Solar and Reactor Neutrino Oscillations

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International Neutrino
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Outline

LECTURE I

- Neutrino Sources
- Discovery of neutrinos at reactor
- Solar Neutrino Puzzle
- Neutrino oscillations: solar neutrinos and experiments

LECTURE II

- Reactor neutrino oscillations in KamLAND experiment
- Measuring the last unknown neutrino mixing angle θ_{13} with the Double Chooz, Daya Bay and RENO reactor neutrino experiment
- Open questions in neutrino oscillations:
  - CP-violation effect in leptons;
  - Neutrino mass ordering
- JUNO reactor experiment and neutrino mass ordering
- Search for sterile neutrinos at reactors with PROSPECT experiment
- Importance of geoneutrinos
- Conclusion

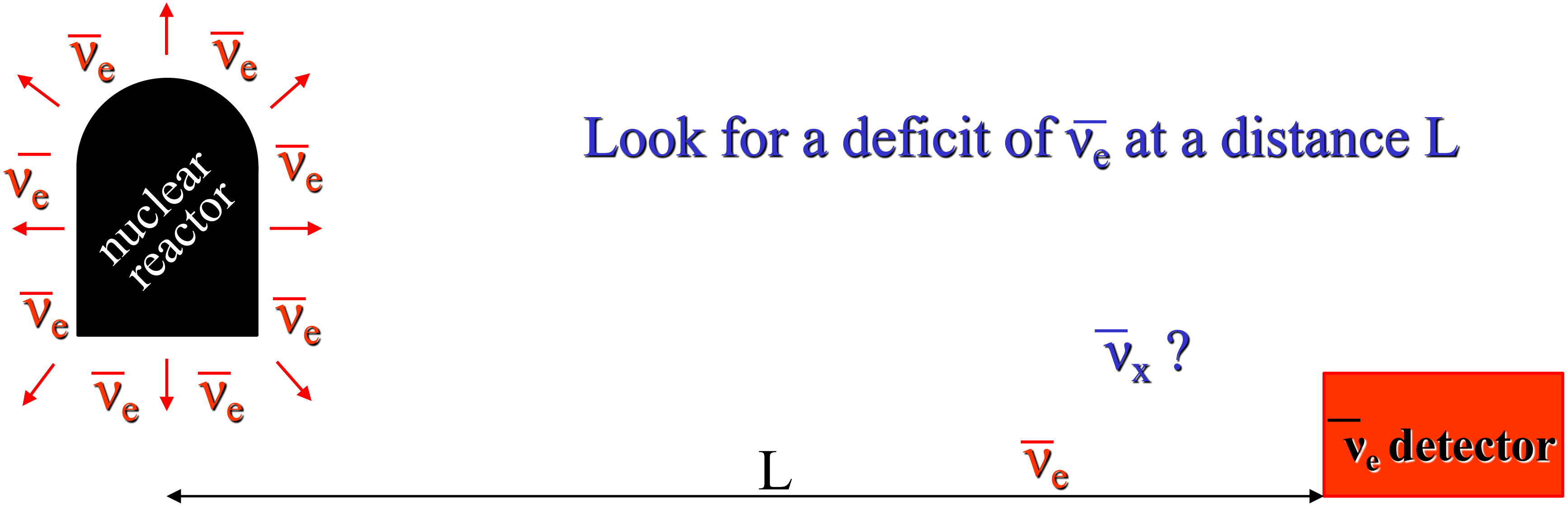
Reactor Neutrino Oscillations

Search for oscillations with reactor neutrinos

- Reactor neutrinos provide opportunity to study neutrinos in lab like conditions
- Well understood fission process
- Known source, can be turned off to cross-check background estimates.
- A number of experiments searched for oscillations at 100 m - 1 km baseline.
  - < 100 m: ILL, Savannah River, Bugey, Rovno, Goesgen Krasnoyarsk
  - 1 km: Palo Verde, Chooz

Reactors as Neutrino Sources

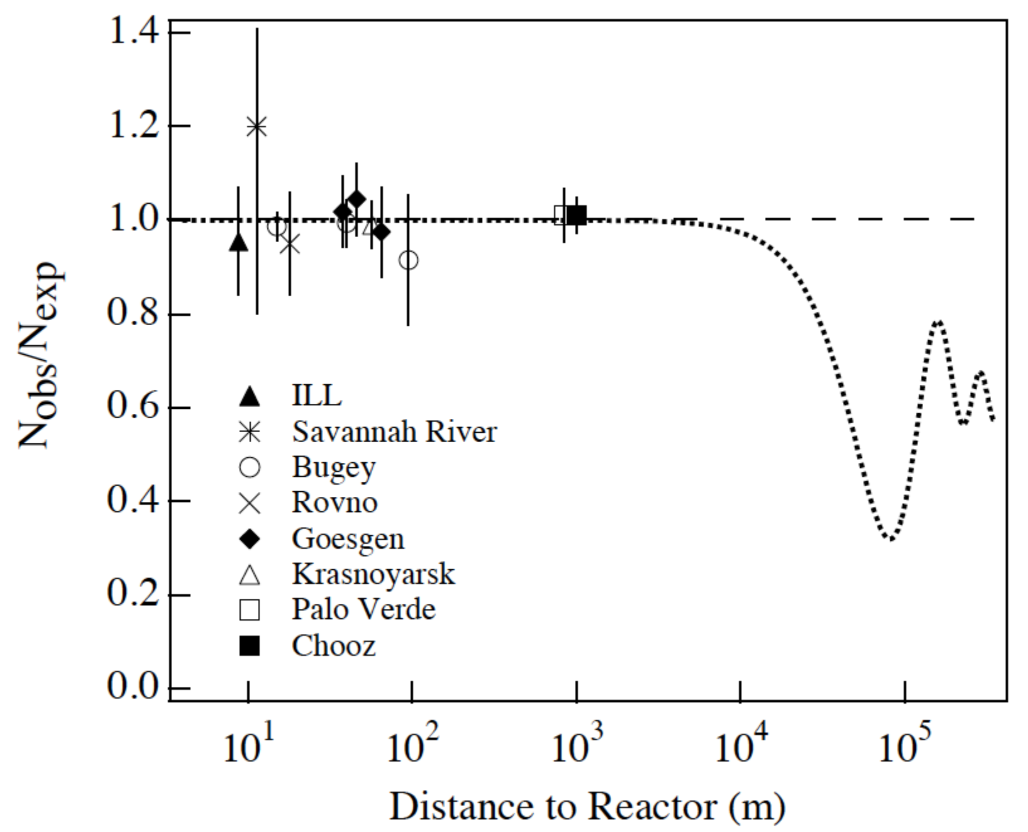
- Nuclear reactor is an excellent source of $\bar{\nu}_e$ from β decay.
- Large power reactor produces about $6 \cdot 10^{20}$ $\bar{\nu}_e$ /s
- Disappearance experiments



Look for a deficit of $\bar{\nu}_e$ at a distance L

Reactor Experiment Neutrino Oscillation Search

- Reactor experiments status until 2001
- No **large** oscillation effect observed at 1 km or less.



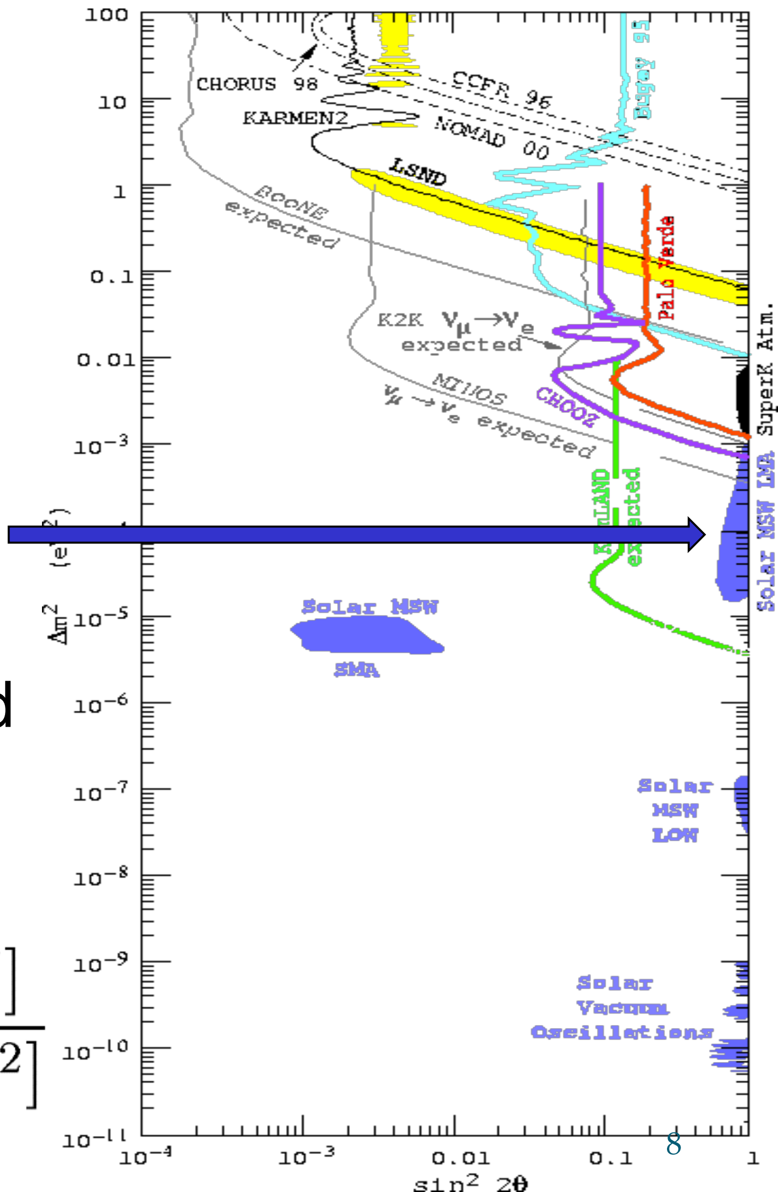
Search for Neutrino Oscillations with Reactor $\bar{\nu}_e$ in KamLAND

Advantages and Difficulties with Reactor Antineutrino Experiments

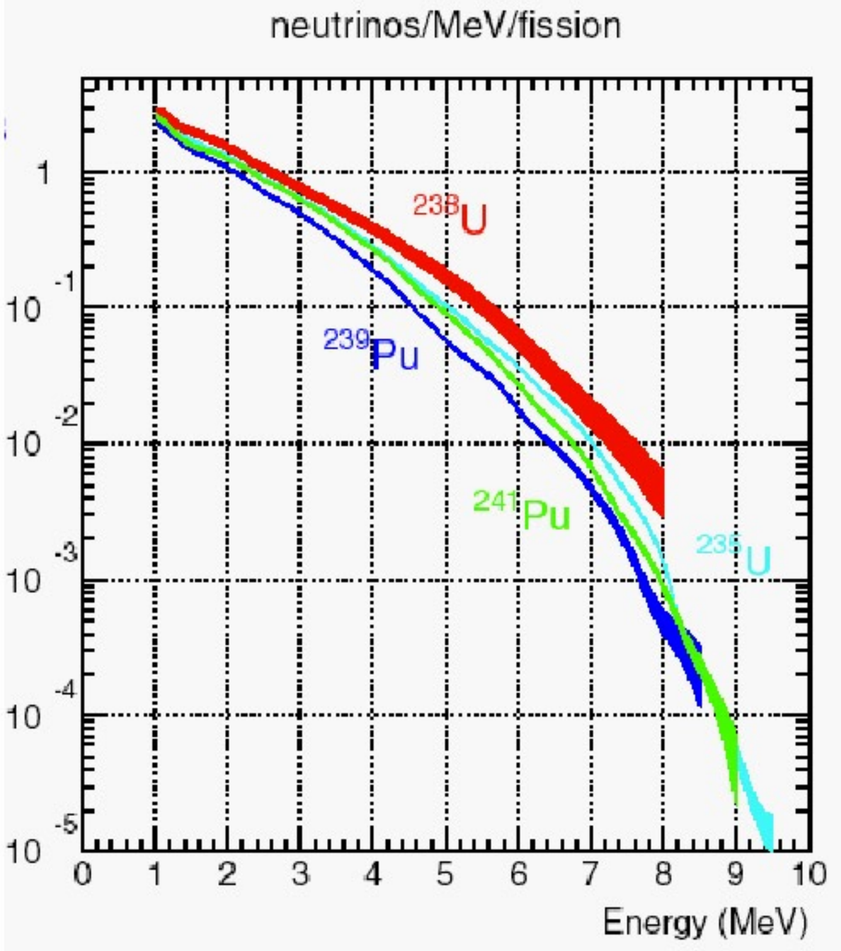
- $E_\nu \sim$ few MeV => Backgrounds have to be small and carefully evaluated.

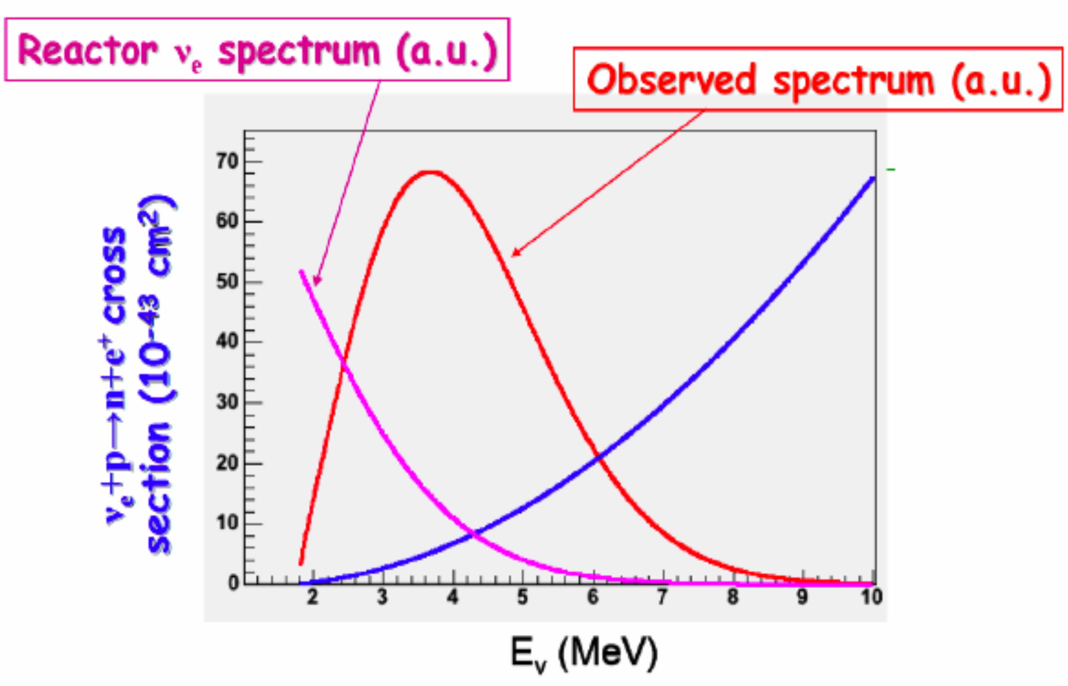
- Disappearance experiments initial reactor neutrino flux has to be carefully calculated.
- Very small Δm^2 can be measured
- Sensitive to $\sin^2 2\theta$ measurement and oscillation parameters.
- Well-known baseline L.

$$L_{osc} = 2\pi\hbar c \frac{E[MeV]}{\Delta m^2[eV^2]} = 2.48\frac{E[MeV]}{\Delta m^2[eV^2]}$$



Neutrino Flux and Expected Spectrum





1.5 neutrinos/fission detectable

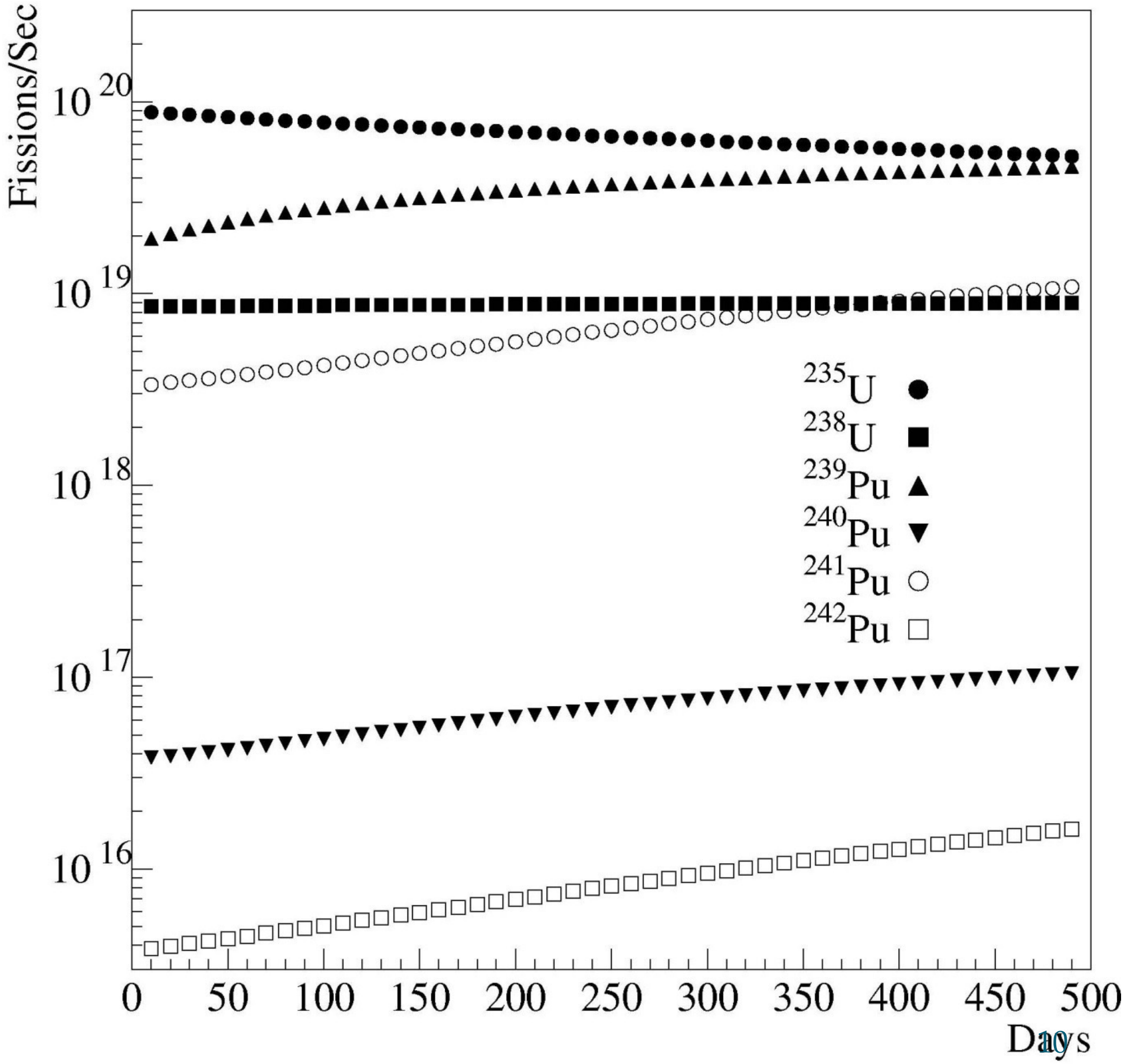
Contributions of Different Decay Chains to Reactor Neutrino Flux

More than 99.9%
of $\bar{\nu}_e$'s are product
of fissions in

^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.

In a commercial reactor.

Flux know at 2% level.



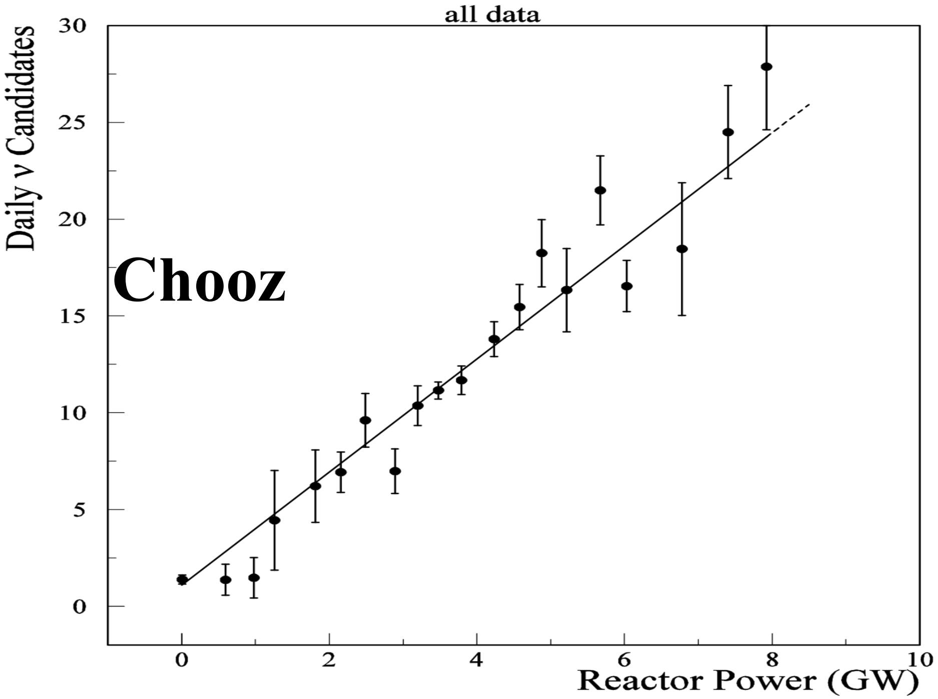
Reactor Power vs. Neutrino Flux

Reactor neutrino rate is proportional to reactor power

Neutrino flux decreases with square root of distance from reactor

If we are to search for small Δm_2, we need combination of:

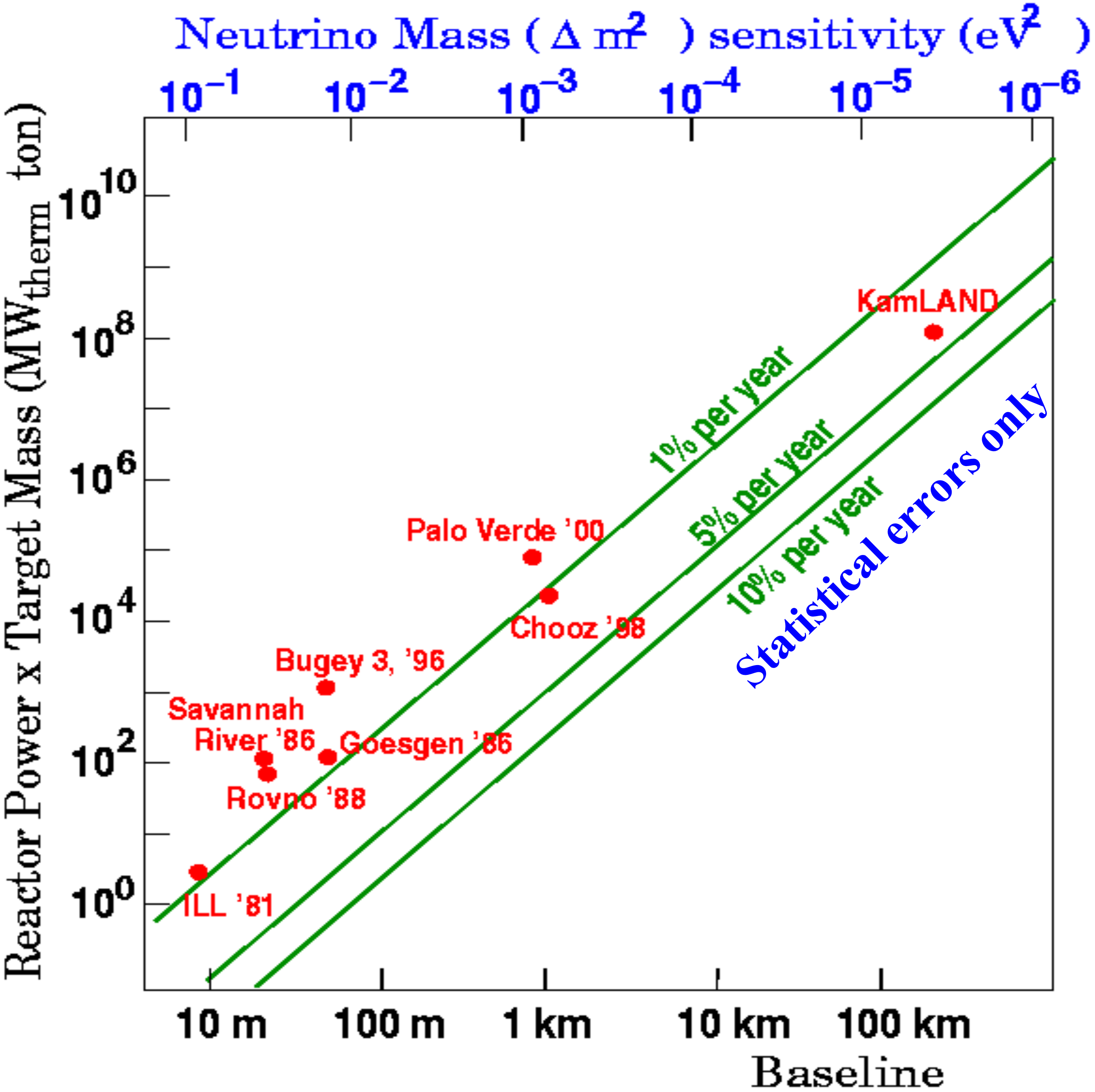
- long distance
- large nuclear power
- giant detector



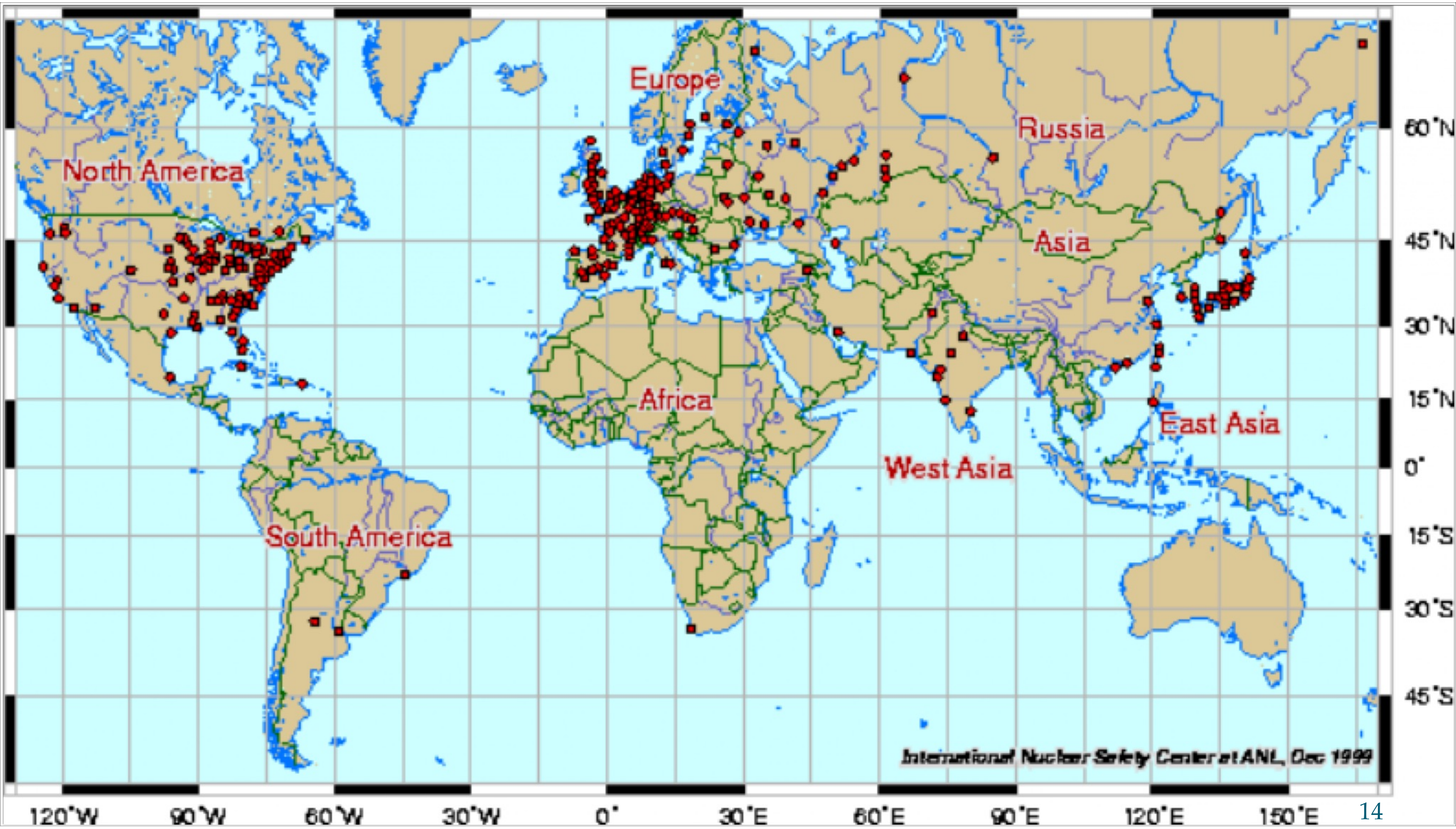
$$L_{osc} = 2\pi\hbar c \frac{E[MeV]}{\Delta m^2[eV^2]} = 2.48 \frac{E[MeV]}{\Delta m^2[eV^2]}$$

KamLAND Makes a Giant Step Forward

Superiority of KamLAND

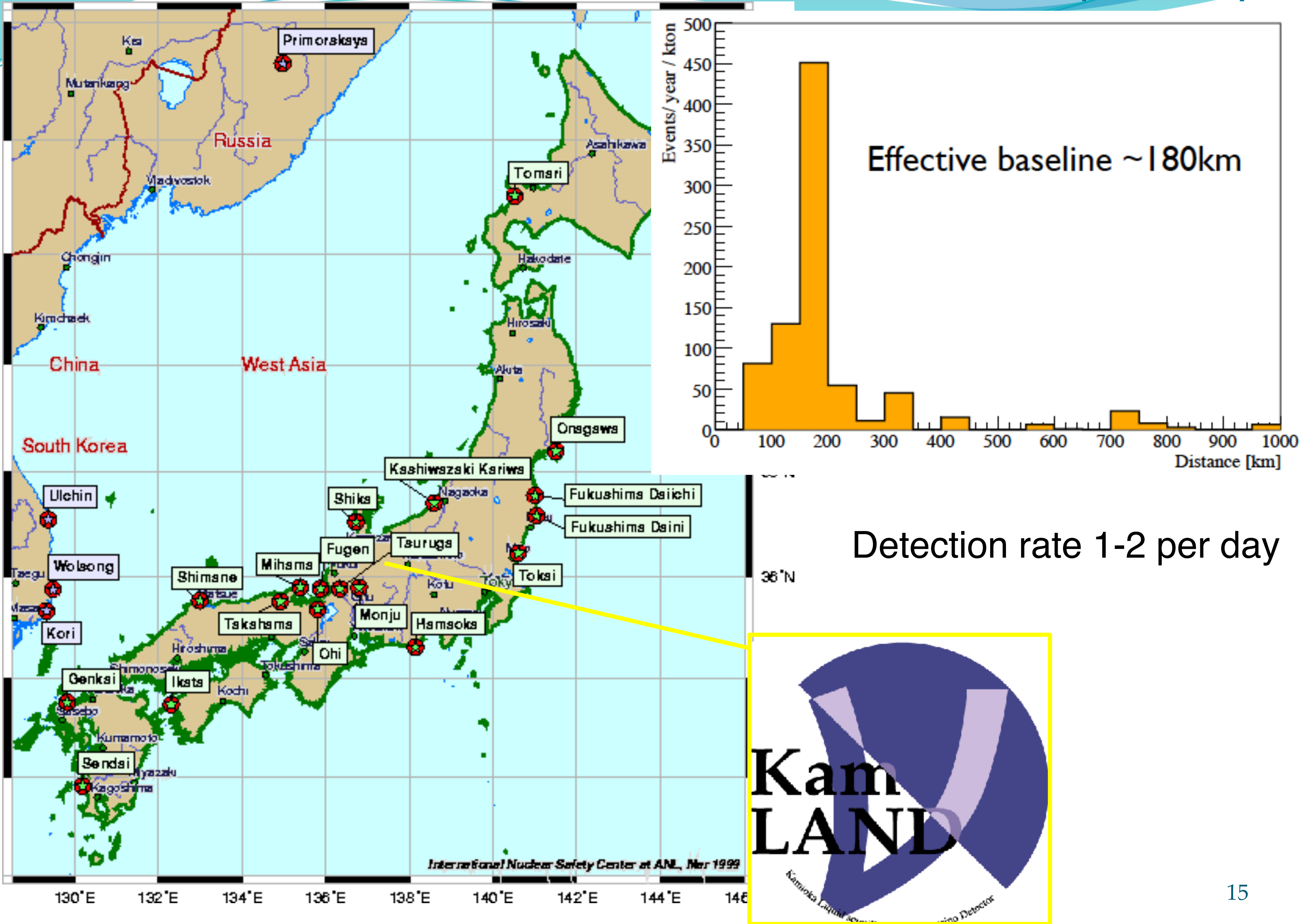


World Map of Nuclear Reactors in 2001 (not today)



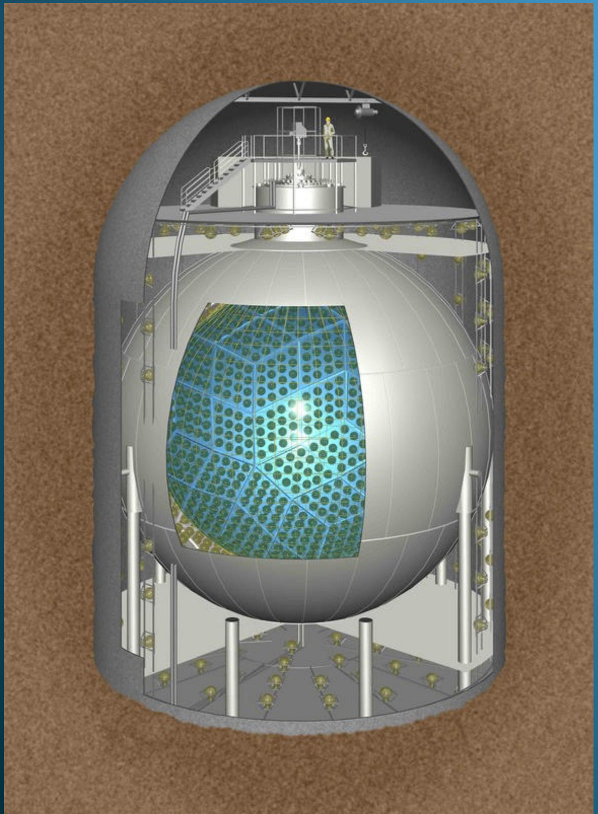
International Nuclear Safety Center at ANL, Dec 1999

Excellent Position of KamLAND (2001)

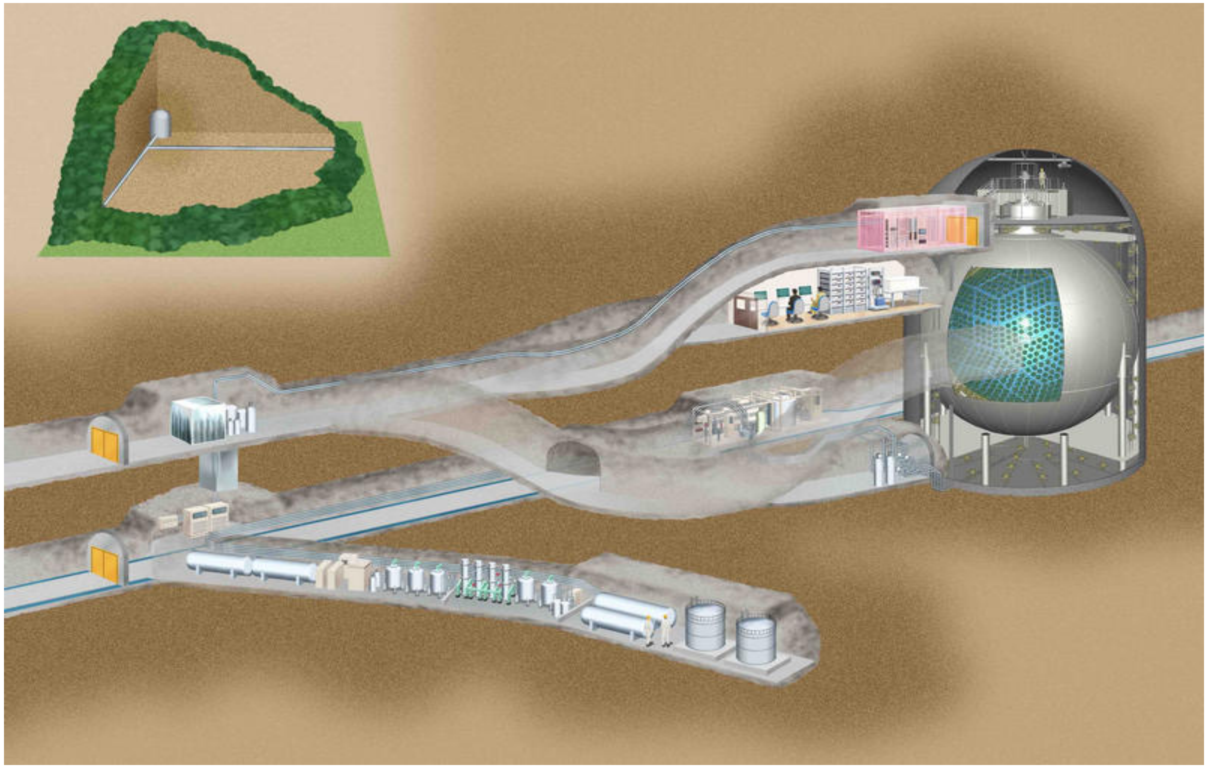


Detection rate 1-2 per day

Description of KamLAND Detector



KamLAND Detector Site



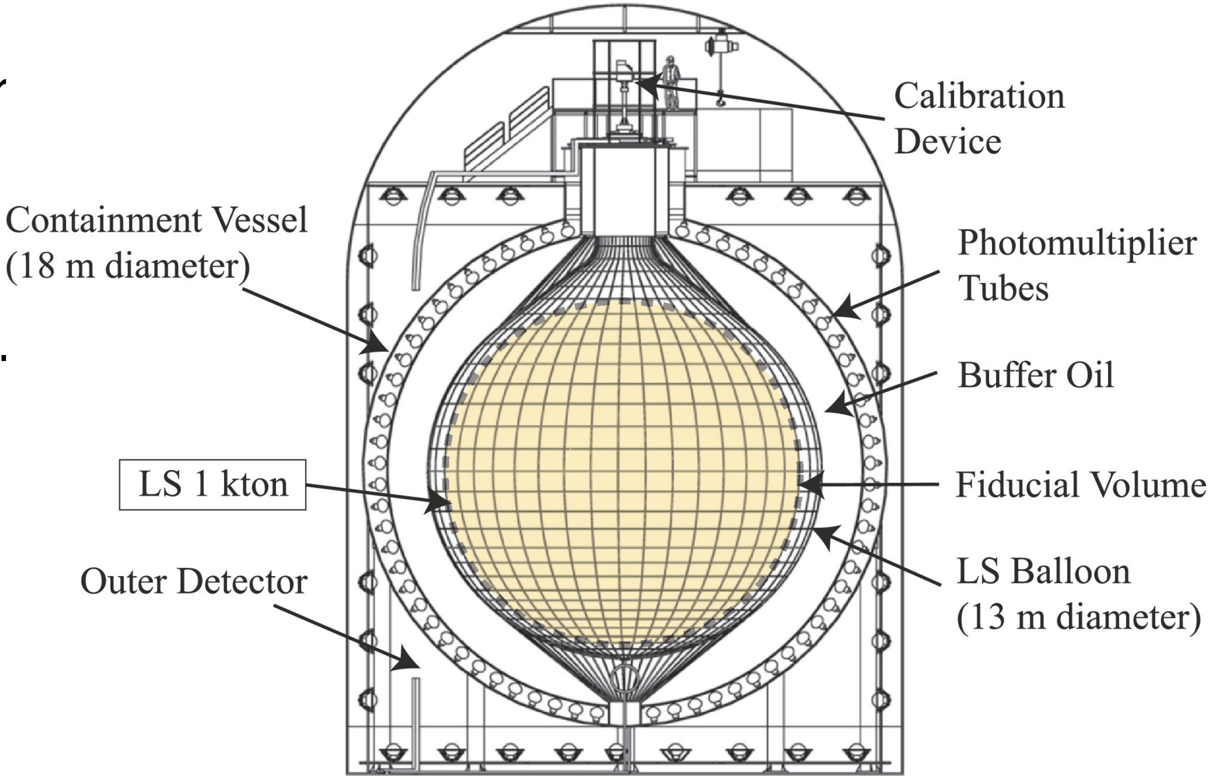
- KamLAND is situated about 1km underground which corresponds to 2700 mwe and provides good shielding from cosmic rays.
- In Kamioka mine – neighbor to SuperKamiokande

Detector Design

- 1kton of Liquid Scintillator (LS) surrounded by buffer oil and acrylic Rn barrier.
- LS is target and detector.

- Inner detector:
  - 1325 17” PMTs
  - 554 20” PMTs
  - 34% photocatode coverage
- Veto detector
  - 225 20” PMTs - water Cherenkov detector

- 260 p.e./MeV observed at the detector center.



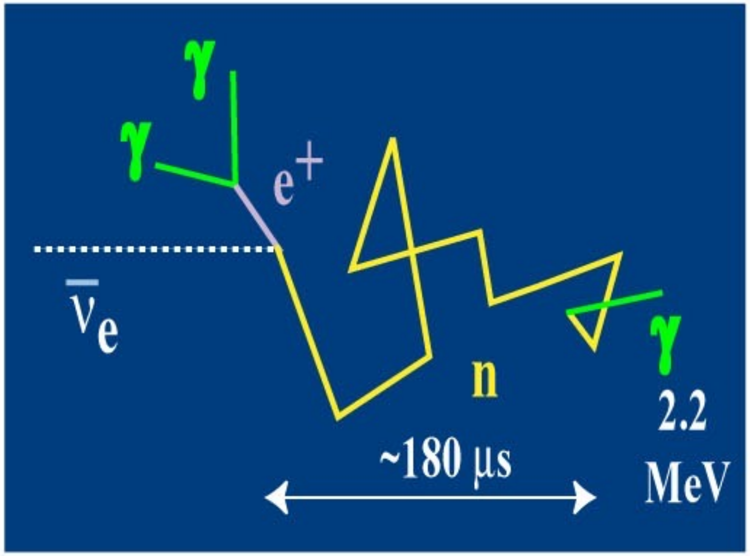
N.B: Liquid scintillator is proton rich target that emits isotropic scintillation light when particle deposits energy.
LS detectors are calorimeters, but not directional.

Detection of Reactor $\bar{\nu}_e$’s

reaction process : **inverse- β decay** ($\bar{\nu}_e + p \longrightarrow e^+ + n$)

$+ p \longrightarrow d + \gamma$

distinctive two-step signature



$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806\ MeV$$

- **prompt part :** e^+

  $\bar{\nu}_e$ **energy measurement**

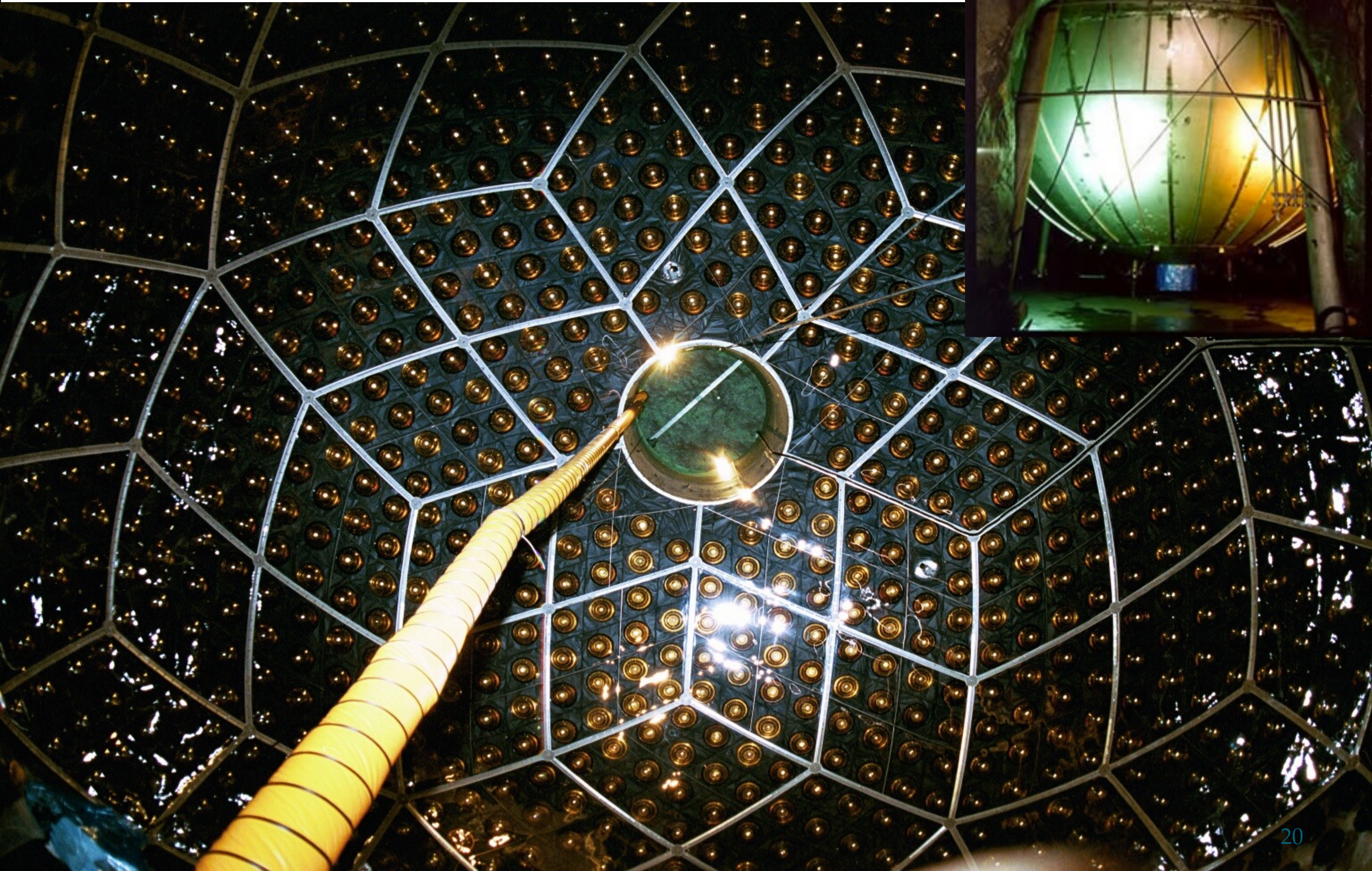
  $$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

  $$\Delta = M_n - M_p$$

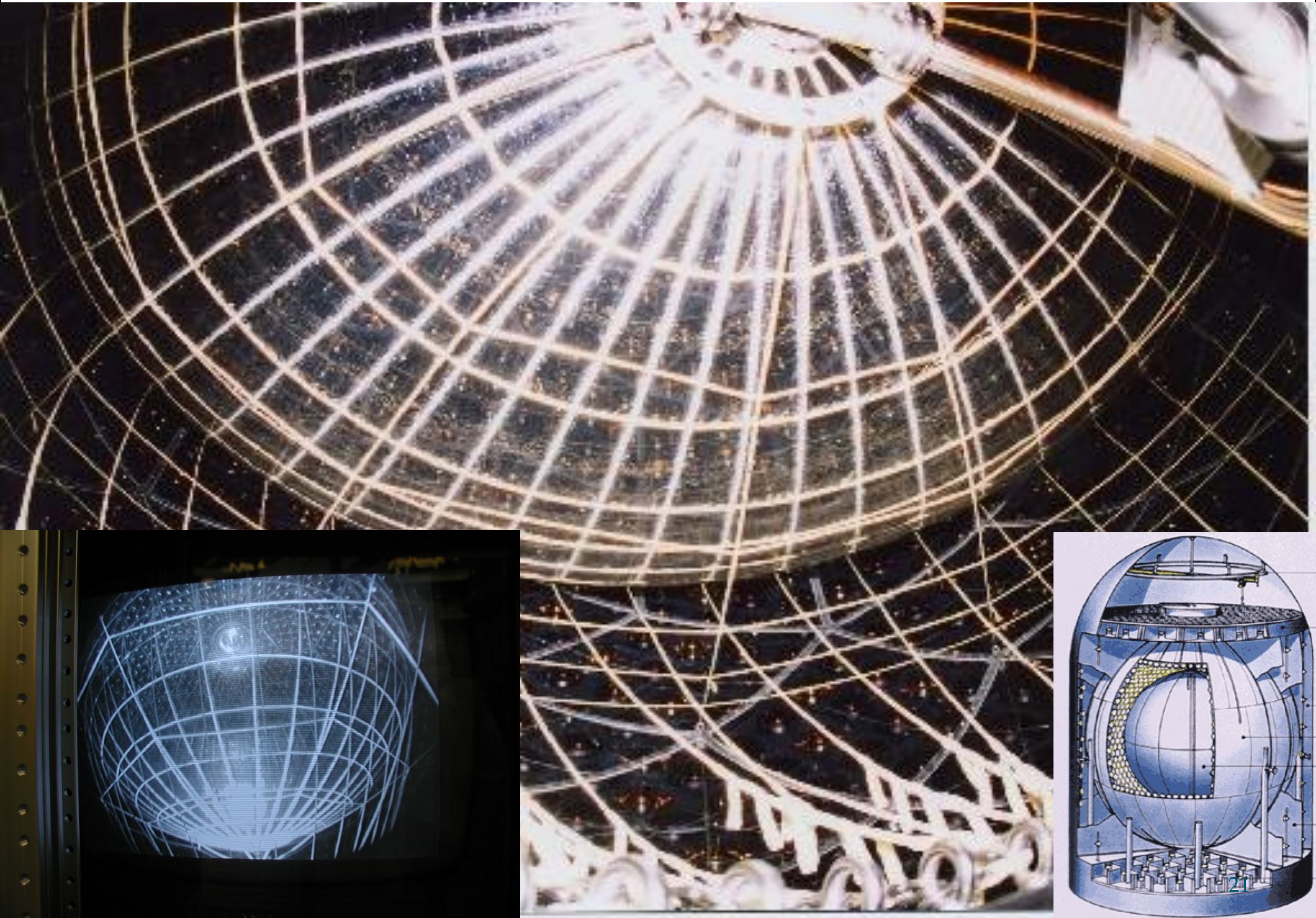
- **delayed part :** γ **(2.2 MeV)**

- **tagging : correlation of time, position and energy between prompt and delayed signal**

Construction of the Inner Detector

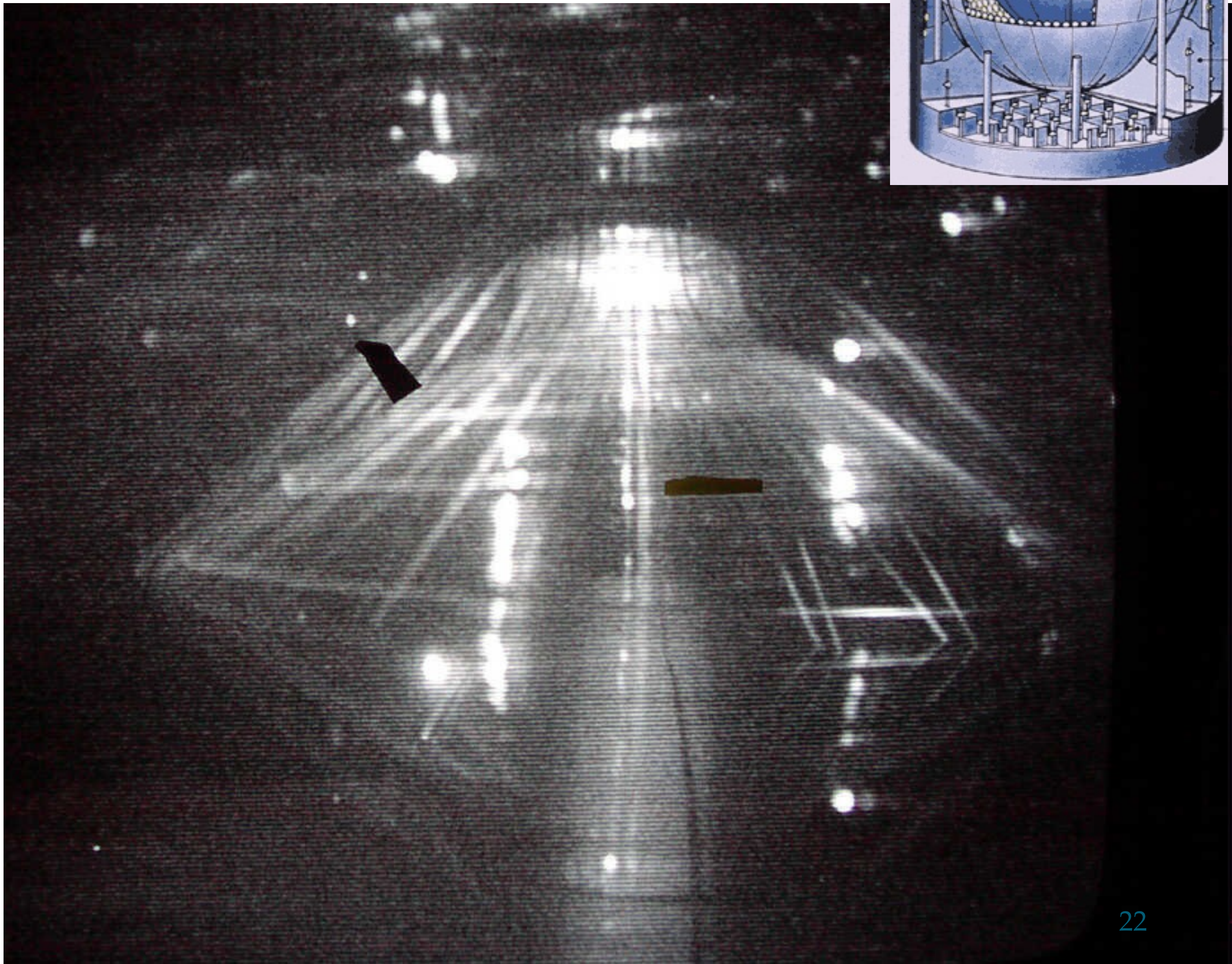


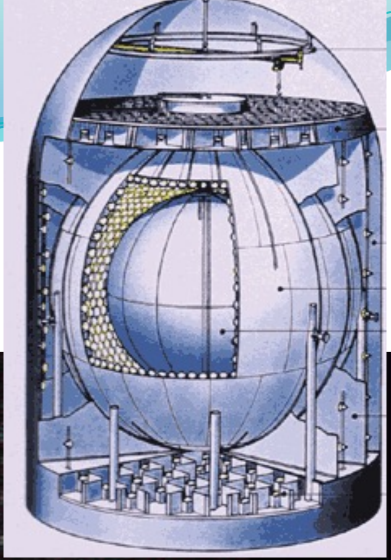
Balloon Installation



Balloon Filling Took 5 Months

- 13m diameter
- 135 µm thick
- made of nylon+
- supported by network of kevlar ropes





Buffer Oil and Liquid Scintillator

Scintillator is a blend of 20% pseudocumene and 80% paraffine oil.

LS is proton rich.

Different density paraffines are used to obtain similar (0.04% different) density inside and out of the balloon.

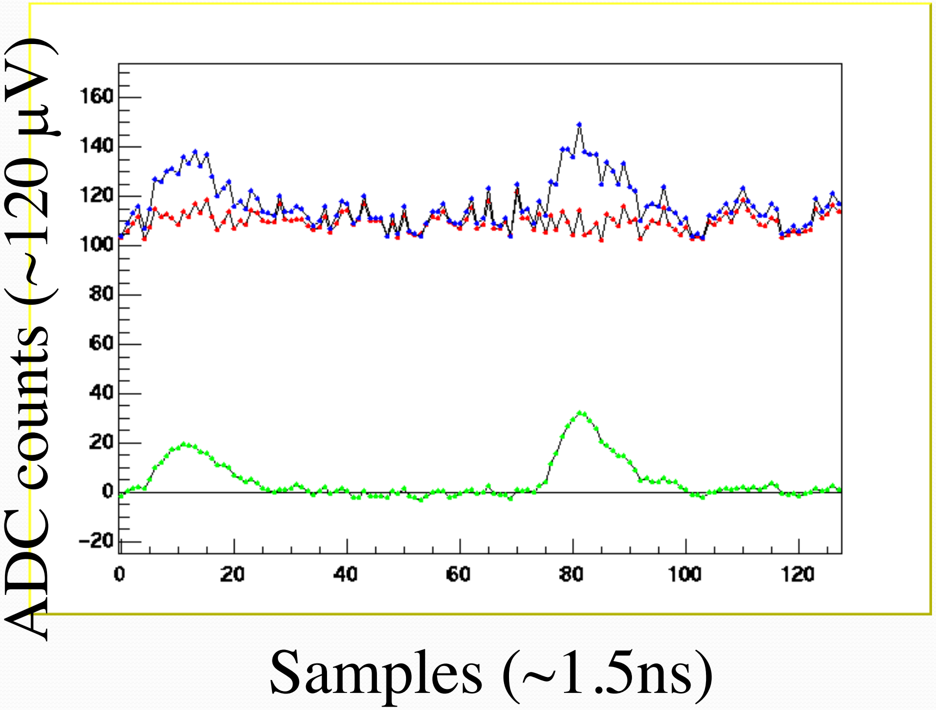
PPO concentration is 1.5 g/l of the final blend.

LS and BO purification plant.

KamLAND Data Recording

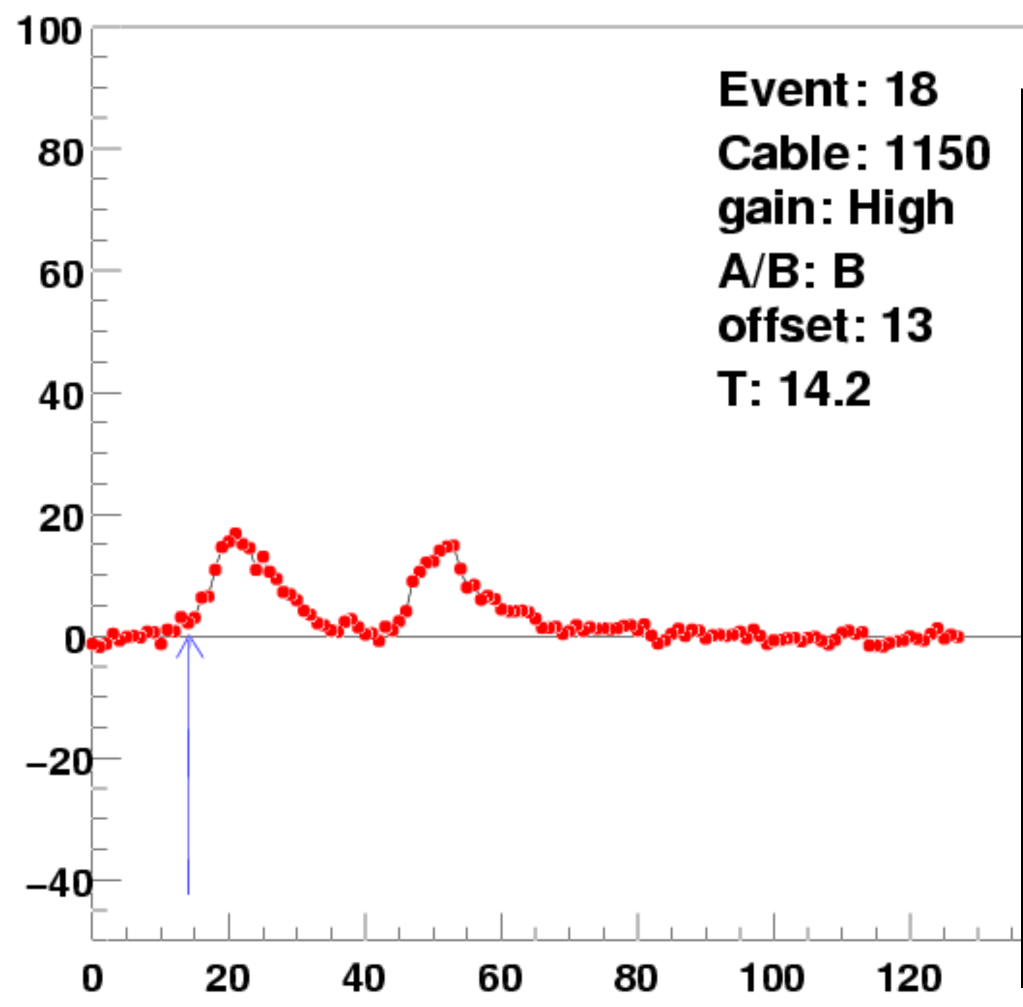
- Each PMT is connected to a waveform digitizer and trigger system analysis all PMT channels before it issues a trigger and saves all waveforms.
- PMT waveforms are recorded using Digitizers allowing multi p.e. resolution
- ~1/3 p.e. digitizer threshold and dynamic range ~1 mV to ~1 V
- ~1.5 ns sampling

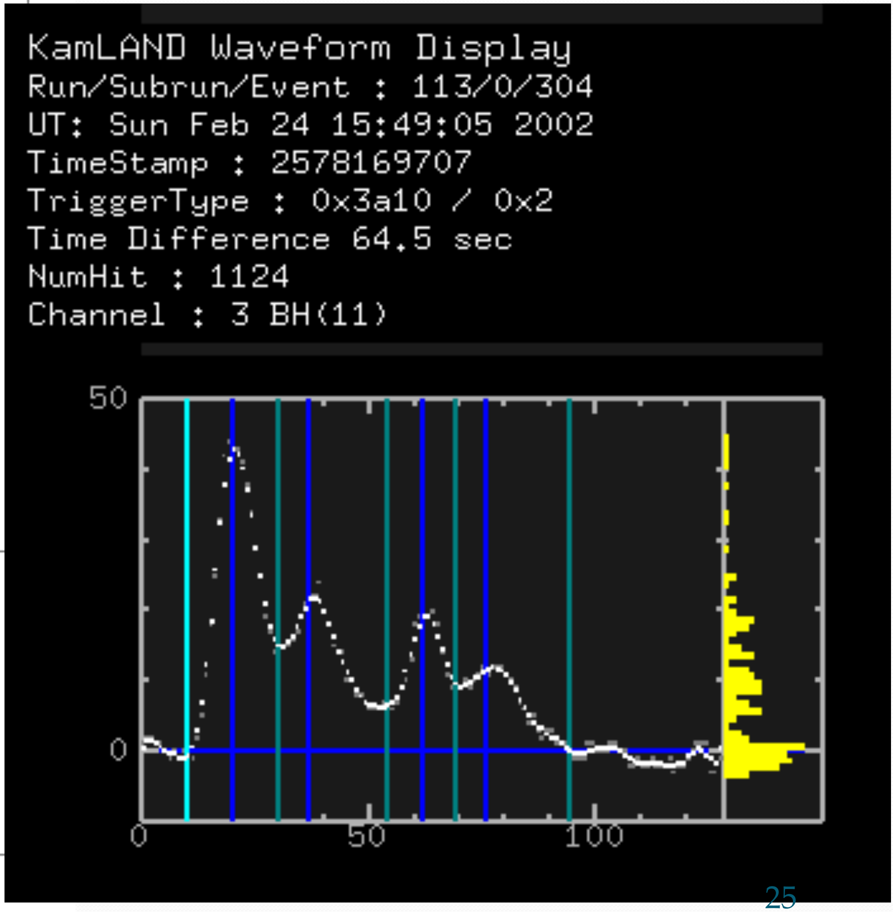
Blue: raw data
red: pedestal
green: pedestal subtracted



KamLAND data

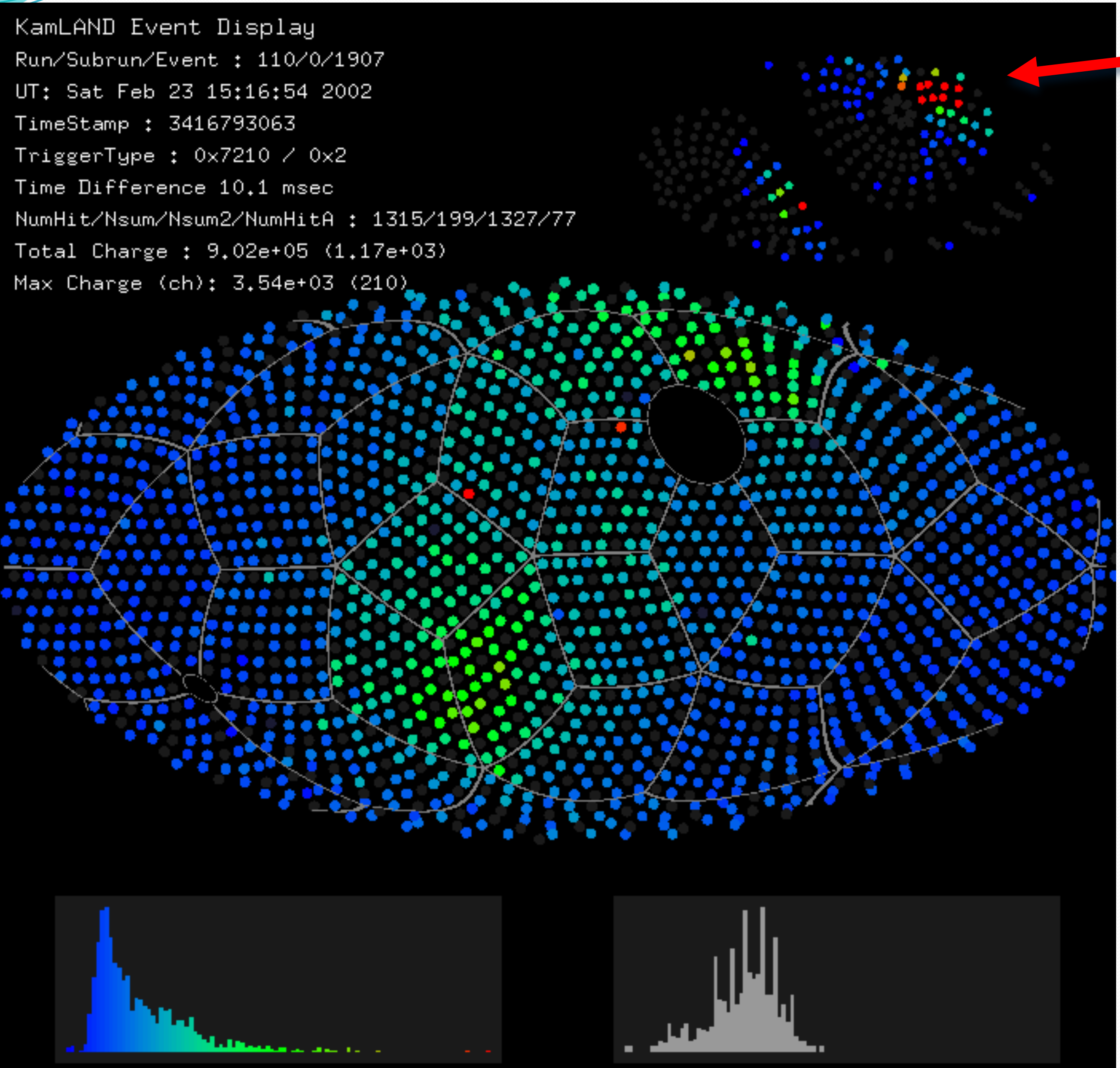
- Convert **waveforms** into **time** and **charge** information for each PMT





```
KamLAND Waveform Display
Run/Subrun/Event : 113/0/304
UT: Sun Feb 24 15:49:05 2002
TimeStamp : 2578169707
TriggerType : 0x3a10 / 0x2
Time Difference 64.5 sec
NumHit : 1124
Channel : 3 BH(11)
```

Event display



```
KamLAND Event Display
Run/Subrun/Event : 110/0/1907
UT: Sat Feb 23 15:16:54 2002
TimeStamp : 3416793063
TriggerType : 0x7210 / 0x2
Time Difference 10.1 msec
NumHit/Nsum/Nsum2/NumHitA : 1315/199/1327/77
Total Charge : 9.02e+05 (1.17e+03)
Max Charge (ch): 3.54e+03 (210)
```

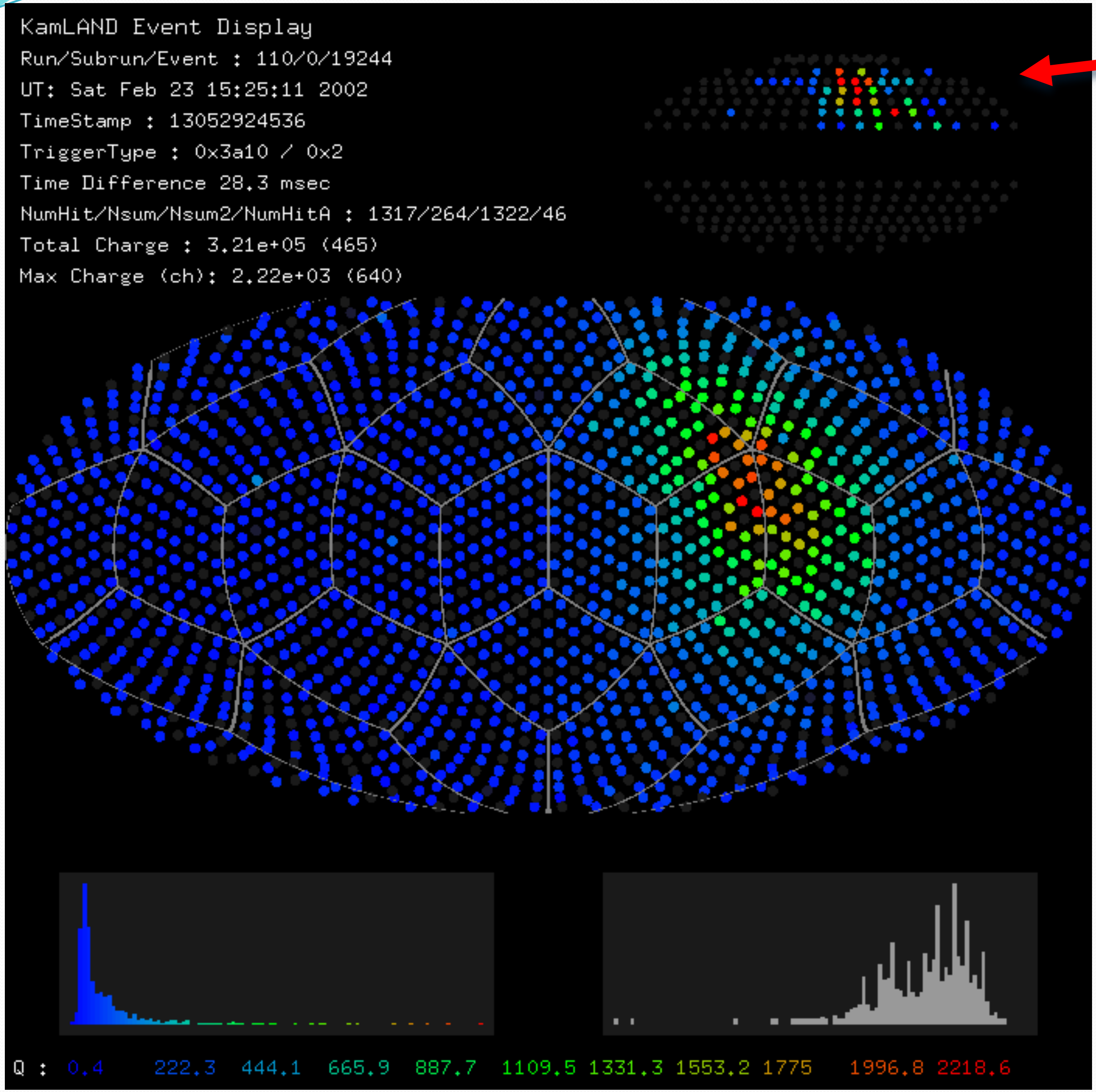
Outer detector display

Event Display: throughgoing muon

color is pulse height

all tubes illuminated

Event display

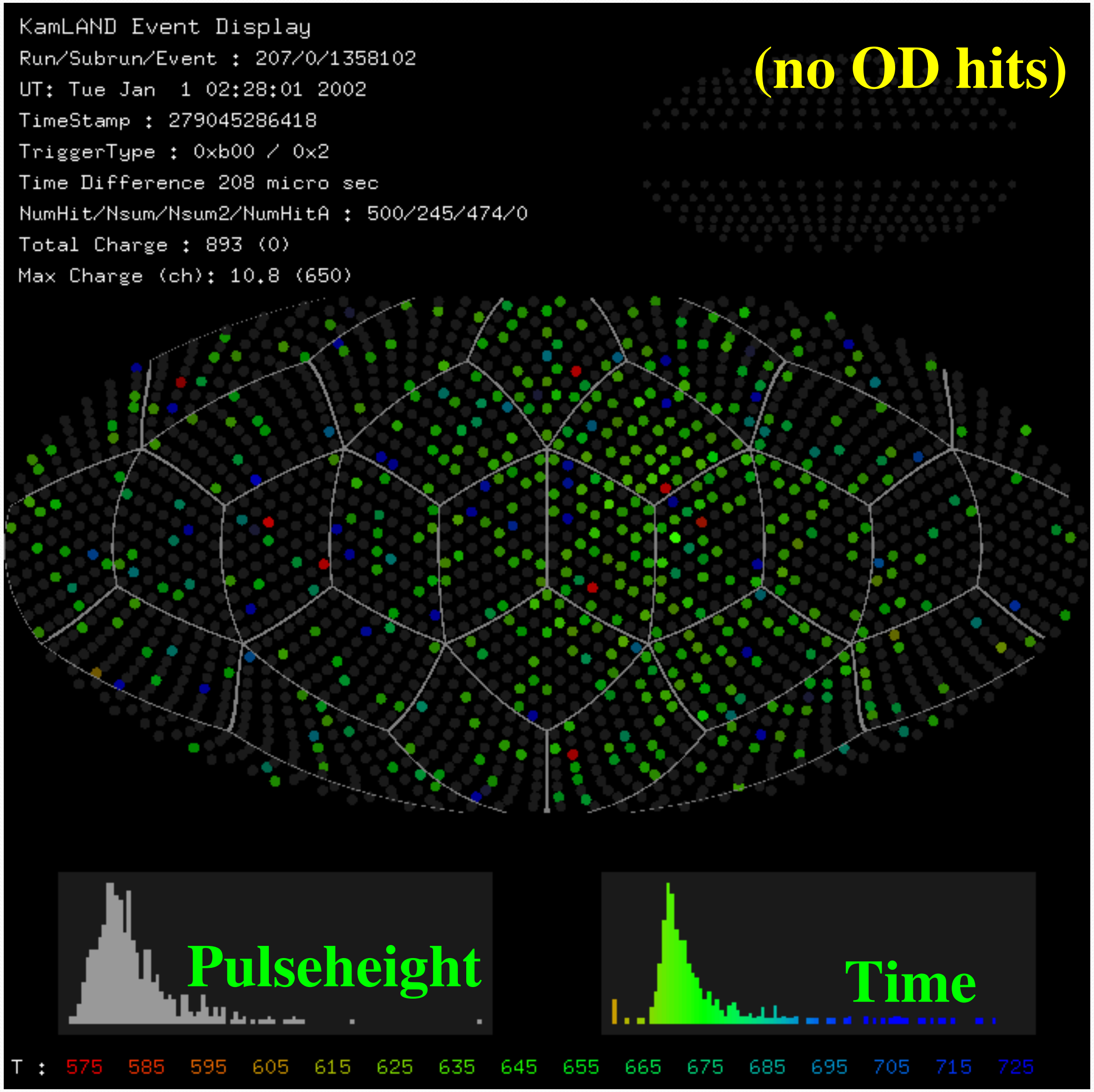


```
KamLAND Event Display
Run/Subrun/Event : 110/0/19244
UT: Sat Feb 23 15:25:11 2002
TimeStamp : 13052924536
TriggerType : 0x3a10 / 0x2
Time Difference 28.3 msec
NumHit/Nsum/Nsum2/NumHitA : 1317/264/1322/46
Total Charge : 3.21e+05 (465)
Max Charge (ch): 2.22e+03 (640)
```

Outer detector display

Stopped muon

Event display



```
KamLAND Event Display
Run/Subrun/Event : 207/0/1358102
UT: Tue Jan  1 02:28:01 2002
TimeStamp : 279045286418
TriggerType : 0xb00 / 0x2
Time Difference 208 micro sec
NumHit/Nsum/Nsum2/NumHitA : 500/245/474/0
Total Charge : 893 (0)
Max Charge (ch): 10.8 (650)
```

Low energy event

color is time

Detector calibration

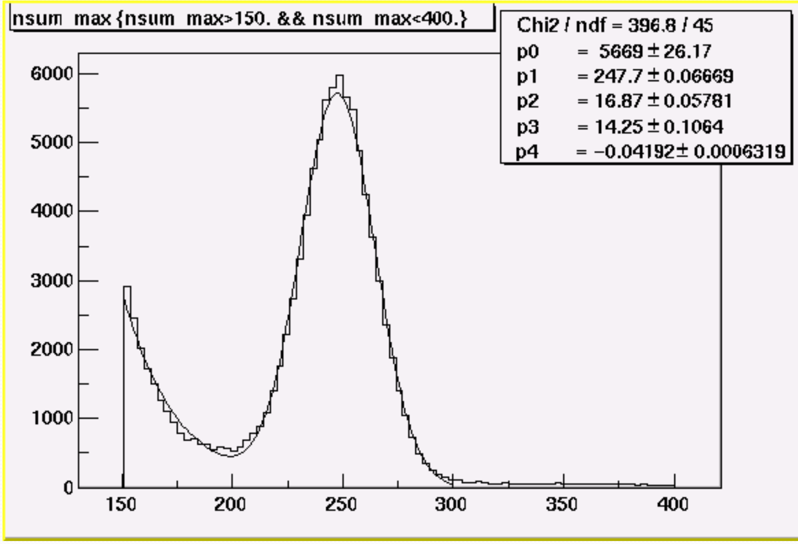
Converting **time** and **charge** information
into event **position** and **energy**:

This requires calibration of the PMT's:
- Timing: done with a blue laser
- Gains: single photoelectron gains with LED's
  high pulse height gains with UV laser

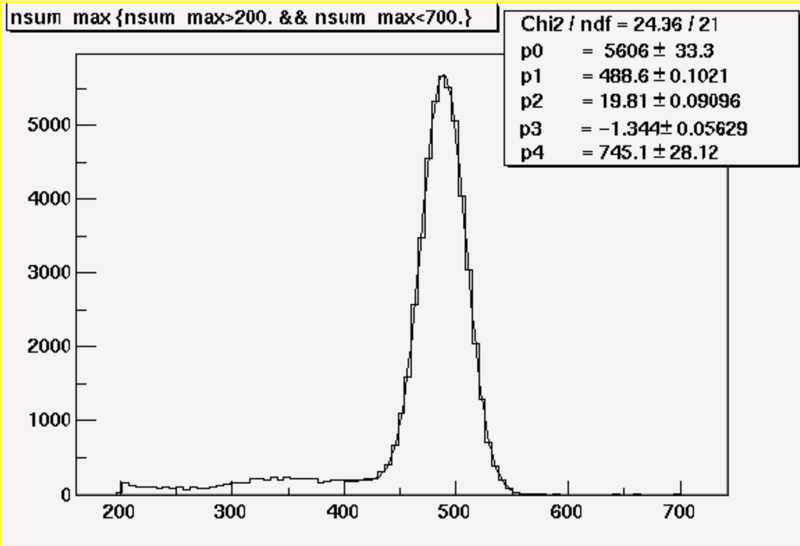
The detector response as a whole
is calibrated with radioactive sources

The **position** is obtained from a **vertex fit**
The **energy** response depends on position

(Note: these are old calibration plots,
(for illustration only)

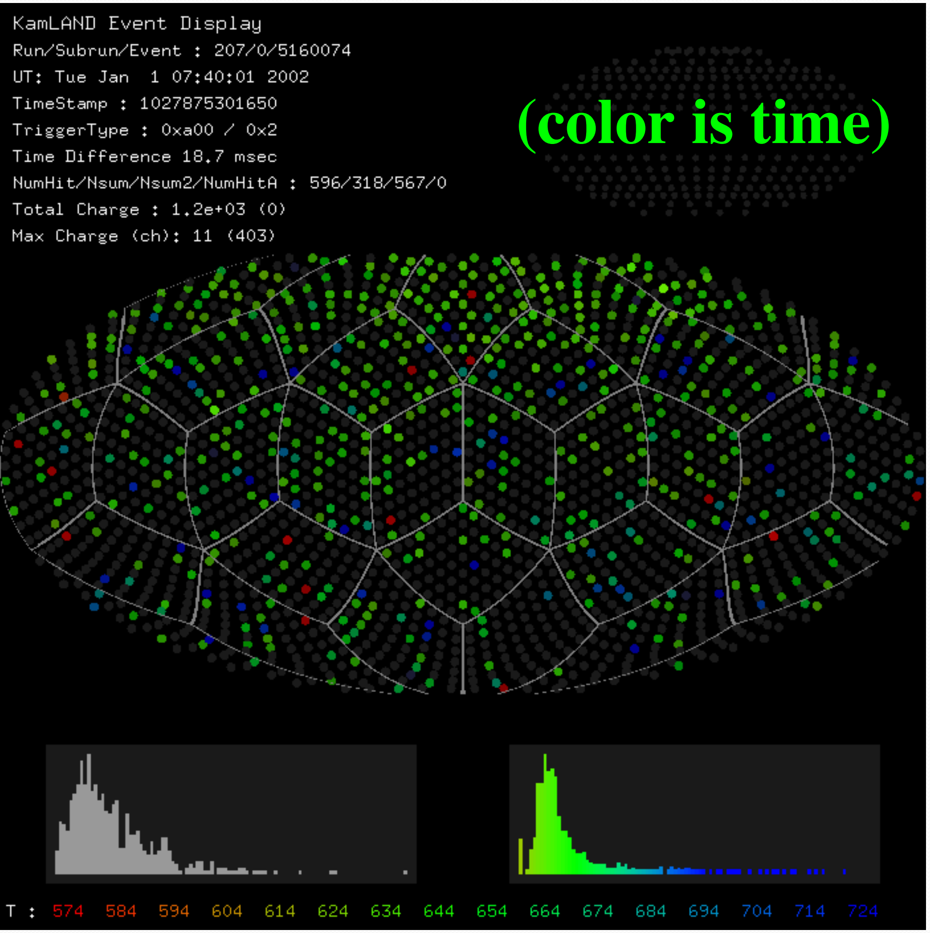


^{65}Zn (1.115 MeV γ)



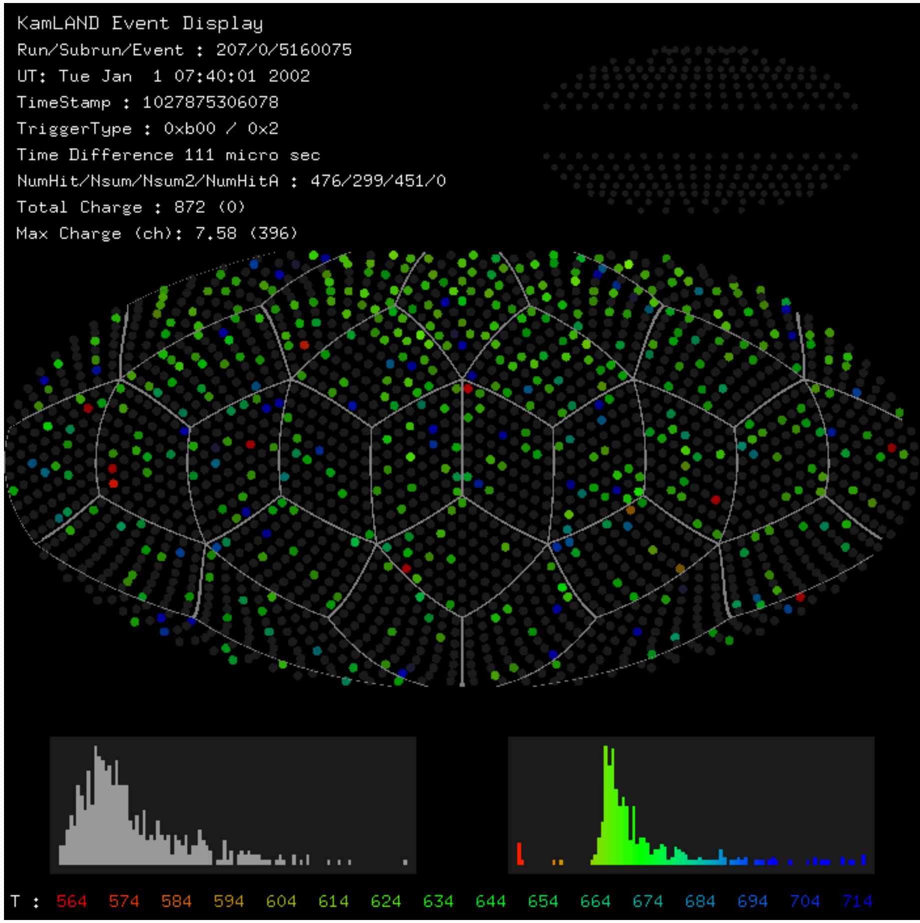
^{60}Co (2.505 MeV γ+γ)

Neutrino Candidate



KamLAND Event Display
Run/Subrun/Event : 207/0/5160074
UT: Tue Jan 1 07:40:01 2002
TimeStamp : 1027875301650
TriggerType : 0xa00 / 0x2
Time Difference 18.7 msec
NumHit/Nsum/Nsum2/NumHitA : 596/318/567/0
Total Charge : 1.2e+03 (0)
Max Charge (ch): 11 (403)

(color is time)



KamLAND Event Display
Run/Subrun/Event : 207/0/5160075
UT: Tue Jan 1 07:40:01 2002
TimeStamp : 1027875306078
TriggerType : 0xb00 / 0x2
Time Difference 111 micro sec
NumHit/Nsum/Nsum2/NumHitA : 476/299/451/0
Total Charge : 872 (0)
Max Charge (ch): 7.58 (396)

Prompt Signal
E = 3.20 MeV

$\Delta t = 111\ \mu s$
$\Delta R = 34$ cm

Delayed Signal
E = 2.22 MeV

Expected Backgrounds in Reactor Neutrino Experiments

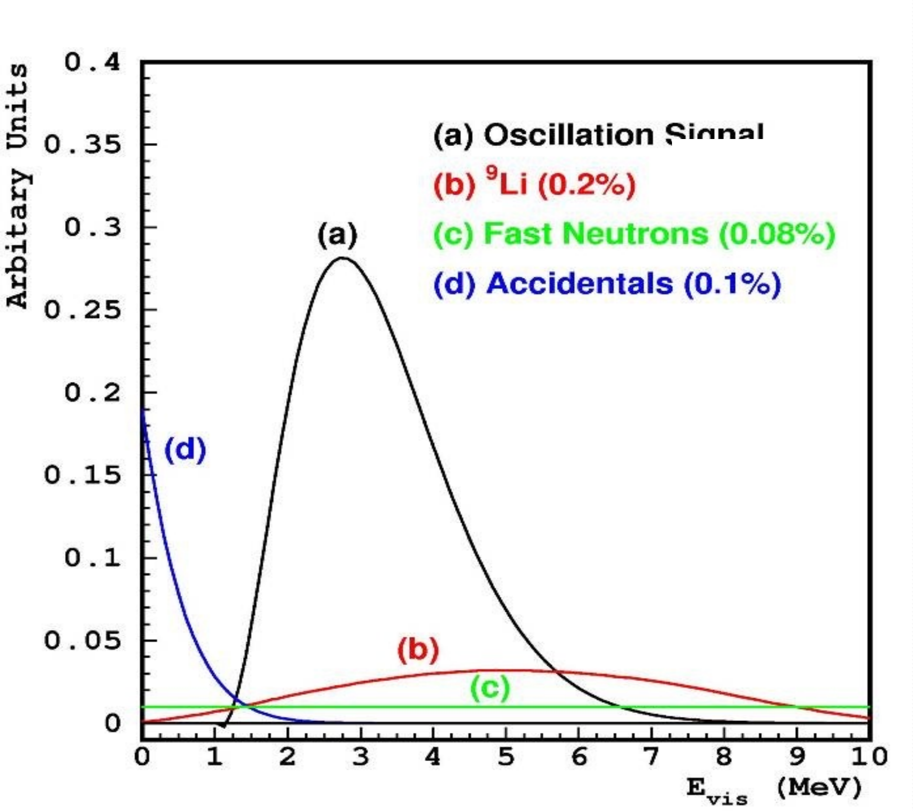
Background event mimics an IBD neutrino interaction, but it is something else…

Accidental bkg:

- e^+-like signal: radioactivity from materials, PMTs, surrounding rock
  Rate=R_e
- n signal: n from cosmic muon spallation, thermalized in detector and captured on H (R_n)

  Þ Accidental coincidence

  Rate = $R_e \times R_n \times \Delta t$

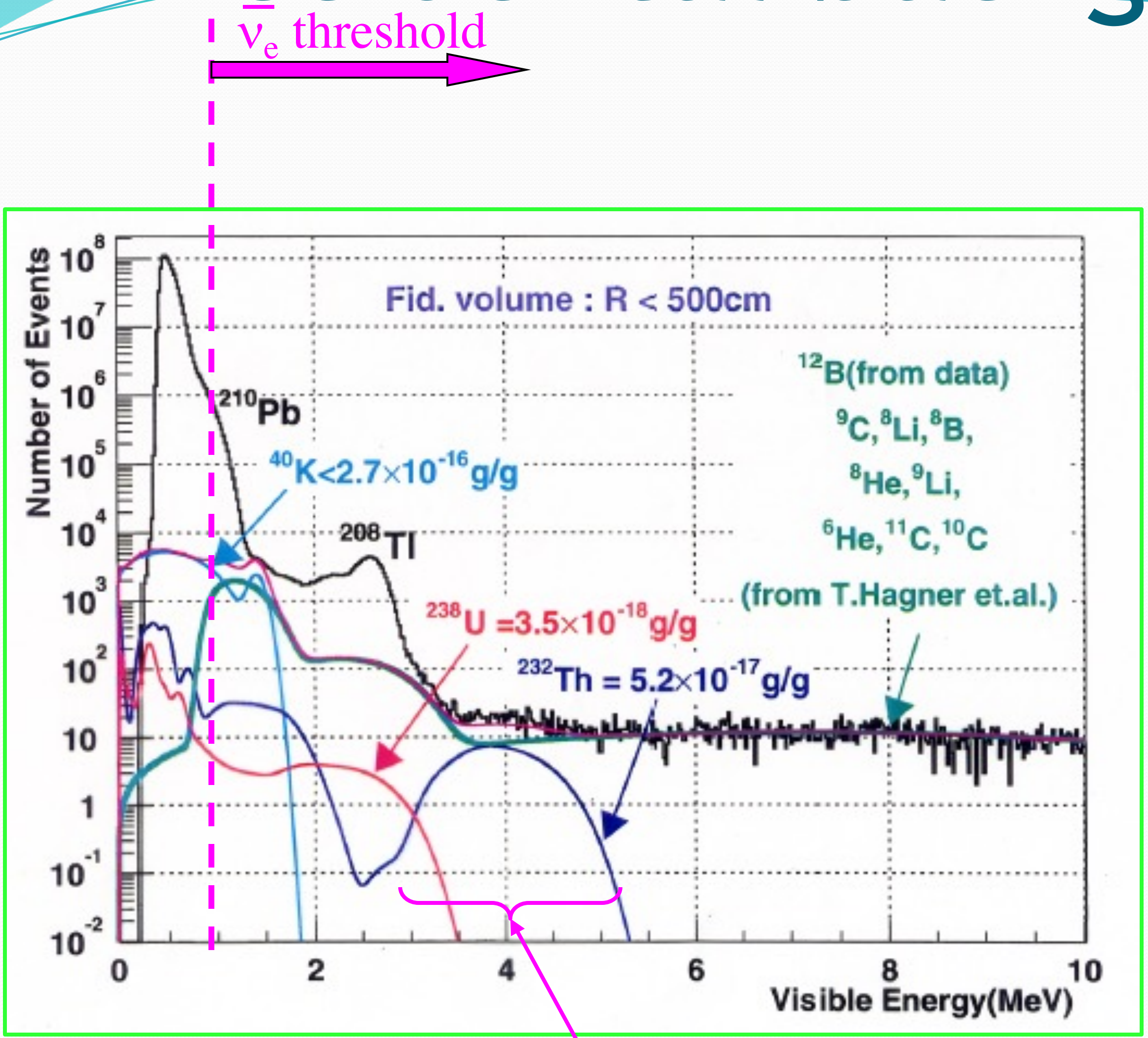


Correlated bkg:

- fast n (by cosmic muon) recoil on proton (low energy) and captured on H
- long-lived (^{9}Li, ^{8}He) β-decaying isotopes induced by muon

Bkg reduction and knowledge is critical for oscillation measurement!

Accidental backgrounds



^{208}Tl decay ~2.5/day

^{238}U/^{222}Rn: 3.5x10^{-18}g/g

= 20μBq

^{232}Th: 5.2x10^{-17}g/g

=100μBq

^{40}K: <2.7x10^{-16}g/g

=<0.04Bq

(cf: sea water contains 10^{-9}g/g of U.)

Backgrounds Summary

After all cuts are applied, background in the analyzed data sample is:

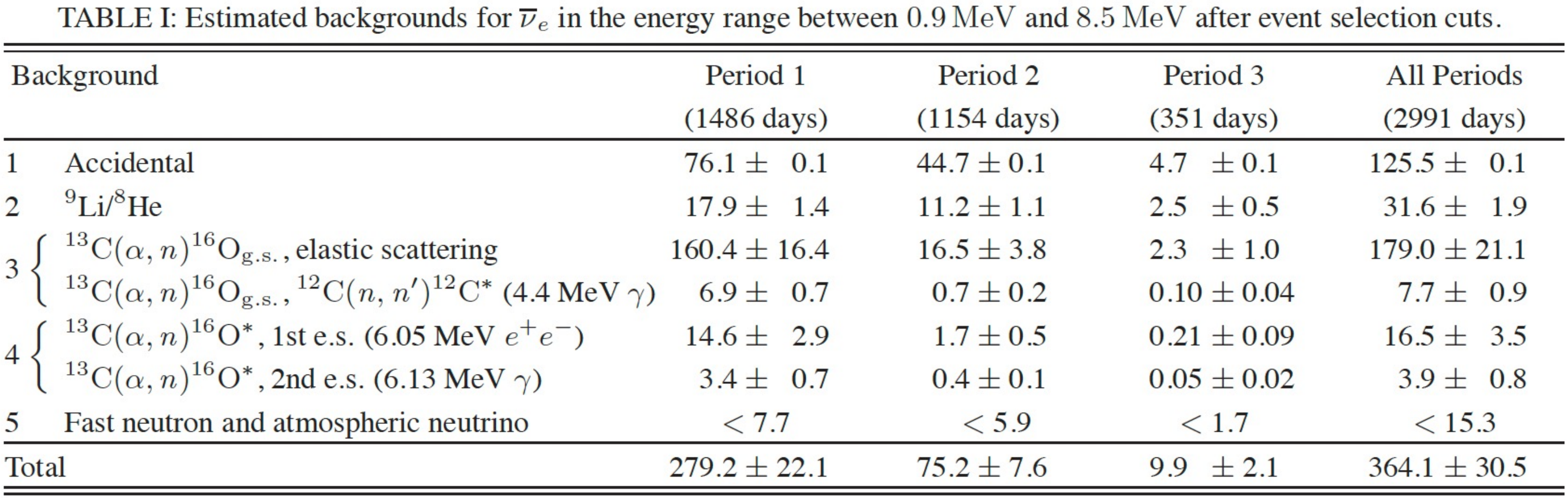


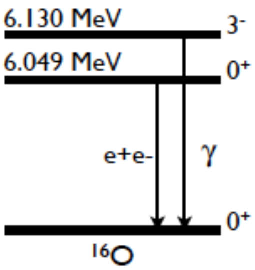
TABLE I: Estimated backgrounds for $\overline{\nu}_e$ in the energy range between 0.9 MeV and 8.5 MeV after event selection cuts.

	Background	Period 1 (1486 days)	Period 2 (1154 days)	Period 3 (351 days)	All Periods (2991 days)
1	Accidental	76.1 ± 0.1	44.7 ± 0.1	4.7 ± 0.1	125.5 ± 0.1
2	^{9}Li/^{8}He	17.9 ± 1.4	11.2 ± 1.1	2.5 ± 0.5	31.6 ± 1.9
3	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}_{\mathrm{g.s.}}$, elastic scattering	160.4 ± 16.4	16.5 ± 3.8	2.3 ± 1.0	179.0 ± 21.1
	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}_{\mathrm{g.s.}}$, $^{12}\mathrm{C}(n, n')^{12}\mathrm{C}^*$ (4.4 MeV γ)	6.9 ± 0.7	0.7 ± 0.2	0.10 ± 0.04	7.7 ± 0.9
4	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}^*$, 1st e.s. (6.05 MeV e^+e^-)	14.6 ± 2.9	1.7 ± 0.5	0.21 ± 0.09	16.5 ± 3.5
	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}^*$, 2nd e.s. (6.13 MeV γ)	3.4 ± 0.7	0.4 ± 0.1	0.05 ± 0.02	3.9 ± 0.8
5	Fast neutron and atmospheric neutrino	< 7.7	< 5.9	< 1.7	< 15.3
Total		279.2 ± 22.1	75.2 ± 7.6	9.9 ± 2.1	364.1 ± 30.5

From ^{222}Rn chain: $^{210}\mathrm{Pb} \xrightarrow{T_{1/2}=22\mathrm{yr}} {}^{210}\mathrm{Bi} \xrightarrow{5\mathrm{d}} {}^{210}\mathrm{Po} \xrightarrow{138\mathrm{d}} {}^{206}\mathrm{Pb}$

α, E=5.3MeV

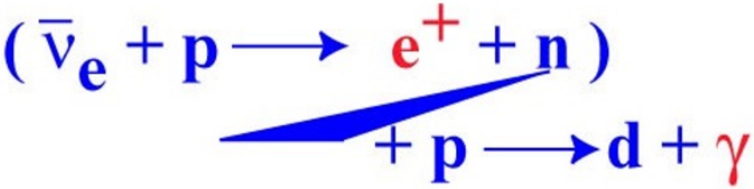
1.1% abundance of ^{13}C in LS → **$^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$**



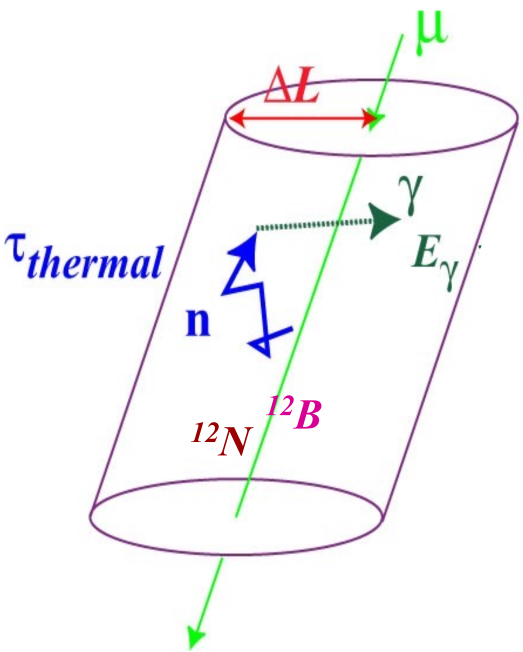
Analysis Cuts

- Analysis cuts are modeled by our understanding of IBD reaction in LS.

- Inverse beta-decay selection:
  - $R_{prompt, delayed} < 6$ m
  - 0.9 MeV $< E_{prompt} <$ 8.5 MeV
  - 1.8 MeV $< E_{delayed} <$ 2.6 MeV
  - $\Delta R < 2$m
  - 0.5 μs $< \Delta T <$ 1000 μs
  - L-selector: Use event characteristics to limit effect of accidental backgrounds at high R

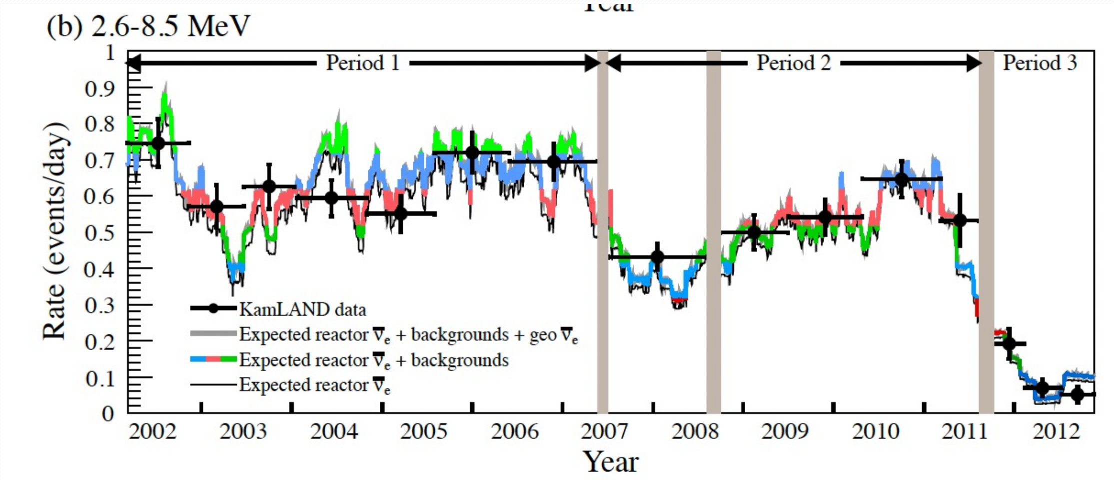


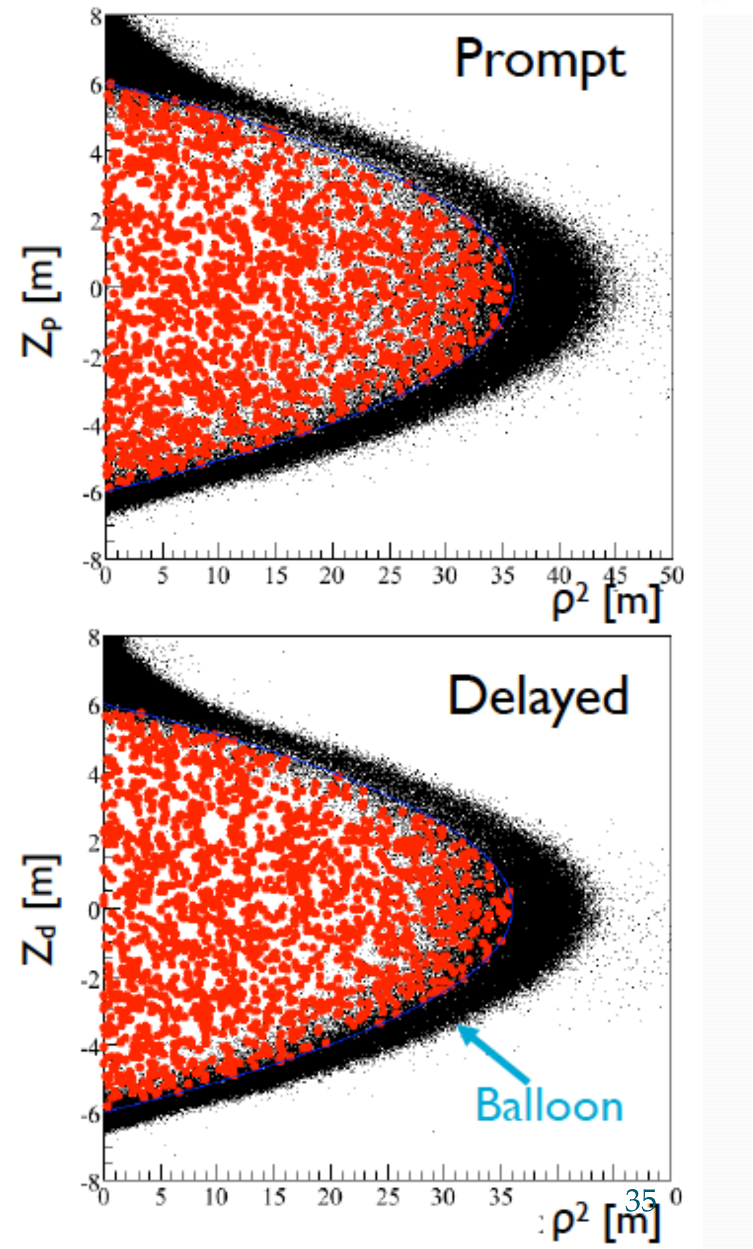
- Muon-induced spallation event cuts:
  - 2 ms veto after every μ
  - 2 s veto for showering/bad μ
  - 2 s veto in a R = 3m tube along track



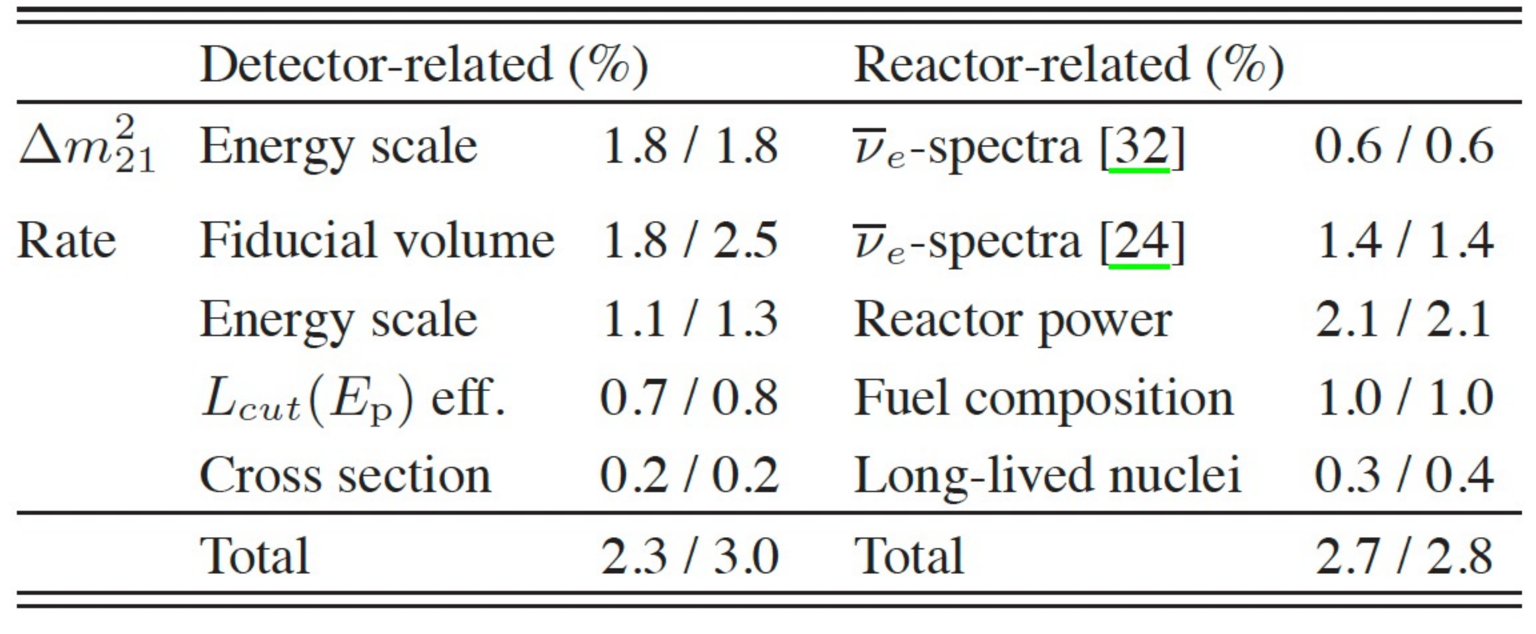
Event Selection

- In the livetime period of 2991 day, the number of antineutrino candidate events is 2611.





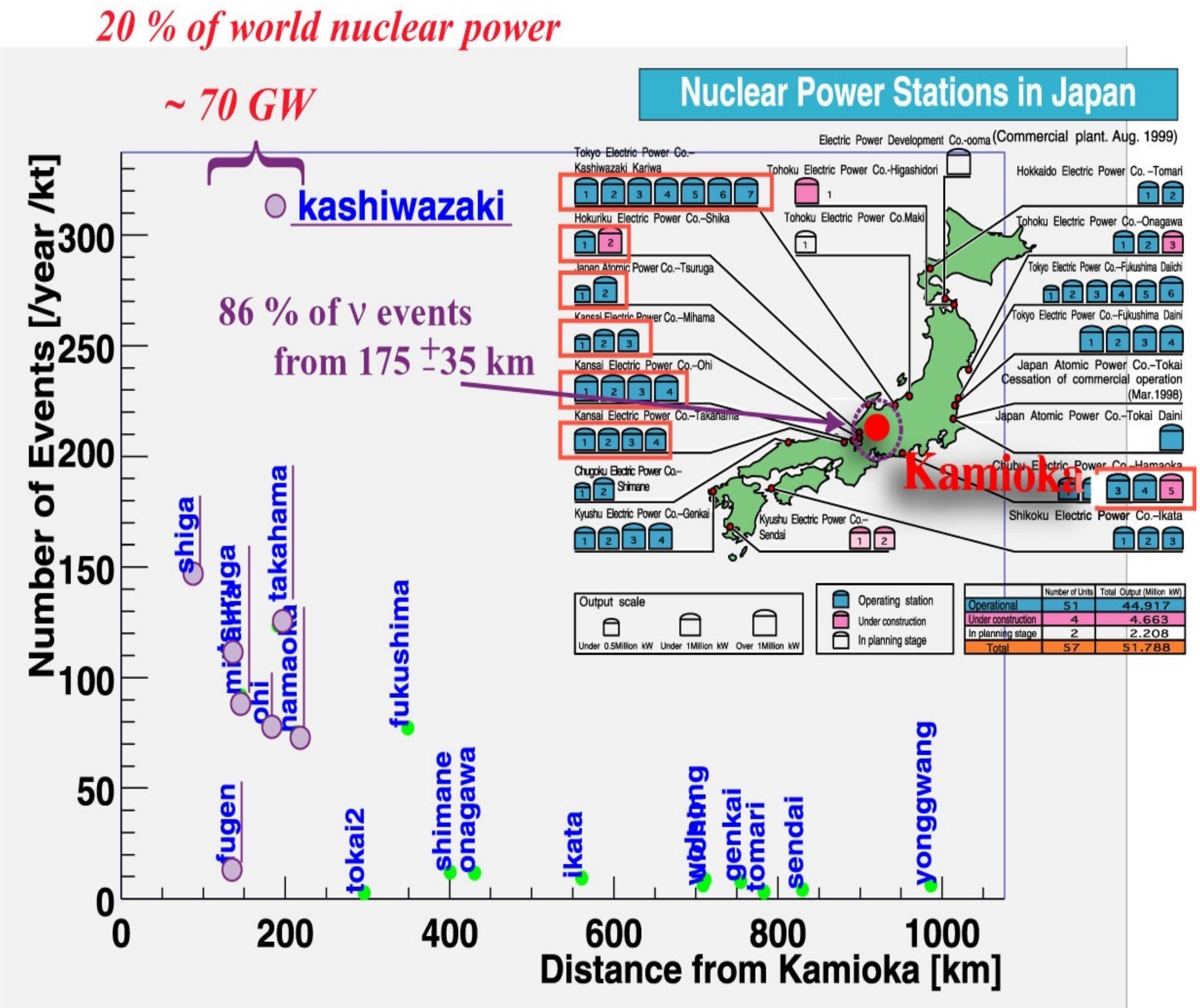
Systematic Errors



	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra [32]	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\overline{\nu}_e$-spectra [24]	1.4 / 1.4
	Energy scale	1.1 / 1.3	Reactor power	2.1 / 2.1
	$L_{cut}(E_{\mathrm{p}})$ eff.	0.7 / 0.8	Fuel composition	1.0 / 1.0
	Cross section	0.2 / 0.2	Long-lived nuclei	0.3 / 0.4
	Total	2.3 / 3.0	Total	2.7 / 2.8

Data set includes 2 phases and some systematic errors.

Reactor Antineutrino Flux at KamLAND Used to be High



	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	2	2.208
Total	57	51.788

Expected rate from reactors for the full volume is

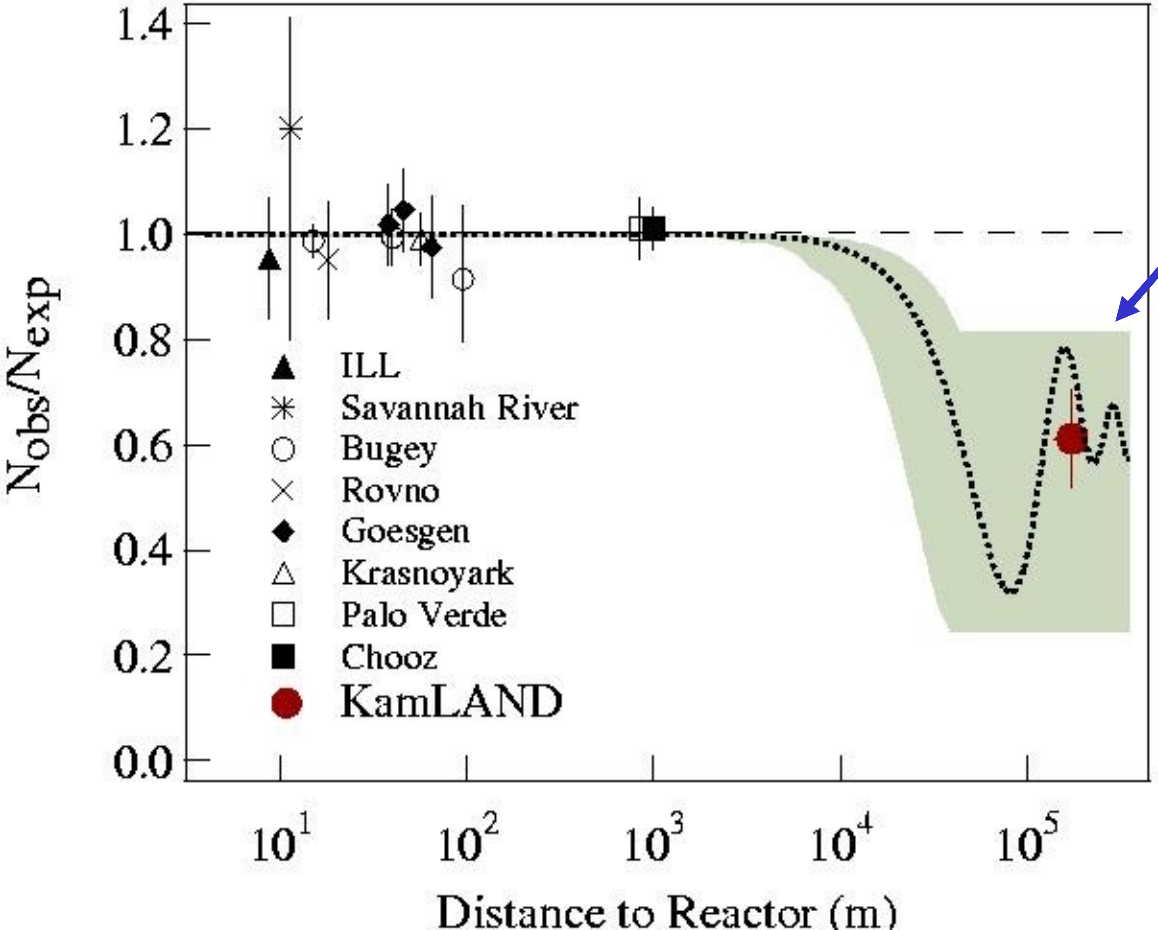
~ 2 events/day

Evidence of $\bar{\nu}_e$ disappearance

- Expected: 3564 ± 145 (without oscillations)
- Observed: 2611
- Background: 364.1 ± 30.5

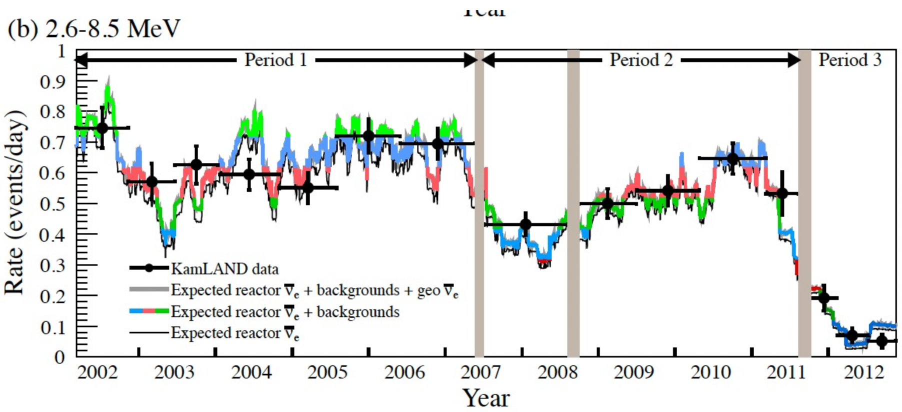
$$P = \frac{\text{Observed - Background}}{\text{Expected}} \sim 0.63$$

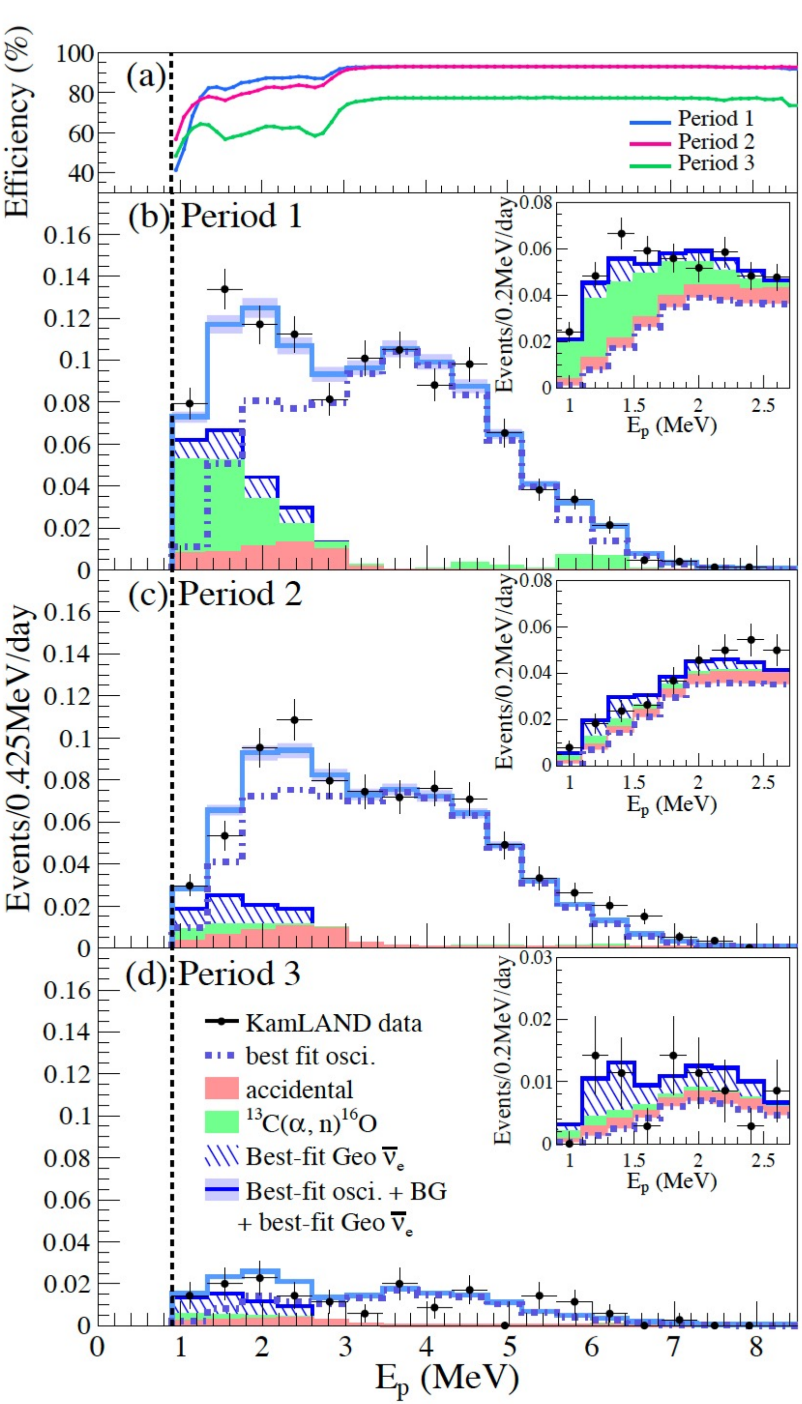
Ratio of Measured to Expected Antineutrino Flux from Reactor Neutrino Experiments



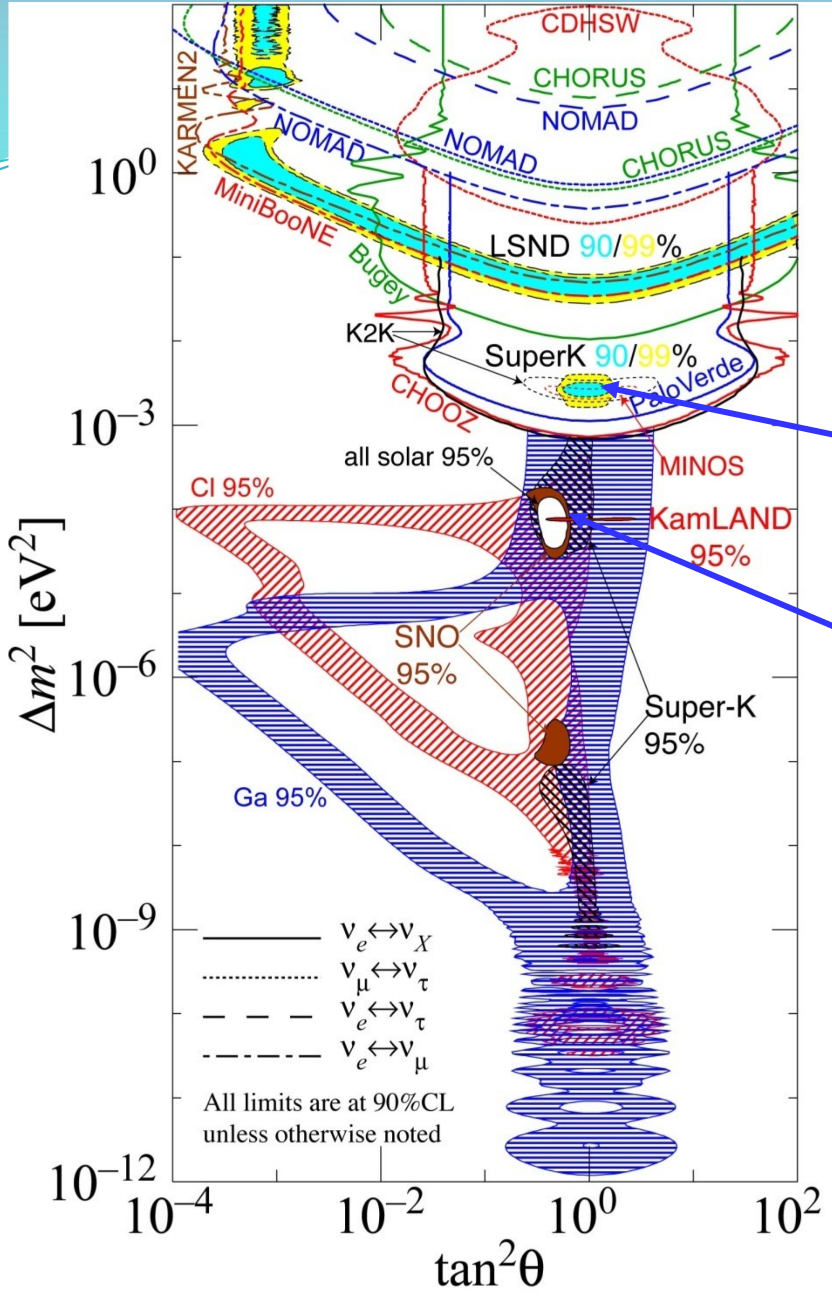
Shaded region LMA solution at 95% C.L.

Neutrino Oscillation Spectrum





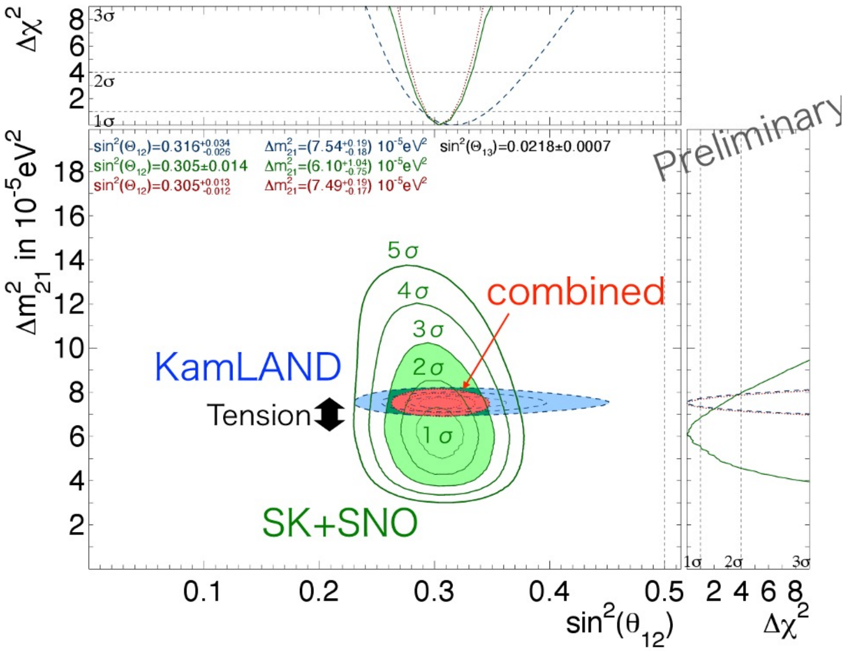
Neutrino Oscillation Parameters Summary



http://hitoshi.berkeley.edu/neutrino

Atmospheric Neutrinos
+ accelerator neutrinos

Solar & Reactor Neutrinos



Thanks to Hitoshi Murayama

Neutrino Oscillation Parameters (2022)

$$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$$

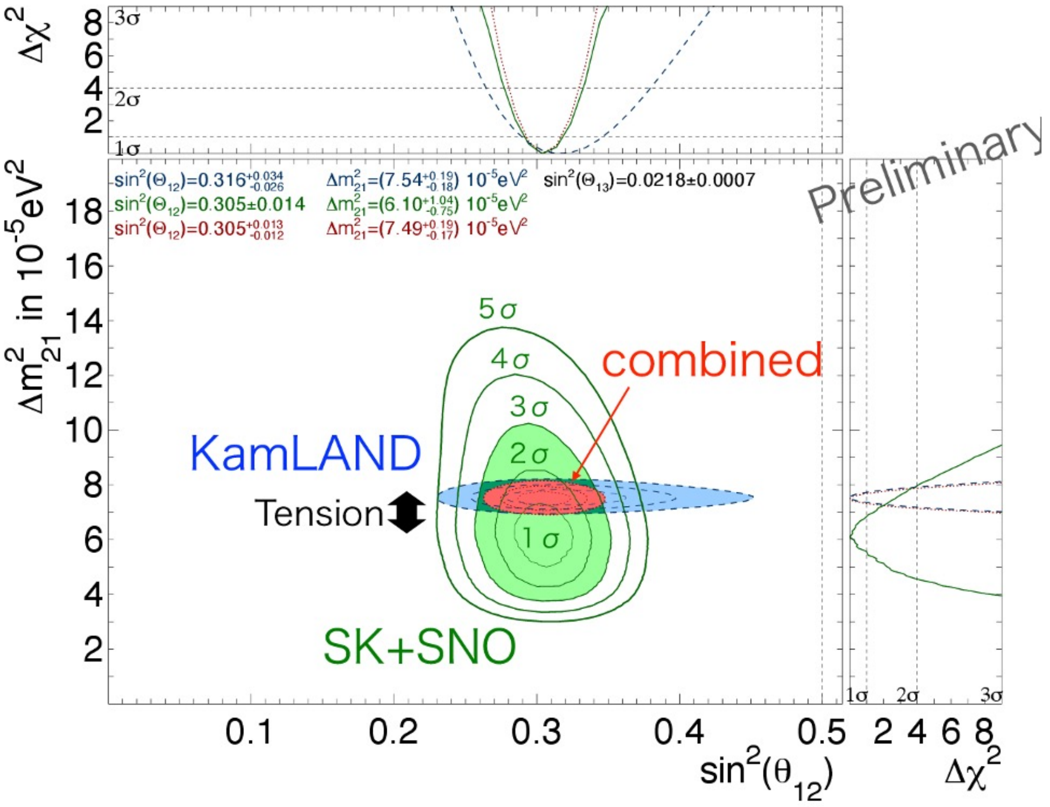
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$

$$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305^{+0.013}_{-0.012}$$

$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$$



$$P^{3\nu}_{ee} \simeq \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right) + \sin^4\theta_{13}$$

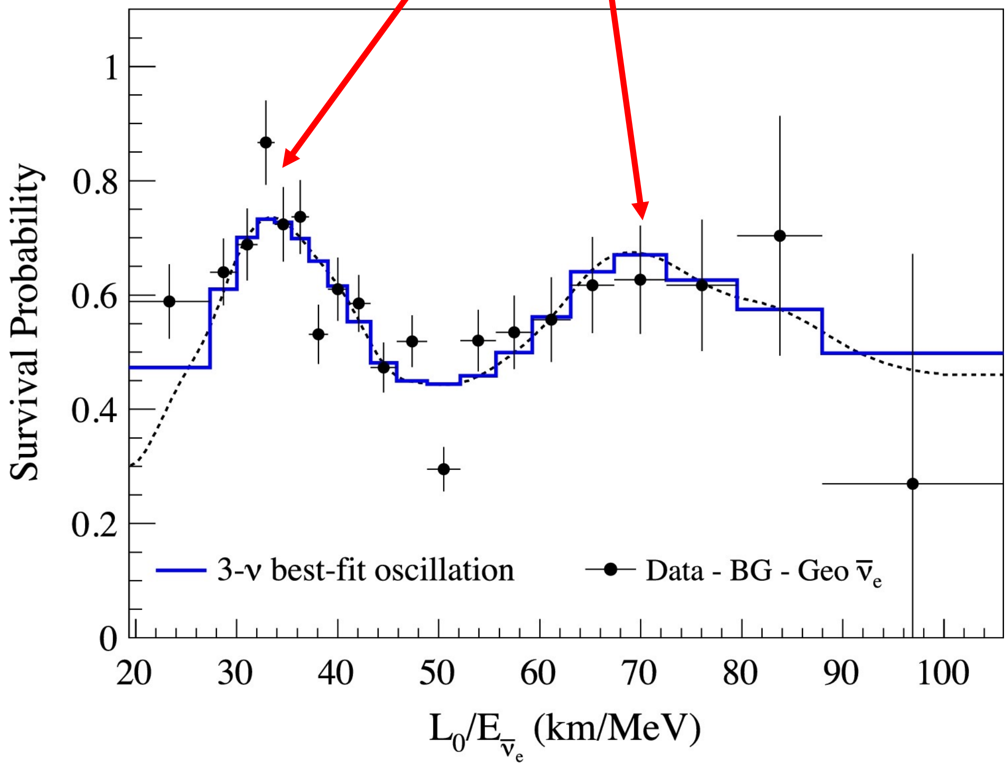
Survival probability L/E variation

L_0 = 180km flux-weighted average reactor distance

Definitely oscillations… alternatives not viable any more.

Expected survival probability for point source at 180km baseline

Oscillations: 1st and 2nd reappearance!



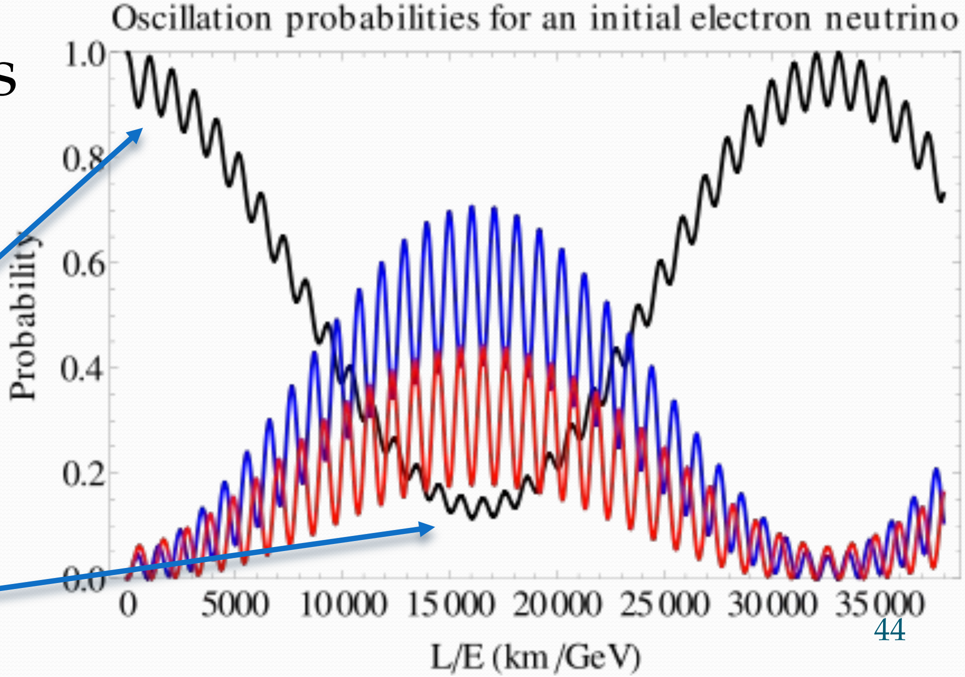
$$P_{ee}^{3\nu} \simeq \cos^4\theta_{13}\left(1-\frac{1}{2}\sin^2 2\theta_{12}\right)+\sin^4\theta_{13}$$

Importance of θ_{13} mixing angle

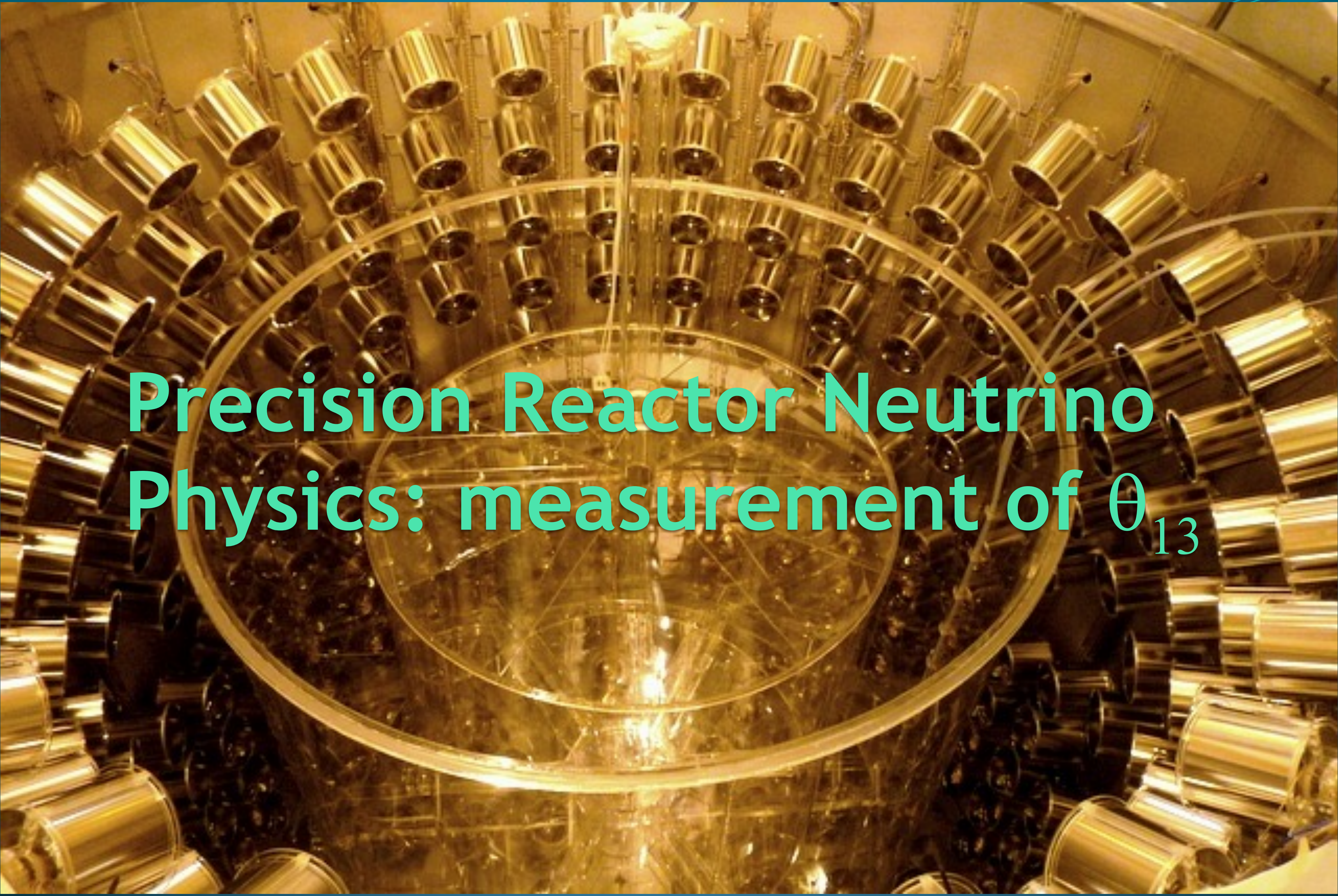
atmospheric $s_{ij} = \sin\theta_{ij}$ $c_{ij} = \cos\theta_{ij}$ solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\theta_{atm}} \underbrace{\begin{pmatrix}c_{13} & 0 & \enclose{circle}{s_{13}e^{i\delta}}\\ 0 & 1 & 0\\ \enclose{circle}{-s_{13}e^{i\delta}} & 0 & c_{13}\end{pmatrix}}_{\theta_{13},\ \delta} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\theta_{sol}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Angle θ_{13} always multiplies δ CP violation phase
- We cannot measure δ CP, until we measure θ_{13}

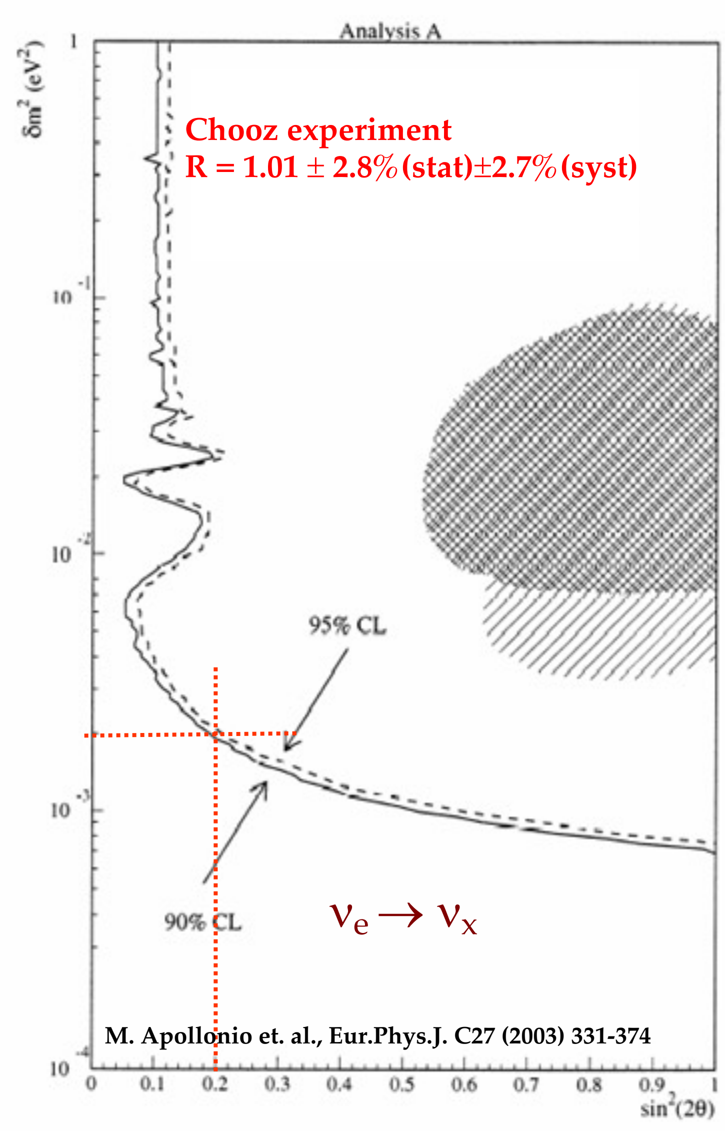


$\Delta m^2_{31}=(2.41\pm0.13)\times10^{-3}$ eV^2
$\Delta m^2_{21}=(7.49\pm0.19)\times10^{-5}$ eV^2



Precision Reactor Neutrino Physics: measurement of θ_{13}

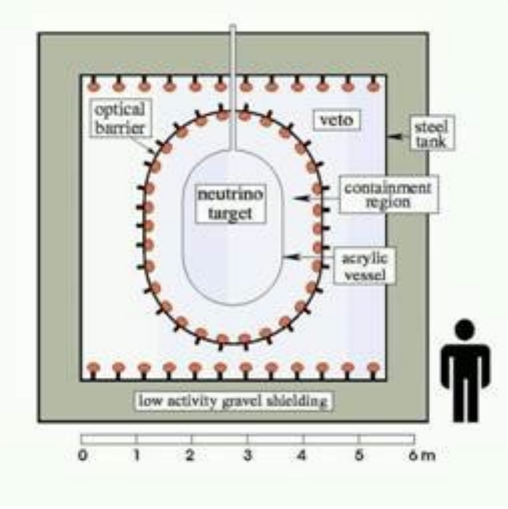
Status Until 2011



Chooz experiment
R = 1.01 ± 2.8% (stat)±2.7% (syst)

$\nu_e \rightarrow \nu_x$

M. Apollonio et. al., Eur.Phys.J. C27 (2003) 331-374



World best constraint:
CHOOZ experiment!

($\nu_e \rightarrow \nu_e$ disappearance exp)

@$\Delta m^2_{atm} = 2\ 10^{-3}$ eV^2

$\sin^2(2\theta_{13}) < 0.15$

(90% C.L)

Challenge: measuring small angles requires excellent control of systematic errors!

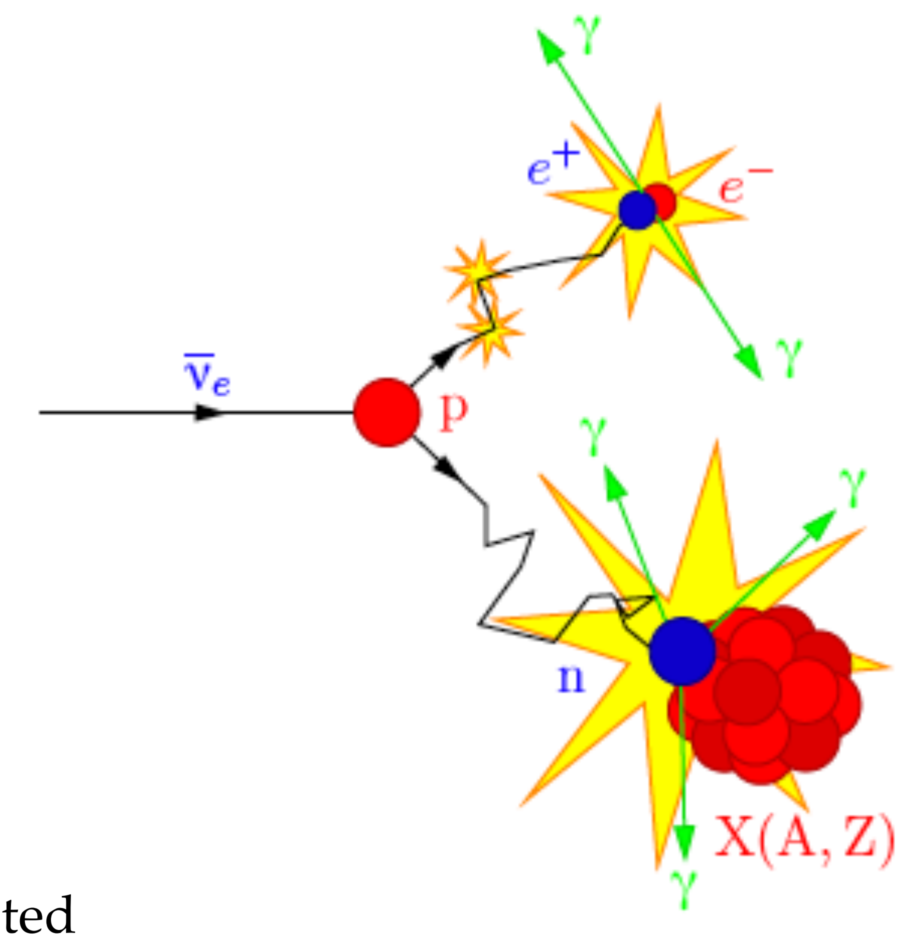
Reactor Neutrino Detection Signature

- Resort to IBD signature for neutrino detection

inverse- β decay $(\bar{\nu}_e + p \longrightarrow e^+ + n)$

$\mathbf{Gd}^{\,-} + \sum \cdot \gamma$

$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806\ MeV$$



Distinctive two-step signature:

-prompt event

Photons from e^+ annihilation

$E_e = E_\nu + 0.8\ \text{MeV} + O(E_e/m_n)$

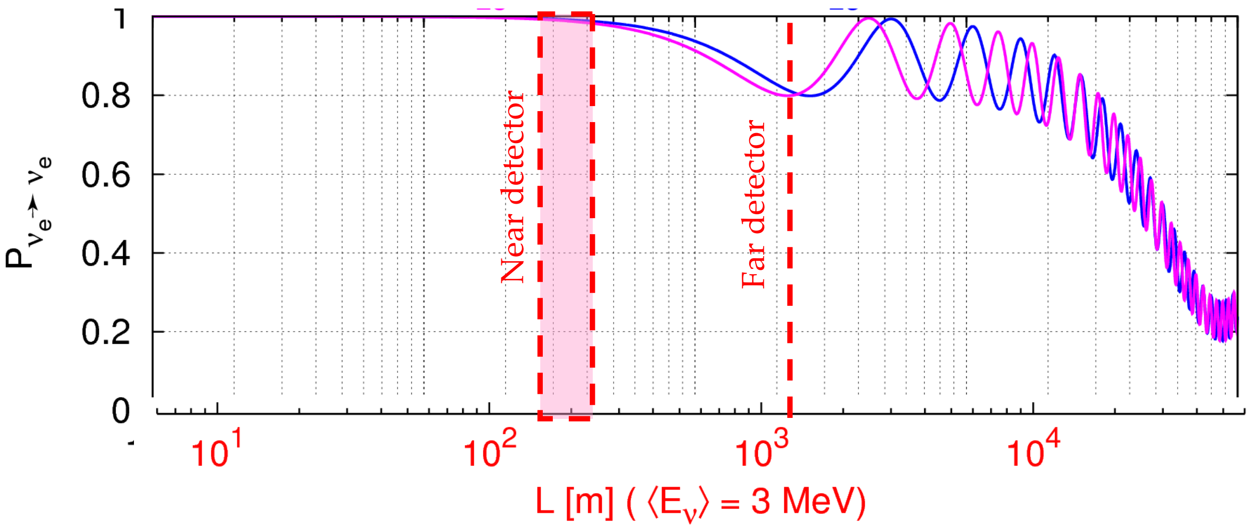
-delayed event

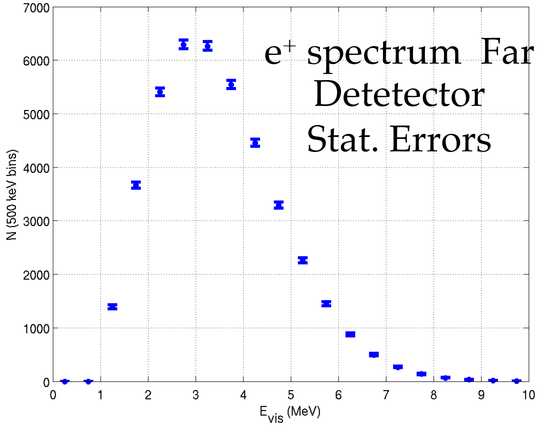
Photons from n capture on dedicated nuclei (Gd)

Δt ~ 30 μs E ~ 8 MeV

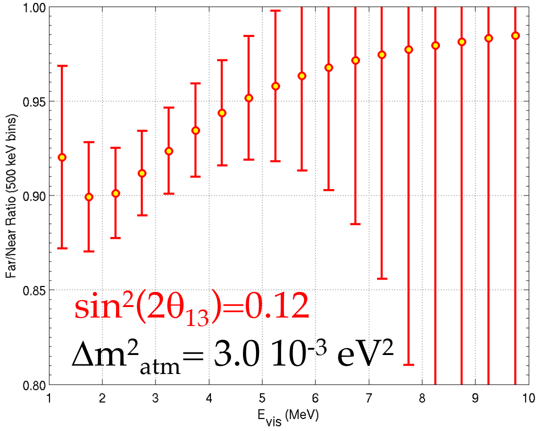
The - New - Concept

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{13})\,\sin^2(\Delta m^2_{31} L/4E)$$



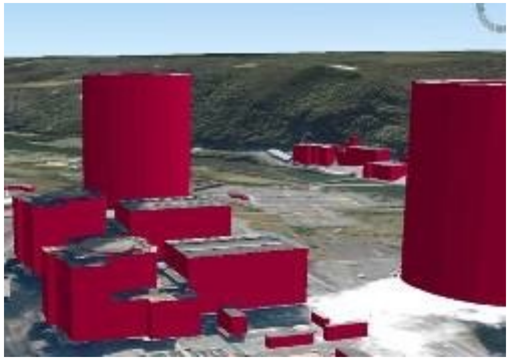


Far/Near ratio



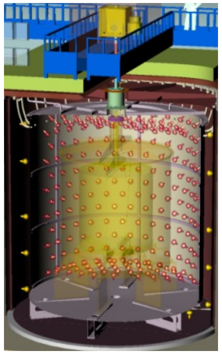
$\sin^2(2\theta_{13})=0.12$

$\Delta m^2_{atm} = 3.0\ 10^{-3}\ \mathrm{eV}^2$



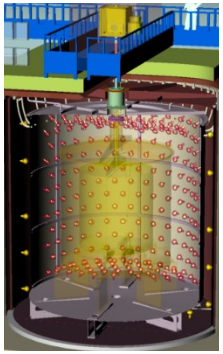
Nuclear Power Station

$\bar{\nu}_e$



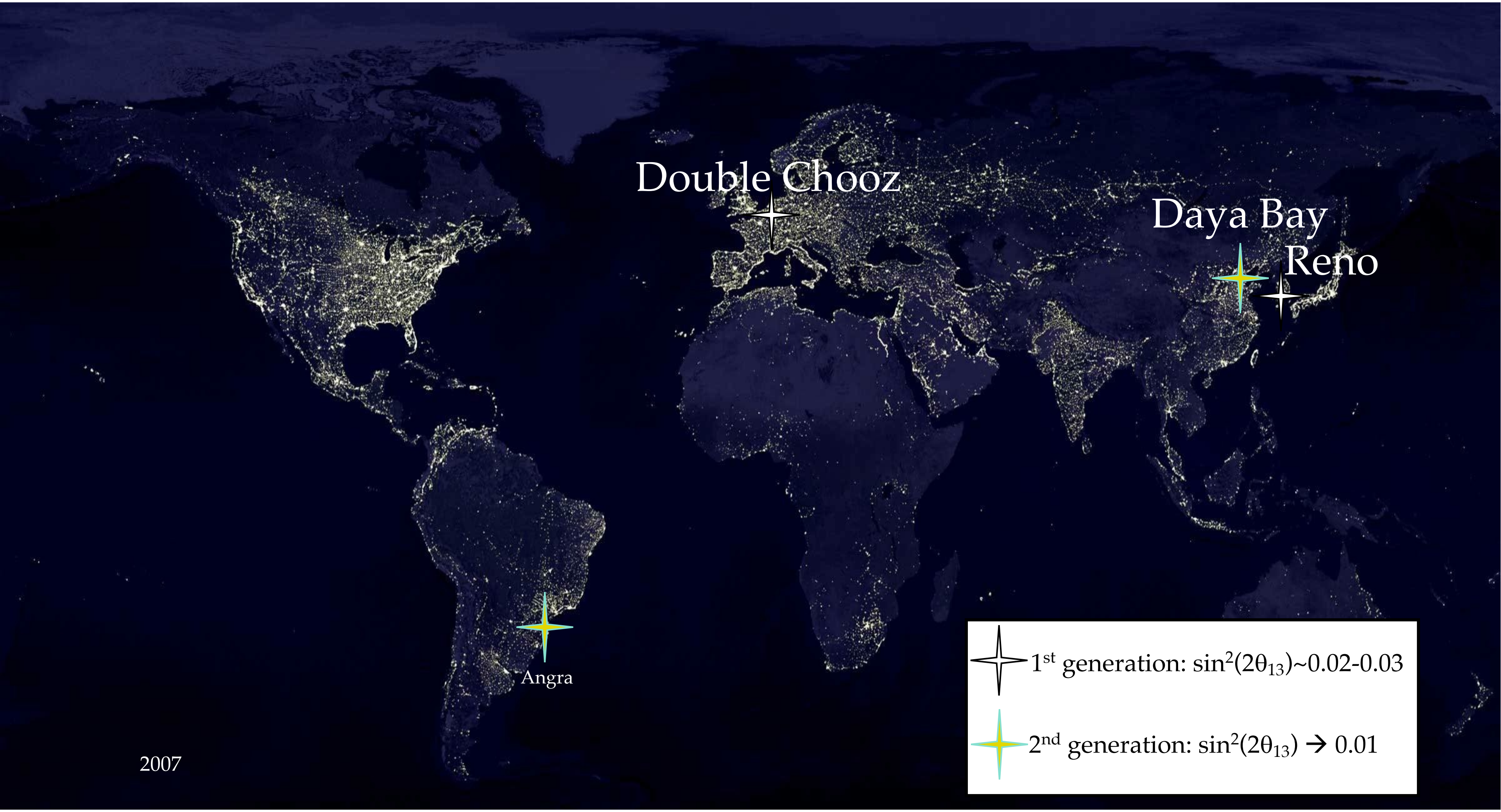
Near detector
400 m

$\bar{\nu}_{e,\mu,\tau}$



Far detector
1050 m

Looking for Sites



Double Chooz

- France
- Spain
- Germany
- U.S.A
- Japan
- Russia
- Brazil
- U.K.

http://doublechooz.in2p3.fr/

Courtesy of T. Lasserre

Improving CHOOZ ?

CHOOZ : $R_{osc} = 1.01 \pm 2.8\%$ (stat) $\pm$ 2.7% (syst)

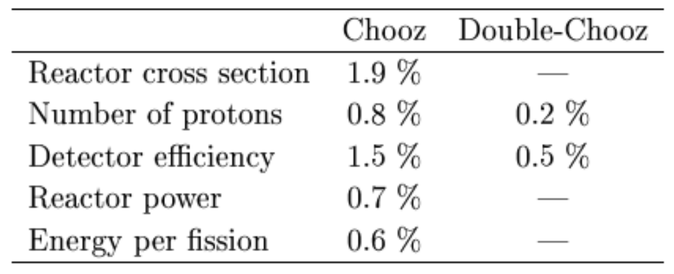
- Statistics
  - More powerful reactor (multi-core)
  - Larger detection volume
  - Longer exposure

	CHOOZ	**Double-Chooz**
Target volume	5,55 m^3	10,2 m^3
Target composition	6,77 10^{28} H/m^3	6,82 10^{28} H/m^3
Data taking period	Few months	3-5 years
Event rate	2700	Far: 60 000/3 y Near: ~3 10^6/3 y
Statistical error	2,7%	0,5%

→ Luminosity increase L = Δt x P(GW) x Np

- Experimental error: ν flux and cross-section uncertainty
  - Multi-detector
  - Identical detectors to reduce inter-detector systematics (goal: towards $\sigma_{relative}$~0,6%)

- Background
  - Improve detector design — larger S/B
  - Increase overburden
  - Improve bkg knowledge by direct measurement
  - subtraction error<1%

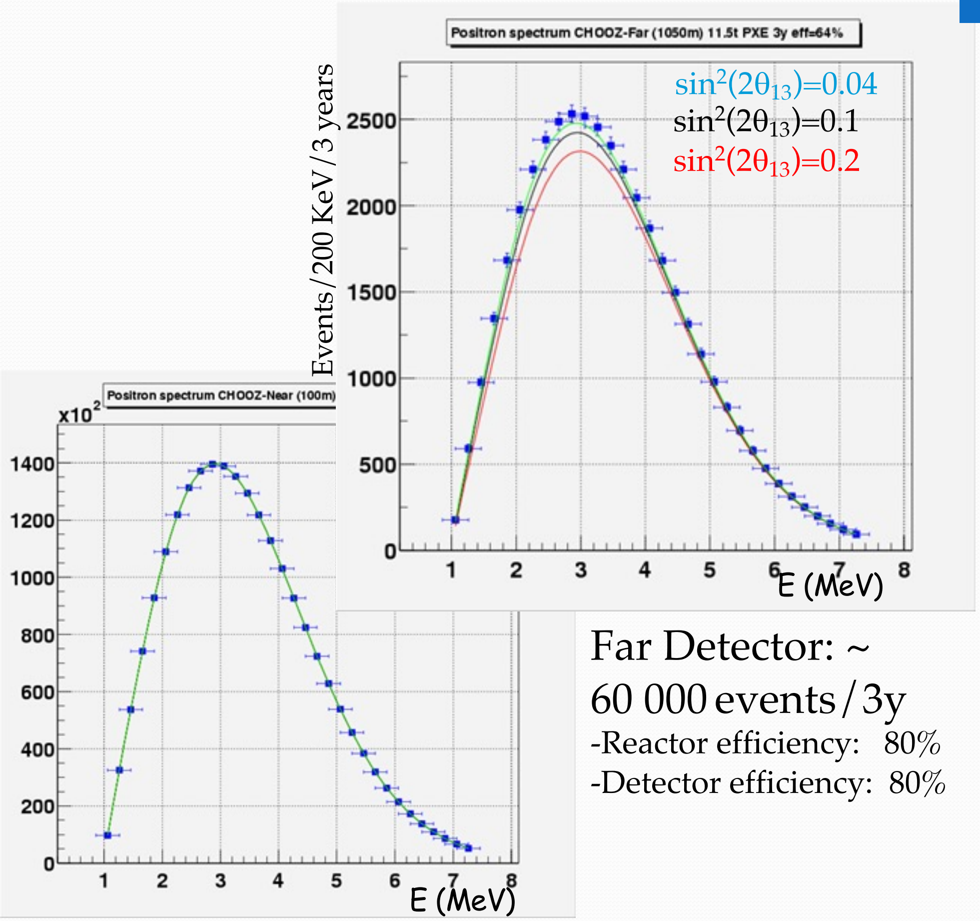


	Chooz	Double-Chooz
Reactor cross section	1.9 %	—
Number of protons	0.8 %	0.2 %
Detector efficiency	1.5 %	0.5 %
Reactor power	0.7 %	—
Energy per fission	0.6 %	—

θ_{13} at Reactors

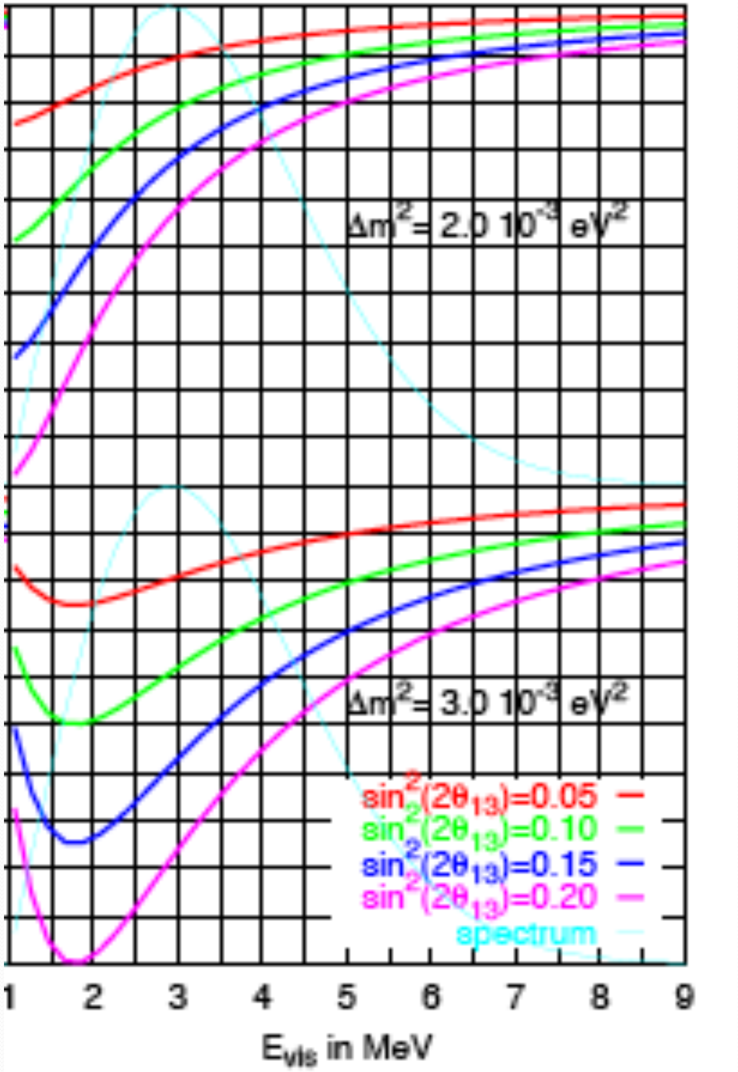
Two independent sets of information: Normalisation + Spectrum distortion

$\Delta m^2_{atm} = 2.0\ 10^{-3}\ eV^2$



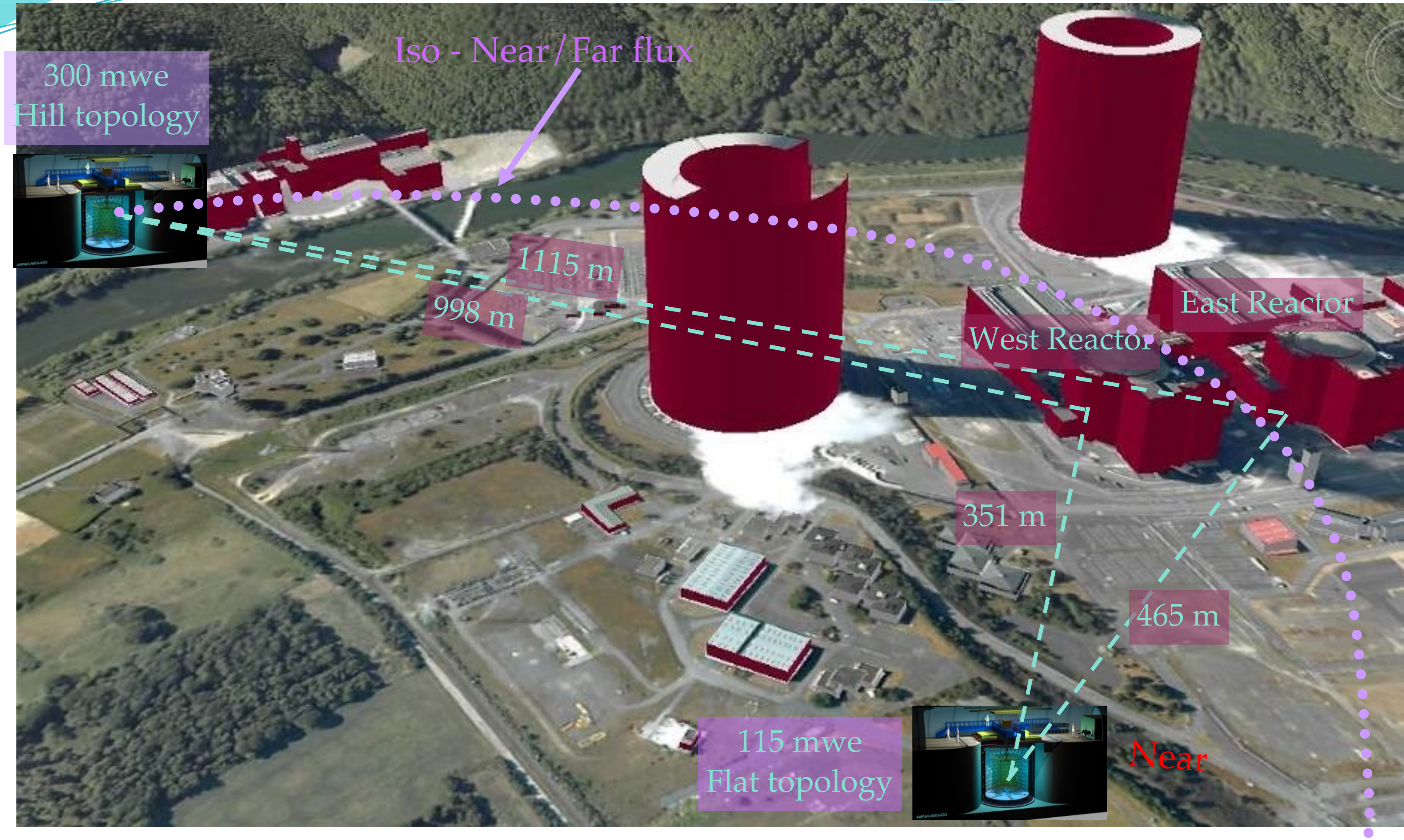
Far Detector: ~ 60 000 events/3y
-Reactor efficiency: 80%
-Detector efficiency: 80%

Near Detector: ~ 3 10^6 events/3y
-Reactor efficiency: 80%
-Detector efficiency: 80%
-Dead time: 50%



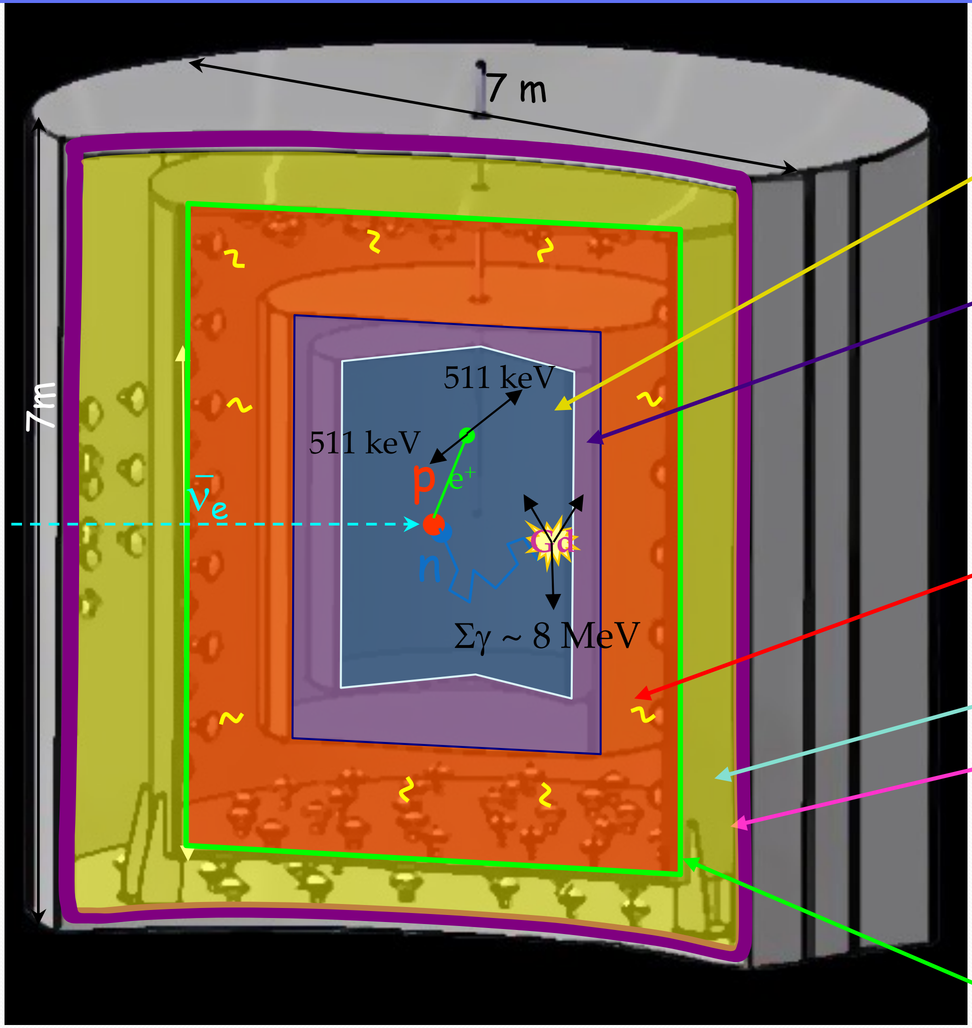
Double Chooz Detector Overview

Site in French Ardennes



The detector design – Onion-like

Muon Outer-VETO:



ν-target: 80% dodecane + 20% PXE + 0.1% Gd
Volume for ν-interaction

γ-catcher: 80% dodecane + 20% PXE
Extra-volume for ν-interaction

Acrylic vessels → «hardware» definition of fiducial volume

Non-scintillating buffer: same liquid (+ quencher?) Isolate PMTs from target area

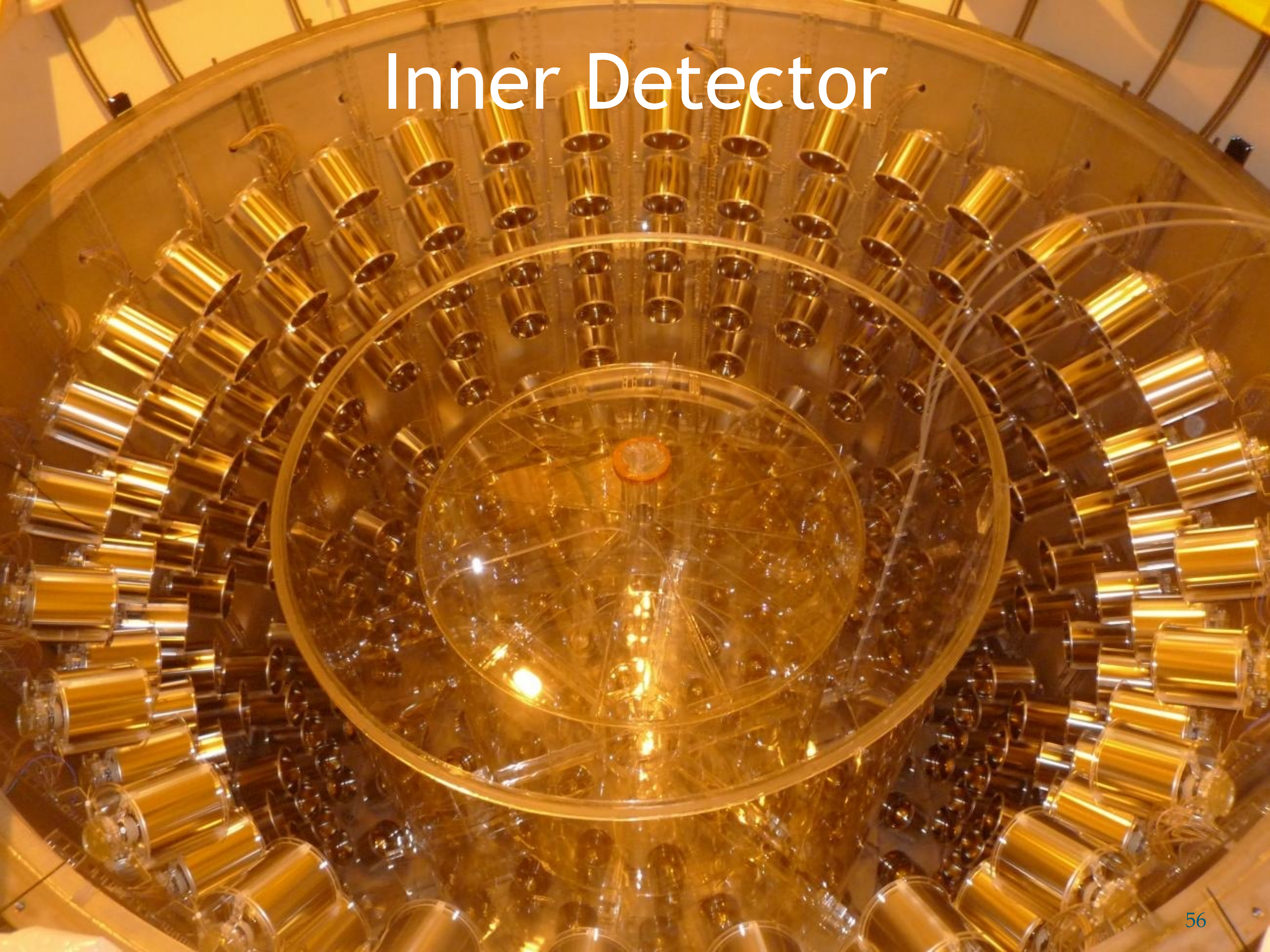
Muon Inner-VETO: scintillating oil

Shielding: steel 17 cm: >7λ(γ).

→ Improved background reduction

PMT support structure: steel tank, optical insulation target/veto

Inner Detector



Inner Detector Lid

Outer Muon Veto Installation

Background in Double Chooz – same types as Kamland

Accidental bkg:

- e^+-like signal: radioactivity from materials, PMTs, surrounding rock Rate=R_e
- n signal: n from cosmic μ spallation, thermalized in detector and

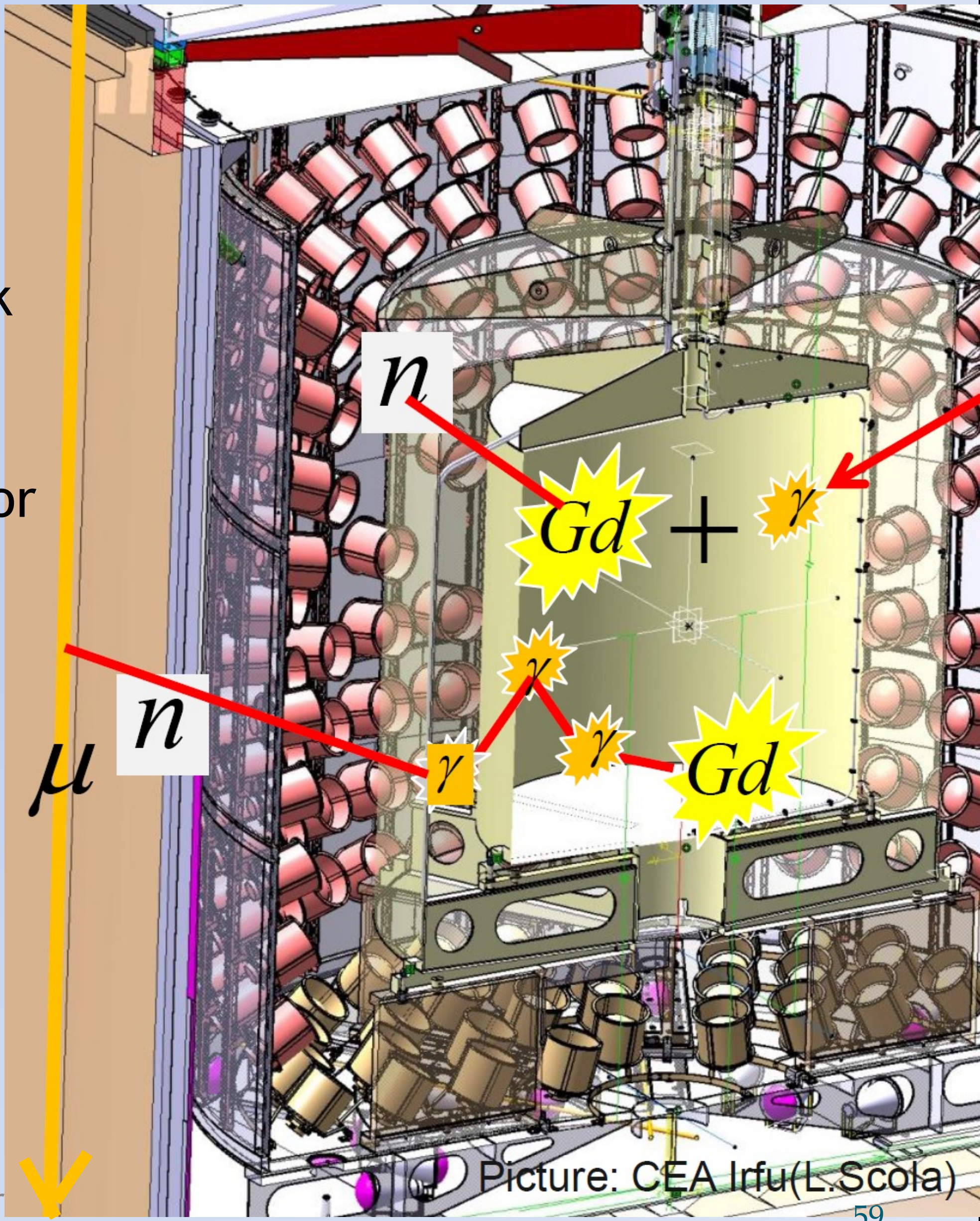
  captured on Gd (R_n)

$\Rightarrow$ Accidental coincidence

Rate = $R_e \times R_n \times \Delta t$

Correlated bkg:

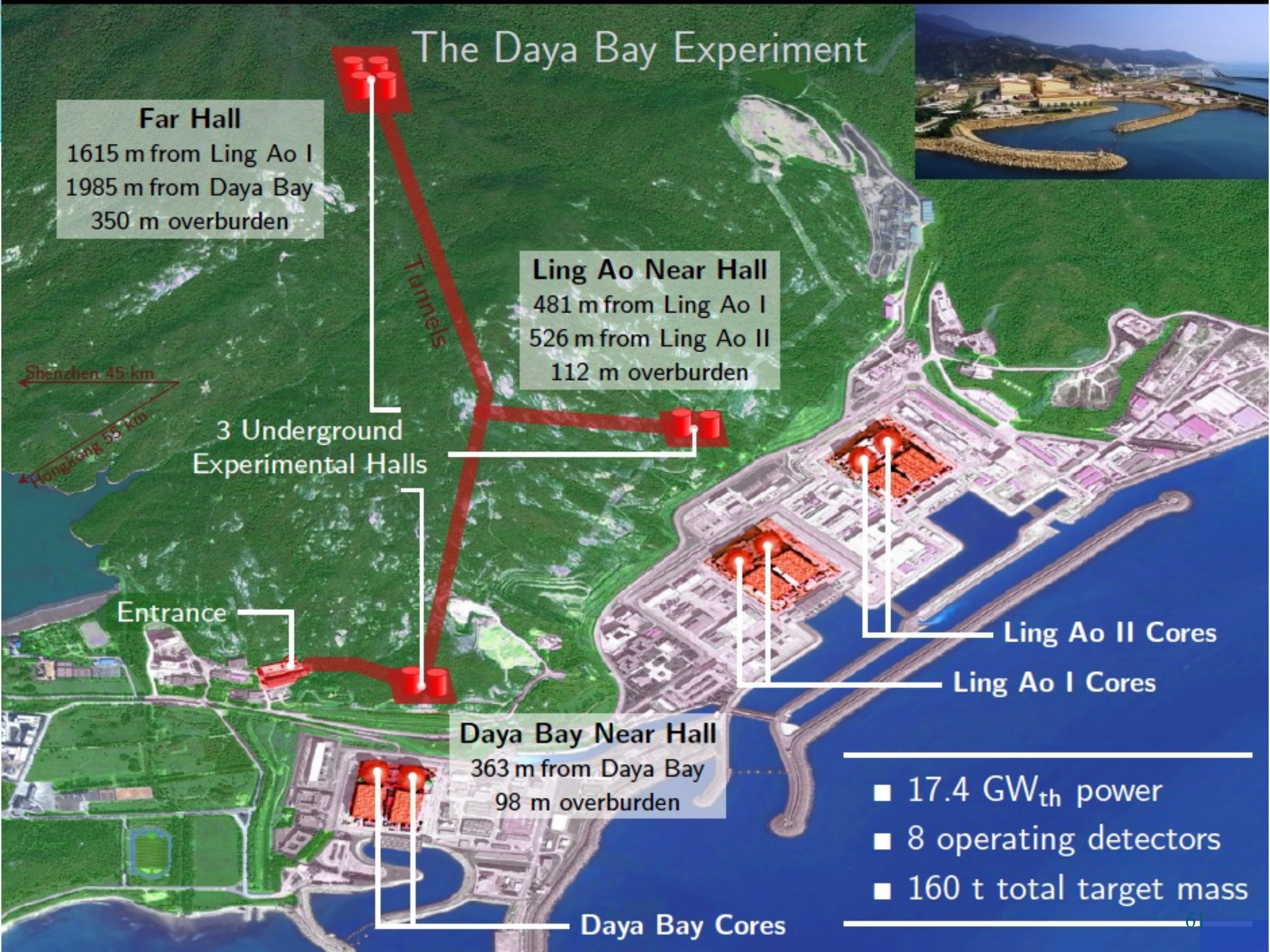
- fast n (by cosmic μ) recoil on p (low energy) and captured on Gd
- long-lived (^{9}Li, ^{8}He) β-decaying isotopes induced by μ



Picture: CEA Irfu(L.Scola)

Multi Detector Measurement of θ_{13} with Multiple Detectors in Daya Bay

The Daya Bay Experiment



- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass

Detectors

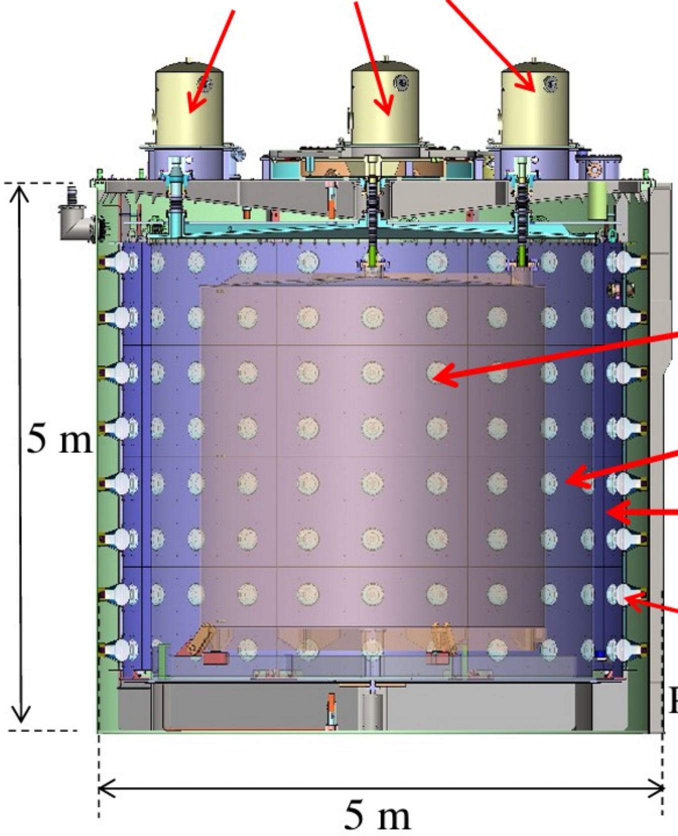
- Detect inverse β-decay reaction (IBD):

$$\bar{\nu}_e + p \to \overset{\text{prompt}}{e^+} + \overset{\text{delayed}}{n}$$

$\xrightarrow{\sim 180\ \mu s}$ $+ p \to d + \gamma$ (2.2 MeV)

$\xrightarrow{\sim 30\ \mu s \text{ for } 0.1\%\ \text{Gd}}$ $+ \text{Gd} \to \text{Gd}^*$

↳ $\text{Gd} + \gamma\text{'s}$ (~8 MeV)



Automated Calibration units (LED, ^{68}Ge, AmC-Co)

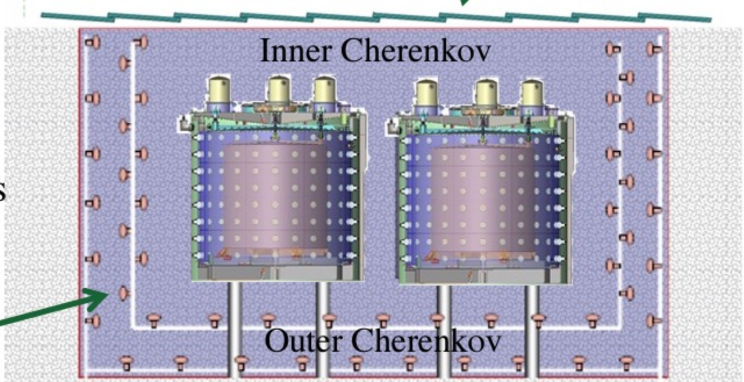
20-t 0.1% Gd-loaded liquid scintillator (target)

22-t LS (gamma catcher)
(LS = LAB + 3 g/l PPO + 15 mg/l Bis-MSB)

40-t mineral oil shield

192 Photomultiplier tubes (PMTs)

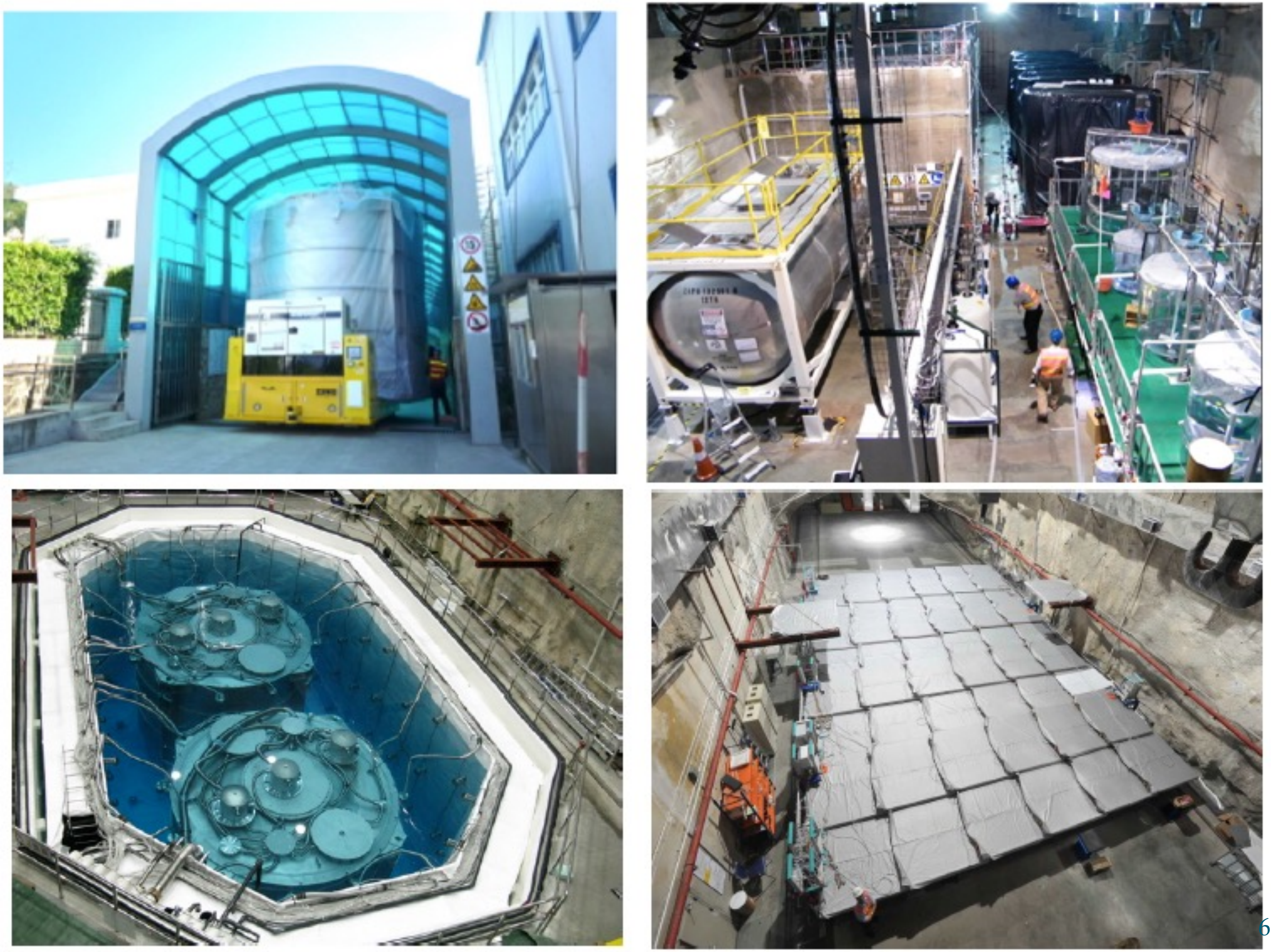
Four layers of RPC's to tag muons



2.5-m water:
- Attenuates gamma rays & neutrons
- Forms two optically decoupled Cherenkov counters

NIM A**773** (2015) 8
NIM A**811** (2016) 133

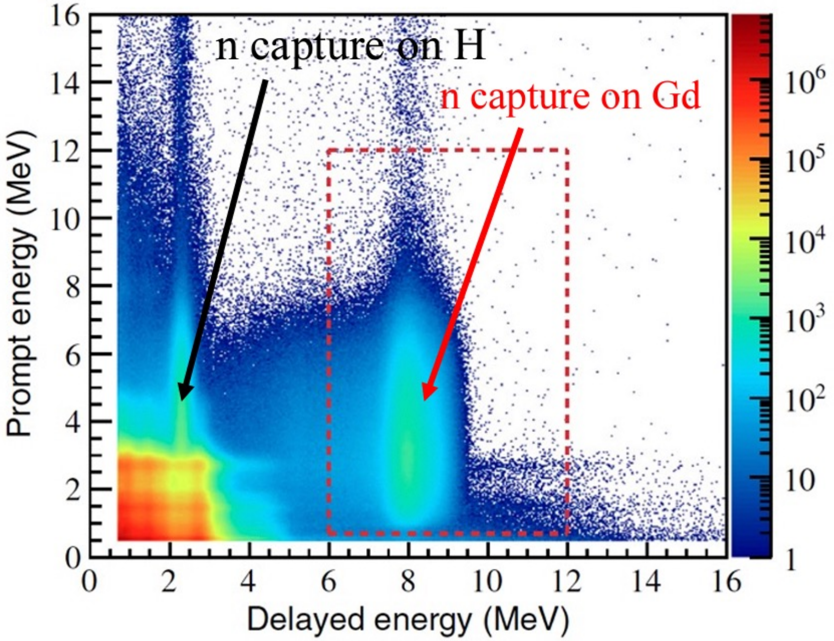
Antineutrino Detector Installation



Selection of $\overline{\nu}_e$ Candidates

PRD**95** (2017) 072006

- Remove flashing PMT events
- Veto muon events
- Require $0.7\ \mathrm{MeV} < E_{\mathrm{prompt}} < 12\ \mathrm{MeV}$, $6\ \mathrm{MeV} < E_{\mathrm{delayed}} < 12\ \mathrm{MeV}$
- Neutron capture time: $1\ \mu\mathrm{s} < \Delta t < 200\ \mu\mathrm{s}$
- Multiplicity cut: select time-isolated energy pairs



Detection efficiencies

	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%

Daya Bay 2011 - 2020

- Statistics of nGd data:

Year	Calendar days	EH1	EH2	EH3	Total IBD's
2018 (PRL **121**, 241805)	1958	1,794,417	1,673,907	495,421	3,963,745
2022	3158	2,236,810	2,544,894	764,414	5,546,118

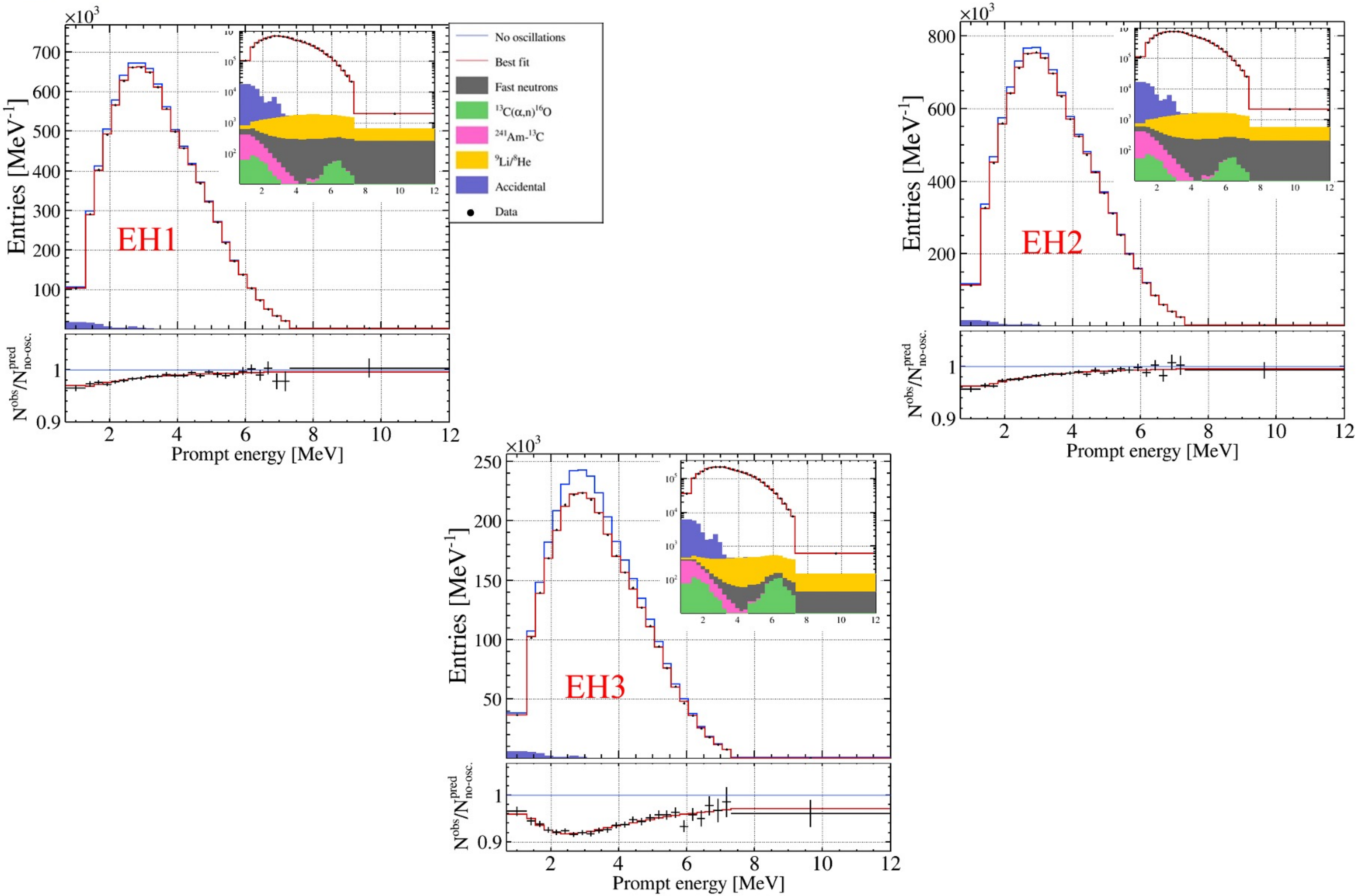
- Analysis:
  - Energy calibration
    - Electronics non-linearity calibrated at the channel-by-channel level
    - Improved non-uniformity correction
  - New correlated background after 2017
    - Remove additional very rare PMT flashers
    - Suppress and identify untagged muon events
  - Correlated background
    - New approach for determining the ^{9}Li/^{8}He background

Background

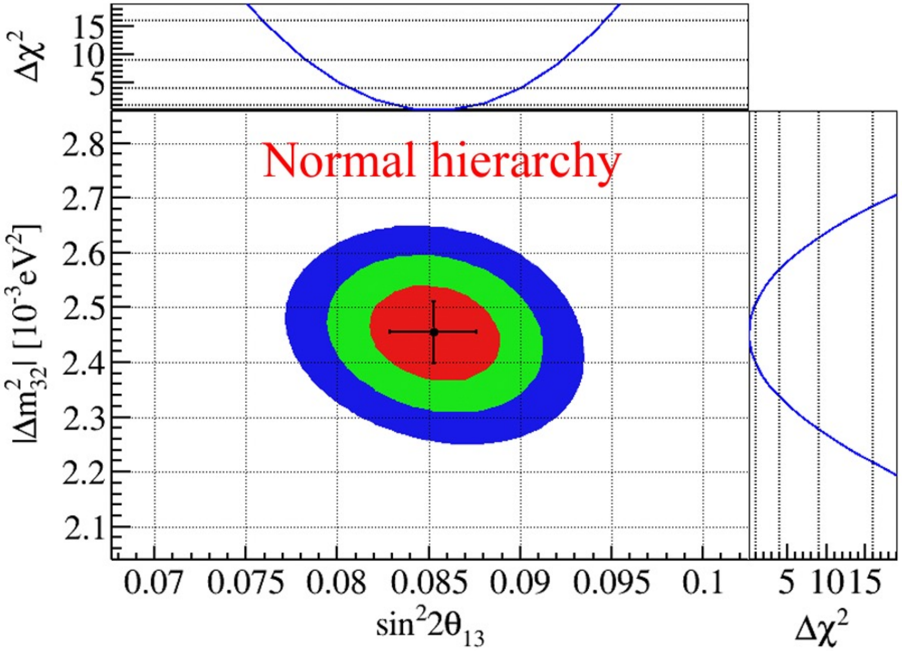
- Uncorrelated background
  - Accidental
- Correlated background
  - Fast neutron
    - produced outside of the AD but enters the active volume of the AD
  - ^{9}Li/^{8}He
    - spallation product produced by cosmic-ray muons inside the AD
  - ^{241}Am-^{13}C
    - neutron calibration source resides inside the ACU
  - $^{13}C(\alpha,n)^{16}O$
    - α from decay of natural radioactive isotope in the liquid scintillator
  - Residual PMT flasher
  - Muon-x

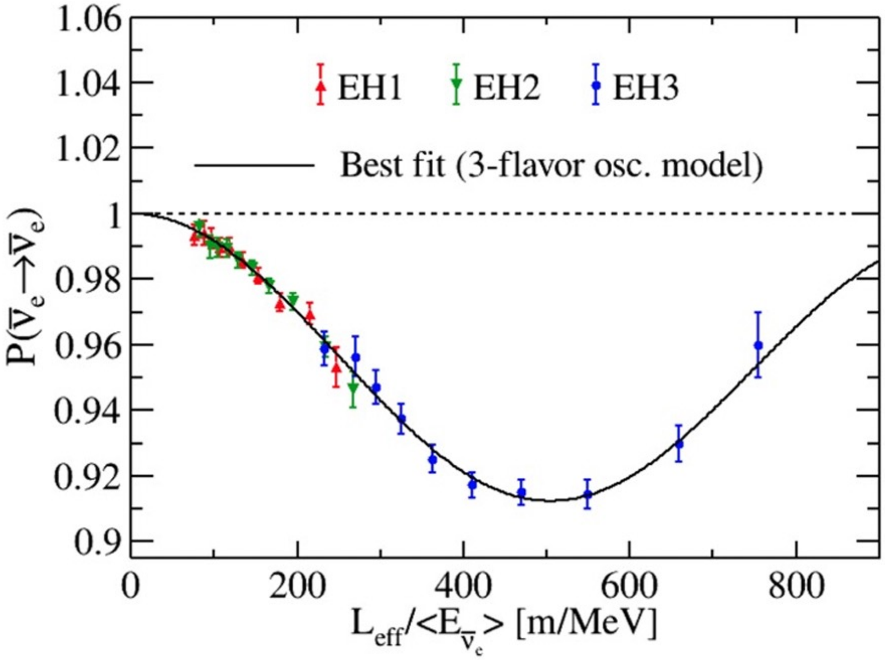
$\left.\begin{matrix}\text{Residual PMT flasher}\\ \text{Muon-x}\end{matrix}\right\}$ new background

Prompt-energy Spectra



$\sin^2 2\theta_{13}$ and Δm^2_{32}





Best-fit results: $\chi^2/\text{ndf} = 559/518$

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$

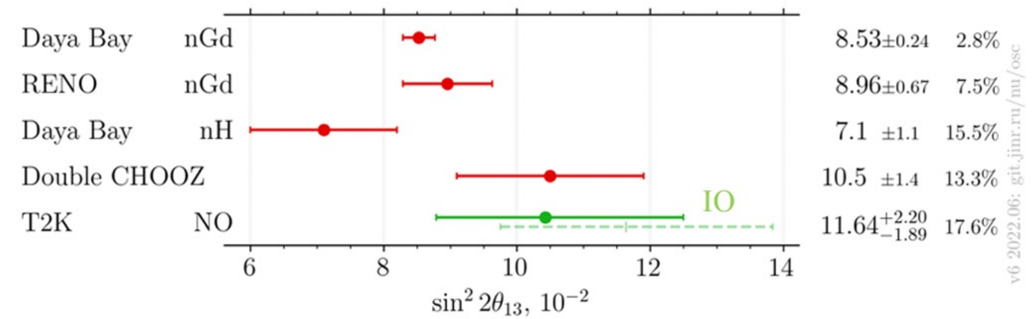
Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$

(2.3% precision)

Present Global Landscape

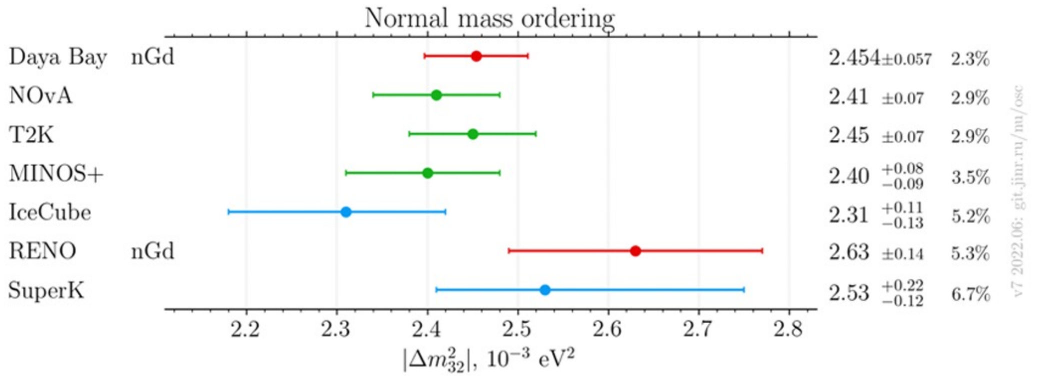
Compare Daya Bay's current results with published results

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

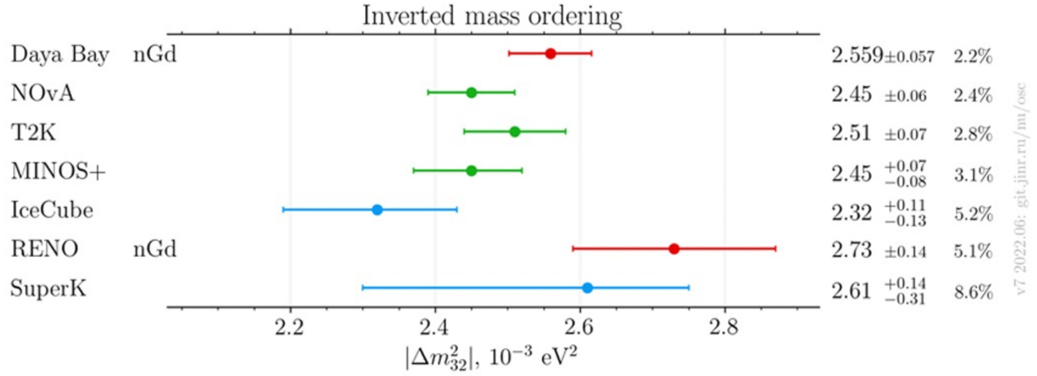


Will likely be the best measurement in the foreseeable future

Δm^2_{32} (NO)



Δm^2_{32} (IO)

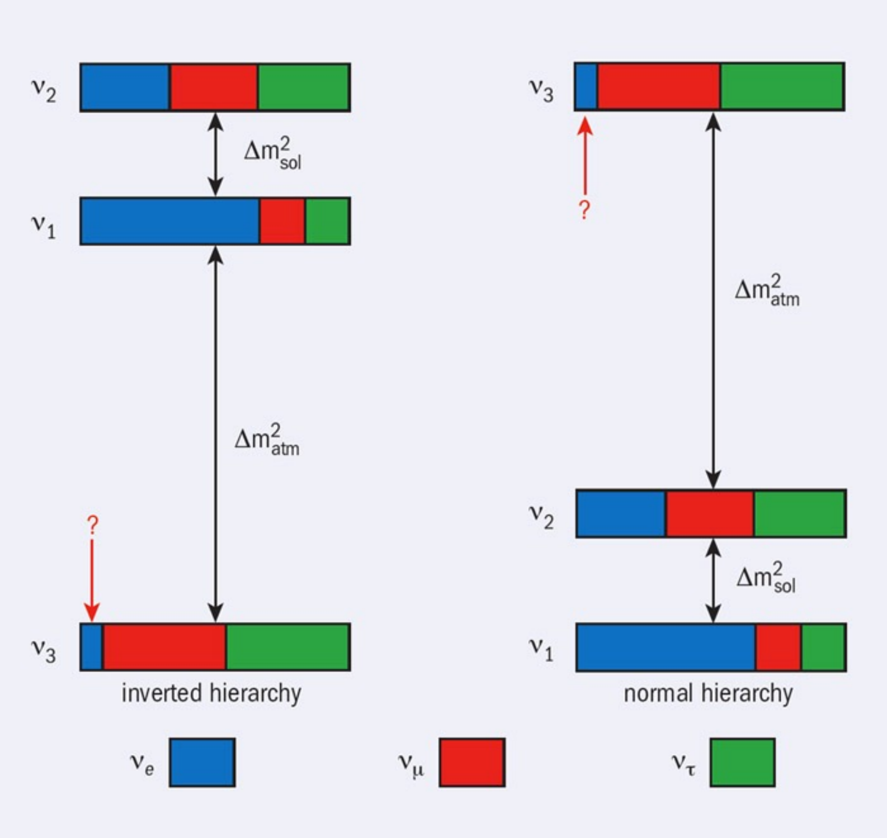


Conclusion on neutrino oscillations and open questions

- With precise measurement of θ_{13} all neutrino oscillation parameters are well known.

- Open questions in neutrino oscillations:
  - neutrino mass ordering → will be measured with accelerators (5 σ) and JUNO reactor experiment (3 σ)
  - CP violation phase in leptons → requires neutrino appearance measurement with accelerator neutrinos (T2K, NOvA → running, DUNE, HyperK → future)

Neutrino Mass Ordering (MO)



Measuring MO with Reactor Neutrinos

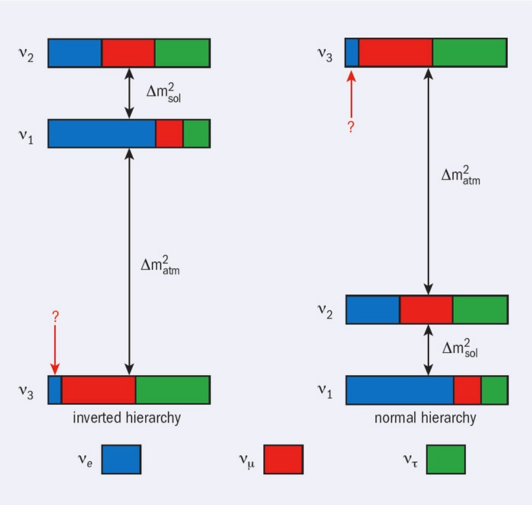
- Originally proposed in 2008 by J.G. Learned et al (arXiv:hep-ex/0612022)
- Requires ~ 10 kton detector at 50 – 64 km from reactor with excellent energy resolution ~3%
- Full 3 flavor survival rate of electron antineutrinos:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\Delta_{ij} = 1.27(|\delta m^2_{ji}|L)/E_\nu$$

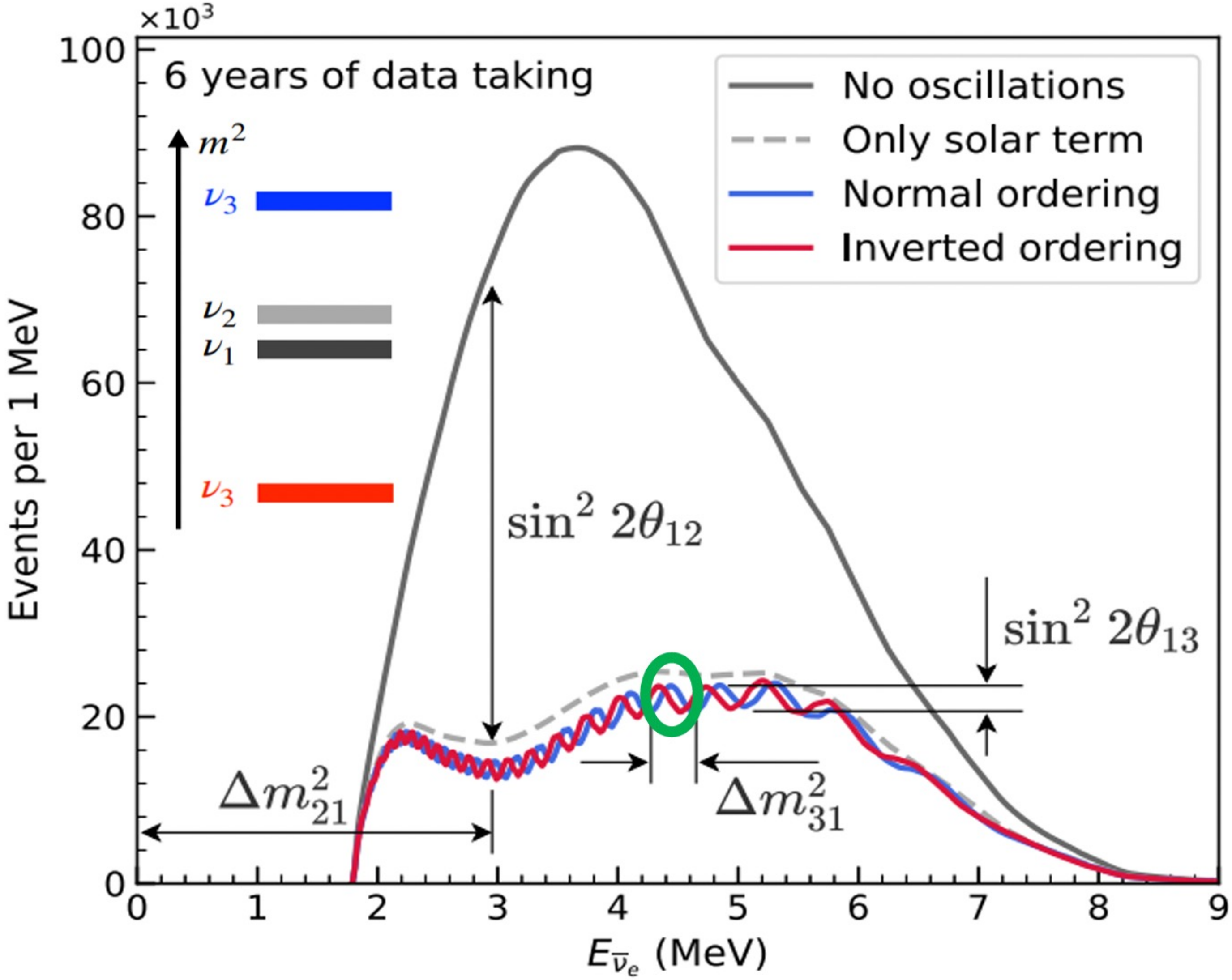
$$\overbrace{|\delta m^2_{32}| > |\delta m^2_{31}|}^{\textbf{IO}} \qquad \overbrace{|\delta m^2_{31}| > |\delta m^2_{32}|}^{\textbf{NO}}$$

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



ν JUNO Expected MO Measurement

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$



JUNO – Reactor Neutrino Experiment to Measure Neutrino Mass Ordering

Jiangmen Underground Neutrino Observatory

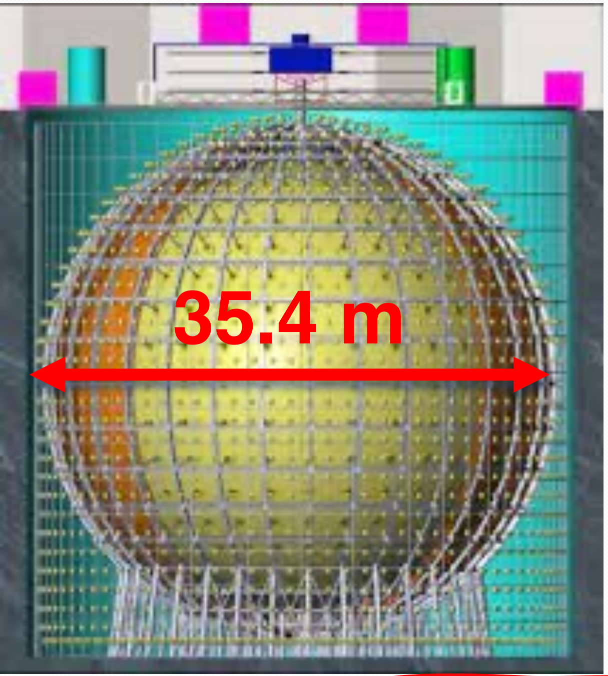
Vertical tunnel: 563 m

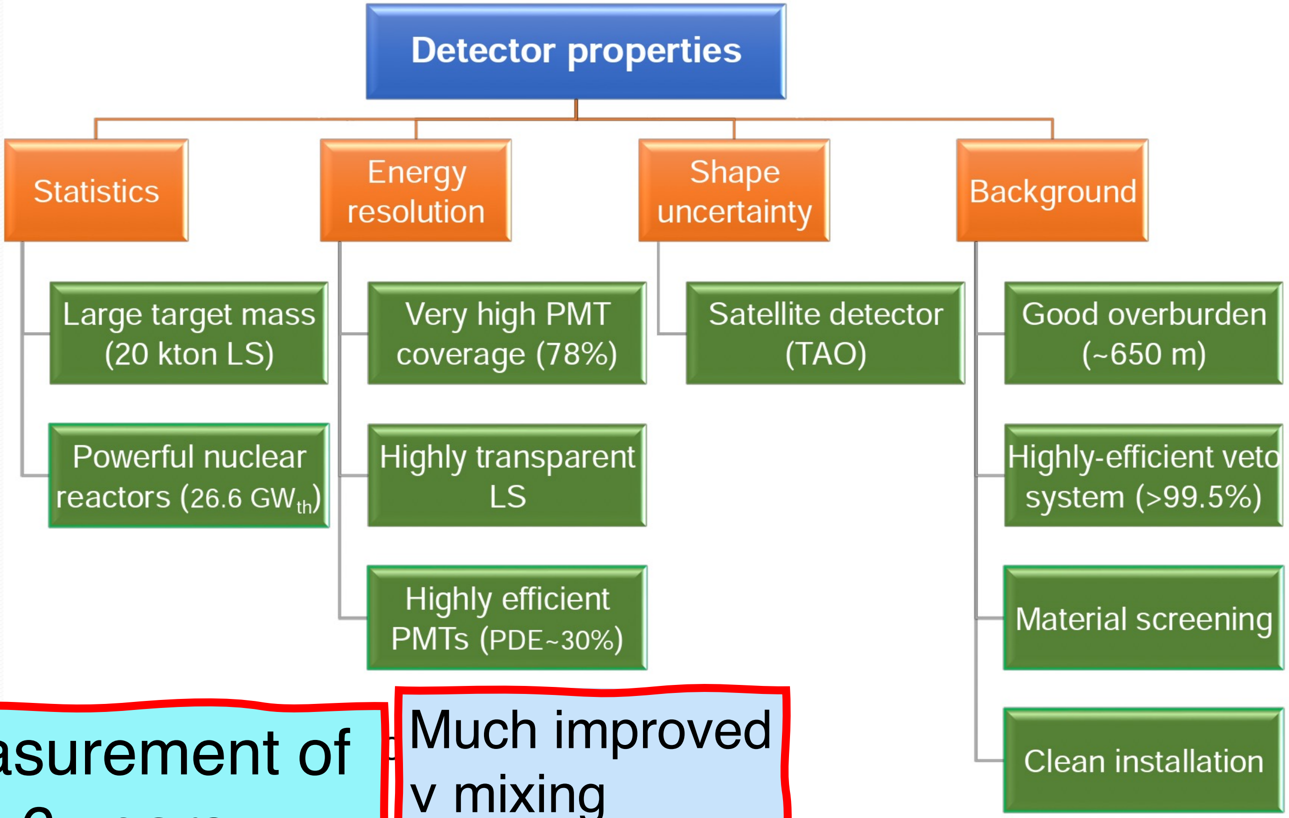
Overburden ~650 m (1800 m.w.e.)

Slope tunnel: 1265 m @ slope of 42%

Civil construction finished in Dec, 2021

JUNO Detector and Sensitivity





Detector properties

- Statistics
  - Large target mass (20 kton LS)
  - Powerful nuclear reactors (26.6 GW_{th})
- Energy resolution
  - Very high PMT coverage (78%)
  - Highly transparent LS
  - Highly efficient PMTs (PDE~30%)
- Shape uncertainty
  - Satellite detector (TAO)
- Background
  - Good overburden (~650 m)
  - Highly-efficient veto system (>99.5%)
  - Material screening
  - Clean installation

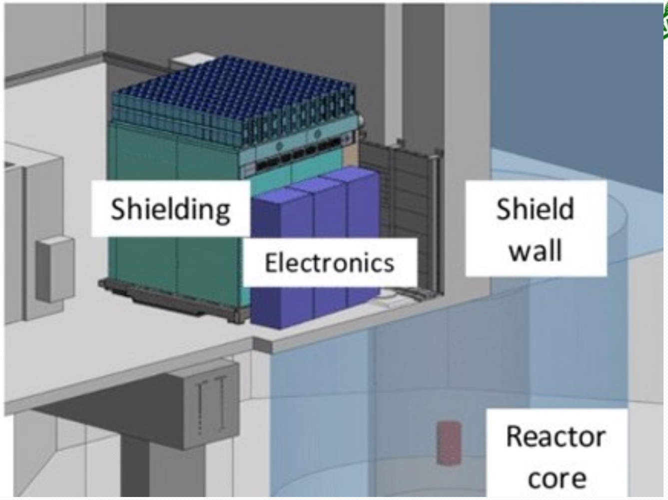
3 σ measurement of ν MO in 6 years

Much improved ν mixing parameters

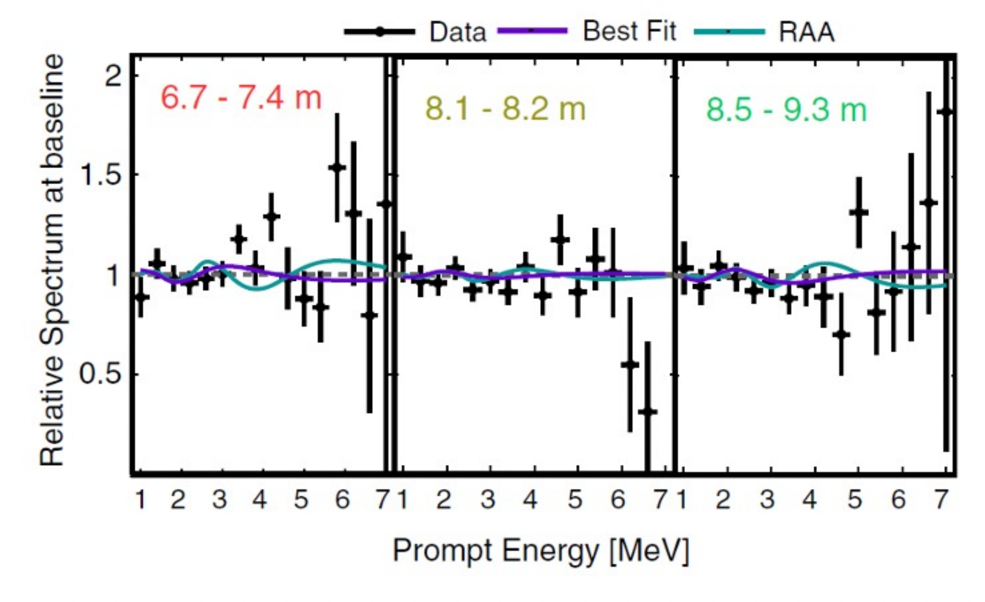
	Central Value	PDG2020	100 days	6 years
Δm^2_{31} $(\times 10^{-3}\ \mathrm{eV}^2)$	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)
Δm^2_{21} $(\times 10^{-5}\ \mathrm{eV}^2)$	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)

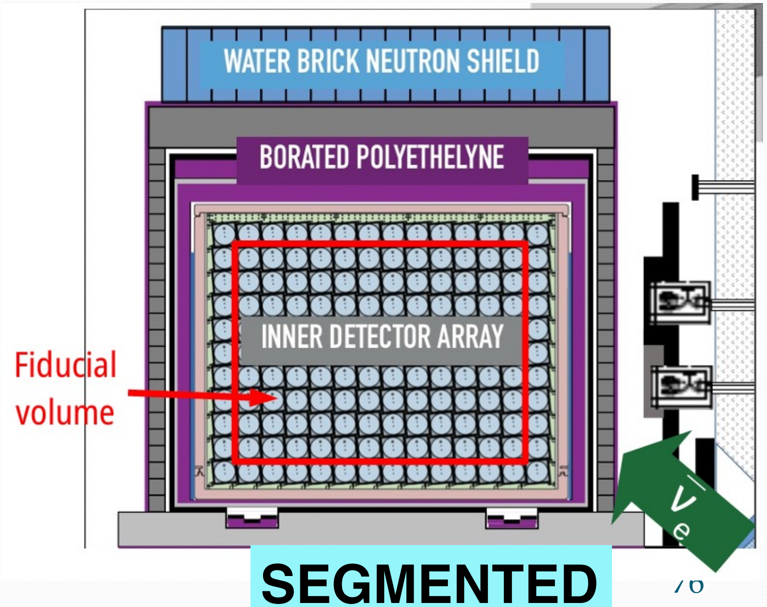
Sterile Neutrino Search with Reactor Neutrinos

- Search for sterile neutrino oscillations (PROSPECT, STEREO, Solid, Neutrino-4) at **distance of few m from reactor core**
  - Proposed sterile neutrinos are “heavy” → oscillate few m from reactor core
  - Ton scale detectors
  - Sterile neutrinos mostly excluded in 1-5 eV^2 mass region at 3σ level.



6.7 m – 9.2 m baseline





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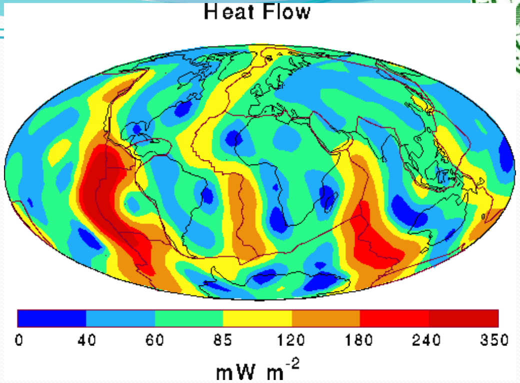
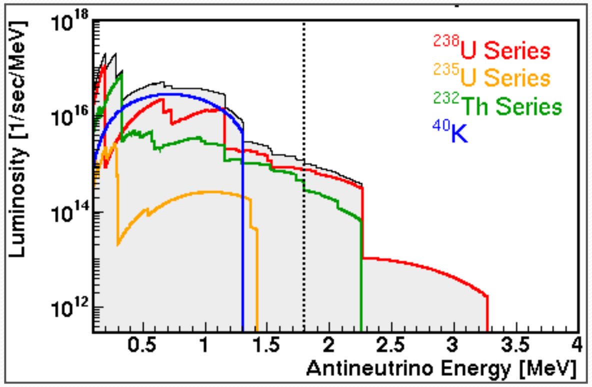
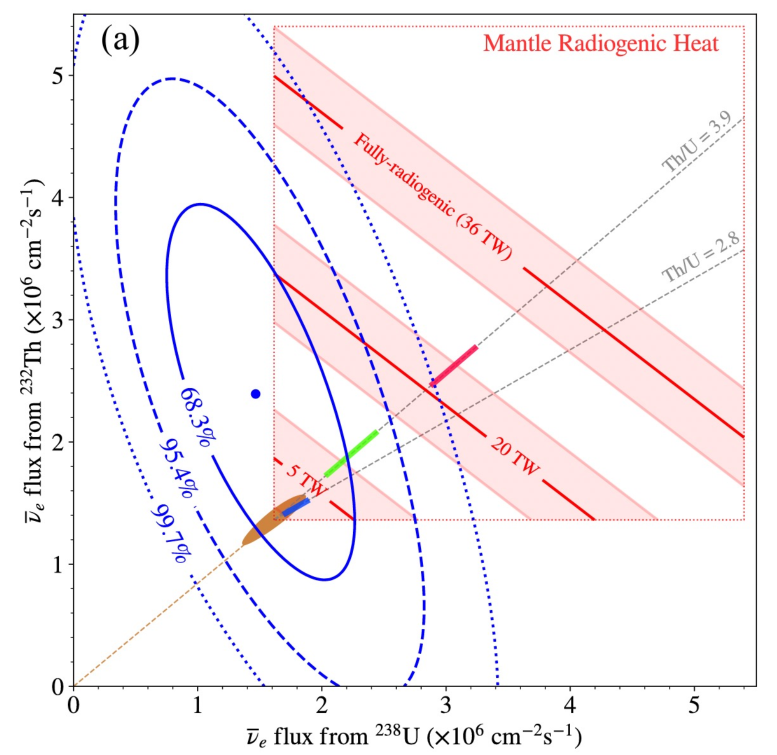
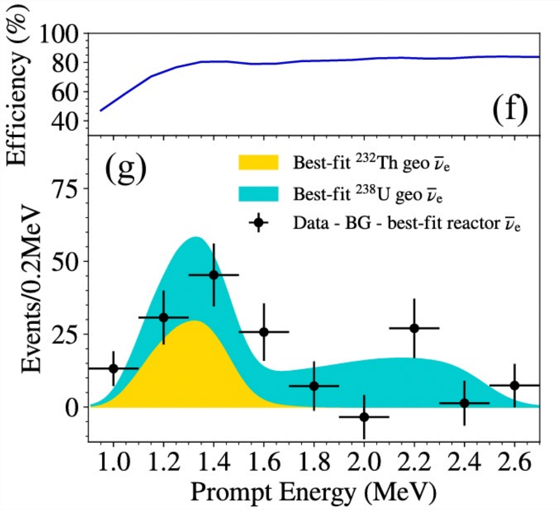
Other Measurements with Reactor Neutrinos

- Earth heat flow of 40 TW comes from primordial and radiogenic heat
- Geoneutrinos (from decays of ^{238}U, ^{232}Th and ^{40}K) → radiogenic heat contribution to crust and mantle (KamLAND and Borexino)
- Favors < 20 TW radiogenic heat contribution









Conclusion

Studying neutrinos is challenging.

Nevertheless, neutrinos carry a promise of great discoveries.

They have already revealed surprises like neutrino mass and neutrino oscillations giving us a window in the Beyond Standard Model physics.

Solar and reactor neutrinos are very useful free sources of neutrinos that have been successfully used for decades.

Liquid scintillator detectors are great in detecting not just reactor but also geoneutrinos telling us about Earth heat flow.

Near future of physics with reactor neutrinos may bring even greater findings in the lepton sector such as fourth neutrino species and solution to the neutrinos mass ordering problem.

Thank you!

And homework!

1) Calculate the energy released in supernova explosion of SN1987A using the data from Kamiokande experiment (relevant references given in the problem)

2) Compare the detection rates and spectrum of neutrinos in KamLAND with and without matter effects included (needed references and reactor spectrum given in the problem)

3) Make the plots of oscillated reactor neutrino spectrum with JUNO in case of inverted and normal mass ordering. Compare the plots for perfect, 3% and 5% resolution. Check what happens to ability to resolve normal and inverted ordering at a oscillation baseline that is different from the current one.