Reactor Neutrino Experiments

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Hue, 2011 BCVSPIN

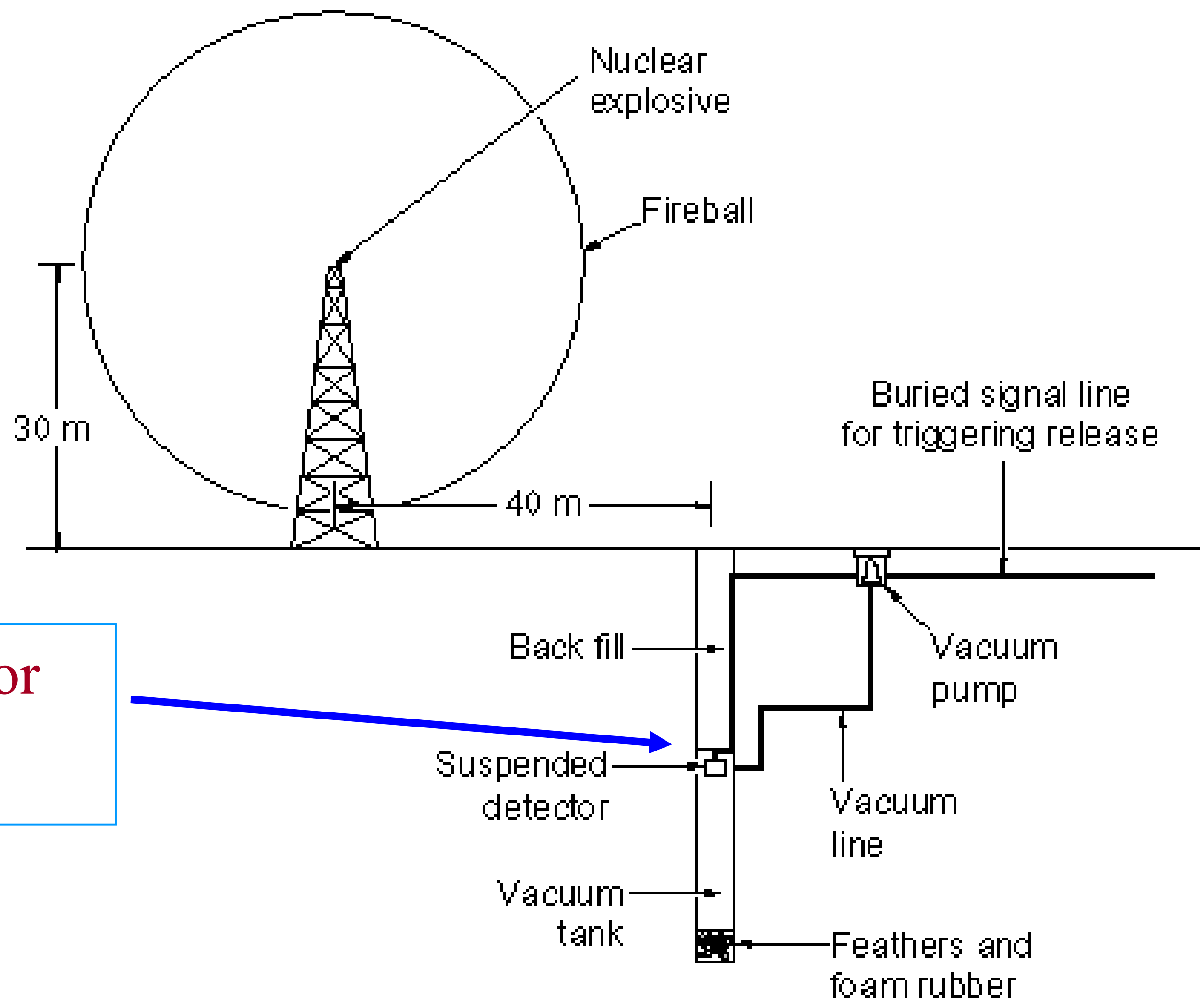
Outline

- History
- Fundamentals
- Current experiments
- Future prospects

- ***Reines's proposal: use nuclear bombs to detect neutrinos***
- ***Fermi suggested to replace bombs by reactors***

Inverse-beta decays:

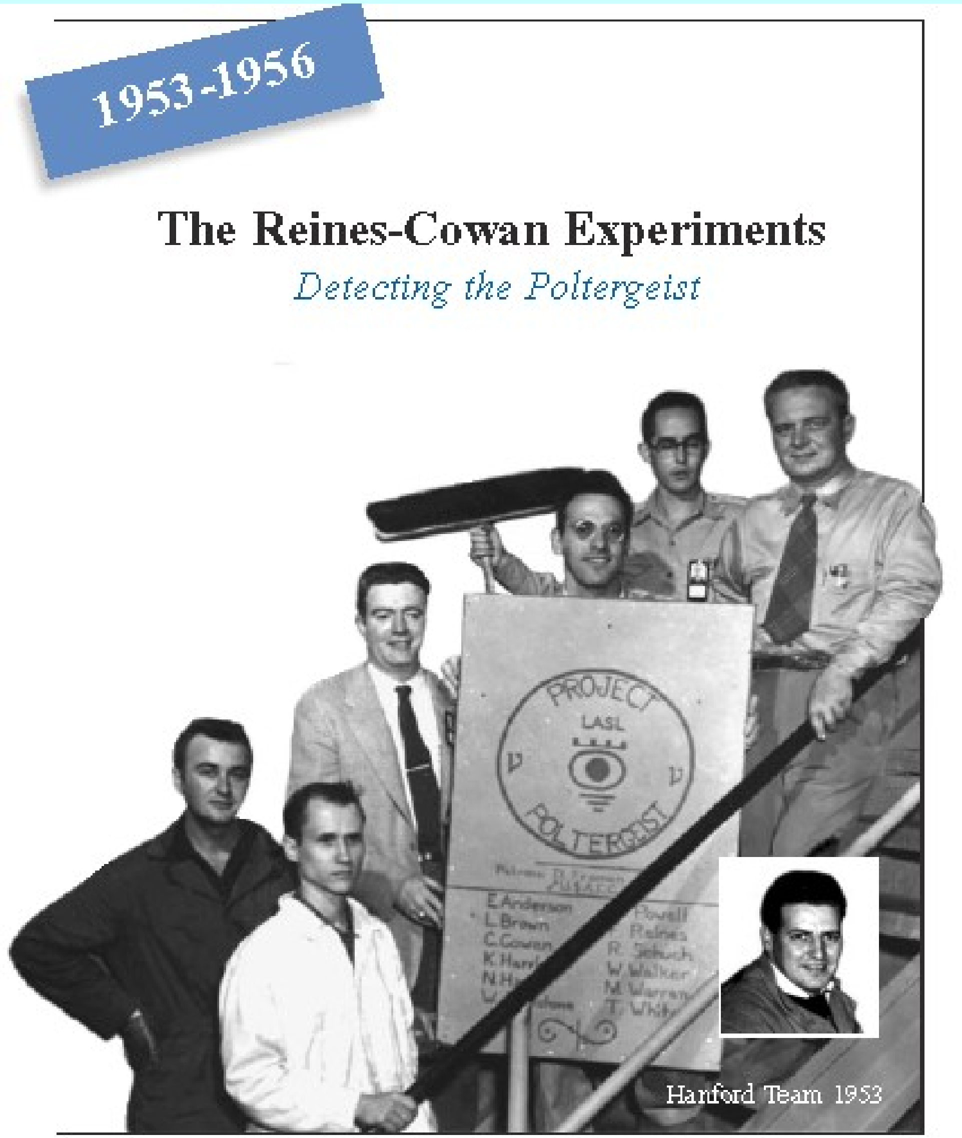
$$\bar{\nu}_e + p \quad e^+ + n$$



$1 m^3$ liquid scintillator

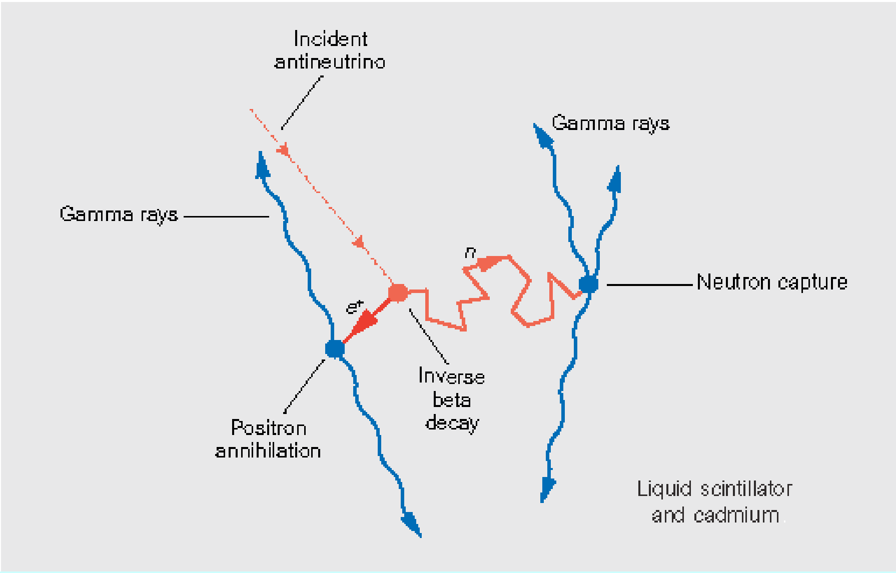
8 2" PMTs

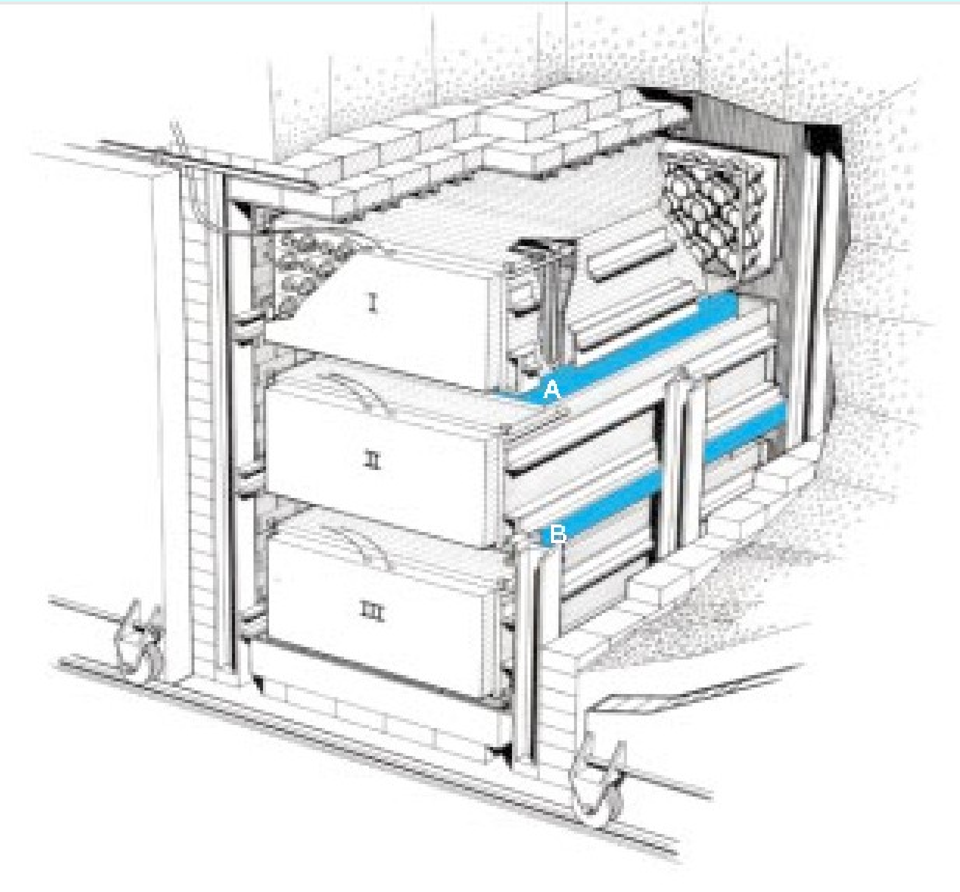
Reines experiments



Savannah River experiment

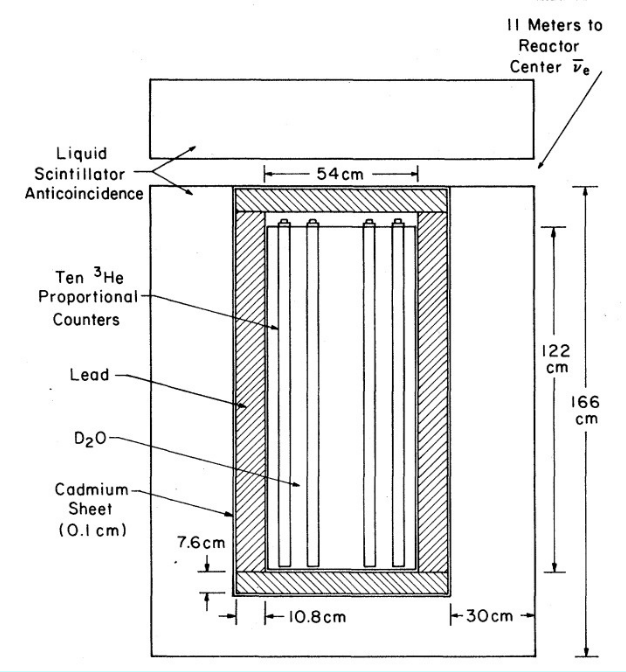
- Anti-coincidence detector to veto cosmic backgrounds
- Detector:
  - A/B: 200 l $CdCl_2$
  - I/II/III: 1400 l LS
  - 110 PMT
- 12 m overburden





Direct observation of neutrinos
95 noble prize

Savannah River experiment ----
"Observation of neutrino oscillation"



- ^{3}He neutron detectors immersed in 268 kg D_2O tank placed 11.2m m from reactor :

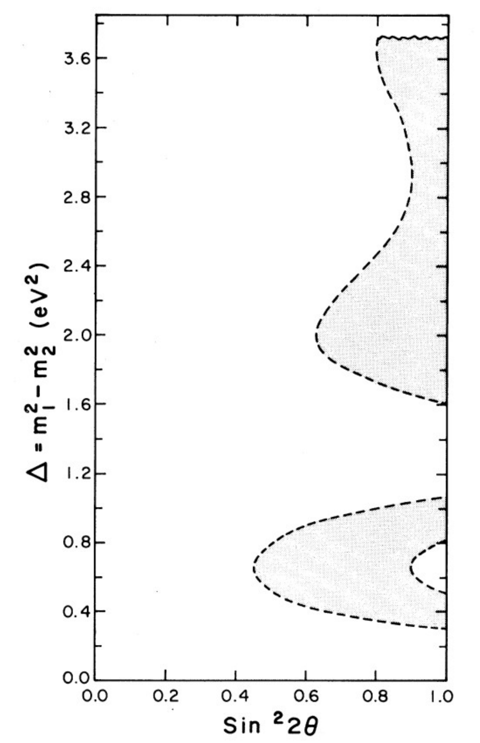
$$\bar{\nu}_e + d \begin{cases} n + n + e^+ & (\text{ccd}) \\ n + p + \bar{\nu}_e & (\text{ncd}) \end{cases}$$

- Neutron signal:

  n+^{3}He → p + ^{3}H + 764 keV

- Single/double neutron rate ➔ ccd/ncd
- Observed R ≡ $r^{exp}_{ccd/ncd} / r^{theo}_{ccd/ncd}$

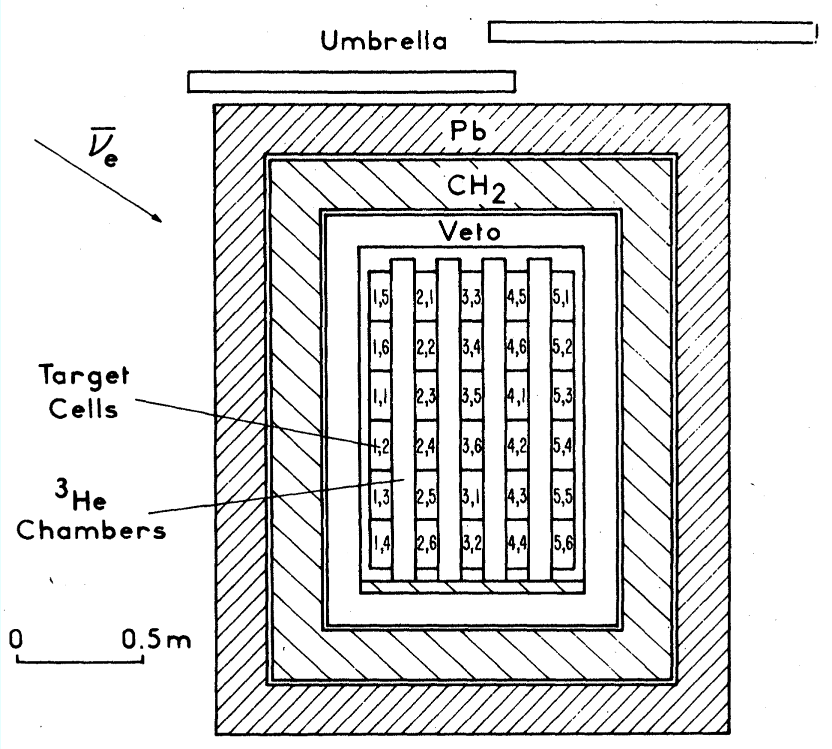
  = 0.40 ± 0.22

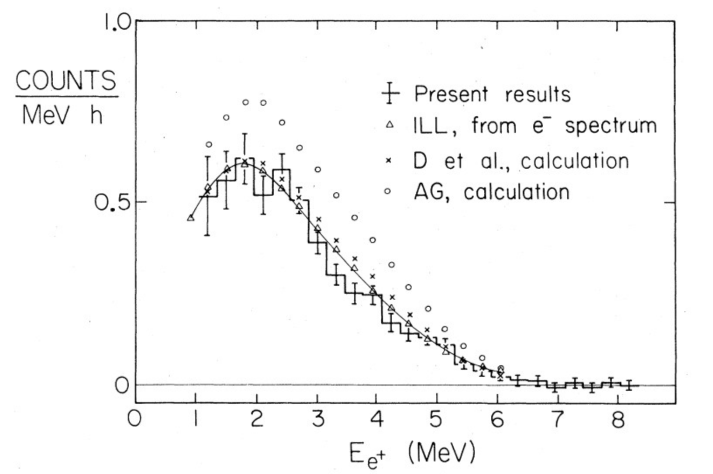


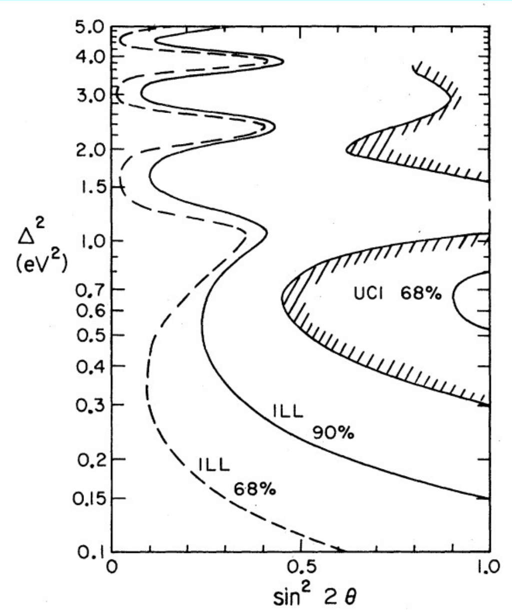
F. Reines et al., PRL 45(1980) 1307

ILL : first debate

- 377 l Liquid scintillator detector placed at 8.7m from reactor
- Neutrons: by 4 ^{3}He planes in between LS cells(τ =150 μ s)
- Techniques used until now: shielding, veto, background, on/off comparison, efficiency, spectrum, stability, etc.
- Source: P. Vogel PRC19(1979)2259
- N_{exp}/N_{theo}.= 0.89± 0.04(stat.)± 0.14(syst.)







F. Boehm et al., PLB97(1980)310
H.Kwon et al., PRD24(1981)1097

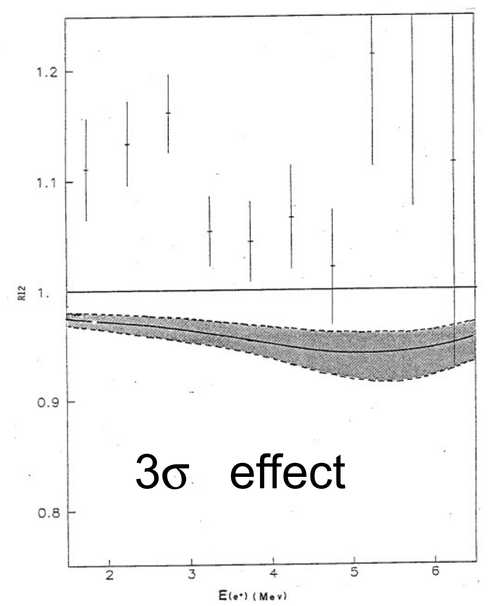
Bugey : a new claim

- Modules made of 98 SS cells, each of 0.85 m long, 8.5 cm × 8.5 cm in cross section, filled with PC based liquid scintillator doped with 0.15% ^{6}Li, and viewed by two PMTs at both ends
- Neutron signal (τ = 30 μs) :

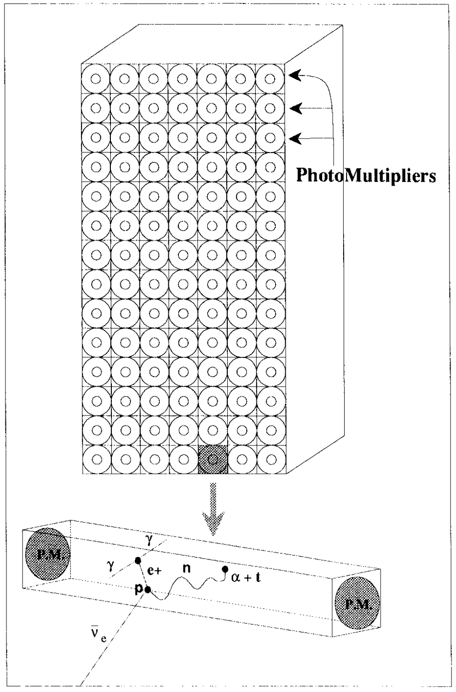
  $n + {}^6Li \rightarrow {}^4He + {}^3H + 4.8 MeV$

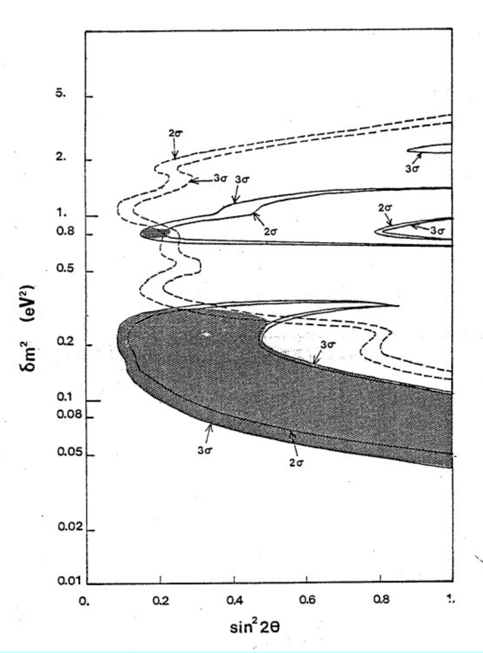
  E_{vis}= 0.53 MeV +

  PSD $Q_{delayed}/Q_{total}$
- Compare neutrino rate at 14 and 18 m from reactors



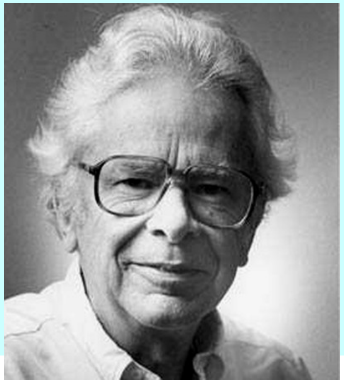
J.F. Cavaignac et al, Phys. Lett. B 148(1984)387



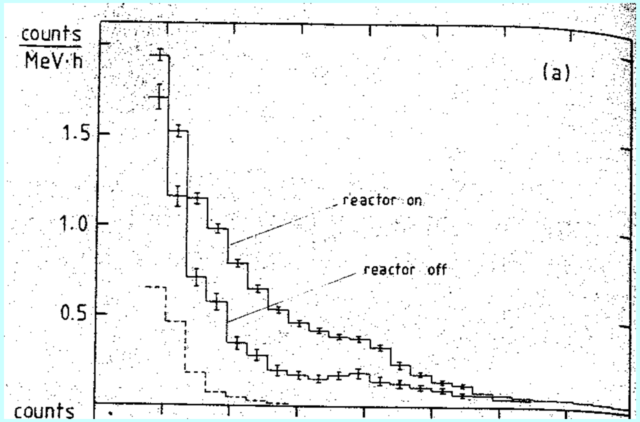


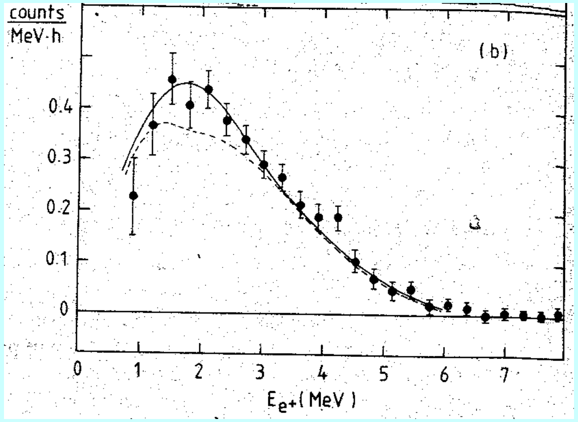
Negative results again by F. Boehm: Goesgen

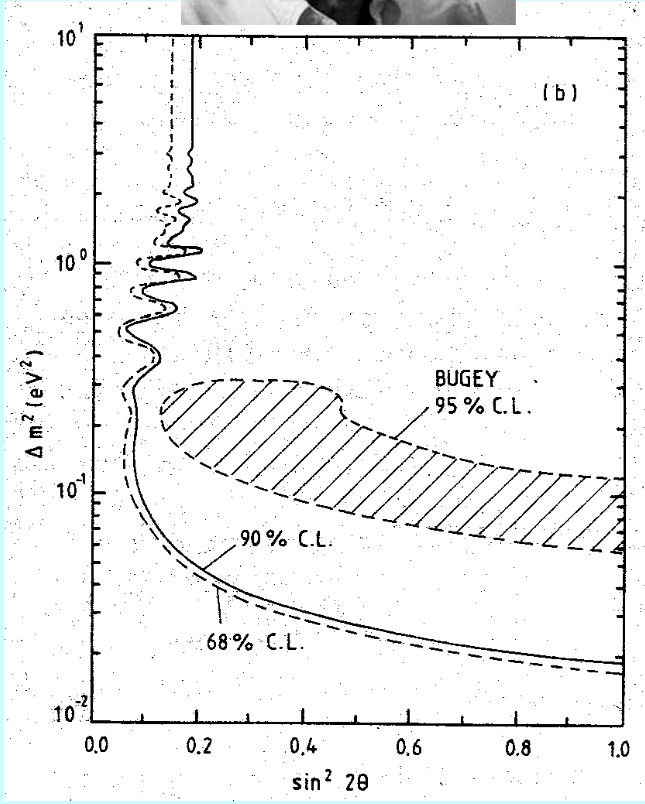
- Nearly the same Detector as ILL
- Baseline: 37.9, 45.9, 64.7
- Good agreement with expectation: rate and spectrum



Distance (m)	Ratio	Statistical error	Individual systematic error	Common (correlated) systematic error
37.9	1.030	±0.019	±0.015	±0.064
45.9	1.056	±0.018	±0.015	±0.064
64.7	0.987	±0.037	±0.030	±0.064





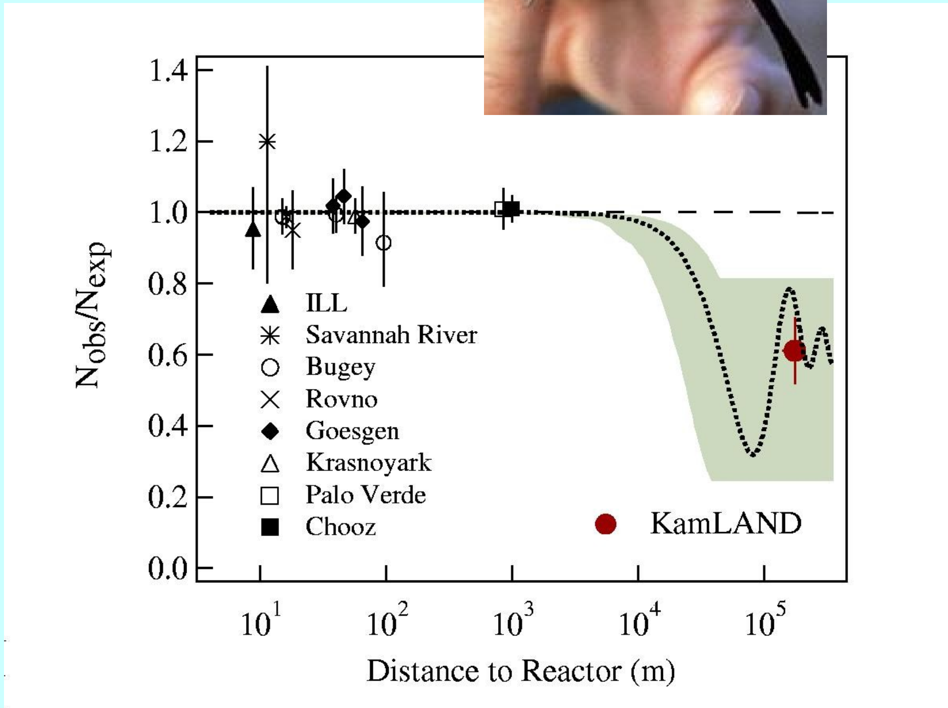


V. Zacek et al., PLB164(1985)193

A new era: Atmospheric neutrino anomaly

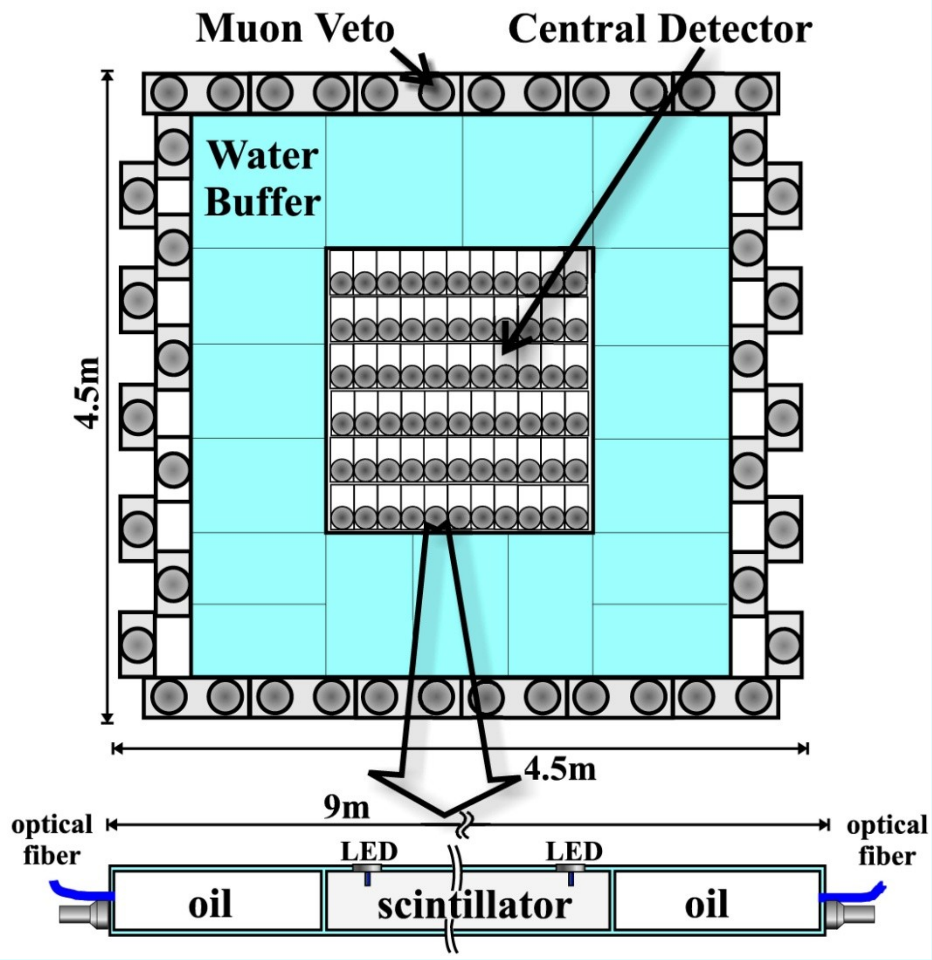
- Atmospheric neutrino results stimulate new experiments
- San Onofre ➔ Palo Verde (early 90’s ➔ 00’s)
  - From Goesgen
  - Difficult stories (California Gnatcatcher)
- Chooz (early 90’s)
  - From Bugey+Russians
  - a successful story
- New techniques:
  larger detector,
  Gd-LS,
  HEP software &
  analysis method …

蚋鹟



Each experiment will be introduced shortly

Palo Verde



Palo Verde

32 mwe shielding

12 ton, Gd loaded, scintillating target

3 reactors: 11.6 GW

Baselines 890 m and 750 m

Expected rate of ~20 evts/day

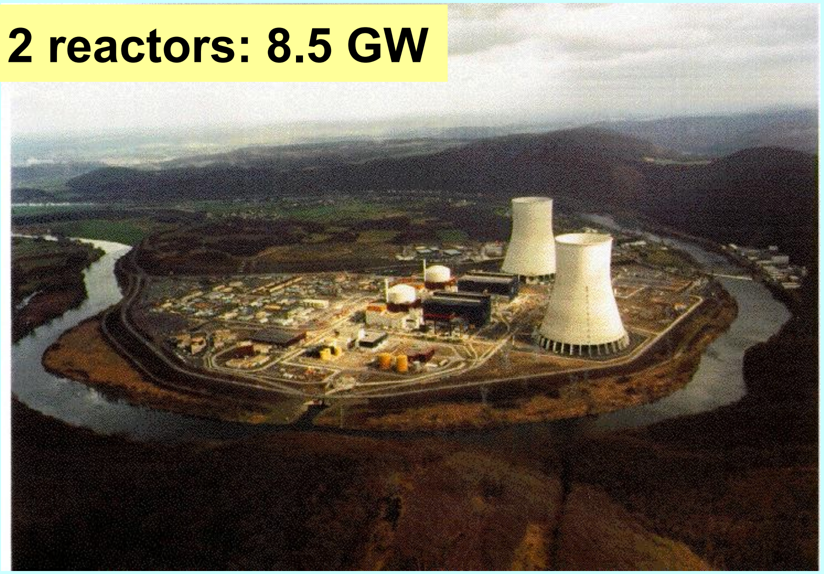
Efficiency ： ~10%

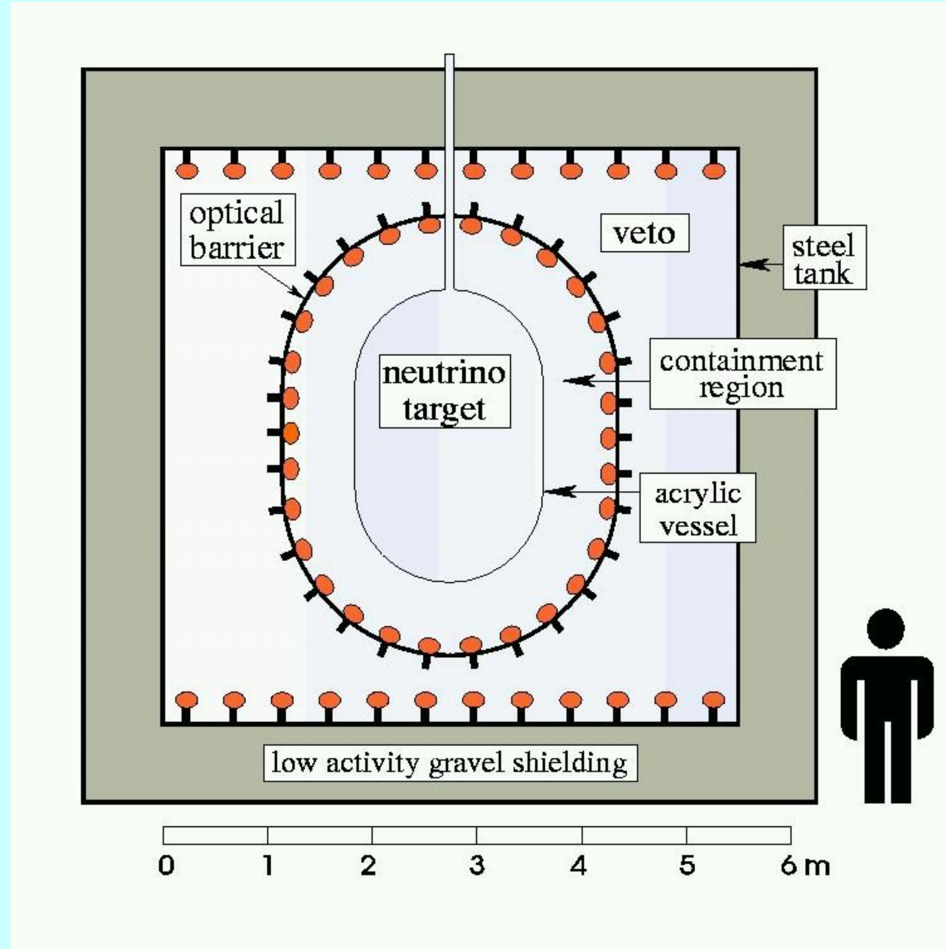
Background ： corr. ~15/day

uncorr. ~7/day

Chooz

2 reactors: 8.5 GW





- 5 ton, Gd loaded scintillator
- 300 mwe shielding
- Baselines 1115 m and 998 m
- Expected signal ~25 evts/day
- Efficiency : 70%
- Background : corr. 1/day
  uncorr. 0.5/day

KamLAND

1000t scintillators

Shielding:

3000 MWE/3m Water

180 km baseline

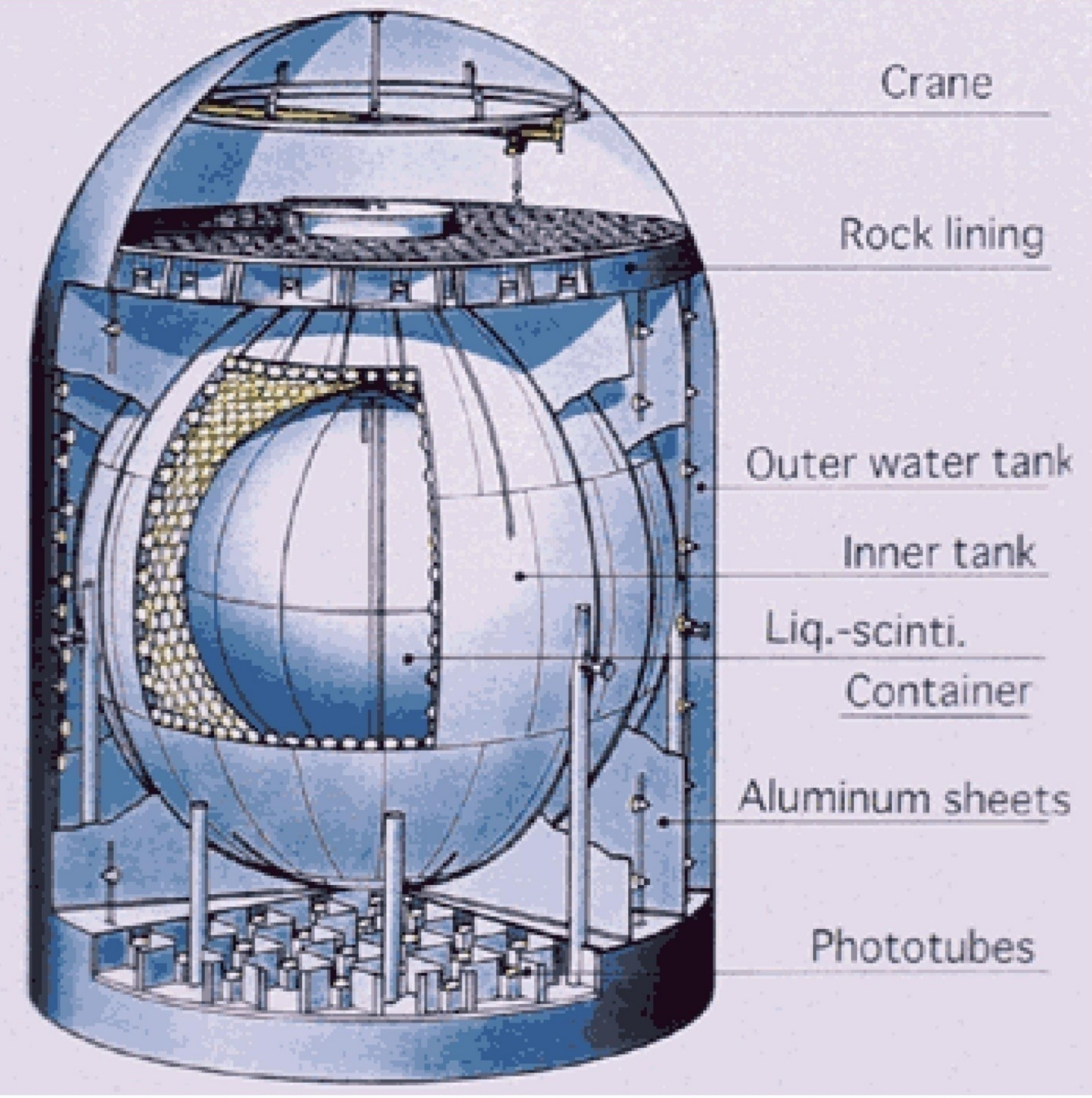
Signal: ~0.5/day

Eff. ~40%

BK:

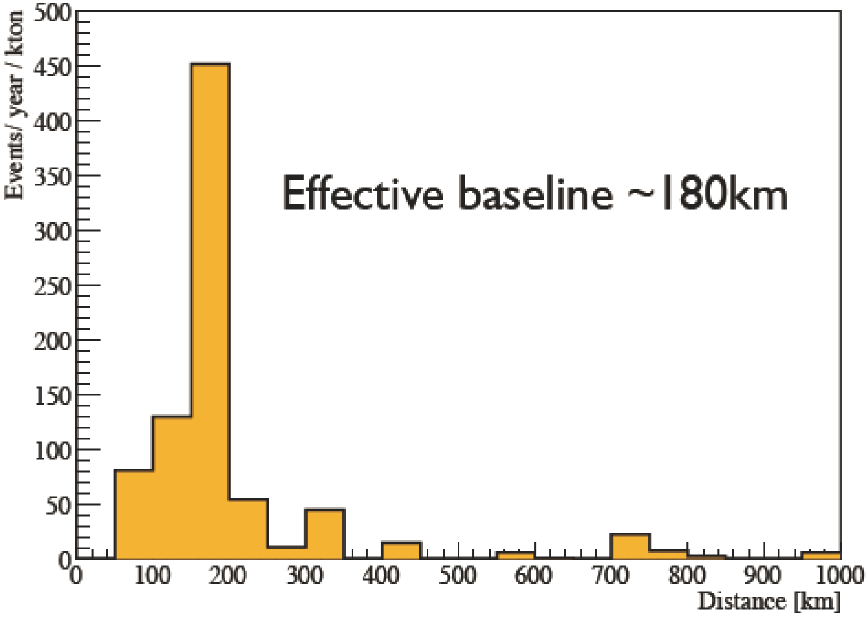
corr.: ~0.001/day

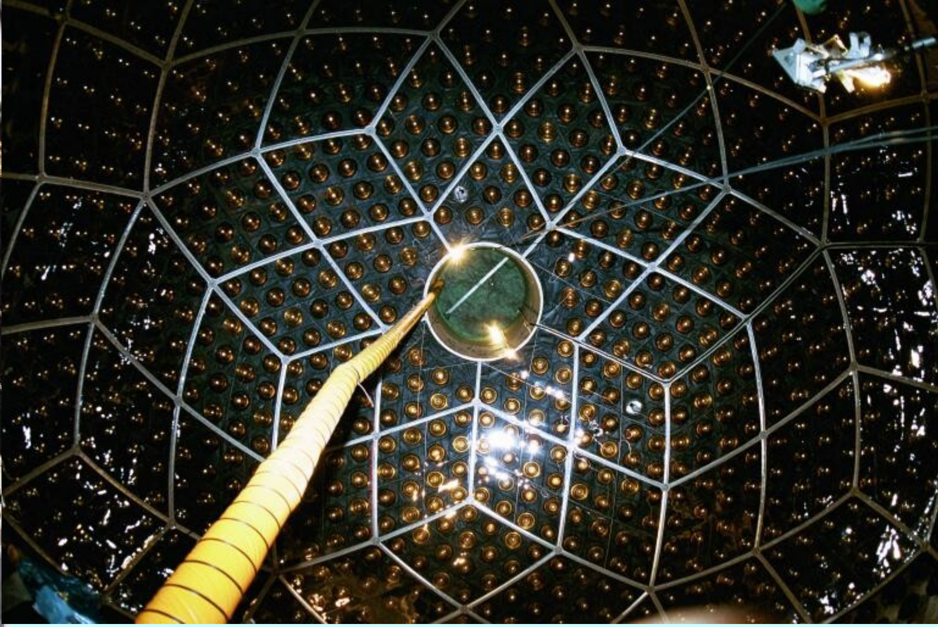
uncorr. ~0.01/day

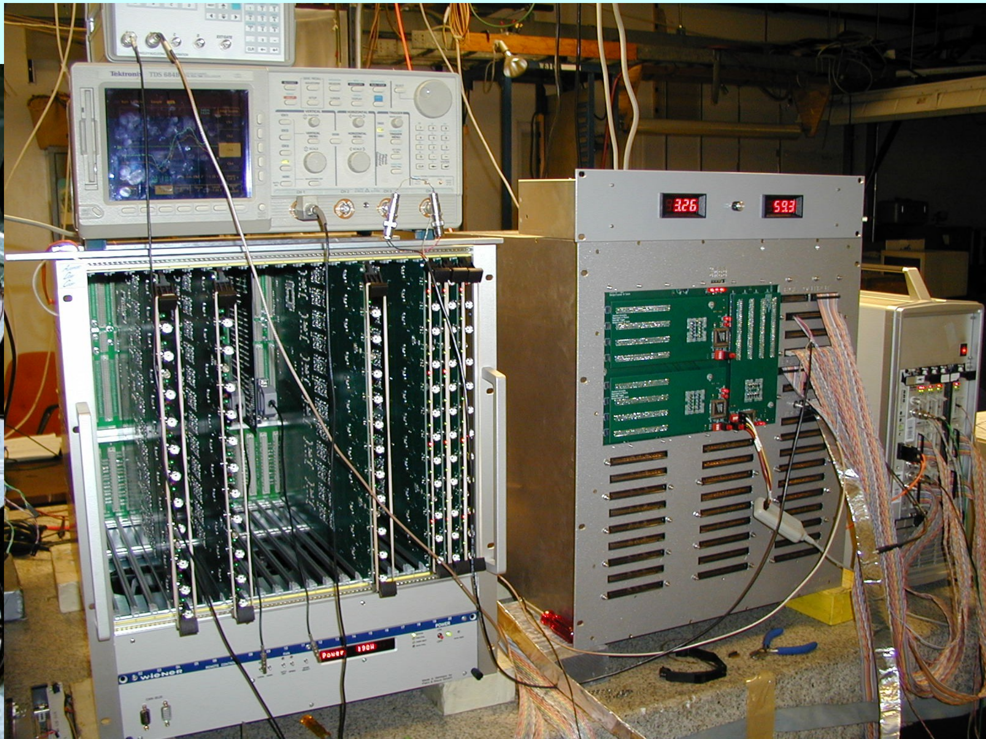


Neutrino reactors near by Kamioka

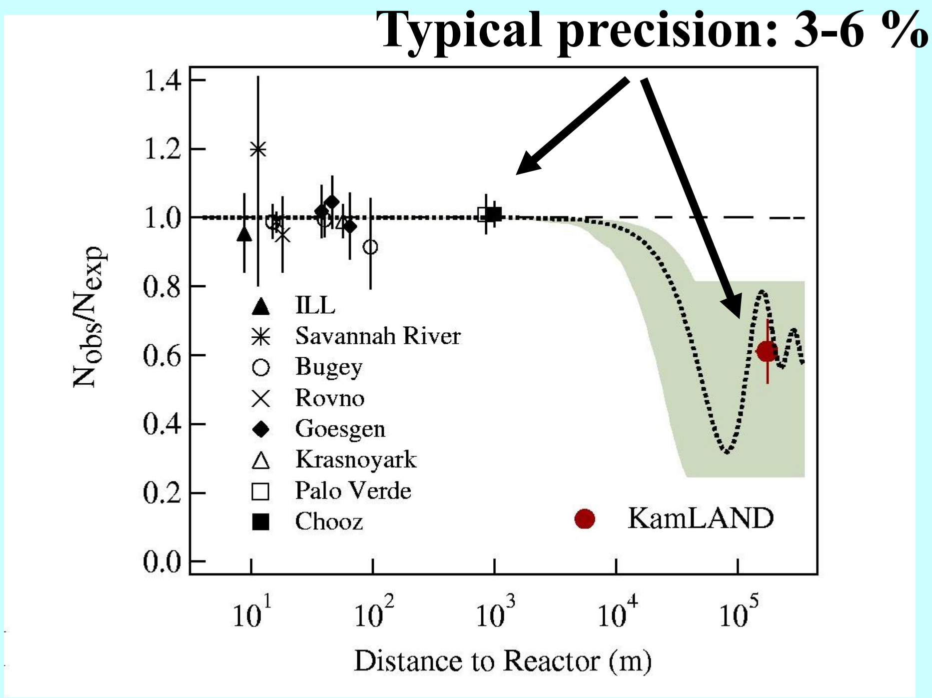
70 GW (7% of world total) is generated at 130-220 km distance from Kamioka






Tektronix
3.26
59.3

Reactor Experiment: comparing observed/expected neutrinos:



Precision of past experiments:

- Reactor power : ~1%
- ν spectrum : ~0.3%
- Fission rate : ~ 2%

- Backgrounds : ~1-3%

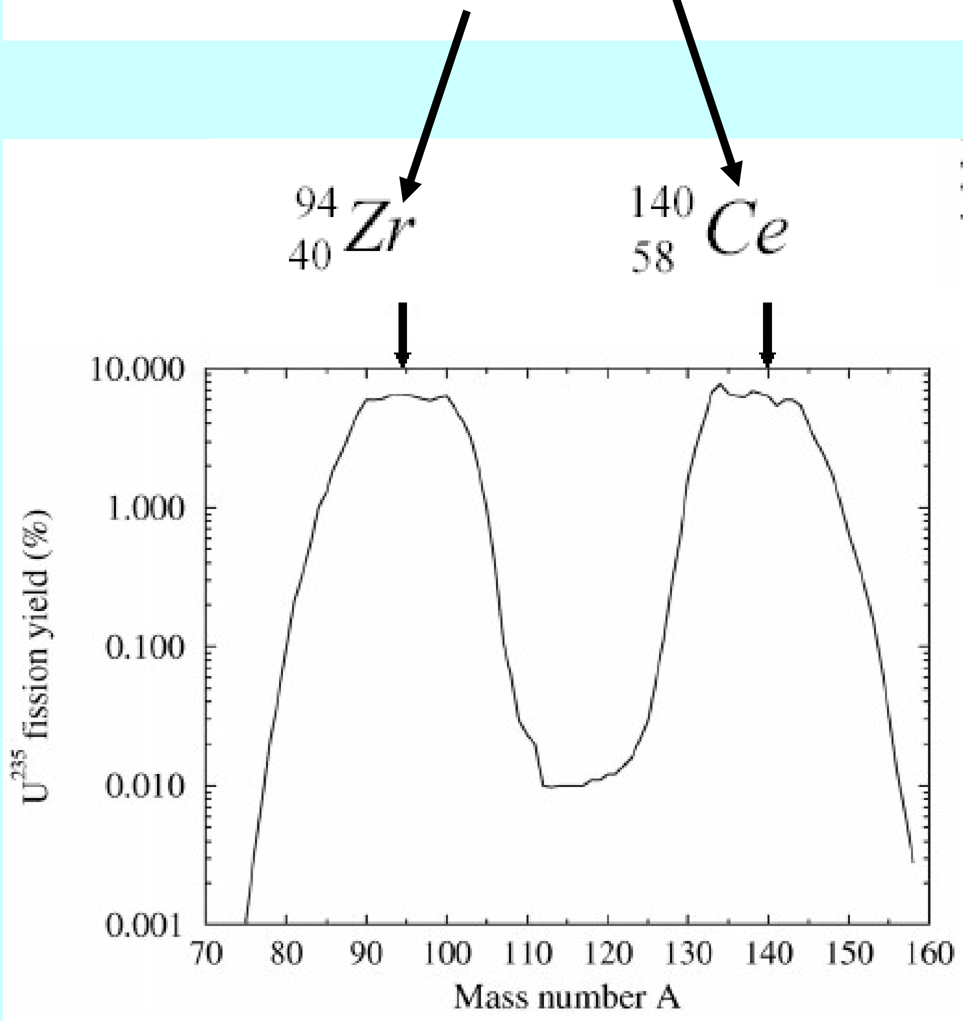
- Target mass : ~1-2%
- Efficiency : ~2-3%

Fundamentals of reactor neutrino experiments

- Source: expectation and uncertainties
- Neutrino detection
- Backgrounds

How Neutrinos are produced in reactors ?

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



The most likely fission products have a total of 98 protons and 136 neutrons, hence on average there are 6 n which will decay to 6p, producing 6 neutrinos

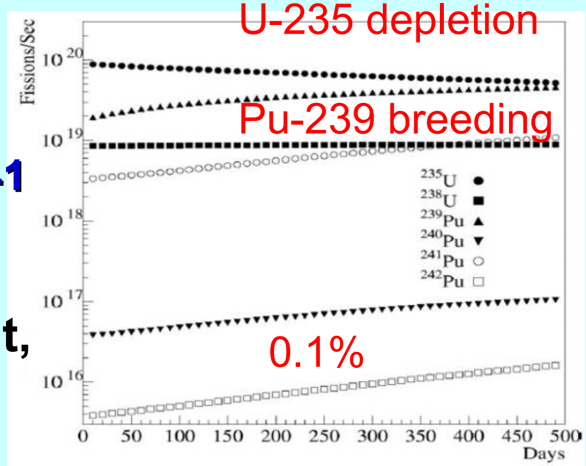
Neutrino flux of a commercial reactor with 3 $GW_{thermal}$: 6×10^{20} / s $\bar{\nu}$

Reactor Neutrino Flux at a Glance

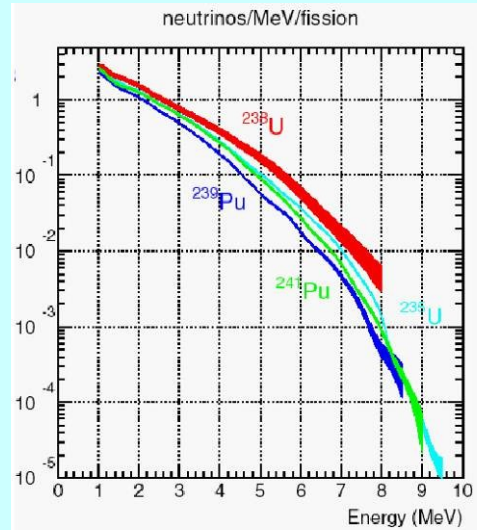
- Using PWR (Pressurized Water Reactor) as examples in the following.

U-235, U-238
Pu-239, Pu-241

Isotope evolvement, Palo Verde



X

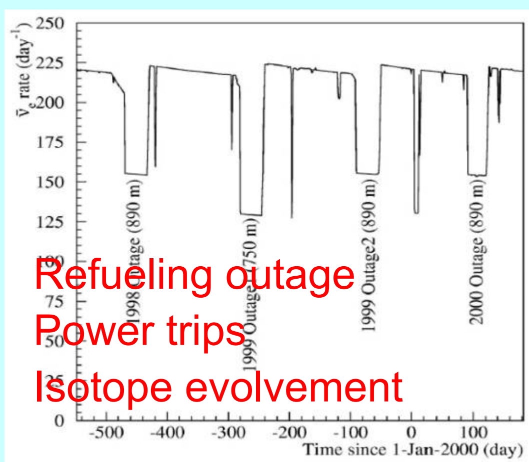


Neutrino spectra, ILL

More neutrinos from a U-235 fission than Pu-239

Neutrino rate,

Palo Verde



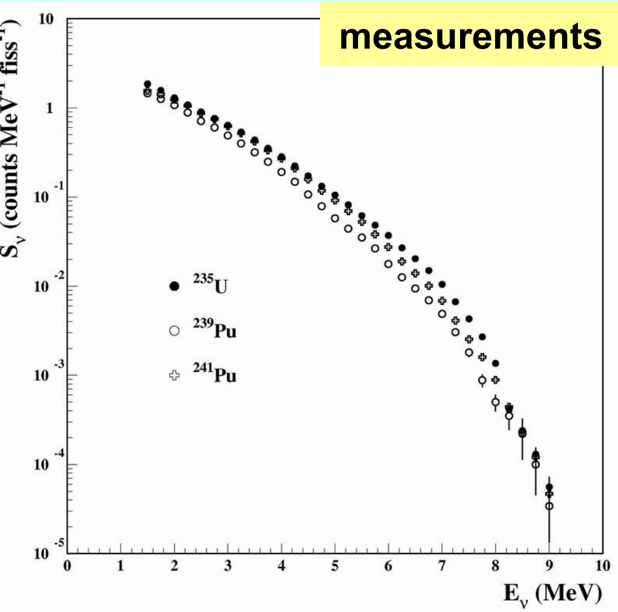
Neutrino Flux $$S(E_\nu) = \sum_i^{istopes} f_i S_i(E_\nu)$$

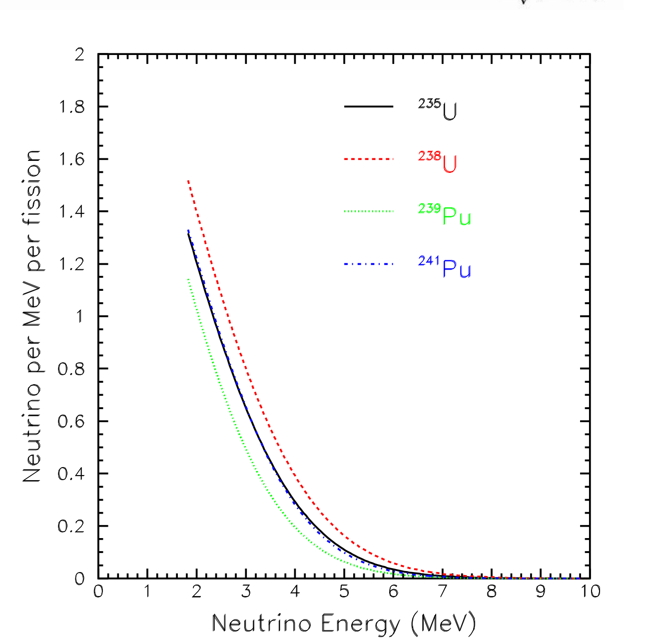
If normalized to the thermal power:

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

$$W_{th} = \sum_i f_i e_i \,, \qquad F = \sum_i f_i$$

Neutrino flux: ILL model and beyond





- **The method:**
  - Obtain the Fission rates of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
  - Use measured β spectrum of ^{235}U, ^{239}Pu, ^{241}Pu

    K. Schreckenbach et al., PLB160(1985)325
    A.A. Hahn et al., PLB218(1989)365
  - Use calculated β spectrum of ^{238}U

    P. Vogel et al., PRC 24(1981)1543
  - Convert β spectra to ν spectra

    P. Vogel et al., PRC 76(2007) 025504
    - Inclusive A/Z Corrections
- **A fitted empirical spectrum:**

  $e^{(-0.8747-0.2171E-0.0888E2)}$
- **Recent development: ➔ + ~3%**
  - Sum up of 800 isotopes and 10000 branches and taking into account off-equilibrium effects, using MURE/BESTIOLE

    T.A. Mueller et al., arXiv[hep-ex] 1101.2663

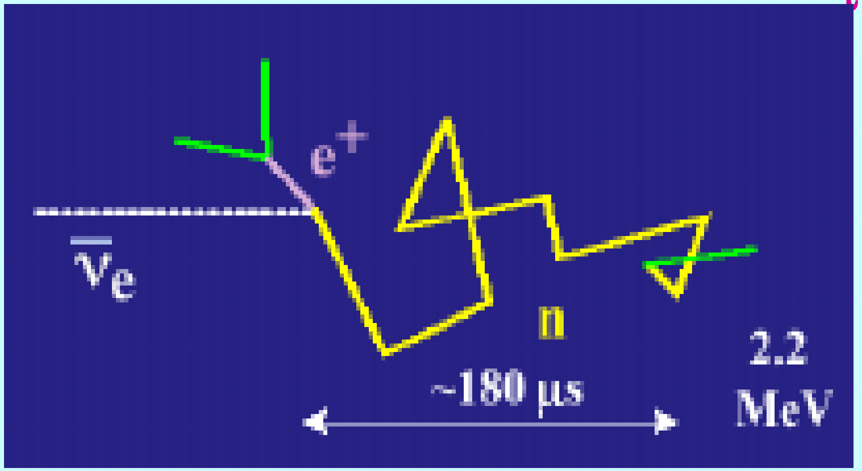
Detector

- Liquid scintillators is almost exclusively used
  - Being both the target and detector
  - Proton rich material
  - Good energy resolution
  - Easy handling for large volume
  - Relatively Cheap
- LS is often doped to reduce neutron capture time and to increase γ energy ➔ to reduce backgrounds ➔ technique challenges: stability and transparency
- Large size: ~ 100 kg ➔ 1000 t ➔ ?
- Often need substantial shielding ➔ underground

Neutrino Detection:
Inverse-β reaction in liquid scintillator

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

$\tau \approx 180$ or 28 μs(0.1% Gd)



n + p → d + γ (2.2 MeV

n + Gd → Gd* + γ (8 MeV

Neutrino Event: coincidence in time, space and energy

Neutrino energy:

$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV *1.8 MeV*: **Threshold**

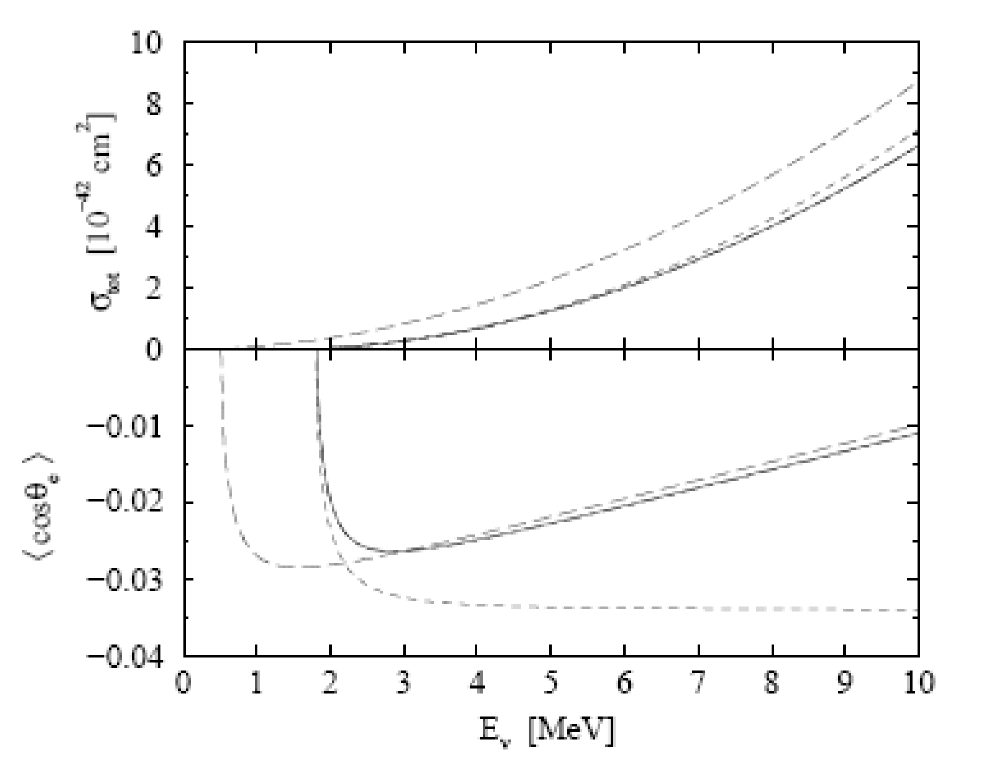
Cross sections on target

At tree level, for $\bar{\nu}_e + p \quad e^+ \; + n$

$$\sigma_{\rm tot}^{(0)} = \frac{2\pi^2/m_e^5}{f^R_{\rm p.s.}\,\tau_n} E_e^{(0)} p_e^{(0)} = \frac{G_F^2 \cos^2\theta_C}{\pi} \left(1+\Delta^R_{\rm inner}\right)\left(f^2+3g^2\right) E_e^{(0)} p_e^{(0)},$$

$$\frac{{\rm d}\sigma}{{\rm d}\cos\theta} \simeq 1 + v_e a(E_\nu)\cos\theta\,,$$

$$a^{(0)} = \frac{f^2-g^2}{f^2+3g^2} \simeq -0.10\,,$$

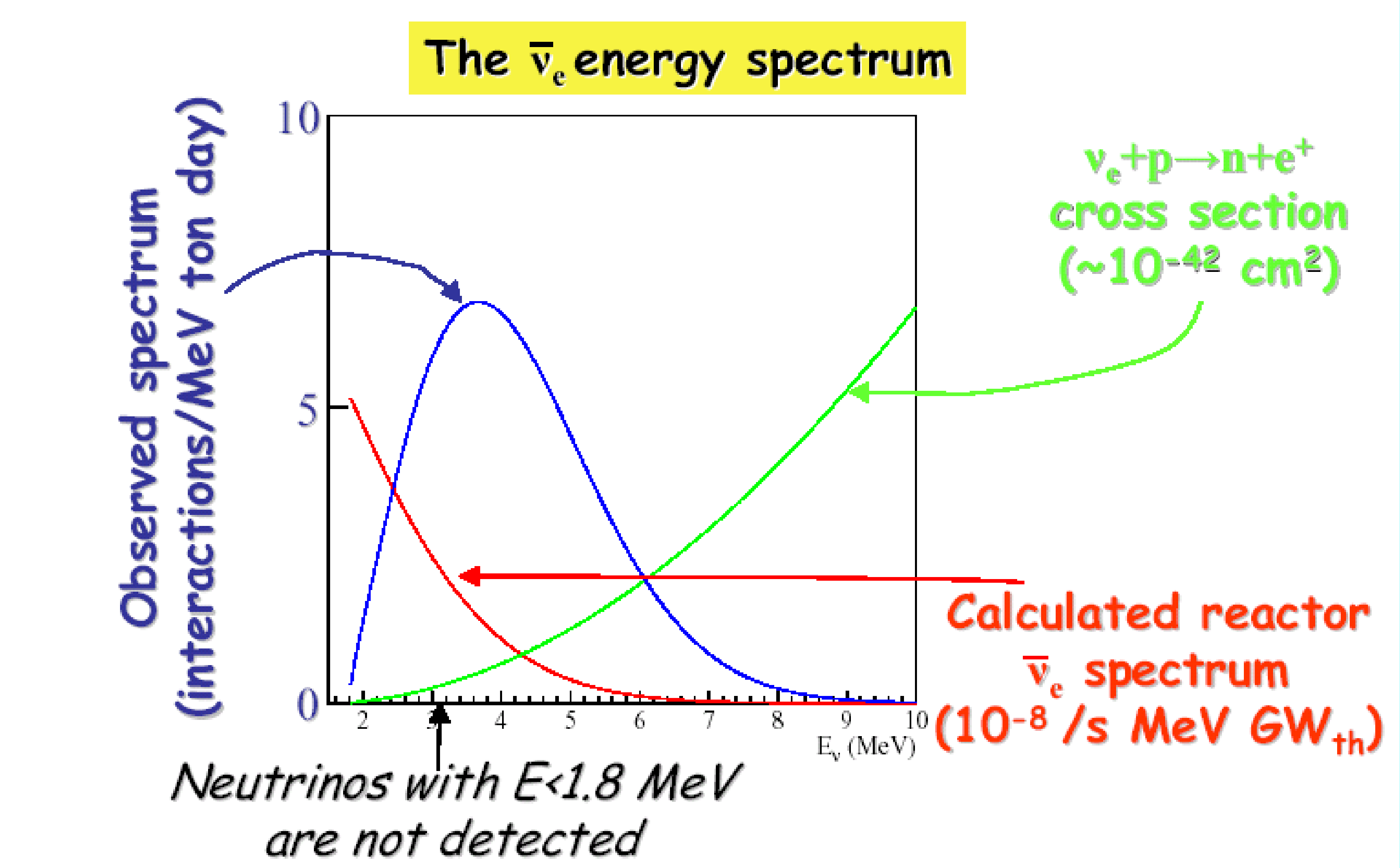


Higher order corrections can be found in

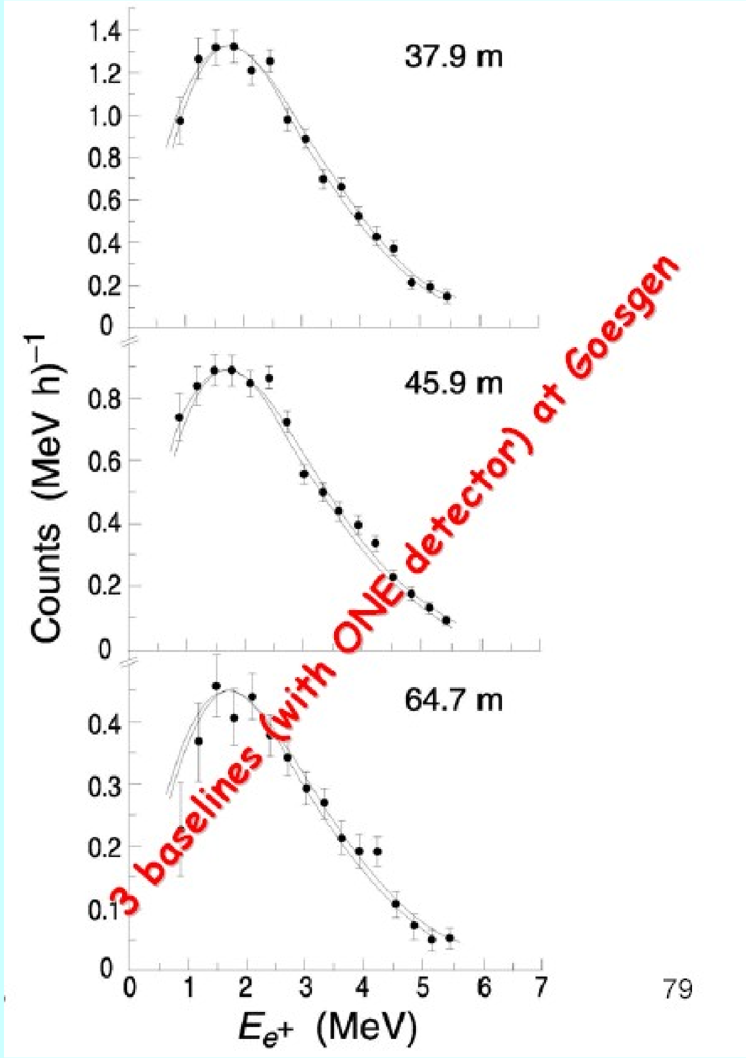
P. Vogel et al., PRD60(1999)053003

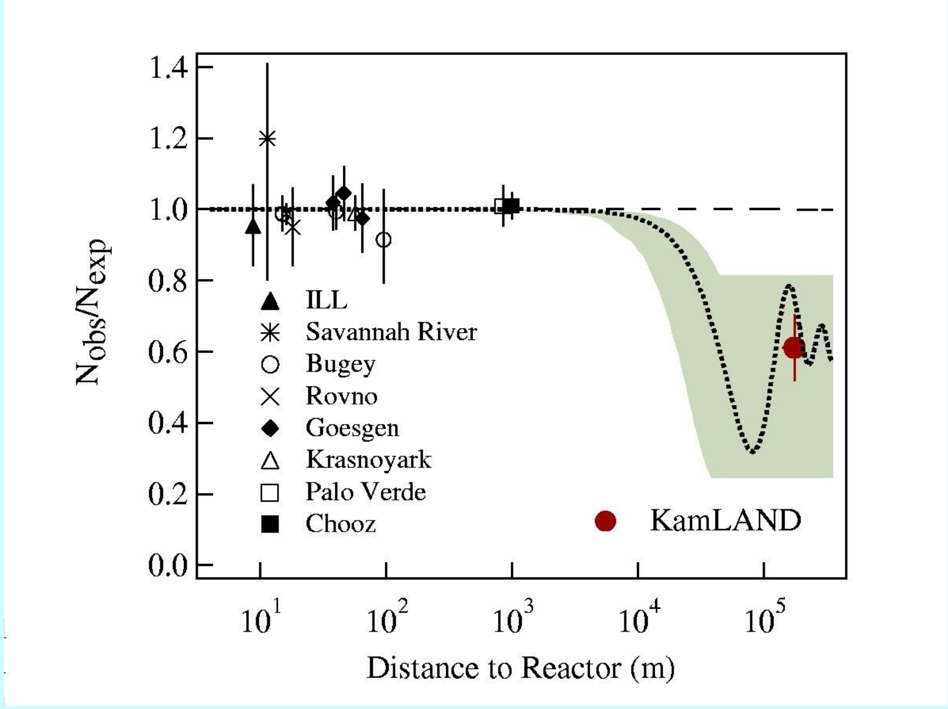
Strumia-Vissani et al., PLB564(2003)42

Observed neutrino spectrum



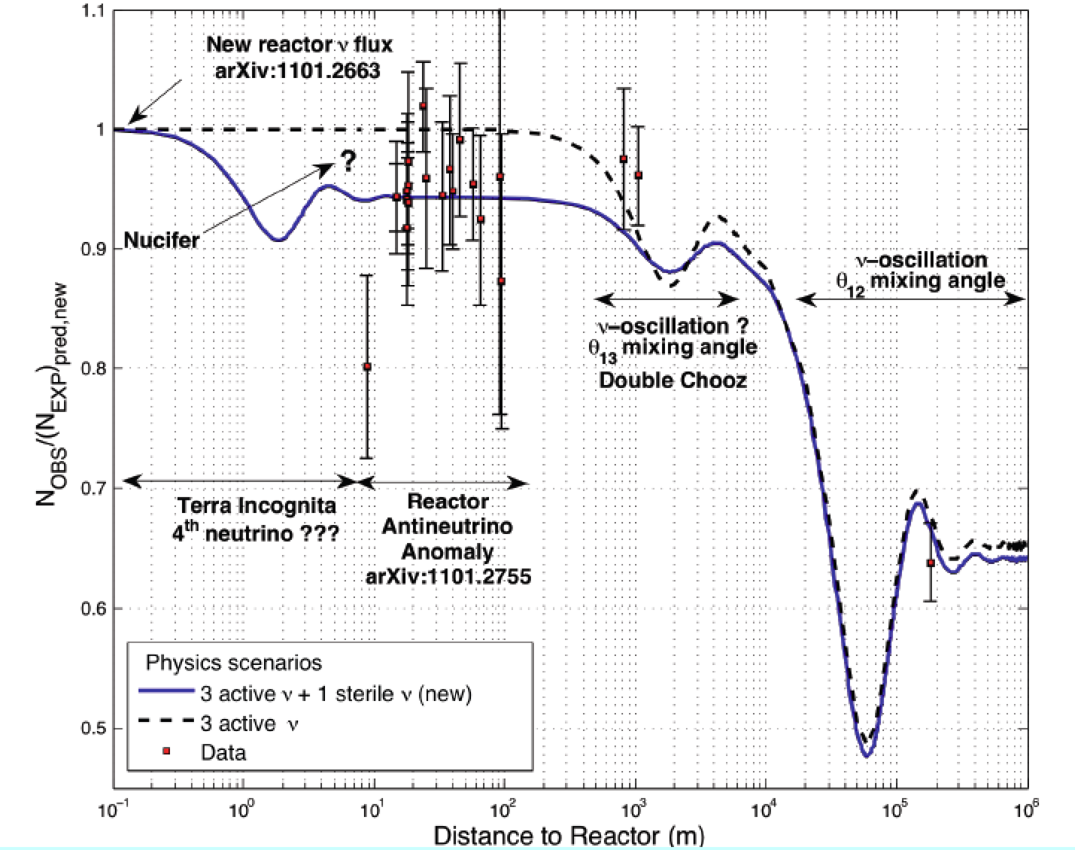
Measured reactor neutrino spectrum





In agreement with prediction,
No oscillation !
But …

New analysis: a deficit ?



- New neutrino flux
- New cross section (neutron life time, …)

G. Mention et al., arXiv [hep-ex]: 1101.2755
Th. Lasserre, talk at NeuTel 11

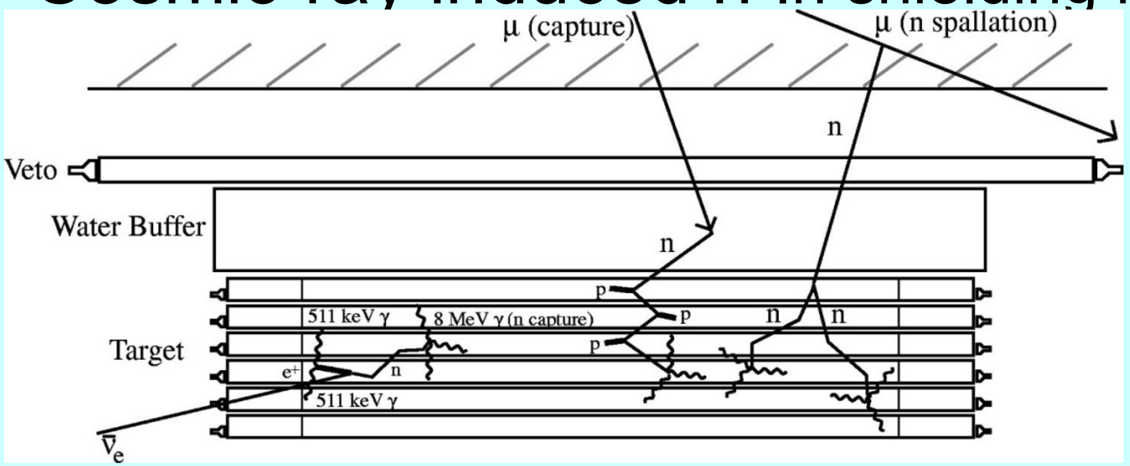
Backgrounds: Uncorrelated

- Three types: $\gamma-\gamma$, γ -neutron, neutron-neutron
- **γ's** mainly from
  - ^{238}U, ^{232}Th, ^{40}K decays
  - ^{222}Rn & ^{85}Kr in air
- **n** mainly from
  - cosmic-ray induced spallation process
  - (α-n) interaction
  - Spontaneous fission
  - Evaporation
- How to deal with these backgrounds:
  - Shielding
  - Clean environment ➔ challenge for detector construction
  - Measurement
    - Vary time correlation window
    - Swap time correlation components

Backgrounds: Correlated

- Chained decays
  - ^{214}Bi → ^{214}Po(164 μ s) → ^{210}Pb (E_α=7.7/6.9 MeV)
  - In ^{222}Rn chain : ^{210}Po→ ^{206}Pb(E_α=5.3 MeV)

    ➔ ^{13}C(α,n)^{16}O
- Cosmic-ray induced n In shielding materials



Y.F. Wang et al., PRD64(2001)013012

M.G. Marino et al, NIM A582(2007)611

- Cosmic-ray induced n-emitting isotopes in LS

^{8}He (τ = 171.7 msec): β^- + n
^{9}Li (τ = 257.2 msec): β^- + n

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

Experiments under construction

- Measuring θ_{13}
- Evolution of ideas
- Experiments under construction
  - Double Chooz
  - Reno
  - Daya Bay

Neutrino oscillation: PMNS matrix

If Mass eigenstates ≠ Weak eigenstates ➔ Neutrino oscillation

Oscillation probability ：

P(ν 1 – > ν 2) ∝ $\sin^2(1.27\Delta m^2 L/E)$

Atmospheric crossing ： CP 与 solar β

ü 13 β decays

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

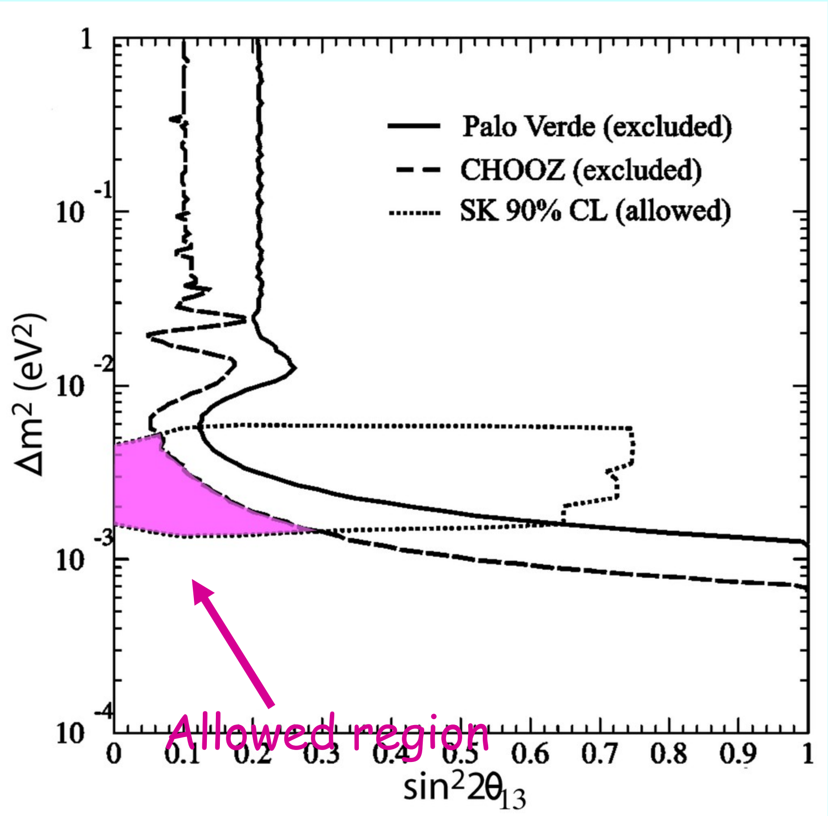
Super-K	Daya Bay	Homestake	EXO
K2K	Double Chooz	Gallex	Genius
Minos	NOVA	SNO	CUORE
T2K		KamLAND	NEMO…

A total of 6 parameters: 2 Δm^2, 3 angles, 1 phases

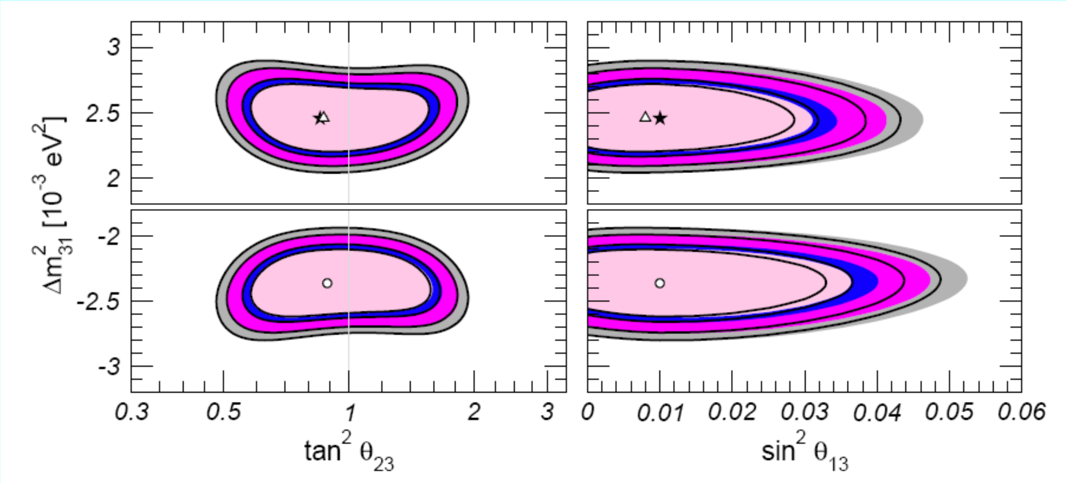
+ 2 Majorana phases

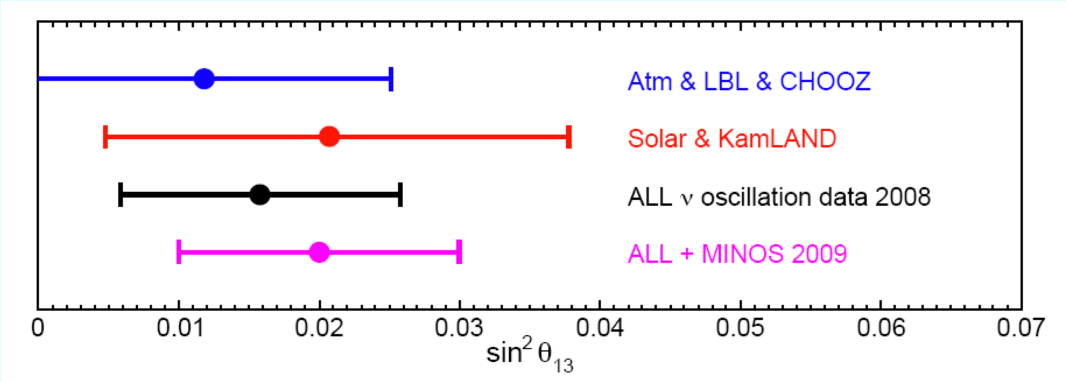
Current Knowledge of θ_{13}

Direct search
PRD 62, 072002



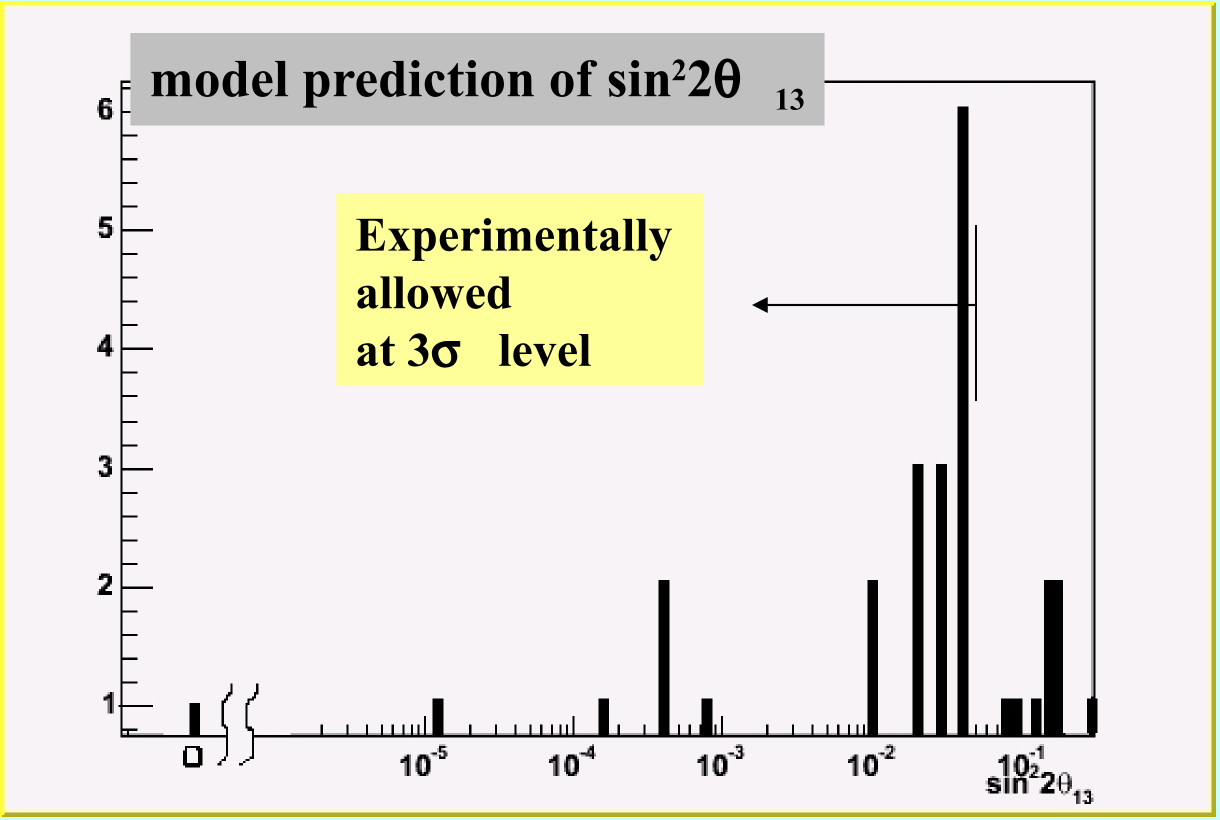
M.C. Gonzalez-Garcia et al., JHEP1004:056,2010





G.L.Fogli et al., J.Phys.Conf.Ser.203:012103

- 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 $\sin^2 2\theta_{13} \sim 0.1\text{-}10$ %

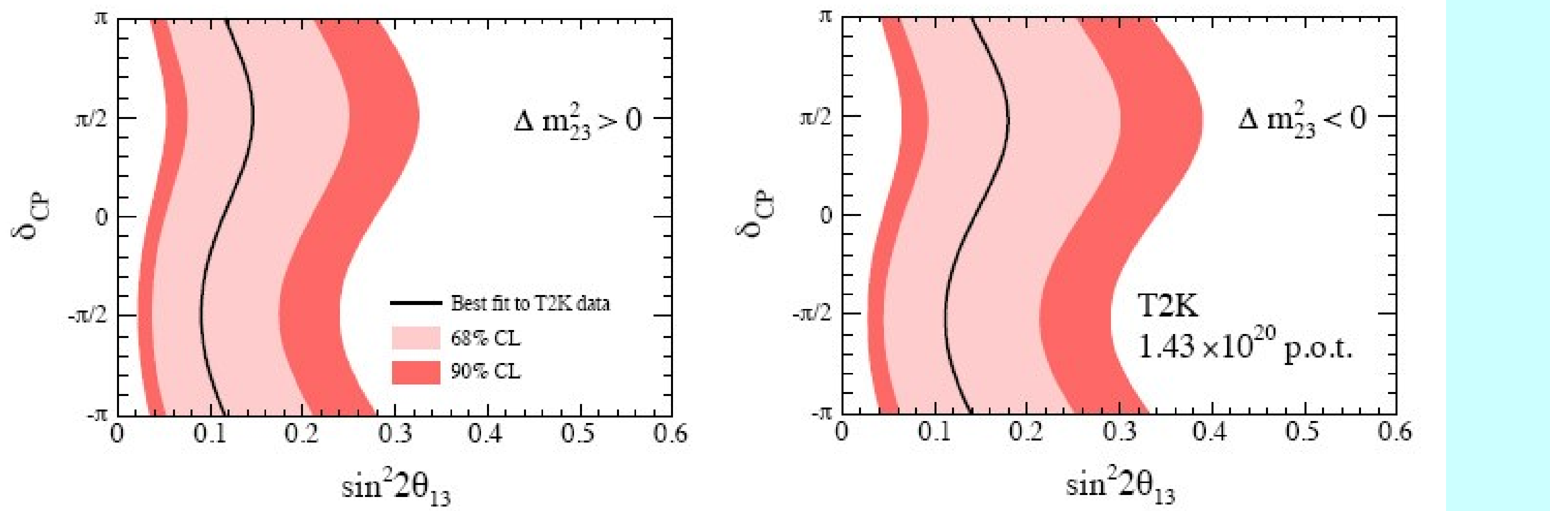


An experiment with a precision for $\sin^2 2\theta_{13}$ less than 1% is desired

T2K Indication

- 6 ν_e events, 1.5$\pm$ 0.3 bkg expected. (1.43$\times$ 10^{20} POT)

  θ_{13} non-zero probability 99.3% (2.5 σ significance)



90% C.L. interval & Best fit point (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$	**$0.04 < \sin^2 2\theta_{13} < 0.34$**
$\sin^2 2\theta_{13} = 0.11$	**$\sin^2 2\theta_{13} = 0.14$**

MINOS

Results on appearance of electron-neutrinos with 8.2×10^{20} POT

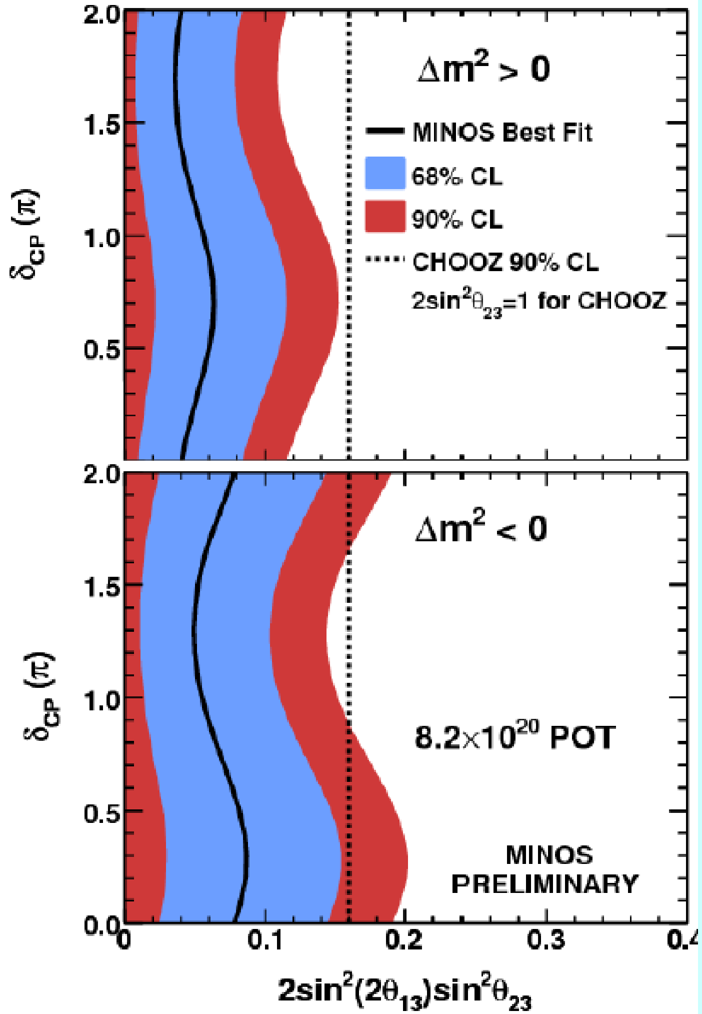
For $\delta_{CP} = 0$ the allowed values of $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ at 90% CL are:

0 to 0.12 (normal) central value: 0.04
0 to 0.19 (inverted) central value: 0.08

Expected background events:
49.5 ± 2.8 (syst) ± 7.0 (stat)

Observed events in FD data:
62

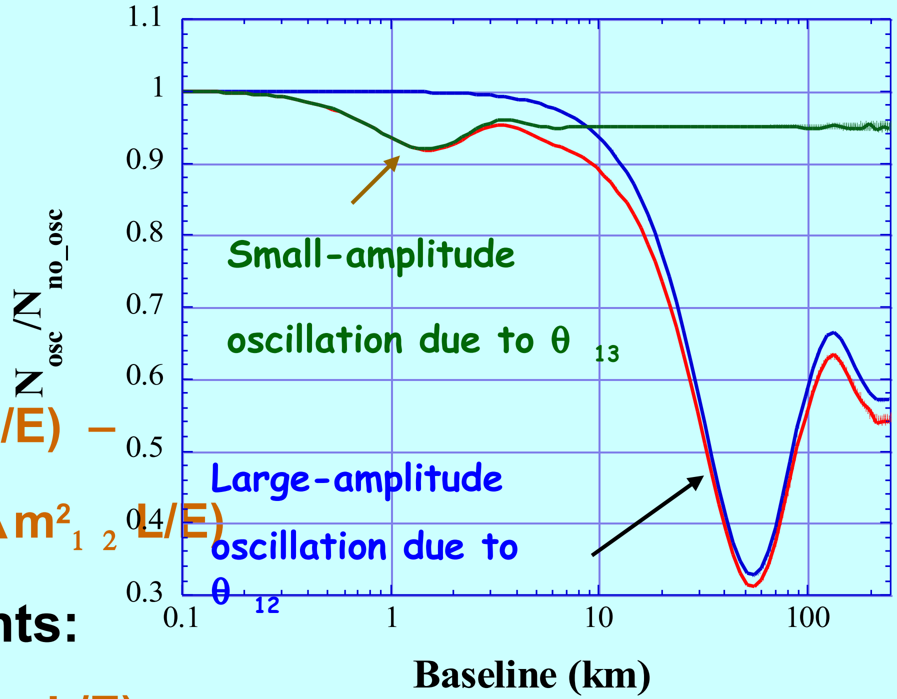
1.7σ excess above background



Exclusion limits based on the selected ν_e candidate event distribution.
Allowed values are in the colored regions

Why at reactors

- Clean signal, no cross talk with δ and matter effects
- Relatively cheap compare to accelerator based experiments
- Can be very quick



Reactor experiments:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{13} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$$

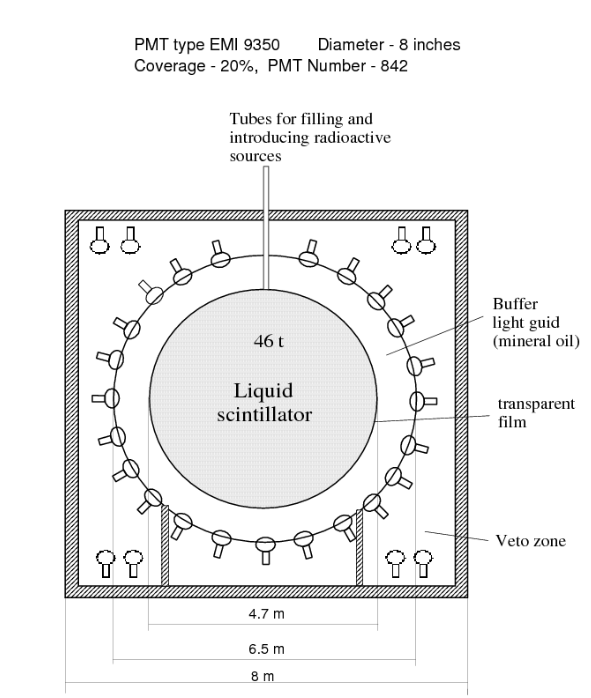
Long baseline accelerator experiments:

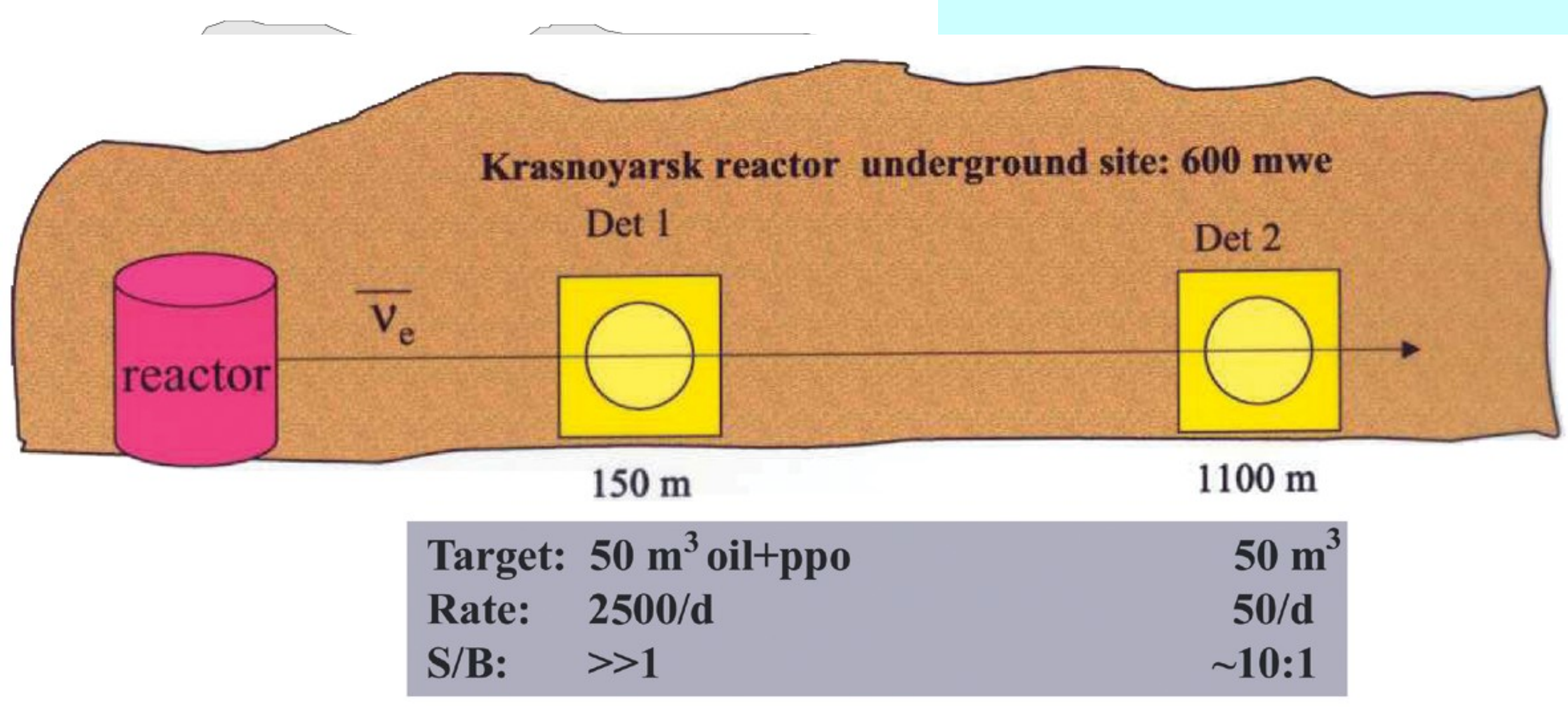
$$P_{\mu e} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{23} L/E) + \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E) - A(\rho) \bullet \cos^2\theta_{13} \sin\theta_{13} \bullet \sin(\delta)$$

First idea: Kr2Det

- Krasnoyarsk underground reactor
- Near-far cancellation

L.A. Mikaelyan et al., hep-ex/9908047
V. Martemyanov et al., hep-ex/0211070

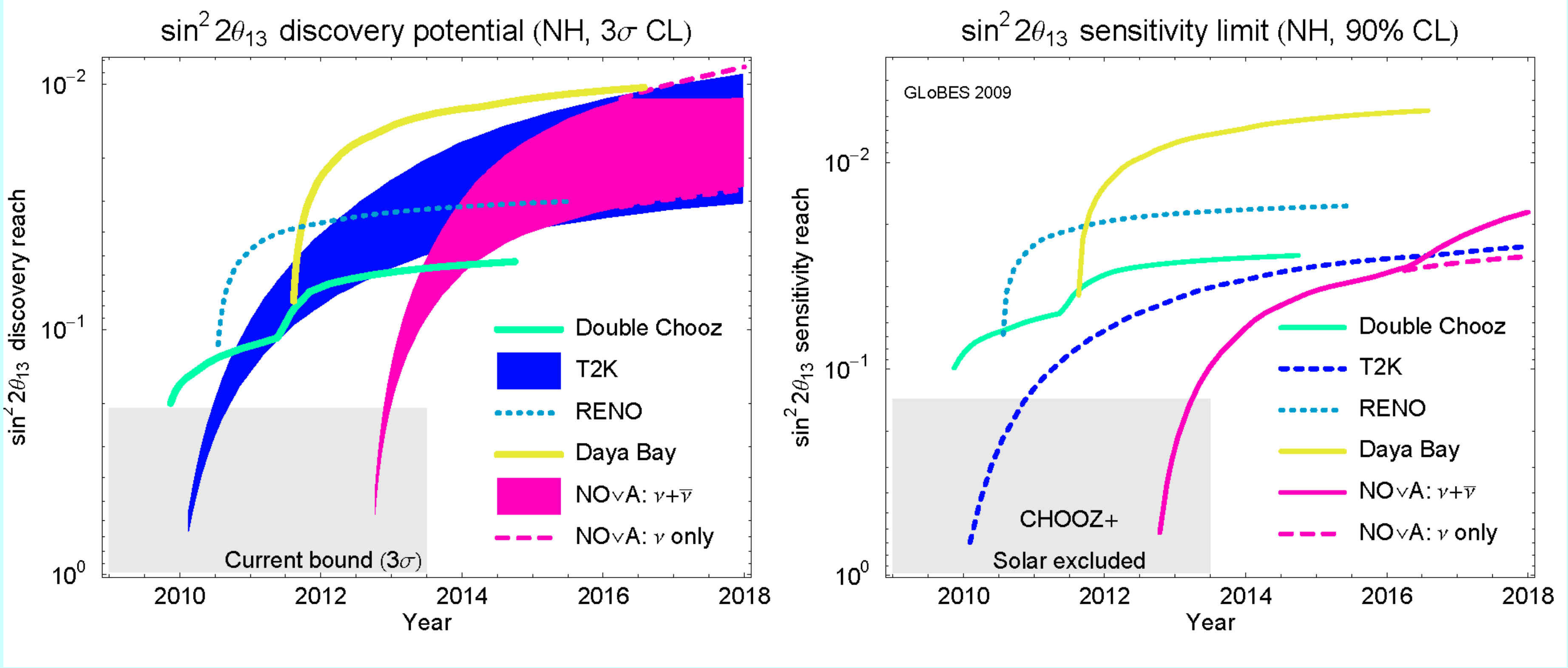




Proposed sites/experiments

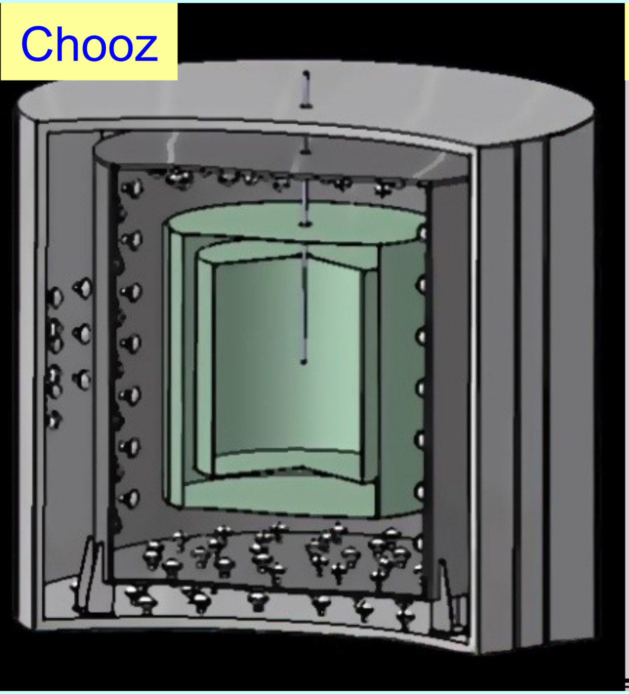
Site (proposal)	Power (GW)	Baseline Near/Far (m)	Detector Near/Far(t)	Overburden Near/Far (MWE)	Sensitivity
Angra(Brazil)	4.1	300/1500	50/500	200/1700	0.005
Braidwood (US)	6.5	270/1800	50/50	450/450	0.01
Double Chooz (France)	8.4	400/1050	10/10	115/300	0.03
Daya Bay (China)	11.6	350/1800	2*20+2*20/4*20	250/1200	0.01
Diablo Canyon (US)	6.4	400/1800	25/50	100/700	0.01
Kashiwazaki (Japan)	24.3	350/1300	8.5/8.5	300/300	0.02
Krasnoyarsk (Russia)	3.2	115/1000	46/46	600/600	0.03
Reno(Korea)	17.3	150/1500	20/20	230/675	0.02

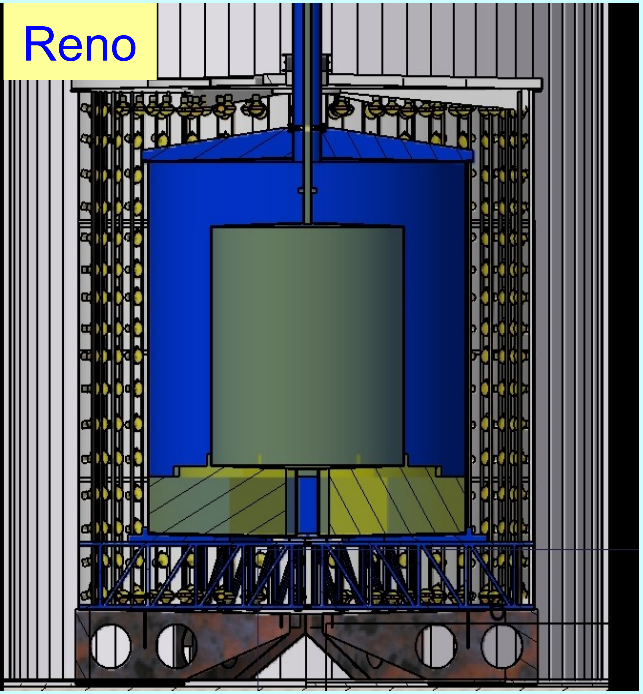
Race to measure θ_{13}

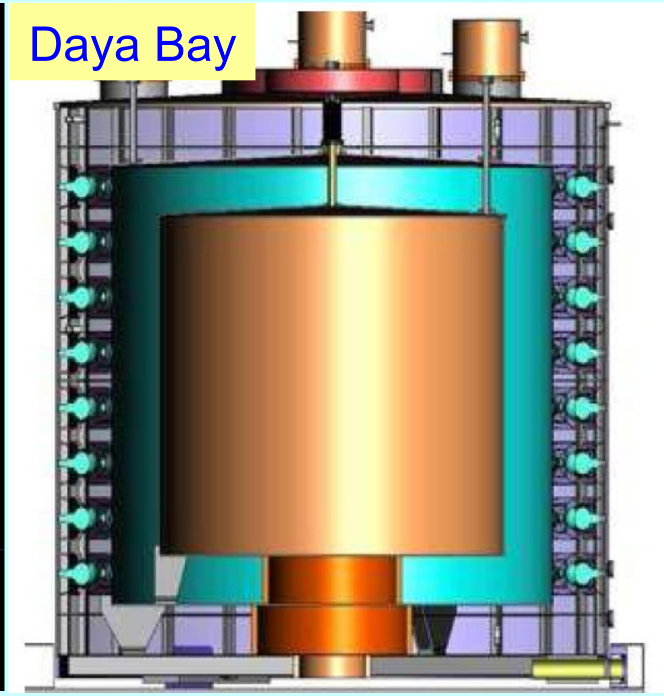


P. Huber, M. Lindner, T. Schwetz, W. Winter JHEP 0911:044,2009, arXiv:0907.1896,

Only three survived



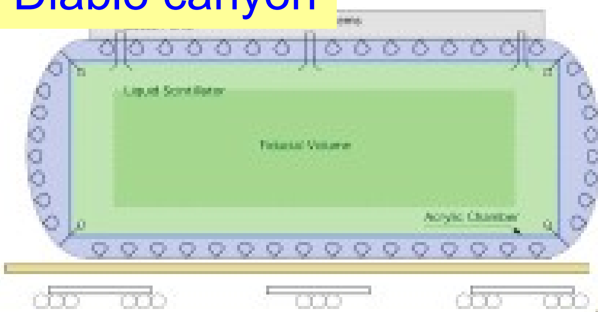


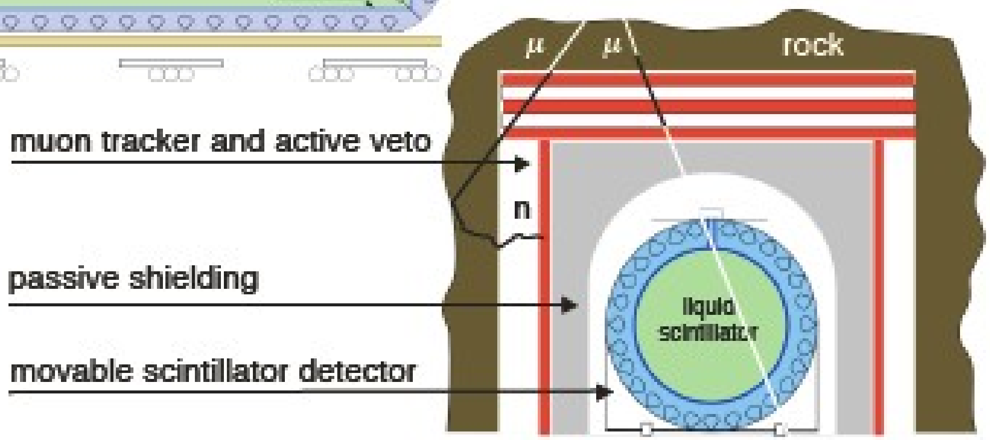


- How they all get here ?
- Coincidence ? all other designs disappeared

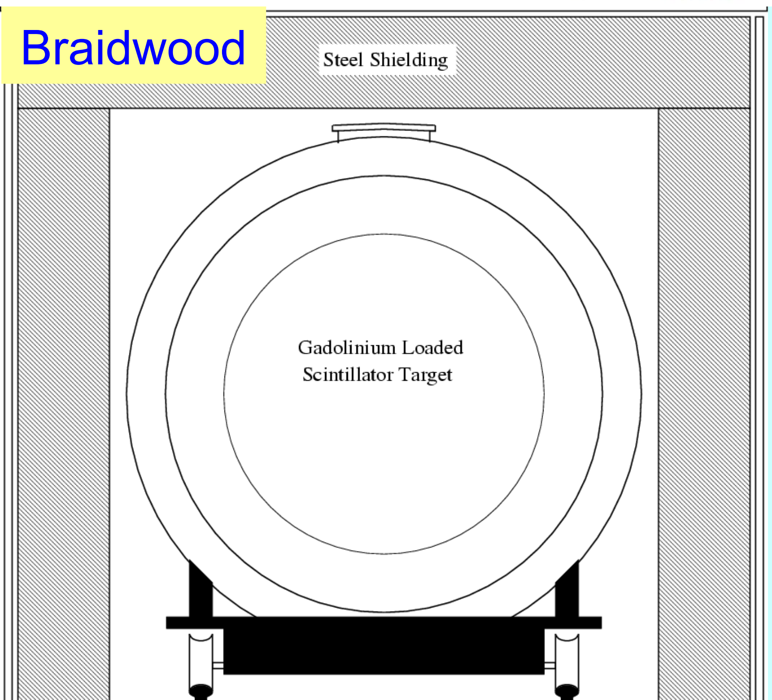
Diablo canyon

Movable Liquid Scintillator Antineutrino Detectors

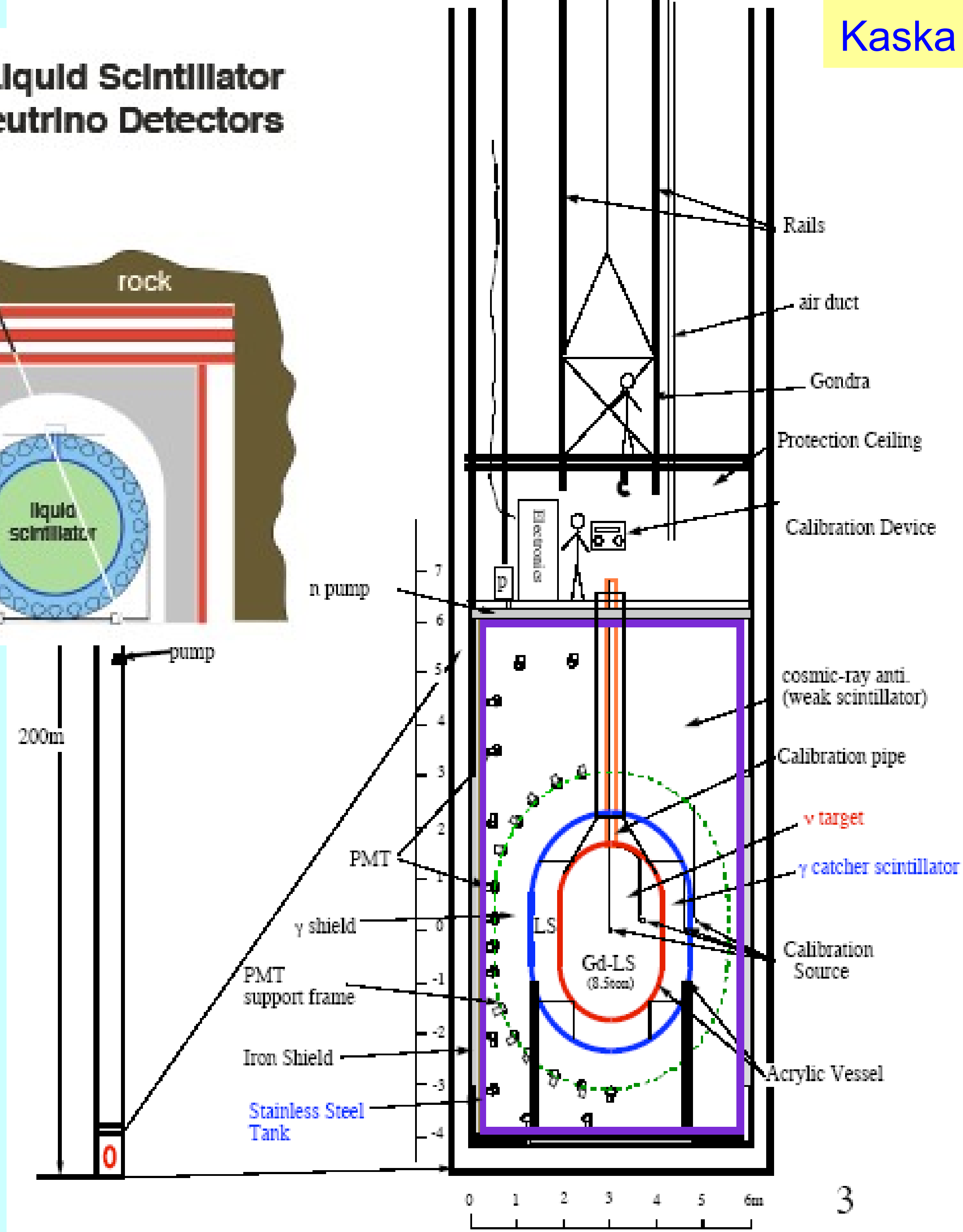




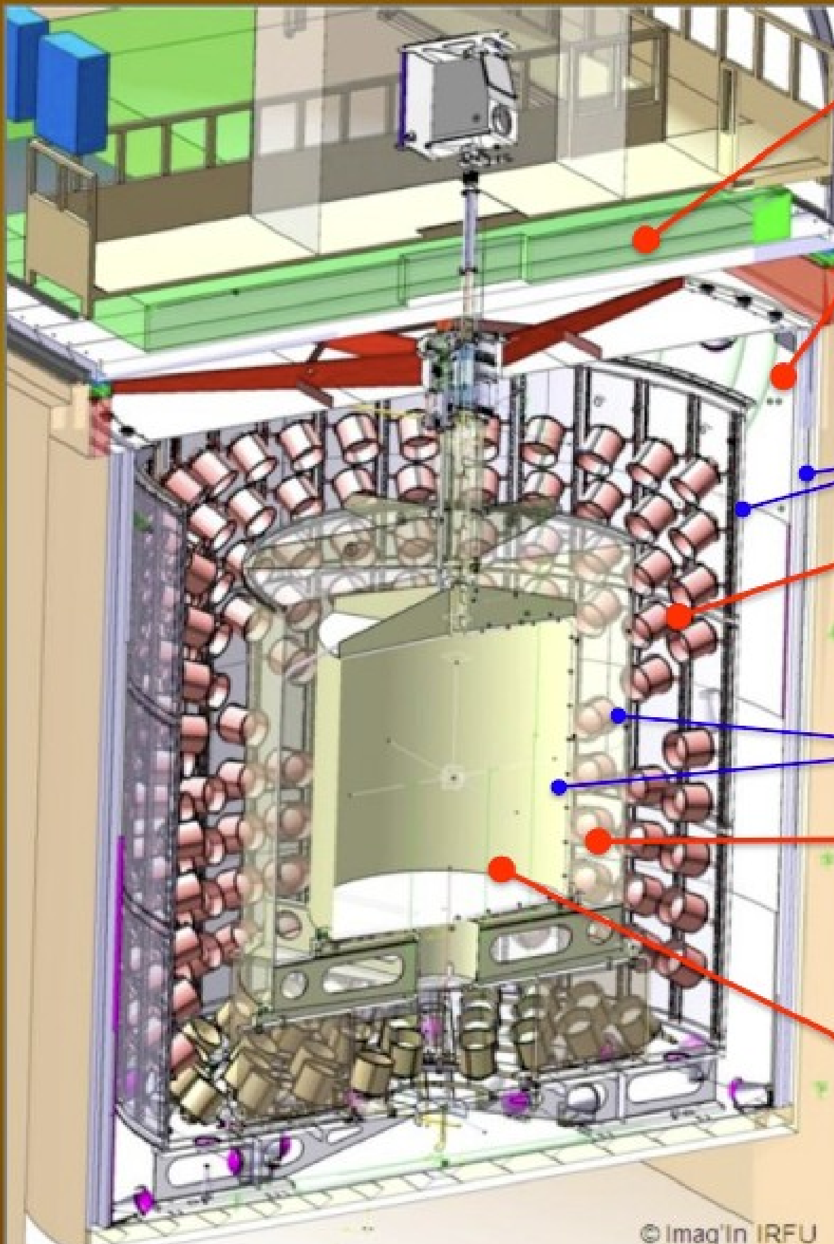
Braidwood



Kaska



Double Chooz detector



Outer Veto (Plastic scint.)
- Identification of cosmic-ray μ

Inner Veto (90m^3 Liquid scint.&78 PMTs)
- Detection of cosmic-ray μ and fast neutrons

Steel vessel & PMT support structure

Buffer (110m^3 Mineral oil & 390 PMT's)
- Reduction of fast neutron and environmental γ from outside

Acrylic vessel

γ-catcher (22.3m^3 Liquid scintillator)
- Measurement of γ's from n-capture by Gd in target volume

ν-target
(10.3m^3 Gd loaded (1g/l) liquid scint.)
- Target for neutrino signals

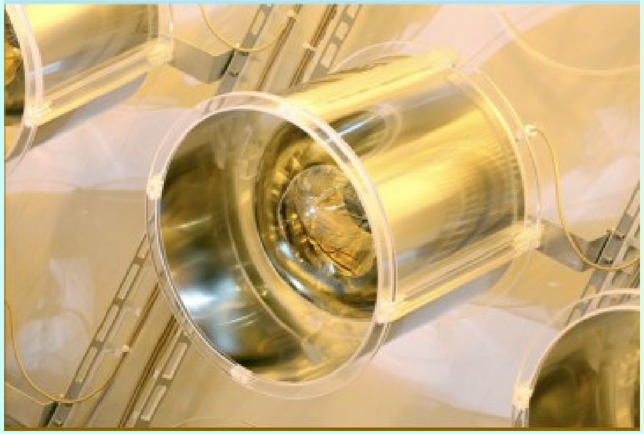
PMT

ID: 10" x 390PMTs

(Hamamatsu R7081 MOD (low-BG for DC))

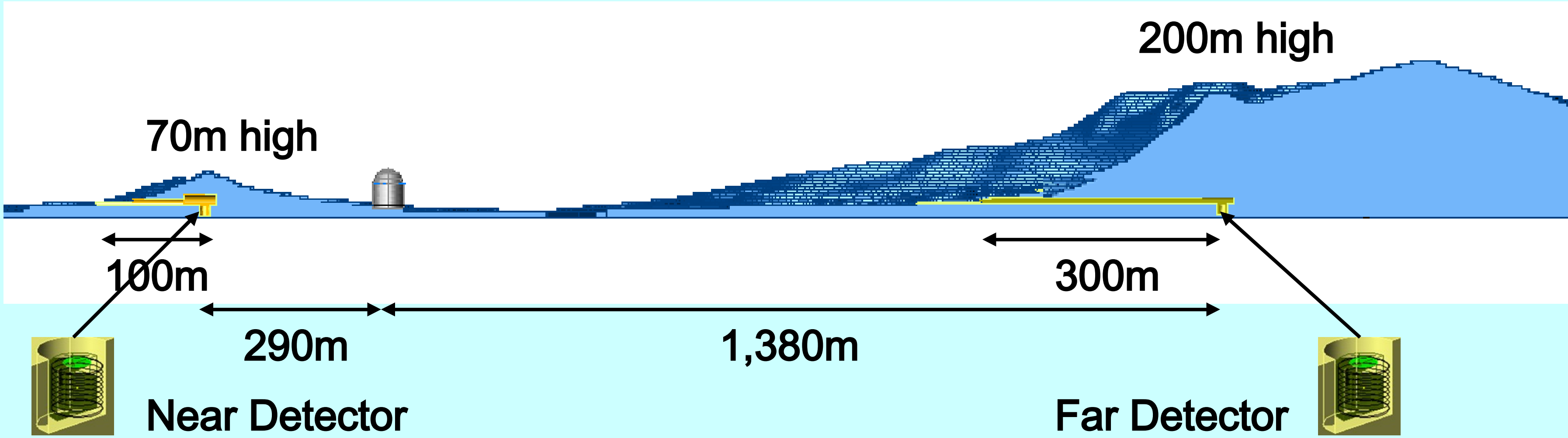
IV: 8" x 78PMTs

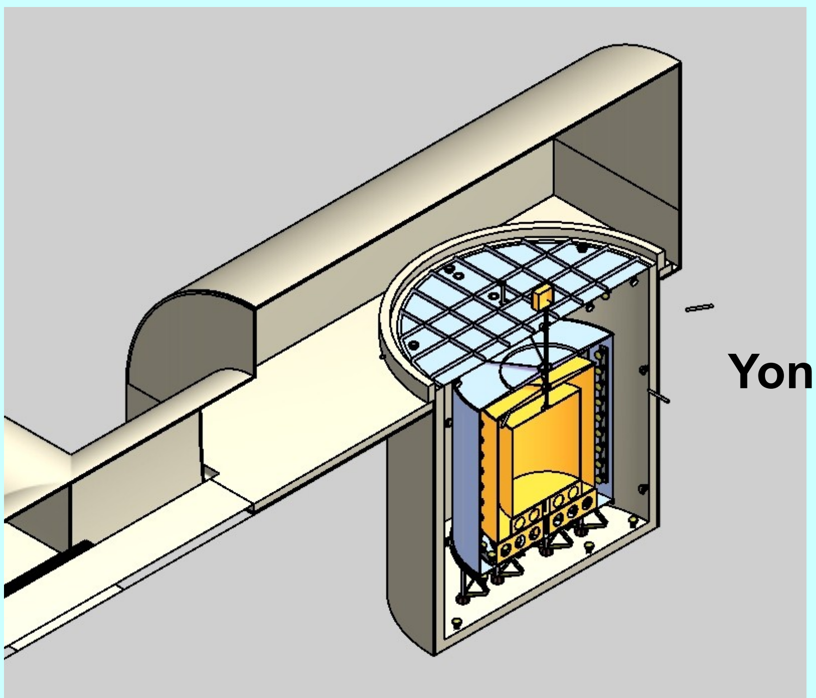
(Hamamatsu R1408)




RENO
2005.01.26 14:52

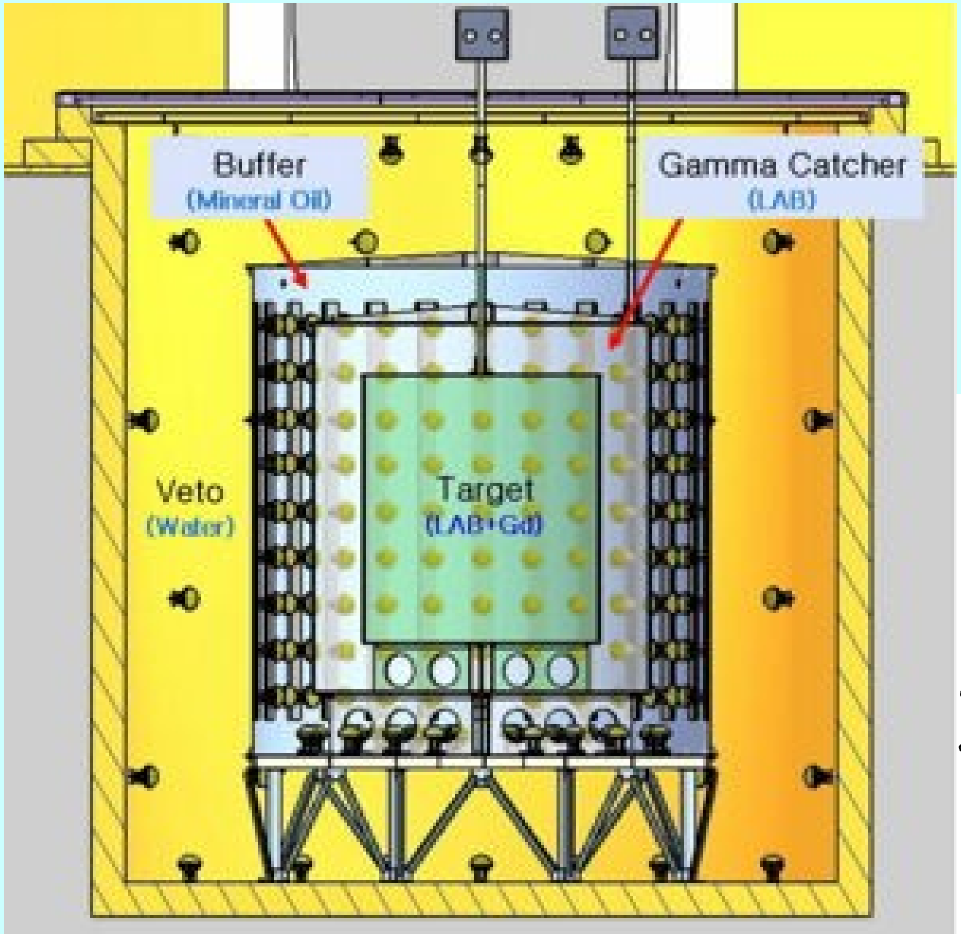
Schematic View of Reno





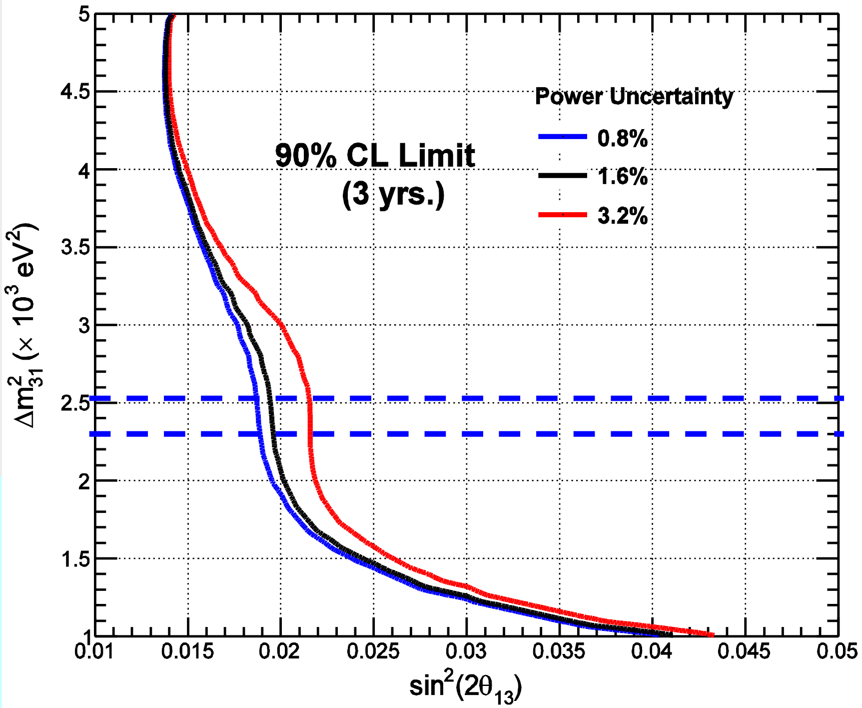
YongGwang (靈光) :
Glorious light

RENO & sensitivity



	Inner Diameter (cm)	Inner Height (cm)	Filled with	Mass (tons)
Target Vessel	280	320	Gd(0.1%) + LS	16.5
Gamma catcher	400	440	LS	30.0
Buffer tank	540	580	Mineral oil	64.4
Veto tank	840	880	water	352.6

90% CL Limits



- 354 10" Inner PMTs : 14% surface coverage
- 67 10" Outer PMTs

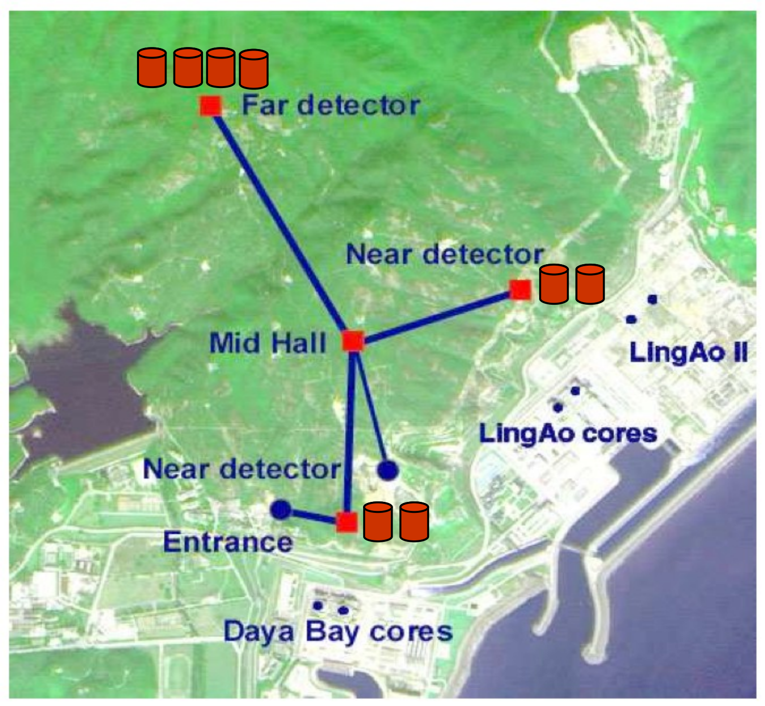
Daya Bay reactor neutrino experiment

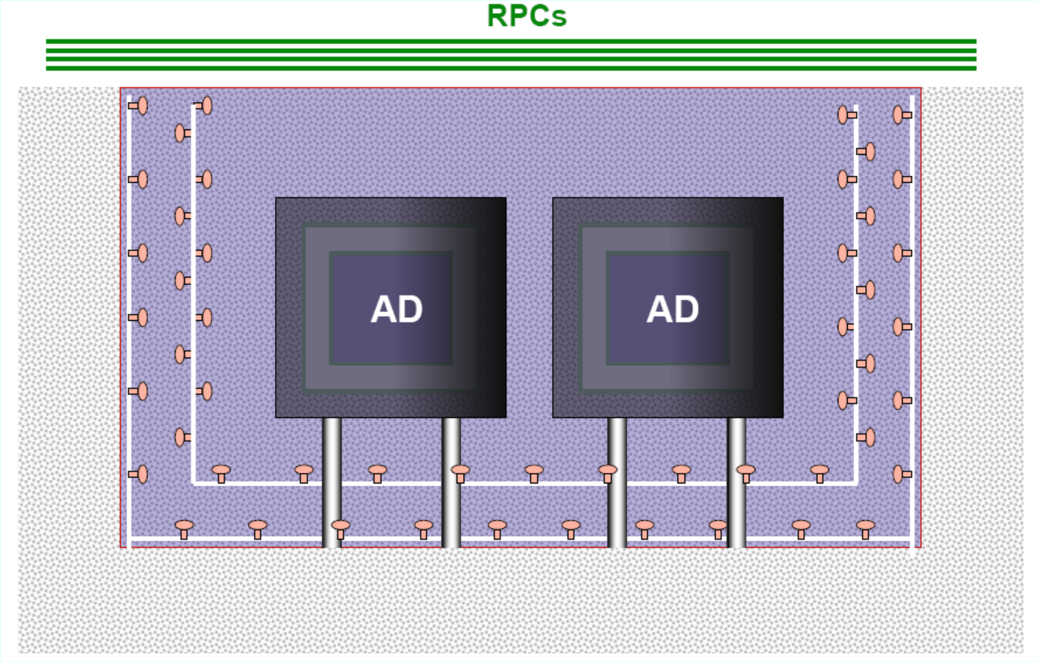
- **Second largest reactor complex: 5 reactor cores operational, 1 more this year, 17.4 GW in total**
- **Mountains near by, easy to construct a lab with enough overburden to shield cosmic-ray backgrounds**
- **Challenges: how to reach 1% ?**
  - **design + good conditions**

How to reach 0.5% precision ?

- **Increase statistics:**
  - **Powerful nuclear reactors(1 GW_{th}: 6 x 10^{20} $\bar{\nu}_e$/s)**
  - **Larger target mass**
- **Reduce systematic uncertainties:**
  - **Reactor-related:**
    - **Optimize baseline for the best sensitivity**
    - **Near and far detectors to minimize reactor-related errors**
  - **Detector-related:**
    - **Use "Identical" pairs of detectors to do *relative* measurement**
    - **Comprehensive programs for the detector calibration**
    - **Interchange near and far detectors (optional)**
  - **Background-related**
    - **Go deep to reduce cosmic-induced backgrounds**
    - **Enough active and passive shielding**

The plan to reach the precision





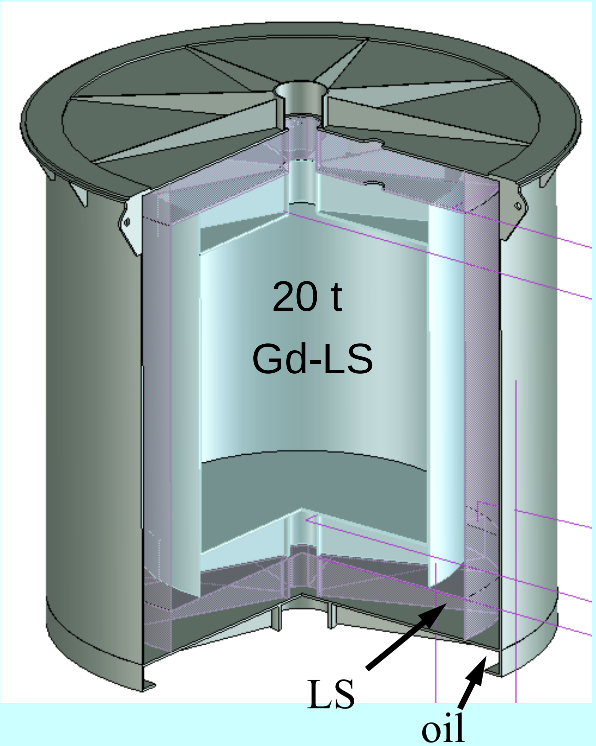
- Near-Far relative mea. to cancel correlated syst. err.
  - 2 near + 1 far
- Multiple modules per site to reduce uncorrelated syst. err. and cross check each other
  - 2 at each near site and 4 at far site
- Multiple muon veto detectors at each site to reach highest possible eff. for reducing syst. err. due to backgrounds

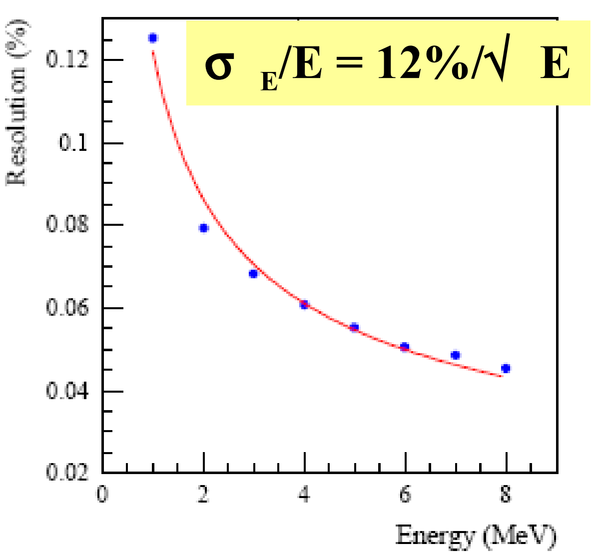
Central Detector modules

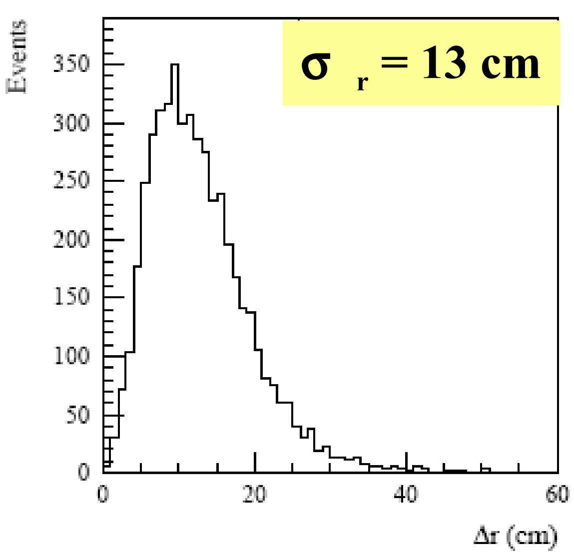
- **Three zones modular structure:**
  - I. target: Gd-loaded scintillator
  - II. γ-catcher: normal scintillator
  - III. Buffer shielding: oil
- **192 8"PMT/module**
- **Reflector at top and bottom:**

Photocathode coverage

5.6 % ➔ 12%(with reflector)







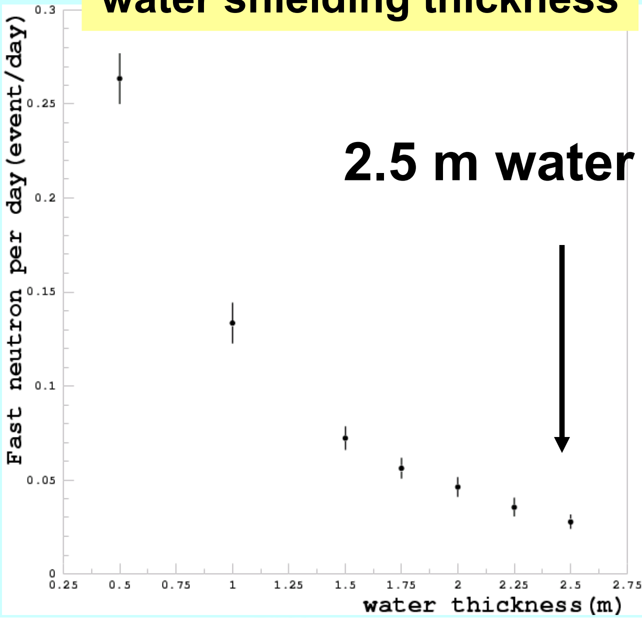
Target: 20 t, 1.6m
γ-catcher: 20t, 45cm
Buffer: 40t, 45cm

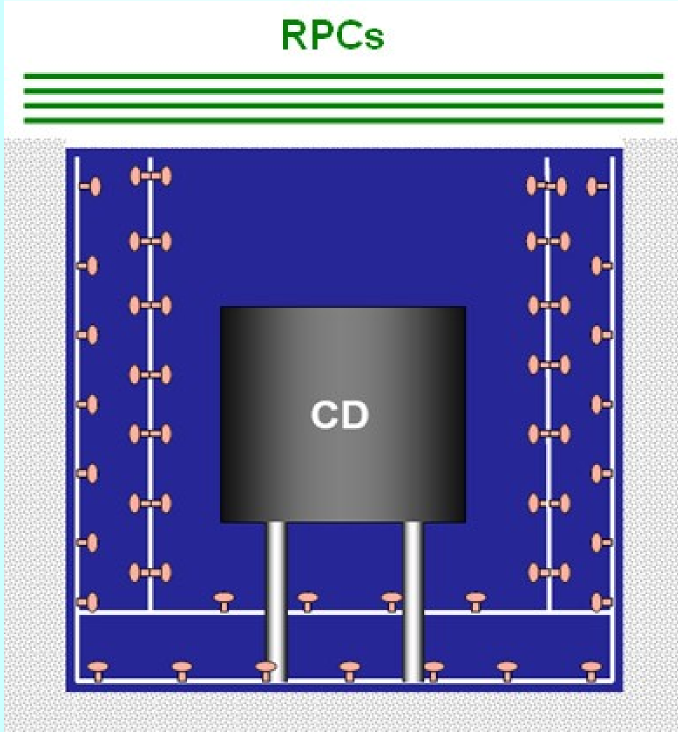
Water Buffer & VETO

- 2.5 m 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: multiple detectors
  - cross check each other to control uncertainties
- Design:
  - 4 layers of RPC at TOP +
  - 2 layers of water detector

RPC over scintillator: insensitive to γ backgrounds

Neutron background vs water shielding thickness





Calibration and Monitoring

- **Source calibration: energy scale, resolutions, …**
  - **Deployment system**
    - **Automatic: quick but limited space points**
    - **Manual: slow but everywhere**
  - **Choices of sources: energy(0.5-8 MeV), activity(<1KHz), γ/n,…**
  - **Cleanness**
- **Calibration with physics events:**
  - **Neutron capture**
  - **Cosmic-rays**
- **LED calibration: PMT gain, liquid transparency, …**
- **Environmental monitoring: temp., voltage, radon, …**
- **Mass calibration and high precision flow meters**
- **Material certification**

Background related error

- **Uncorrelated backgrounds: U/Th/K/Rn/neutron**

  Single gamma rate @ 0.9MeV < 50Hz

  Single neutron rate < 1000/day

  2m water + 50 cm oil shielding

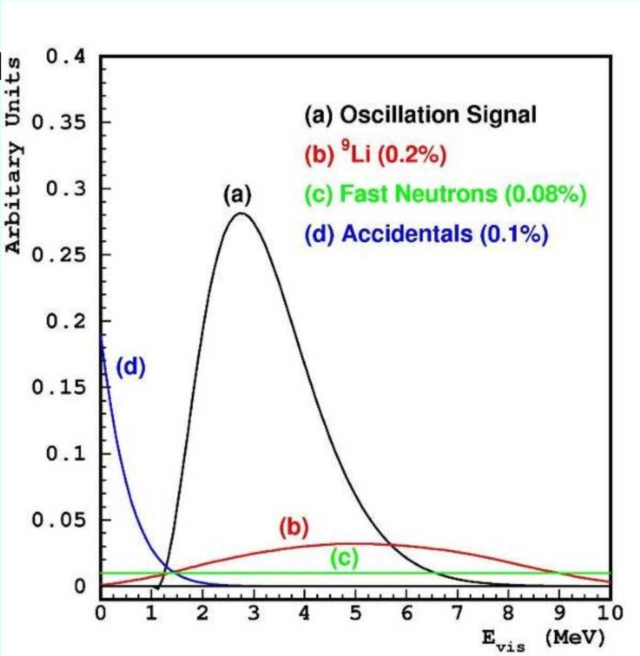
- **Correlated backgrounds: $n \propto E_{\mu}^{0.75}$**

  Neutrons: >100 MWE + 2m water

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

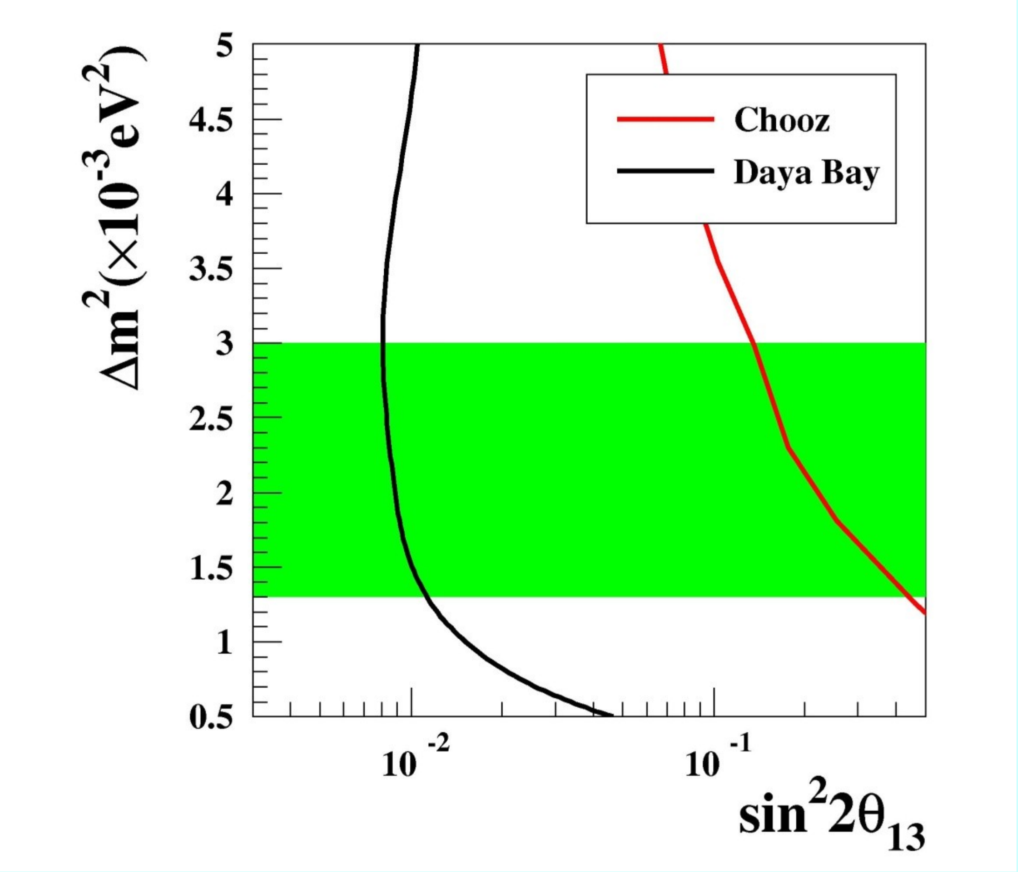
  $^{8}He/^{9}Li$: > 250 MWE(near), >1000 MWE(far)

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



	Daya Bay Near	Ling Ao Near	Far Hall
Baseline (m)	363	481 from Ling Ao 526 from Ling Ao II	1985 from Daya Bay 1615 from Ling Ao's
Overburden (m)	98	112	350
Radioactivity (Hz)	<50	<50	<50
Muon rate (Hz)	36	22	1.2
Antineutrino Signal (events/day)	930	760	90
Accidental Background/Signal (%)	<0.2	<0.2	<0.1
Fast neutron Background/Signal (%)	0.1	0.1	0.1
$^{8}He+^{9}Li$ Background/Signal (%)	0.3	0.2	0.2

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



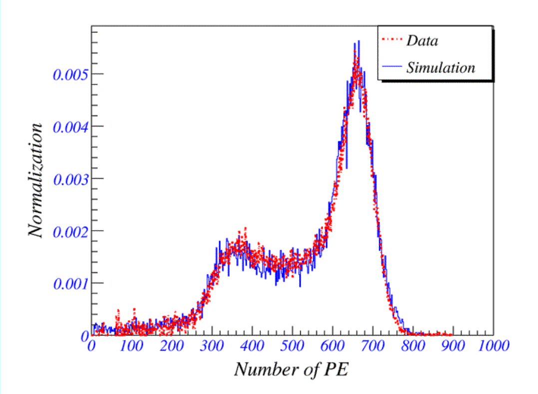
sources	Uncertainty
Reactors	0.087% (4 cores) 0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Backgrounds	0.32% (Daya Bay near) 0.22% (Ling Ao near) 0.22% (far)
Signal statistics	0.2%

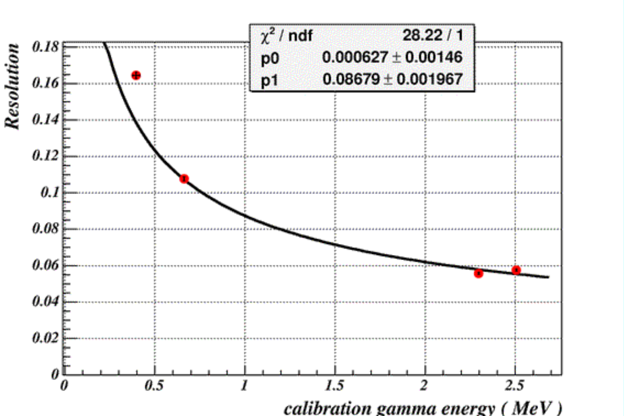
$$\chi^2 = \min_{\alpha s} \sum_{i=1}^{Nbin} \sum_{A=1,3} \frac{\left[M_i^A - T_i^A \left(1 + \alpha_D + \alpha_c + \alpha_d^A + c_i + \sum_r \alpha_r \frac{T_i^{rA}}{T_i^A}\right) + b^A B_i^A \right]^2}{T_i^A + T_i^{A\,2} \sigma_b^2 + B_i^A}$$

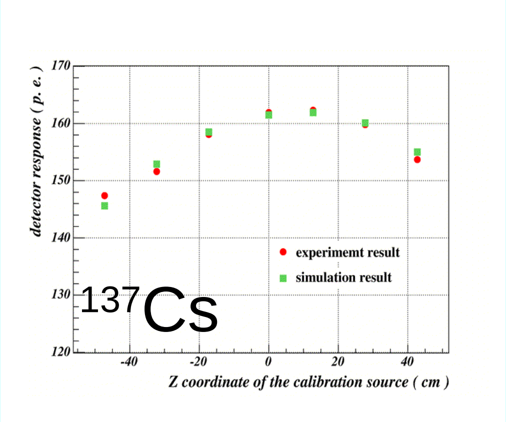
$$+ \frac{\alpha_D^2}{\sigma_D^2} + \frac{\alpha_c^2}{\sigma_c^2} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{i=1}^{Nbin} \frac{c_i^2}{\sigma_{shape}^2} + \sum_{A=1,3} \frac{\alpha_d^{A\,2}}{\sigma_d^2} + \frac{b^{A2}}{\sigma_B^2}$$

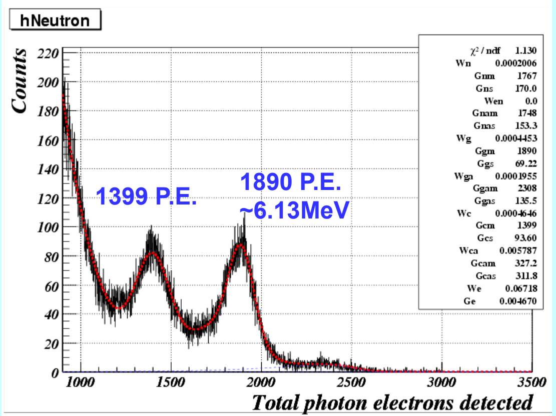
Prototype

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

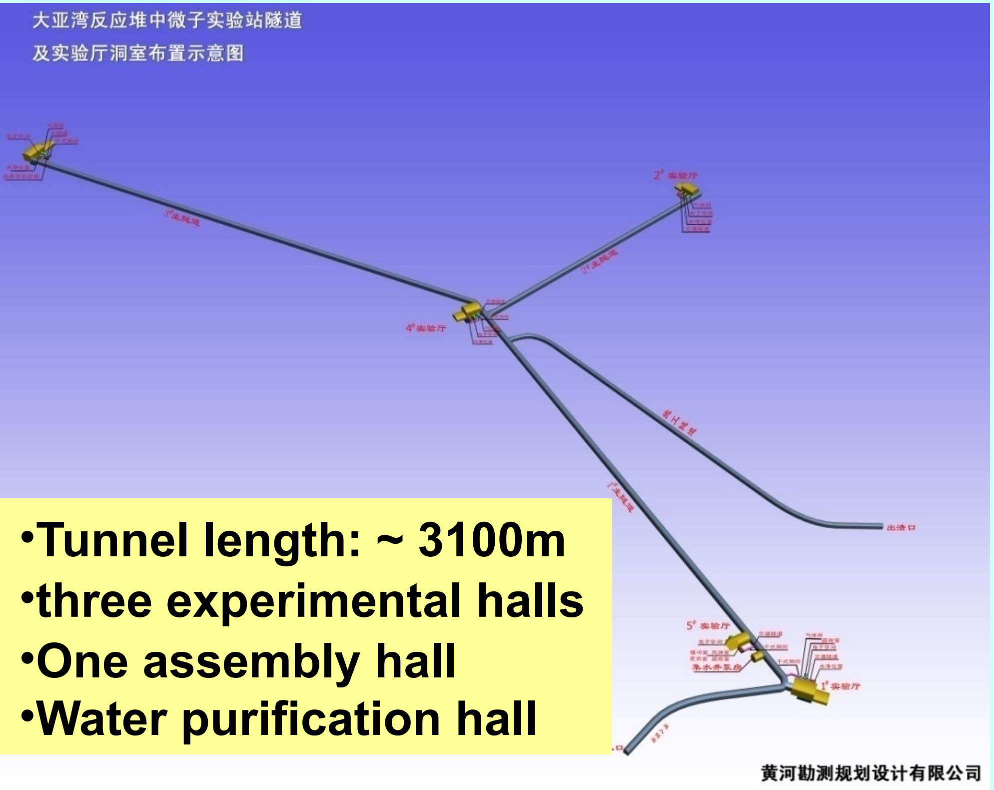




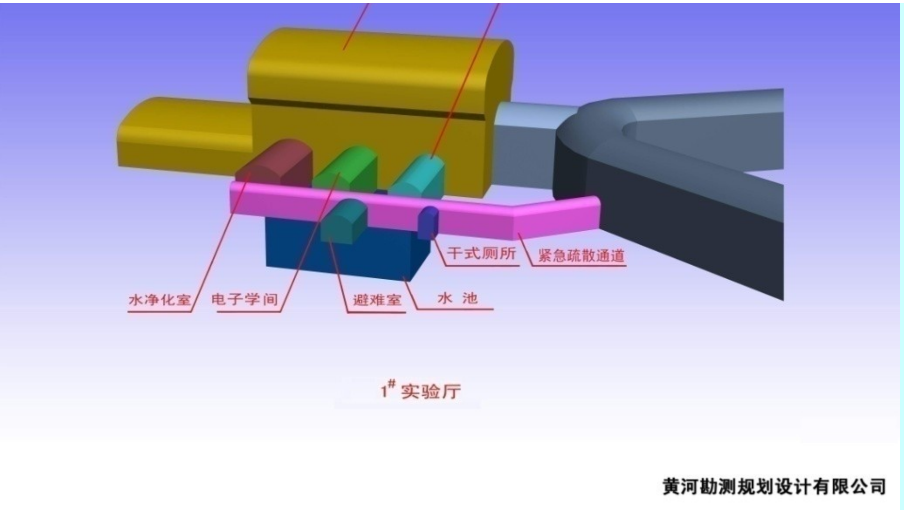




Civil construction



- Tunnel length: ~ 3100m
- three experimental halls
- One assembly hall
- Water purification hall

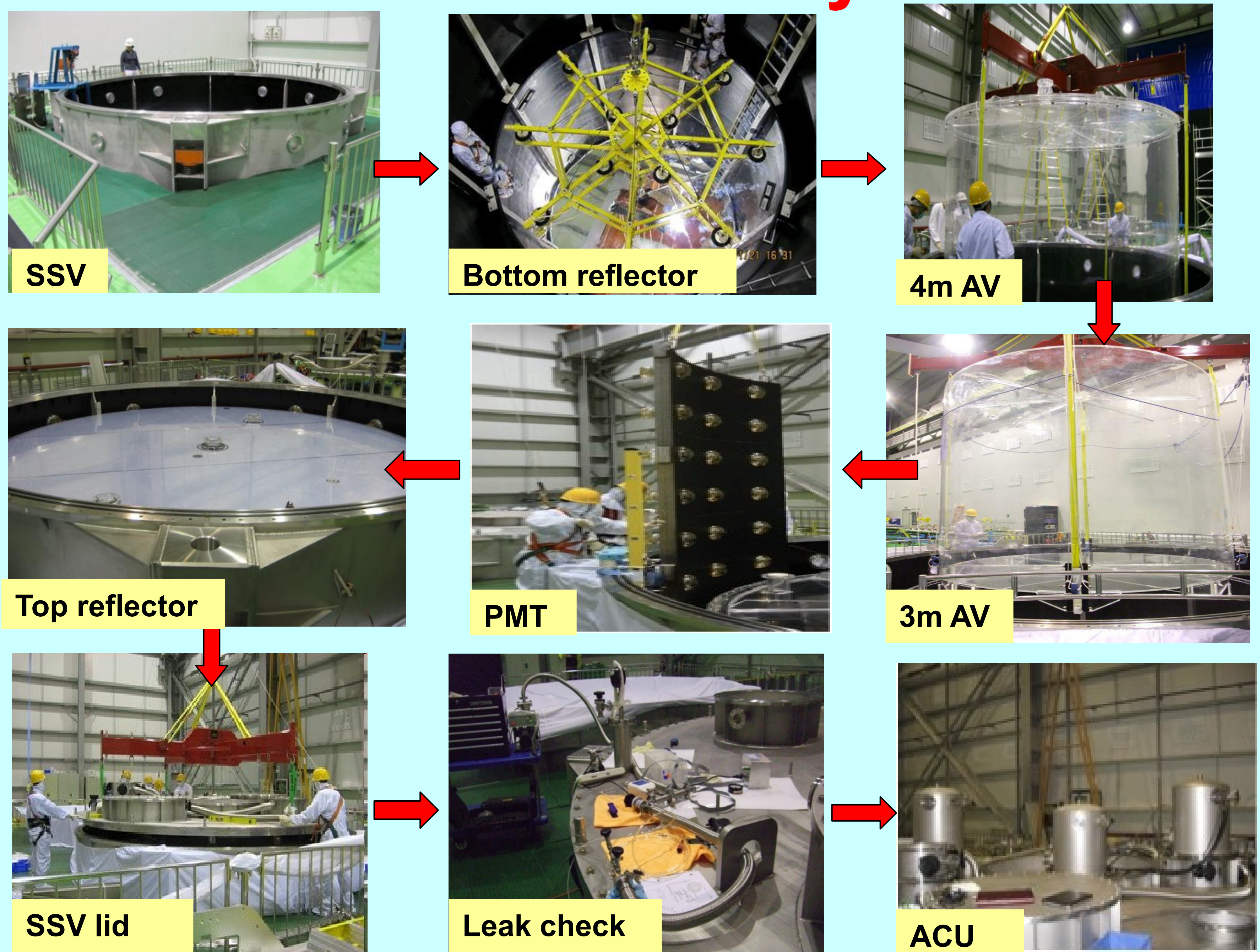



地面安装大厅投入使用，正
在进行中心探测器装配
2009/02/18


隧道入口

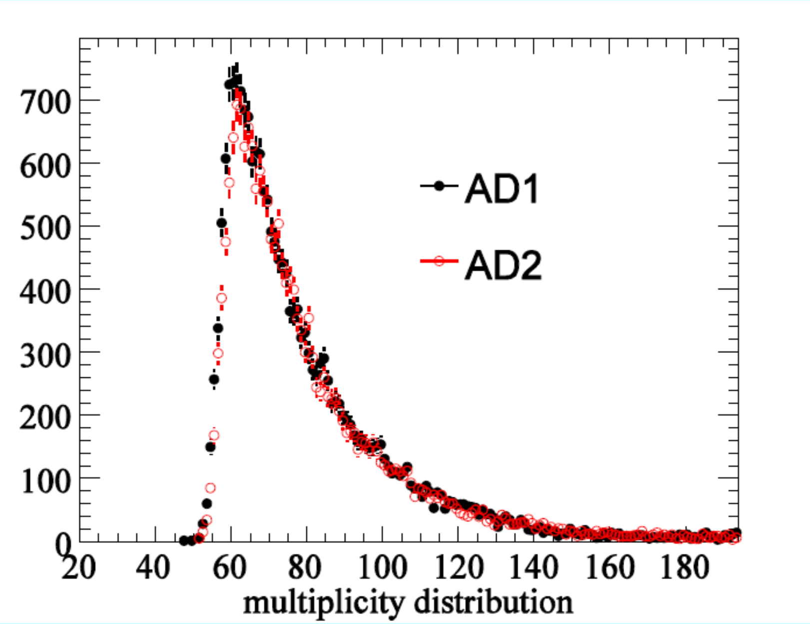

隧道内
2009/09/24 09:59

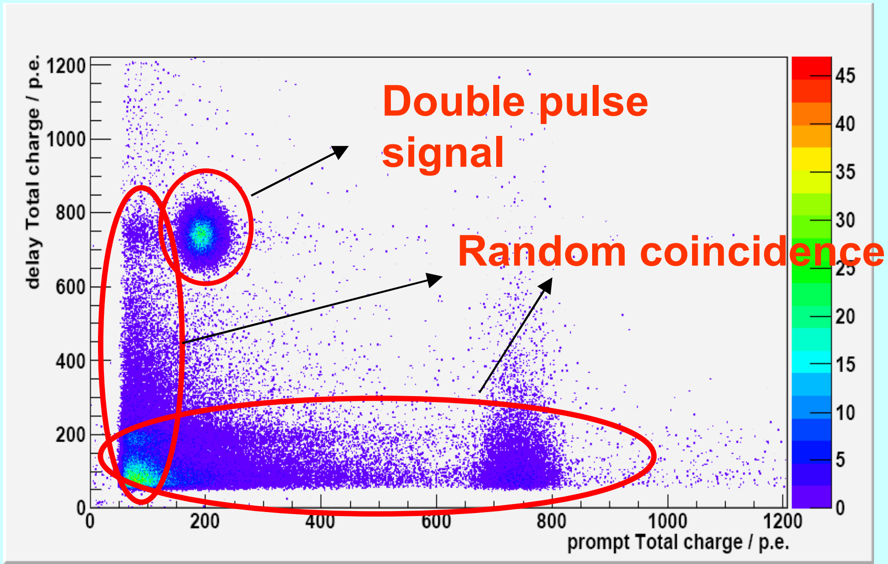
AD assembly

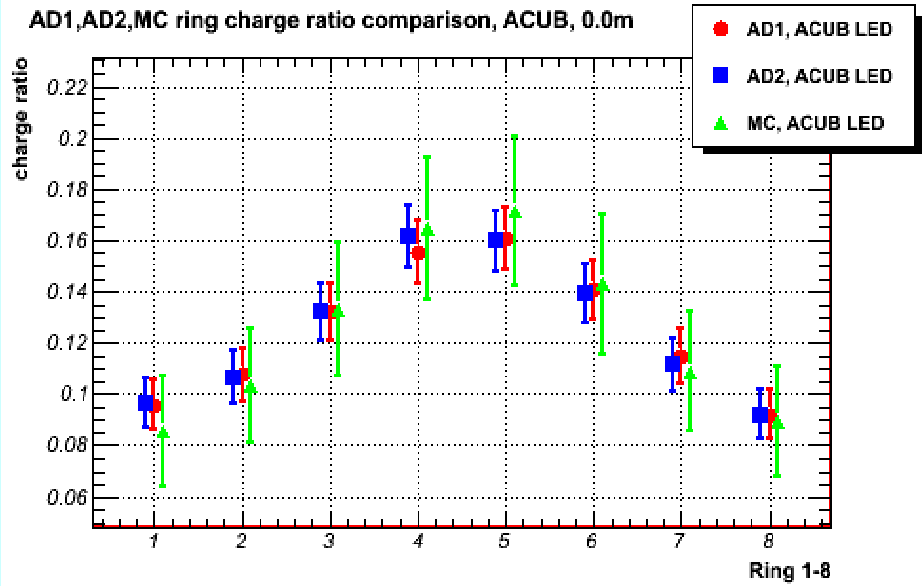

SSV
Bottom reflector
4m AV
3m AV
PMT
Top reflector
SSV lid
Leak check
ACU

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

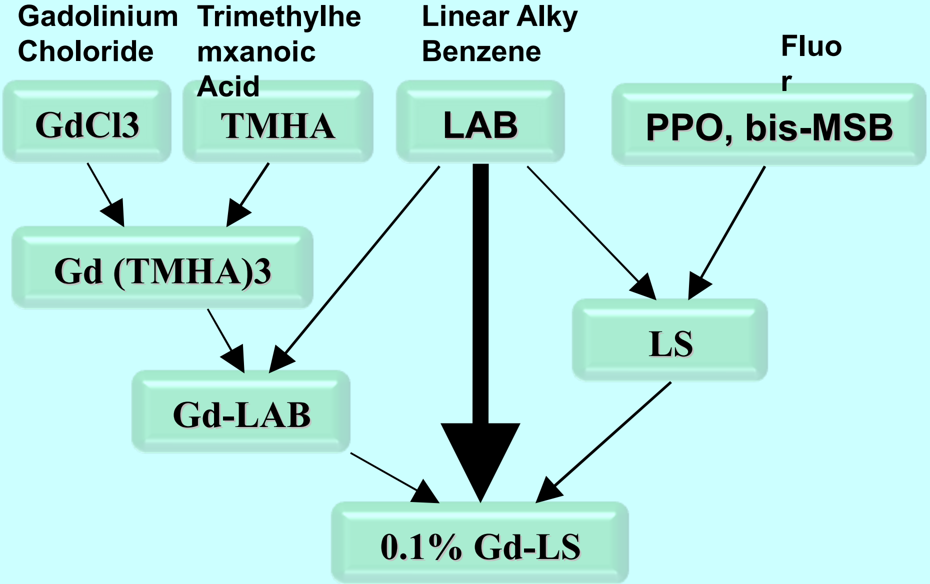




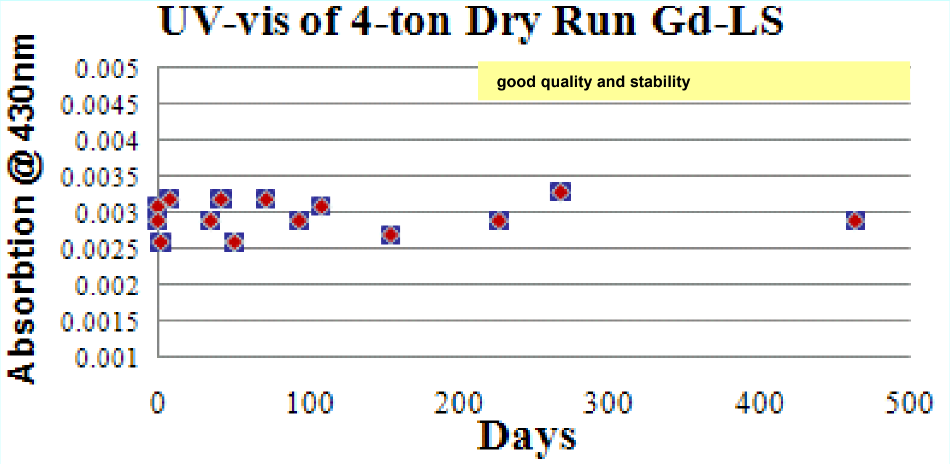


Gd-Loaded LS production at Daya Bay

- Chemical procedures
- Procurement of high quality materials & Purification of PPO/Gdcl3/TMHA
- Gd-compound production & Gd-LS production

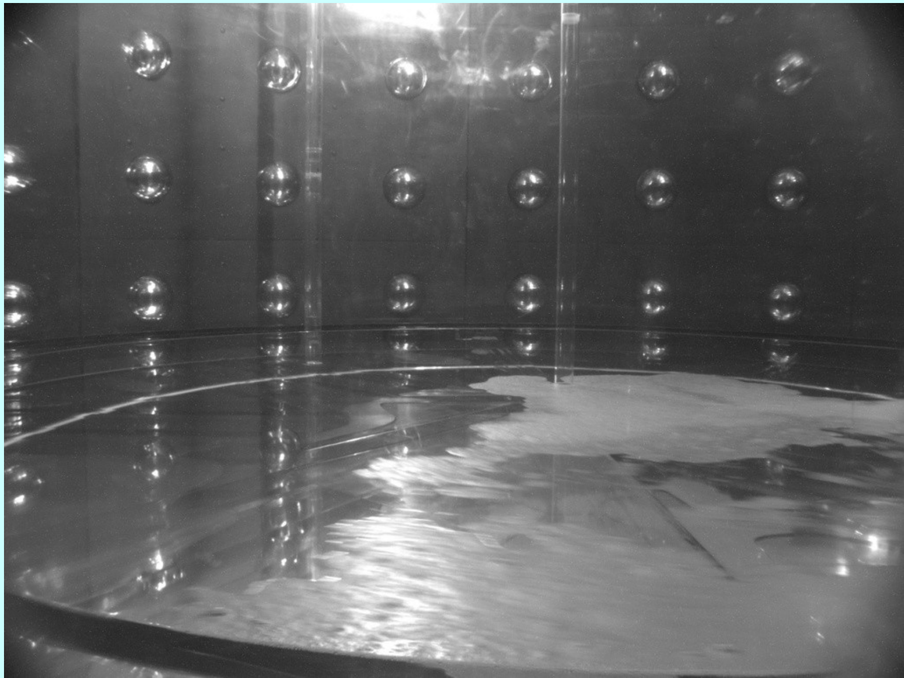


Gd-LS production Equipment tested at IHEP, used at Dayabay



AD filling

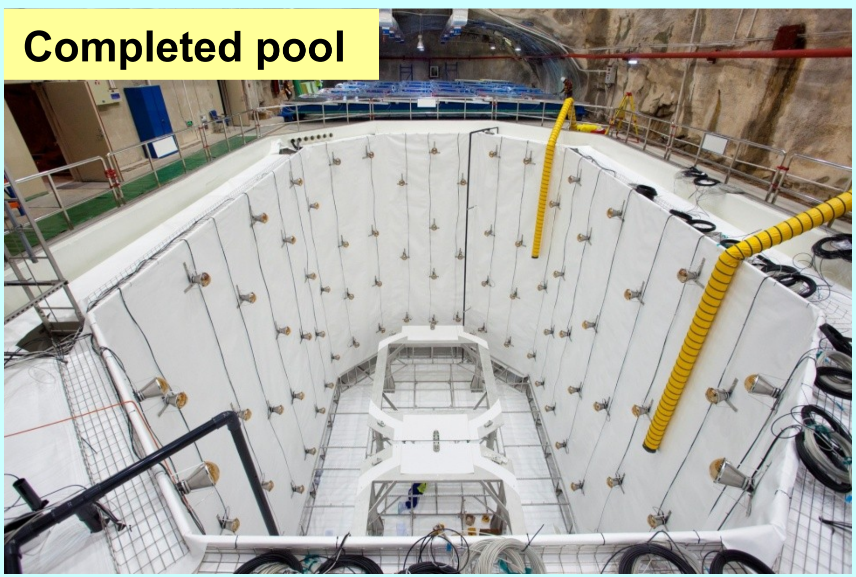
- Requirement: precision mass, equal liquid level and tem., chemical compatibility, …
- Equipment designed, manufactured and fully tested at UW, Madison, re-assembled at Daya Bay Hall 5
- Two ADs have been successfully filled



AD and muon detector installation

200t plastic bag


PMT supporting structure

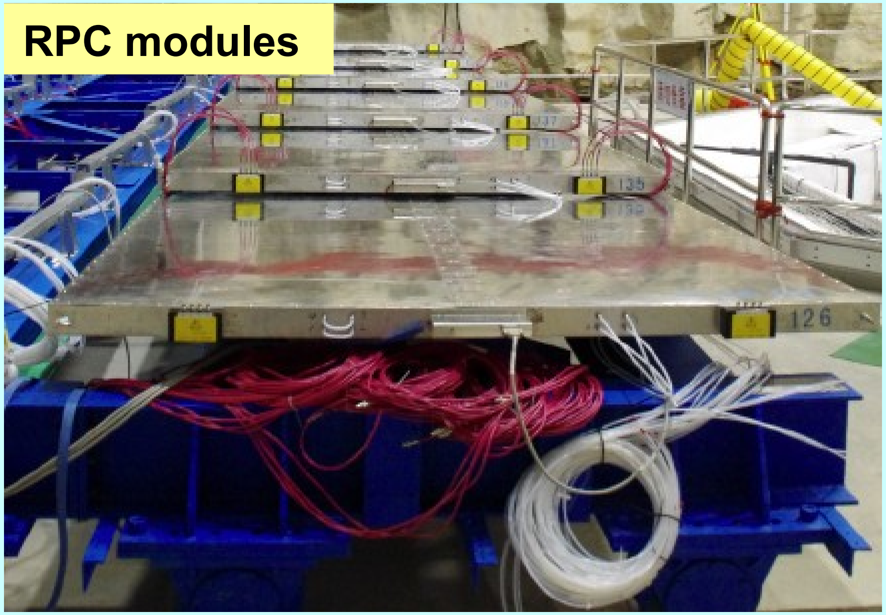

Completed pool

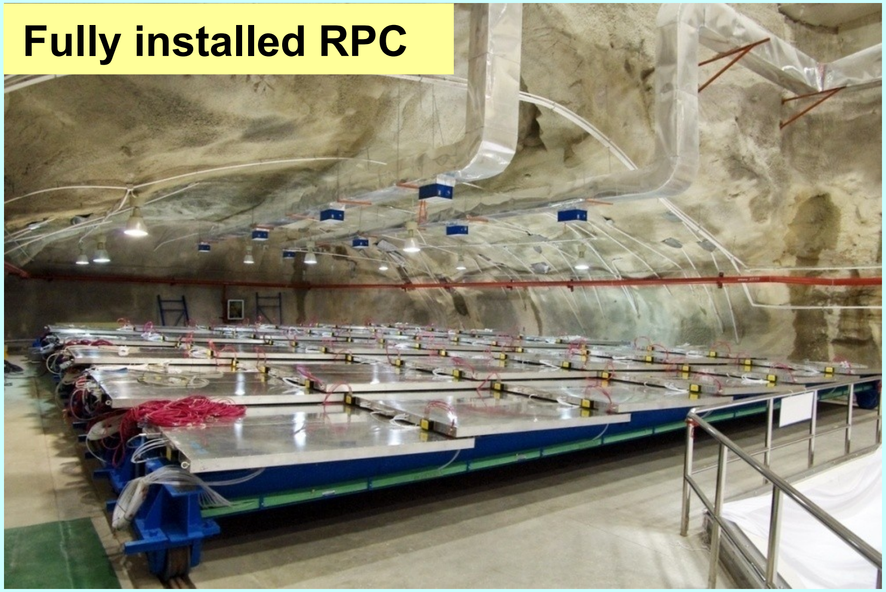

AD1 installed

RPC installation

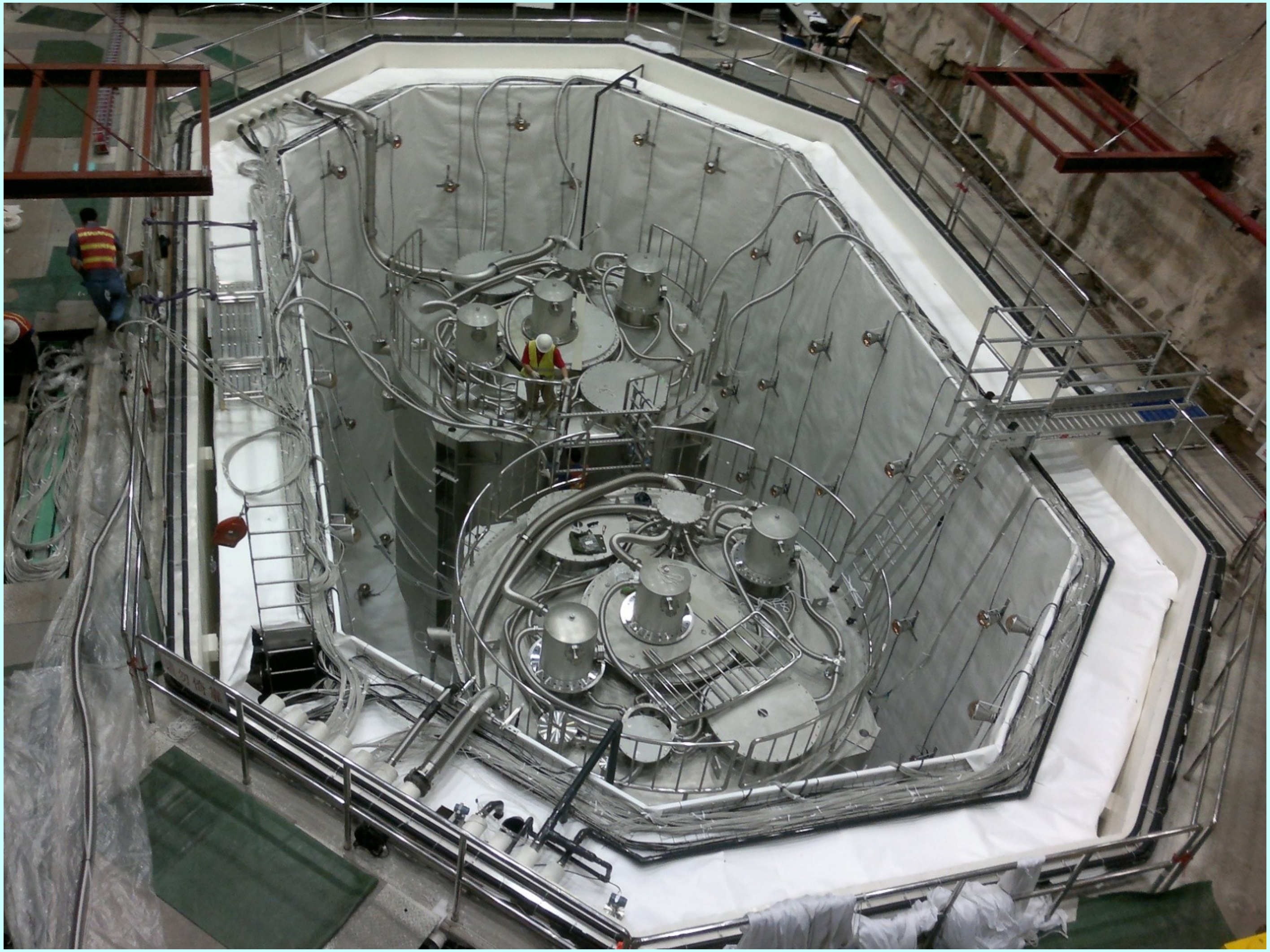

RPC supporting structure


Gas system

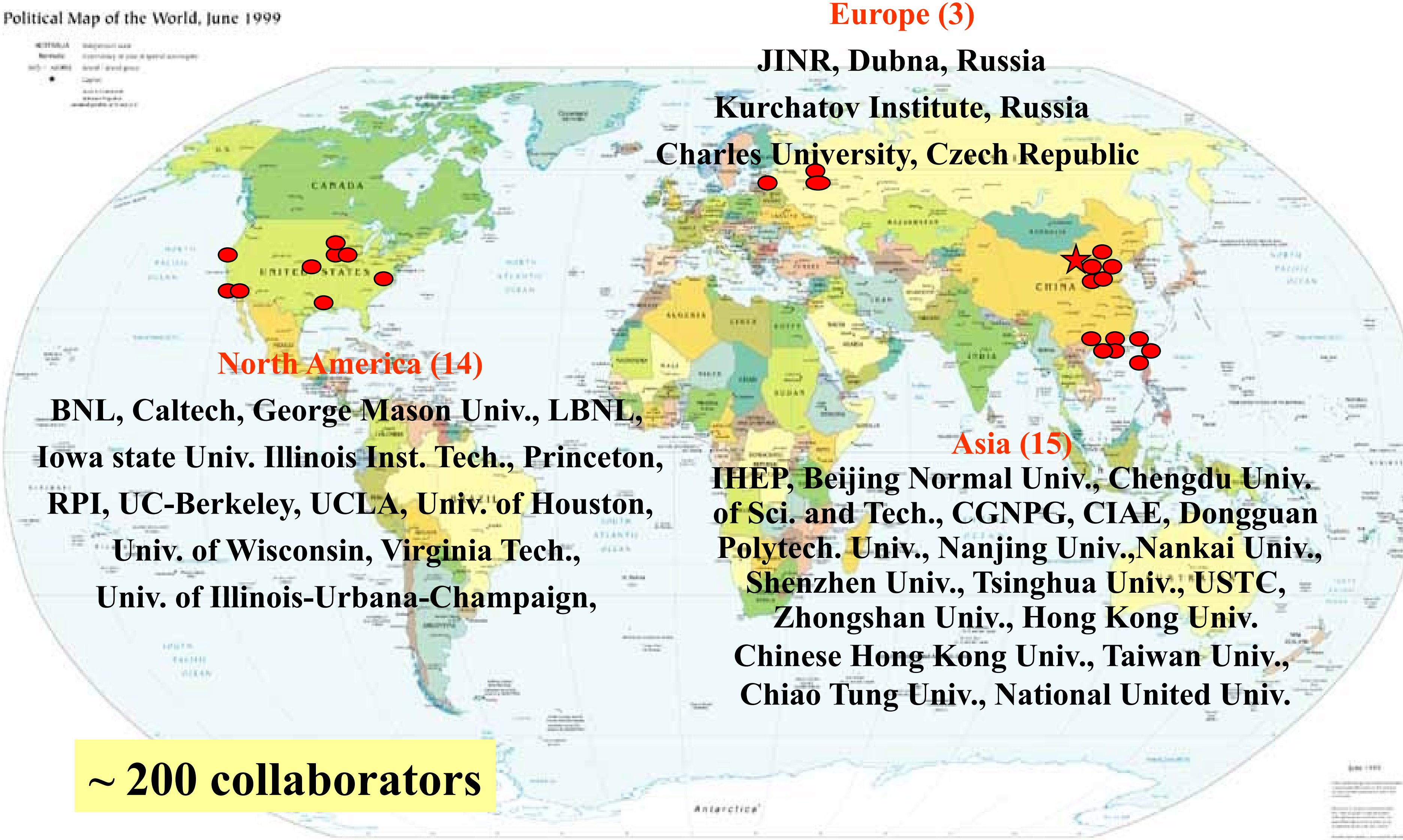

RPC modules


Fully installed RPC

Near site water filling will start in a few days, Data taking in a few weeks, full data taking next summer



Daya Bay collaboration



Europe (3)

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

North America (14)

BNL, Caltech, George Mason Univ., LBNL, Iowa state Univ. Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Houston, Univ. of Wisconsin, Virginia Tech., Univ. of Illinois-Urbana-Champaign,

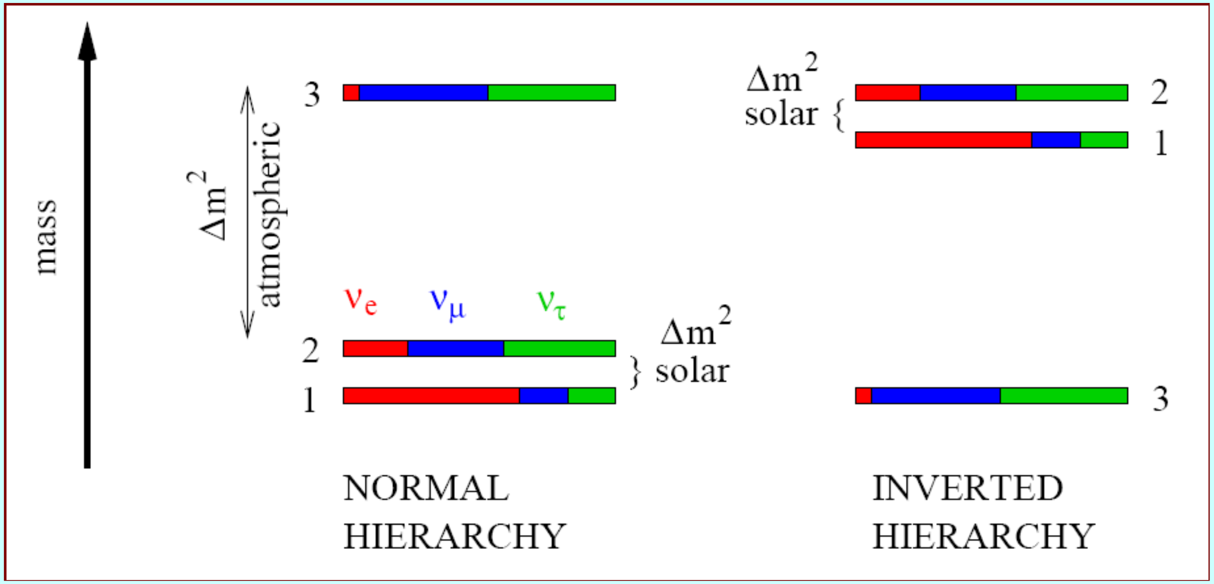
Asia (15)

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

~ 200 collaborators

Future prospects

Neutrino mass hierarchy



$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$
$$\text{NH}: \quad |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\text{IH}: \quad |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

- Three unknowns in neutrino oscillation:
  - 1. delta-CP phase
  - 2. theta13 value
  - 3. mass hierarchy

parameter	best fit	2σ	3σ
$\Delta m^2_{21} [10^{-5} \mathrm{eV}^2]$	7.6	7.3-8.1	7.1-8.3
$\|\Delta m^2_{32}\| [10^{-3} \mathrm{eV}^2]$	2.4	2.1-2.7	2.0-2.8
$\sin^2 \theta_{12}$	0.32	0.28-0.37	0.26-0.40
$\sin^2 \theta_{23}$	0.50	0.38-0.63	0.34-0.67
$\sin^2 \theta_{13}$	0.007	≤ 0.033	≤ 0.050

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 $Sin^2(2\theta_{13}) > 0.02$
    - 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

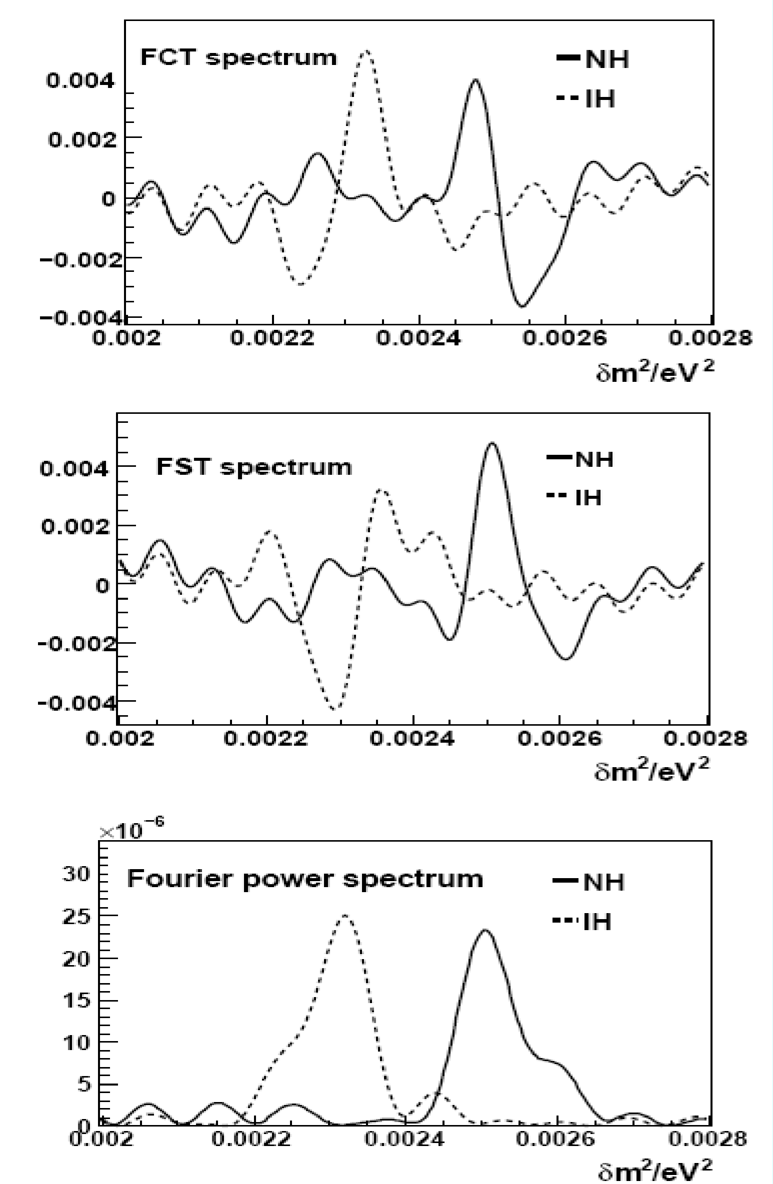
Features of Mass Hierarchy

- **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

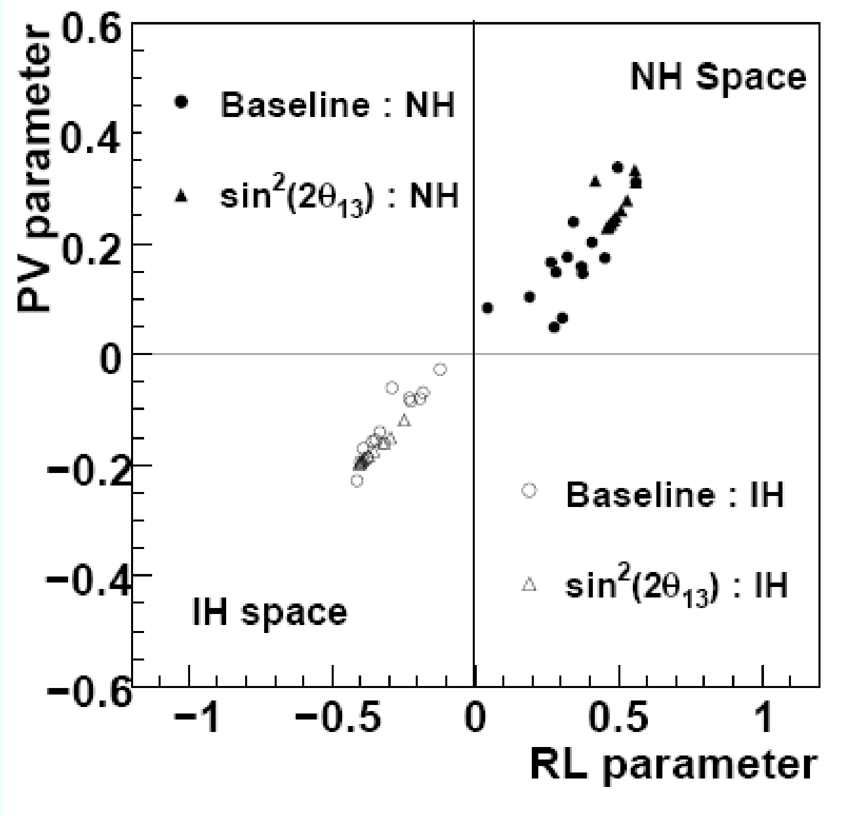
- To quantify the symmetry breaking, we define:

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

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

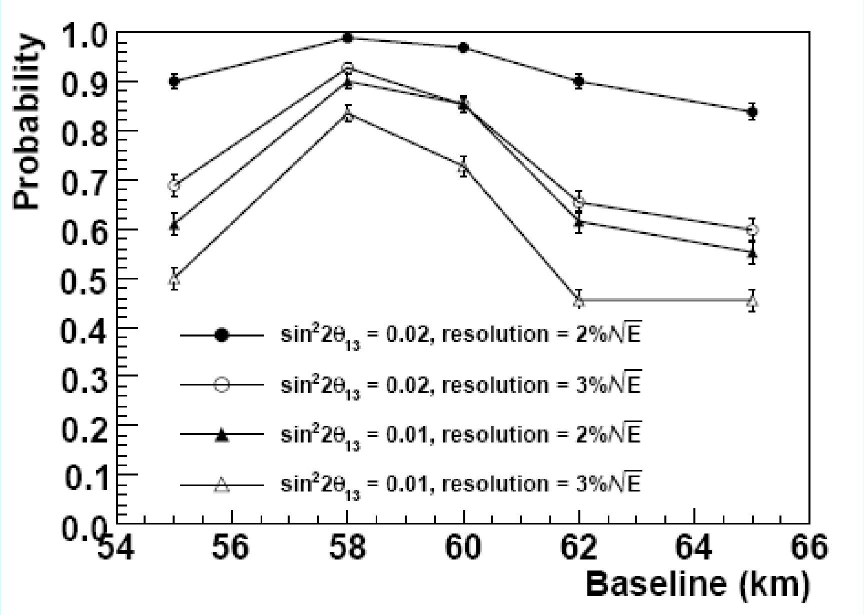
Baseline: 46-72 km

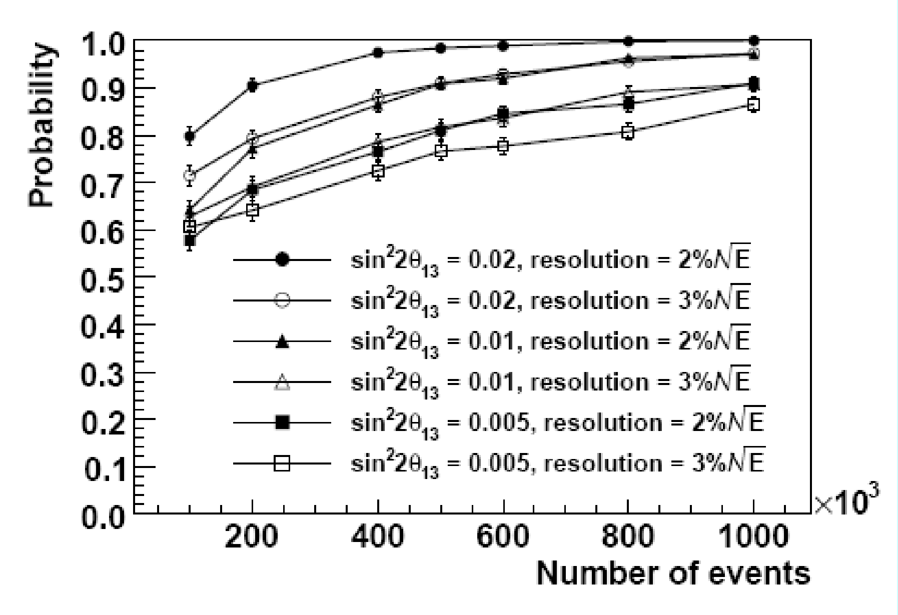
$\sin^2(2\theta_{13})$: 0.005-0.05

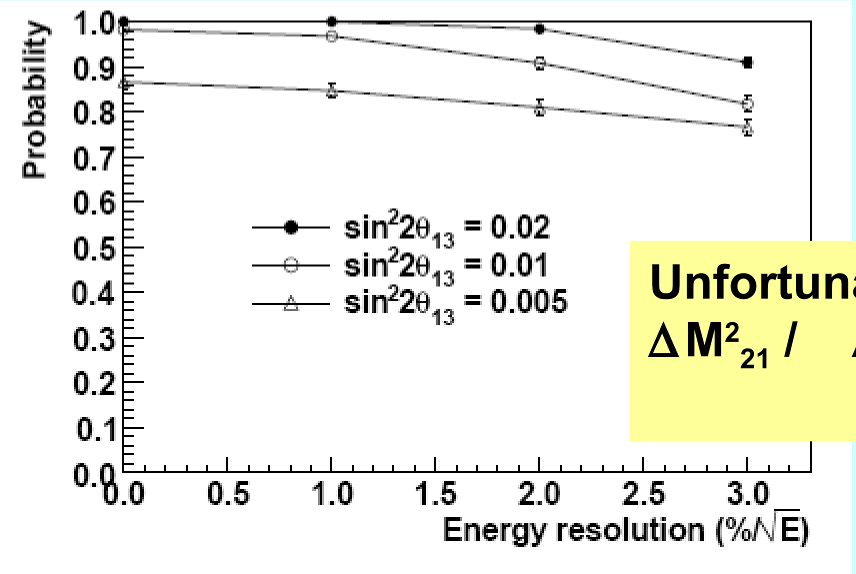
Others from global fit

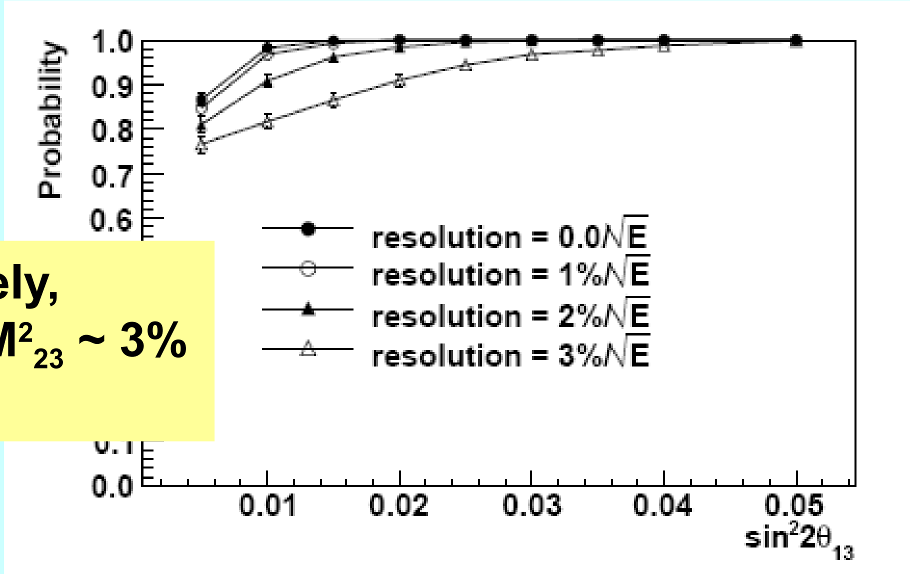
L. Zhan et al., PRD78:111103,2008

In reality





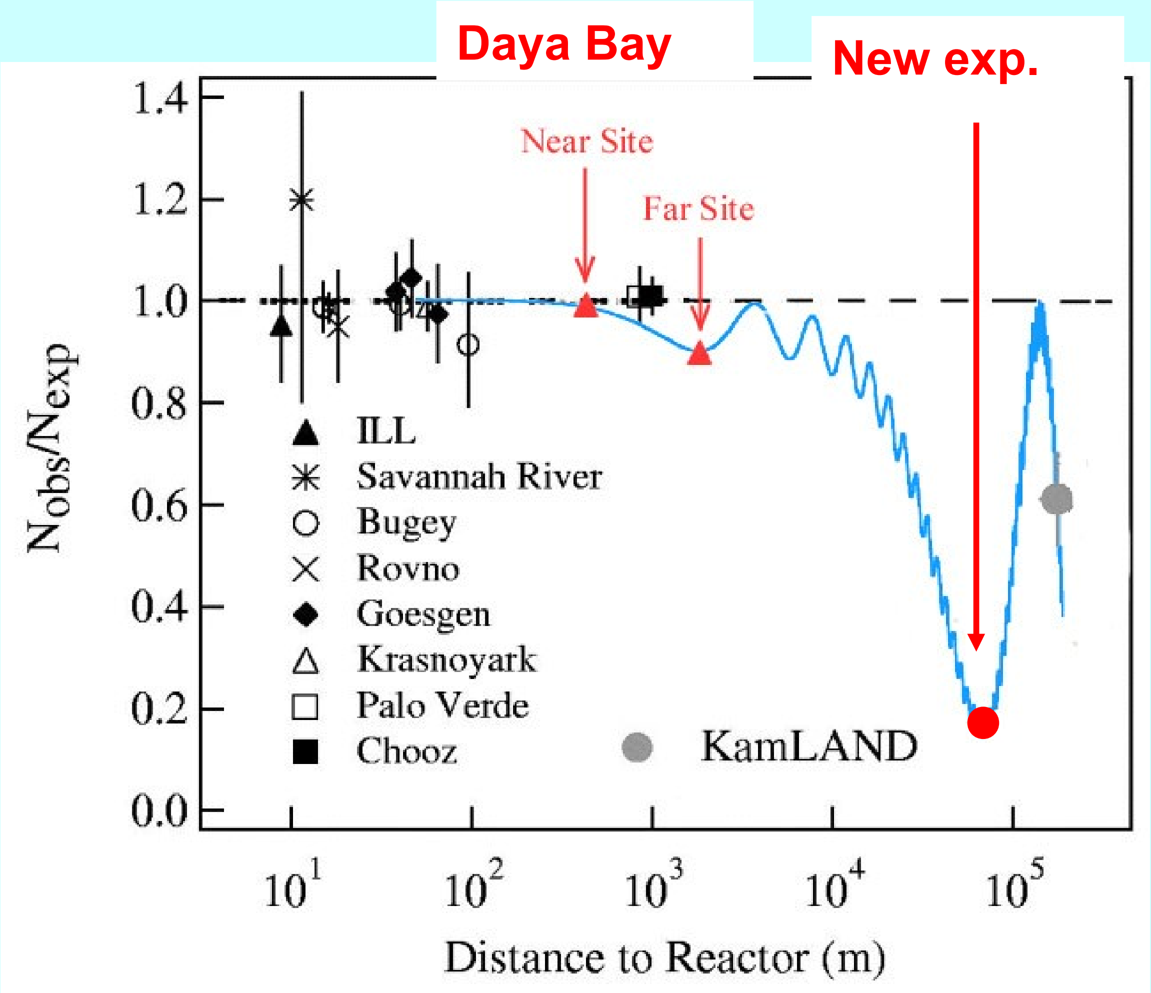




Unfortunately,
ΔM^2_{21} / ΔM^2_{23} ~ 3%

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

A possible Future Neutrino Experiment for mass hierarchy



- **Detector: 10-50kt liquid scintillator**
- **Energy reso.: 2-3%**
- **Scientific goal**
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision meas. of mixing matrix elements**
  - ⇨ **Supernovae**
  - ⇨ **Geo-neutrino**
  - ⇨ **Atmospheric neutrinos**
  - ⇨ **Sterile neutrinos**
  - ⇨ **Exotic searches**

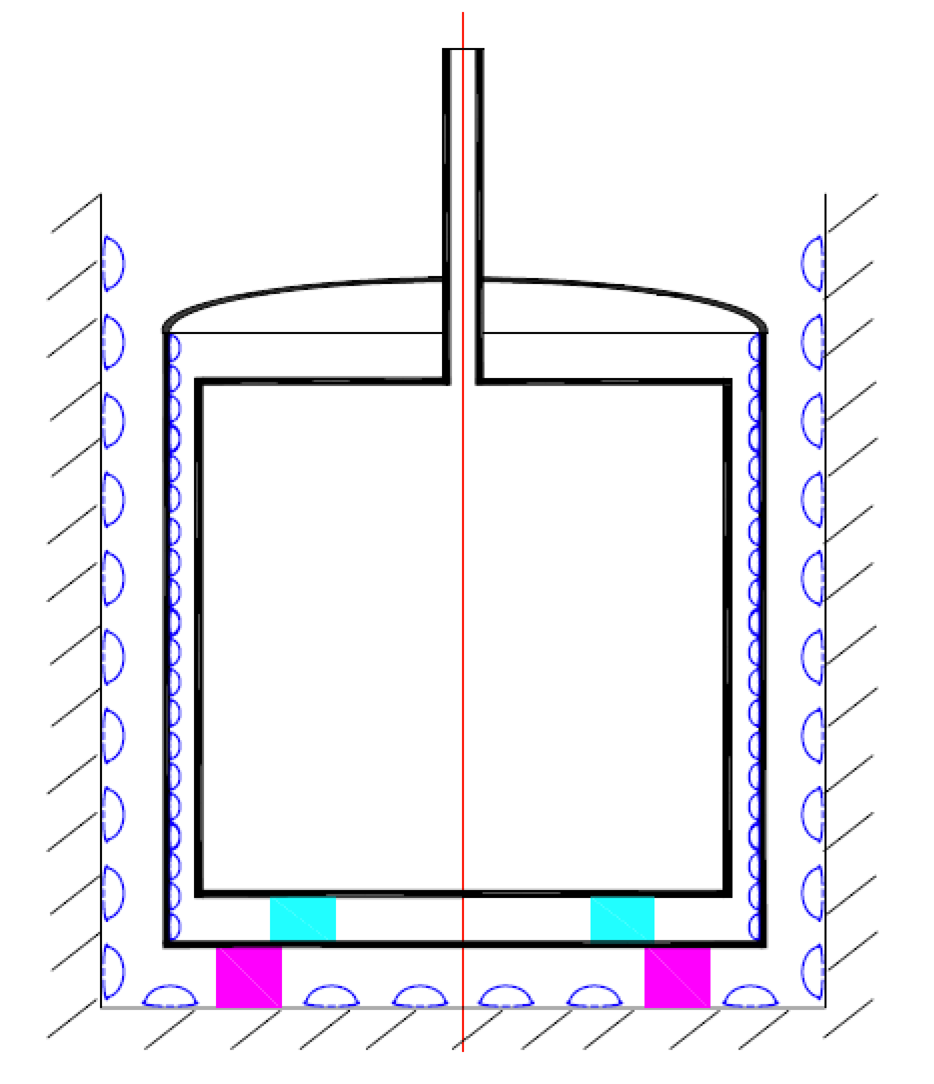
A possible location

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

Detector concept

- Neutrino target: ~20kt LS, LAB based

  30m(D)× 30m(H)
- Oil buffer: 6kt
- Water buffer: 10kt
- PMT: 15000 20”



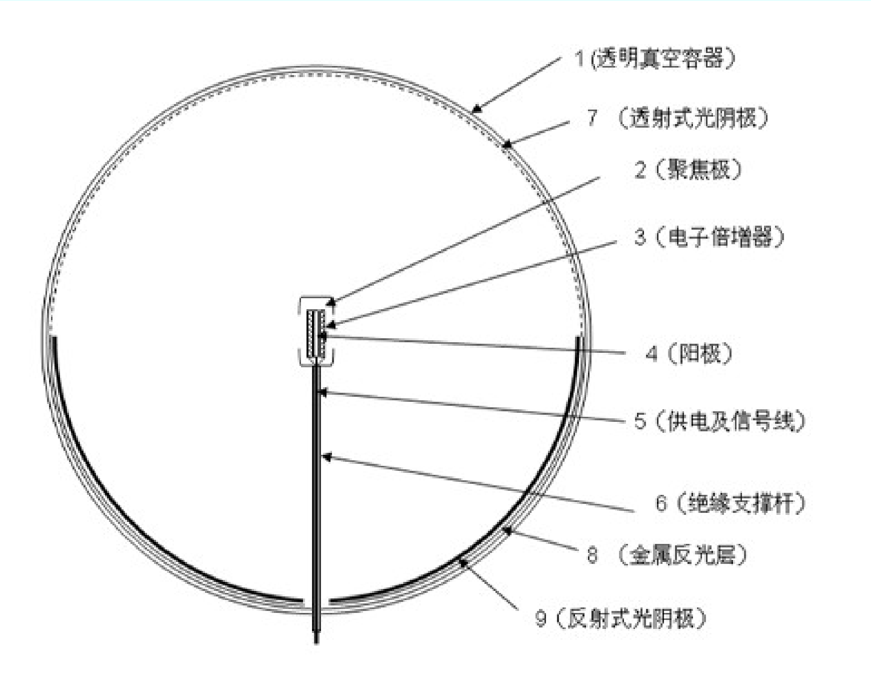
Technical challenges

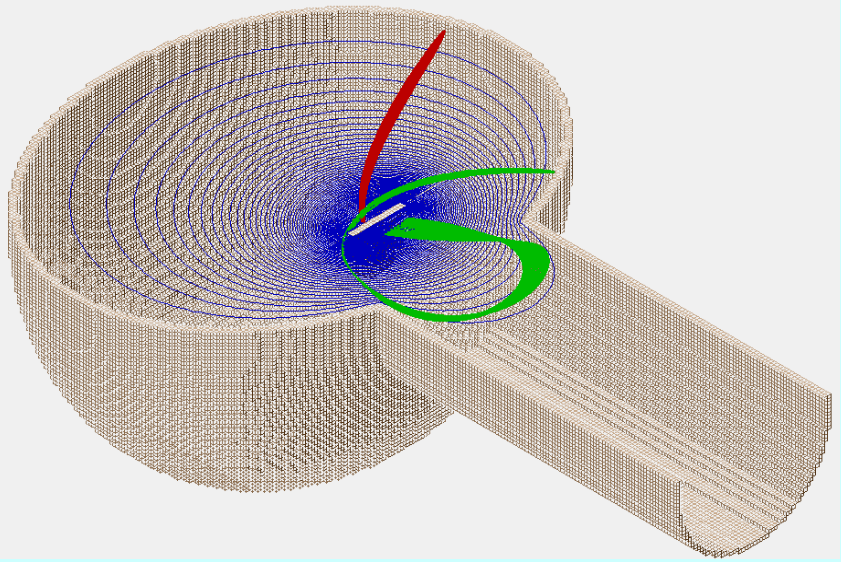
- **Requirements:**
  - Large detector: >10 kt LS
  - Energy resolution: $2\%/\sqrt{E}$ ➔ 2500 p.e./MeV
- **Ongoing R&D:**
  - Low cost, high QE "PMT"
    - New type of PMT
  - Highly transparent LS: 15m ➔ >25m
    - Understand better the scintillation mechanism
    - Find out traces which absorb light,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





5”MCP-PMT

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

~ × 2 improvement

Reactor neutrinos are powerful

- 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
- A free neutrino factory

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} ?

For sure it is not the end of story

Rome, *Cimitero Acattolico*

- Many problems for you to solve
- A bright future for you
- you are (never) not too late