Reactor Neutrino Experiments（I）

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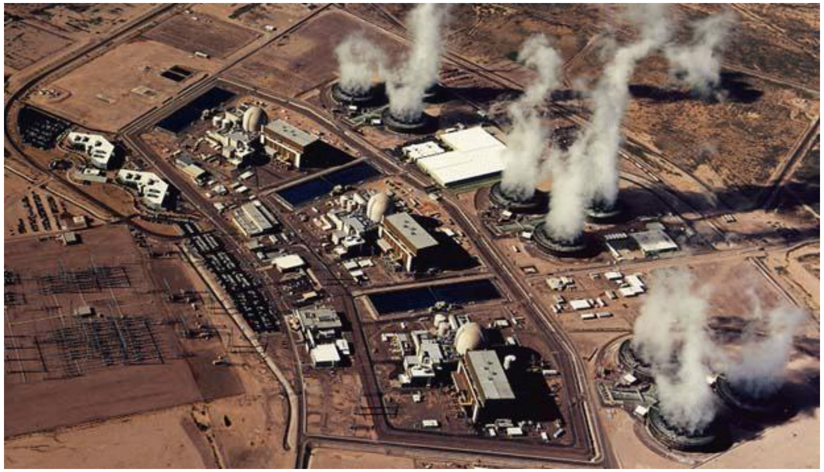
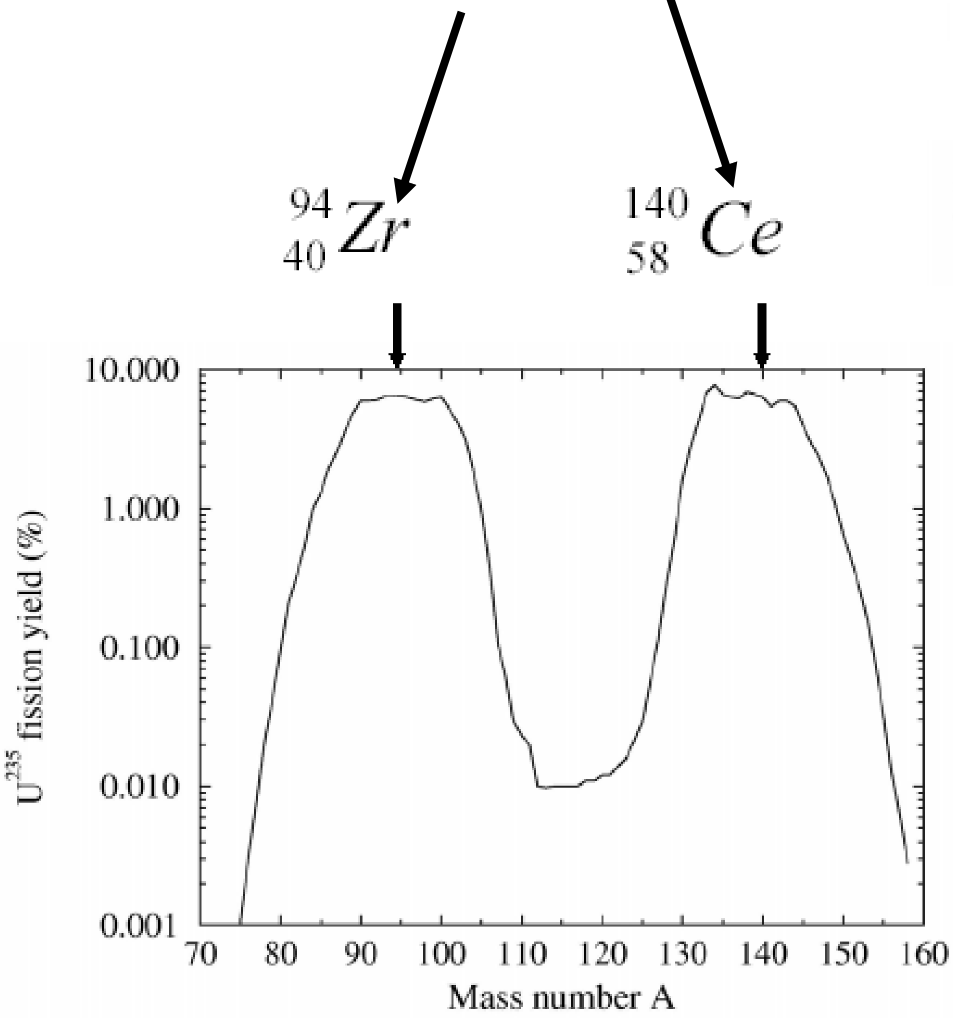
Neutrinos from Reactors



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



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

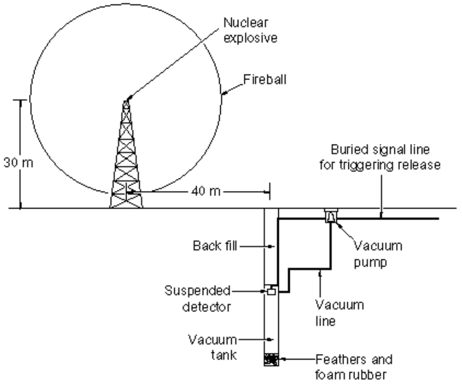
Neutrino flux of a commercial reactor with 3 $GW_{thermal}$: 6×10^{20} /s $\bar{\nu}$

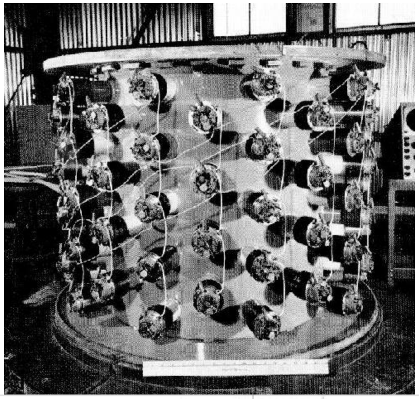
Neutrinos Discovered at Reactors

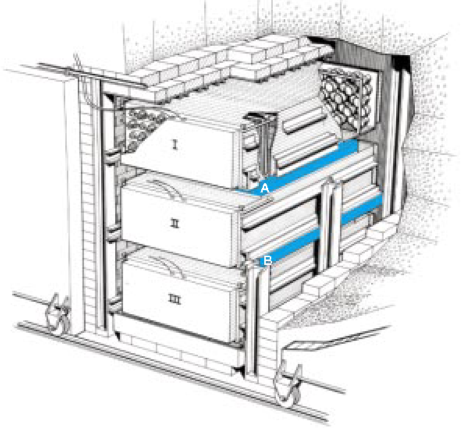
- Reines' first attempt: during nuclear bomb explosion through the reaction using liquid scintillator:

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

- Second attempt— Hanford experiment in 1953: backgrounds more than signals
- Third attempt—Savannah River experiment in 1956: successfully found neutrinos by adding anti-coincidence veto detectors



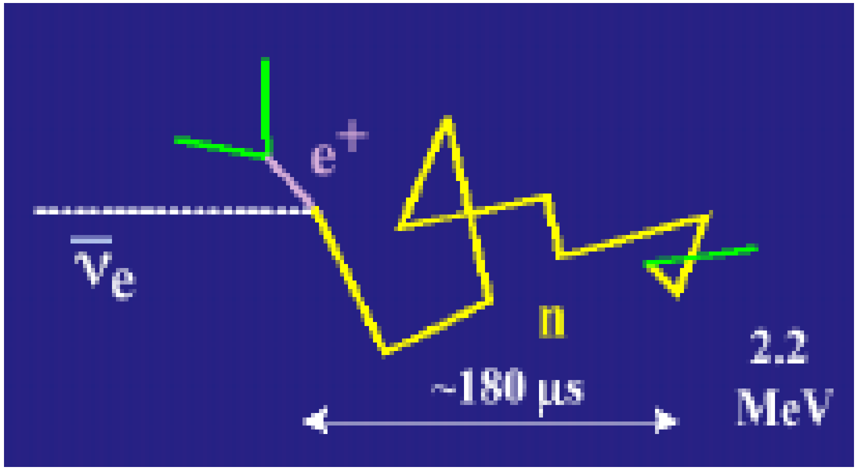




Frederick Reines
1997 Nobel prize

Neutrino Detection: Inverse-β Decays in Liquid Scintillator

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



$\tau \approx 180$ or $28\ \mu s$(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:

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV: Threshold}}$$

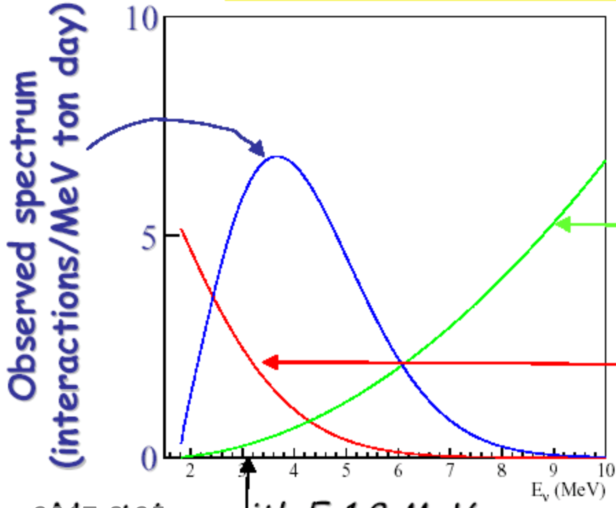
Why LS:

Being both the target and detector
Proton rich material
Good energy resolution
Easy handling for large volume
Relatively Cheap

Reactor Neutrino Spectrum

- **Three ways to obtain reactor neutrino spectrum:**
  - **Direct measurement**
  - **First principle calculation**
  - **Sum up neutrino spectra.** **^{235}U, ^{239}Pu, ^{241}Pu from their measured β spectra, ^{238}U from calculation (10%)**

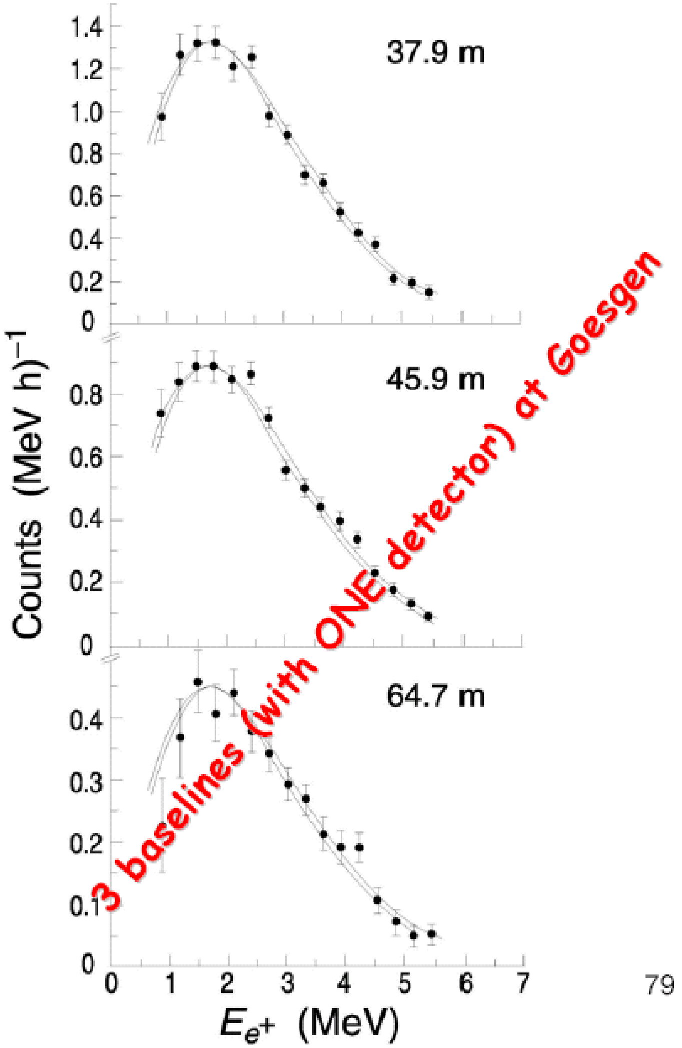
The $\bar{\nu}_e$ energy spectrum



ν_e+p→n+e$^+$ cross section (~10^{-42} cm^2)

Calculated reactor $\bar{\nu}_e$ spectrum (10^{-8} /s MeV GW$_{th}$)

Neutrinos with E<1.8 MeV are not detected

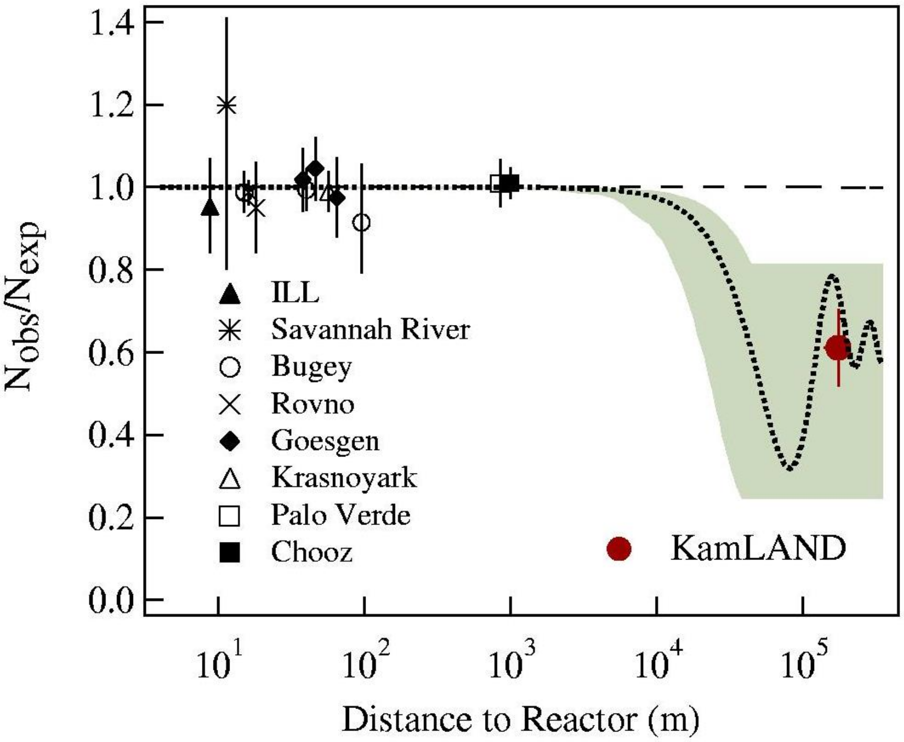


3 baselines (with ONE detector) at Goesgen

Reactor Neutrinos: a Brief History

- **Oscillation:**
  - **Early searches(70's-90's):**
    - ✓ **Reines, ILL, Bugey, … Palo Verde, Chooz**
  - **Determination of θ_{12}(90's-00's):**
    - ✓ **KamLAND**
  - **Discovery of θ_{13} (00's-10's):**
    - ✓ **Daya Bay, Double Chooz, RENO**
  - **Mass hierarchy(10's-20's):**
    - ✓ **JUNO, RENO-50**
- **Magnetic moments（90's-now)**
  - **Texono, MUNU, GEMMA, …**
- **Sterile neutrinos(10's):**
  - **Nucifer, Stereo, Solid …**

Oscillation signal:
$N_{obs}/N_{exp} < 1$



Savannah River experiment —

"Observation of neutrino oscillation"

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

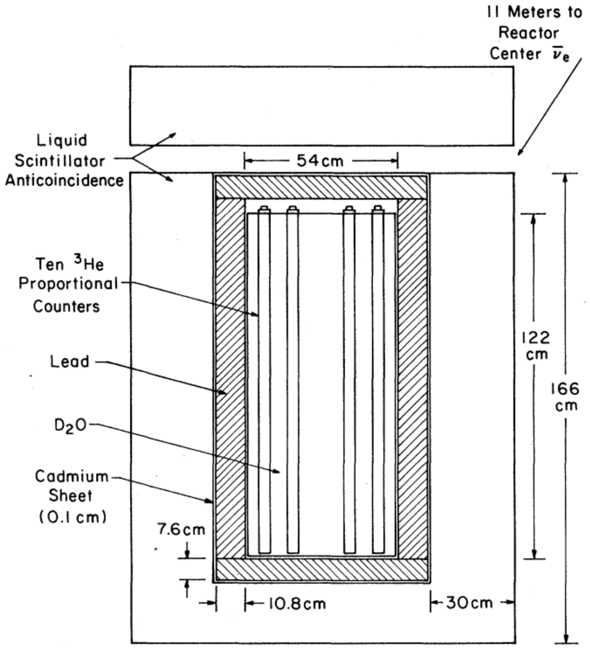
$$\bar{\nu}_e + d \begin{array}{ll} \nearrow n+n+e^+ & (ccd) \\ \searrow n+p+\bar{\nu}_e & (ncd) \end{array}$$

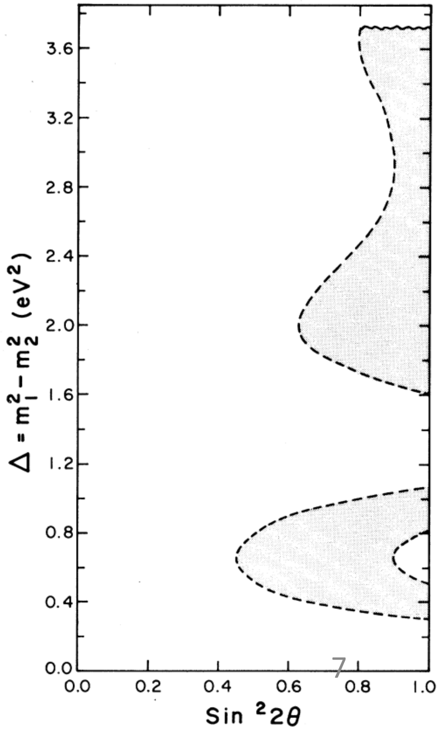
- Neutron signal:

$$n + {}^3He \rightarrow p + {}^3H + 764\ \text{keV}$$

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

$$= 0.40 \pm 0.22$$

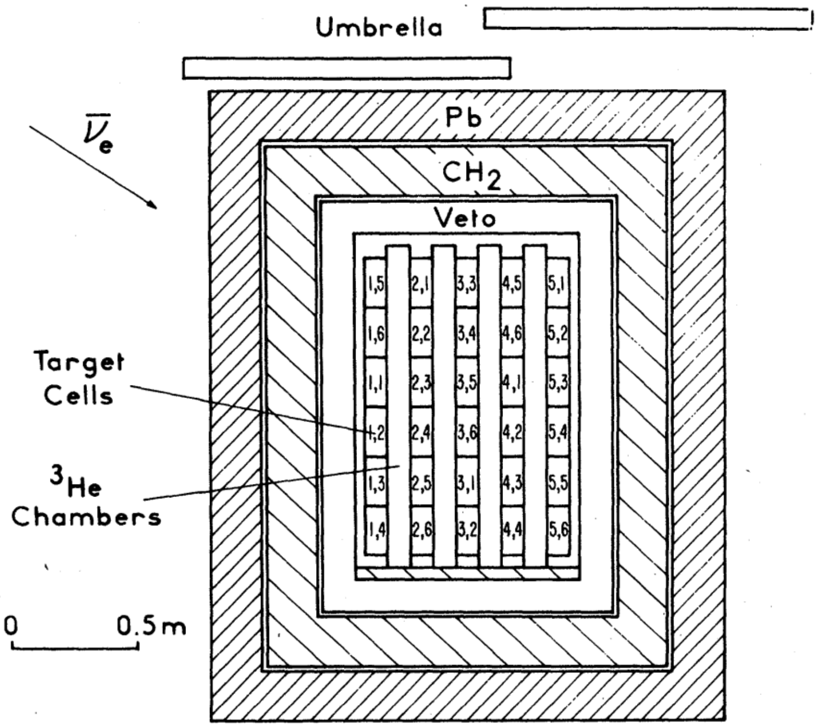


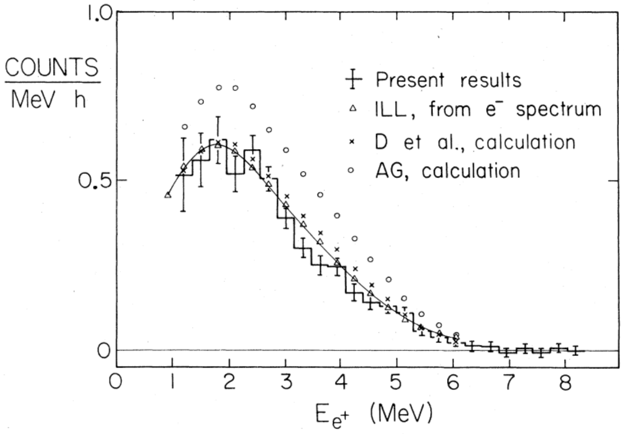


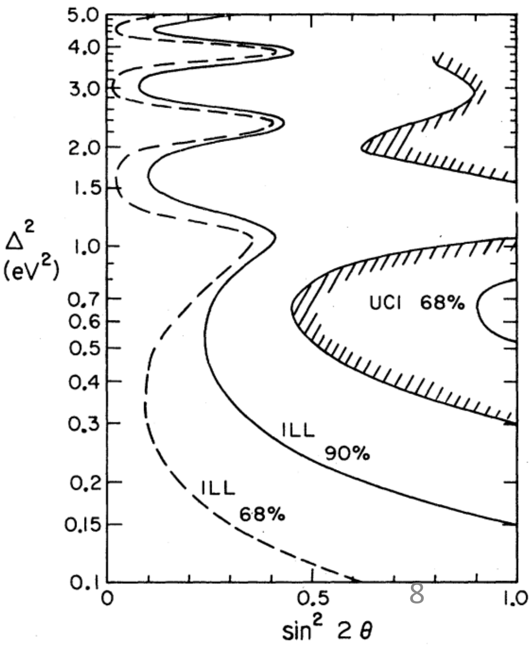
F. Reines et al., PRL 45(1980) 1307

ILL： First Debate

- Baseline: 8.7 m
- 377 l Liquid scintillator detector
- Neutrons: by 4 ^{3}He planes in between LS cells(τ=150 μs)
- Techniques used until now: shielding, veto, background, on/off Comparison, efficiency, spectrum, stability, etc.
- Neutrino flux: 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

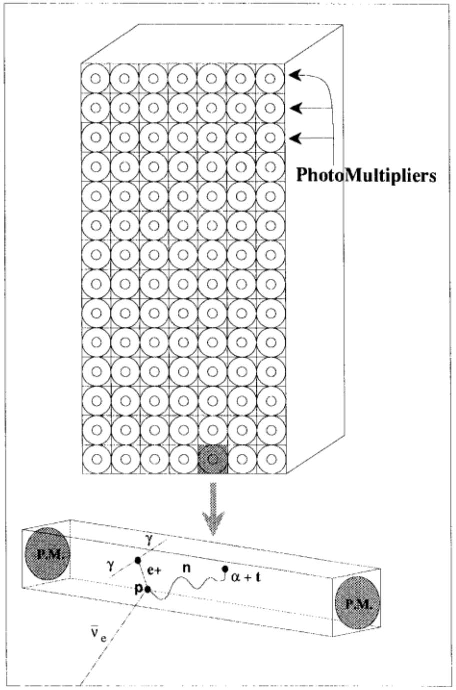
- Modules made of 98 SS cells, each of 0.85 m long, 8.5 cm ×8.5 cm in cross section, filled with PC based liquid scintillator doped with 0.15% ^{6}Li, and viewed by two PMTs at both ends
- Neutron signal (τ = 30 μs) :

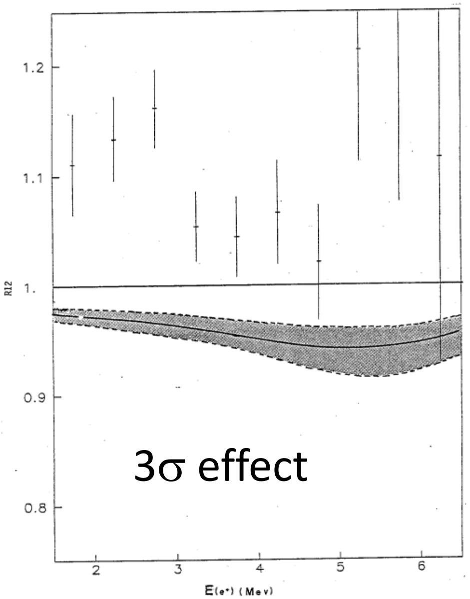
  $n+^6Li \rightarrow ^4He+^3H+4.8MeV$

  E_{vis}= 0.53 MeV +

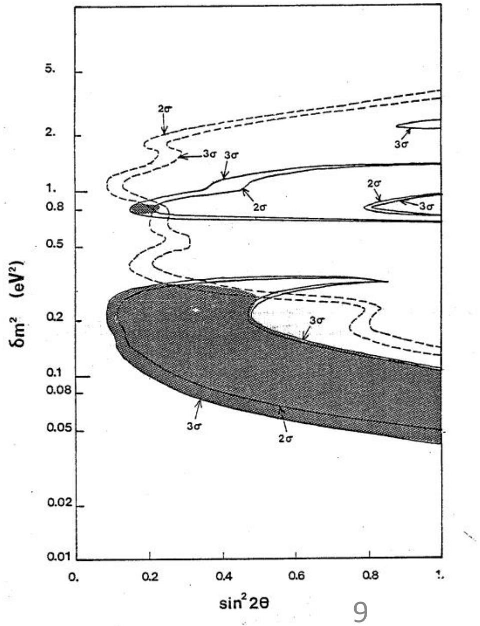
  PSD $Q_{delayed}/Q_{total}$
- Compare neutrino rate at

  14 and 18 m from reactors





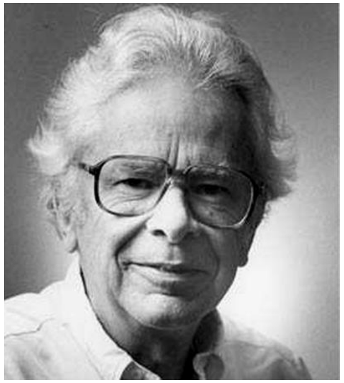
3σ effect

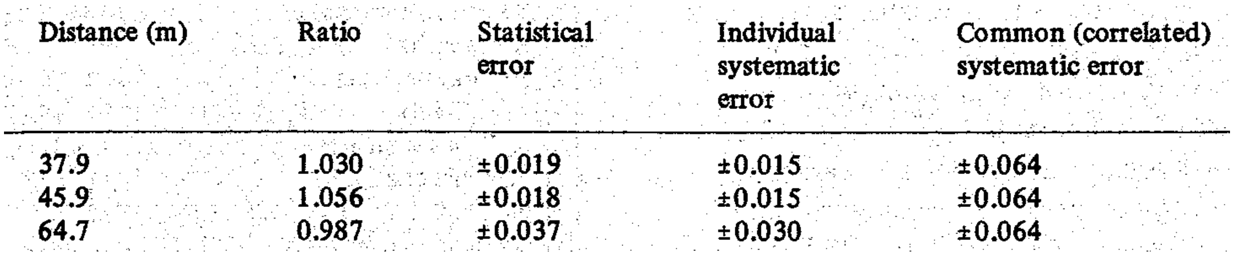


J.F. Cavaignac et al, Phys. Lett. B 148(1984)387

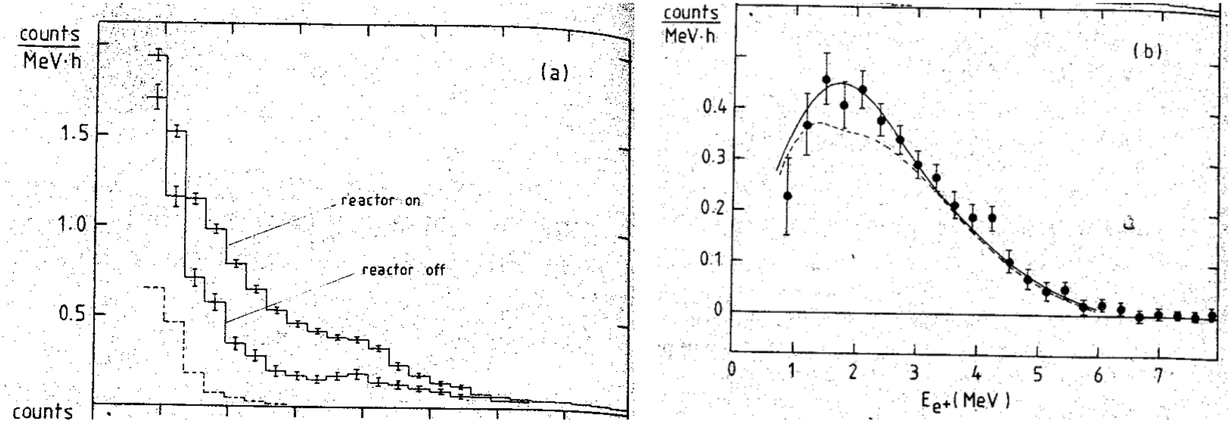
Disapproved Again by F. Boehm: Goesgen

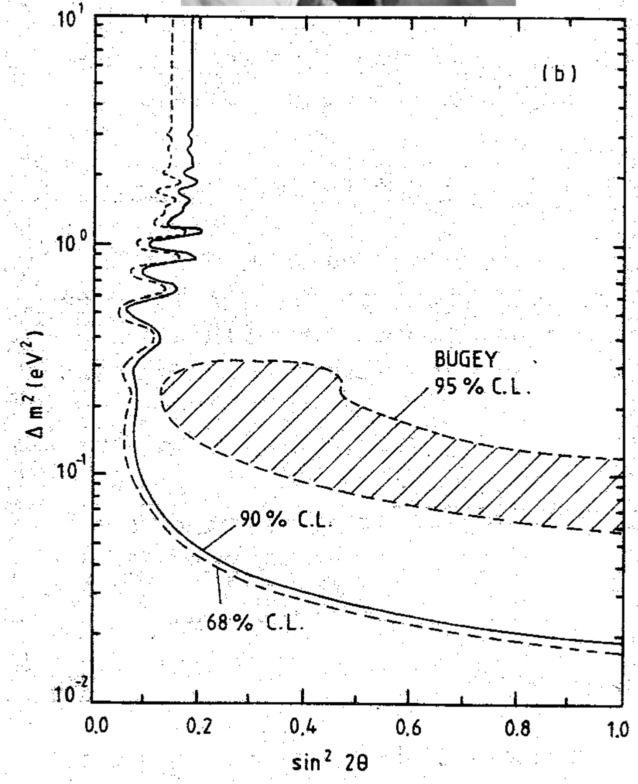
- Nearly the same Detector as ILL
- Baseline: 37.9, 45.9, 64.7
- Good agreement with expectation: rate and spectrum





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

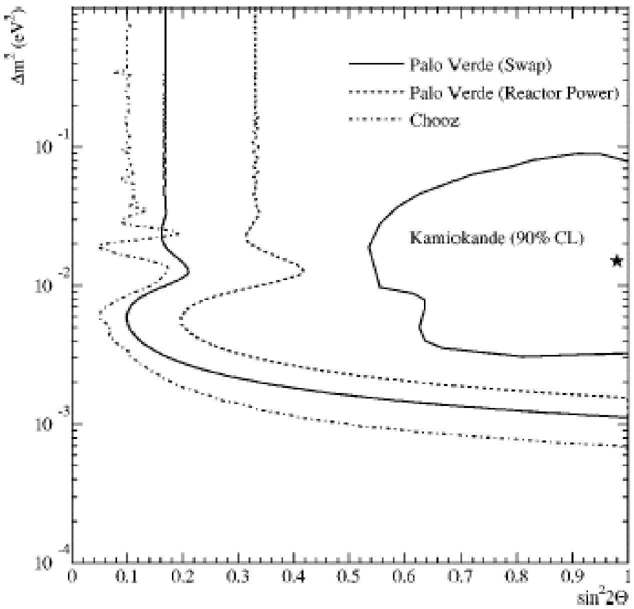
- Atmospheric neutrino results stimulate new experiments
  - If atmospheric $\nu_\mu \rightarrow \nu_e$
  - Baseline: ~1km
- F. Boehm: San Onofre ➔ Palo Verde (early 90's ➔ 00's)
  - From Goesgen
  - Difficult stories (California Gnatcatcher)
- Chooz (early 90's)
  - From Bugey+Russians
  - a successful story
- New techniques:

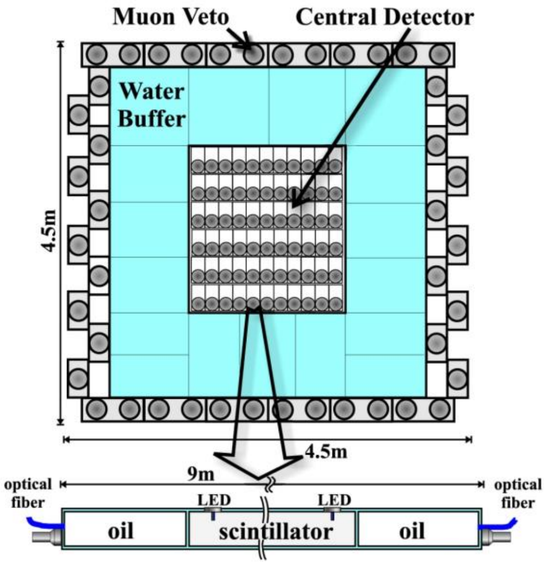
  larger detector,

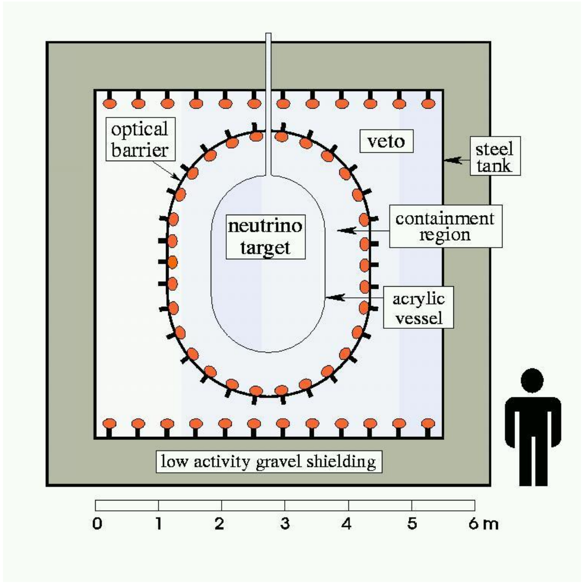
  Gd-LS, MC,

  HEP software &

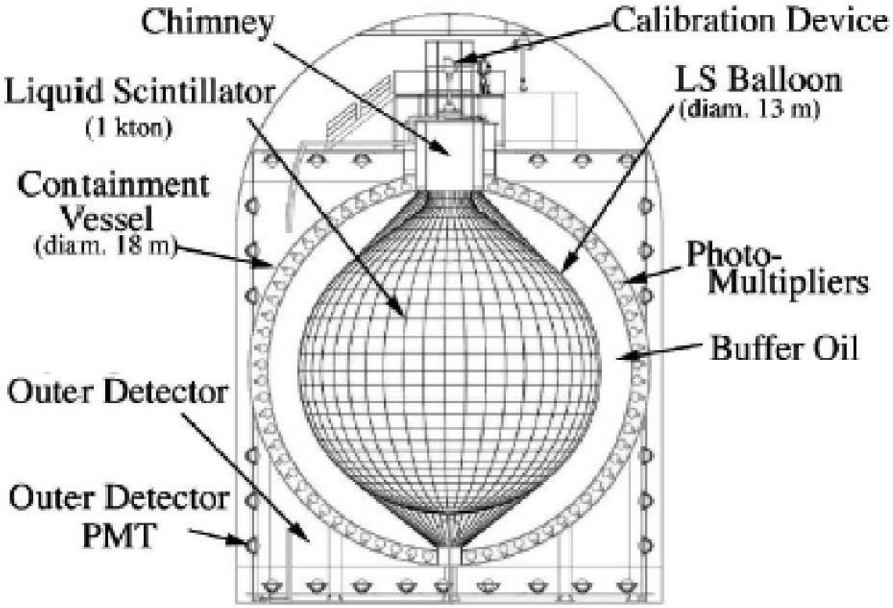
  analysis method …





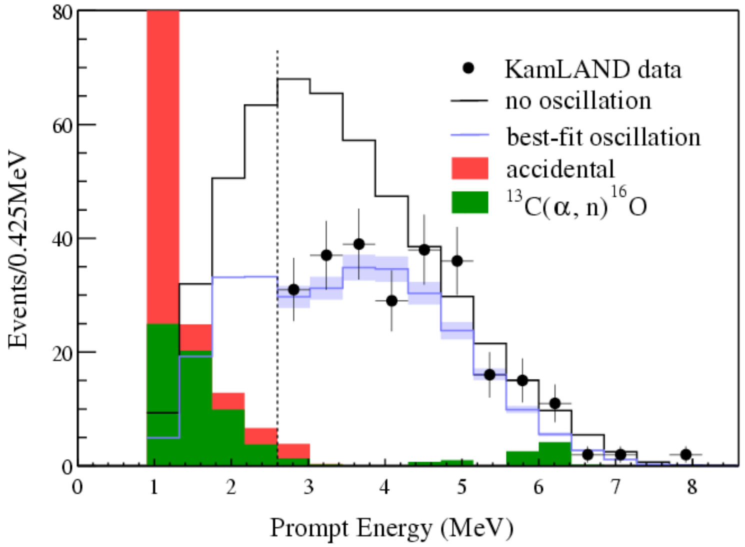


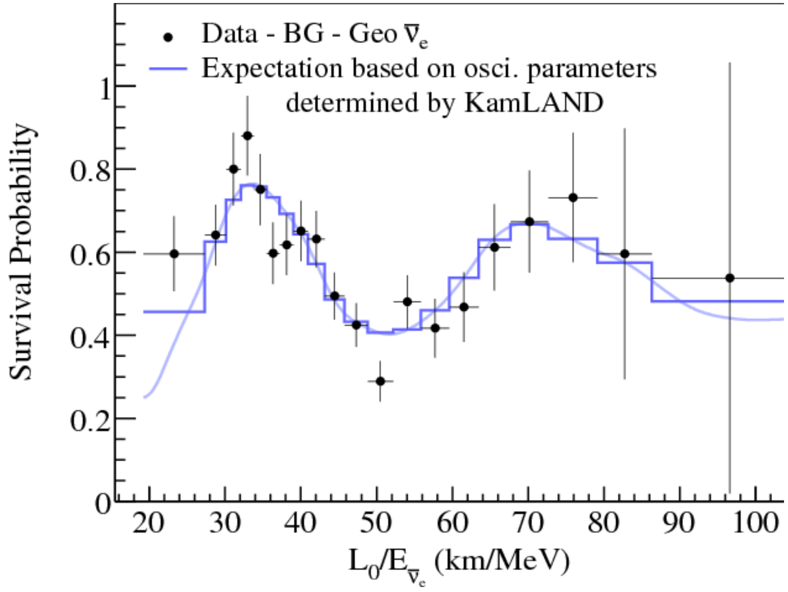
KamLAND



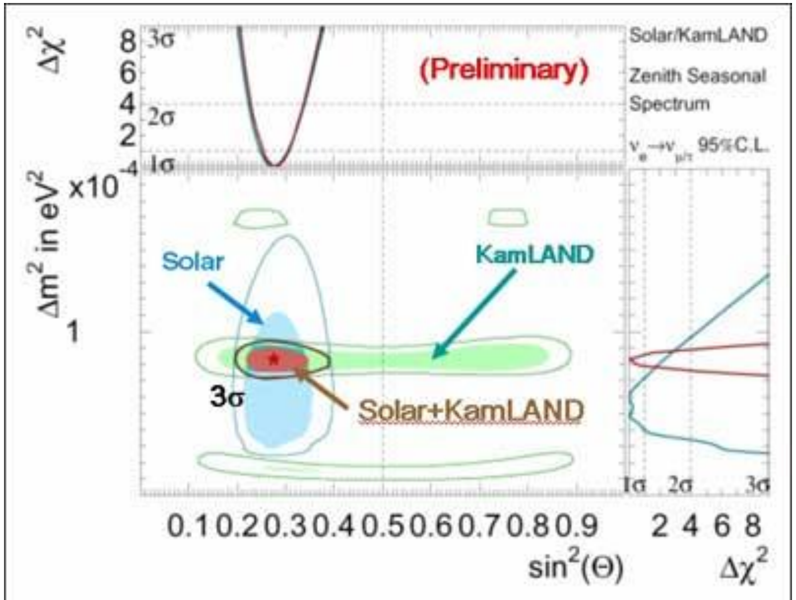
If solar neutrino problem is due to ν_e oscillation, reactor ν_e can be used to look at it, if CPT is valid and if LMA solution is correct ➔ a very brave move

KamLAND Results





R=0.658±0.044(stat) ±0.047(syst)



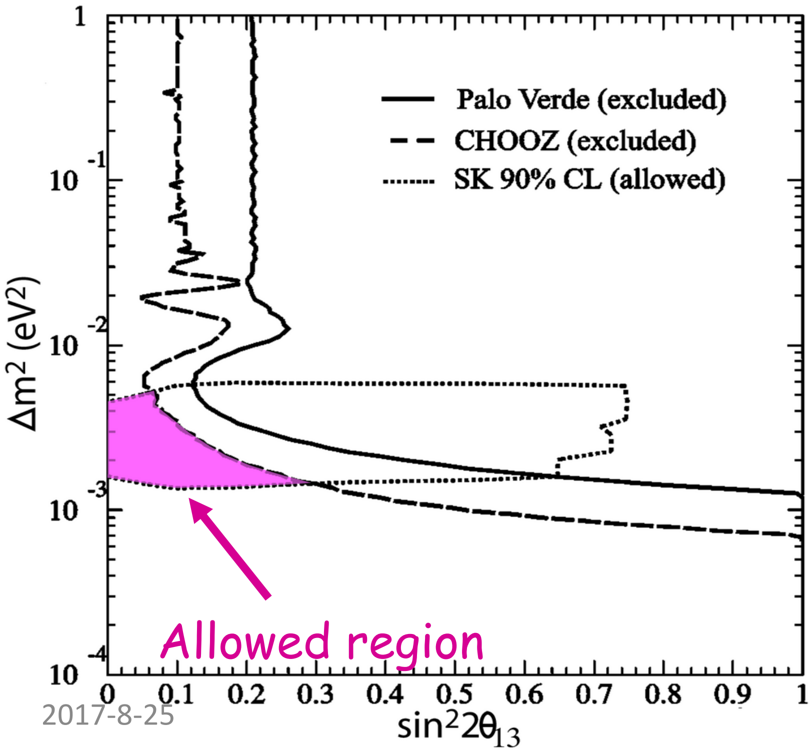
Excluded neutrino decay at 99.7% CL

Excluded decoherence at 94% CL

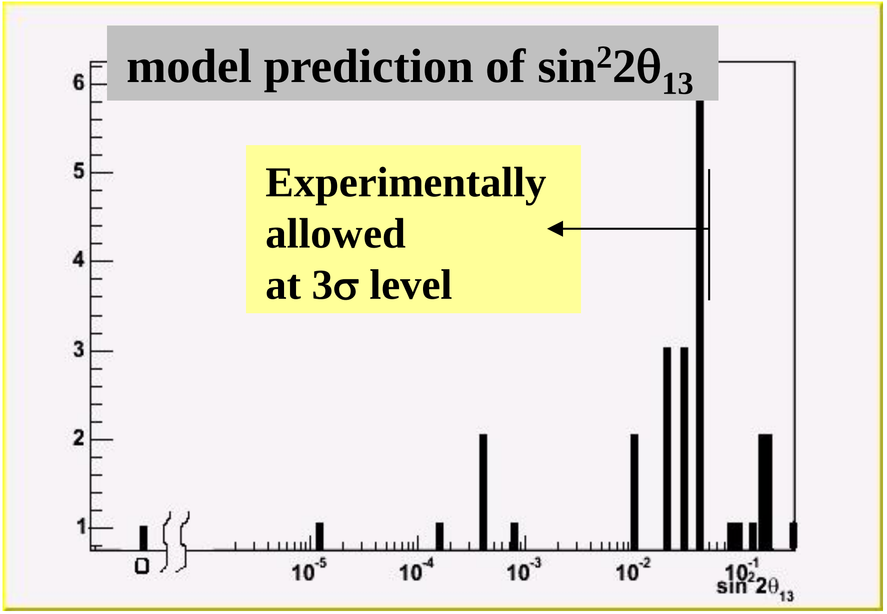
Firmly established neutrino oscillation

Experiments for θ_{13}

- Once θ_{23} and θ_{12} established in 2003, interests mount on θ_{13}
- 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 $\sin^2 2\theta_{13}$ ~ 0.1-10 %



Allowed region



model prediction of $\sin^2 2\theta_{13}$

Experimentally allowed at 3σ level

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

Why at reactors

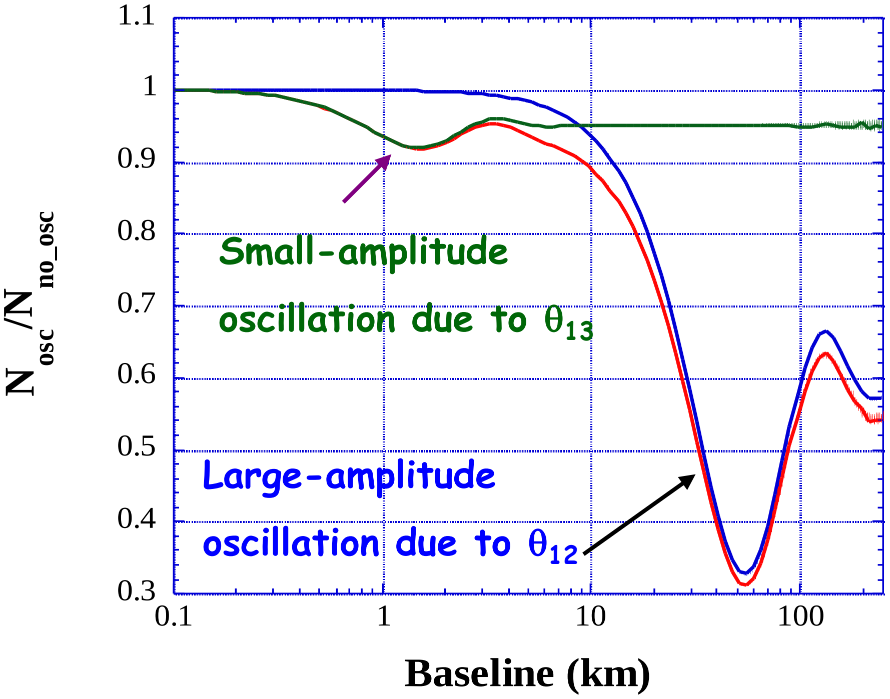
- Clean signal, no cross talk with δ and matter effects
- Relatively cheap compare to accelerator based experiments
- Can be very quick

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:

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

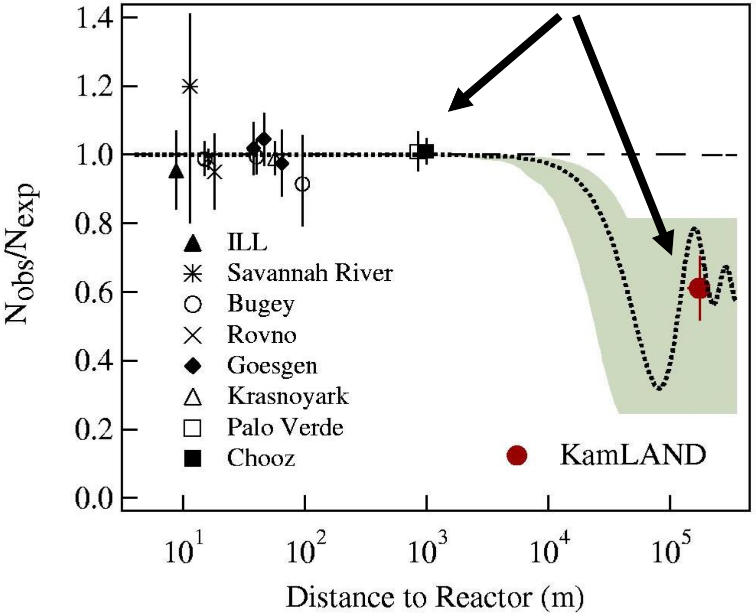


Small-amplitude oscillation due to θ_{13}

Large-amplitude oscillation due to θ_{12}

Reactor Experiment: comparing observed/expected neutrinos:

Typical precision: 3-6 %



Precision of past experiments:

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

- **Backgrounds： ~1-3%**

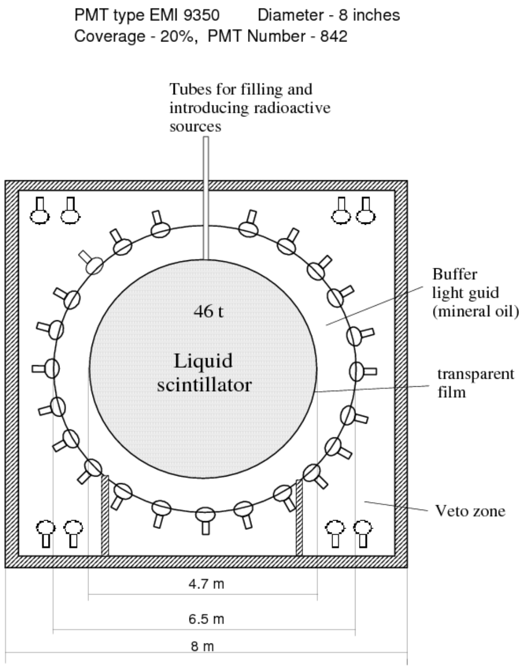
- **Target mass： ~1-2%**
- **Efficiency： ~2-3%**

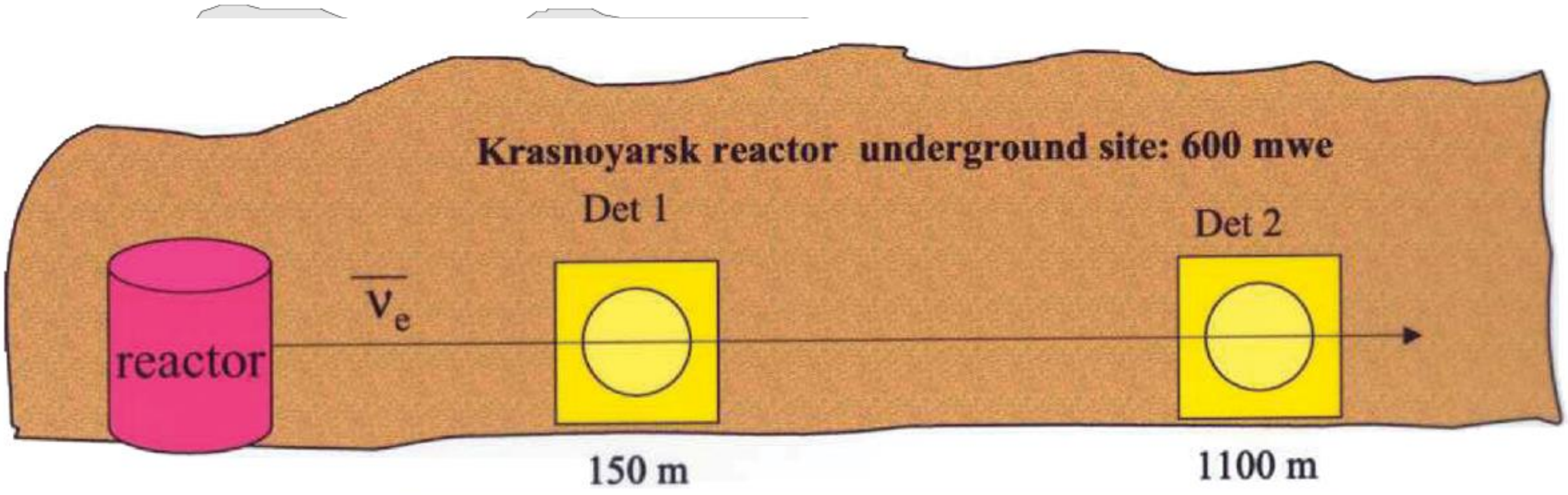
We need a precision of ~ 0.4%

First idea: Kr2Det

- Krasnoyarsk underground reactor
- Near-far cancellation

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

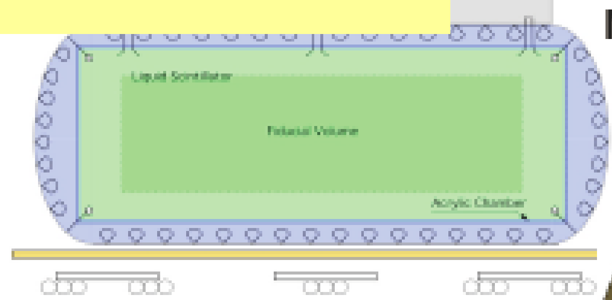


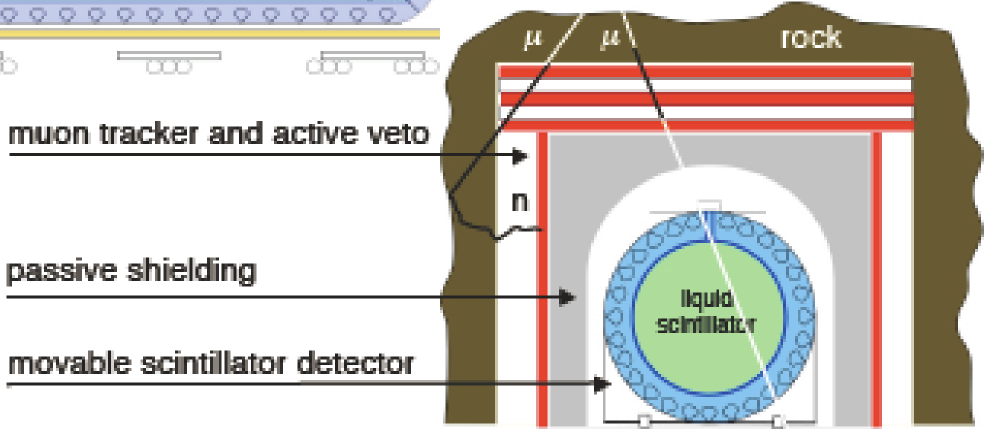


Target:	50 m^3 oil+ppo	50 m^3
Rate:	2500/d	50/d
S/B:	>>1	~10:1

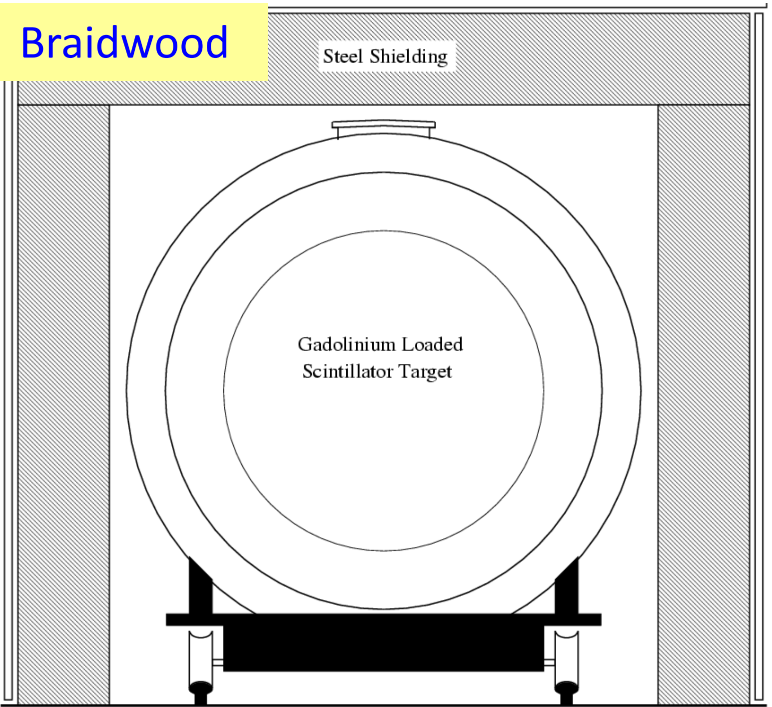
Movable Liquid Scintillator Antineutrino Detectors

Diablo canyon

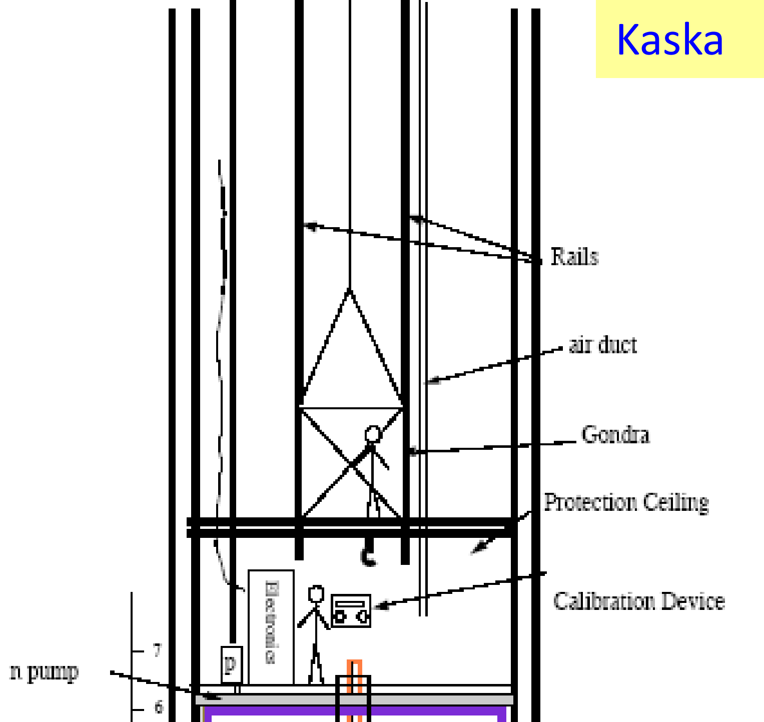


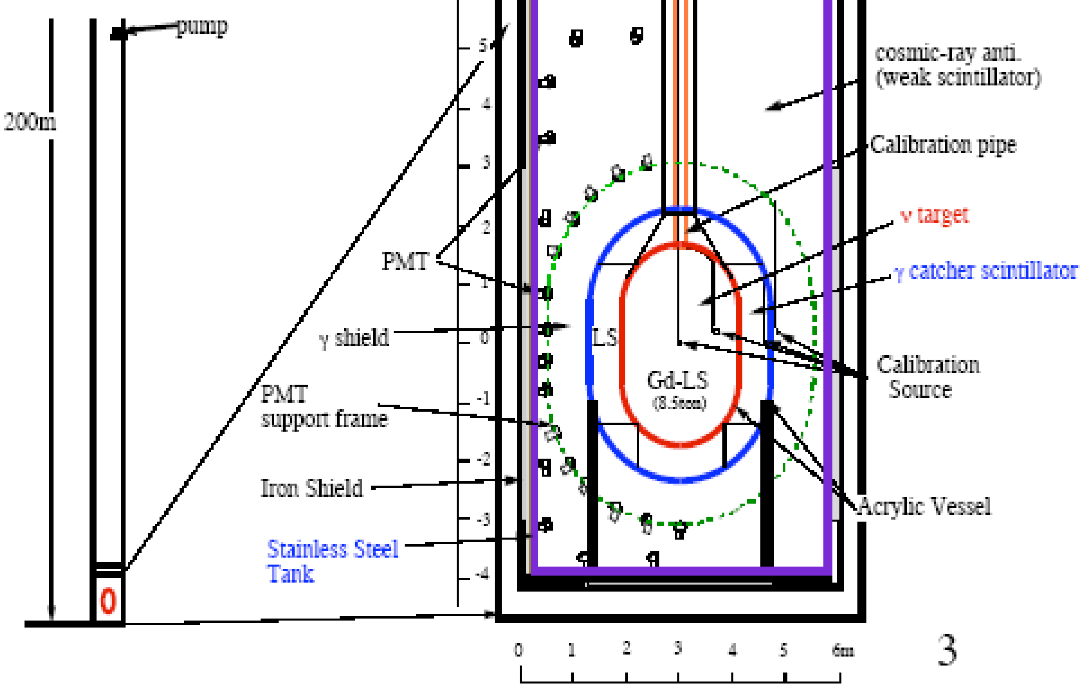


Braidwood



Kaska





Proposed Reactor Experiments

8 proposals, most in 2003 (3 on-going)

- **Fundmental parameter**
- **Gateway to ν-CPV and Mass Hierachy measurements**
- **Less expensive**

How to Reach 0.5% Precision ?

- Increase statistics:
  - Powerful nuclear reactors
  - 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

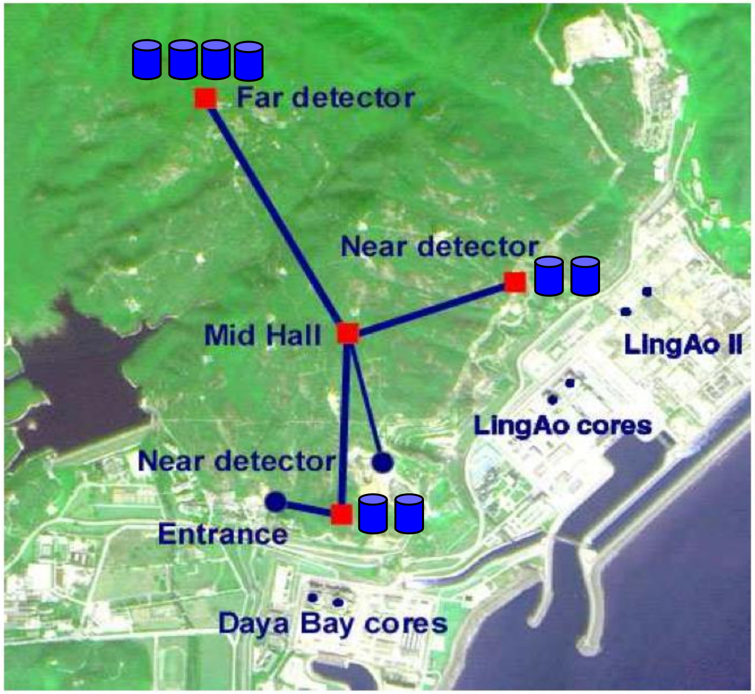
How to Design a Good Detector ?

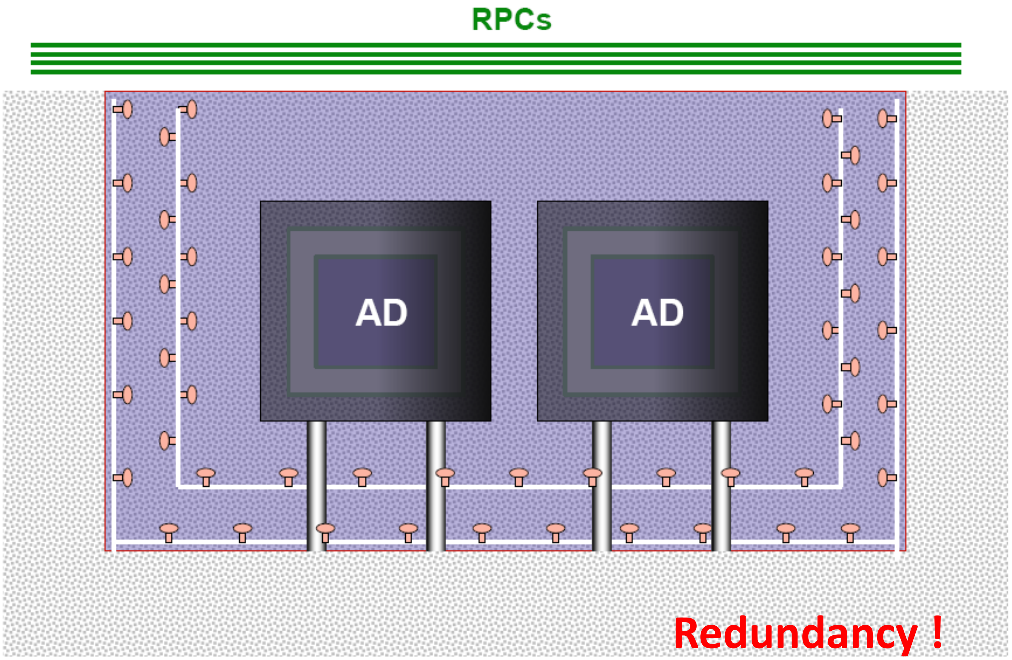
Lessons from past:

- **CHOOZ:**
  - ⇨ **bad Gd-LS**
  - ⇨ **PMT in contact with LS**
- **Palo Verde:**
  - ⇨ **Bad shielding**
  - ⇨ **Segmented detctor**
- **KamLAND:**
  - ⇨ **Fiducial volume cut introduce uncertainties on target mass**

- Energy threshold less than 0.9 MeV
- Homogeneous detector
- Scintillator mass well determined
- Target scintillator all from one batch, mixing procedures well controlled
- Not too large detector
- 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

Layout of the Daya Bay Experiment





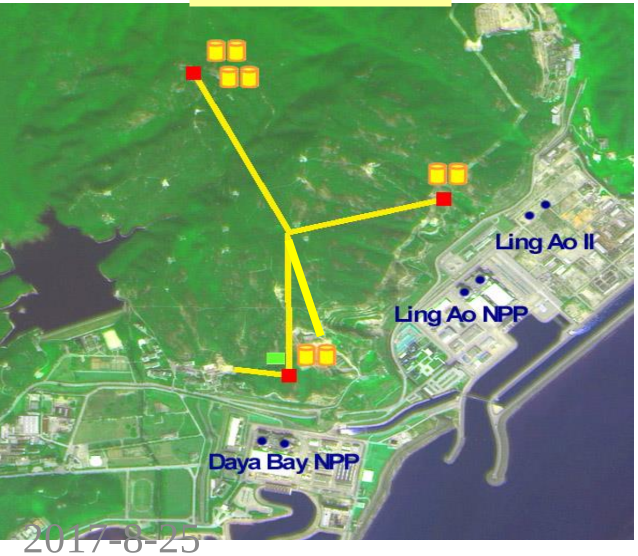
Redundancy !

- 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 (1/sqrt(N))
  - 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
  - 4 layer of RPC + 2 layer of Cerenkov detector

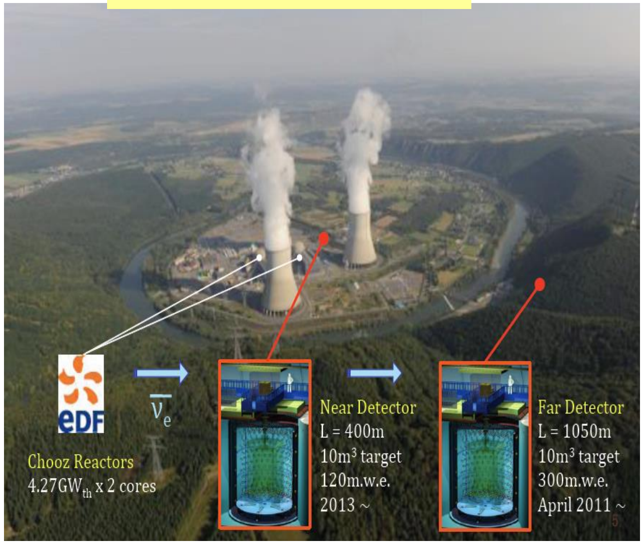
θ_{13}: Three on-going experiments

Experiment	Power (GW)	Baseline(m) Near/Far	Detector(t) Near/Far	Overburden (MWE) Near/Far	Designed Sensitivity (90%CL)
Daya Bay	17.4	470/576/1650	40//40/80	250/265/860	~ 0.008
Double Chooz	8.5	400/1050	8.2/8.2	120/300	~ 0.03
Reno	16.5	409/1444	16/16	120/450	~ 0.02

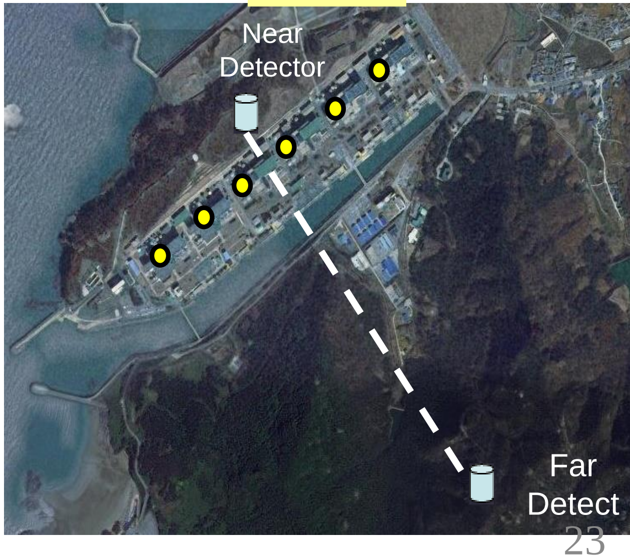
Daya Bay



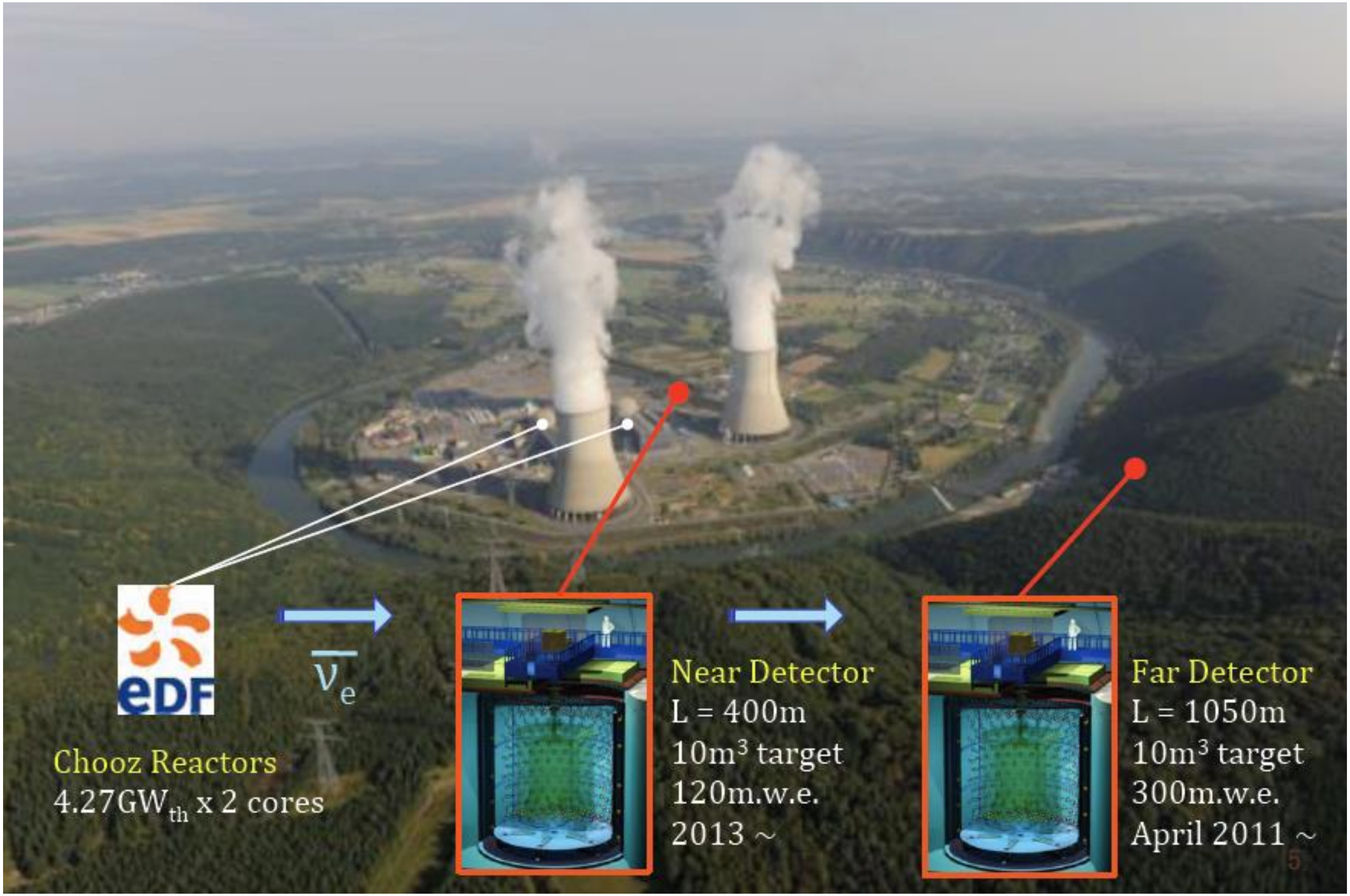
Double Chooz



Reno



Three experiments: Double Chooz



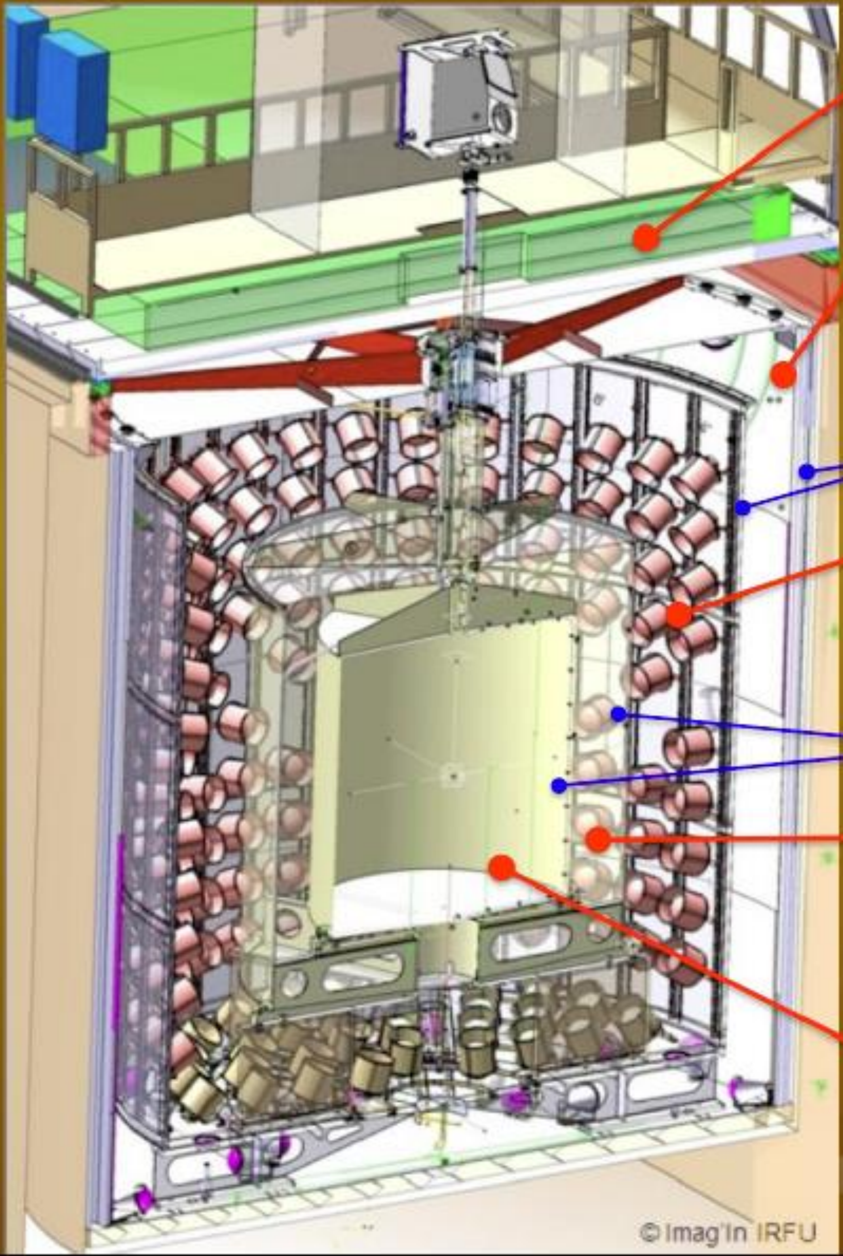
$\overline{\nu}_e$

Chooz Reactors
4.27GW$_{th}$ x 2 cores

Near Detector
L = 400m
10m^3 target
120m.w.e.
2013 ~

Far Detector
L = 1050m
10m^3 target
300m.w.e.
April 2011 ~

Double Chooz detector


© Imag'In IRFU

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

Inner Veto (90m³ Liquid scint.&78 PMTs)
- Detection of cosmic-ray μ and fast neutrons

Steel vessel & PMT support structure

Buffer (110m³ Mineral oil & 390 PMT's)
- Reduction of fast neutron and environmental γ from outside

Acrylic vessel

γ-catcher (22.3m³ Liquid scintillator)
- Measurement of γ's from n-capture by Gd in target volume

ν-target
(10.3m³ Gd loaded (1g/l) liquid scint.)
- Target for neutrino signals

Construction @ DC far lab.

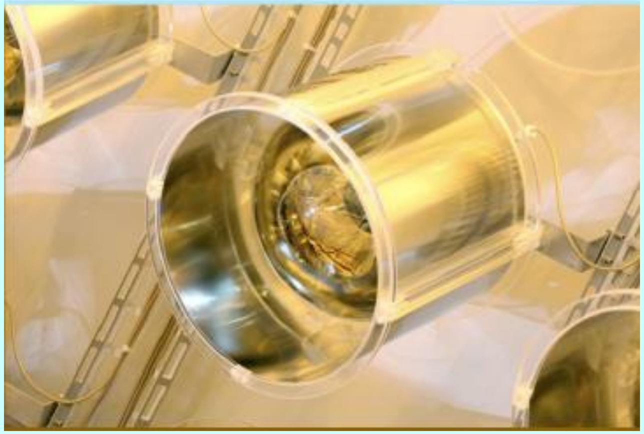
PMT

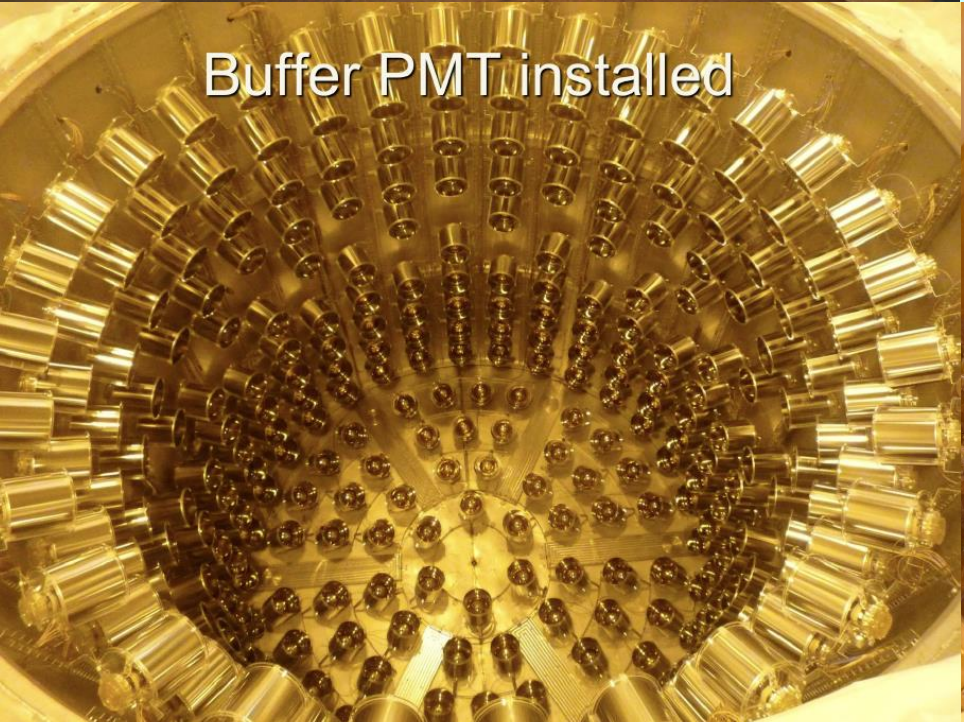
ID: 10″ x 390PMTs

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

IV: 8″ x 78PMTs

(Hamamatsu R1408)



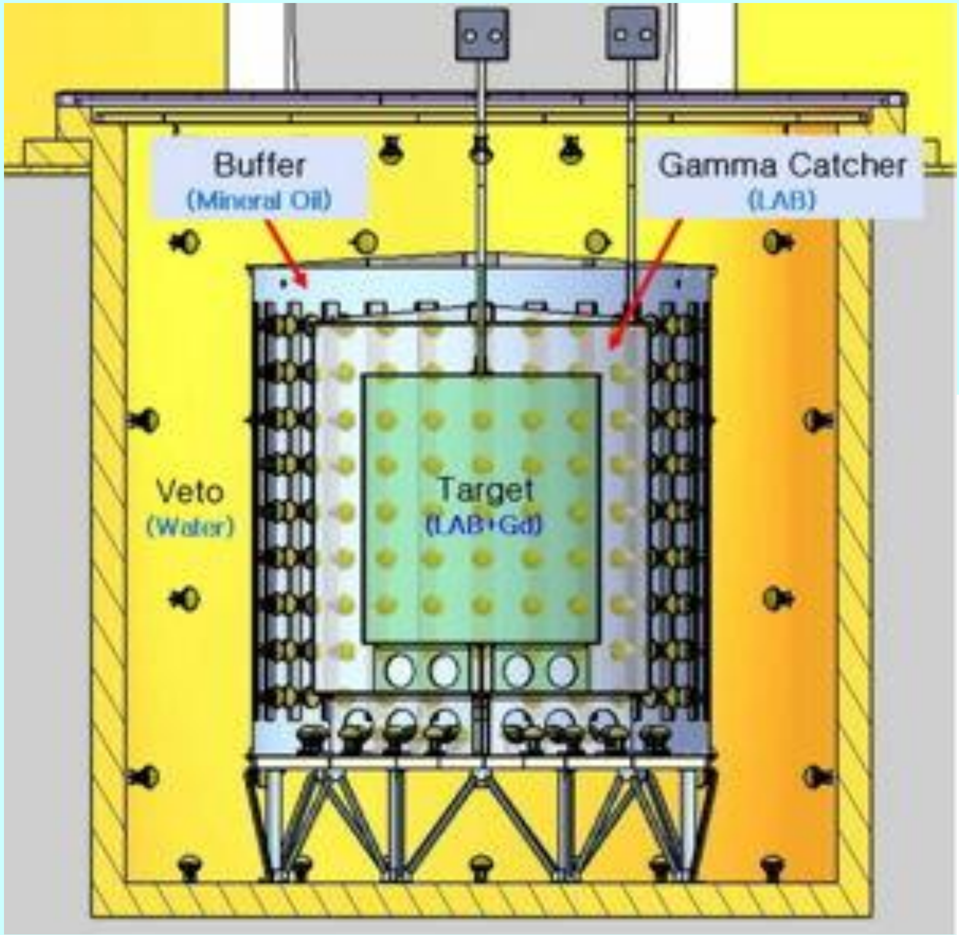


Buffer PMT installed

Target and γ-catcher acrylic vessels installed

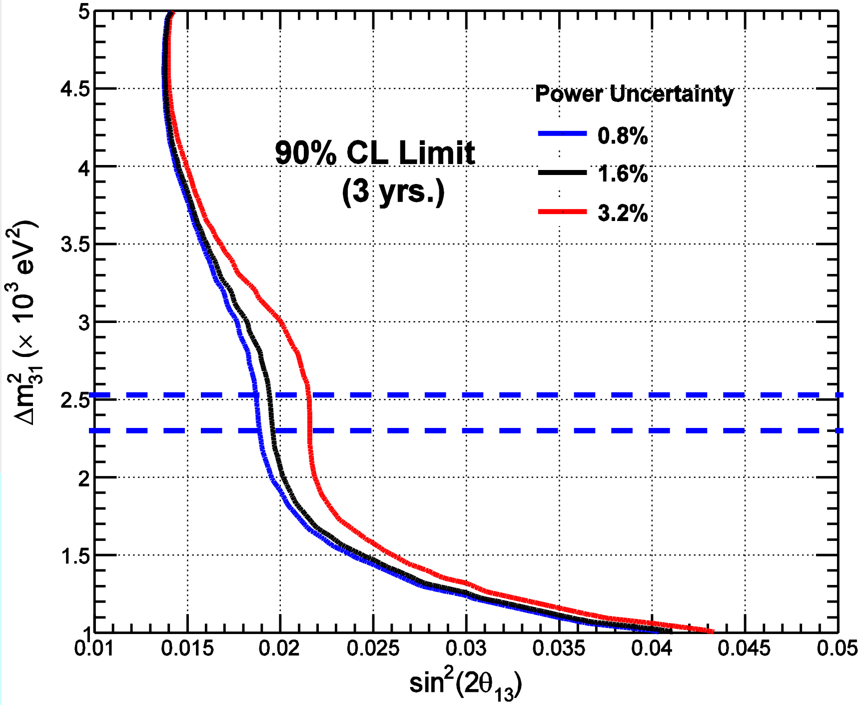
RENO

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

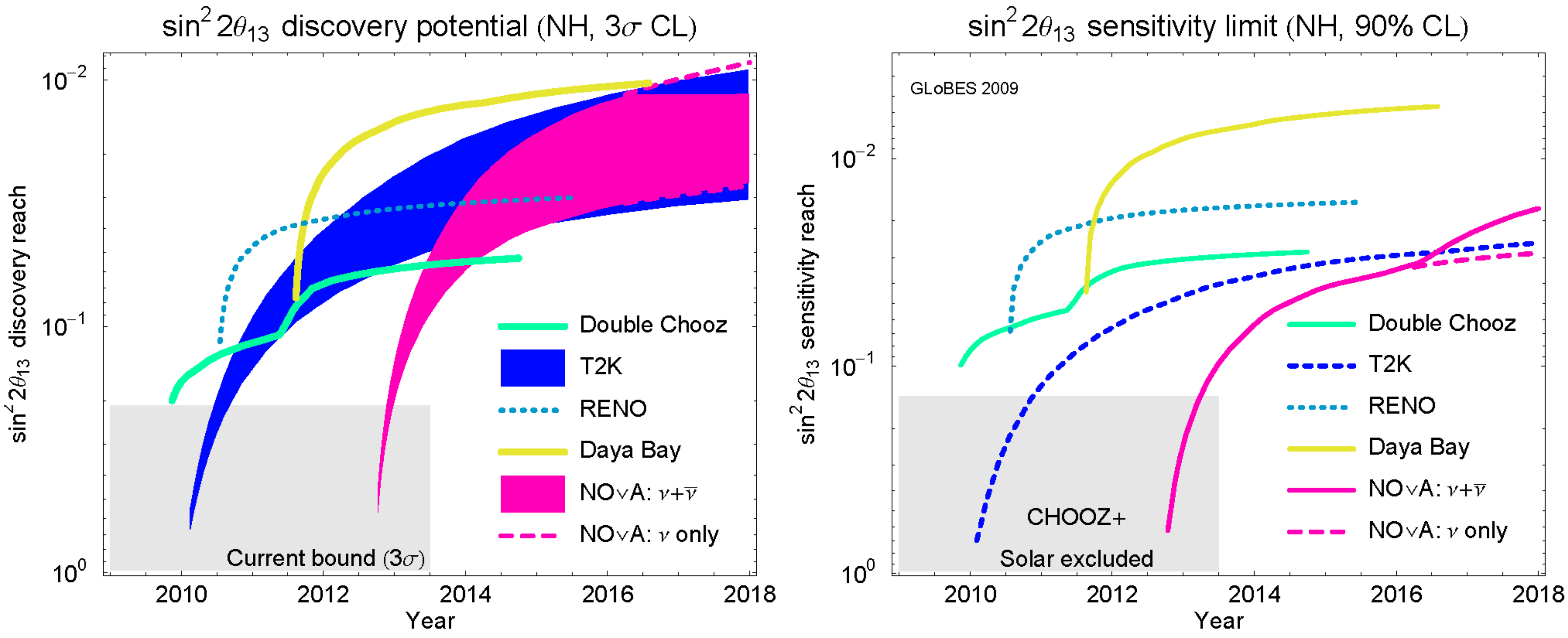
90% CL Limits



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

Race to Measure θ_{13}

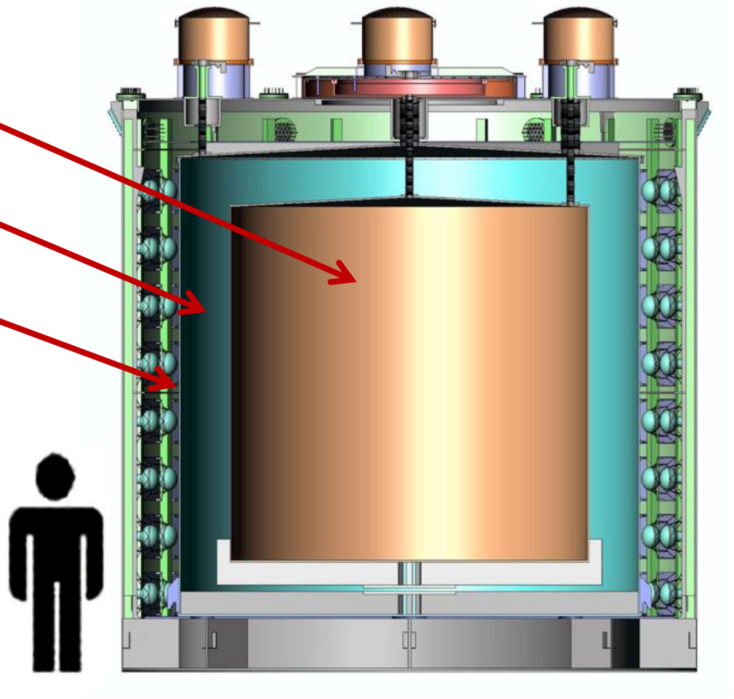
P. Huber et al., JHEP 0911:044,2009

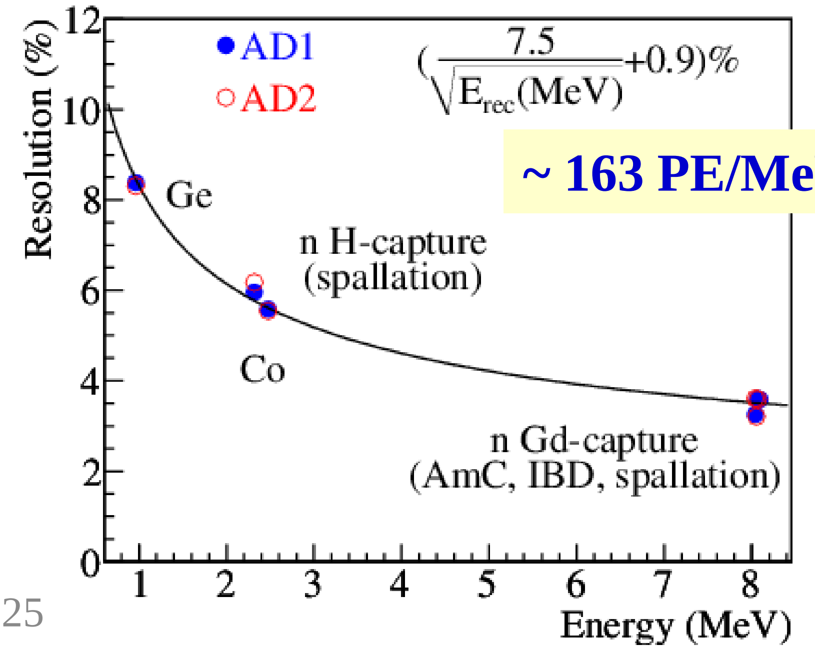


- Proposals from Russia, Japan, US and Brazil not approved

Anti-neutrino Detector (AD)

- **Three zones modular structure:**
  - I. target: Gd-loaded scintillator
  - II. γ-catcher: normal scintillator
  - III. buffer shielding: oil
- **192 8” PMTs/module**
- **Two optical reflectors at the top and the bottom,** Photocathode coverage increased from 5.6% to 12%





~ 163 PE/MeV

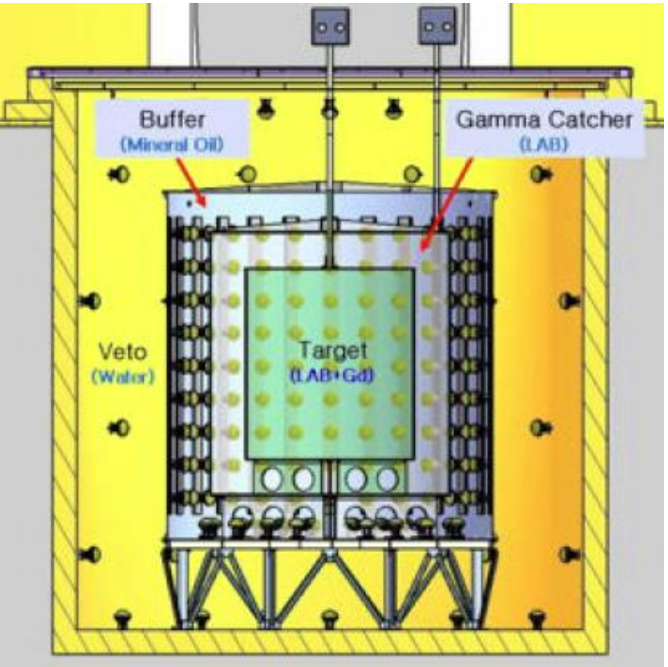
Target: 20 t, 1.6m

γ-catcher: 20t, 45cm

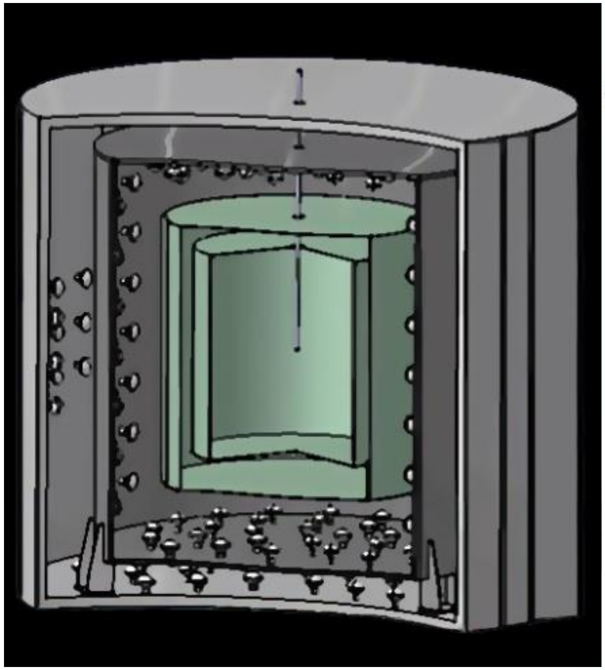
Buffer: 40t, 45cm

Total weight: ~110 t

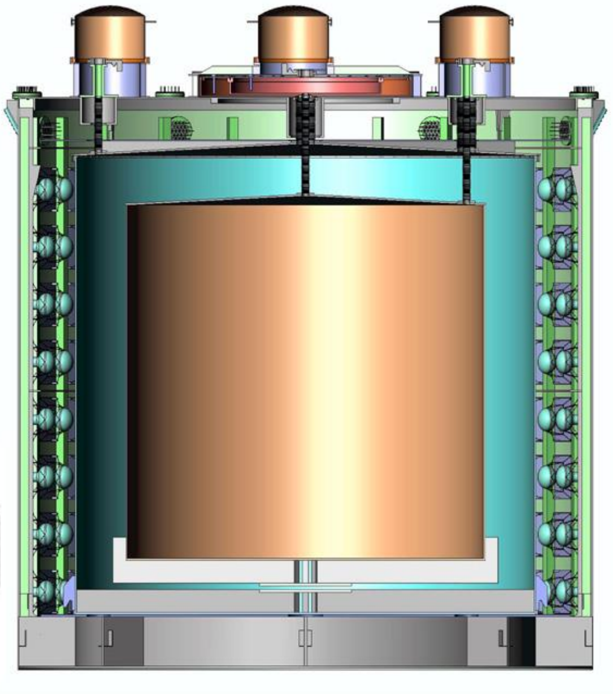
Comprision with other detectors



RENO



Double Chooz



Daya Bay

	PMT	Coverage	pe yield	MO	Acc. Bkg.	ΔB/B
Daya Bay	192 8"	~6%	163 pe/MeV	50 cm	1.4%/4.0%	1.0%/1.4%
RENO	354 10"	~15%	230 pe/MeV	70 cm	0.56%/0.93%	1.4%/4.4%
Double Chooz	390 10"	~16%	200 pe/MeV	105 cm	0.6%	0.8%

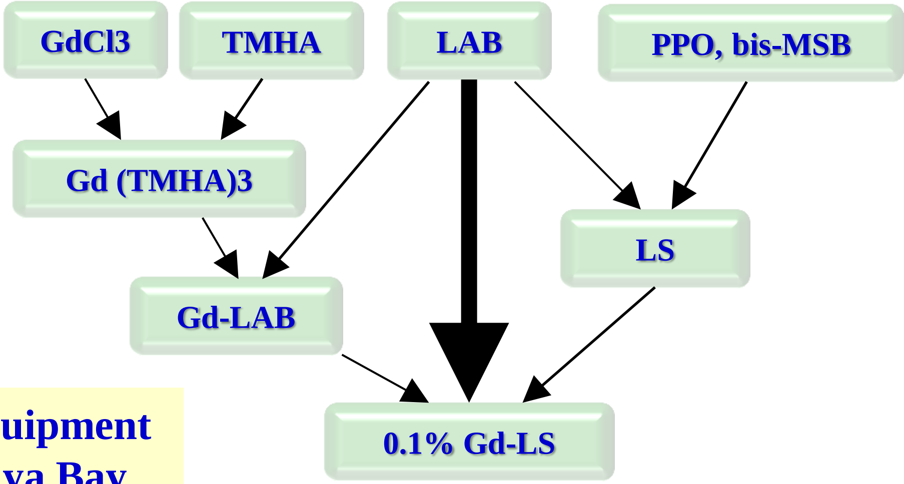
Gd-Loaded Liquid Scintillator: a challenge

◆ **Issue: transparency, aging, …**

Currently produced Gd-loaded liquid scintillators

Groups	Solvent	Complexant for Gd compound	Quantity(t)
Chooz	IPB	alcohol	5
Palo Verde	PC+MO	EHA	12
Double Chooz	PXE+dodecane	Beta-Dikotonates	8
Reno	LAB	TMHA	40
Daya Bay	LAB	TMHA	185

Gd-LS production Equipment and the process by Daya Bay



GdCl3

TMHA

LAB

PPO, bis-MSB

Gd (TMHA)3

LS

Gd-LAB

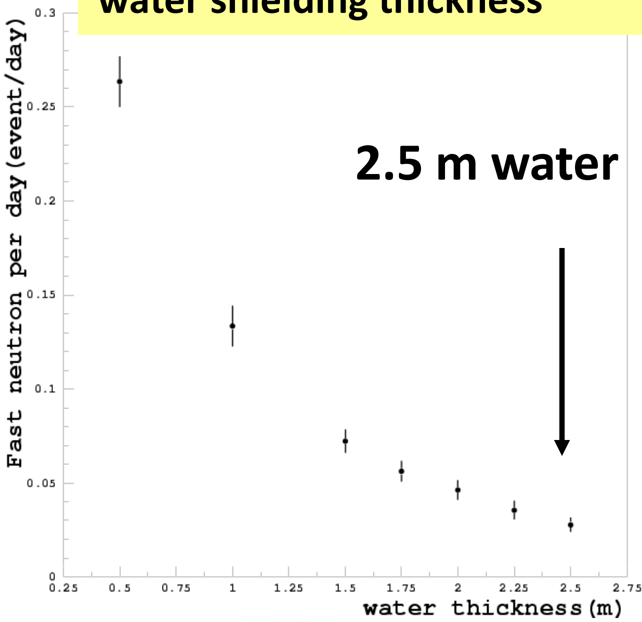
0.1% Gd-LS

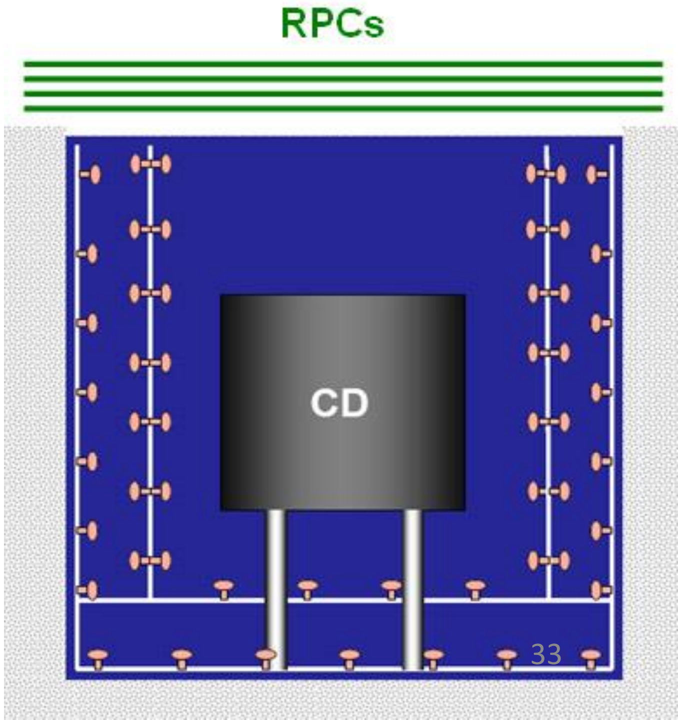
Water Buffer & VETO

- 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





Background Estimate

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

  Single gamma rate @ 0.9MeV < 50Hz

  Single neutron rate < 1000/day

  2m water + 50 cm oil shielding

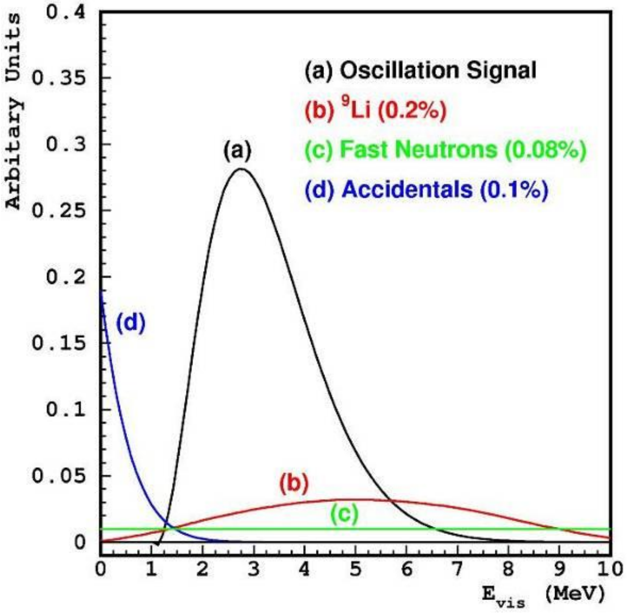
- **Correlated backgrounds:** $n \propto E_{\mu}^{0.75}$

  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

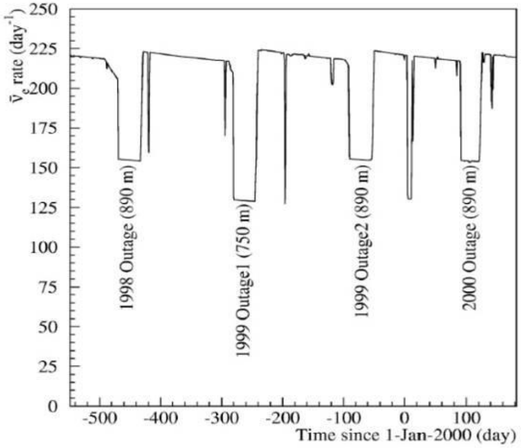
Reactor Neutrino Flux

$$S(E_\nu) = \frac{W_{th}}{\sum_i \left(\frac{f_i}{F}\right) \cdot e_i} \sum_i \left(\frac{f_i}{F}\right) \cdot S_i\,(E_\nu)$$

- Energy release per fission e_i (database）
- Thermal Power W_{th} (Provided by NPP)
- Neutrino spectra of Isotopes (ILL+Vogel, Huber+Mueller, Vogel, Fallot, etc.)
- Fission Fraction (f_i/F) (Provided by NPP or independent core simulation)
- Small corrections
- Correlation among uncertainties.

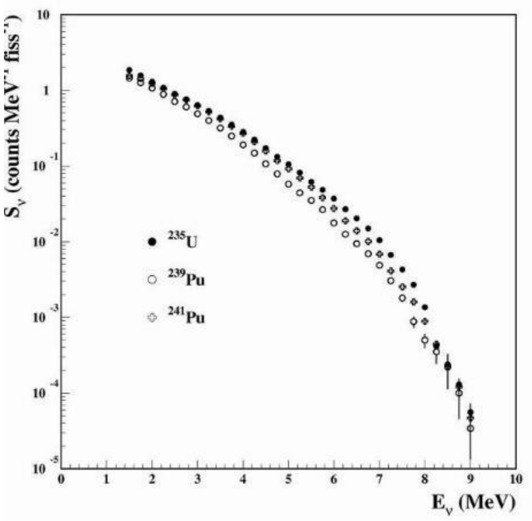
Isotope	E_{fi}, MeV/fission
^{235}U	201.92 ± 0.46
^{238}U	205.52 ± 0.96
^{239}Pu	209.99 ± 0.60
^{241}Pu	213.60 ± 0.65

Kopeikin et al, Physics of Atomic Nuclei, Vol. 67, No. 10, 1892 (2004)



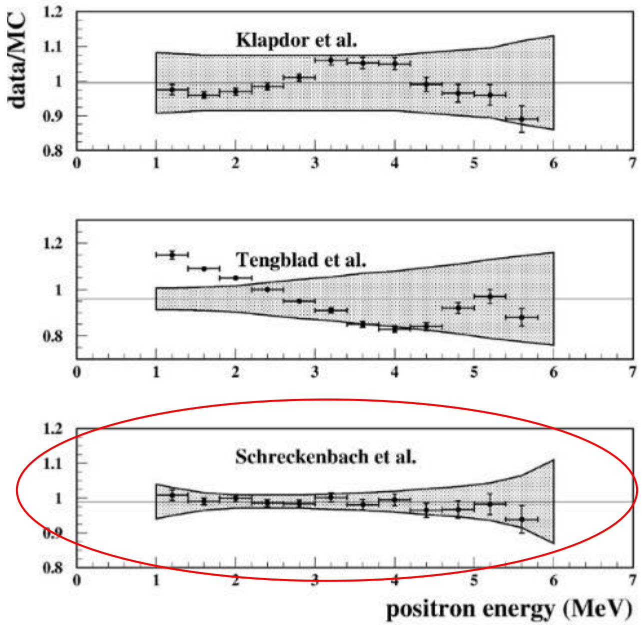
Neutrino Spectra of Isotopes

- **Ab initio: Nuclear database, Σ fragments, Σ chains, Σ branches → 10% uncertainty** (e.g. Vogel et al., PRC24, 1543 (1981)).
- **Conversion: ILL measured the β-spectra → convert to neutrino spectra**
  - ILL spectra: Use spectra of 30 virtual (allowed) decays, fit amplitude and endpoints (ILL-Vogel spectra)
  - Mueller: 90% ab initio + 10% fit → rate anomaly
  - Huber: fit w/ improved nuclear effects (Huber-Mueller spectra)
  - 1.34% at 3 MeV to 9.2% at 8 MeV.



K. Schreckenbach et al. PLB118, 162 (1985)

A.A. Hahn et al. PLB160, 325 (1985)

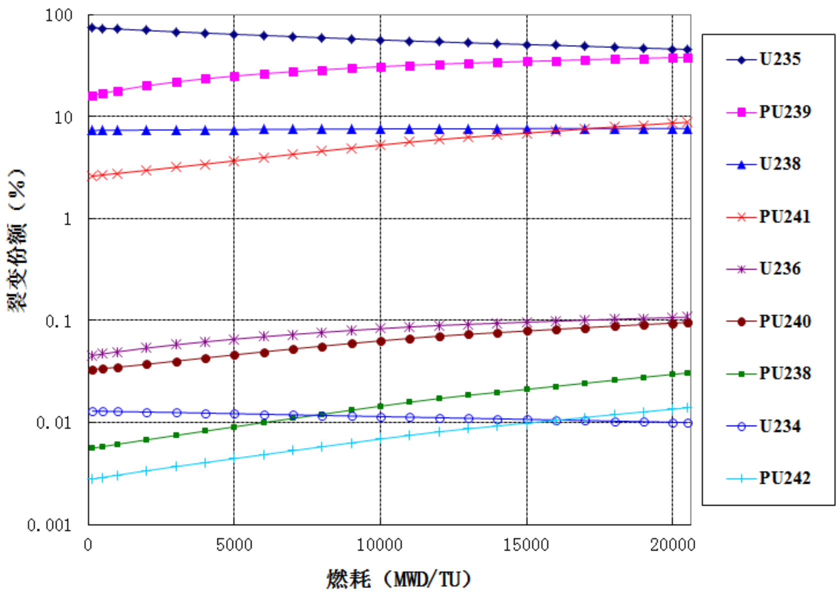


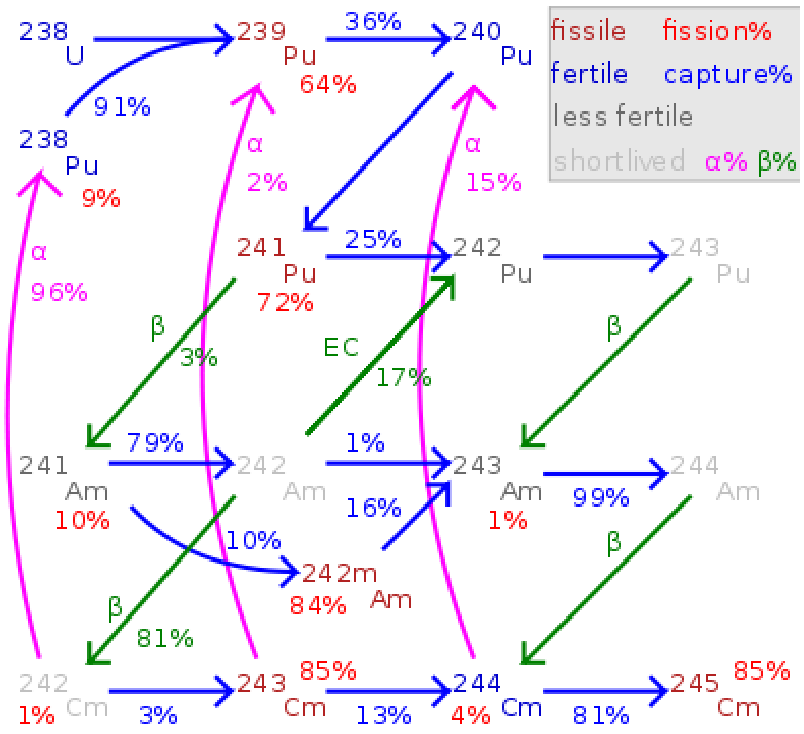
Shape verified by Bugey-3 data

Normalization by Bugey-4, 1.6%

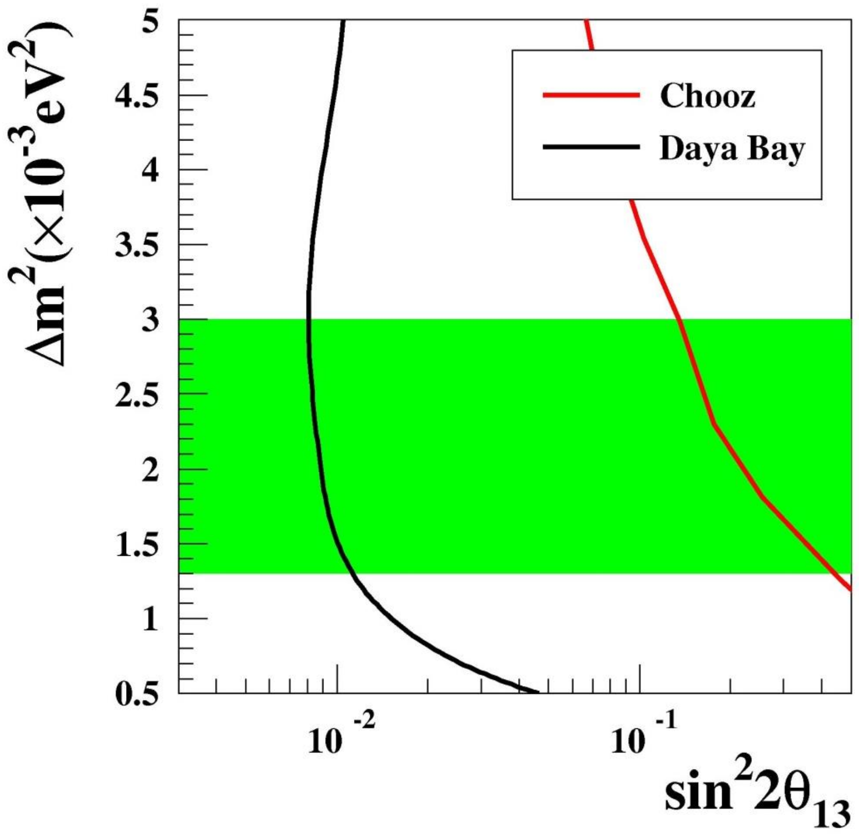
Fission Fraction

- **Initial 4.45% U235, Others:U238 and O**
- **U238 → n capture → Pu239 →2x n capture → Pu241**
- **Four major fission isotopes**
  - U235, Pu239, Pu241
  - U238 fission w/ fast n
- **Burnup: MW·day/ton U**





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

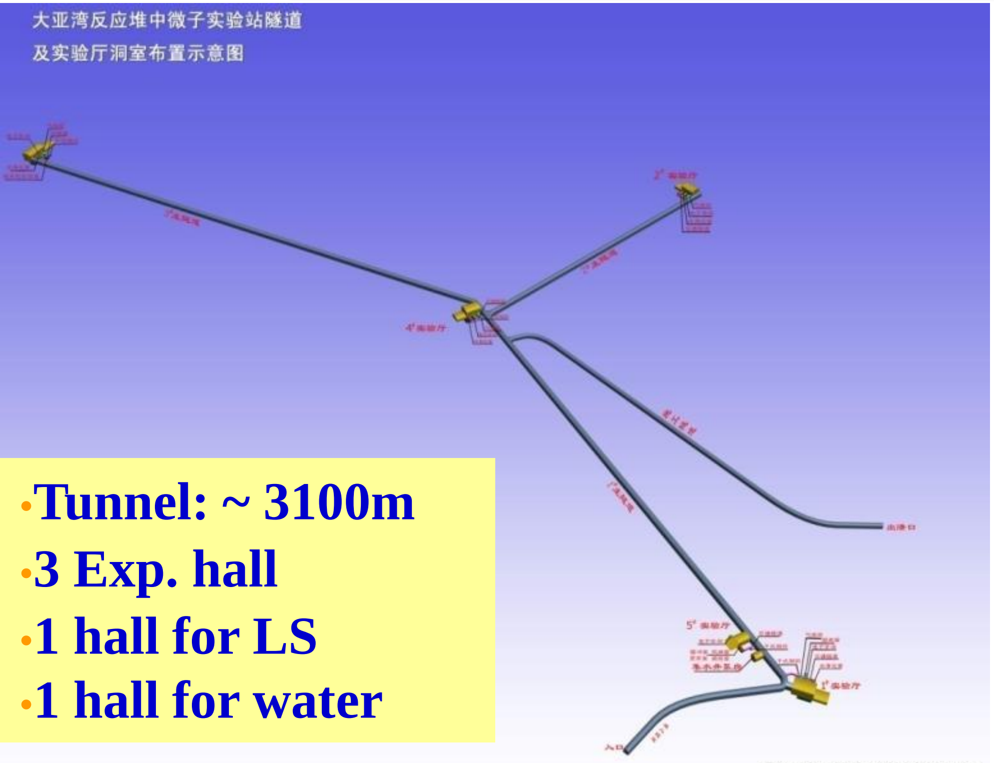


sources	Uncertainty
Reactor neutrino flux	0.087% (4 cores) 0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Backgrounds	0.32% (Daya Bay near) 0.22% (Ling Ao near) 0.22% (far)
Signal statistics	0.2%

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

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

Tunnel and Underground Lab

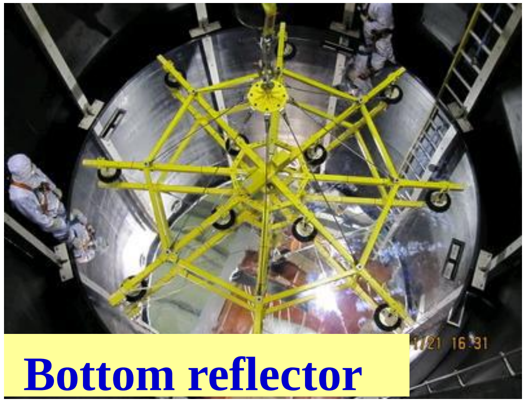


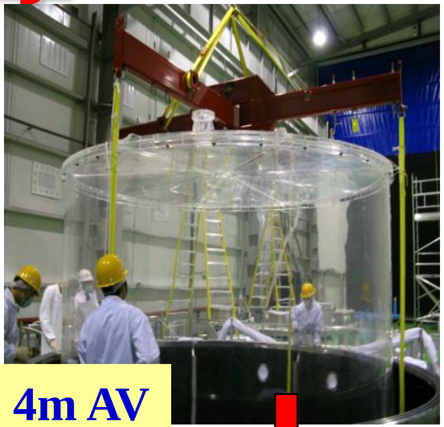
- Tunnel: ~ 3100m
- 3 Exp. hall
- 1 hall for LS
- 1 hall for water

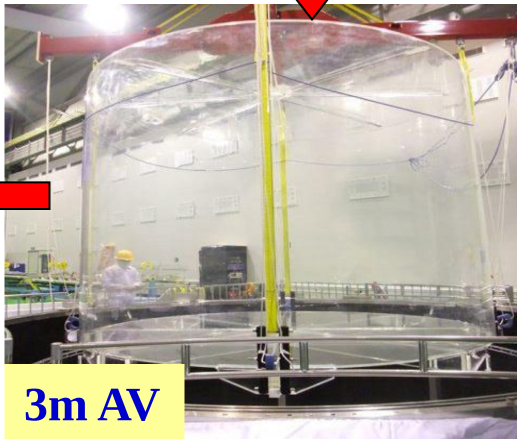
A total of ~ 3000 blasting right next reactors. No one exceeds safety limit set by National Nuclear Safety Agency（0.007g）

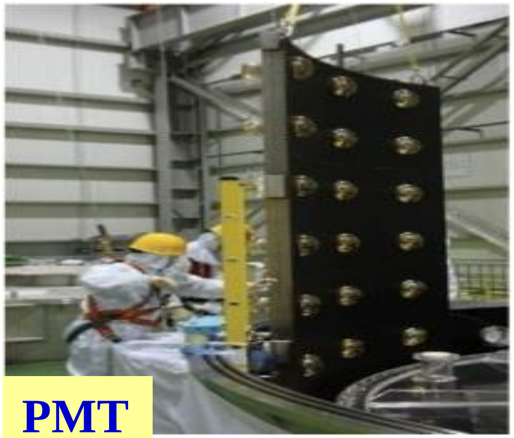
Detector Assembly

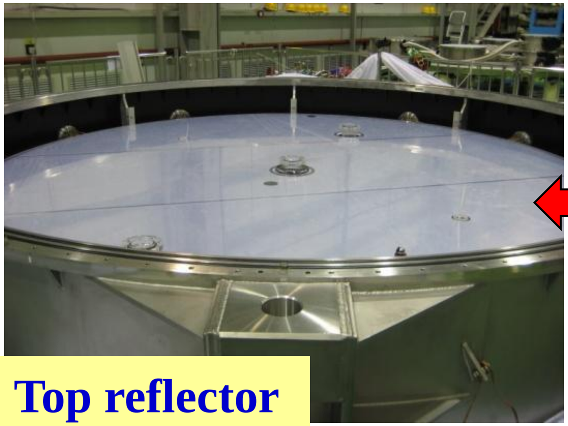

SSV


Bottom reflector

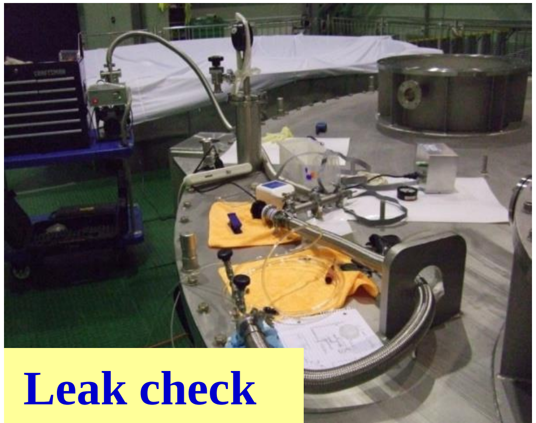

4m AV


3m AV


PMT


Top reflector


SSV lid


Leak check


ACU

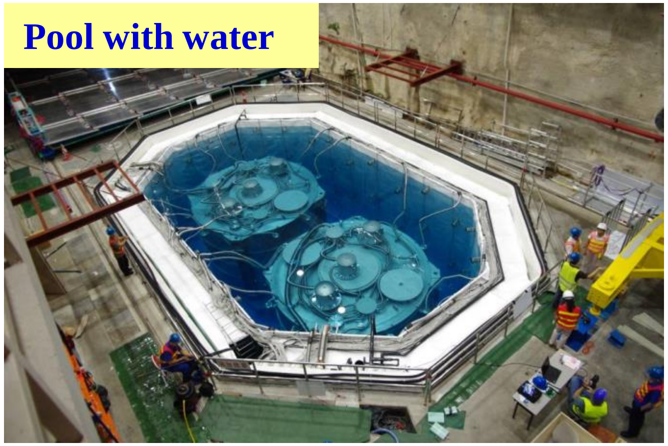
Detector Installation

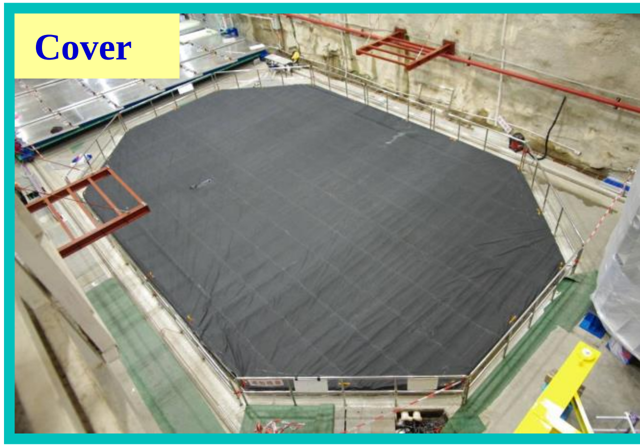

PermaFlex painting


PMT frame & Tyvek

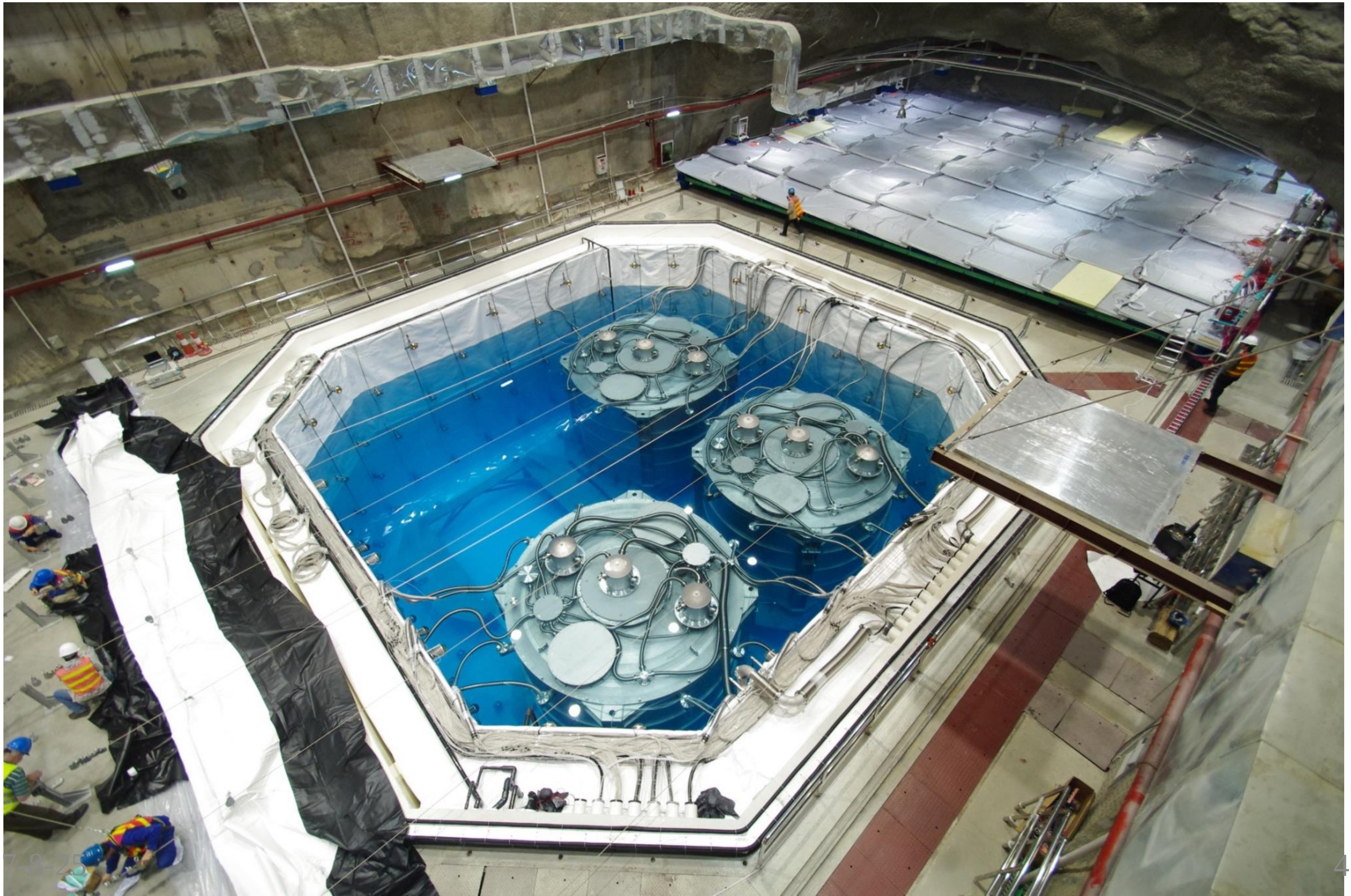

Completed pool


Install AD


Pool with water


Cover

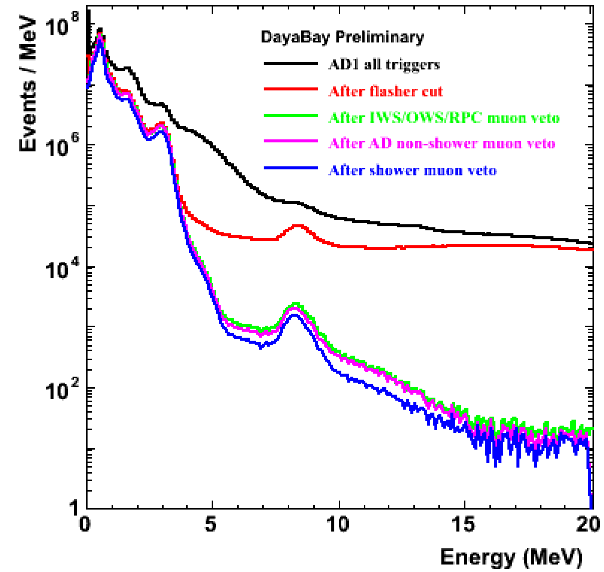
Three ADs installed in Hall 3
Physics Data Taking Started on Dec.24, 2011

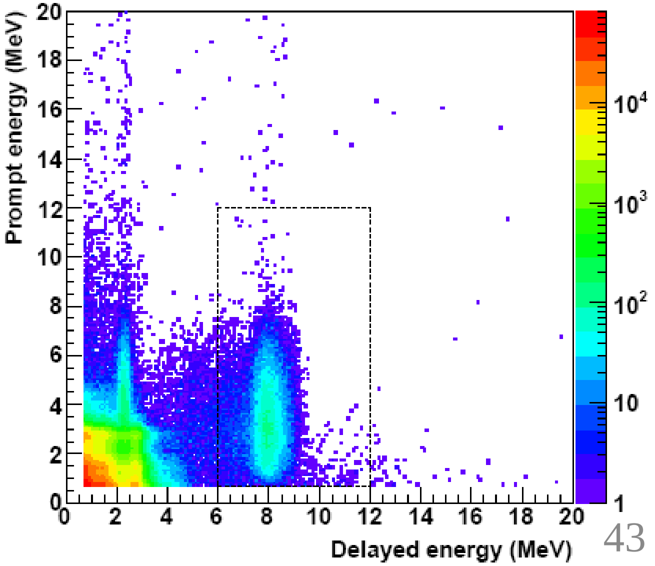


Neutrino Event Selection

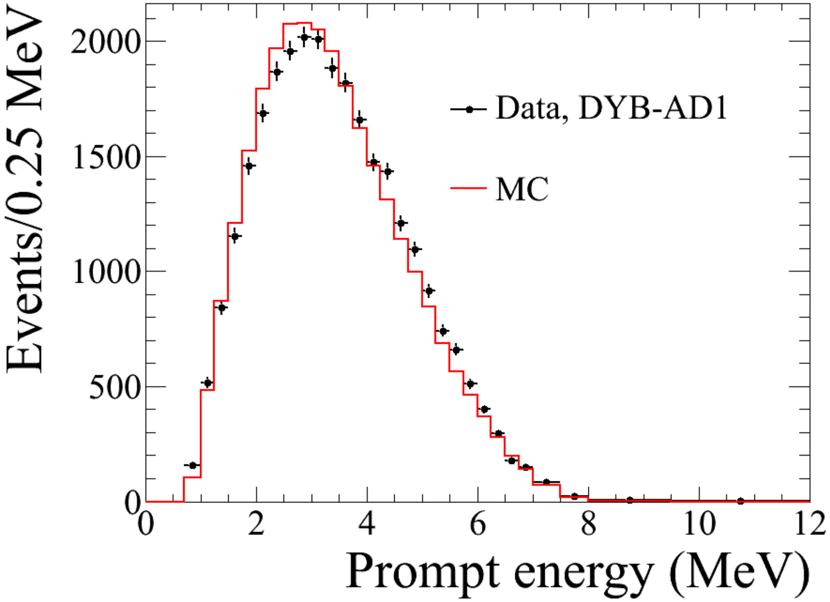
- **Pre-selection**
  - ⇨ **Reject Flashers**
  - ⇨ **Reject Triggers within (-2 μs, 200 μs) to a tagged water pool muon**
- **Neutrino event selection**
  - ⇨ **Multiplicity cut**
    - ✓ Prompt-delayed pairs within a time interval of 200 μs
    - ✓ No triggers(E > 0.7MeV) before the prompt signal and after the delayed signal by 200 μs
  - ⇨ **Muon veto**
    - ✓ *1s* after an AD shower muon
    - ✓ *1ms* after an AD muon
    - ✓ *0.6ms* after an WP muon
  - ⇨ **$0.7\text{MeV} < E_{\text{prompt}} < 12.0\text{MeV}$**
  - ⇨ **$6.0\text{MeV} < E_{\text{delayed}} < 12.0\text{MeV}$**
  - ⇨ **$1\mu s < \Delta t_{e^+\text{-}n} < 200\mu s$**

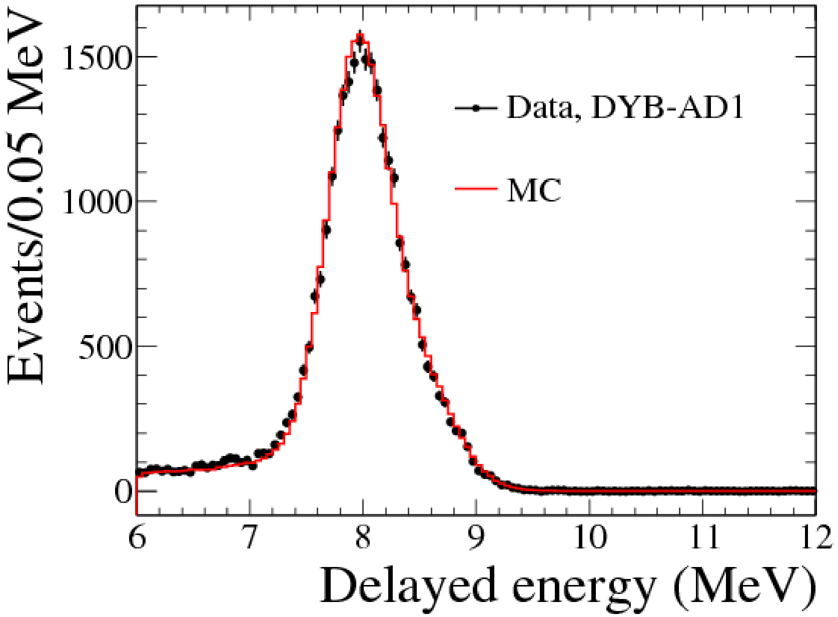
Data reduction

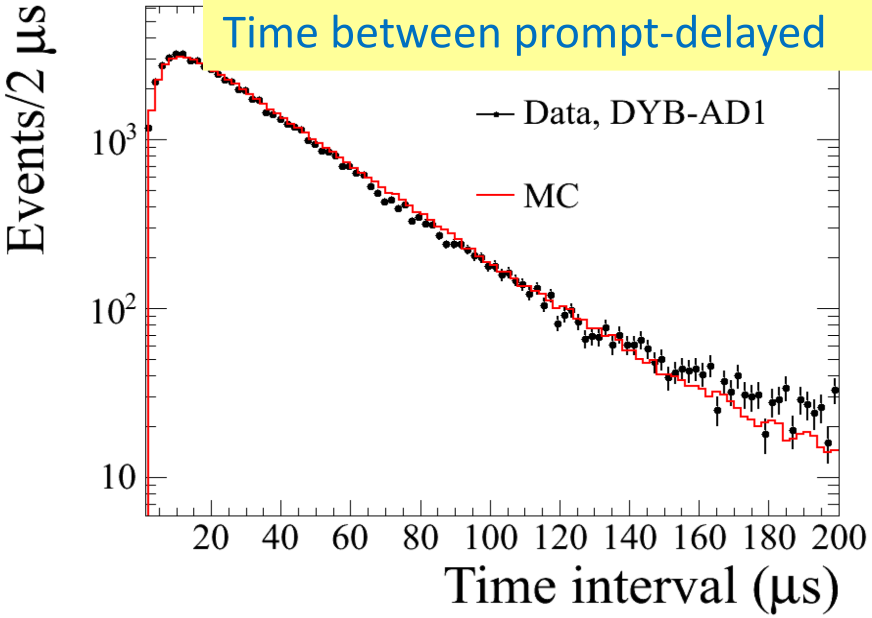


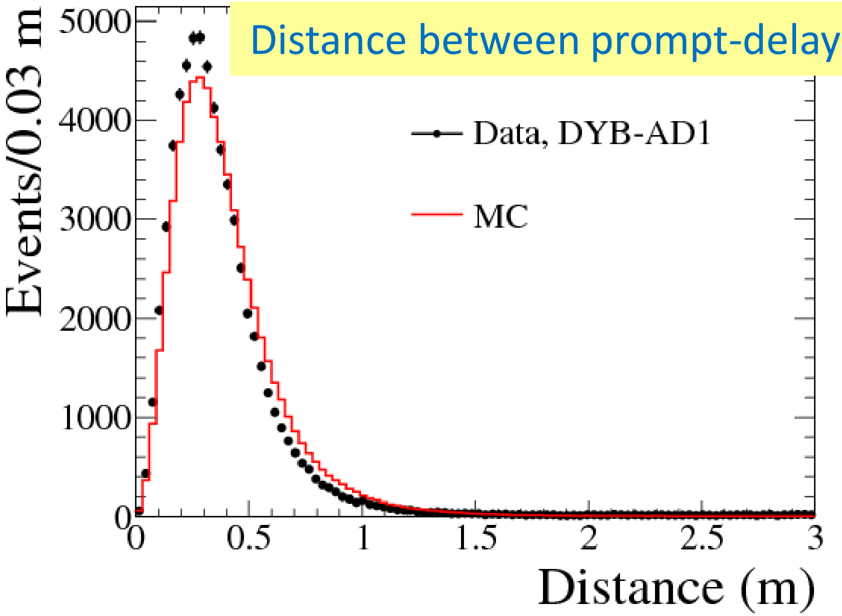


Selected Signal Events

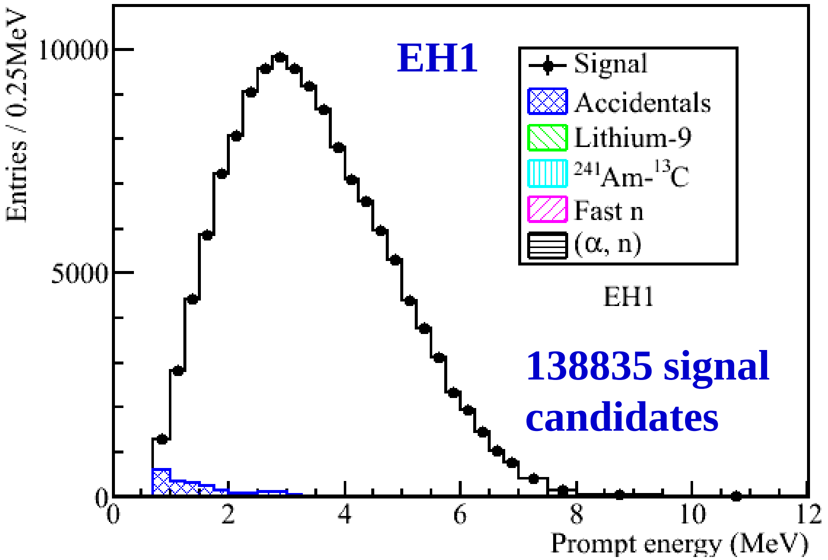





Time between prompt-delayed

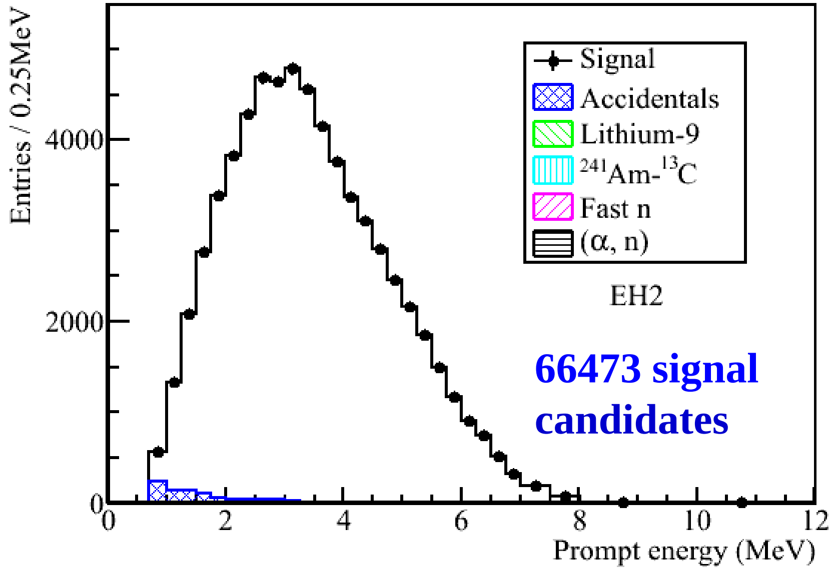

Distance between prompt-delayed

Signal+Backgound Spectrum

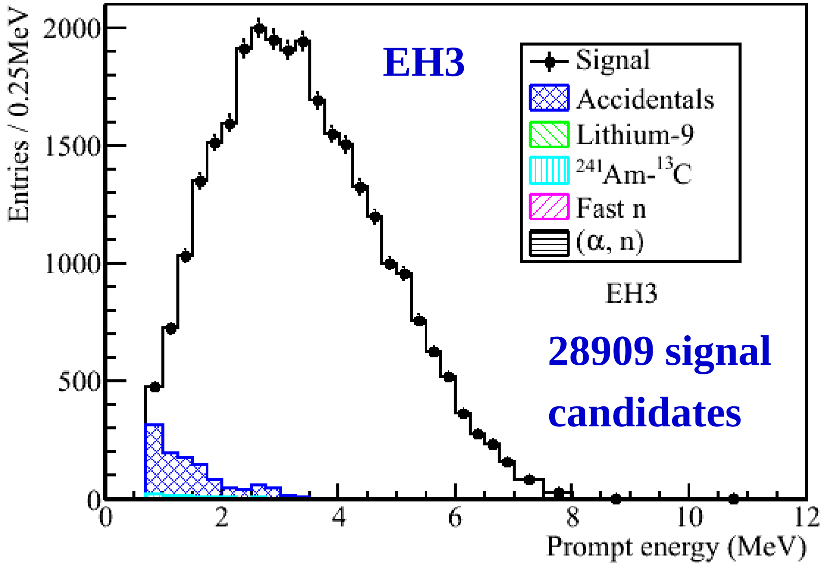


EH1

138835 signal candidates



66473 signal candidates



EH3

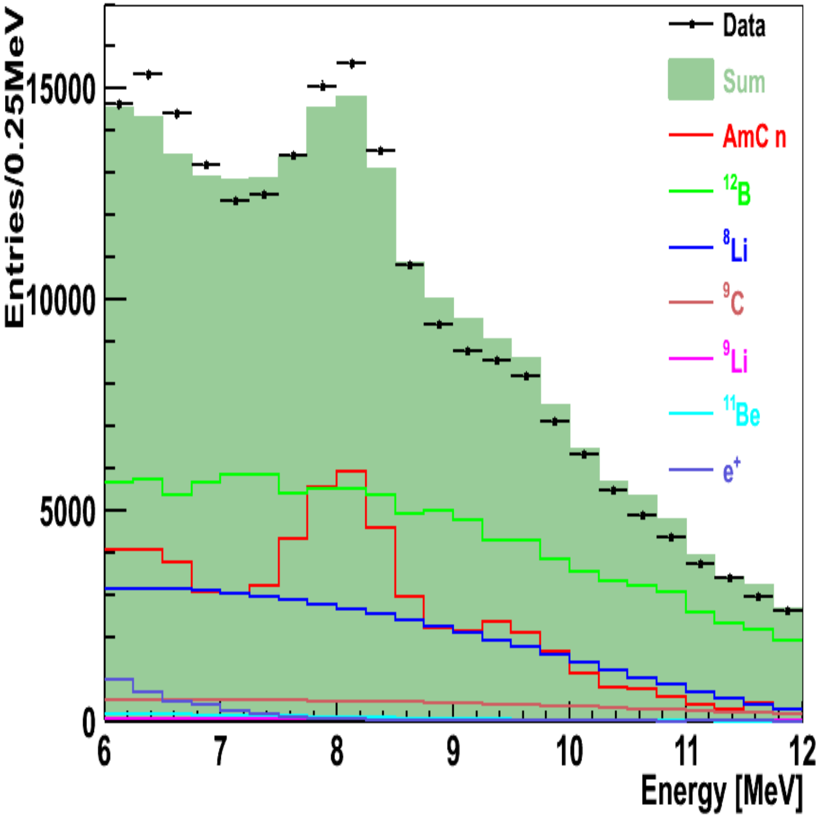
28909 signal candidates

	B/S @EH1/2	B/S @EH3
Accidentals	~1.4%	~4.5%
Fast neutrons	~0.1%	~0.06%
^{8}He/^{9}Li	~0.4%	~0.2%
Am-C	~0.03%	~0.3%
α-n	~0.01%	~0.04%
Sum	~2%	~5%

Backgrounds

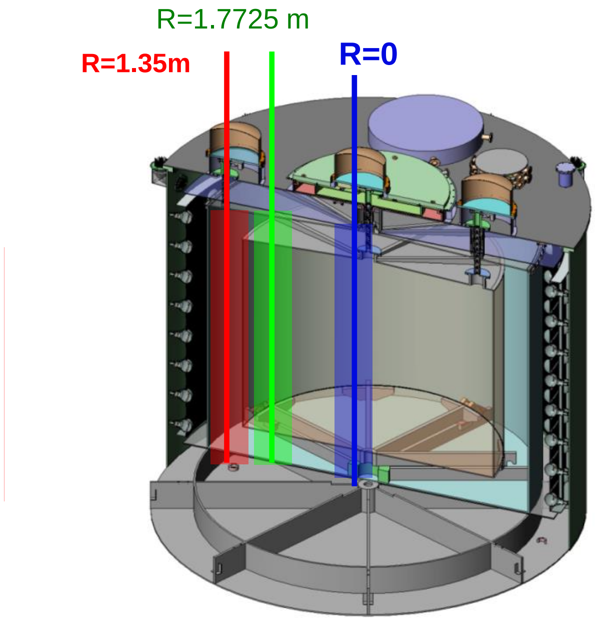
- Fully understood all backgrounds. No unknown components.

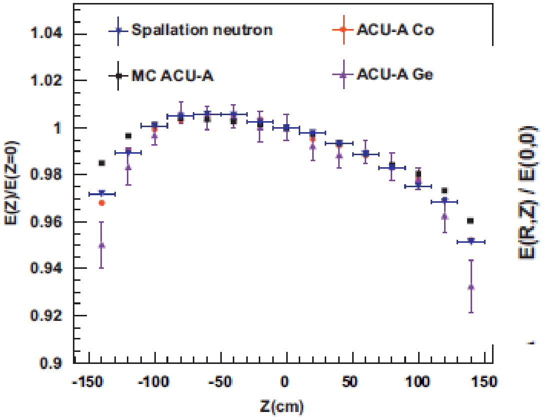
Sources	EH1	
	Rate (/day/AD)	Fraction
AmC neutron	271+-10	26.3+-1.0
^{12}B/^{12}N	478+-13	46.4+-1.3%
^{8}Li/^{8}B	216+-18	21.0+-1.8%
^{9}C	40+-16	3.8+-1.6%
^{9}Li/^{8}He	4+-2	0.4+-0.2%
^{11}Be	7+-4	0.7+-0.4%
IBD e^+ (n captured on H)	14+-1	1.4+-0.1%
Sum	**1030+-29**	**100.0+-2.9%**
All singles	1030+-7	-----

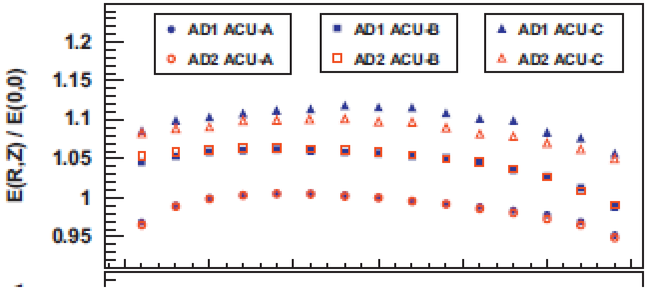


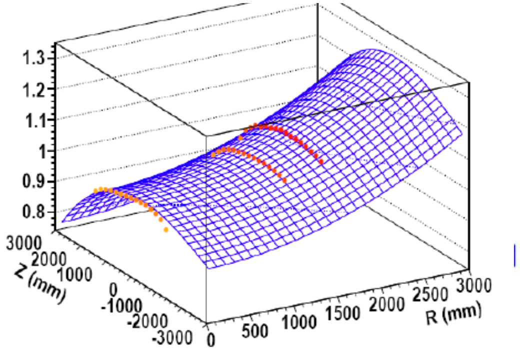
Energy Calibration

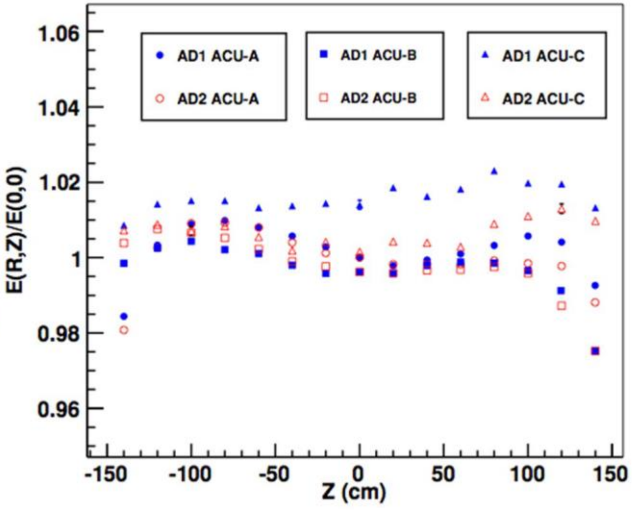
- LED (PMT gain， timing)
- Ge68 (positron threshold 1.022 MeV)
- Co60 (2.506 MeV) + Am-C (neutron)











Ge68: 15 Hz
0.511x2 MeV

Am-C:
0.5 Hz

Co60: 100 Hz
1.173 + 1.332 MeV

Functional Identical Detectors

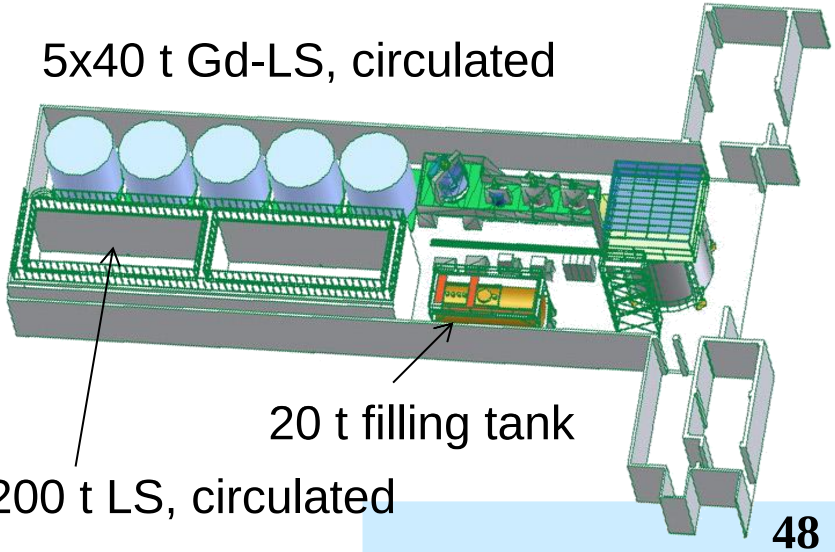
- **Why systematics is so small?** c.f. An et al. NIM. A 685 (2012) 78
  - ⇨ **Idea of "identical detectors" throughout the procedures of design / fabrication / assembly / filling.**
  - ⇨ **For example: Inner Acrylic Vessel, designed D=3120±5 mm**
    - Variation of D by geometry survey=**1.7mm**, Var. of volume: 0.17%
    - Target mass var. by load cell measurement during filling: 0.19%

Diameter	IAV1	IAV2	IAV3	IAV4	IAV5	IAV6
Surveyed(mm)	**3123.12**	**3121.71**	**3121.77**	**3119.65**	**3125.11**	**3121.56**
Variation (mm)	**1.3**	**2.0**	**2.3**	**1.8**	**1.5**	**2.3**

- ⇨ **"Same batch" of liquid scintillator**

4-m AV in pairs

Assembly in pairs



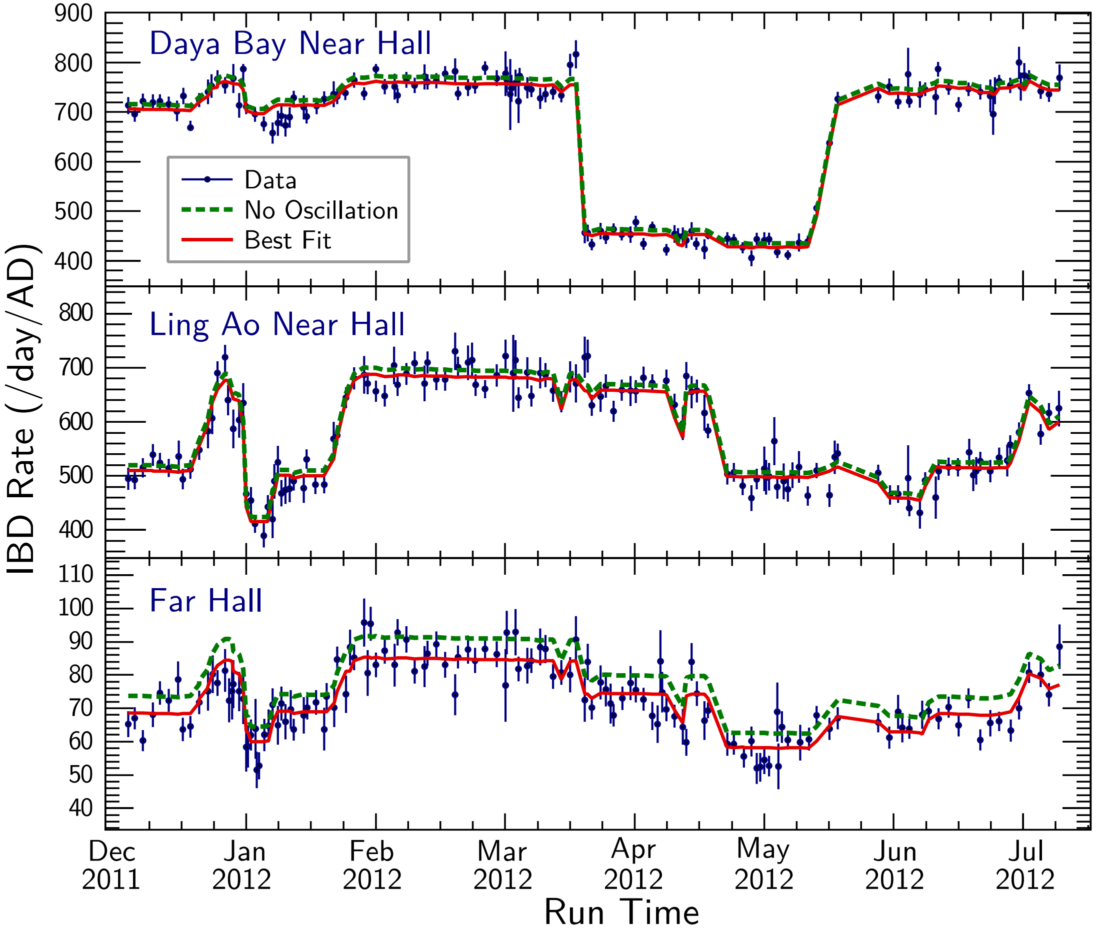
5x40 t Gd-LS, circulated

20 t filling tank

200 t LS, circulated

Daily Neutrino Rate

- **Three halls taking data synchronously allows near-far cancellation of reactor related uncertainties**
- **Rate changes reflect the reactor on/off.**

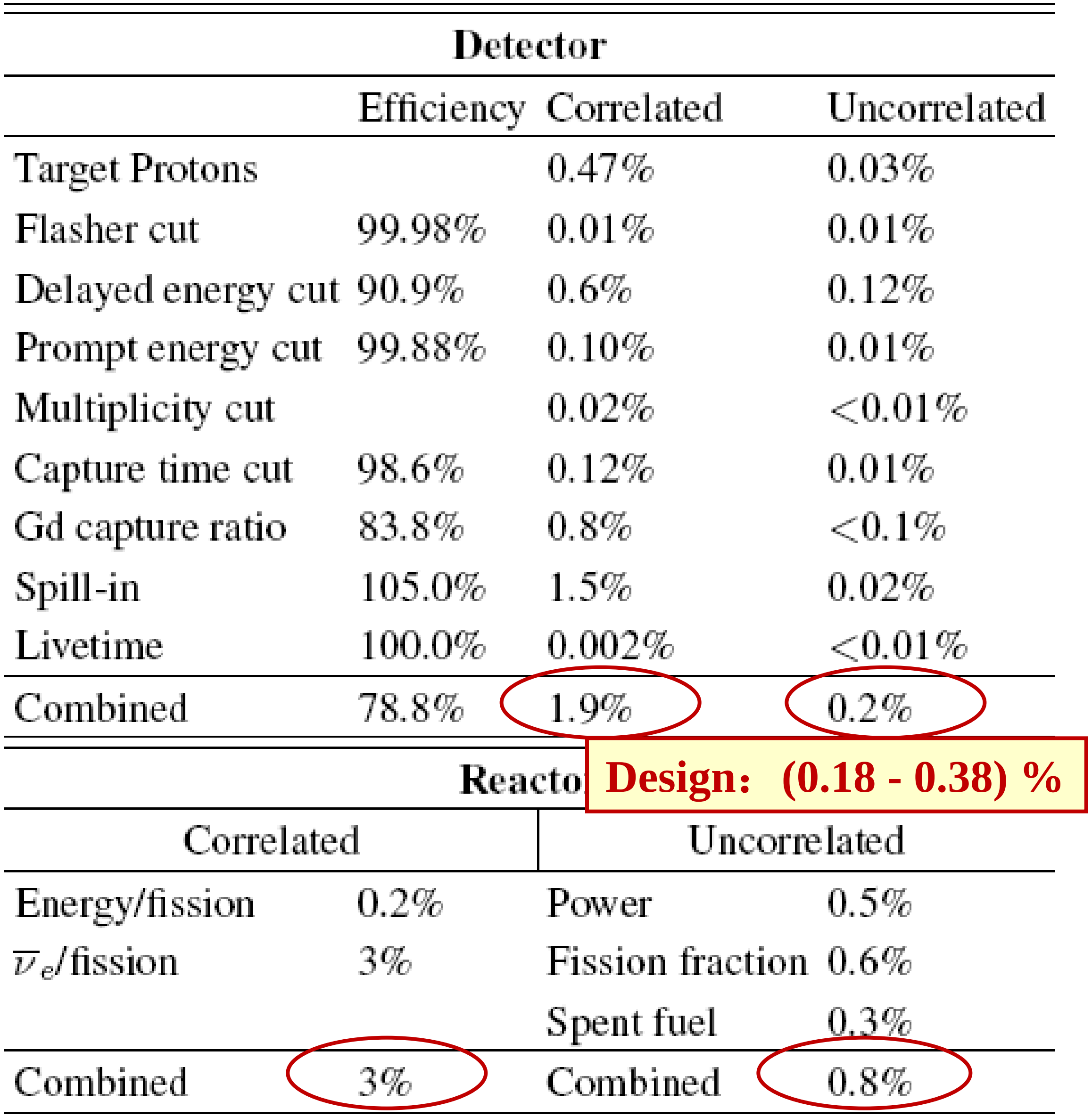


Prediction:

- **Baseline（ 3.5cm，~0.002%）**
- **Target mass（3kg，0.015%）**
- **Reactor neutrino flux**

Predictions are absolute, multiplied by a normalization factor from the fitting

Uncertainties



Detector

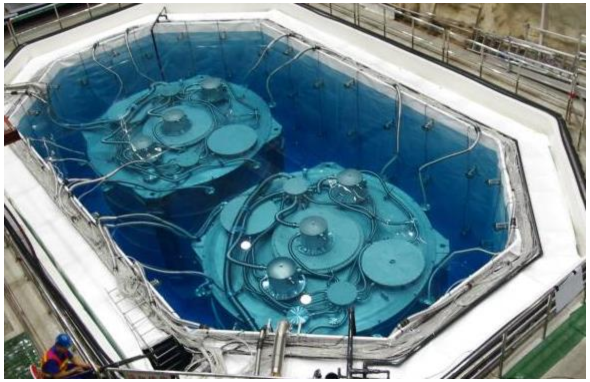
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reacto

Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Design: (0.18 - 0.38) %

Side-by-side Comparison



Expectation:

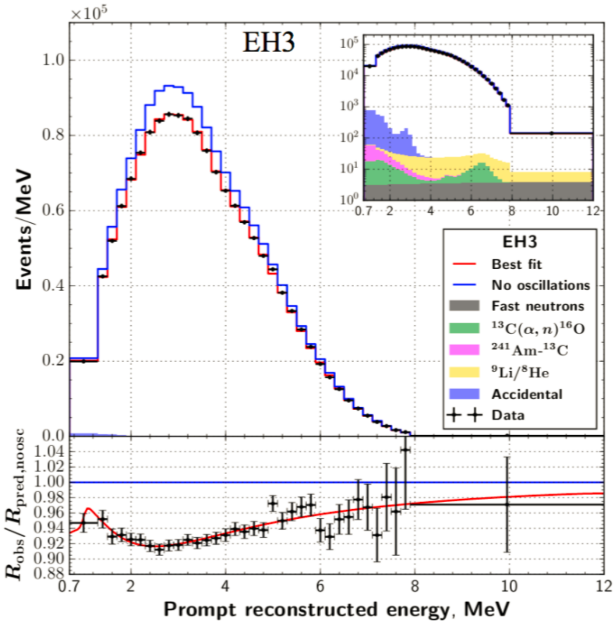
R(AD1/AD2) = 0.982

Measurement:

0.981± 0.004

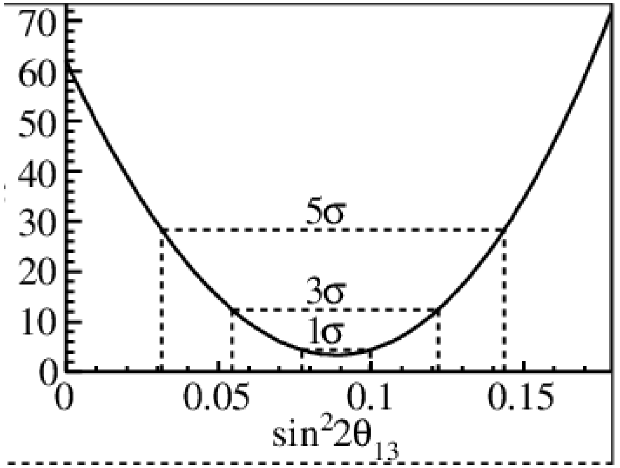
χ^2 Analysis

$$\chi^2 = \sum_{d=1}^{6} \frac{[M_d - T_d(1+\varepsilon+\sum_r \omega_r^d \alpha_r + \varepsilon_d) + \eta_d]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right),$$



3 equivalent χ^2 function:

- K parameter fitting, where K is number of correlated errors.
- K×K matrix inversion
- N×N matrix inversion, where N is number of data points



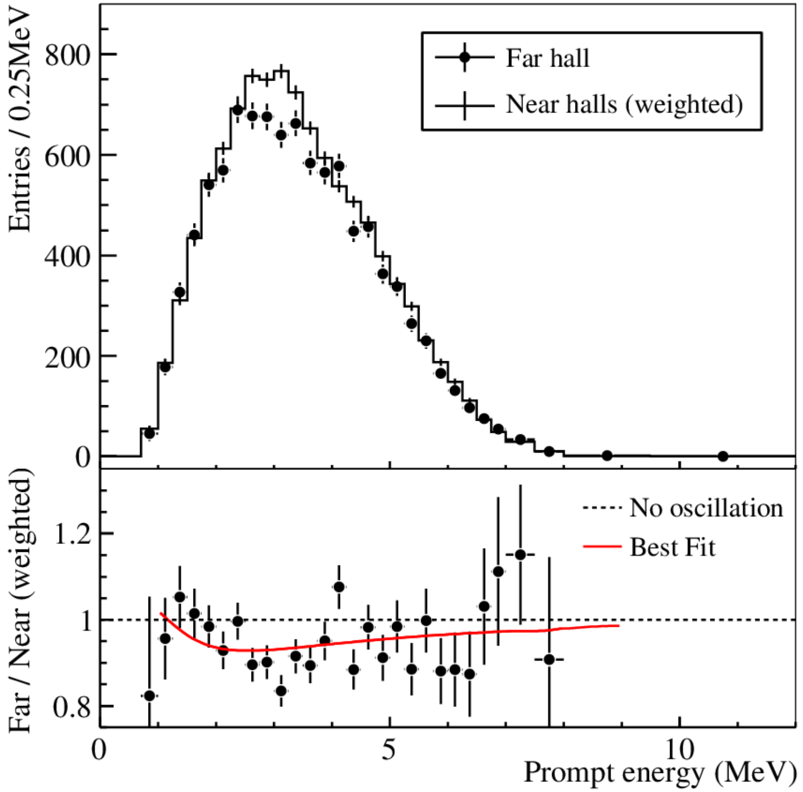
J. Pumplin et. al. PRD65,014011(2001)

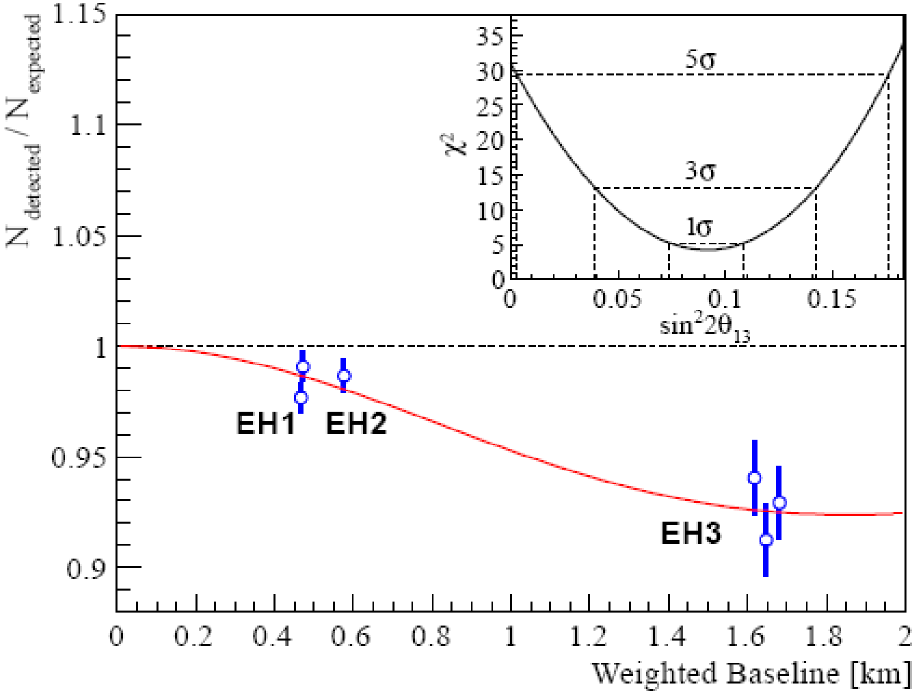
A New Type of Oscillation Discovered

- **Electron anti-neutrino disappearance:**

R = 0.940 ±0.011 (stat) ±0.004 (syst)

announced on Mar. 8, 2012





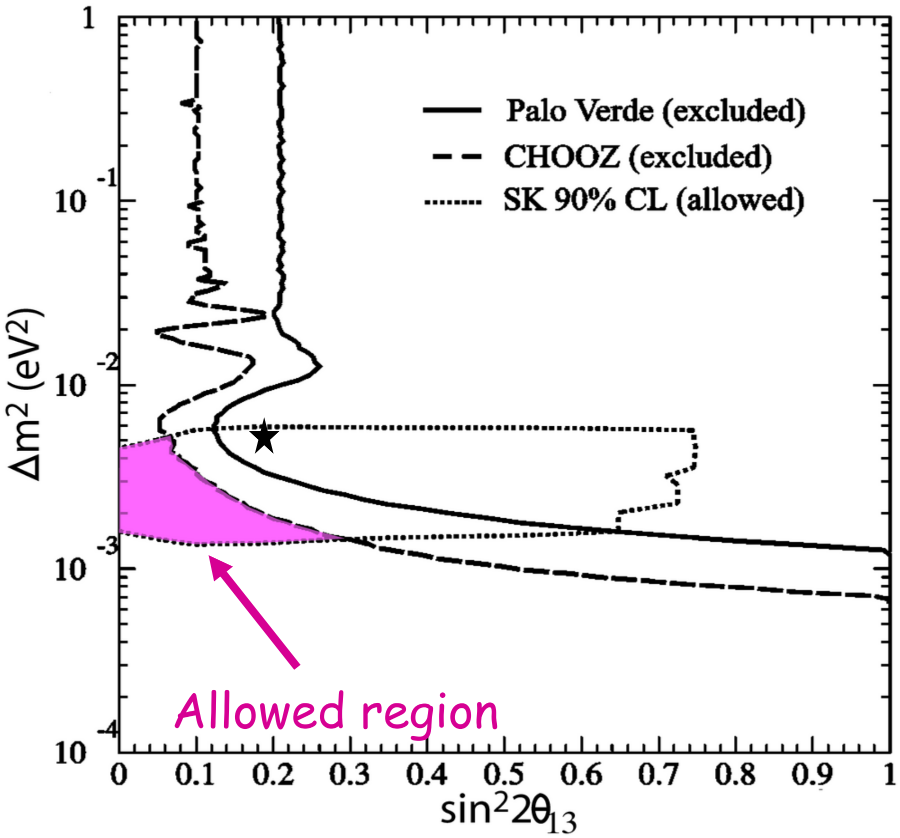
$\sin^2 2\theta_{13}$ = 0.092 ± 0.016(stat) ± 0.005(syst)

χ^2/NDF = 4.26/4, 5.2 σ for non-zero θ_{13}

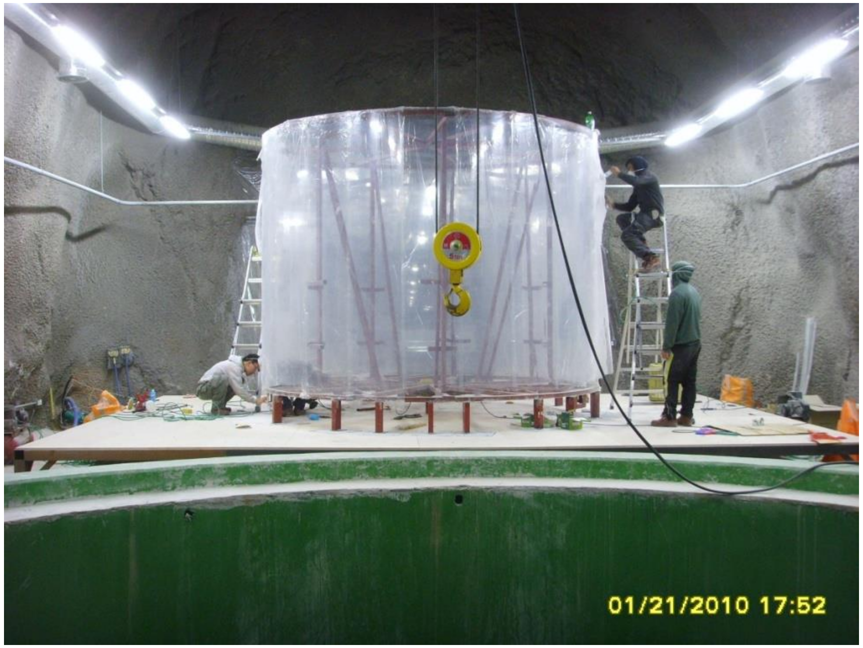
F.P. An et al., Phys. Rev. Lett. 108, (2012) 171803

Another Lucky Story

- It is big !
- Everybody can see it
- Easy for future experiments: mass hierarchy, CP phase, etc.



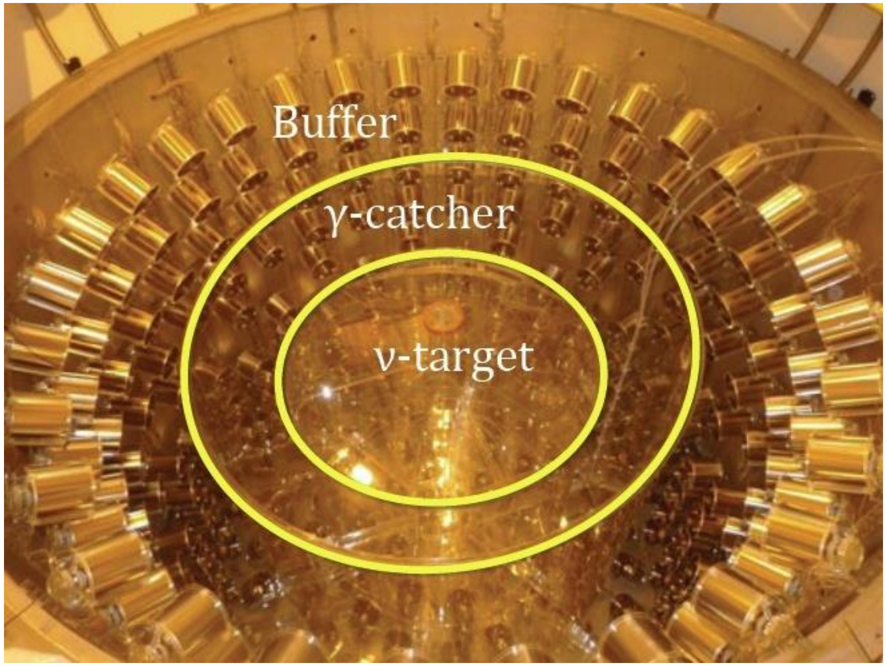
Reno



- **Data taking started on Aug. 11, 2011**
- **First physics results based on 228 days data taking(up to Mar. 25, 2012) released on April 3, 2012, revised on April 8, 2012, published on May 11, 2012:**

$\mathrm{Sin}^2 2\theta_{13}$=0.113±0.013(Stat)±0.019(Syst), 4. 9σ for non-zero θ_{13}

Double Chooz



- Far detector starts data taking at the beginning of 2011
- First results based on 85.6 days of data taking reported in Nov. 2011

$\sin^2 2\theta_{13}=0.086\pm0.041(\mathrm{Stat})\pm0.030(\mathrm{Syst})$, 1.7σ for non-zero θ_{13}

- Updated results based on 228 days of data taking reported on June 4, 2012 at Neutrino 2012

$\sin^2 2\theta_{13}=0.109\pm0.030(\mathrm{Stat})\pm0.025(\mathrm{Syst})$, 3.1σ for non-zero θ_{13}

Spectral Information

Rate-only Analysis:

$$\frac{N_{far}}{N_{near}} = \frac{N_{protons,far}}{N_{protons,near}} \frac{L^2_{near}}{L^2_{far}} \frac{\epsilon_{far}}{\epsilon_{near}} \frac{\int_{E_{min}}^{E_{max}} dE\, P_{surv}(E, L_{far}; \theta_{13}, \Delta m^2_{ee})\, \sigma(E)\, \Phi(E)}{\int_{Emin}^{Emax} dE\, P_{surv}(E, L_{near}; \theta_{13}, \Delta m^2_{ee})\, \sigma(E)\, \Phi(E)}$$

Advantages: Fewer systematic uncertainties

Disadvantages: Less sensitive, Unable to constrain Δm^2_{ee}

Rate + Spectrum Analysis:

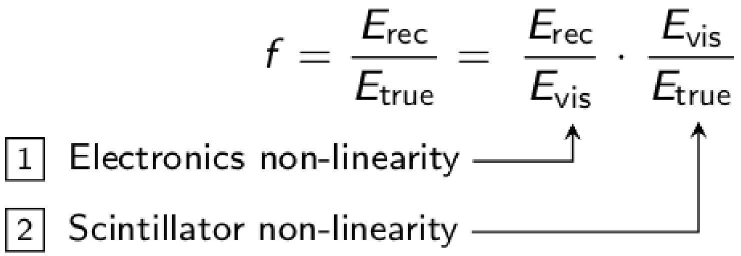
$$\frac{\frac{dN_{far}}{dE}}{\frac{dN_{near}}{dE}} = \frac{N_{protons,far}}{N_{protons,near}} \frac{L^2_{near}}{L^2_{far}} \frac{\epsilon_{far}}{\epsilon_{near}} \frac{P_{surv}(E, L_{far}; \theta_{13}, \Delta m^2_{ee})\, \sigma(E)\, \Phi(E)}{P_{surv}(E, L_{near}; \theta_{13}, \Delta m^2_{ee})\, \sigma(E)\, \Phi(E)}$$

Advantages: Each energy bin is an independent oscillation measurement, Δm^2_{ee}

Disadvantages: Requires detailed understanding of detector energy response.

Energy Response Model

Mapping the true energy E_{true} to the reconstructed kinetic energy E_{rec}:

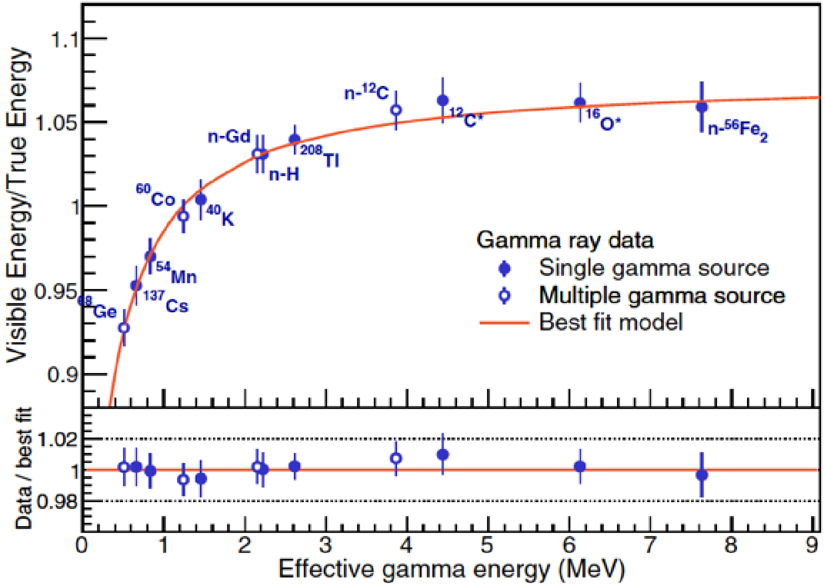


$$f = \frac{E_{rec}}{E_{true}} = \frac{E_{rec}}{E_{vis}} \cdot \frac{E_{vis}}{E_{true}}$$

1 Electronics non-linearity

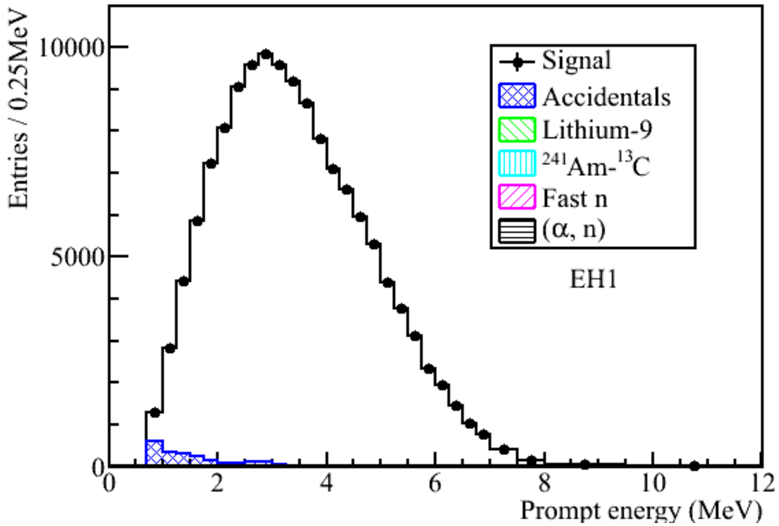
2 Scintillator non-linearity

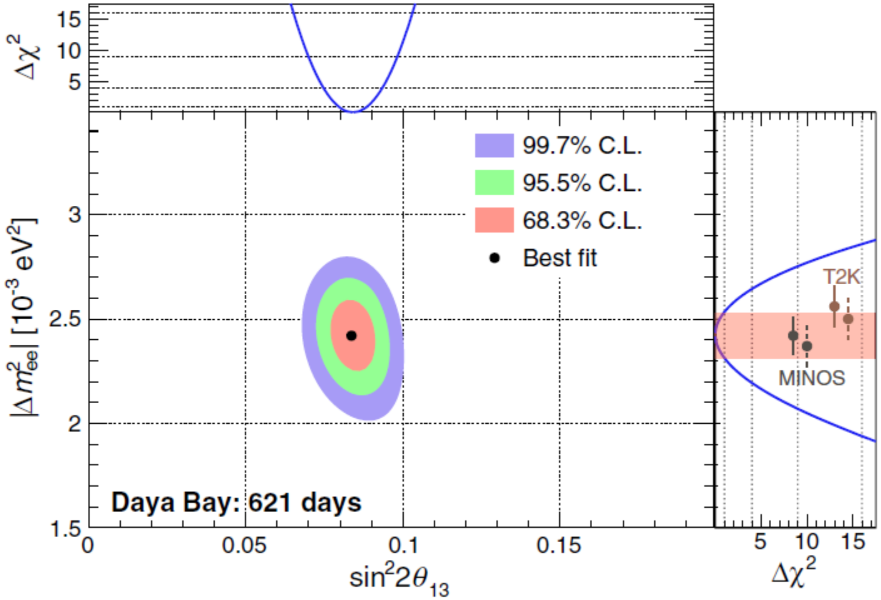
- Build models taking into account:
  - Electronics non-linearity: time-dependent charge collection efficiency
  - Scintillator non-linearity: Quench effect & Cerenkov radiation
  - Complicated e^+,e^-, γ's interactions in LS, from simulation
- Constraint parameters by a fit to all calibration data
- **Model difference ➔ systematic errors < 1%**

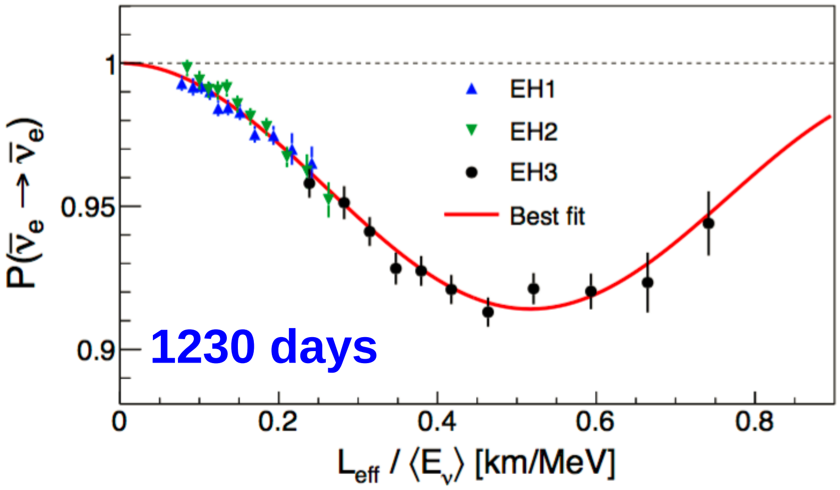


PRD 95, 072006 (2017)

Latest Result: Rate + Spectral Analysis







$\sin^2 2\theta_{13} = 0.0841 \pm 0.0033$

NH: $\Delta M^2_{32} = (2.45 \pm 0.08) \times 10^{-3}$ eV^2

IH: $\Delta M^2_{32} = (-2.55 \pm 0.08) \times 10^{-3}$ eV^2

PRD 95, 072006(2017)

Latest Results on $\mathrm{Sin}^2 2\theta_{13}$

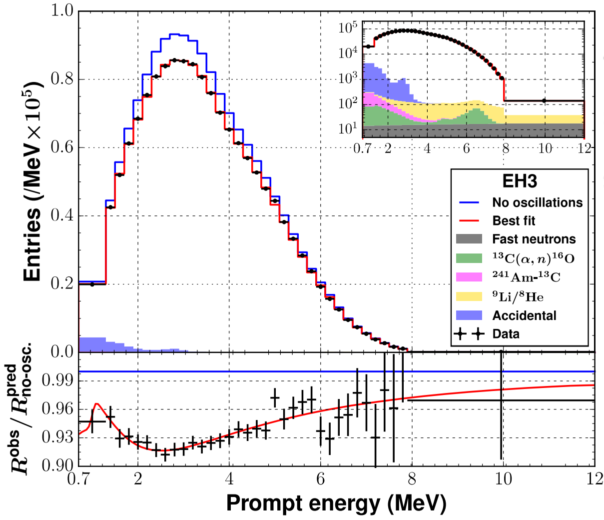
(EPS2017)

$$\sin^2 2q_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.) \quad \text{Daya Bay} \quad (\pm 3.9\%)$$

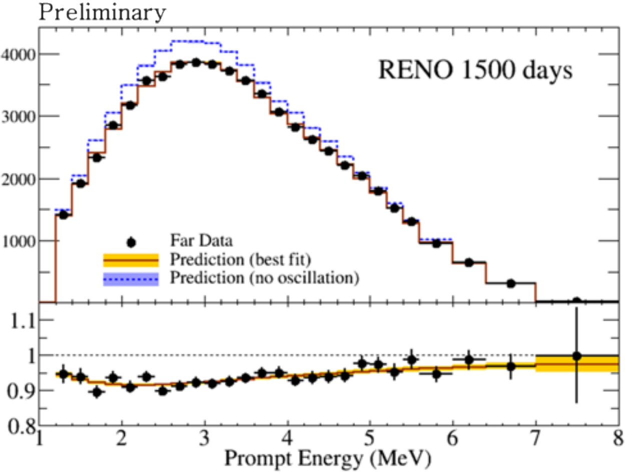
$$= 0.086 \pm 0.006(stat.) \pm 0.005(syst.) \quad \text{RENO} \quad (\pm 9.1\%)$$

$$= 0.119 \pm 0.016(stat. + syst.) \quad \text{Double Chooz} \quad (\pm 13.4\%)$$

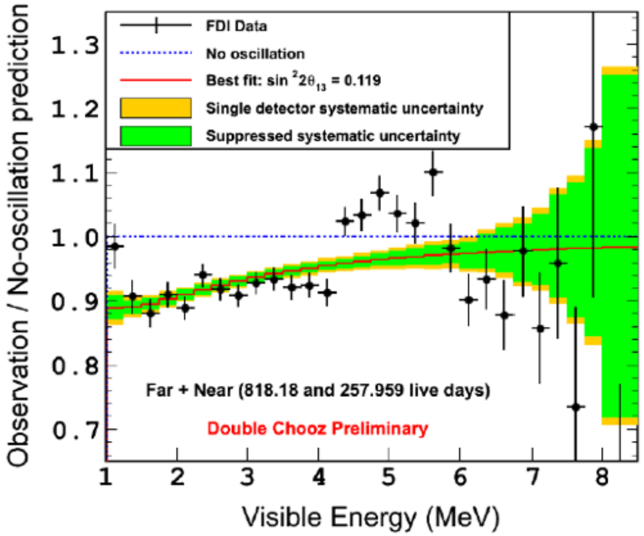
DYB



RENO



DC



using data collected up to July 2015 (1230 days, >2.5 million IBDs)

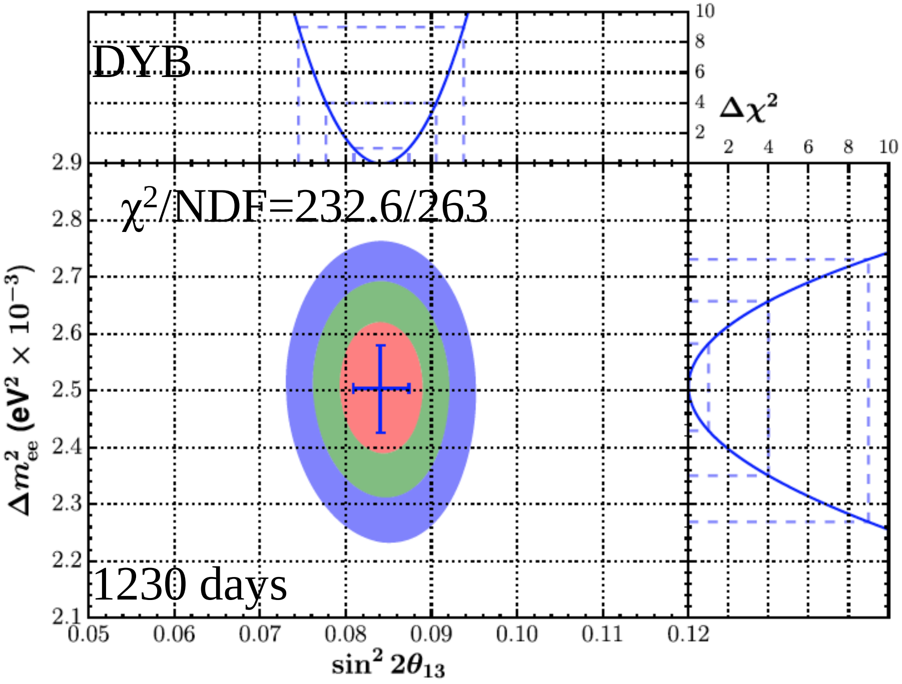
(PhysRevD.95.072006)

new results presented at EPS2017 (up to Sep. 2015)

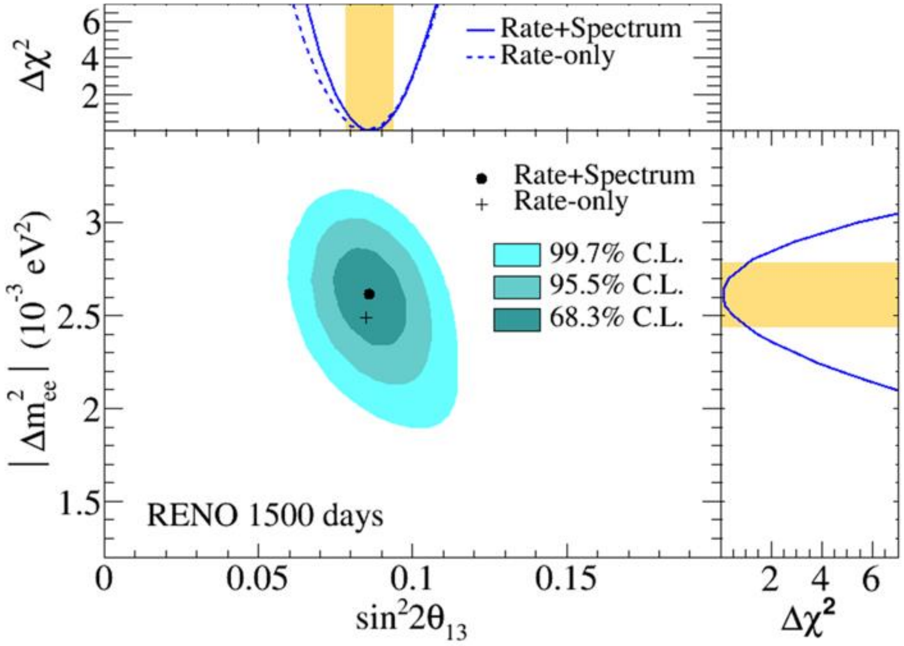
not yet publication with near+far detectors (near detector since beginning of 2015)

Latest Results on Δm^2_{ee}

PRD 95, 072006 (2017)



Preliminary



$$\left|\Delta m^2_{ee}\right| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} eV^2$$

±3.4%

$$\left|\Delta m^2_{ee}\right| = [2.61^{+0.15}_{-0.16}(stat.)^{+0.09}_{-0.09}(syst.)] \times 10^{-3} eV^2$$

±7%

$$\Delta m^2_{32} = [2.45 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} eV^2 \quad \text{for NH}$$

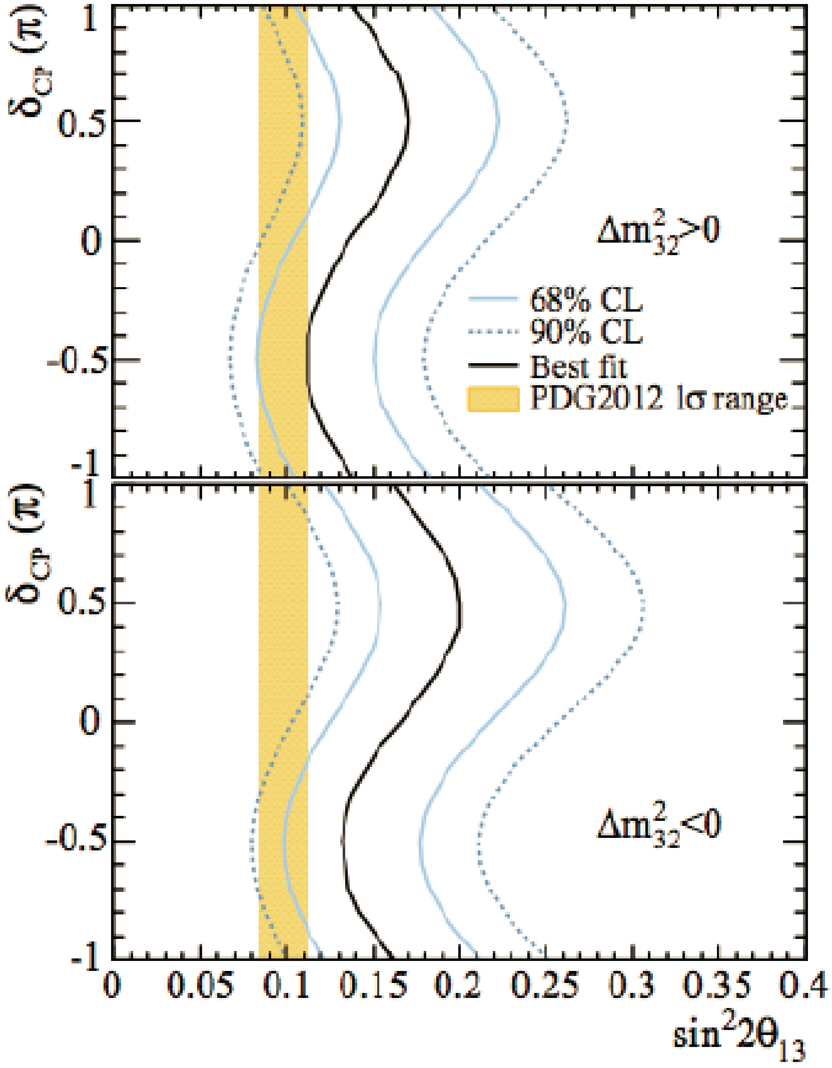
$$= [-2.56 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} eV^2 \quad \text{for IH}$$

systematic error ~ statistical error

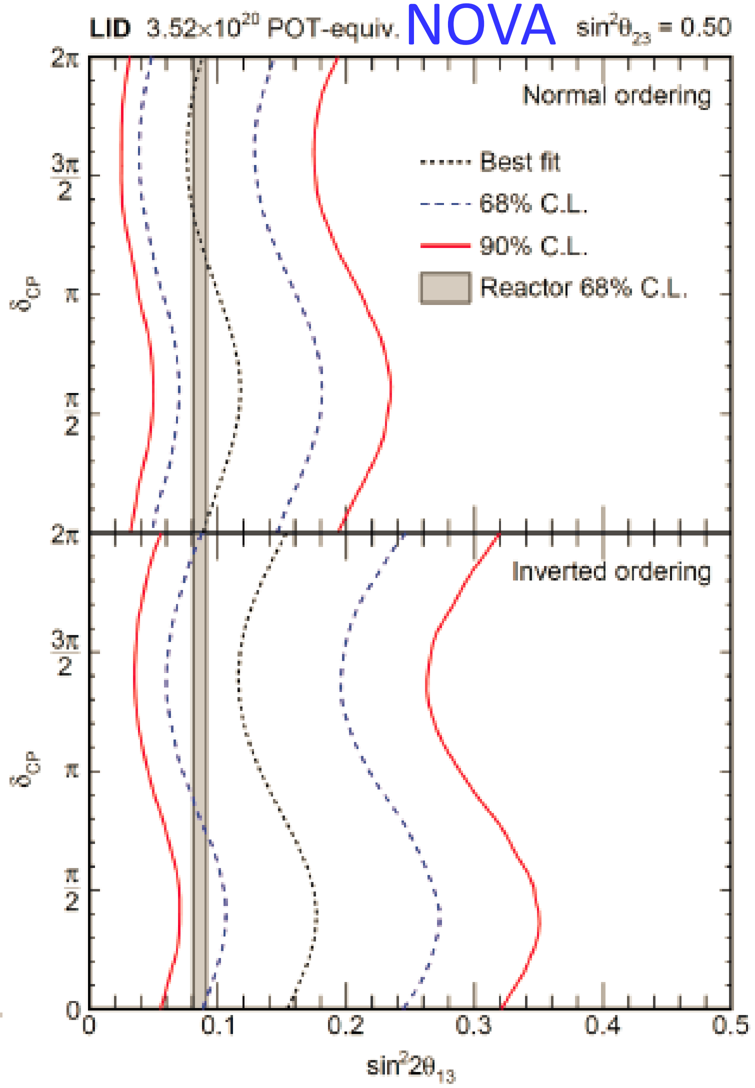
(=2.52 ±0.04 from all experiments, NH)

Jointly Determine CP ？

T2K



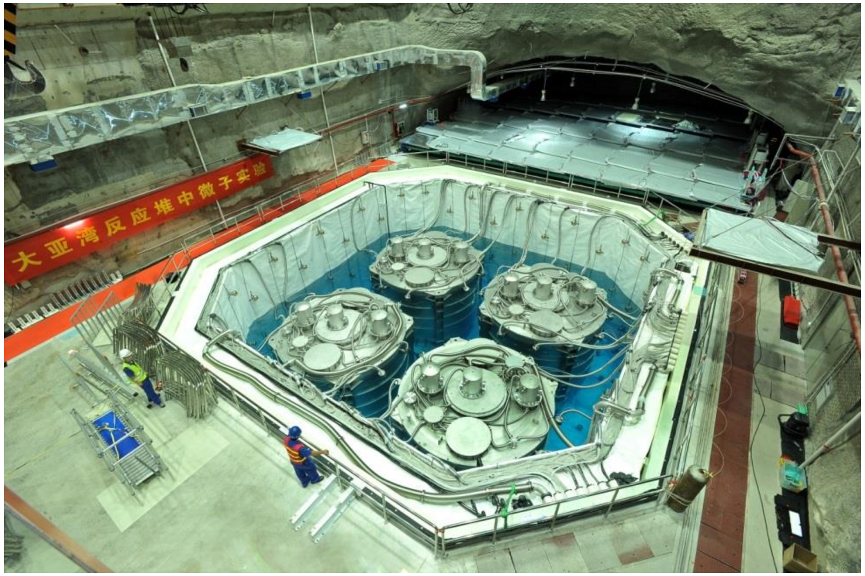
NOVA

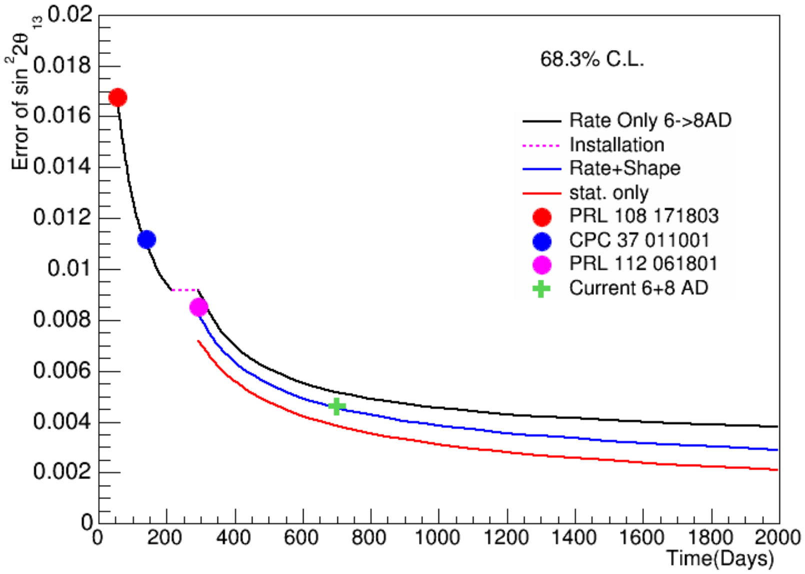


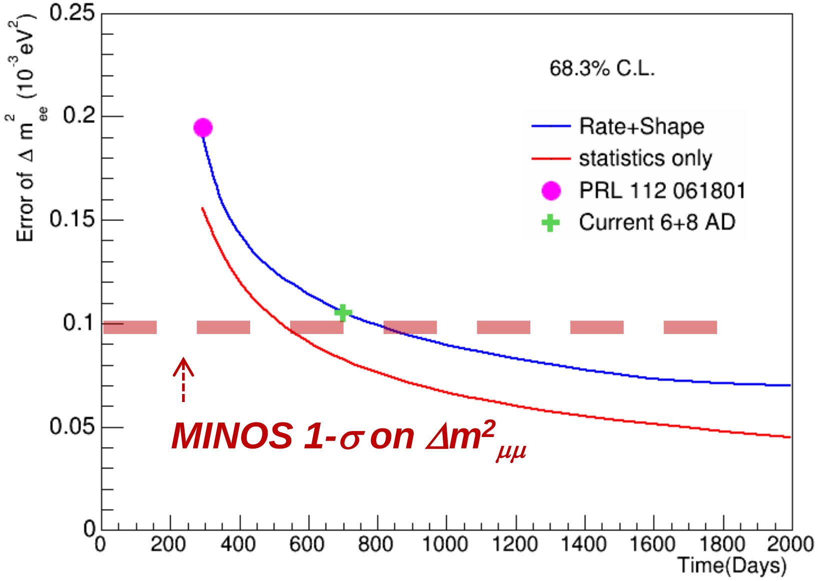
CP phase is ~ -90° at ~ 2σ level !

Future Prospects: Daya Bay

- **Data taking for θ_{13} until 2020**
- **Precision can reach $\Delta(\sin^2 2\theta_{13})$ ~ 3%; the best for the foreseeable future**
- **Other physics topics:**
  - ⇨ **Cosmogenic isotope production**
  - ⇨ **Supernova neutrinos**
  - ⇨ **Correlated cosmic-ray events**



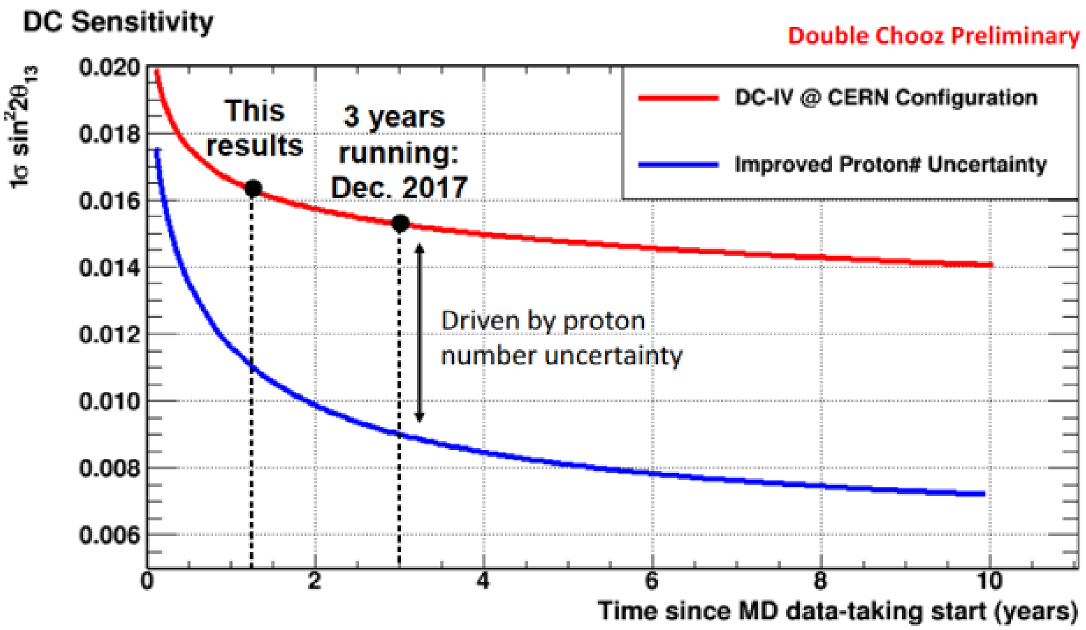




MINOS 1-σ on $\Delta m^2_{\mu\mu}$

Future Prospects: Other Experiments

- **Double Chooz**
    - end of data taking: ~end of 2017
- **RENO**
    - end of data taking: end of 2018
        - possible extension up to 2021
    - goal: reach 6% precision on θ_{13}



Reactor Flux and Spectrum

- Daya Bay measured the flux and energy spectrum:
  - ⇨ Absolute flux
  - ⇨ Absolute e^+ energy spectrum
  - ⇨ Unfolded absolute ν energy spectrum
  - ⇨ Evolution of neutrino flux

Reactor anomaly？

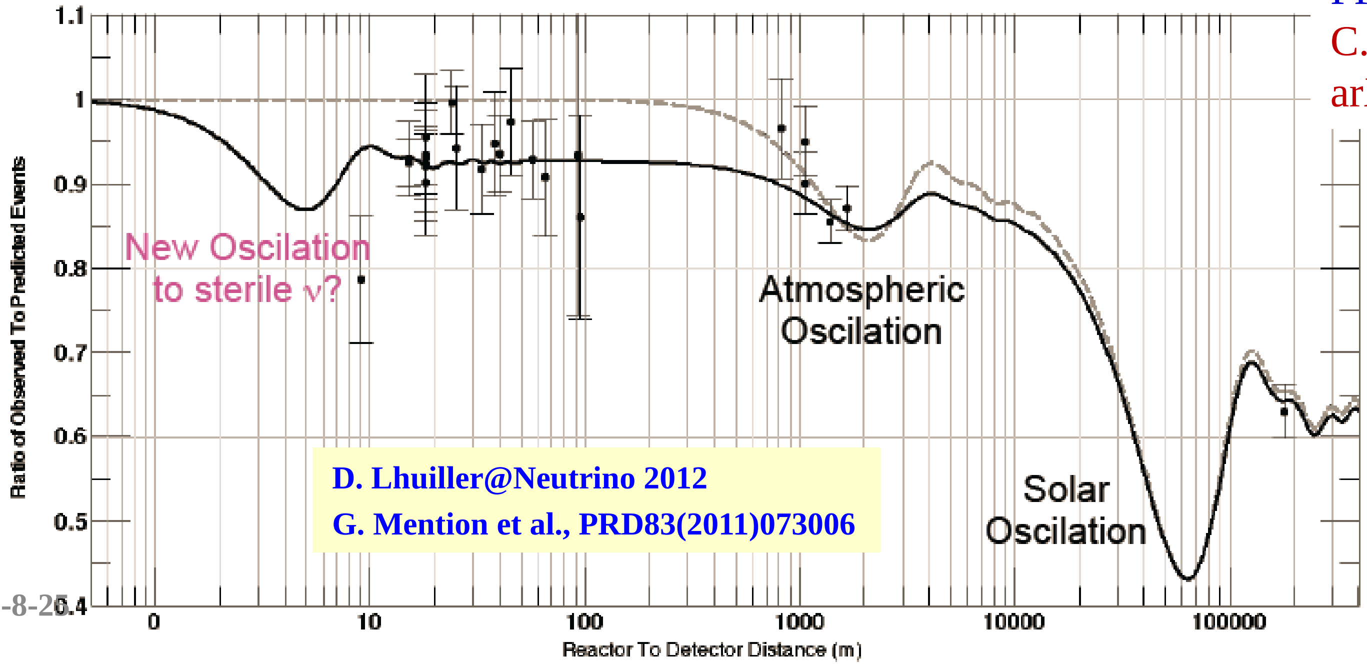
Sterile neutrinos？

- All three experiments, Daya Bay, Double Chooz and RENO, observed a "bump" at ~5 MeV
  - ⇨ No effect to θ_{13} if near-far configuration applied(Daya Bay & RENO)
  - ⇨ Under control even if only far detector is used(Double Chooz)
  - ⇨ Not large enough to explain the reactor anomaly

Reactor Neutrino Anomaly

- By a new flux calculation, there may exist a reactor neutrino flux deficit: 0.943±0.023. A 3σ effect ?
- Later confirm by other calculations
- Oscillation with sterile neutrinos ?
  - Other experimental “hints”: LSND, MiniBooNE, Gallex…
  - Global fit of all “hints”: severe tensions
  - Cosmological bounds: not so favored

T.A. Mueller et al., PRC83:054615,2011
P. Huber et al., PRC84:024617,2011.
C. Zhang et al., arXiv: 1303.0900



D. Lhuiller@Neutrino 2012
G. Mention et al., PRD83(2011)073006

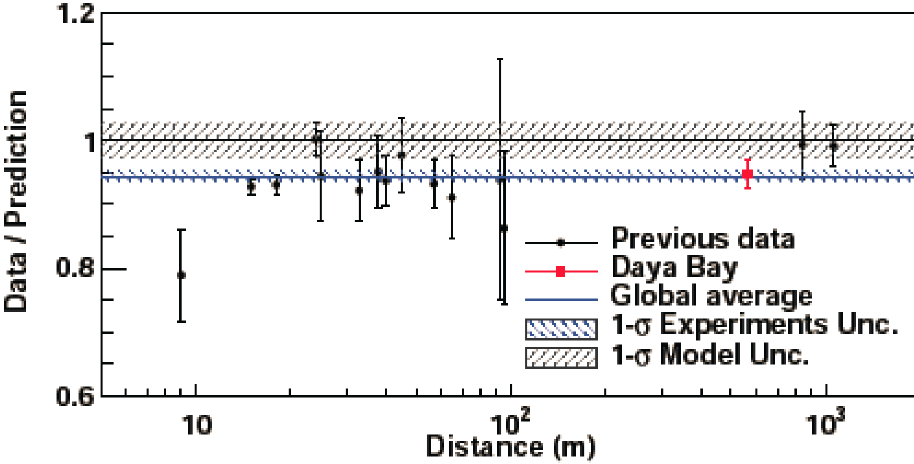
Reactor anomaly ➔ Sterile Neutrinos ?

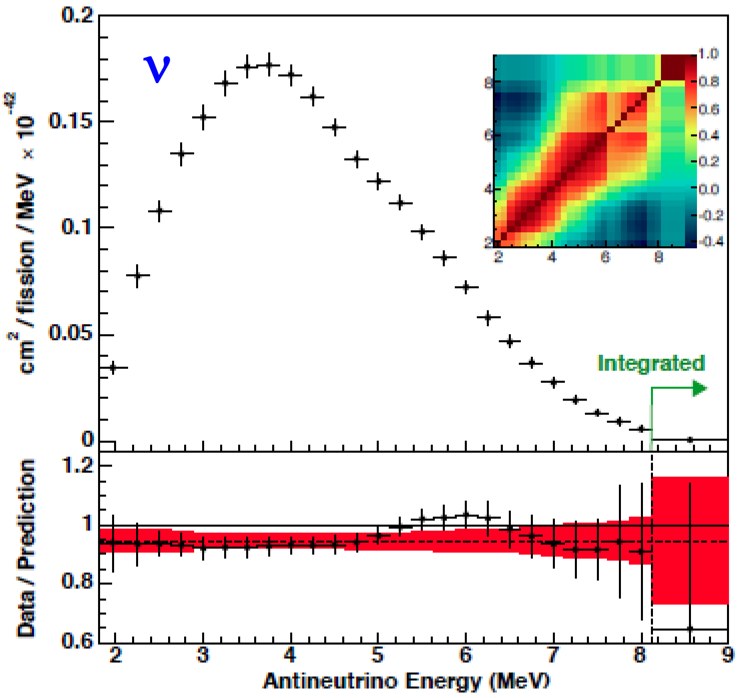
- **Radioactive source exp.:**
  - **CeLAND(^{144}Ce in KamLAND), SoX(^{51}Cr in Borexino),…**
- **Accelerator exp.:**
  - **IsoDAR, Icarus/Nessie, nuSTORM…**
- **Reactor exp.:**
  - **Nucifer, Stereo, Solid, Prospect, SCARR, …**
    - Backgrounds near reactors
    - Precision better than 1%

Absolute Flux and Spectrum

PRL 116, 061801(2016)

- Absolute Flux
  - Data/(Huber+Mueller)： 0.946±0.022
  - Data/(ILL+Vogel)： 0.991 ± 0.023
  - Consistent with others
- Absolute ν spectrum：
  - After non-linearity correction
  - Unfolding the e+ spectrum
    - Between 1.5 and 7MeV: 1.0% at 3.5 MeV, 6.7% at 7 MeV
    - Above 7 MeV it is larger than 10%
- New prediction from direct measurement for future experiments
- Aim at 1% for JUNO





Precision Spectrum with Gas TPC

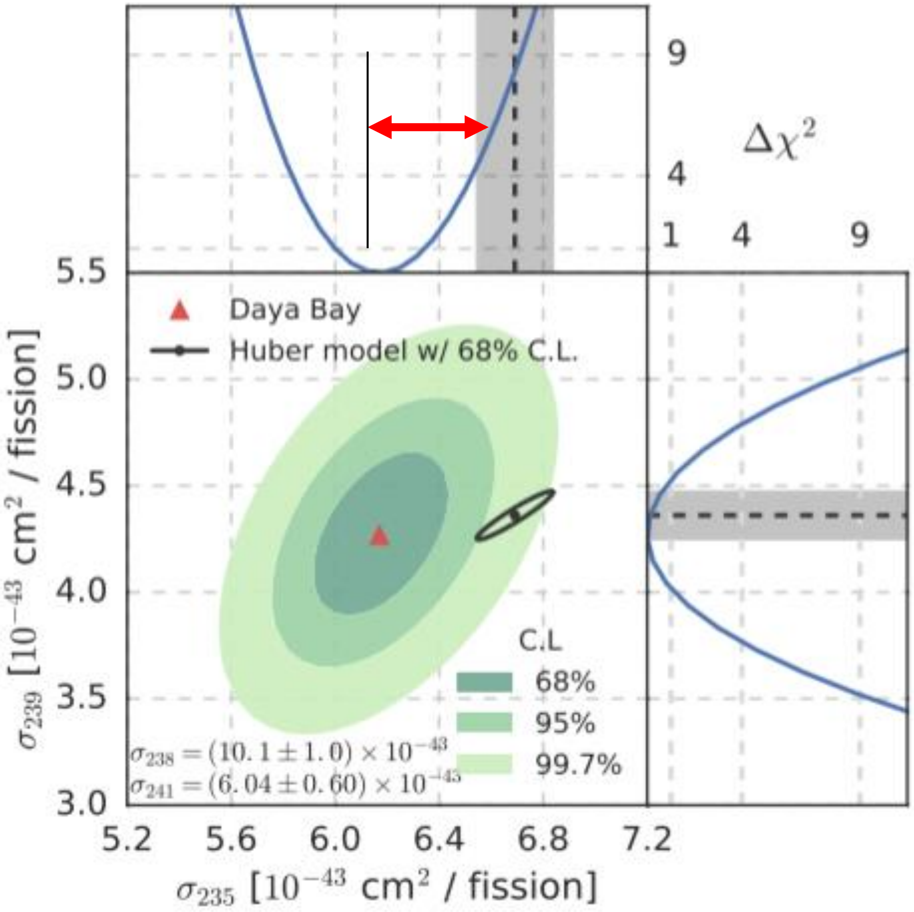
- **How to reach 1% spectrum uncertainty?**
- **Improving Daya Bay**
  - **Electronics non-linearity**
    - 192 channels Flash ADC for AD1. Data taking completed.
  - **Liquid scintillator non-linearity**
    - Replaced LS in AD1 for JUNO R&D

      → Consequence: Daya Bay from 8 AD to 7 AD since Dec. 2016
    - Testing detector responses with 13 different LS configurations (PPO from 0.5g/L to 4g/L, bis-MSB from 0.1-15 mg/L)

      → Building precision Monte Carlo
  - **Relative meas. to cancel non-linearity btwn Daya Bay and JUNO**
- **Other experiments, like PROSPECT (4.5% energy resolution)**
- **Gas TPC detector at ~20 m from a reactor (Prototyping at IHEP)**
  - **ν-e scattering**
  - **High energy resolution (1%/sqrt(E), Daya Bay 8%, JUNO 3%)**
  - **Other motivations: θw, abnormal magnetic moment (to 10^{-12})**

Fuel Evolution

- correlations between fuel evolution and changes in the reactor antineutrino flux and energy spectrum.
- Combined fit for major fission isotopes ^{235}U and ^{239}Pu
- σ235 is (7.8±2.7)% lower than Huber-Mueller model
- σ239 is consistent with the prediction (6% meas. uncertainty)
- 2.8σ disfavor equal deficit (H-M model & sterile hypothesis)



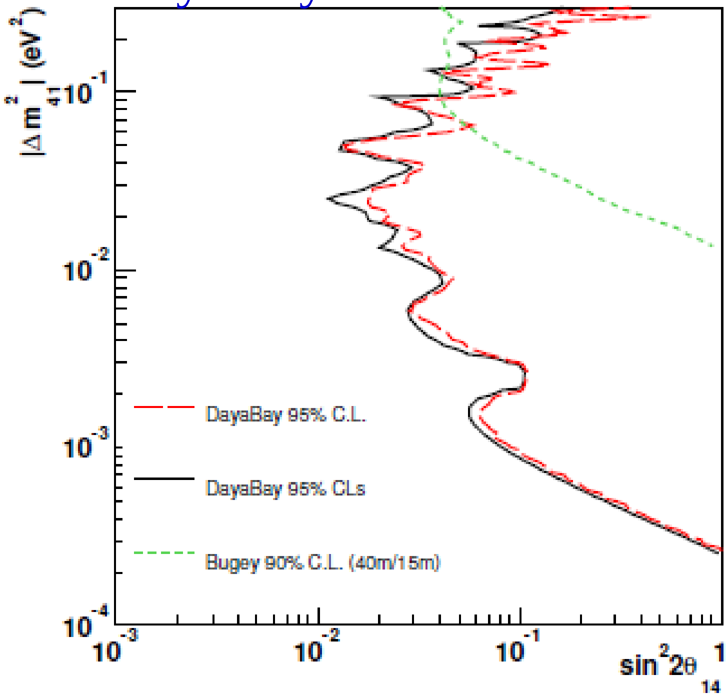
PRL118, 251801 (2017)

Search for Sterile Neutrinos

- Precise reactor neutrino spectrum from Daya Bay near site can test the sterile neutrino hypothesis
- But ~400 m baseline is not ideal for the reactor anomaly
- In addition to accelerator and radioactive source experiment for sterile neutrinos, we also need experiments very close to the reactor for sterile neutrinos AND JUNO type of experiments:
  - High precision reactor spectrum measurement(statistics ~ 1-10 M events, energy resolution ~ 1-2%, event vertex ~ 10 cm, …)

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \boxed{\sin^2 2\theta_{14}}\sin^2\left(\frac{\boxed{\Delta m^2_{41}}L}{4E_\nu}\right)$$

Daya Bay: arXiv:1407.7259

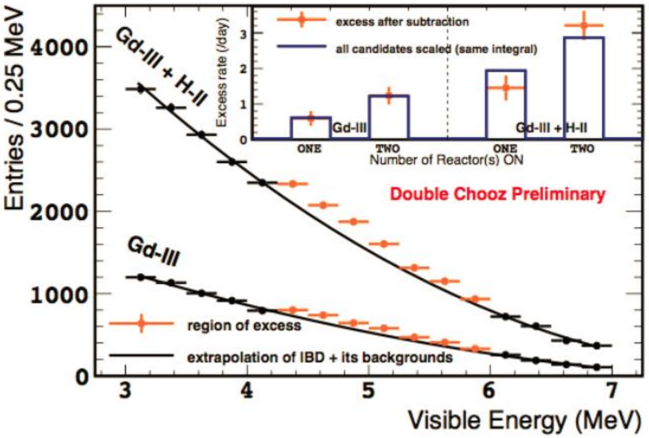


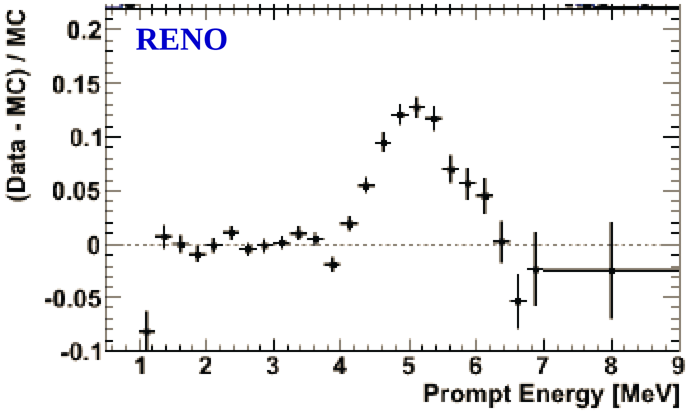
Excess in [4,6] MeV Region

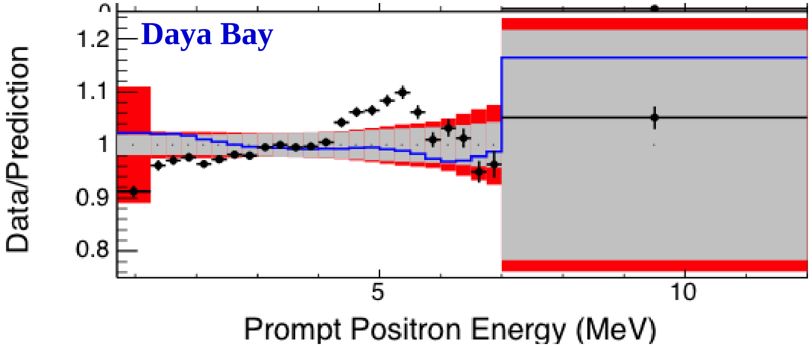
- Significance ~ 4 σ
- Events are reactor power related & time independent
- Events are IBD-like:
  - Disfavors unexpected backgrounds
- A single β-branch or mono-energetic line cannot simulate the bump
- Possible explanations:
  - Decays of prominent fission daughter isotopes (~ 42% rate from ^{96}Y, ^{92}Rb, ^{142}Cs, ^{97}Y, ^{93}Rb, ^{100}Nb, ^{140}Cs, ^{95}Sr)

    PRL112: 2021501; PRL114:012502
  - Energy non-linearity calibration

    arXiv: 1705.09434





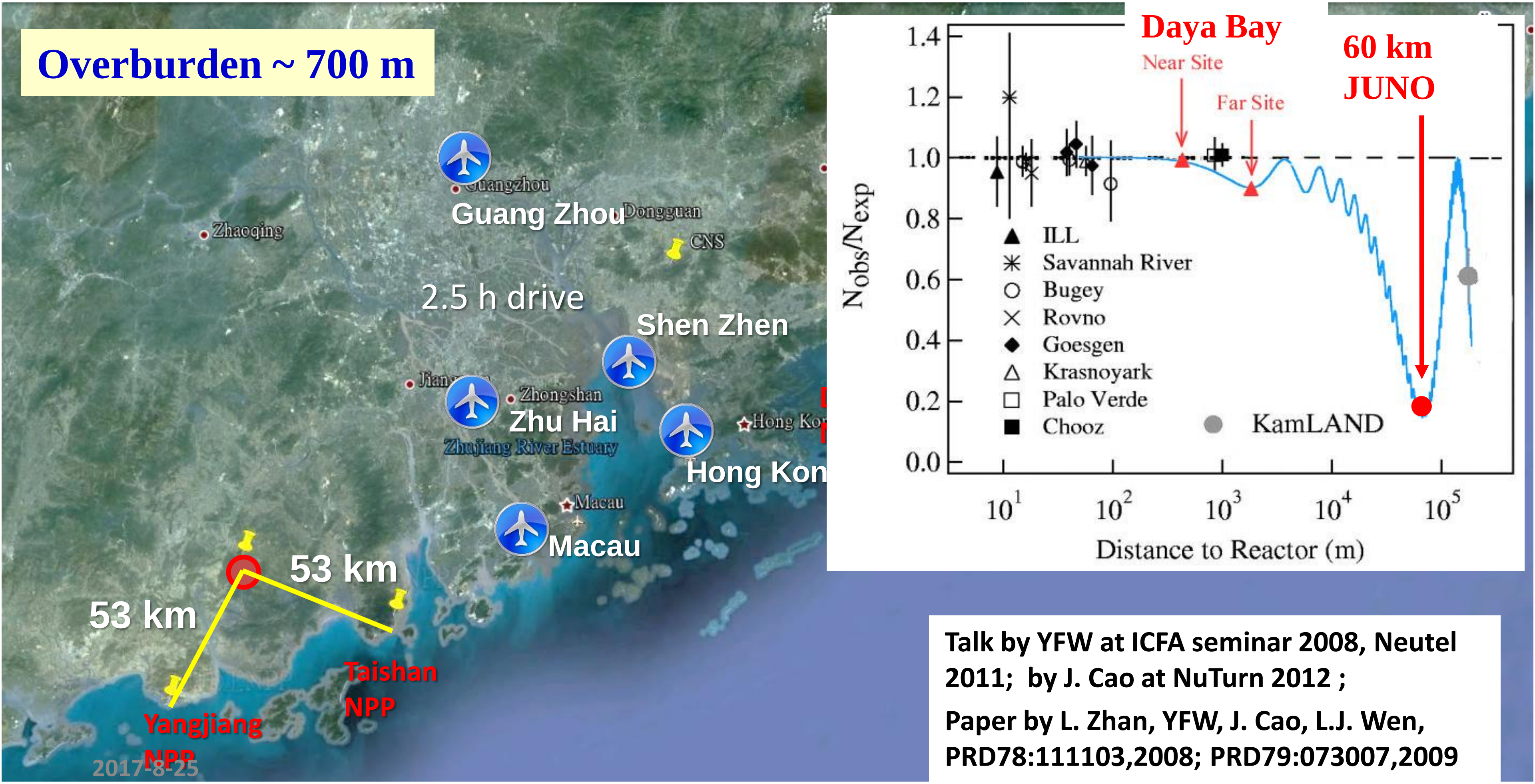


Still a Lot of Unknowns

- **Neutrino oscillation：**
  - **Neutrino mass hierarchy ?**
  - **Unitarity of neutrino mixing matrix ？**
  - **Θ_{23} is maximized ?**
  - **CP violation in the neutrino mixing matrix as in the case of quarks ? Large enough for the matter-antimatter asymmetry in the Universe ?**
- **What is the absolute neutrino mass ?**
- **Neutrinos are Dirac or Majorana ?**
- **Are there sterile neutrinos？**
- **Do neutrinos have magnetic moments ？**
- **Can we detect relic neutrinos ?**
- **……**

The JUNO Experiment

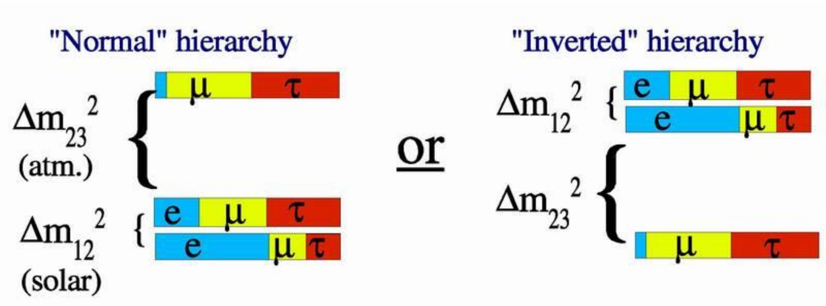
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



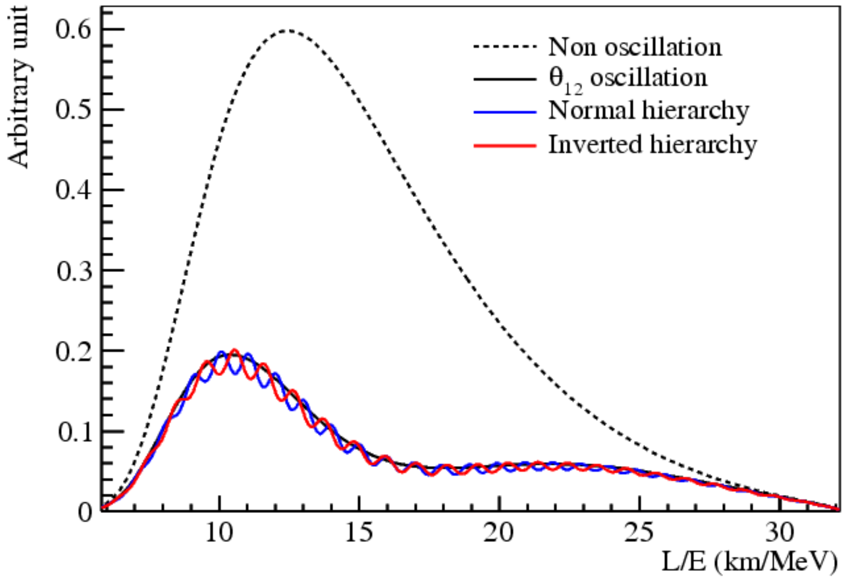
Talk by YFW at ICFA seminar 2008, Neutel 2011; by J. Cao at NuTurn 2012 ;

Paper by L. Zhan, YFW, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

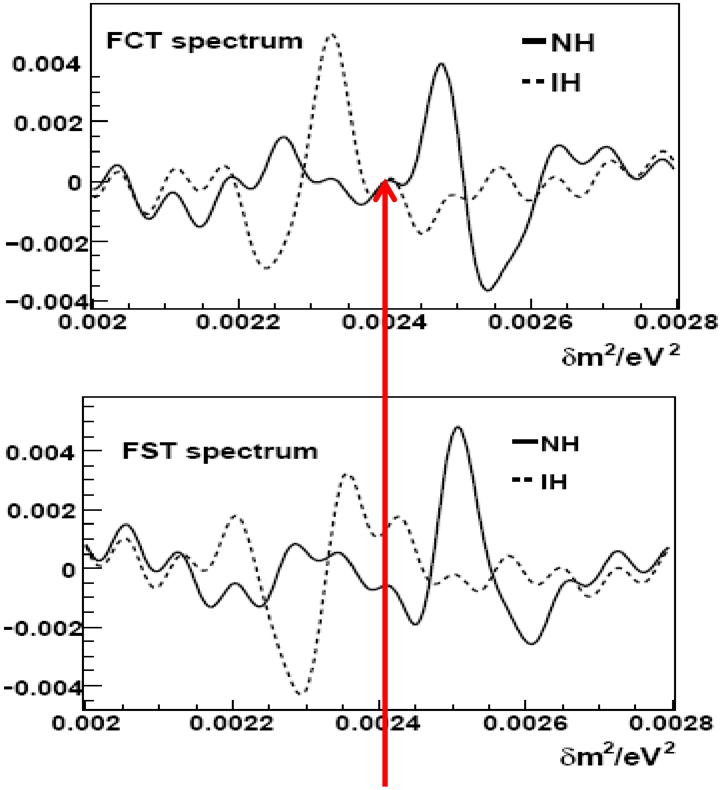
Mass Hierarchy at Reactors



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



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



ΔM^2_{23}

L. Zhan et al., PRD78:111103,2008; PRD79:073007,2009

How to Get Enough Photons ?

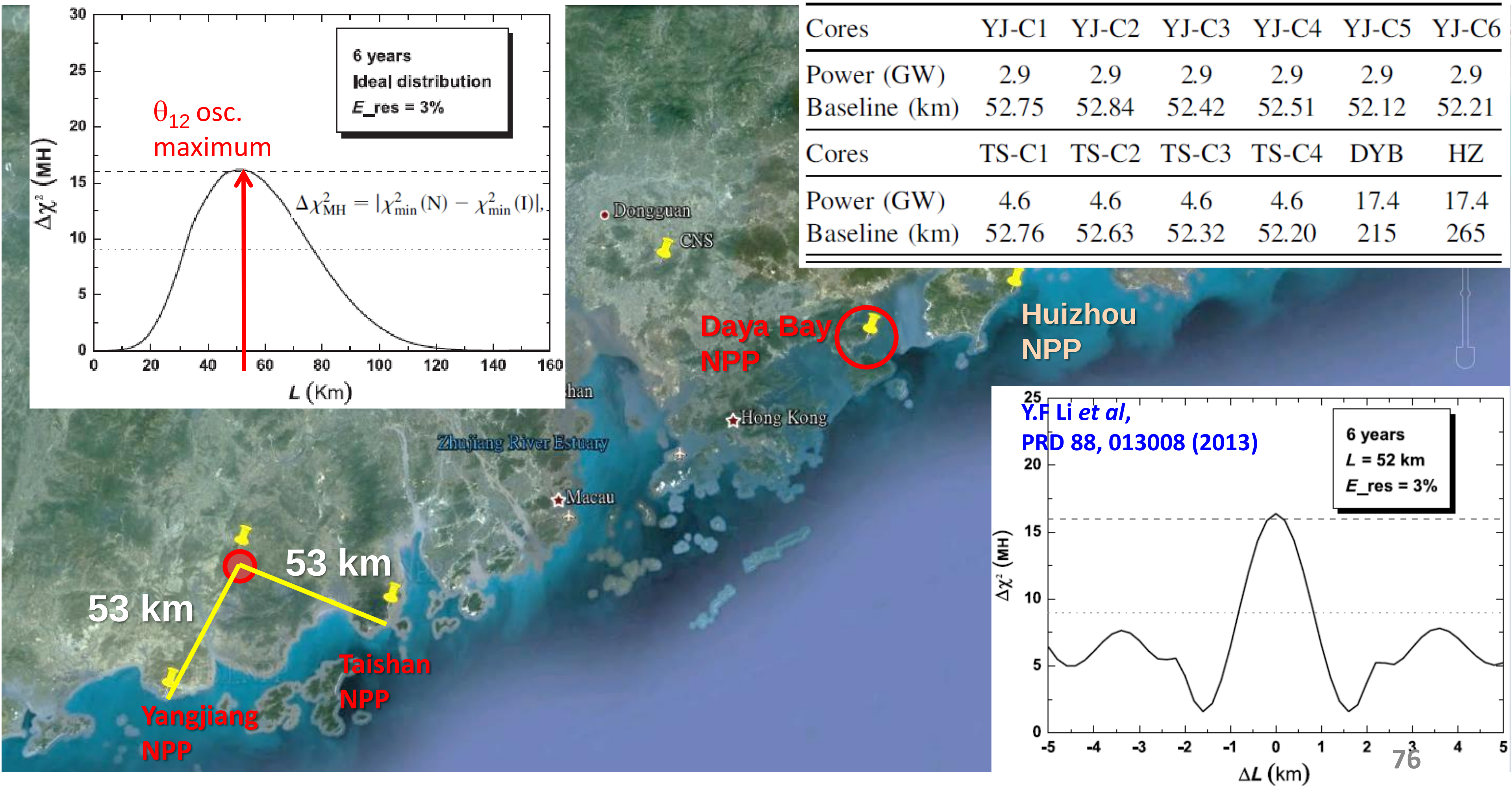
	KamLAND	JUNO	Needed gain
Light yield	**250 p.e./MeV**	**1200 p.e./MeV**	**5**
Photocathode coverage	34%	75%	2.2
Light yield	1.5g/l PPO	3-5g/l PPO	1.5
Attenuation length/R	15 m/16m	25m/35m	~ **0.8**
PMT QE*CE	20%*60%	25-30%	~ 2

Where to get all these factors ?

Are the estimate of these factors reasonable ?

Optimum baseline for MH

- **Optimum at the oscillation maximum of θ_{12}**
- **Multiple reactors may cancel the oscillation structure**
  - **Baseline difference cannot be more than 500 m**



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

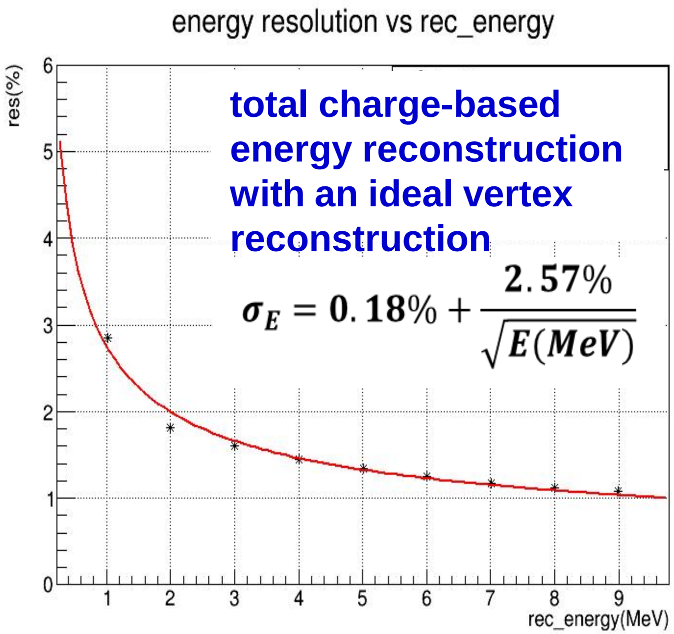
Y.F Li *et al*,
PRD 88, 013008 (2013)

MC Study：Energy Scale & Resolution

- **Resolution: based on DYB with:**
  - ⇨ **JUNO Geometry**
  - ⇨ **80% photocathode coverage**
  - ⇨ **PMT QE from 25% ➔ 35%**
  - ⇨ **Attenuation length of 20 m ➔**
    - ✓ **abs. 60 m + Rayleigh scatt. 30m**
- **Energy scale**
  - ⇨ **By introduce a self-calibration (based on ΔM^2_{ee} periodic peaks), effects can be corrected and sensitivity is un-affected**

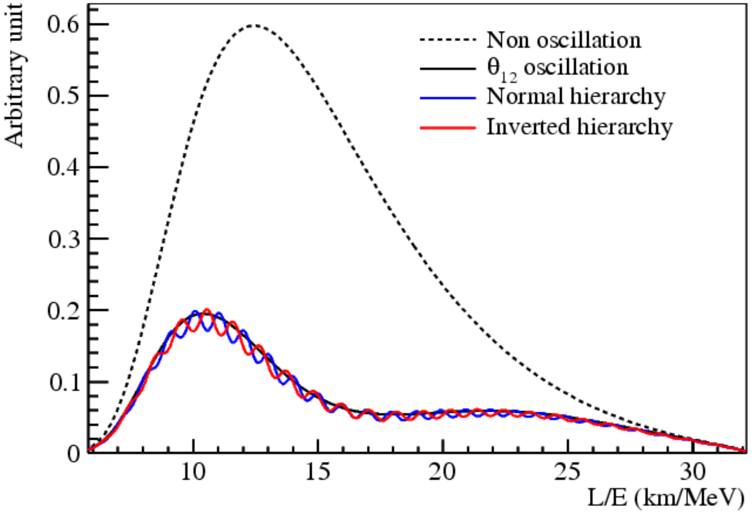
Y.F. Li et al., arXiv:1303.6733

  - ⇨ **Application of this method:** **Relatively insensitive to continuous backgrounds, non-periodic structures**



total charge-based energy reconstruction with an ideal vertex reconstruction

$$\sigma_E = 0.18\% + \frac{2.57\%}{\sqrt{E(MeV)}}$$

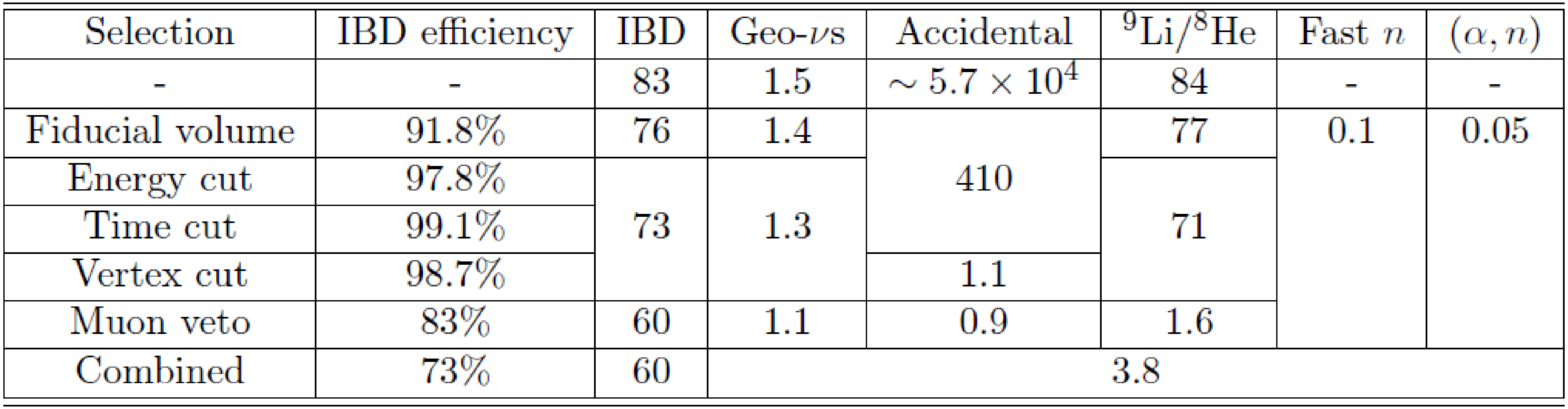


Signals & Backgrounds

$\tau \sim 200\ \mu s$

- **LS without Gd-loading for**
  - ⇨ Better attenuation length ➔ better resolution
  - ⇨ Lower irreducible accidental backgrounds from LS, important for a larger detector:
    - ✓ With Gd: ~ 10^{-12} g/g ➔ 50,000 Hz
    - ✓ Without Gd: ~ 10^{-16} g/g ➔ 5 Hz
- **IBD Signal and Backgrounds**

Overburden 700m:
$E_\mu \sim 211$ GeV, $R_\mu \sim 3.8$ Hz
Single rates:
5 Hz by LS and 5Hz by PMT
muon efficiency ~ 99.5%



Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

Physics Reach: Mass hierarchy

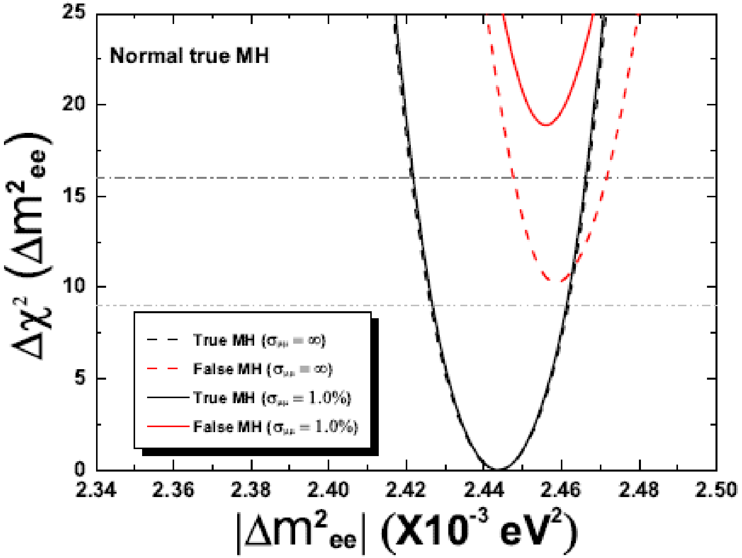
For 6 years, JUNO can determine the mass hierarchy:

$\sin^2 2\theta_{13} = 0.09$
Detector size: 20kt LS
Energy resolution: 3%/√E
Thermal power: 36 GW

	Relative Meas.	[(a)]Use absolute Δm^2
Ideal case	4σ	5σ
[(b)]Realistic case	3σ	4σ

[(a)] If accelerator experiments(NOvA, T2K and ICECUBE) can measure $\Delta M^2_{\mu\mu}$ to ~1% level

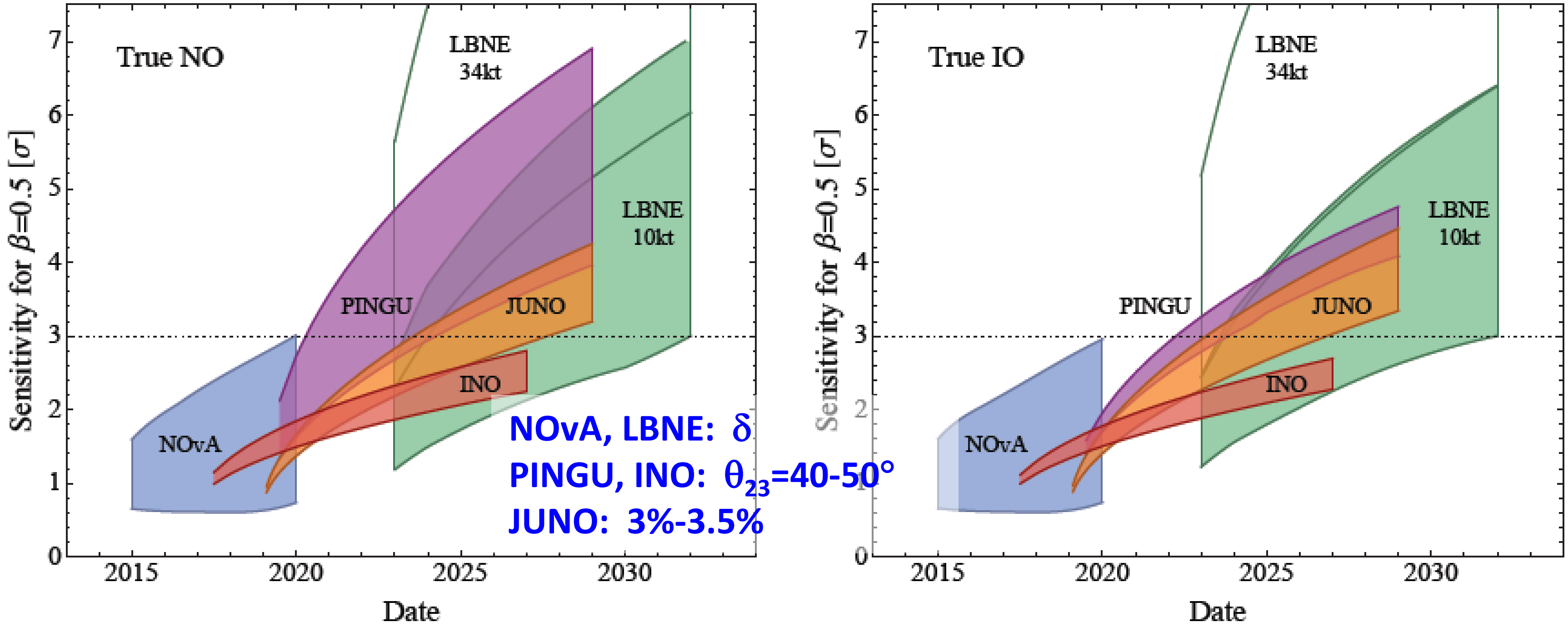
[(b)] Taking into account multiple reactor cores, uncertainties from energy non-linearity, etc.



Y.F. Li et al., *PRD 88, 013008 (2013)*
arXiv:1303.6733

Race for the Mass Hierarchy

M. Blennow et al., JHEP 1403 (2014) 028



NOvA, LBNE: δ

PINGU, INO: θ_{23}=40-50°

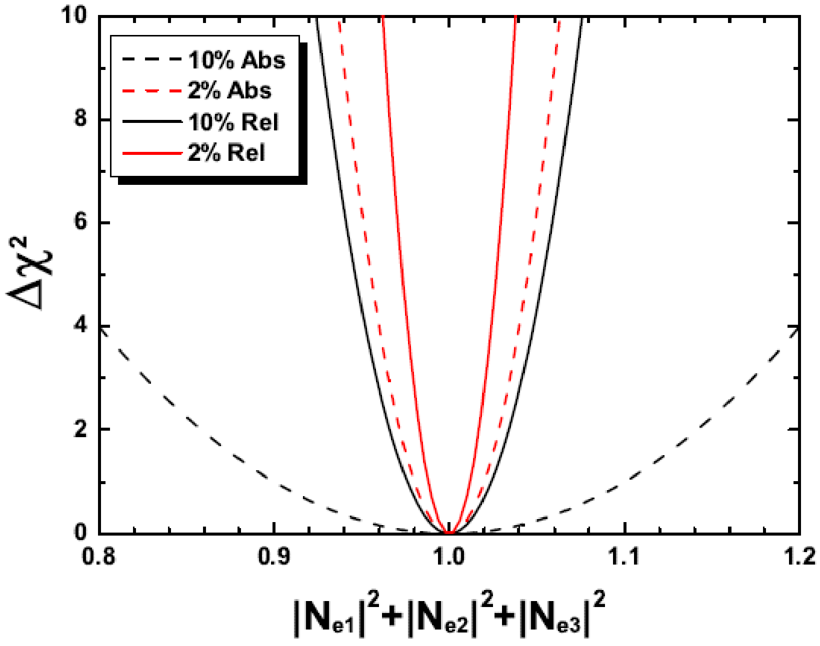
JUNO: 3%-3.5%

- **JUNO is competitive for measuring MH using reactor neutrinos**
  - **Independent of the yet-unknown CP phase, matter effects and θ_{23}**
- **Many other science goals:**
  - **Precision measurement of Δm_{31}^2, θ_{12}, Δm_{21}^2**
  - **Geo-, solar, supernova, …, neutrinos**

Precision Measurement of Mixing Parameters

- **Fundamental to the Standard Model and beyond**
- **Probing the unitarity of U_{PMNS} to ~1% level !**
  - ⇨ **Uncertainty from other oscillation parameters and systematic errors, mainly energy scale, are included**

	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	3%	0.6%
$\sin^2\theta_{12}$	4%	0.7%
$\sin^2\theta_{23}$	11%	N/A
$\sin^2\theta_{13}$	10%	-



More precise than CKM matrix elements !

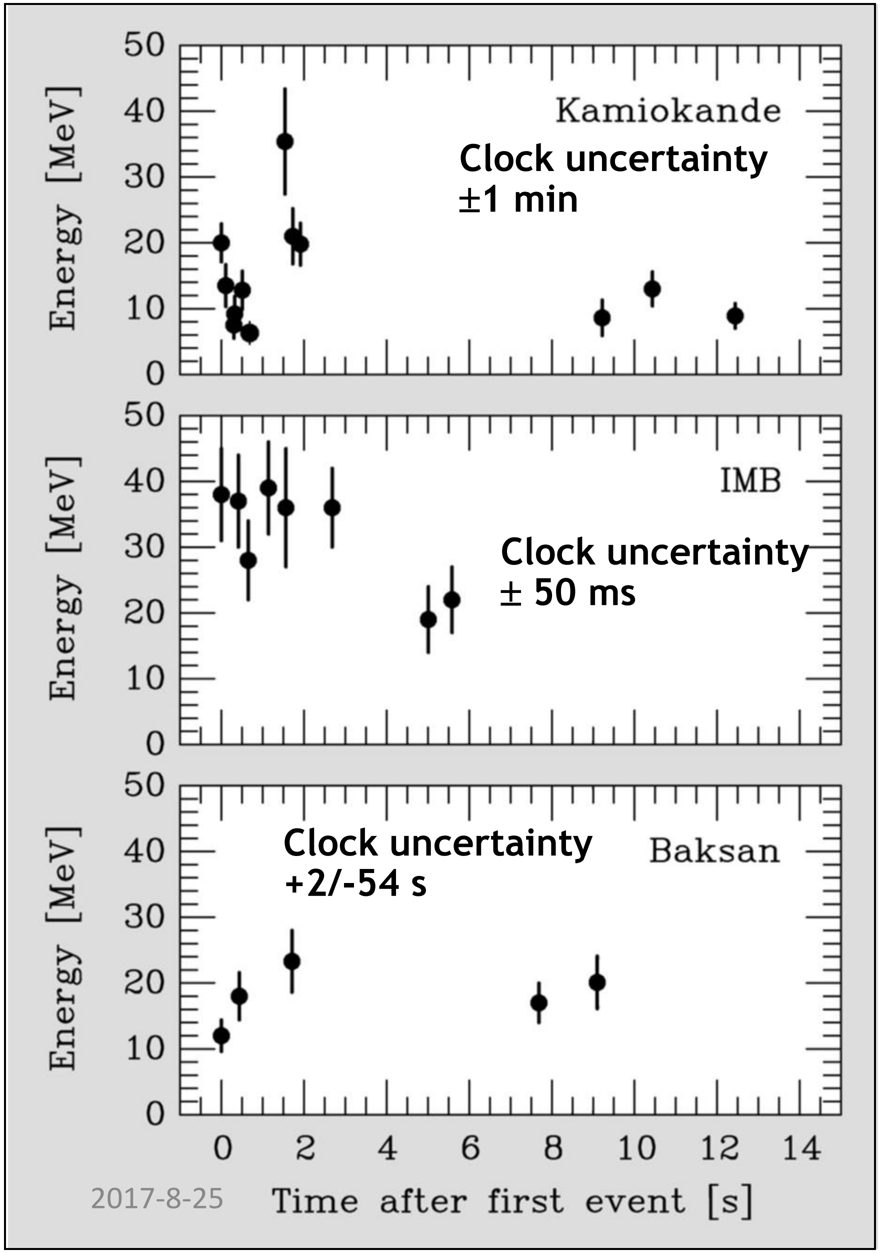
Supernova Neutrinos

- Basic facts:
  - Energy:
    - Gravitational binding energy:

      $E_b \approx 3 \times 10^{53}$ erg
    - 99% Neutrinos
    - 1% Kinetic energy of explosion (1% of this into cosmic rays)
    - 0.01% Photons, outshine host galaxy
  - Neutrino Energy: 1 - 50 MeV
- Very good for Supernova study, neutrino mass measurement, and many others
- Frequency: ~ 1/galaxy/100 years

Within our galaxy(~10 kpc), a supernova explosion can happen at any time from now

1987A Supernova Neutrinos



Clock uncertainty ±1 min

Clock uncertainty ± 50 ms

Clock uncertainty +2/-54 s

- On Feb. 23, 1987A Supernova exploded, two weeks after the completion of the Kamiokande upgrade.
- Distance: 50 kpc
- No. of neutrino events seen:
  - Kamiokande: 12/3000t
  - IMB: 8/8000t
  - Baksan: 5/ 200t
- Within clock uncertainties, signals are contemporaneous

Lesson learned:

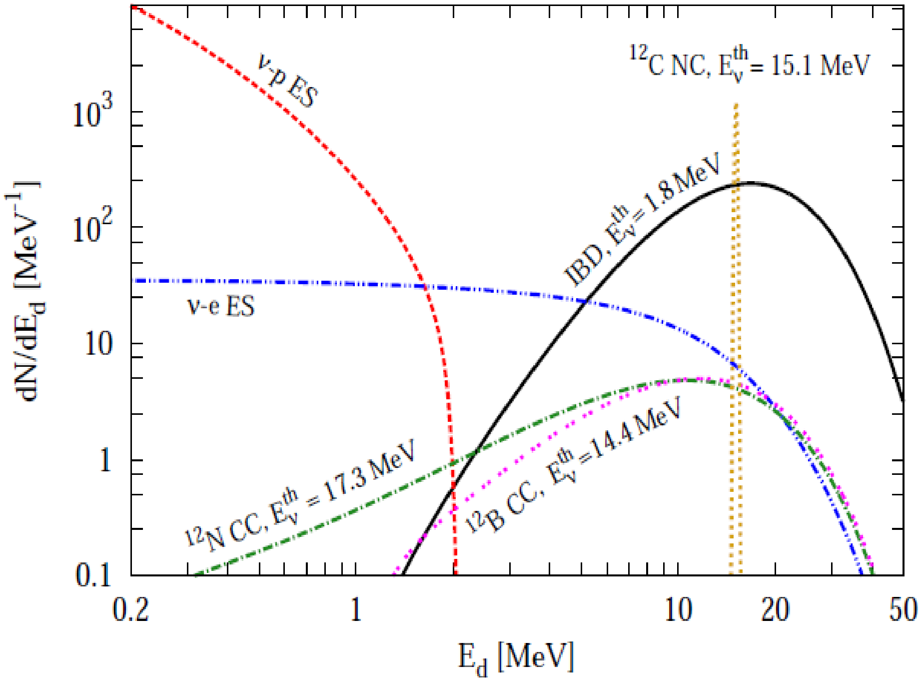
Large mass

Low energy threshold

Always on

Supernova neutrinos in Giant LS detector

- ~ 20 events observed so far
- JUNO can do a lot:
  - ν mass: < 0.83±0.24 eV at 95% CL (arXiv:1412.7418)
  - Locating the SN: ~9°
  - Pre-SN ν (> 1 day)
  - SN Nucleosynthesis via ν_x spectra
  - Collective ν oscillation
  - Mass hierarchy



Distance: 10 kpc
Energy: 3×10^{53} erg

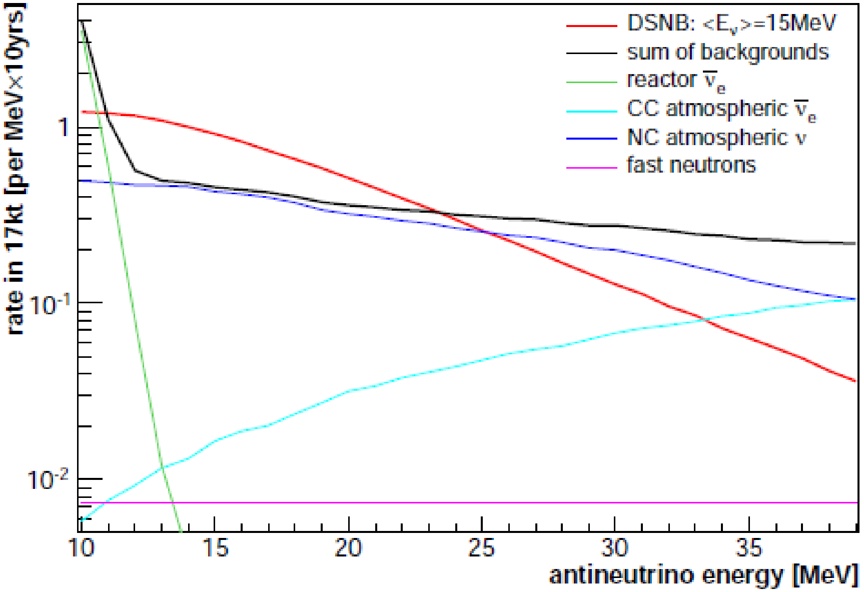
Estimated numbers of neutrino events in JUNO (preliminary)

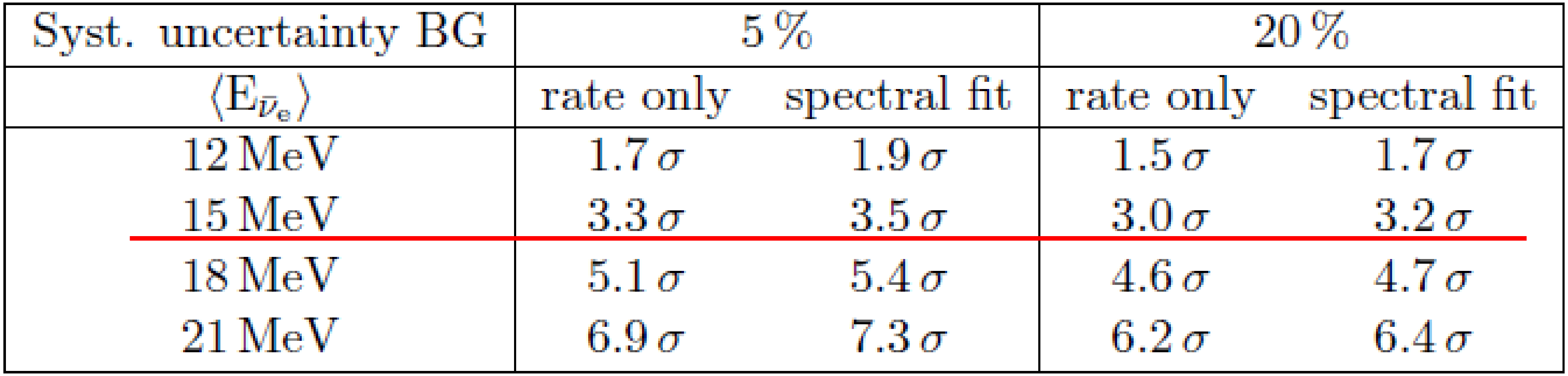
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Measure energy spectra & fluxes of almost all types of neutrinos

Diffused Supernova Neutrinos

- **Important for star-formation rate, average core-collapse neutrino spectrum, rate of failed SNe, etc.**
- **Very likely to see them above the 3σ level**
- **Significantly improve the current limit by SuperK**

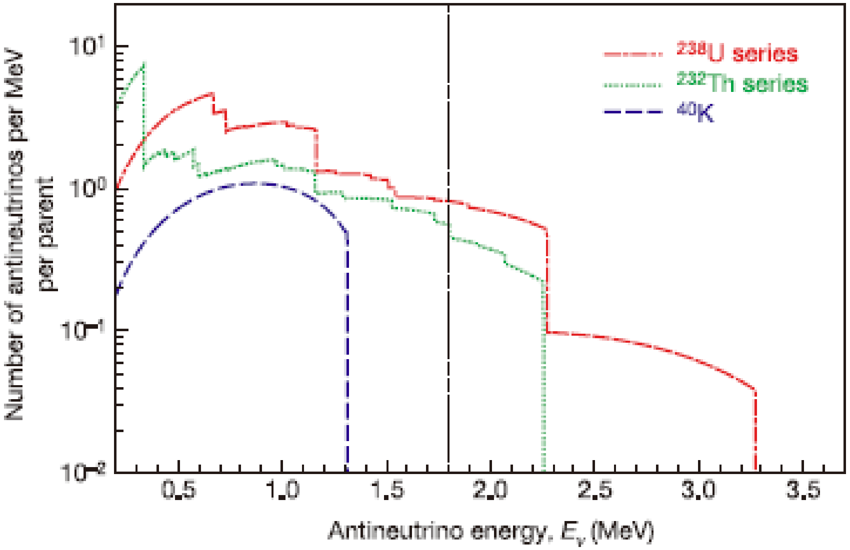


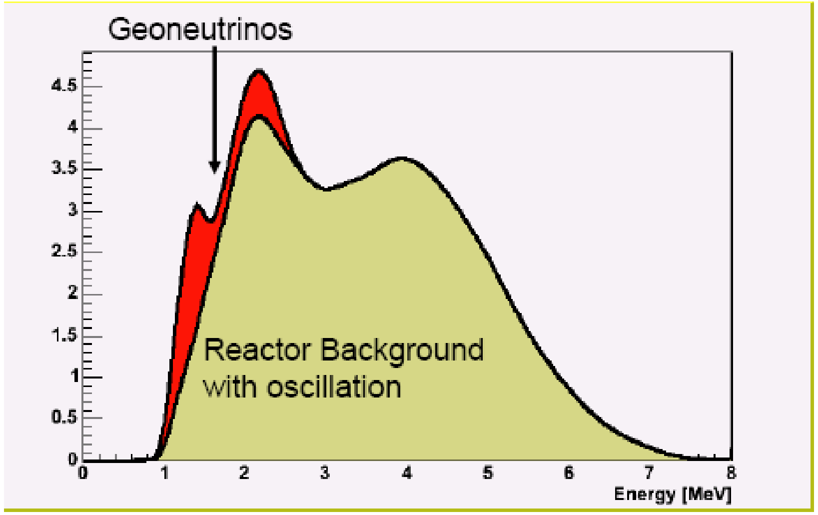


Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$
21 MeV	$6.9\,\sigma$	$7.3\,\sigma$	$6.2\,\sigma$	$6.4\,\sigma$

Geo-neutrinos

- ^{238}U, ^{232}Th and ^{40}K decays account for 40% of earth's power, which is related to earthquakes, volcanoes, geomagnetism, plate tectonics, …
- They are mainly from mantle and crust, but not the core
- Geo-neutrinos can tell ^{238}U: ^{232}Th, good for geo-models
- Only way looking inside the earth ?





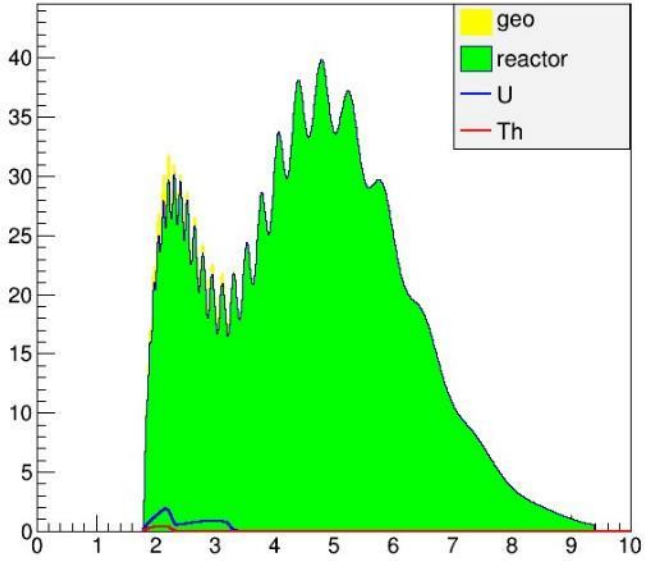
Geo-neutrinos at JUNO

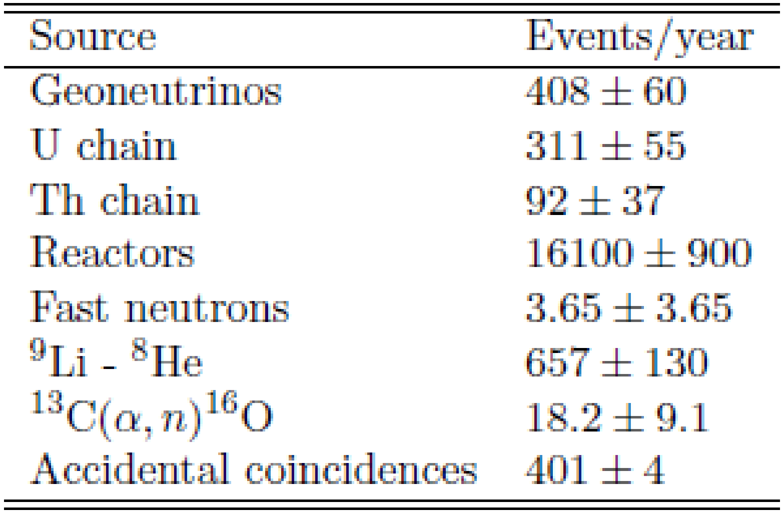
- **Geo-neutrinos**
  - **Current results**

    KamLAND: 30±7 TNU ***(PRD 88 (2013) 033001)***

    Borexino: 38.8±12.2 TNU ***(PLB 722 (2013) 295)***

    Statistics dominant
  - **Desire to reach an error of 3 TNU**
  - **JUNO: ×20 statistics**
    - Huge reactor neutrino backgrounds
    - Need accurate reactor spectra





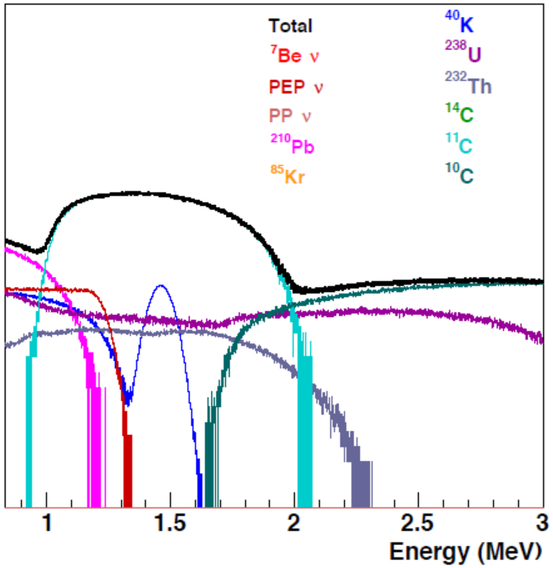
Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	3.65 ± 3.65
^{9}Li - ^{8}He	657 ± 130
^{13}C$(\alpha, n)^{16}$O	18.2 ± 9.1
Accidental coincidences	401 ± 4

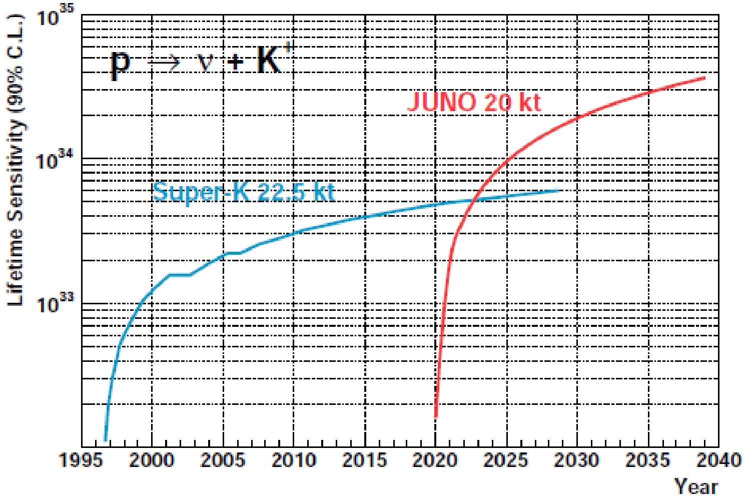
Combined shape fit of geo-ν and reactor-ν

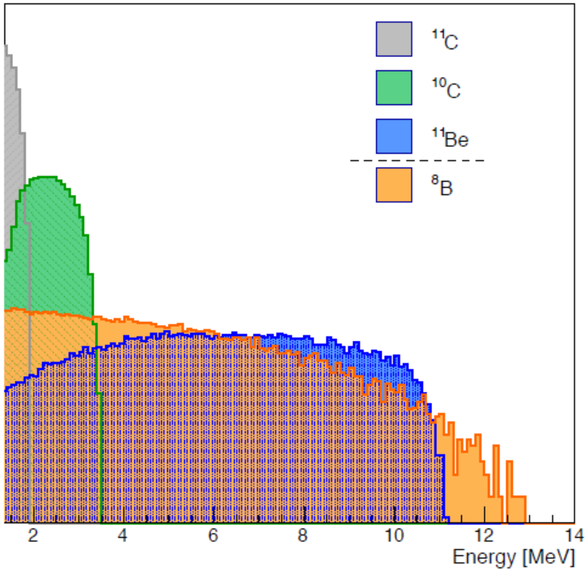
	Best fit	1 y	3 y	5 y	10 y
U+Th fix ratio	0.96	17%	10%	8%	6%
U (free)	1.03	32%	19%	15%	11%
Th (free)	0.80	66%	37%	30%	21%

Other Physics with JUNO

- **Solar neutrinos**
  - Possible to see 8B and 7Be neutrinos with a huge statistics (> × 20 Borexino) with special care for backgrounds:
    - LS purification
    - Dust control
    - Special LAB with low 14C
    - Rn & Kr control
- **Atmosphere neutrinos**
- **Sterile neutrinos**
- **Nucleon Decay and exotic searches**



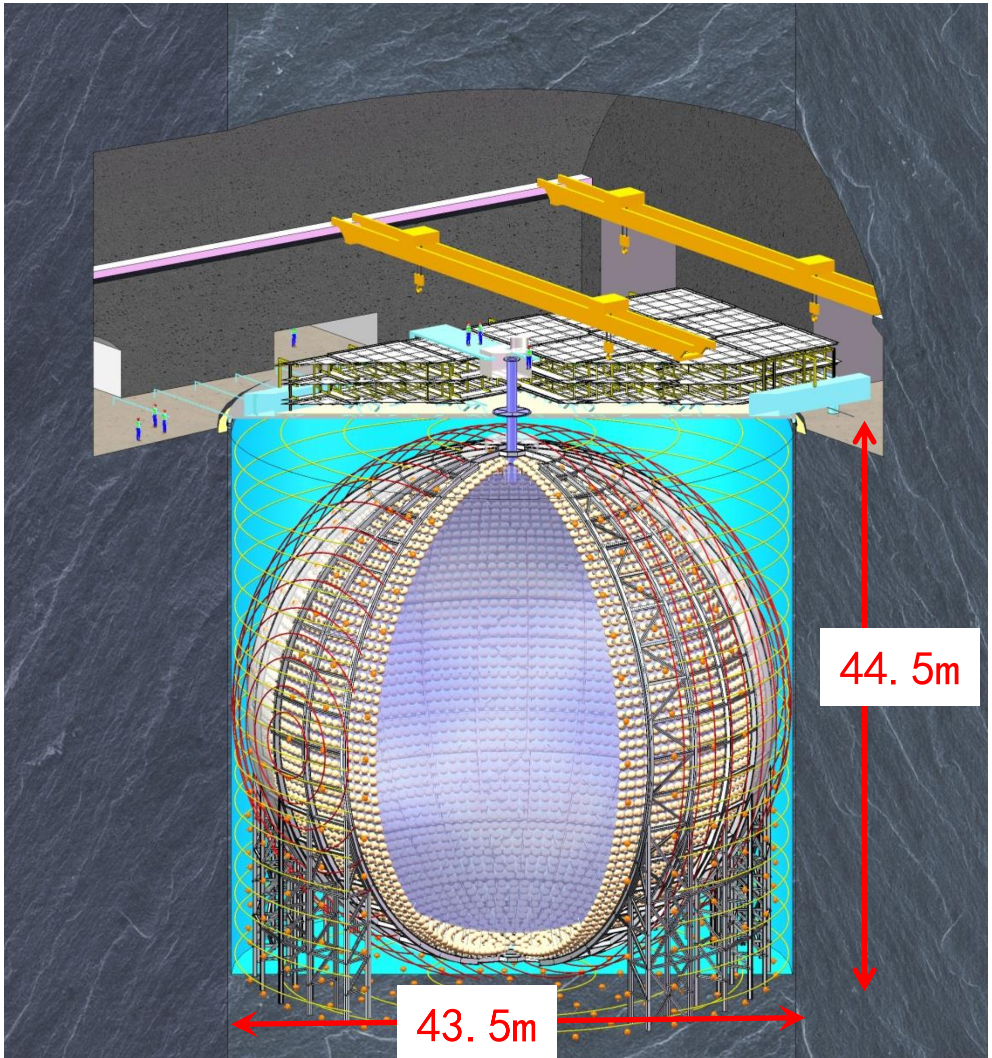




JUNO Physics Book: arXiv: 1507.05613

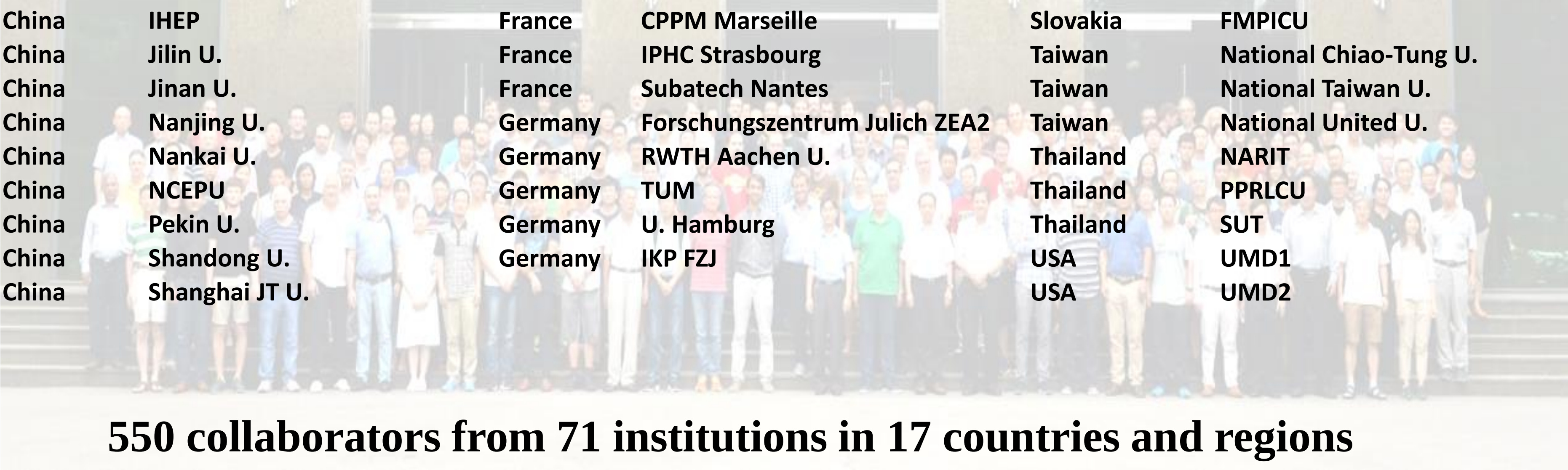
JUNO Detector and Challenges

- Largest LS detector → × 20 KamLAND， × 40 Borexino
- Highest light yield → × 2 Borexino， × 5 KamLAND



- Hugh cavern:
  - ~ 48m× 70m
- Largest Acrylic tank:
  - Φ 35.4米(13m@SNO)
- 20 kt LS
  - Best attenuation length: 25m (15m @ Daya Bay)
- 20000 20” PMT
  - Highest photon detection efficiency : 30%*100% = 30%（25%*60%=15% @ SuperK）

JUNO Collaboration

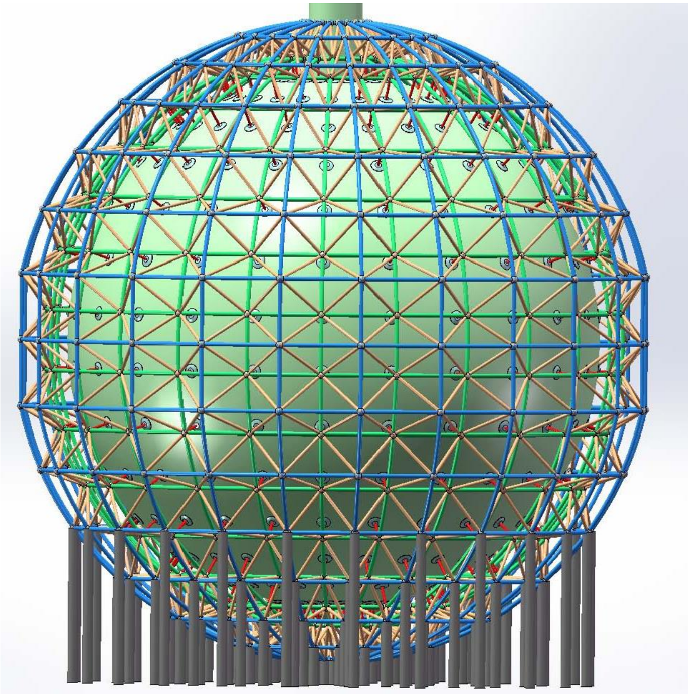


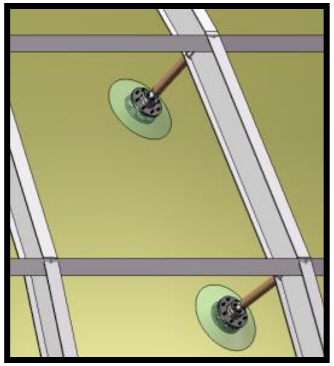
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC	Italy	INFN-Ferrara
Chile	UTFSM	China	U. of South China	Italy	INFN-Milano
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano Bicocca
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Padova
China	CAGS	China	Xi'an JT U.	Italy	INFN-Perugia
China	ChongQing University	China	Xiamen University	Italy	INFN-Roma 3
China	CIAE	China	NUDT	Latvia	IECS
China	DGUT	Czech Rep.	Charles U.	Pakistan	PINSTECH (PAEC)
China	ECUST	Finland	University of Oulu	Russia	INR Moscow
China	Guangxi U.	France	APC Paris	Russia	JINR
China	Harbin Institute of Technology	France	CENBG	Russia	MSU
China	IHEP	France	CPPM Marseille	Slovakia	FMPICU
China	Jilin U.	France	IPHC Strasbourg	Taiwan	National Chiao-Tung U.
China	Jinan U.	France	Subatech Nantes	Taiwan	National Taiwan U.
China	Nanjing U.	Germany	Forschungszentrum Julich ZEA2	Taiwan	National United U.
China	Nankai U.	Germany	RWTH Aachen U.	Thailand	NARIT
China	NCEPU	Germany	TUM	Thailand	PPRLCU
China	Pekin U.	Germany	U. Hamburg	Thailand	SUT
China	Shandong U.	Germany	IKP FZJ	USA	UMD1
China	Shanghai JT U.			USA	UMD2

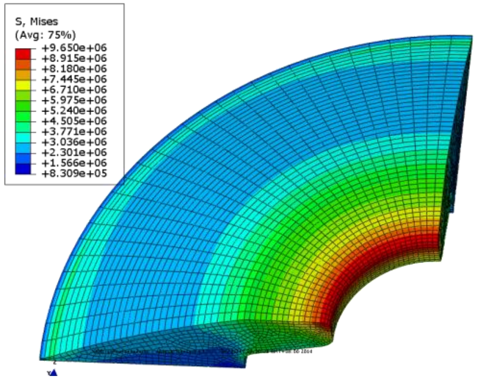
550 collaborators from 71 institutions in 17 countries and regions

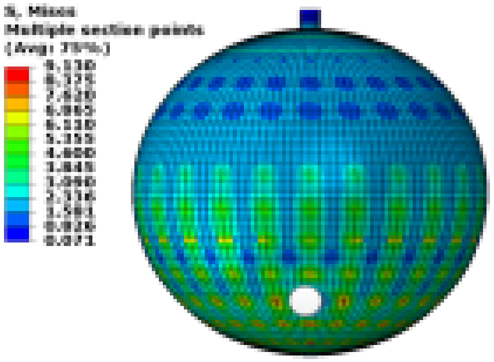
Central Detector

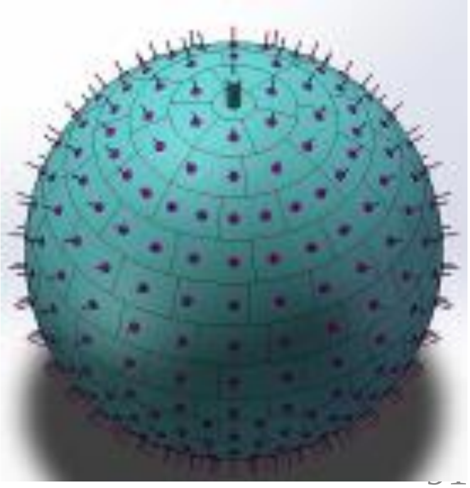
- **A huge detector in the water pool:**
  - **Mechanics，optics, chemistry, …**
  - **How to keep it clean ?**
  - **Possibility of assembly within 1 years**
- **Two main options: acrylic vs balloon**
- **Final choice: A SS structure to hold the acrylic sphere and to mount PMTs**
  - **Detailed FEA calculation in agreement with experimental data, particularly at the supporting point**
  - **Acrylic sheets: 9m × 3m ×12 cm**
  - **Stress less than 5 MPa everywhere**





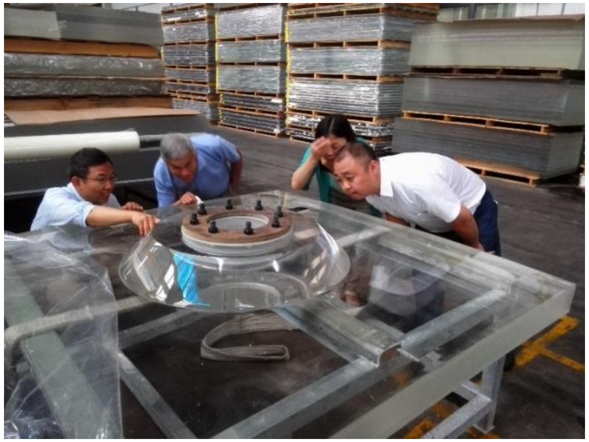


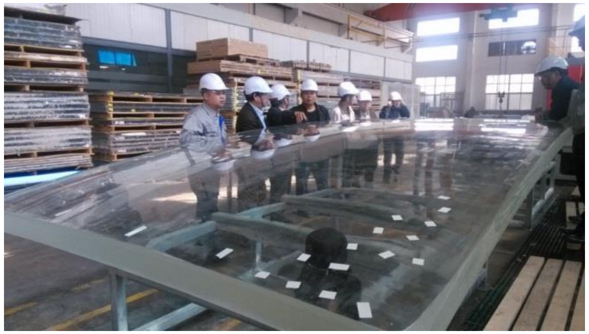




R&D and Prototyping

- Study of acrylic:
  - Property test: aging, creep, crazing,
    - 80% after 20 years
    - No creep & crazing under 5.5 Mpa
  - Bonding test: fast bonding, T-shape bonding
    - 70 -80 % strength
  - Strength of the supporting point:
    - ~ 50 t (safety factor ~ 4)
- Prototyping:
  - ⇨ Thermal shaping of acrylic sheets
  - ⇨ Bonding of large sheets: ~ 1/100 in area
- Manufacturing method understood:
  - ⇨ SS Truss from bottom to top (2~3 months)
  - ⇨ Acrylic sphere from top to bottom(8 months)
- Contract signed





Liquid Scintillator

- Current Choice: LAB+PPO+BisMSB
- Requirements:
  - Long attenuation length: 15m → 30m
  - Radio-purity: $< 10^{-15}$ g/g
  - Engineering issues: Equipment & handling for 20kt
- R&D Progress
  - Transparancy
    - ✓ Improve raw materials
    - ✓ Improve the production process
    - ✓ Purification
      - Distillation, Filtration, Water extraction, …
  - High light yield: Optimization of PPO & BisMSB concentration
  - Radiopurity
    - ✓ Purification
      - Distillation, Water extraction, Nitrogen stripping…

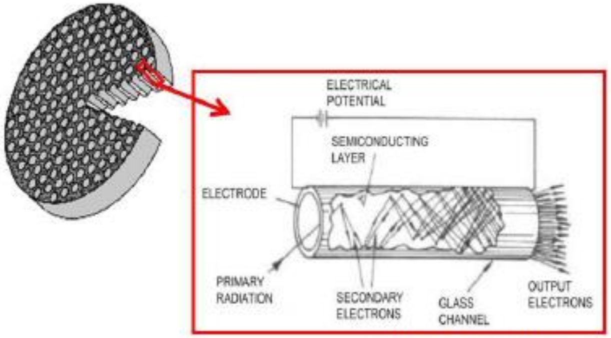
Linear Alky Benzene	Atte. L(m) @ 430 nm
RAW	14.2
Vacuum distillation	19.5
SiO_2 coloum	18.6
Al_2O_3 coloum	22.3
LAB from Nanjing, Raw	20
Al_2O_3 coloum	25

Successful prototype at 20 t level

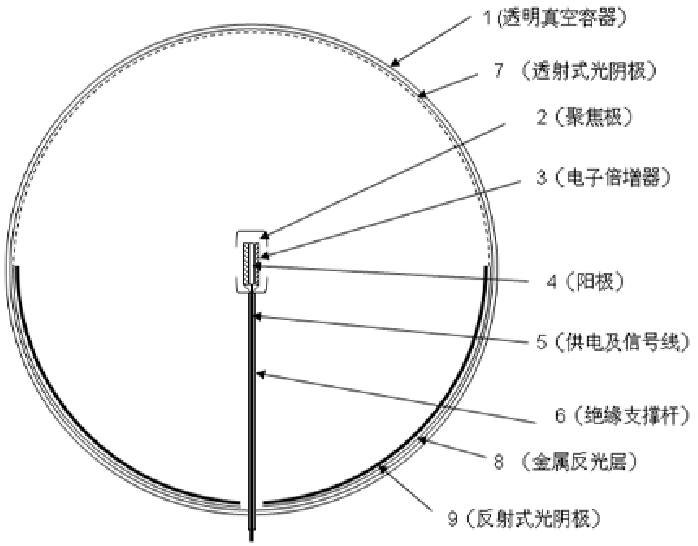
Radiopurity ~ a few 10^{-15} g/g

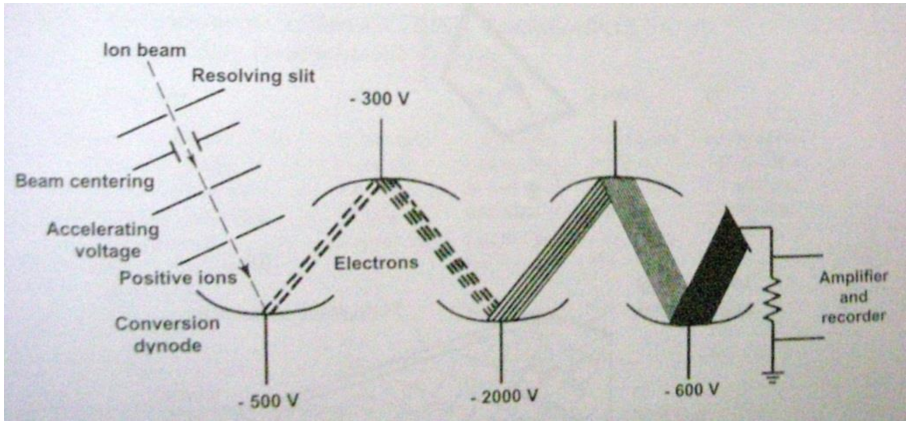
MCP-based PMTs for High QE ?

- **Advantages:**
  - Higher QE: transmmissive photocathode at top + reflective photocathode at bottom
  - High CE: less shadowing effect
  - Easy for production: less manual operation and steps
  - Good MCP production capabilities in China
- **Disadvantages:**
  - Higher cost ?
  - No one knows how to make it



Nuclear Instruments and Methods, 162, 1979



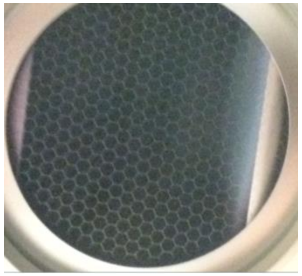


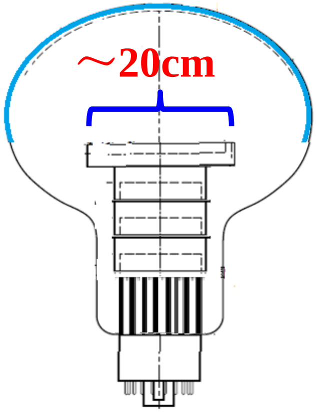
An R&D collaboration between IHEP & NNVC established

High QE PMT

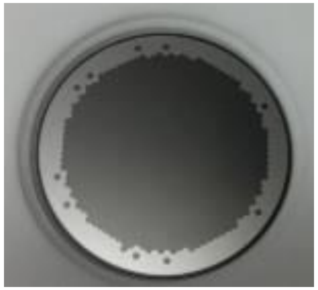
- A new design(to avoid gain mis-match) after many failures:
  - ⇨ Intrinsically high collection efficiency
    - ✓ No wire mesh in front of dynode
    - ✓ transparent + reflective photocathode
  - ⇨ Easy for mass production

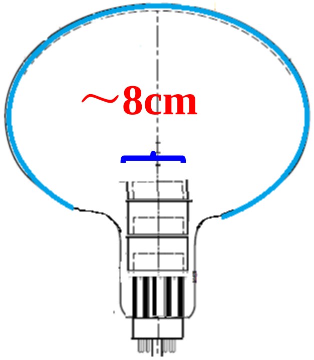
Dynode PMT





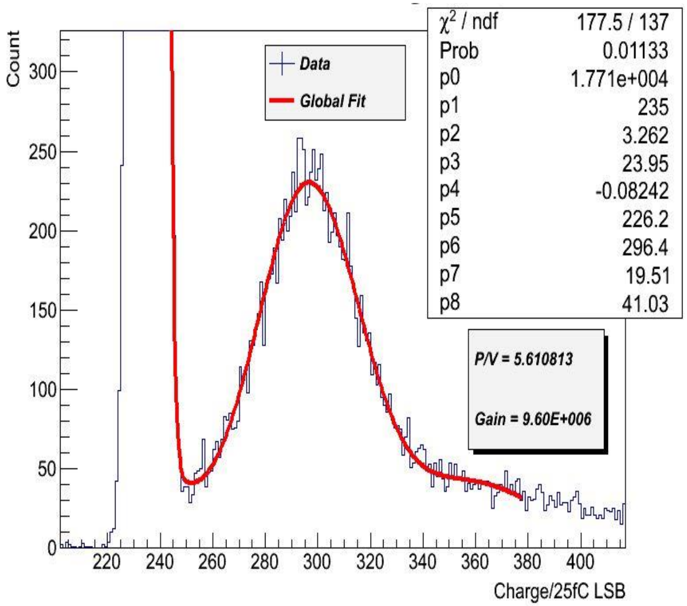
MCP-PMT



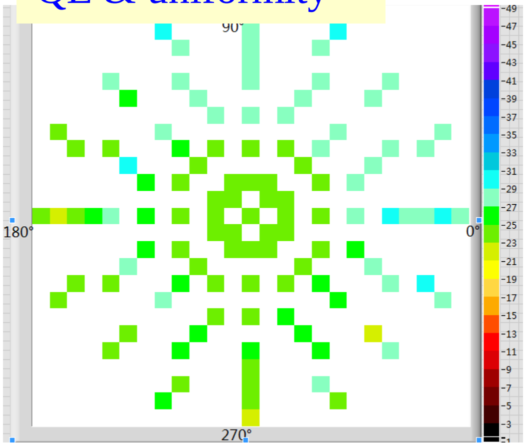


Successful Prototyping

	R12860	MCP-PMT
QE@410nm	~ 30% (T)	~ 26%(T), 30%(T+R)
Collection eff.	90%	100%
Total eff.	27%	26-30 %
P/V of SPE	> 3	> 3
Rise time	7 ns	2ns
TTS	3 ns	~10 ns
Dark noise	30K	30K
After pulse	< 10%	< 3 %

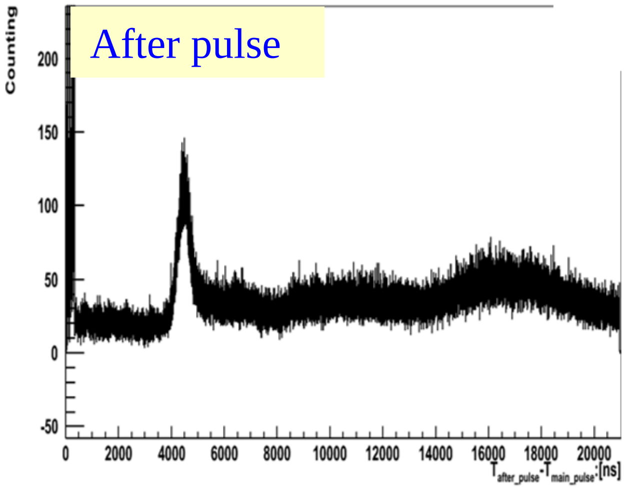


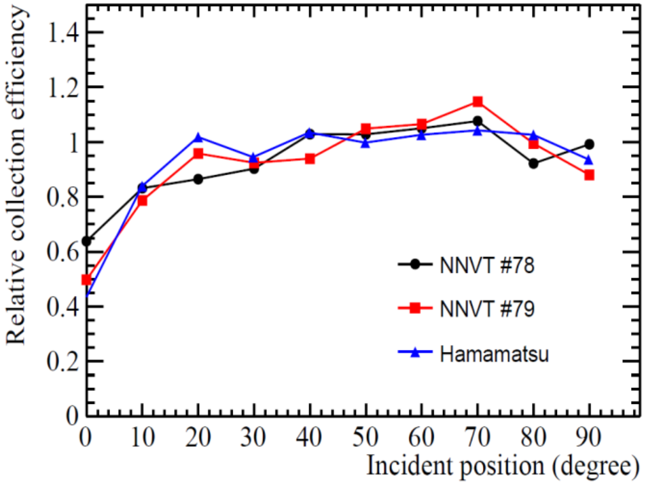
QE & uniformity



Min:24.5%; Max:29%
Average:26.5%

After pulse





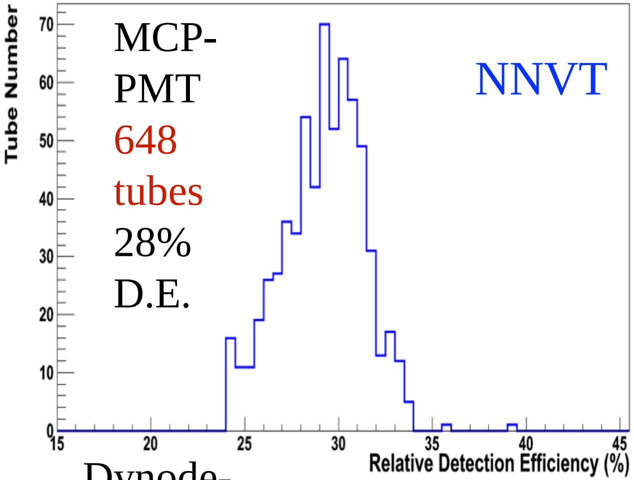
Mass Production Started

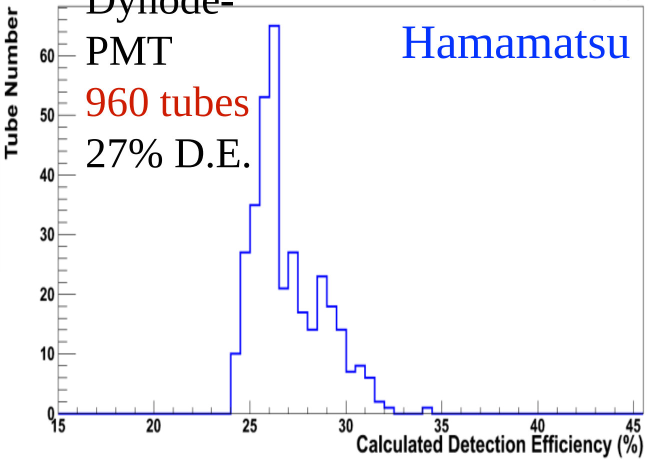
We started from a wrong design, but ended up with a good product

Two vendors:

NNVC: 15000

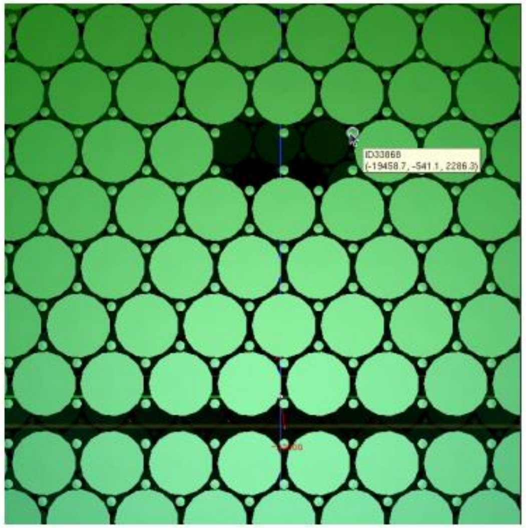
Hammamatzu: 5000


MCP-PMT
648 tubes
28% D.E.
NNVT


Dynode-PMT
960 tubes
27% D.E.
Hamamatsu

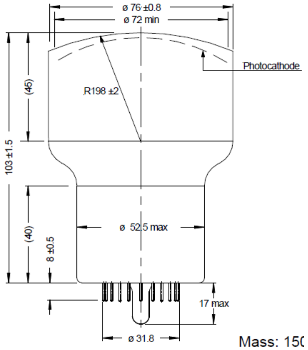
Small PMT system

- Calibrate non-uniformity and non-linearity of Large-PMTs
  - ⇨Reduce energy scale uncertainty
  - ⇨Improve energy resolution (non-stochastic term)
- Increase optical coverage (~5%)
  - ⇨Improve energy resolution (stochastic term)
- Extend energy measurement
  - ⇨Improve muon physics
- Supernova

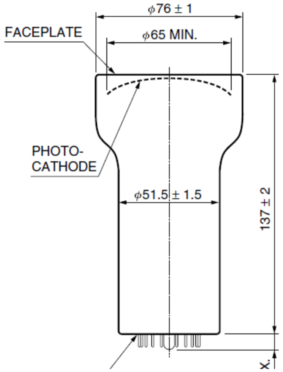


- 20” PMTs: 17746
- 3” PMT: 35794

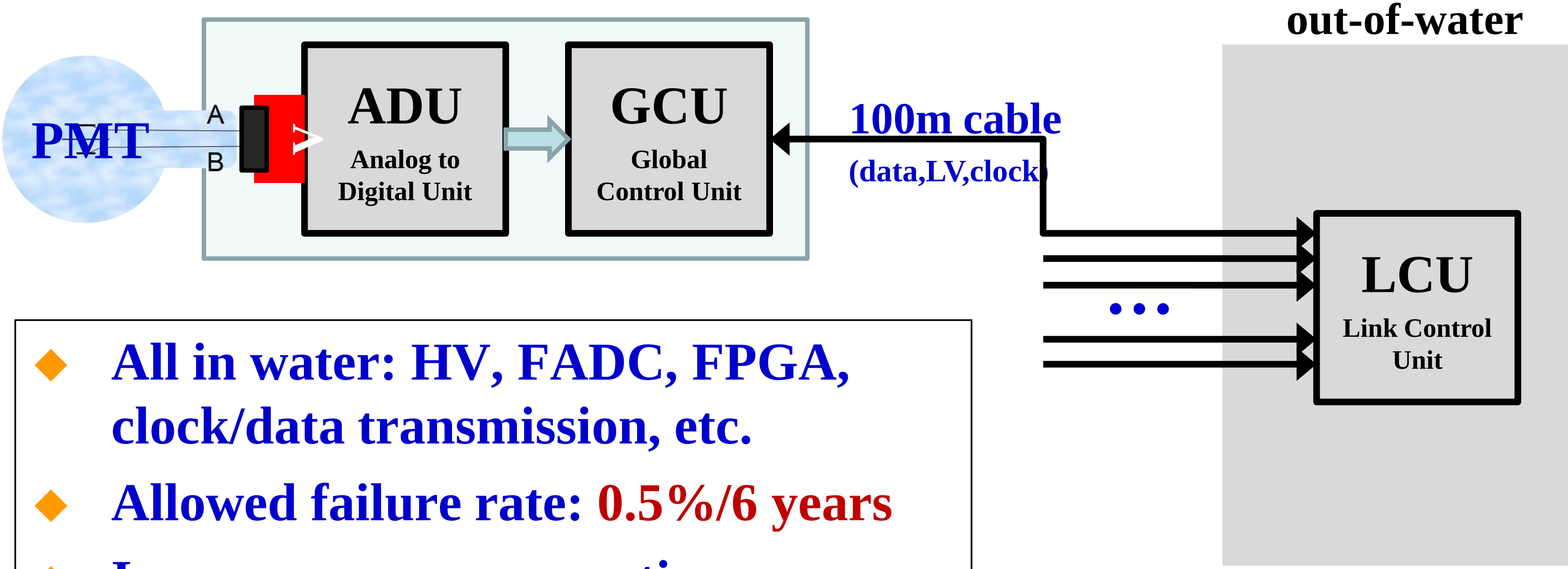
HCZ XP53B20



Hamamatsu R6091

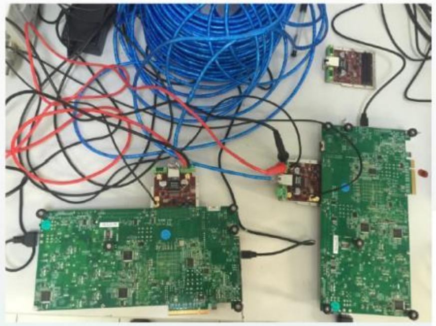


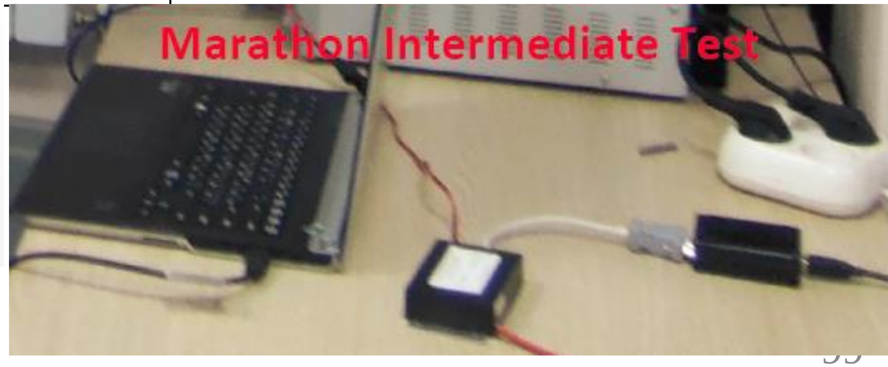
Electronics



- **All in water: HV, FADC, FPGA, clock/data transmission, etc.**
- **Allowed failure rate: 0.5%/6 years**
- **Issues: power consumption, reliability, etc**

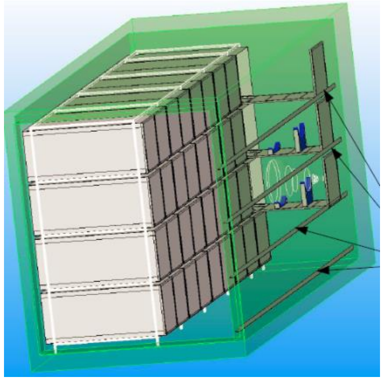
Recovered clock

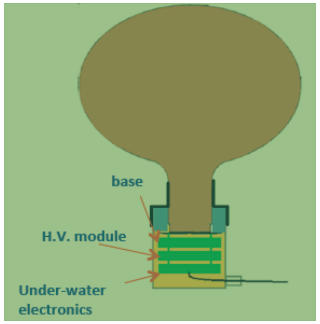


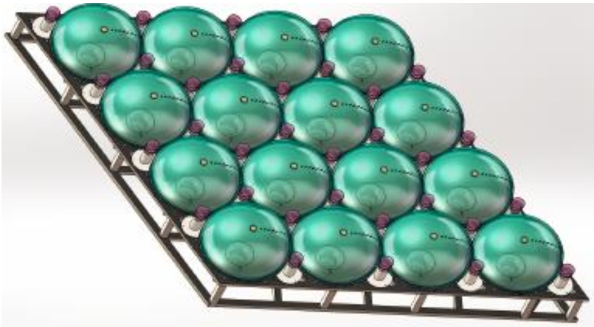


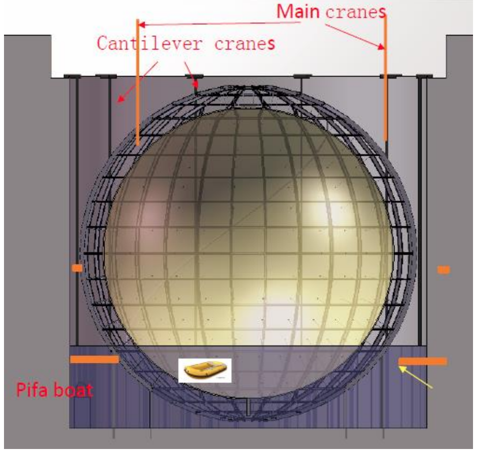
PMT Instrumentation

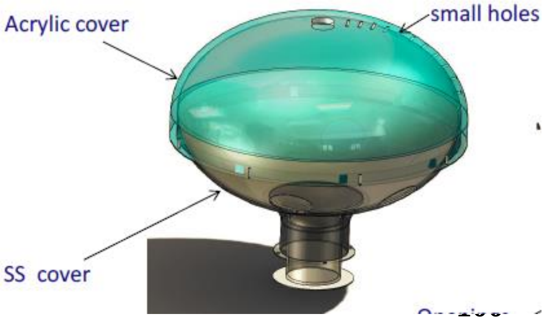
- **PMT testing**
  - 18,000 20” PMTs & 36,000 3” PMTs
  - 4 instrumented Containers for mass testing
- **PMT potting**
  - With base/HV/electronics
  - Failure rate < 0.5%/6 years
- **PMT protection**
  - Mechanism & requirements understood
  - Acrylic + steel cover with holes(plus film ?)
- **PMT installation**





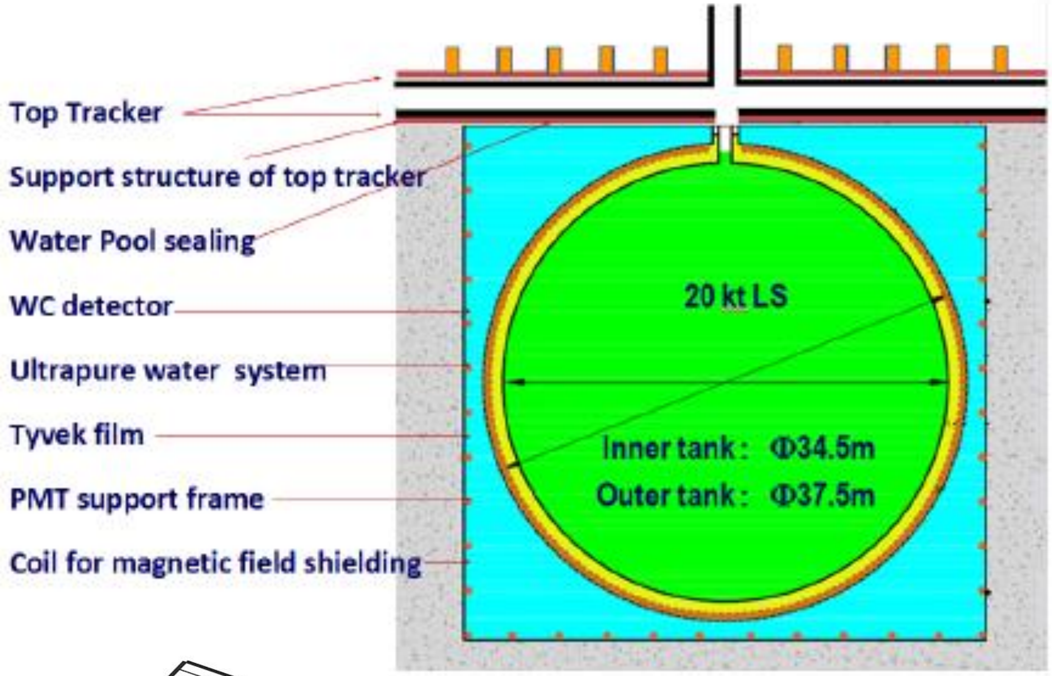


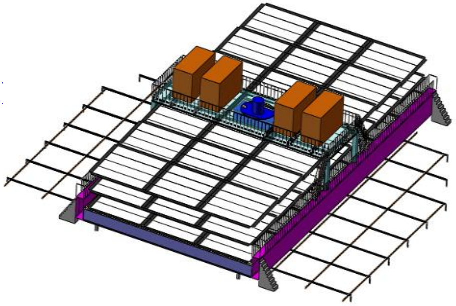


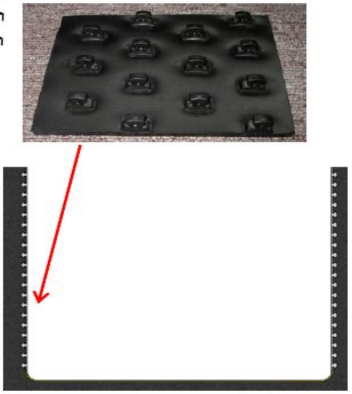


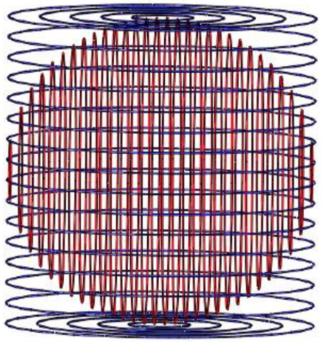
VETO

- **Tasks:**
  - ⇨ Shield rock-related backgrounds
  - ⇨ Tag & reconstruct cosmic-rays tracks
- **Detector:**
  - ⇨ Top tracker: refurbished OPERA scintillators
  - ⇨ Water Č detector unde optimization
- **Pool lining: HDPE**
- **Coil for magnetic field shielding: under design**



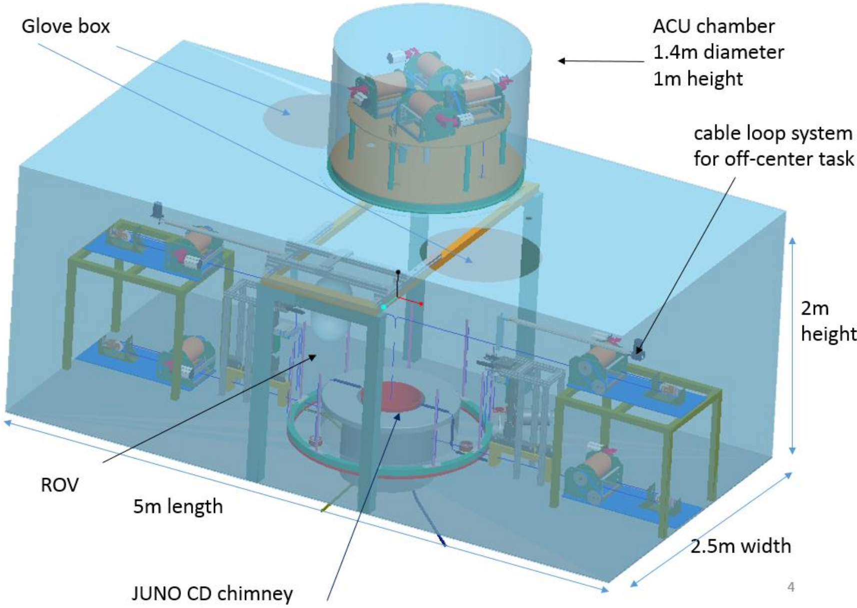


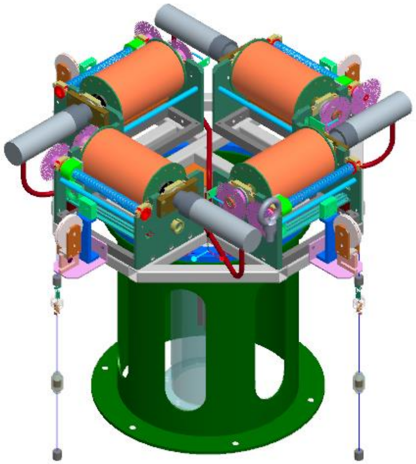


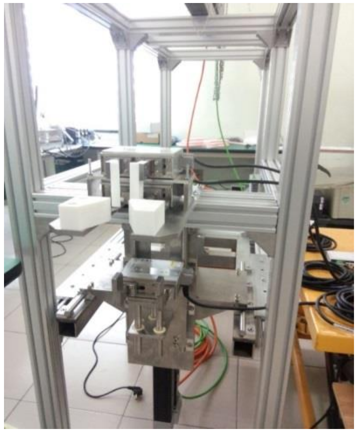


Calibration

- **Main method**
  - ⇨ Routinely Source into LS by
    - ✓ ACU
    - ✓ rope loop
    - ✓ “sub-marine”
  - ⇨ Source into Guided tube
  - ⇨ Mini-balloon
  - ⇨ Pulsed light source
- **Under discussion**
  - ⇨ Diffused short-lived isotopes
  - ⇨ Pelletron-based beam
- **Key technical issues**
  - ⇨ Source deployment
  - ⇨ Source locating system



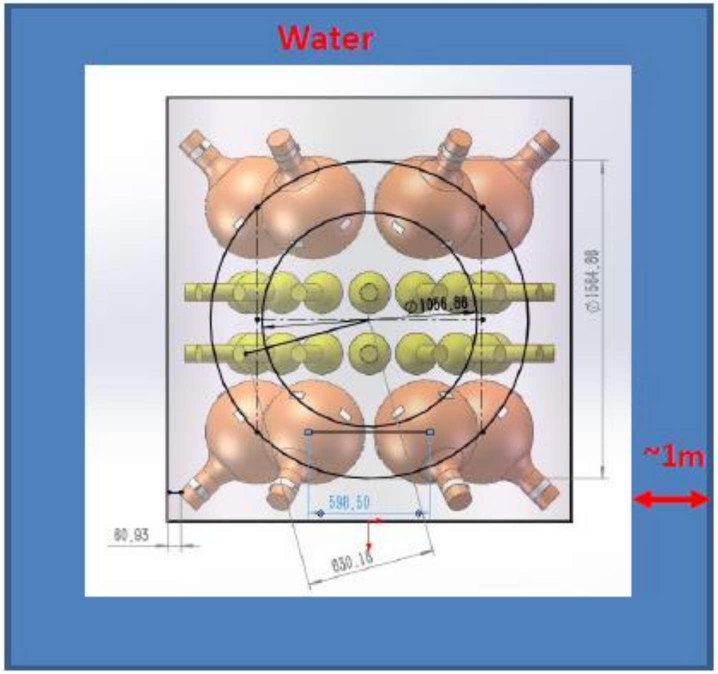


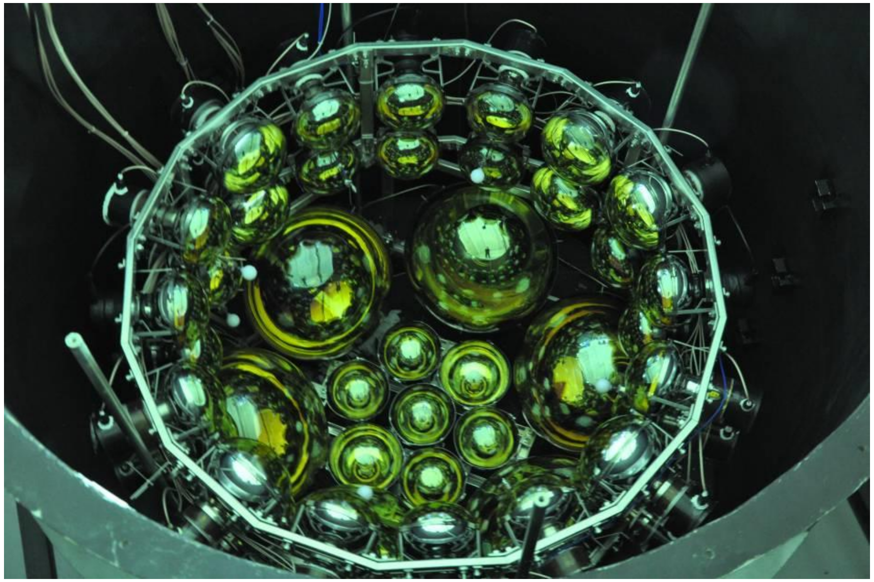


By Prof. J.L. Liu from SJTU

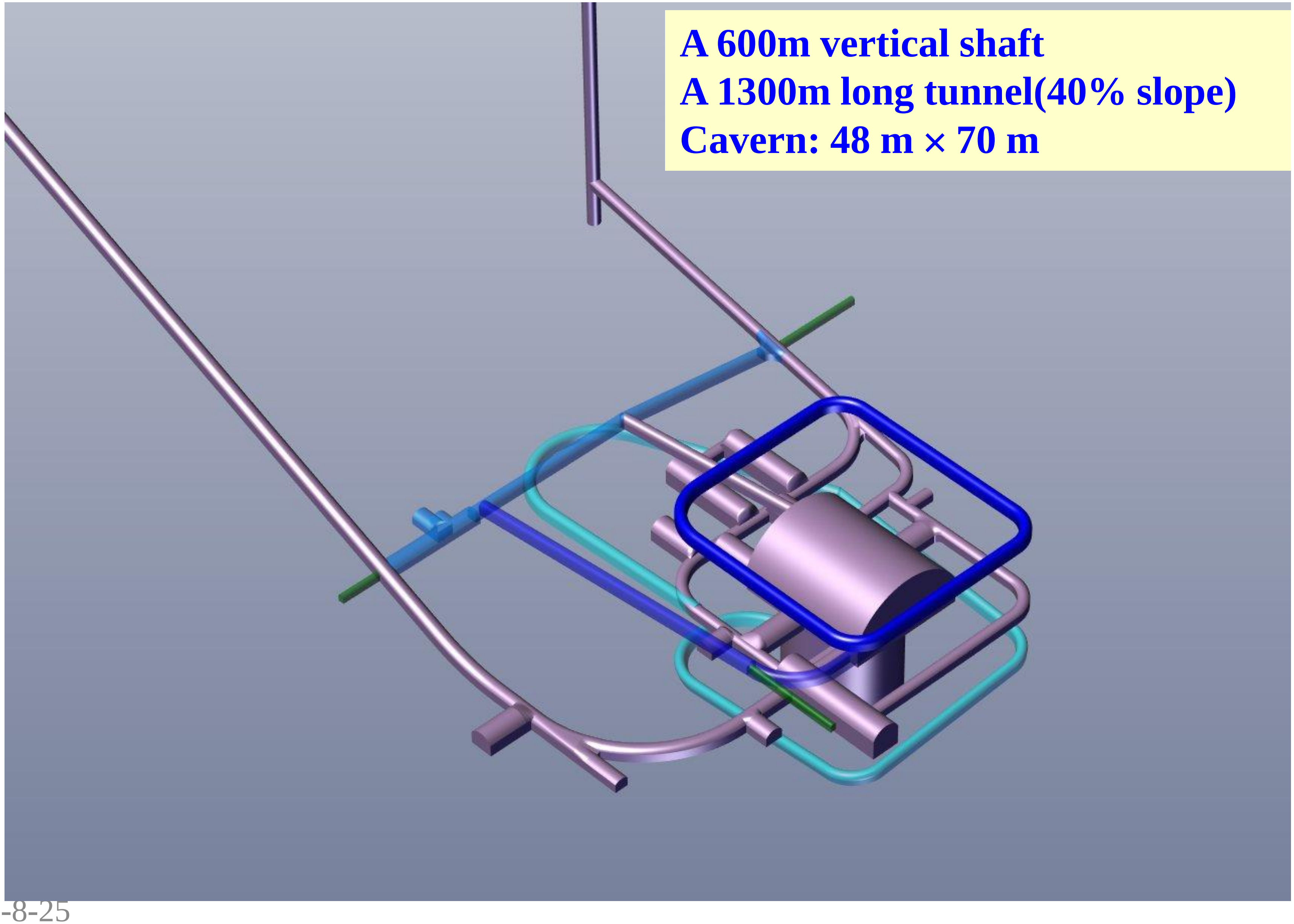
A Prototype to Test Everything

- **Test all parts to the CD**
  - Type of PMTs
  - PMT supporting structure
  - HV, PMT base and potting
  - Readout electronics & DAQ
  - LS & water system
  - Calibration system



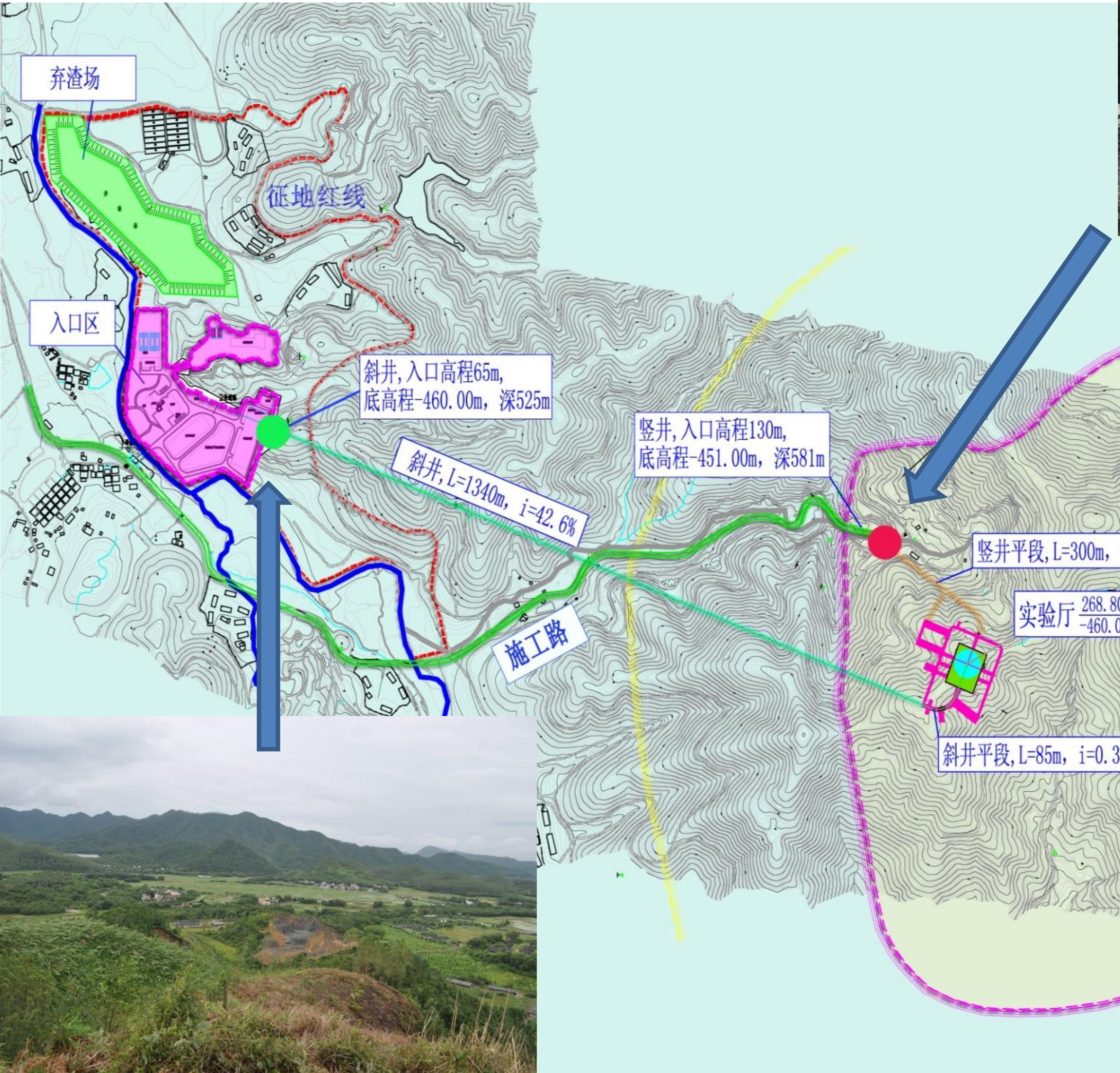


Civil Construction



A 600m vertical shaft
A 1300m long tunnel(40% slope)
Cavern: 48 m × 70 m

Layout


弃渣场
入口区
征地红线
斜井,入口高程65m,
底高程-460.00m，深525m
斜井,L=1340m，i=42.6%
竖井,入口高程130m,
底高程-451.00m，深581m
施工路


花岗岩范围
竖井平段,L=300m，i=3.0%
实验厅 $\frac{268.80}{-460.00}$
斜井平段,L=85m，i=0.3%
0m地面
201.55m
孔底

Status of Civil Construction

- **Completed:**
  - ✓ Sloped tunnel
  - ✓ Vertical shaft
- **Issues:**
  - ✓ A lot more water than anticipated, ~ 600 m^3/h

Plan: start data taking at ~2020

Grounding breaking on Jan. 10, 2015

Summary

- Reactor is a powerful man-made source: a free neutrino factory
  - If not too far, more powerful than solar, atmospheric, and accelerator neutrinos
- Great achievements: θ_{12}, θ_{13}
- Great future:
  - mass hierarchy
  - "All" mixing parameters