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

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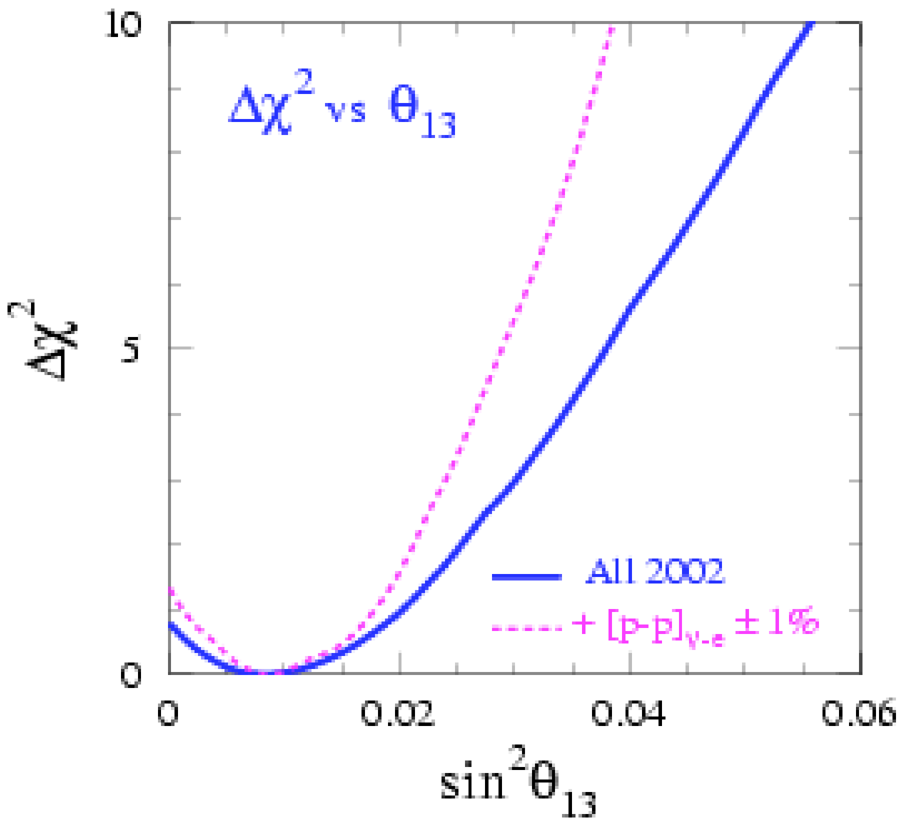
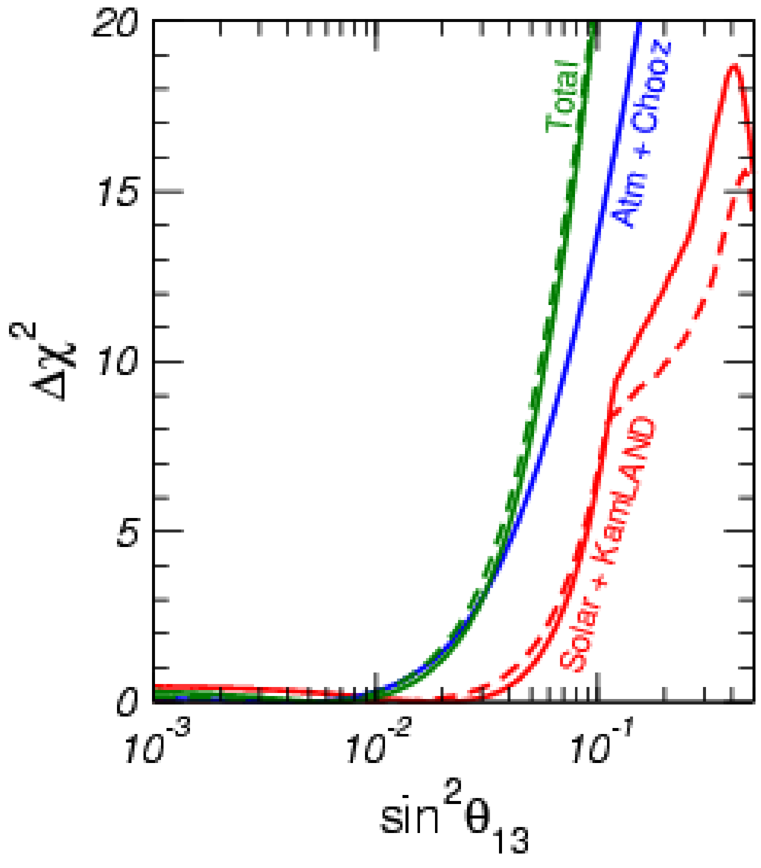
March 20, 2004

Contents

How big $\sin^2 2\theta_{13}$?





J. Bahcall et al., hep-ph/0305159

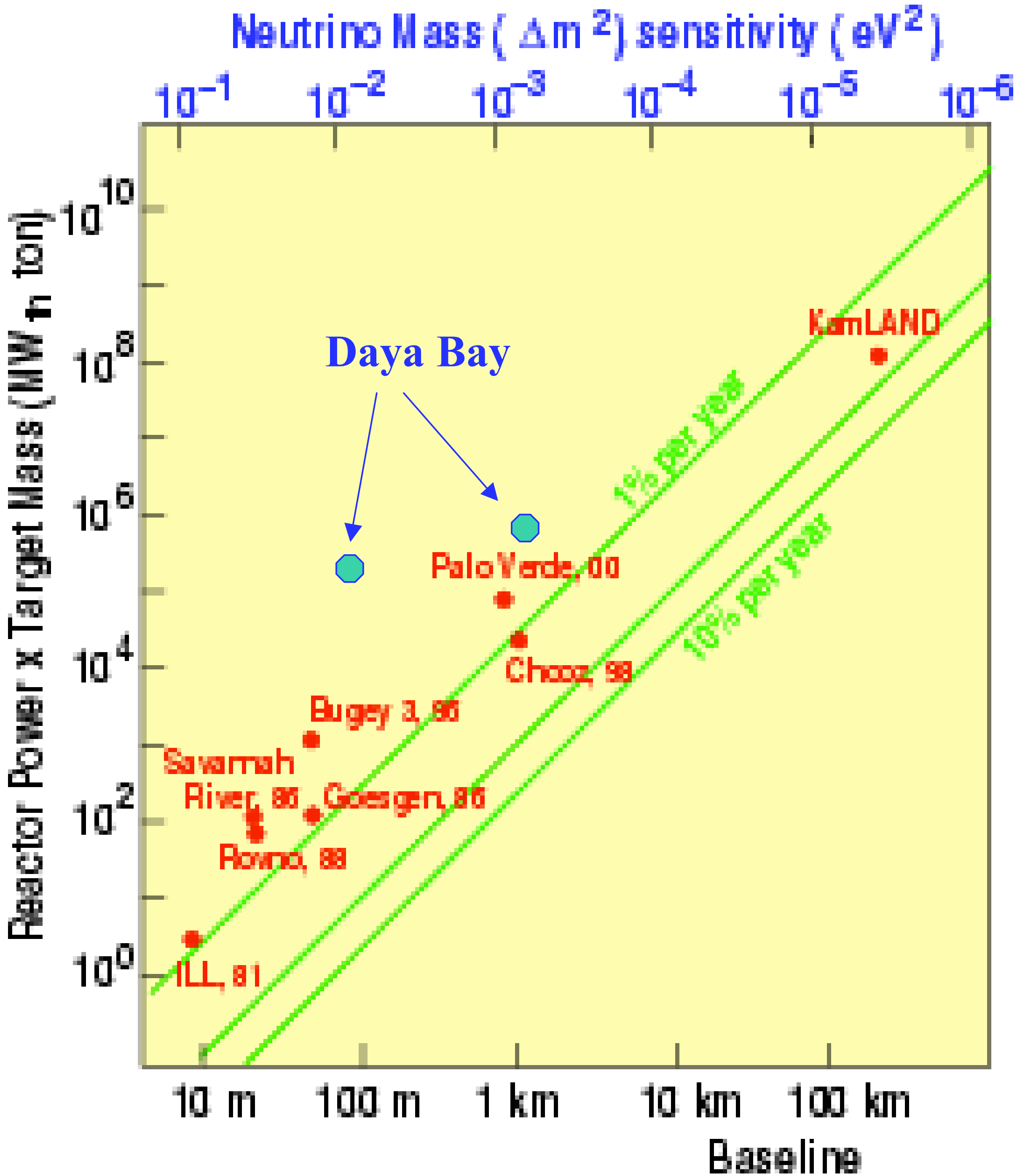
M. Maltoni et al., hep-ph/0309130

Main approximation: one mass scale dominance for 3 types of experimental data ($\Delta m^2_{sun} << \Delta m^2_{atm}$, 커s decoupled)

$\sin^2 2\theta_{13} \sim 3\%$, Chooz limit: $\sin^2 2\theta_{13} < 10\%$

- Analysis based on 2-generation neutrinos
- Global fit with 3-generations still underway
- No good reason(symmetry) for $\sin^2 2\theta_{13} = 0$
- Even if $\sin^2 2\theta_{13} = 0$ at tree level, at low energies with radiative corrections, $\sin^2 2\theta_{13}$ will not vanish
- Theoretical models typically predict $\sin^2 2\theta_{13} \sim 0.1\text{-}10\ \%$

An experiment with a precision
< 1% is vital



Neutrino Mass (Δm 2) sensitivity (eV2)
10−1
10−2
10−3
10−4
10−5
10−6
Reactor Power x Target Mass (MW th ton)
10 10
10 8
10 6
10 4
10 2
10 0
Daya Bay
KamLAND
1% per year
10% per year
Palo Verde, 00
Chooz, 98
Bugey 3, 95
Savannah
River, 86
Goesgen, 86
Rovno, 88
ILL, 81
10 m
100 m
1 km
10 km
100 km
Baseline

Systematic errors of past experiments

- There are three main types of errors: reactor related(~3%), background related(~2%) and detector related(~3%)
- Use two detectors, far/near to cancel reactor related errors "completely" and some of detector/background related errors
- Use movable detectors, near-far, to cancel all backgrounds and some of detector related errors
- Sufficient shielding to reduce backgrounds

Can we really do <1% ?

5t 0.1% Gd-loaded scintillators

Shielding:
300 MWE
2 m scintillator +
0.14m Fe
1km baseline
Signal: ~30/day
Eff. : ~70%
BK:
corr. 1/day
uncorr. 0.5/day

Systematics

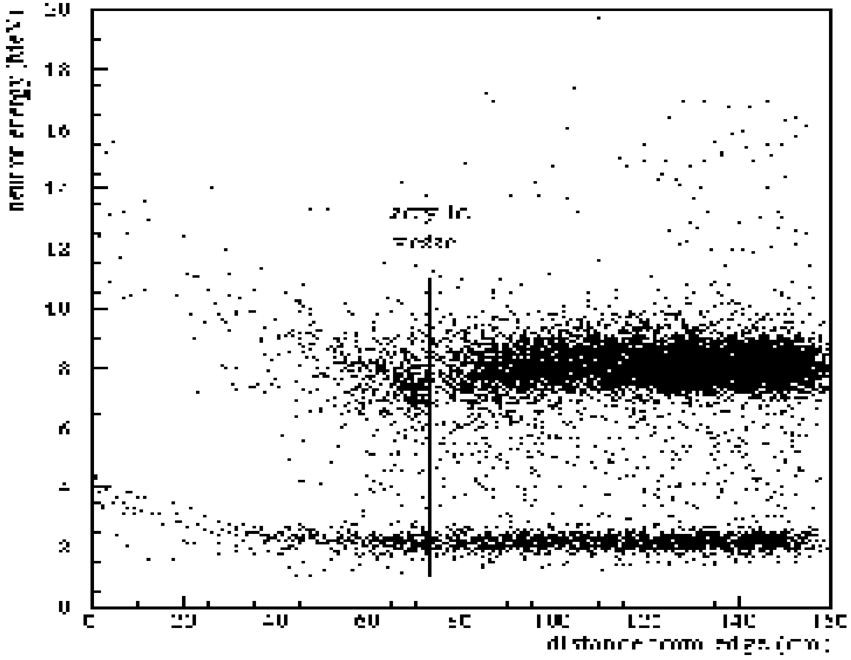
sources	Relative error (%)
Reaction cross section	1.9
Number of protons	0.8
Detection efficiency	1.5
Reactor power	0.7
Energy released per fission	0.6
total	2.7

Closer look -- Detection efficiency

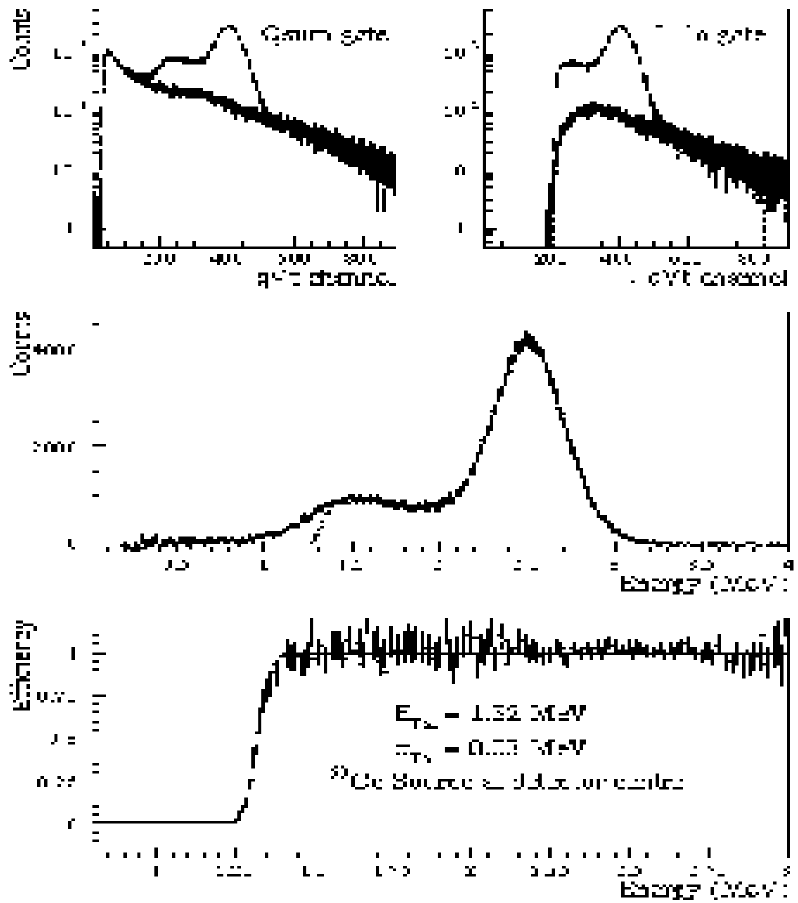
Table 6. Summary of the neutrino detection efficiencies.

selection	ϵ(%)	rel. error (%)
positron energy*	97.8	0.8
positron-geode distance	99.9	0.1
neutron capture	84.6	1.0
capture energy containment	94.6	0.4
neutron-geode distance	99.5	0.1
neutron delay	93.7	0.4
positron-neutron distance	98.4	0.3
neutron multiplicity*	97.4	0.5
combined*	69.8	1.5

*average values



Position cut



Energy cut

Experience gained

- Not stable Gd-loaded scintillator (λ~5–2m)
- PMT directly in contact with scintillator ➔ too high uncorr. Background → too high E_{th}(1.32 MeV)
- Good shielding ➔ low background
- Homogeneous detector ➔ Gd peak at 8 MeV
- 2m scintillator shielding gives a neutron reduction of $0.8*10^6$.

12t 0.1% Gd-loaded scintillators

Shielding:

32 MWE /1m water

0.9 km baseline

Signal: ~20/day

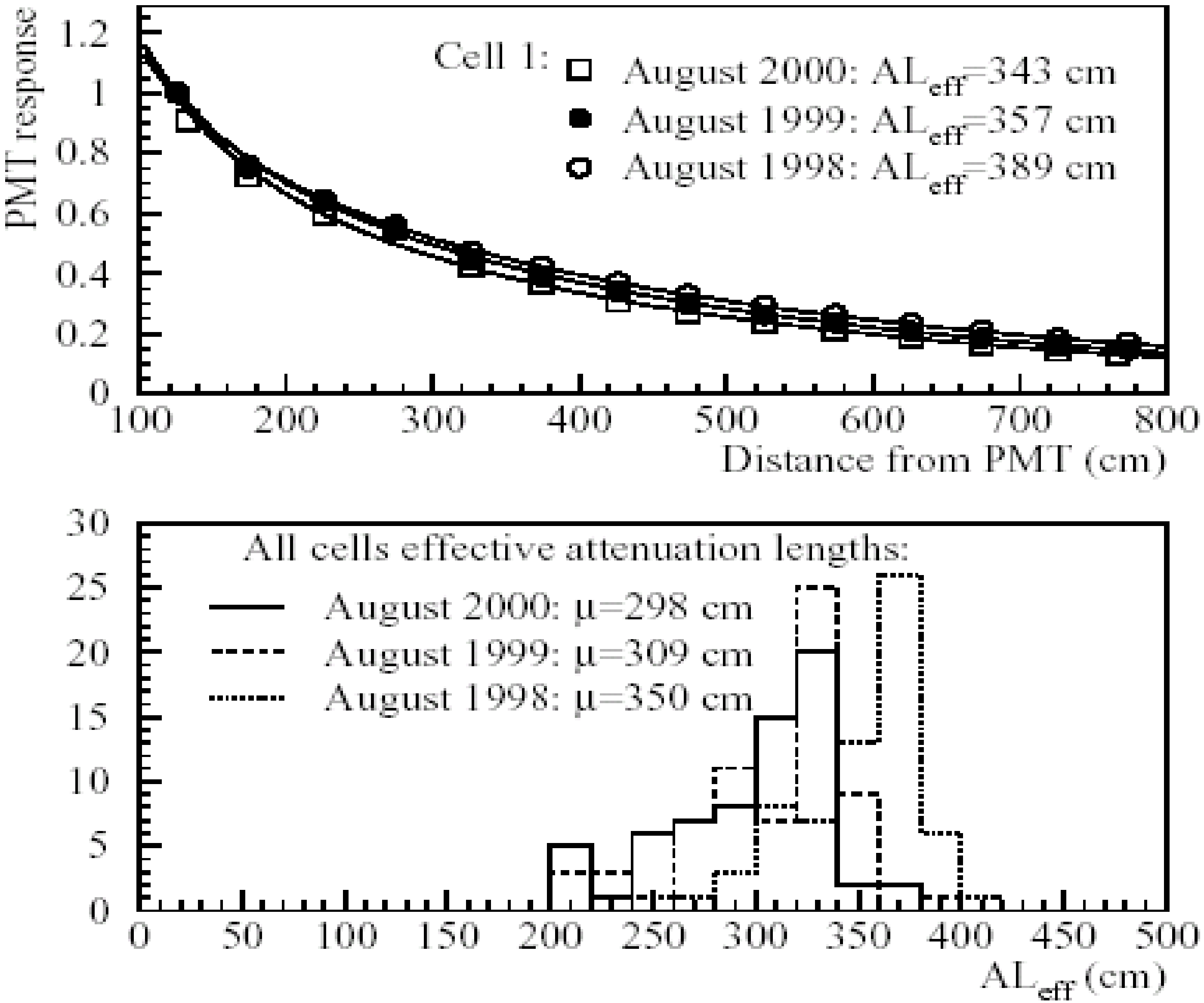
Eff. ~ 10%

BK:

corr.: ~ 15/day

uncorr. ~ 7/day

Very stable Gd-loaded liquid scintillator



Systematics

Sources	power method	Swap method
e+ trigger efficiency	2.0	2.0
n trigger efficiency	2.1	2.1
ν flux prediction	2.1	2.1
ν selection cuts	4.5	2.1
Background variation	2.1	N/A
$(1-\varepsilon_1)\ B_{pn}$	N/A	3.3
Total	6.1	5.3

Error on ν selection cuts obtained from multi-variable analysis

Experience gained

- Good Gd-loaded scintillator($\lambda \sim$ 11m)
- Not enough shielding ➔ too high corr./uncorr. Background
- Segmentation makes Gd capture peak <6MeV ➔ too high uncorr. Background
- Rn may enter the detector, problem ?
- Veto eff. is not high enough(97.5%)
- Swap method to measure/cancel backgrounds → key to success
- 1m water shielding gives a neutron reduction of 10^6 (lower energy, complicated event pattern).

KamLAND

1000t scintillators

Shielding:

3000 MWE/3m Water

180 km baseline

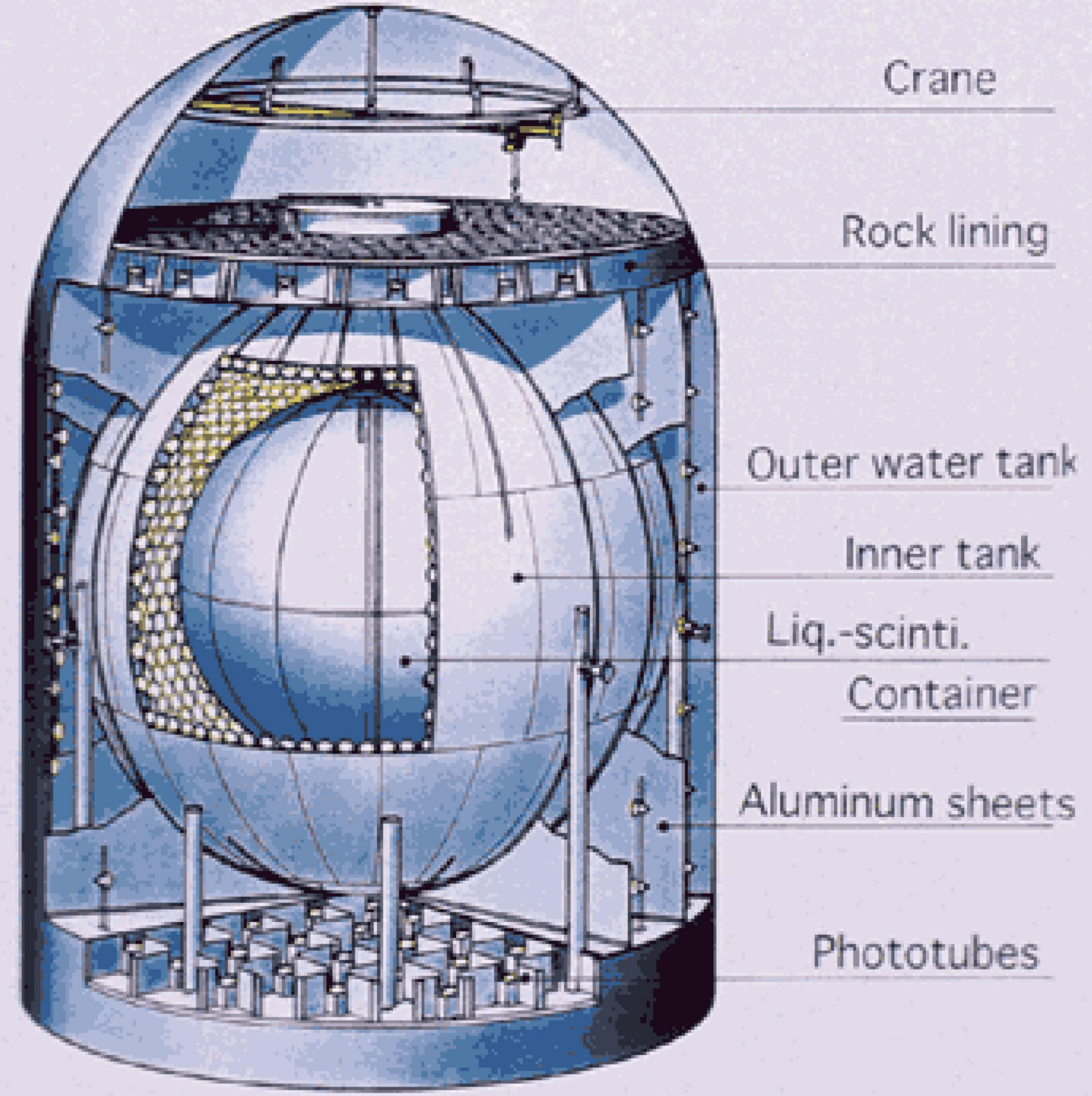
Signal: ~0.5/day

Eff. ~40%

BK:

corr.: ~0.001/day

uncorr. ~0.01/day

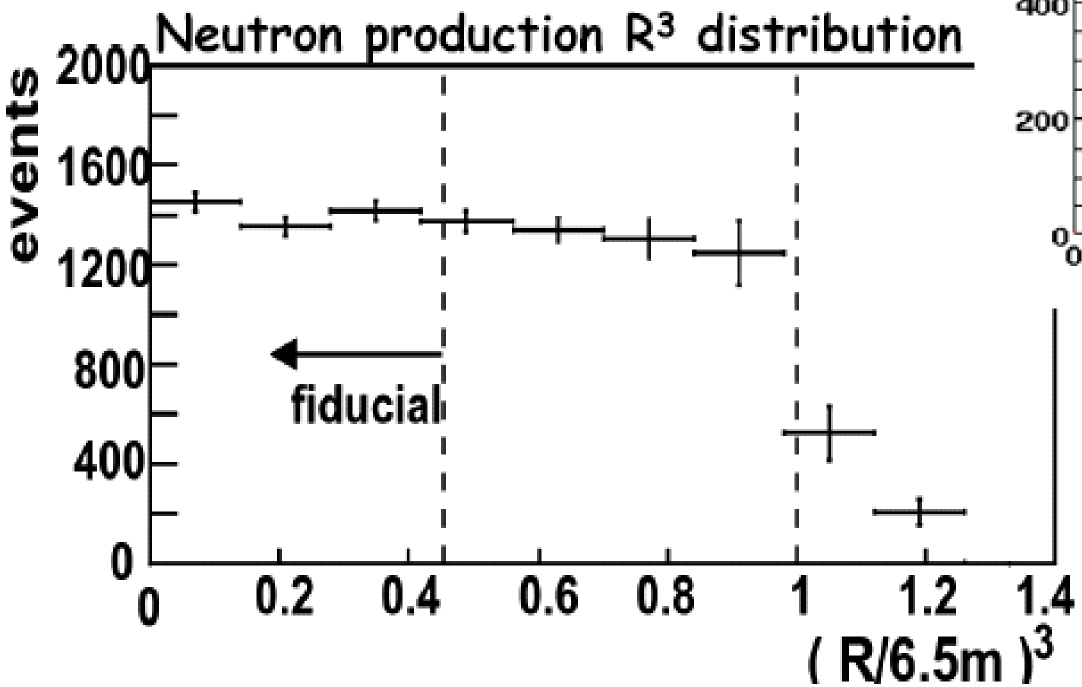


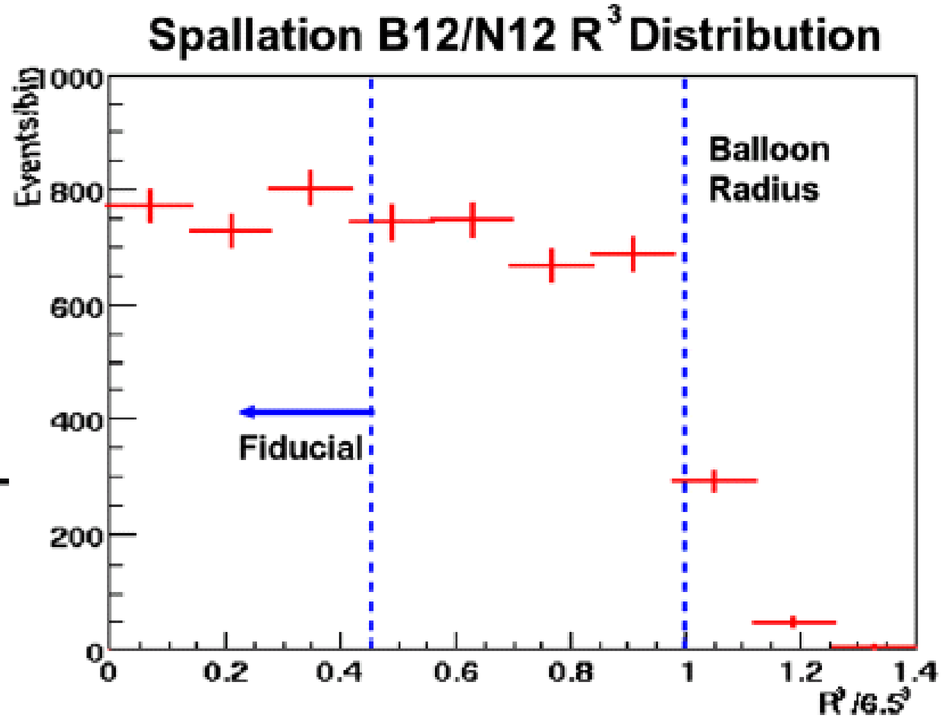
Systematic errors

Systematic errors	E>0.9 MeV	E>2.6 MeV
Total LS mass	2.13	2.13
Fiducial mass ratio	4.03	4.03
Energy threshold	--	2.13
Efficiency of cuts	2.06	2.06
Live time	0.07	0.07
Reactor power	2.05	2.05
Fuel composition	1.0	1.0
Time lag	0.28	0.28
ν spectra	2.25	2.48
Cross section	0.2	0.2
Total	6.0	6.4

Large error on fiducial volume

$R_{fid} = 6.5\ m$
$R_{fid} = 5\ m$
$\Delta V_{fid}/V_{fid} = 4.6\ \%$





Fiducial mass 408 ton (out of 1000)

Experience gained

- Very good shielding
- Balloon not good → target mass not well defined
- Light transport in scintillator unknown → particularly bad for Large detectors → large error on position reconstruction
- Significant backgrounds from 8He/9Li
- Not good enough veto tracking system
- 3m water shielding gives a neutron reduction of $>13*10^6$(high energy).

Important point to have small systematic error

- Energy threshold less than 0.9 MeV
- Homogeneous detector
- target mass well determined → rigid container
- Target scintillator all from one batch, mixing procedures well controlled
- Not too large detector (<50t ?)
- Comprehensive calibration program
- Background well controlled → good shielding
- Be able to measure everything(Veto ineff., background, energy/position bias, …)
- A lot of unforeseen effects will occur when looking at 0.1% level

Systematic error comparison

		Chooz	Palo Verde	KamLAND	Cancel ?
Reactor power		0.7	0.7	2.05	<0.2%
Reactor fuel/ν spectra		2.0	2.0	2.7	
ν cross section		0.3	0.2	0.2	0
No. of protons	H/C ratio	0.8	0.8	1.7	0
	Mass	-	-	2.1	<0.1
Efficiency	Energy cuts	0.89	2.1	0.26	0.2
	Position cuts	0.32		3.5	0.2
	Time cuts	0.4		0.	0.1
	P/Gd ratio	1.0		-	0
	n multiplicity	0.5		-	<0.1
background	correlated	0.3	3.3	1.8	<0.1
	uncorrelated	0.3	1.8	0.1	<0.1
Trigger		0	2.9	0	<0.1
livetime		0	0.2	0.2	<0.1

Possibly best systematic errors

- Reactor < 0.2%
- Background < 0.2%
- Energy cut ~ 0.2%
- Position cut ~ 0.2%
- Time cut < 0.1%
- Livetime ~ 0.1%
- Other unexpected <0.2%
- Total < 0.5%

Background related error

- **Just to have enough shielding and active veto**
- **How much is enough ?**
  - **Uncorrelated backgrounds: U/Th/K/Rn**

    MC
  - **Correlated backgrounds:** $n \propto E_{\mu}^{0.75}$

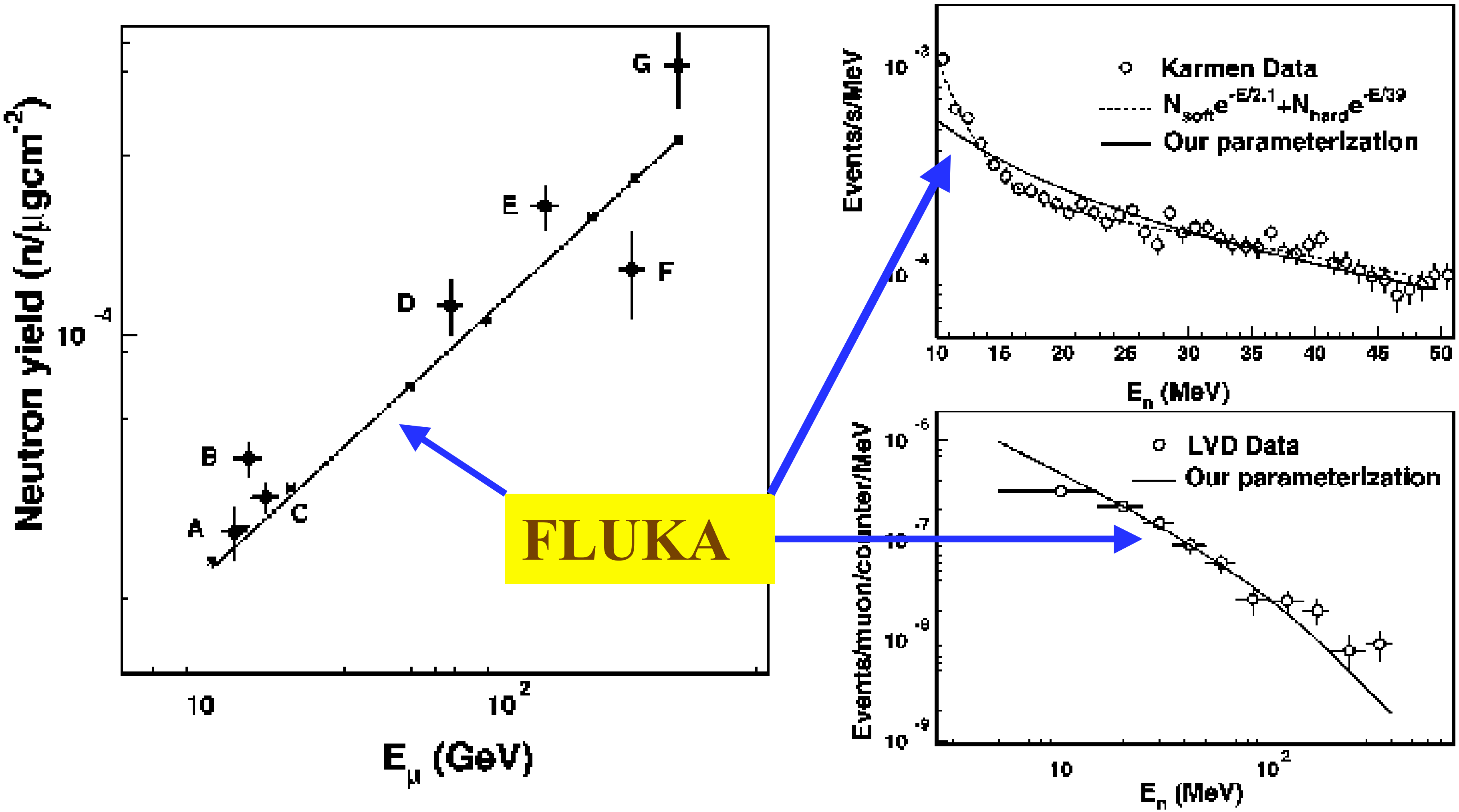
    Neutrons: go deep and buffer shielding

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

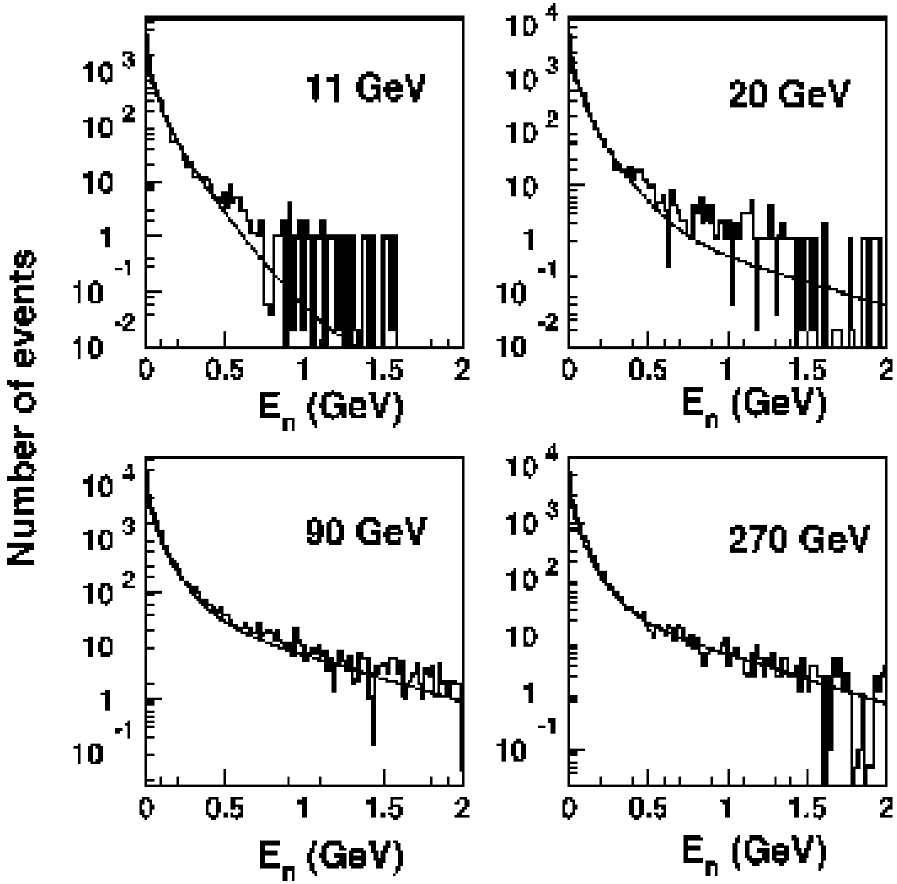
    $^{8}He/^{9}Li$: go deep

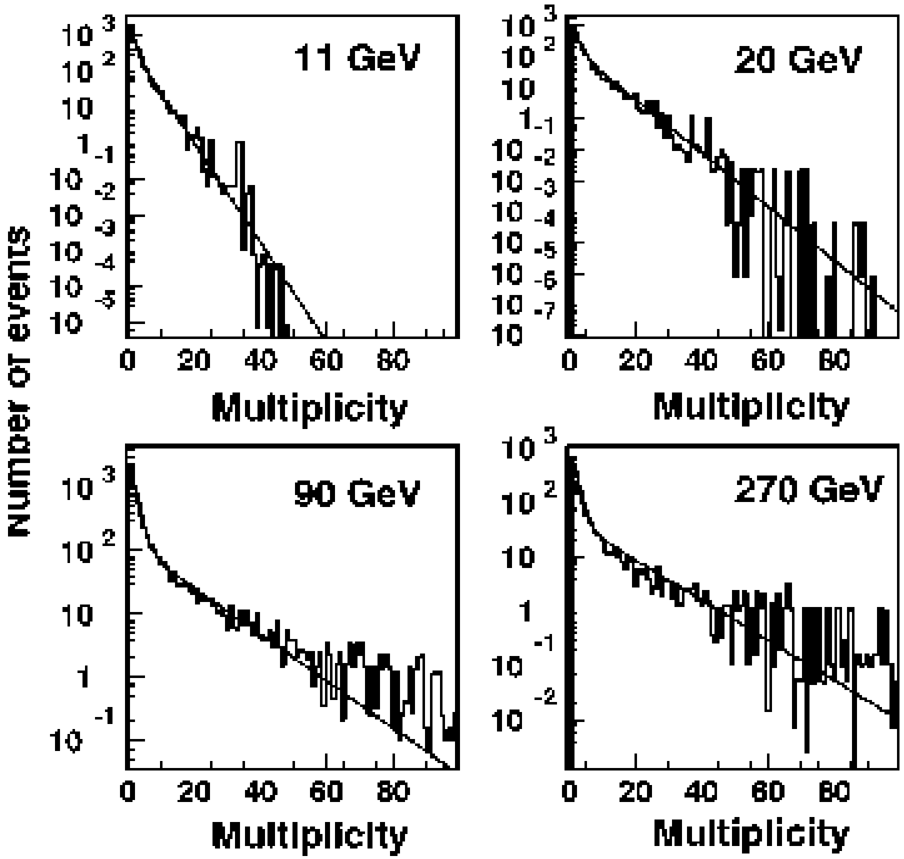
    T. Hagner et al., Astroparticle Phys. 14(2000) 33

n-production well reproduced by FLUKA



Y.F. Wang et al, Phys. Rev. D. 64(2001)013012

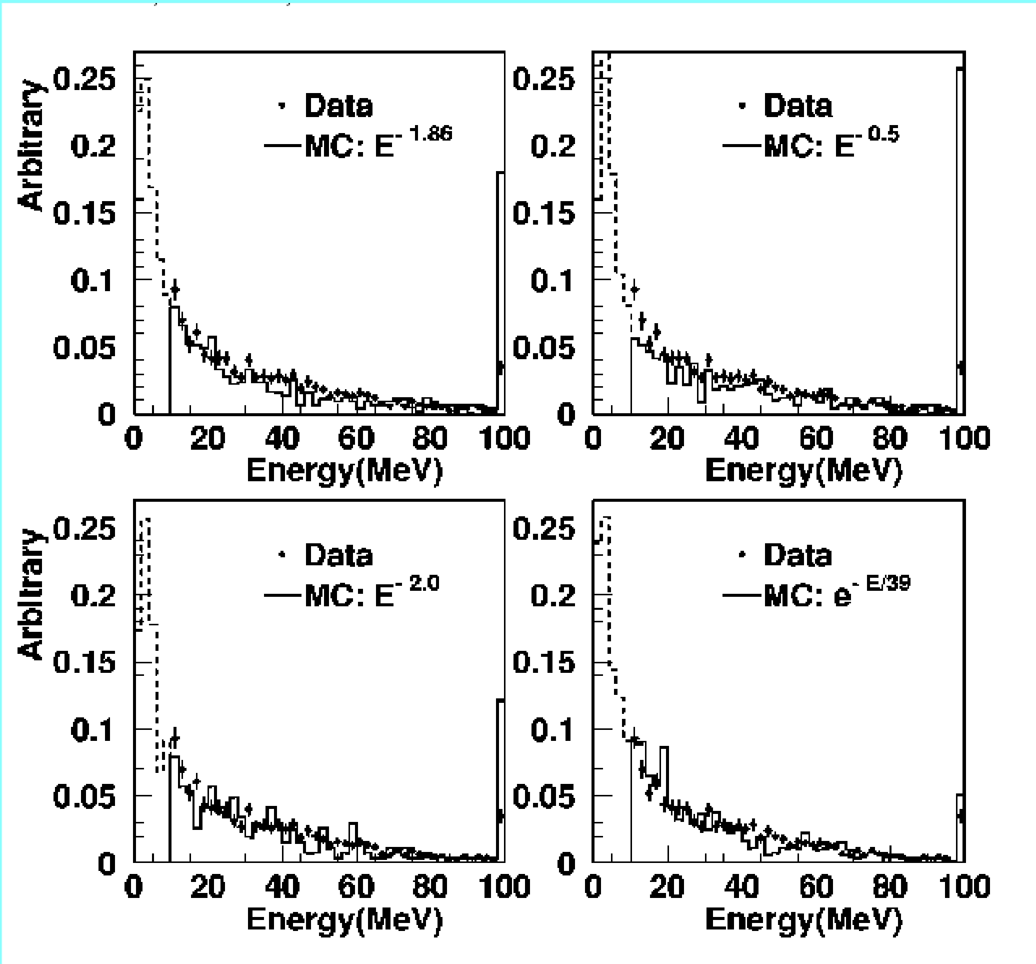




FLUKA predictions are in good agreement with current experimental data

n-measurement by high energy neutrons and/or tagged muons

- n by tagged muons need to know tagging eff. precisely
- Veto ineff. for:
  - **μ spallation in buffer**
  - **μ capture in buffer**



Y. F. Wang et al., Phys. Rev. D 62(2000)013012

Irreducible Background: Go Deep

46 T. Hagner et al. / Astroparticle Physics 14 (2000) 33–47

Table 6
Muon-induced background rates in BOREXINO, calculated for different energy regions that are relevant for solar neutrino physics[a]

Isotopes	Muon-induced background rates in BOREXINO given in counts/(day × 100 tons) for the different energy regions			
	Full energy range	$250 < E < 800$ keV ^{7}Be-ν region	$0.8 < E < 1.4$ MeV pep-ν region	$2.8 < E < 5.5$ MeV ^{8}B-ν region
^{11}C	14.55 ± 1.49	0	7.36 ± 0.75	0
^{7}Be	0.34 ± 0.04	0.34 ± 0.04	0	0
^{11}Be	<0.034	$<4.3 \times 10^{-4}$	$<1.0 \times 10^{-4}$	<0.01
^{10}C	1.95 ± 0.21	0	0	0.56 ± 0.06
^{8}Li	0.070 ± 0.017	$(2.5 \pm 0.6) \times 10^{-4}$	$(8.0 \pm 2.0) \times 10^{-4}$	0.020 ± 0.005
^{6}He	0.26 ± 0.03	0.040 ± 0.004	0.07 ± 0.01	0.011 ± 0.001
^{8}B	0.11 ± 0.02	0	$(3.3 \pm 0.6) \times 10^{-5}$	0.020 ± 0.004
^{9}C	0.077 ± 0.025	0	0	0.016 ± 0.005
$^{9}Li + ^{8}He$	0.034 ± 0.007	$<6.8 \times 10^{-4}$	$<1.0 \times 10^{-3}$	<0.014

[a] The rates are given in counts/day normalized to 100 tons of target mass.

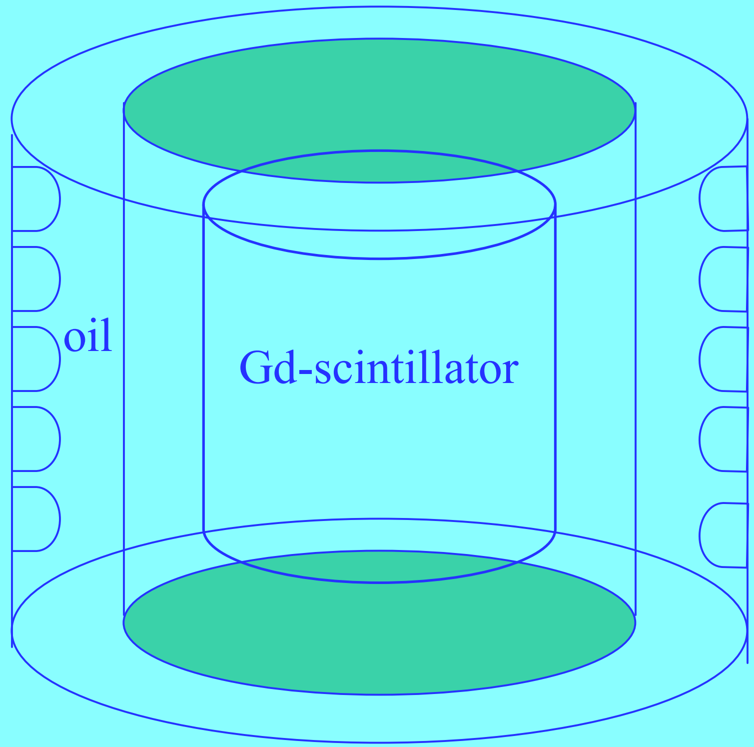
Detector design: multiple modules

- **Many modules, ~10t each, 100-200 8"PMT/module**
- **1-2 at near, 4-8 at far, small enough for movable calibration**
- **Correlated error cancelled by far/near**
- **Uncorrelated error can be reduced**
- **Event rate:**

  near: ~500-2000/day/module

  Far: ~40/day/module
- **100 days calibration at the near pit**

  → 0.2-0.5% statistical error
- **Two reference modules 100 days, others ~ 10 days calibration**

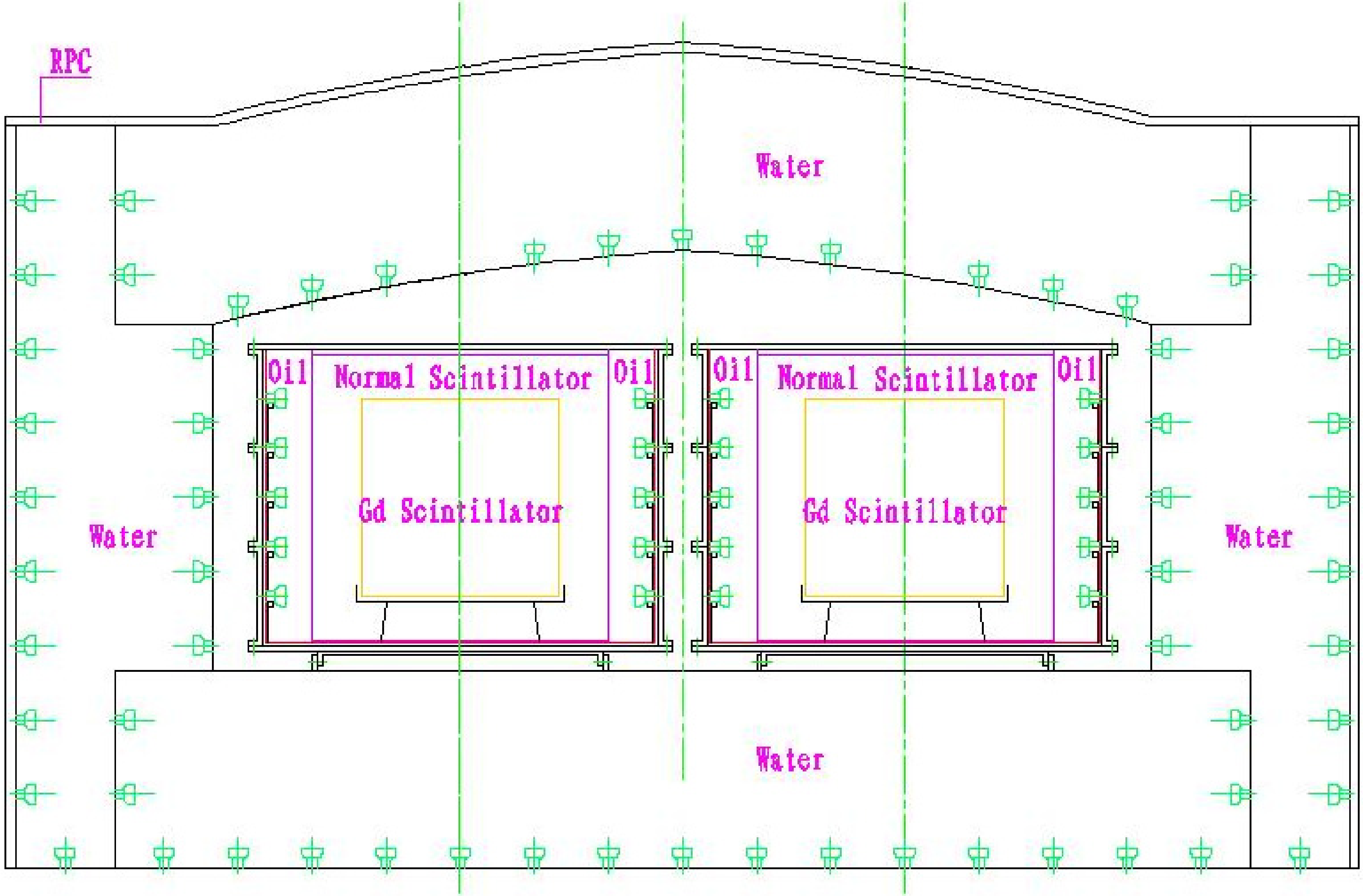


Advantages with multiple modules

- Smaller modules have less unknowns
- Smaller modules, less sensitive to scintillator aging
- Multiple handling to control systematic error(1/√N ?)
- Easy construction
- Easy movable detector
- Scalable
- Easy to correct mistakes

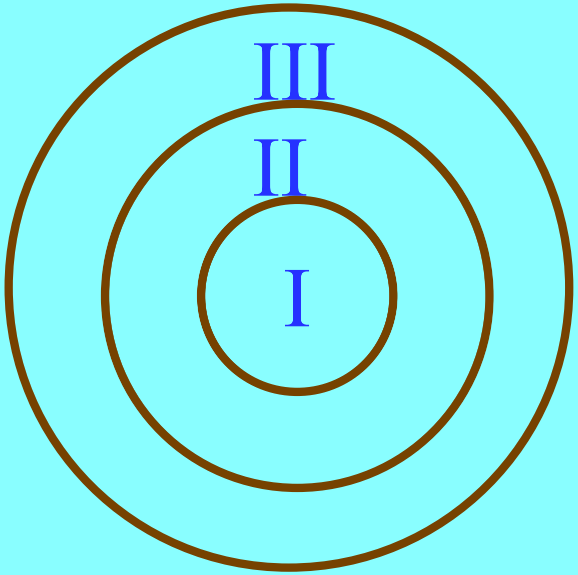
- Higher cost
- More trouble with calibration

Schematics of a multi-module detector



Structure of the module

- Three layers module structure
  I. target: Gd-loaded scintillator
  II. γ-ray catcher: normal scintillator
  III. Buffer shielding: oil



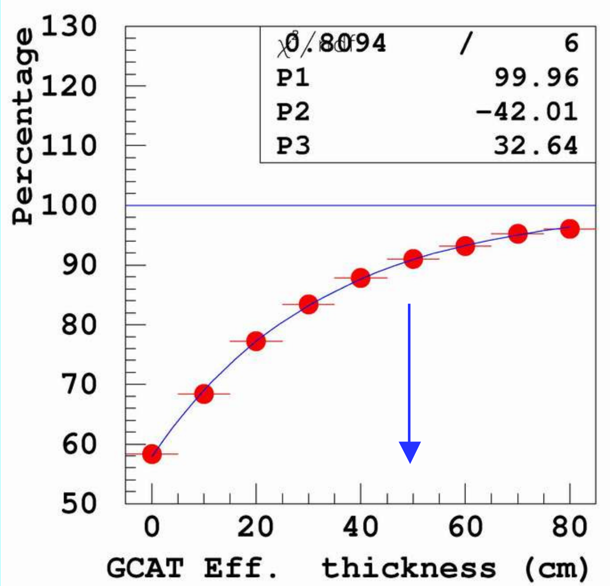
- Advantages:
  - Well defined fiducial volume
  - No cut on position → small systematics

40cm: 87.80%

50cm: 91.04%

70cm: 95.23%

Thickness of Layer II determined by neutrino efficiency



Structure of the module: MC simulation

- Cylinder is much better than cubic
- Small module, no vertex → time not important
- reflection at the top and the bottom of the cylinder to increase light yield

Case	Total PE	ΔE/E @8MeV	ΔR (cm)
No refl., λ=11m	419	14.2	11
No refl., λ= 7 m	388	14.9	11
90% Refl. λ= 11m	719	5.3	17
90% Refl. λ= 7m	646	5.8	17

Light yield 7000/MeV, QE=20%, QE_{D1}=60%, 100 8" PMT

What resolution we need ?

Criteria:

1) σ_E @ 1MeV → e^+ cut

2) σ_E @ 8MeV → n cut

3) Energy scale

4) Low energy backgrounds

For 5%@8MeV

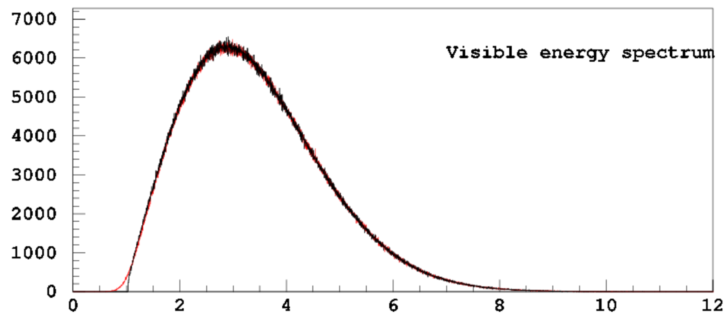
1) ineff. at 0.9 MeV is 0.04%

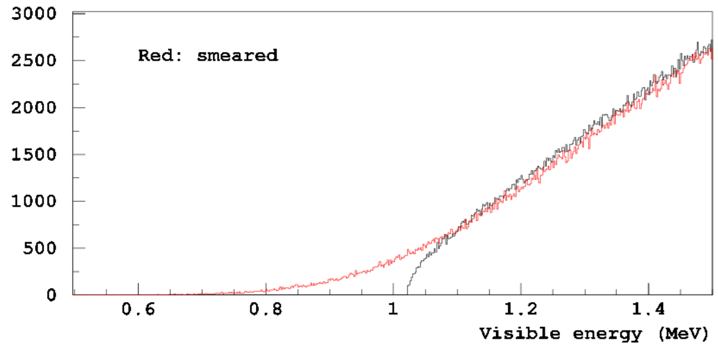
2) 6MeV cut for n is 4σ

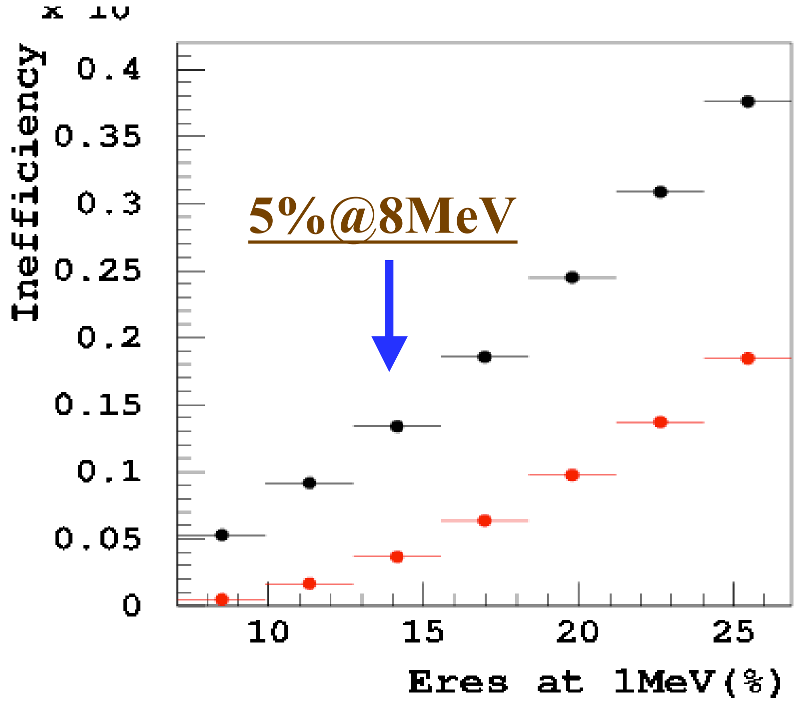
3) Energy scale: σ/√N:

1 MeV ~ 0.2%,
6 MeV ~ 0.08%

4) Could be a problem, cheaper to work on







Background - correlated

- Cosmic-muon-induced neutrons:
  - B/S < 0.005 → 0.2/day/module @ ~2km
  - Can be measured by veto tagging, accuracy<20%
  - Veto rate < 1KHz, 2-3 layers RPC(1600-2400 m^2) ?
  - Methods:
    - Overburden > 100 MWE
    - Active Veto, ineff. < 0.5%, known <0.2%
  - Three scenarios:

	100 MWE	300 MWE	1000 MWE
muon rate/m^2 (Hz)	4	0.4	0.02
n rate in rock/m^3 (/day)	11000	1600	160
reduction required (10^6)	9.2	1.4	0.14
Shielding (water equivalent) (m)	2.5m	2.1m	1.5m

Other correlated backgrounds

- β-neutron instable isotopes from cosmic μ
  - $^8He/^9Li$, Br(n) = 12%/48%, ^9Li dominant
  - Production rates = $f_\mu \cdot N_A \cdot \sigma \cdot Br$

	100 MWE	300 MWE	1000 MWE
Average E_μ (GeV)	36	64	160
muon rate/m^2 (Hz)	4	0.4	0.02
Cross section (μb)	0.61	0.94	1.86
$^8He/^9Li$ (1/day/module)	3.4	0.53	0.053
B/S @far(near) site(%)	8.5(0.7)	1.3(0.1)	0.13(0.01)

- Depth > 250 MWE@400m
  > 1000 MWE@1500m

Background - Uncorrelated

- B/S < 0.05 ➔ < 2/day/module @ far site
- Can be measured by swap method, precision ~ $\sqrt{B/s}$=3.5%/day/module
- single rate @ 0.9MeV < 50Hz

  $2\cdot R_\gamma \cdot R_n \cdot \tau < 0.04$/day/module

- Methods:
  - Low activity glass for PMT
  - 3 MWE shielding, low activity sand/aggregate or Fe ?
  - Rn concentration < 20 Bq/m^3, N_2 flushing ?
  - (U, Th, K) in Scintillator < 10^{-13} g/g, clean Gd
  - All mechanical structure made of low activity materials
  - Calibration gadget made of clean materials such as Teflon, …
  - Clean everywhere, no dust, no …

Thickness of Layer III is determined by backgrounds from PMT glass and position reconstruction

Background from PMT glass

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

Hamamatzu R5912: 1/3 of R1408 (used by SNO)

Total rates << 50Hz

Radiation from PMT glass is not a problem with 20cm shielding.

Background from rock

Based on measured rock purity and GEANT3 simulation

Isotopes	Purity (ppm)	Rejection (E>1 MeV) for 2.5 MWE shielding	Backrounds rate (E>1 MeV) (Hz)
^{238}U	8.8	$11/3*10^8$	5.4
^{232}Th	28.7	$34/3*10^8$	20.4
^{40}K	4.5	$5/3*10^8$	1.8
Total			27.6

Total rates < 50Hz

Background from Radon

- ^{238}U in rock: 8.78 ppm
- Rock density: 3.0 g/cm^3, 10cm thick
- Rn density in the hall: 1173 atoms/cm^3/day
- Rn in fresh air: 100 atoms/cm^3, Kr ? atoms/cm^3

A fresh air exchange of 10 volume/day is a minimum requirement ➔ 200 atoms/cm^3

A problem to be solved

Scintillator

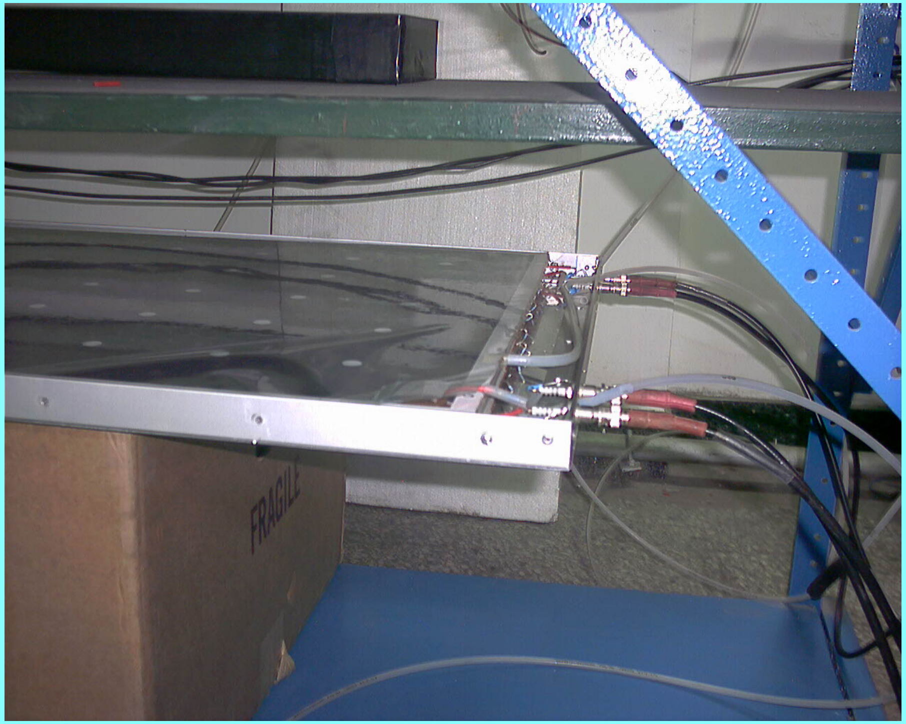
- Gd-loaded liquid scintillator is desirable
- PV scintillator: 11m, 55% antracene
- PV aging: 0.03%/day, Chooz aging: 0.4%/day
- PV scintillator: $Gd(CH_3(CH_2)_3CH(C_2H_5)CO_2)_3$
  4% 2-ethoxyethanole, 36% pseudocumene, 60% mineral oil plus PPO, BisMSb, BHT, and Gd compounds
- More pseudocumene, more stable, 50% ?
- But
  - **Compatibility with acrylic**
  - **Flush point**
  - **Cost**

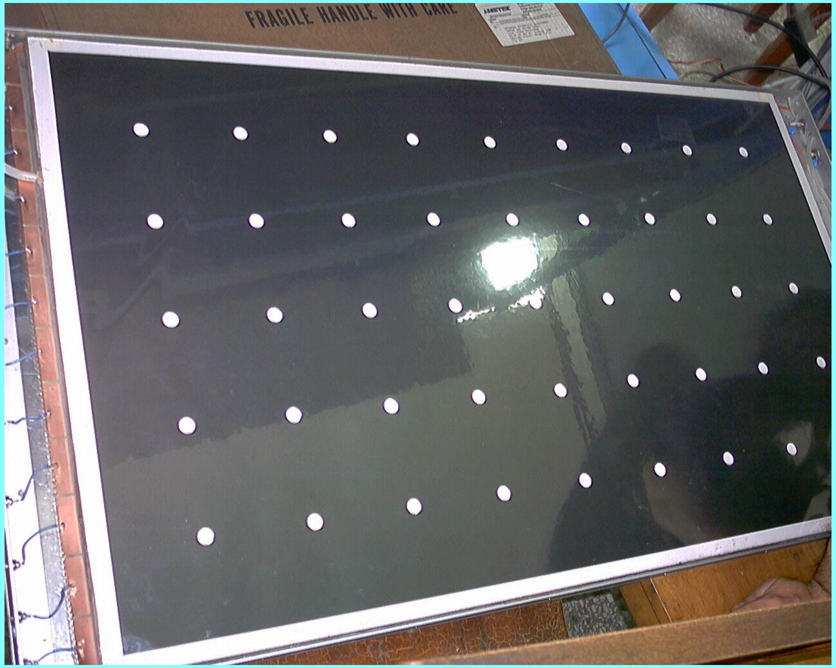
Buffer & VETO

- 2m water buffer to shield backgrounds from neutrons and γ's from lab walls
- Active buffer as veto is even better
- 800 8" PMT from Macro available
- Inefficiency < 0.5%, known to <0.25%, in order to control neutron background uncertainty
- Need multiple handling
- RPC(>90%) + active water buffer(>95%) ➔

  total ineff. = 10%*5% = 0.5%
- Two layers RPC, each with 4cm width XY strips

RPC prototypes made in IHEP





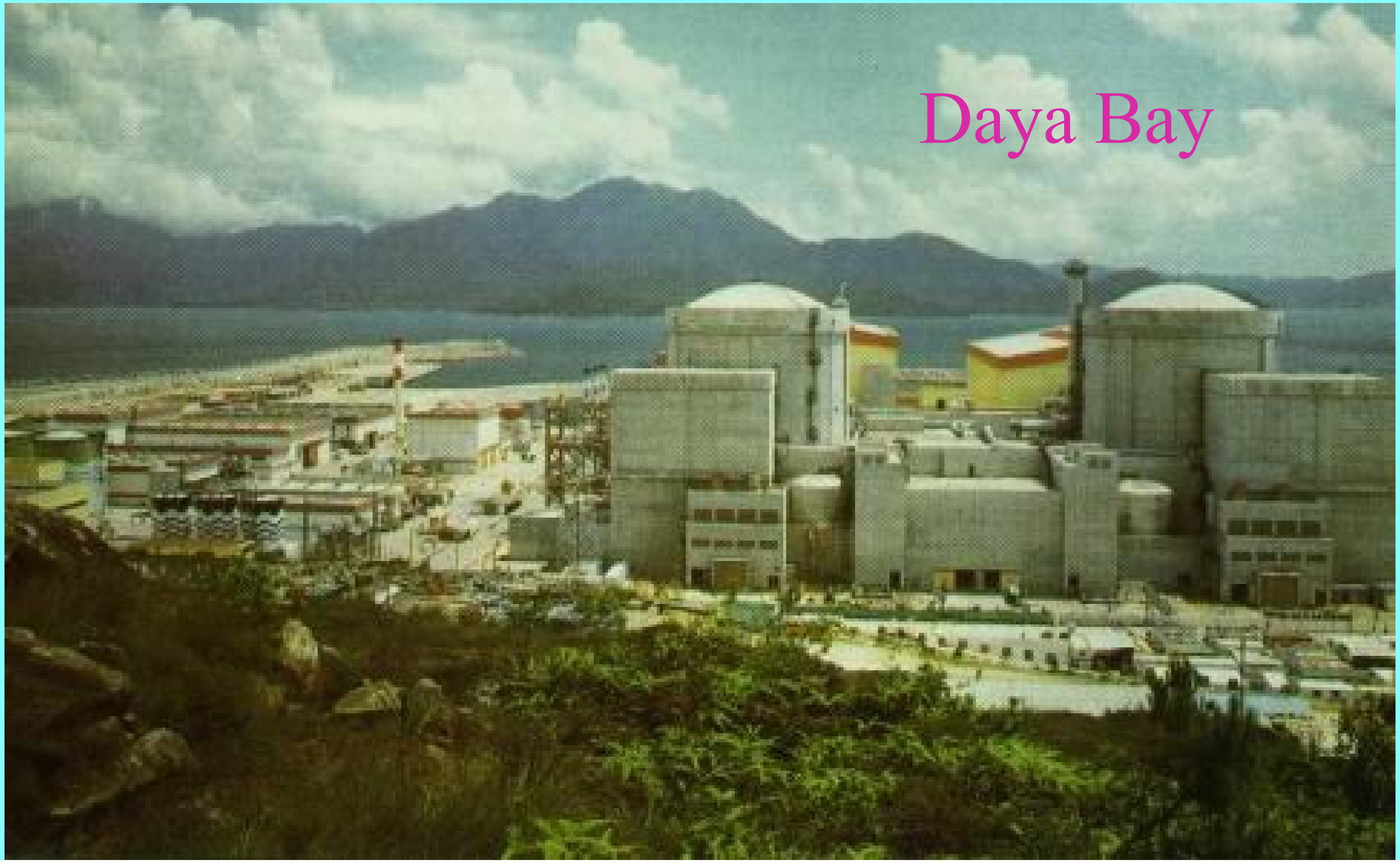
Redundancy !

Redundancy !

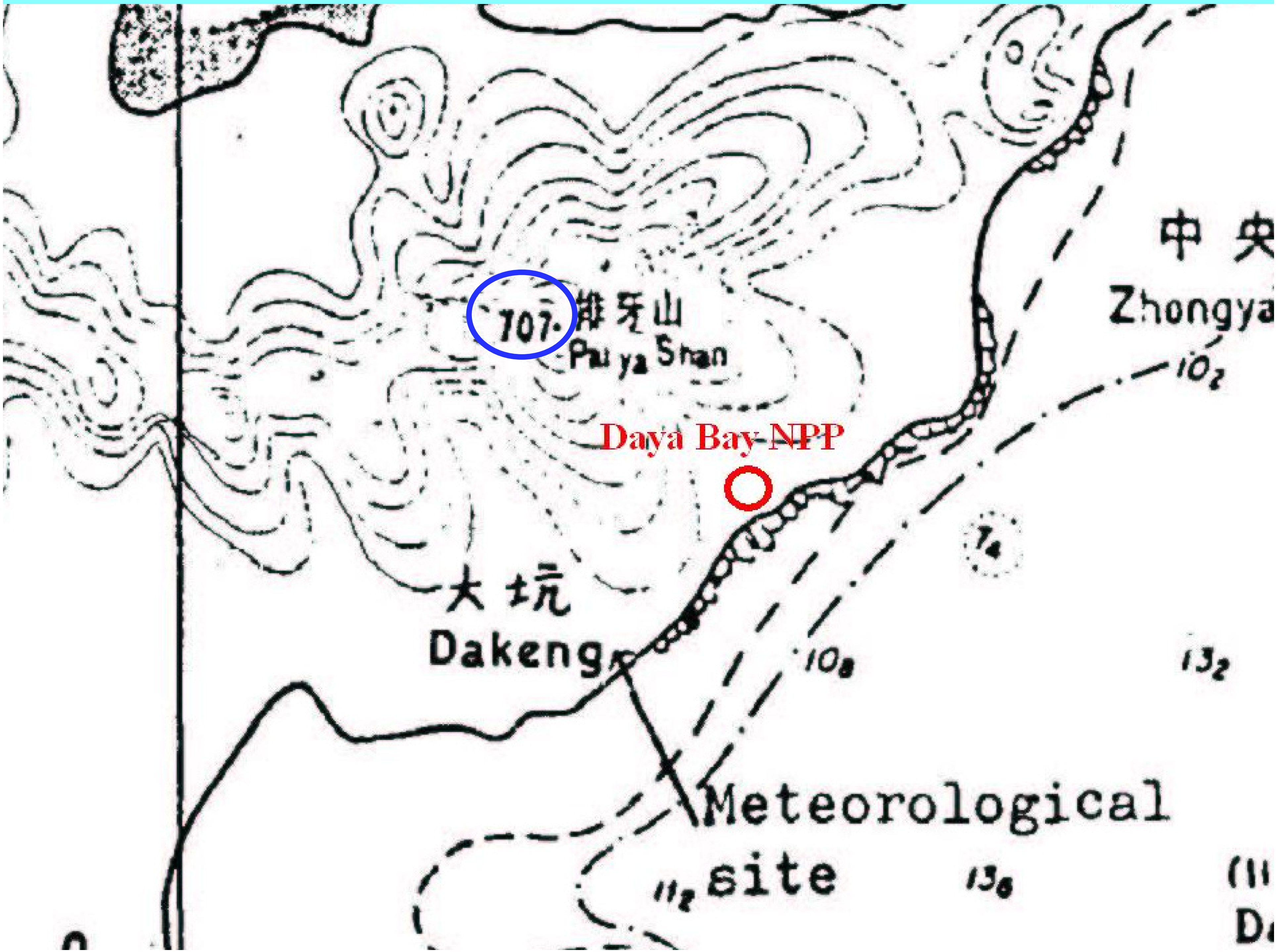
Redundancy !

The site: Daya Bay power plant

- A total of 4 reactor cores in two clusters, each with a thermal power of 2.9 GW, total: 11.6 GW
- Two more cores with a total thermal power more than 6 GW are expected to be online in 2011




Ling Ao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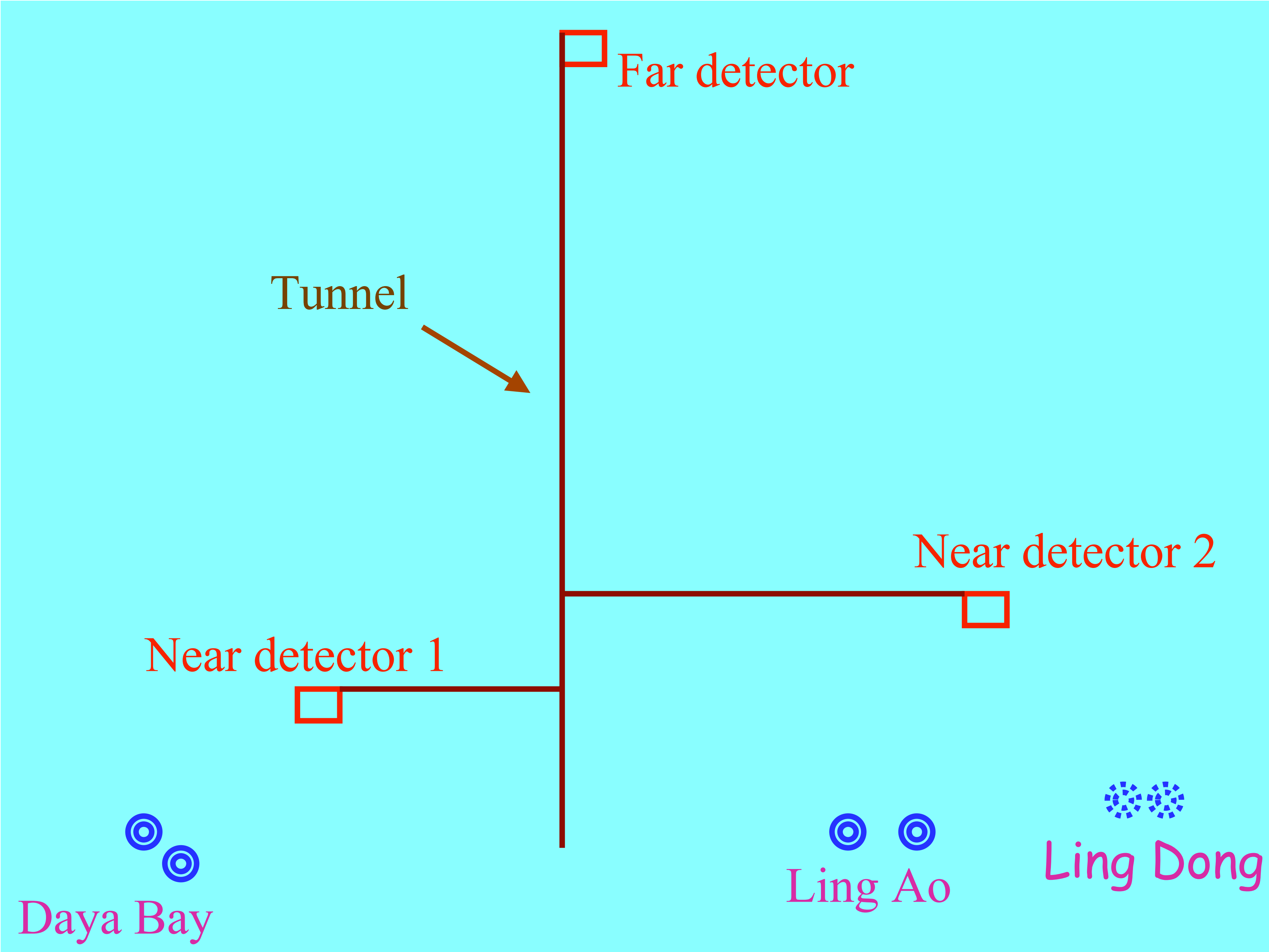
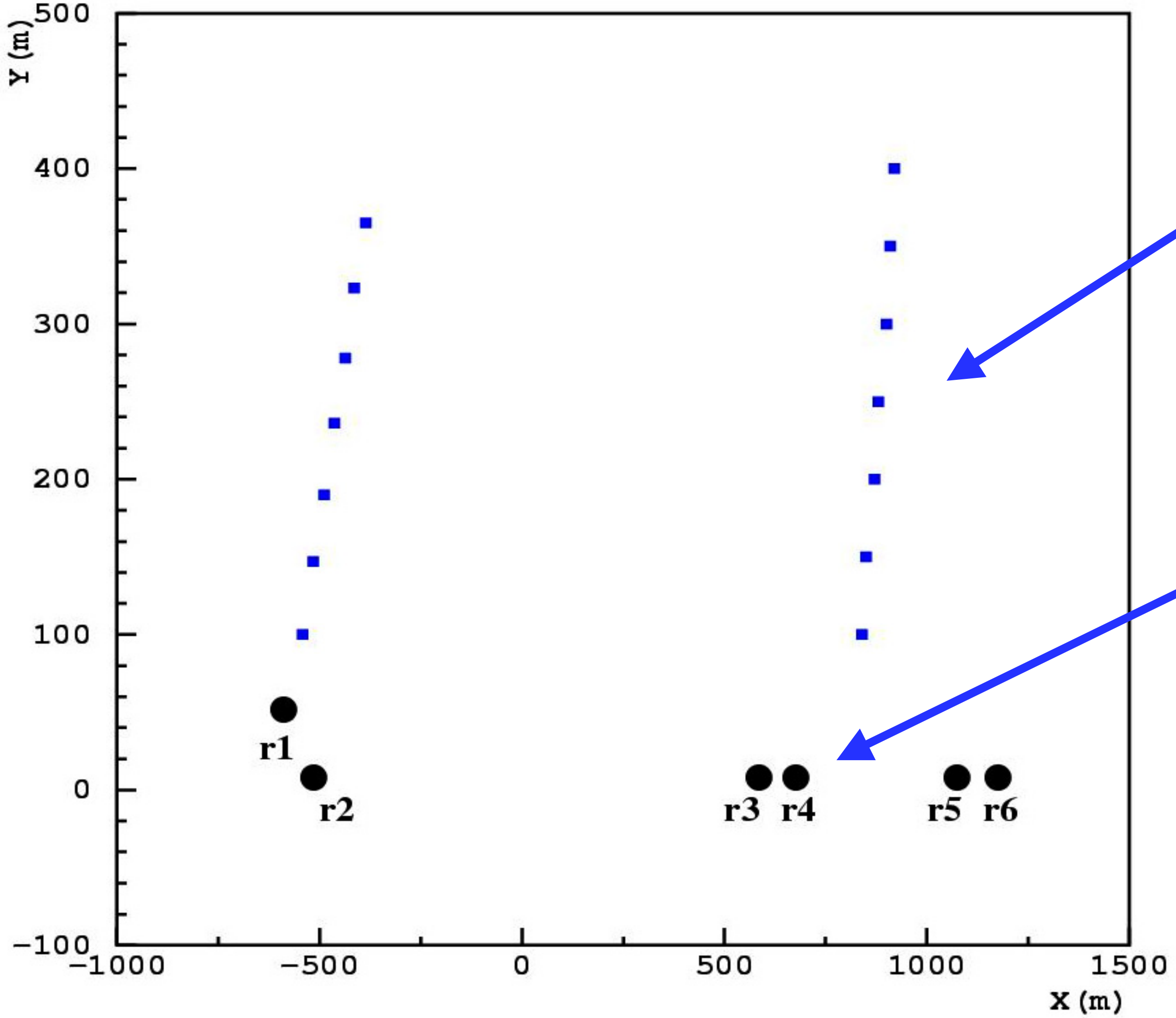
排牙山
Pai ya Shan
Daya Bay NPP
中 央
Zhongya
大坑
Dakeng
Meteorological
site


Far detector
Tunnel
Near detector 2
Near detector 1
Daya Bay
Ling Ao
Ling Dong

Reactor related error

- Use two detectors, far/near to cancel reactor related errors and some of detector related errors
- For one/two reactors, cancellation is exact
- For multiple reactors, cancellation is NOT exact
  - Multiple near detectors may be needed
  - Only uncorrelated errors contribute to final errors
  - Optimum positions can always be found with errors of 0.1-0.2%

Best location for near detectors

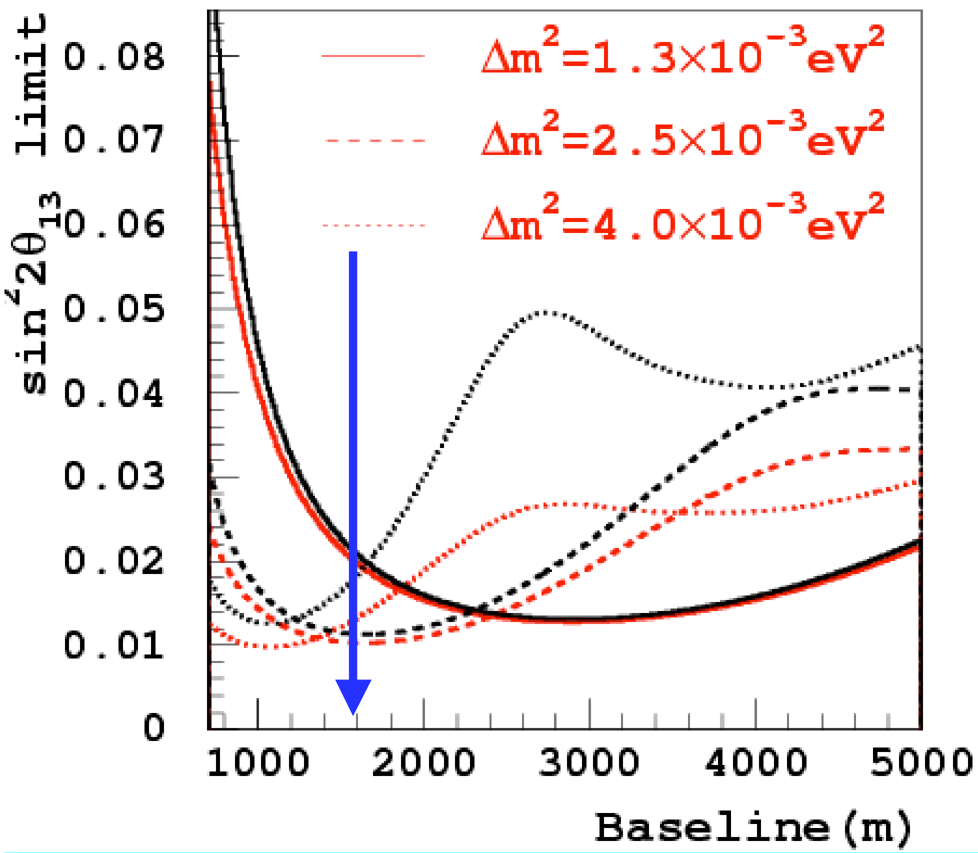


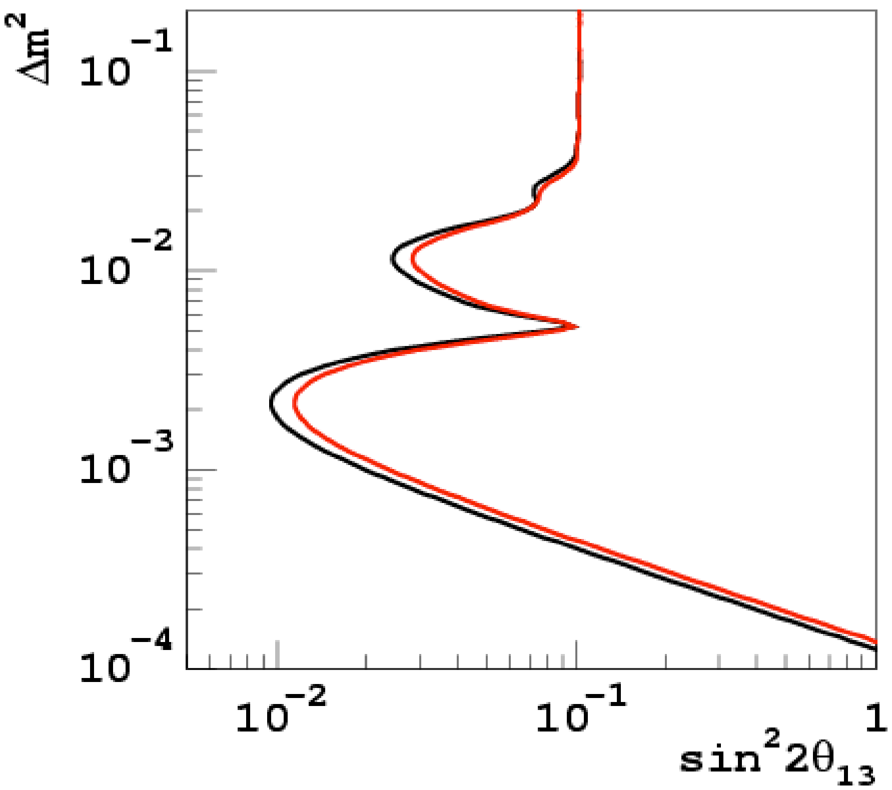
Near detector locations

Reactor core location

Far detector at 1800m from the center of reactor cores

Sensitivity





Near @ 350m

Near @ 150m

0.5% systematic error

4 modules@far, 2 modules@near, 3 years running

w/o stat. Error

with stat. Error

Far @ 1800m, near 350m

Possible staging

- **Phase 0**

  1 module @near

- **Phase I**

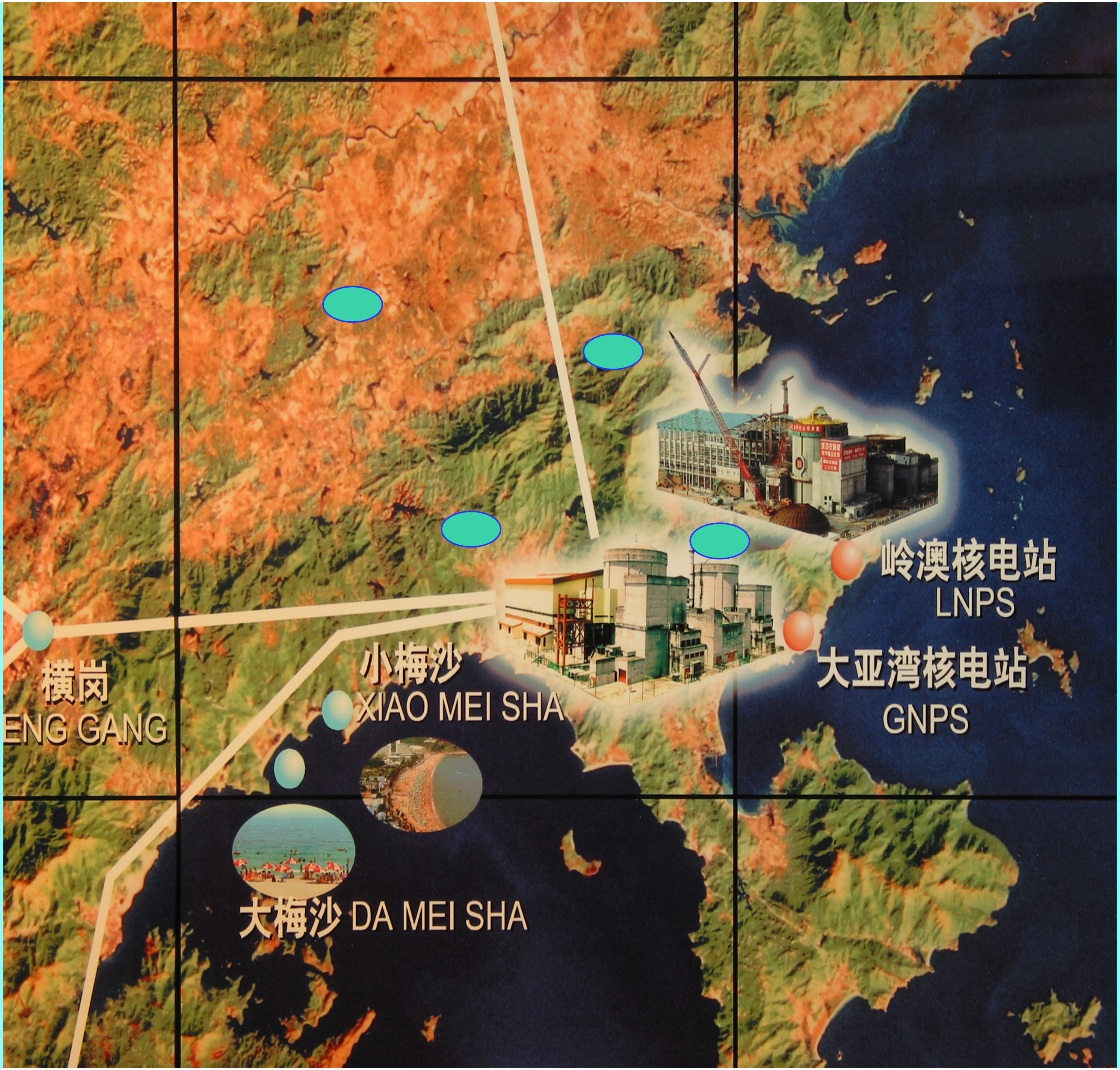
  2 module@near + 4 module@far

- **Phase II**

  2 module@near + 4 module@far +

  8 module@far*2

  ➔ sensitivity 0.5% ?



岭澳核电站
LNPS
大亚湾核电站
GNPS
小梅沙
XIAO MEI SHA
横岗
ENG GANG
大梅沙 DA MEI SHA

Near tunnel entrance
以核养核 滚动发展
建好岭核 再创辉煌
Near detector Daya
Near detector LingAo
Far detector

Currently Proposed sites/experiments

Site (proposal)	Power (GW)	Baseline Near/Far (m)	Detector Near/Far(t)	Overburden Near/Far (MWE)
Angra dos Reis (Brazil)	4.1	300/1300	25/25	60/600
Braidwood (US)	6.5	200/1500	25/50	250/250
Chooz-II (France)	8.4	150/1050	10/10	50/300
Daya Bay (China)	11.6	300/1500	25/50	200/1000
Diablo Canyon (US)	6.4	400/1800	25/50	100/700
Kashiwazaki (Japan)	24.3	300/1300	8.5/8.5	140/600
Krasnoyarsk (Russia)	3.2	115/1000	46/46	600/600

Status of the project(I)

- Chinese Atomic Energy Agency and the Daya Bay nuclear power plant are supportive to the project
- Funding agencies in China are supportive
- R&D funding applied, seeds money from IHEP available
- Conceptual design of the civil construction is finished
- Detector R&D and MC simulation started
- Collaborators in China:
  - **Institute of High Energy Physics**
  - **China institute of atomic energy**
  - **Tsinghua University**
  - **Hong Kong University**
  - **Hong Kong Chinese University**

Status of the project(II)

- Two workshops dedicated to this project
- People who are involved:

K.B. Luk, Berkeley;

B.L. Young, K. Whistnat, Iowa State;

J. Peng, Urbana-Champaign;

K. Lau, Houston

- Collaboration on R&D

S. Freedman, K.B. Luk, R. Kadel, K. Heeger

----- Berkeley

R. McKeown ------ Caltech

Status of the project(III)

- Cost estimate
  - Civil construction ~ US$ 6M
  - Detector ~ US$ 6M
- Schedule
  - 2004-2005 R&D, engineering design, secure funding
  - 2006-2007 construction
  - 2008 running

We propose to have the next meeting in Hong Kong

Organizers:

Hong University,

Chinese University of Hong Kong

IHEP

A visit to Daya Bay NPP with be organized

Summary

- Measuring $\mathrm{Sin}^2 2\theta_{13}$ is a very important experiment
- Errors from from reactor well under control: Near vs Far (~ 0.2%)
- Errors from backgrounds: just need "enough" shielding and go deep (~ 0.2%)
- Errors from detector: hope to be ~ 0.4%
- Daya bay power plant is one of the best site

$\mathrm{Sin}^2 2\theta_{13}$ experiment at 0.5% level is possible !

Let's do it !!!