Neutrino Mass Hierarchy in Reactor ν Experiments

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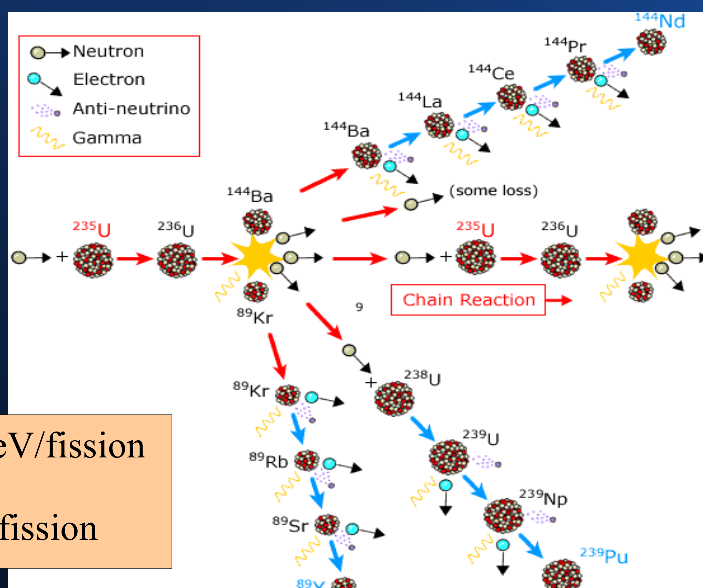
Overview

- Reactor neutrino experiments
- Measurements of the mixing angle θ_{13}
- Mass hierarchy with reactor neutrinos
- Daya Bay II and RENO-50 projects

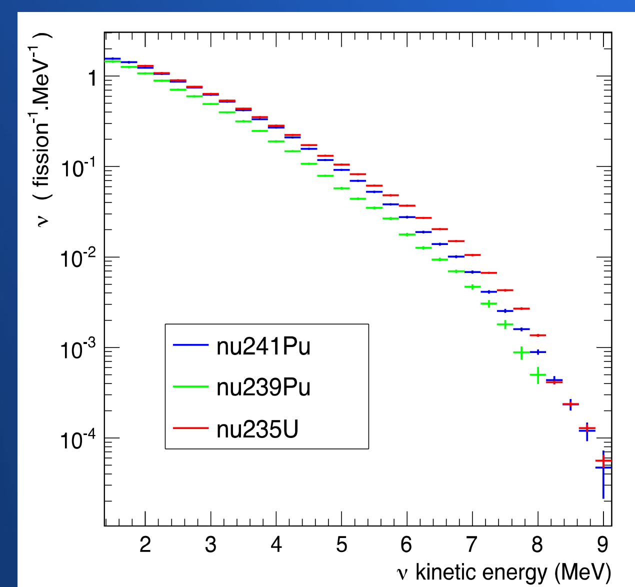
Nuclear Reactors as a ν source

- Intense and pure source of $\bar{\nu}_e$
  - fission products from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu
  - Flux depends on fuel composition (varies with time): $1GW_{th}$ -> 2×10^{20} $\bar{\nu}$/s



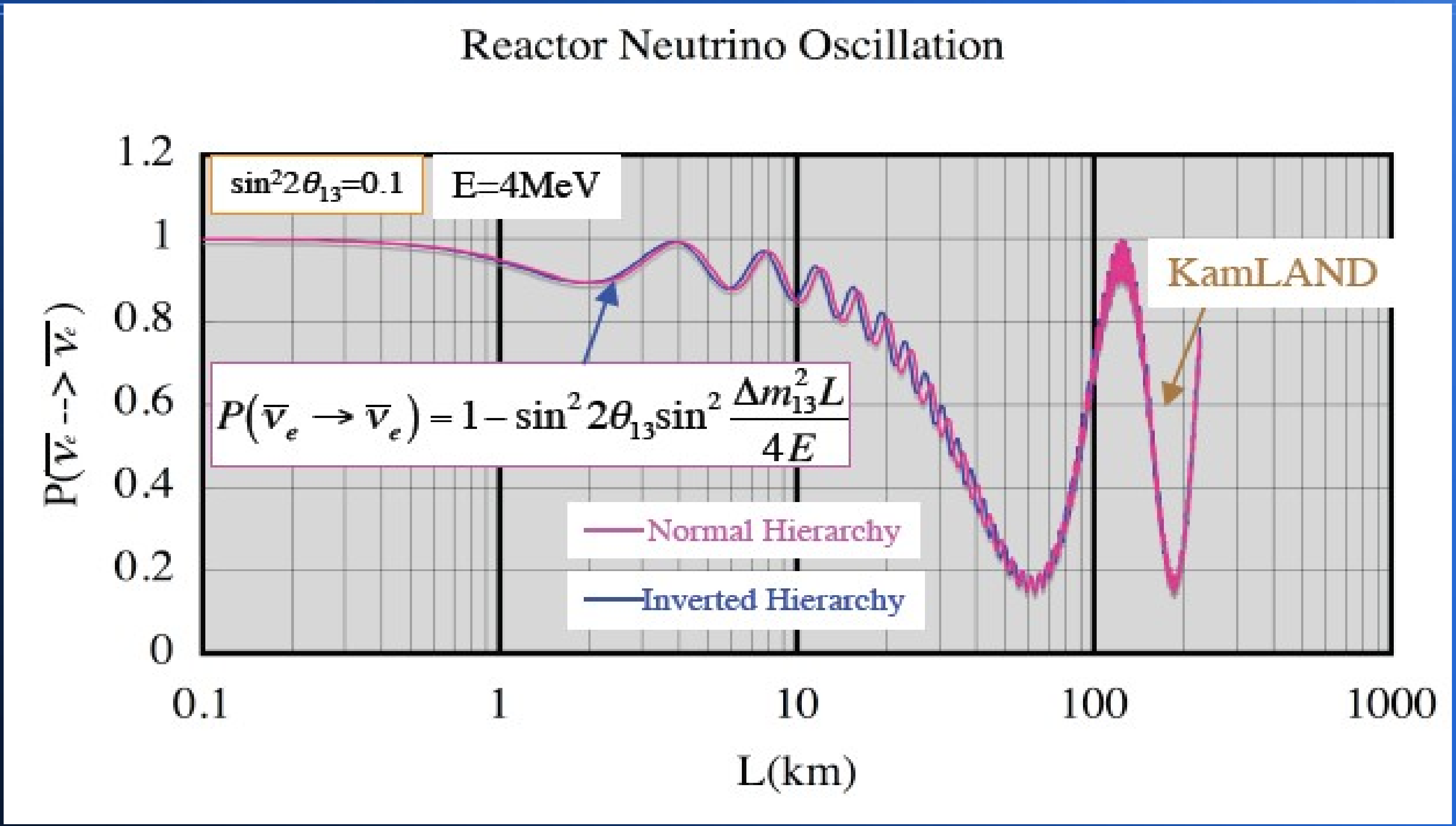
~200 MeV/fission

~6 $\bar{\nu}$/fission



- *Well known* neutrino source: ~2%

Reactor neutrino oscillation



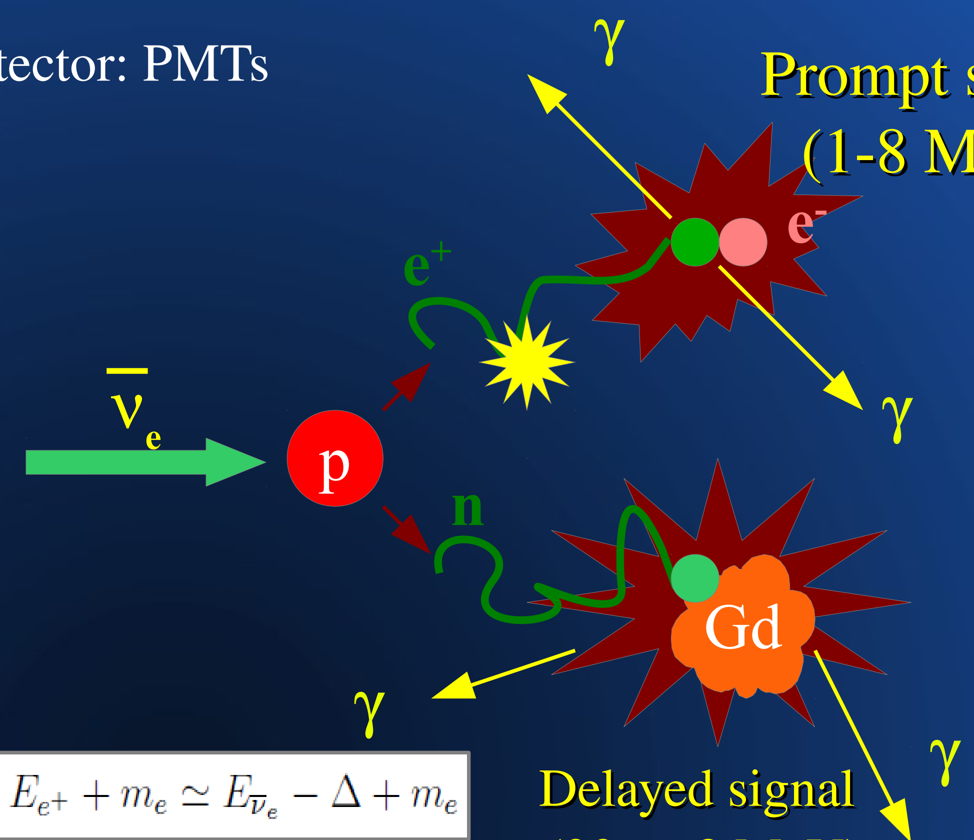
- Reactor $\overline{\nu}$: probe for solar and interference sectors, and for MH

Detecting reactor neutrinos

IBD: $\overline{\nu}_e + p \rightarrow e^+ + n$

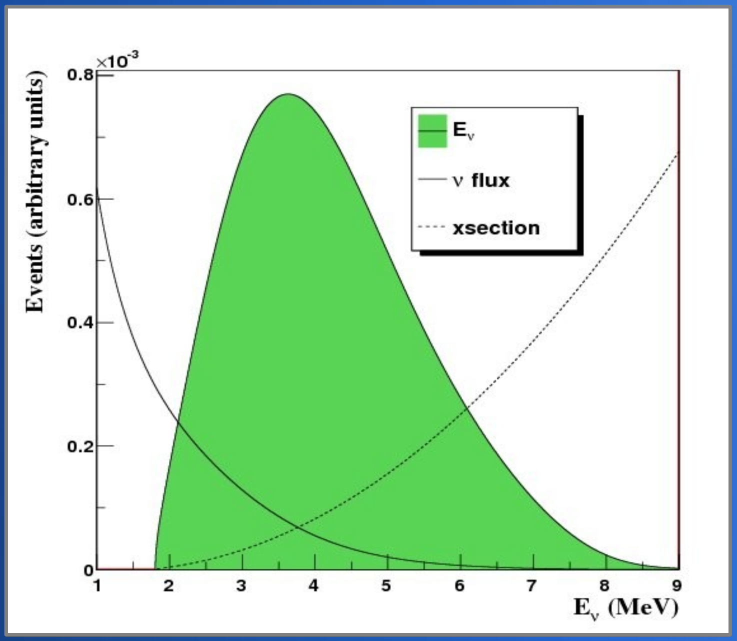
Th: 1.8 MeV. **Disappearance!**

- Target: scintillator + n-catcher (Gd)
- Detector: PMTs



$$E_{\text{vis}} = E_{e^+} + m_e \simeq E_{\overline{\nu}_e} - \Delta + m_e$$

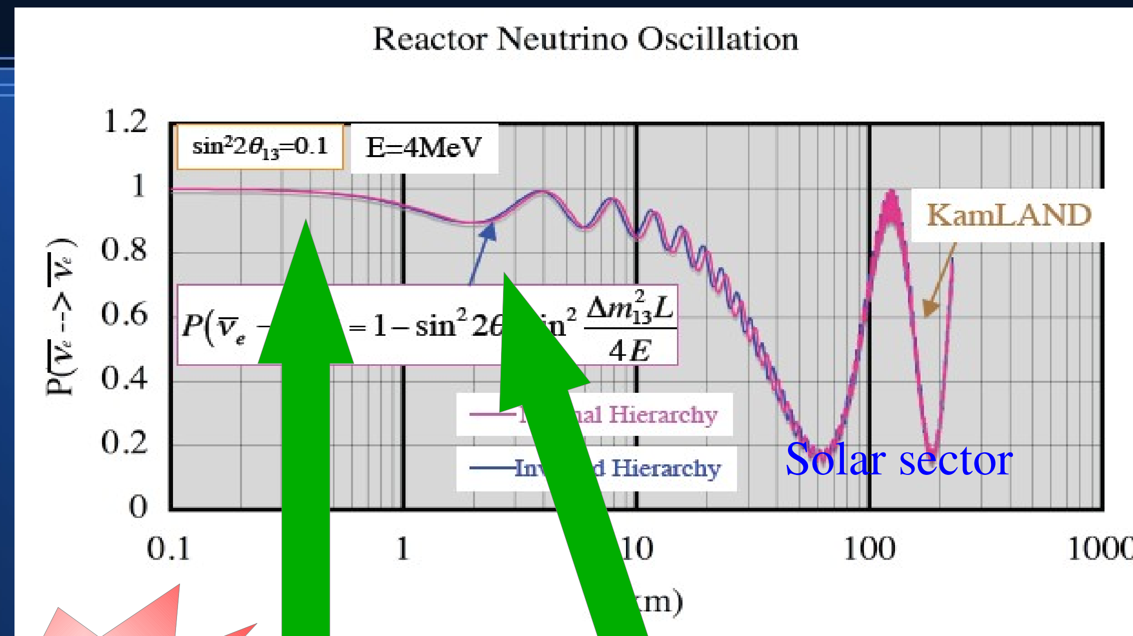
Eν spectrum



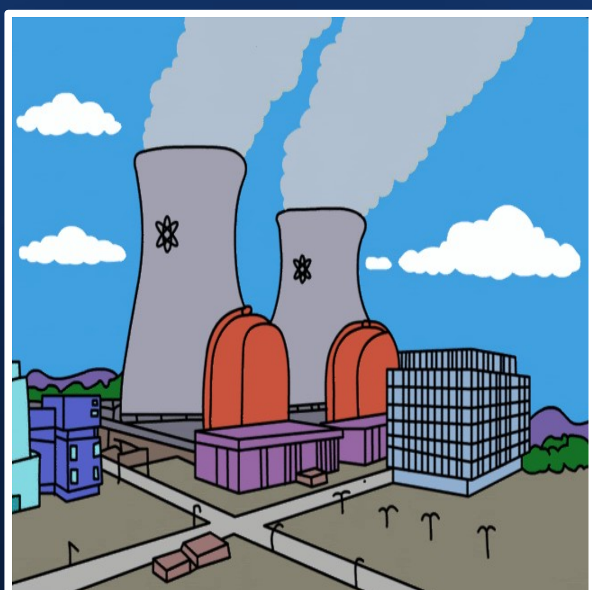
θ_{13}: Setting up the experiment

Reactor neutrinos:

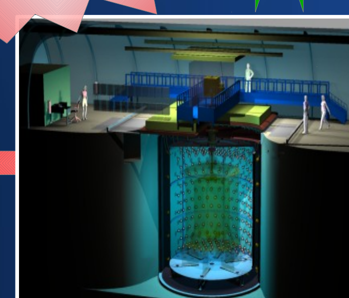
$<E_\nu> \sim 4$ MeV

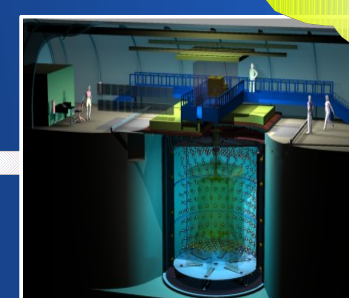


Solar sector



Systematics!





Oscillation!

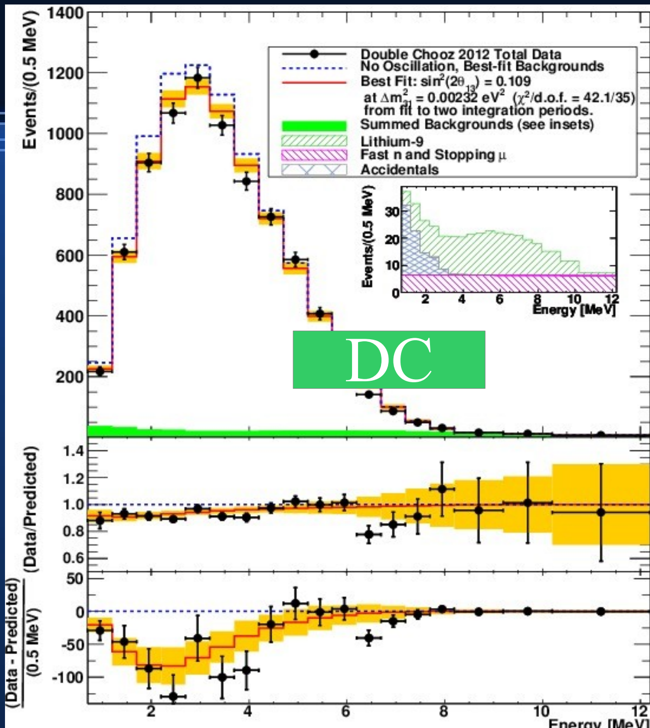
~ 100 m

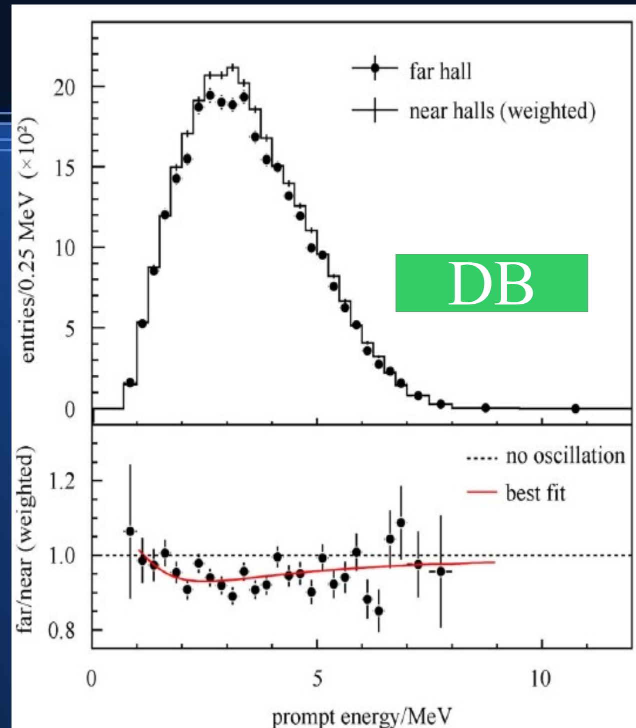
~ 1 km

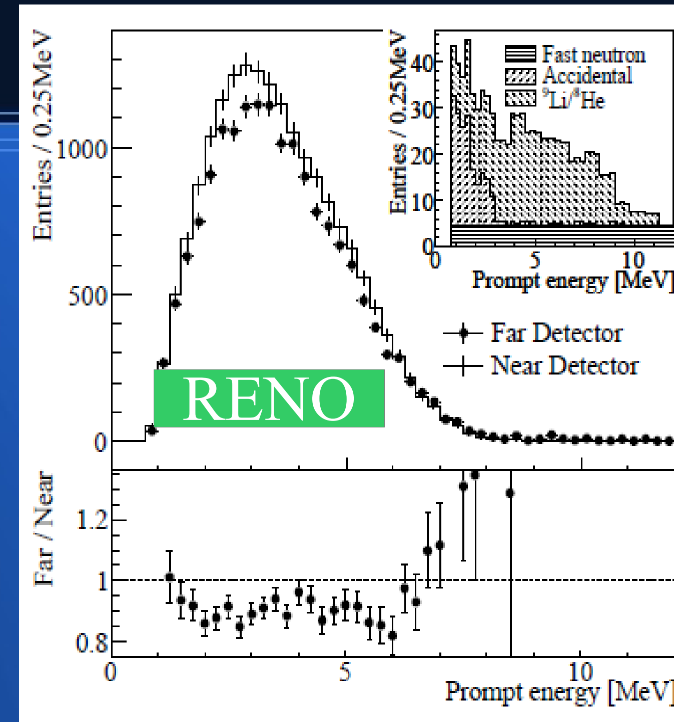
Reactor neutrino experiments

IBD detection in Gd-doped scint.
Multi-detector setups

Summary of 2012 results



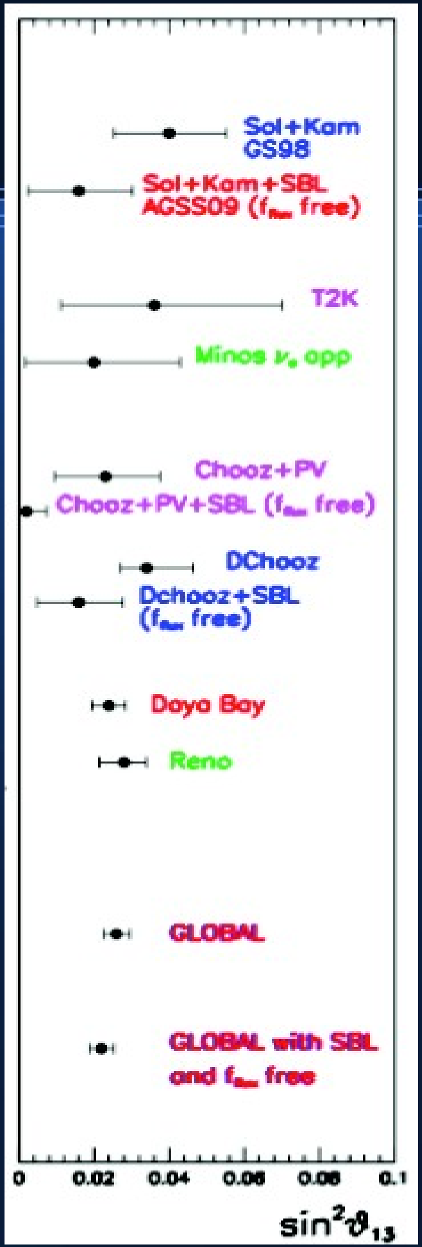




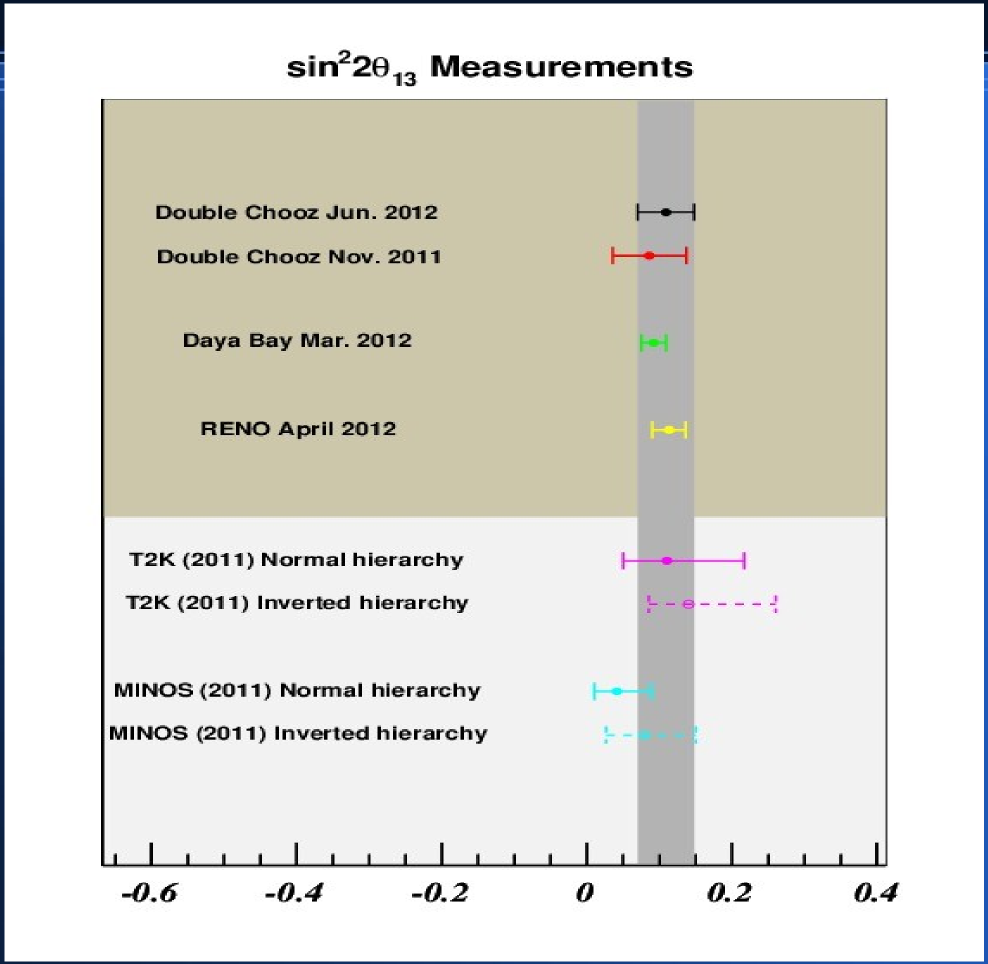
2 integration periods!

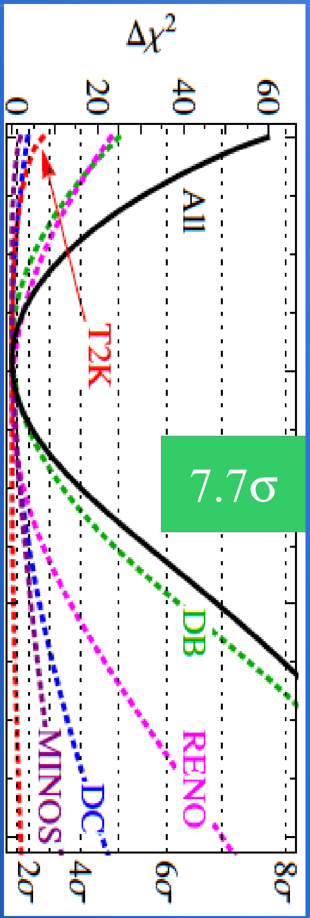
	$\sin^2(2\theta_{13})$	days	arXiv
DC-I(rate+shape)	$0.086\pm0.051(0.041^{stat}\pm0.030^{sys})$	96.8	1112.6353
DB(rate only)	$0.092\pm0.017(0.016^{stat}\pm0.005^{sys})$	55	1203.1669
RENO(rate only)	$0.113\pm0.023(0.013^{stat}\pm0.019^{sys})$	229	1204.0626
DC-II(rate only)	$0.170\pm0.053(0.035^{stat}\pm0.040^{sys})$	251	1207.6632
DC-II(rate+shape)	$0.109\pm0.039(0.030^{stat}\pm0.025^{sys})$	251	1207.6632
DB-II(rate only)	$0.089\pm0.011(0.010^{stat}\pm0.005^{sys})$	126	Nu2012

Summary on θ_{13}



T.Schwetz





H. Minakata

- 5% precision in ~3 years

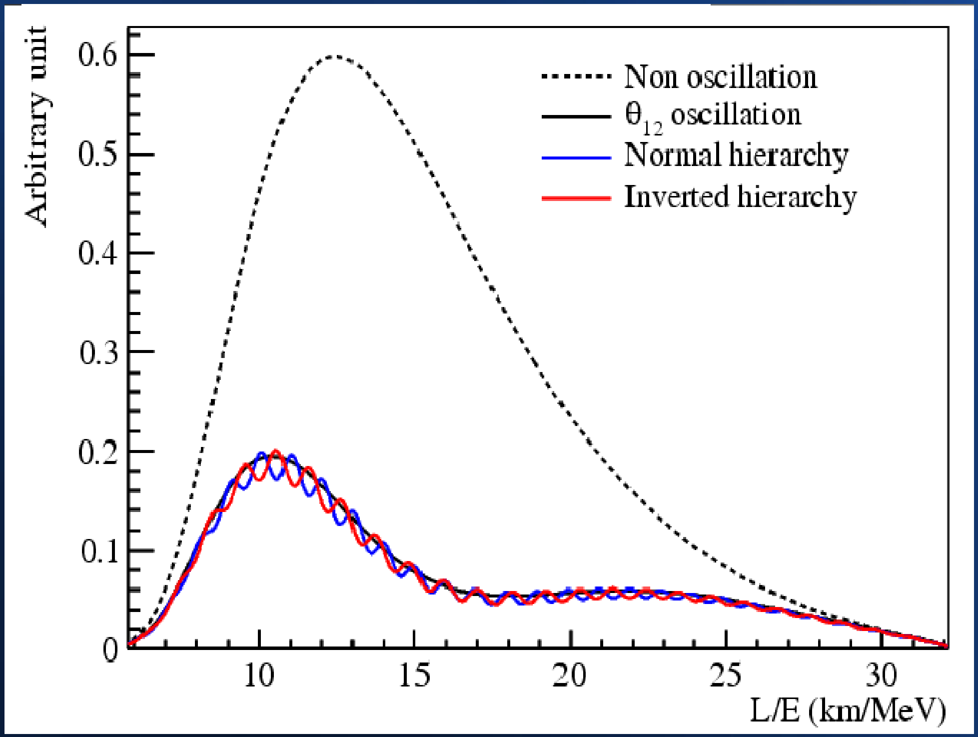
Now that θ_{13} is large...

MH with Reactor Neutrinos

MH with Reactor Neutrinos

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022 L.

- Sensitivity to MH: $\Delta m^2_{31}/\Delta m^2_{32}$ interference



- Different E distortion for NH and IH

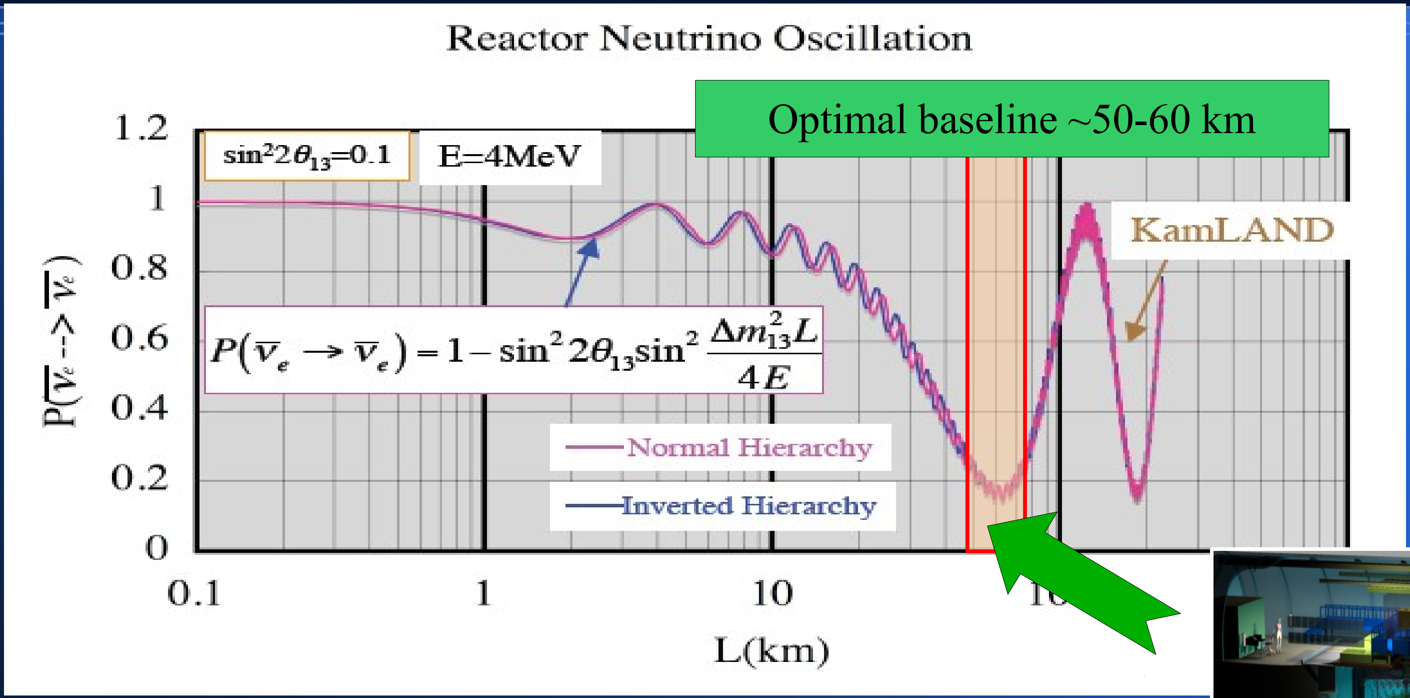
$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH:}\ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH:}\ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

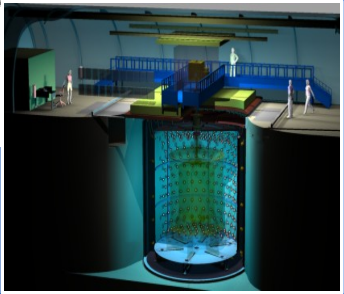
$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009

Experimental Setup



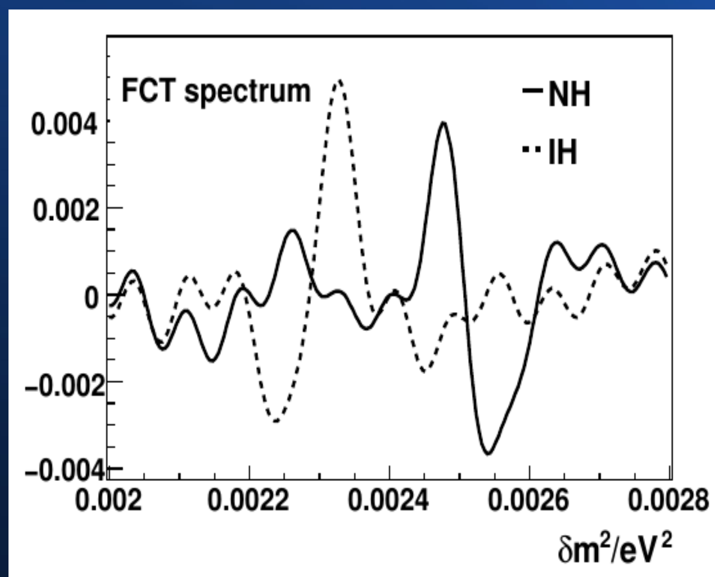


- No CP phase or matter effects involved
- “Small” detector (w.r.t. LBL, atmospheric)
- Neutrino sources already exist and baseline length adjustable

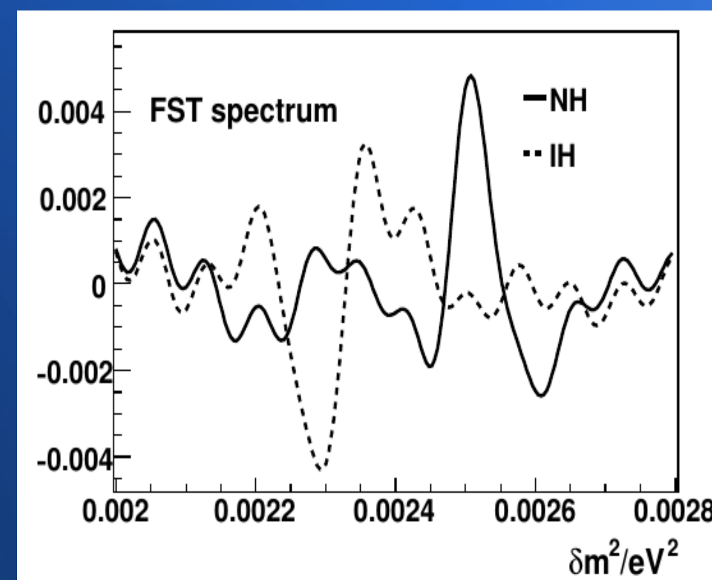
Fourier Transform Analysis

- Fourier Transform of L/E into δm^2 spectrum (oscillation frequency)

hep-ph/0612022 J.G. Learned et al.
arXiv: 0807.3203 L. Zhan et al.
arXiv: 0901.2976 L. Zhan et al.
arXiv: 1208.1551 X. Qian et al.
arXiv: 1208.1991 E. Ciuffoli et al.



- NH: *valley after the peak*
- IH: *valley before the peak*



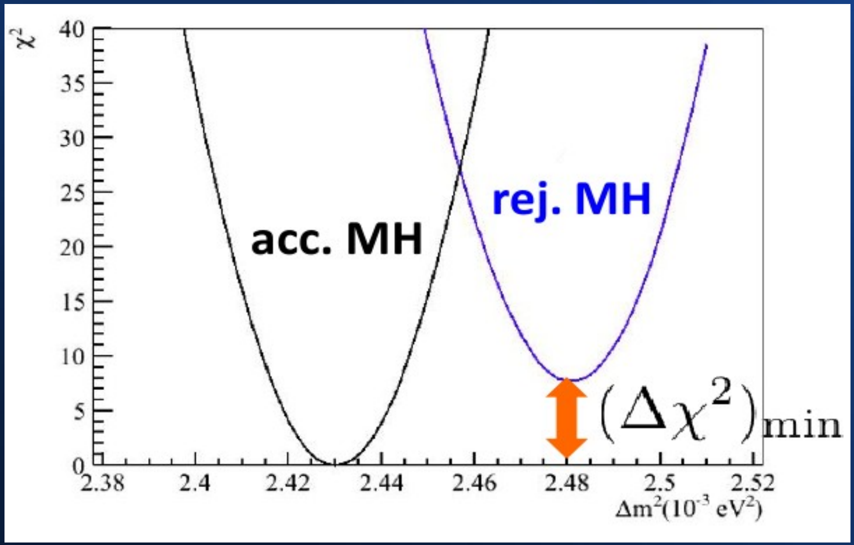
- NH: *prominent peak*
- IH: *prominent valley*

- No need for a priori value of Δm^2_{32} (features independent of peak position)

χ^2 Analysis

- Data are fit assuming both NH and IH and known oscillation params
- Hierarchy determined as the one with smallest χ^2_{min}

Y. Takaesu.



hep-ph/030601 S. Choubey et.al.
arXiv: 0810.2580 M. Batygov et.al.
arXiv: 1011.1646 P. Ghoshal et.al.

$$\chi^2 = \sum_{i=1}^{\mathrm{nbin}} \left(\frac{N_i^{\mathrm{fit}} - N_i^{\mathrm{data}}}{\sqrt{N_i^{\mathrm{data}}}} \right)^2 + \underbrace{\sum_{i=1}^{\mathrm{nparam}} \left(\frac{X_i - X_i^{\mathrm{input}}}{\delta X_i} \right)^2}_{\text{Penalty term}}$$

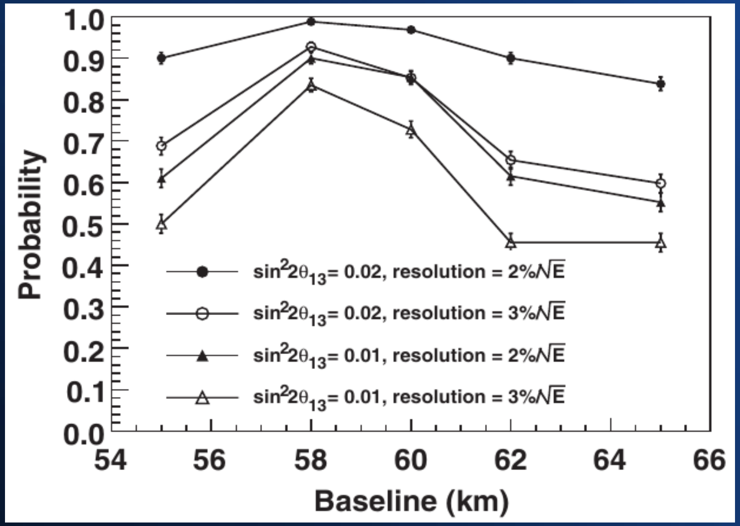
- Addition of systematics
- Sensitivity estimation
  - Experiment optimization

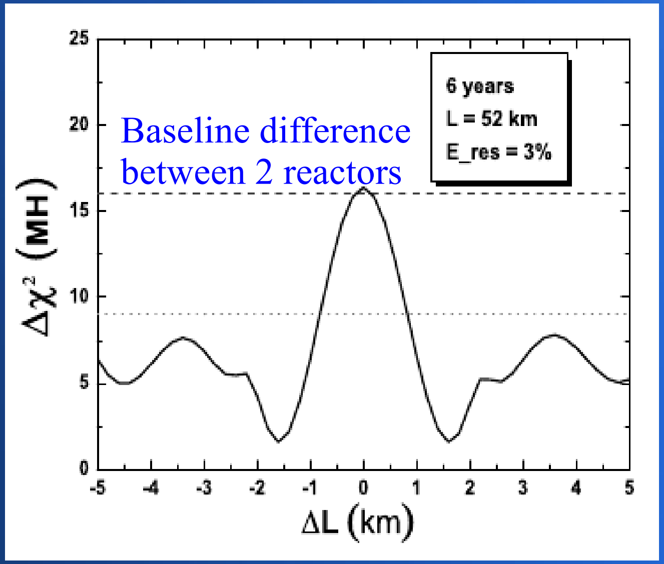
$$\Delta\chi^2_{\mathrm{MH}} = |\chi^2_{\mathrm{min}}(\mathrm{N}) - \chi^2_{\mathrm{min}}(\mathrm{I})|$$

Experiment optimization

- $\mathcal{F}$ and χ^2 analysis used to optimize experiments:
  - Baseline, number of reactors and detector performance/size
    - Correlated among them!!!

L. Zhan et Al., PRD79, 073007,2009



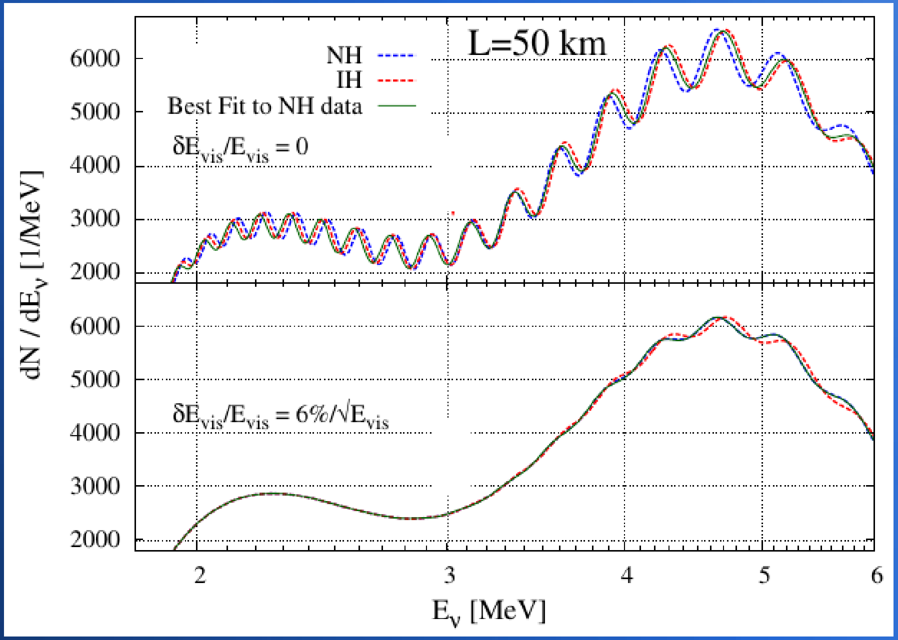


ArXiv:1303.6733.2013

- Optimal configuration: 50-60 km, <3% E_{res}, baseline diff < 1 km

Experimental Challenges

- Energy resolution and scale:
  - <3%/√E, <1%
  - High QE PMTs
  - very transparent LS
- Detector size: $\mathcal{O}(10)$ kt



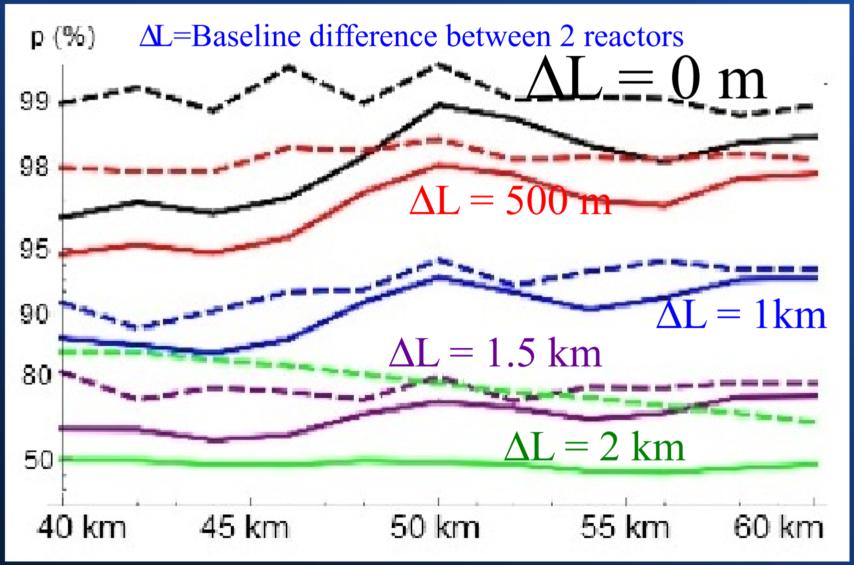
arXiv: 1210814

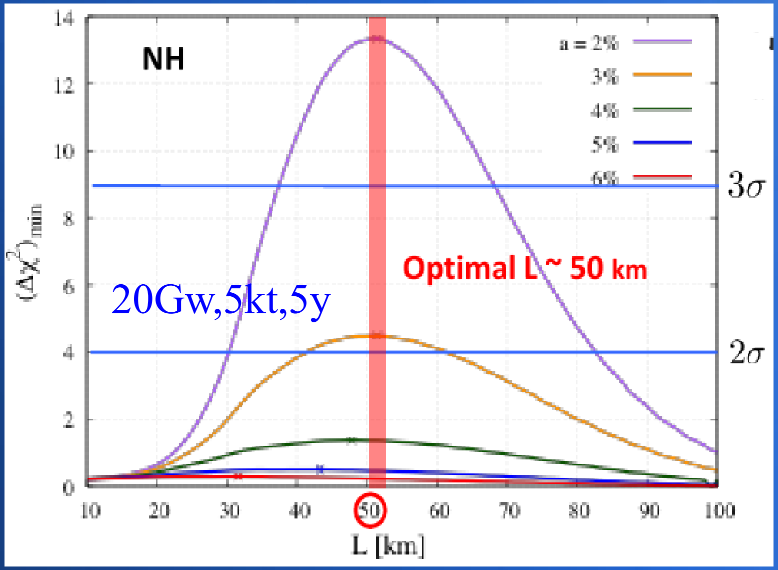
	KamLAND	MBL Reactor Exp
Detector Size	~ 1kton	O(10) kton
Energy resolution	6%√E (250 pe/MeV)	~2%√E (2500 pe/MeV)
LS attenuation L	15 m	~25 m

Physics Case

- Sensitivity to MH depends on several parameters...

E. Ciuffoli et al, ArXiv: 1302.0624





Y. Takaesu.

- But if basic experimental requirements are met
  - MH to be determined @ 90 C.L.
  - Accuracy <1% for $\sin^2 2\theta_{12}$, Δm^2_{21}, Δm^2_{32}

Future MBL reactor experiments

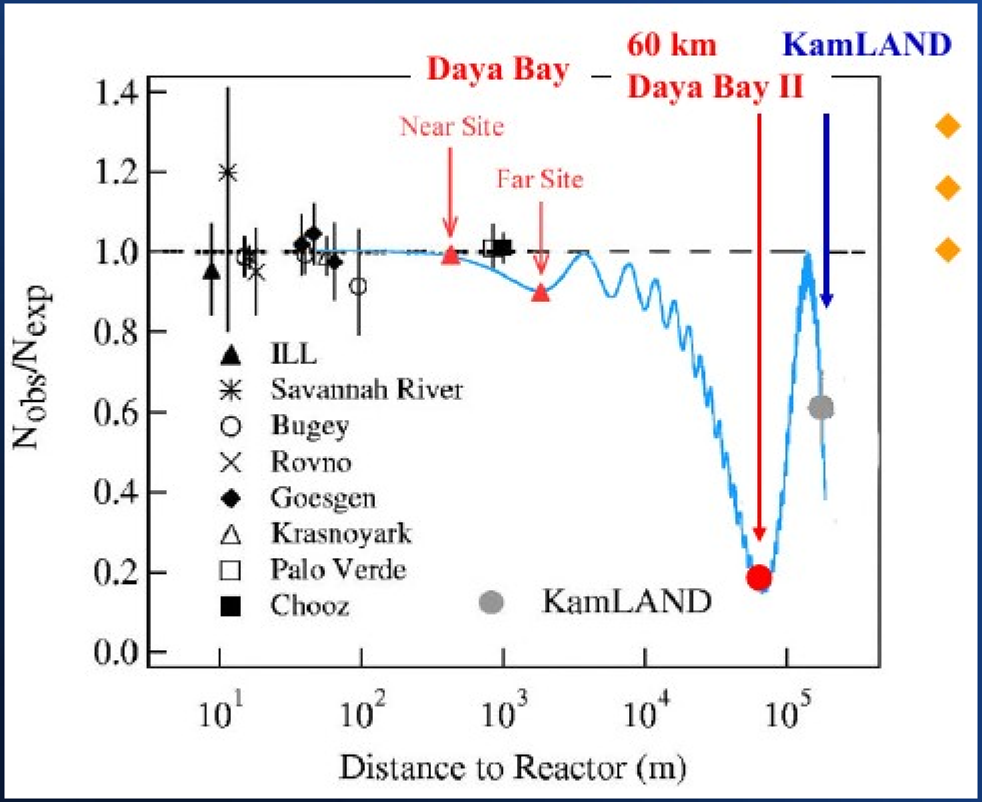
Daya Bay II and RENO-50

Daya Bay II: C. Yang, NuMass 2013

RENO-50: S. Kim, Workshop on ν Physics, Pittsburgh 2013

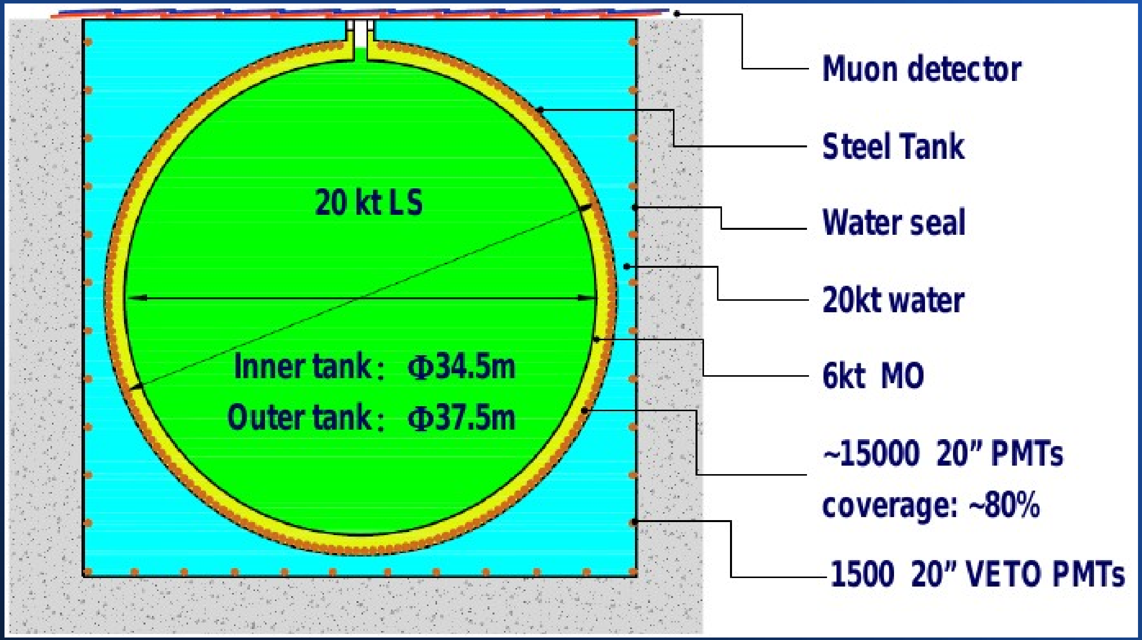
Daya Bay II

- MBL experiment: 20 kt LS detector, 2-3% E_{res}, 60 km



- Physics program:
- **Mass hierarchy**
- **Precision measurements**
  - 4 mixing parameters
- Supernovae neutrino
- Geoneutrino
- Atmospheric neutrinos
- ….

Daya Bay II: Detector

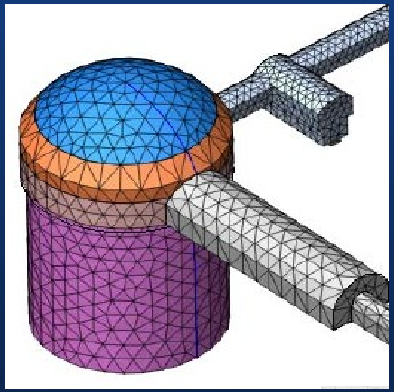


- Know-how from DB I
- Details to be worked out
- R&D on PMTs and LS
  - $E_{res} < 3\%$!

	KamLAND	Daya Bay II
LS mass	~1 kt	20 kt
Energy Resolution	6%/√E	3%/√E
Light yield	250 p.e./MeV	1200 p.e./MeV

Daya Bay II: Location

- Location optimized according to interferences from several reactors



Contruction: 3 years

- Conceptual design completed on Dec. 2012. Engineering study soon...
- Funding for civil preparation: geological survey, engineering designs, ...
- Total cost (detector and civil engineering): 300 M$

Daya Bay II: Physics Case

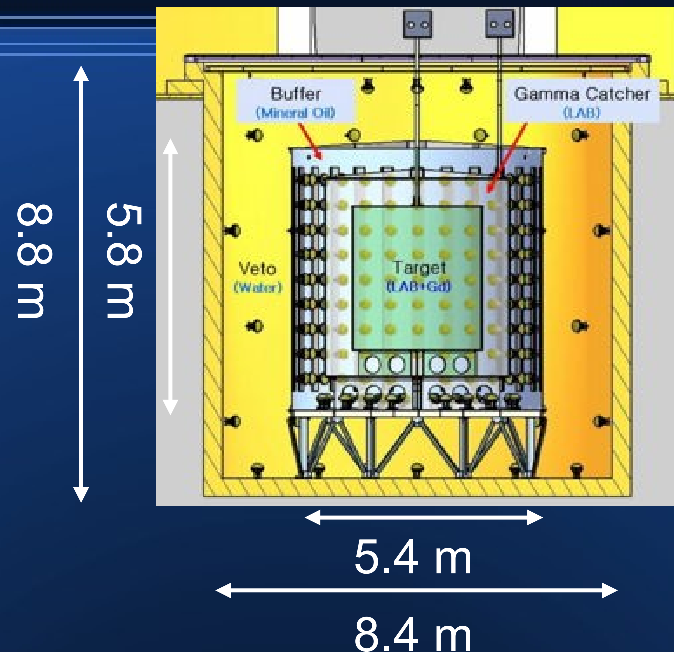
- 2014-2017: civil construction, while prototyping
- 2017-2019: detector installation, while prod. PMT and LS
- Physics goals:

	Current	Daya Bay II
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	14% → 4%	~ 15%

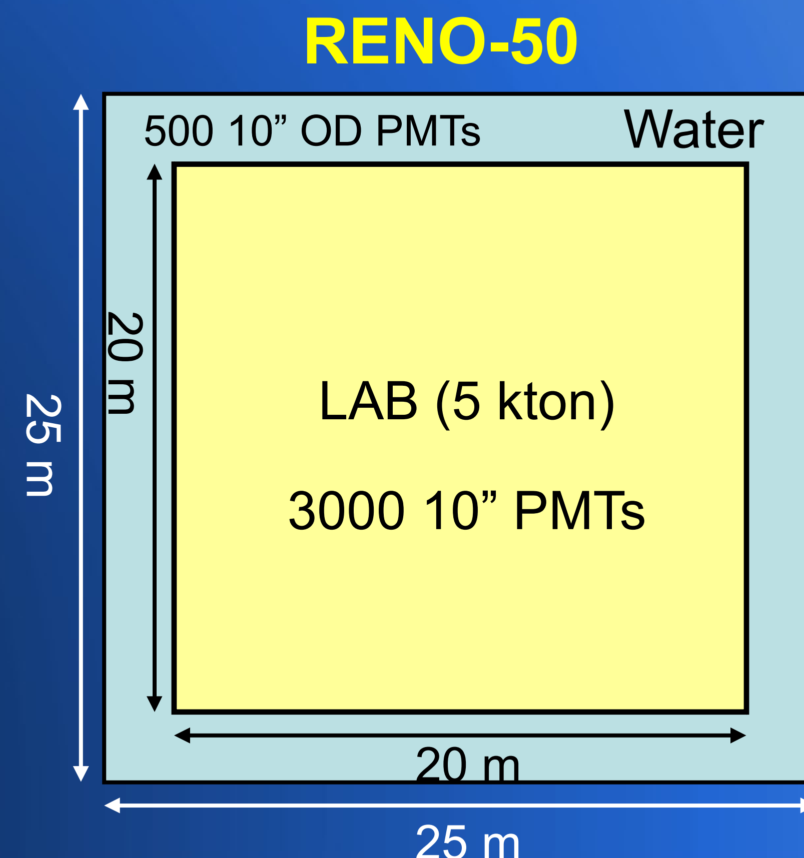
- ArXiv 1303.6733: MH determination @ 3.7σ in 6 years
  - 4.4σ incorporating $\Delta m^2_{\mu\mu}$ with ~1% precision

RENO-50

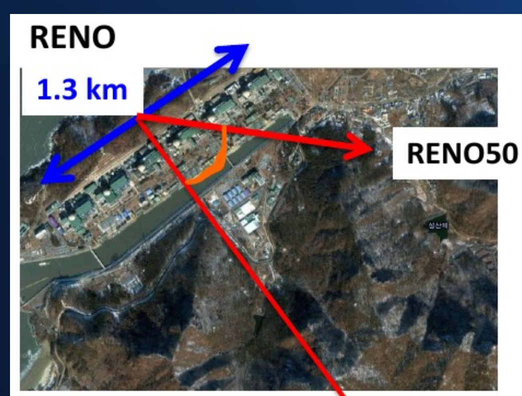
RENO



- 5 kton, E_{res} ~3%, 50 km



Penalized by reactor interference?



RENO-50: Physics Case

- Precise measurement of θ_{12} and Δm^2_{21}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} \sim 1.0\%(1\sigma) \text{ in a year } (\leftarrow 5.4\%)$$

$$\frac{\delta \Delta m^2_{21}}{\Delta m^2_{21}} \sim 1.0\%(1\sigma) \text{ in 2~3 years } (\leftarrow 2.6\%)$$

- Determination of MH: challenging due to E_{res}
  - *Plan B:* addition 1 kton detector ~10 km

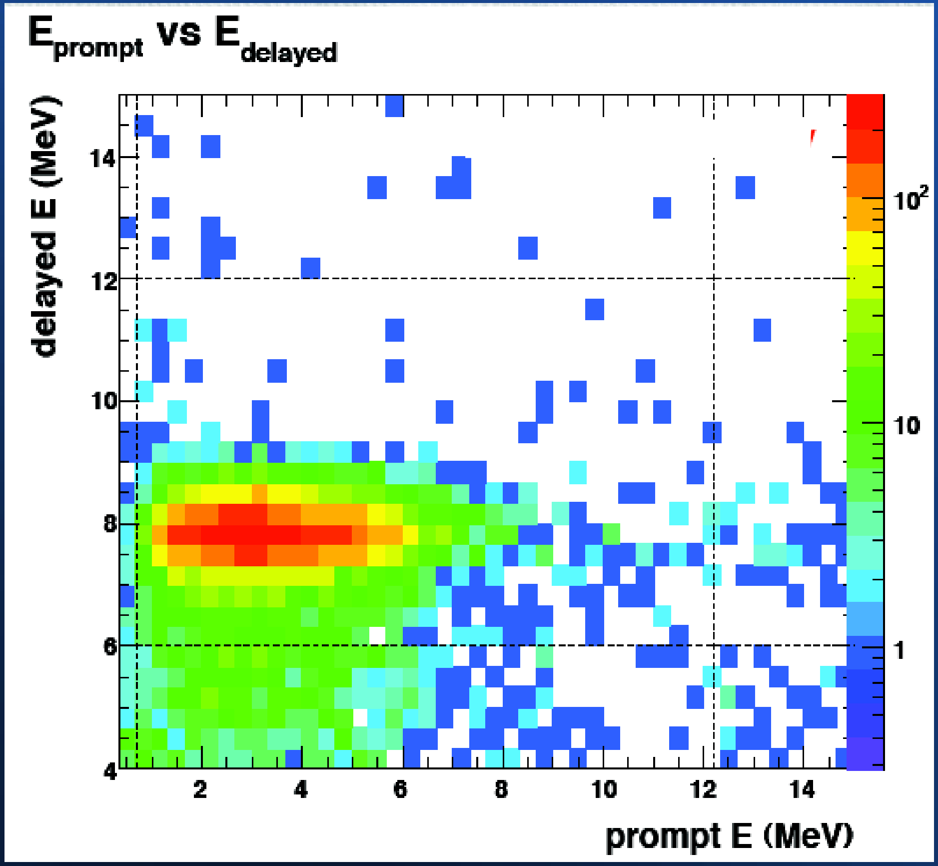
- Geoneutrinos, solar neutrinos, supernovas, JPARC...

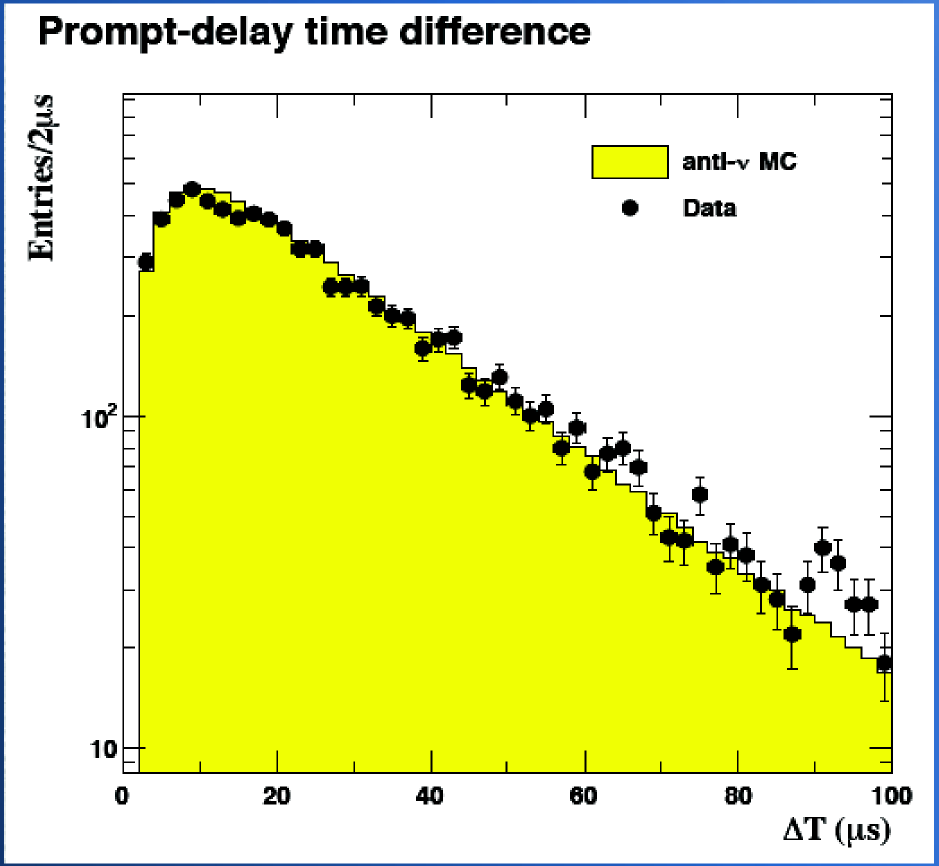
Summary

- Reactor neutrino experiments have measured θ_{13}
- The last mixing angle is large: $\sin^2(2\theta_{13}) \sim 0.1$
  - Precision measurements with reactor ν
  - MH determination can be achieved with reactor ν
- Future MBL reactor experiments:
  - Several works on optimization and sensitivity
    - Oscillation parameters with <1% accuracy, MH @ ~3-4σ
  - Daya Bay II and RENO-50 in ~10 years

Thank You!

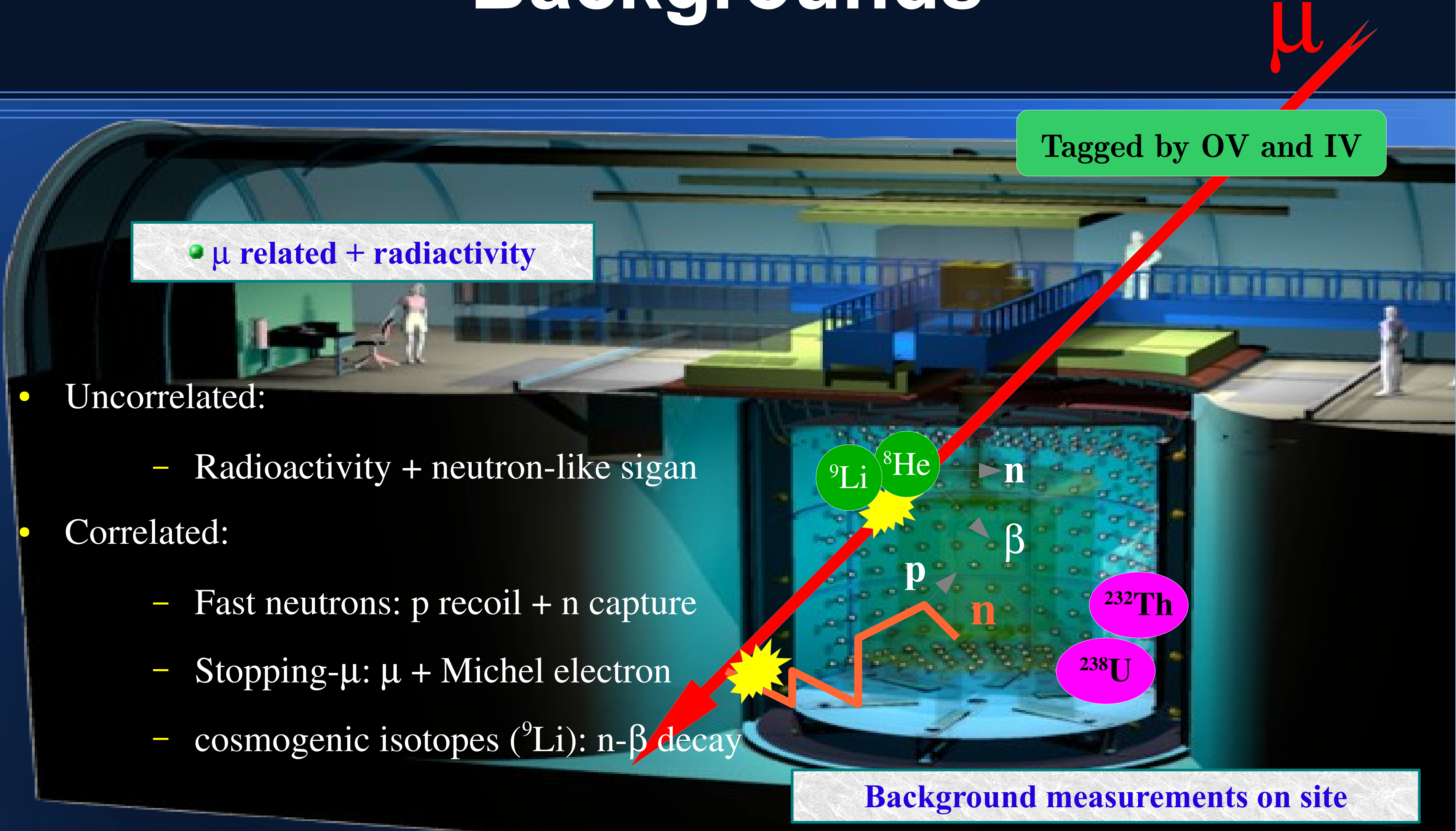
Neutrino Selection





- Prompt signal energy cut
- Delayed signal energy cut
- ΔT between prompt-delayed
- Multiplicity cut

Backgrounds



- Uncorrelated:
  - Radioactivity + neutron-like sigan
- Correlated:
  - Fast neutrons: p recoil + n capture
  - Stopping-μ: μ + Michel electron
  - cosmogenic isotopes (^{9}Li): n-β decay

Independent Analysis

- Double Chooz provides 2 independent analysis

ArXiv:1301.2948