RENO: Reactor Neutrino Experiment at Yonggwang

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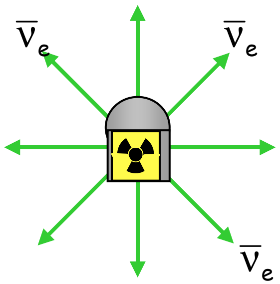
DBD07 Int'l Workshop
Osaka

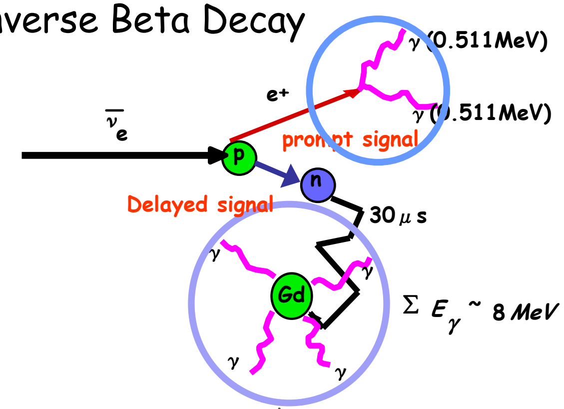
What is RENO?

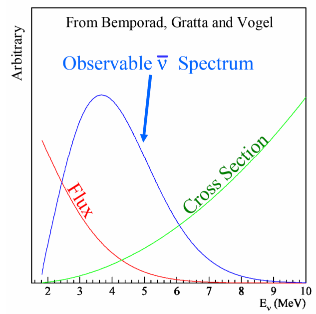
RENO = Reactor Experiment Neutrino Oscillation

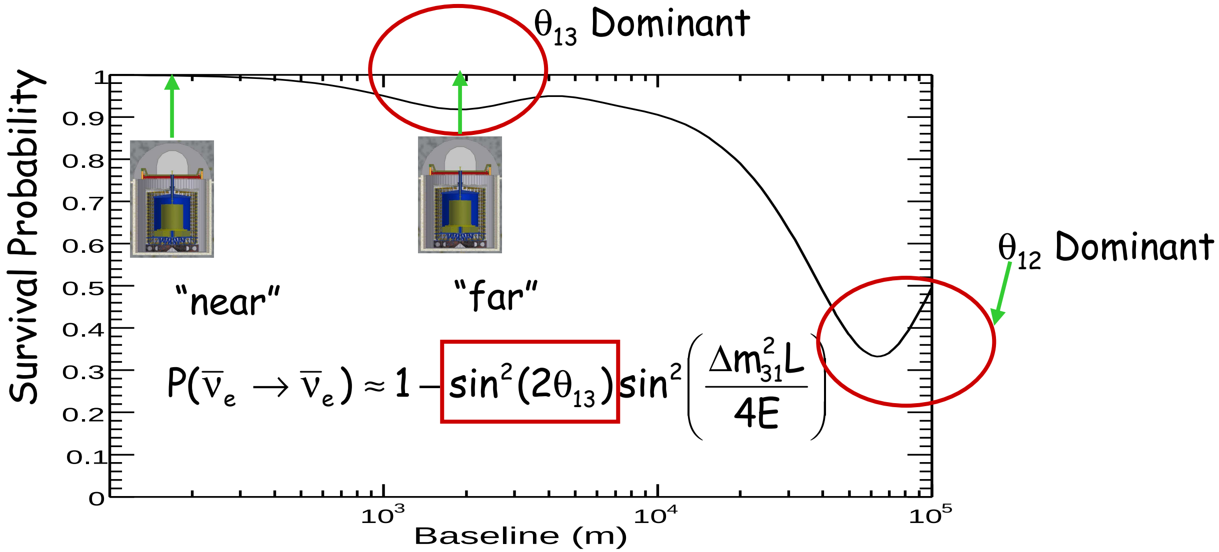
E_ν<10 MeV



Inverse Beta Decay



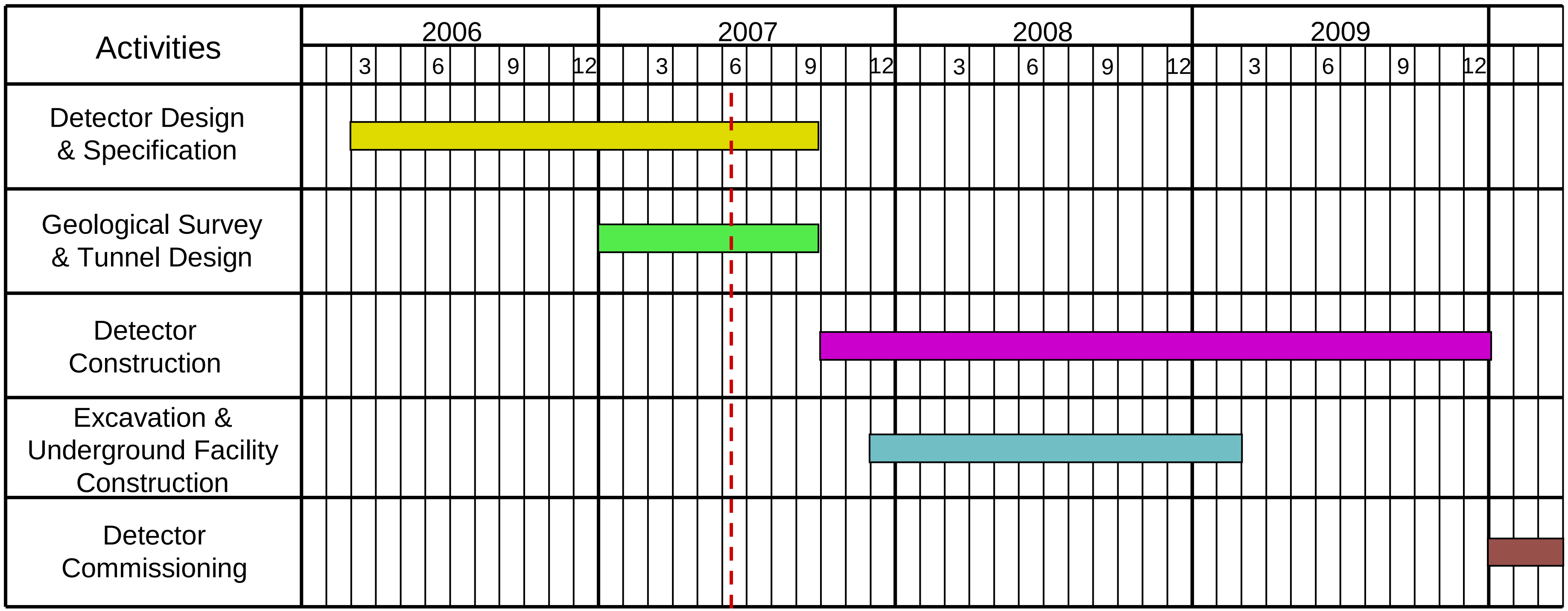




Project Summary

- Feasibility study began in early 2004.
- Announced the intention for the project at FLENE05 workshop in Brazil in 2005.02.
- Submitted the proposal to MOST (Ministry of Science and Technology) in 2005.04 and it was approved with $10M (US).
- The budget was allocated in 2005.12
- The project began in 2006.03.
- Data –taking is expected to start in early 2010
- Technical Design Report will be ready in July 2007
- International collaborators are being invited

Schedule



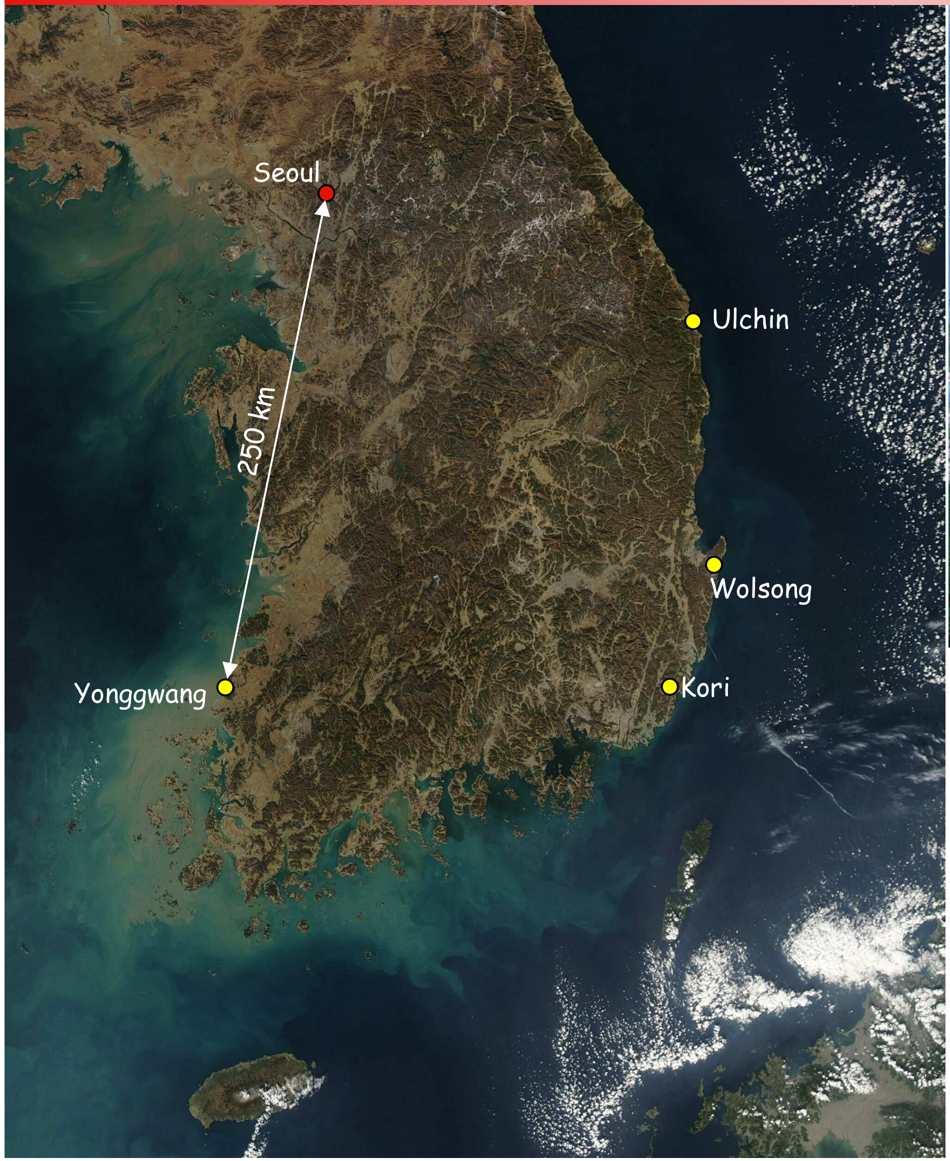
Activities
2006
2007
2008
2009
3
6
9
12
Detector Design & Specification
Geological Survey & Tunnel Design
Detector Construction
Excavation & Underground Facility Construction
Detector Commissioning

RENO Collaboration

12 Institutions/43 Collaborators

- Chonnam National University
- Dongshin University
- Gyeongsang National University
- Institute of Nuclear Physics RAS (Russia)
- Institute of Physical Chemistry and Electrochemistry RAS (Russia)
- Kyungpook National University
- Pohang Accelerator Laboratory
- Pusan National University
- Sejong University
- Seoul City University
- Seoul National University
- Sungkyunkwan University

Yonggwang Nuclear Power Plant



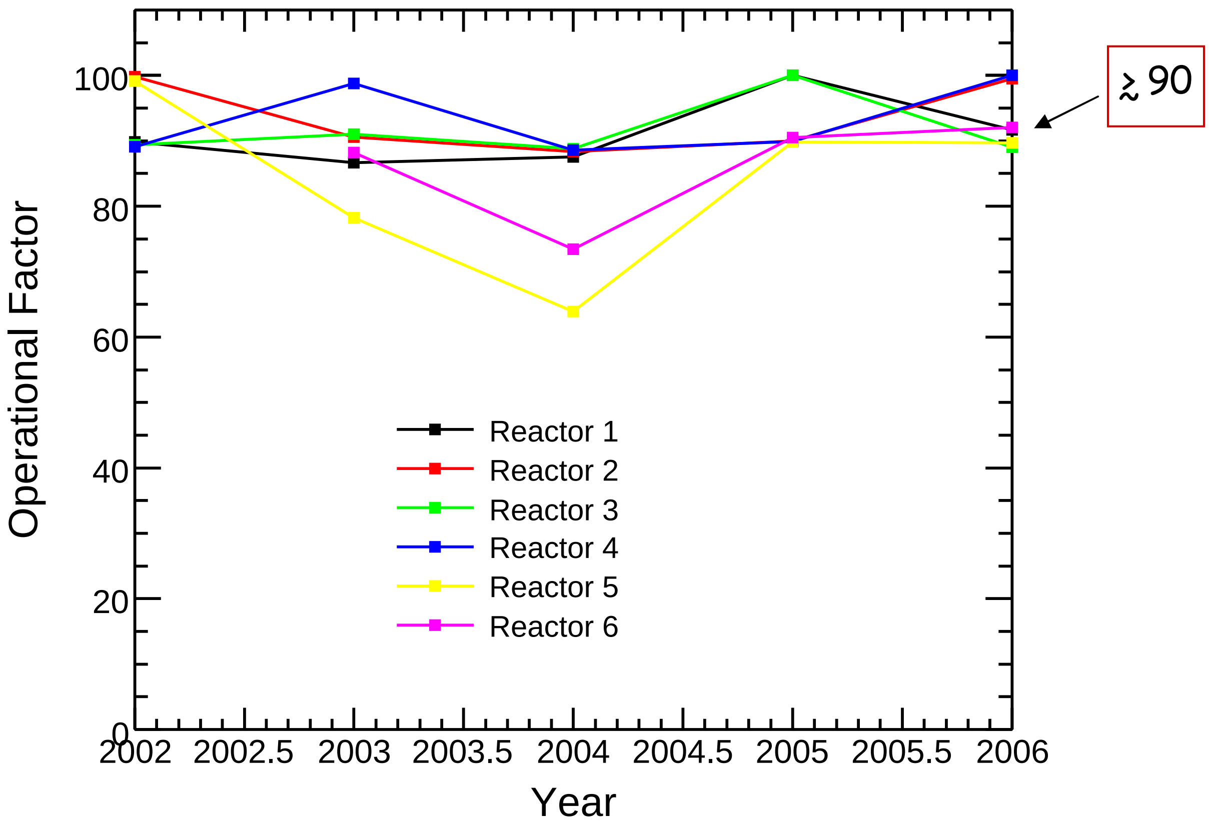
Yonggwang Nuclear Power Plant

- Six ~1000 GW_e class PWRs
- Total average thermal output of 16.4 GW (max 17.3 GW)
- Started operation in 1986~2002.
- Operational factor ≳ 90

Reactor Operation History

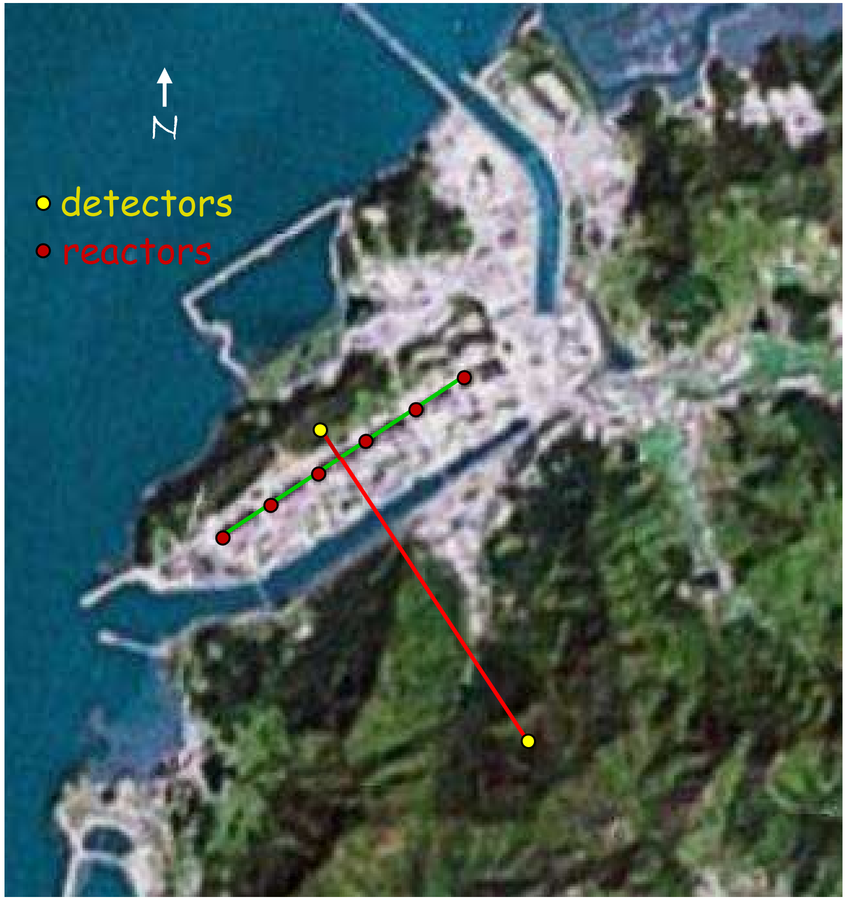
Operation factor of Yonggwang nuclear reactors

$$\text{operational factor} = \frac{\text{generated GWh in a year}}{\text{365x24xGW of installed rated capacity}}$$

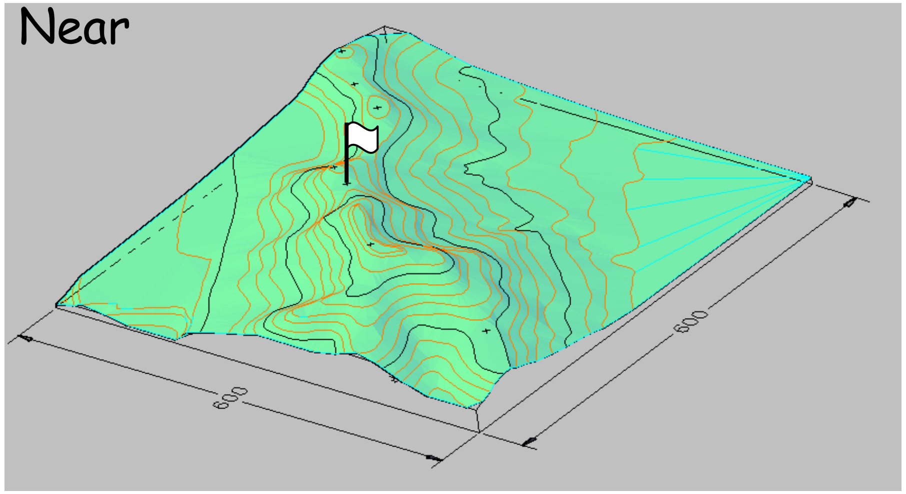


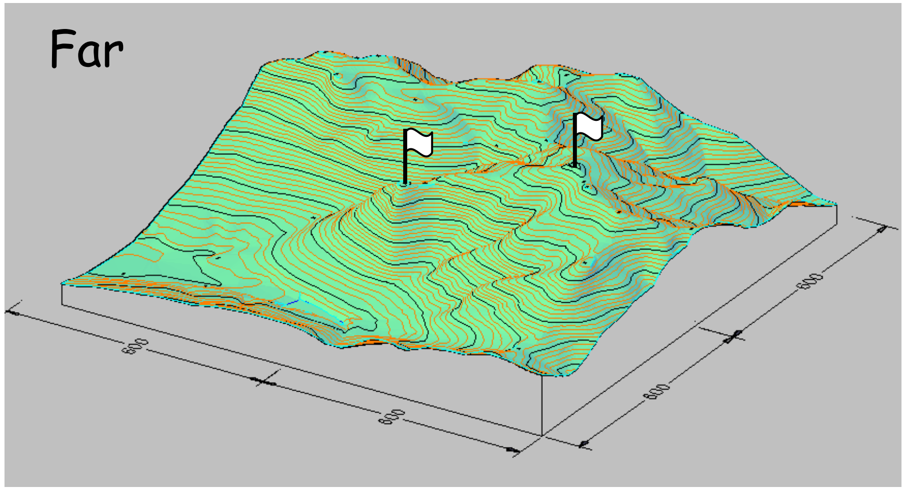
Yonggwang Site

six reactors aligned in equal distance.

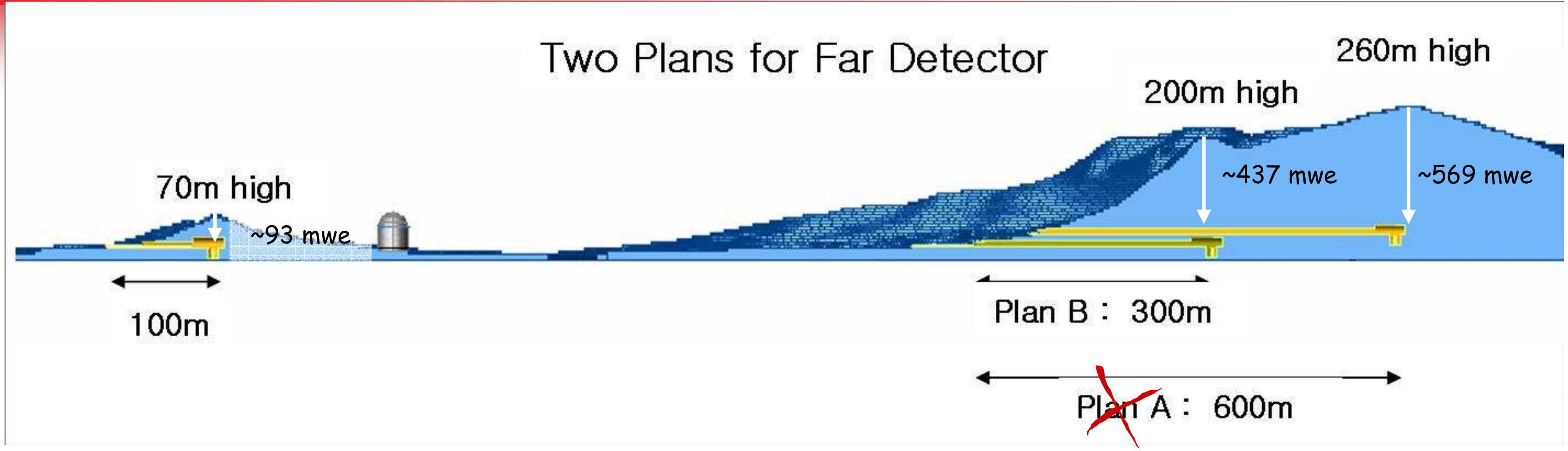


Yonggwang Site



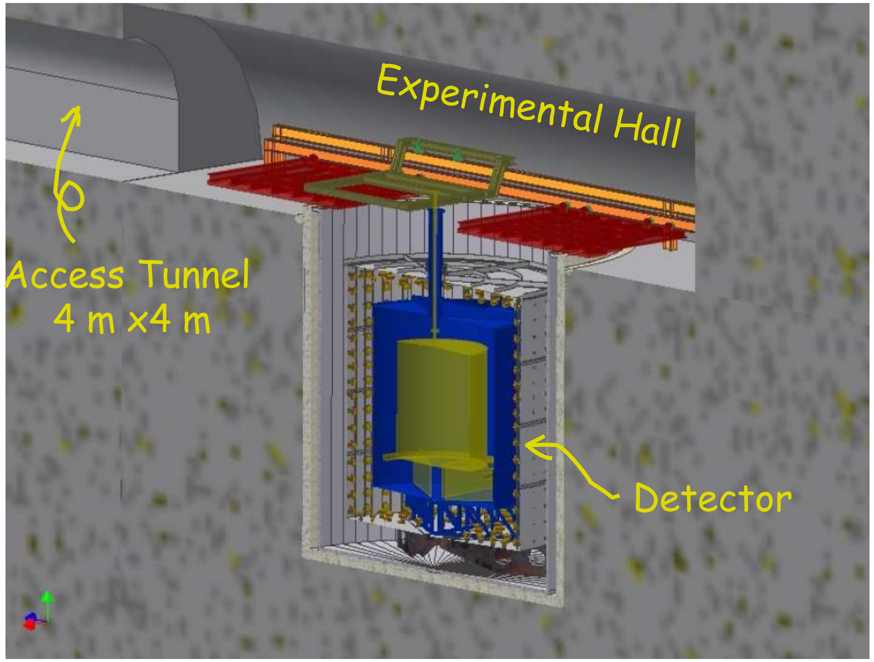


Detector Location



Exp. hall@35 m AMSL

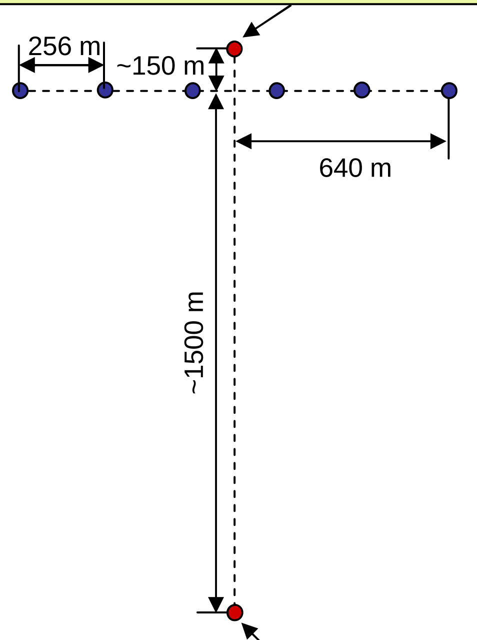
	Vertical Depth (m/mwe)
Near	35/93
~~Far A~~	225/596
Far B	165/437



Expected Inverse Beta Decay Event Rates

- Each reactor has power output of 2.73 GW_{th} (=16.4/6)
- $^{235}U:^{238}U:^{239}Pu:^{241}Pu$=0.556:0.071:0.326:0.047

near detector @ 150 m:
8.12×10^4 IBD events/(10^{29} protons·yr)



near detector: 1.02×10^6 IBD events/yr

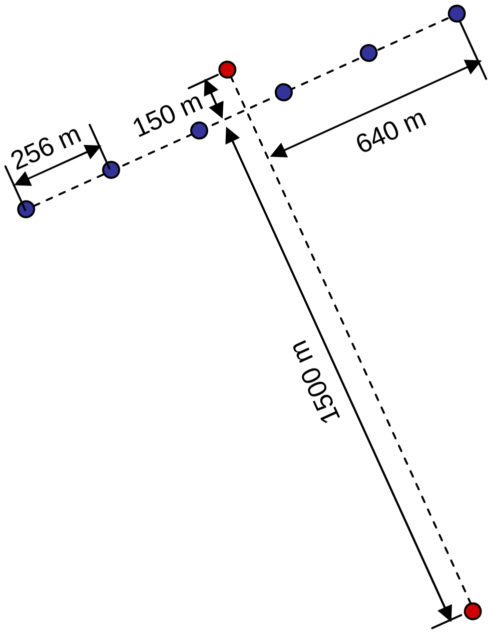
15 ton targets
with PC (20%)+Dodecane (80%)

far detector: 3.73×10^4 IBD events/yr

far detector @ 1500 m:
2.96×10^3 IBD events/(10^{29} protons·yr)

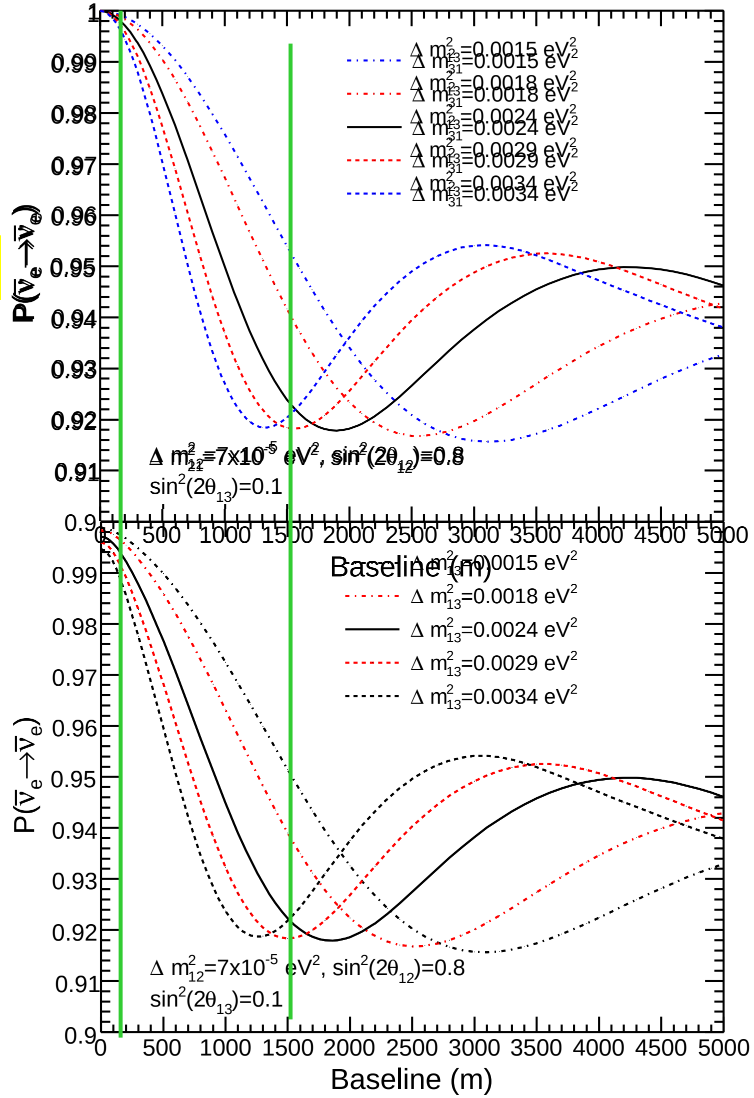
Survival Probability

What effect on survival probability due to a wide spread reactor array?



single reactor

6-reactor



Working Group Activities

Civil Construction & Underground Facility

(geological survey, excavation, on-site lab utilities, etc.)

→ Negotiation with local government, residents, power company

→ Construction of underground facility (tunnel design & excavation)

MC & Detector Design

(MC, performance study, detector drawing, detector optimization, etc.)

→ Full detector simulator & analysis

→ Detector design

Gd+Liquid Scintillator R&D

(purification, selection, production & purchase, etc.)

→ R&D of recipe and study of characteristics

Prototype Detector

(PMT test, background study, construction scheme R&D, etc.)

→ Test of detection method using a prototype detector and a mockup version detector

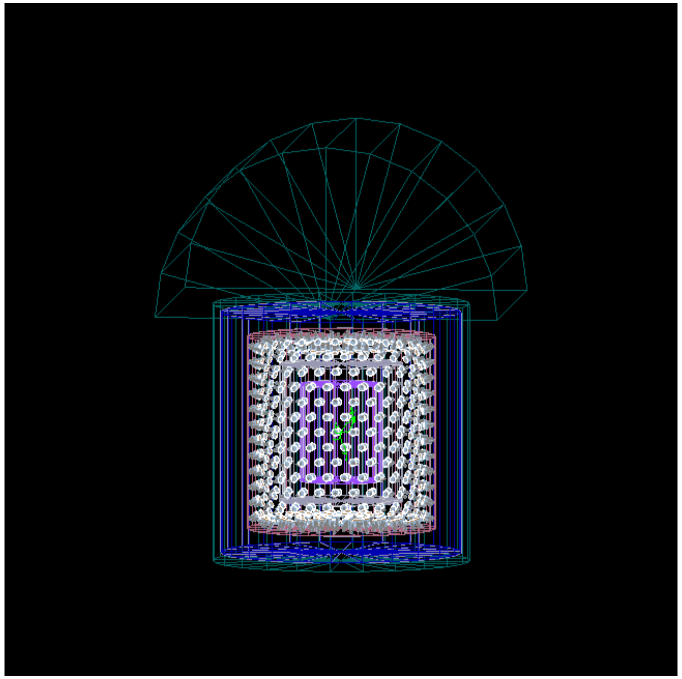
On-Site Facility

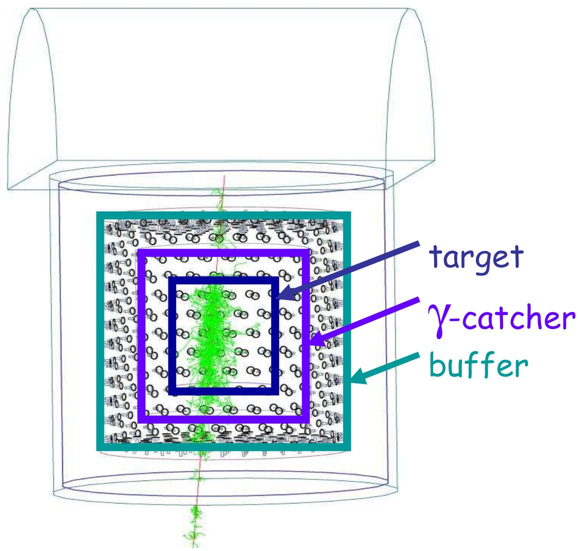
•2006.03-08	Townhall meetings with local residents, NGOs, and local government
•2006.07	endorsement by local government
•2006.11	endorsement by KHNP
•2007.02	Contract awarded for geological survey and tunnel design
•2007.03	Land usage agreement between KHNP and RENO
•2007.05	Geological survey completed
•2007.06	Tunnel design in progress
•2007.10	Issue contract for tunnel construction

Borehole Rock Samples

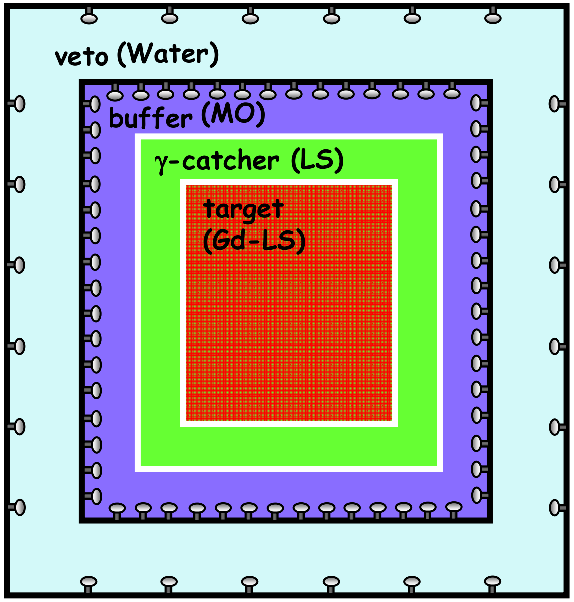
MC Simulation

- Detector simulation based on GLG4sim.
- Used to determine detector geometry and size
- detector performance
- background studies





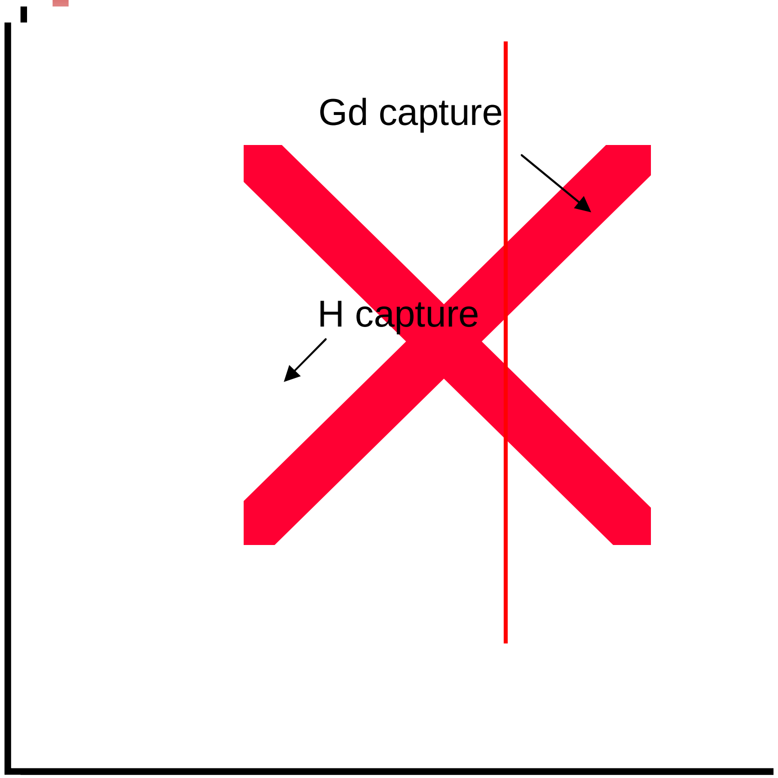
RENO Detector at a Glance



- Concentric cylindrical design
- 15 ton target
- 537 8" PMTs on the buffer vessel wall
  - 87x2 top/bottom
  - 363 on cylinder wall
  - solid angle coverage @centre = 12.6%
- Undetermined number of undetermined size PMTs in VETO

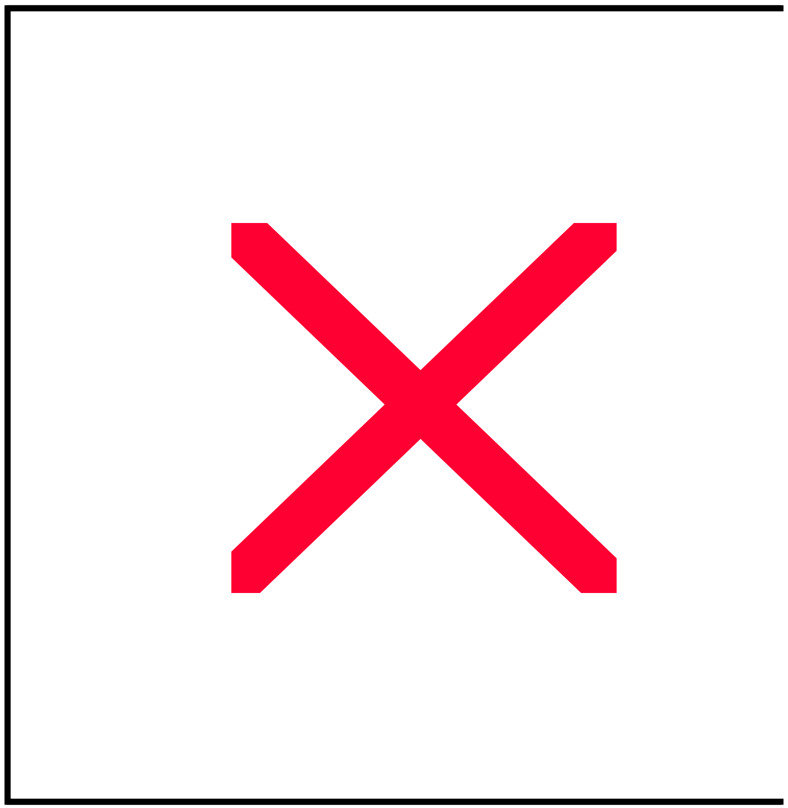
	Inner Diameter (cm)	Inner Height (cm)	vessel	Vessel Thickness (mm)	Filled with	Volume (m^3)	Mass (tons)
Target	280	320	Transparent Acrylic	12	Gd(0.1%) +LS	19.7	15.4
Gamma catcher	400	440	Transparent Acrylic	8	LS	35.2	27.5
Buffer	540	580	Stainless Steel	4	Mineral oil	76.9	59.2
Veto	740	780	Steel	15	water	201.8	201.8

Gamma Catcher Thickness



Gamma catcher thickness determined by the efficiency of Gd captured neutron identification

60cm: (93.0+/-0.6)%



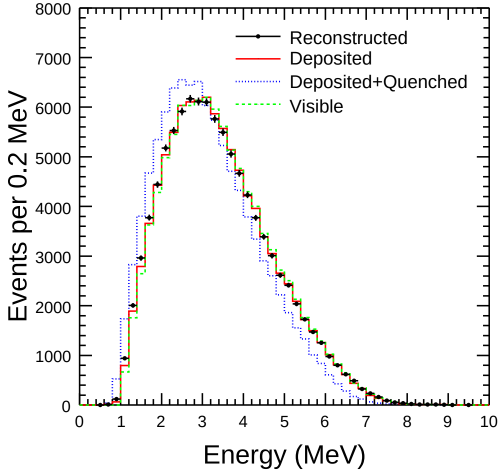
Event Reconstruction

- Energy Reconstruction

1 MeV (KE) e^+

~200 photoelectrons per MeV

positron energy spectrum



- Reconstructed vertex: σ ~8 cm at the centre of the detector

4 MeV (KE) e^+

y

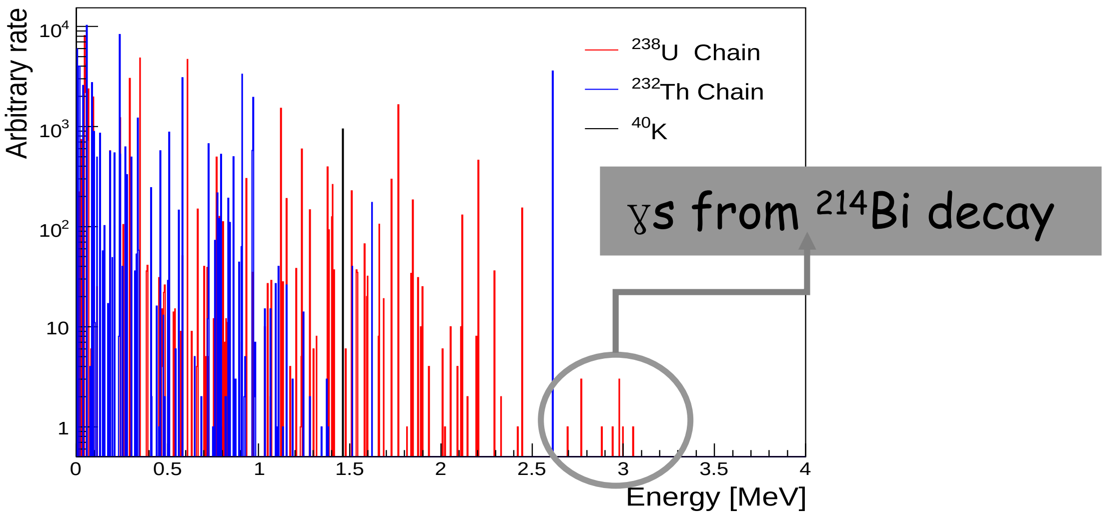
σ_y (mm)

|y|

E_{vis} (MeV)

Gamma Background from PMT

- Used almost all energy lines from ^{40}K, ^{232}Th, and ^{238}U decay chains



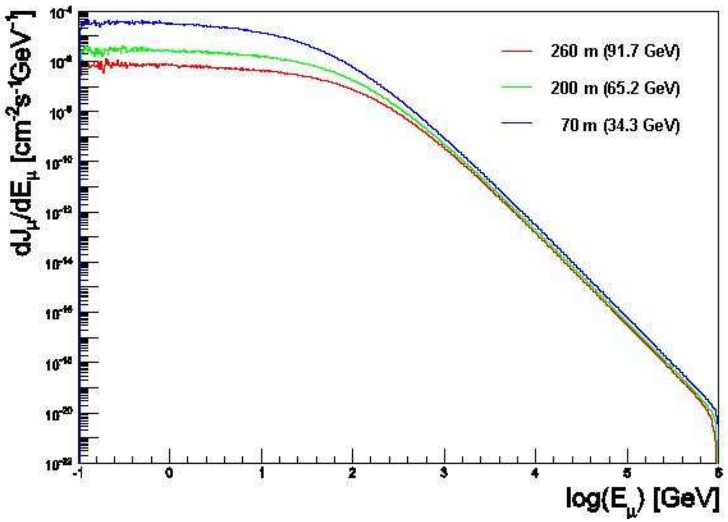
	^{40}K	^{232}Th	^{238}U	Total
Bq/PMT	1.63	0.41	0.70	
Rate (E>1MeV)	1.5Hz	4.2Hz	5.5Hz	11.2Hz

Hamamatsu 8" → Bq/PMT

70 cm buffer → Rate (E>1MeV)

Muon Rates

- Modified Gaisser paramerisation for muon flux @sea level
- MUSIC for muon propagation
- Used site topology.



	Vertical Depth (m/mwe)	Φ_μ ($m^{-2}s^{-1}$)	$\langle E_\mu \rangle$ (GeV)
~~Far A~~	225/596	2.9×10^{-1}	91.7
Far B	165/437	8.5×10^{-1}	65.2
Near	35/93	5.5×10^{0}	34.3

- Other background studies are in progress

Liquid Scintillator R&D

Aromatic	Oil	Fluor	WLS	Gd-compound
PC(Pseudocumene), PXE, LAB	Mineral oil, Dodecane, Tetrdecane, LAB	PPO, BPO	Bis-MSB, POPOP	0.1% Gd compounds with CBX or BDK

Requirements:

- Should satisfy physical, technical characteristics:
  high transparency, good scintillation properties, ease of purification
- Safety consideration: high flash point, low toxicity.
- easy availability,

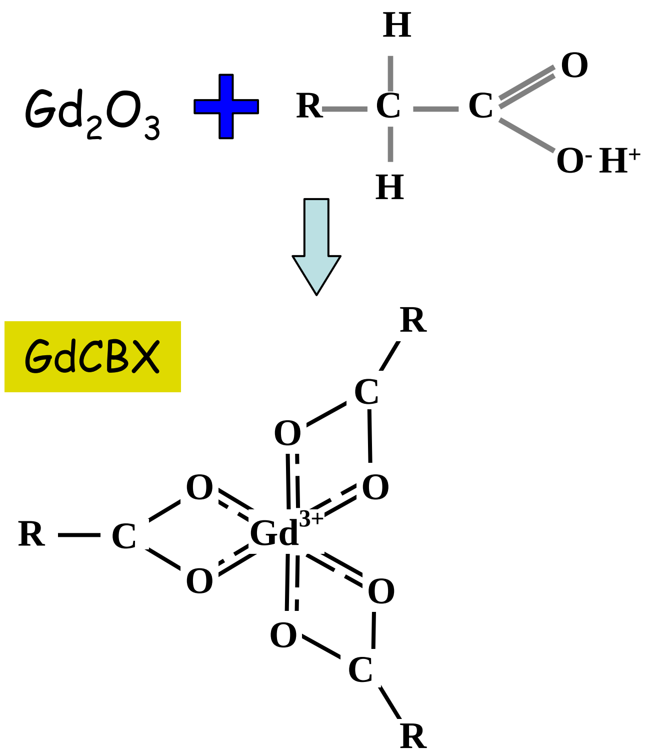
- Gd-LS must have long attenuation length, good light yield, and be stable for several years

- Gd+LS R&D with the Russian INR/IPCE group
- Performance study of various recipes :
  - light yield
  - transmission & attenuation lengths
- Development of purification system
  - Al_2O_3 adsorption
  - Filtration
  - Vacuum distillation
  - Water extraction, etc
- Long-term stability test
- Reaction with acrylic, stainless steel

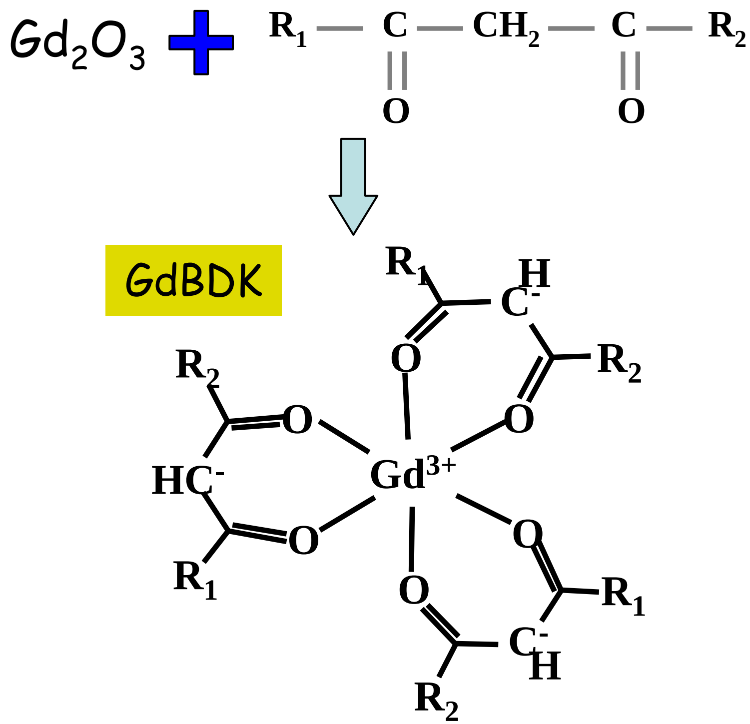
Baseline for Gd-loaded Liquid Scint.

- ❑ Baseline Recipe :
  - PC(20%) + Dodecane(80%) + (PPO with bis-MSB or BPO)
  - 0.1% Gd compounds with CBX or BDK
- ❑ Extensive study on LAB this year

Carboxylic acids



β-diketonates

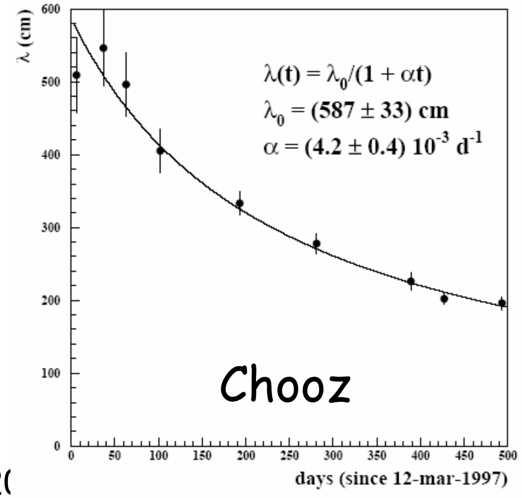


❑ Gd loading created degradation in light yield

	Chooz	Palo Verde
Gd	$Gd(NO_3)_3$	Gd_2O_3
Loading Methods	Dissolved in hexanol + LS	Converted to carboxylate + LS
Light yield degradation	0.4 % / day	0.03 % / day
Remarks	Unstable → Turned Yellow	Stable → still usable

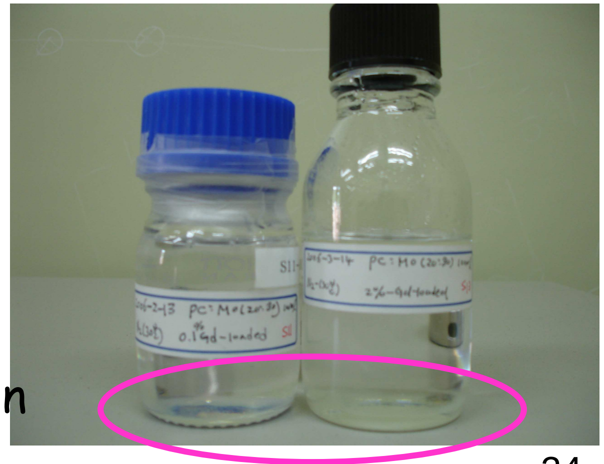
❑ Gd loading is not trivial :

- collaborating with experienced Russian groups (INR/IPCE)
  → 6 months stable Gd-LS

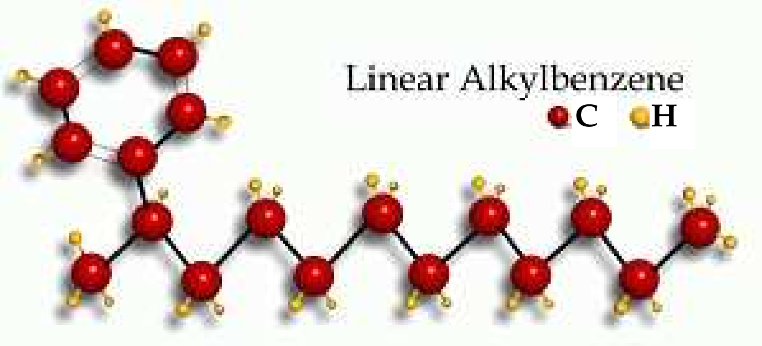


Two problems reported
- ❑ Degradation
- ❑ Yellowish problem

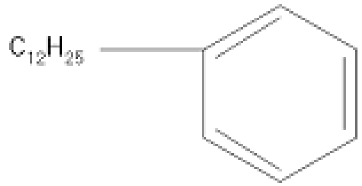
precipitation



R&D with Linear Alkylbenzene (LAB)



LAB : $(C_6H_5)C_NH_{2N+1}$ (N=10~13)



Linear Alkyl Benzene (LAB)

Pro

- High light yield
- Good transparency: better than PC
- High flash point: ~140 °C > PC 48 °C
- Environment friendly: PC is toxic
- domestically available: Isu Chemical Ltd.
- VERY CHEAP!!!

Con

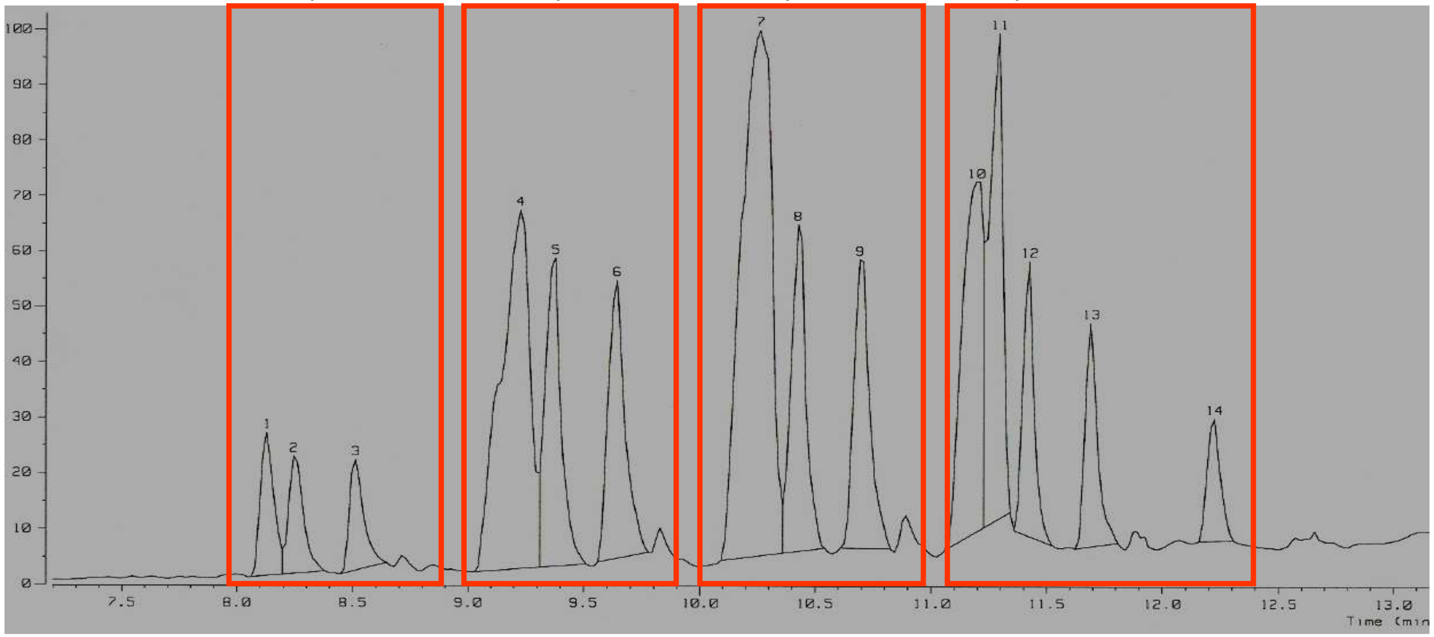
- composition variation

Composition of LAB

Gas Chromatography/Mass Spectroscopy

LAB : $(C_6H_5)C_NH_{2N+1}$ (N=10~13)

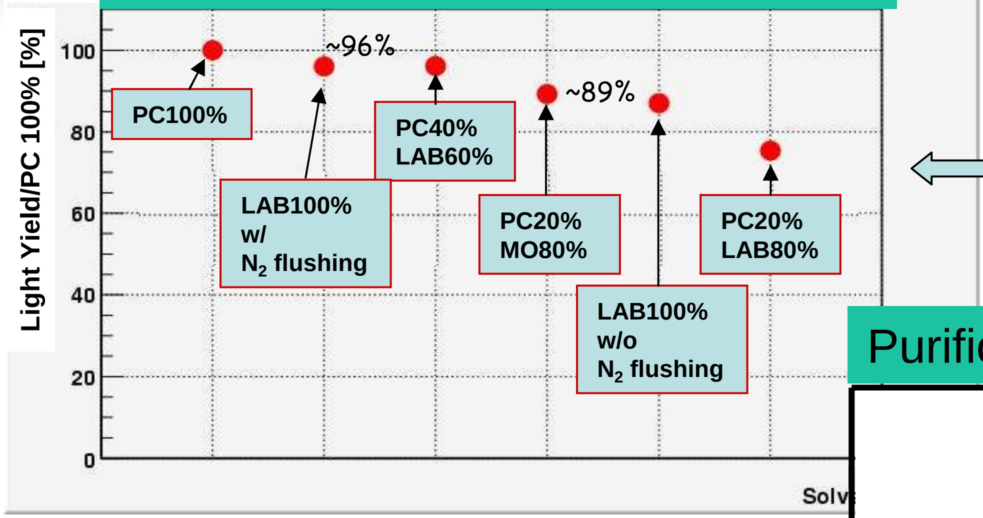
$C_{16}H_{26}$	$C_{17}H_{28}$	$C_{18}H_{30}$	$C_{19}H_{32}$
7.2%	27.6%	35.0%	30.2%



# of H = 0.631 x $10^{29}/m^3$
H/C = 1.66

R&D with Linear Alkylbenzene (LAB)

Gd loaded LS Light yield measurements



Using ^{137}Cs.

UV/Vis Spectrometer

Purification by Al_2O_3 adsorption

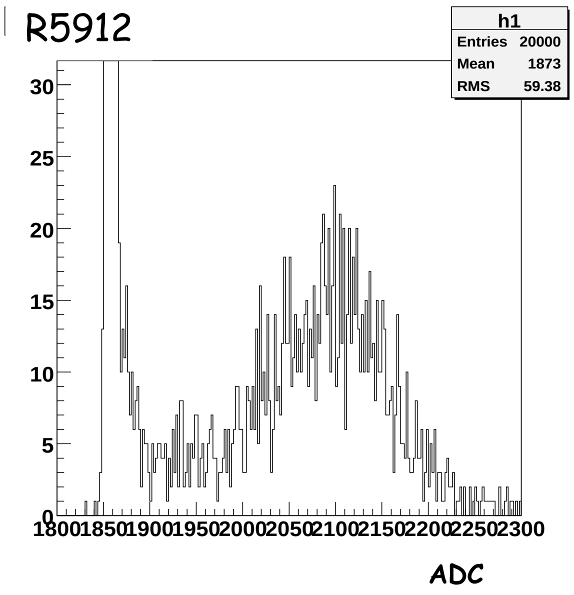
	Attenuation Length (m)	
	Before	After
PXE	1.0	1.3
Dodecane	15.2	16.2
PC	5.9	8.2
MO	9.7	N/A
LAB (batch1)	9.5	15.2
LAB (batch2)	7.7	14.7

PMT Test

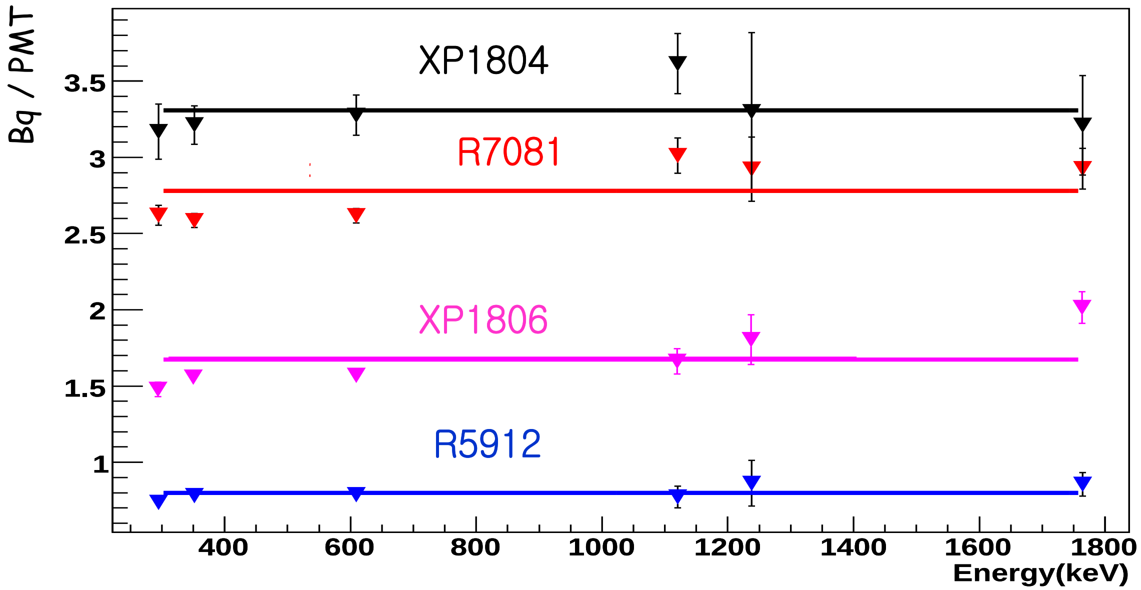
- PMTs considered.
  - Hamamatsu : R5912(8"), R7081(10")
  - Photonis : XP1806(8"), XP1804(10.6")
  - ETL : 9354 (to be tested)

Tested single photoelectron resolution and radioactive background

R5912 with LED illumination



^{238}U Radioactivity



HPGe measurements show that backgrounds are secular equilibrium.

Comparison between PMTs

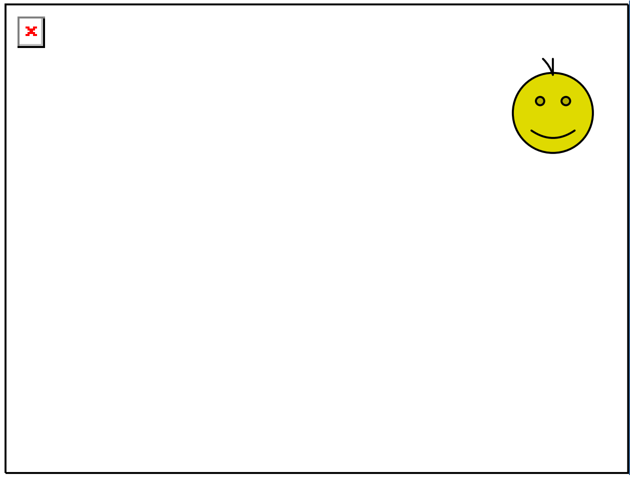
		R9512	R7081	XP1806	XP1804
Gain ($X10^7$)		1.0 @1500V	1.0 @ 1500V	1.0 @1600V	1.0 @1600V
QE @ peak		22% @390	25% @390	24% @420	24% @420
DC (nA)		50	50	30	30
Size (inch)		8	10	8	10.6
Weight (g)		720	1150	880	1744
Rise Time (ns)		3.8	4.3	5	5
TTS (ns)		2.4	2.9	2.4	2.4
Afterpulse		2%	2%	12%	12%
Peak/Valley ratio		~4	~3.5	~3.5	~3.5
Radioactivity (Bq/PMT)	K	2.1	8.3	3.12	6.1
	Th	0.52	1.14	0.22	0.32
	U	0.78	2.68	1.57	3.26
Bg (E>1MeV) (Hz) With G4 simulation		12.4	37.5	16.2	32.1

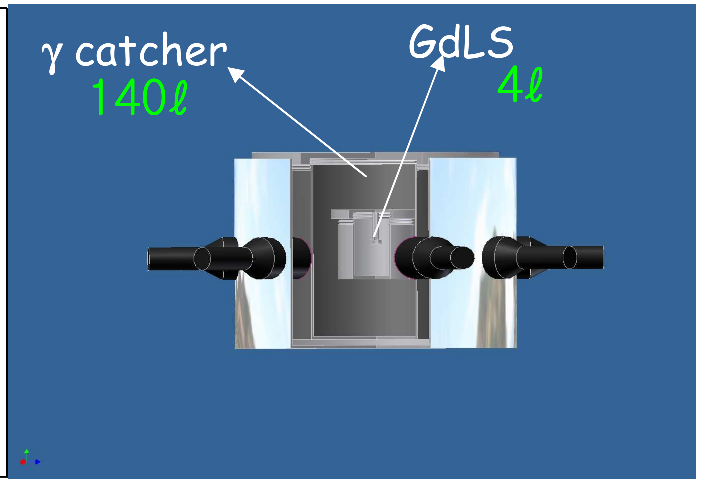
"Prototype" Detector

- Small size working detector for
  - Checking the validity of MC and tuning it
  - Developing data analysis method
  - R&D of detector structure
  - PMT performance test and background studies
  - Optical properties of acrylic vessel

Liquid Scintillator mixture

	Target	γ catcher
PC	1.6 L	56 L
MO	2.4 L	84 L
PPO	3 g/L	3 g/L
Bis-MSB	0.05 g/L	0.05 g/L
Gd	1 g/L	0





Prototype Construction

Acrylic vessels

Inner acrylic vessel

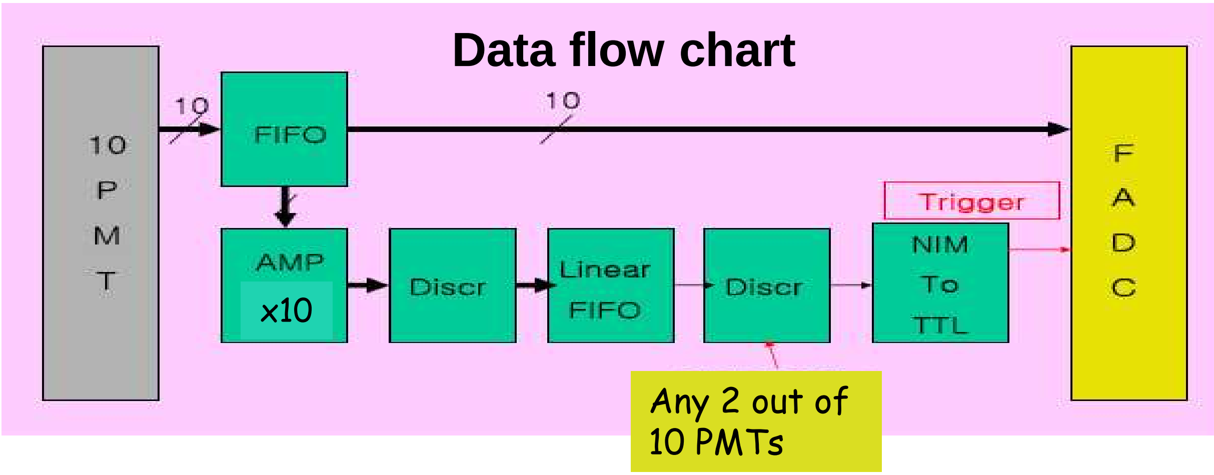
Mounting PMTs

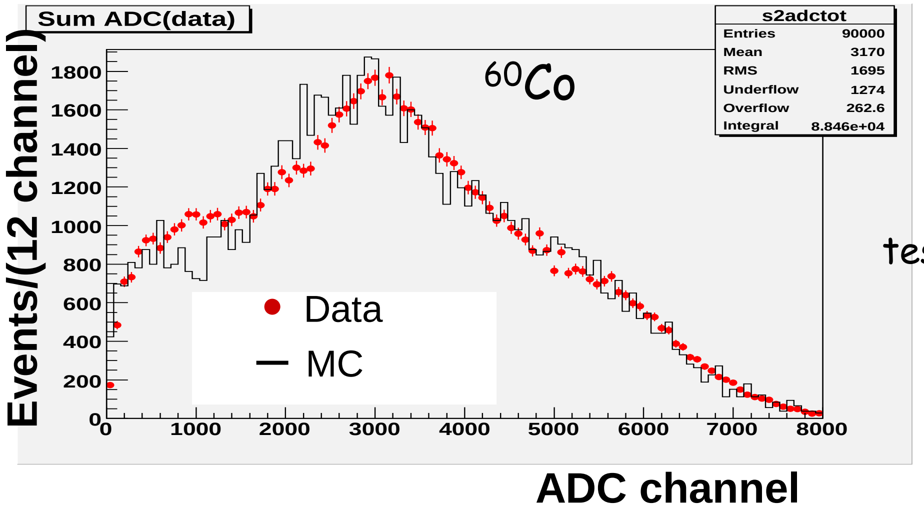
Nitrogen flushing of LS

Filling with liquid scintillator

assembled prototype

Calibration of Prototype Detector



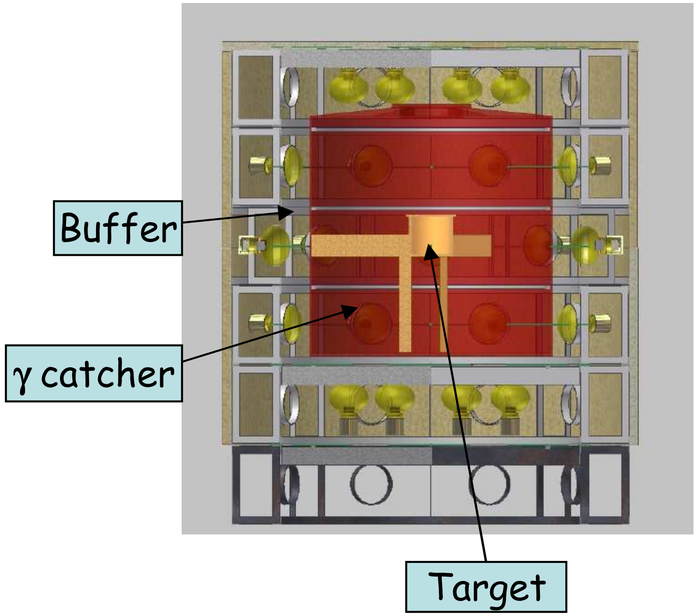


Radioactive sources

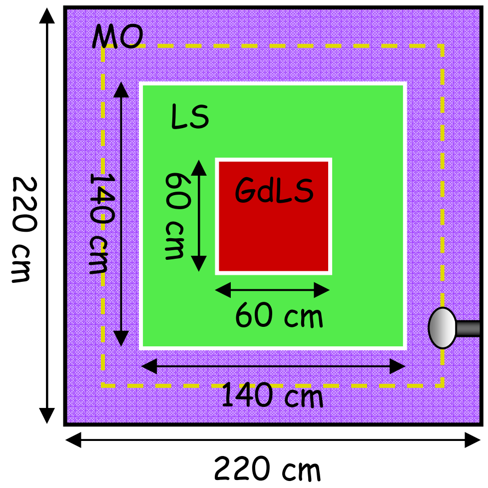
	isotope	activity (μCi)	$E_{particle}$ (MeV)	E_γ (MeV)
tested	^{137}Cs	2.47		0.662
tested	^{60}Co	9.79		1.173, 1.333
	^{22}Na	1.00	E_{e+}, 0.545	1.275
	^{252}Cf	0.1	$4 \times E_n$, 2.14	$20\times < 1$

Working "Mock-up" Detector

- Smaller size fully functioning detector (sans veto).
- Exercise for building and running a sizable scale detector
  - fluid handling
  - electronics
  - data handling
- basis for very near detectors?
- will start construction shortly



- 45 8" PMTs
- target 17 ℓ
- γ catcher 199 ℓ
- buffer 621 ℓ

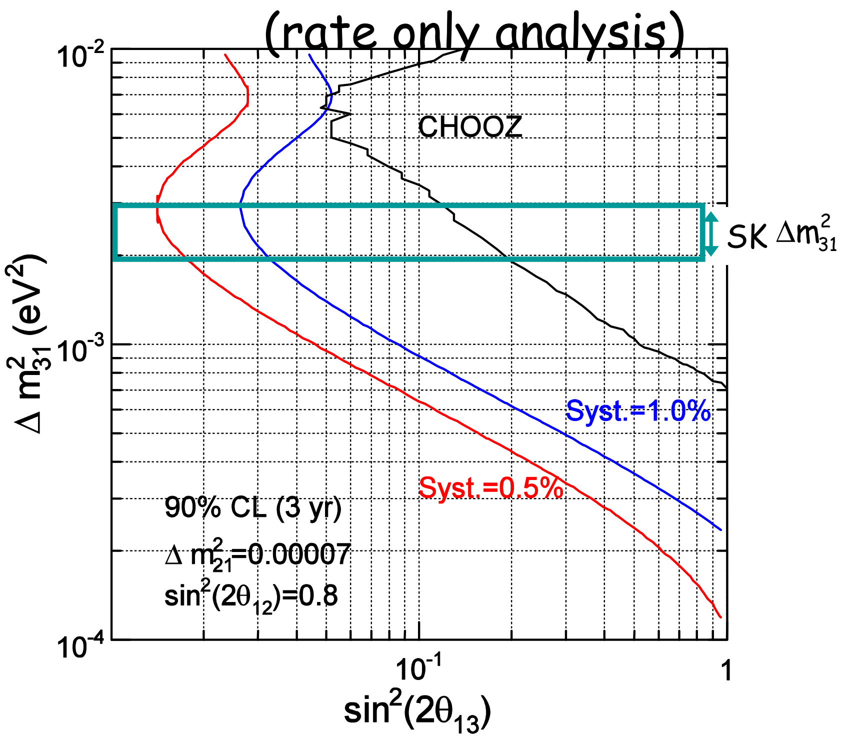


expected Gd captured neutron tagging efficiency

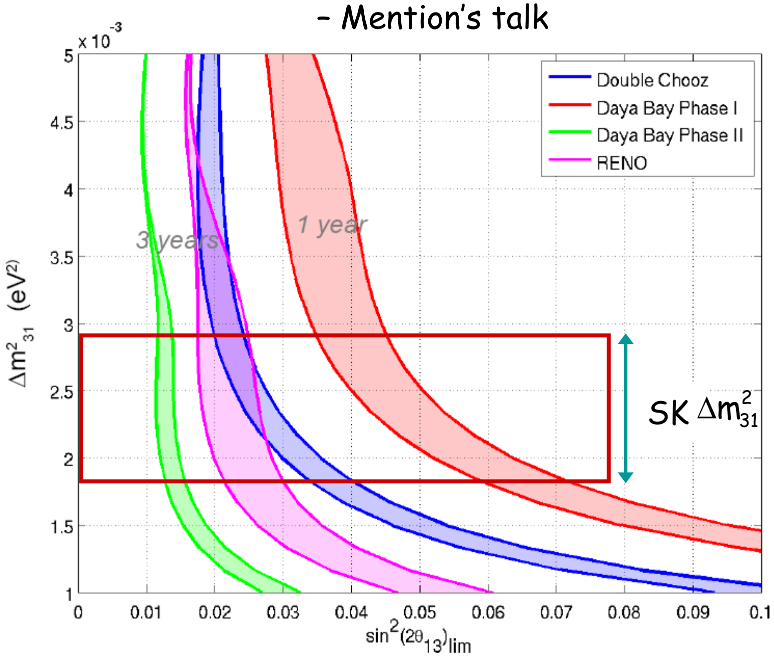
Eff. = 73.5 +/- 1.5 %

Sensitivity

90%CL sensitivity after 3 years of data taking



GLoBES group workshop@Heidelberg
- Mention's talk



Best constraint

σ_{rel} = 0.38 %

$\varepsilon_{elt} = 10^{-4}$

Worst constraint

σ_{rel} = 0.6 %
σ_{pwr} = 3.0 %
σ_{abs} = 3.0 %

Summary

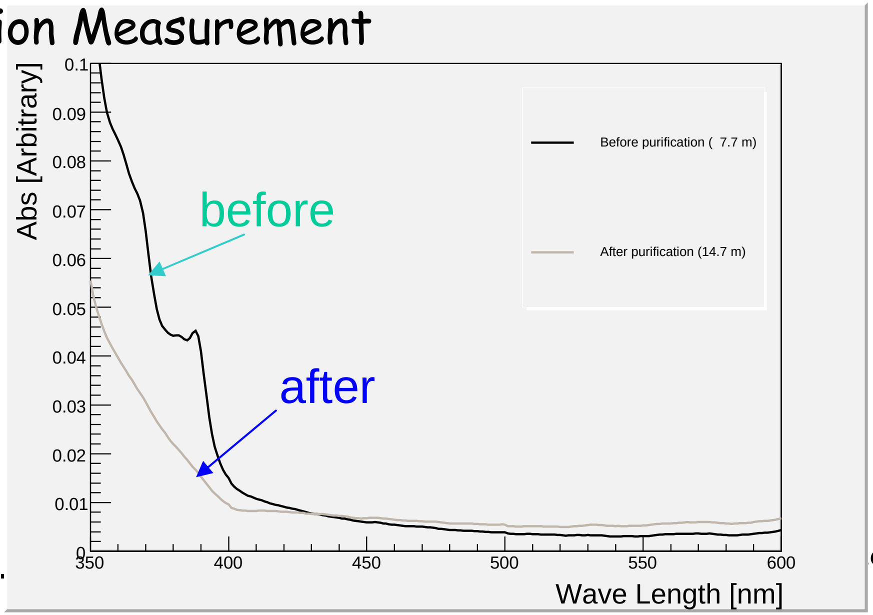
- Project was approved for funding in 2005.
- Budget allocated in Dec. 2005.
- Experiment site usage has been approved.
- Geological survey carried out and rock samples obtained.
- Technical Design Report is expected to be ready by July 2007.
- Detector Construction will begin in Oct. 2007.
- Data taking expected to start in early 2010.
- International Collaborators are being invited.

Backup Slides

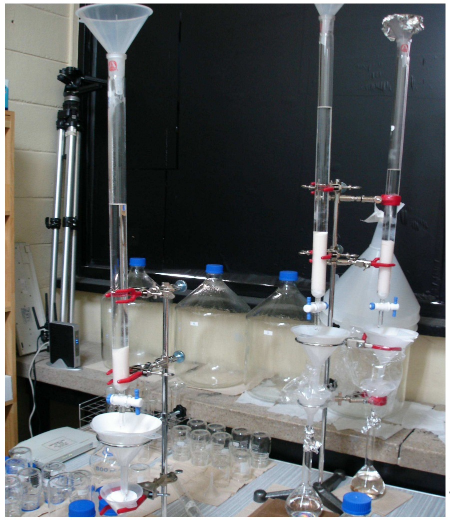
Attenuation Lengths of different solvents before/after purification

	Before (m)	After (m)
PXE	1.0	1.3
Dodecane	15.2	16.2
PC	5.9	8.2
MO	9.7	N/A
LAB (batch1)	9.5	15.2
LAB (batch2)	7.7	14.7

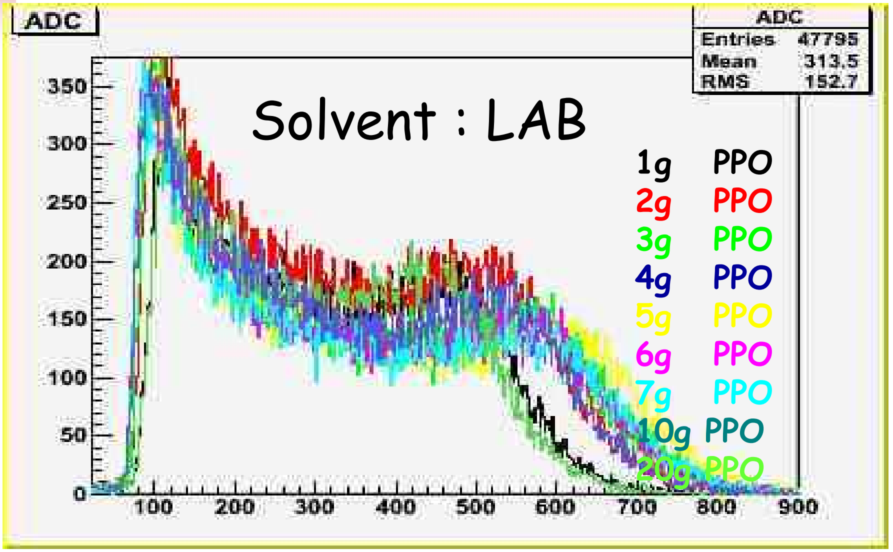
Absorption Measurement

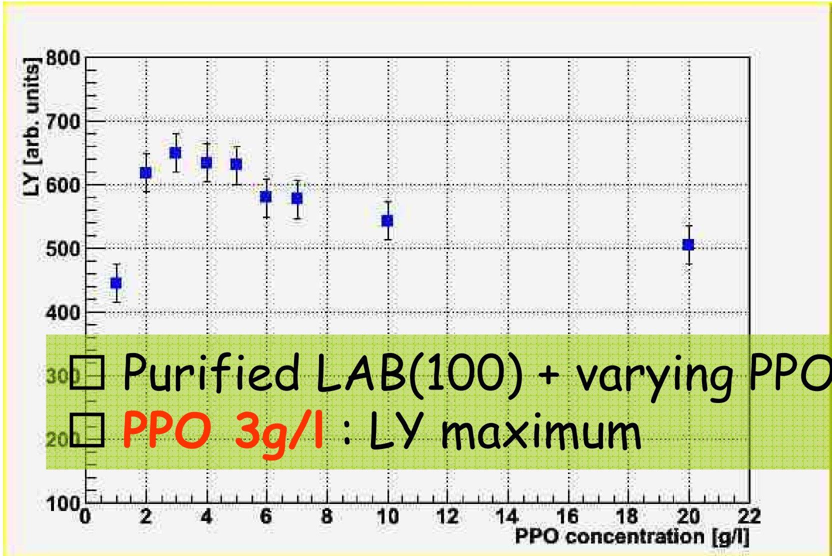


Purification by Al_2O_3 adsorption

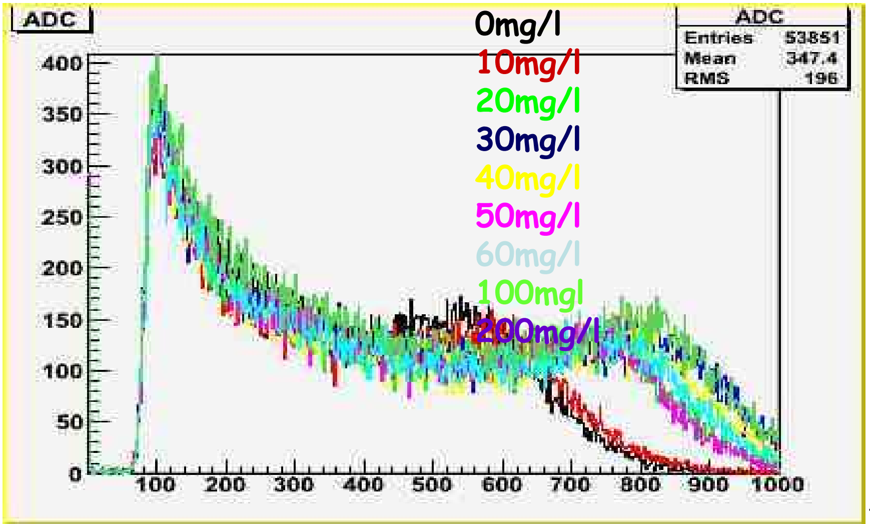


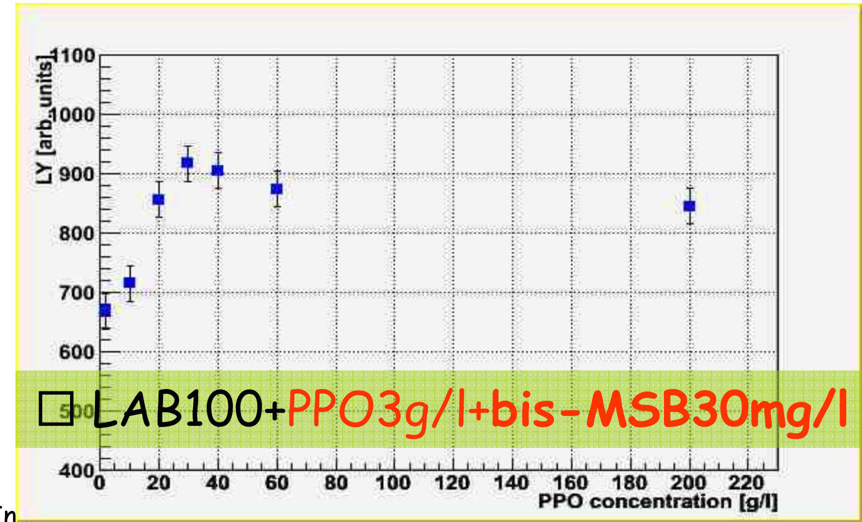
Optimization of PPO, bis-MSB Concentration for LAB





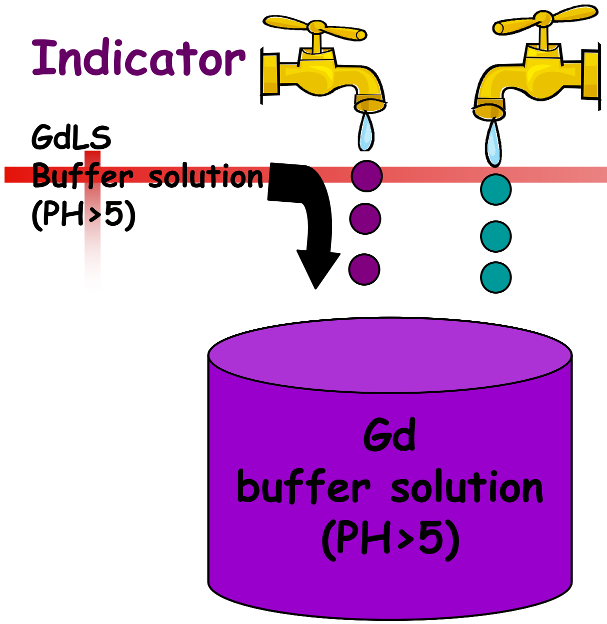
- Purified LAB(100) + varying PPO
- **PPO 3g/l** : LY maximum





- LAB100+PPO3g/l+**bis-MSB30mg/l**

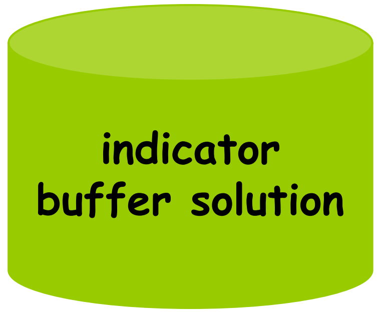
Measurement of Gd Concentration



① For PH> 5, Gd reacts with EDTA

② EDTA reacts with indicator, then **violet** color changes into **yellow**

③ $V_{EDTA} * C_{EDTA} = V_{sample} * C_{sample}$



Result

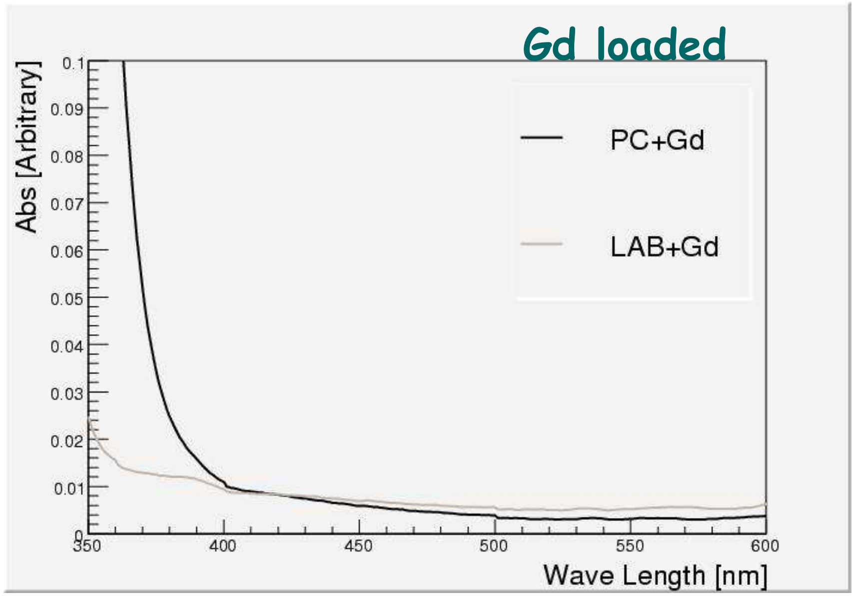
Sample	Composition (ligand)	Date of preparation	[Gd](%)	Remarks additive
1	*3HR	2007.03.03	0.109	HR(0.92m)
2	*3TBP	2007.03.06	0.108	TBP(0.5m)
3	*2TOPO	2007.03.07	0.118	TOPO(99%)
4	*3TOPO	2007.03.07	0.110	TOPO(99%)

Characteristics of Various Solvents

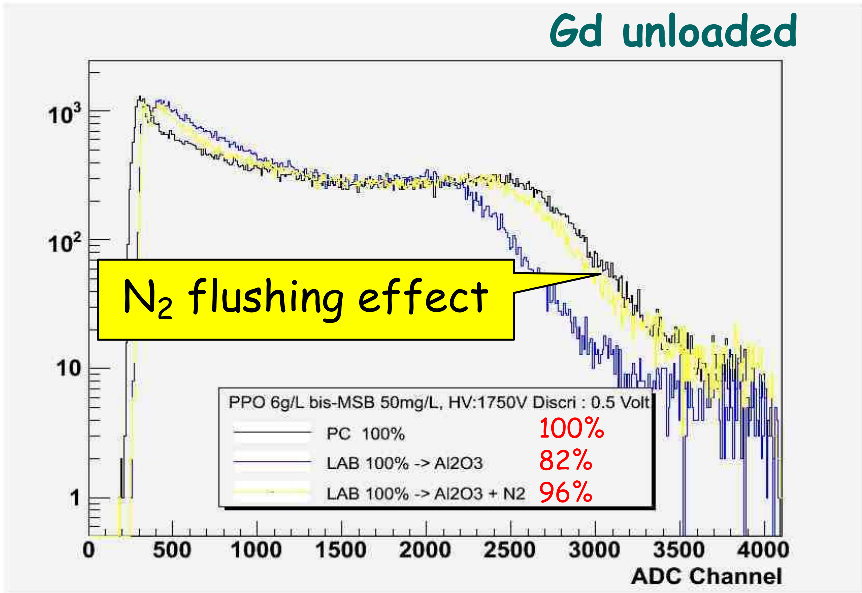
	Chemical elements	H:C	M.W. (g/mol)	Density (g/ml)	Boiling Point	Flash Point	Viscosity @20℃	comments
decane	C10H22		142.29	0.73	174	46	0.92cps	Domestically available
dodecane	C12H26	2.17	170.34	0.7493	216.2	71		Expensive
tetradecane	C14H30		198.3922	0.767	253	99		
PC(=TMB)	C9H12	1.33	120.2	0.89(0.876)	169	48		Toxic Low FP
LAB	C6H5 (CnH2n+1)		233-237	0.86	275-307	130	5-10cps	R&D in progress Nontoxic Inexpensive
PXE	C16H18	1.12	210.3	0.988	295	145	5.2cSt@40	Less toxic Supply limited
MO	CnH2n+2, n=10-44			~0.8		~110	10-80cSt@40	Uncertainty in no. of protons
PC20dod80		2		0.78				
PXE20dod80		1.96		0.80		>80		
PC20MO80				0.857				
PC40MO60				0.866				

Performance of Gd in PC & LAB

Absorption spectra



Light output spectra



- LAB has lower optical absorption, better attenuation length
- 100% LAB and PC have similar light outputs
- We got similar results with BNL & Daya Bay experiment
- Nitrogen flushing effect is seen