原子炉ニュートリノ

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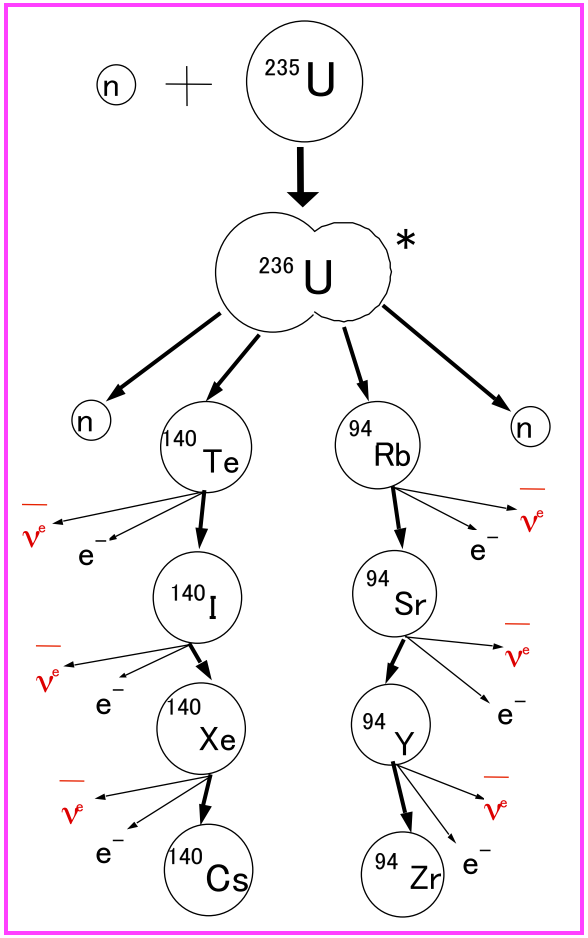
@高エネルギー研究者会議将来検討小委員会
東京大学理学部
05/09/2009

内容

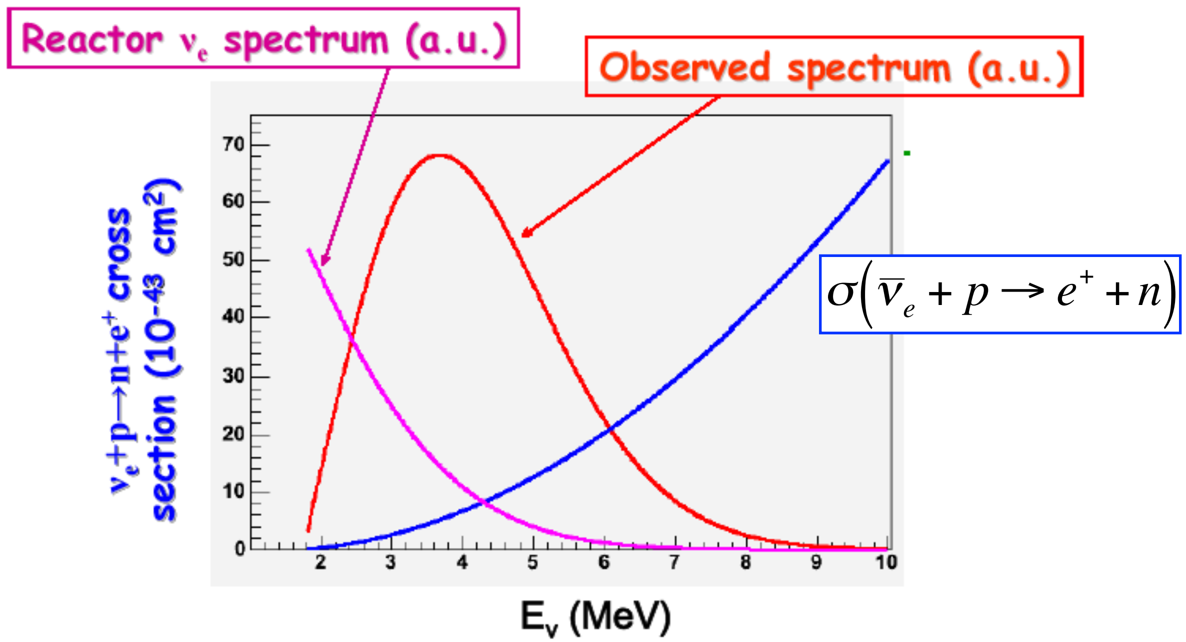
* DoubleChooz, RENO, Dayabayの現状
* 将来の原子炉ニュートリノ実験の可能性
* まとめ

原子炉ニュートリノのエネルギー



ν are produced in
β-decays of fission products.

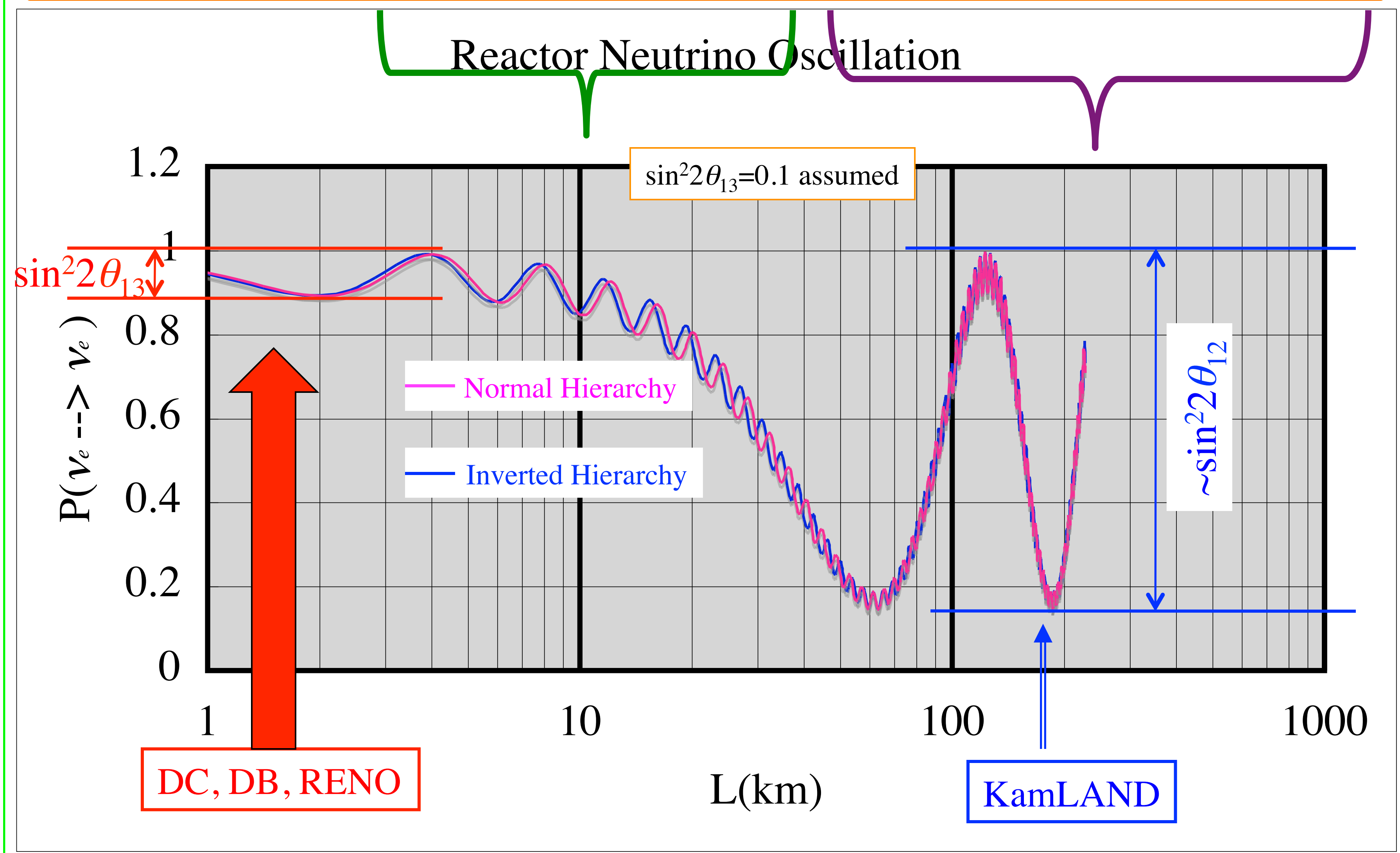
$$\sim 6 \times 10^{20}\, \bar{\nu}_e / s / reactor$$



$$E_\nu \sim 4\,^{+4}_{-2}\, MeV$$

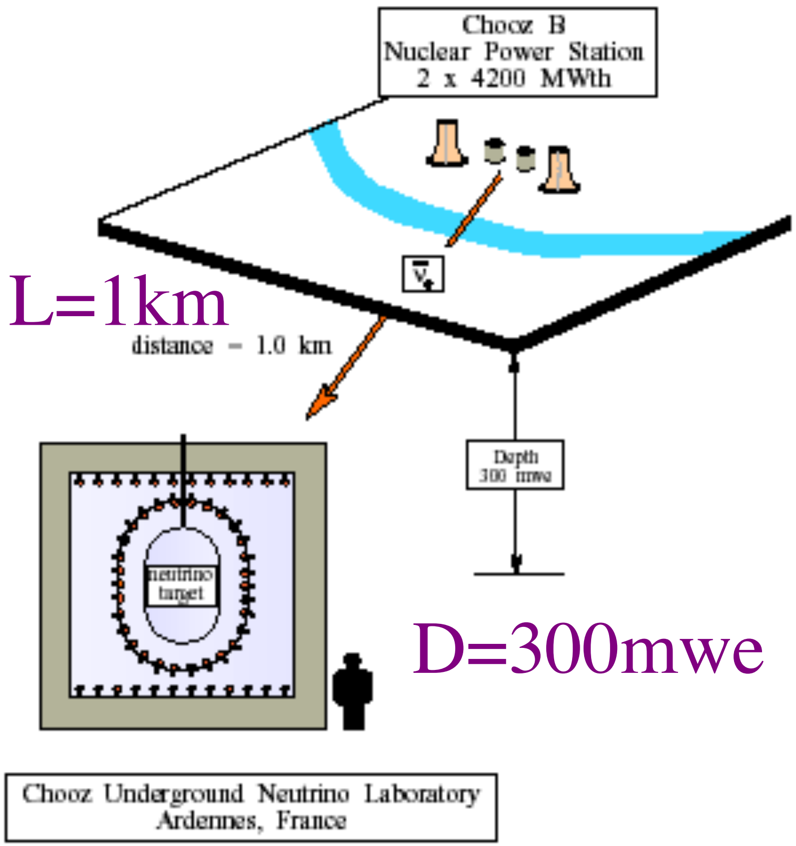
原子炉ニュートリノの振動

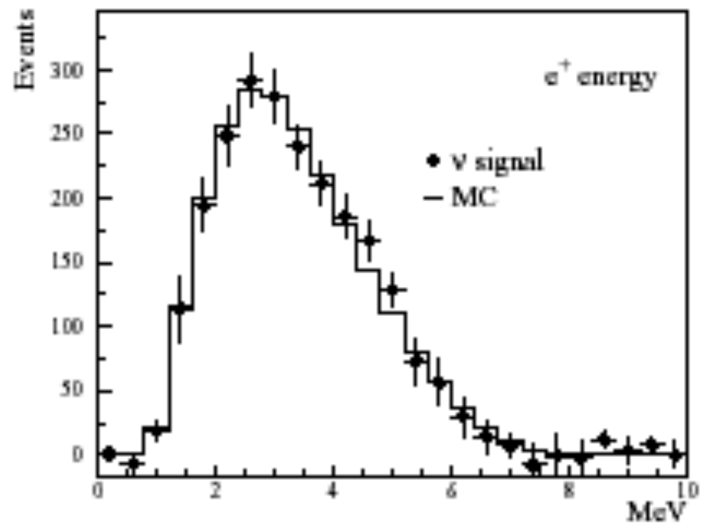
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$

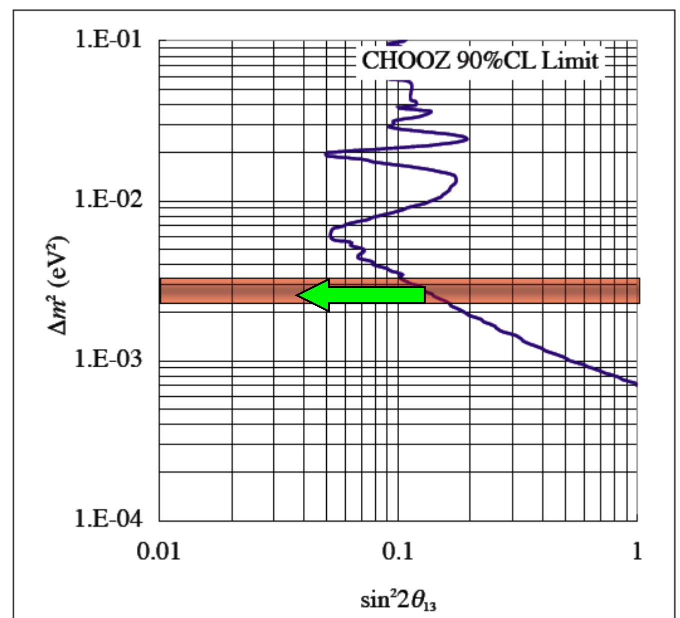


$\sin^2 2\theta_{13}$のupper limit

CHOOZ reactor ($\bar{\nu}_e$ --> $\bar{\nu}_e$) experiment

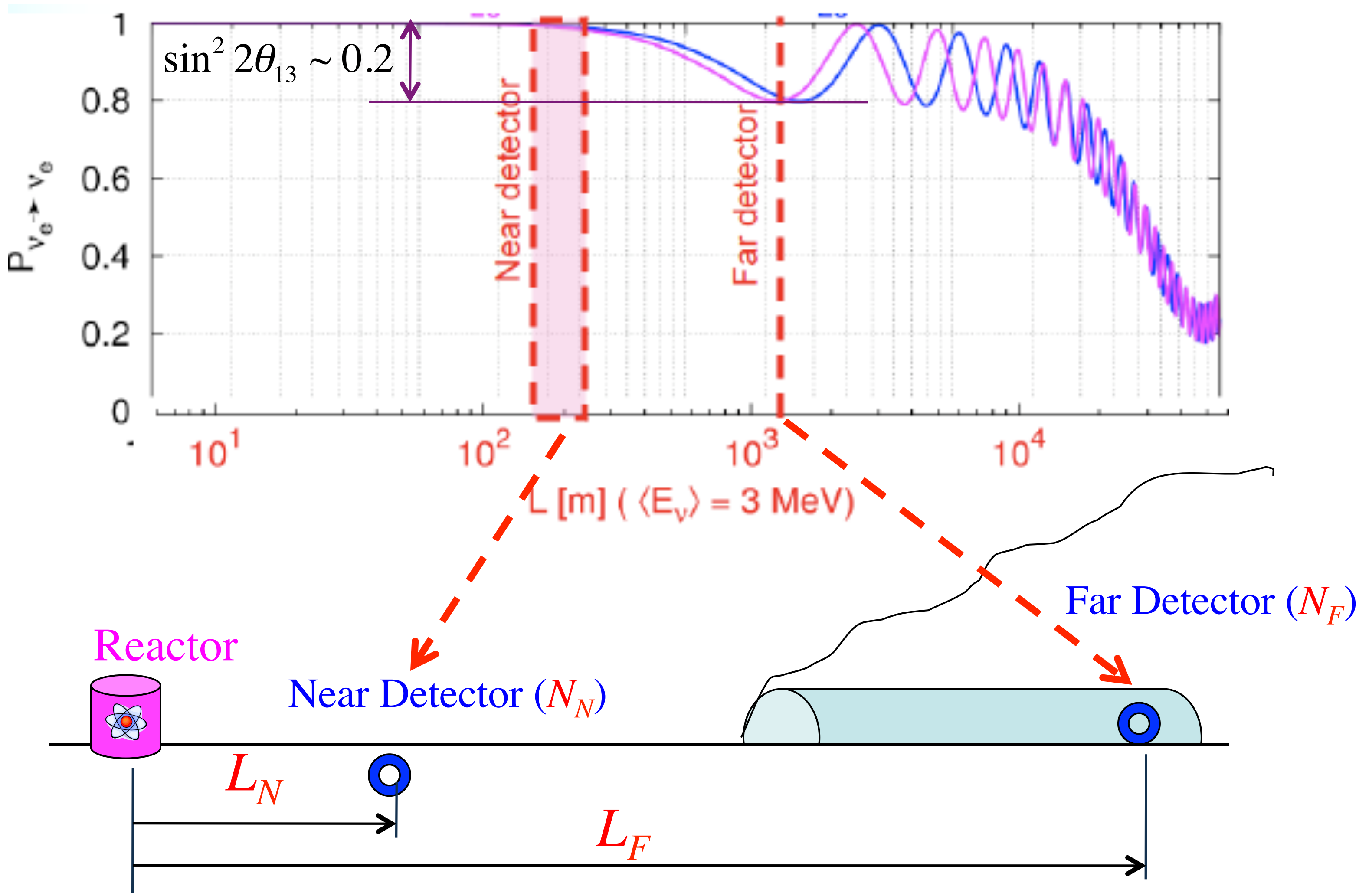






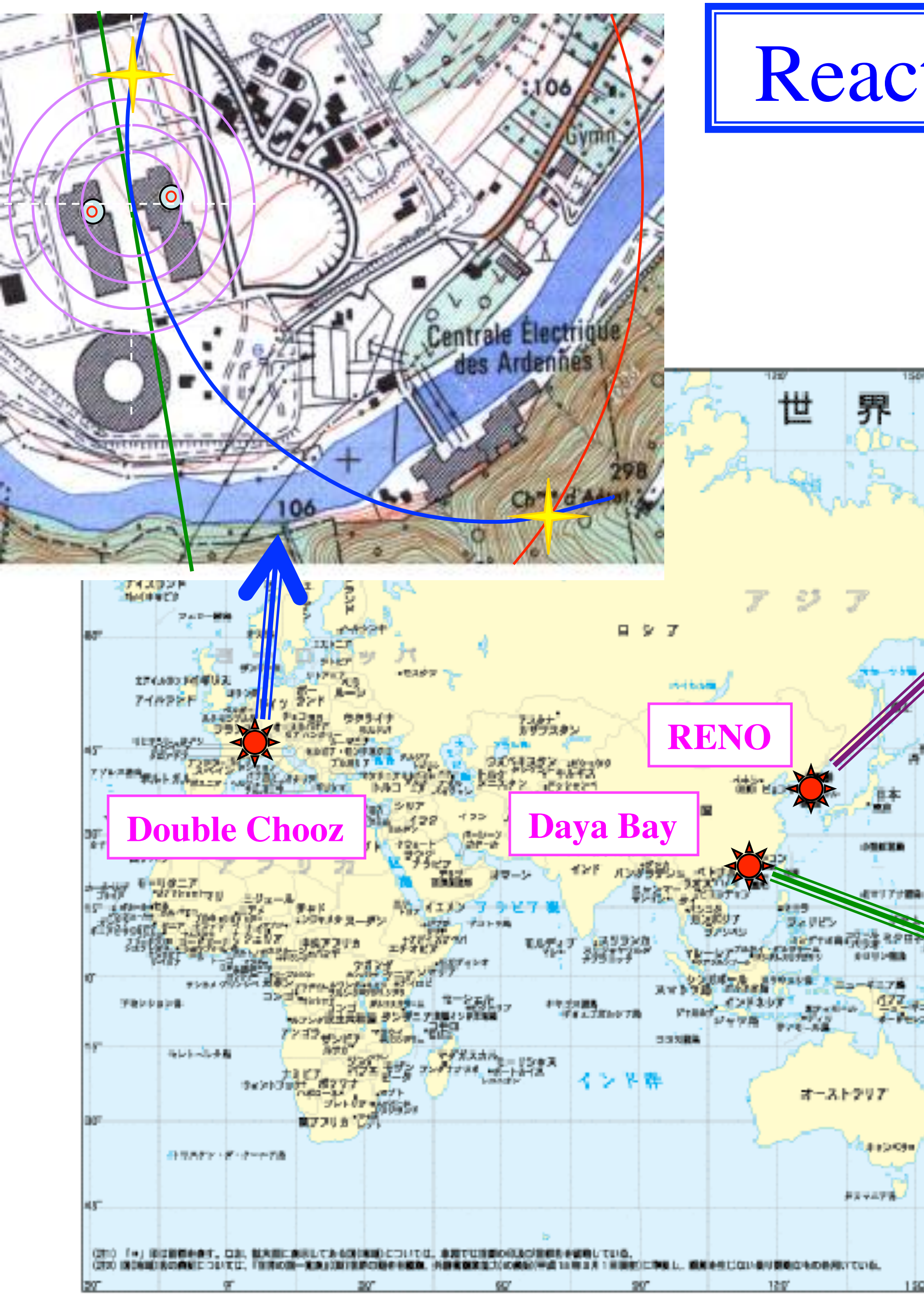
$\sin^2 2\theta_{13} < 0.15$ @$\Delta m^2 = 2.5 \times 10^{-3}$eV^2

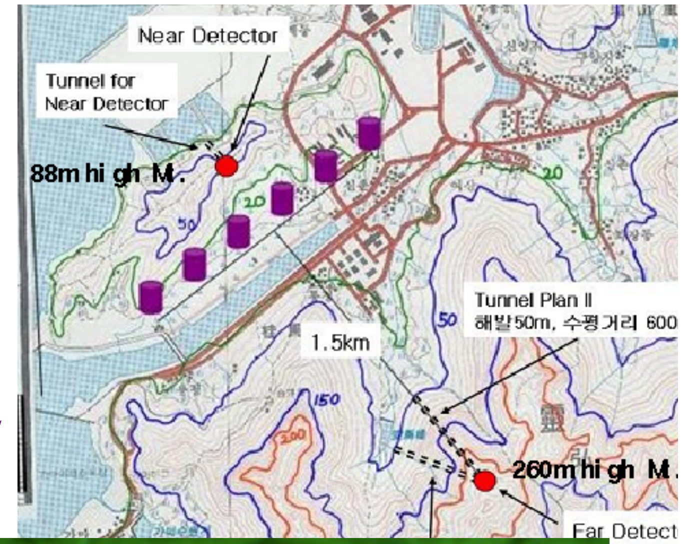
CHOOZ 実験からの精度の改善方法



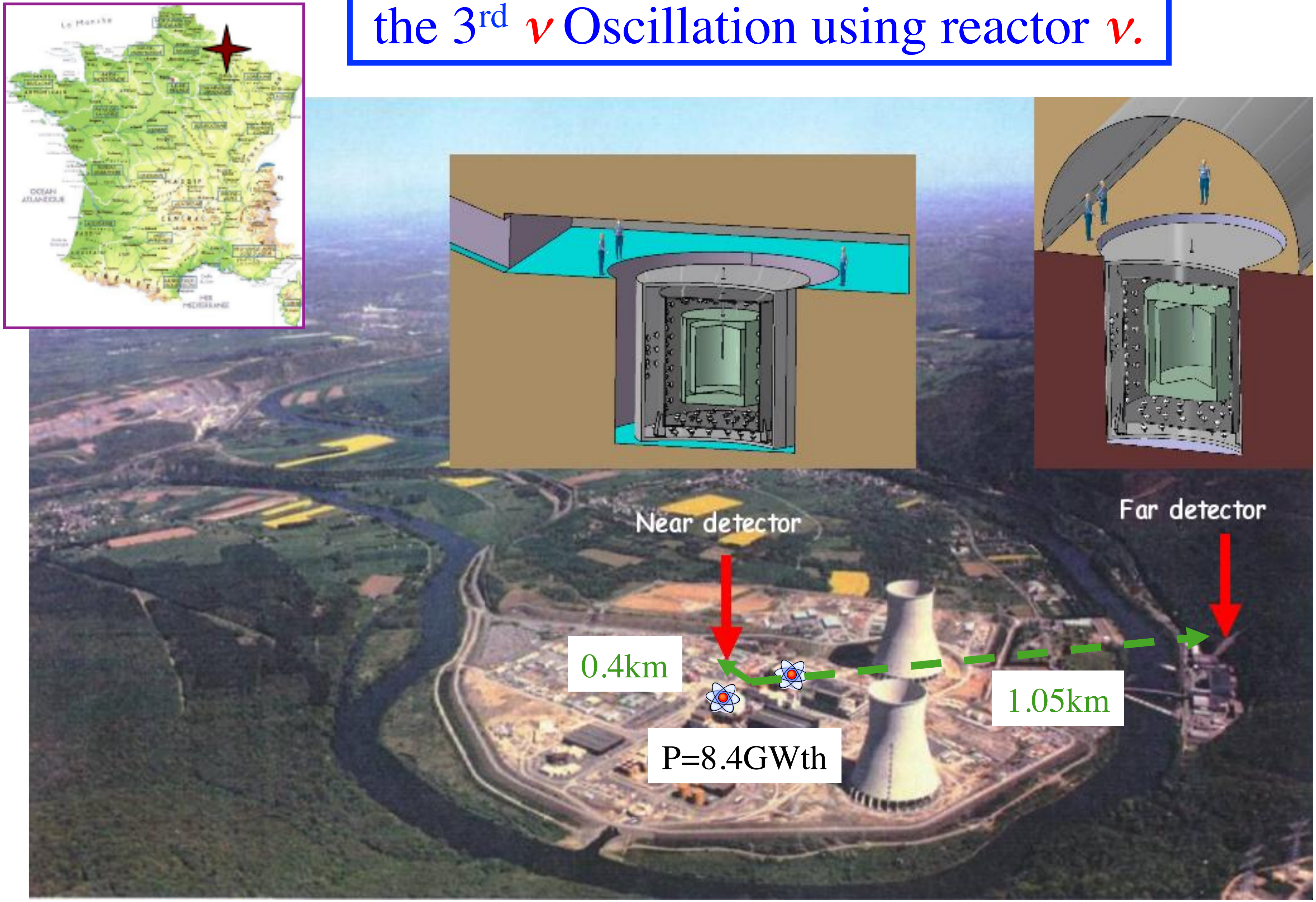
Use near and far detector of identical structure to cancel systemaic uncertainties of ν flux and detector response.

Reactor-θ_{13} Site Map >2007





Double Chooz Experiment to detect the 3rd ν Oscillation using reactor ν.



2004-2007: Detector Design

Calibration Glove-Box :

Outer Veto :
Scintillator panels

Target ν : 10,3 m^3
LS; 80% $C_{12}H_{26}$+ 20% PXE +0,1% Gd
+ PPO + Bis-MSB

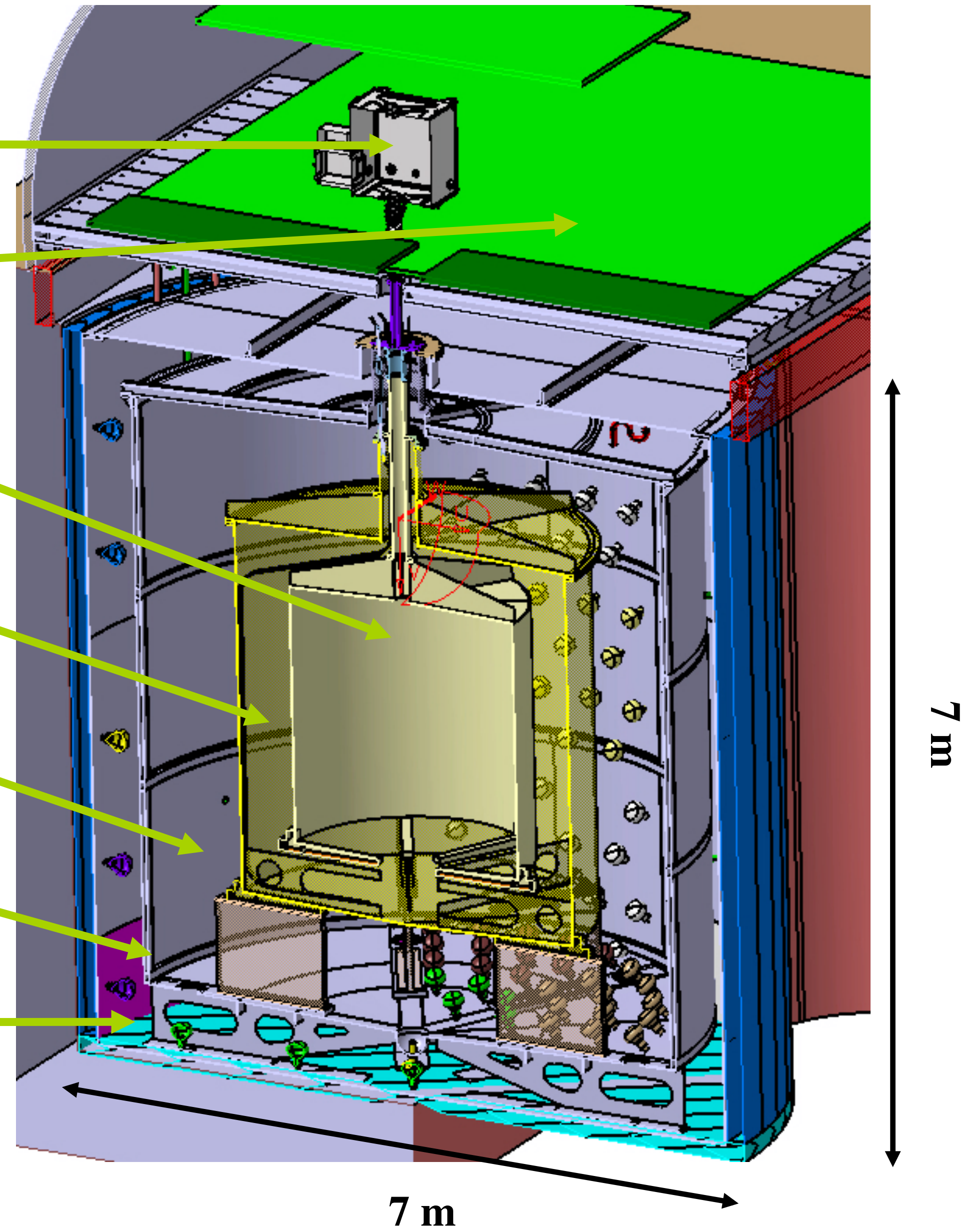
γ Catcher : 22,6 m^3
LS; 80% $C_{12}H_{26}$ + 20% PXE + PPO + Bis-MSB

Non scintillating Buffer : 114 m^3
mineral oil

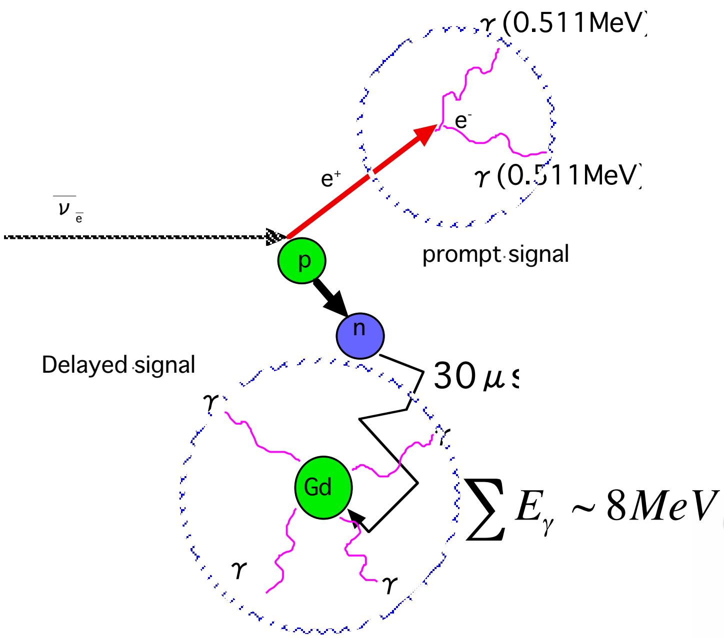
Buffer vessel & 390 10" PMTs :
Stainless steel 3 mm

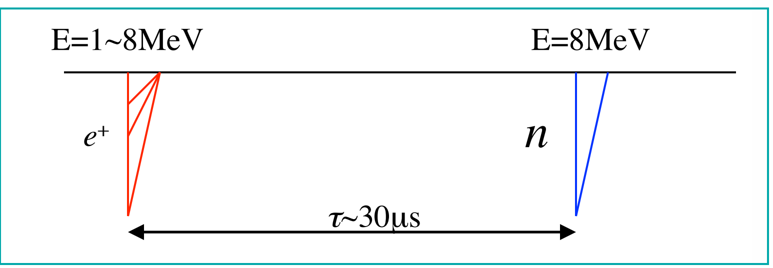
Inner Muon Veto : 90 m^3
mineral oil + 70 8" PMTs

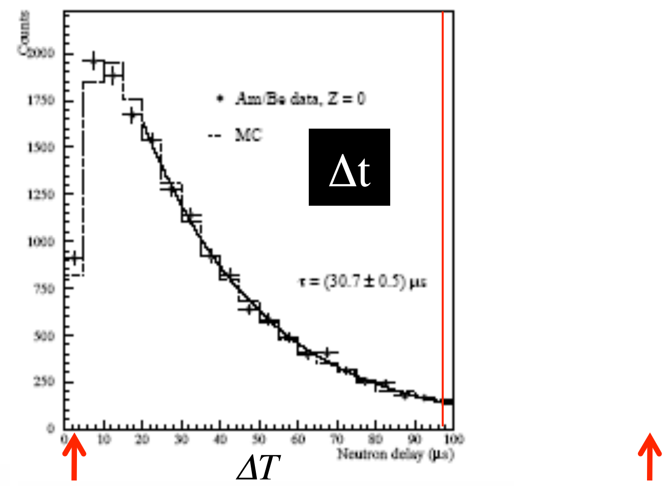
Steel Shielding :
17 cm steel, All around

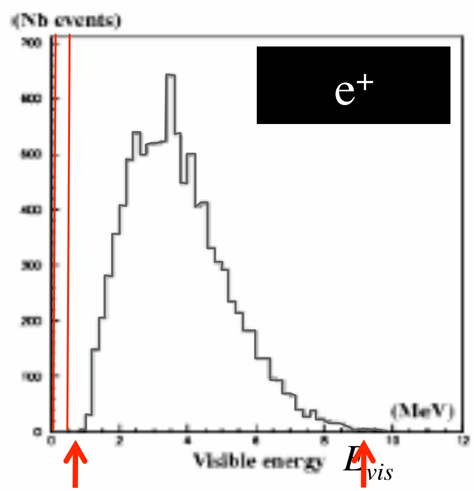


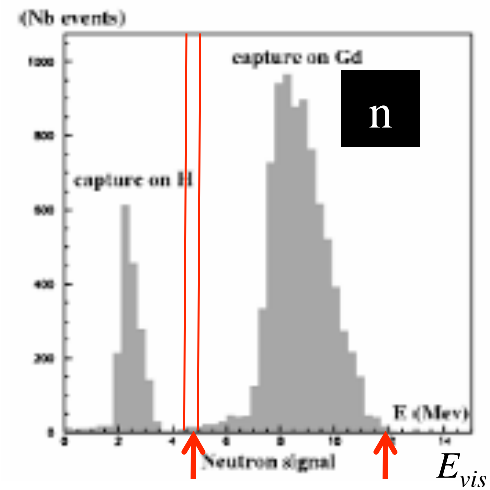
$\bar{\nu}_e$ event selection





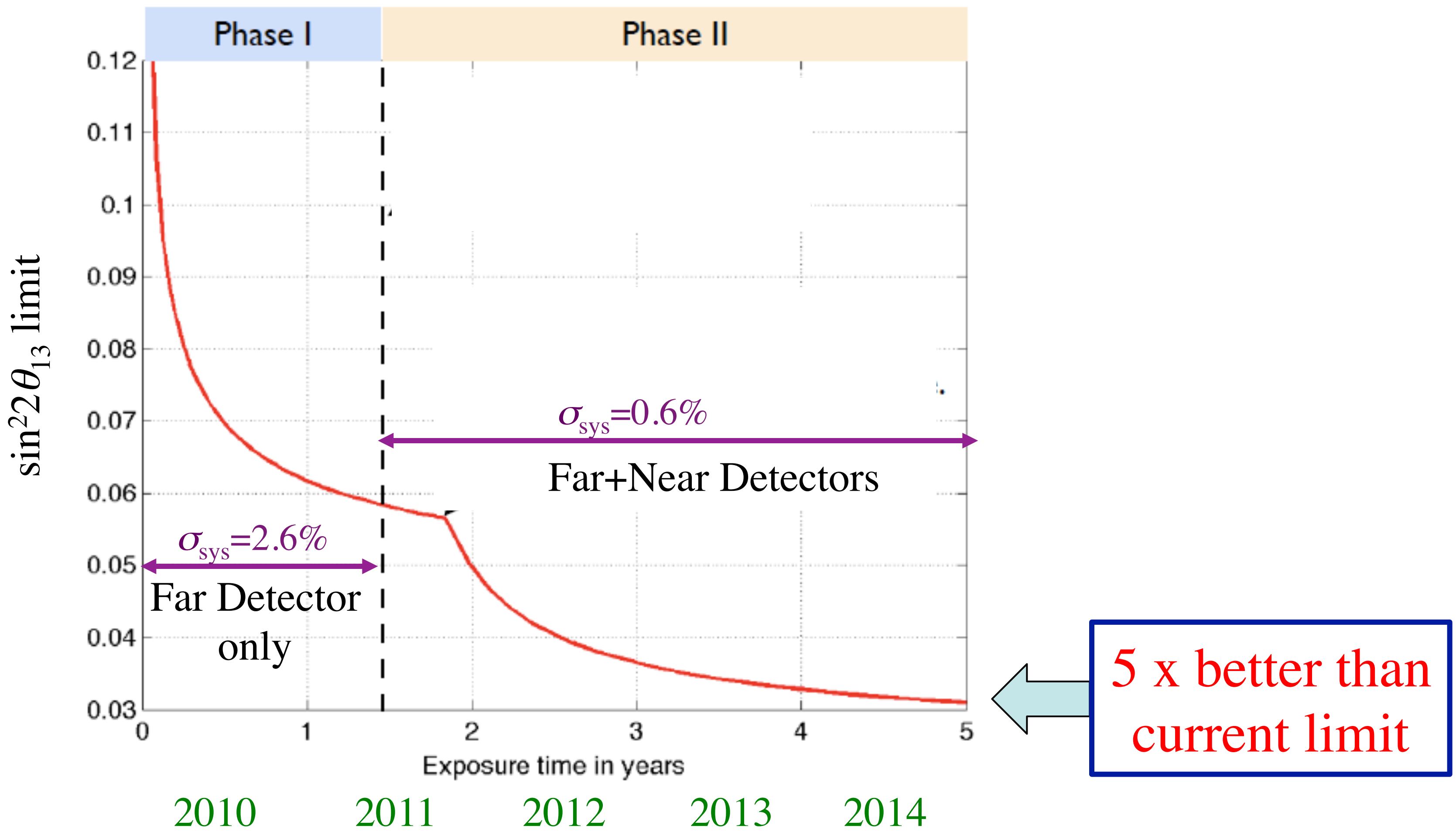






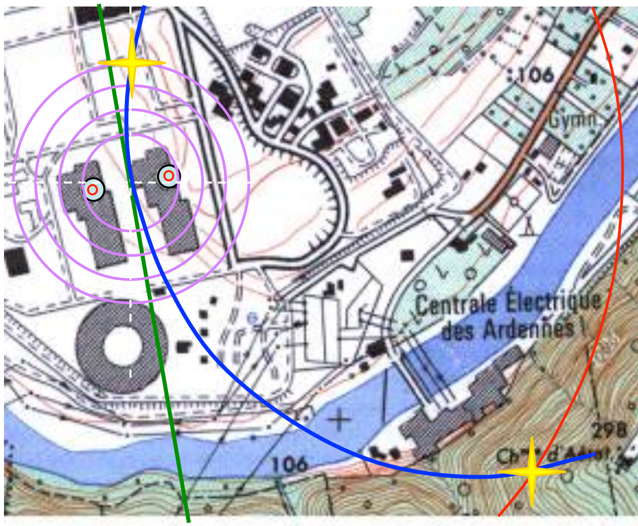
- Only 3 main cuts. => small room for systematic uncertainty
- Detection Efficiency is insensitive to the cut parameters

Sensitivity in Time



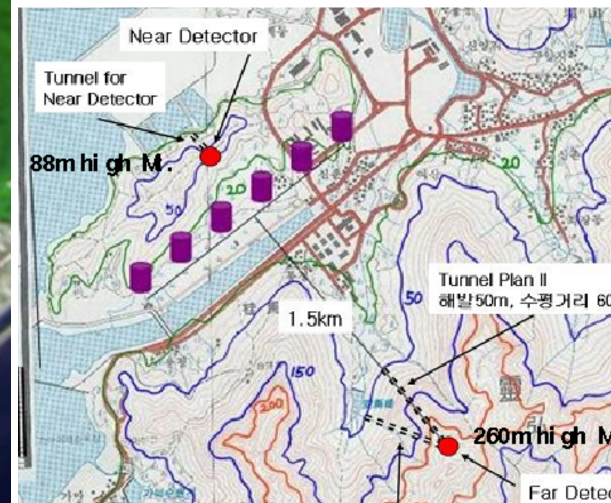
DC, Dayabay, RENO

Double Chooz



Daya Bay

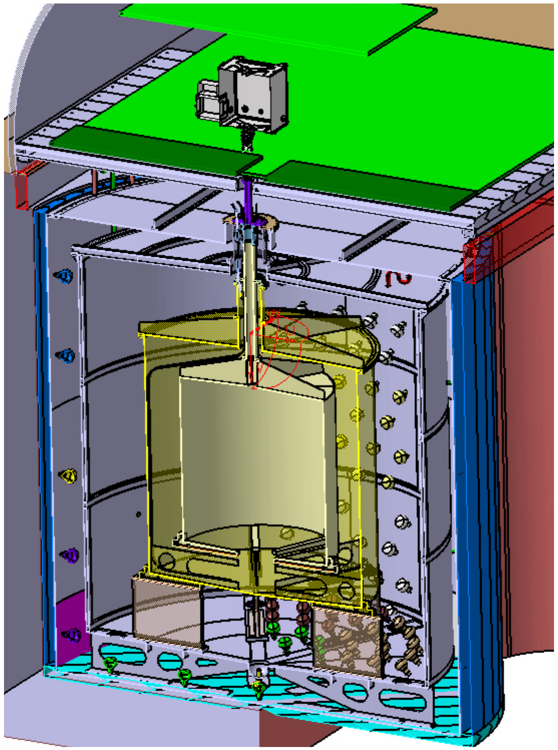
RENO



	Double Chooz	Dayabay	RENO
Power(GWth)	8.2GW	11.6GWth (17.4GW>2012)	16.1GW
Detector(ton)	8	80	16
Baseline(km)	1.05	1.8	1.4
$\sin^2 2\theta_{13}$ Sensitivity	~0.03	~0.01	~0.02

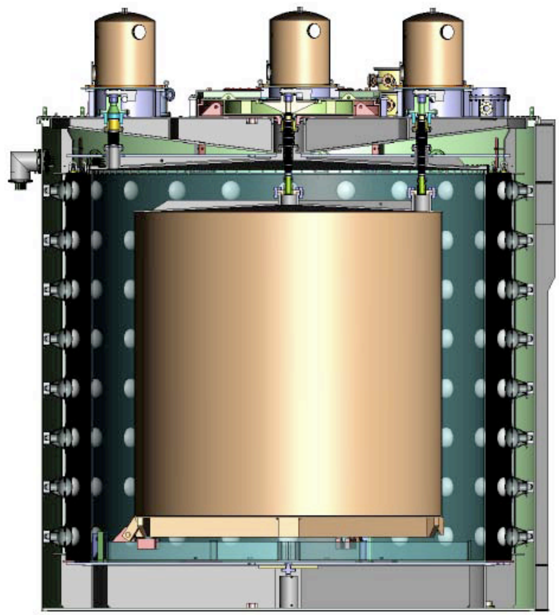
ν-Detector

Double Chooz



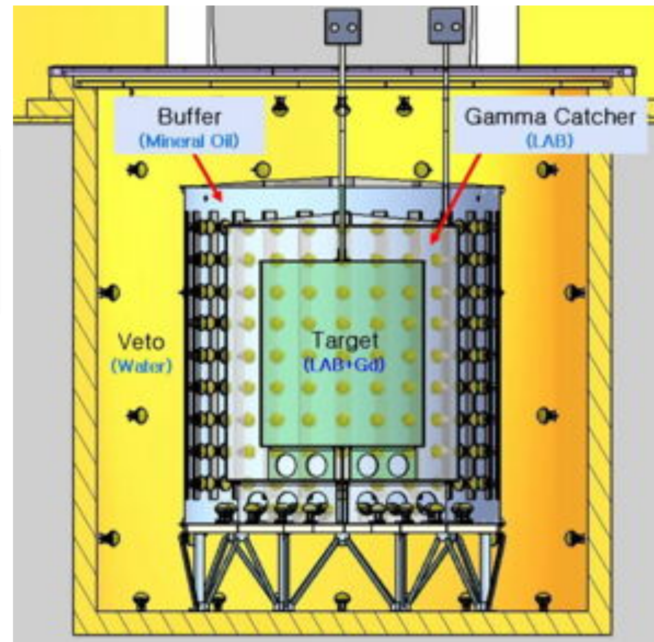
M=8ton
N=1+1

Daya Bay



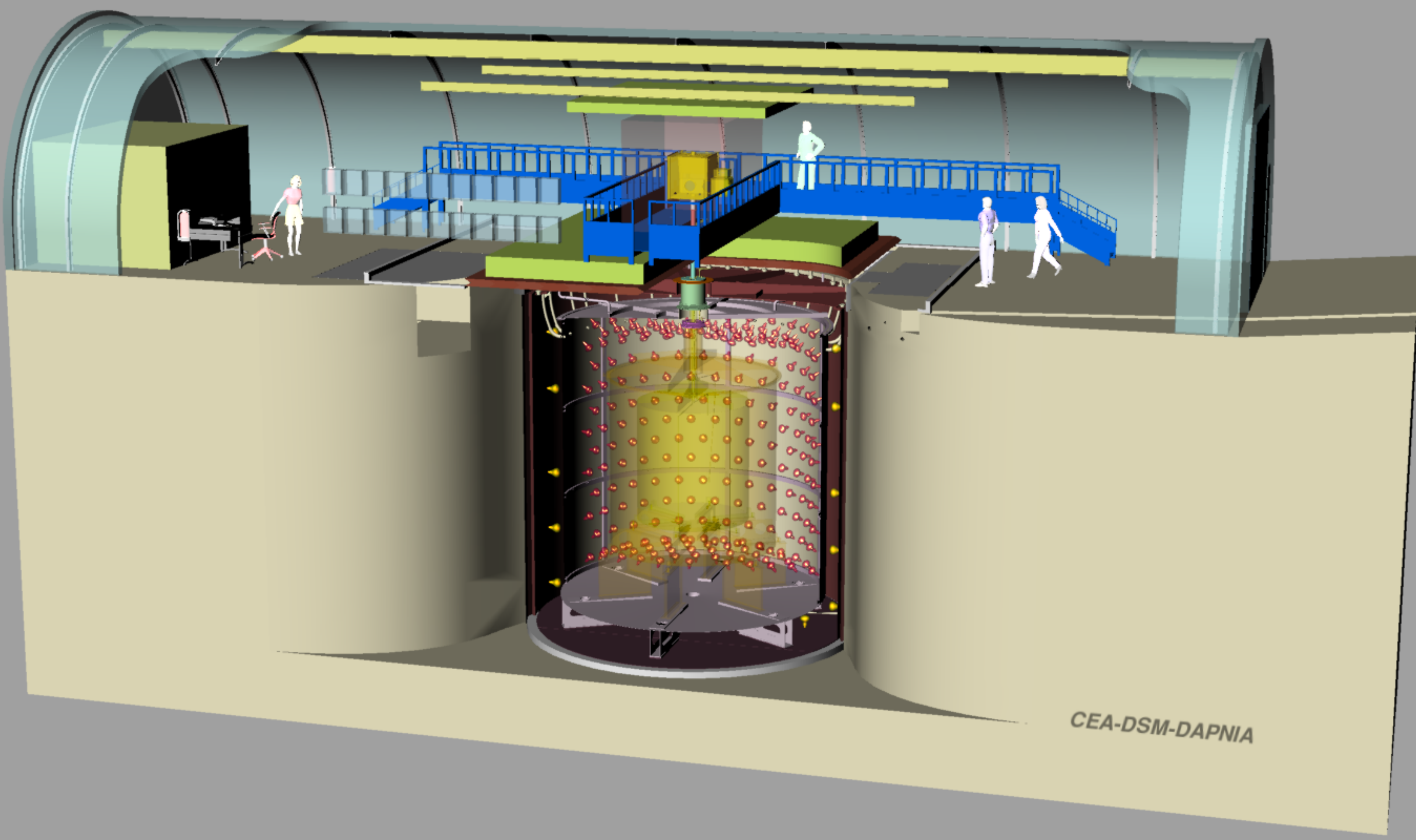
M=20ton
N=2+2+4

RENO

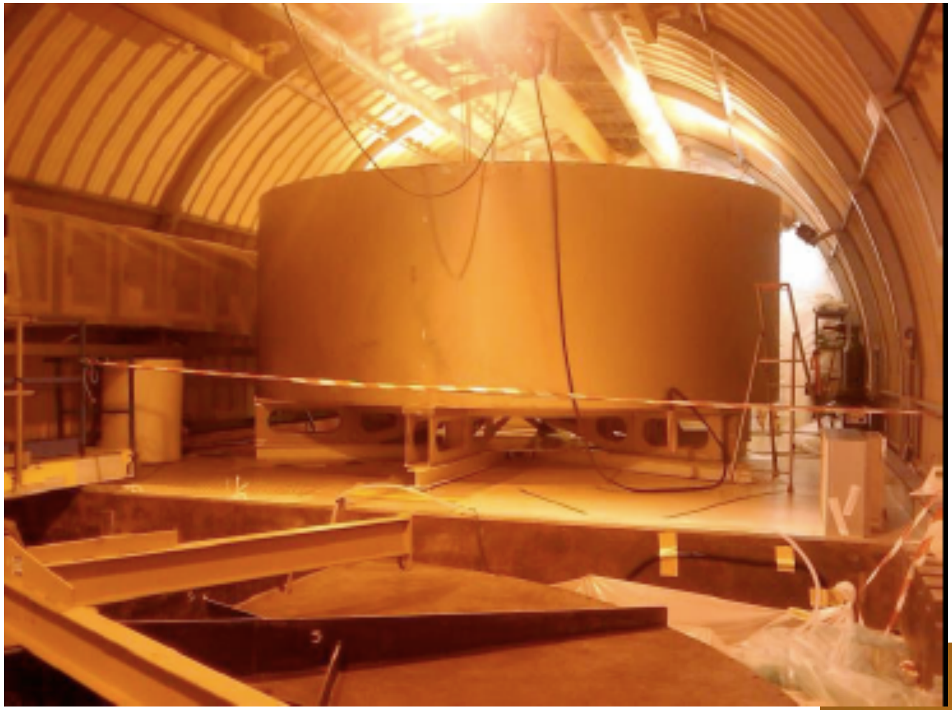


M=16ton
N=1+1

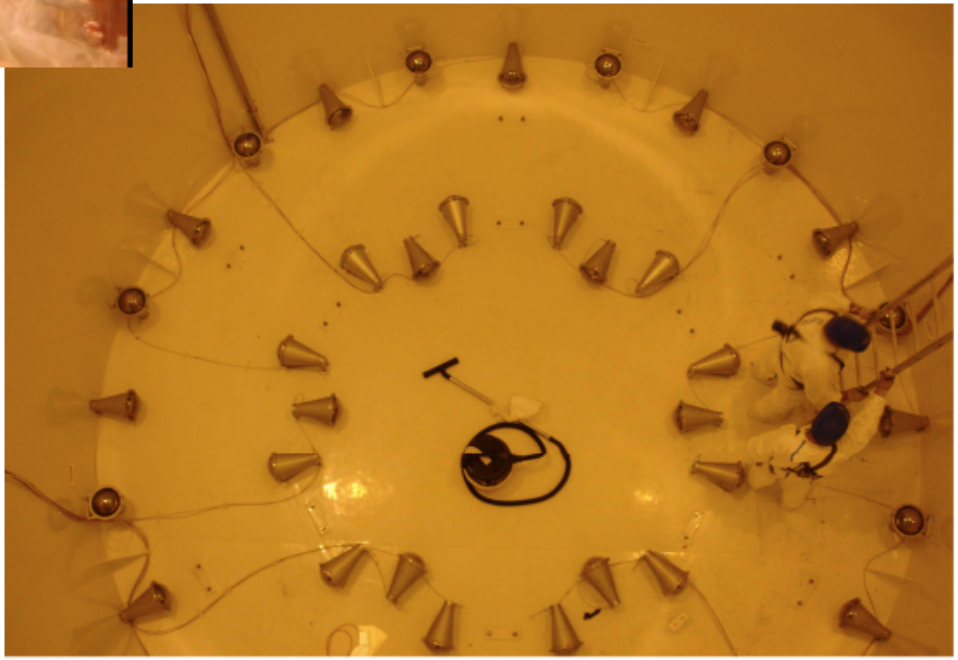
Double Chooz Status



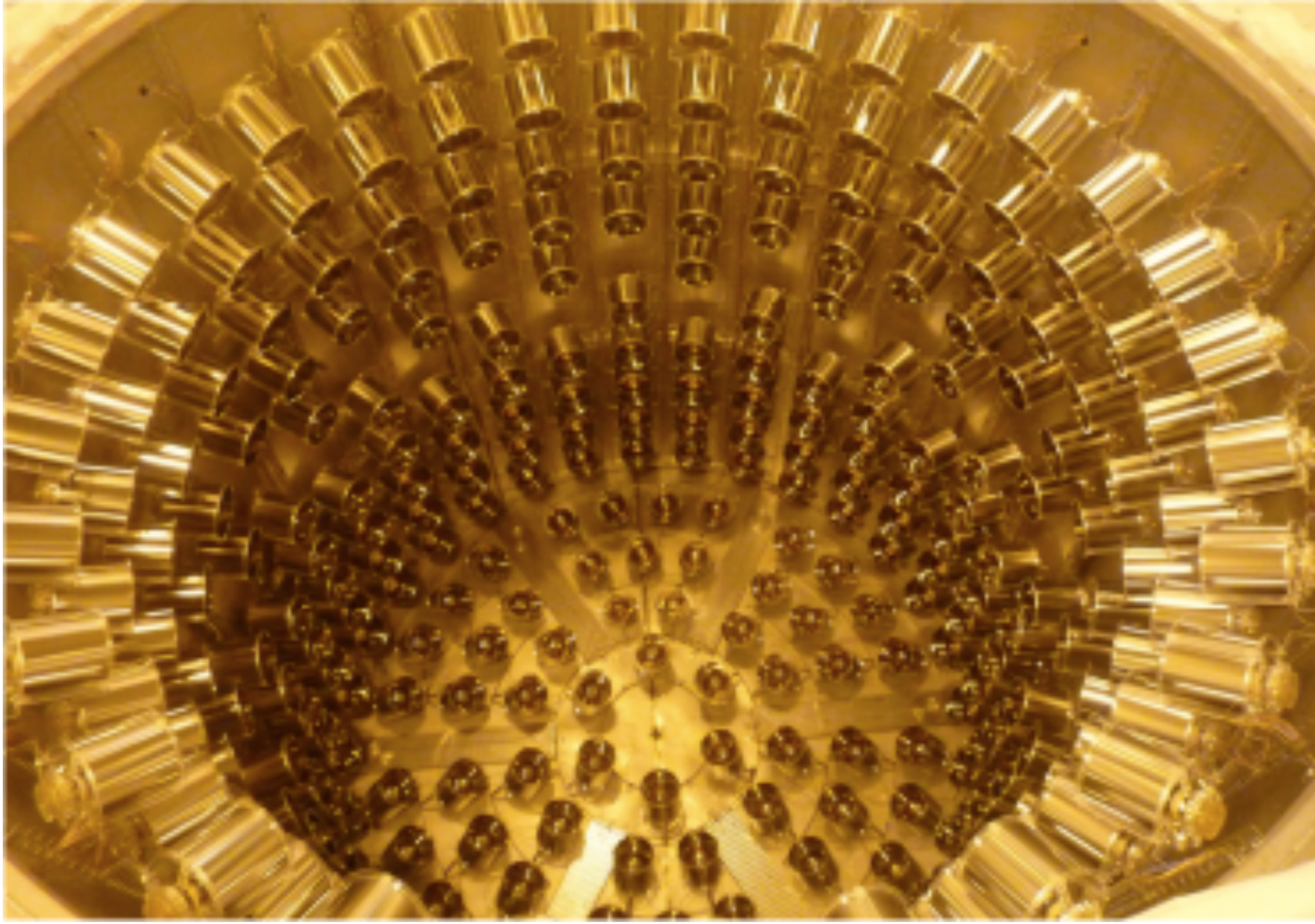
DOUBLE CHOOZ far detector



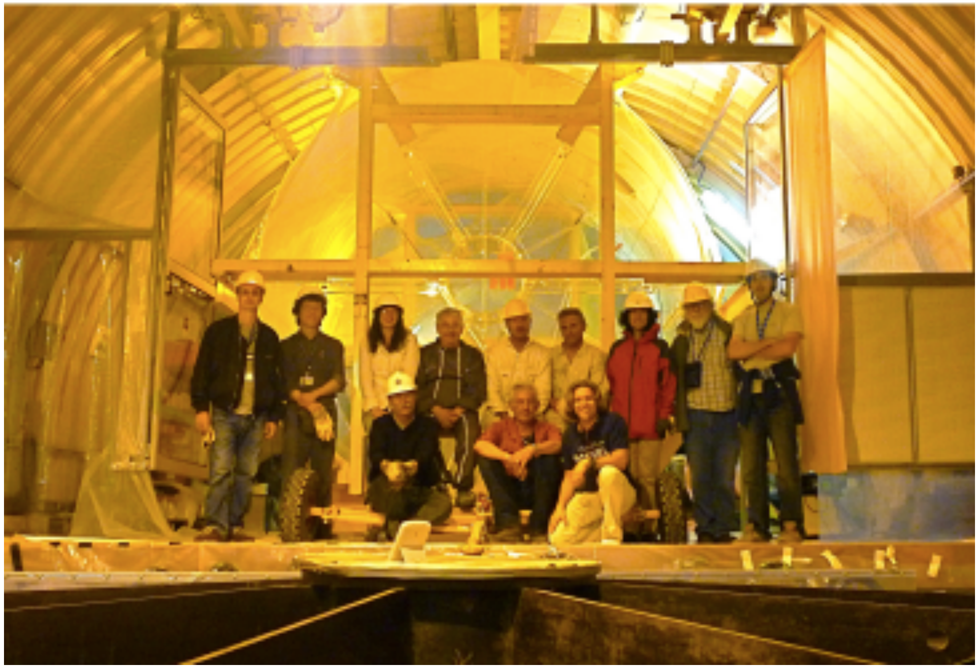
Detector Tank is ready.
(2008.



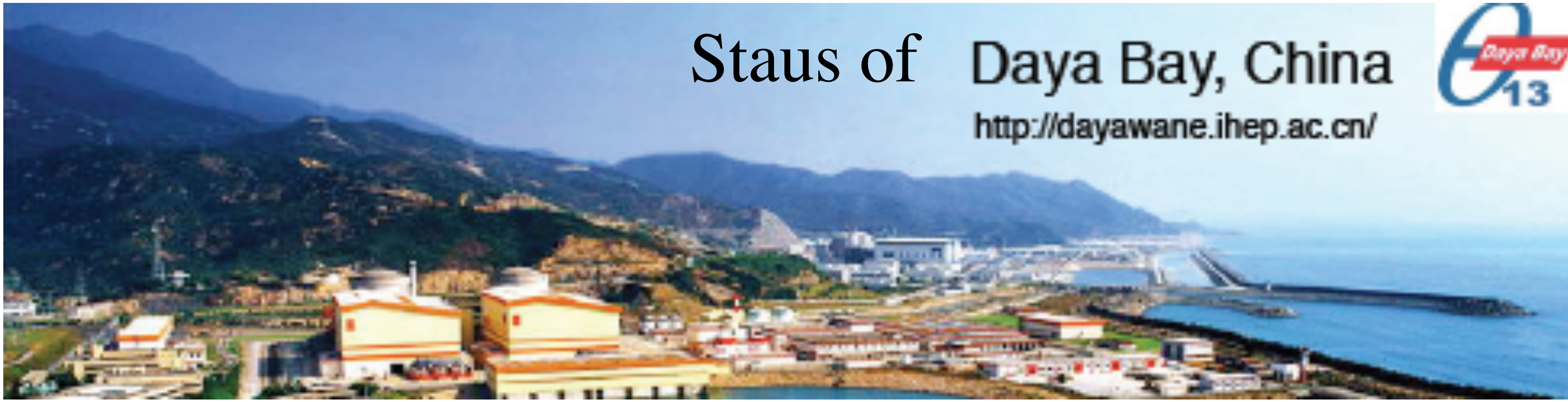
Veto PMT Installed.
(2009.2)



6/2009 Botton & Side PMT (330) installation finished (under Japanese leadership)

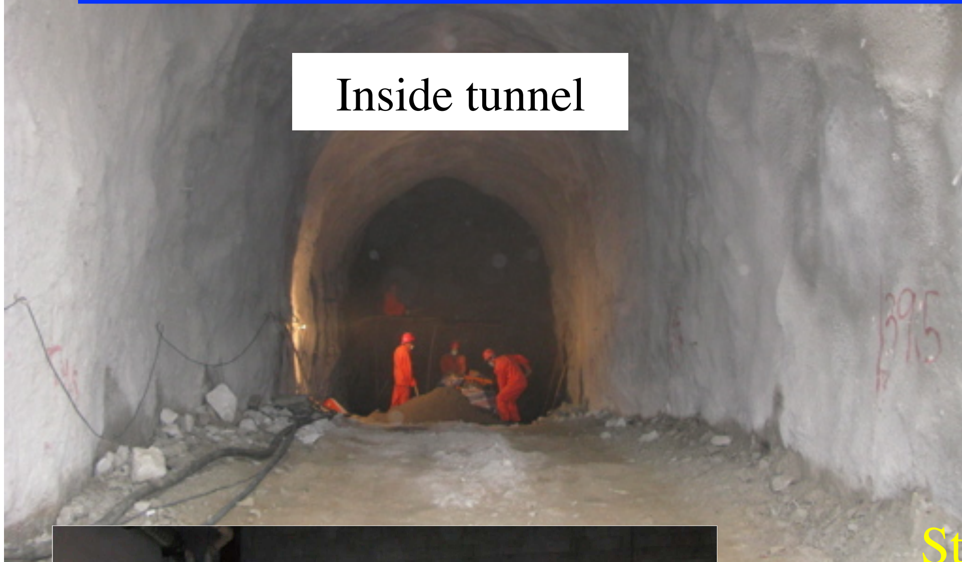


9/2009	Acrylic Vessels being installed
12/	Electronics installation
1/2010	Scintillator filling
4/2010	Commissioning



Slides: from Courtesy of Prof. Kam_Biu Luk & Prof. Karsten Heeger
(2009.3)

Civil Construction



Inside tunnel

Stainless steel tank in China

4-m vessel in the U.S.

Daya Bay: Milestones

(by Kam Bieu)

• Daya Bay is fully funded.

• Civil and detector construction is well on the way.

• Beneficial occupancy of
Surface Assembly Building March 2009

• Assembly of first two ADs in SAB Summer 2009

• Data-taking in Near Halls Summer 2010

• Data-taking with all eight detectors Summer 2011

Current Status of RENO

Slides: Courtesy of Prof. Soo Bong Kim
2009.3

❑ RENO Near and Far Tunnels are ready

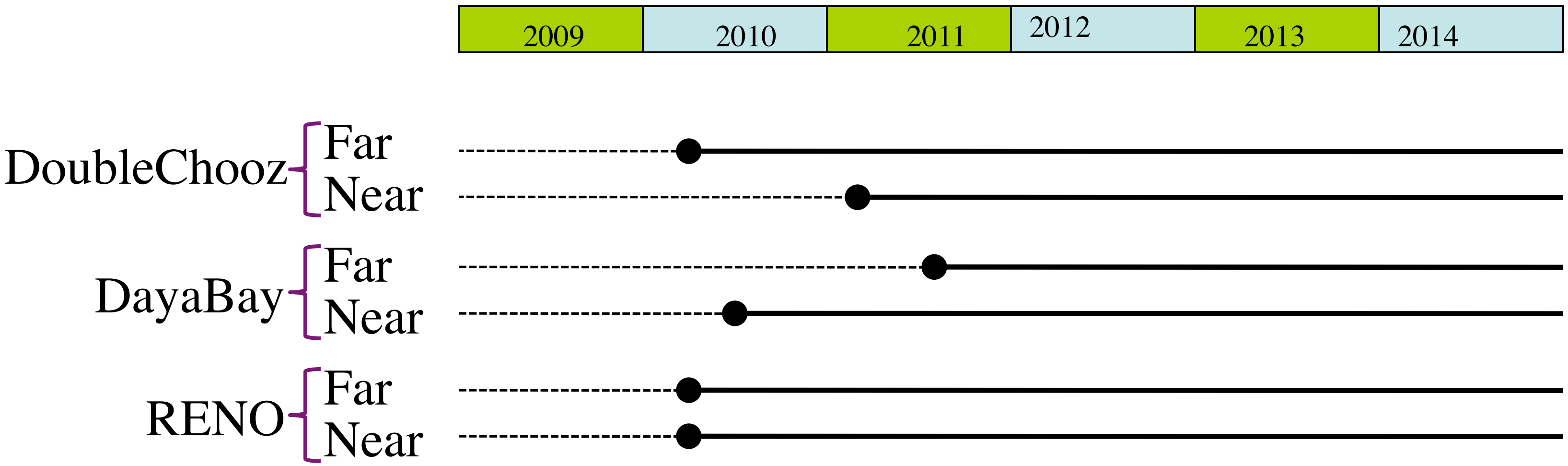
No Detector Photos

Summary of Construction Status

- 03~10, 2007 : Geological survey and tunnel design are completed.
- 07~11, 2008 : Construction of both near and far tunnels are completed.
- 12, 2008 ~ 02, 2009 : Veto tanks and peripheral facilities (electricity, air circulation, drainage, etc.) are completed.
- 10, 2008 : A mock-up detector (~1/10 in volume) is built and being tested.
- 11, 2008 : SK new electronics are adopted and ready.
- Steel/acrylic containers and mechanical structure will be prepared and installed until Aug. 2009.
- Both near and far detectors are expected to be ready for data-taking in early 2010.

(by Soo Bong Kim)

Summary of DC, DB, RN



（注、言値をそのまま記述）

DC, Dayabay and RENO finally start data taking within a year.

今後の原子炉ニュートリノ振動実験の役割

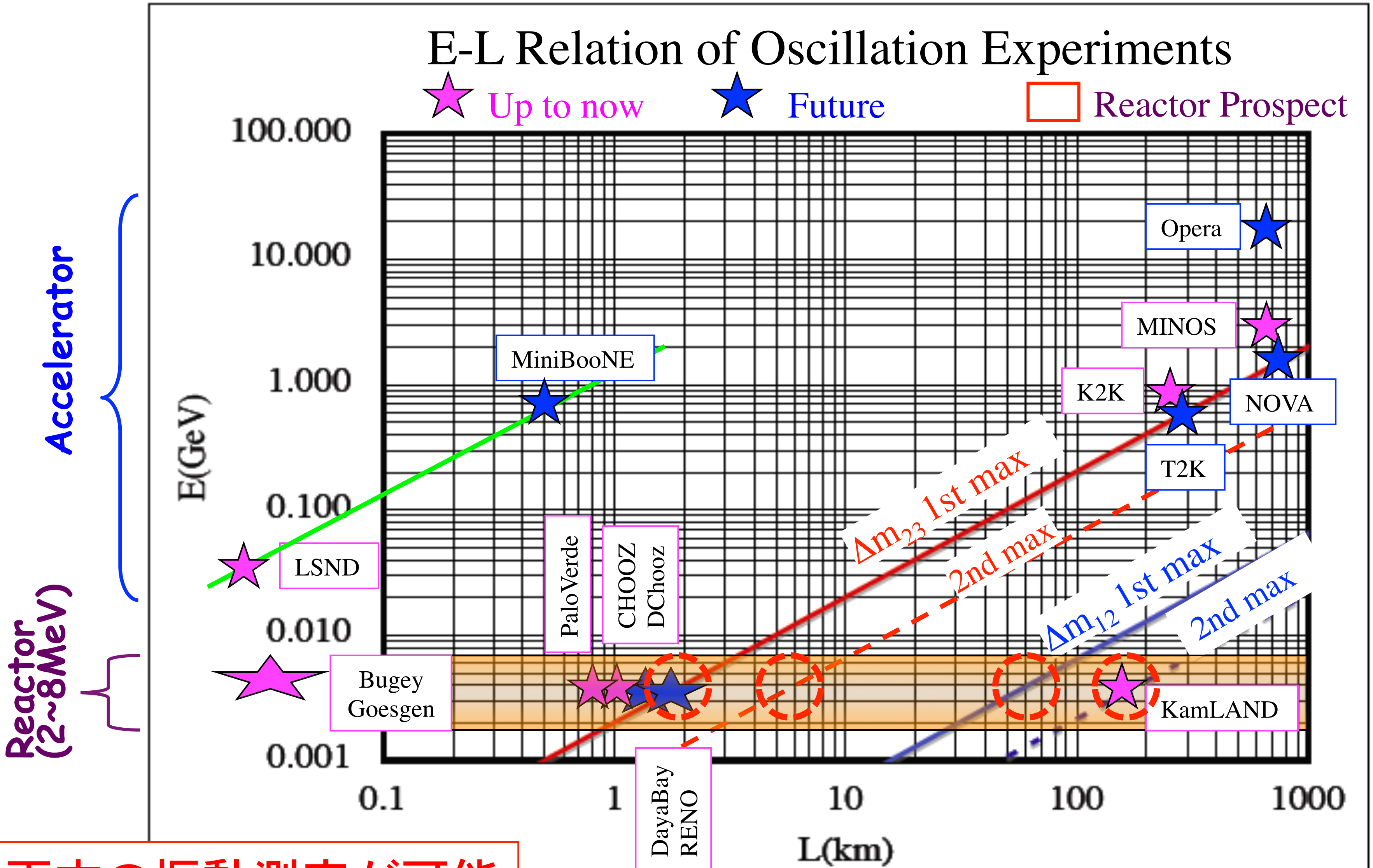
ニュートリノ振動の4つの課題

(1) $\sin^2 2\theta_{13}$の測定
(2)Mass Hierarchyの決定
(3)θ_{23}縮退の決定
(4) CP 非保存δの測定

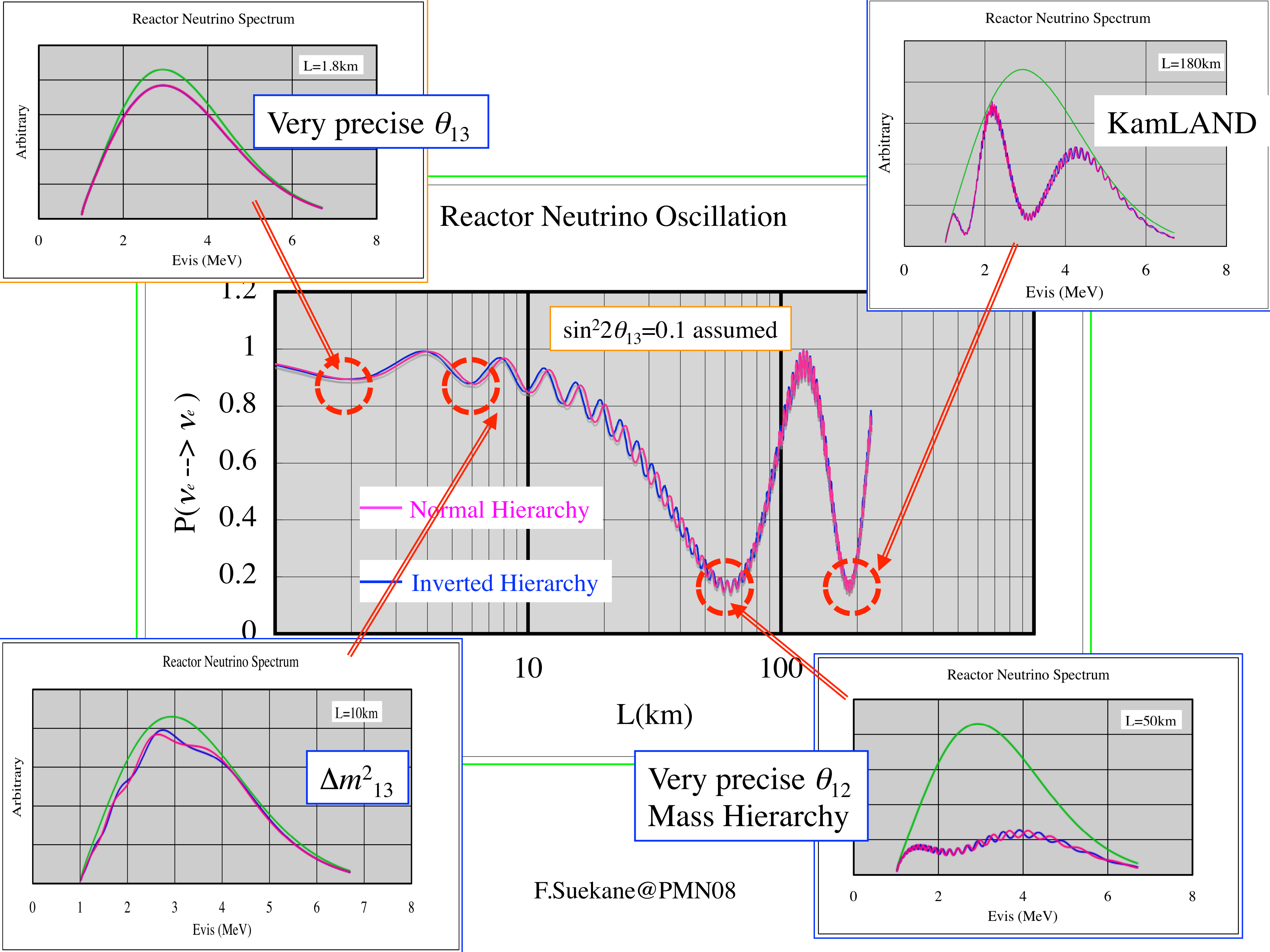
利用できる情報

(1) 加速器によるν_μ=>ν_e
(2) 加速器による$\bar{\nu}_\mu$=>$\bar{\nu}_e$
(3) Matter effect（baselineの差）
(4) 原子炉による$\bar{\nu}_e$=>$\bar{\nu}_e$

原子炉ニュートリノで手が届くパラメータ範囲

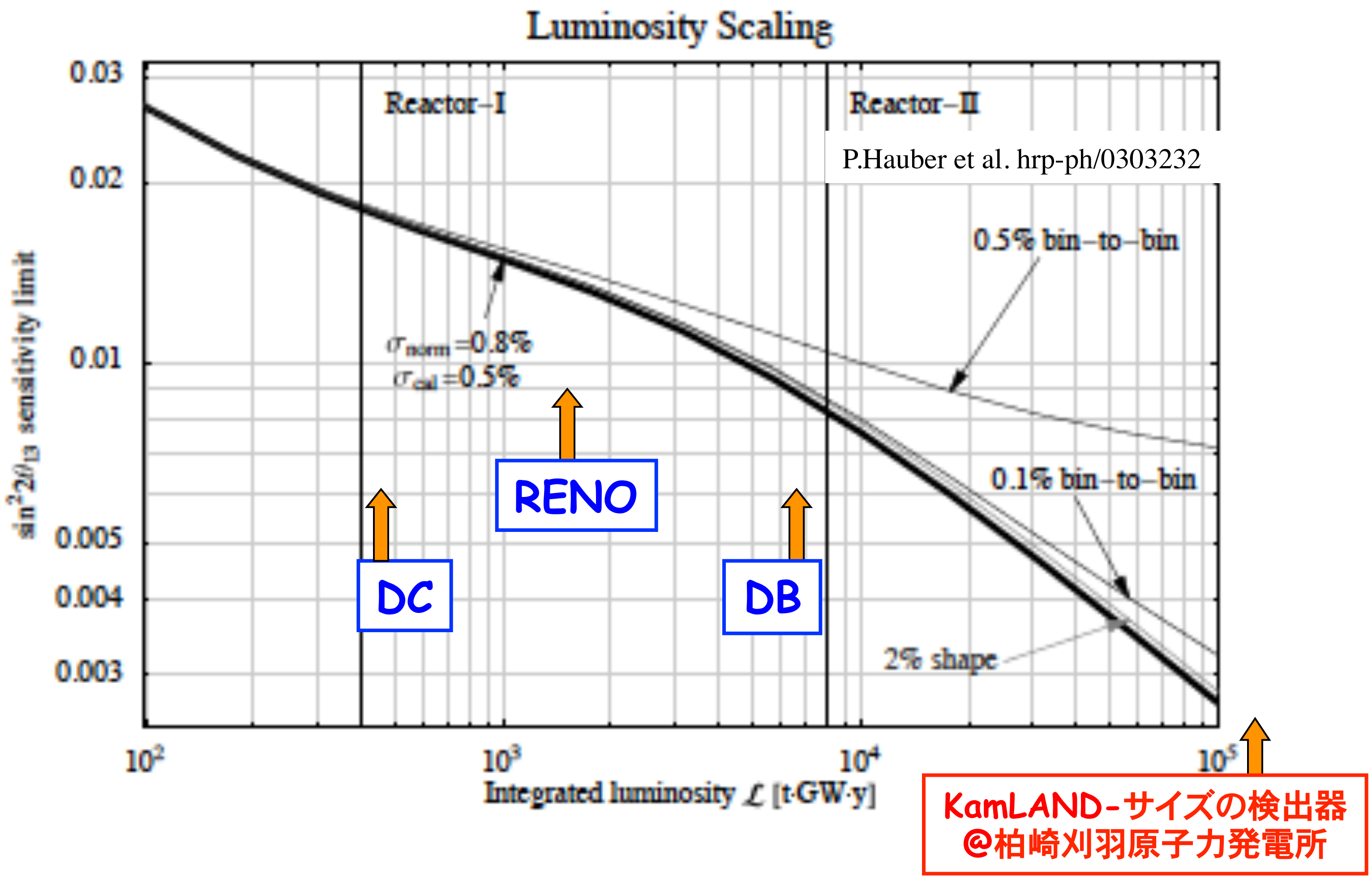


両方の振動測定が可能



Reactor Neutrino Oscillation
Reactor Neutrino Spectrum
L=1.8km
Arbitrary
Evis (MeV)
Very precise θ_{13}
Reactor Neutrino Spectrum
L=180km
KamLAND
$\sin^2 2\theta_{13}$=0.1 assumed
$P(\nu_e \text{-->} \nu_e)$
L(km)
Normal Hierarchy
Inverted Hierarchy
Reactor Neutrino Spectrum
L=10km
Δm^2_{13}
Reactor Neutrino Spectrum
L=50km
Very precise θ_{12}
Mass Hierarchy
F.Suekane@PMN08

Physics @ 1st Δm^2_{13} Maximum (L~1.5km) = Very Precise θ_{13}



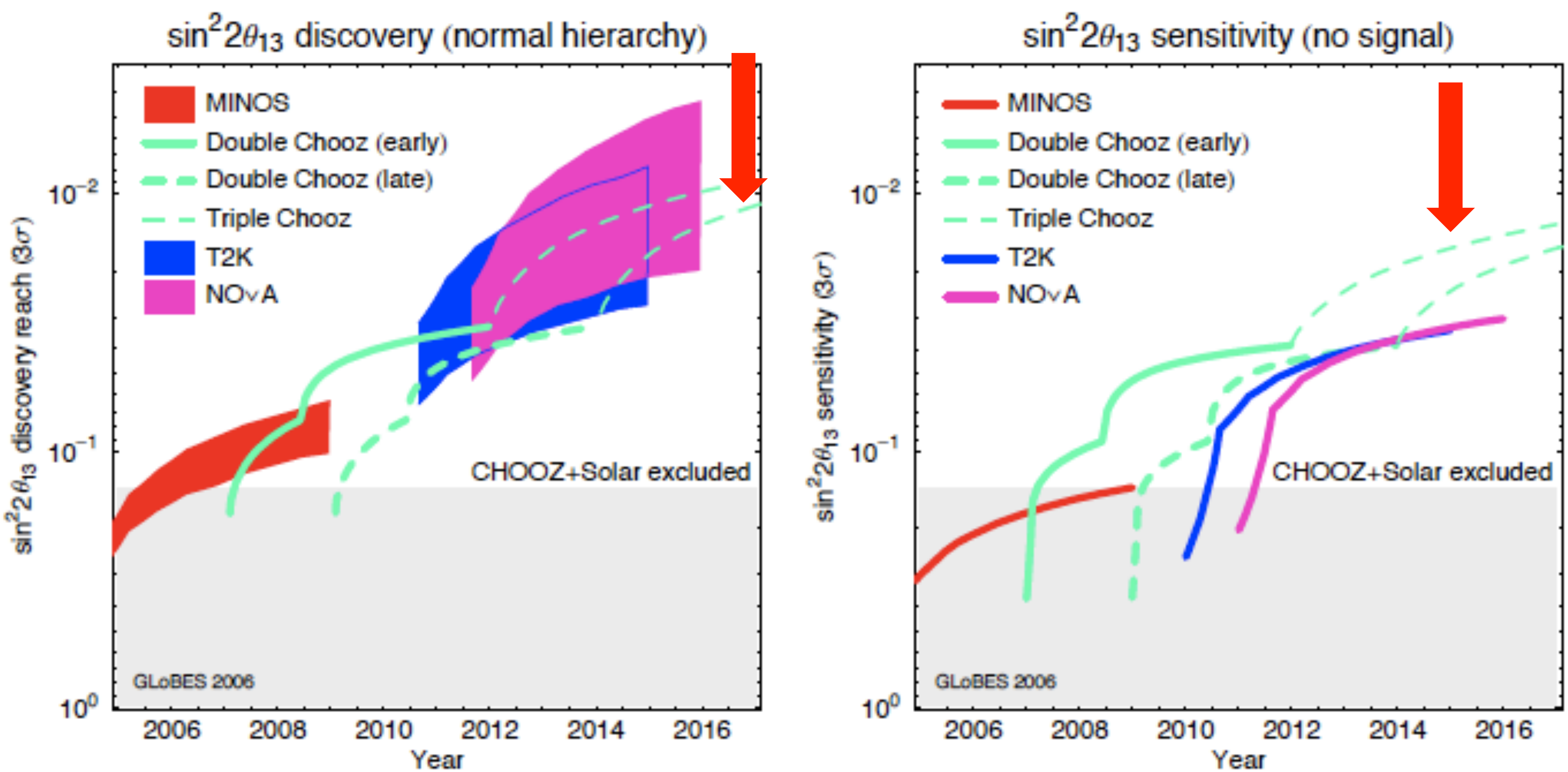
統計が大きくなると、エネルギースペクトルのDistortionの測定が効果的になり、normalizationの誤差の影響を受けなくなる。=> $\delta\sin^2 2\theta_{13}<0.01$が可能。

Arxive hep-ph/0601266v1

From Double Chooz to Triple Chooz — Neutrino Physics at the Chooz Reactor Complex

P. Huber[a], J. Kopp[b], M. Lindner[c], M. Rolinec[d], W. Winter[e]

Target 質量を8トンから210 ton にする



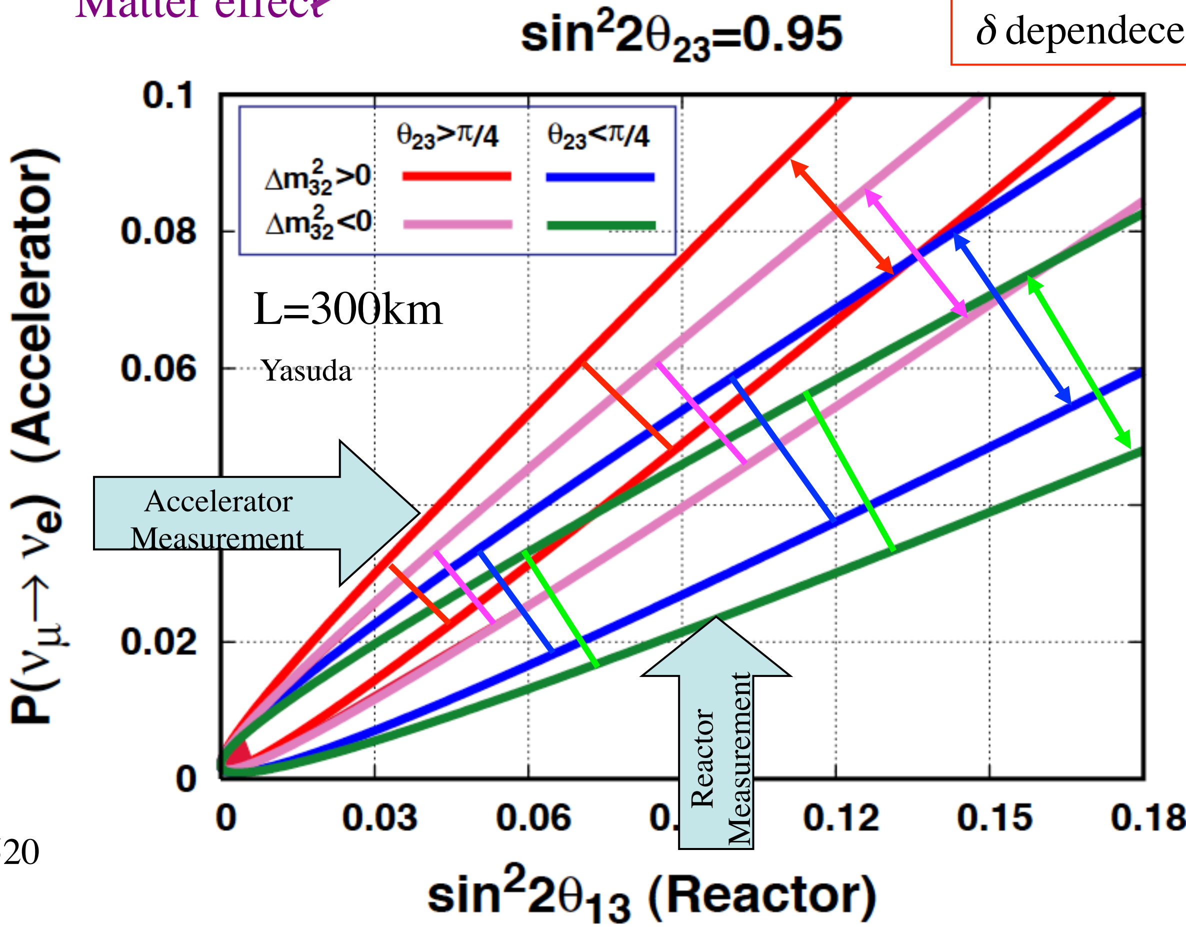
Complementarity of Reactor-accelerator θ_{13} measurement

θ_{23} degeneracy

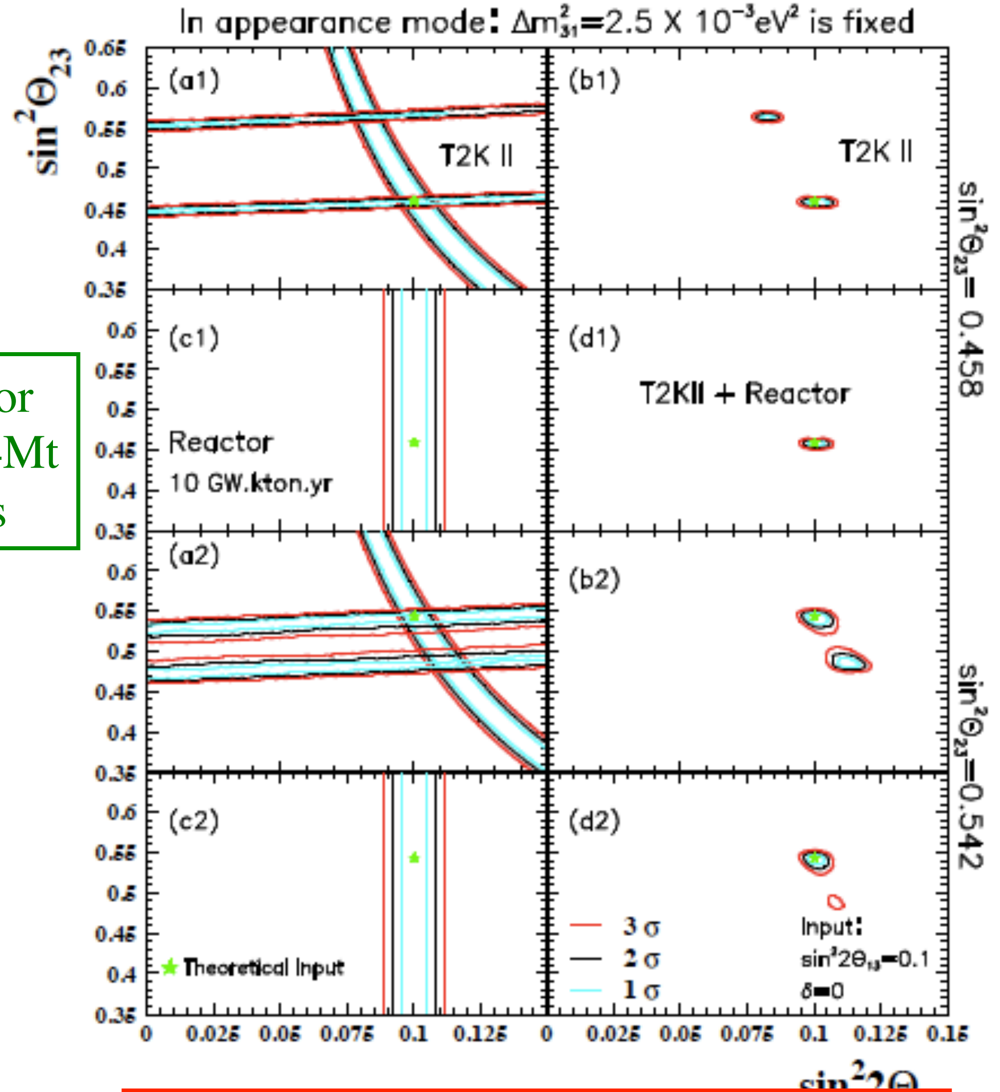
$$P_{AC}(\nu_\mu \to \nu_e) = \frac{0.50 \pm 0.11}{(1 \mp 0.00017L[km])^2}\sin^2 2\theta_{13} \pm 0.045\sin 2\theta_{13}\sin\delta$$

Matter effect

δ dependece



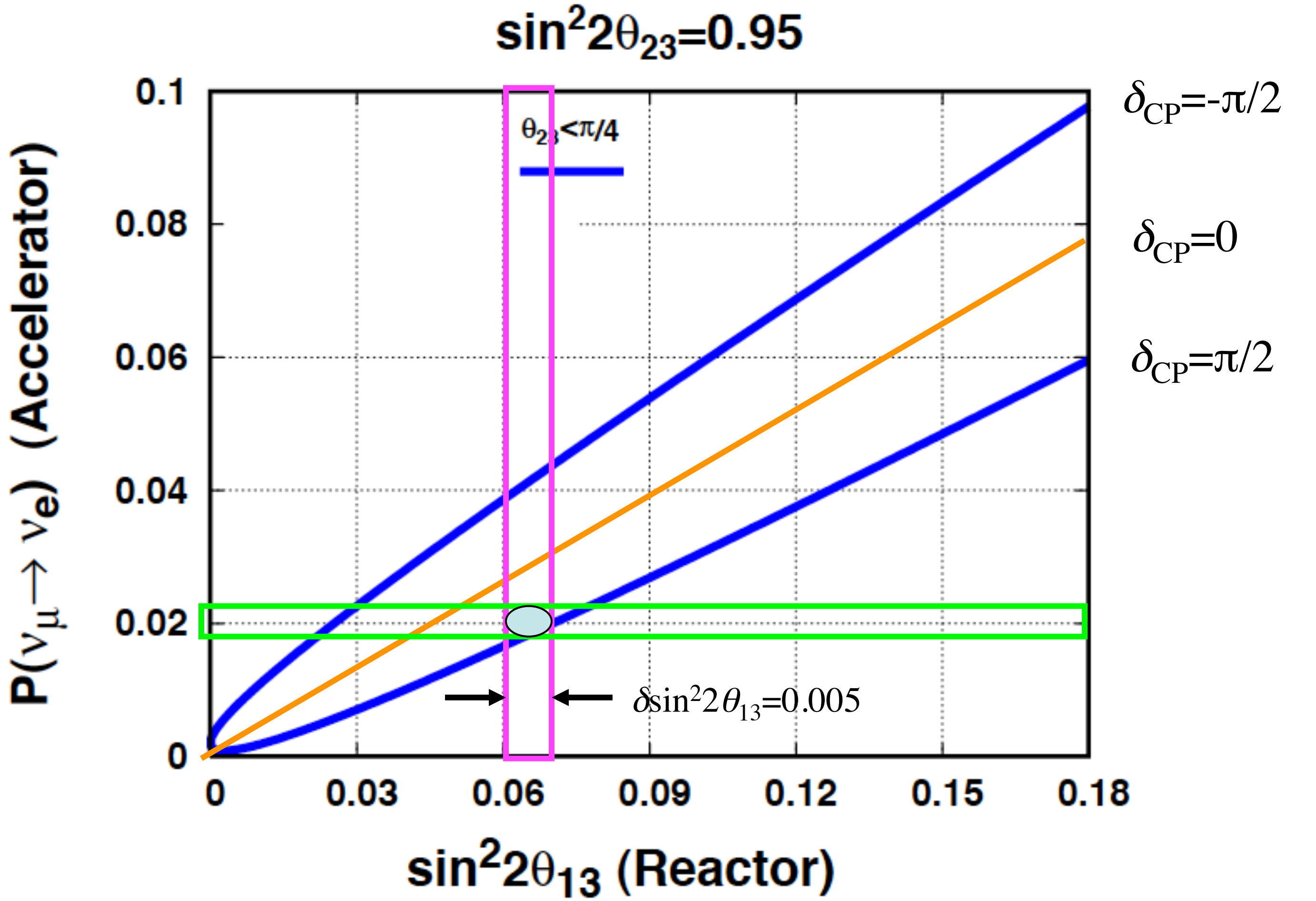
θ_{23}縮退の決定



Accelerator
4MW*0.54Mt
2+6years

Reactor: 100t*4.2y@柏崎刈羽（24GW）

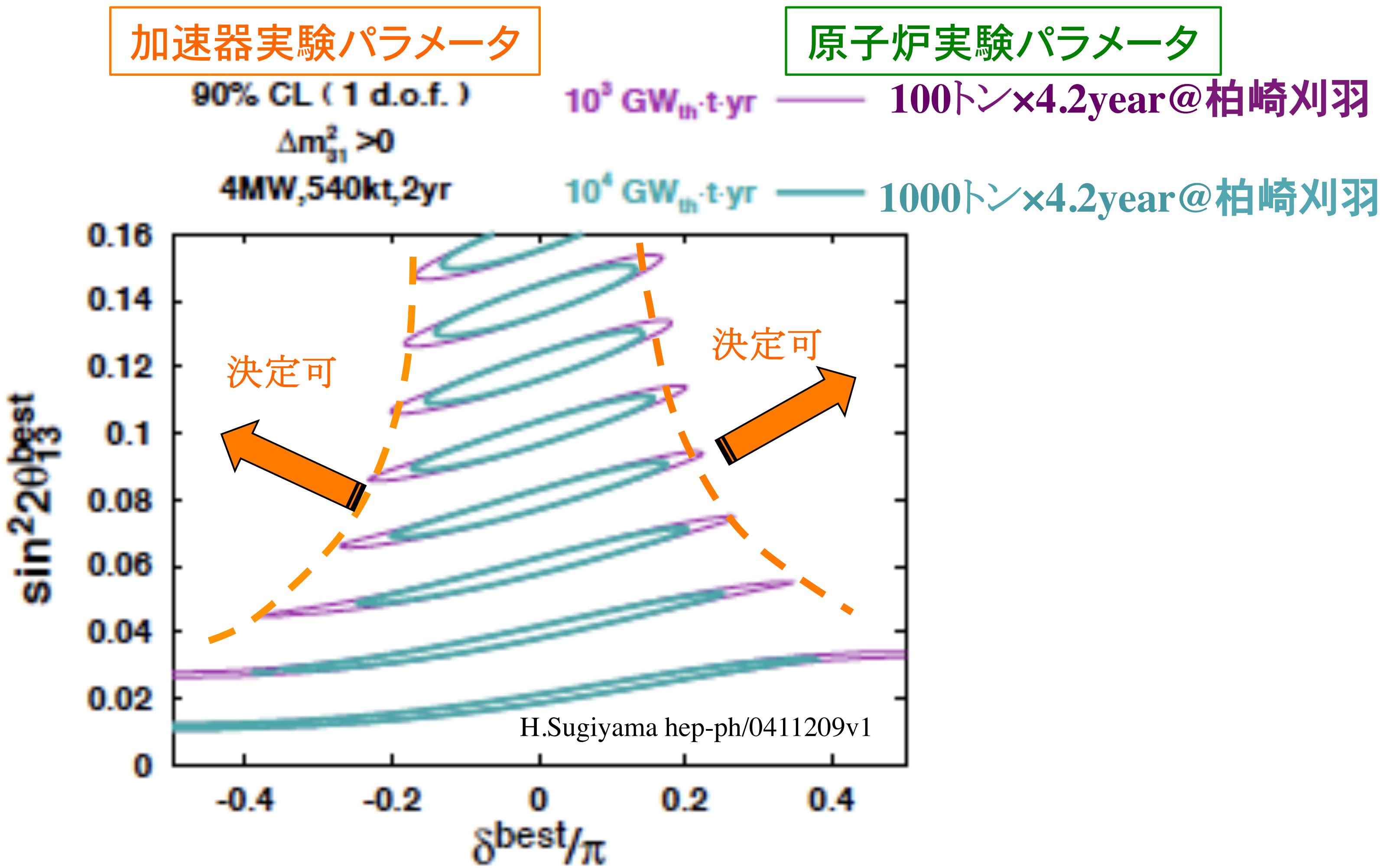
Quick Access to δ_{CP}



もしθ_{23} degeneracyとMass Hierarchyが決定されれば、放物線の数は一つになる。

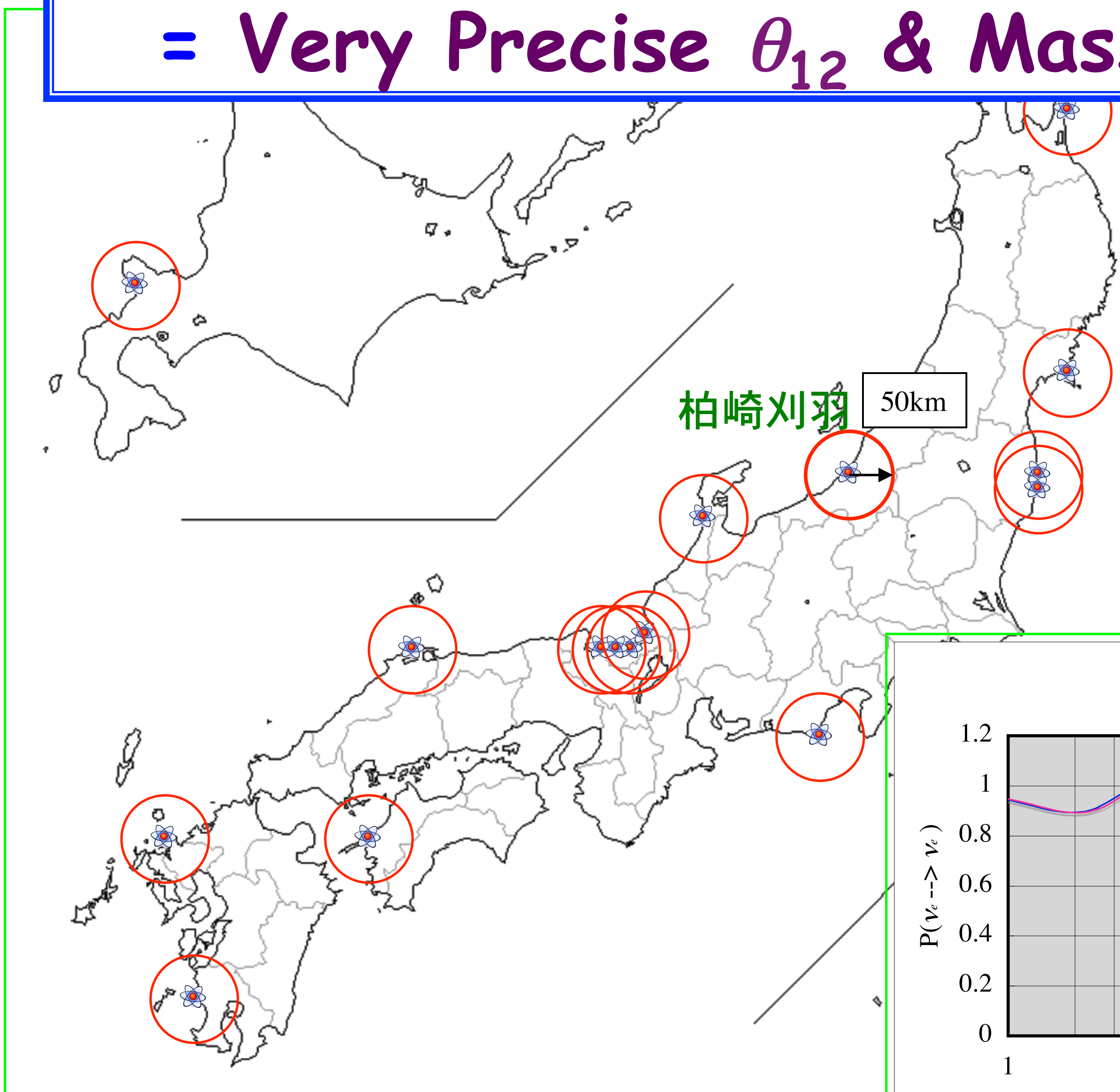
原子炉によるθ_{13}の精度が良くなれば、加速器のνモードのデータと組み合わせることによりsinδを早く決定できる可能性がある。

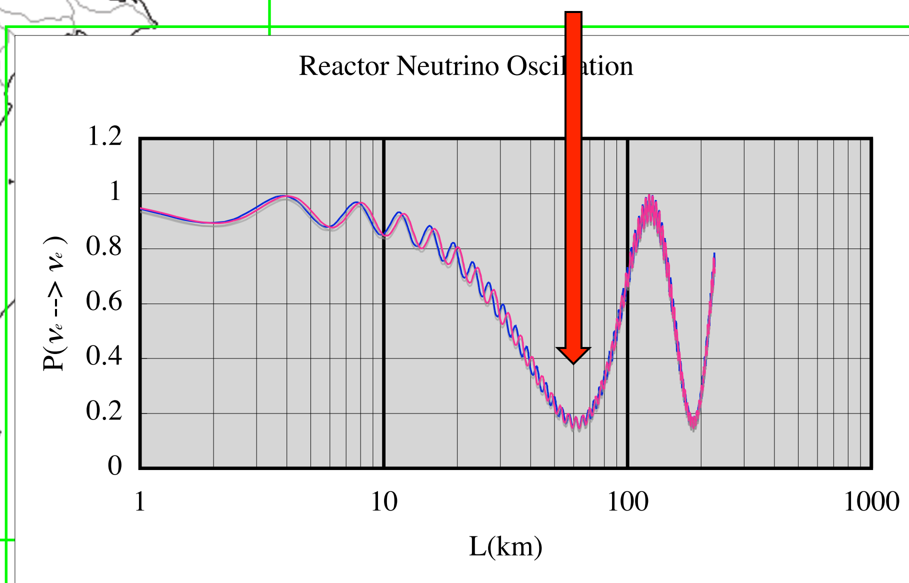
non-0のδ決定可能なパラメータ領域



$\sin^2 2\theta_{13}>0.05$ならば、可能性あり。

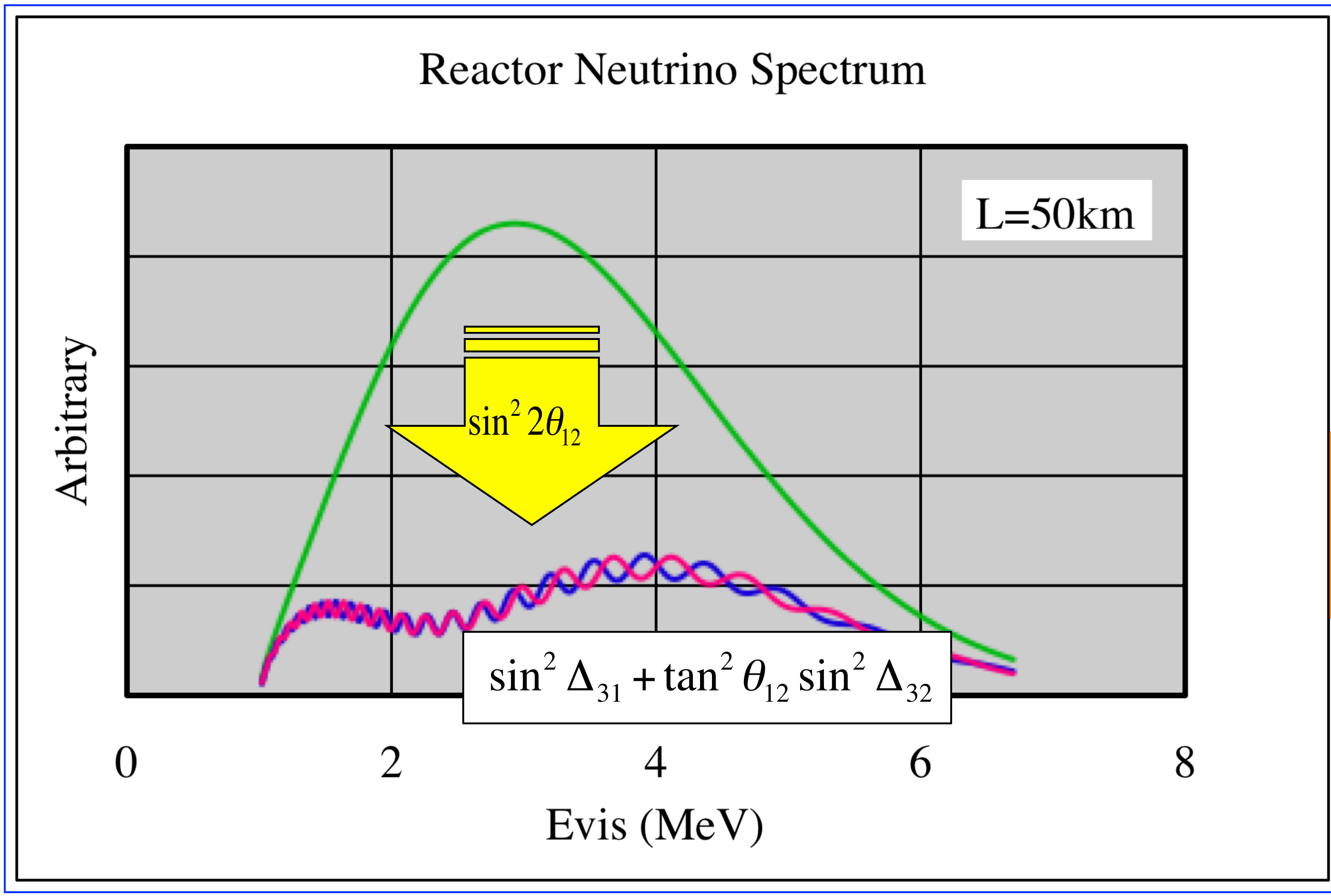
Physics @ 1st Δm^2_{12} Maximum(L~50km) = Very Precise θ_{12} & Mass Hierarchy





Physics @ 1^{st} Δm^2_{12} Maximum

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \left\{ \begin{array}{l} \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ +\underline{\sin^2 2\theta_{13}}\cos^2\theta_{12}\left(\sin^2\Delta_{31} + \tan^2\theta_{12}\sin^2\Delta_{32}\right) \end{array} \right\}$$



$1 - \sin^2 2\theta_{12}$
で大きく欠損

↓

θ_{12}の精密測定

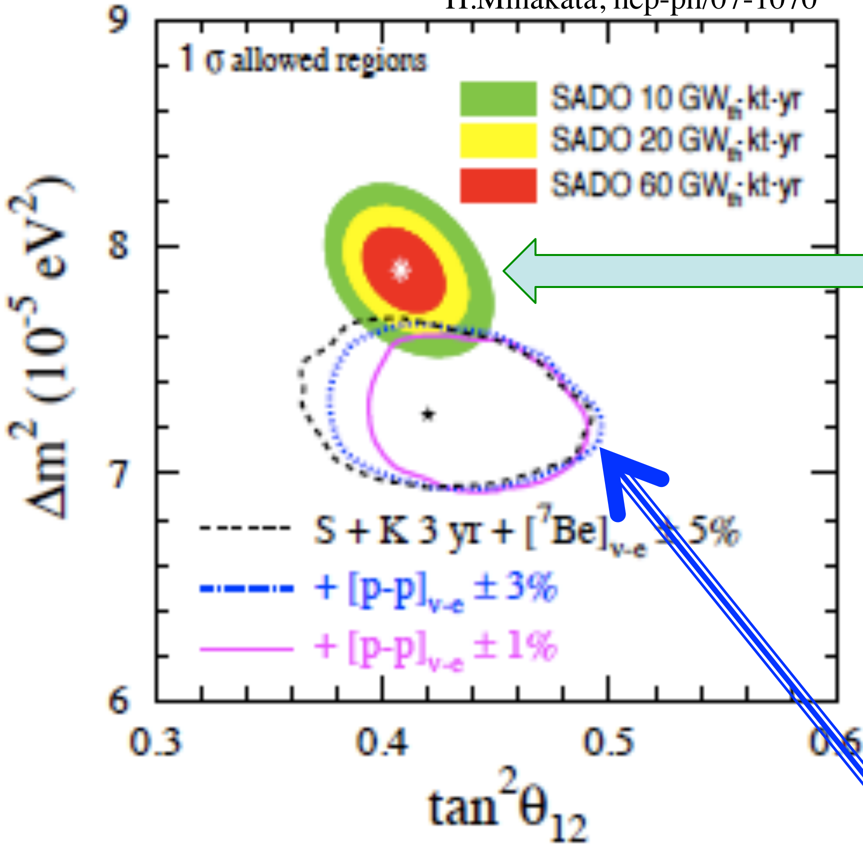
$\sin^2\Delta_{31} + \tan^2\theta_{12}\sin^2\Delta_{32}$
の波が重なる

↓

Mass Hierarchy
の決定

θ_{12}の精密測定

H.Minakata, hep-ph/07-1070



1kton ×2.5y@柏崎刈羽

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} \sim 2.4\%(1\sigma)$$

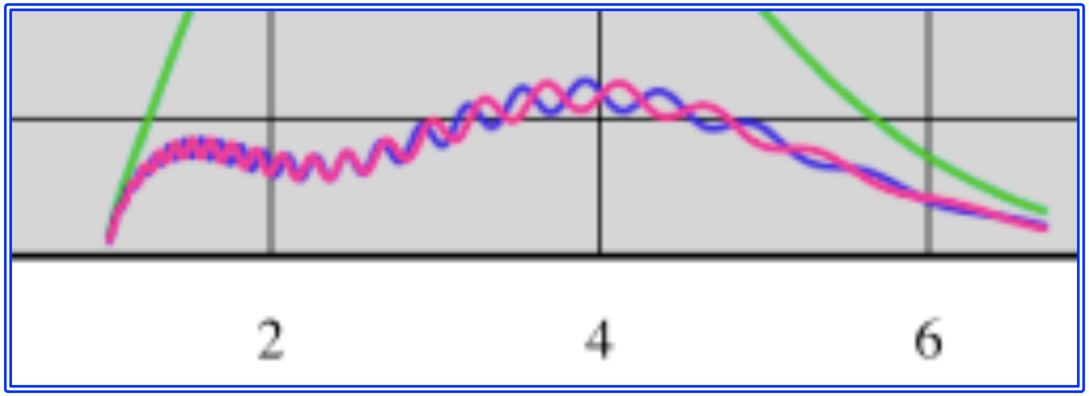
現在のGlobal fit

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} \sim 6.3\%(1\sigma)$$

将来のsolar + KamLAND

Mass Hierarchyの決定

原理



$$\propto \sin^2 2\theta_{13}\left(\sin^2 \Delta_{31} + \tan^2 \theta_{12} \sin^2 \Delta_{32}\right); \quad \Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

~0.4

2種類の周期が重ね合わさったものになっている。

=> フーリエ解析で、$\Delta m^2{}_{23}$と$\Delta m^2{}_{13}$が分離でき、
そのamplitudeが比較できれば良い。

J.Learned et al. arXive-0612022

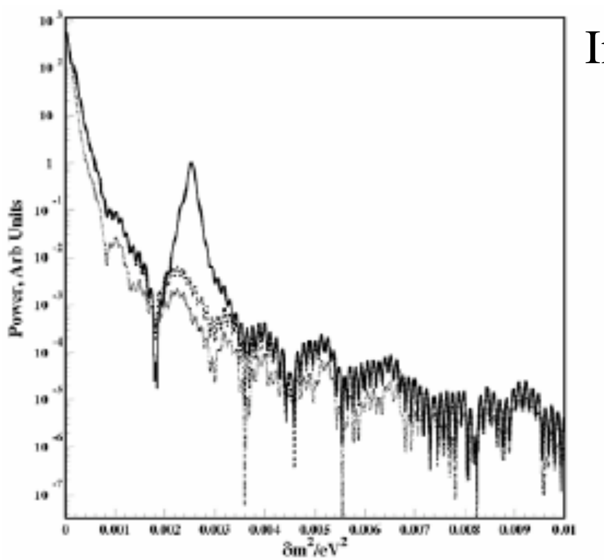


FIG. 2: Fourier power spectrum with modulation in units of eV^2 and power in arbitrary units on the logarithmic scale. The peak due to Δ_{31} with $\sin^2(2\theta_{13})$=0.1 is prominent.

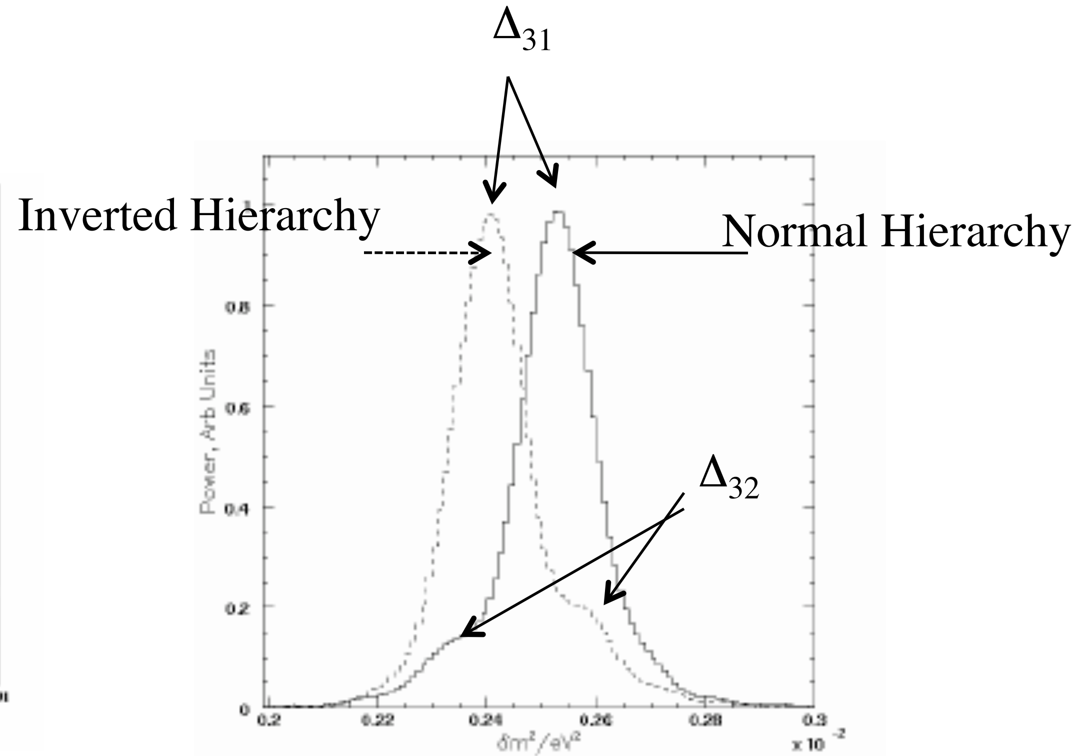
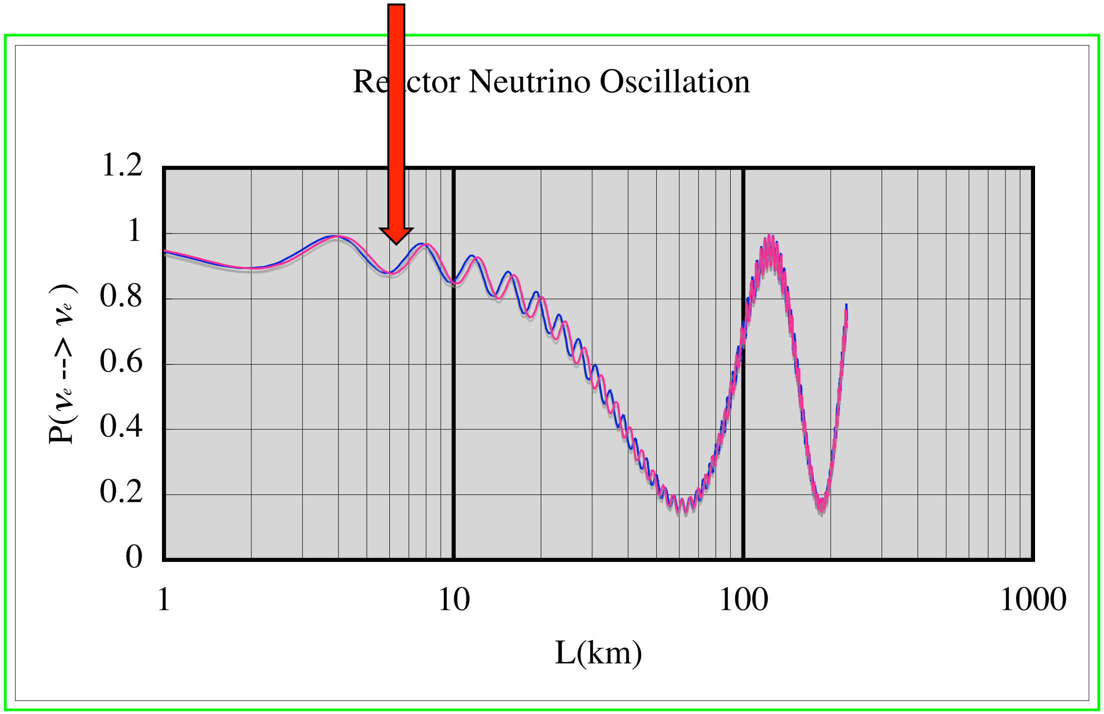


FIG. 3: Neutrino mass hierarchy (normal=solid; inverted=dashed) is determined by the position of the small shoulder on the main peak.

パワースペクトルのsimulation

$\sin^2 2\theta_{13} = 0.05$ の時、3kton*5yr @柏崎刈羽で
1σの信頼度でM.H. が決定できる。

Physics @ Δm^2_{13} 2nd Maximum (L~5km)



Precise Δm^2_{13}

It is not yet clear about the significance of this measurement.

まとめ

現在

θ_{13}: DoubleChooz, RENO, Dayabayが2010稼働開始予定

あと数年で Sensitivity $\sin^2 2\theta_{13}$=0.01~0.03

Future

*High Precision θ_{13};

M~100トン@K-K で$\sin^2 2\theta_{13}<0.01$

KASKA-II, Triple Chooz

➔ θ_{23} Degeneracy with accelerator

➔ early $\sin\delta$ detection with accelerator

L=50km, M~3Kton(KKの場合)で、

*High Precision θ_{12}; $\left(\delta\sin^2\theta_{12}/\sin^2\theta_{12} \sim 2.4\%(1\sigma)\right)$

*Mass hierarchy

=> パラメータの関係が複雑なので、第一世代のθ_{13}測定後、
それ以後の戦略を 加速器-原子炉実験で総合的に検討することが必要。