Daya Bay Experiment and its Future

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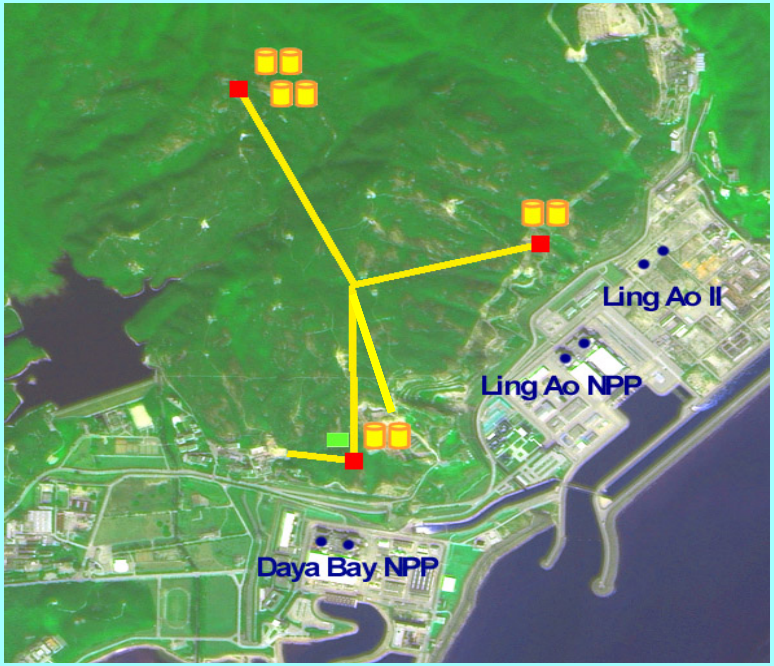
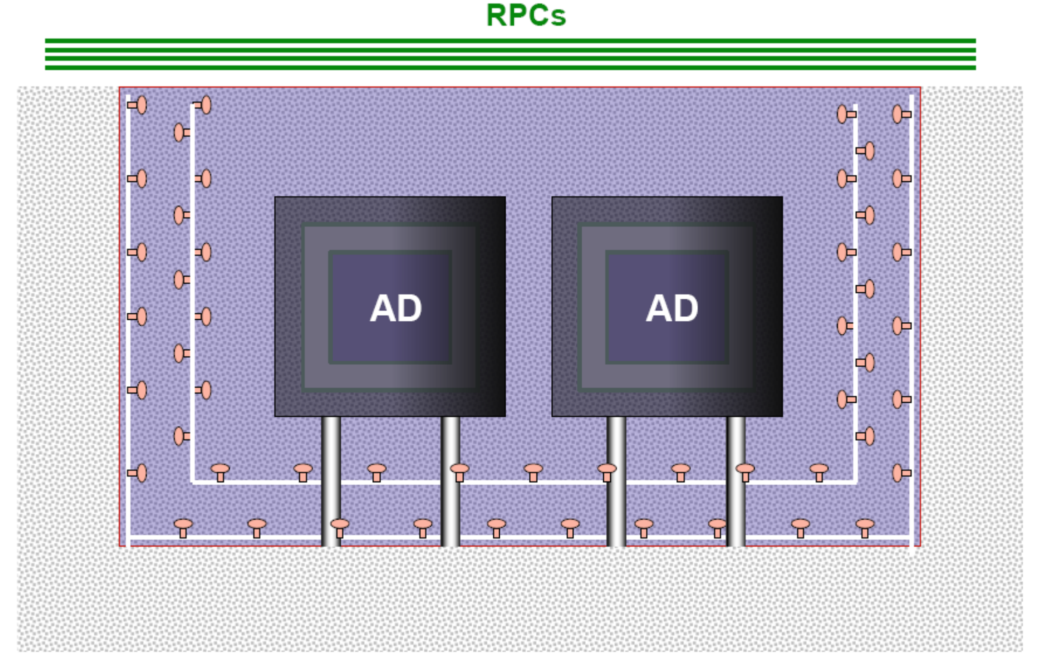
Daya Bay reactor neutrino experiment

- Second largest reactor complex: 5 reactor cores operational, 1 more this year, 17.4 GW_{th} in total
- Mountains near by, easy to construct a lab with enough overburden to shield cosmic-ray backgrounds
- Challenges: how to reach a precision less than 0.5 % ?
  - Design + good conditions

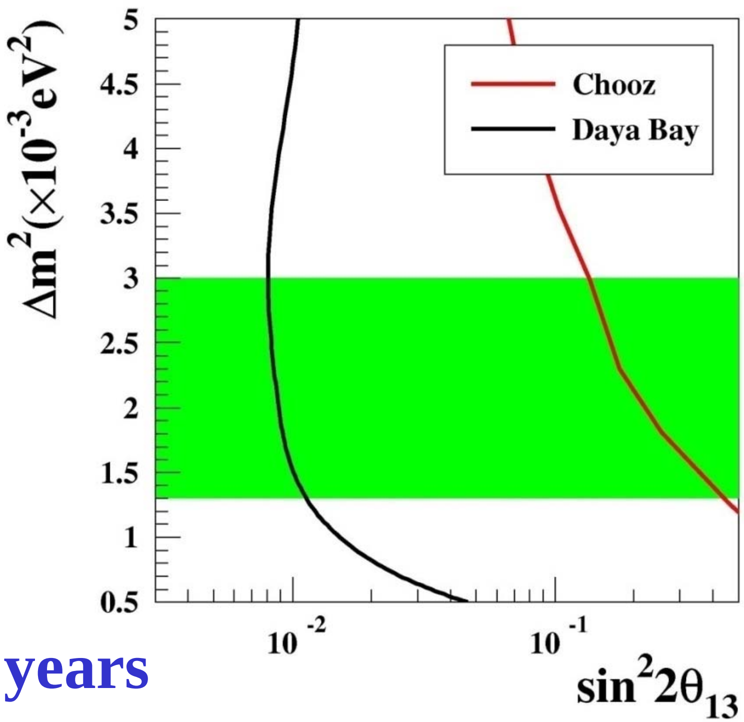
The Experiment





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

Sensitivity to $Sin^2 2\theta_{13}$



3 years

	Uncertainty
Reactors	0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Backgrounds	0.32% (Daya Bay near) 0.22% (Ling Ao near) 0.22% (far)
Signal statistics	0.2%

$$\chi^2 = \min_{\alpha's} \sum_{i=1}^{Nbin} \sum_{A=1,3} \frac{\left[M_i^A - T_i^A (1 + \alpha_D + \alpha_c + \alpha_d^A + c_i + \sum_r \frac{T_i^{rA}}{T_i^A} \alpha_r) - b^A B_i^A \right]^2}{T_i^A + T_i^{A2} \sigma_b^2 + B_i^A}$$

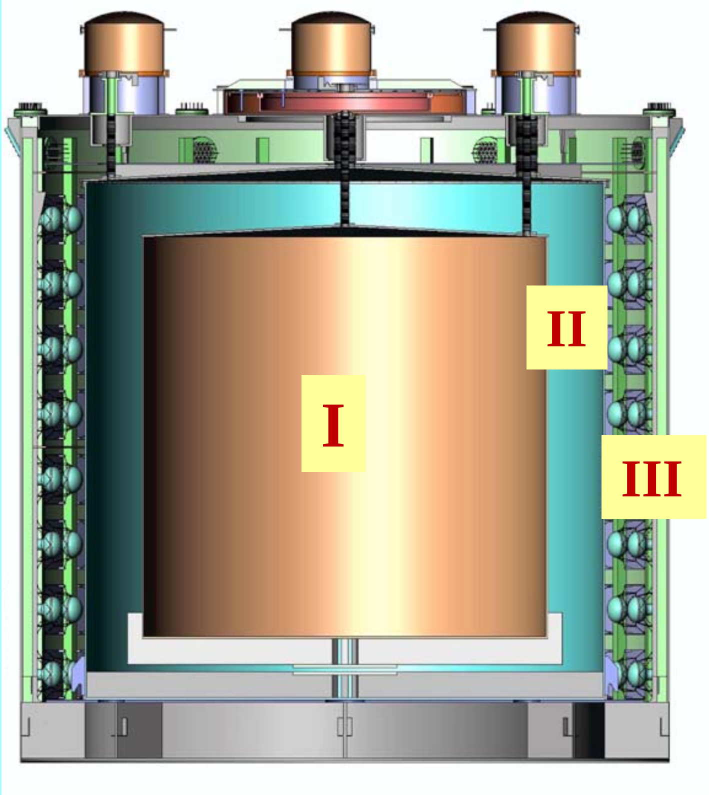
$$+ \frac{\alpha_D^2}{\sigma_D^2} + \frac{\alpha_c^2}{\sigma_c^2} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{i=1}^{Nbin} \frac{c_i^2}{\sigma_{shape}^2} + \sum_{A=1,3} \left(\frac{\alpha_d^{A2}}{\sigma_d^2} + \frac{b^{A2}}{\sigma_B^2} \right)$$

Civil construction

- •Tunnel length: ~ 3100m
- •Three exp. halls (1-3)
- •One assembly hall (5)
- •One water prod. hall (4)

- All blasting safely completed, no one exceeded vibration limit (0.007g)
- Hall 1, 4, 5 completed last year
- Hall 2 completed last month
- Hall 3 to be completed this summer

Anti-Neutrino detector(AD)



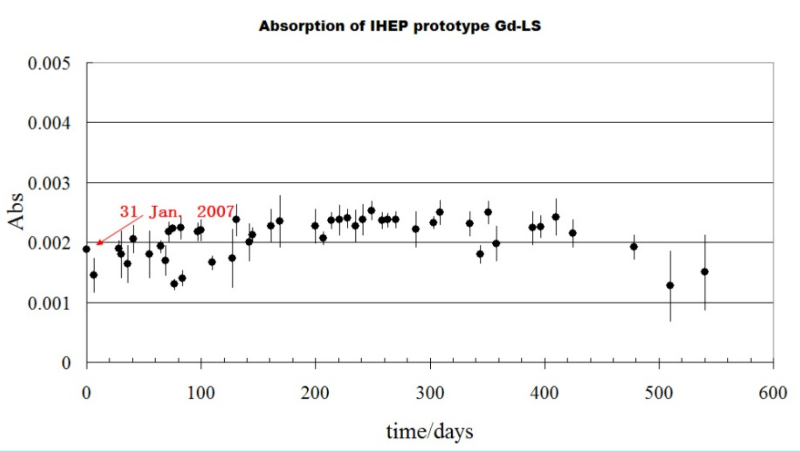
192 8"PMT/module
Reflectors at top and bottom ➔
Photocathode coverage 5.6 % ➔ 12%

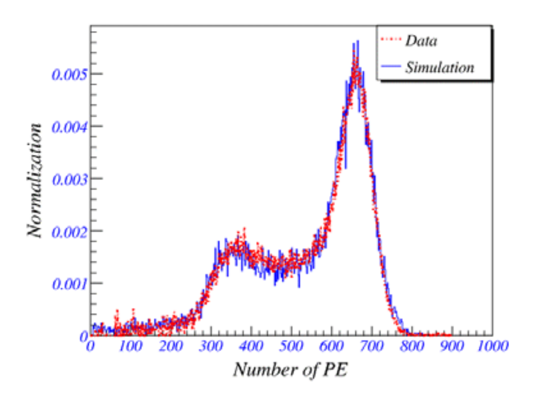
- R &D successful
- Component production mostly finished
- Detector assembly underway, two ADs completed
- Dry-run test of completed AD shows that they are fully functional within spec.
- Remaining AD will be finished by next Spring

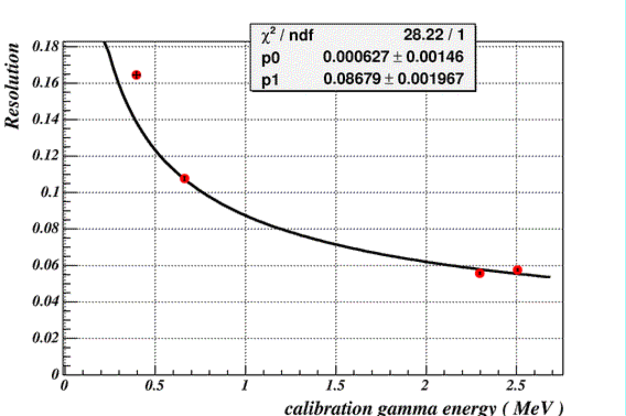
I. Target: 20 t, 1.6m
II. γ-catcher: 20t, 45cm
III. Buffer: 40t, 45cm
Total weight: ~100 t

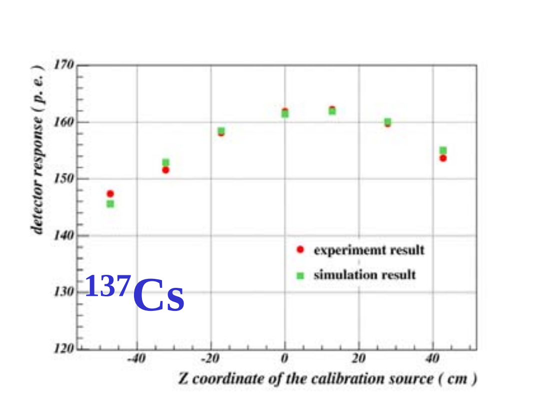
Prototype studies

- **Motivation**
  - Validate the design principle
  - Test technical details of tanks
  - Test Gd-LS
  - Test calibration and Pu-C source
- **Achievements**
  - Energy response & MC Comparison
  - Reconstruction algorithm
  - Neutron response & Pu-C source
  - Effects of reflectors
  - Gd-LS









Detector Component Production

Stainless steel vessel

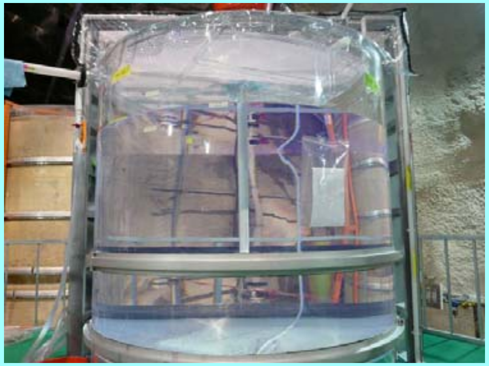
4m Acrylic vessel

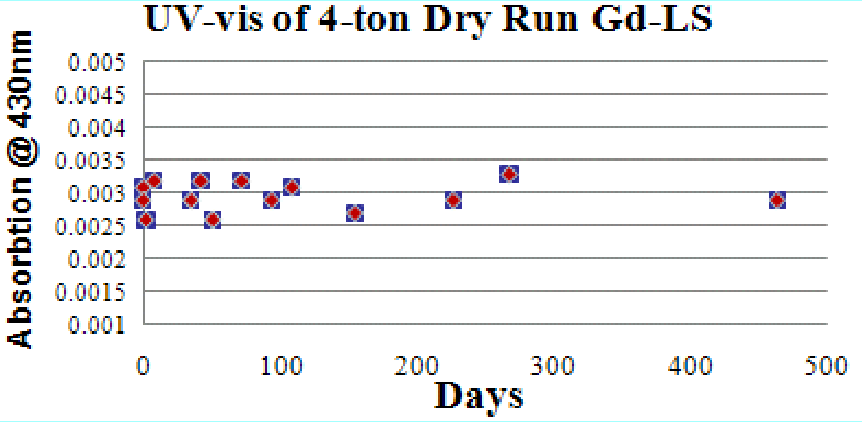
Reflector

3m acrylic vessel

Liquid Scintillator Production

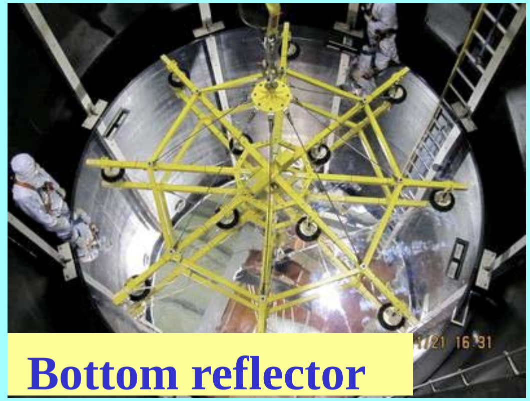
- **What we need:**
  - **185t Gd-LS, ~180t LS, ~320t oil**
- **Equipment designed, manufactured and fully tested at IHEP and then re-installed onsite**
- **4-ton Gd-LS test run successful: good quality and stability**
- **Gd-LS production completed and stored in Hall 5**
- **LS production almost finished**
- **AD Filling will start next month**



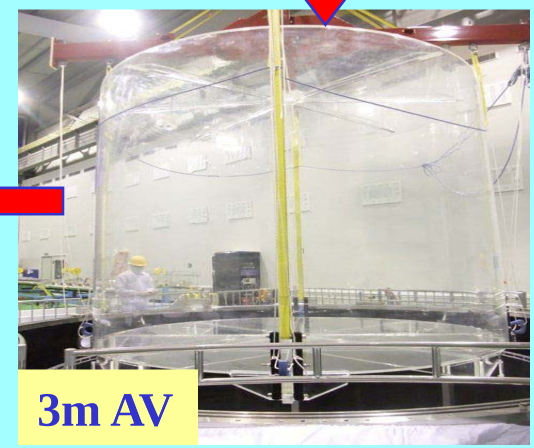


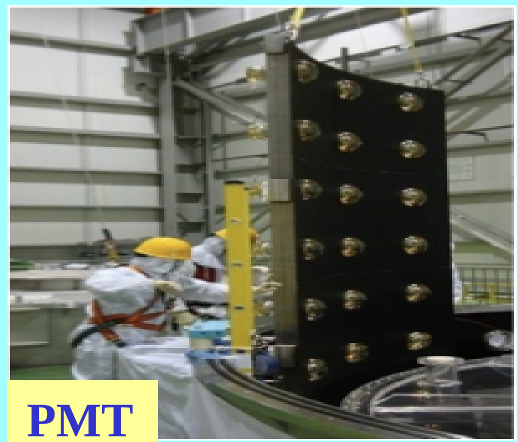
AD assembly

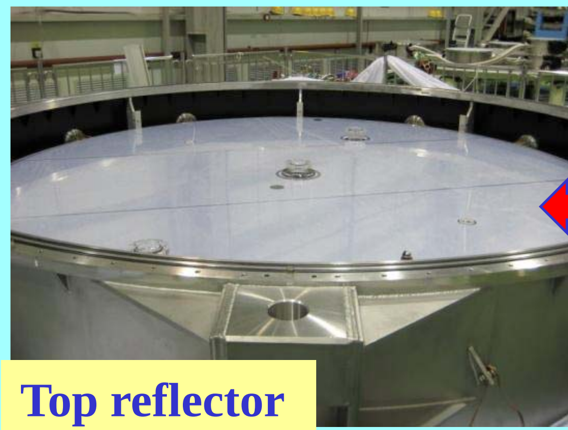

SSV


Bottom reflector


4m AV


3m AV


PMT

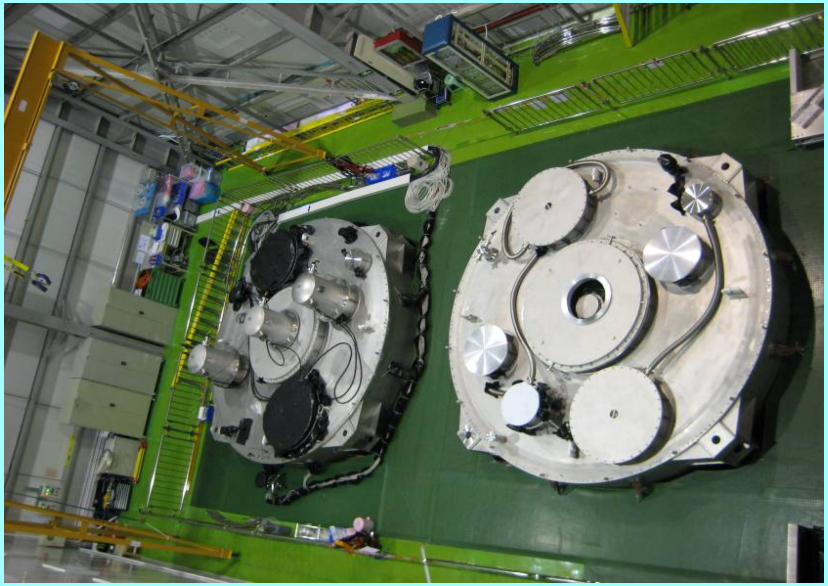

Top reflector


SSV lid


Leak check

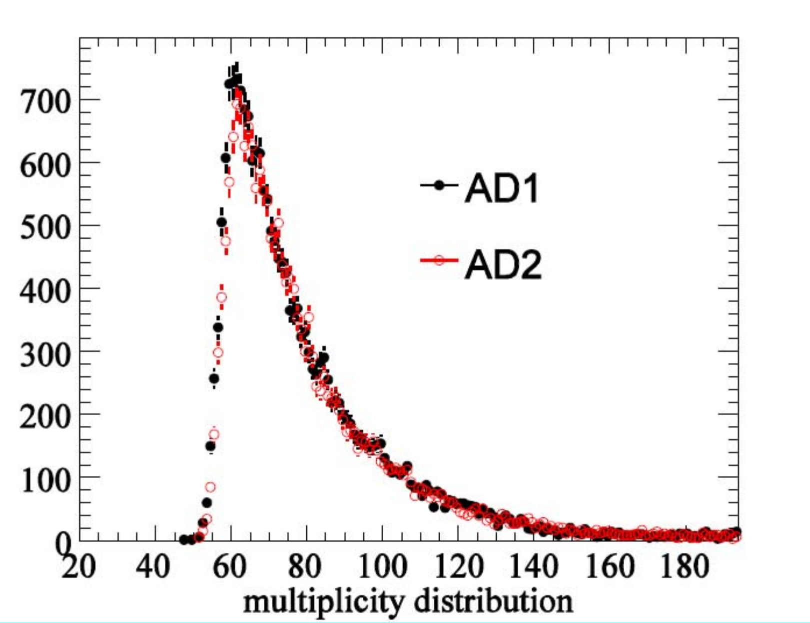

ACU

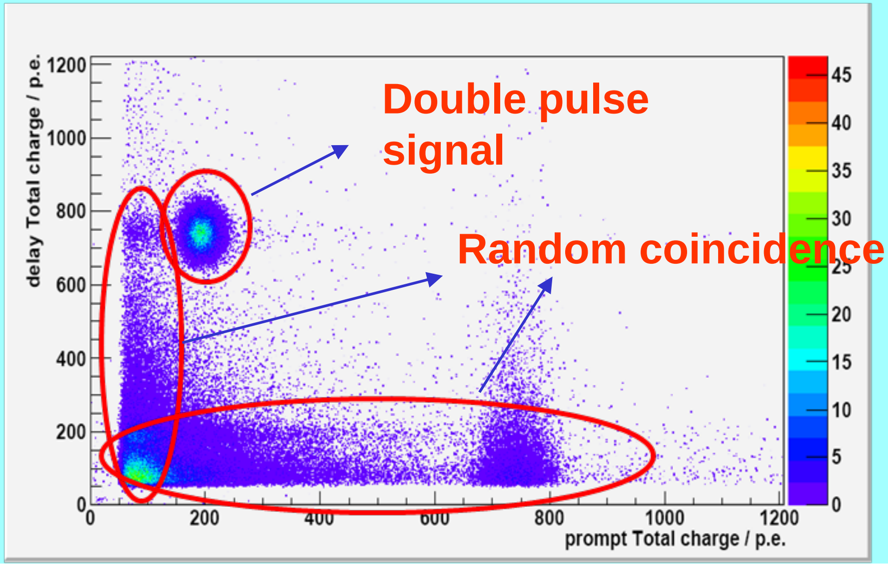
Two completed ADs

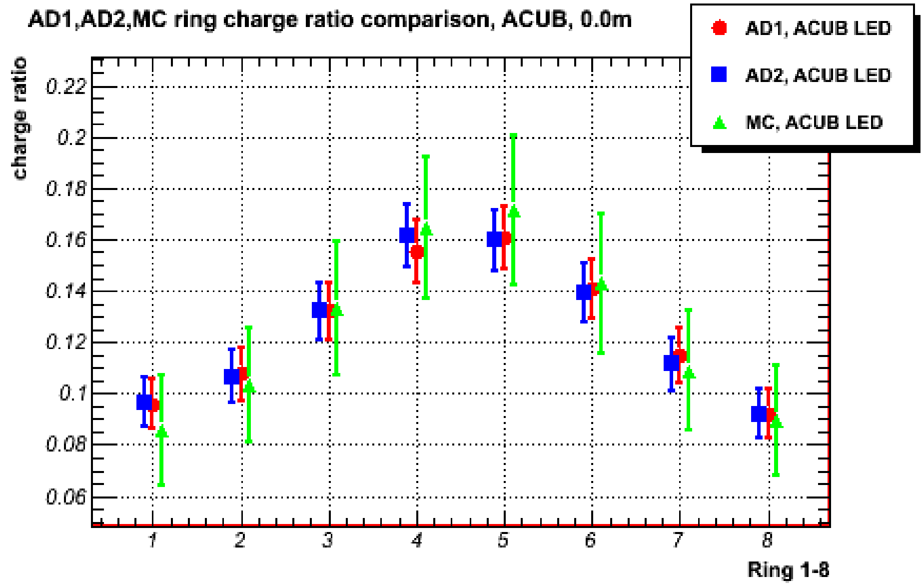


AD Dry-run

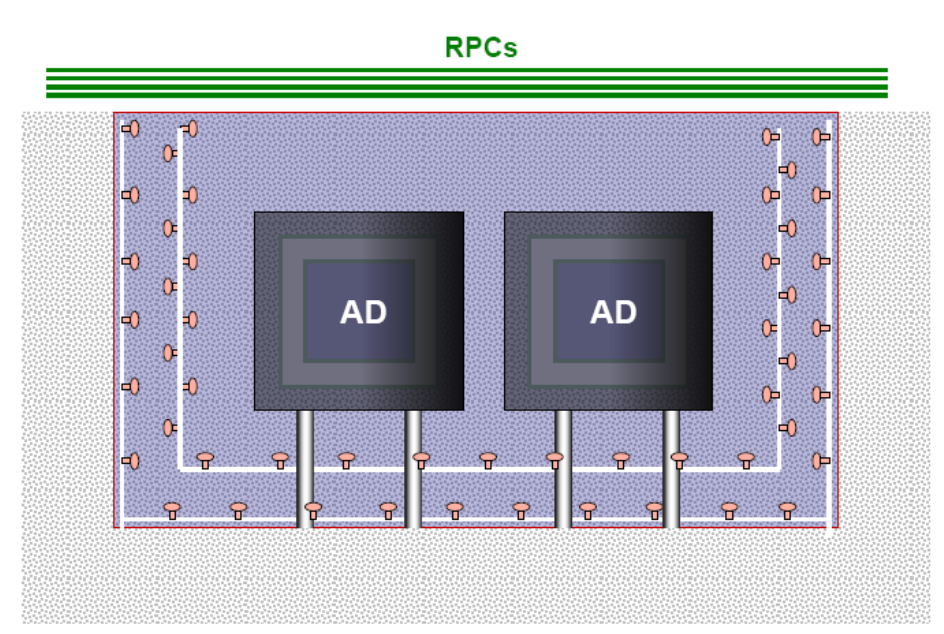
- Complete test of assembled ADs with final electronics, trigger and DAQ
- Results show that:
  - Both ADs are fully functional
  - Their response to LED & cosmic-rays agrees with MC expectations
  - Two ADs are identical
  - Electronics, trigger, DAQ and offline software are all tested







Muon veto detector

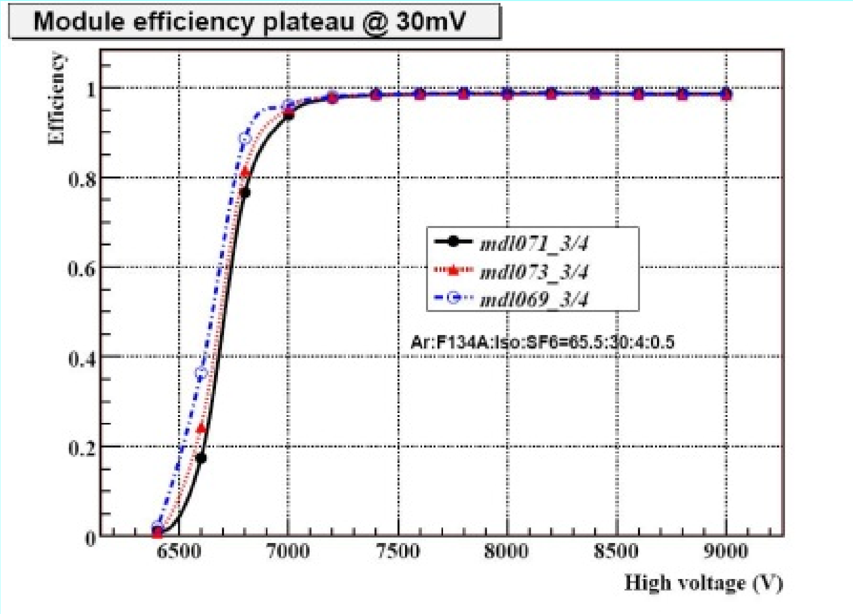


- **RPCs**
  - bare chamber production almost completed
  - Chamber assembly and testing mostly finished and shipped to Daya Bay
- **Water Cerenkov detector**
  - R&D successful
  - All PMTs & support structure are onsite
  - Installation for Hall 1 almost completed
  - Dry-run successful: PMT works as expected

- **2.5 m water shielding**
- **Two active Cosmic-muon veto's to cross check each other and control systematic errors**
  - **Water Cerenkov: Eff.>95%**
  - **RPC Muon tracker: Eff. > 90%**
  - **total ineff. = 10%*5% = 0.5%**

RPC production & assembly

- Each module consists of 4 layers of bare chambers made of bakelite without linseed oil(BESIII-type)
- RPC bare chamber testing shows good performance
- Module assembly almost finished
- 2/3 modules shipped to Daya Bay



RPC installation

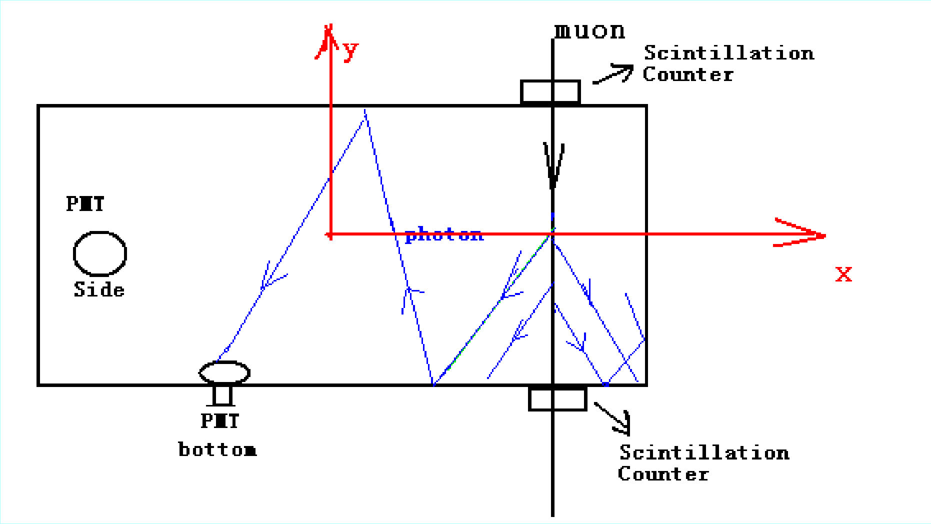
RPC supporting structure

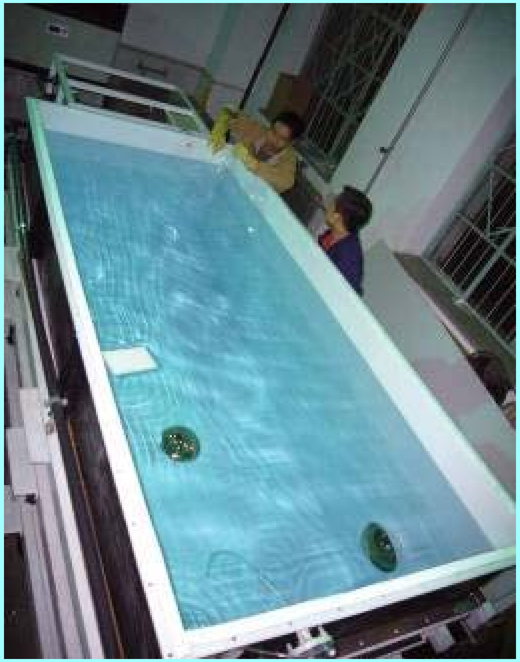
Gas system

RPC modules

Fully installed RPC

Water detector: R&D with a prototype





- Compatibility tests of materials in water
- Established a water circulation model ➔ purification system design
- MC modeling for light transport & light collection

Water Cerenkov detector installation

PermeFlax Painting

PMT supporting structure

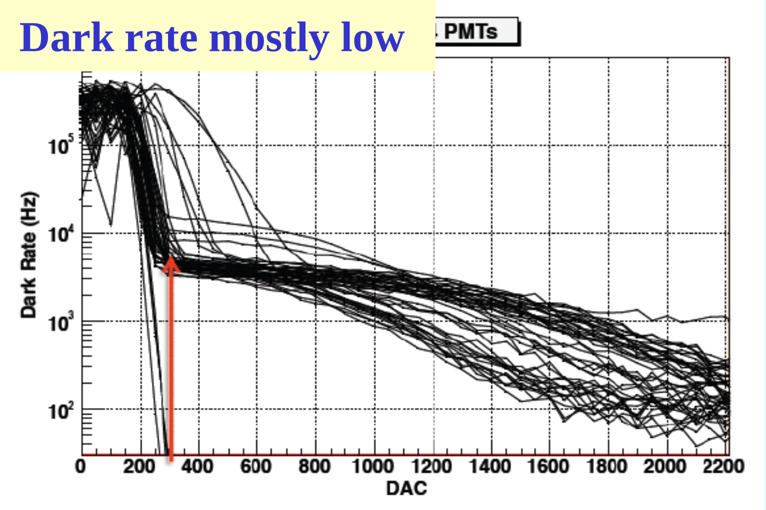
Tyvek barrier

Completed pool

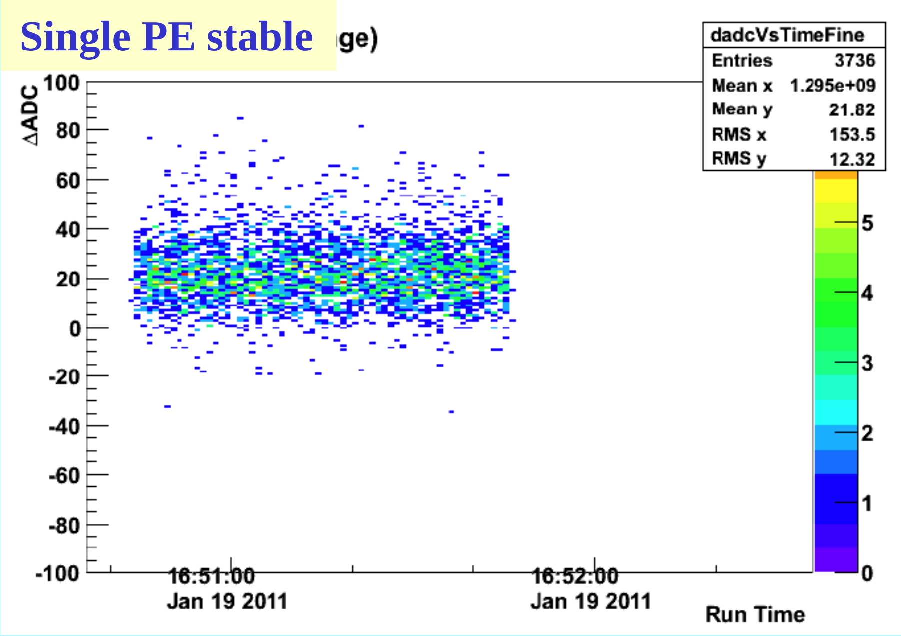
Muon Dry-run

- Test of all installed PMTs
  - All PMTs and LEDs functional
  - PMT performance within expectations
  - No grounding problems

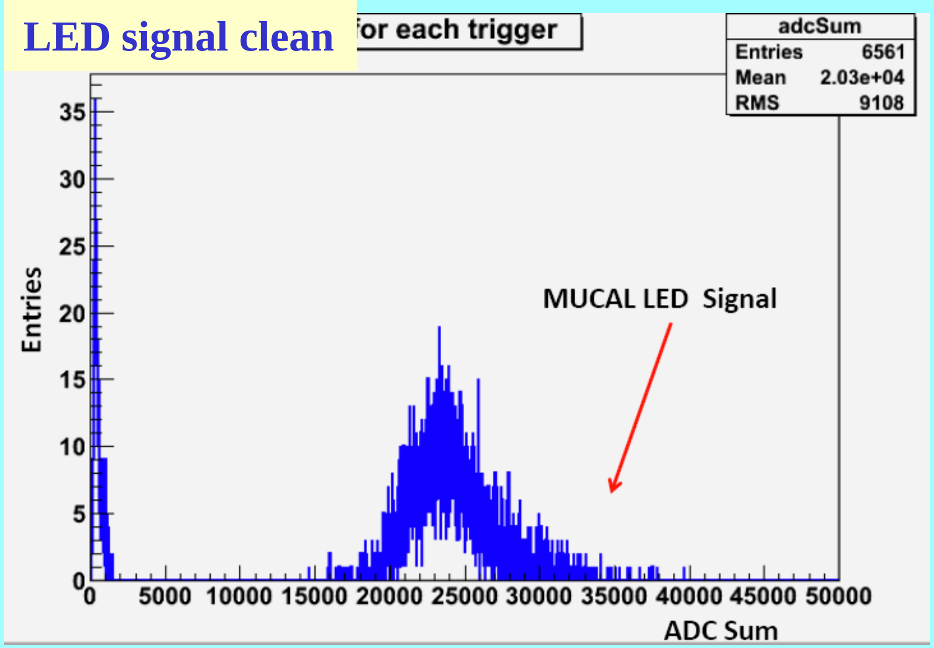
Dark rate mostly low



Single PE stable

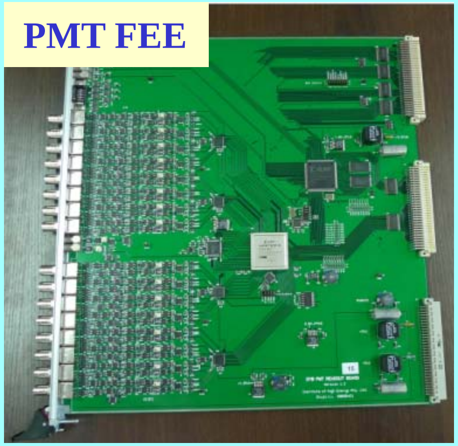


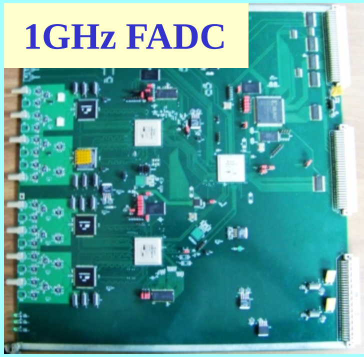
LED signal clean

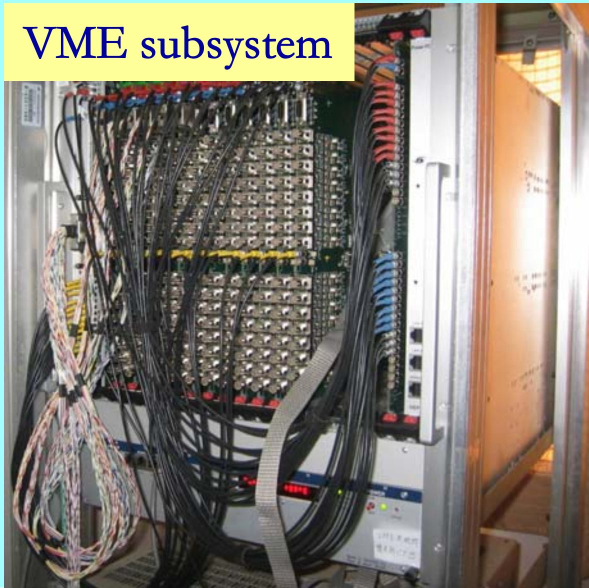


Electronics, Trigger, and DAQ

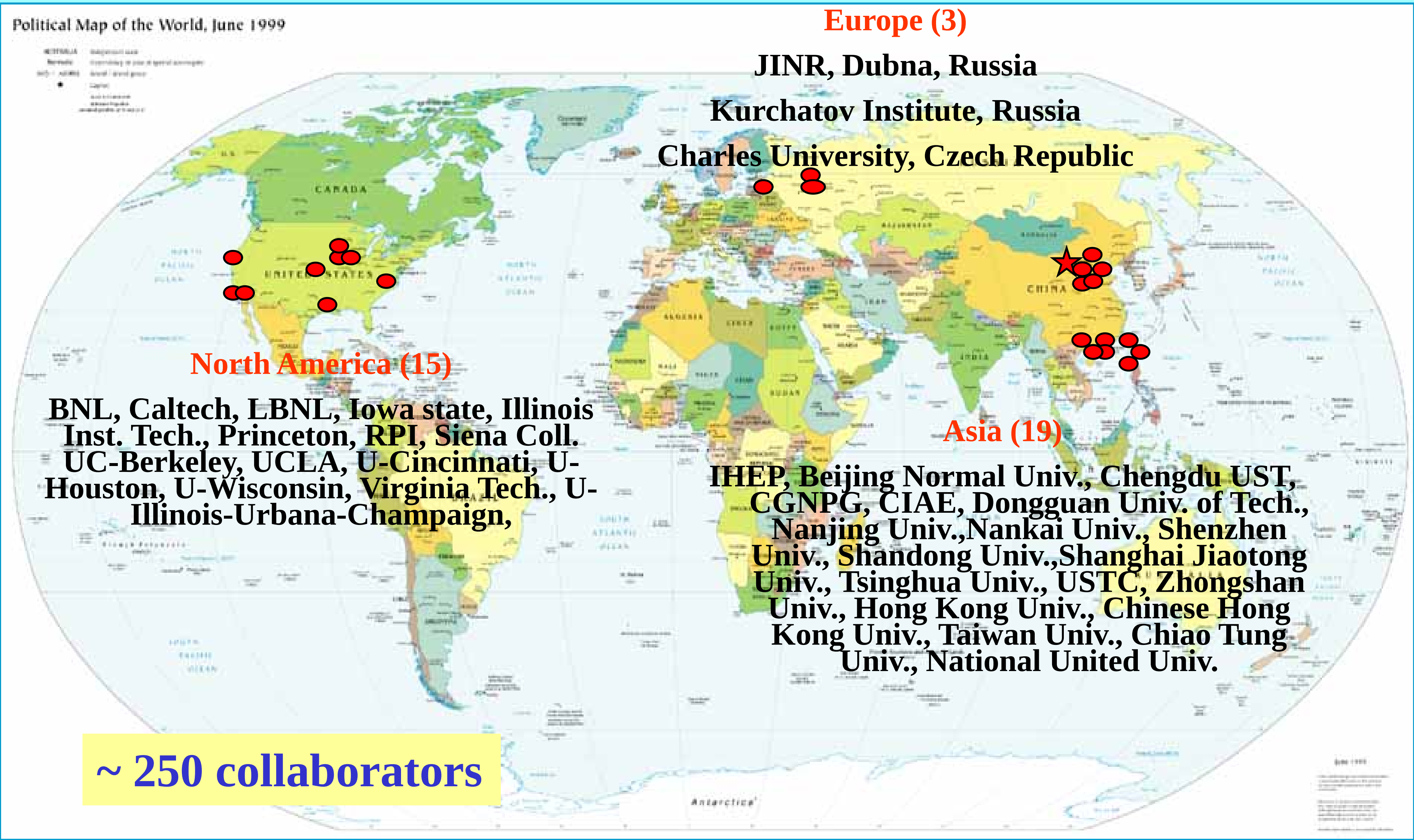
- PMT readout electronics
  - Fully tested during dry run
  - Ready for Hall 1 AD & muon-veto
- RPC readout electronics
  - All components ready for Hall 1
  - Tested with trigger & DAQ, ready for Hall 1
- Trigger
  - Fully tested with FEE
- DAQ hardware and software
  - Successful integration test with FEEs and trigger
  - Successful Online/offline integration test
  - Ready for hall 1 data taking







Daya Bay collaboration



Europe (3)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (15)

BNL, Caltech, LBNL, Iowa state, Illinois Inst. Tech., Princeton, RPI, Siena Coll. UC-Berkeley, UCLA, U-Cincinnati, U-Houston, U-Wisconsin, Virginia Tech., U-Illinois-Urbana-Champaign,

Asia (19)

IHEP, Beijing Normal Univ., Chengdu UST, CGNPG, CIAE, Dongguan Univ. of Tech., Nanjing Univ.,Nankai Univ., Shenzhen Univ., Shandong Univ.,Shanghai Jiaotong Univ., Tsinghua Univ., USTC, Zhongshan Univ., Hong Kong Univ., Chinese Hong Kong Univ., Taiwan Univ., Chiao Tung Univ., National United Univ.

~ 250 collaborators

What we can do after Daya Bay ?

A possibility

Measuring Mass Hierarchy

- Long baseline accelerator neutrinos
  - Through Matter effects
  - Project-X/LBNE in Fermilab/BNL ?
- Atmospheric neutrinos
  - Very weak signal, need huge detector
- Reactor neutrinos
  - Method: distortion of energy spectrum
  - Enhance signature: Transform reactor neutrino L/E spectrum to frequency regime using Fourier formalism
    - need $\mathrm{Sin}^2(2\theta_{13}) > 0.02$
    - Need to know ΔM^2_{23}

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006

J. Learned,
PRD 78(2008)071302

Fourier transformation of L/E spectrum

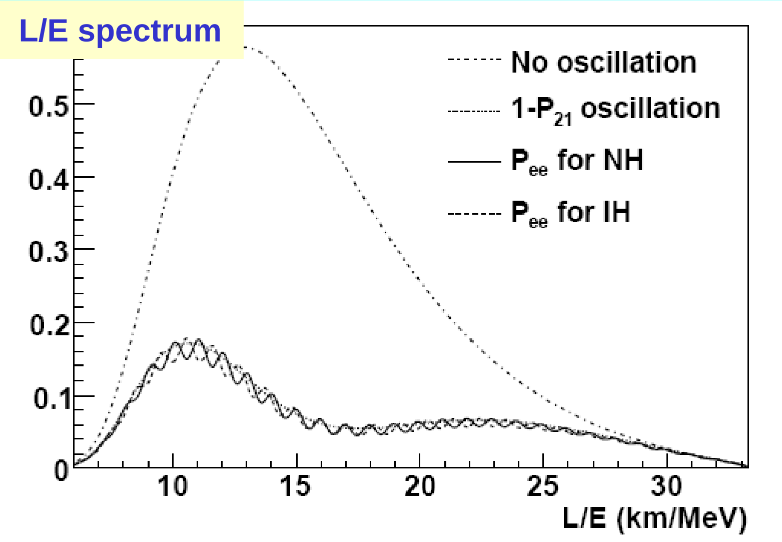
- **Frequency regime is in fact the ΔM^2 regime → enhance the visible features in ΔM^2 regime**
- **Take ΔM^2_{32} as reference**
  - **NH: $\Delta M^2_{31} > \Delta M^2_{32}$, ΔM^2_{31} peak at the right of ΔM^2_{32}**
  - **IH: $\Delta M^2_{31} < \Delta M^2_{32}$, ΔM^2_{31} peak at the left of ΔM^2_{32}**

$$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E)$$

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij}L/E$$

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$



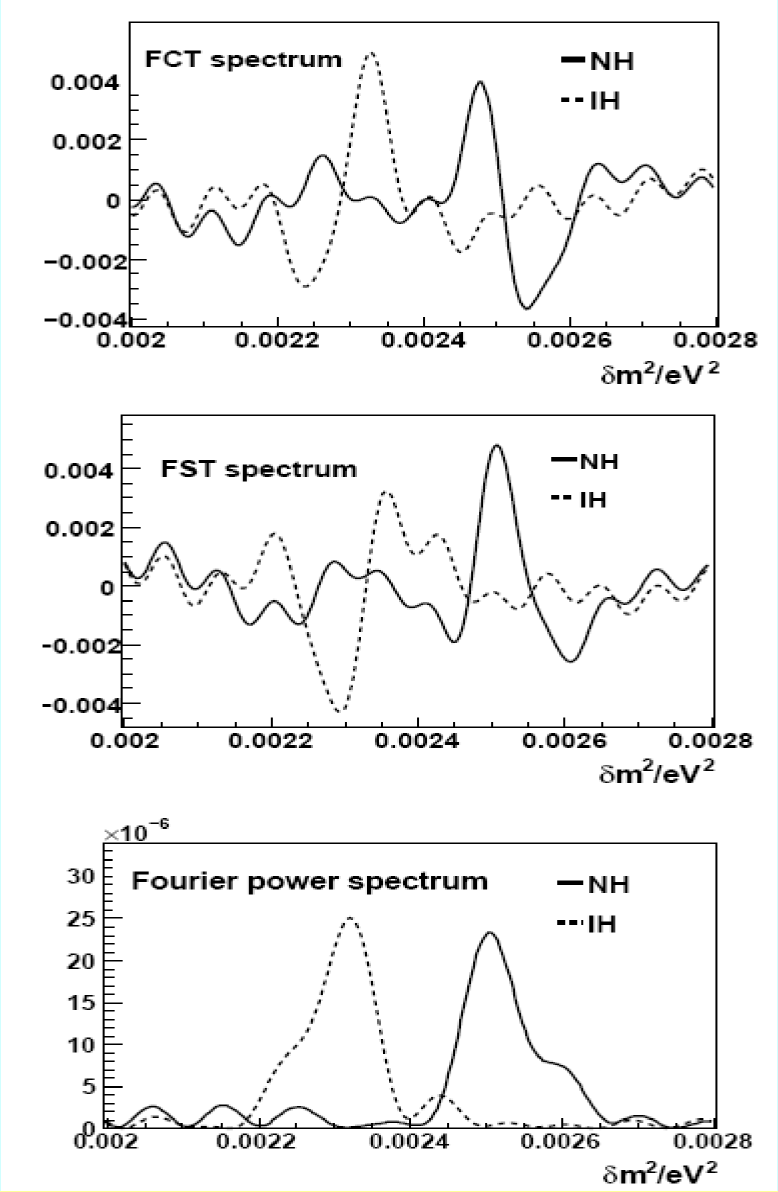
Features of Mass Hierarchy

- **A different Fourier formalism:**

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

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

- **Clear distinctive features:**
  - **FCT:**
    - **NH: peak before valley**
    - **IH: valley before peak**
  - **FST:**
    - **NH: prominent peak**
    - **IH: prominent valley**
- **Better than power spectrum**
- **No pre-condition of Δm^2_{23}**



L. Zhan et al., PRD78(2008)111103

Quantify Features of FCT and FST

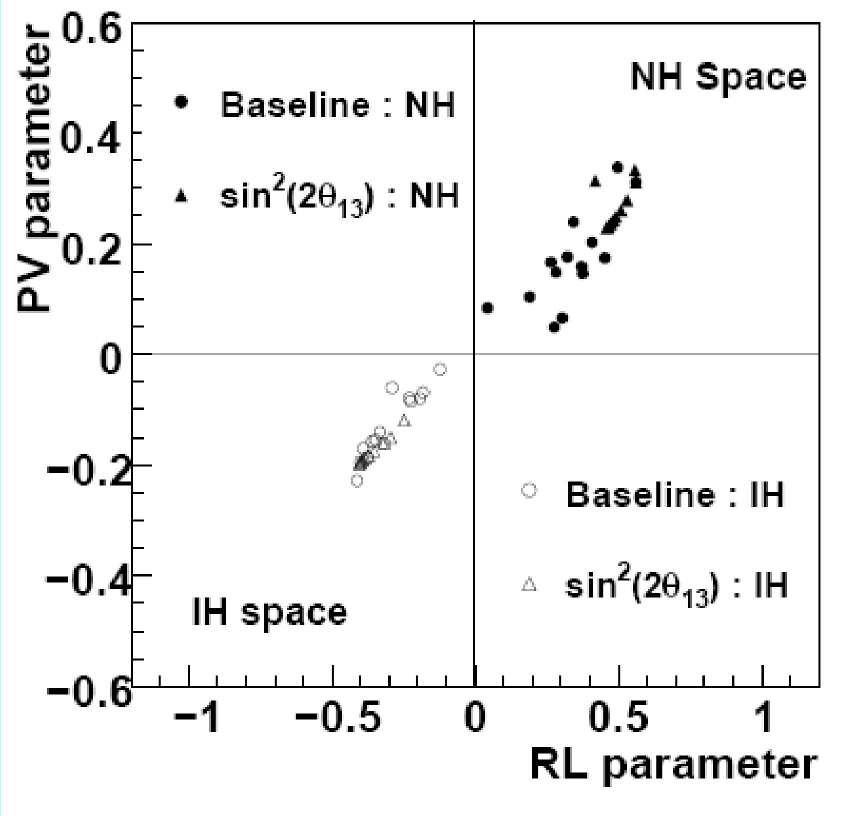
- To quantify the symmetry breaking, we define:

$$RL = \frac{RV - LV}{RV + LV}, \quad PV = \frac{P - V}{P + V}$$

RV/LV: amplitude of the right/left valley in FCT

P/V: amplitude of the peak/valley in FST

- For asymmetric P_{ee}
  - NH: RL>0 and PV>0
  - IH: RL<0 and PV<0

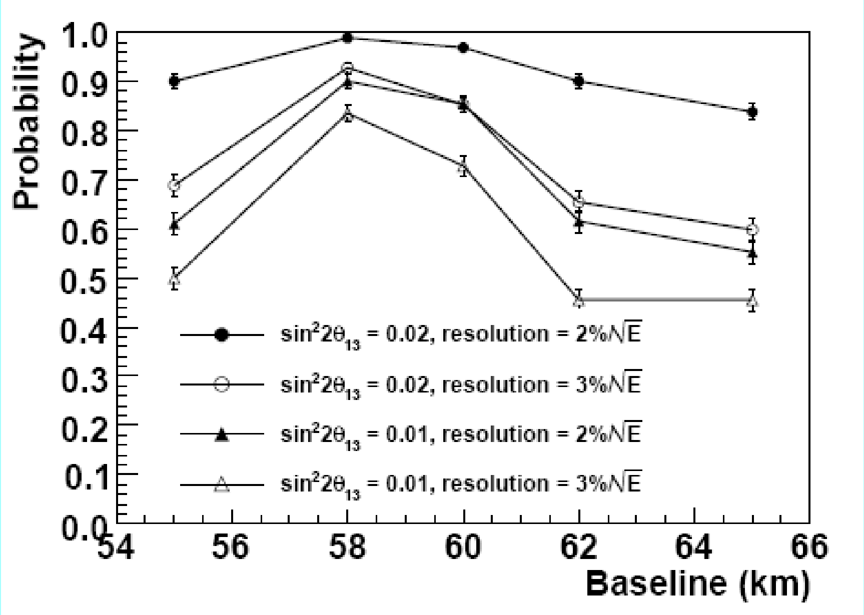


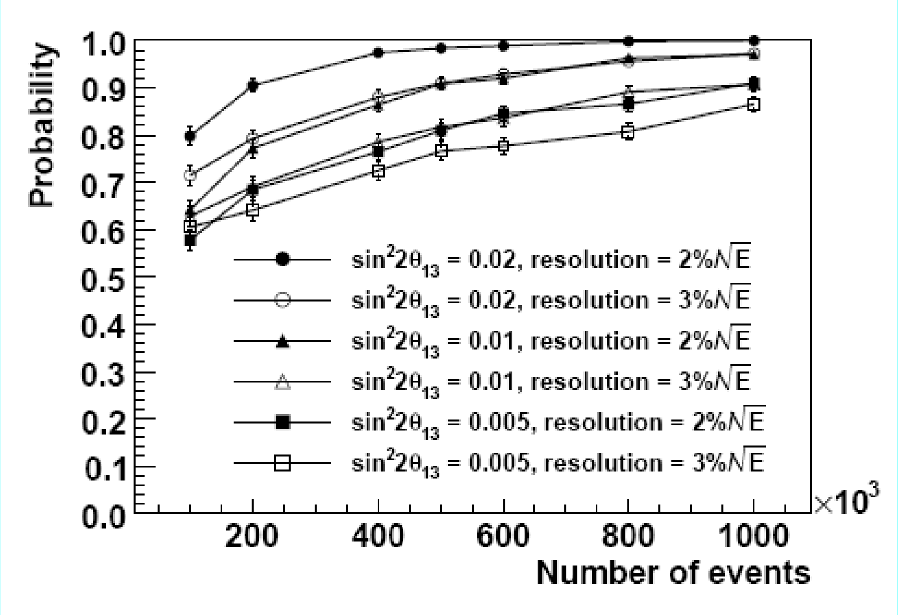
Two clusters of RL and PV values show the sensitivity of mass hierarchy determination

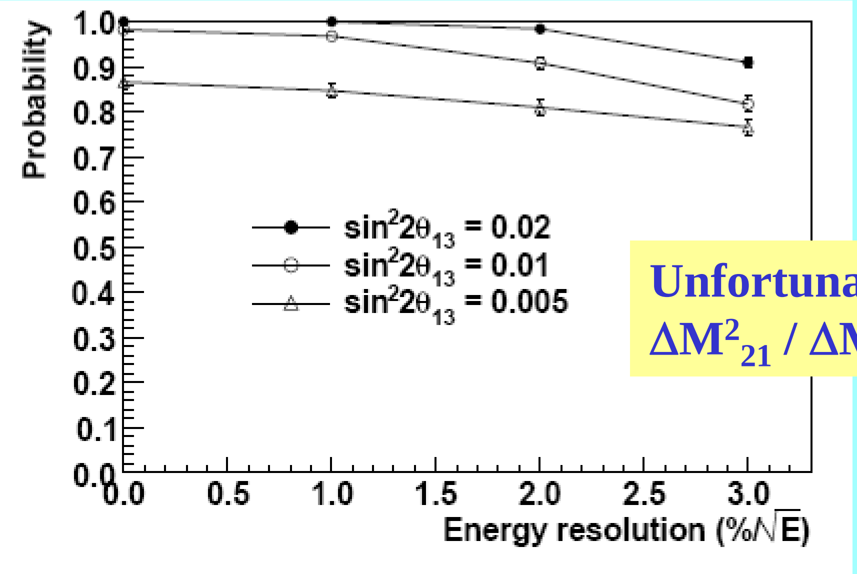
Baseline: 46-72 km
$\sin^2(2\theta_{13})$: 0.005-0.05
Others from global fit

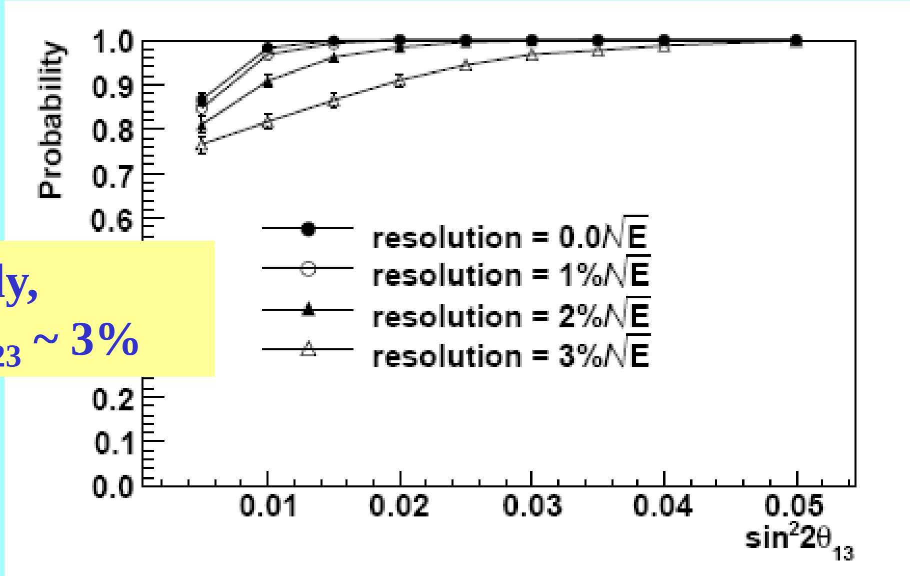
L. Zhan et al., PRD78:111103,2008

In reality









Unfortunately,
$\Delta M^2_{21} / \Delta M^2_{23} \sim 3\%$

L. Zhan, et. al., Phys.Rev.D79:073007,2009

Requirement

- **To determine mass hierarchy at > 90% CL:**
  - **Baseline: ~ 58 km, determined by θ_{12}**
  - **Reactor power > 24 GW_{th}**
  - **Flux and detector size: ~ (250-700) kt•year**
  - **Ideally, $\sin^2 2\theta_{13}$ > 0.02 & energy resolution < 2%**
    - **IF $\sin^2 2\theta_{13}$=0.01, energy resolution < 2% & 700 kt•year**
    - **For $\sin^2 2\theta_{13}$=0.02 , energy resolution < 3% & 700 kt•year**
- **Overburden > 1000 MWE**
- **A huge $\bar{\nu}_e$ detector with mass >20kt**
  - **currently the largest on is 1kt (KamLAND & LVD)**

Scientific goal: a l0-50kt underground LS detector 60km from reactor

1. Neutrino Mass hierarchy
2. Precision mixing para. measurement: θ_{12}, ΔM^2_{12}, ΔM^2_{31} ➔ Unitarity of the mixing matrix
3. Supernova neutrinos ==〉 better than SuperK
4. Geo-neutrinos ==〉 ×10 better than KamLAND
5. Atmospheric neutrinos ==〉 ≈ SuperK
6. Solar neutrinos
7. High energy neutrinos
   1. Point source: GRB, AGN, BH, …
   2. Diffused neutrinos
8. High energy cosmic-muons
   1. Point source: GRB, AGN, BH, …
   2. Dark matter
9. Exotics
   1. Sterile neutrinos
   2. Monopoles, Fractional charged particles, ….

Precision measurement of mixing parameter

- **Fundamental to the Standard Model and beyond**
- **Similarities point to a Grand unification of leptons and quarks**
- **Constrain all PMNS matrix elements to < 1% ! Probing Unitarity of U_{PMNS} to <1% level !**

	Current	BESIII
V_{ub}	25%	5%
V_{cd}	7%	1%
V_{cs}	16%	1%
V_{cb}	5%	3%
V_{td}	36%	5%
V_{ts}	39%	5%

	Current	Daya Bay II
Δm^2_{12}	5%	< 1%
Δm^2_{23}	12%	< 1%
$\sin^2\theta_{12}$	10%	< 1%
$\text{Sin}^2\theta_{23}$	20%	-
$\sin^2\theta_{13}$	∞	-

If we can spend (0.1-0.5)B$ for each B/C/superB factories to understand U_{CKM} (~ 1-2 elements for each factory), why not a super-reactor neutrino experiment(~ 3 elements) to understand U_{PMNS} ?

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

$T(\bar{\nu}_e) = 3.5$ MeV, $\langle E(\bar{\nu}_e)\rangle = 11$ MeV
$T(\nu_e) = 5$ MeV, $\langle E(\nu_e)\rangle = 16$ MeV
$T(\nu_x) = 8$ MeV, $\langle E(\nu_x)\rangle = 25$ MeV

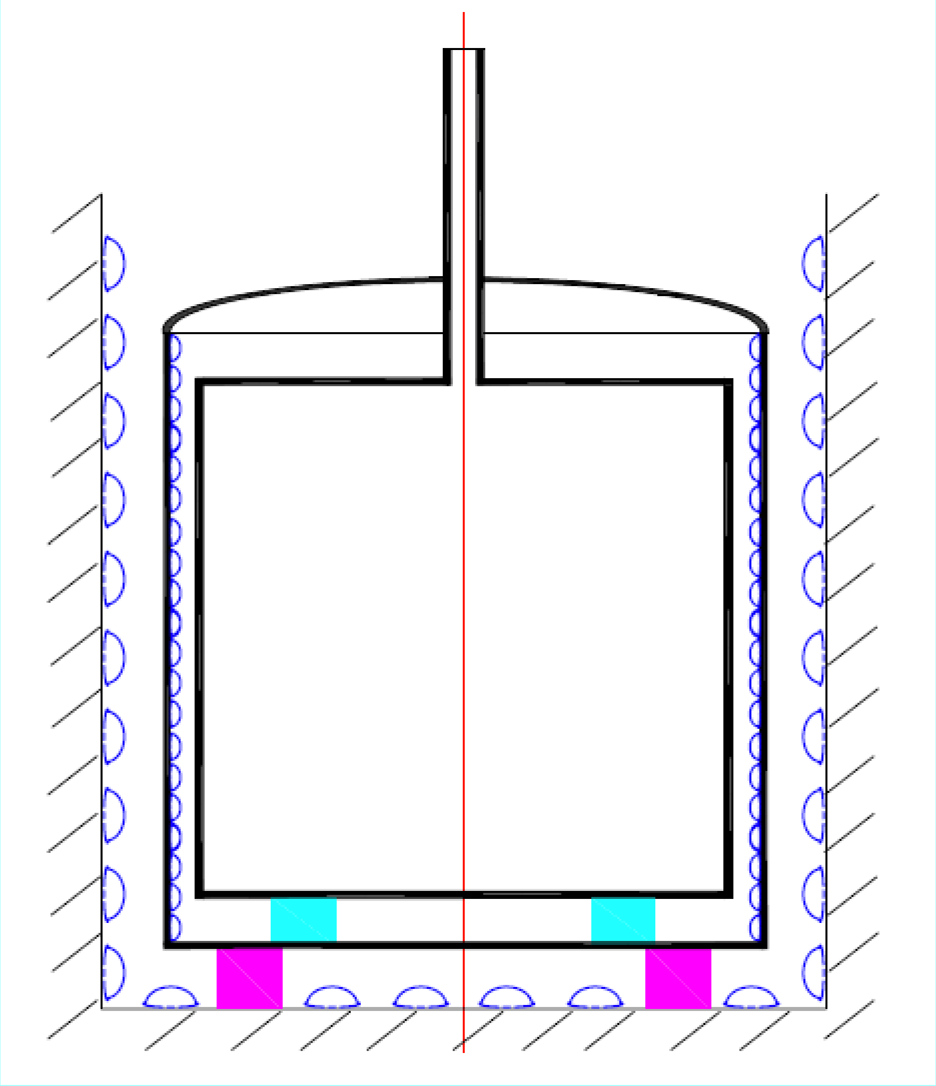
- Many types of events:
  - $\bar{\nu}_e + p \rightarrow n + e^+$, ~ 3000 correlated events
  - $\bar{\nu}_e + {}^{12}C \rightarrow {}^{13}B^* + e^+$, ~ 10-100 correlated events
  - $\nu_e + {}^{12}C \rightarrow {}^{11}N^* + e^-$, ~ 10-100 correlated events
  - $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$, ~ 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

SuperK can not see these correlated events

Energy spectra & fluxes of all types of neutrinos

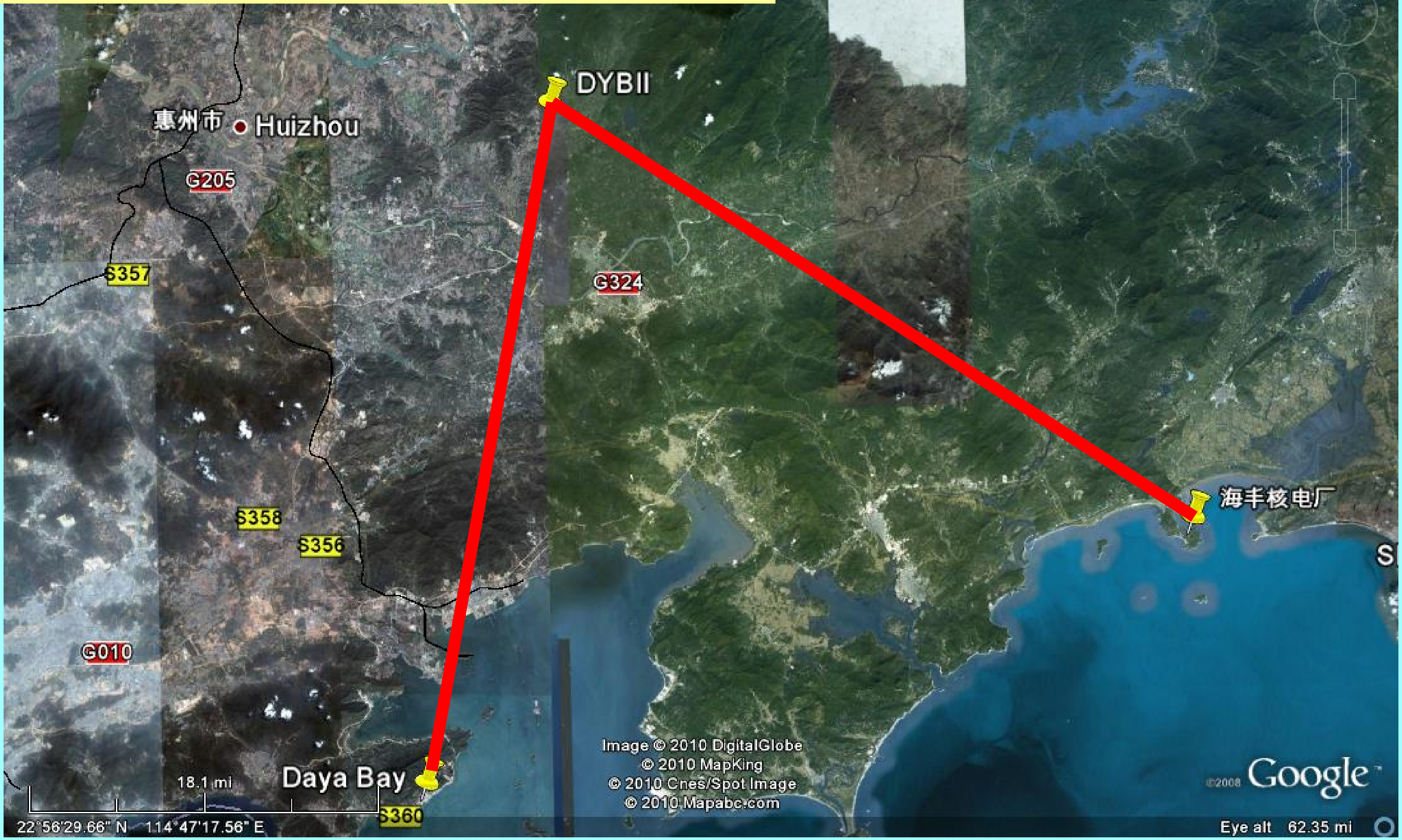
Detector concept

- Neutrino target: ~20kt LS, LAB based
  30m(D)×30m(H)
- Oil buffer: 6kt
- Water buffer: 10kt
- PMT: 15000 20”



A possible location

60 km from Daya Bay and Haifeng
Thermal power > 40 GW



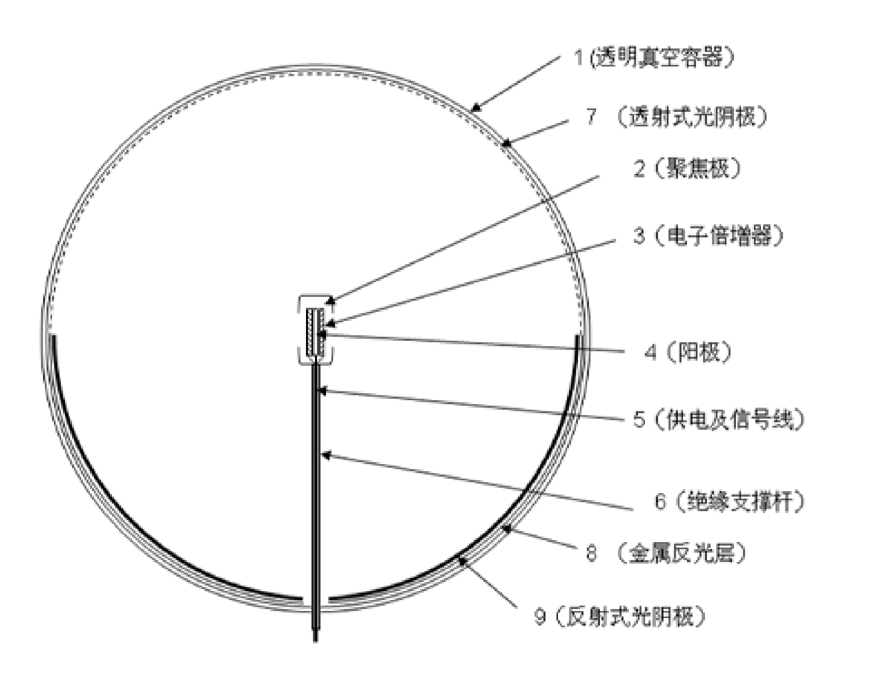
Technical challenges

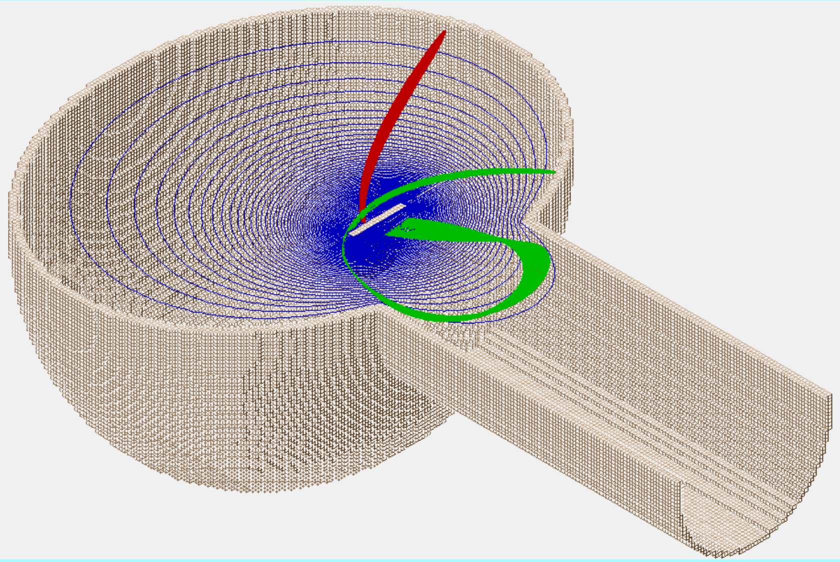
- **Requirements:**
  - Large detector: >10 kt LS
  - Energy resolution: 2%/√E ➔ 2500 p.e./MeV
- **Ongoing R&D:**
  - Low cost, high QE "PMT"
    - New type of PMT
  - Highly transparent LS: 15m ➔ >25m
    - Understand better the scintillation mechanism
    - Find out traces which absorb light, remove it from the production

Now:
1kt
250 p.e./MeV

20" UBA/SBA photocathode PMT is also a possibility

A new type of PMT: high photon detection eff.





- **Top: transmitted photocathode**
- **Bottom: reflective photocathode**
  additional QE: ~ 80%*40%
- **MCP to replace Dynodes ➔ no blocking of photons**

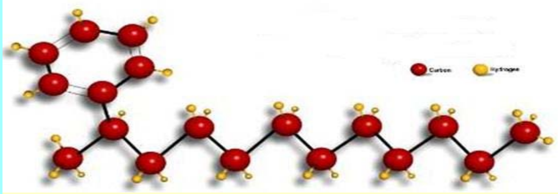
~ ×2 improvement

5” MCP-PMT

LAB based liquid scintillator studies

IHEP, Nanjing Uni.

- Composition of LAB： ~4.5% impurities
- How to remove light absorbers:
  - Measure all impurities up to ppm level
  - Use calculation techniques in solid state physics and quantum chemistry, identify structures which may absorb visible and UV light
  - Study element traces(S,N,O,…) and their origin
  - Study removing method



Linear- Alkyl- Benzene (C_6H_5 -R)

Compound	λ (f)	Concentration in ppm and mol/L	
		NJ12-4	Canada 1(reference sample)
$C_{14}H_{19}NOS$	312nm(0.0011)	412, 0.001428	0
$C_{11}H_{13}NOS$	313nm(0.0040)	491, 0.002047	143, 0.000596
$C_{19}H_{17}N_3S$	358nm(0.0308)	385, 0.001075	118, 0.000329
$C_{20}H_{15}ClN_2O_3$	377nm(0.1351) 351nm(0.0023)	138, 0.000325	36, 0.000085

Powerful reactor neutrinos

- A powerful man-made source
  - If not too far, more powerful than solar, atmospheric, and accelerator neutrinos
- A well understood source（~2% ➔ ~ 0.1%）
  - Better than solar(~5-10%), atmospheric(~10%), and accelerator(~5-10% ➔ 2-3% ??) neutrinos
- Adjustable baseline
  - Of course, accelerator can do it also, but
- Reactor is a free neutrino factory

Summary

- Knowing $Sin^2 2\theta_{13}$ to 1% level is crucial for the future of the neutrino physics, including the mass hierarchy and the leptonic CP violation
- The Daya Bay experiment, located at an ideal site, will reach a sensitivity of <0.01 for $sin^2 2\theta_{13}$
- The construction of the Daya Bay experiment is going on well, Daya Bay near site data taking will start by this summer， full data taking in 2012
- Daya bay experiment is only the start of neutrino physics programs in China