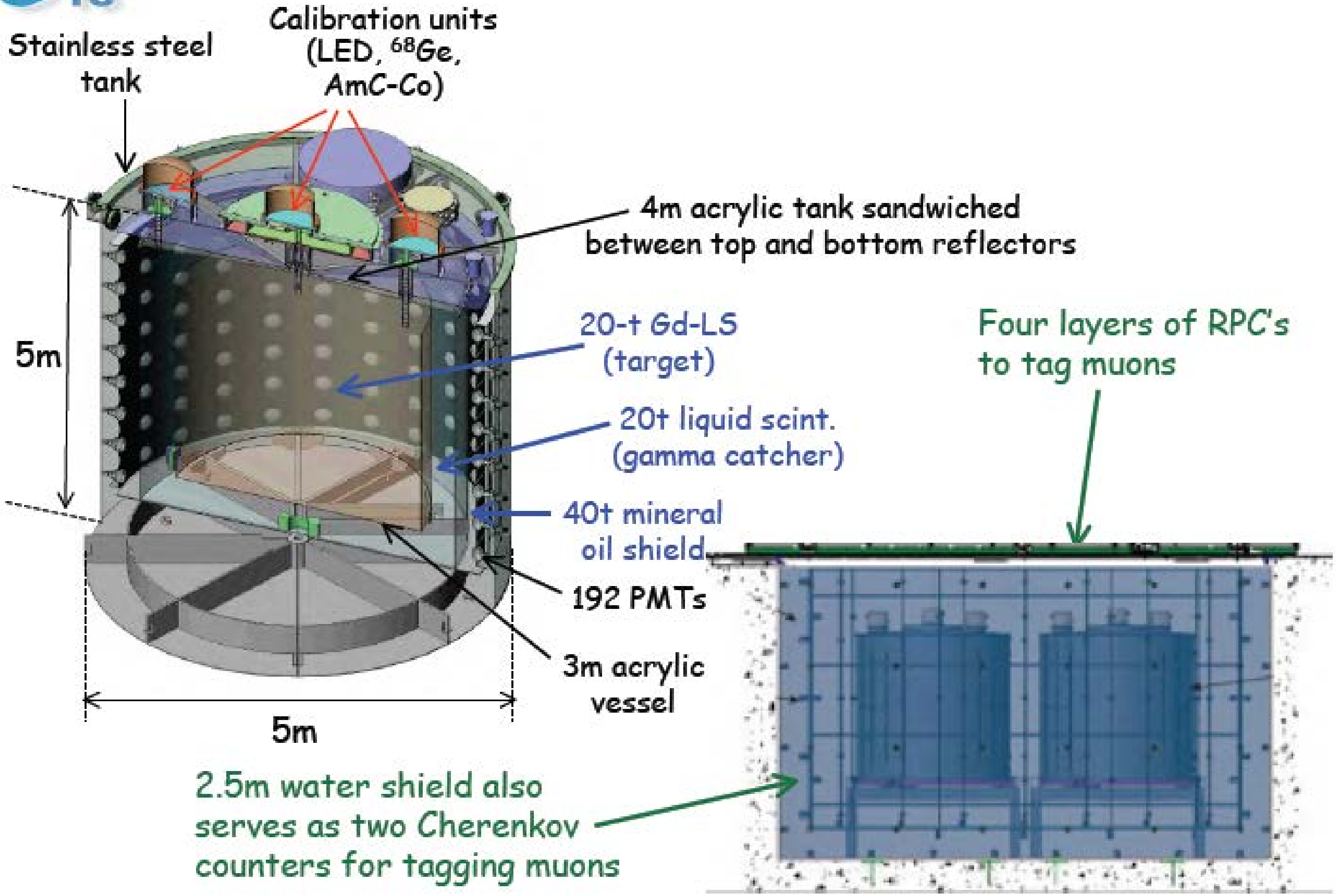
**IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.**

**~ 250 collaborators**

# Eight Identical detectors in three underground sites connected by tunnels



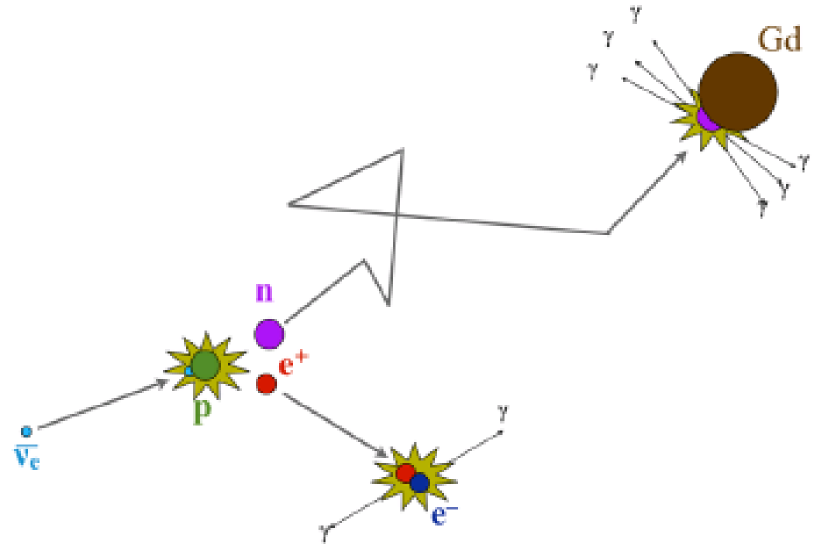

# Antineutrino Detector (AD)



# Detection of antineutrinos

**Inverse Beta Decay**

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



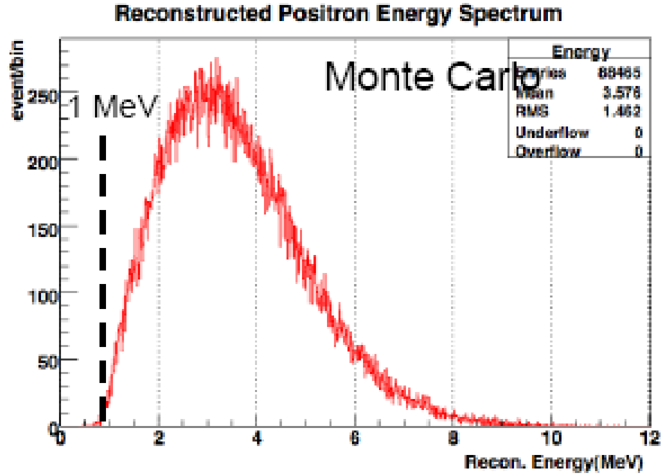

**Coincidence signal: detect**

**Prompt**: $e^+$ annihilation $E_\nu = KE_{e+} + 1.8$ MeV

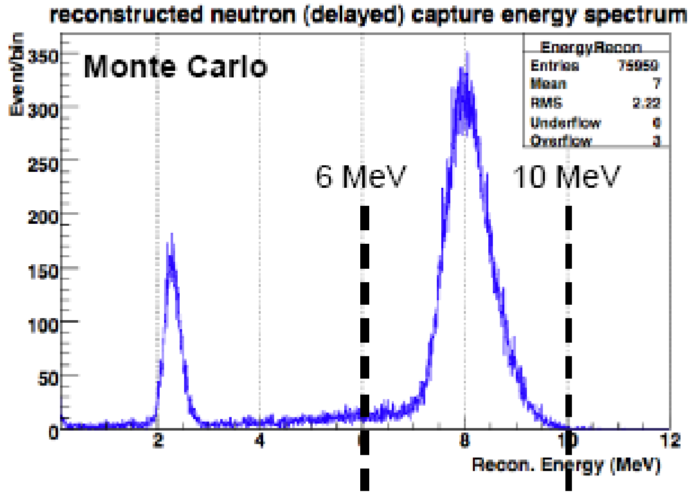
**Delayed**: **n** capture on proton (2.2 MeV) or Gd (8 MeV)

# Expected neutrino signals and rates

**Prompt Energy Signal**




**Delayed Energy Signal**



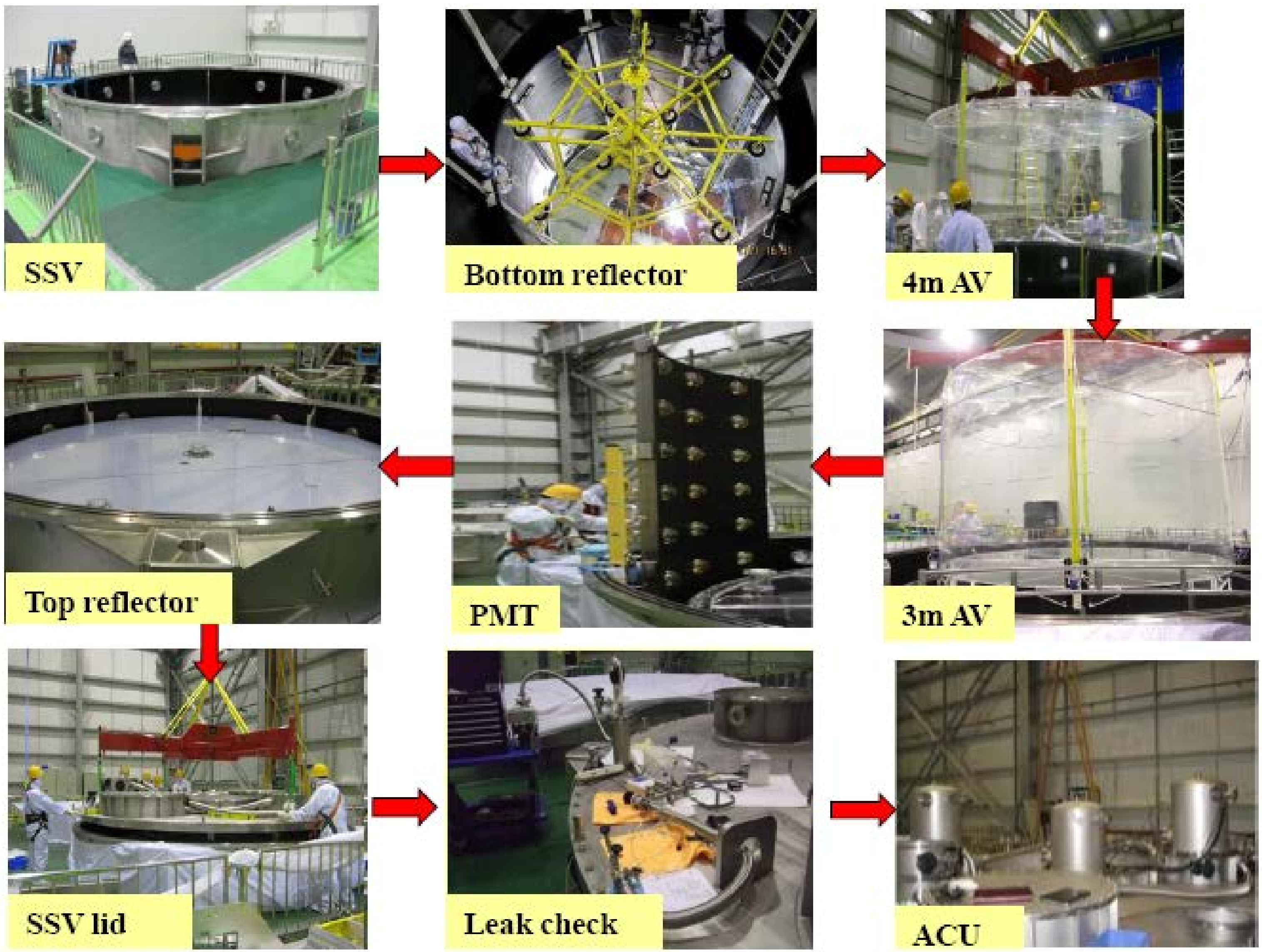

**Near sites**

~700/day/detector

**Far site**

~90/day/detector

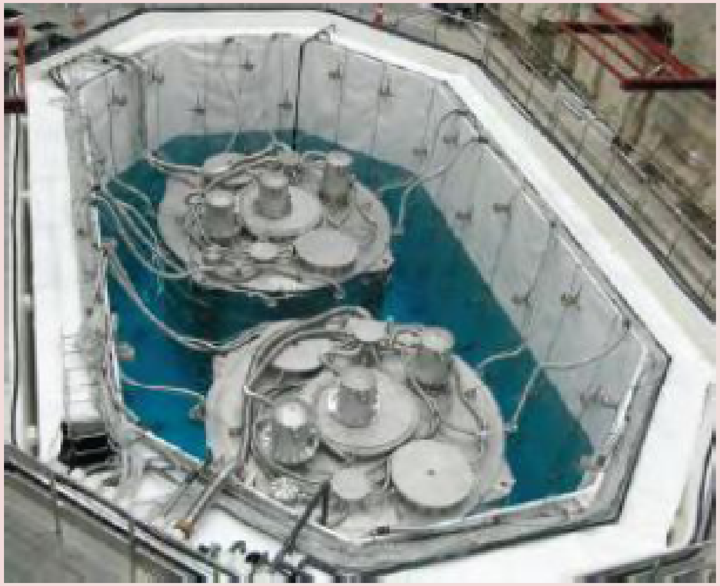
# Assembly of Antineutrino Detector (AD)

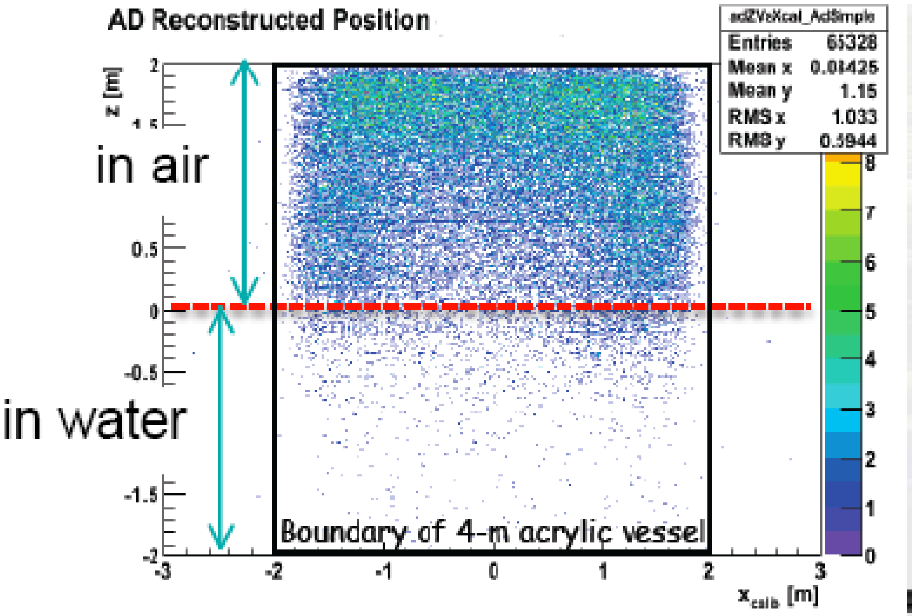


# View of the assembled Antineutrino Detector (AD)

# AD1 and AD2 installed in Hall 1

# Filling water into Hall 1

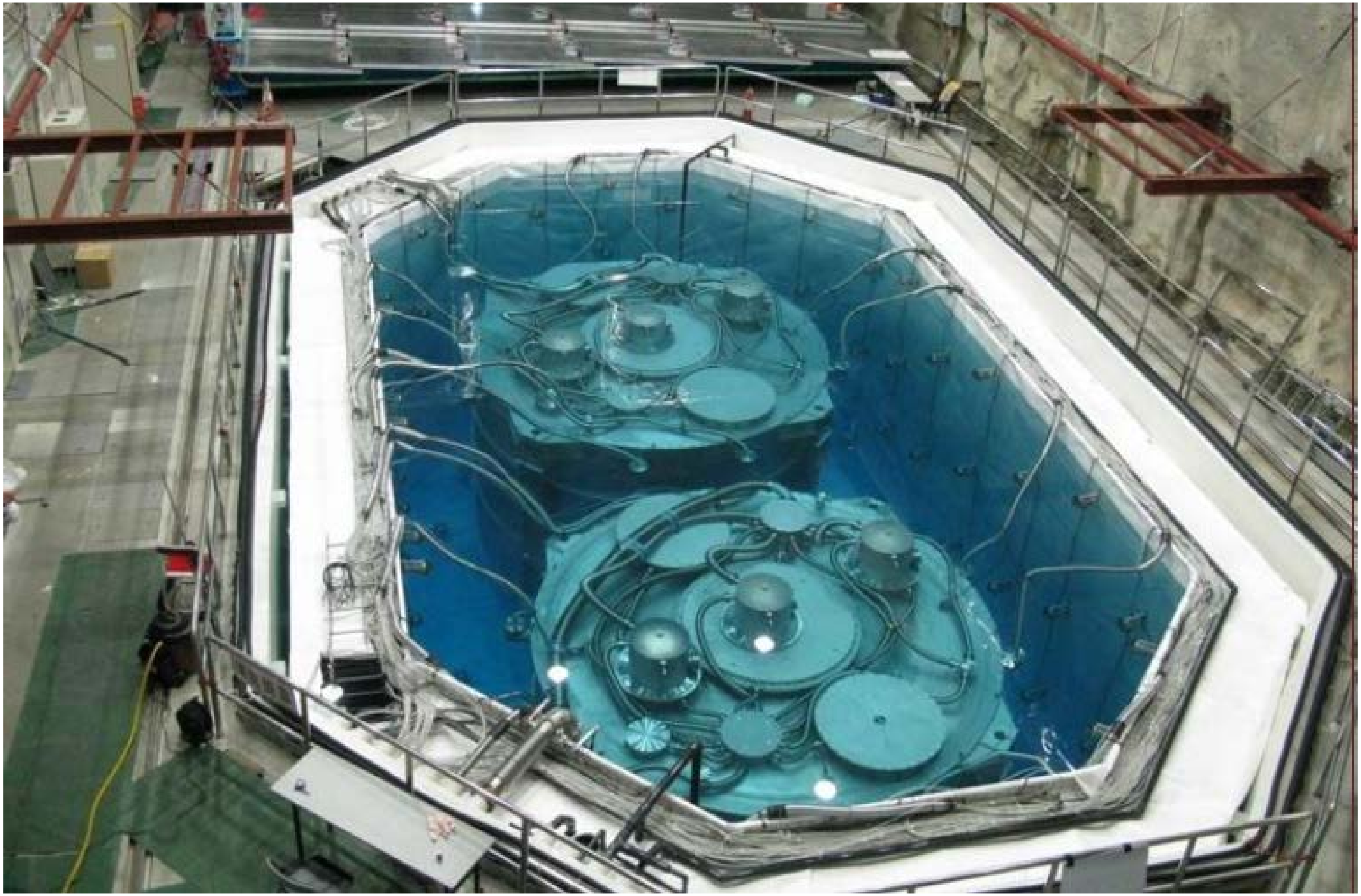




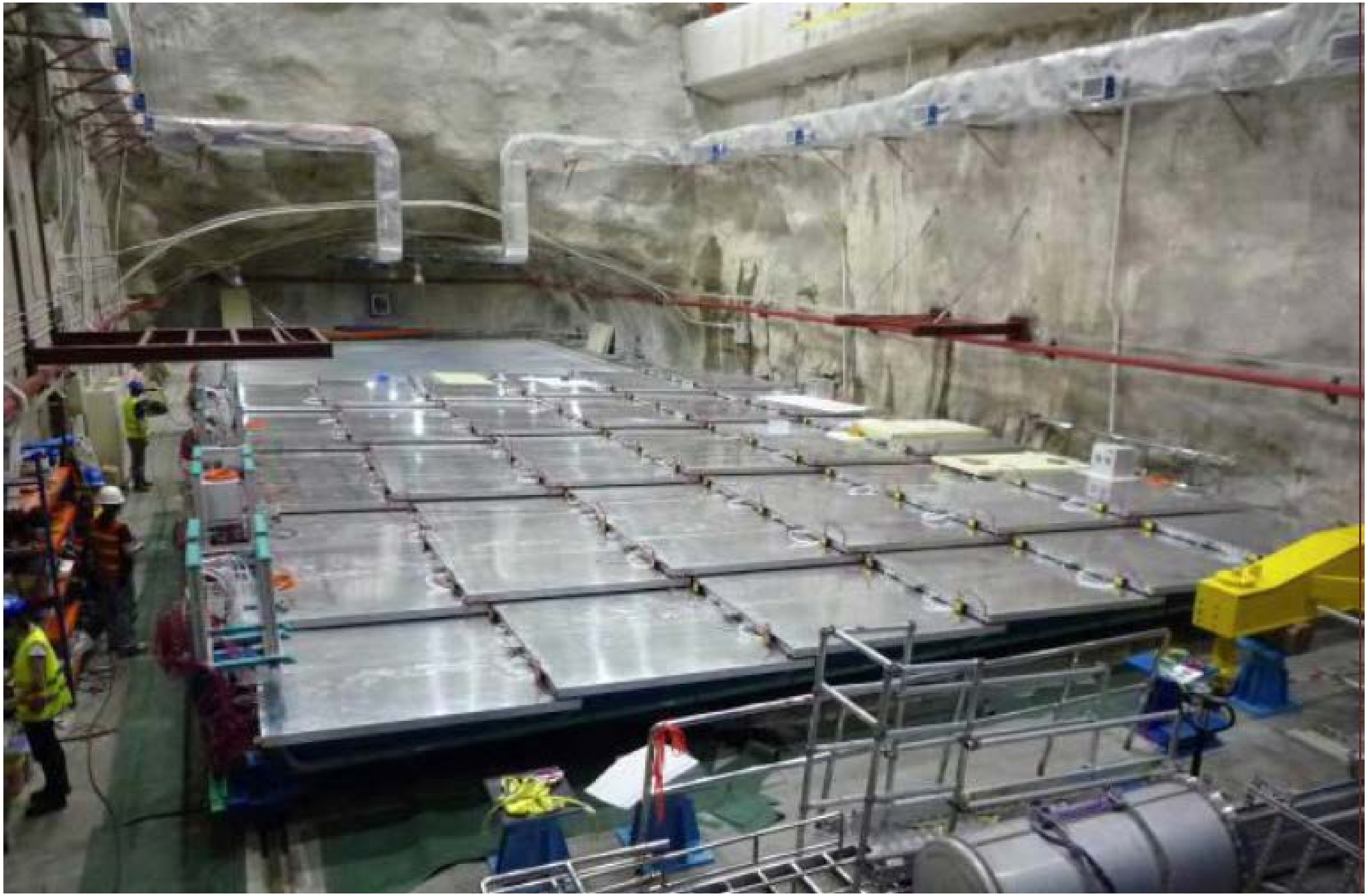

Reconstructed vertices during water-filling

Clear demonstration of the water shielding effect.

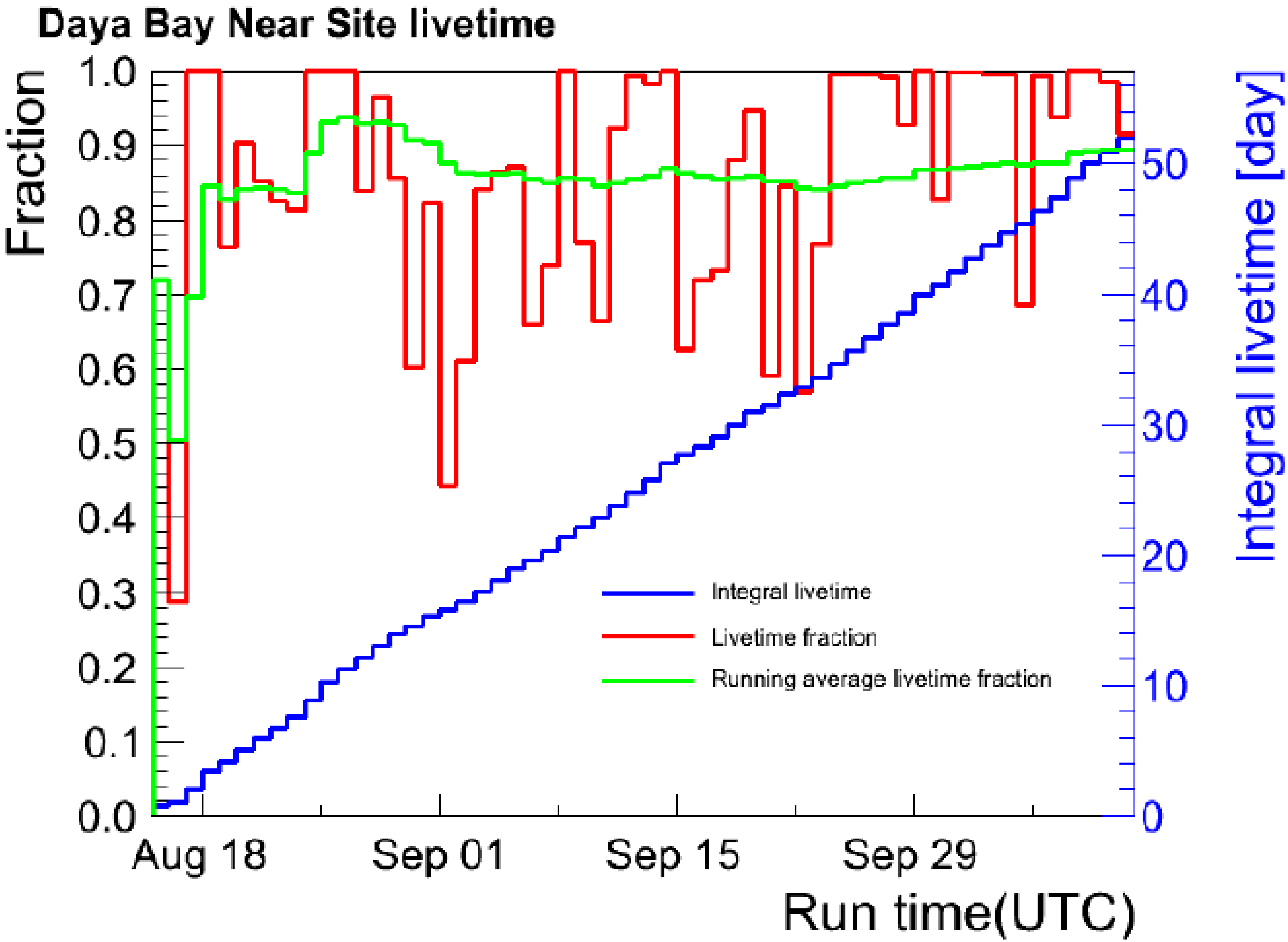
# Filled pool in Hall 1



# Hall 1 ready for data-taking



# Hall 1 started data-taking since August 15



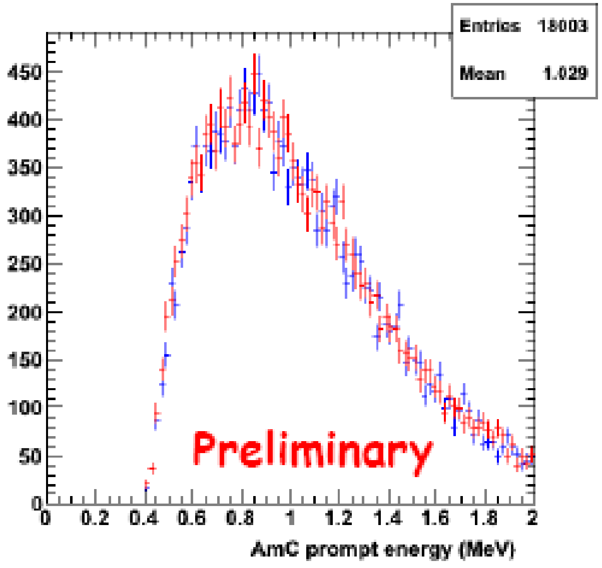
# Comparison between AD1 and AD2 (with Am-C source)

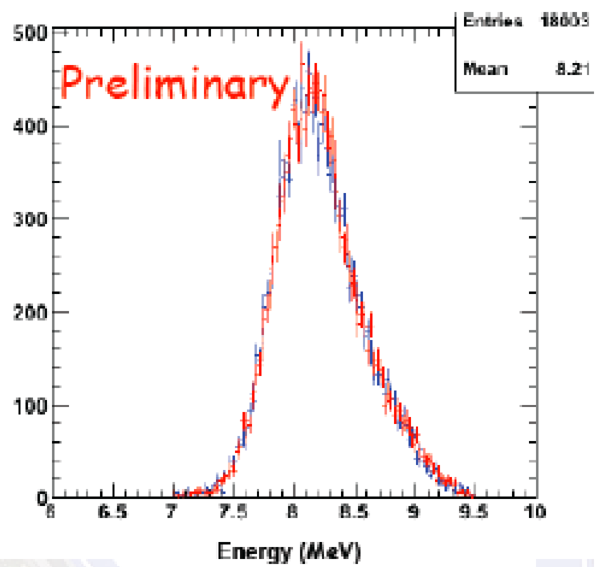
**Proton recoil spectrum in AD**

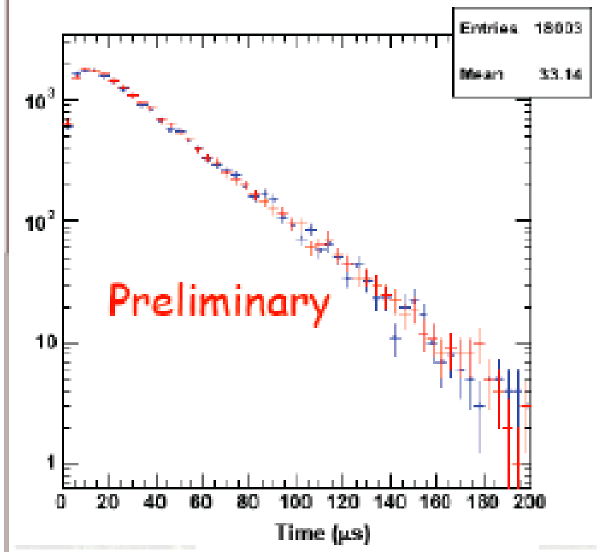
**Neutron-capture energy spectrum**

**Neutron capture time**

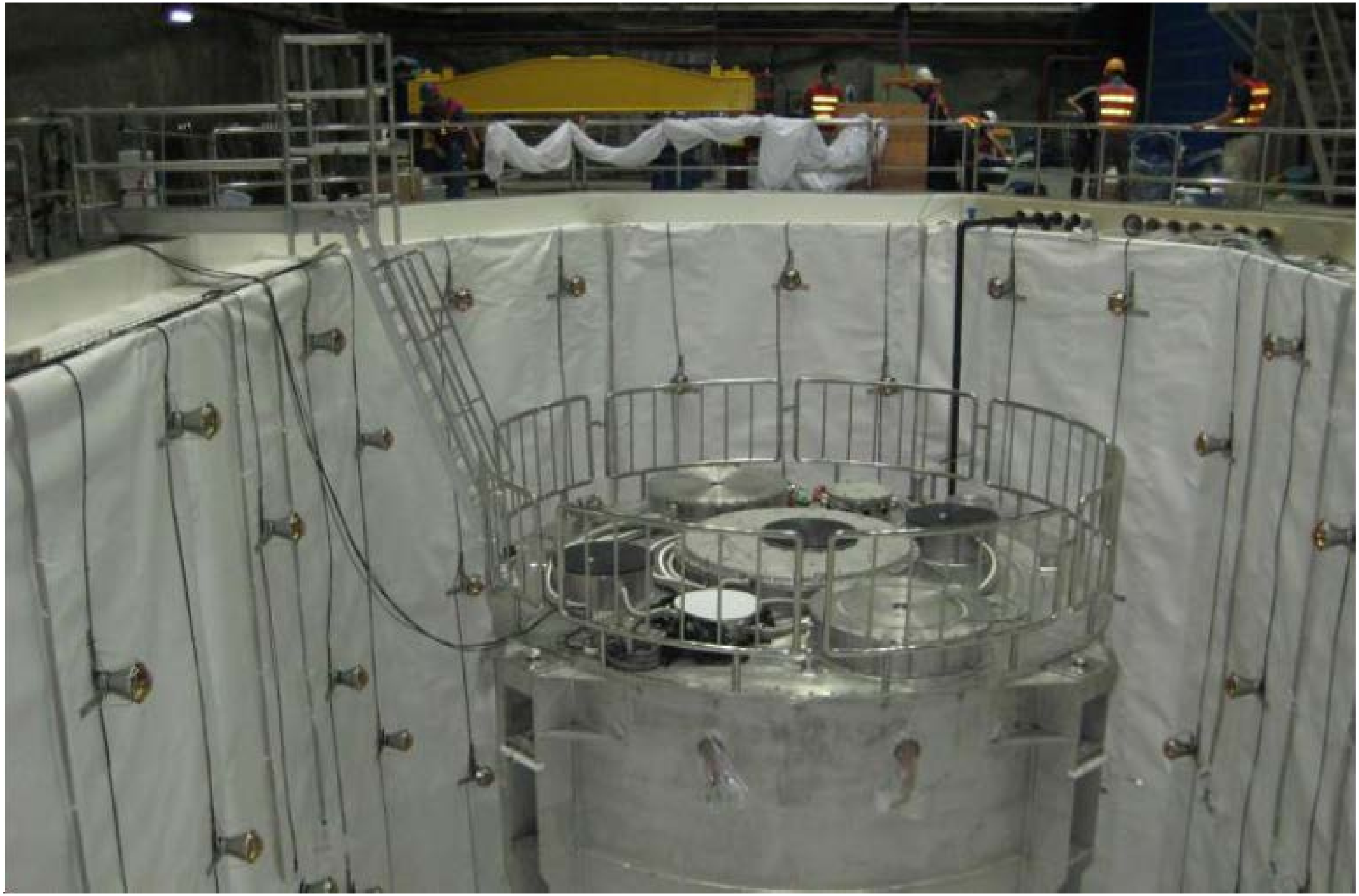
AD1: Blue; AD2: Red



# Hall 2 installation started



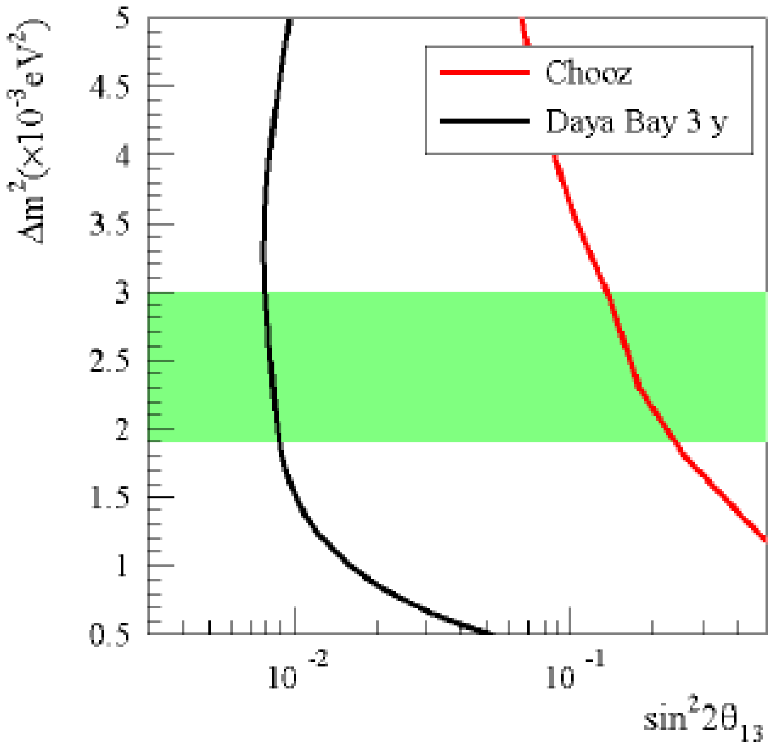
# Hall 3 (Far hall) getting ready

# Current status of Daya Bay

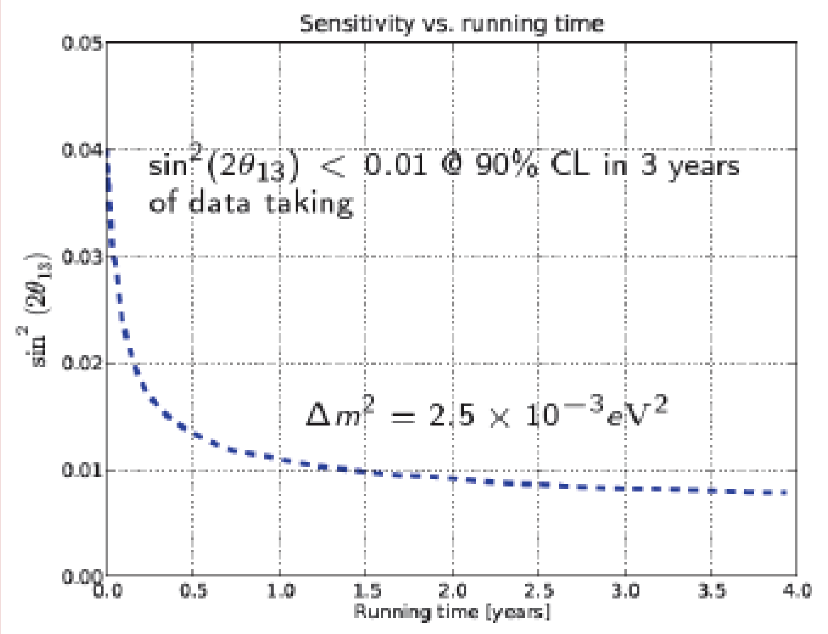
- Daya Bay has finished 4 out of 8 ADs
- AD5 and 6 assembly nearly finish
- AD7 and 8 completion in spring 2012
- Hall 1 taking data since Aug 2011
- Hall 2 being installed
- Hall 3 getting ready for installation
- Summer 2012, data taking with full experiment

# Projected sensitivity

**3 Years,**
**90% Confidence Level**




**1 Year Of Data Taking = 300 Days**



# Backup Slides

# Relic neutrinos and the inverse beta decays

## Expected properties cosmic neutrino background (CNB) versus cosmic microwave background (CMB)

| | CMB | CNB | Relation |
|---|---|---|---|
| Temperature | 2.73K | 1.9 K<br>(1.7 x $10^{-4}$ ev) | $T_\nu/T_\gamma = (4/11)^{1/3}$<br>=0.714 |
| Decouple time | 3.8 x $10^5$ years | ~ 1 sec | |
| Density | ~ 411 / $cm^3$ | ~ 56 / $cm^3$ (per flavor, $n_\nu = n_{\nu\text{-bar}}$ ) | $n_\nu = (3/22)\, n_\gamma$ |

- CNB took a snapshot of the Universe at a much earlier epoch than CMB $n_\nu$
- Since $\Delta m_{21}^2 = (8.0\pm0.3) \times 10^{-5}$ $ev^2$, and $|\Delta m_{32}^2| = (1.9 \rightarrow 3.0) \times 10^{-3}$ $ev^2$, at least two of the three neutrinos have masses higher than $10^{-2}$ ev, and these two types of CNB are non-relativistic ($\beta$<<1)

# Capture of CNB on radioactive nuclei

A very old idea: S. Weinberg, 1962

Consider tritium beta-decay:

$$a)\ {}^3H \rightarrow {}^3He + e^- + \overline{\nu}_e$$

This is a 3-body $\beta$-decay with $Q$-value of

$$Q_a = M({}^3H) - M({}^3He) - M(e^-) - M(\overline{\nu}_e)$$

where $M(x)$ refers to mass of particle $x$

Now consider the CNB capture reaction:

$$b)\ \nu_e + {}^3H \rightarrow {}^3He + e^-$$

This is a 2-body reaction with the $Q$-value of

$$Q_b = M(\nu_e) + M({}^3H) - M({}^3He) - M(e^-)$$

It follows that

$$Q_b = Q_a + 2M(\nu)$$

# Capture of CNB on radioactive nuclei (continued)

For massless neutrinos, $M(\nu) = 0$, and we have

$$Q_a = Q_b$$

Note that the conventional definition of Q-value for the $\beta$-decay, $Q_\beta$, assumes $M(\nu) = 0$, hence

$$Q_\beta = Q_a + M(\nu)$$

The maximal energy for electrons from the

$$^3H \to {}^3He + e^- + \bar{\nu}_e$$

$\beta$-decay is the end-point energy (ignoring recoil energy)

$$T_a = Q_a = Q_\beta - M(\nu)$$

Electrons from CNB capture reaction are mono-energetic:

$$T_b = Q_b = Q_\beta + M(\nu)$$

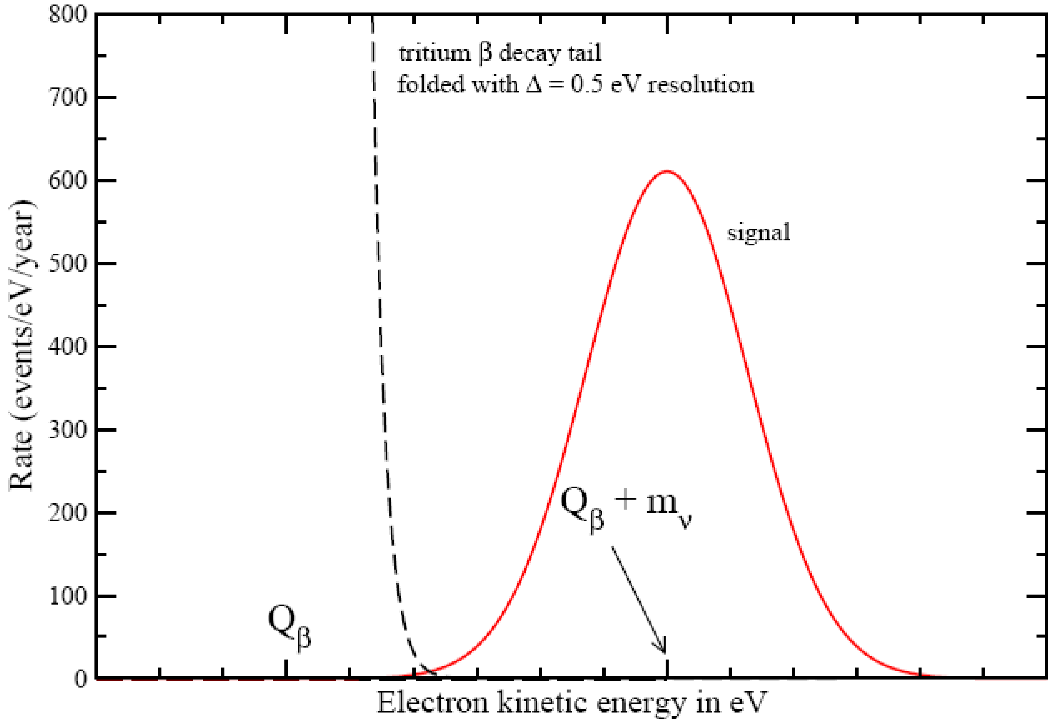
($Q_\beta$ = 18.6 KeV for tritium $\beta$-decay)

It follows that

$$T_b = T_a + 2M(\nu)$$

# Capture of CNB on radioactive nuclei (continued)

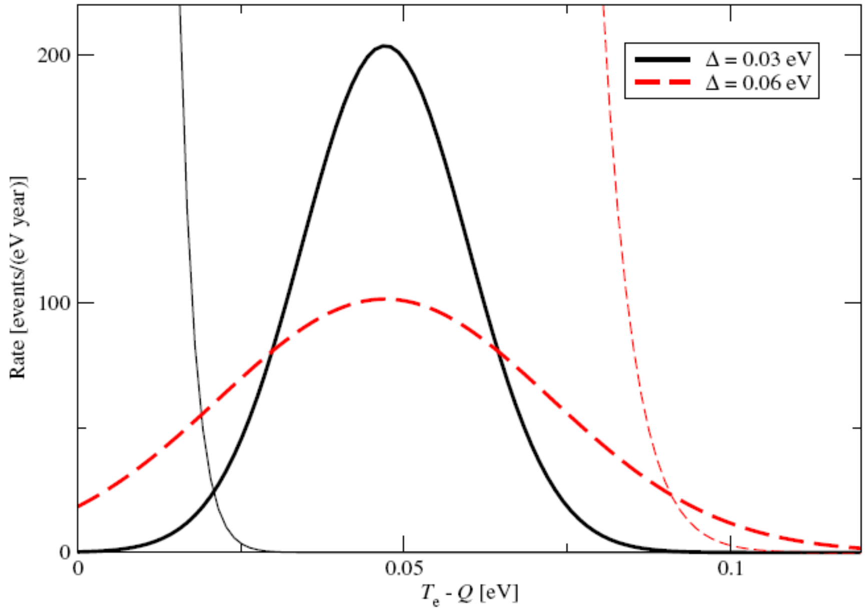
- Neutrino masses: $M(\nu)$=1ev (mass degeneracy of three neutrinos)
- Experimental energy resolution : $\Delta$=0.5ev
- Any local clustering of CNB due to gravity? $n_\nu / < n_\nu > = 50$
- Size of the tritium source: 100 grams




Lazauskas, Vogel, Volpe, J. Phys. G. 35 (2008) 025001

# Capture of CNB on radioactive nuclei (continued)

- Neutrino masses: $M(\nu)$=0 ev (for the lightest neutrino, assuming inverted mass hierarchy, the other two massive neutrinos are nearly degenerate)
- Experimental energy resolution : $\Delta$=0.03 (0.06) ev
- Any local clustering of CNB due to gravity? $n_\nu / < n_\nu >= 1$
- Size of the tritium source: 100 grams




M. Blennow, Phys. Rev. D 77 (2008) 113014

# Capture of CNB on radioactive nuclei (continued)

- Is there a way to INCREASE the energy separation between the electrons from the $\beta$-decay background and the CNB capture signals?
- How about boosting the momentum of the tritium relative to the sea of CNB? (by accelerating the tritium)?
- Now consider a tritium accelerated to an energy corresponding to $E(^3H)/m(^3H)=\gamma$. It is simple to show that in the center-of-mass frame of $^3H+\nu$, the total energy is equal to $\sqrt{s}=m(^3H)+\gamma\cdot m(\nu)$
- This means that electron emitted from the CNB capture would have an energy larger by $\gamma\cdot m(\nu)$ relative to case when a tritium is at rest.
- On the other hand, electrons from the tritium $\beta$-decay would still have the same end-point energy in the tritium rest frame.
- This implies the separation between the energy of CNB capture electron and $\beta$-decay end-point is now increased by an amount $\sim\gamma\cdot m(\nu)$.

# Capture of CNB on radioactive nuclei (continued)

- We need to boost the electrons back to the lab frame, since the detectors will only measure the electron energy in the lab frame.
- It is interesting that one would gain another important factor for electrons emitted along the direction of the tritium momentum. Consider the Lorentz transformation:

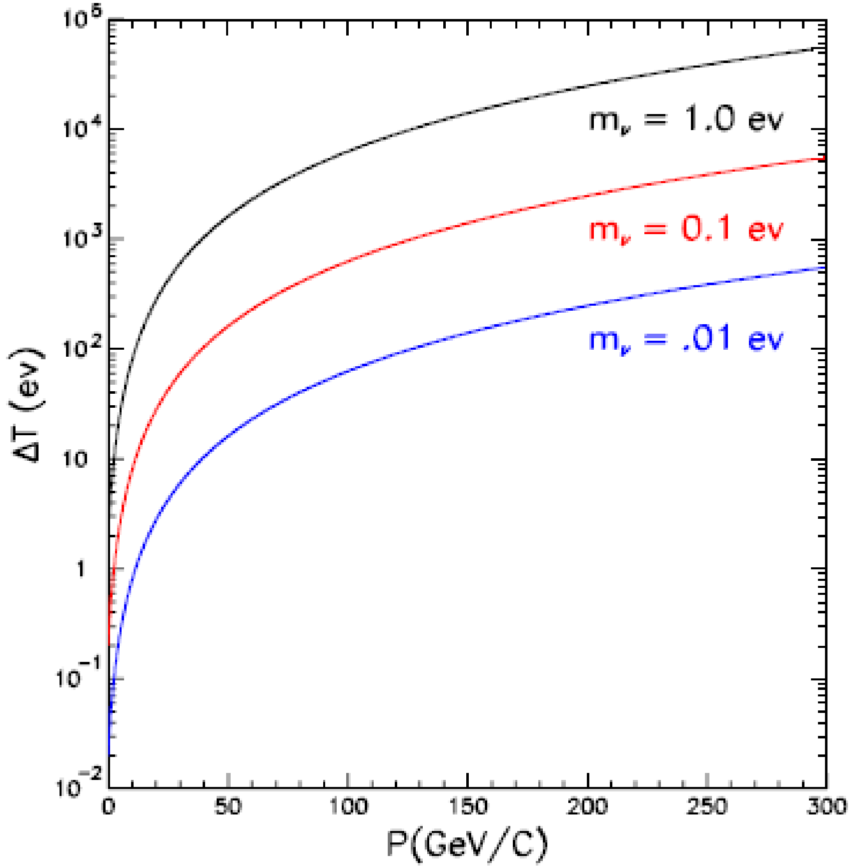
  $E_1' = \gamma E_1 + \beta\gamma P_1; \quad E_2' = \gamma E_2 + \beta\gamma P_2$

  where $E$ and $E'$ are the electron energies in the c.m. frame and the lab frames ,respectively. The subscripts 1 and 2 refer to electrons emitted in the CNB capture and $\beta$-decay, rspectively. We have

  $E_1' - E_2' = \gamma(E_1 - E_2) + \beta\gamma(P_1 - P_2) \sim 2\gamma(E_1 - E_2)$ for $\beta \to 1$
- This shows that the energy separation between electrons emitted in the forward angles from the CNB capture and the electrons from the $\beta$-decay is further increase by a factor of $\sim 2\gamma$!! This amounts to a separation of $\sim 2(1+\gamma)\gamma m_\nu$ in the relativistic limit.

# Capture of CNB on radioactive nuclei (continued)

- We have carried out calculations for various neutrino masses over a wide range of tritium momentum:




ΔT is the separation of the kinetic energy for electrons emitted at forward angle from the CNB capture and electrons at end-point from the tritium β-decay.

The figure shows that ΔT becomes very large for high energy tritium beam. Note that P=300 GeV/c can be achieved at the RHIC accelerator.