Measuring $\sin^2 2\theta_{13}$ with the Daya Bay nuclear power reactors

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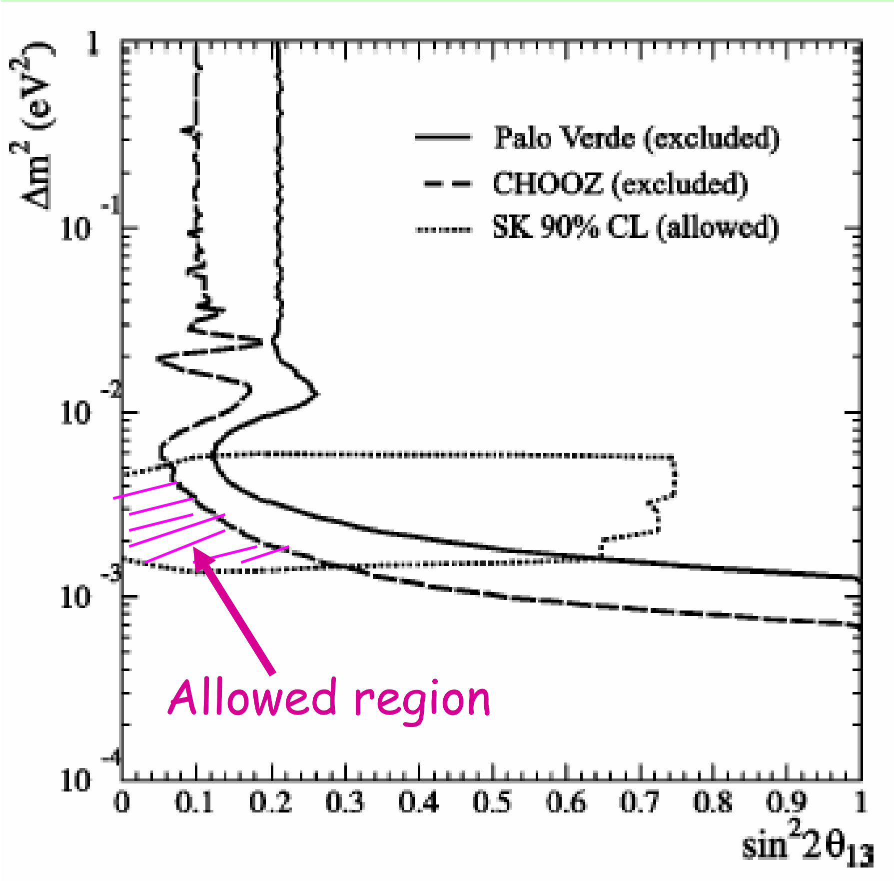
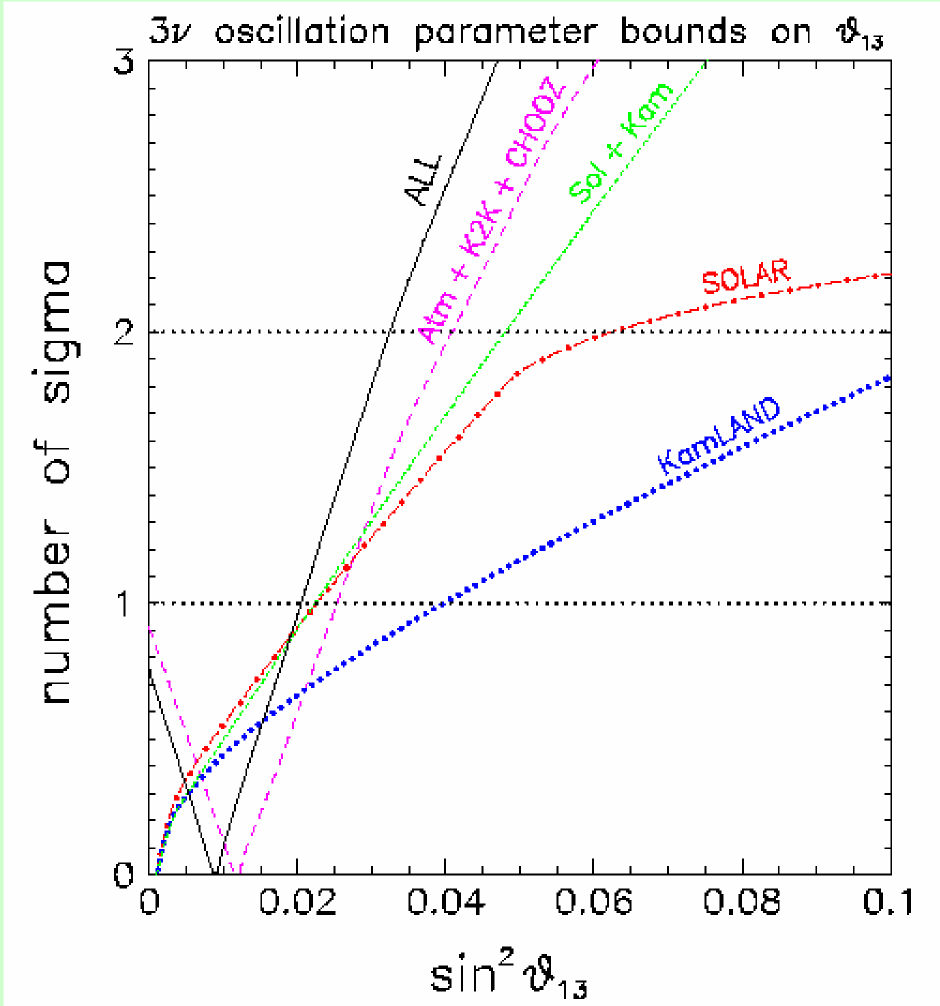
Current Knowledge of θ_{13}

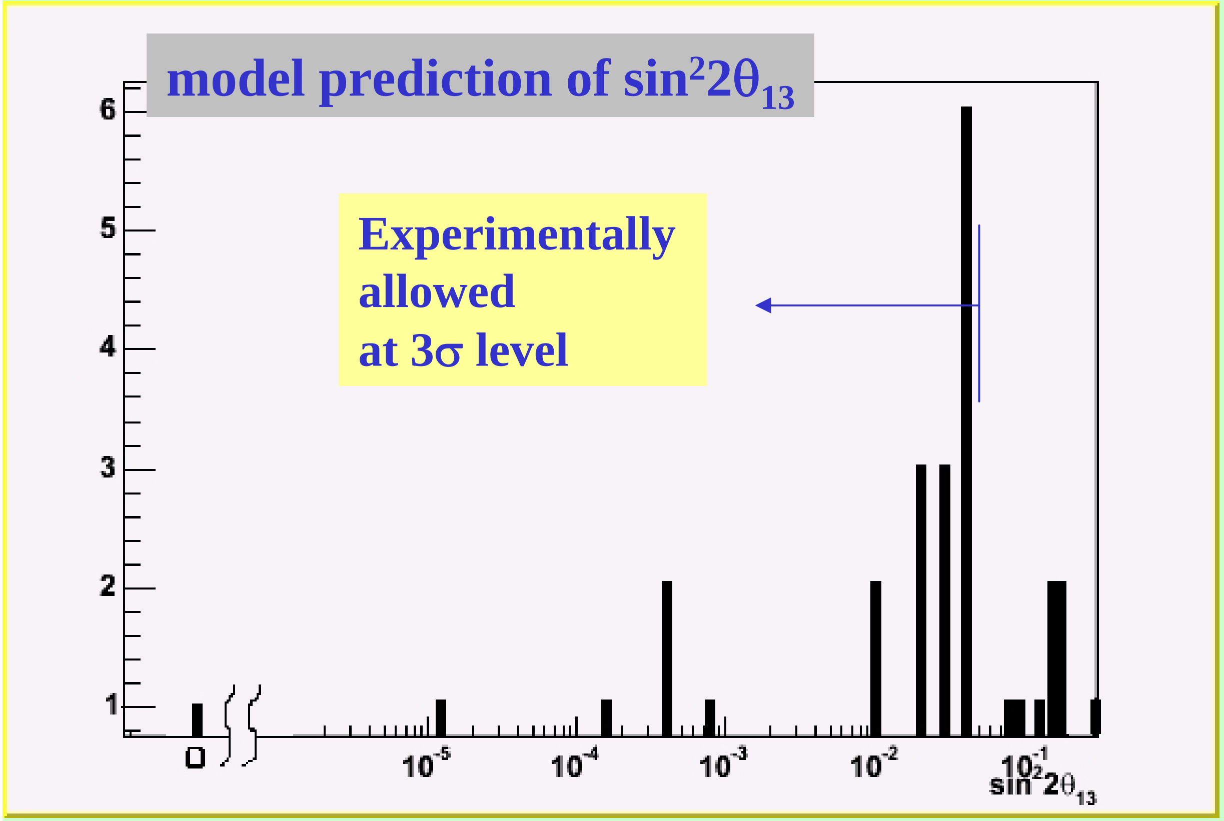
Direct search
PRD 62, 072002

Global fit
fogli etal., hep-ph/0506083





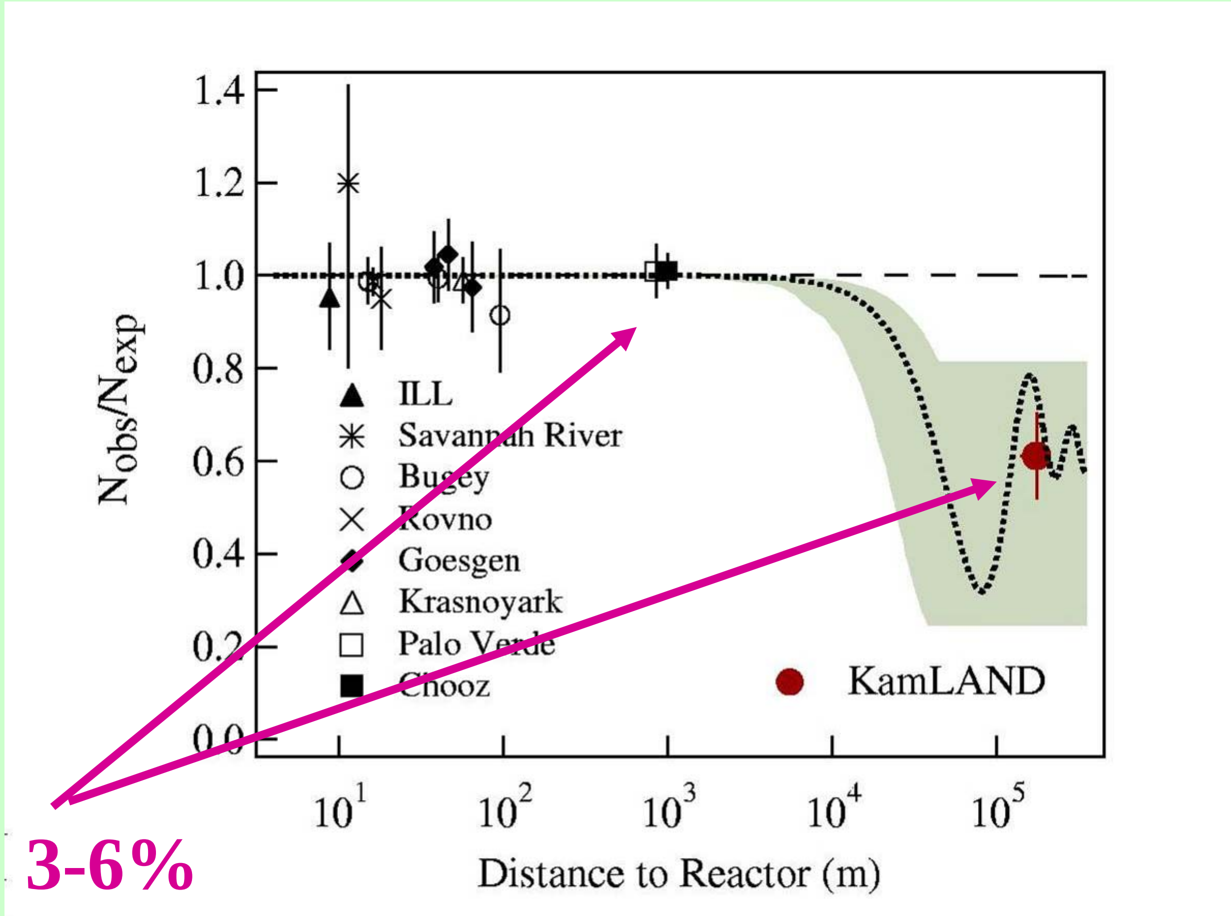
- No good reason(symmetry) for $\sin^2 2\theta_{13}=0$
- Even if $\sin^2 2\theta_{13}=0$ at tree level, $\sin^2 2\theta_{13}$ will not vanish at low energies with radiative corrections
- Theoretical models predict $\sin^2 2\theta_{13} \sim 0.1\text{-}10\ \%$



An experiment with a precision for $\sin^2 2\theta_{13}$ less than 1% is desired

Reactor Experiment: comparing observed/expected neutrinos:

- Palo Verde
- CHOOZ
- KamLAND



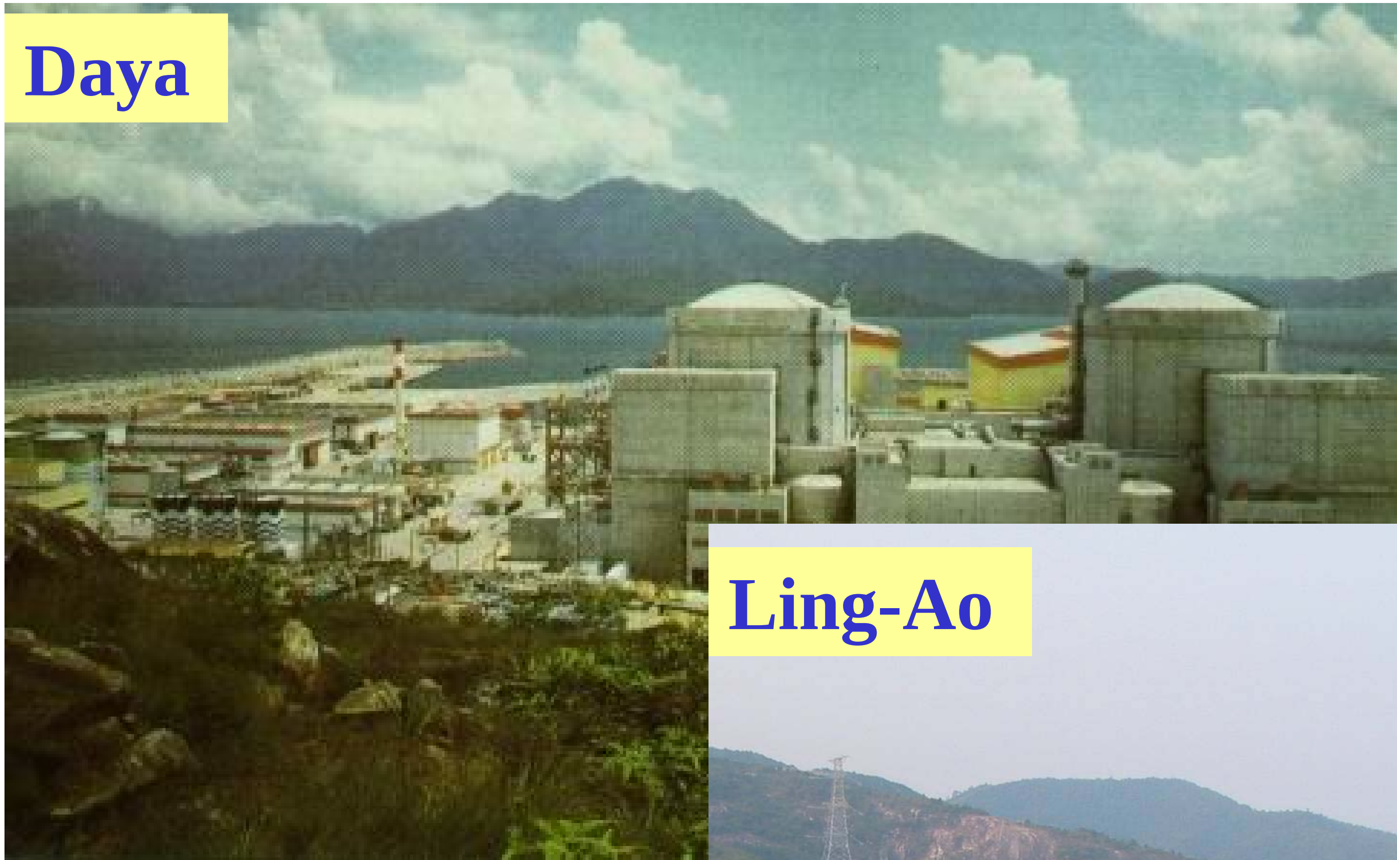
Typical precision: 3-6%

How to reach 1% precision ?

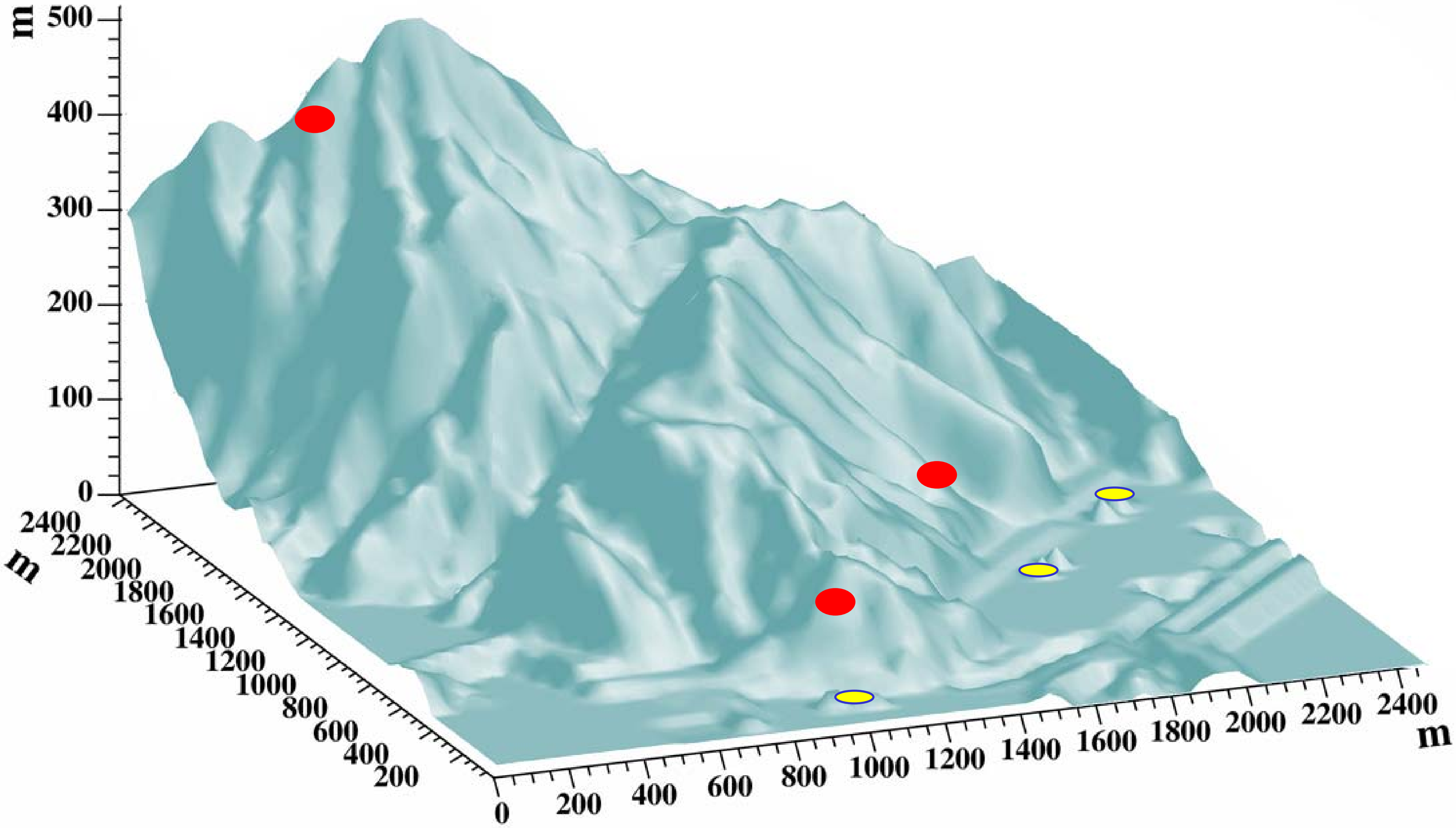
- Three main types of errors: reactor related(~2-3%), background related (~1-2%) and detector related(~1-2%)
- Use far/near detector to cancel reactor errors
- Optimize baseline to have best sensitivity and reduce reactor related errors
- Movable detectors, near ↔ far, to cancel part of detector systematic errors
- Sufficient shielding to reduce backgrounds
- Comprehensive calibration to reduce detector systematic errors
- Careful design of the detector to reduce detector systematic errors
- Large detector to reduce statistical errors

Daya Bay nuclear power plant

- 4 reactor cores, 11.6 GW
- 2 more cores in 2011, 5.8 GW
- Mountains near by, easy to construct a lab with enough overburden to shield cosmic-ray backgrounds


Daya

Ling-Ao


m
500
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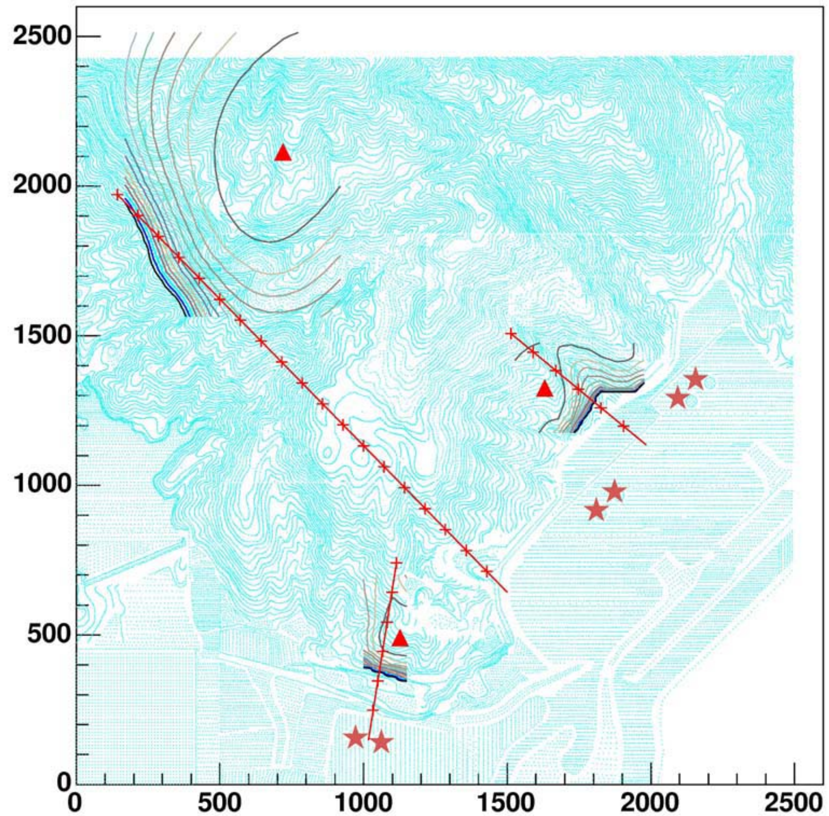
1200
1400
1600
1800
2000
2200
2400
m

Baseline optimization and site selection

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

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

- **Neutrino spectrum and their error**
- **Neutrino statistical error**
- **Reactor residual error**
- **Estimated detector systematical error:**
  total, bin-to-bin
- **Cosmic-rays induced background (rate and shape) taking into mountain shape: fast neutrons, 9Li, …**
- **Backgrounds from rocks and PMT glass**



The Layout

Total Tunnel length

3200 m

Detector swapping

in a horizontal tunnel cancels most detector systematic error. Residual error ~0.2%

Backgrounds

B/S of DYB,LA ~0.5%

B/S of Far ~0.2%

Fast Measurement

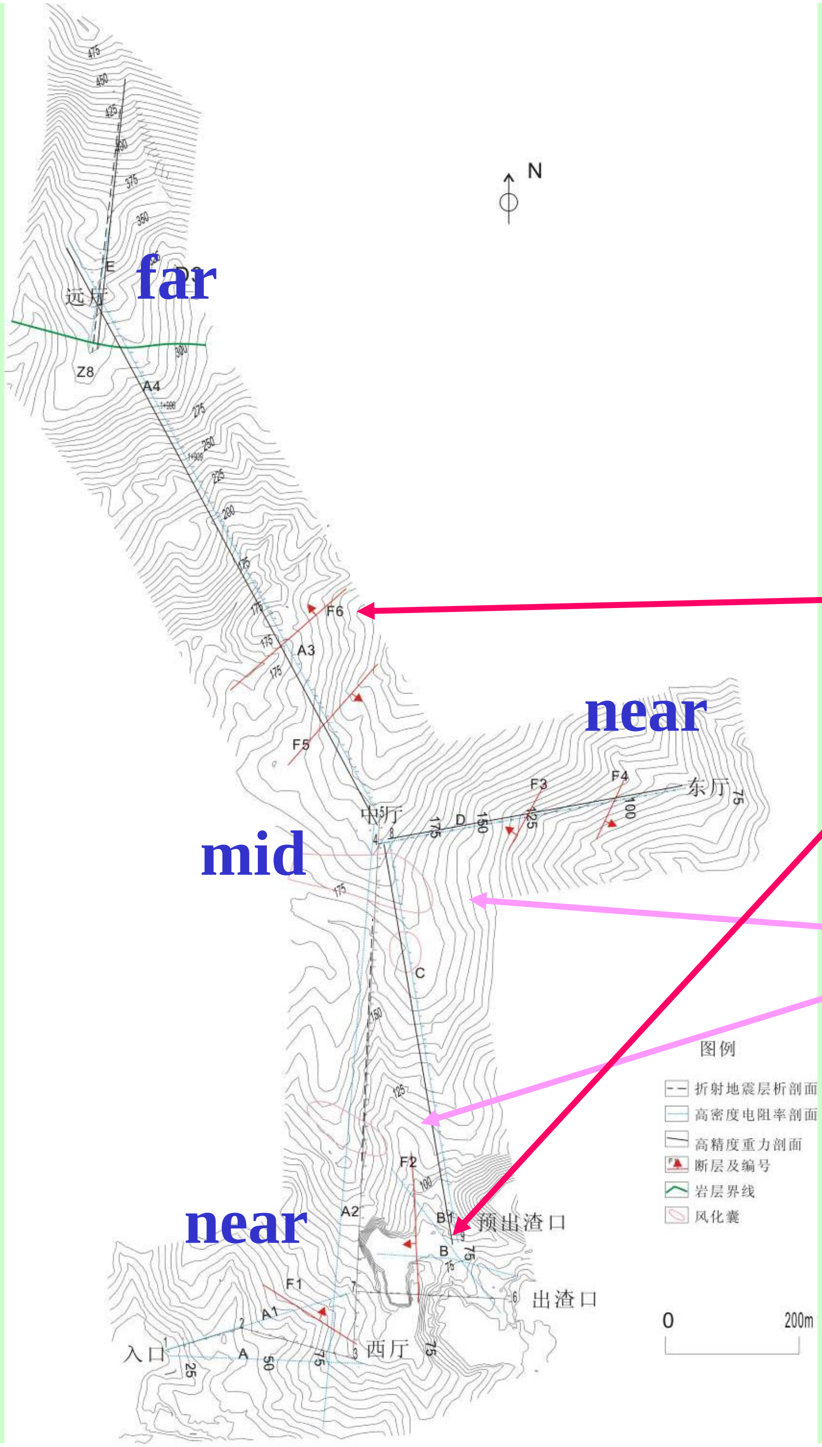
DYB+Mid, 2008-2009

Sensitivity (1 year) ~0.03

Full Measurement

DYB+LA+Far, from 2009

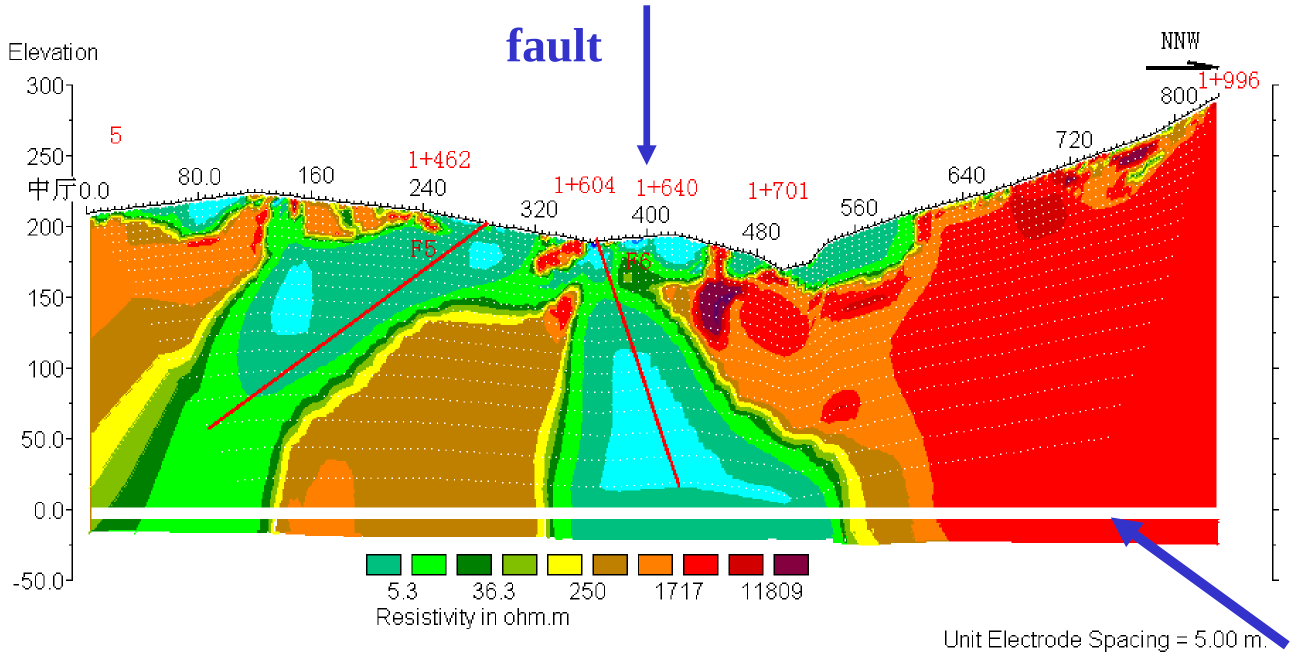
Sensitivity (3 year) <0.01



Geologic survey completed, hole boring will start soon

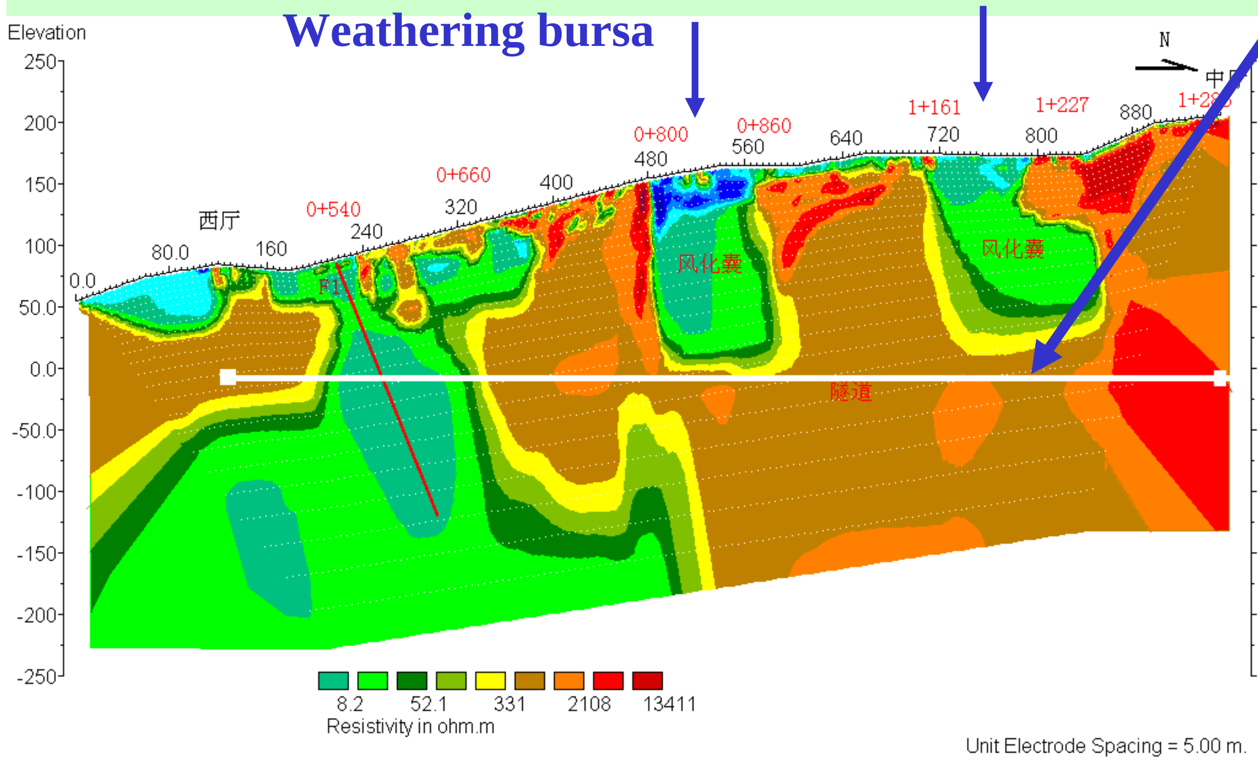
Faults(small)

Weathering bursa
(风化囊)



From mid site to far site： a fault

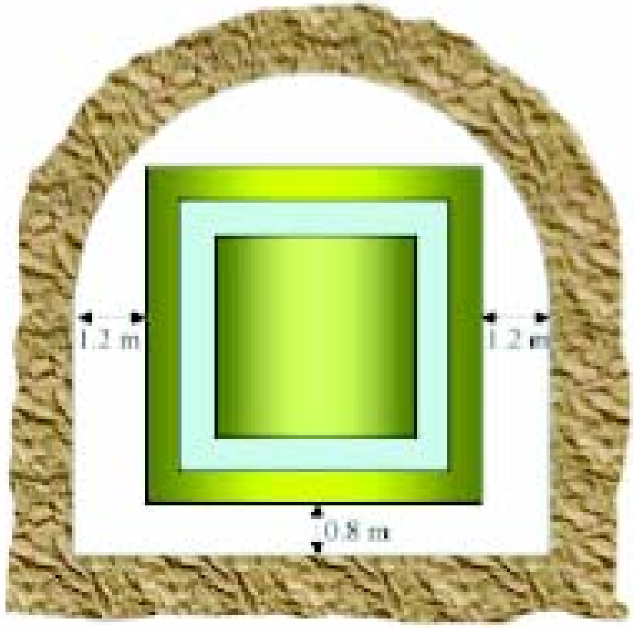
tunnel



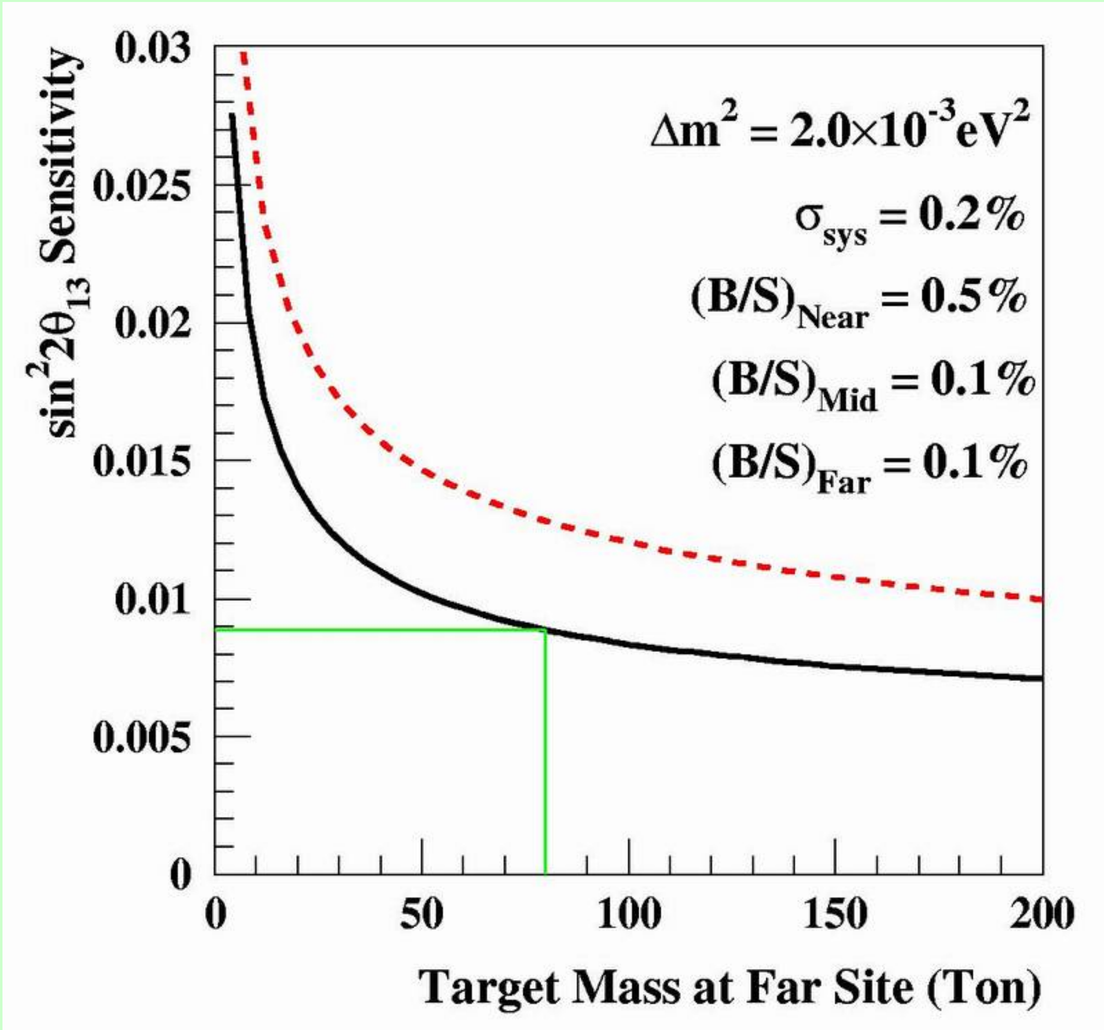
From Daya near site to mid point: Weathering bursa

Tunnel construction

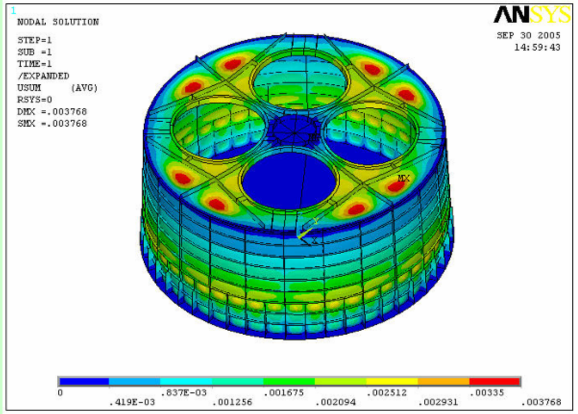
- The tunnel length is about 3000m
- Local railway construction company has a lot of experience(similar cross section)
- Cost estimate by professionals
- Construction time is ~15-24 months
- A similar tunnel on site as a reference



How large the detector should be？



Detector: Multiple modules



Two modules at near sites
Four modules at far site:
Cross checks at all sites
Keep the neutrino statistics in balance and identical detectors

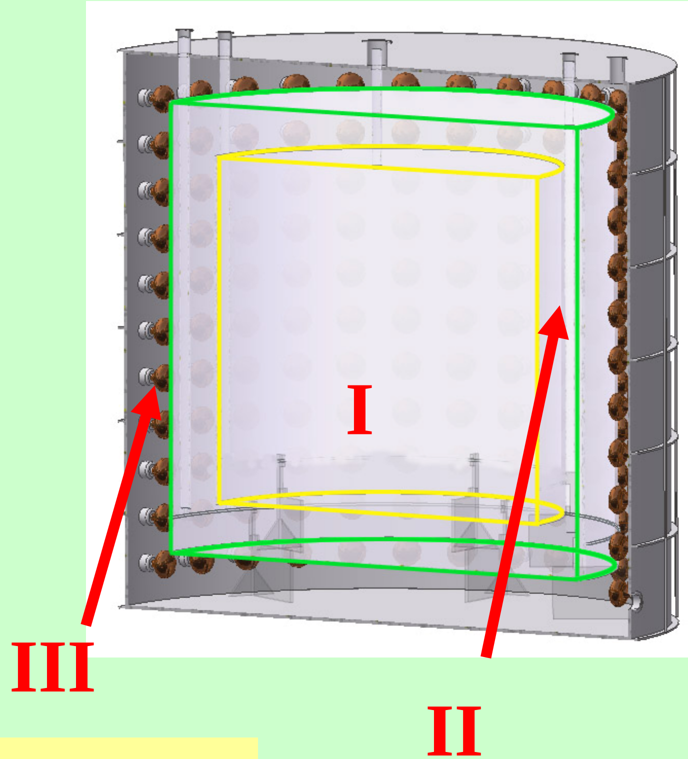
- **Multiple modules for cross check, reducing uncorrelated errors**
- **Small modules for easy construction, moving, handing, …**
- **Small modules for less sensitive to scintillator aging**
- **Scalable**
- **Higher cost**
- **More trouble for calibration**

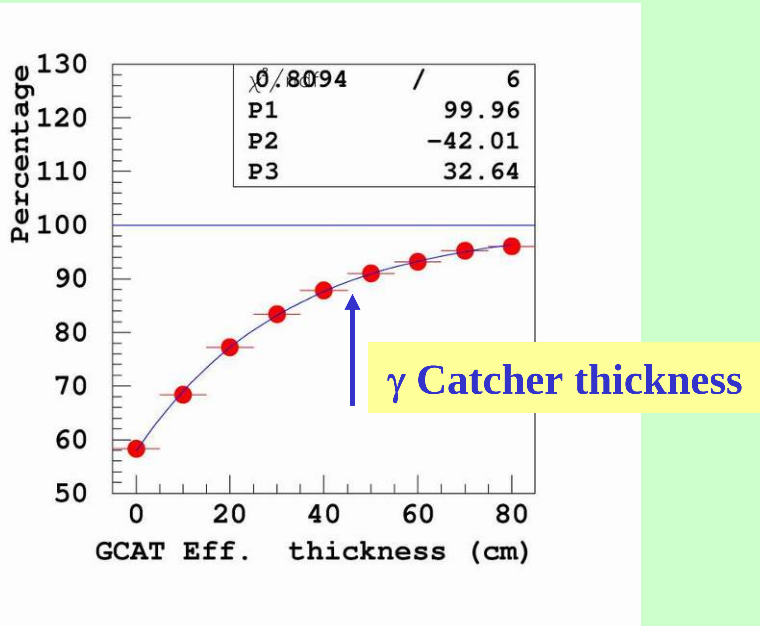
Idea was first proposed at the Niigata meeting in 2003, and now both Braidwood and Kaska have multiple modules at one location

Central Detector modules

- Three zones modular structure:
  - **I.** target: Gd-loaded scintillator
  - **II.** γ-ray catcher: normal scintillator
  - **III.** Buffer shielding: oil
- Reflection at two ends
- 20t target mass, ~200 8"PMT/module

σ_E = 6%@8MeV, σ_s ~ 14 cm





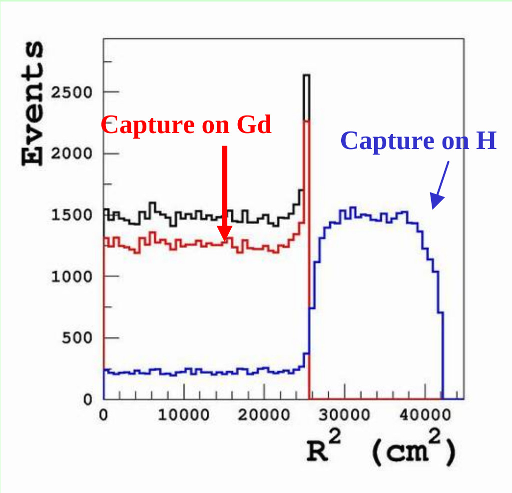
Oil buffer thickness

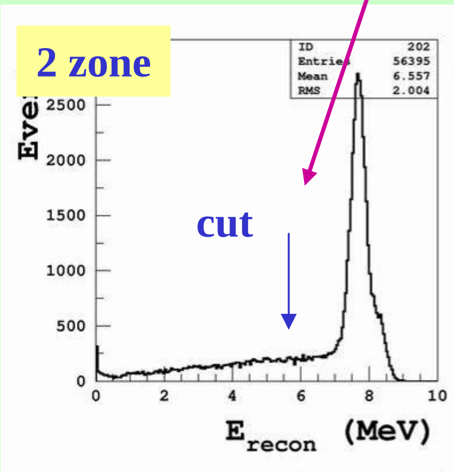
Isotopes	Purity (ppb)	20cm (Hz)	25cm (Hz)	30cm (Hz)	40cm (Hz)
^{238}U(>1MeV)	50	2.7	2.0	1.4	0.8
^{232}Th(>1MeV)	50	1.2	0.9	0.7	0.4
^{40}K(>1MeV)	10	1.8	1.3	0.9	0.5
Total		5.7	4.2	3.0	1.7

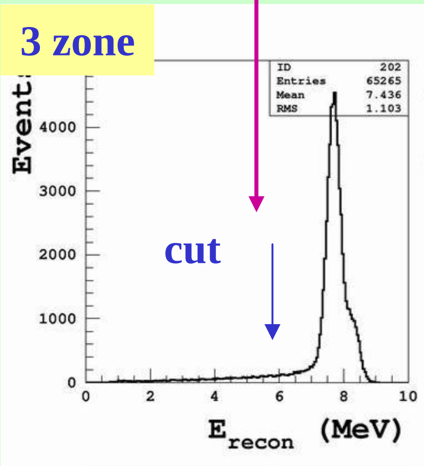
Why three zones ?

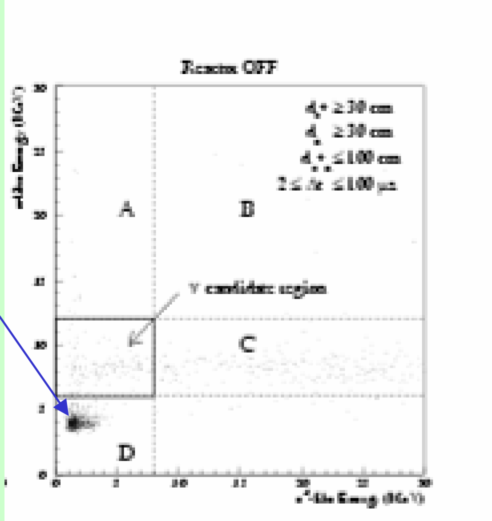
- Three zones:
  - Complicated acrylic tank construction
  - γ backgrounds on walls
  - Less fiducial volume
- Two zones:
  - Neutrino energy spectrum distorted
  - Neutron efficiency error due to energy scale and resolution:

    two zones: 0.4%, three zones 0.2%
  - Using 4 MeV cut can reduce the error by a factor of two, but backgrounds from β+γ do not allow us to do so





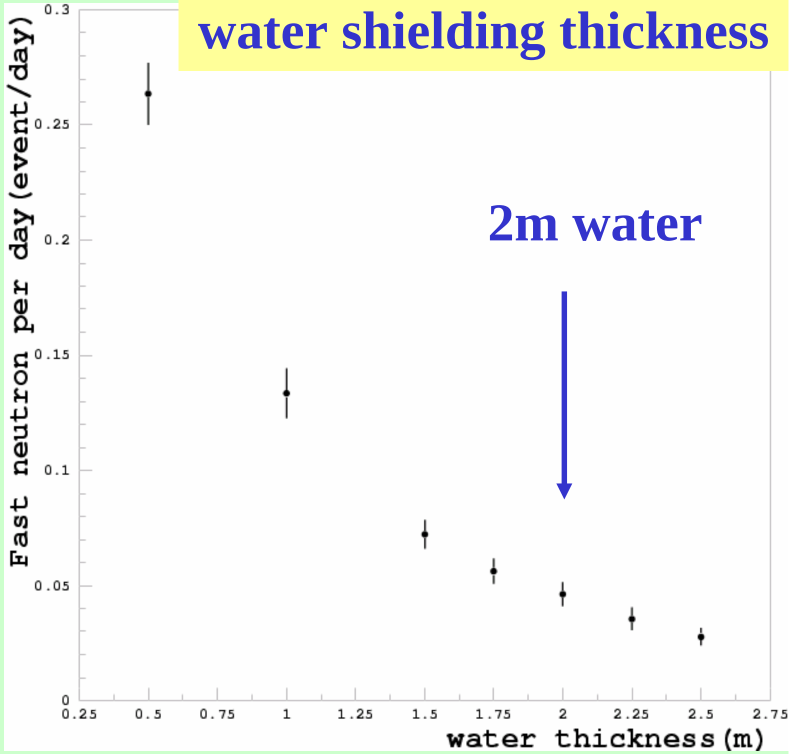




Water Buffer & VETO

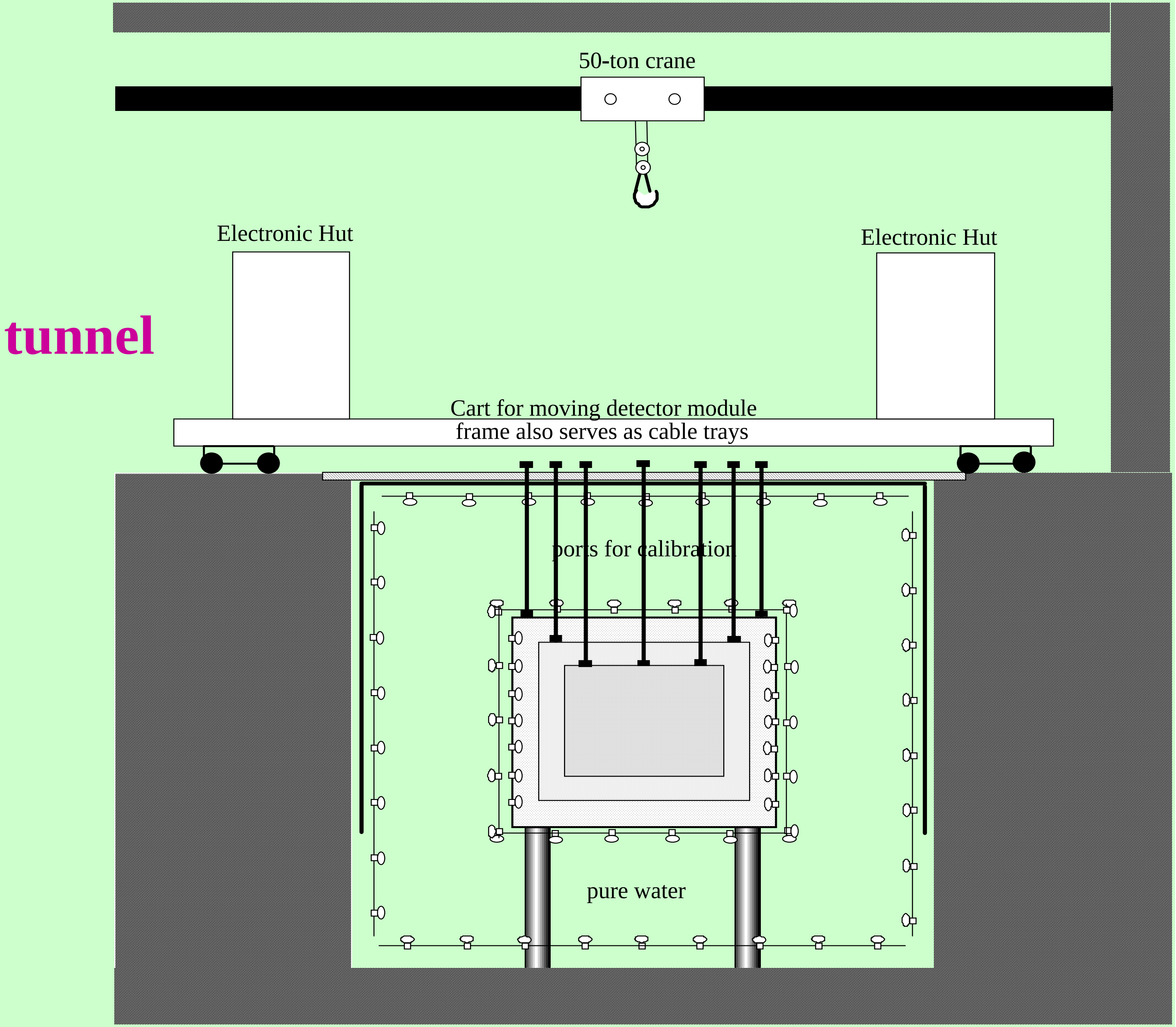
- **2m water buffer to shield backgrounds from neutrons and γ's from lab walls**
- **Cosmic-muon VETO Requirement:**
  - **Inefficiency < 0.5%**
  - **known to <0.25%**
- **Solution: Two active vetos**
  - **active water buffer, Eff.>95%**
  - **Muon tracker, Eff. > 90%**
    - **RPC**
    - **scintillator strips**
  - **total ineff. = 10%*5% = 0.5%**

Neutron background vs water shielding thickness



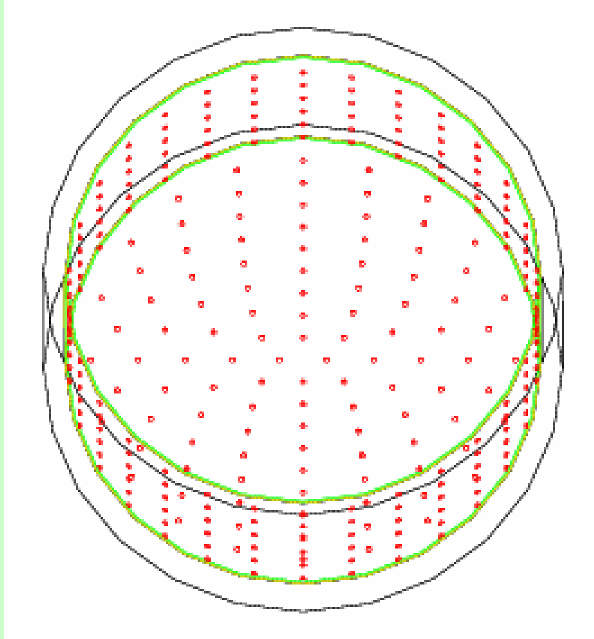
Water pool

- Safe
- cheap

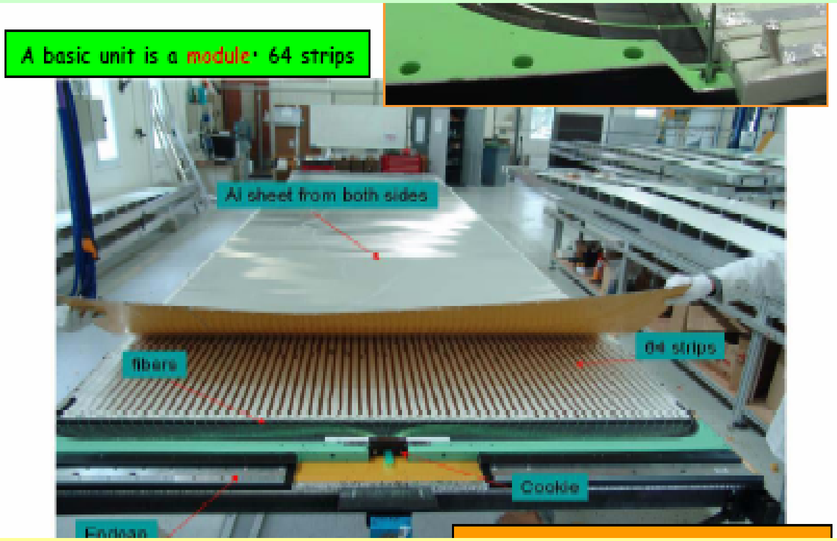


Conceptual design of a underground water pool-based experimental hall

- Two tracker options :
  - RPC outside the steel cylinder
  - Scintillator Strips sink into the water



RPC from IHEP



Scintillator Strips from Ukrania Contribution of JINR,Dubna

25/01/05

Daya Bay Meeting, Yu.Gornushkin

Background related error

- **Need enough shielding and an active veto**
- **How much is enough ? ➔ error < 0.2%**
  - **Uncorrelated backgrounds: U/Th/K/Rn/neutron**

    single gamma rate @ 0.9MeV < 50Hz

    single neutron rate < 1000/day

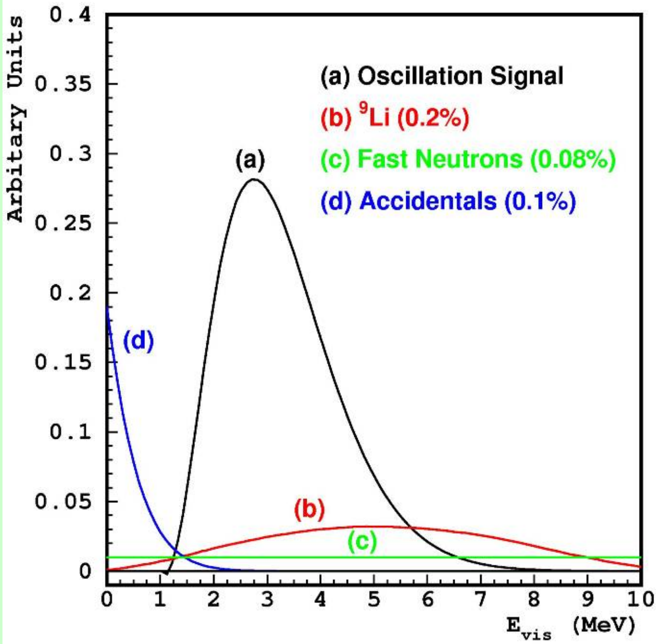
    2m water + 50 cm oil shielding
  - **Correlated backgrounds: $n \propto E_\mu^{0.75}$**

    Neutrons: >100 MWE + 2m water

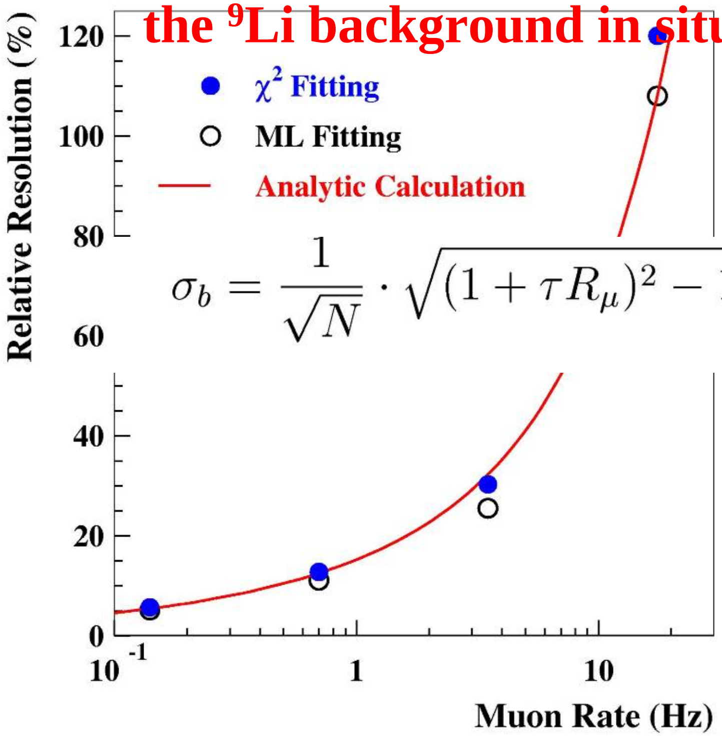
    Y.F. Wang et al., PRD64(2001)0013012

    $^8He/^9Li$: > 250 MWE(near) & >1000 MWE(far)

    T. Hagner et al., Astroparticle. Phys. 14(2000) 33

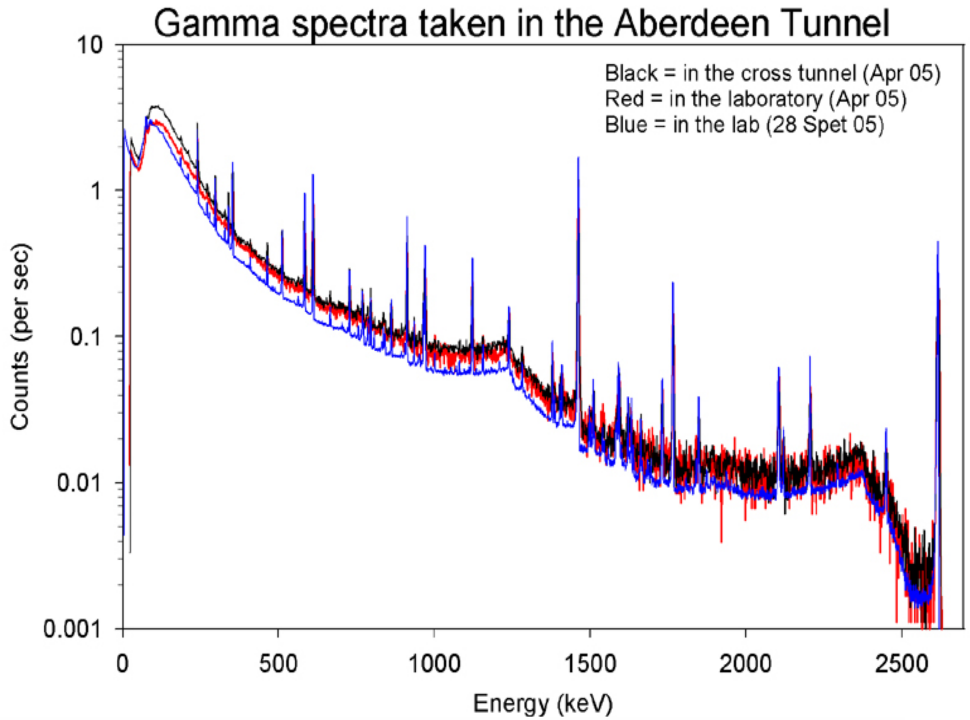


Precision to determine the ^{9}Li background in situ

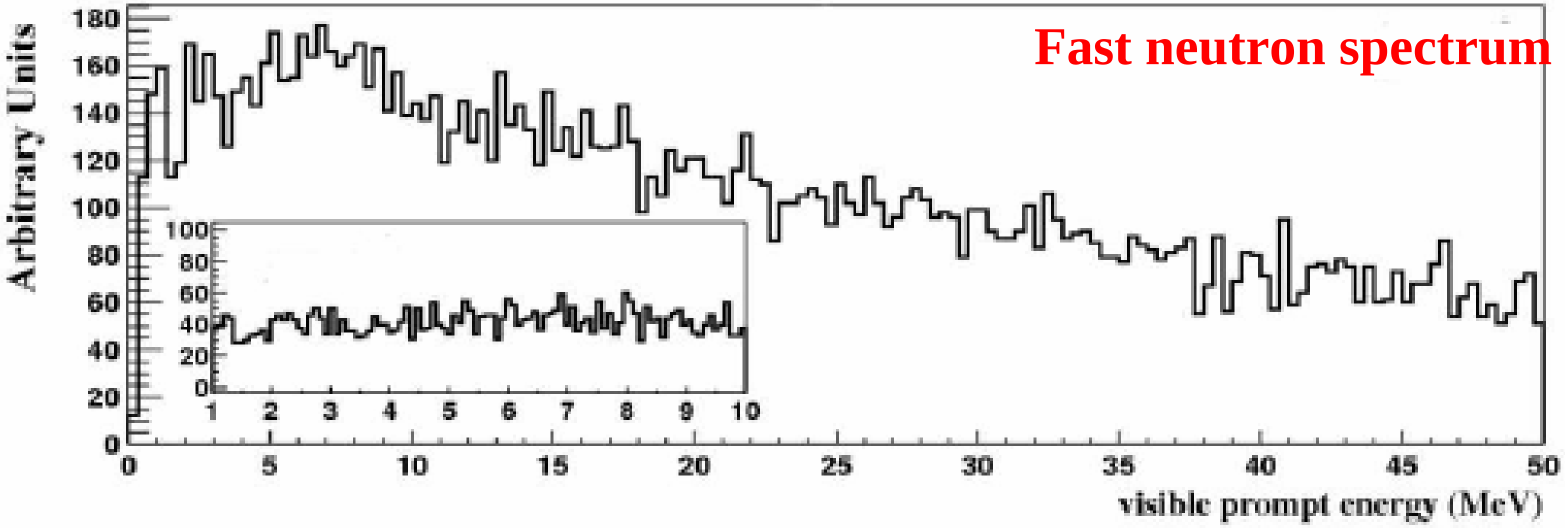


$$\sigma_b = \frac{1}{\sqrt{N}} \cdot \sqrt{(1 + \tau R_\mu)^2 - 1},$$

Spectrum of accidental background



Fast neutron spectrum



Background estimated by GEANT MC simulation

	Near	far
Neutrino signal rate(1/day)	560	80
Natural backgrounds(Hz)	45.3	45.3
Single neutron(1/day)	24	2
Accidental BK/signal	0.04%	0.02%
Correlated fast neutron Bk/signal	0.14%	0.08%
$^{8}He+^{9}Li$ BK/signal	0.5%	0.2%

Calibration

- Radioactive Source

  ^{137}Cs, ^{22}Na, ^{60}Co, ^{54}Mn, ^{65}Zn , ^{68}Ge, Am-Be

  ^{252}Cf, Am-Be

- Gamma generator

KI & CIAE

  $p+^{19}F \rightarrow \alpha + ^{16}O^{*} + 6.13MeV$; $p+^{11}B \rightarrow \alpha + ^{8}Be^{*} + 11.67MeV$

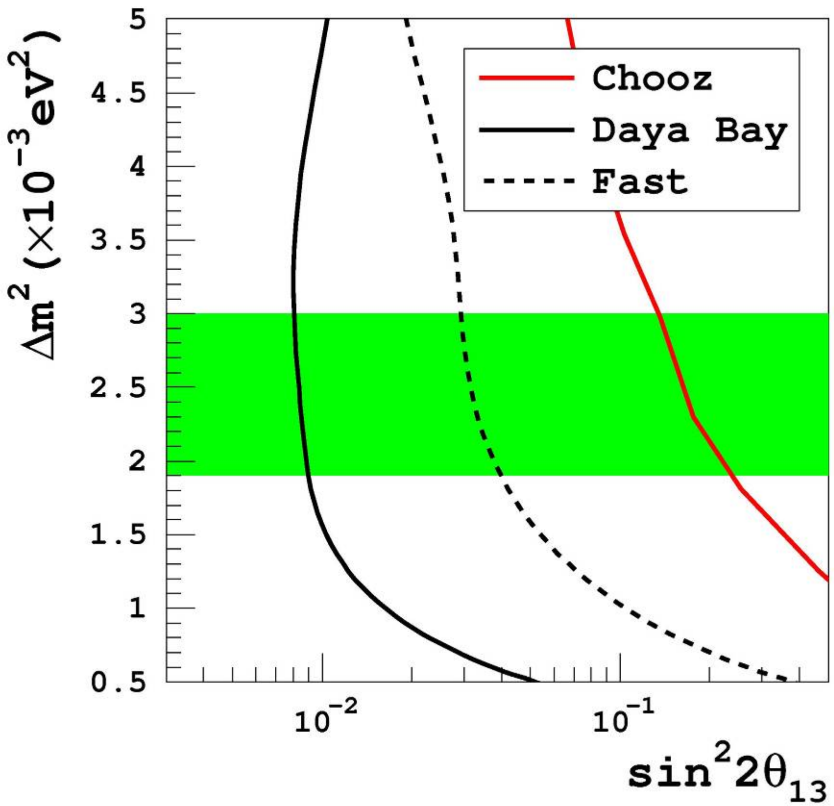
- Backgrounds

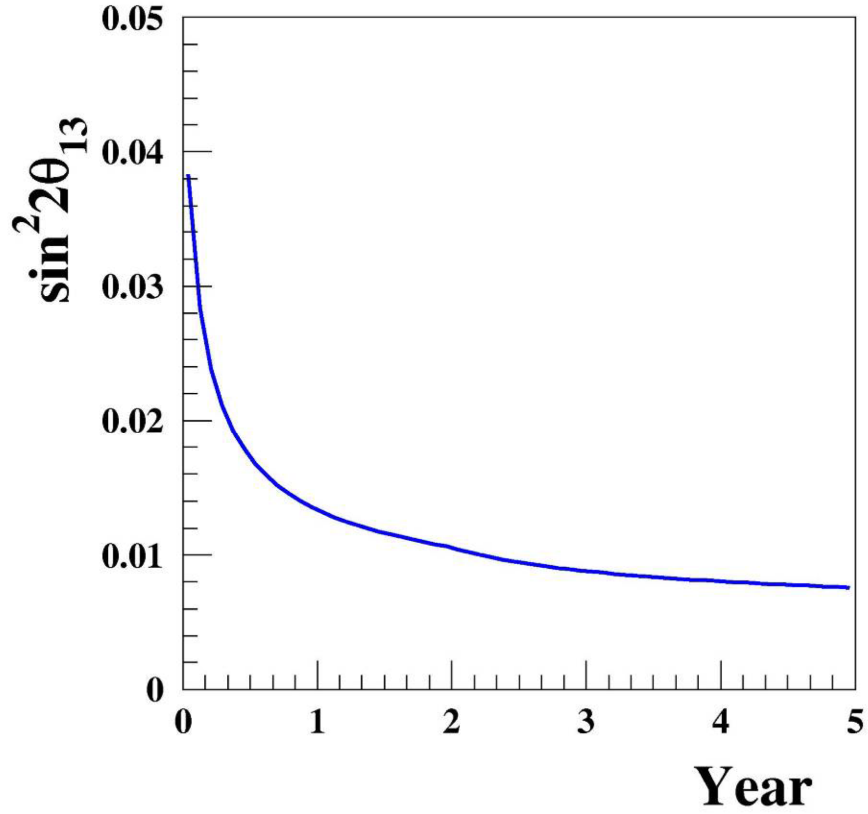
  ^{40}K, ^{208}Tl, cosmic-induced neutrons, Michel's electrons, …

- LED calibration

Hong Kong

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

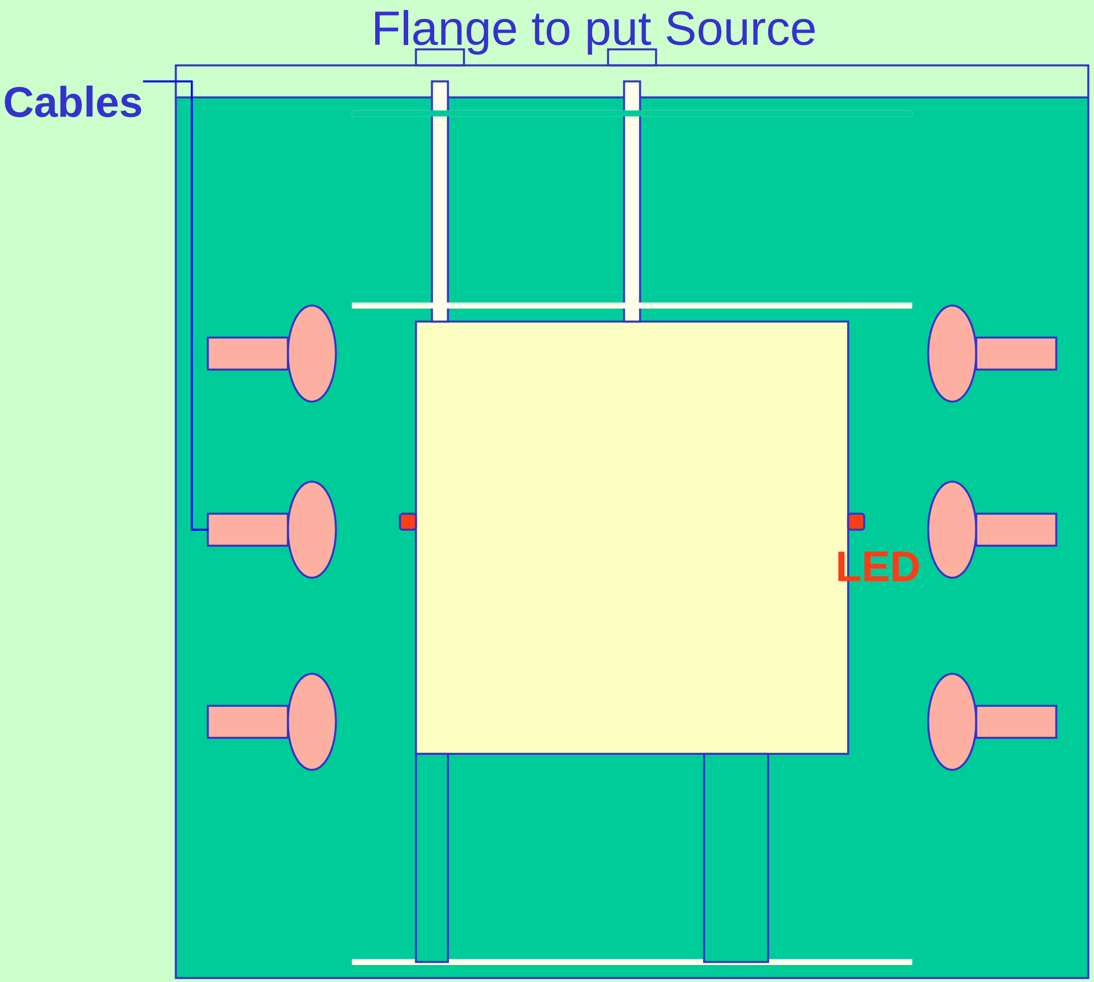




Other physics capabilities:

Supernova watch, Sterile neutrinos, …

Prototype setup



Aluminum film for light refl.

D_{ss}=2.0 m, h=2.1m

$D_{acry.}$=1.0m, h=1.0m

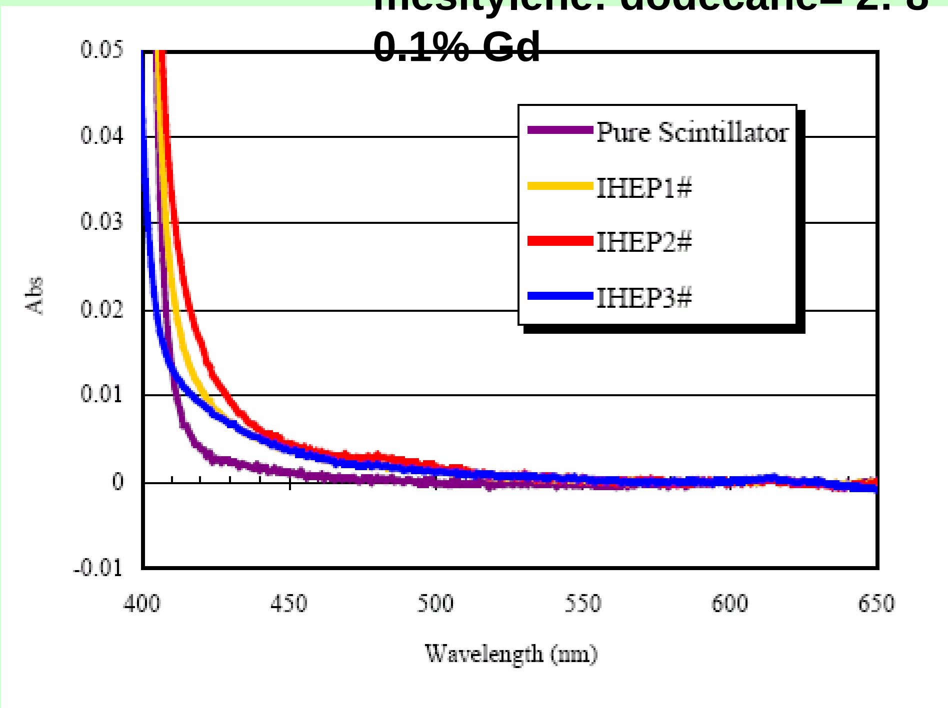
D_{refl}=1.3m

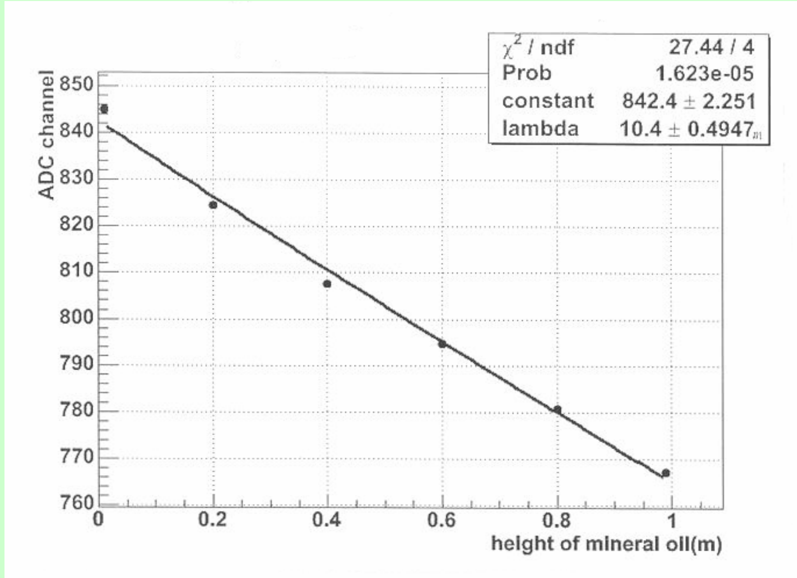
$d_{PMT\_acry.}$=13cm

Development of Gd-Loaded Liquid scintillator

Pgeneral UV-Vis Spectrophotometer

mesitylene: dodecane= 2: 8
0.1% Gd



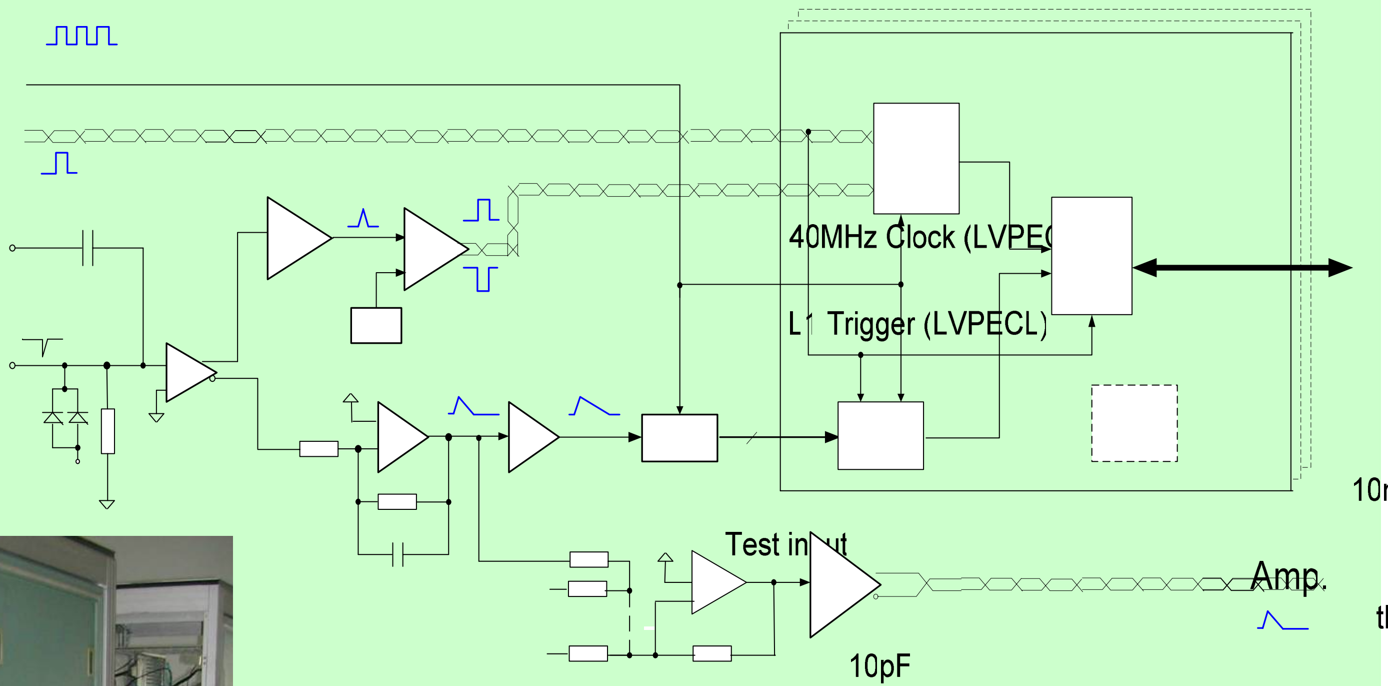


Light yield: 91% of LS stable after 5 months

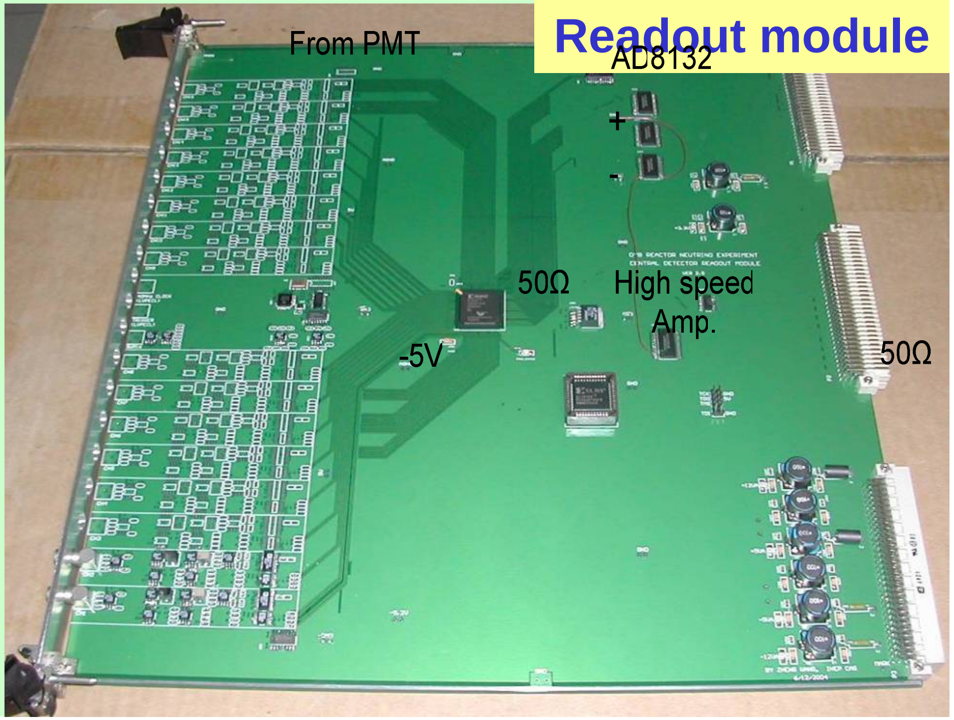
Gd-TOPO
Gd-D2EHP
Gd-TEP

Spectra of optical absorption of three LS samples

Readout Electronics



Electronics for the prototype



Readout module

10ns width

threshold

D

DAC

AD8065

+

-

10KΩ

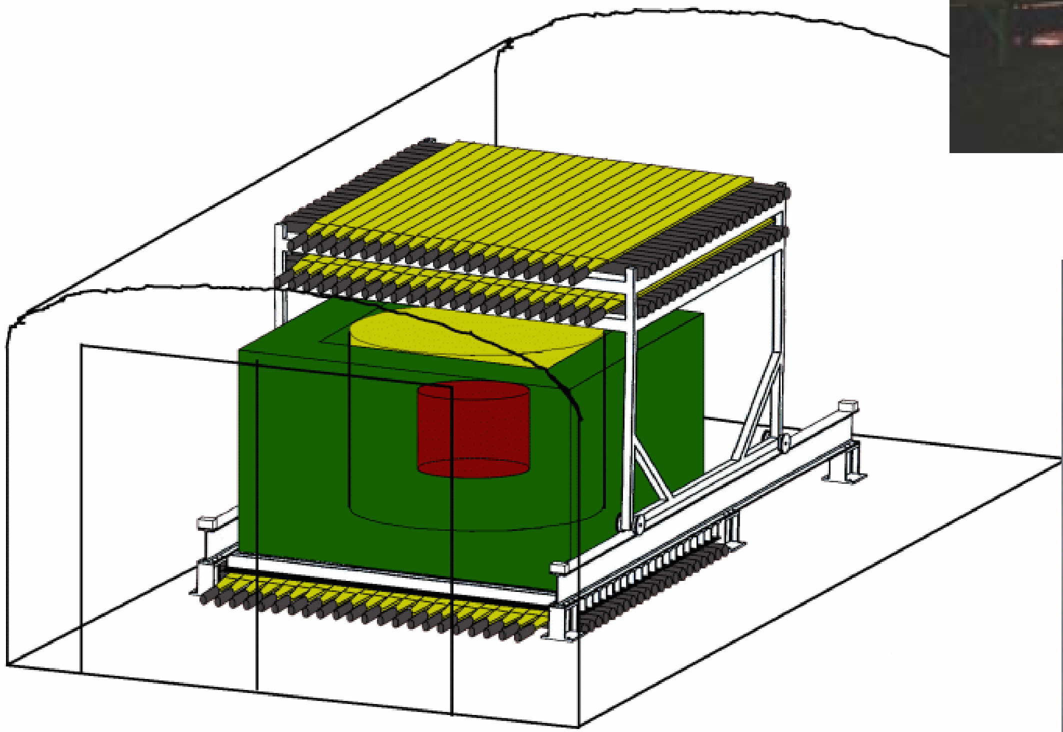
10pF

RC=50n

integra

Aberdeen tunnel in HK:

- background measurement



Status of the project

- Cost estimate (Chinese cost)
  - Civil construction ~ US$ 8-10 M
  - Detector ~ US$ 15-20 M
- Schedule
  - 2004-2005 R&D, engineering design, secure funding
  - 2006-2008 proposal, construction
  - 2009 running

Summary

- Knowing $Sin^2 2\theta_{13}$ to 1% level is crucial for the future of neutrino physics
- Reactor experiments to measure $Sin^2 2\theta_{13}$ to the desired precision are feasible in the near future
- Daya Bay NPP is an ideal site for such an experiment
- A preliminary design is ready, R&D work is going on well, proposal can be submitted soon
- US-China collaboration on this project is crucial
- The collaboration is formed, Kam-Biu will talk about the organization of the collaboration