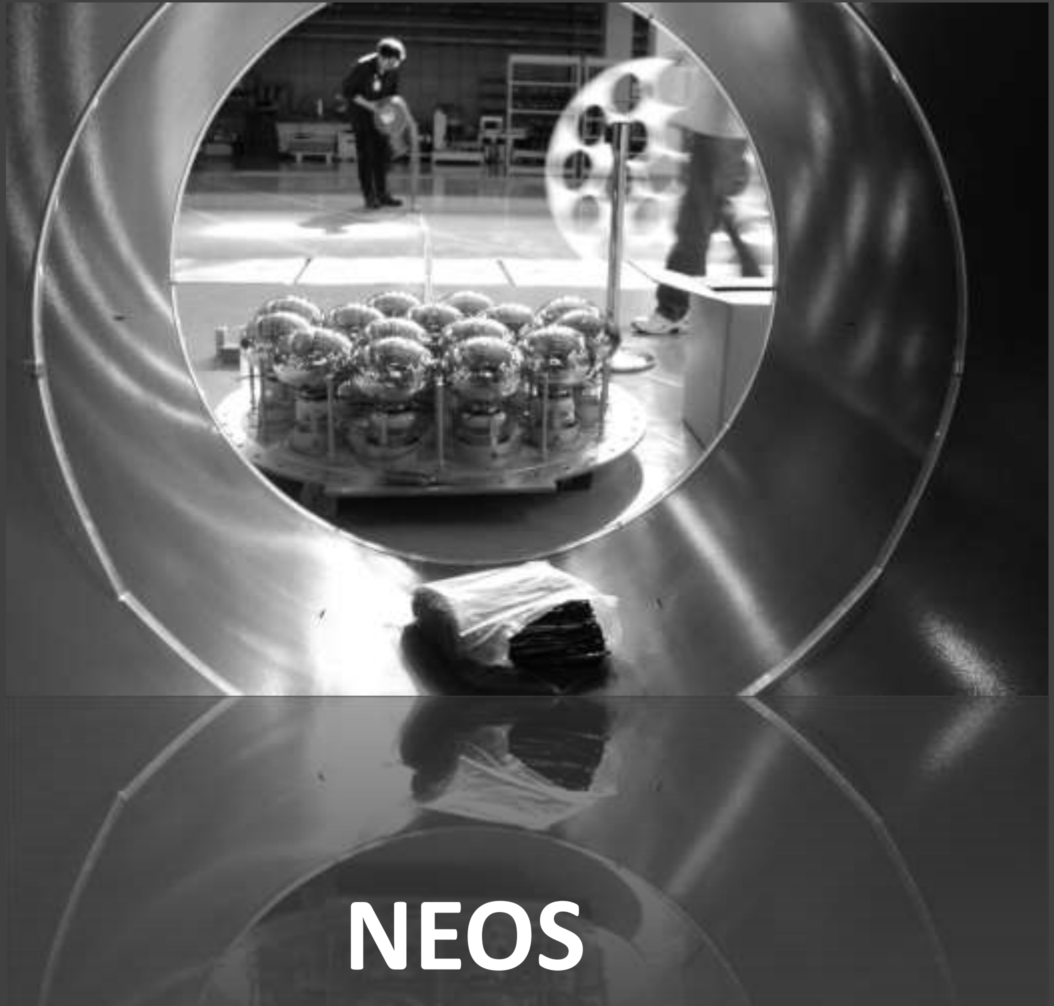
Status and Prospect of
NEOS
Neutrino Experiment for Oscillation at Short Baseline

Kim Siyeon
Chung-Ang University

to be presented at KEK / IPNS July 14, 2015



NEOS

Neutrino Experiment for Oscillation at Short Baseline

중앙대 김시연
中央大 金始衍

on behalf of NEOS Collaboration

Outline

CUP and NEOS

Motivation:
Sterile Neutrino Search
Reactor Antineutrino 5-MeV Excess

STATUS:
Hanbit Reactor

Prototype Detector
Detector Construction

NEOS Collaboration

Affiliation (7)	Members (20)
Chonnam Nat'l Univ.	**Joo**, K., **Kim**, B. R.
Chung-Ang University	**Ko**, Y., **Siyeon**, K.
Institute for Basic Science	**Jeon**, E. J., **Kim**, Y.(*), **Lee**, J., **Lee**, J. Y., **Lee**, M. H., **Oh**, Y.(*), **Park**, H.K., **Park**, K. S.
Korea Atomic Energy Res. Inst.	**Han**, B., **Sun**, K. M.
Korea Res. Inst. of Standards & Sciences	**Park**, H.
Kyungpook Nat'l University	**Kim**, H., **Lee**, J.,
Sejong University	**Kim**, H. S., **Kim**, J., **Ma**, K.
	Changhwan (CAU) and Kyungmin (CNU)
	(*) Director of CUP : Kim, Youngduk (*) Contact : Oh, Yoomin (ohyoumean@ibs.re.kr, ohyoumean@gmail,com)

Time Table

<table>
<tr><th>HANARO</th><th></th><th colspan="2">NEOS</th></tr>
<tr><td>Project starts</td><td>2012 Jul</td><td colspan="2" rowspan="3">- HANARO is a research reactor in KAERI (Korea Atomic Energy Research Institute)
- “HANARO” and “SBL” were used for our experiment.
- In October 2014, “NEOS” was confirmed as official title of experiment and collaboration.</td></tr>
<tr><td>Prototype Detector Construction</td><td>2013 Dec</td></tr>
<tr><td>Prototype Data taking until</td><td>2014 Mar</td></tr>
<tr><td>Plan with HANARO CANCELLED</td><td>2014 Dec</td><td colspan="2">- Plan with Hanbit-5 and KJRR (Kijang Research Reactor)</td></tr>
<tr><td rowspan="8"></td><td>2015 May</td><td>- Target Assembly</td><td>- Dry run</td></tr>
<tr><td>2015 Jun</td><td>- LS/ MO ready</td><td>- Muon Veto</td></tr>
<tr><td rowspan="2">2015 Jul</td><td colspan="2">- Moving from KAERI to HANBIT (13)</td></tr>
<tr><td colspan="2">- Installation on site (14~17)</td></tr>
<tr><td>2015 Aug</td><td colspan="2">- Data w/ reactor off: Overhaul of Reactor 5 (Aug 10 ~ Sep 25)</td></tr>
<tr><td>2015 Sep</td><td colspan="2">- Data w/ reactor on: Hanbit-5 starts cycle 11 at ‘15.09.25 23:30</td></tr>
<tr><td>2016 Mar</td><td colspan="2">- Closure of DAQ (expected)</td></tr>
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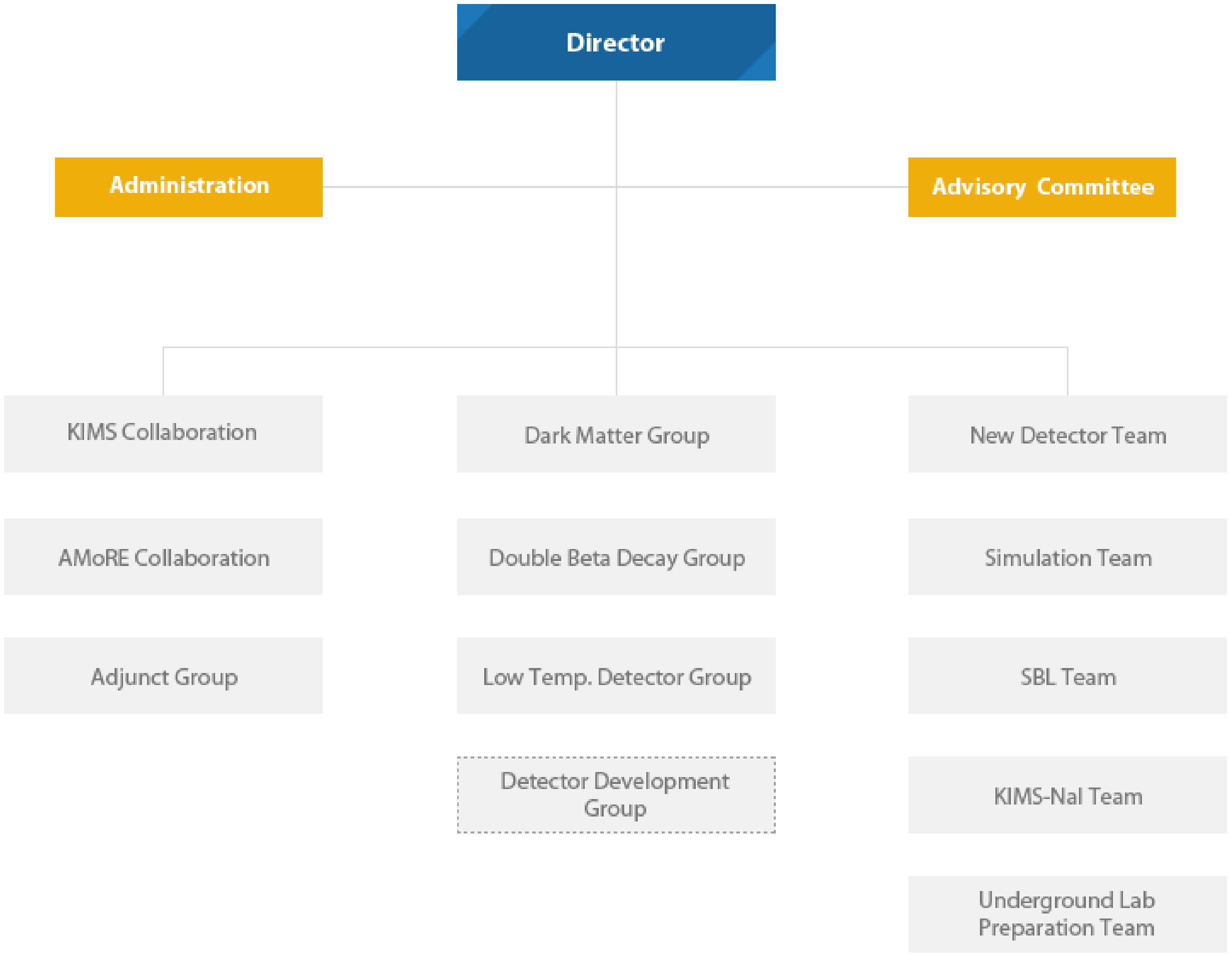
Center of Underground Physics

CUP Kickoff Meeting at KT1 research building, in Daejeon , July 2013

- Institute of Basic Science
- Director
  Kim, Youngduk
- Established in July 1, 2013
- Location
  - Main Office: IBS Center in Daejeon
  - Lab at KT1 Center in Daejeon
  - Lab at Y2L, Yangyang, Gangwon-do
  - Underground facility in Samcheok ?
- http://cupweb.ibs.re.kr

Center of Underground Physics



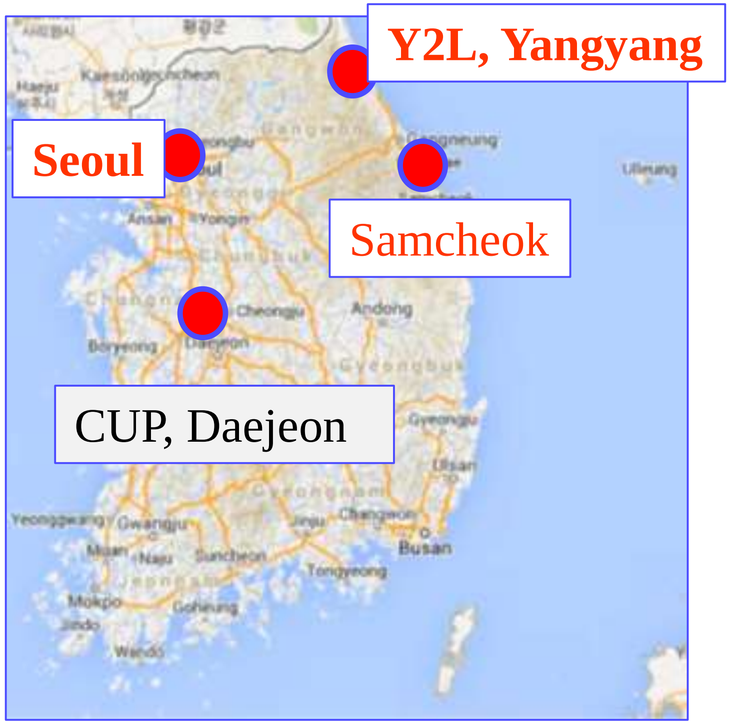
AMoRE
(Advanced Mo-based Rare process Experiment)

KIMS-NaI
(Korea Invisible Matter Search, cf., KIMS-CsI)

NEOS
(Neutrino Experiment for Oscillation of Sterile neutrino)

Center of Underground Physics

Workshop on Particle Astrophysics
in Samcheok, Jan 2014



Center of Underground Physics

How deep underground?

From
H. S. Lee 's slide
for AMoRE
Collaboration

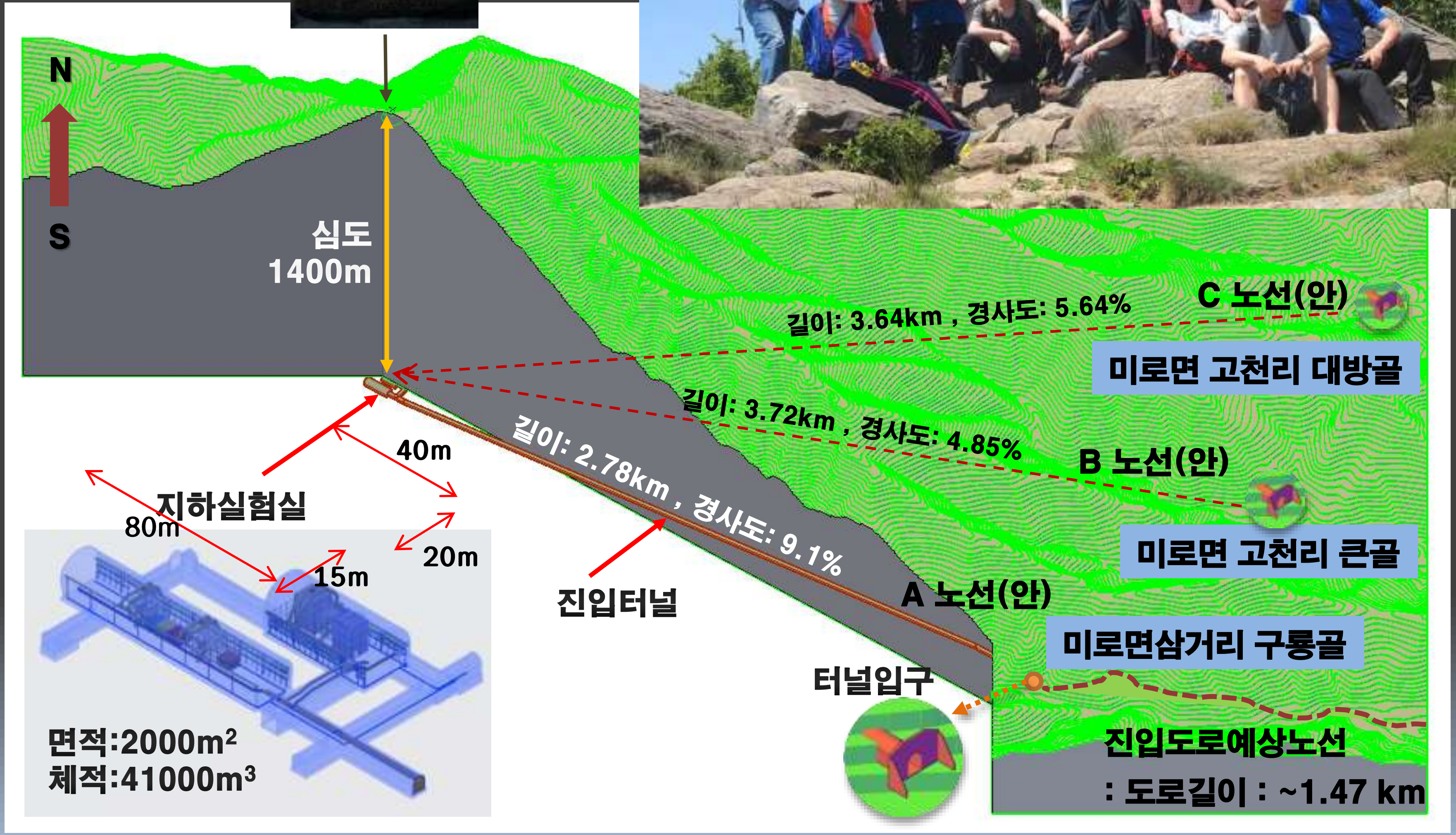
Yangyang Underground Laboratory

Korea Middleland Power Co.
Yangyang Pumped Storage Power Plant

Minimum depth : 700 m
Access to the lab by car (~2km)

From
Stephen Lars Olsen's slide
at AMoRE Collaboration

Doota Mt.



Plan A

Samcheok
Astro-particle
Research Center?

Outline

CUP and NEOS

Motivation:

Reactor Antineutrino Anomaly

Reactor Antineutrino 5-MeV Excess

Sterile Neutrino Search

STATUS:

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Reactor Antineutrino Oscillation

In 3 neutrino oscillation

Far-to-near ration indicates the slope of oscillation

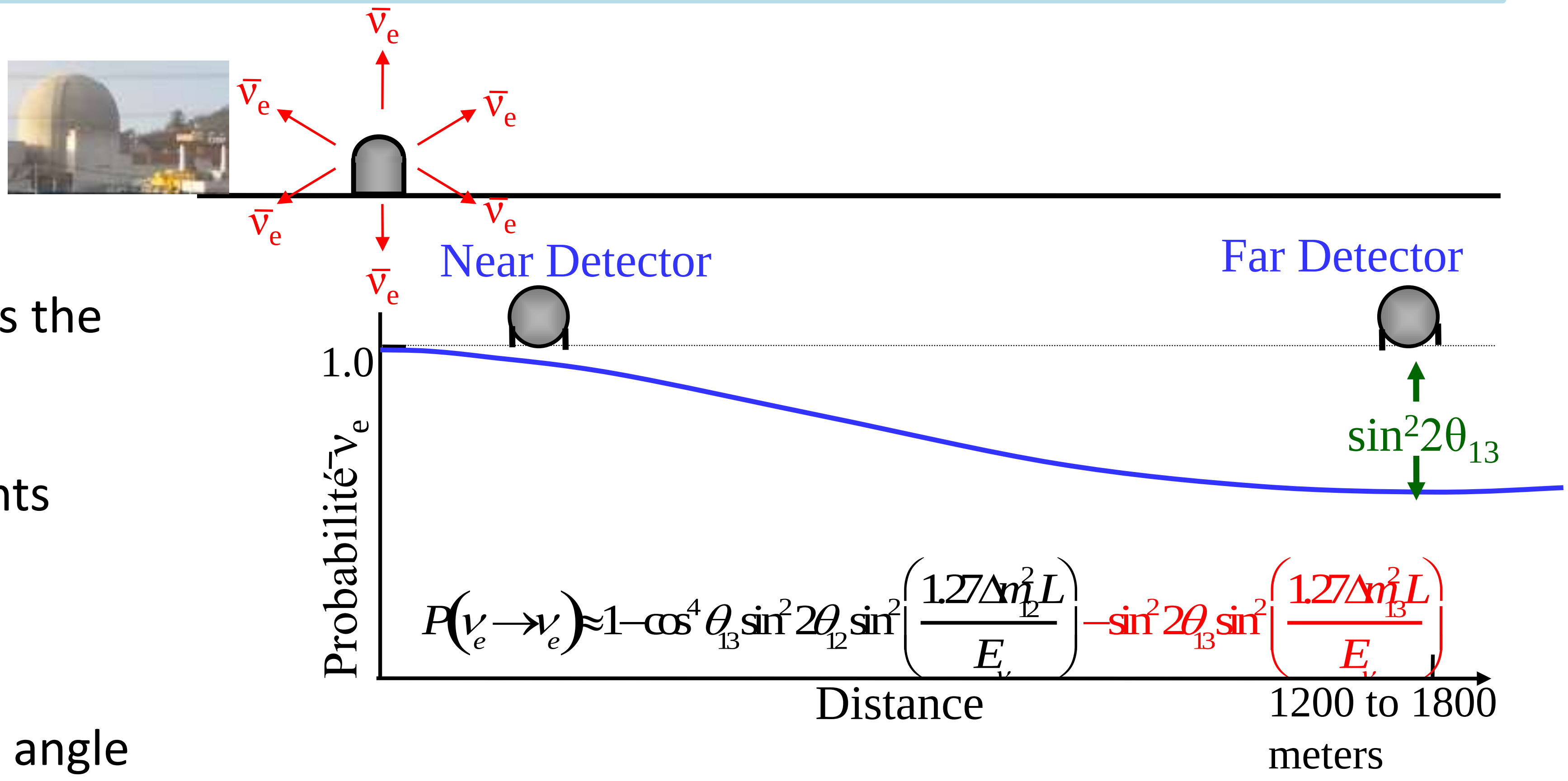
Multi-detection experiments

RENO

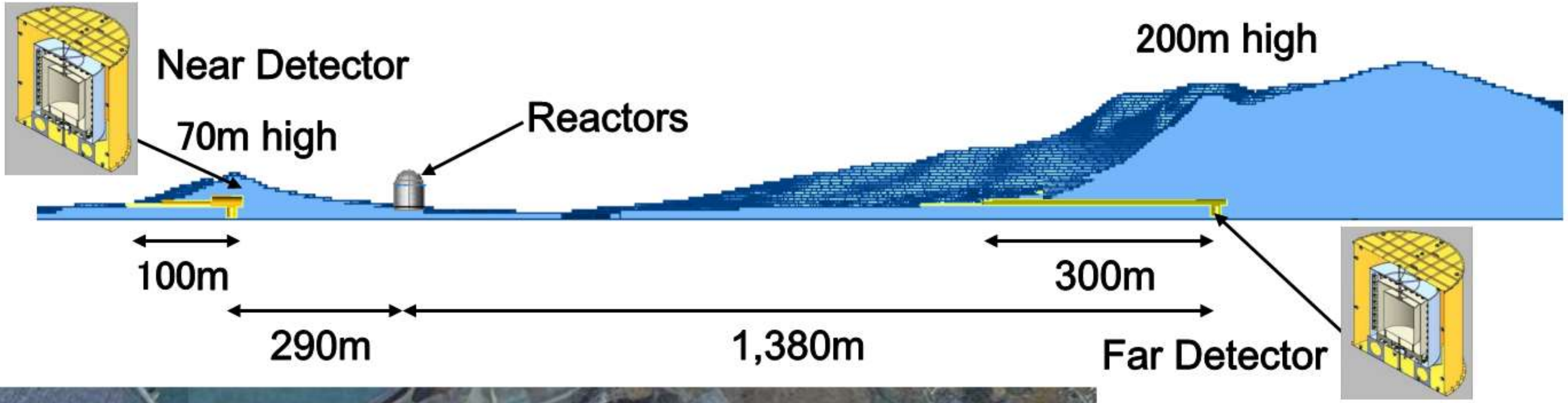
Daya Bay

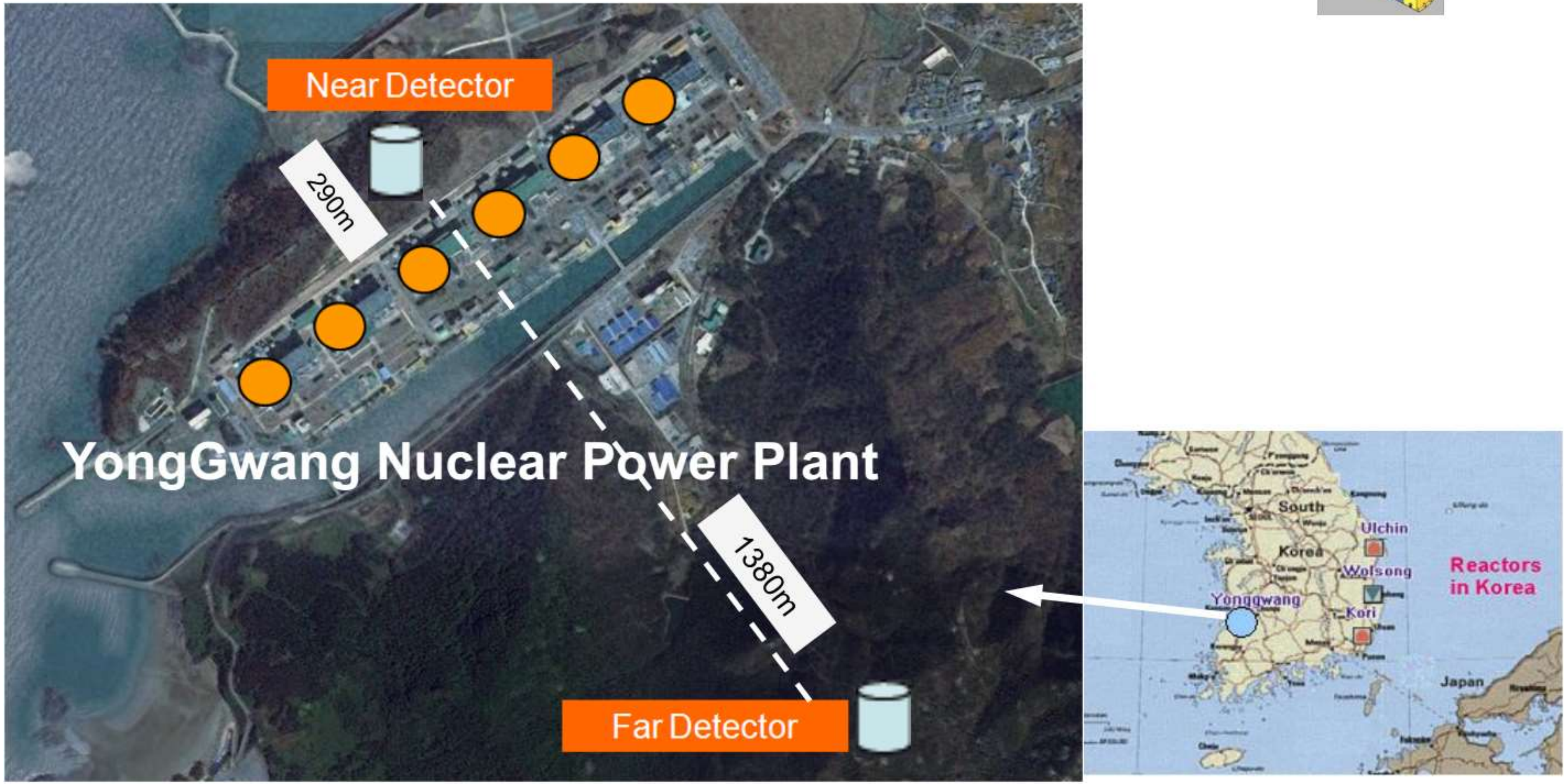
Double Chooz

Successfully measured the angle theta13.



RENO


Near Detector
70m high
Reactors
200m high
100m
290m
1,380m
300m
Far Detector

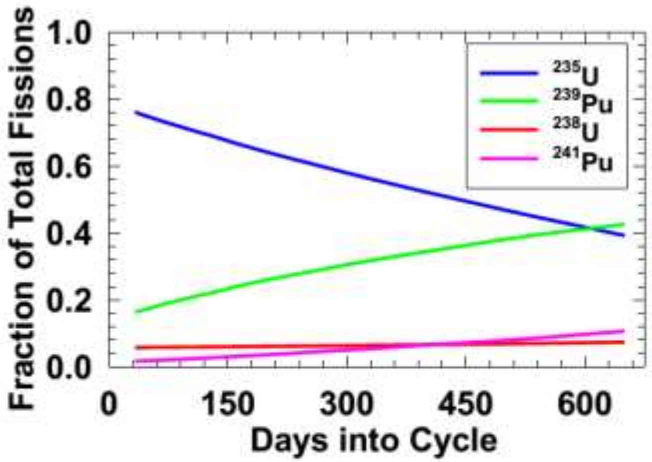

Near Detector
290m
YongGwang Nuclear Power Plant
1380m
Far Detector
South
Korea
Ulchin
Wolsong
Yonggwang
Kori
Reactors
in Korea
Japan

RENO

Slide presented
by J.C. Park at CUP
07-02-2015

How many anti-electron neutrinos we have ?

- Fuel burn-up evolution (typical reactor)



Contribution of each reactor to neutrirno flux at Far and Near Detector

Reactor #	Far (%)	Near (%)
1	13.73	6.78
2	15.74	14.93
3	18.09	34.19
4	18.56	27.01
5	17.80	11.50
6	16.08	5.58

- Hanbit Neclear Power Plant
  - Thermal Power : ~2.73 GW (× 6 reactors)
  - Assumed Isotope Fraction : 55.6%(^{235}U), 7.1%(^{238}U), 32.6%(^{239}Pu), 4.7%(^{241}Pu)
  - Nuclear fission rate : 2.73×10^{9} W/[energy released per fission (eV)]

$$= (2.73\times10^{9})(\mathrm{eV/s})/(1.6\times10^{-19})/[205\times10^{6}(\mathrm{eV})] \approx 8.3\times10^{19}/\mathrm{s}$$

  - Anti-electron neutrino : 8.3×10^{19}/s ×6 ≈ 5×10^{20}/s/reactor

RENO

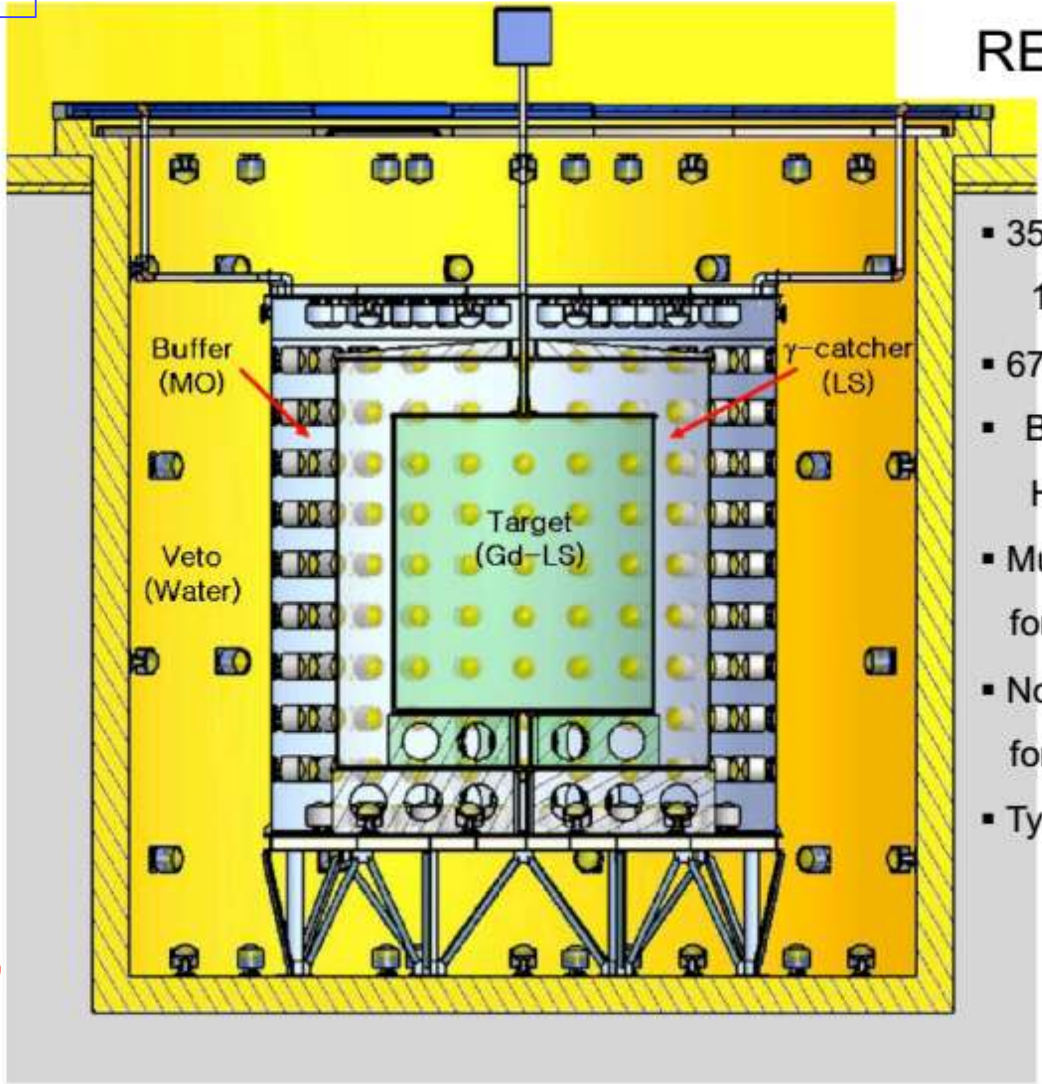
Slide presented by J.C. Park at CUP 07-02-2015

RENO Detector

RENO consists of 4 different size cylinders (symmetric & coaxial) for different purposes.

Inner detector	Inner Diameter (cm)	Inner Height (cm)	Container Material	Filled with	Mass (ton)
Target vessel	280	320	Acryl	Gd (0.1%) + LS	16.5
Gamma catcher	400	440	Acryl	LS	30.0
Buffer tank	540	580	Stainless steel	Mineral oil	64.4
Veto tank	840	880	concrete	Water	352.6

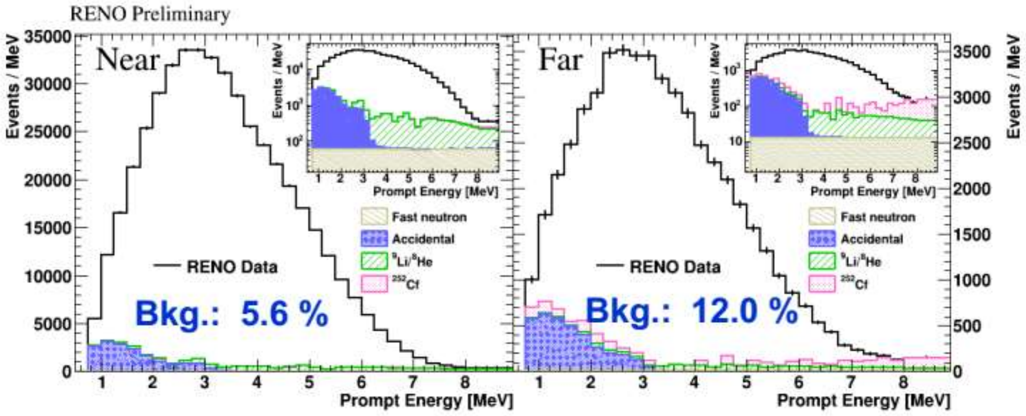
outer detector



- 354 10" ID PMTs : 13% surface coverage
- 67 10" OD PMTs
- Both PMTs are HAMAMATSU, R7081
- Mu-metal shielding for each PMT. (-5cm)
- No special reflector for ID
- Tyvek reflector at OD

RENO (presented at NDR 2015, WIN2015)

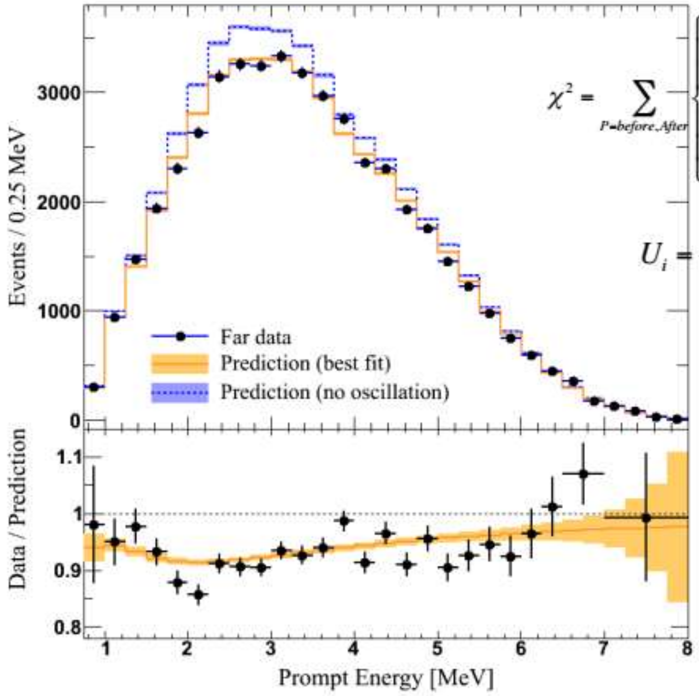
Measured Spectra of IBD Prompt Signal (NDM 2015)



Near	Far
Near Live time = 761.11 days	Far Live time = 794.72 days
# of IBD candidate = 470,787	# of IBD candidate = 52,250
# of background = 26,375 (5.6 %)	# of background = 6,292 (12.0 %)

Far/Near Shape Analysis for Δm_{ee}^2

(work in progress)



Minimize X^2 Function

$$\chi^2 = \sum_{P=before,After} \left\{ \sum_{i=1\sim N_b} \frac{\left(\frac{N_{obs}^{F,P,i}}{N_{obs}^{N,P,i}} - \frac{N_{Exp}^{F,P,i}}{N_{Exp}^{N,P,i}} \right)^2}{(U_i)^2} \right\} + Pull\_Terms$$

$$U_i = \frac{N_{obs}^{F,i}}{N_{obs}^{N,i}} \cdot \sqrt{\frac{N_{obs}^{F,i} + N_{bkg}^{F,i}}{(N_{obs}^{F,i})^2} + \frac{N_{obs}^{N,i} + N_{bkg}^{N,i}}{(N_{obs}^{N,i})^2}}$$

RENO (presented at NDR 2015, WIN2015)

Systematic Errors of θ_{13} & Δm_{ee}^2

(work in progress)

$$\sin^2 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$$

$$\Delta m_{ee}^2 = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \times 10^{-3}\ \text{eV}^2$$

Uncertainties sources	Uncertainties (%)	Errors of $\sin^2 2\theta_{13}$ (fraction)	Error of $\lvert\Delta m_{ee}^2\rvert$ [$\times 10^{-3}$eV²]
Statistics (near) (far)	0.21 % 0.54 %	0.008	0.19
Total Systematic (near) (far)	0.94 % 1.06 %	0.007	0.17
Reactor	0.9 %	0.0025 (34.2 %)	-
Detection efficiency	0.2 %	0.0025 (34.2 %)	-
Energy Scale Difference	0.15 %	0.0015 (15.6 %)	0.07
Backgrounds (near) (far)	0.14 % 0.51 %	0.0060 (82.2 %)	0.15

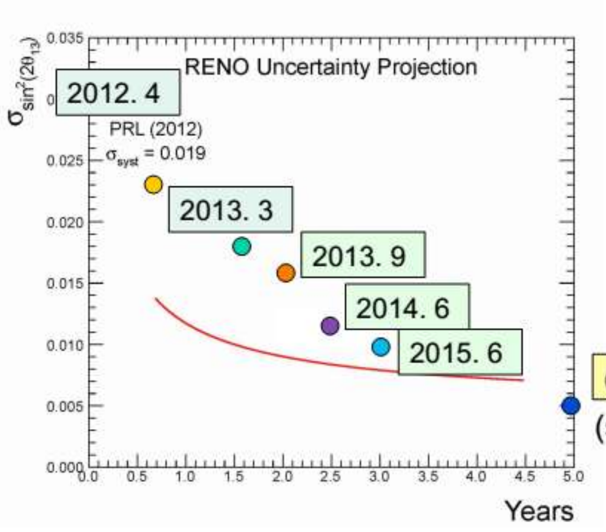
(* tentative)

Projected Sensitivity of θ_{13} & Δm_{ee}^2

NDM 2015 $\sin^2 2\theta_{13} = 0.088 \pm 0.011$ (~800 days)

± 0.005 (5 % precision) (5 years of data)

* Expected precision of Δm_{ee} : ~ 0.1×10^{-3} eV²



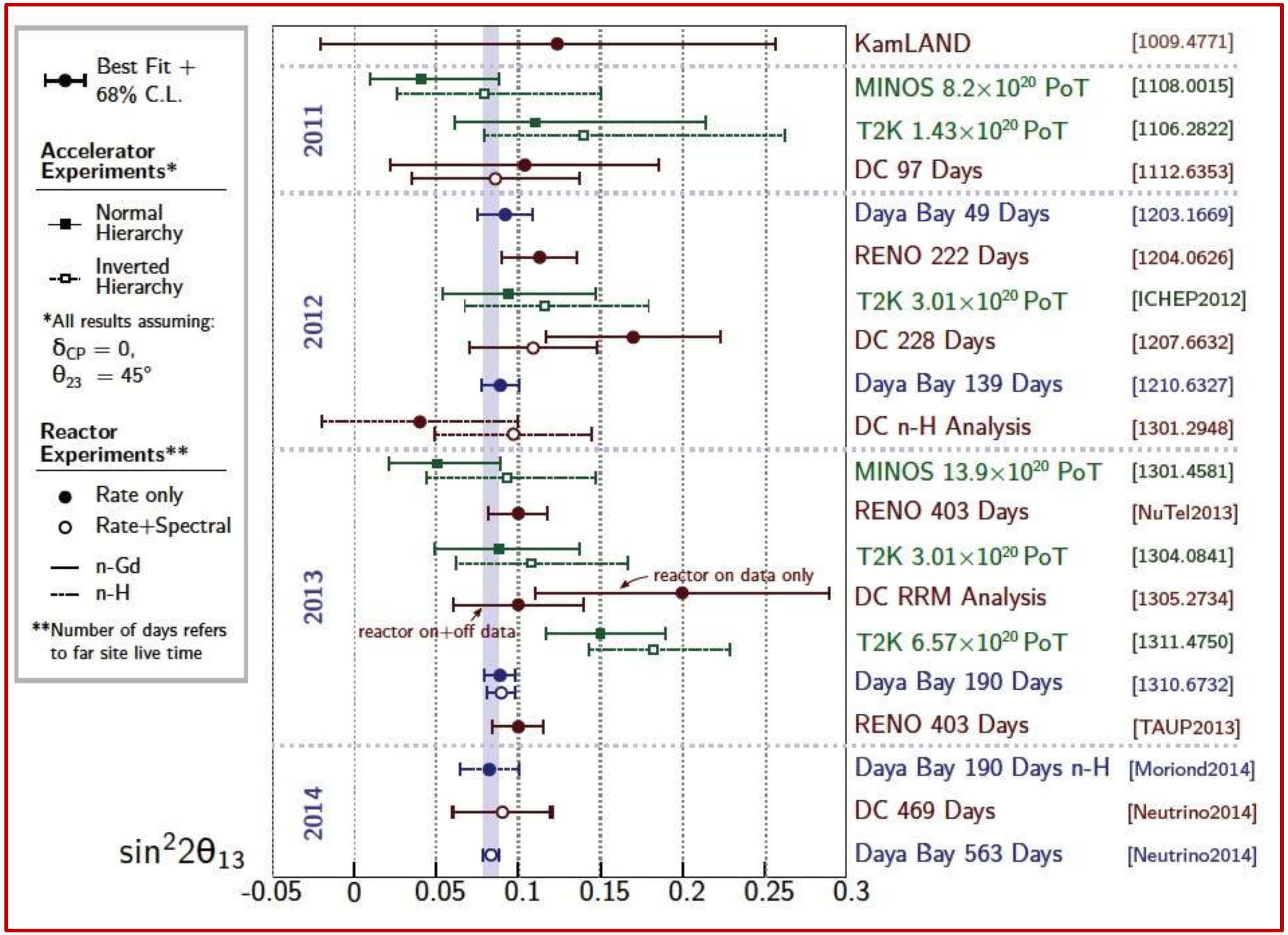
(5 % precision)

(sensitivity goal of θ_{13})

Reactor Antineutrino Oscillation

A brief history of θ_{13} from reactor experiments:

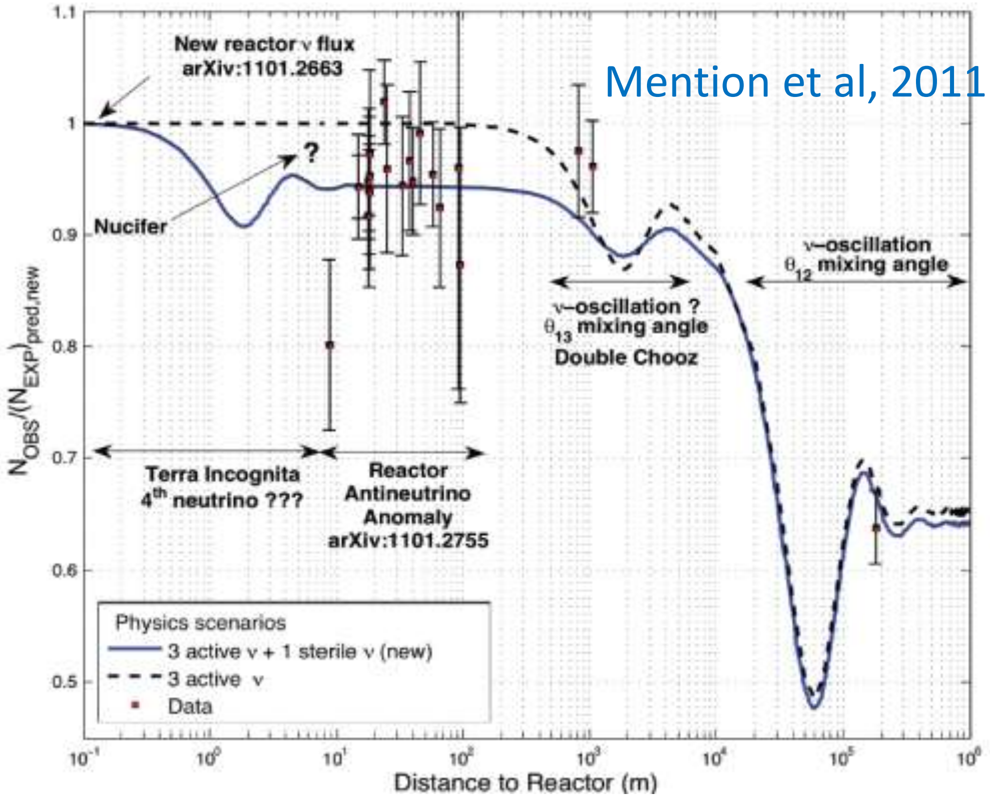
Taken from slides by Wei Wang @ ICHEP 2014

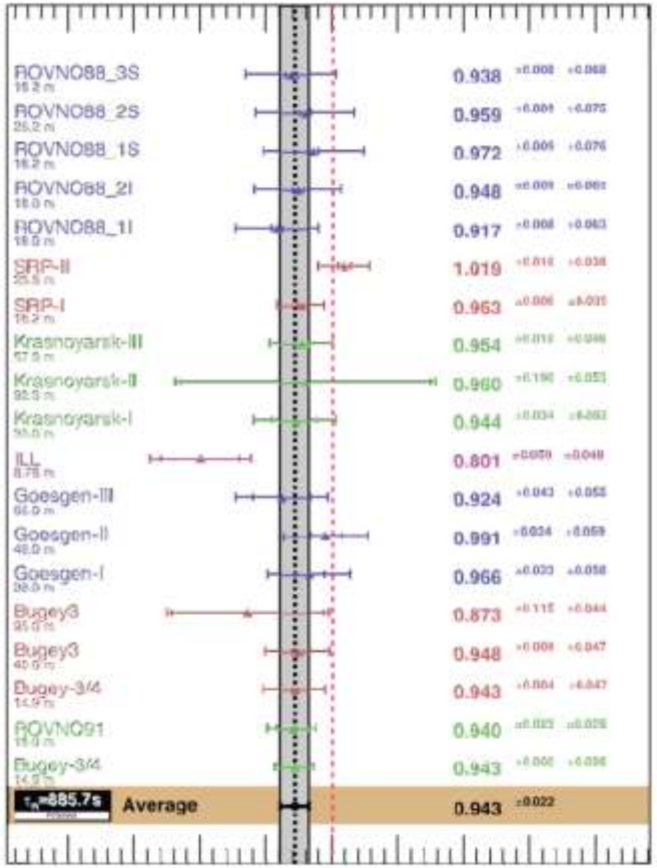


Reactor Antineutrino Anomaly

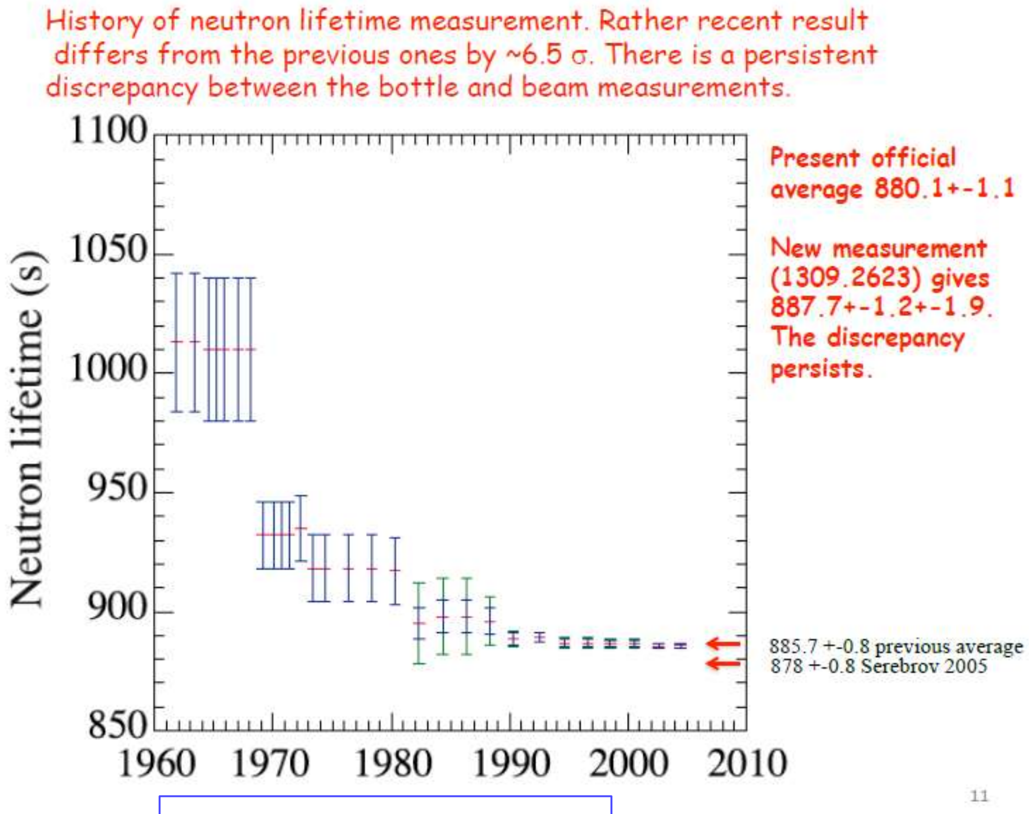
- Modification of observed-to- expected ratio based on old & new spectra.
- Neutron life time: 885.7s (PDG2012)
- Mention et al., PRD83 (2011),

Mention et al, 2011

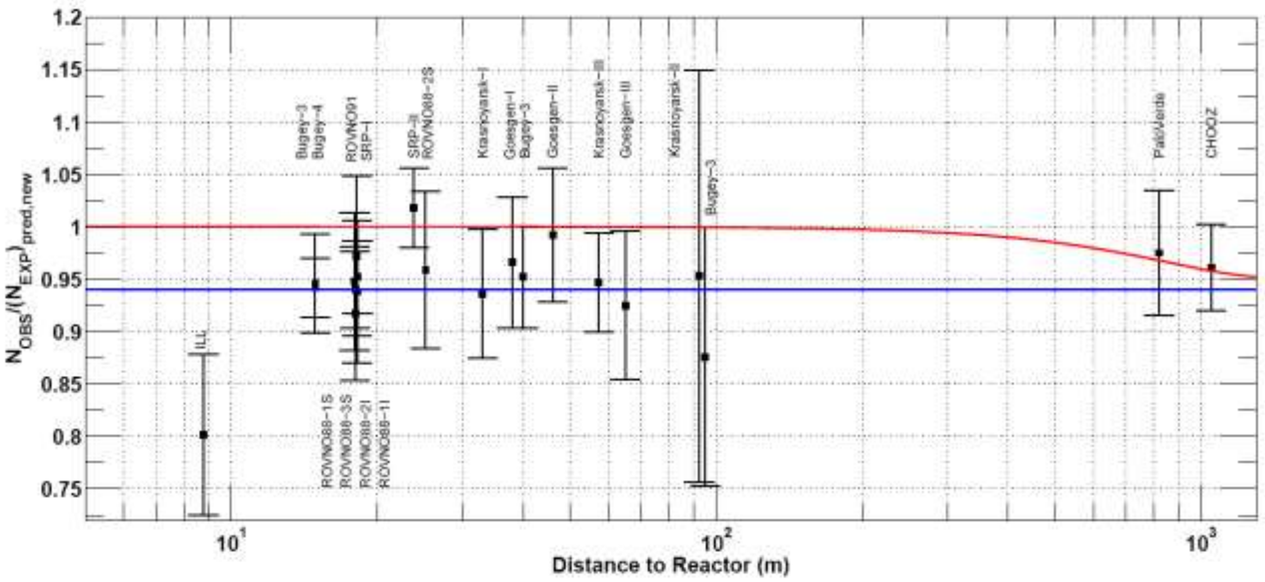




Reactor Antineutrino Anomaly



By P. Vogel, 2011



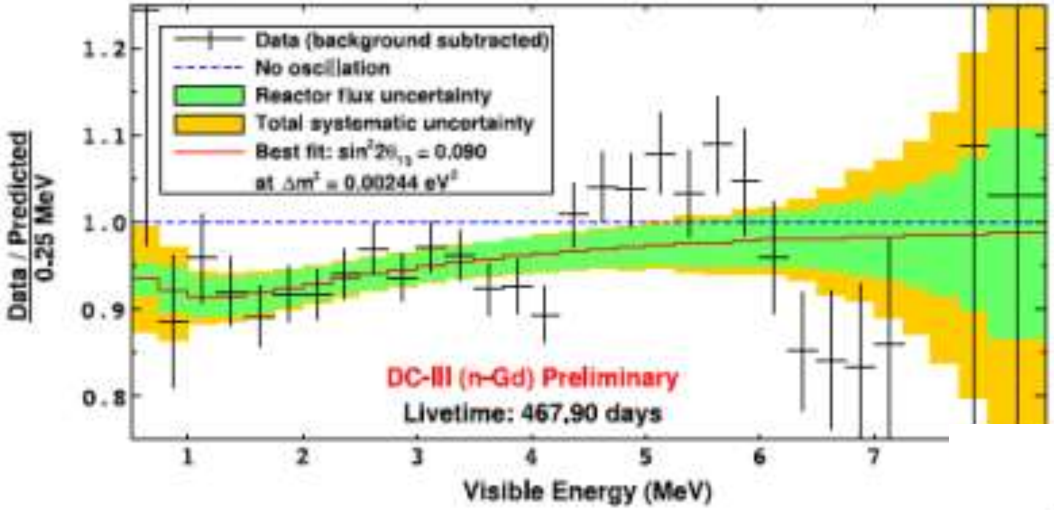
- The change in expected rate is from the increase in IBD cross section and off-equilibrium nuclei. Mueller et al., PRC83 (2011), Kopp et al., JHEP 05 (2013)
- The sum of probability of three neutrinos is less than one?

Reactor Antineutrino Anomaly

Which is your stance?	
con	The flux measurements of previous experiments were biased to satisfy the prediction in those days.
con	There are uncertainties in the beta-to-neutrino spectrum conversion.
pro	It is due to the deficit resulted from sterile neutrino oscillation with large mass.
?	None of the above.

Which is your strategy?	
Answer 1	Short-baseline neutrino oscillation to check the deficit of absolute flux.
Answer 2	Multi-detector for a single reactor to check sterile neutrino oscillation.
Answer 3	Comparison of different fuel composition. HEU vs. LEU
Answer 4	Complementary study with excessive appearance as in LSND and MiniBooNE

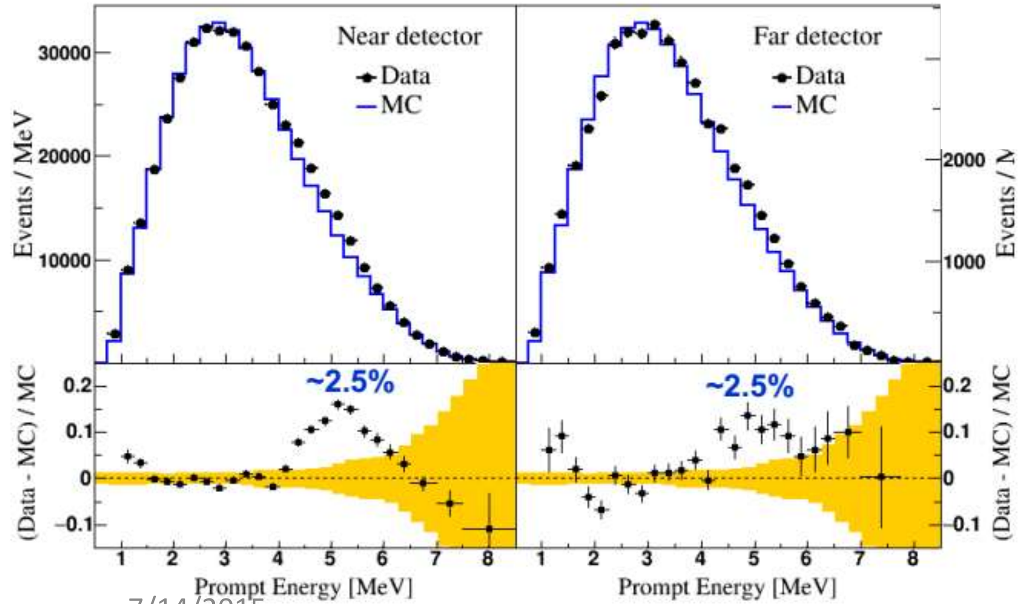
Reactor Antineutrino 5 MeV Excess



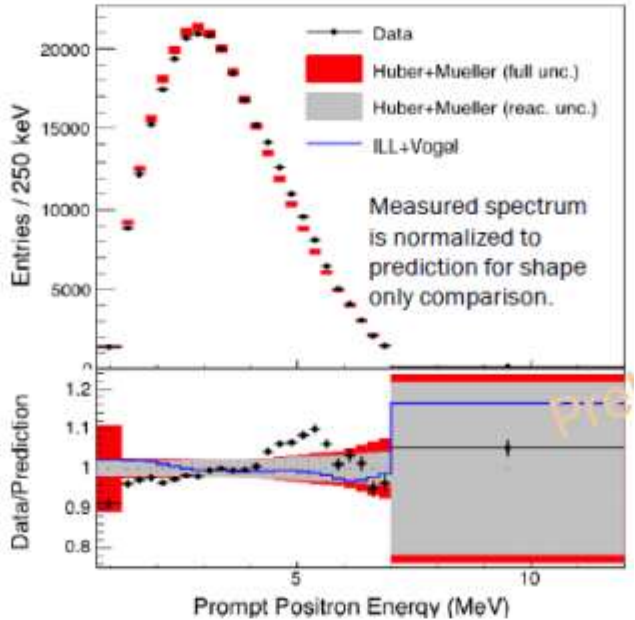
Double-Chooz, Neutrino 2014

RENO

Observation of an excess at 5 MeV



Daya Bay, ICHEP 2014

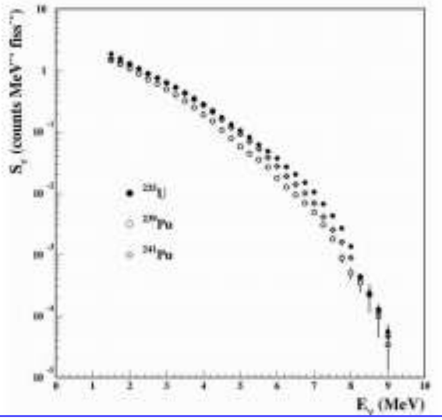


Reactor Antineutrino 5 MeV Excess

- Ways to understand the bump (or shoulder) :
  - **(1) Uncertainties in forbidden transitions and conversion of beta spectrum.**
    >> Nuclear calculation
  - (2) Enhanced phase of fourth neutrino oscillation
    >> Short baseline oscillation experiment

A. Hayes at WIN2015

The antineutrino flux used in oscillations experiments is from a conversion of the aggregate beta spectra from ILL



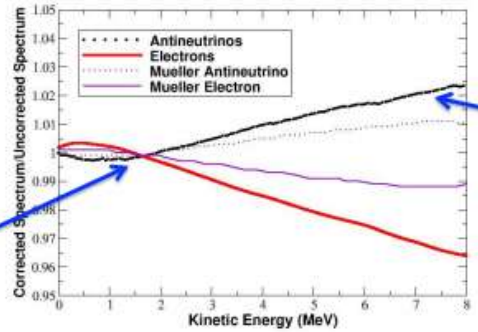
- Measurements at ILL of thermal fission beta spectra for ^{235}U, ^{239}Pu, ^{241}Pu
- Converted to antineutrino spectra by fitting to 30 end-point energies
- Use Vogel *et al.* ENDF estimate for ^{238}U
  ^{238}U ~ 7-8% of fissions =>small error
- All transitions were treated as allowed GT

- Known corrections to beta spectrum caused the neutrino spectrum anomaly.

$$\left\{\begin{array}{lll} \delta_{\rm rad} & = & \text{Radiative correction (used formalism of Sirlin)} \\ \delta_{FS} & = & \text{Finite size correction to Fermi function} \\ \delta_{\rm WM} & = & \text{Weak magnetism} \end{array}\right.$$

- If all forbidden transitions are treated as allowed GT, the corrections indicate the anomaly deficit.

$\overline{E}_0/2$



$$\cong \frac{1}{2}\left[\frac{4(\mu_v - \frac{1}{2})}{6M_n g_A} - \frac{3Z\alpha R}{2\hbar c}\right]$$

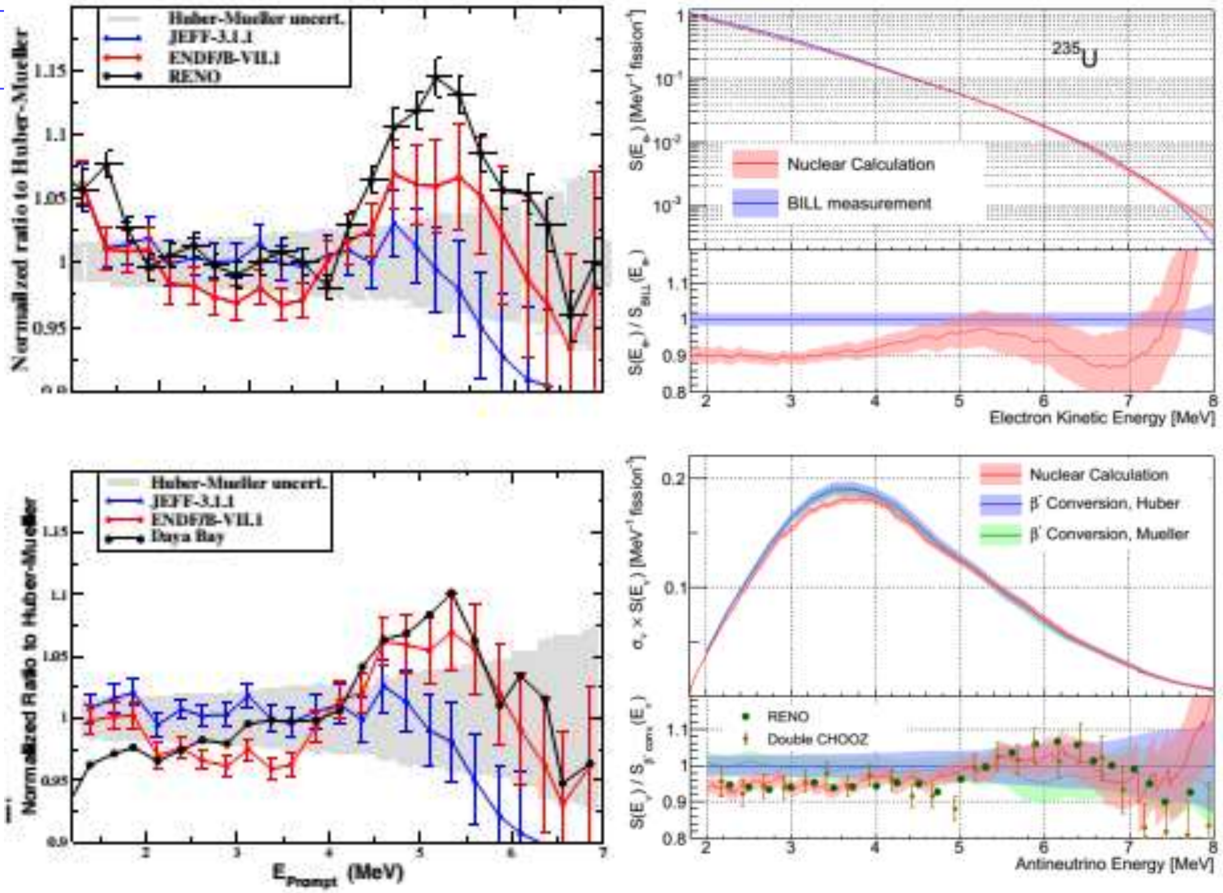
- 30% of the transitions are forbidden.

Reactor Antineutrino 5 MeV Excess

A. Hayes at WIN2015

Dwyer & Langford, PRL 114 (2015)

- Different nuclear databases do not agree on the origin of 5-MeV excess >> The uncertainties in databases should be propagated significantly.
- Suggestion:
  - HEU-fuel reactor has the advantage such that antineutrino flux is originated from a single isotope.
  - If U(238) or Pu(239) has a significant role in the 5-MeV excess or the anomaly deficit, the comparison of measurement of LEU will be necessary. >> OSIRIS or NEOS Kijang(20% 235) in comparison with RENO, Daya Bay, Double Chooz and NEOS Hanbit.

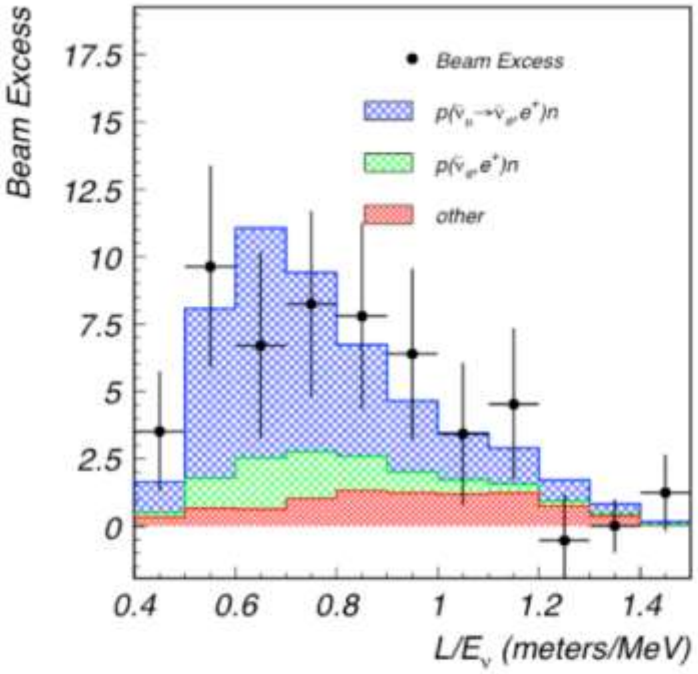


- ENDF/B-VII.1 predicts that it results from an analogous shoulder in the ILL ^{235}U β spectrum
  -Also predicts a large bump for ^{238}U
- JEFF-3.1.1 does not predict a bump for ^{235}U or ^{239}Pu
  - Agrees with Schreckenbach for both these nuclei
  - But predicts a significant bump for ^{238}U

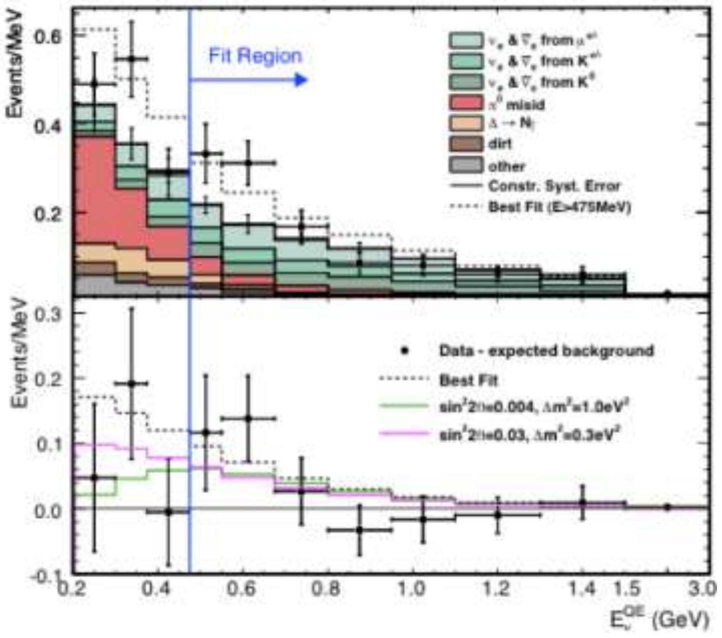
Sterile Neutrino Search

- Reactor antineutrino anomaly >> Deficit in disappearance probability
- LSND and MiniBooNE >> Excess in appearance probability

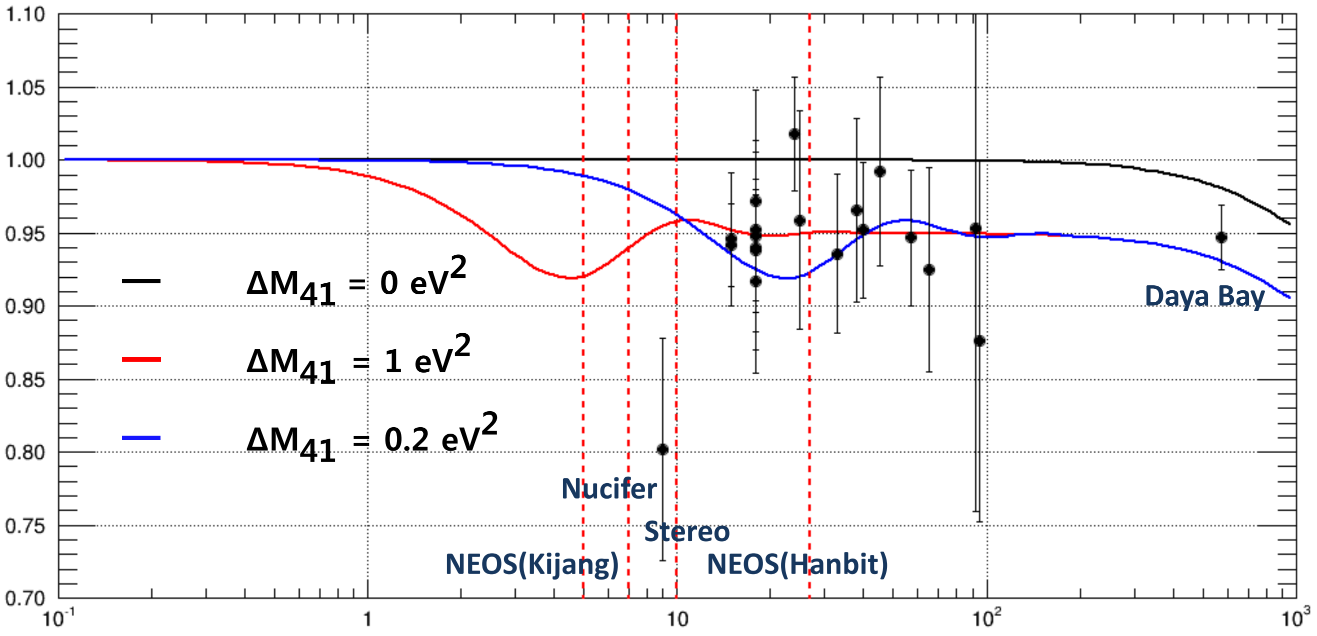
LSND



MiniBooNE



Sterile Neutrino Search

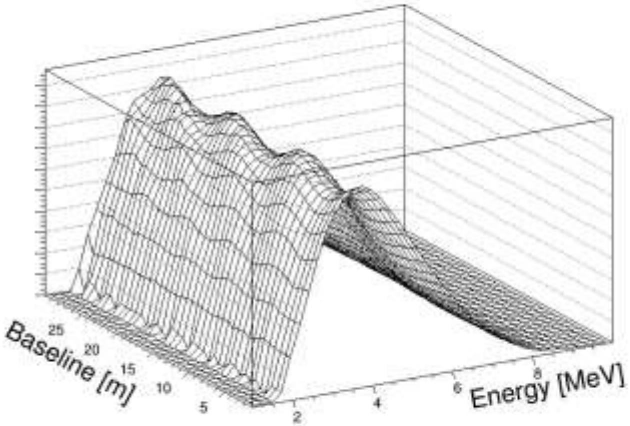


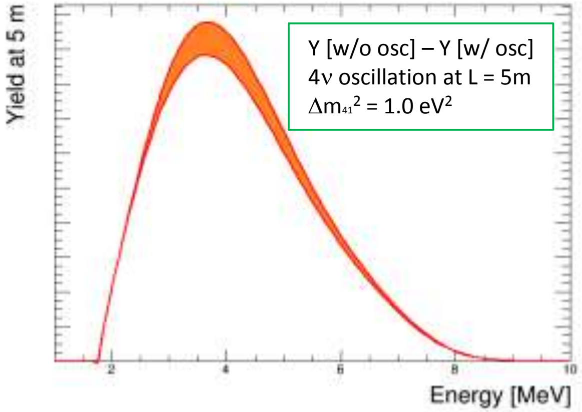
- # of events for 6 months will be about 180,000 at NEOS Hanbit.
- The character of anomalous deficit at baseline O(10m)~O(100m) will be understood with the observation at NEOS Hanbit.

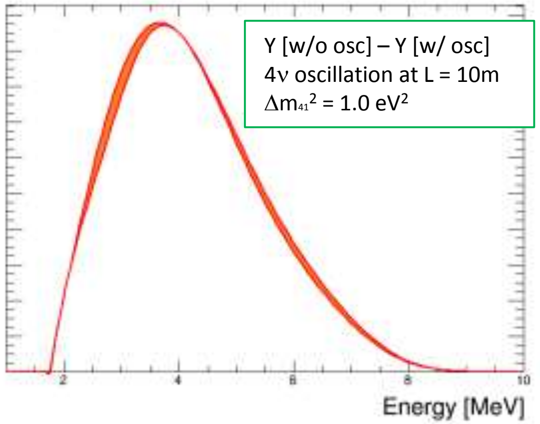
	NEOS Hanbit	NEOS Kijang	Nucifer	Stereo	DANSS	PROSPECT
Power	2.8GW	15 MW	56MW	100MW	2.7 GW	185MW
Baseline	25m	5 ~ 7m	7m	9 ~ 11m	9.7 ~ 12m	7 ~ 11m
Fuel	LEU(U^{235} 5%)	LEU(U^{235} 20%)	HEU	HEU	LEU	HEU

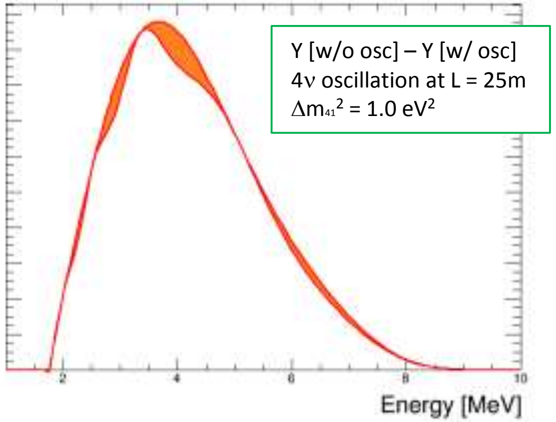
Sterile Neutrino Search

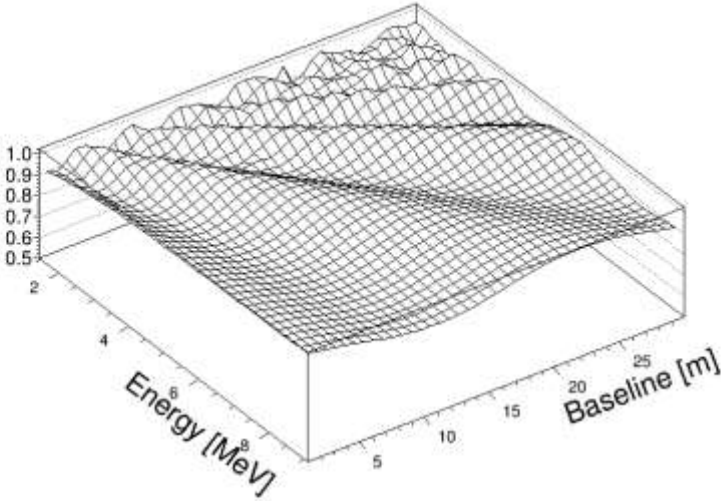
C.H. Jang @CAU

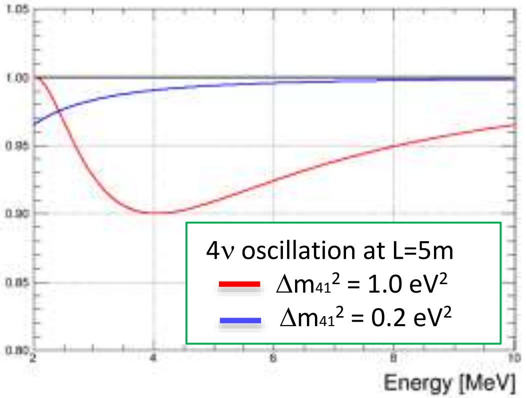


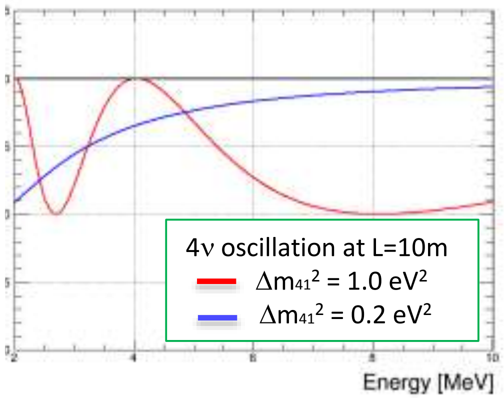


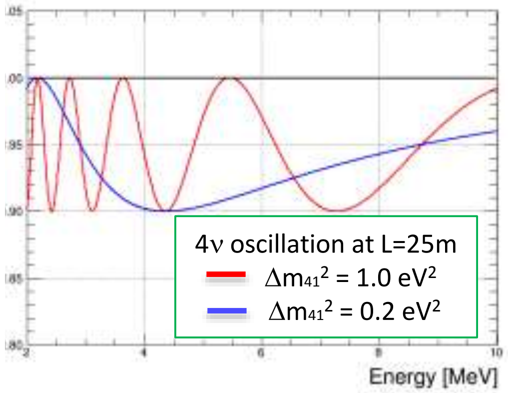






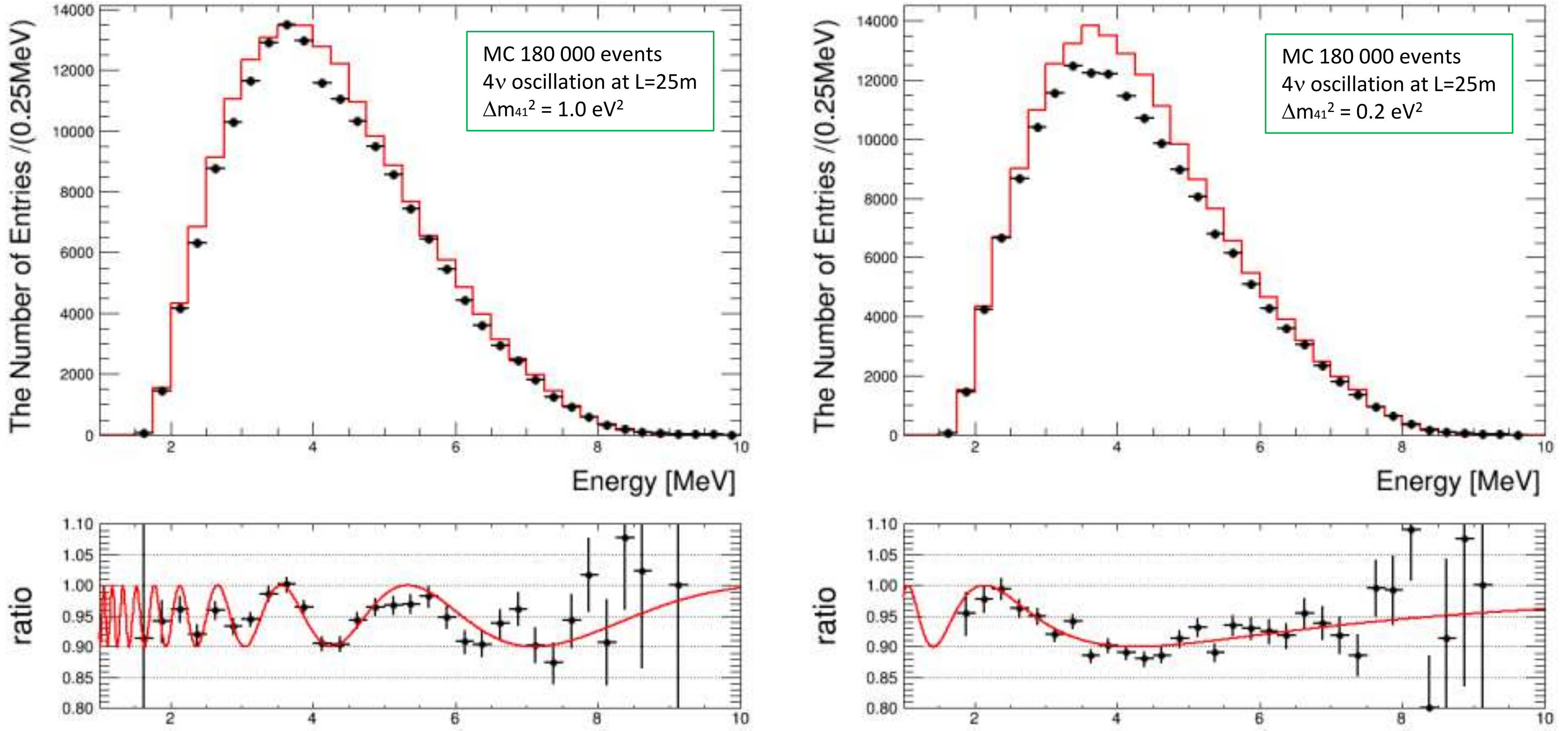






Sterile Neutrino Search

C.H. Jang @CAU



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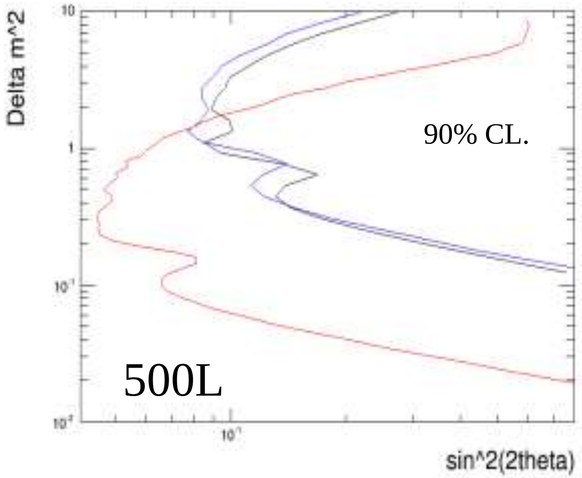
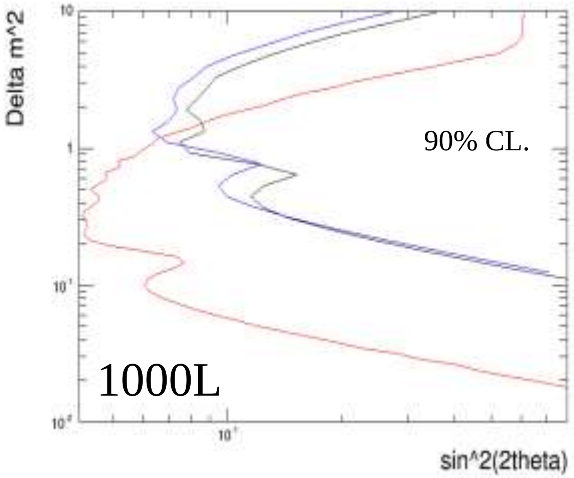
HANARO and KIJANG

candidate	baseline	thermal power	# of ibd event / day	overburden	remarks	signal to bkgd
HANARO	6m	30MW	~250	-	cancelled	0.3
KIJANG	5m	15MW	~180	~23 m.w.e.		1
HANBIT	25m	2.7GW	~1,200	16~23 m.w.e.		5

Detector Sensitivities





Hanbit-5

- The name was changed from Younggwang NPP to Hanbit NPP
- 靈光 : ghost signal

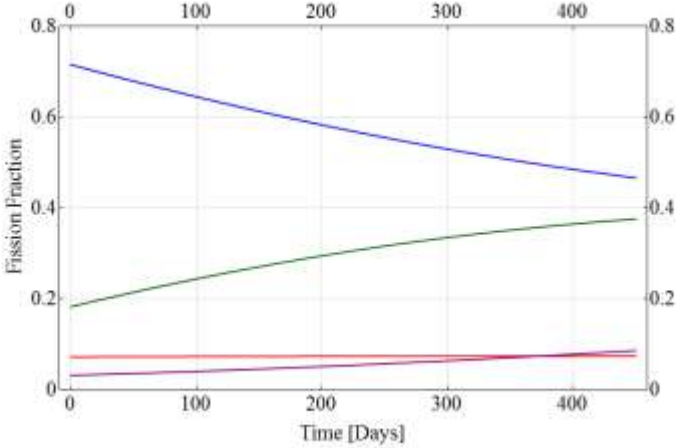
- Unit: Hanbit -5
  994MWe, 2825MWt
  Operation started on 21 May, 2002
  (from PRIS database, IAEA)
  Owner: Korea Hydro and Nuclear Power Co.

  Overhaul schedule: (cycle # 11)
  10 August ~ 25 September, 2015

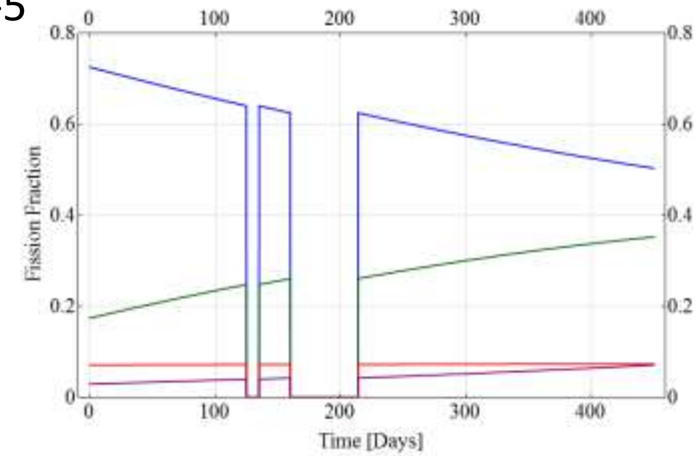
Candidate	Baseline (m)	Thermal Power (W)	Overburden (m.w.e.)	Expected S / B	Consideration
Hanaro	6	30 M	0~	<0.2	off during 2015
Kijang	5	15 M	~23	>~1?	After 2017
Hanbit	25	2.8 G	15~30	5	Commercial

Reactor Neutrino Spectrum

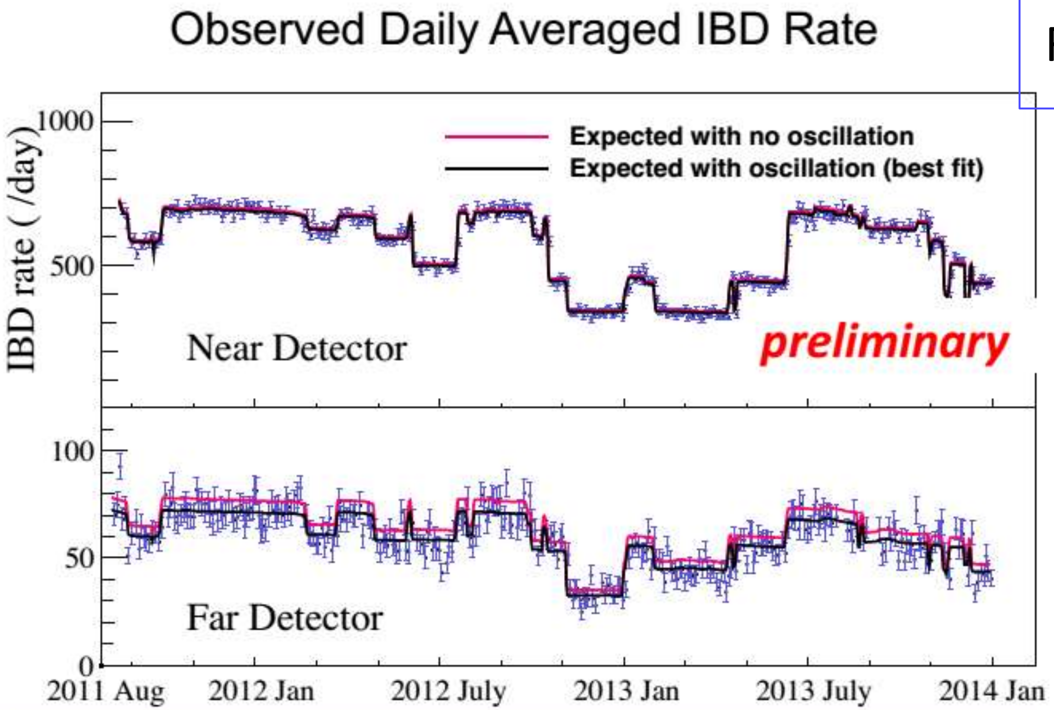
Hanbit-5
Cycle 8



Hanbit-5
Cycle 9

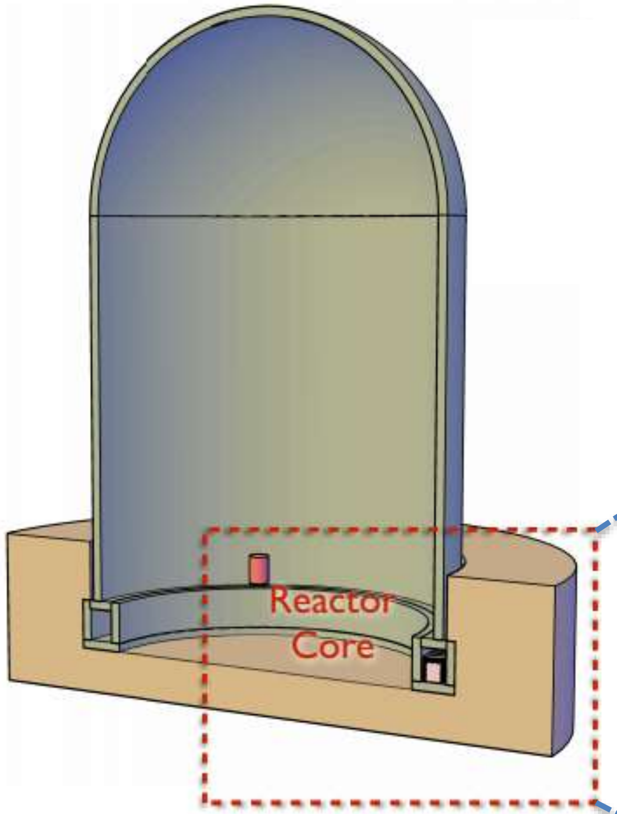


From RENO

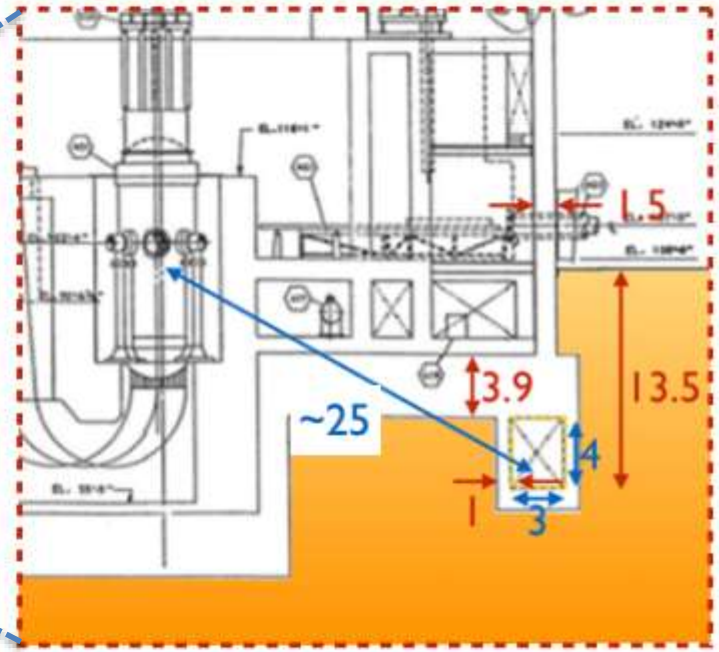


- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos

Tendon Gallery in Hanbit-5



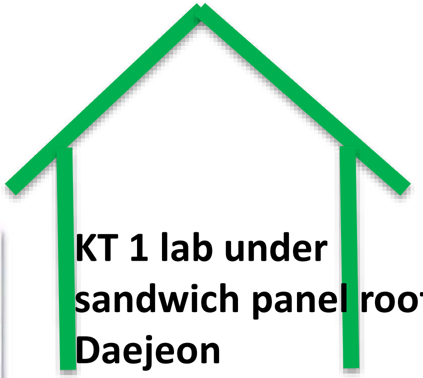
- 25-m distance from reactor core
- 10-m concrete overburden
- Expected signal / background >~ 5
- Expected number of ν_e event is about 100 /day /ton LS

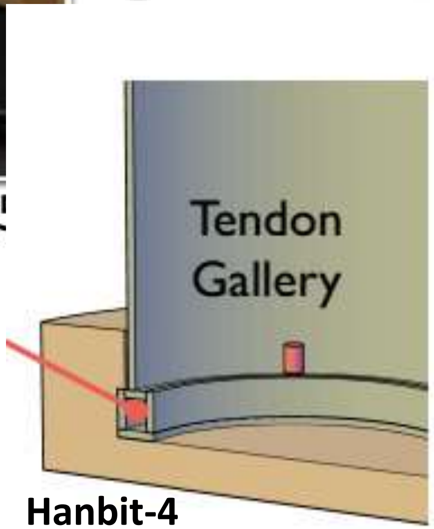


- Dimension
  - Fuel vessel in core
    r = 1.56 m
    h = 3.81 m
  - Detector
    r = 0.52 m
    h = 1.2 m

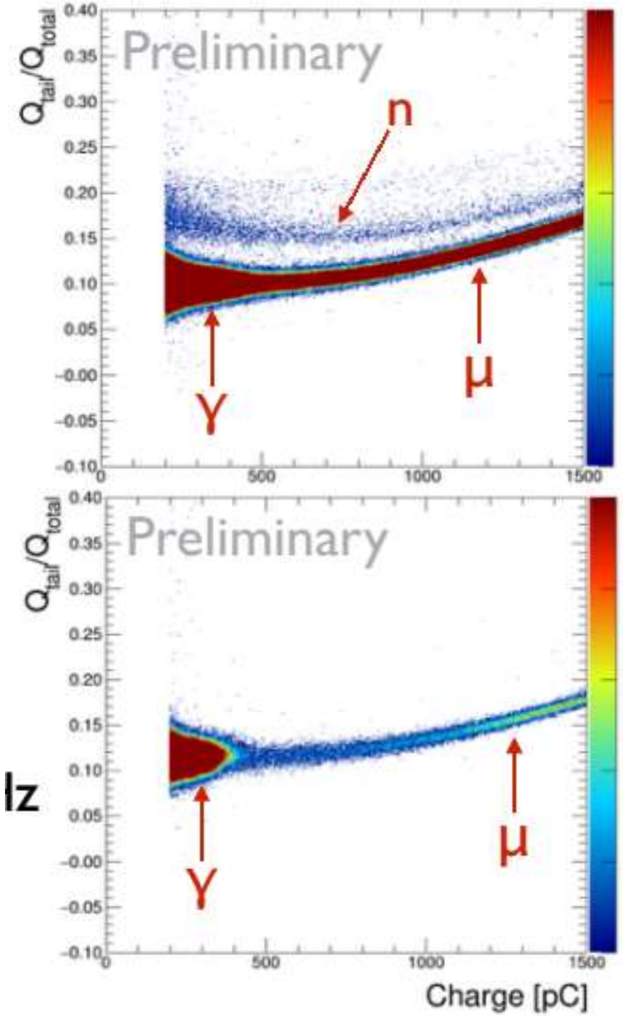
Background in Tendon Gallery

UG-F 700 mL + R877-100 (5





Hanbit-4
Younggwang



- Performance comparison in KT1 vs. Hanbit-5
- Triggered rate: 78Hz vs. 90Hz
- Neutron rate: .025 vs. below .001Hz

Outline

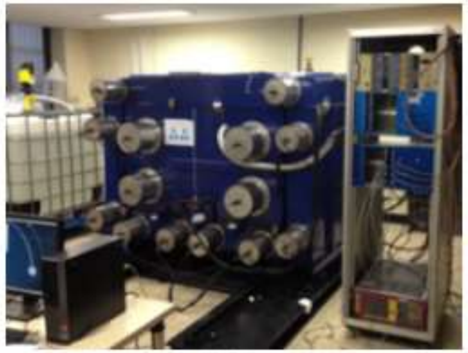
CUP and NEOS

Motivation:
Sterile Neutrino Search
Reactor Antineutrino 5-MeV Excess

STATUS:
Hanbit Reactor
Main Detector Construction

Slide presented
by Y. Oh at WIN2015

Study with Prototype

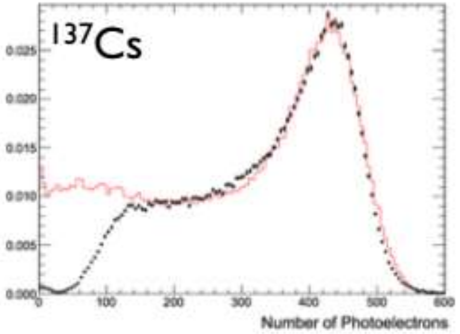


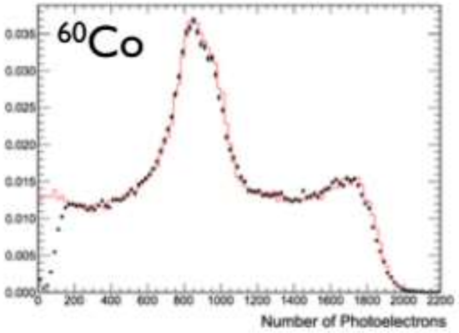
Sejong University

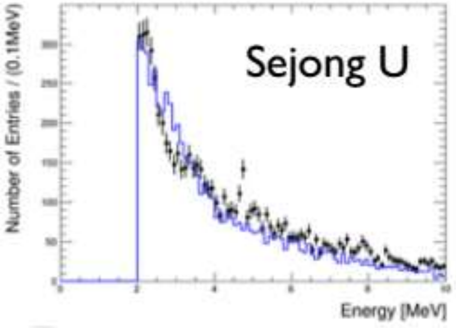
CUP Lab in Daejeon

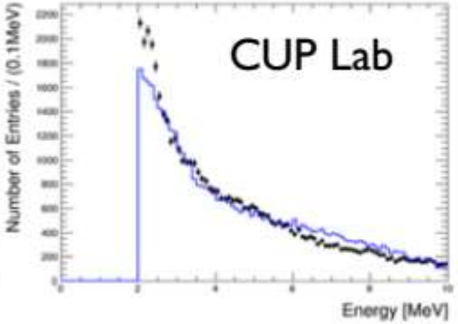
Hanaro Reactor

- 50L 0.5% Gd-LS in acrylic cylinder seen by 6 R5912.
- 4π LS μ-veto and 10 cm Pb shield.
- DAQ / calibrations / background & shielding / MC.

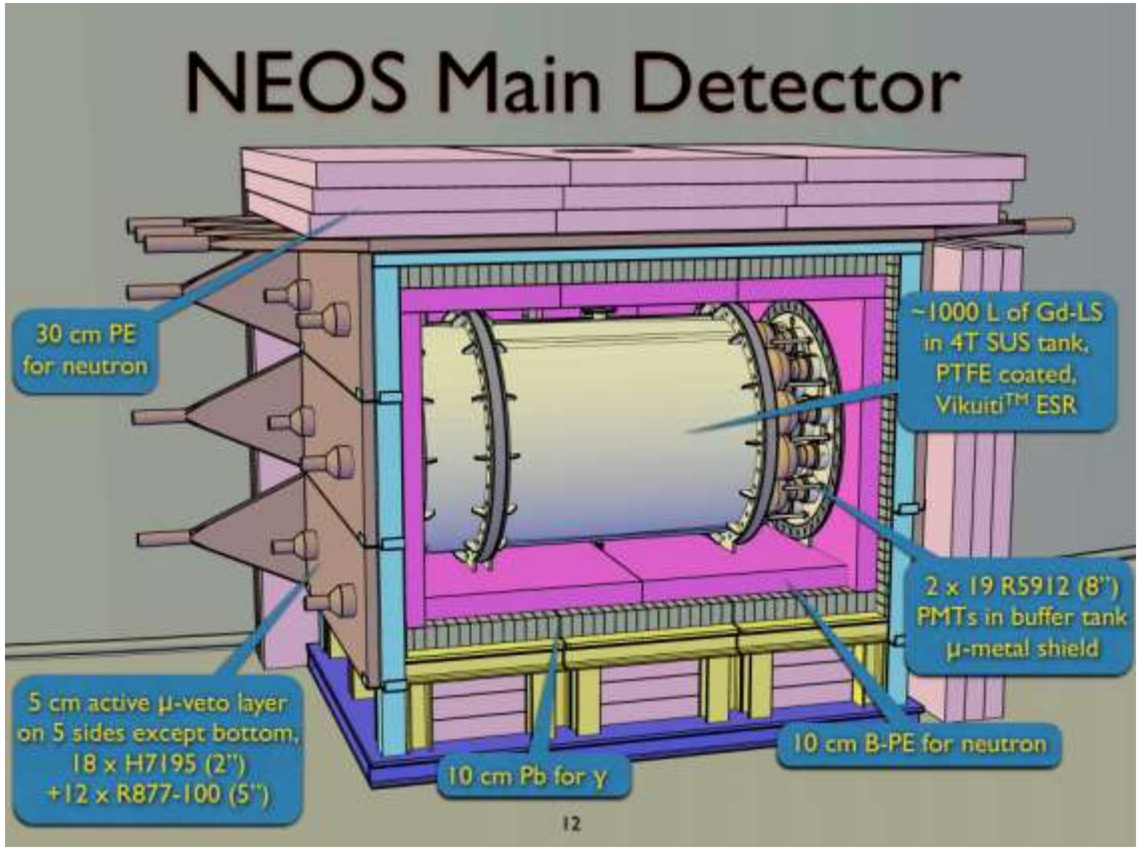








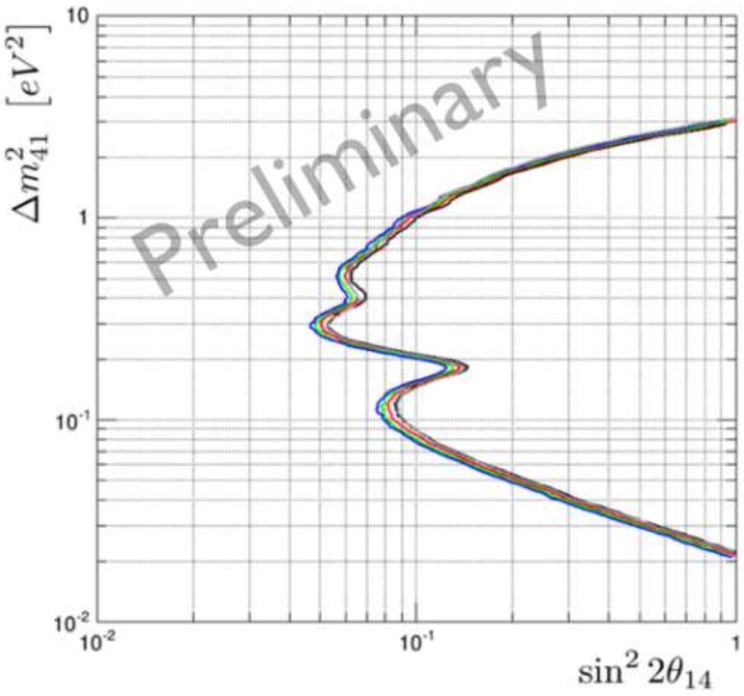
Detector Construction



Design Check Point	
Large enough to collect neutrino events efficiently?	√
Small enough to fit in a limited space in a tendon gallery? (width 3m * height 4m)	√
To minimize the loss of scintillation photons - Phototube configuration - Reflecting material (Teflon sheet)	√
Radioactive source calibration	√
Active/Passive shielding from μ, γ, n…	√

Detector

Design and Sensitivity

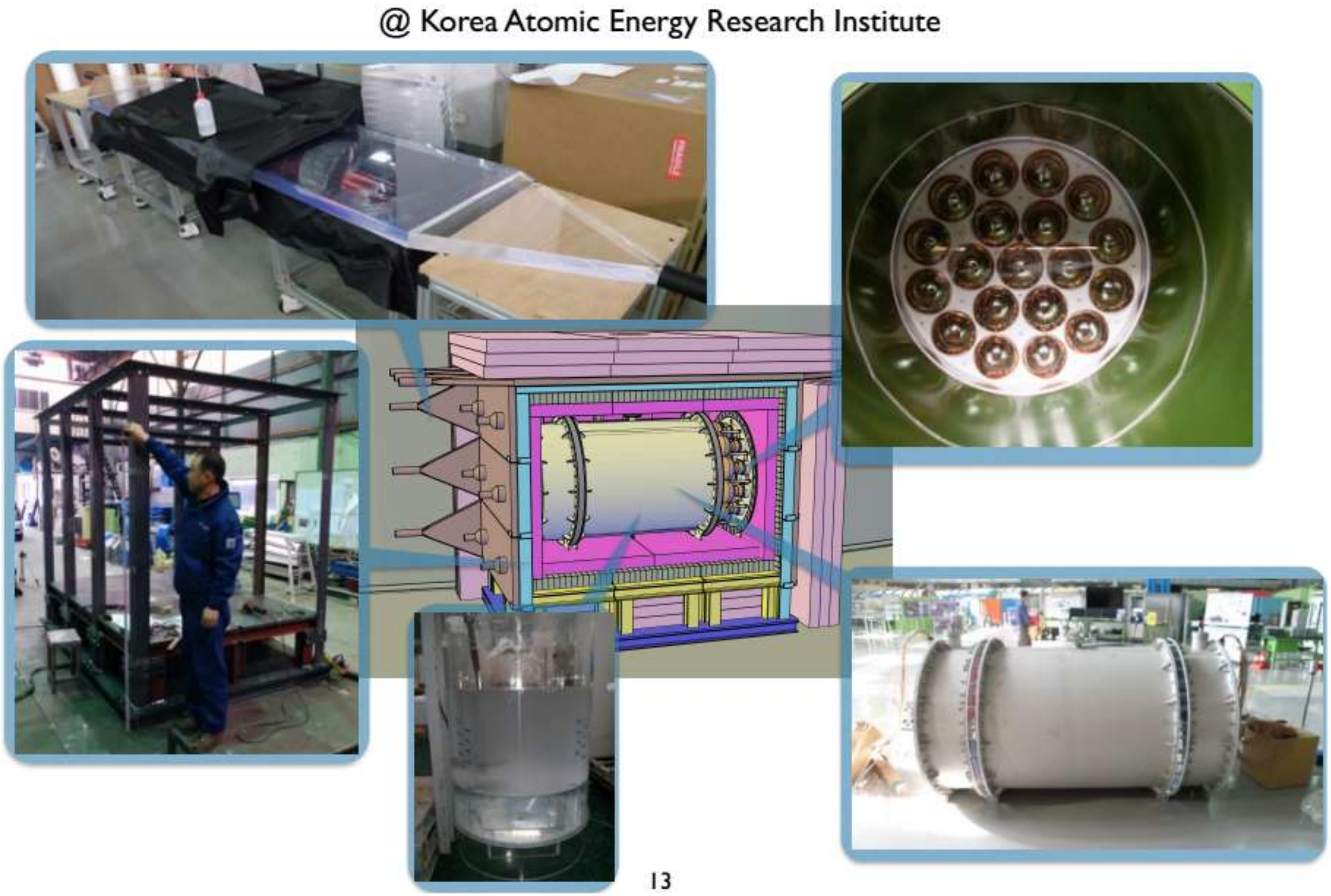


0.5 years data / 95% C.L.

Radius (cm)	Length (cm)	γ-catcher thickness
42.5	100	0
42.5	100	15 cm
47.5	100	0
52.5	100	0
52.0	120	0

Detector Assembly

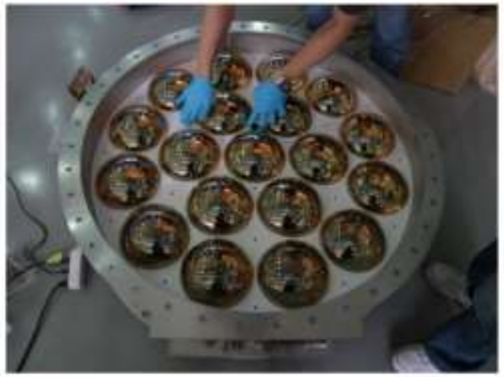
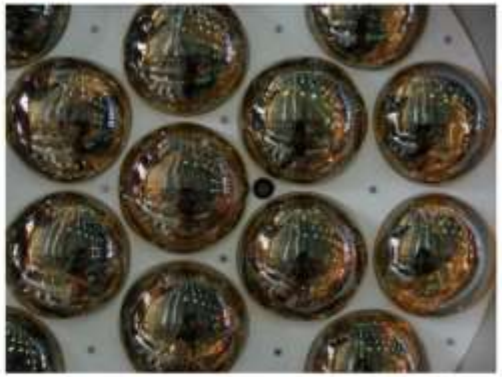
Slide presented
by Y. Oh at WIN2015



Detector Construction

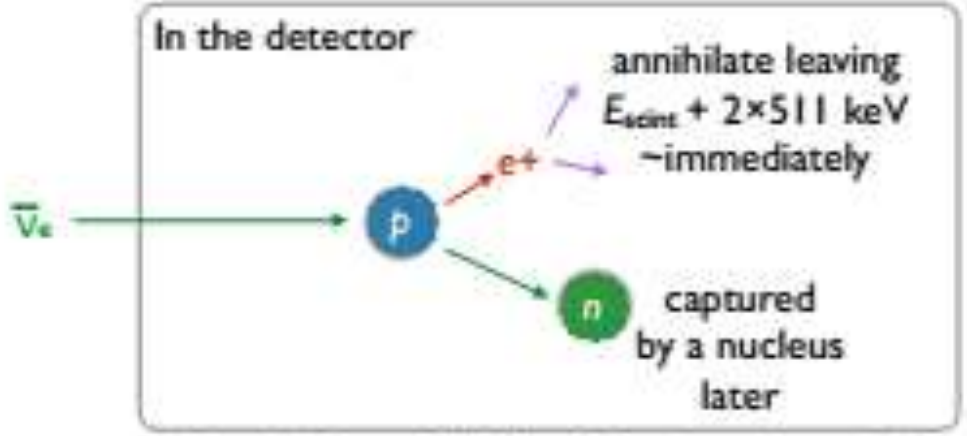




Side presented by Y. Oh
@ADFD 2015, Taiwan

$\overline{\nu}_e$ Detection: Inverse β-Decay

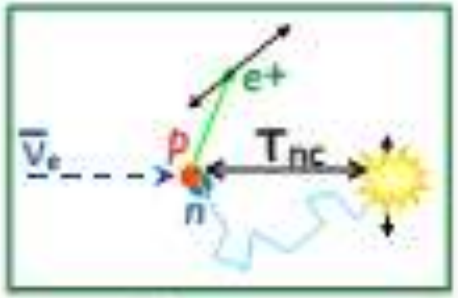


$\sigma_{IBD}(E_{\overline{\nu}_e}$~MeV) ~ O($10^{-42}$ cm^2) and scales with E^2

Detector of many hydrogen atoms,
with signals (lights) from e+ and *n*-capture.

Backgrounds

IBD:



and its mimics:

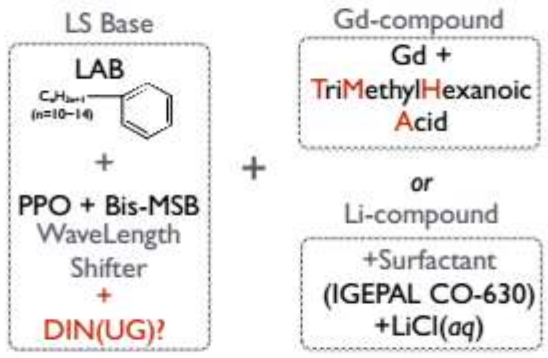
N. Bowden @ AAP 2014

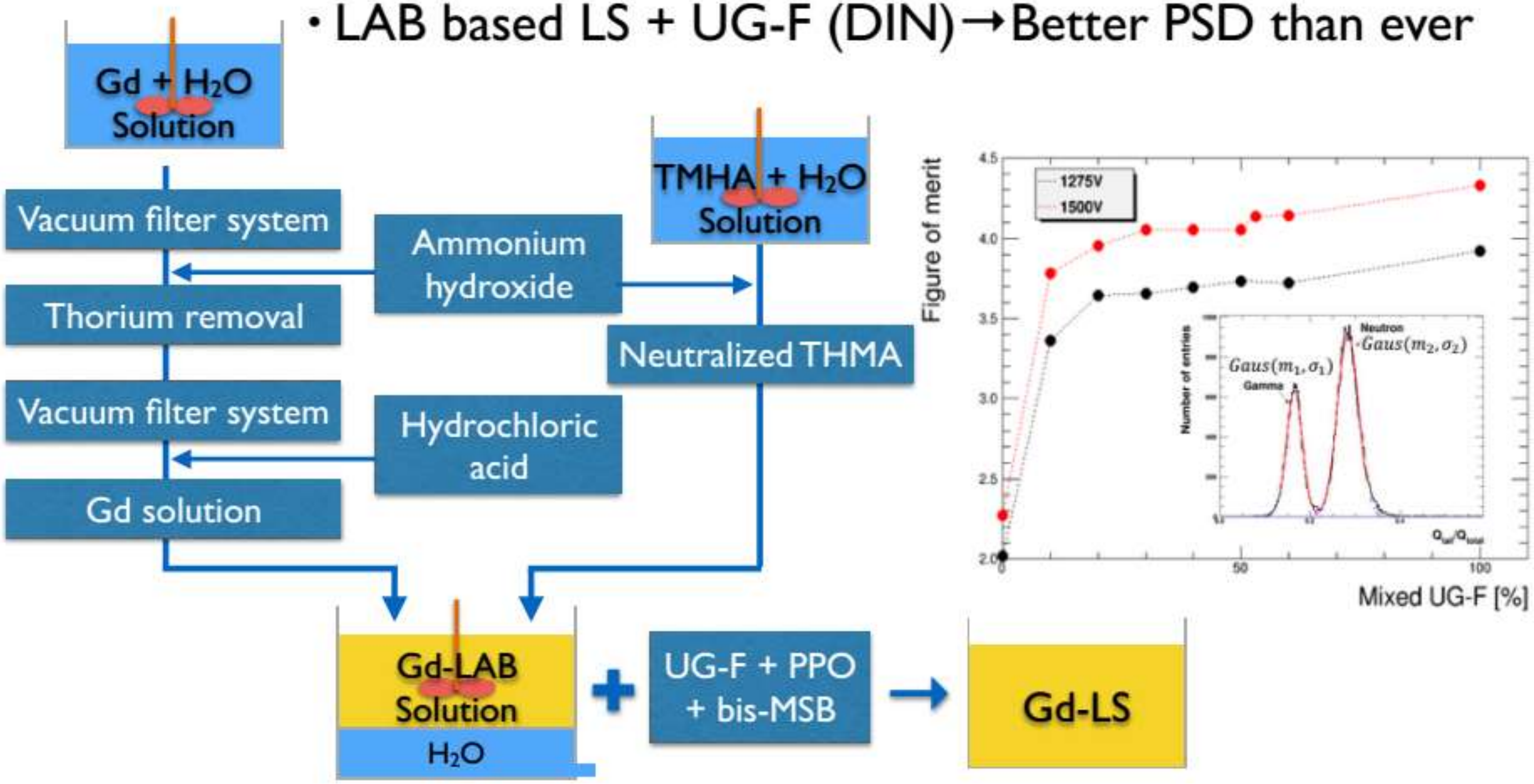
neutron recoils and correlated capture | Correlated two neutron capture | e-like deposition followed by *n*-capture

Liquid Scintillator

Slide presented
by Y. Oh at WIN2015

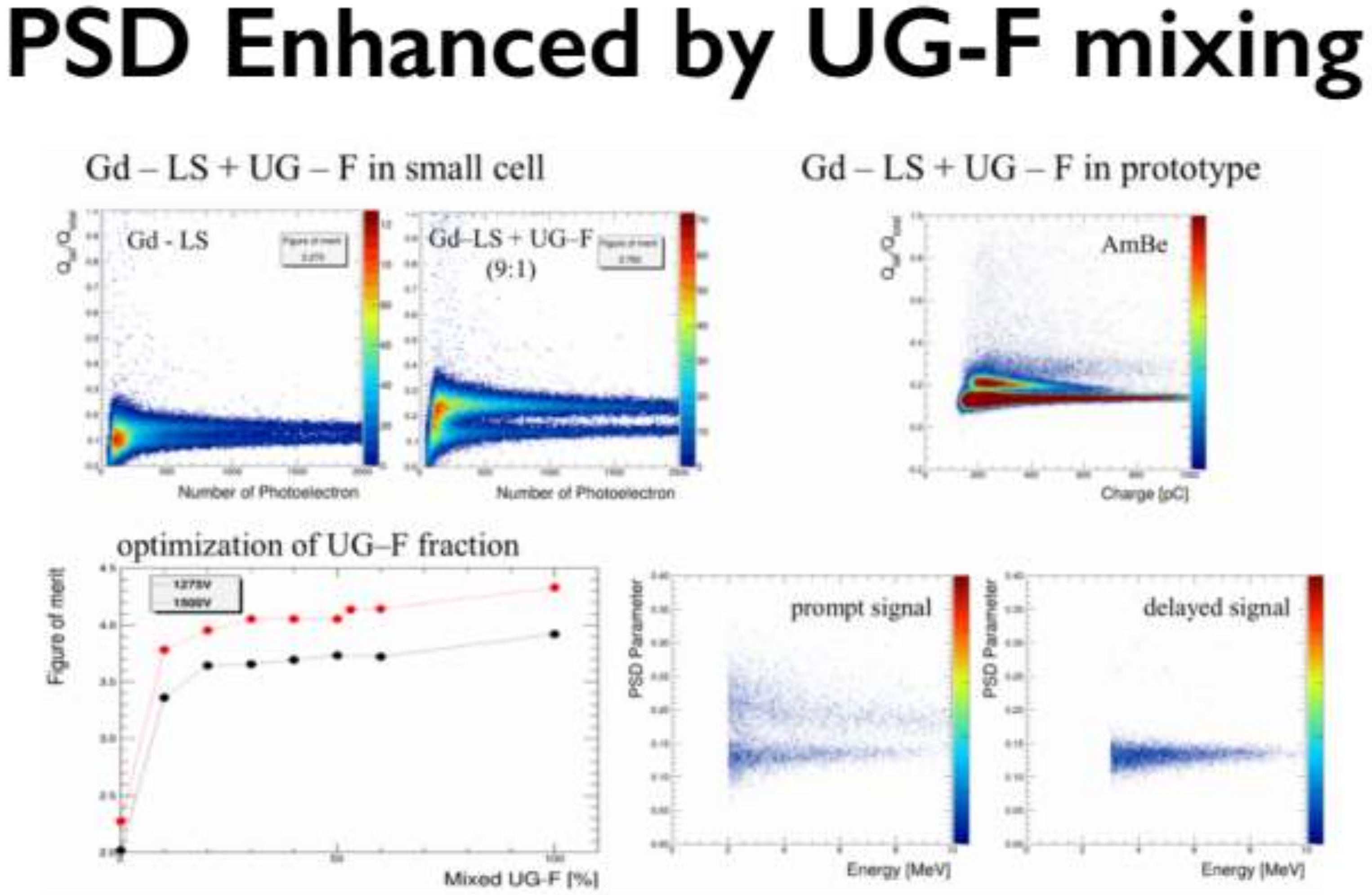
- 1020 litres of 0.5% Gd LS for the main detector
- LAB based LS + UG-F (DIN)→Better PSD than ever

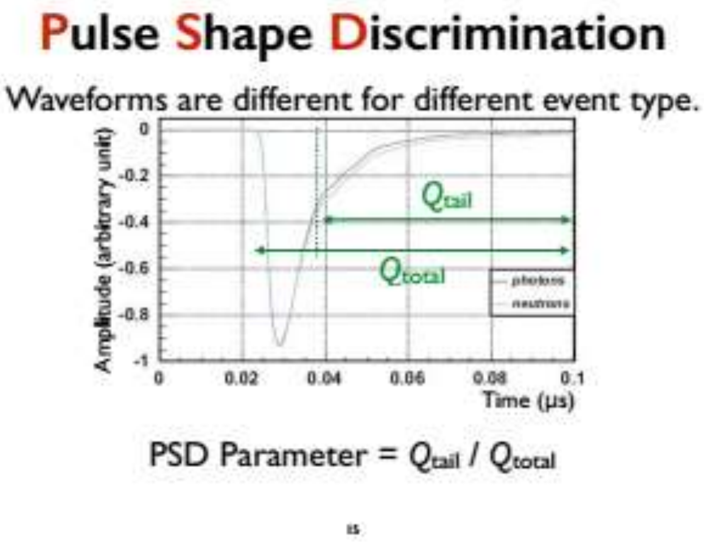




Liquid Scintillator

Slide presented
by Y. Oh at WIN2015





DAQ

40 (8*5) channels for 38 PMTs in the main detector

- 500 MHz FADC for waveform analysis (PSD)

Trigger Board

- Multiplicity trigger
- Synchronization control

30 channels for muon veto

- 64 MHz slow ADC only for veto purpose

Estimated data size: about 600 Gbytes / day /kHz

Timetable

HANARO		NEOS	
Project starts	2012 Jul		
Prototype Detector Construction	2013 Dec		
Data taking until	2014 Mar		
Plan with HANARO CANCELLED	2014 Dec	- Plan with Hanbit-5 >> Kijang	
Loading √ Moving √ Unpacking (in process) Deployment	2015 May	- Target Assembly	- Dry run
	2015 Jun	- LS/ MO ready	- Muon Veto
	2015 Jul	- Moving from KAERI to HANBIT (13)	
		- Installation on site (14~17)	
	2015 Aug	- Data w/ reactor off: Overhaul of Reactor 5 (Aug 10 ~ Sep 25)	
	2015 Sep	- Data w/ reactor on: Hanbit-5 cycle 10 starts at ‘15.09.25 23:30	
	2016 Mar	- Closure of DAQ (expected)	

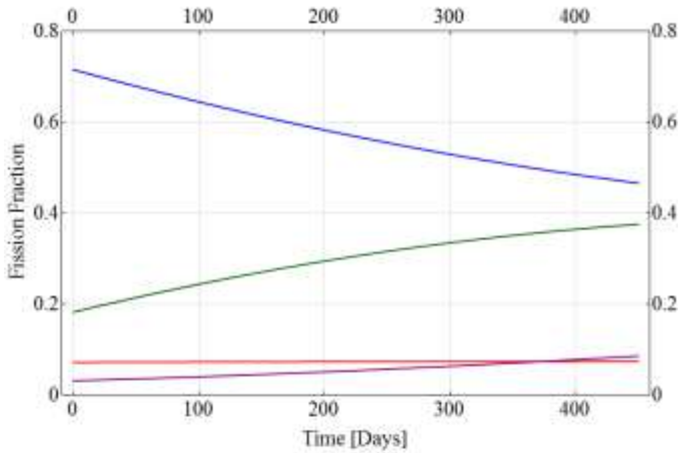
Prospect

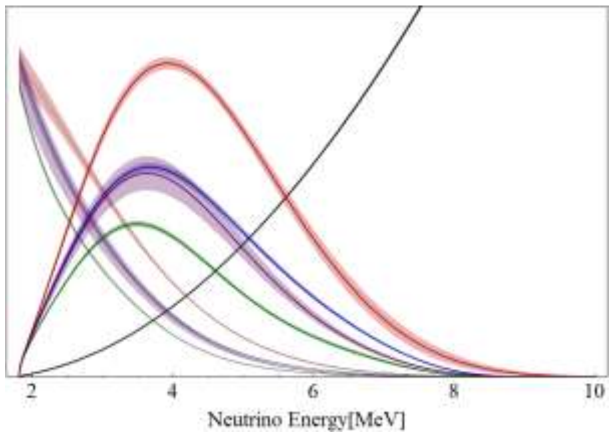
- Earliest measurement of short-baseline oscillation is expected.
- Anomaly shown in old reactor experiments will be clearly tested.
- Mass range of 4th neutrino can be directly or indirectly indicated.

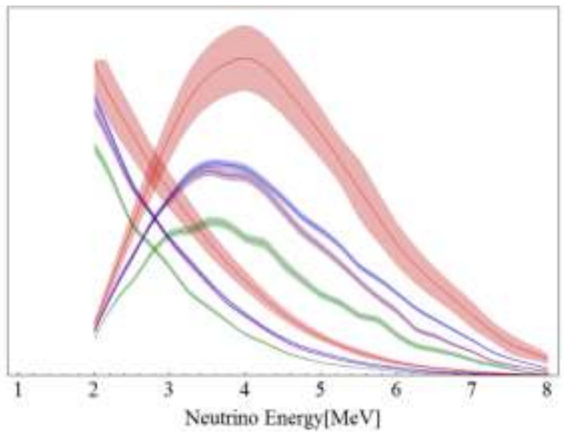
- Soon, NEOS will bring a news with data.
- Thank you very much for your interests in NEOS.

Reactor Neutrino Spectrum

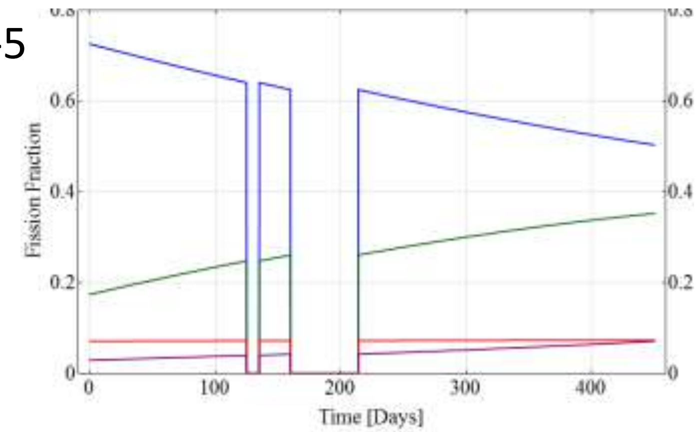
Hanbit-5
Cycle 8



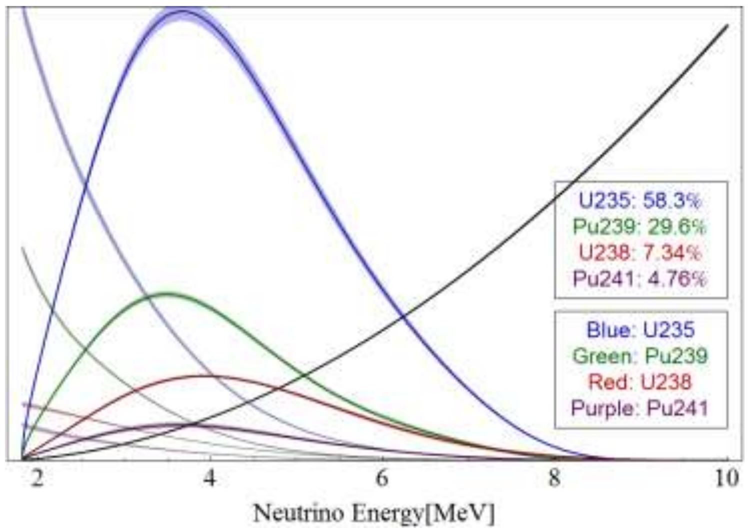




Hanbit-5
Cycle 9



U235 blue
U238 red
Pu239 green
Pu241 purple



Forbidden transitions typically involve several operators and the corrections are operator dependent

Allowed: Fermi τ and Gamow-Teller $\Sigma = \sigma\tau$

Forbidden: $\Delta L \neq 0$; $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J = \Delta L}$, $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J = \Delta L - 1}$, $\vec{r}^{L}\vec{\tau}$, $\frac{\vec{\nabla}\vec{\tau}}{\mathrm{M}}$, ...

$$S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 C(E) F(E_e, Z, A)(1 + \delta(E_e, Z, A))$$

Classification	ΔJ^π	Operator	Shape Factor $C(E)$	Fractional Weak Magnetism Correction $\delta_{WM}(E)$
Allowed GT	1^+	$\Sigma \equiv \sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v - 1/2}{M_N g_A}\right](E_e\beta^2 - E_\nu)$
Non-unique 1^{st} Forbidden GT	0^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e$	0
Non-unique 1^{st} Forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	λE_0^2	0
Non-unique 1^{st} Forbidden GT	1^-	$[\Sigma, r]^{1-}$	$p_e^2 + E_\nu^2 - \frac{4}{3}\beta^2 E_\nu E_e$	$\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2 + E_\nu^2)(\beta^2 E_e - E_\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2 + E_\nu^2 - 4\beta^2 E_\nu E_e/3)}\right]$
Unique 1^{st} Forbidden GT	2^-	$[\Sigma, r]^{2-}$	$p_e^2 + E_\nu^2$	$\frac{3}{5}\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2 + E_\nu^2)(\beta^2 E_e - E_\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2 + E_\nu^2)}\right]$
Allowed F	0^+	τ	1	0
Non-unique 1^{st} Forbidden F	1^-	$r\tau$	$p_e^2 + E_\nu^2 + \frac{2}{3}\beta^2 E_\nu E_e$	0
Non-unique 1^{st} Forbidden $\vec{J}_V$	1^-	$r\tau$	E_0^2	-