原子炉 θ_{13} 実験 DoubleChooz の現状

(for young theorists)

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2011.3.10

素粒子物理学の進展2011

@京都大学基礎物理学研究所

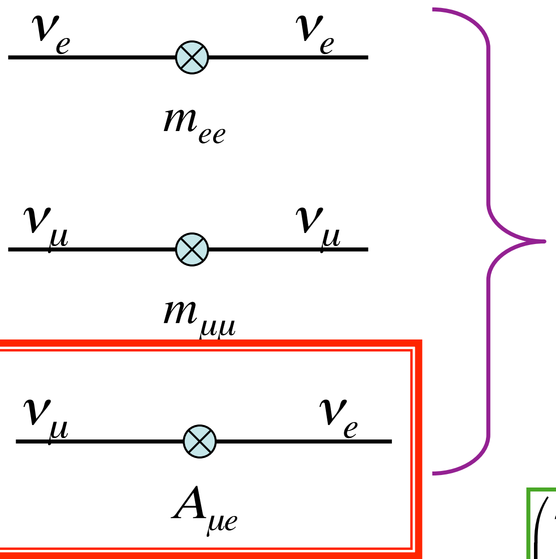
内容

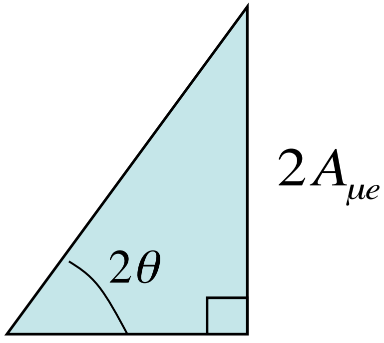
* ニュートリノ振動
* 原子炉ニュートリノ振動実験
* DoubleChooz実験
* 現在の状況
* θ_{13}以降

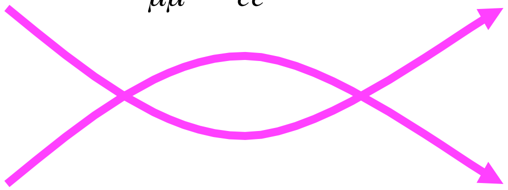
ν Mixing

Charged lepton ≡ mass eigenstate, Simplified view.

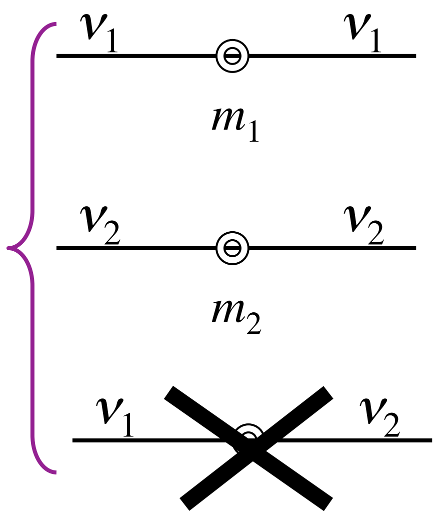
Transition amplitudes







Mix state



$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

Mass eigenstate

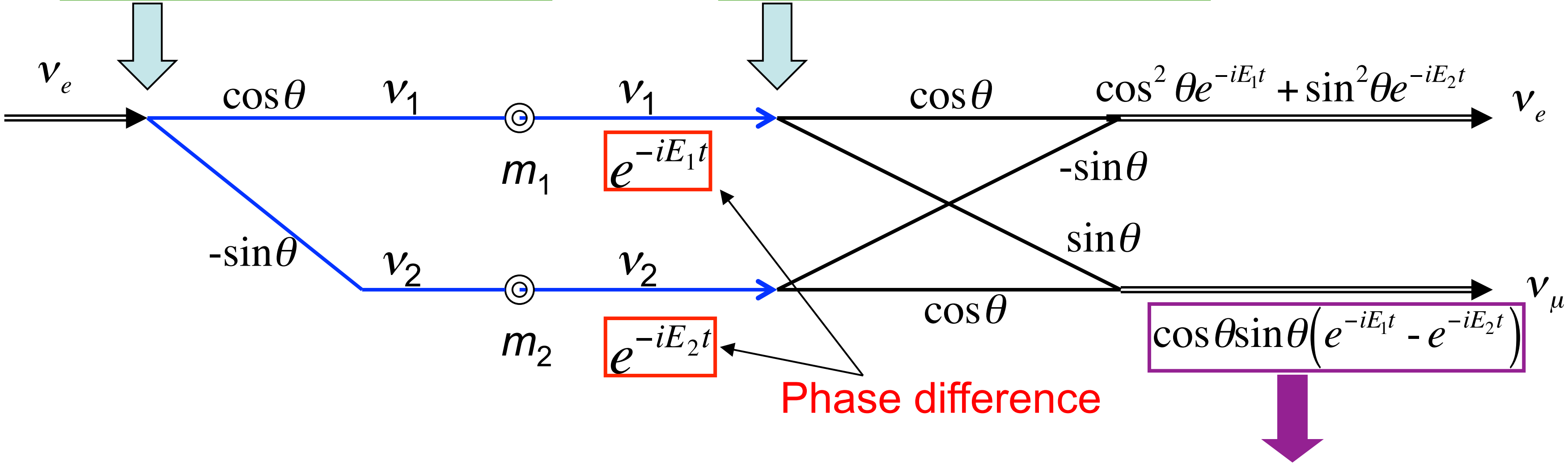
ν equation of motion:

$$\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = -i\begin{pmatrix} m_{ee} & A_{\mu e} \\ A_{\mu e} & m_{\mu\mu} \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \longrightarrow \frac{d}{dt}\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = -i\begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

ν Oscillation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$$\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}=\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

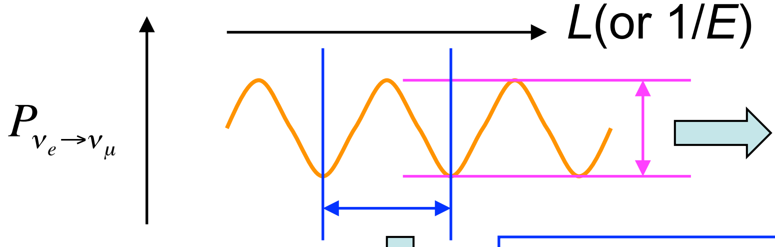


$$P(\nu_e\to\nu_\mu)\sim\left|\cos\theta\sin\theta\left(e^{-iE_1t}-e^{-iE_2t}\right)\right|^2=\sin^2 2\theta\sin^2\frac{(E_2-E_1)t}{2}$$

assume $p_1=p_2$ $\xrightarrow{m<<E}\sin^2 2\theta\sin^2\frac{(m_2^2-m_1^2)L}{4E}$

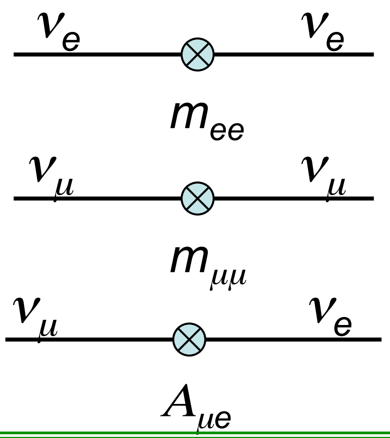
What we measure by ν oscillation

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$

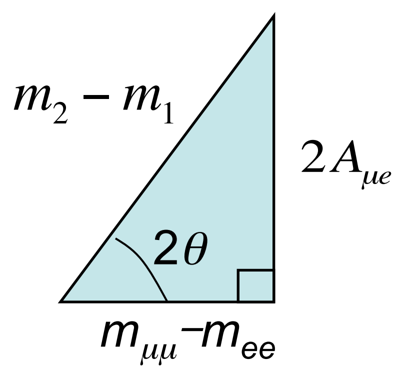


Amplitude ==> $\sin^2 2\theta$

Wavelength => $\Delta m^2 = \left| m_2^2 - m_1^2 \right|$



$$\begin{cases} \sin 2\theta = \dfrac{2A_{\mu e}}{\sqrt{(m_{\mu\mu} - m_{ee})^2 + 4A_{\mu e}^2}}, \\ \Delta m_{12}^2 = (m_{\mu\mu} + m_{ee})\sqrt{(m_{\mu\mu} - m_{ee})^2 + 4A_{\mu e}^2} \end{cases}$$

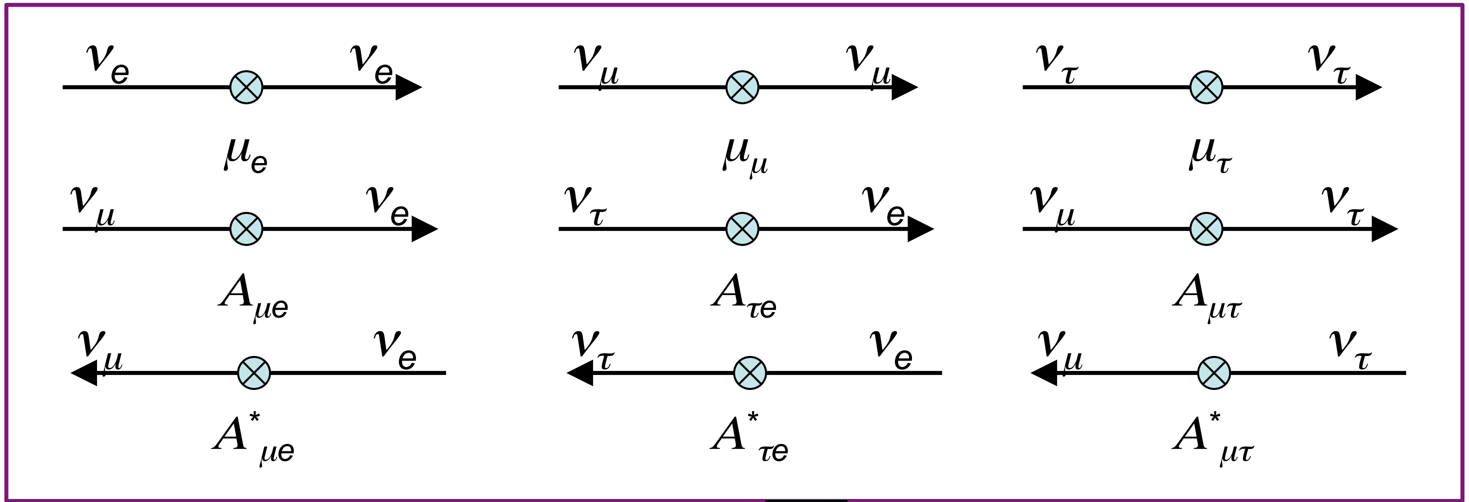


Mass and Mixing are a combination of flavor transition amplitudes.

⇒Measurment of mixing angle is as importnat as measurement of mass.

3 Flavors Case

Transition amplitudes



3 mixing angles + 1 phase

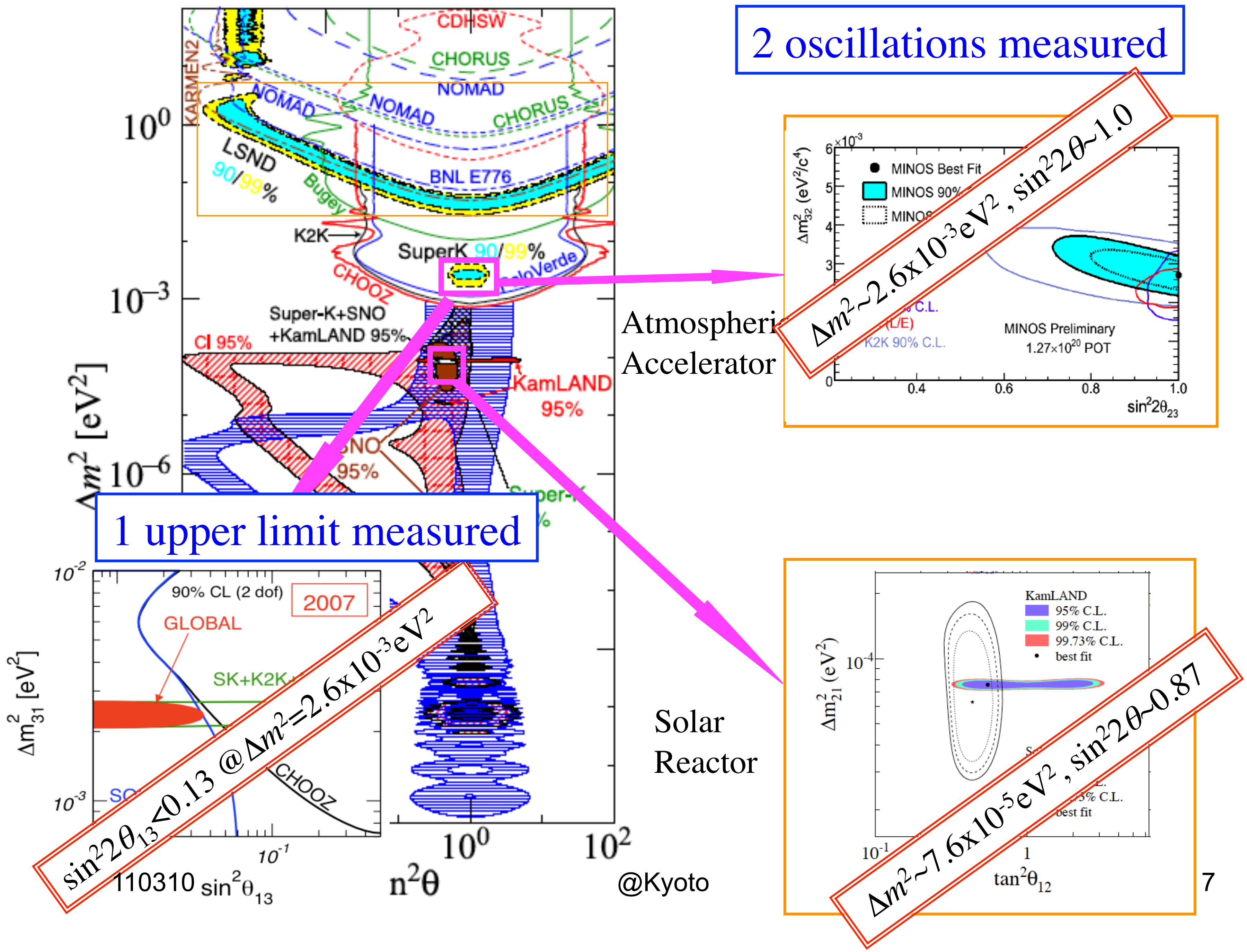
Mixing

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

2 mass square differences

Oscillation formula

$$\begin{matrix}P(\nu_\alpha \to \nu_\beta)\\ P(\bar\nu_\alpha \to \bar\nu_\beta)\end{matrix} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\Delta_{ij} \mp 2\sum_{i>j}\mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin 2\Delta_{ij}$$

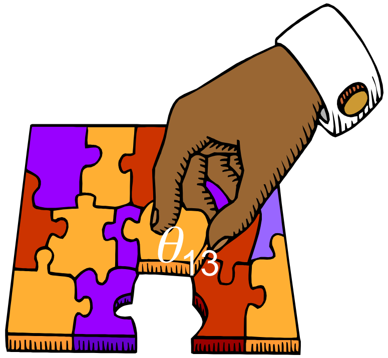

2 oscillations measured
1 upper limit measured
Atmospheric
Accelerator
Solar
Reactor
$\Delta m^2 \sim 2.6\times10^{-3}eV^2$, $\sin^2 2\theta \sim 1.0$
$\Delta m^2 \sim 7.6\times10^{-5}eV^2$, $\sin^2 2\theta \sim 0.87$
$\sin^2 2\theta_{13} < 0.13$ @$\Delta m^2 = 2.6\times10^{-3}eV^2$
CDHSW
CHORUS
NOMAD
KARMEN2
LSND 90/99%
Bugey
BNL E776
K2K
SuperK 90/99%
PaloVerde
CHOOZ
Super-K+SNO
+KamLAND 95%
Cl 95%
KamLAND
95%
SNO
95%
Δm^2 [eV^2]
10^0
10^{-3}
10^{-6}
10^2
MINOS Best Fit
MINOS 90%
MINOS Preliminary
1.27×10^{20} POT
K2K 90% C.L.
Δm^2_{32} (eV^2/c^4)
$\sin^2 2\theta_{23}$
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
best fit
Δm^2_{21} (eV^2)
$\tan^2\theta_{12}$
90% CL (2 dof)
2007
GLOBAL
SK+K2K
CHOOZ
Δm^2_{31} [eV^2]
$\sin^2\theta_{13}$

Our Current Knowledge

$$\left|m_3^2 - m_2^2\right| \sim 2.6\times10^{-3}\,\mathrm{eV}^2,\quad \left(m_2^2 - m_1^2\right) \sim 8\times10^{-5}\,\mathrm{eV}^2$$

4 parameters were already measured.
θ_{13} and δ to be measured

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & s_{13}e^{i\delta} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix} \qquad |s_{13}| < 0.2$$



Transition Amplitudes, if $m_3>m_2>m_1\sim0$

ν_e — ν_e: $m_{ee}\sim5$meV

ν_μ — ν_μ: $m_{\mu\mu}\sim30$meV

ν_τ — ν_τ: $m_{\tau\tau}\sim30$meV

ν_e — ν_μ: $A_{e\mu}\sim(30s_{13}e^{i\delta}+3)$meV

ν_e — ν_τ: $A_{e\tau}\sim(30s_{13}e^{i\delta}-3)$meV

ν_μ — ν_τ: $A_{\mu\tau}\sim20$meV

* Measurement is important to complete the puzzle
* θ_{13} controls size of imaginary part of ν_e <=> ν_μ, ν_τ

θ_{13} 測定の重要性

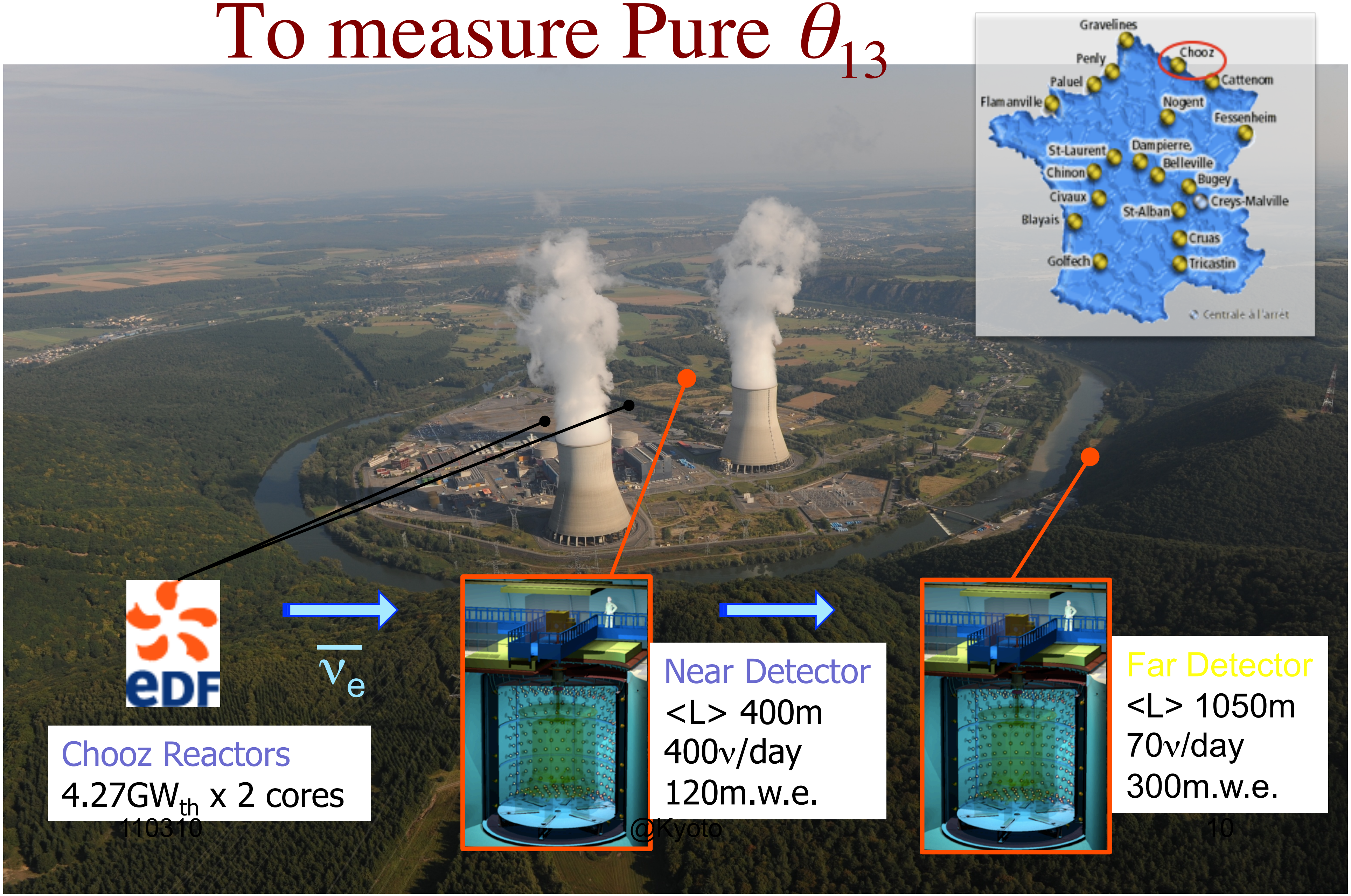
It is one of the fundamental parameters.
Future ν experiments strongly depends on θ_{13}.

Parameter	Measurement Method
δ_{CP}	$\left[P_A(\nu_\mu \to \nu_e) - P_A(\bar{\nu}_\mu \to \bar{\nu}_e)\right]_{@\Delta_{23}} \sim 0.1 \underline{\sin 2\theta_{13}} \sin\delta$
θ_{23} degeneracy	$\left[P_A(\nu_\mu \to \nu_e) + P_A(\bar{\nu}_\mu \to \bar{\nu}_e)\right]_{@\Delta_{23}} \sim 2\sin^2\theta_{23} \underline{\sin^2 2\theta_{13}}$
Mass Hierarchy	$\left[P_A(\nu_\mu \to \nu_e; L) + P_A(\nu_\mu \to \nu_e; L')\right]_{@\Delta_{23}} \sim sign(\Delta m^2_{23})(L' - L) \underline{\sin^2 2\theta_{13}}$ $P_R(\bar{\nu}_e \to \bar{\nu}_e)_{@\Delta_{12}} \sim 1 - 0.5 \underline{\sin^2 2\theta_{13}} (\sin^2\Delta_{31} + \tan^2\theta_{12} \sin^2\Delta_{32})$

θ_{13}の値が分からないと先に進めない

Double Chooz experiment

To measure Pure θ_{13}



Double Chooz collaboration

Brazil
CBPF
UNICAMP
UFABC

France
CEA/DSM/IRFU:
- SPP
- SPhN
- SEDI
- SIS
- SENAC

CNRS/IN2P3:
- APC
- Subatech
- IPHC

ULB

Germany
EKU Tübingen
MPIK Heidelber
TU München
U. Aachen
U. Hamburg

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst Tech.

Russia
INR RAS
IPC RAS
RRC Kurchatov

Spain
CIEMAT-Madrid

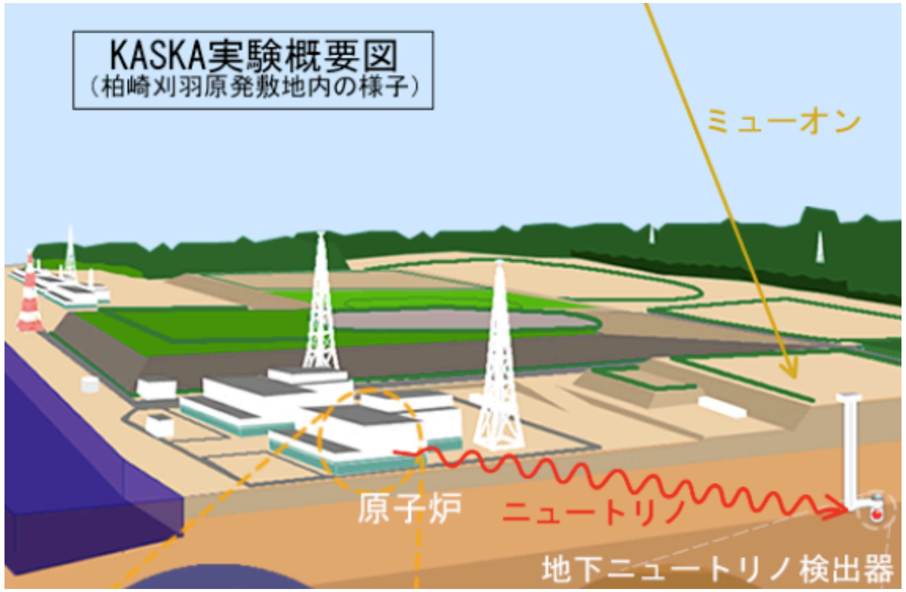
UK
Sussex

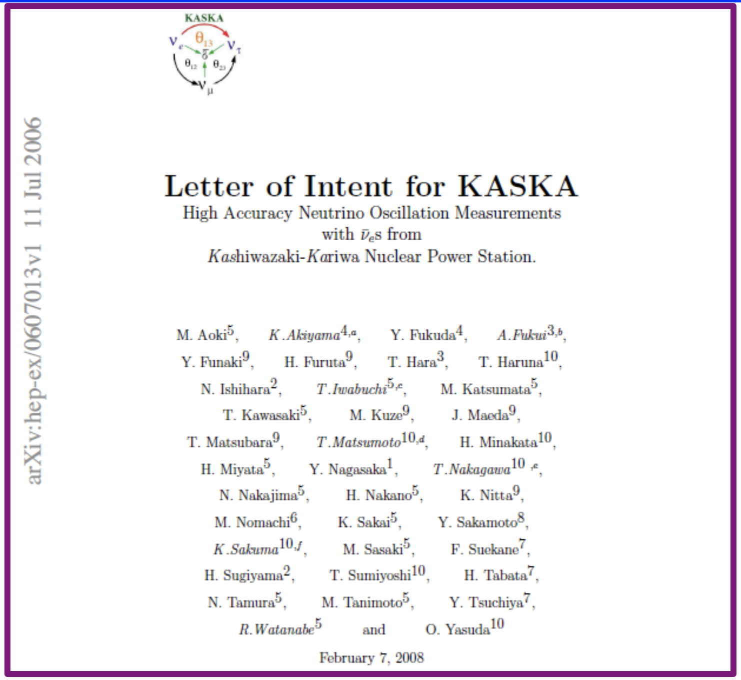
USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
Sandia National Laboratories
U. Tennessee

Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.org/

我々も柏崎刈羽原発(世界最強)でKASKA実験を提案した. (2003~)




KASKA

arXiv:hep-ex/0607013v1 11 Jul 2006

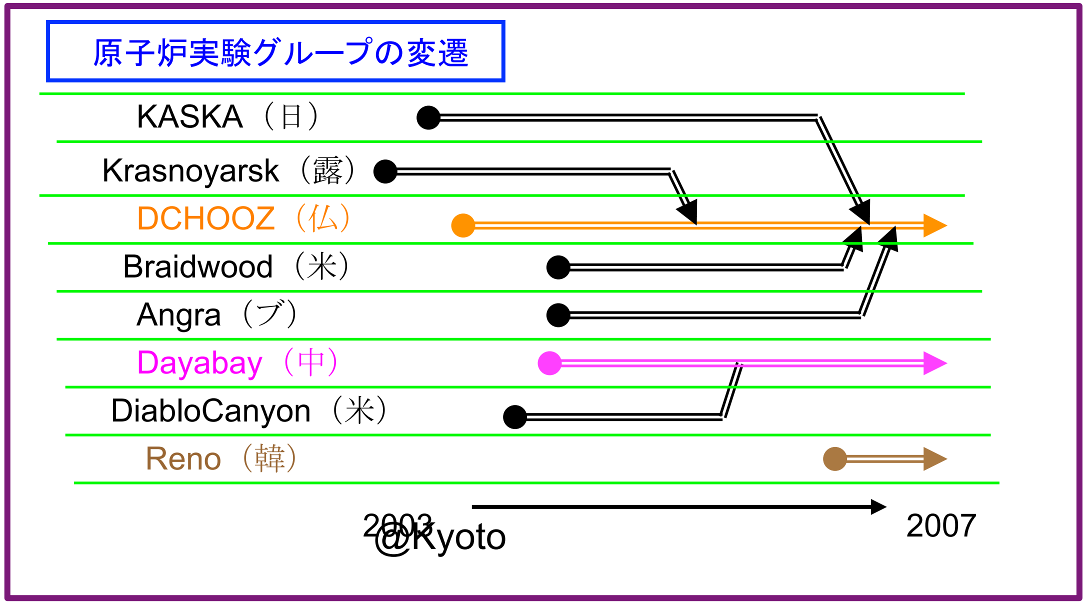
Letter of Intent for KASKA

High Accuracy Neutrino Oscillation Measurements
with $\bar{\nu}_e$s from
Kashiwazaki-Kariwa Nuclear Power Station.

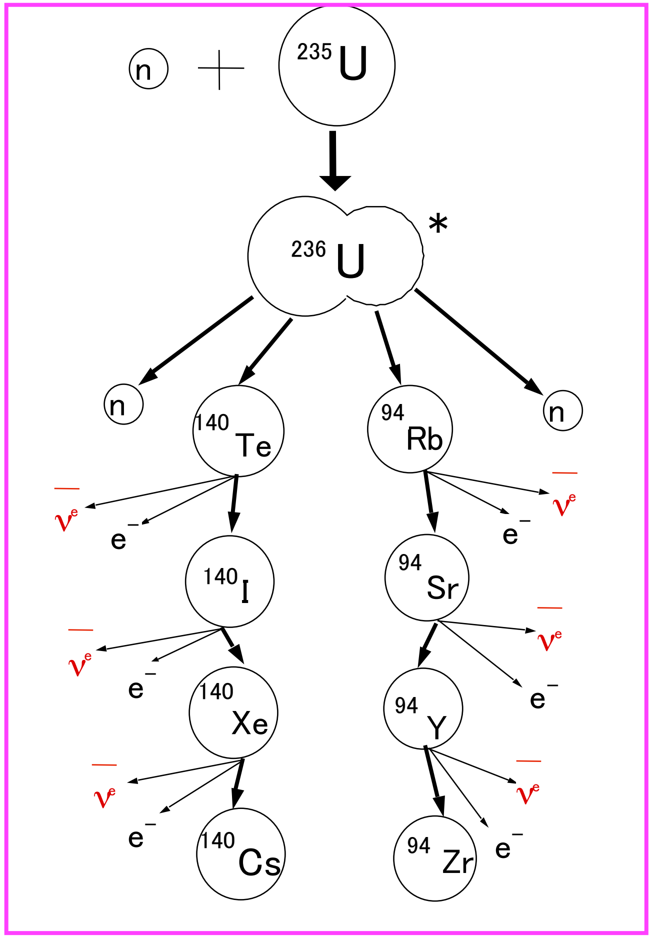
M. Aoki[5], *K. Akiyama*[4,a], Y. Fukuda[4], *A. Fukui*[3,b],
Y. Funaki[9], H. Furuta[9], T. Hara[3], T. Haruna[10],
N. Ishihara[2], *T. Iwabuchi*[5,c], M. Katsumata[5],
T. Kawasaki[5], M. Kuze[9], J. Maeda[9],
T. Matsubara[9], *T. Matsumoto*[10,d], H. Minakata[10],
H. Miyata[5], Y. Nagasaka[1], *T. Nakagawa*[10,e],
N. Nakajima[5], H. Nakano[5], K. Nitta[9],
M. Nomachi[6], K. Sakai[5], Y. Sakamoto[8],
K. Sakuma[10,f], M. Sasaki[5], F. Suekane[7],
H. Sugiyama[2], T. Sumiyoshi[10], H. Tabata[7],
N. Tamura[5], M. Tanimoto[5], Y. Tsuchiya[7],
R. Watanabe[5] and O. Yasuda[10]

February 7, 2008

が，2007年
DCに参加する
ことになった.

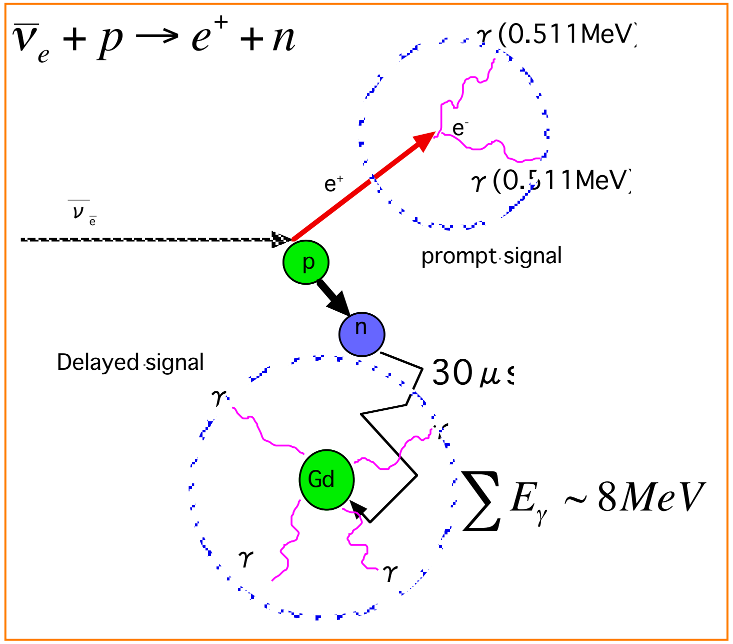


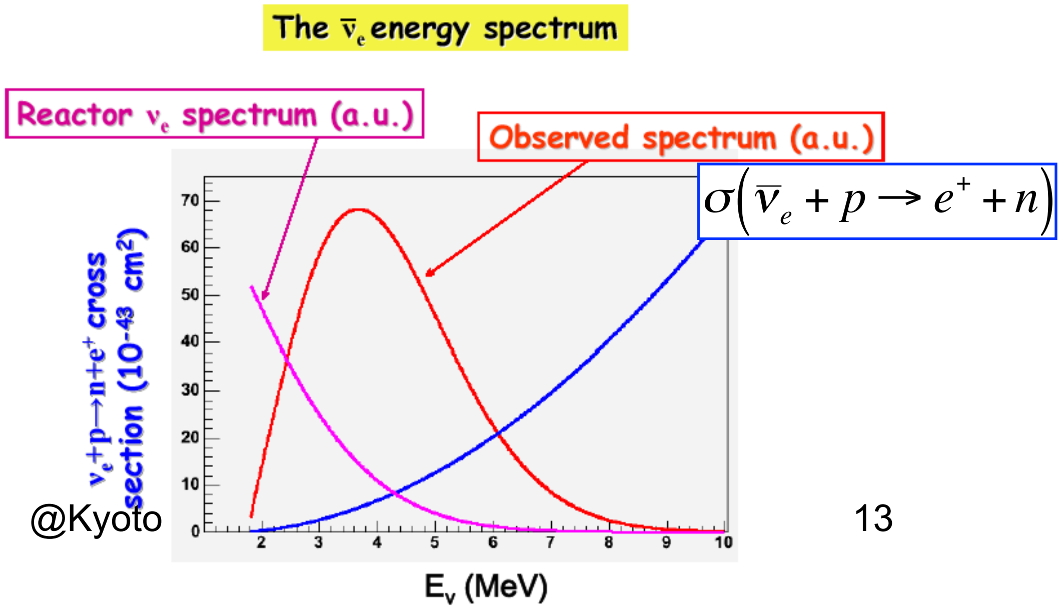
Reactor neutrino & Its detection



ν are produced in
β-decays of fission products.

$$\sim 6\times10^{20}\,\bar{\nu}_e\,/\,s\,/\,reactor$$





How to measure θ_{13} by reactor neutrinos

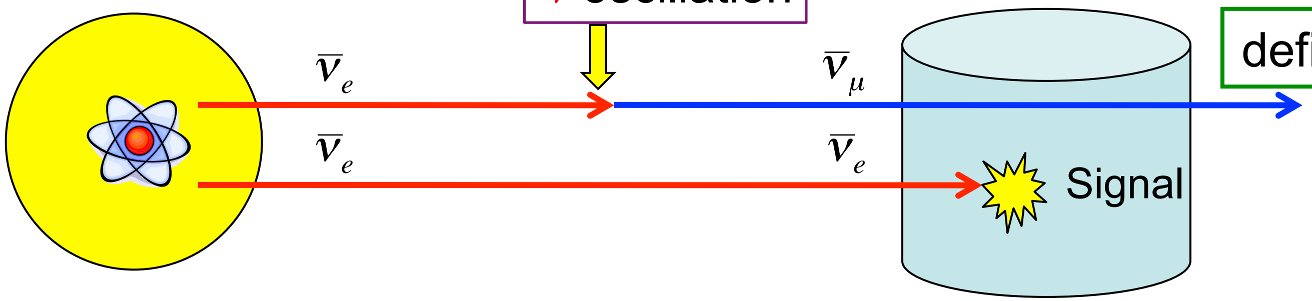
Reactor= Rich $\bar{\nu}_e$ Generator

$\bar{\nu}_e$ Detector

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

sensitive only to $\bar{\nu}_e$

ν oscillation

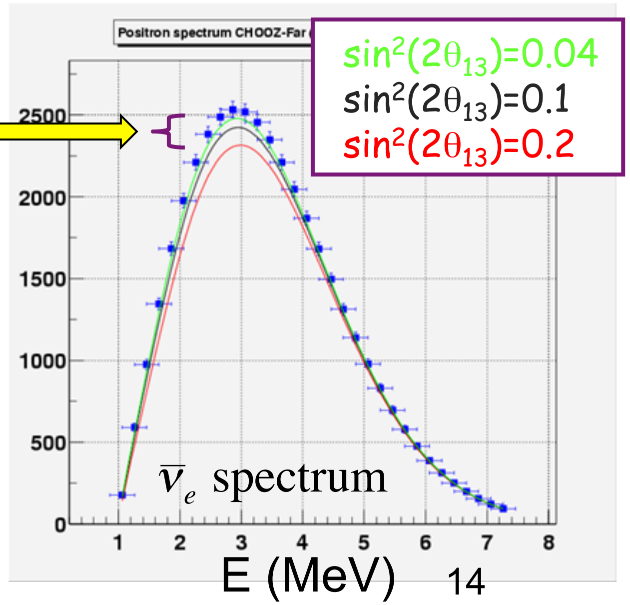


deficit of $\bar{\nu}_e$

$1.5\text{x}10^{21}\,\nu$/s

@Chooz reacors

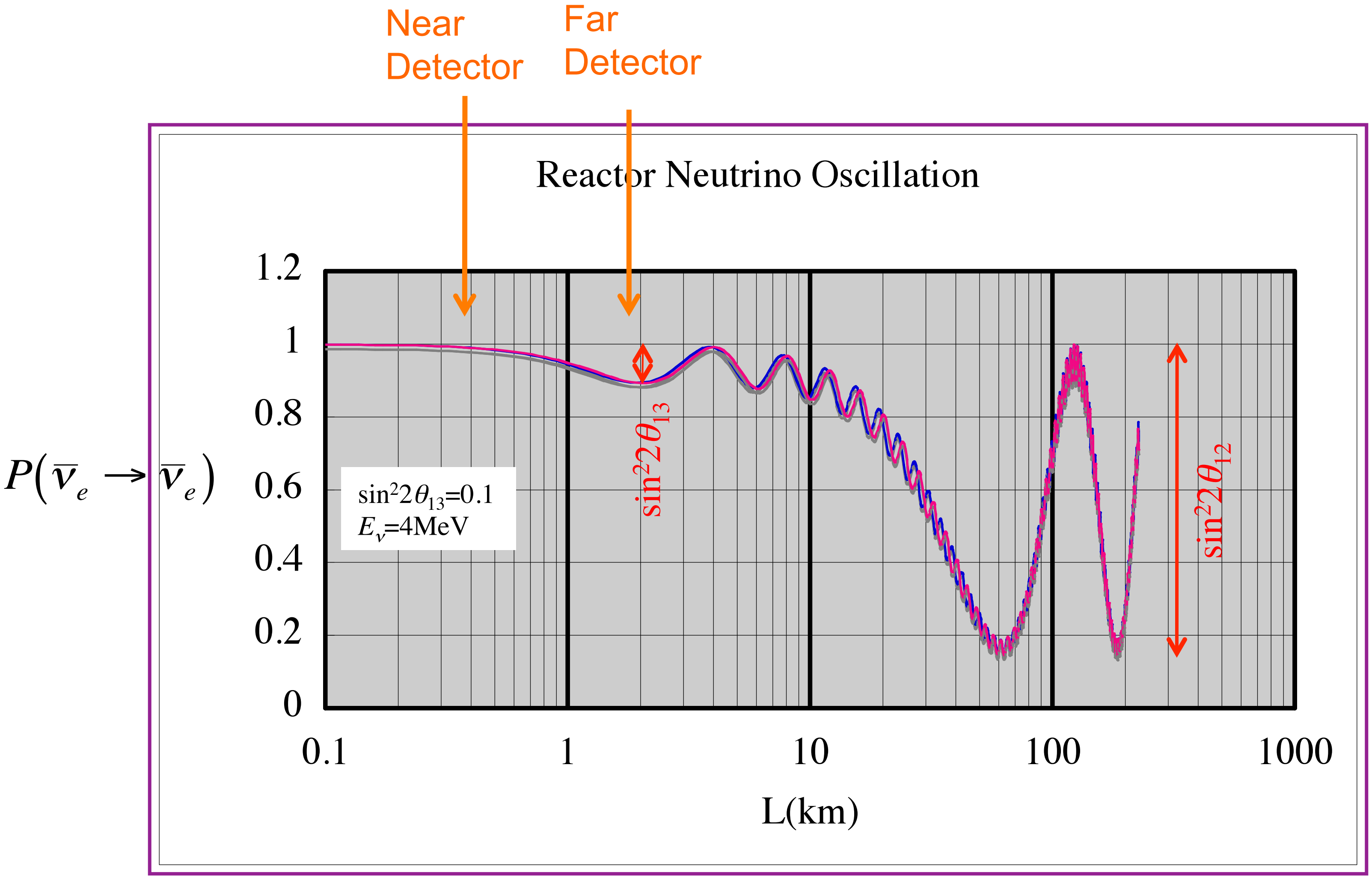
Deficit of $\bar{\nu}_e$ $\propto \sin^2 2\theta_{13}$



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}$$

The probability for $\bar{\nu}_e$ to remain $\bar{\nu}_e$

How to measure θ_{13} and to improve precision: 2 detector scheme



Ratio measurement Far/Near Detectors
=> Cancels most systematics

Statistic and systematic errors

		CHOOZ	Double Chooz
Reactor (neutrino flux)	Production x-sec	1.9%	-
	Reactor power	0.7%	-
	Energy per fission	0.6%	-
	Solid angle	-	0.1%
Detector	Detection x-sec	0.3%	-
	Target mass	0.3%	0.2%
	Fiducial volume	0.2%	-
	H/C ratio	0.8%	-
	Dead time	0.25%	-
Analysis	Selection efficiency	1.4%	0.4%
Total systematic error		**2.7%** →	**<0.5%**
Statistical error		**2.8%** →	**<0.5%**

G. Mention et al., arXiv:0704.0498 [hep-ex]

Main Components of DC Detector

Target ν :
10m^3 Gd loaded Liquid Scintllator
8mmt Acrylic Tank

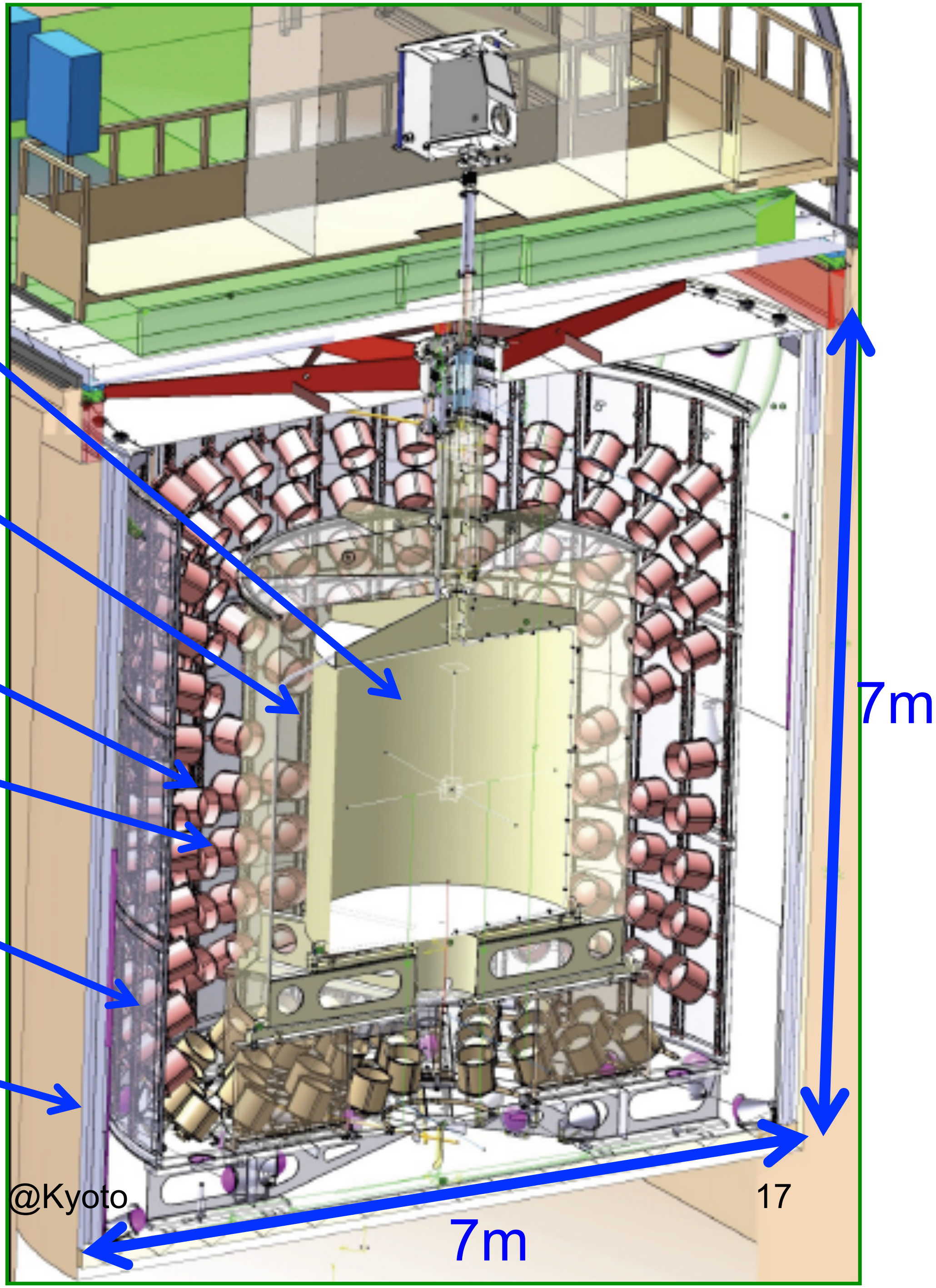
γ Catcher :
22m^3 Liquid Scintillator
12mmt Acrylic Tank

Light Detection:
390 Low BKG 10" PMTs

Buffer oil :
110m^3 Paraffine Oil
3mmt Stainless Steel Tank

Inner Muon Veto :
90m^3 LS + 78 8" PMTs

Iron shield:
15cmt



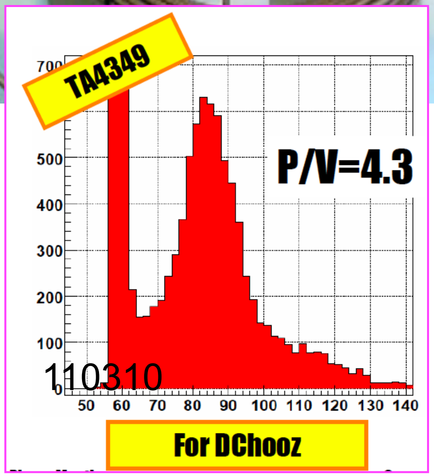
DC-Japan

東北大，首都大，東工大，新潟大，
神戸大，東北学院大，広島工大

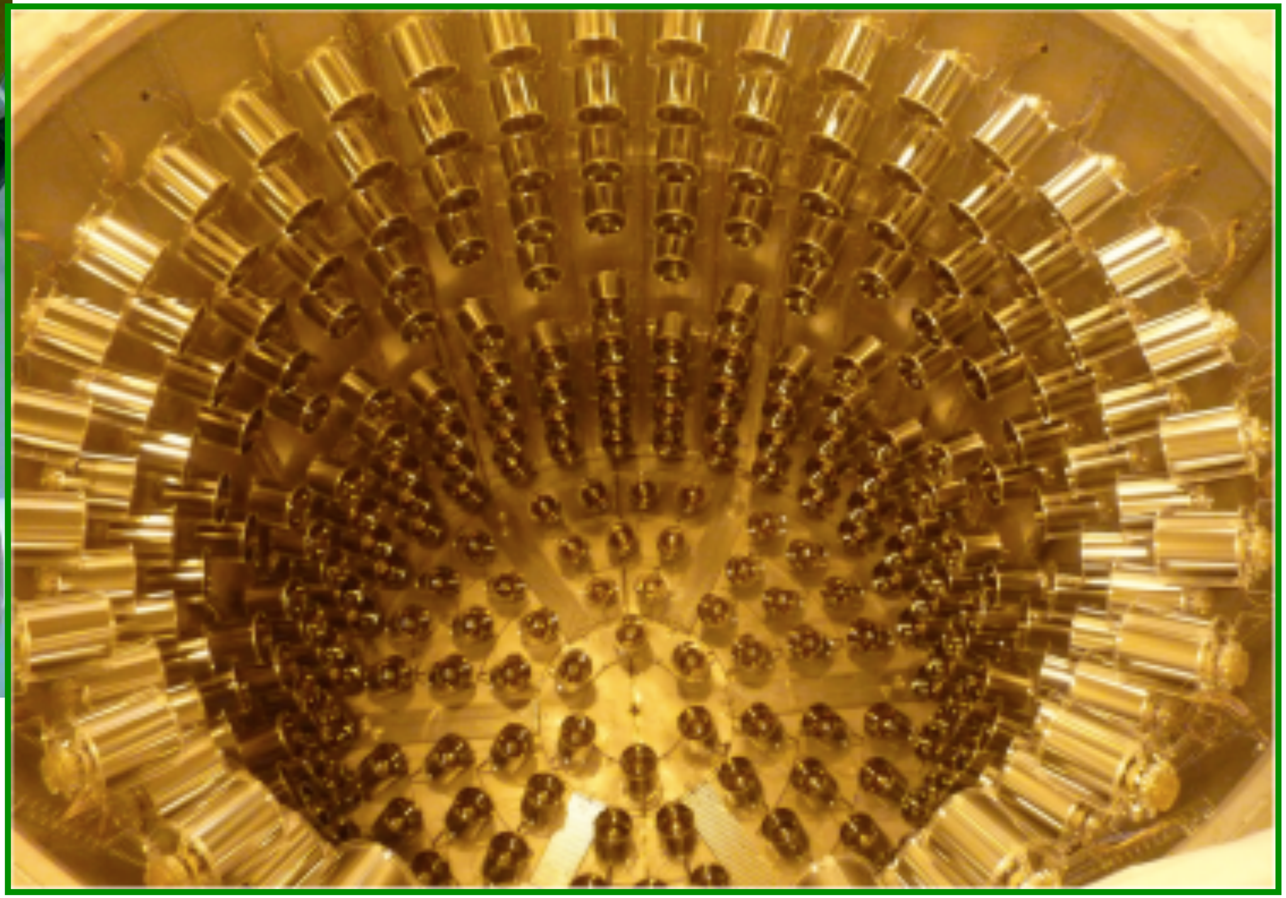
光電子増倍管システム，高電圧システム
DAQ/monitorシステム，LEDキャリブレーションシステム
コミッショニングなど担当

日本グループ担当

Large & Low back ground PMTs

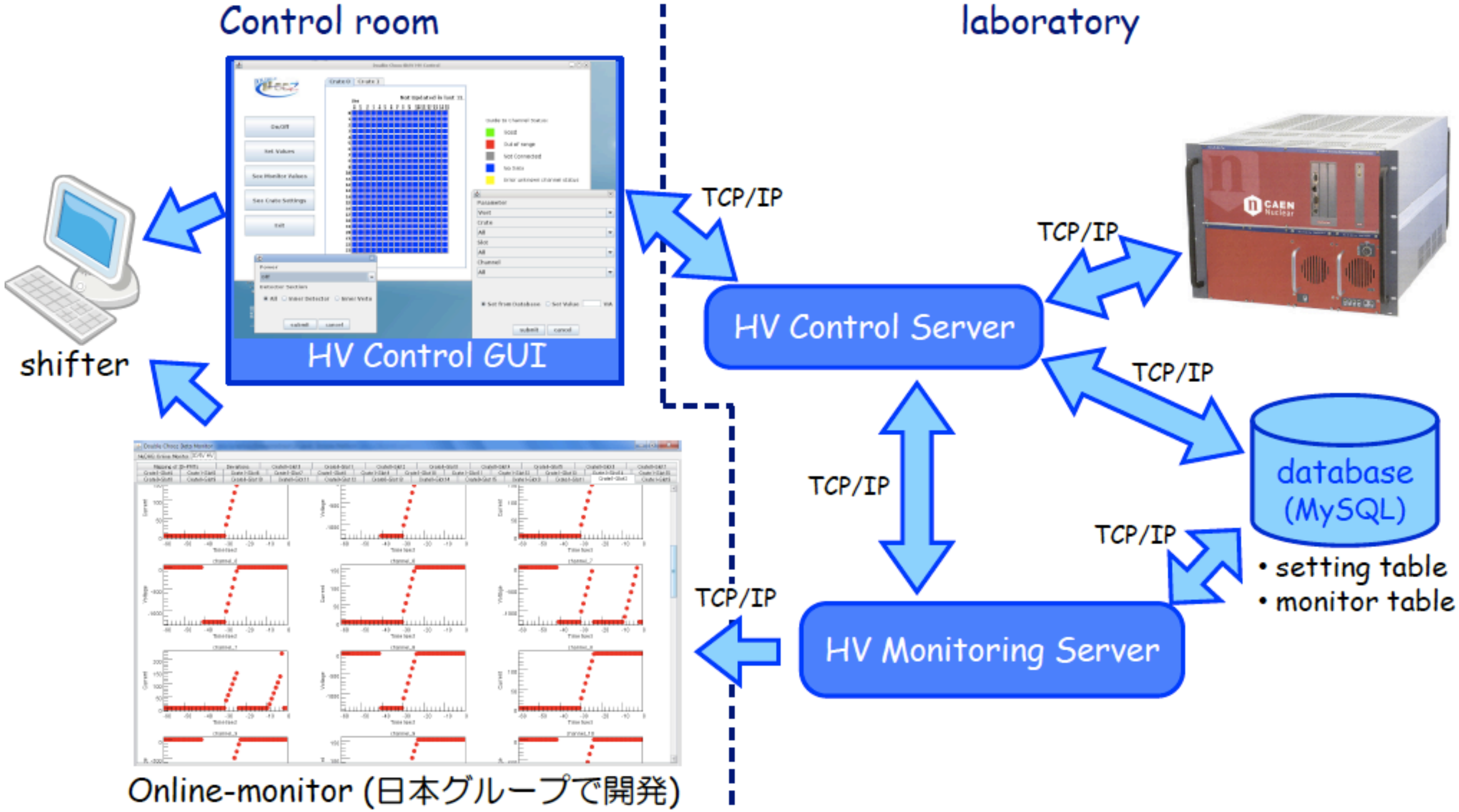


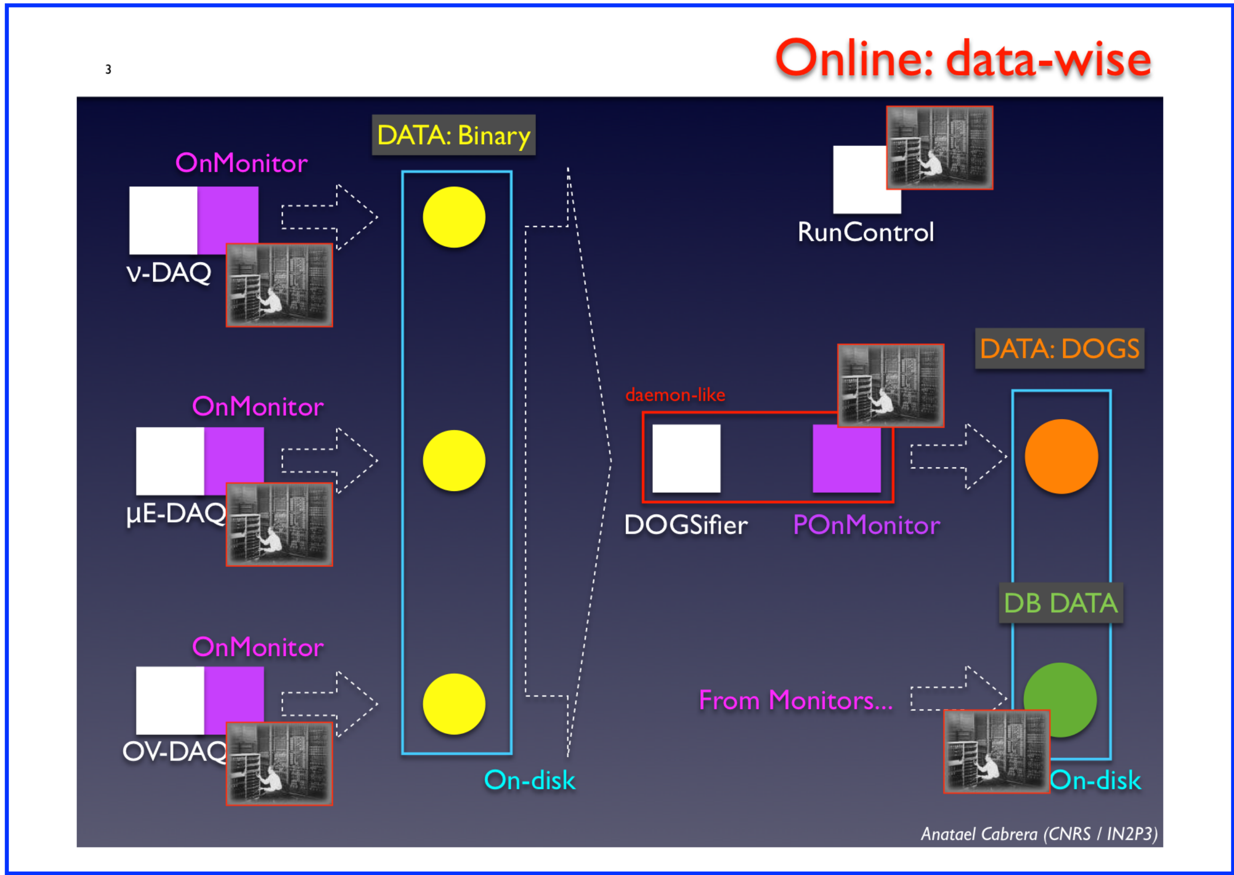
1pe peak



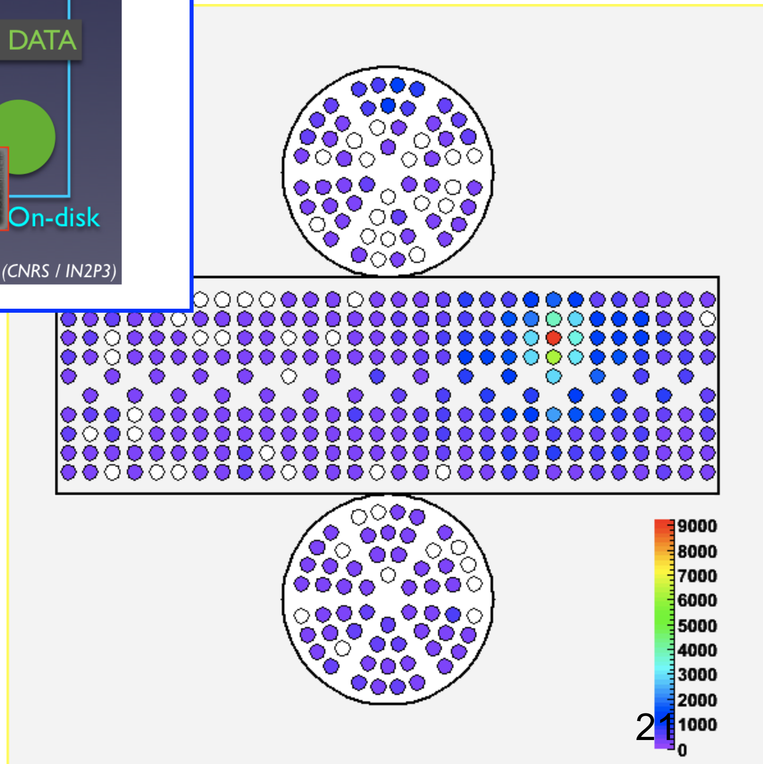
日本グループ担当　高電圧装置 system

- 二つのserver process (controlとmonitoring)とGUIで構成
- 各間の通信はソケットによるTCP通信で行う



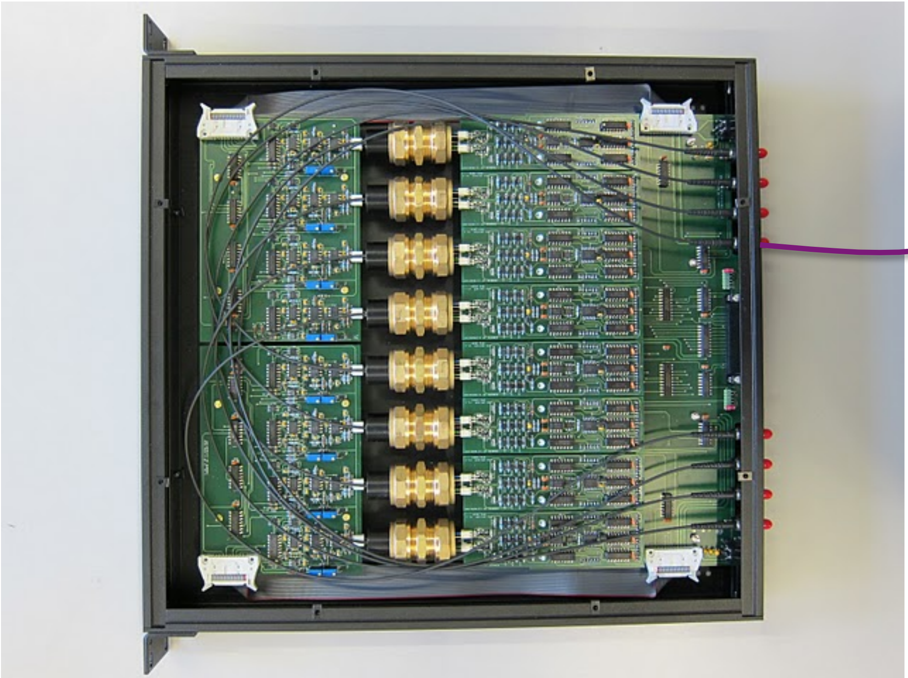


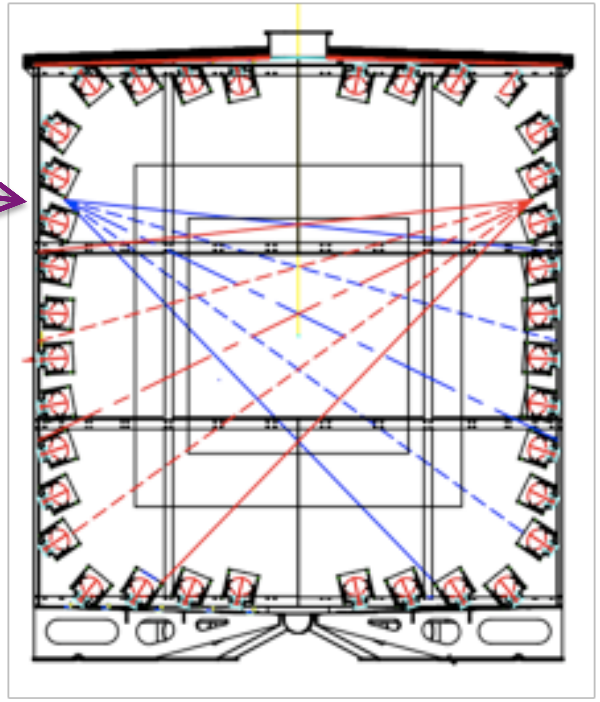
Event display



DAQ & online monitor
日仏で開発

ライトインジェクションキャリブレーションシステム

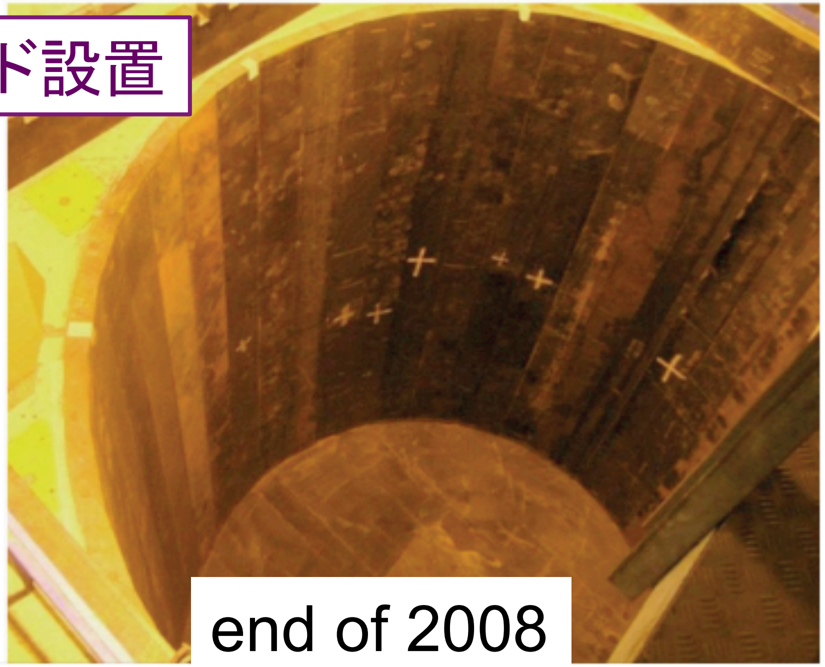




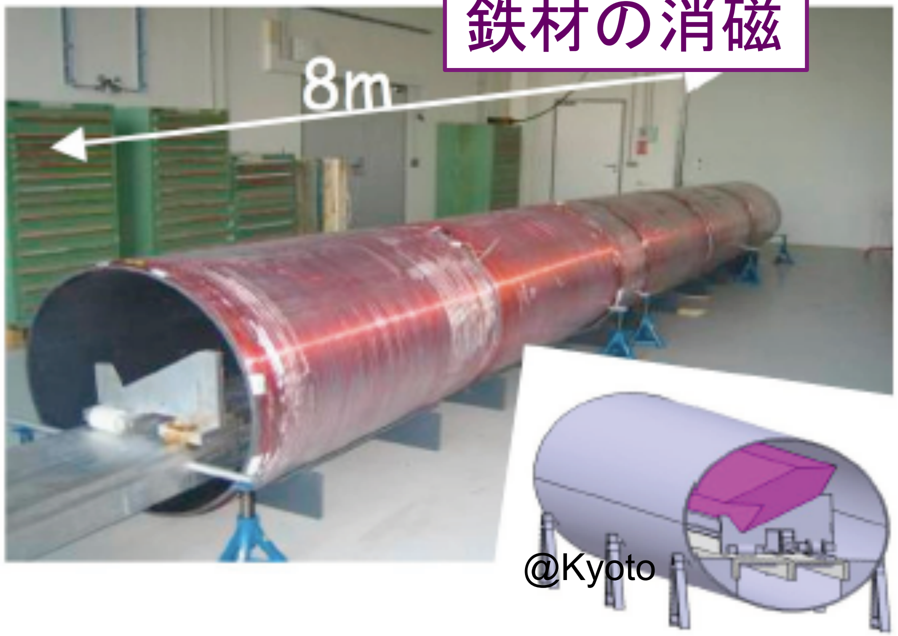
- LED光源からの光をファイバーを通して検出器内に入れ、拡散板を通して照射する。
- 日本グループが中心となって運用し、光電子増倍管、液体シンチレータの透過率のキャリブレーションなどを行う（装置の開発はイギリスのサセックス大学）。
- 検出器内部に設置されているため常時運用が可能であり、検出器の安定性の測定にも有用である。

DC 検出器建設

鉄シールド設置

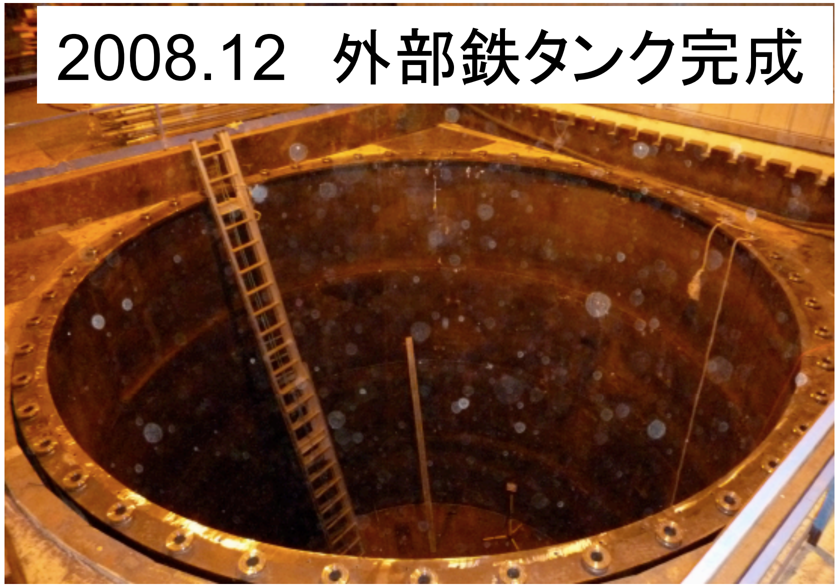


鉄材の消磁



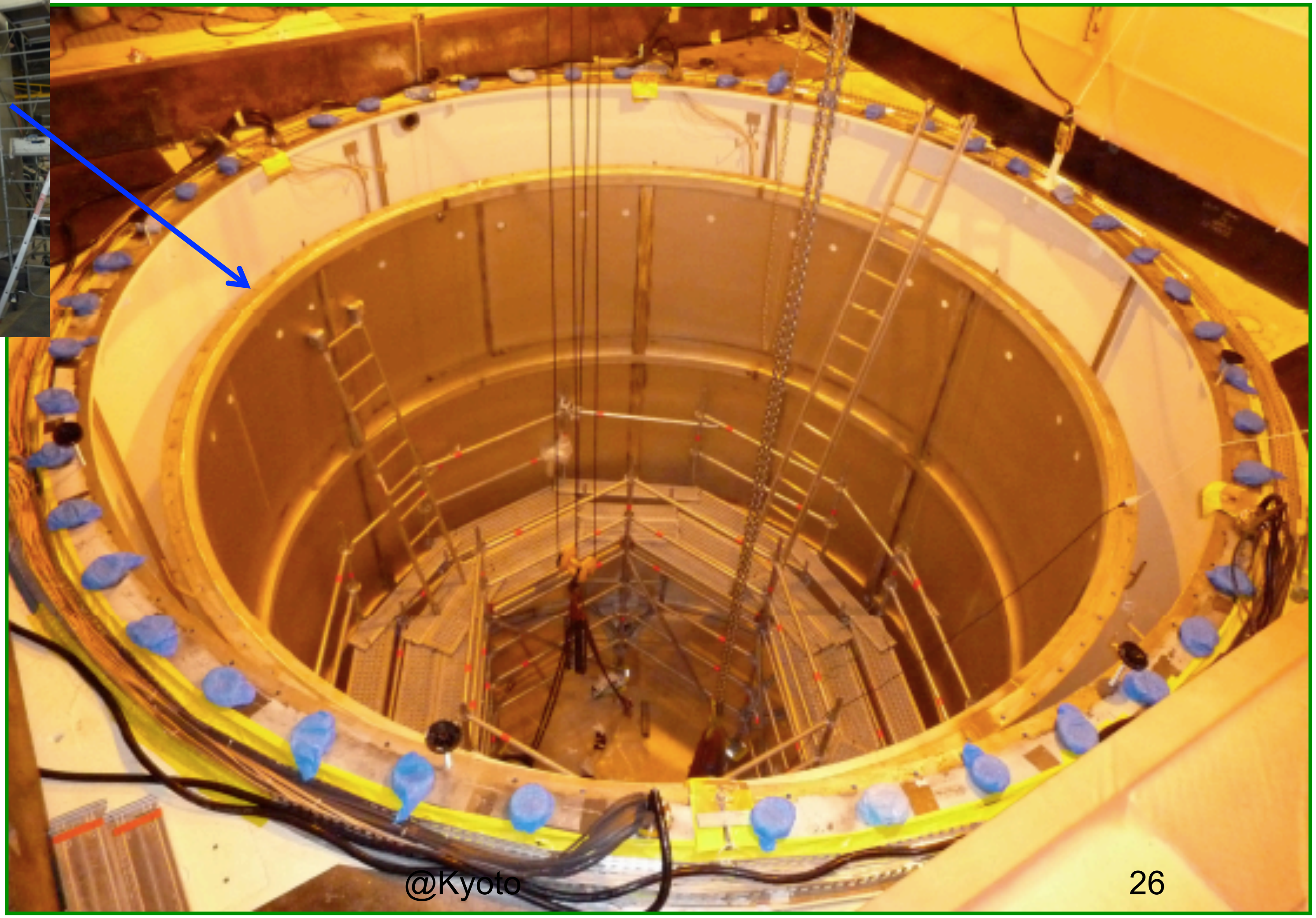
2008.11 外部鉄タンク設置

2008.12 外部鉄タンク完成

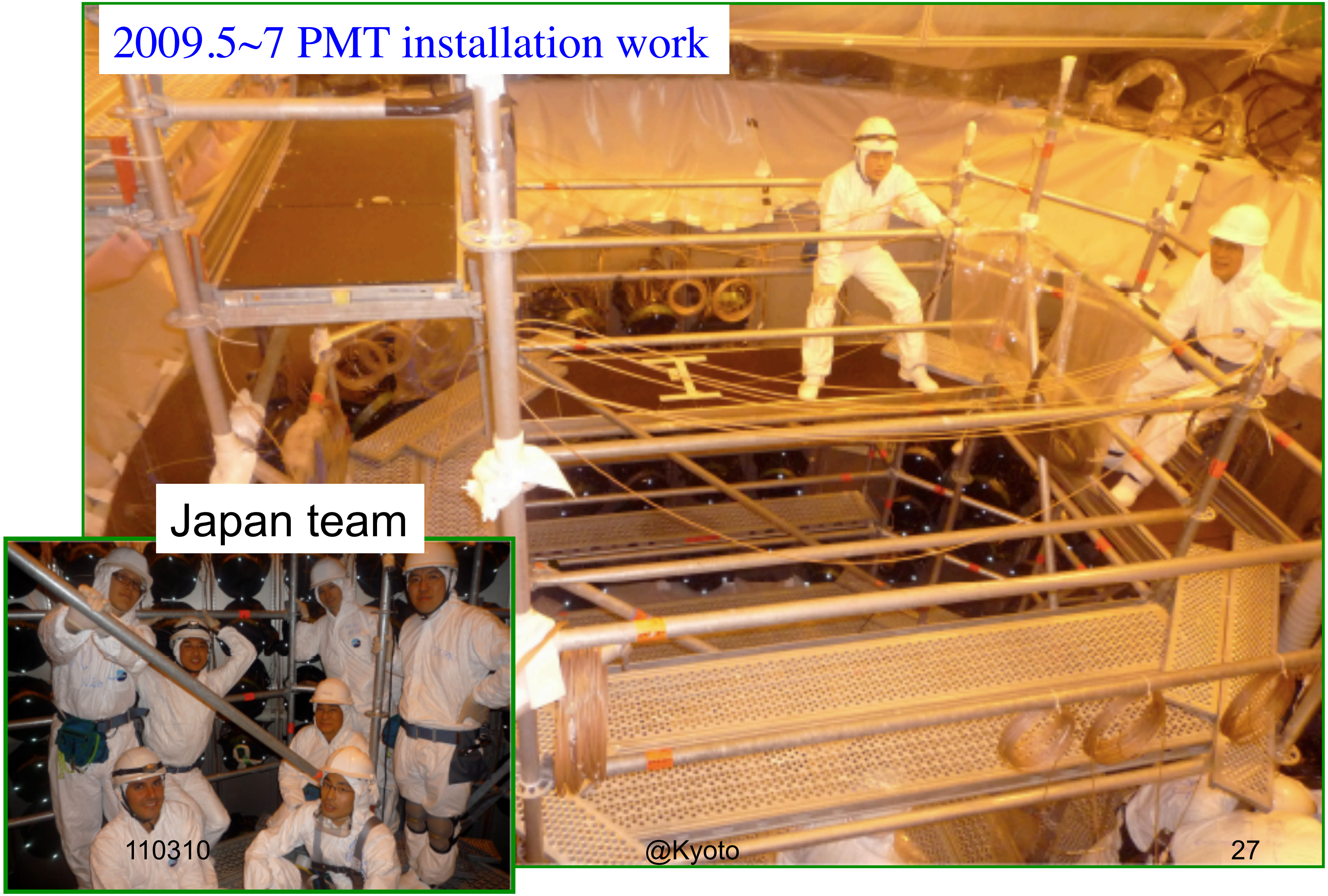


2009.2 Inner Veto PMT 設置

2009.4 ステンレス内部タンク設置



2009.5~7 PMT installation work

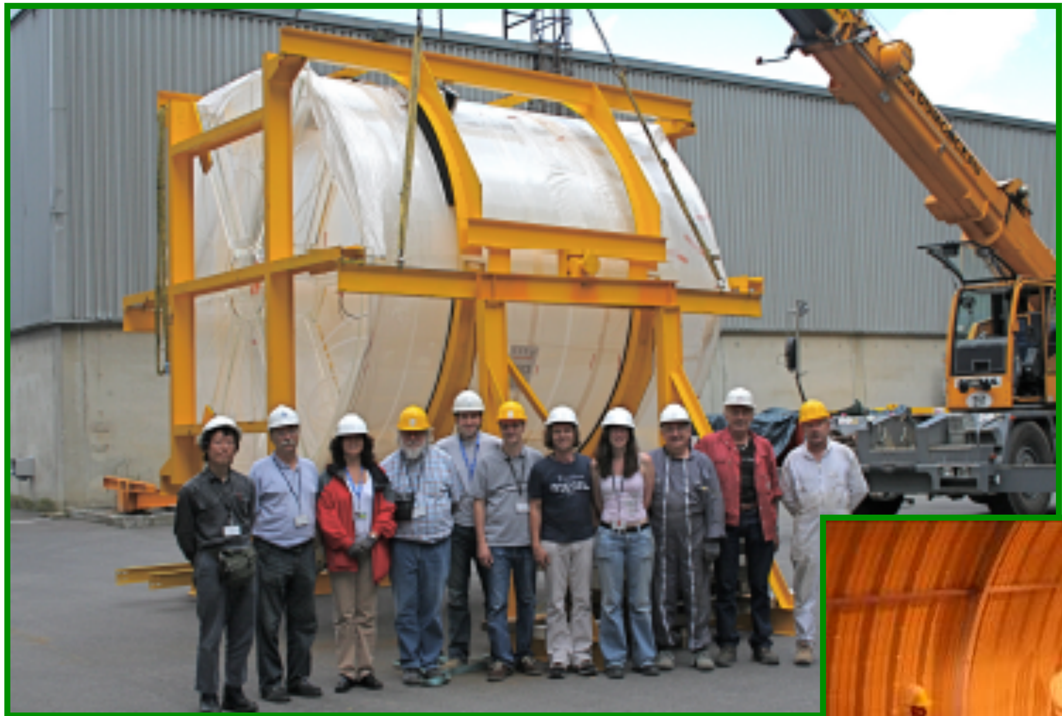


Japan team


PMT ケーブル敷設作業

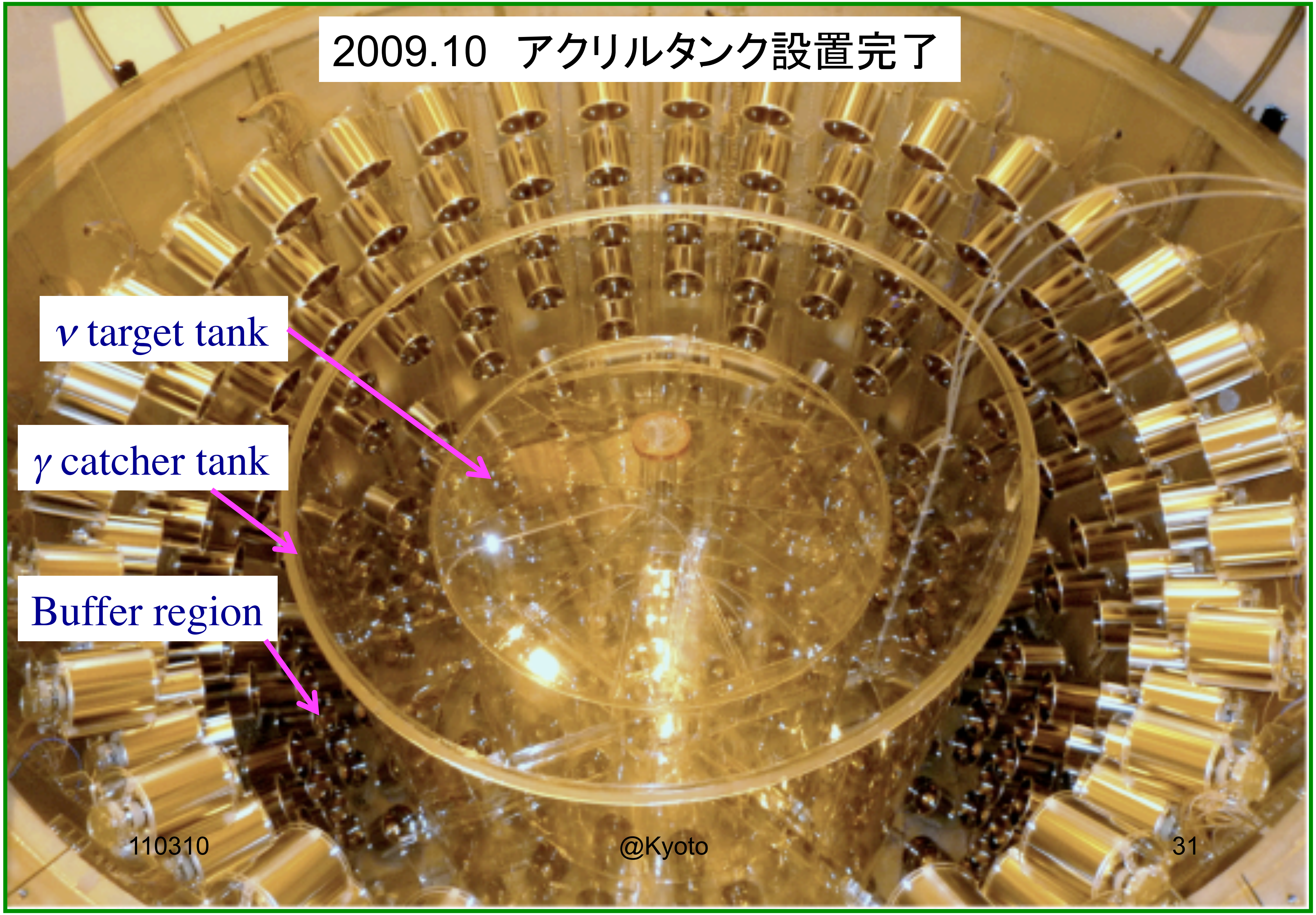
Bottom & wall PMTs installation complete (2009.07)

French team



Acrylic tank installation (8~9/2009)

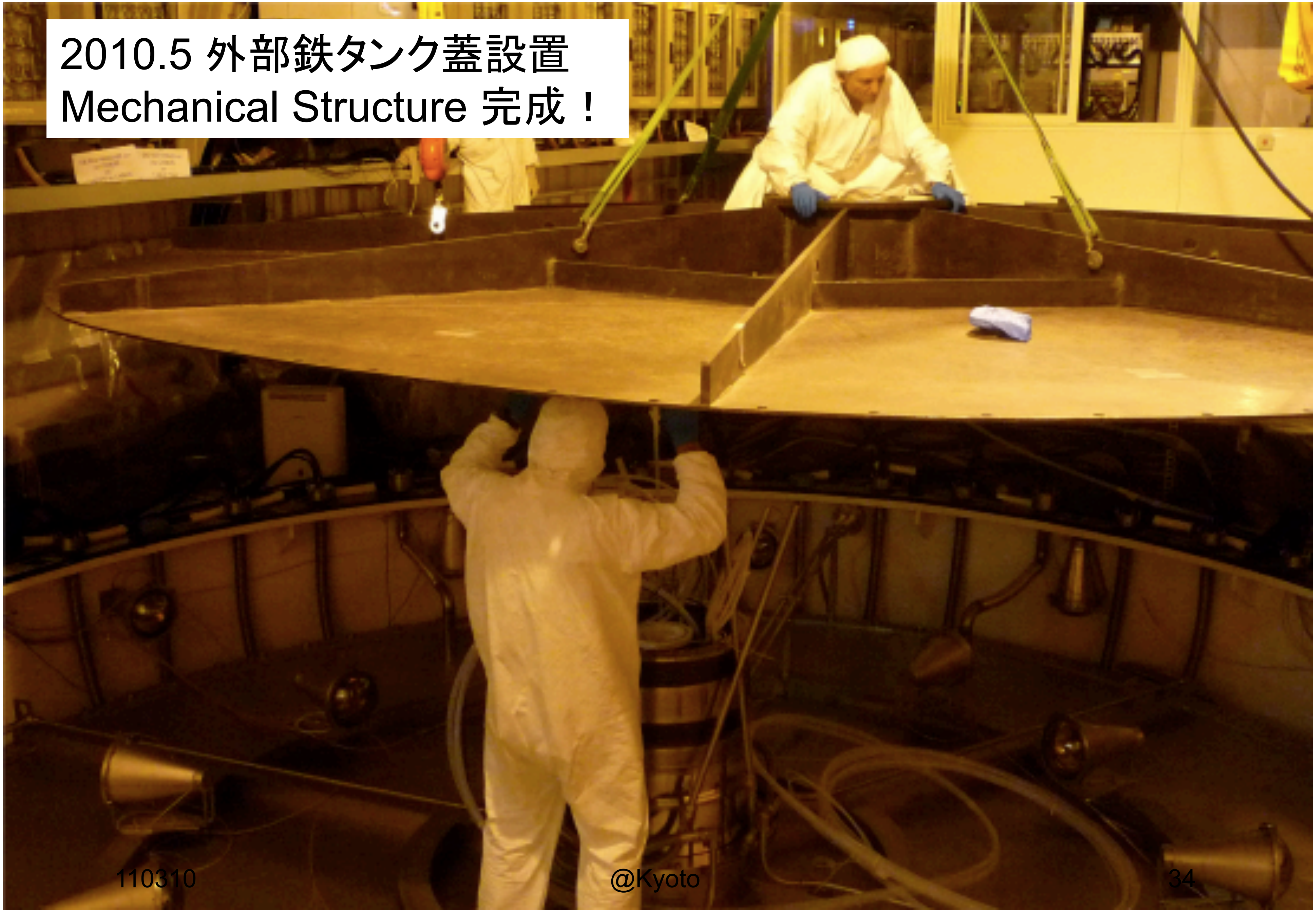
2009.10 アクリルタンク設置完了



2010.12 Then top lid & its PMTs were installed

2009.12 ステンレスタンク蓋設置

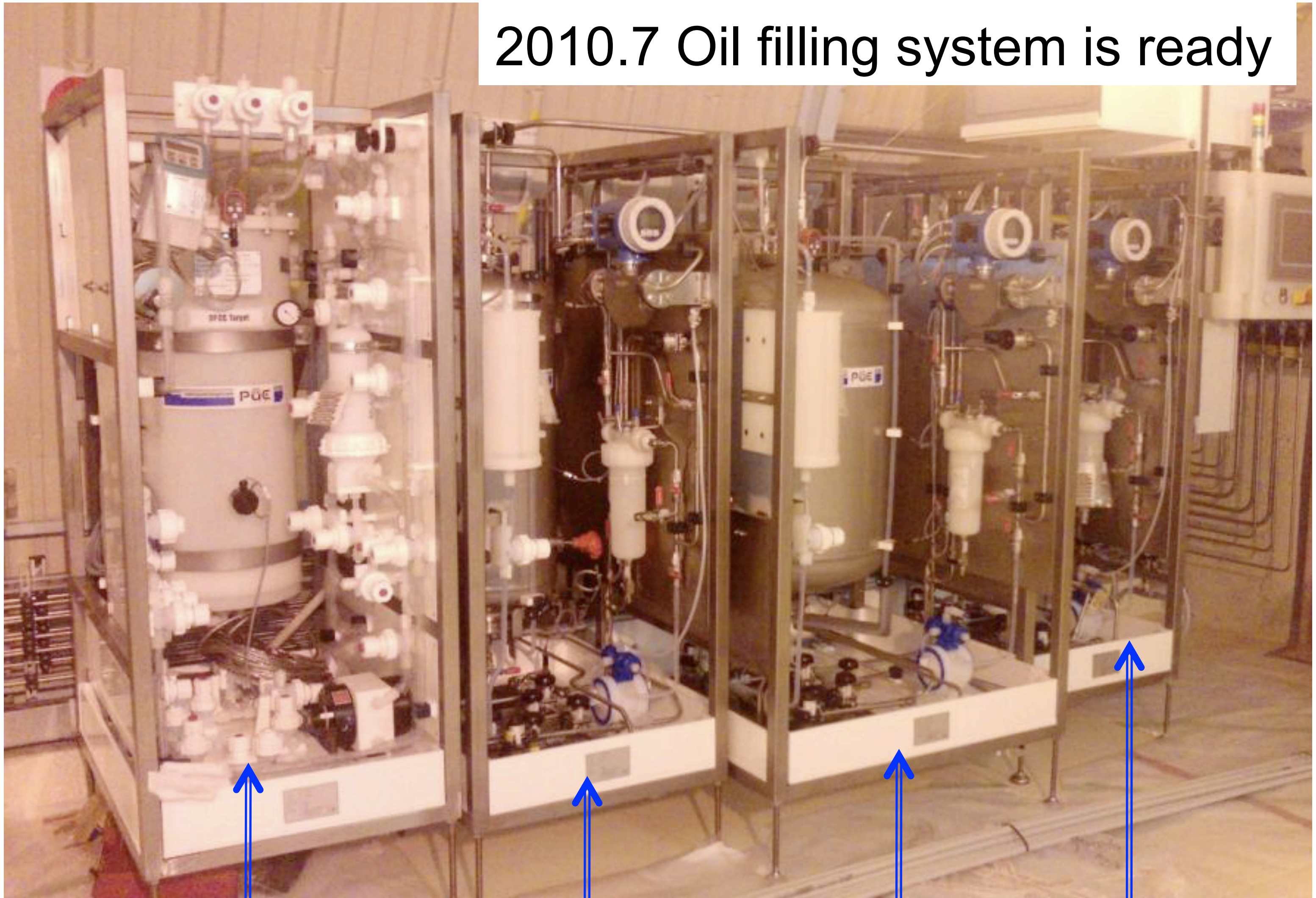
2010.5 外部鉄タンク蓋設置
Mechanical Structure 完成！



2009.8~ 液体シンチレーター類タンク設置

All the liquids have been formulated by German group

2010.7 Oil filling system is ready



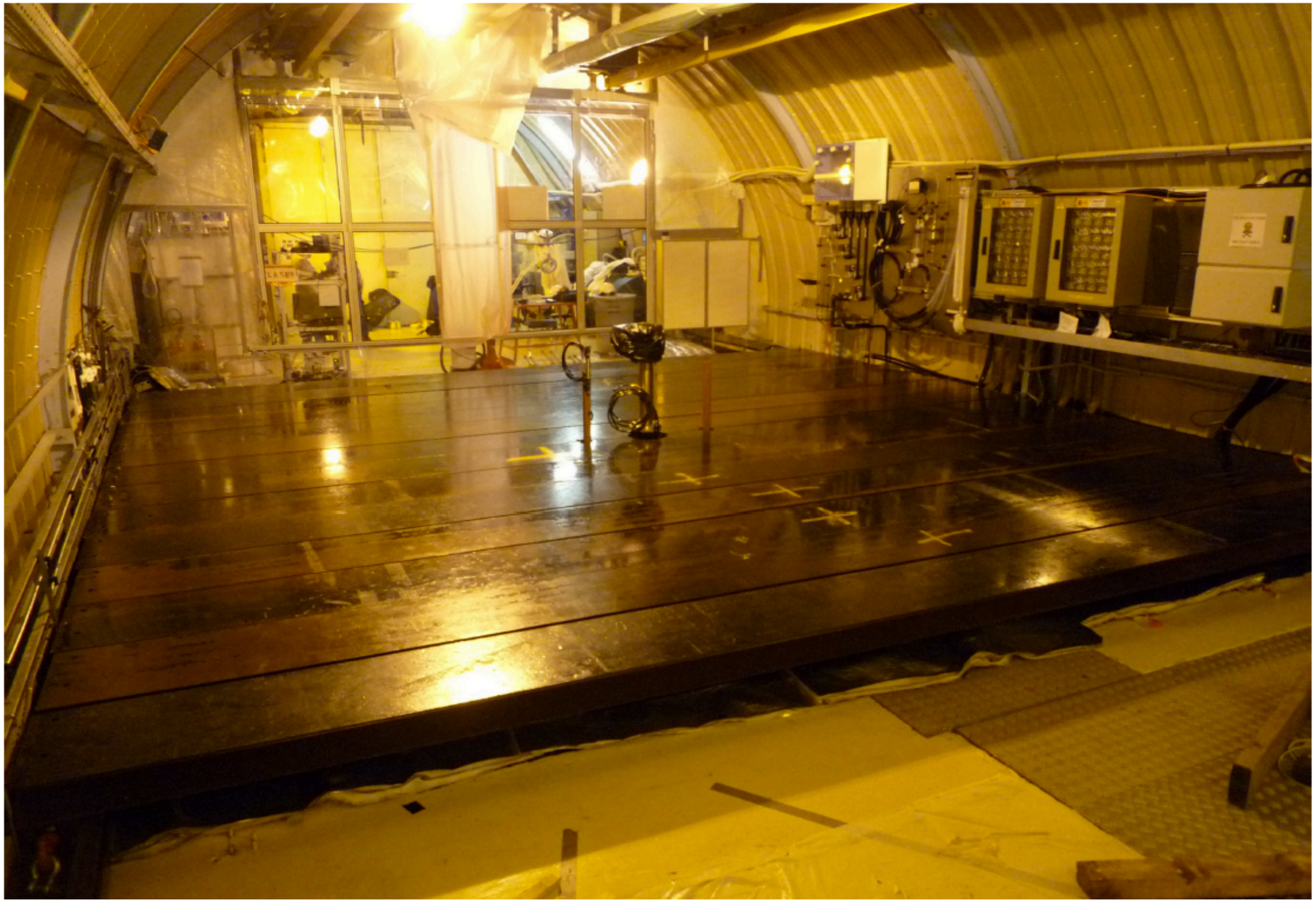
ν-target LS line

γ-catcher LS Line

Buffer Oil Line

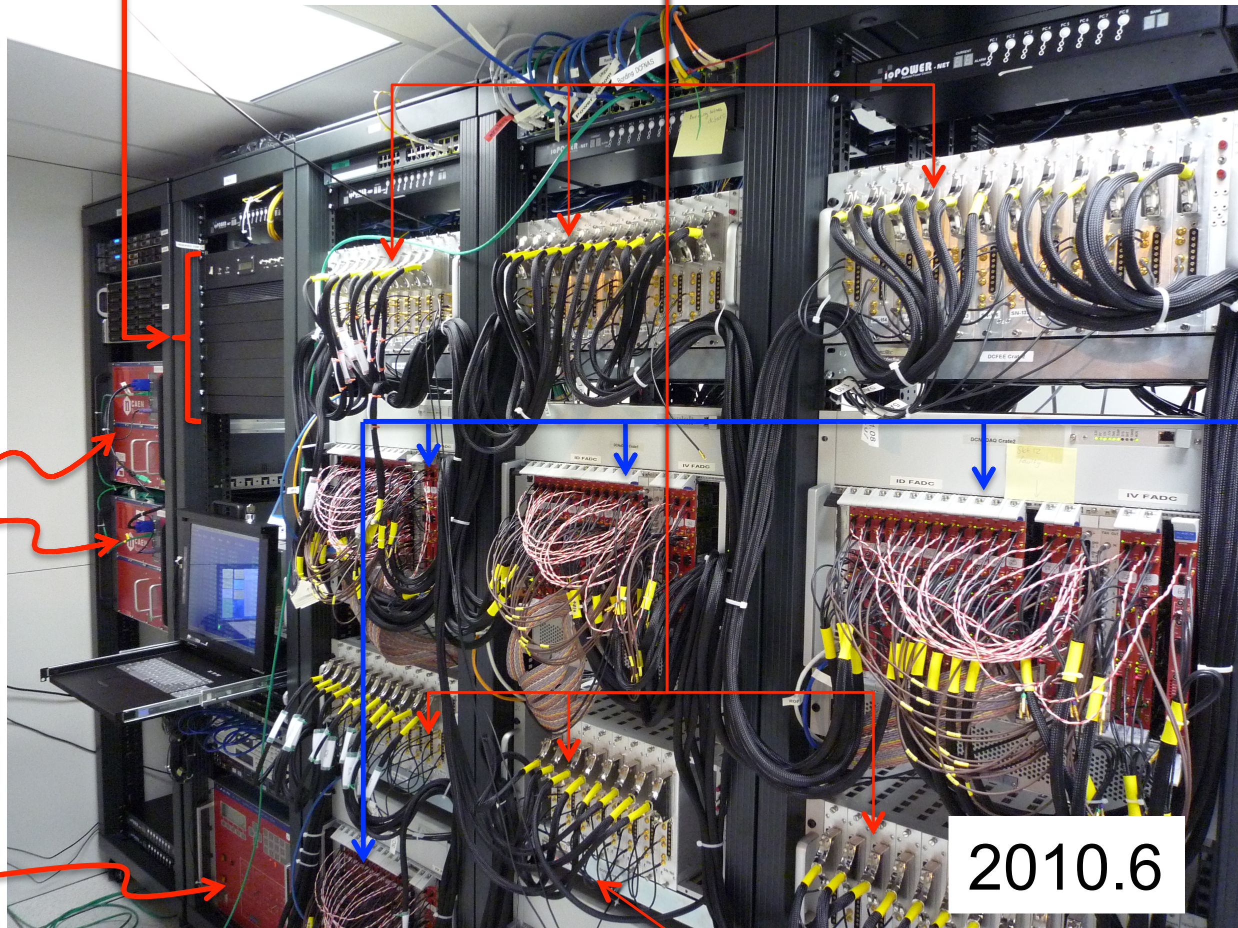
Veto LS Line

Far Detector – Filled and Shielded



ID Light Injection System
(Controller + 6 x LED box)

Frontend Electronics

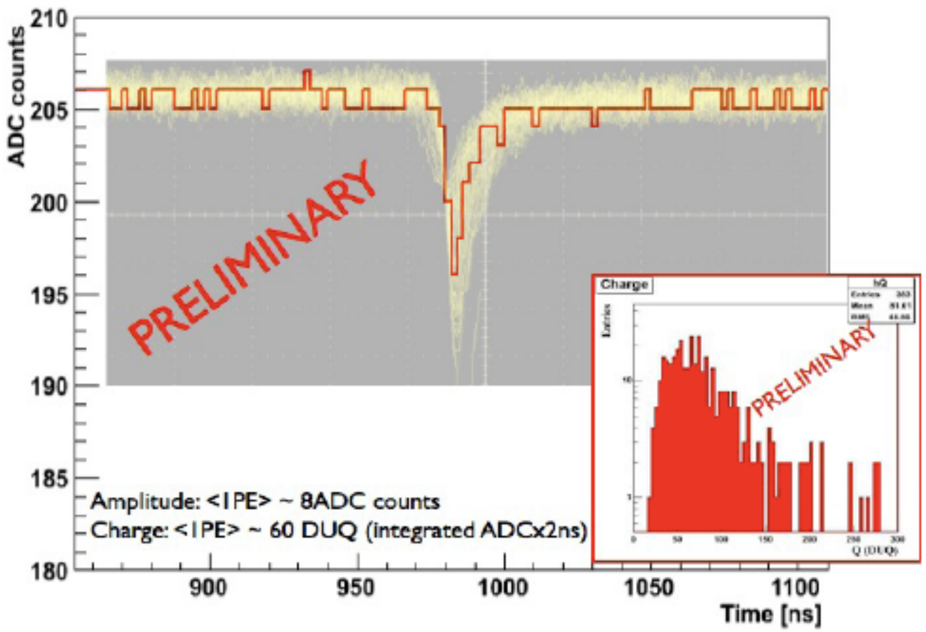


ID & IV
νFADC

ID & IV
HV
System

OV HV
System

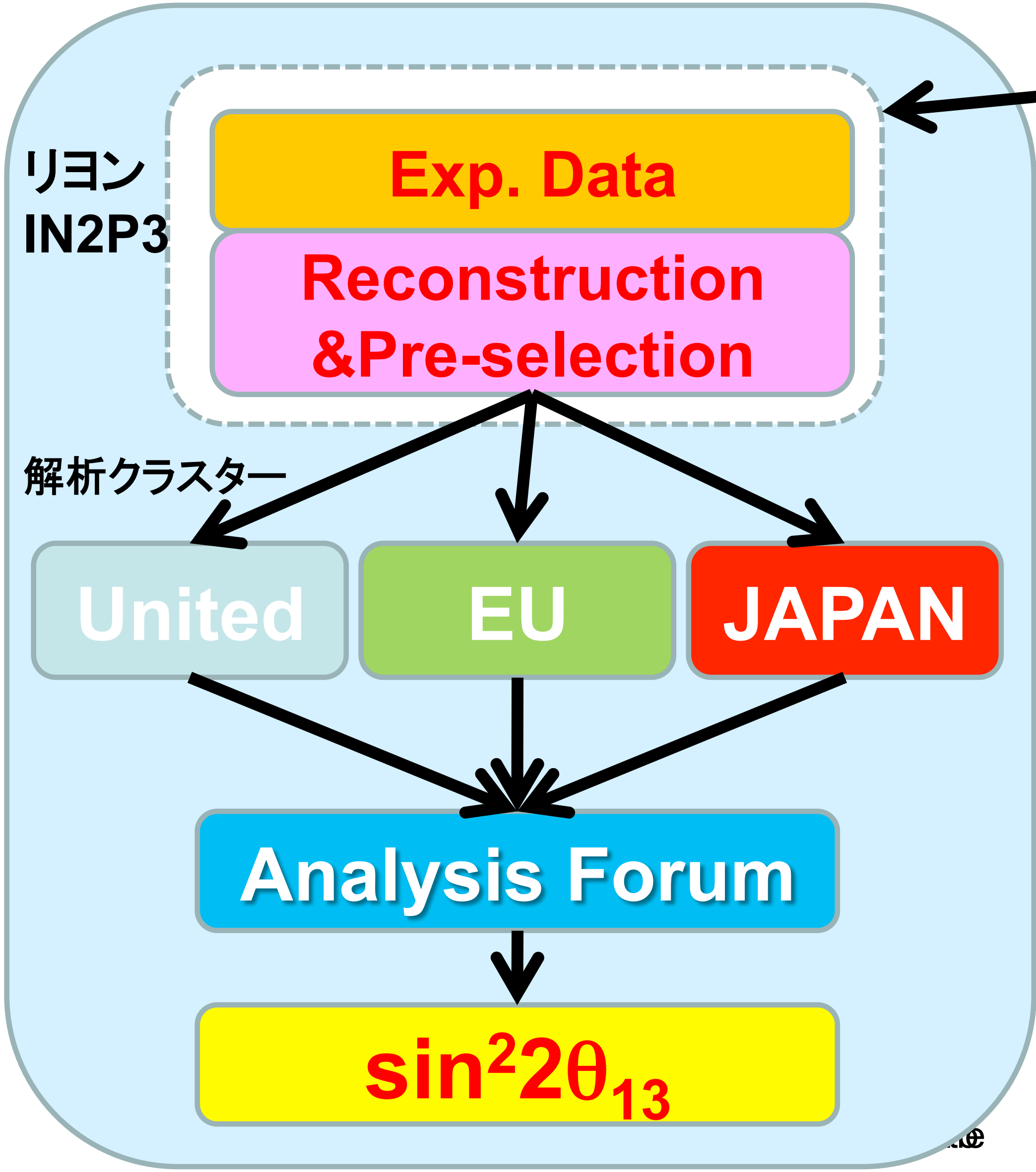
Trigger

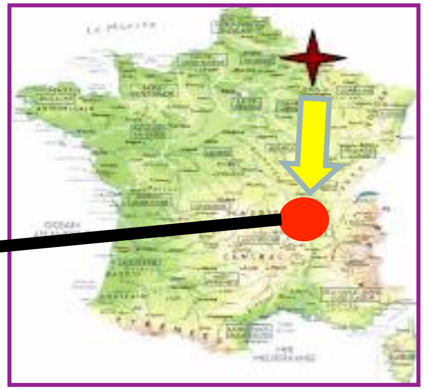


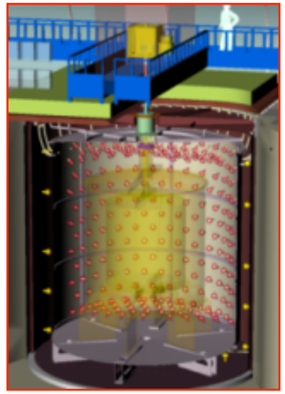
Checking the electric noise & signal using light injection system (2010.5~8)

All inner PMTs are alive after the harsh detector construction work!!

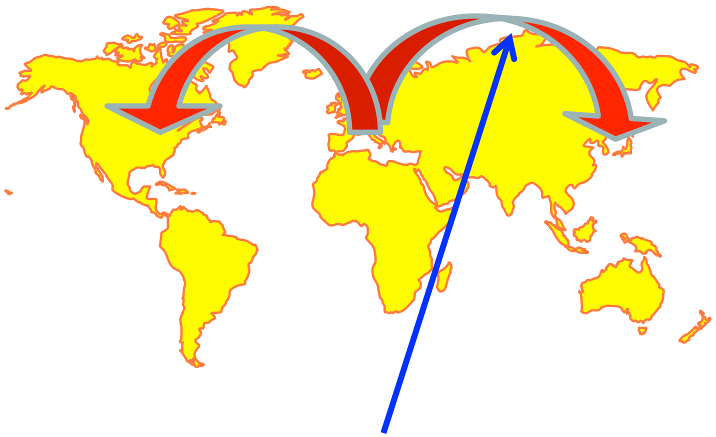
データ転送/解析体制







実験データは、IN2P3へ送られた後、
日(欧)米へネットワーク転送される。



この部分アトラスにおんぶ

23/12/2010: Official start of Double Chooz

Press release 23/12/2010

Double Chooz detector filled and measuring reactor neutrino oscillations

The Double Chooz collaboration recently completed its neutrino detector which will see anti-neutrinos coming from the Chooz nuclear power plant in the French Ardennes. The experiment is now ready to take data in order to measure fundamental neutrino properties with important consequences for particle and astro-particle physics.

ダブルショー原... | 受賞・成果等 | 東北大学 –TOHOKU UNIVERSITY–

東北大学
TOHOKU UNIVERSITY

2011年 | 受賞・成果等

2011年1月 6日 15:23 | 受賞・成果等 , 研究成果

ダブルショー原子炉ニュートリノ振動実験開始

本学ニュートリノ科学研究センターが参加しているダブルショー原子炉ニュートリノ振動国際共同実験*では，ニュートリノ主検出器の建設が完成し，ニュートリノデータ収集を開始することになり，2010年12月23日にフランスでプレスリリースされました．この研究により素粒子の重要な性質の一つが明らかになるとともに将来のニュートリノ研究がさらに進展することになります．
（*ダブルショー実験は，フランスのショー原子力発電所で新しいニュートリノ振動を検出し，θ13（しーたいちさん）と呼ばれる最後のニュートリノ混合角を測定する実験です．）

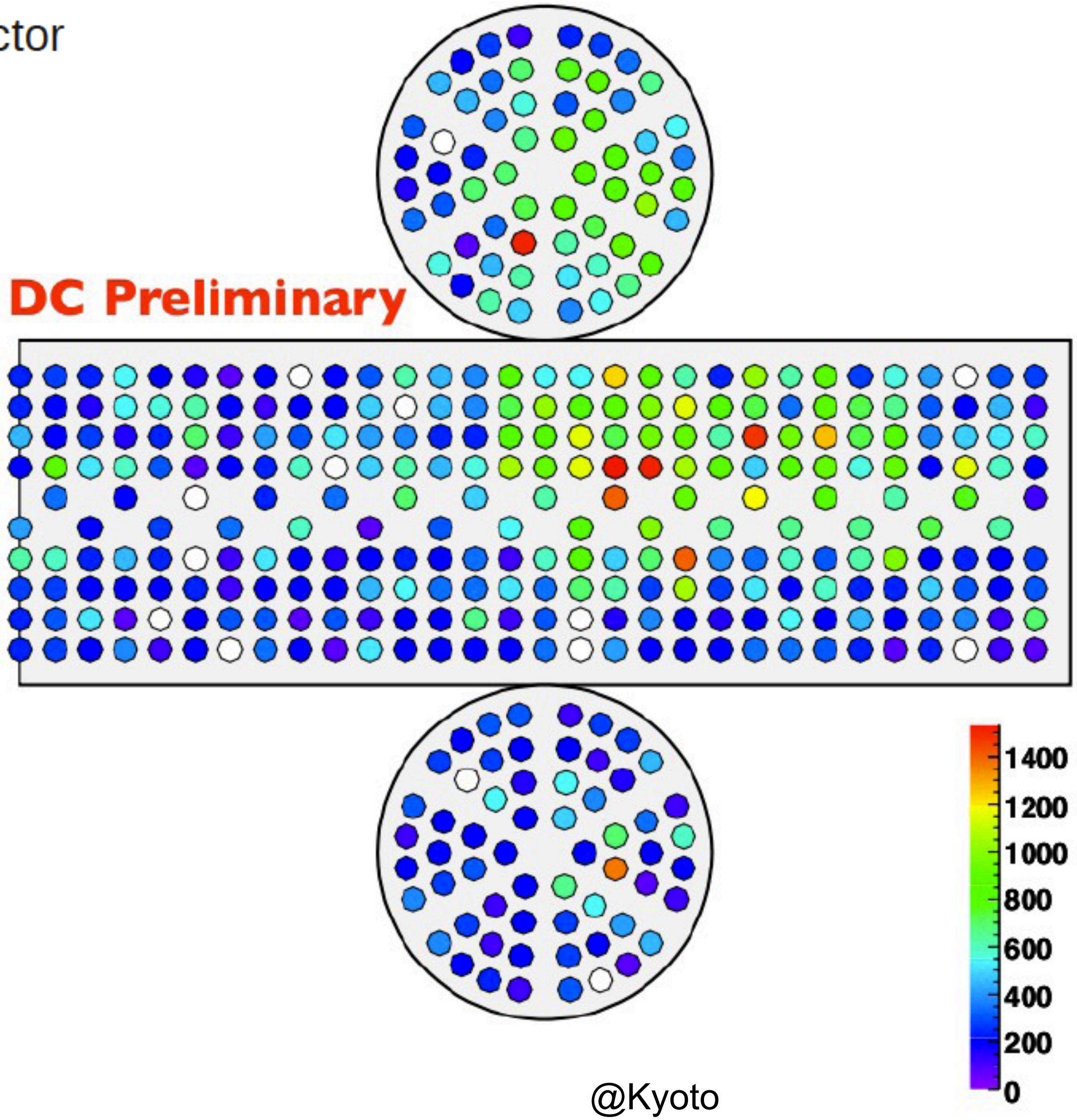
詳細

ダブルショー実験装置．今回は右側のニュートリノ検出器により実験が開始される．

東北大ニュース

Real data hits

Detector

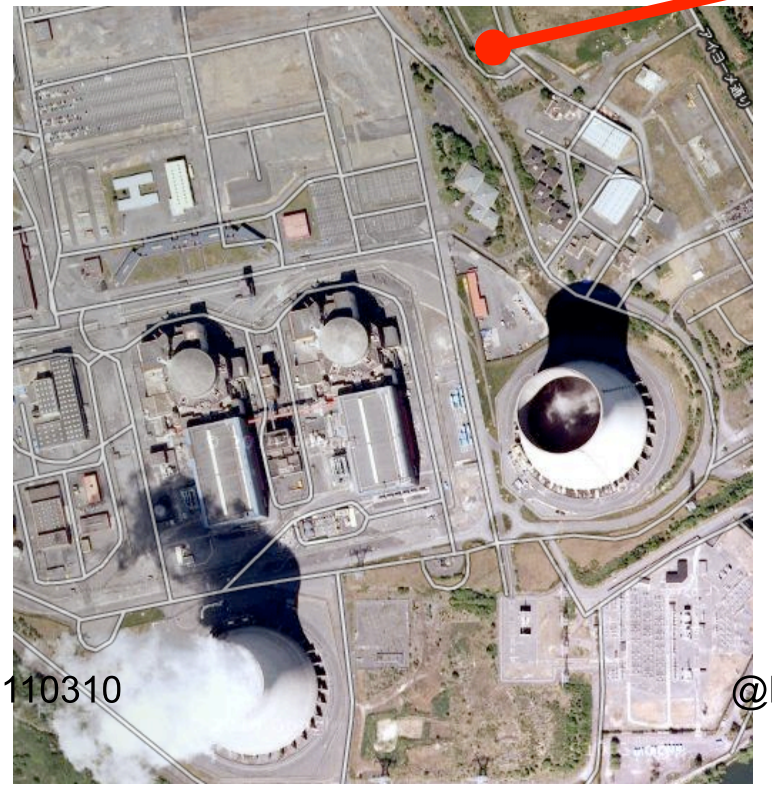


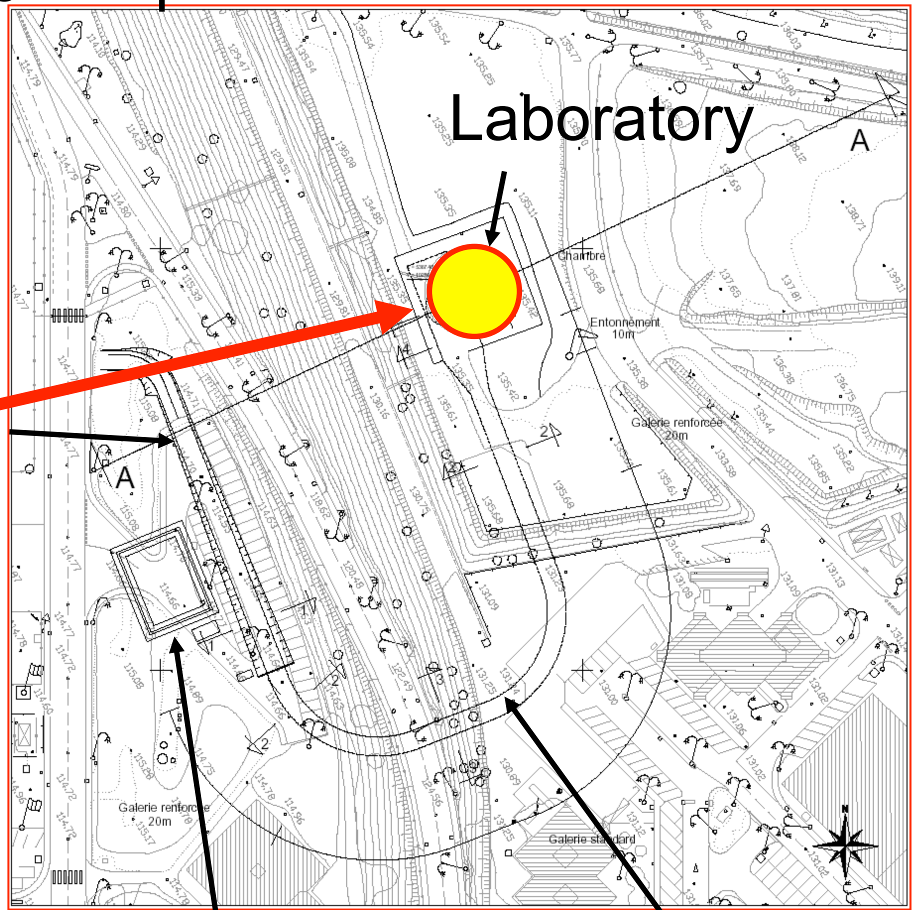
現在
run parameter
を調整中.

Status of the Near site

Far検出器のスケジュールとはindependent

- Site engineering study completed
  - ⇒Start excavation 2011
  - Site will be ready 2012
- Neutrino fluxes: 2.5×10^5 events in 3 years
- Depth: 120 m.w.e. (μ flux: ~ 3-4 $\mu/m^{-2}s^{-1}$)

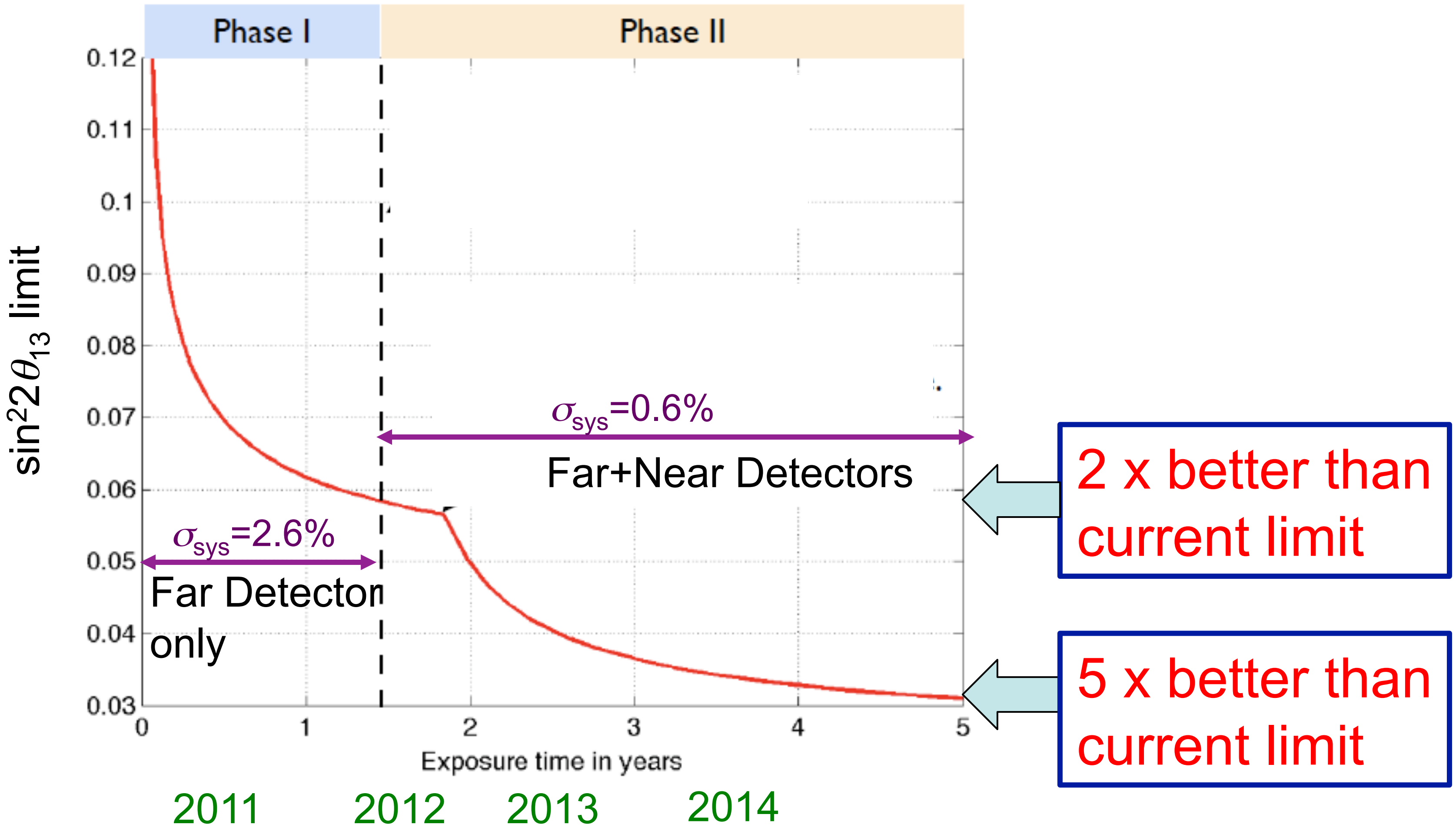


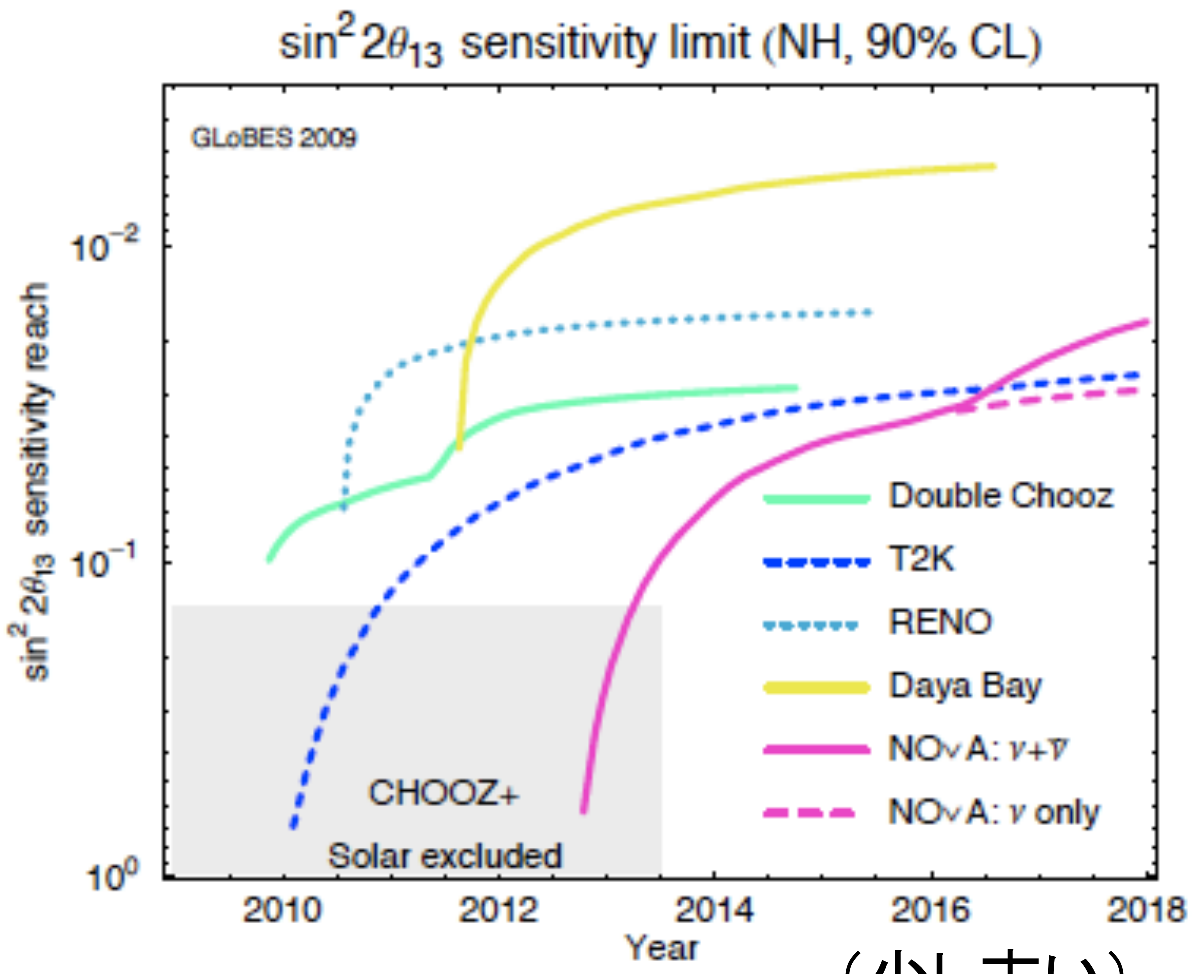


Liquid storage

Tunnel (155 m),
12% slope

θ_{13} Sensitivity in Time

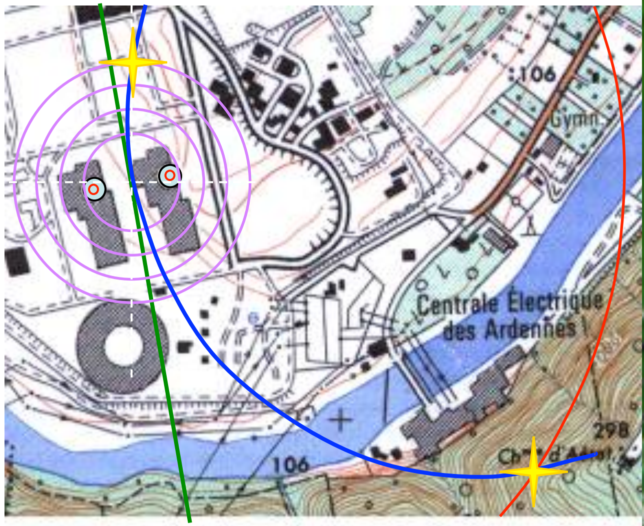


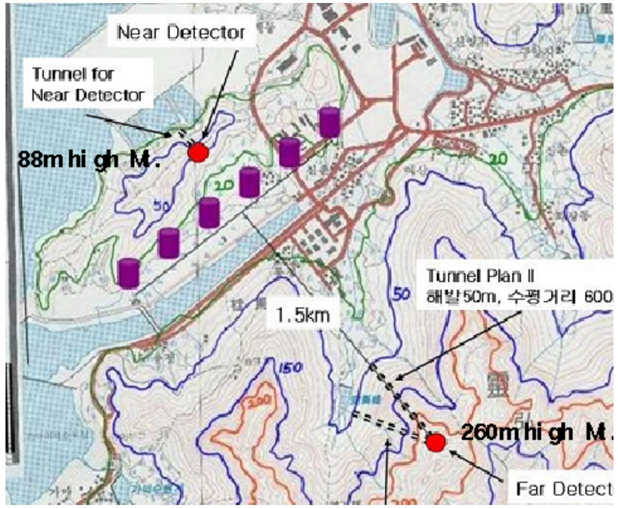

sin$^2 2\theta_{13}$ sensitivity limit (NH, 90% CL)
GLoBES 2009
10^{-2}
10^{-1}
10^{0}
sin$^2 2\theta_{13}$ sensitivity reach
CHOOZ+
Solar excluded
Double Chooz
T2K
RENO
Daya Bay
NOνA: ν+ν̄
NOνA: ν only
2010
2012
2014
2016
2018
Year

（少し古い）

ライバル

Double Chooz	Daya Bay	RENO



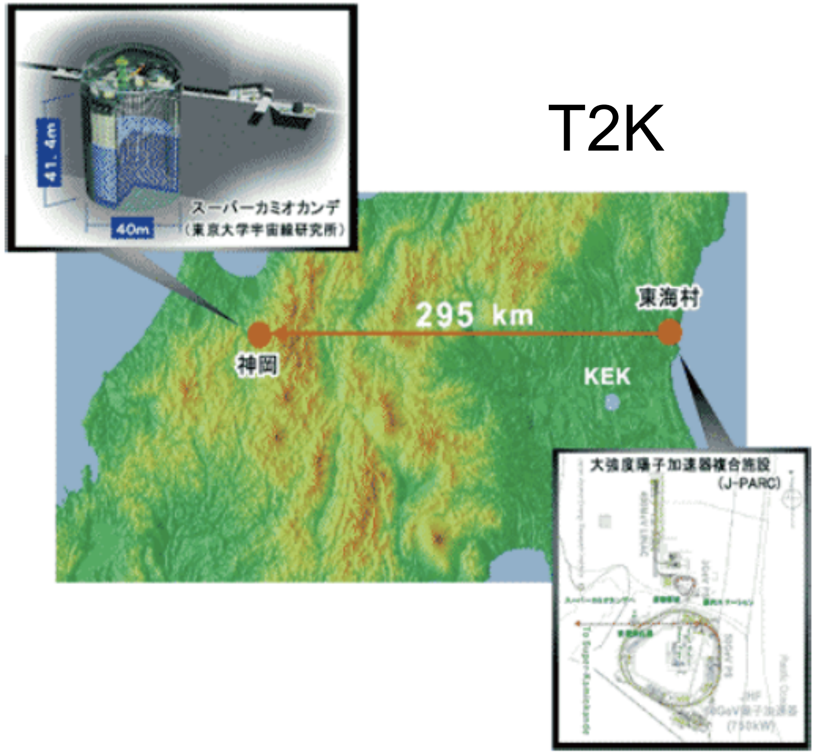


P=8.2GWth/2
L=1.05km
(2010)

P=11.6GWth/4
17.4GWth/6(2011~)
L~1.8km
(2012?)

P=16.1GWth/6
L~1.4km
(2011?)

T2K（東海to神岡）実験との関係



東海村のJParc加速器でν_μを作り、300km離れたSuperKamiokandeまで飛ばし、その間に$\nu_\mu \rightarrow \nu_e$の振動を測定する。

$$P(\nu_\mu \rightarrow \nu_e) \sim \frac{1}{2}\sin^2 2\theta_{13}$$ でθ_{13}を測定

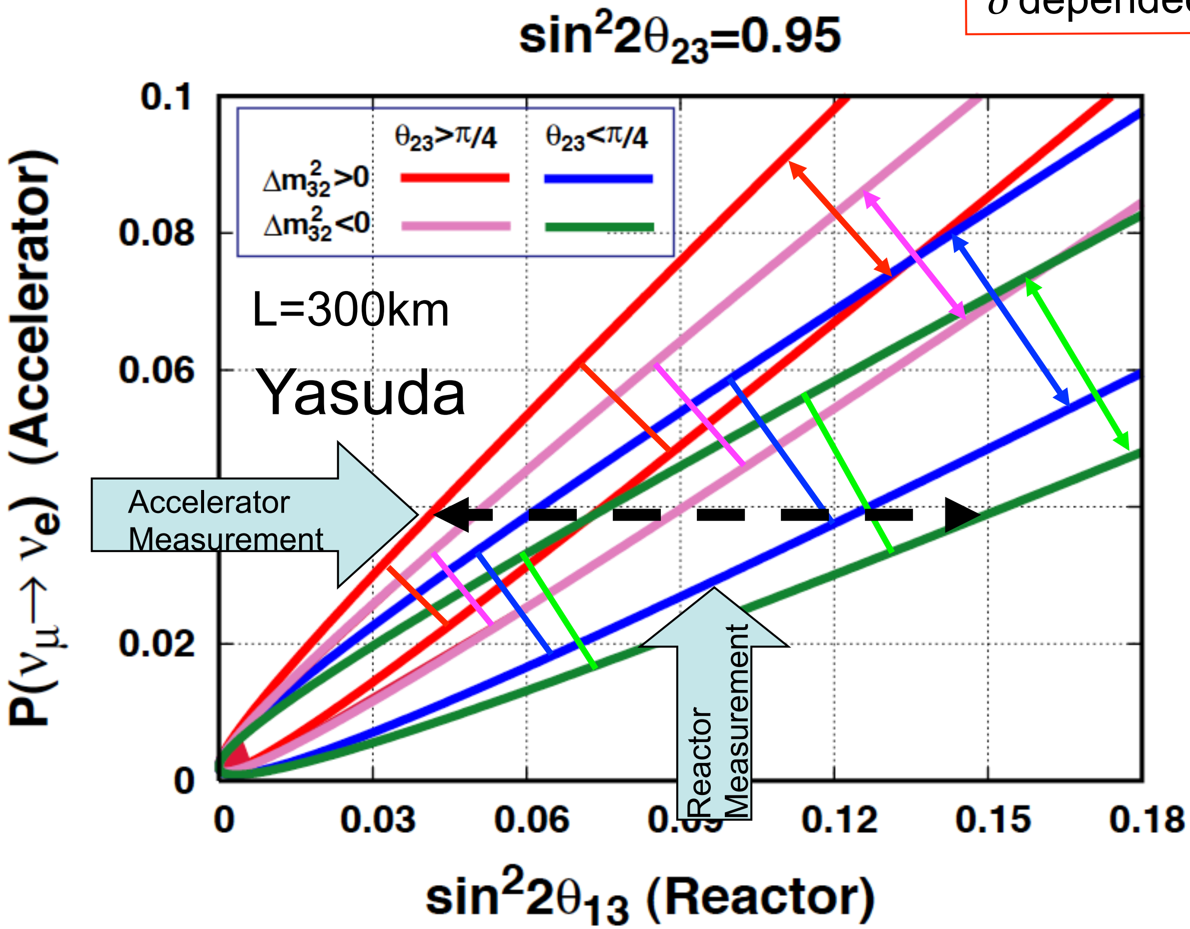
T2Kの測定

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



原子炉実験を組み合わせることにより様々な不定性を決定できる可能性がある。

Issues for ν oscillation & solving methods

4 still unknowns

(1) $\sin^2 2\theta_{13}$
(2)Mass Hierarchy ($m_3>m_1$ or $m_1>m_3$?)
(3)θ_{23} degeneracy ($\theta_{23}>\pi/2$ or $\theta_{23}<\pi/2$?)
(4) CP violating δ

Available information

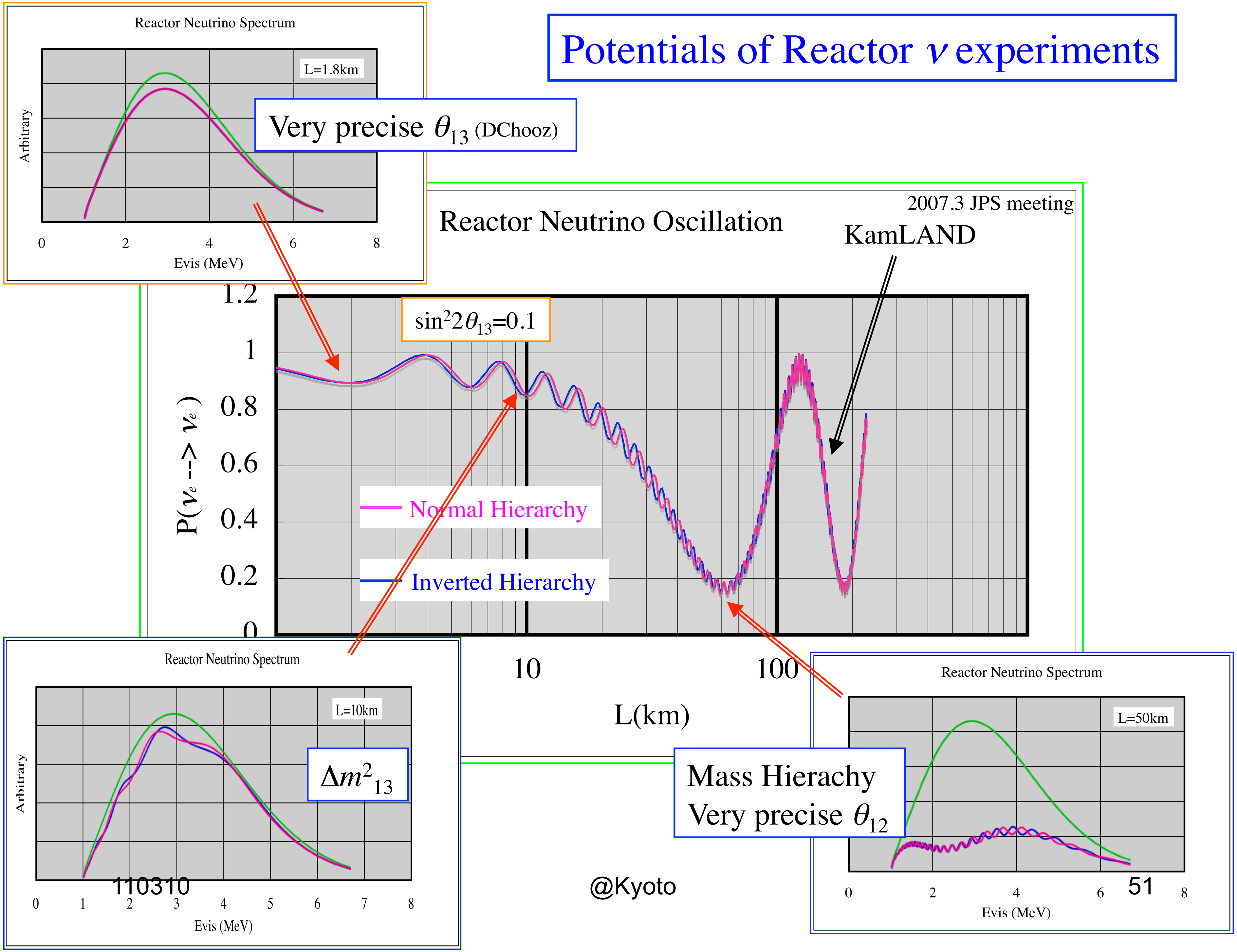
(1) $\nu_\mu => \nu_e$ (accelerator)
(2) $\overline{\nu}_\mu => \overline{\nu}_e$ (accelerator)
(3) Matter effect (accelerator)
(4) $\nu_\mu => \nu_\mu$ (accelerator)
(5) $\overline{\nu}_e => \overline{\nu}_e$ (reactor)
(6) Solar, Atmospheric

(1)–(4): Construction($$$) + ν production=$$

(5): Construction($~$$) ν production = free

Reactor ν experiments are cost-effective way to obtain important information.

Potentials of Reactor ν experiments



Possible Spin-off of reactor neutrino detection technique

Neutrinos can not be hidden.

Very sensitive reactor neutrino detection technique.

➔ Detect hidden reactor operation to breed plutonium.

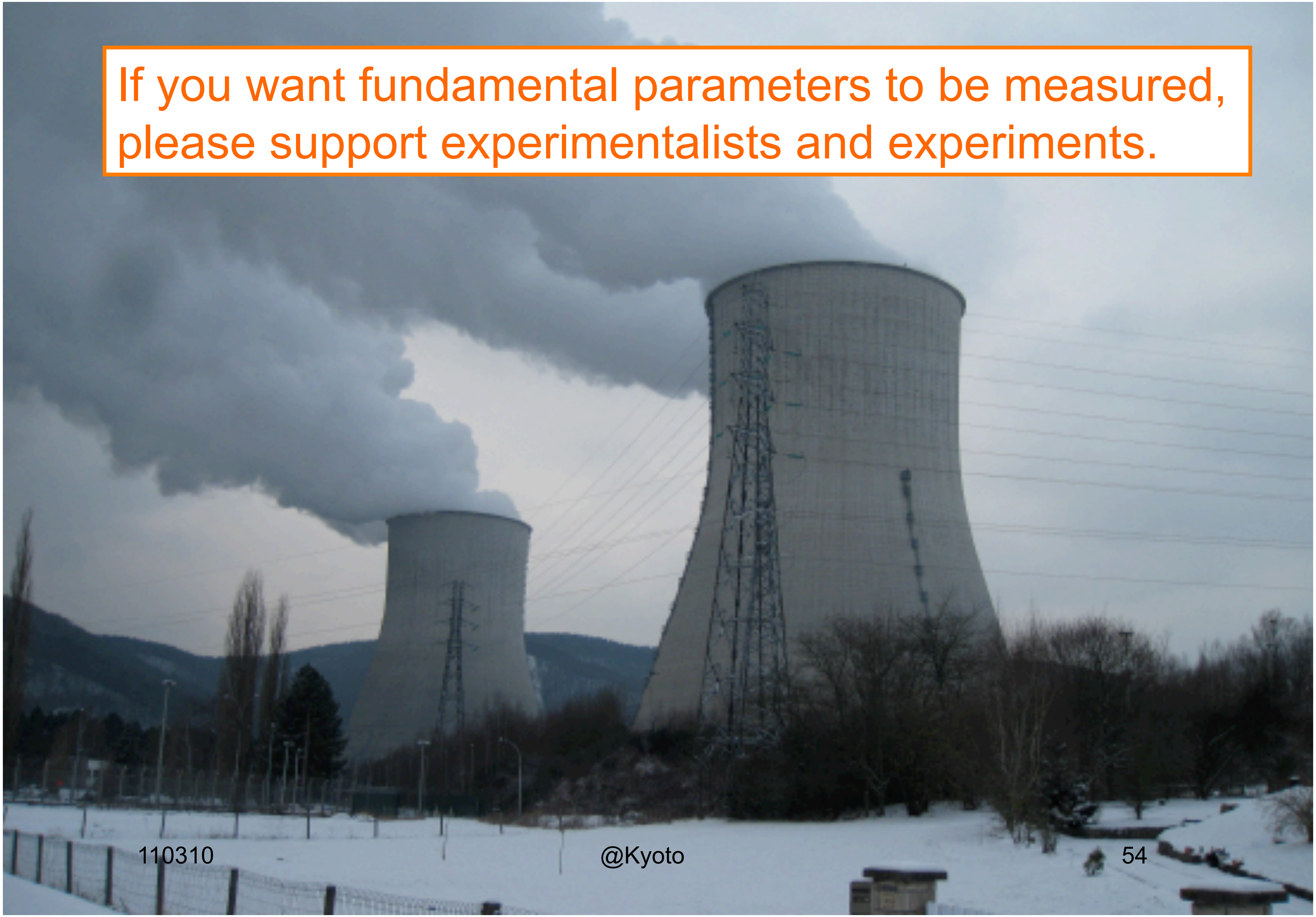
➔ IAEA is interested in and forms workshops.

Neutrinos may be useful
for safeguards of the world.

Summary

* 23/12/2010 DC started.
  $\delta \sin^2 2\theta_{13} \sim 0.06$ in 2011
* Near detector will start from 2012
  $\delta \sin^2 2\theta_{13} \sim 0.035$ in 2013
* There are more physics potentials for reactor neutrino physics in the future.

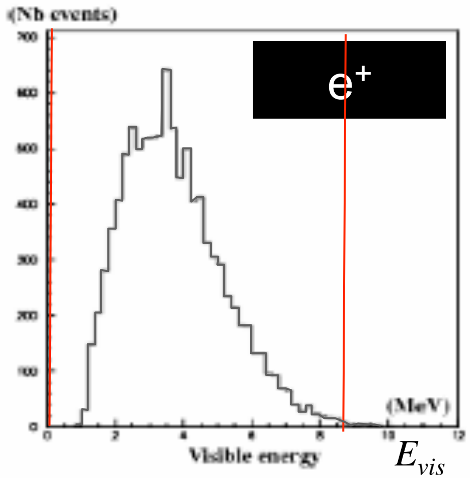
If you want fundamental parameters to be measured, please support experimentalists and experiments.

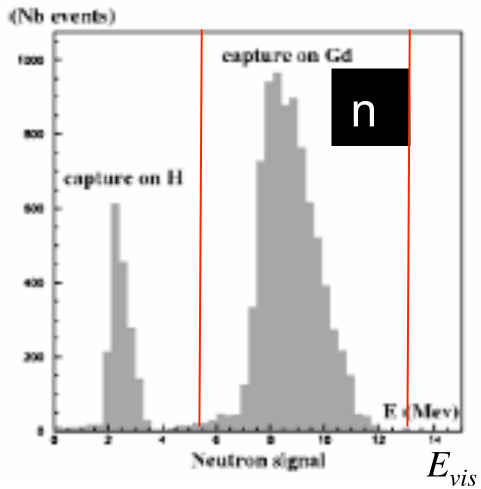


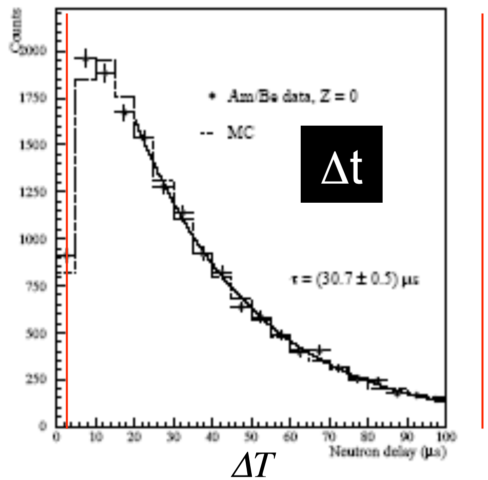
Back up slides

Improvement from CHOOZ

* Near/Far systematic cancellations
* Efficiency is insensitive to the energy scale error
- No fiducial volume cuts
- Reduced Backbrounds
- Reactor OFF data in Chooz experiment

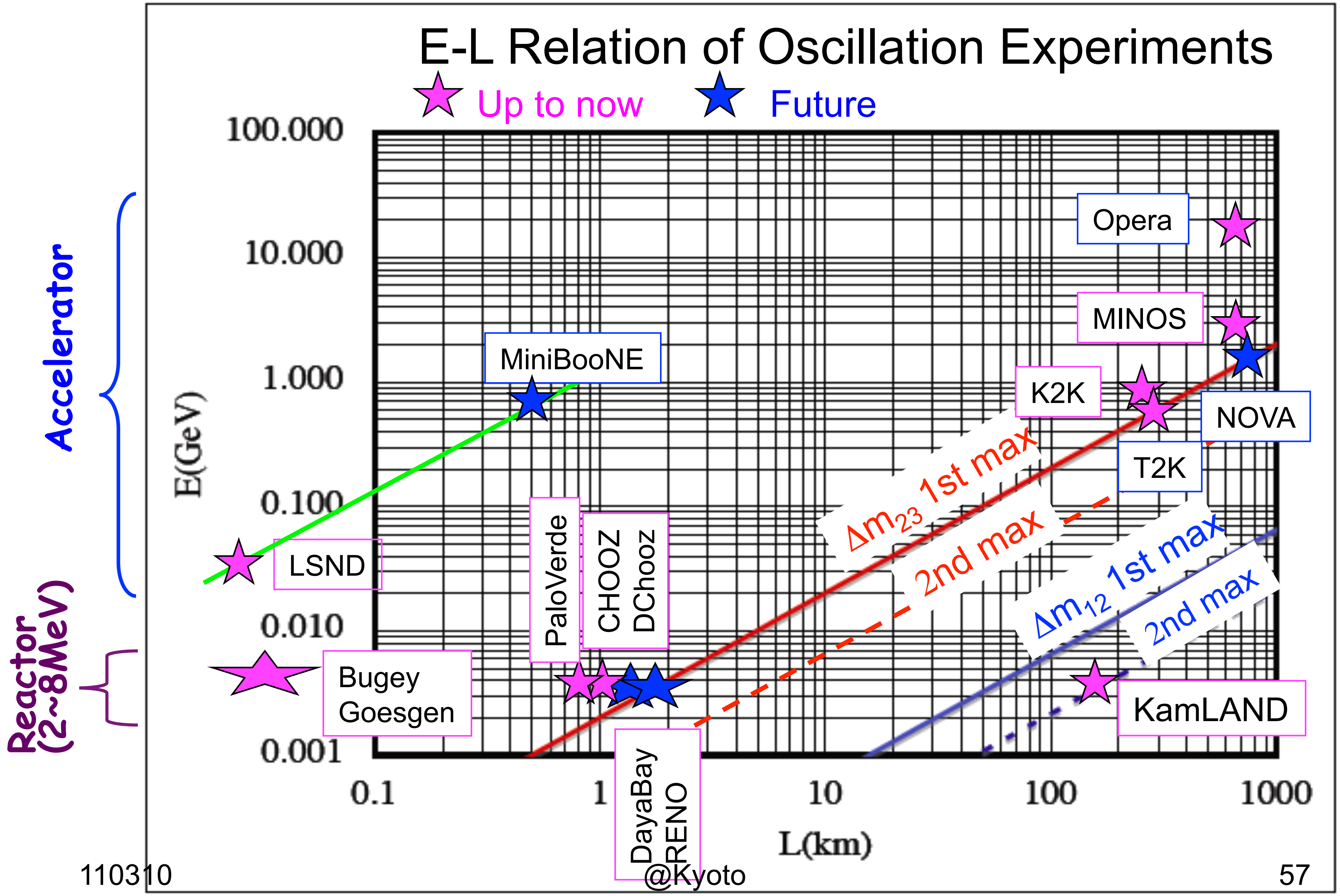






	CHOOZ	Double CHOOZ
Statistical Error:	2.7%	0.5%
Systematic Error	2.7%	<0.6%
Total error	3.8%	<0.8%
$\delta\sin^2 2\theta_{13}$(90%CL)	0.13	<0.03

Accessible Oscillations by Reactor ν



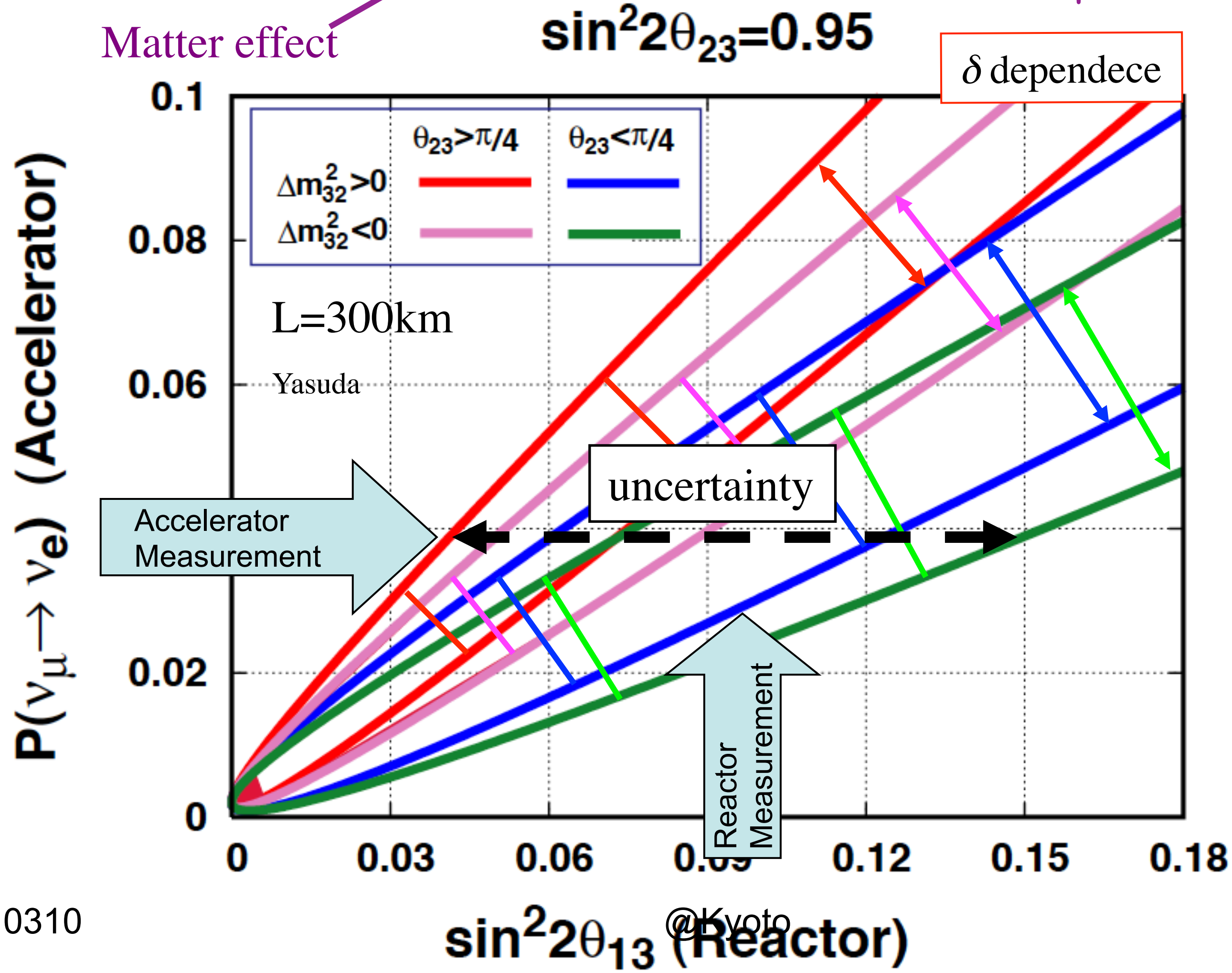
Comprementarity to accelerator θ_{13} measurement

θ_{23} degeneracy

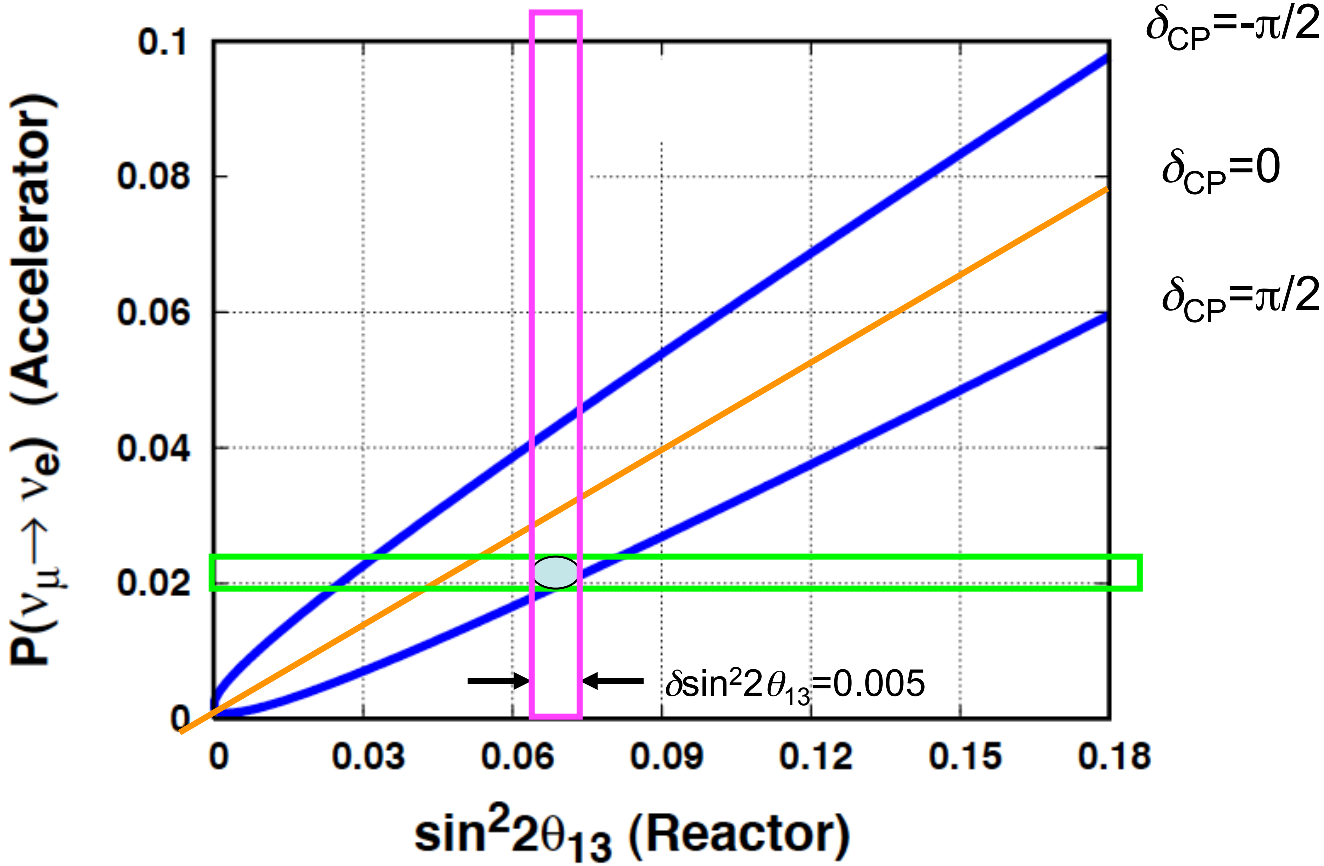
$$P_{AC}(\nu_\mu \to \nu_e) = \frac{0.50 \pm 0.11}{(1 \mp 0.00017L[km])^2}\sin^2 2\theta_{13} \pm 0.045\sin 2\theta_{13}\sin\delta$$

Matter effect

δ dependece



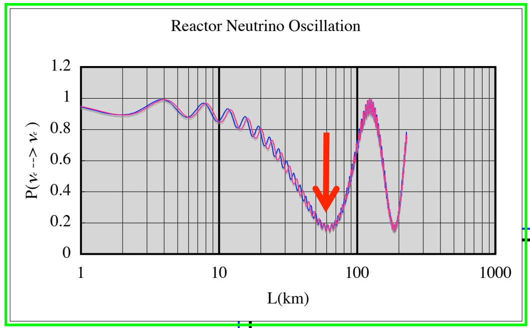
Quick Access to δ_{CP} by reactor & accelerator combination



If θ_{23} degeneracy and Mass Hierarchy are solved, only δ remains to be solved.

Combination of high precision Reactor-θ_{13} and Accelerator ν_e appearance may determine non-0 δ before anti-neutrino mode operation.

Physics @ 1^{st} Δm^2_{12} Maximum(L~50km)



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