Double Chooz 1st Results
and Related Topics

Fumihiko Suekane
RCNS, Tohoku Univ.

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25th 宇宙ニュートリノ研究会

I made the following talk on Nov./2002 here.
It was my 1st workshop talk on this subject.

A High Precision Measurement of

$\sin^2 2\theta_{13}$

using Kashiwazaki Kariwa

Nuclear Power Plant

2002/11/22

第１０回　特定・宇宙ニュートリノ研究会

＠東京大学宇宙線研究所（柏）

F.Suekane

RCNS,

Tohoku University

Sendai, Japan

And we published this paper on 2003.
This is the 1st paper pointing out reactor-accelerator complementarity.
(Cited 166 times (Spires))

PHYSICAL REVIEW D **68**, 033017 (2003)

Reactor measurement of θ_{13} and its complementarity to long-baseline experiments

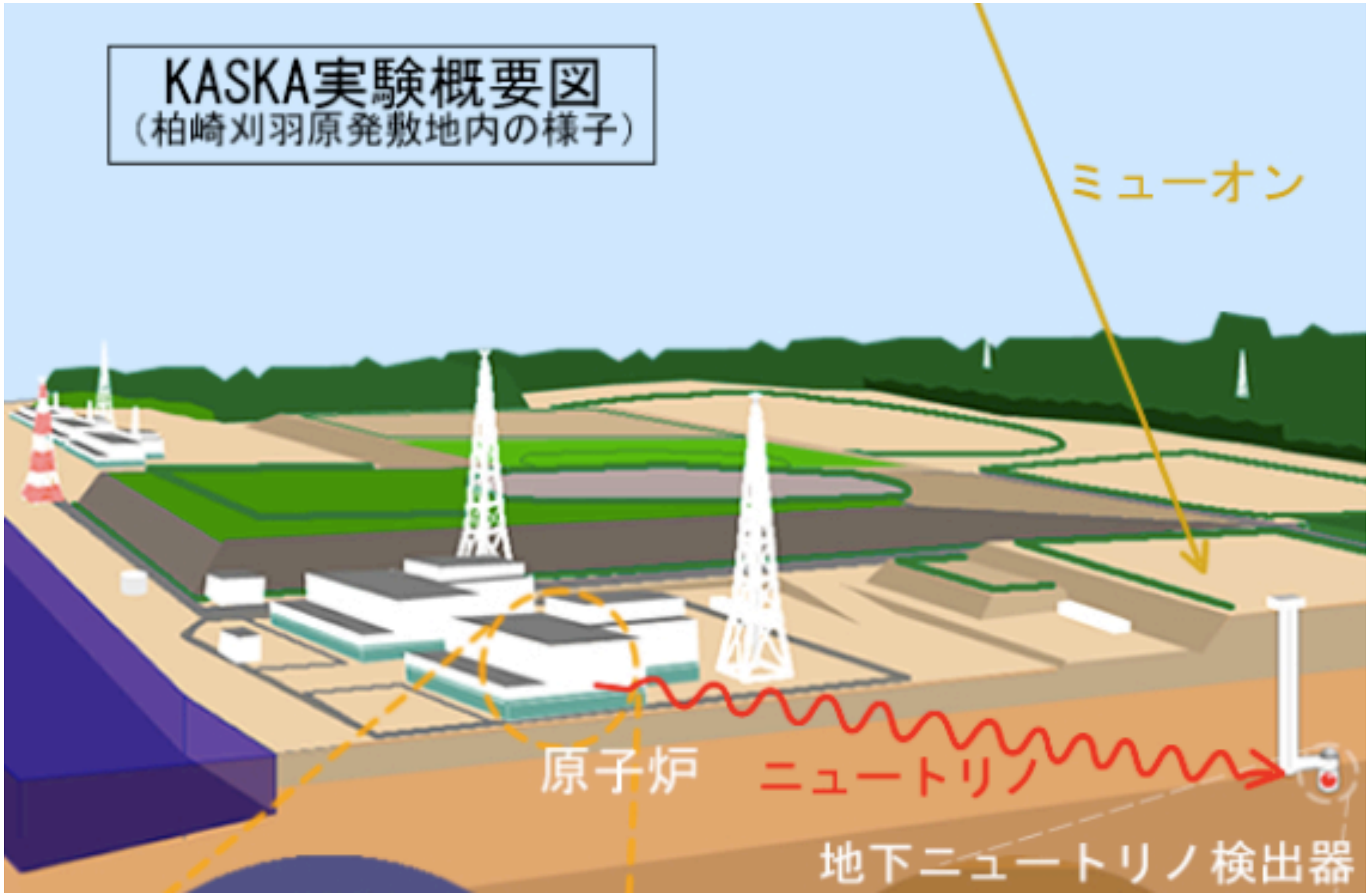
H. Minakata,* H. Sugiyama,† and O. Yasuda‡
Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

K. Inoue§ and F. Suekane‖
Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi, 980-8578, Japan
(Received 8 November 2002; revised manuscript received 18 April 2003; published 28 August 2003)

The possibility of measuring $\sin^2 2\theta_{13}$ using reactor neutrinos is examined in detail. It is shown that the sensitivity $\sin^2 2\theta_{13}>0.02$ can be reached with 40 ton yr data by placing identical CHOOZ-like detectors at near and far distances from a giant nuclear power plant whose total thermal energy is 24.3 GW_{th}. It is emphasized that this measurement is free from the parameter degeneracies that occur in accelerator appearance experiments, and therefore the reactor measurement is complementary to accelerator experiments. It is also shown that the reactor measurement may be able to resolve the degeneracy in θ_{23} if $\sin^2 2\theta_{13}$ and $\cos^2 2\theta_{23}$ are relatively large.

9 years have passed

Then we formed KASKA project which uses Kashiwazaki-Kariwa Nuclear Power Station in 2002 and performed R&D and wrote LoI. However, it was not funded and we joined Double Chooz in 2007.



Contents

* Motivation
* Reactor Neutrino Experiment
* Double Chooz Experiment
* Results
* Relation with Other Results
* Future possibilities of reactor experiments
* Summary

Why we study neutrino oscillation

There are many oscillations (Irrespective to it is observable or not)

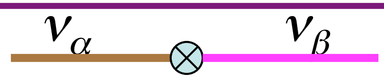
* $K^0 \Leftrightarrow \overline{K^0}$, $B^0 \Leftrightarrow \overline{B^0}$ Oscillation. ➔ CP violation
* spin precession by B (= $|\Uparrow\rangle \Leftrightarrow |\Downarrow\rangle$ oscillation) ➔ Formation of Q.M.
* 21cm wave of H $p(\Uparrow)e(\Downarrow) \Leftrightarrow p(\Downarrow)e(\Uparrow)$ oscillation ➔ Astronomy
* $|u\bar{u}\rangle \Leftrightarrow |d\bar{d}\rangle$ oscillation in π^0 ➔ Hadron structure, mass pattern. QCD
* $d \Leftrightarrow s$ oscillation ➔ Cabbibo angle, Higgs-Quark coupling
* $B \Leftrightarrow W_3$ oscillation ➔ EW theory, Weinberg angle, Higgs-GB coupling.

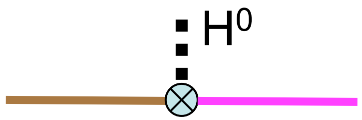
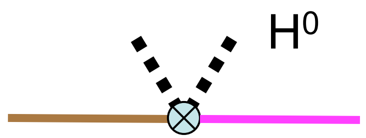
➔ These oscillations are related to important physics.

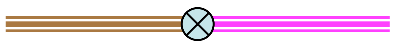
➔ Neutrino Oscillation $\nu_\alpha \Leftrightarrow \nu_\beta$ should be related to important physics, too.

Purpose of ν oscillation *experiments*

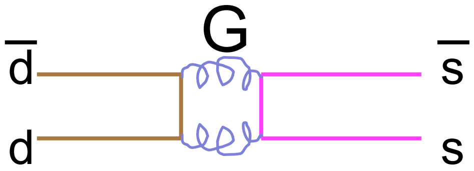
is to measure ν flavor transition amplitudes
and to give hints to theorists to explain our world
and to construct unified theory.

Now we know  exists.

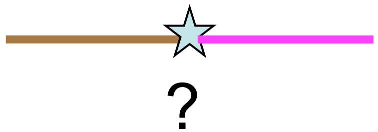
Non Standard Higgs?  or  ?

Sub Structure?? 

PS mixing

For Example, 

$$\begin{pmatrix}\pi^0\\ \eta\\ \eta'\end{pmatrix} \sim \begin{pmatrix}0.7 & 0.7 & 0\\ -0.4 & 0.4 & 0.8\\ 0.6 & -0.6 & 0.6\end{pmatrix}\begin{pmatrix}|u\bar{u}\rangle\\ |d\bar{d}\rangle\\ |s\bar{s}\rangle\end{pmatrix}$$

Or something else?? 

CKM matrix & MNS matrix

CKM mixing matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.9743 & 0.2253 & 0.0035 \\ 0.2252 & 0.9735 & 0.041 \\ 0.0086 & 0.040 & 0.9992 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Neutrino mixing matrix (MNS matrix) before 2011

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \sim \begin{pmatrix} 0.8 & 0.5 & \underline{\underline{\sin\theta_{13} e^{i\delta}}} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad \sin\theta_{13} < 0.2$$

* Finite size of θ_{13} was not known
* CP violation depends much on θ_{13} (as well as on other angles)

➔ Need to measure

Importance of determinatin of θ_{13}

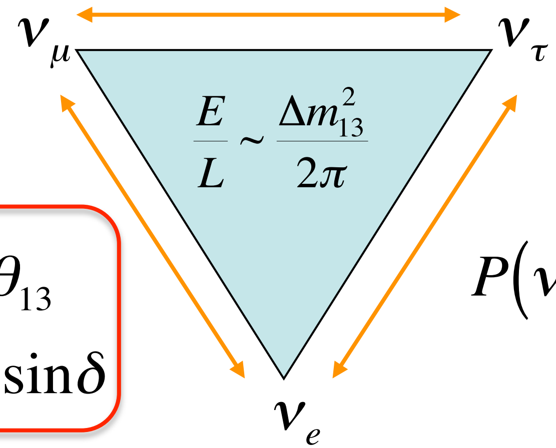
* It is one of the fundamental parameters.
* Future ν experiments strongly depends on θ_{13}.

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

We can not go further without knowing θ_{13}.

How θ_{13} can be measured

$@\frac{\Delta m_{13}^2 L}{4E} \sim \frac{\pi}{2}$
- E~MeV, L~1km — Reactor Experiments
- E~GeV, L=100~1000km; Accelerator experiments



$$\mathrm{P}(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13} - 0.045 \cdot \sin 2\theta_{13}\sin\delta$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^2\theta_{23}\sin^2 2\theta_{13} + 0.045 \cdot \sin 2\theta_{13}\sin\delta$$

Accelerator Measurements

T2K, MINOS, NO*v*A

$$P(\nu_e \rightarrow \nu_\mu) + P(\nu_e \rightarrow \nu_\tau) = \sin^2 2\theta_{13}$$

Reactor measurements

DoubleChooz, Dayabay, RENO

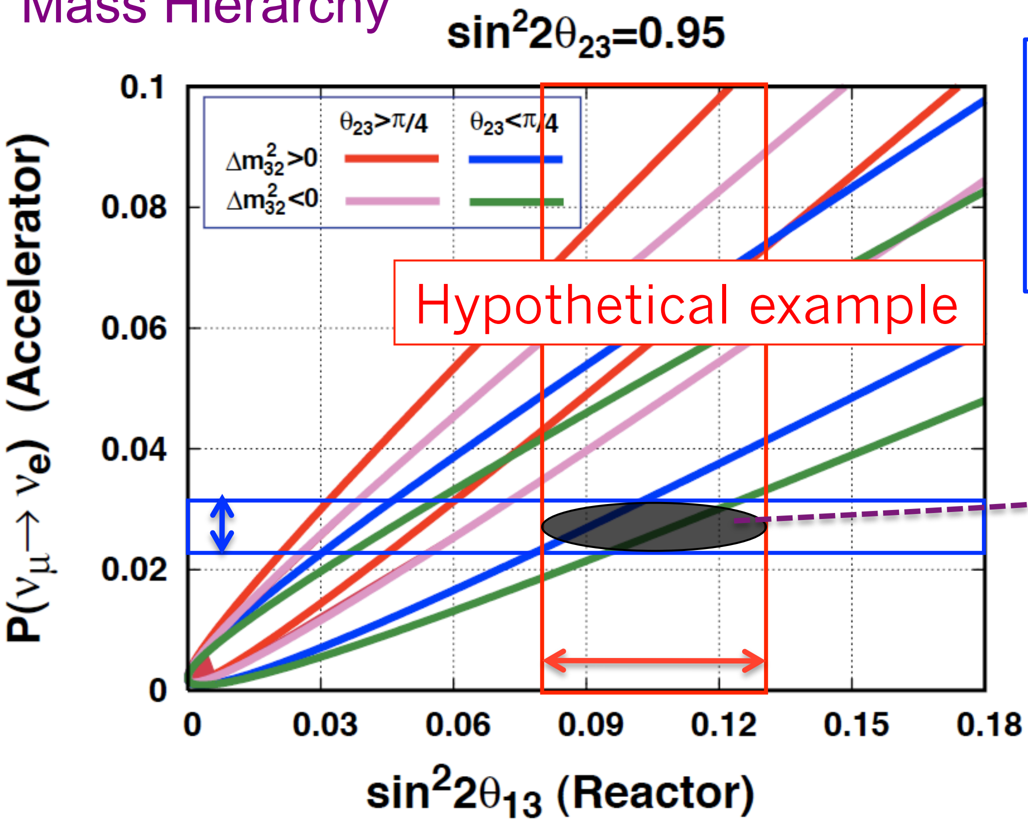
Why reactor measurement is important

θ_{23} degeneracy

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

Mass Hierarchy

δ dependece

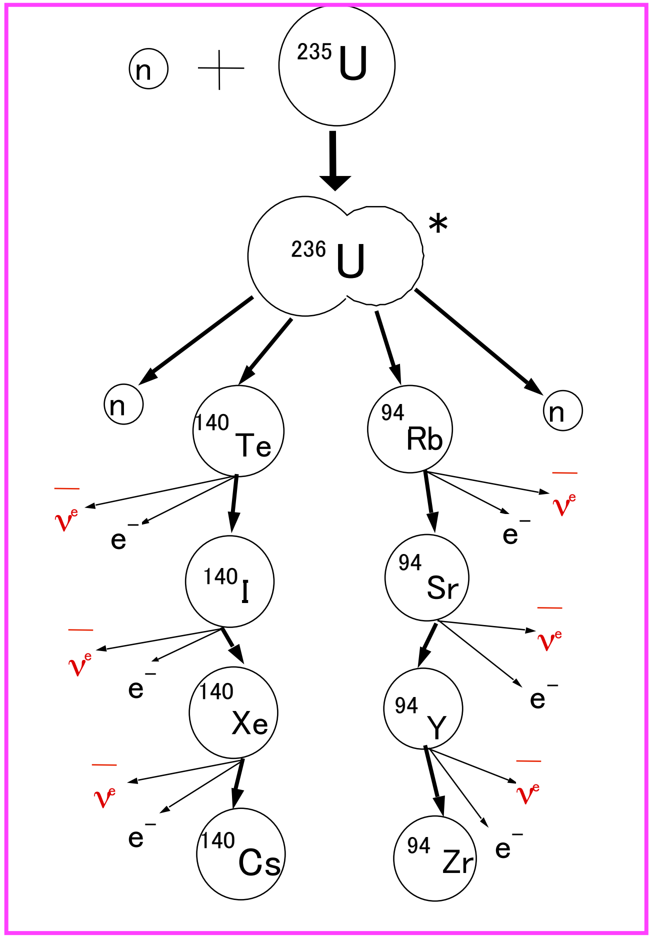


Contrary, reactor measurement is pure $\sin^2 2\theta_{13}$ measurement

&

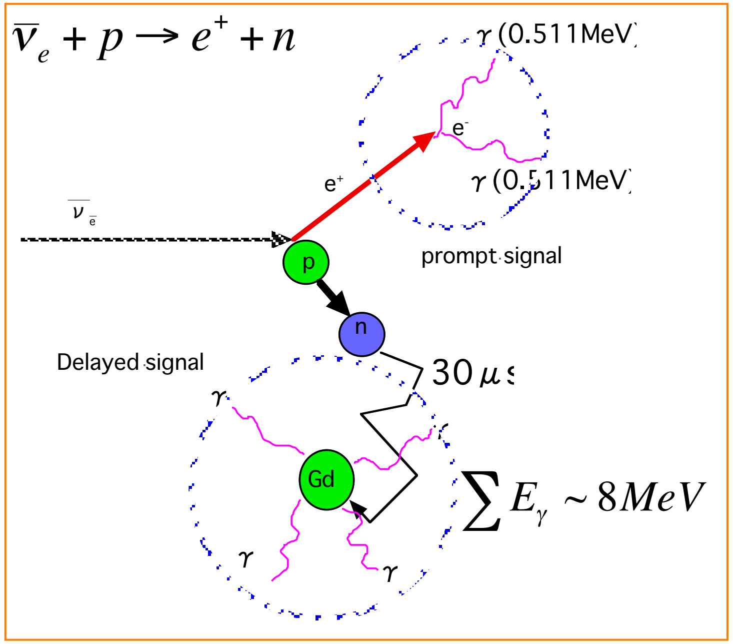
Combining Reactor and Accelerator will restrict parameter space.

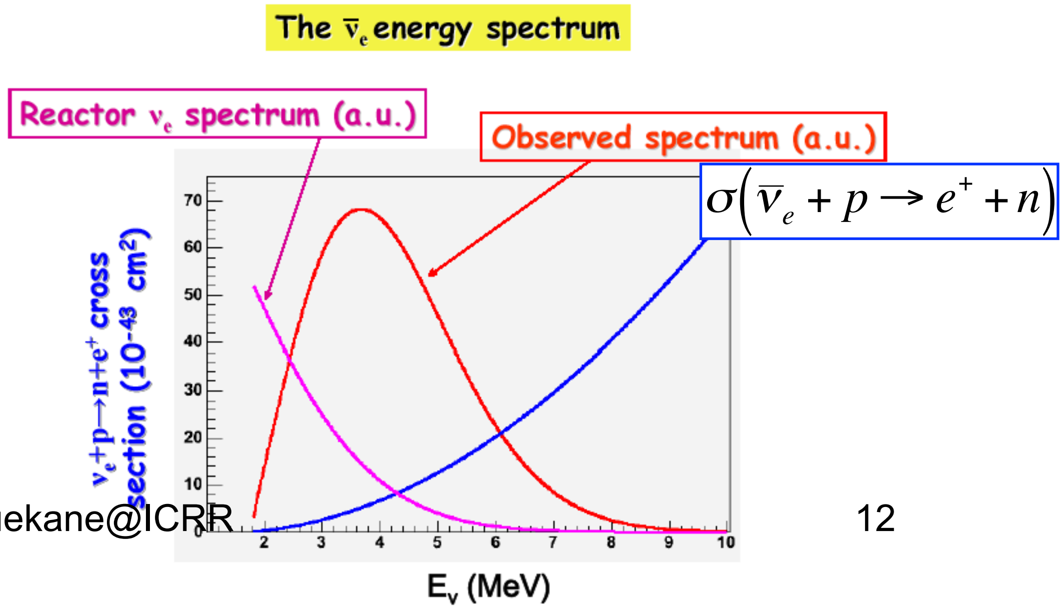
Reactor neutrino & Its detection



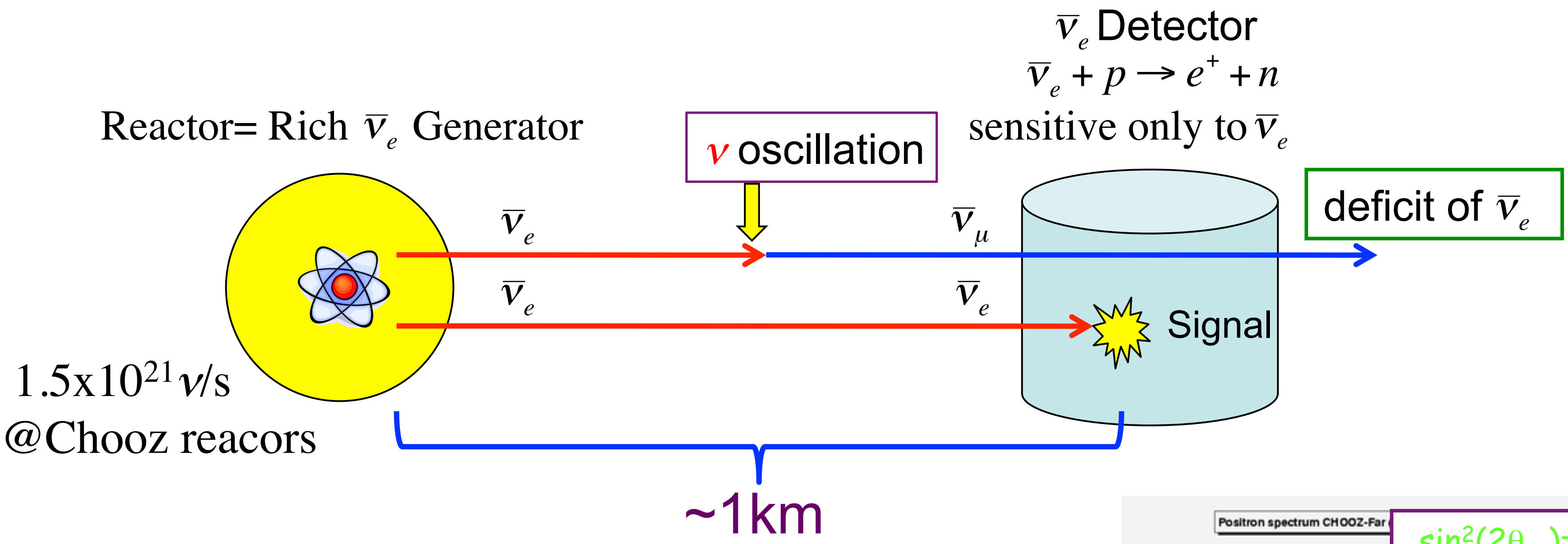
ν are produced in
β-decays of fission products.

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





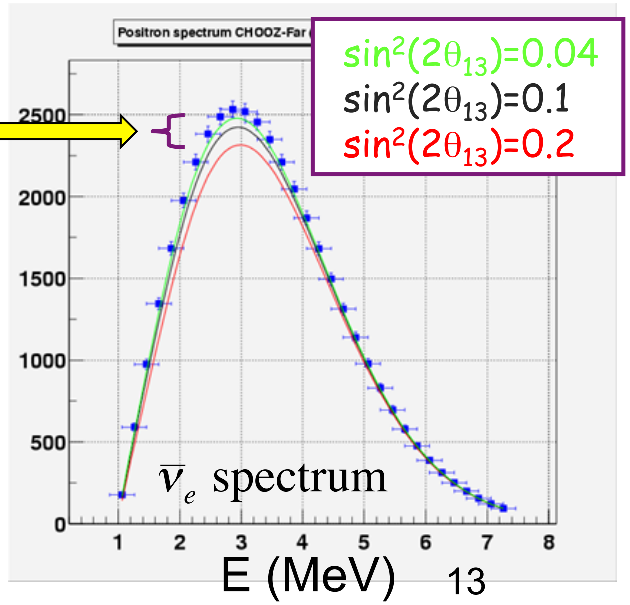
How to measure θ_{13} by reactor neutrinos



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

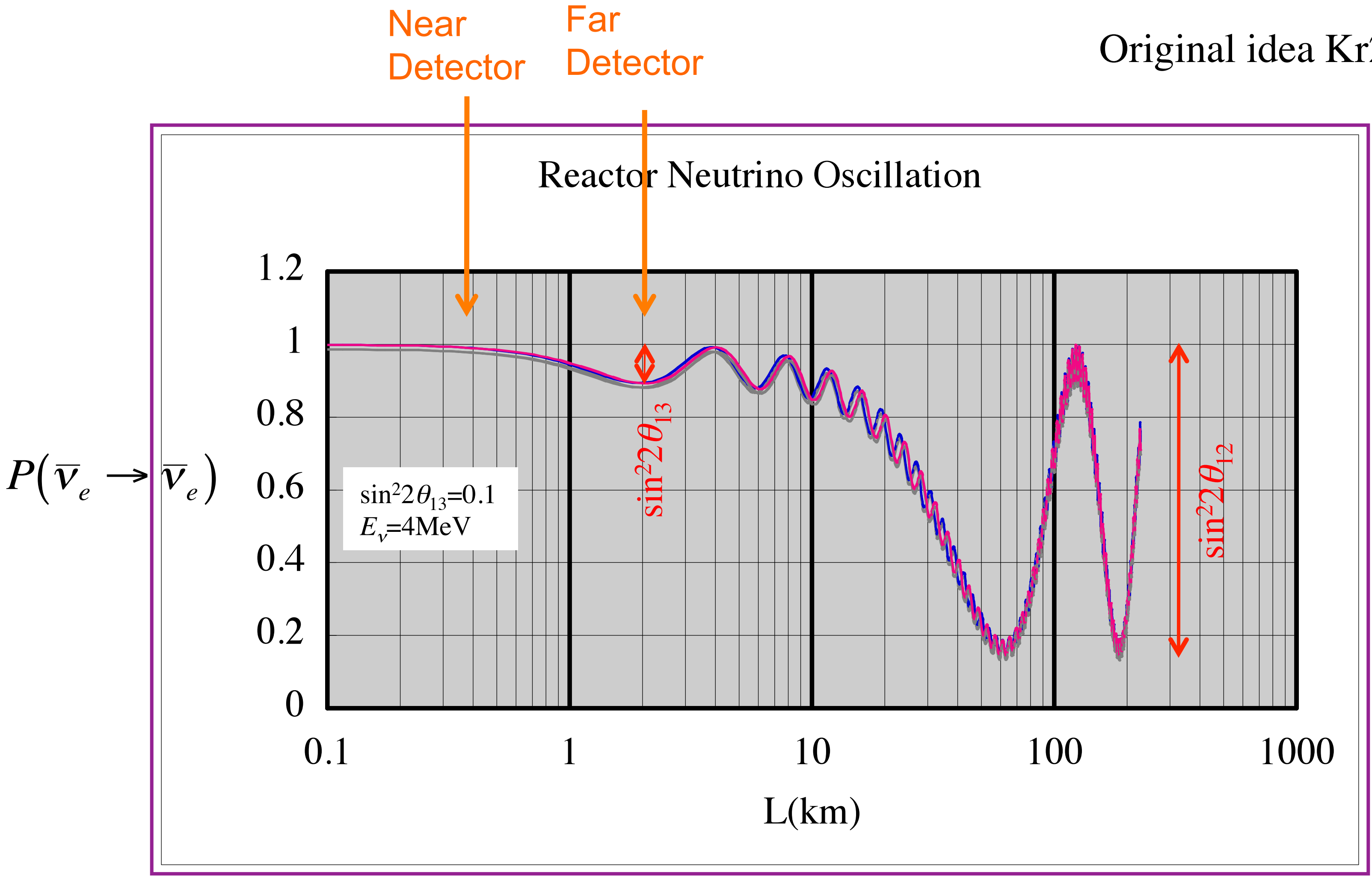
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}$$

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



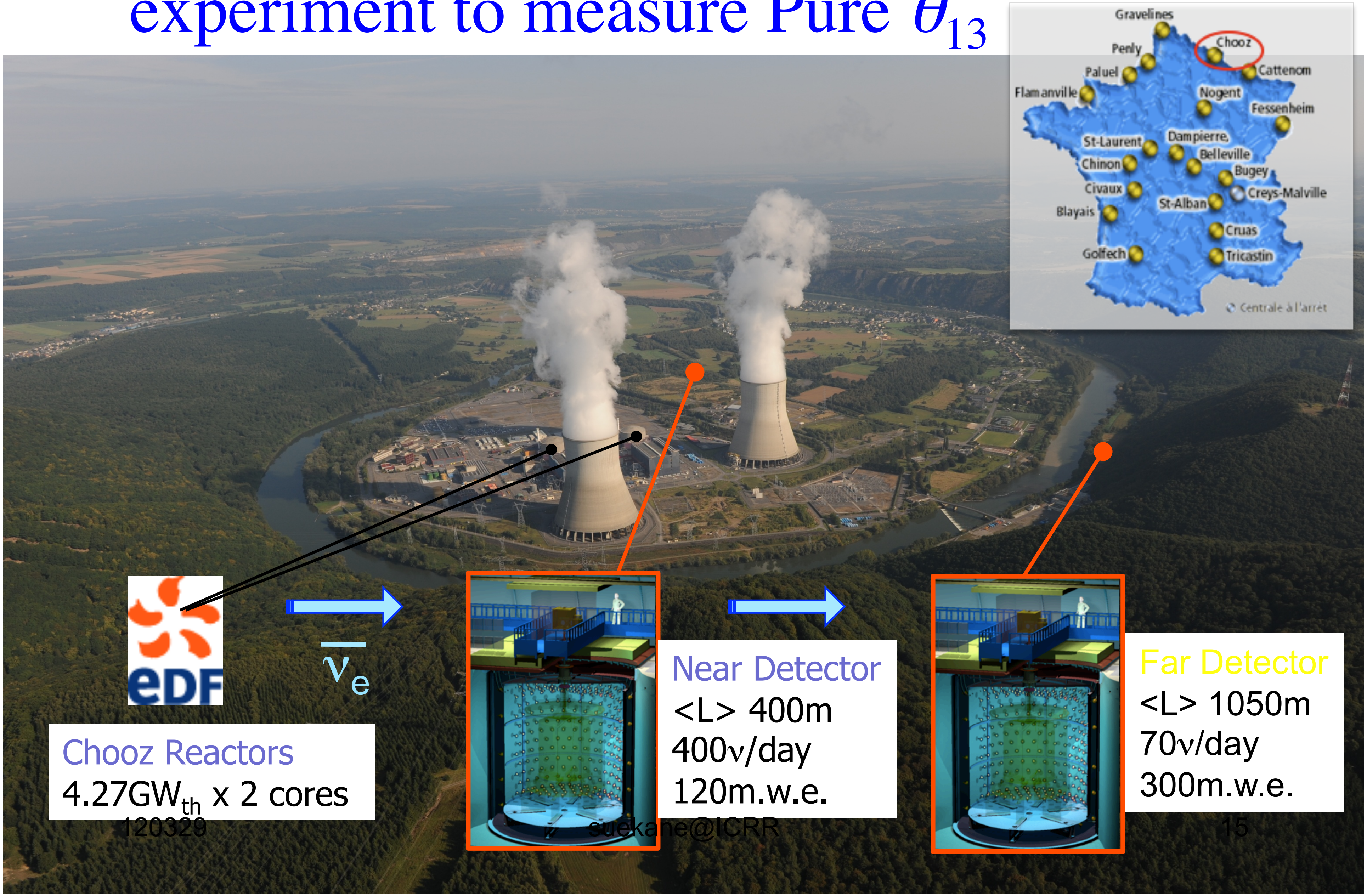
How to realize good precision: 2 detector scheme

Original idea Kr2Det

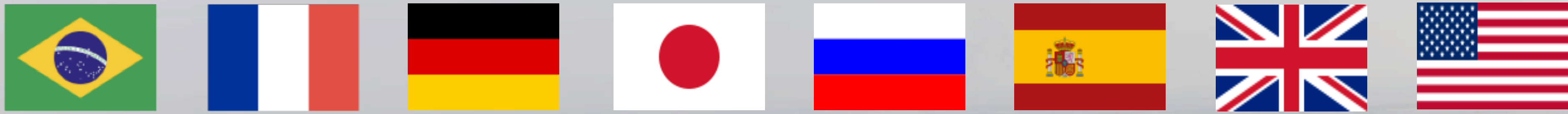


Ratio measurement Far/Near Detectors => Cancels most systematics

Then we are performing 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

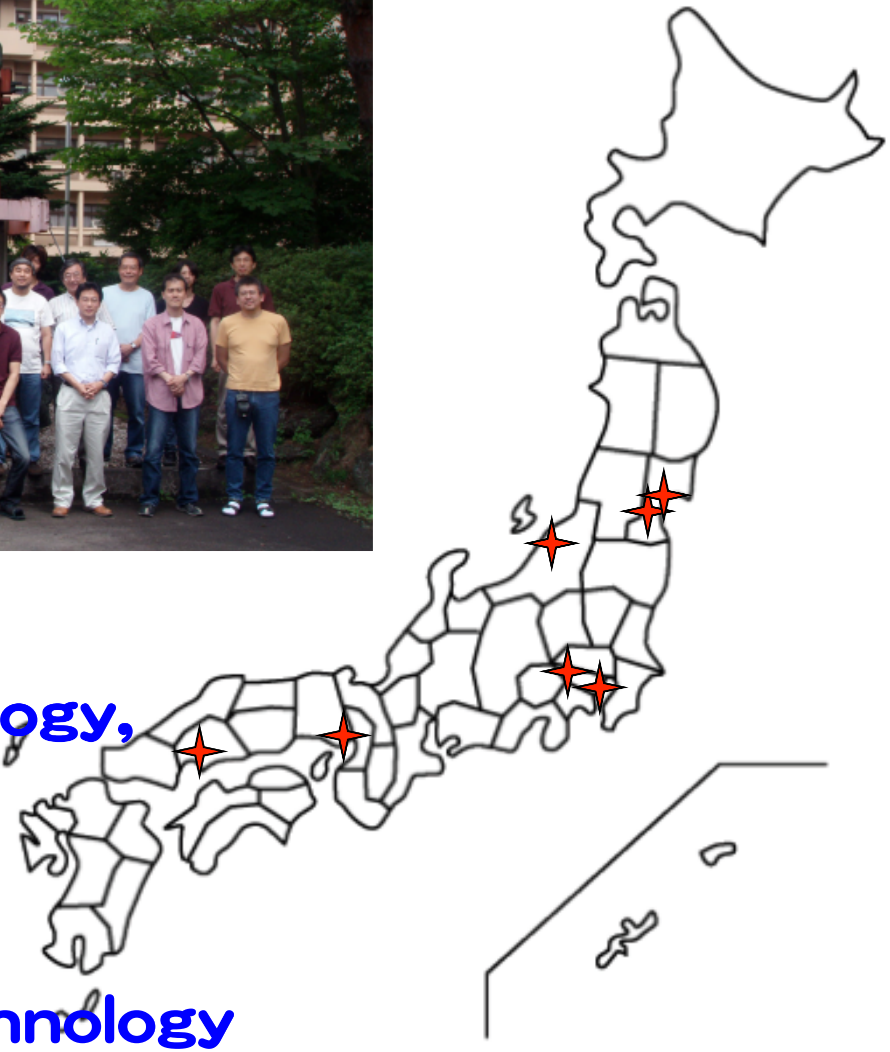
USA
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- Sandia National Laboratories
- U. Tennessee

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

Web Site: www.doublechooz.org/

DoubleChooz Collaborationmeeting @ Tohoku 2012

DC-Japan



*Tohoku Univ.,
*Tokyo Institute of Technology,
*Tokyo Metropolitan Univ.,
*Niigata U., Kobe Univ.,
*Tohoku Gakuin Univ.,
*Hiroshima Institute of Technology

Main Components of DC Detector

Target ν :
10m³ Gd loaded Liquid Scintllator
8mmt Acrylic Tank

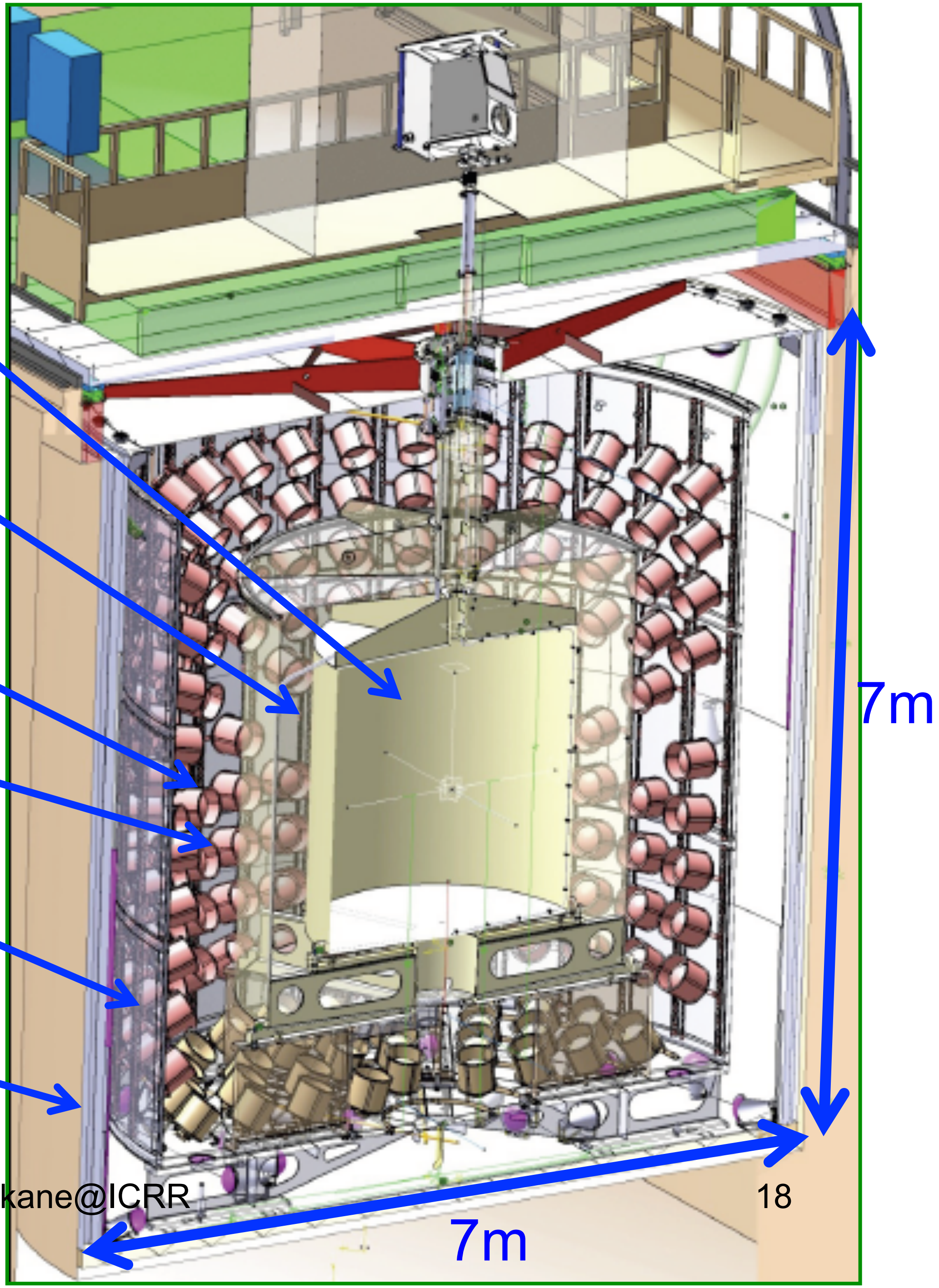
γ Catcher :
22m³ Liquid Scintillator
12mmt Acrylic Tank

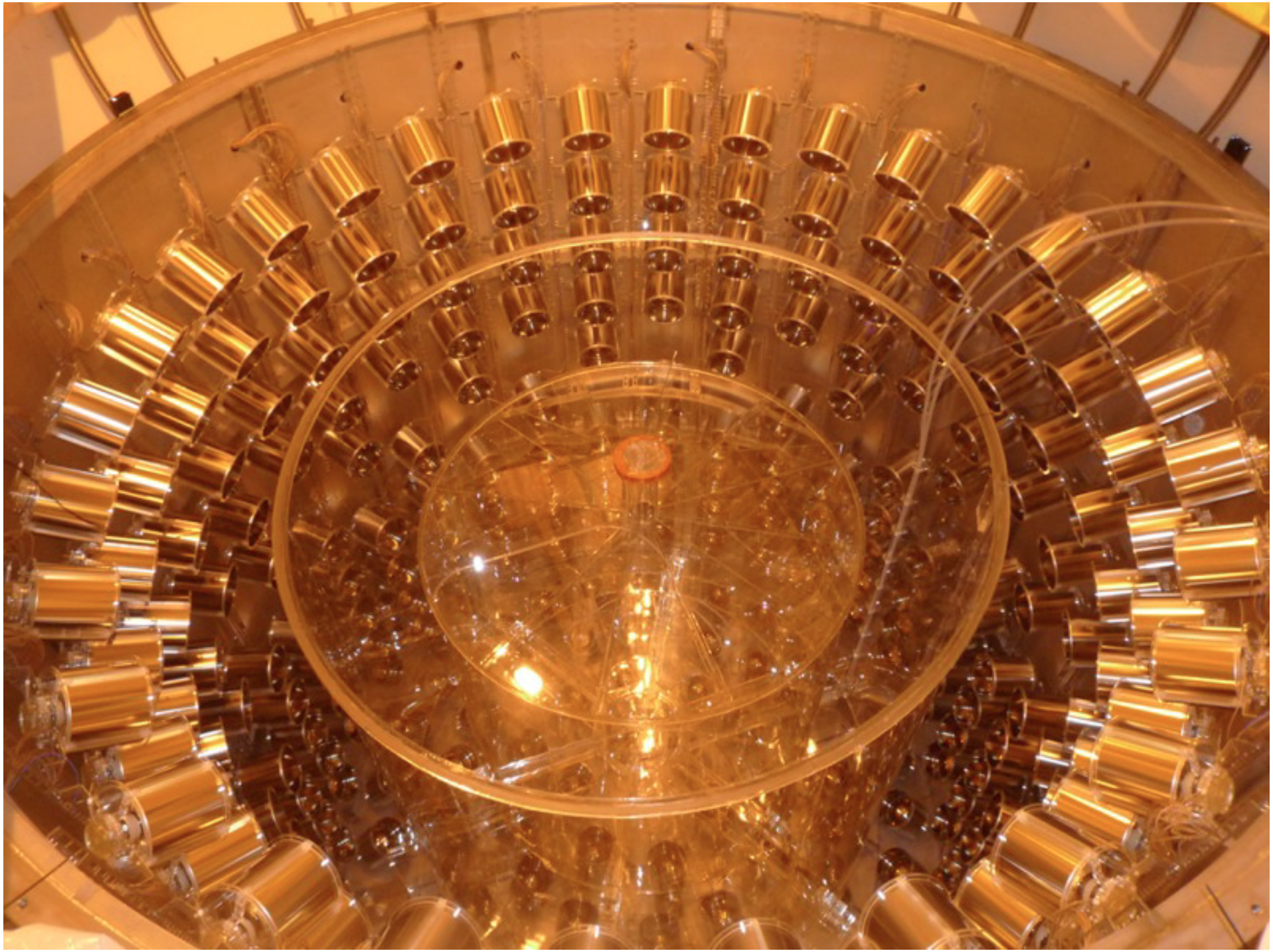
Light Detection:
390 Low BKG 10" PMTs

Buffer oil :
110m³ Paraffine Oil
3mmt Stainless Steel Tank

Inner Muon Veto :
90m³ LS + 78 8" PMTs

Iron shield:
15cmt





DC Milestones

(2008/5~) 2010/10	Far Detector Structure complete
2010/12/	Liquid Scintillator Loading
2011/4	Far detector commissioning
	Physics data taking started.
	Excavation of near tunnel started
2011/7	Outer Veto Detector in Operation
2011/11	1st Result @ LowNu conference
	(Accepted by PRL)
2013	Near Detector will be in Operation

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
will see anti-neutrinos coming from the C
French Ardennes. The experiment is now
measure fundamental neutrino propertie
particle and astro-particle physics.

Tohoku Univ. News

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 I 受賞・成果等

2011年1月 6日 15:23 I 受賞・成果等 , 研究成果

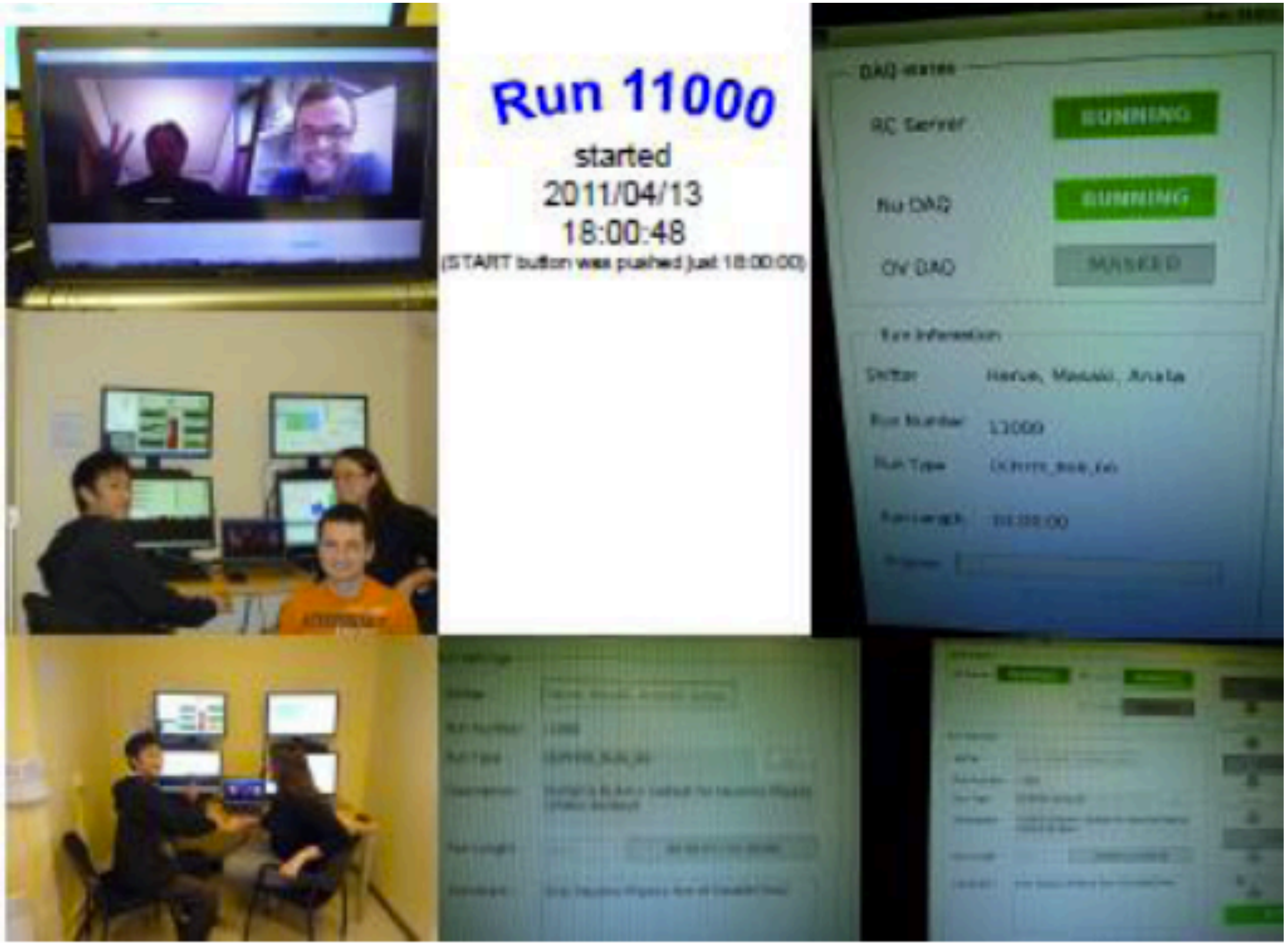
ダブルショー原子炉ニュートリノ振動実験開始

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．）

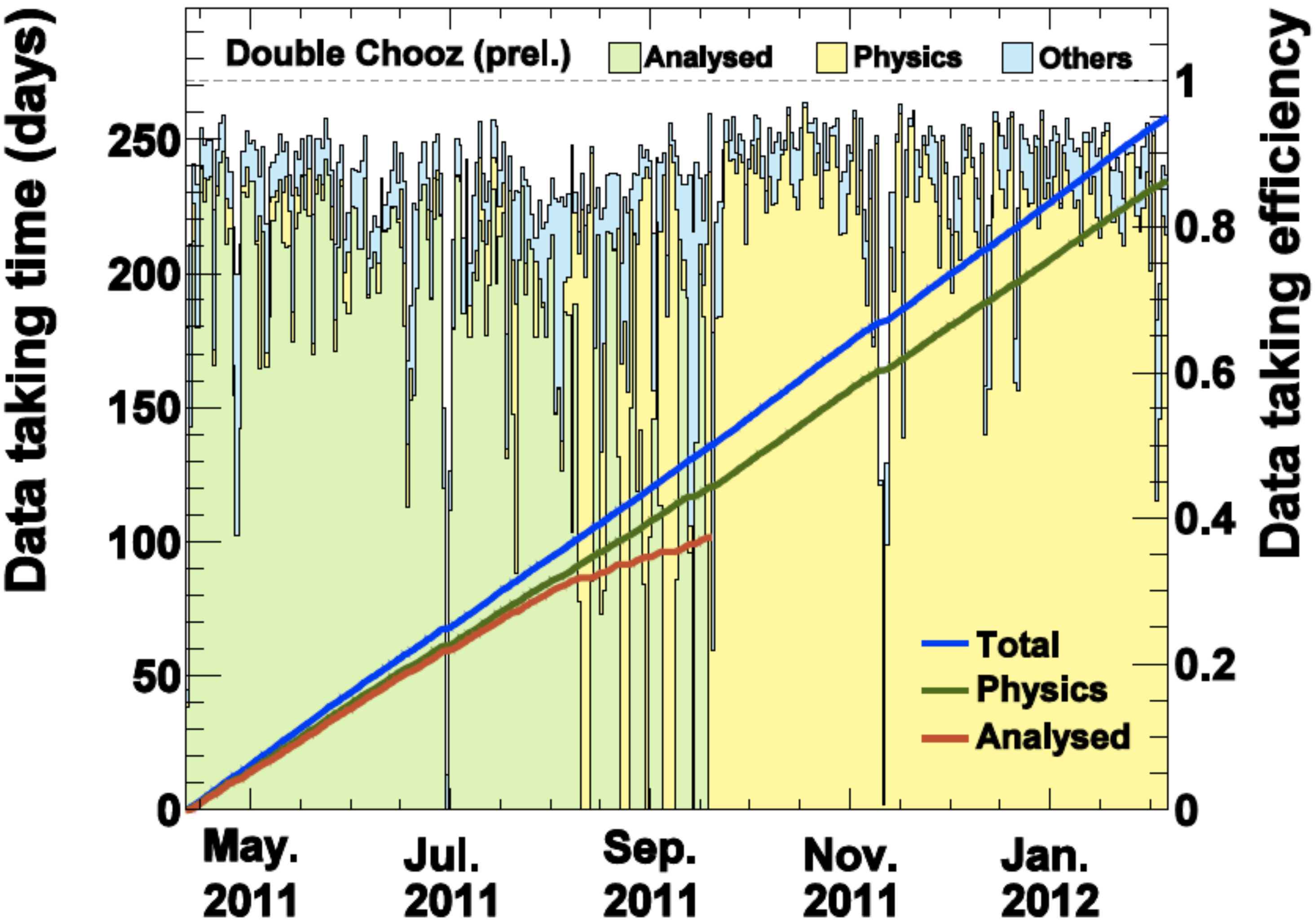
詳細

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．

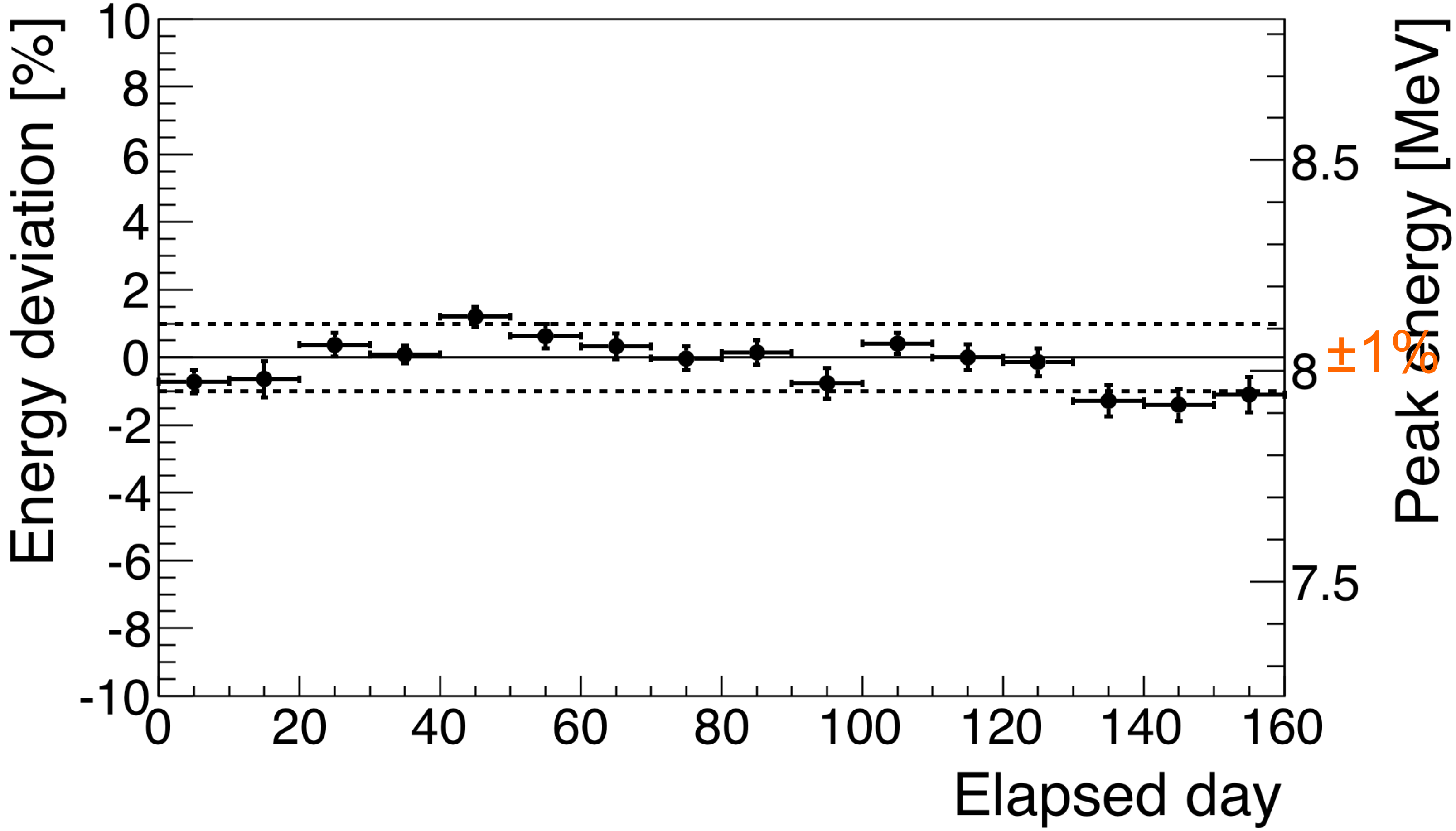
Pysics Run Start 2011/4/13



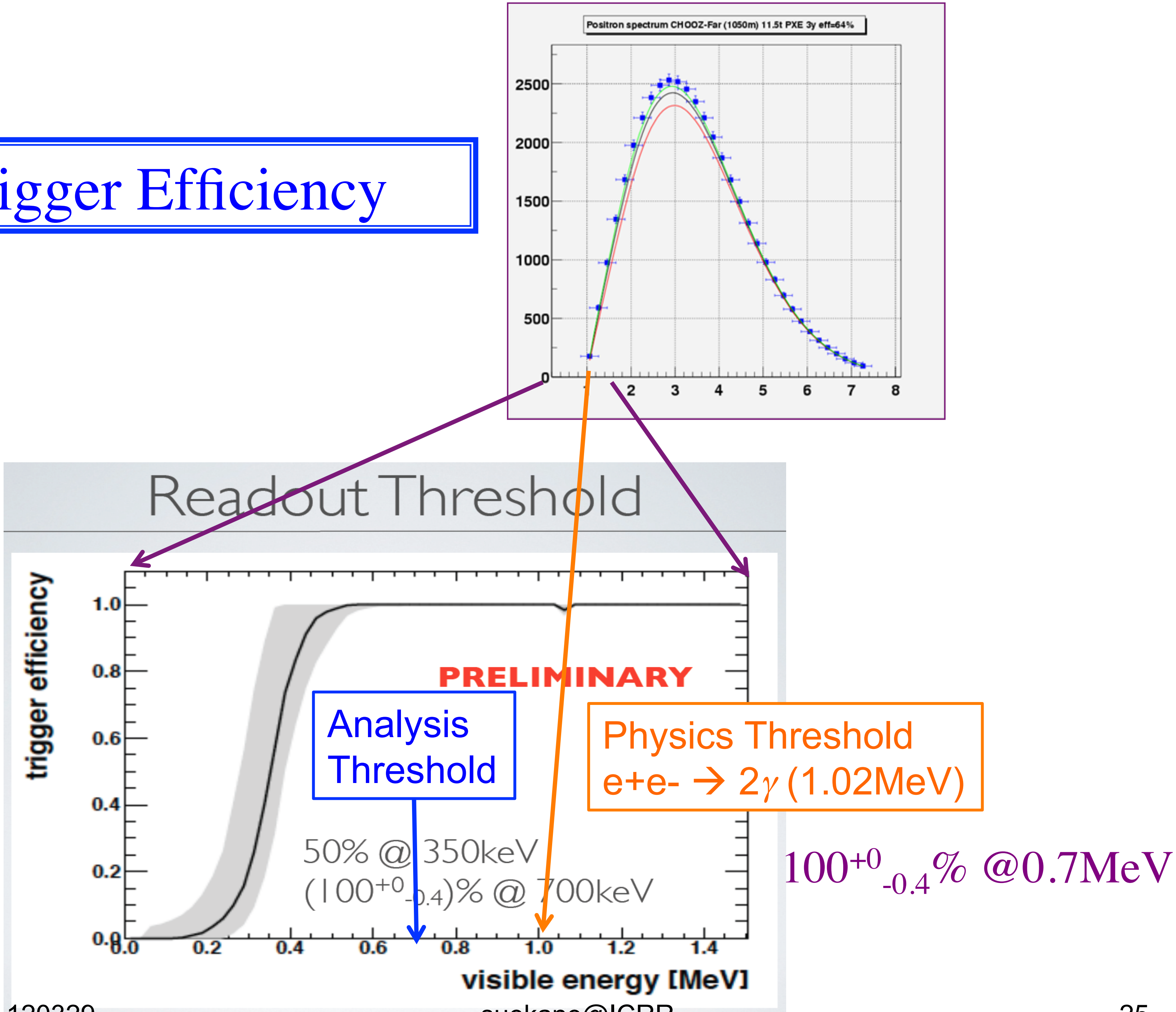
Data taking time and efficiency



Stability of Liquid scintillator

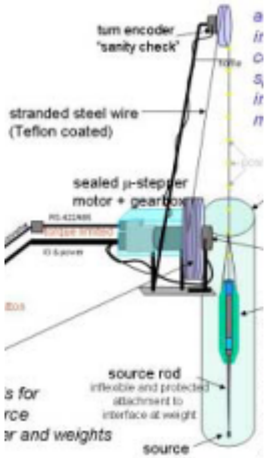


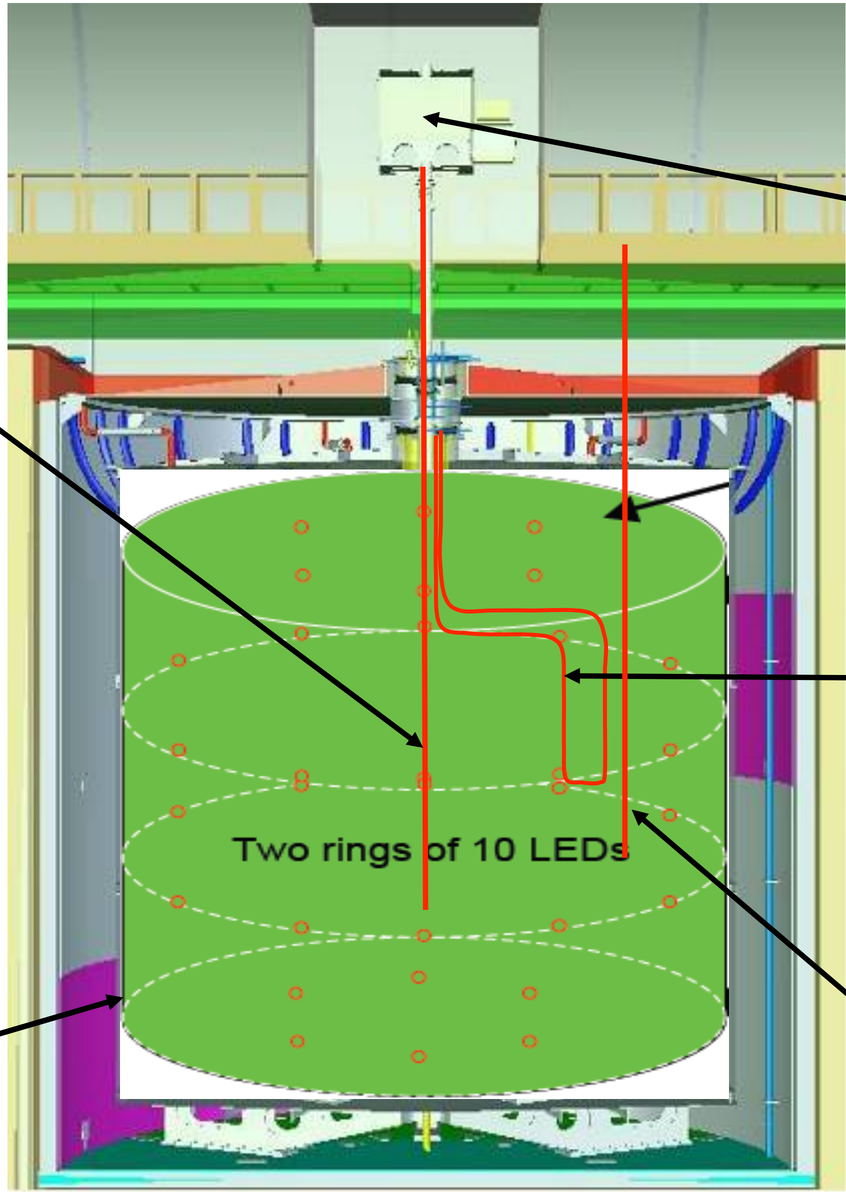
Trigger Efficiency



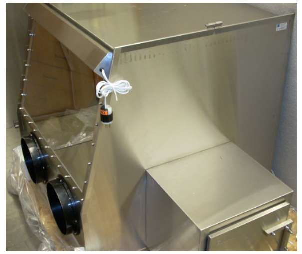
Calibration Systems

Fish-line



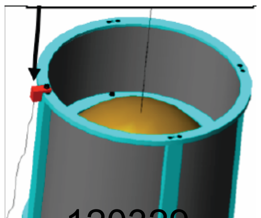


Glove Box



GC guide Tube

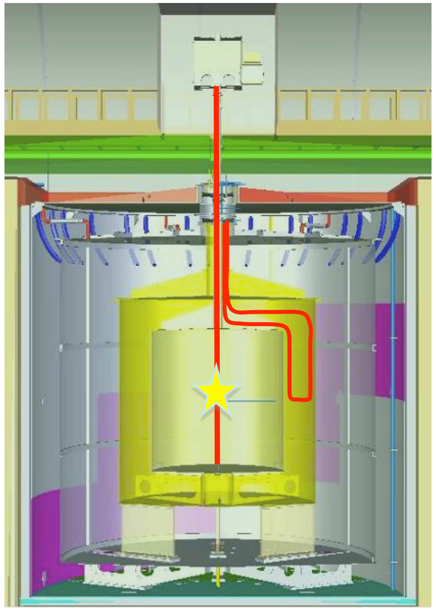
Embedded LED calibration system 385, 420, 470 nm



Buffer guide Tube

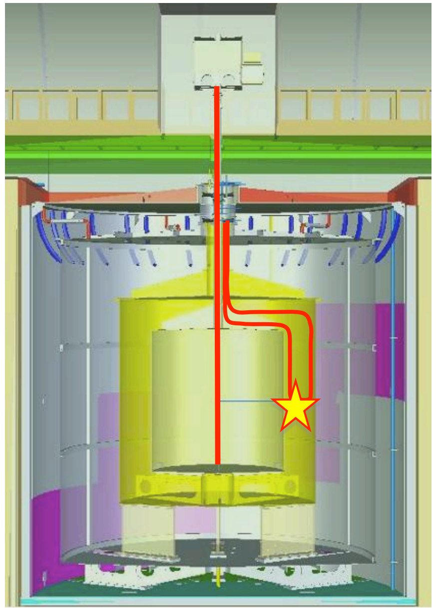
F. Ardellier, Ch. Veyssière, Th. Lasserre, D. Lhuillier, CEA-Saclay, Nov. 09th 2011

Energy calibration



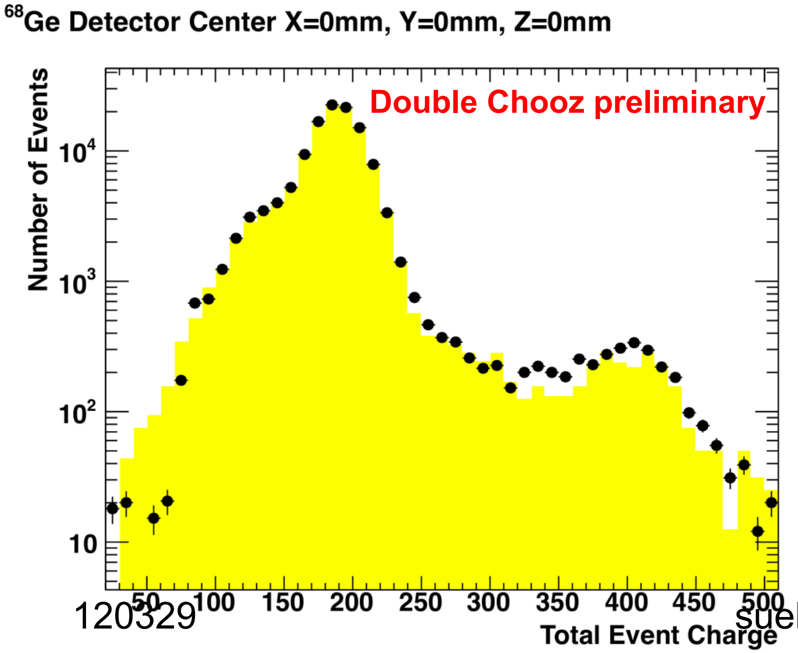
e.g.) ^{68}Ge positron source

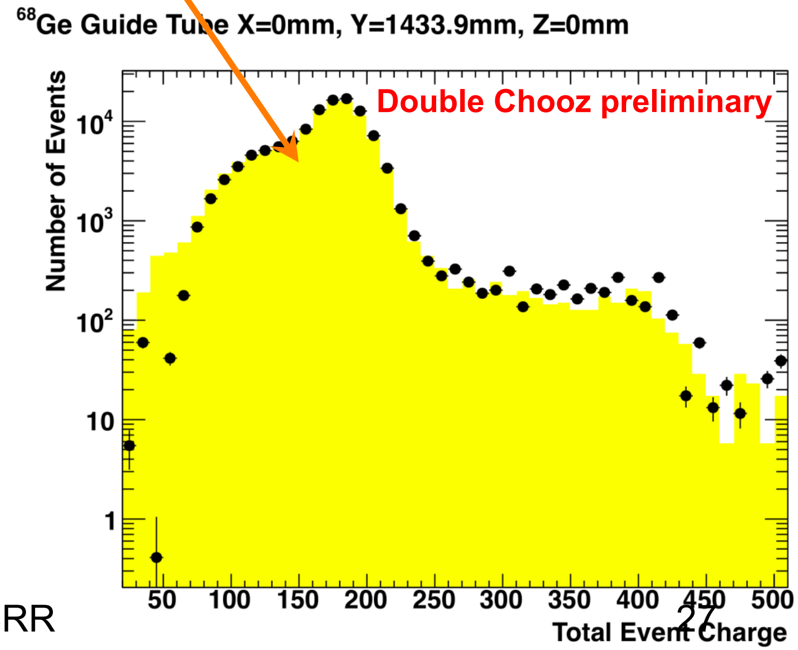
(e+e- annihilation1.02 MeV γs)



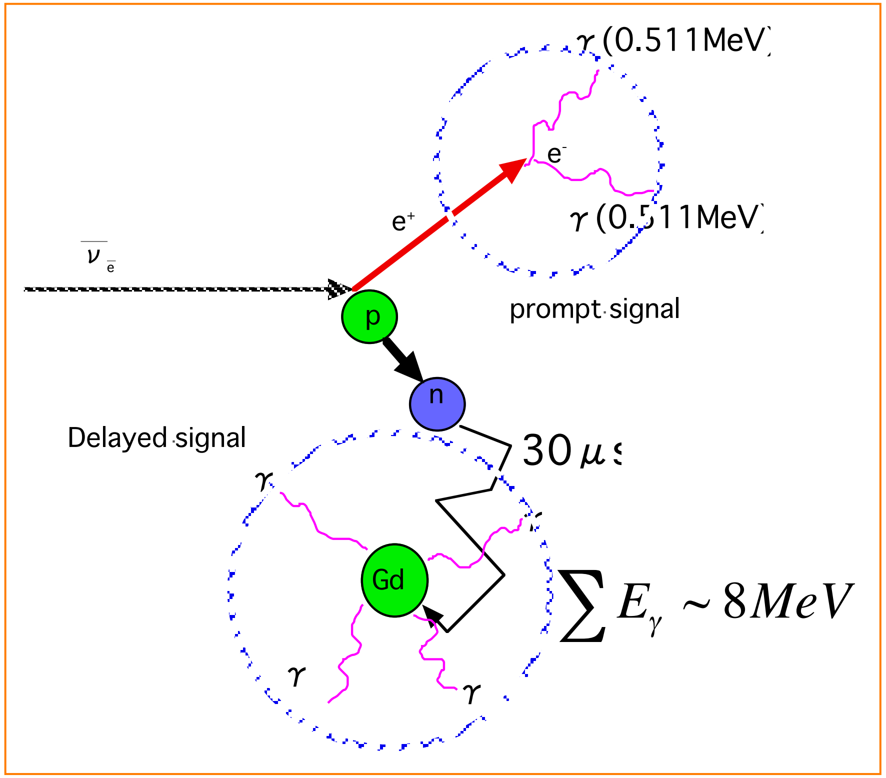
@ Detector Center

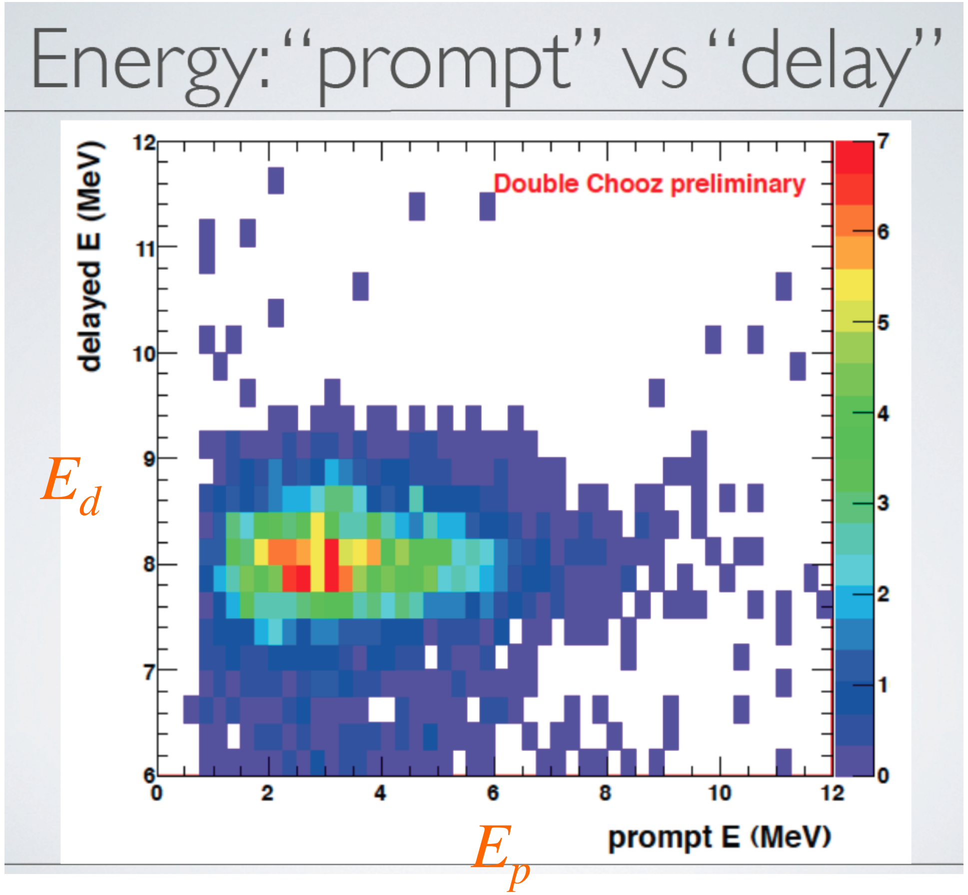
Guide-tube system in γ-catcher

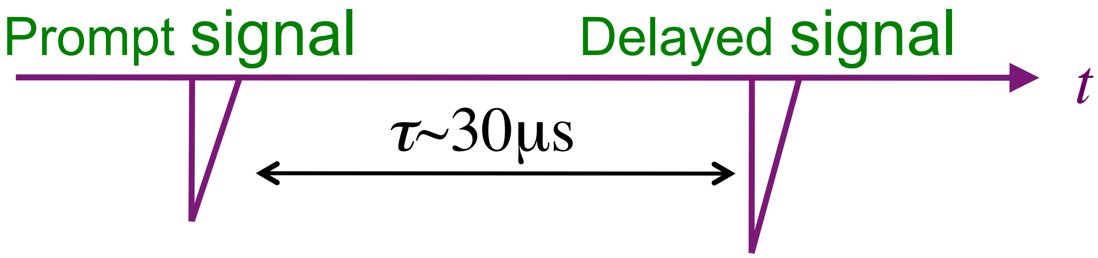




Neutrino Signal



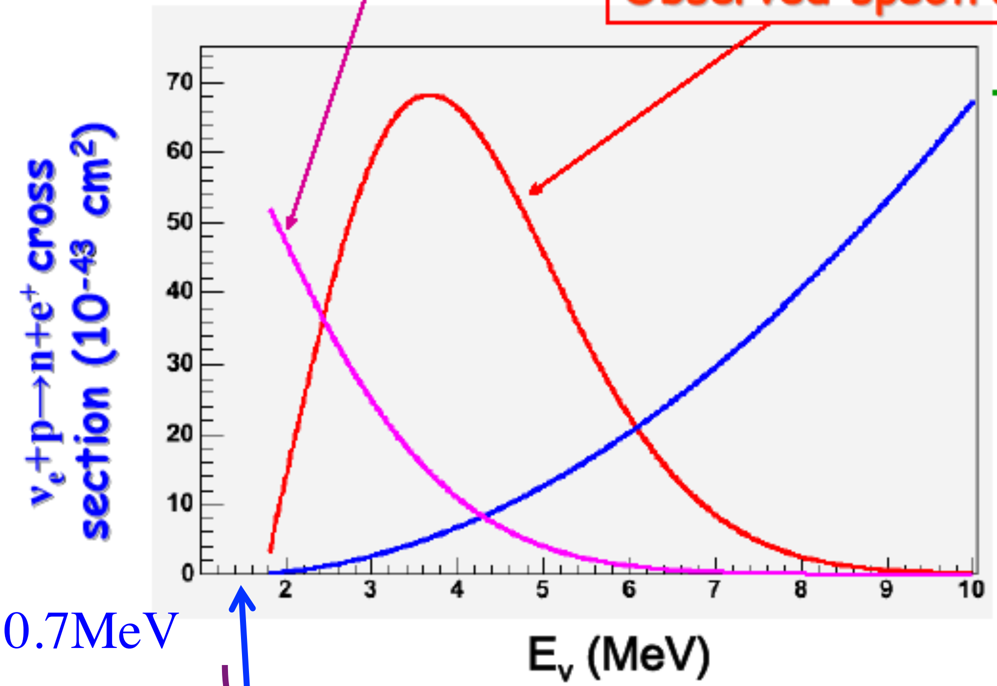




The $\bar{\nu}_e$ energy spectrum

Reactor ν_e spectrum (a.u.)

Observed spectrum (a.u.)



12MeV for rate analysis

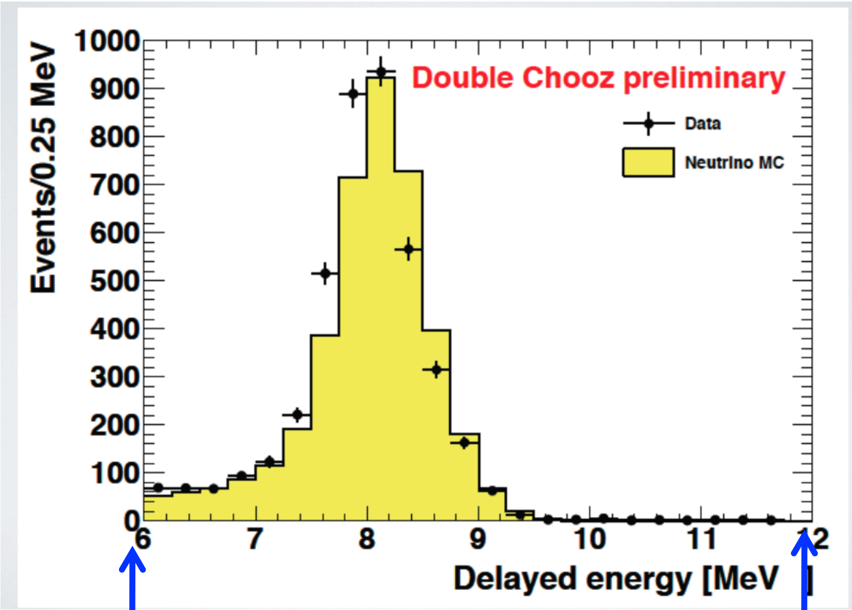
0.7MeV

E_p cut (ε=99.9±0.1%)

Physics threshold
e+e- → 2γ (1.02MeV)

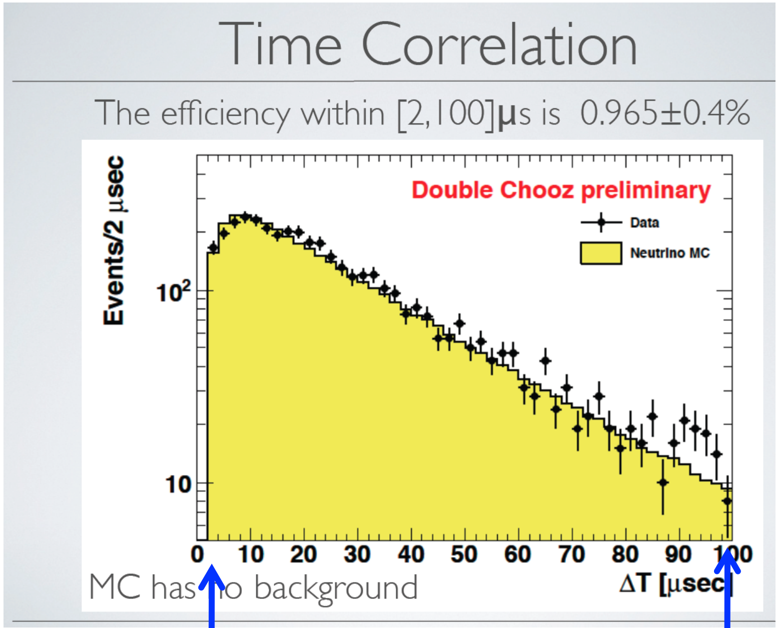
(Actual data will be shown at result page.)

E_{delay} cut



ε=94.5±0.6%

T_{Delay} - T_{Prompt} cut



ε=96.5±0.5%

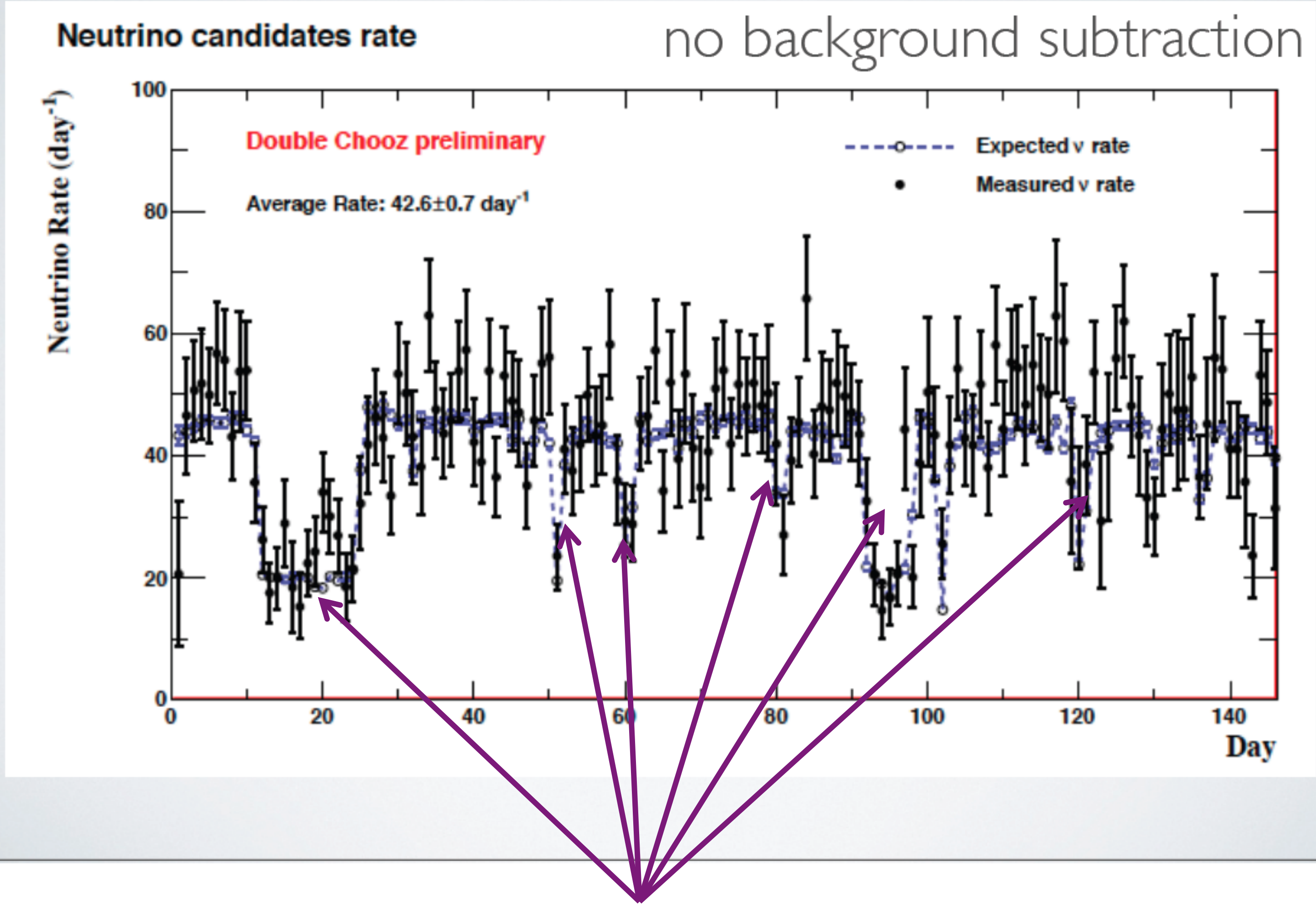
Difference (~1%) is taken into account in the error.

Event Selection Summary

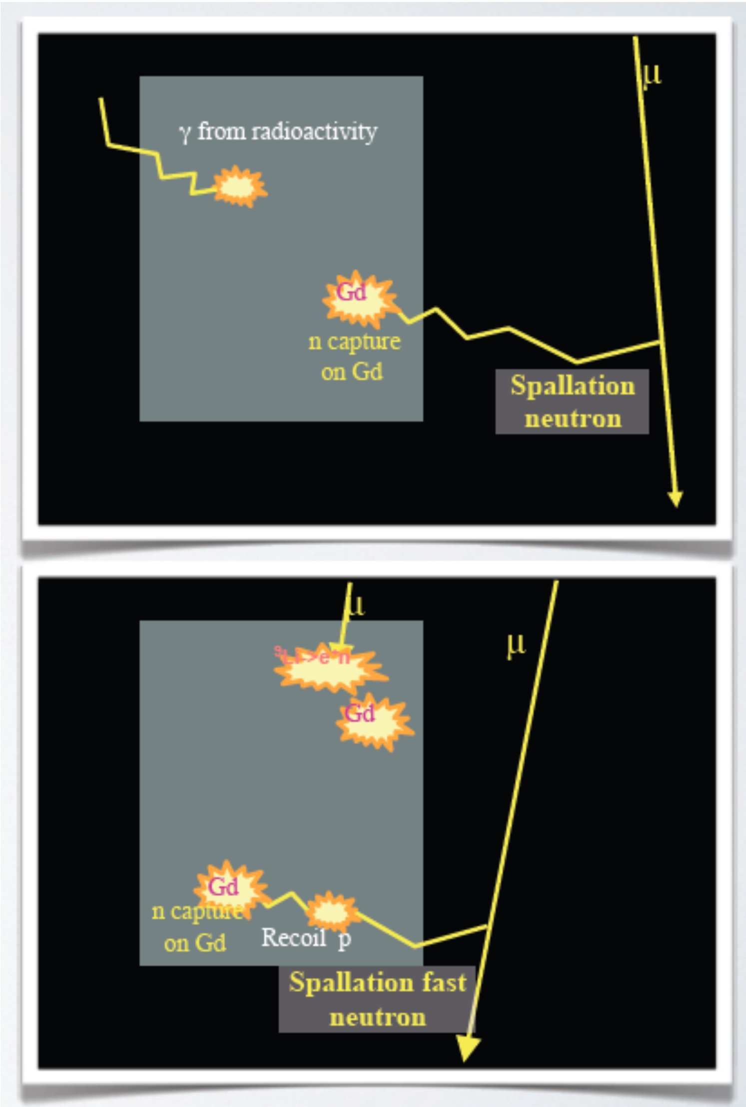
	Condition	Efficiency [Inefficiency]
Trigger efficiency	$0.7\text{MeV} < E$	100+0-0.4% [0+0.4-0.0%]
Neutrino Selection	$0.7\text{MeV} < E_p < 12\text{MeV}$	99.9±0.1% [0.1±0.1%]
	$6\text{MeV} < E_d < 12\text{MeV}$	94.5±0.6% [14.0±0.6%]
	$2\mu s < \Delta T_{\text{p-d}} < 100\mu s$	96.5±0.5% [3.5±0.5%]
After Muon Cut	$1\text{ms} < \Delta T_{\text{m-p}}$	95.5±0.0% [4.5±0.0%]
Multi Neutron rejection	<3 triggers @ $-100\mu s < \Delta T_p < 400\mu s$	99.5±0.0% [0.5±0.0%]
Light noise rejection	MaxQ/TotalQ signal time structure	100±0.0% [0.0±0.0%]
Gd Capture efficiency		86.0±0.5% [14.0±0.5%]
Total		74±1.0%

4121 events Remained

Candidate vs Time



Back grounds



Accidental BG

* e^+-like signal: γ-rays from radioactivity (^{208}Tl, etc.).

n-signal: n from muon induced spallation

ΔT accidentally <100us

Correlated BG

* Long Life (^{9}Li, ^{8}He)

β+n –decaying spallation isotopes

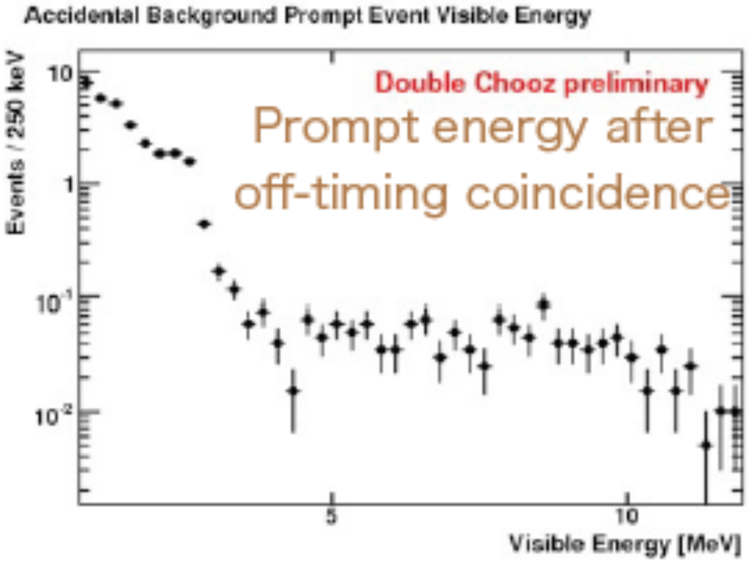
* Fast neutrons:

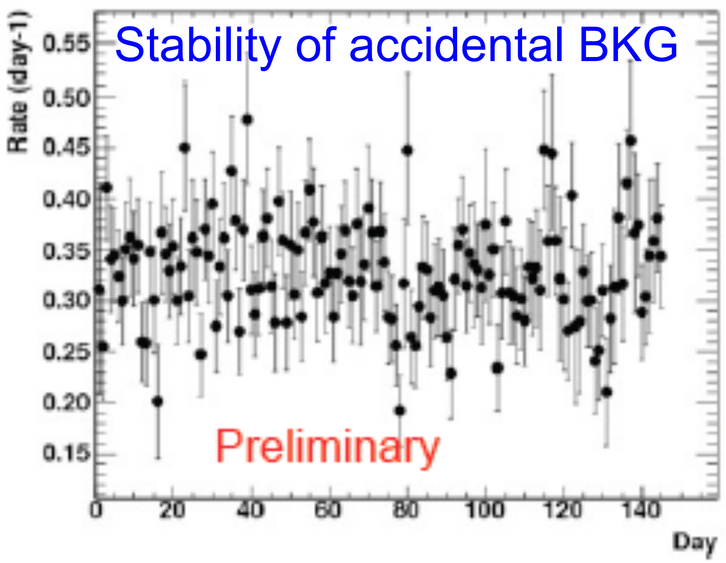
Recoil proton + neutron capture

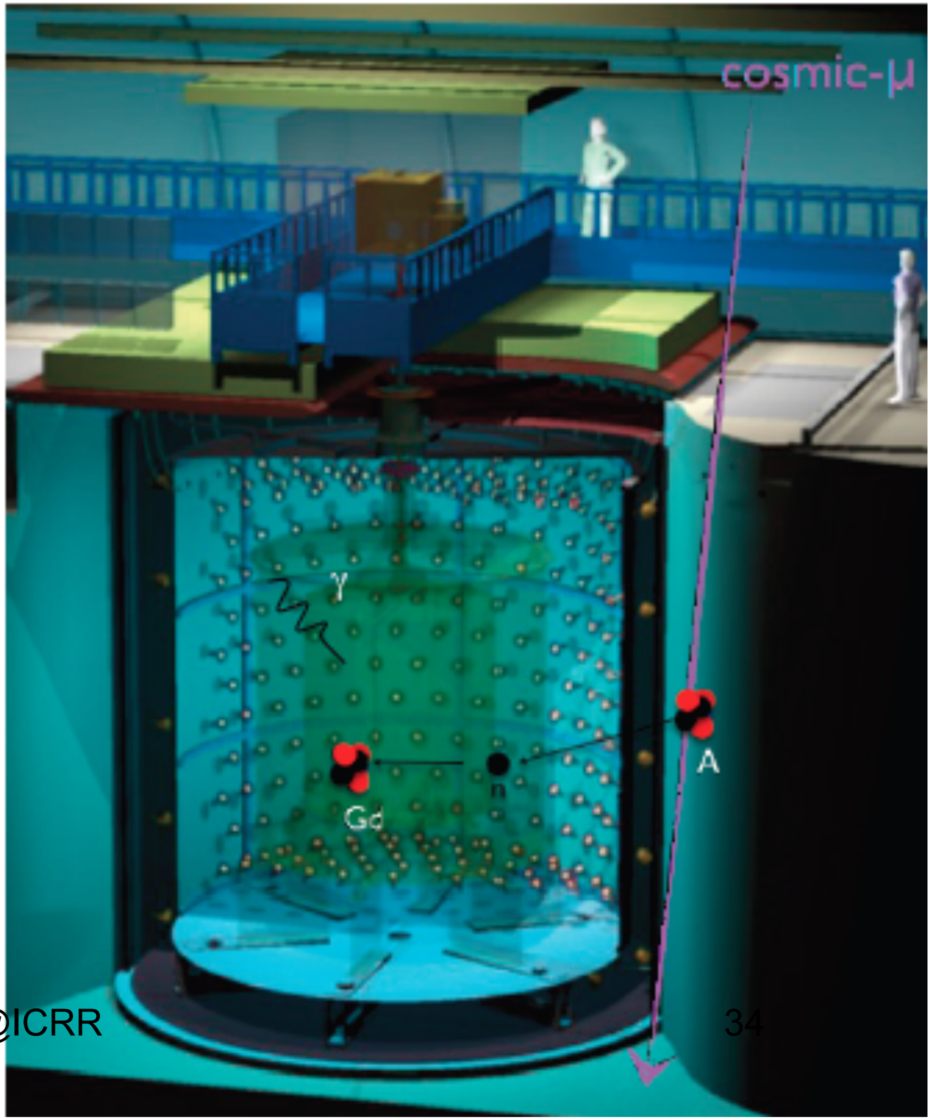
* Stopping muon + its decay

(Michel electron)

Accidental BG







Rate: 0.33 ±0.03 evt/day

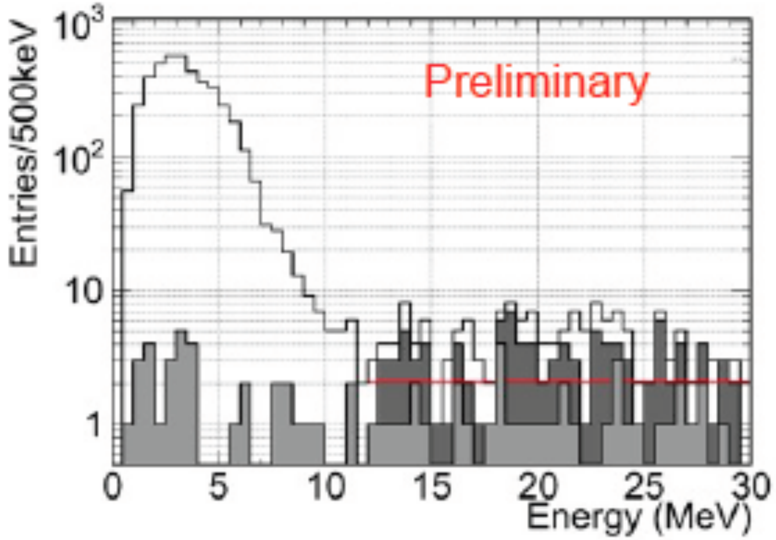
Correlated BG: fast neutron

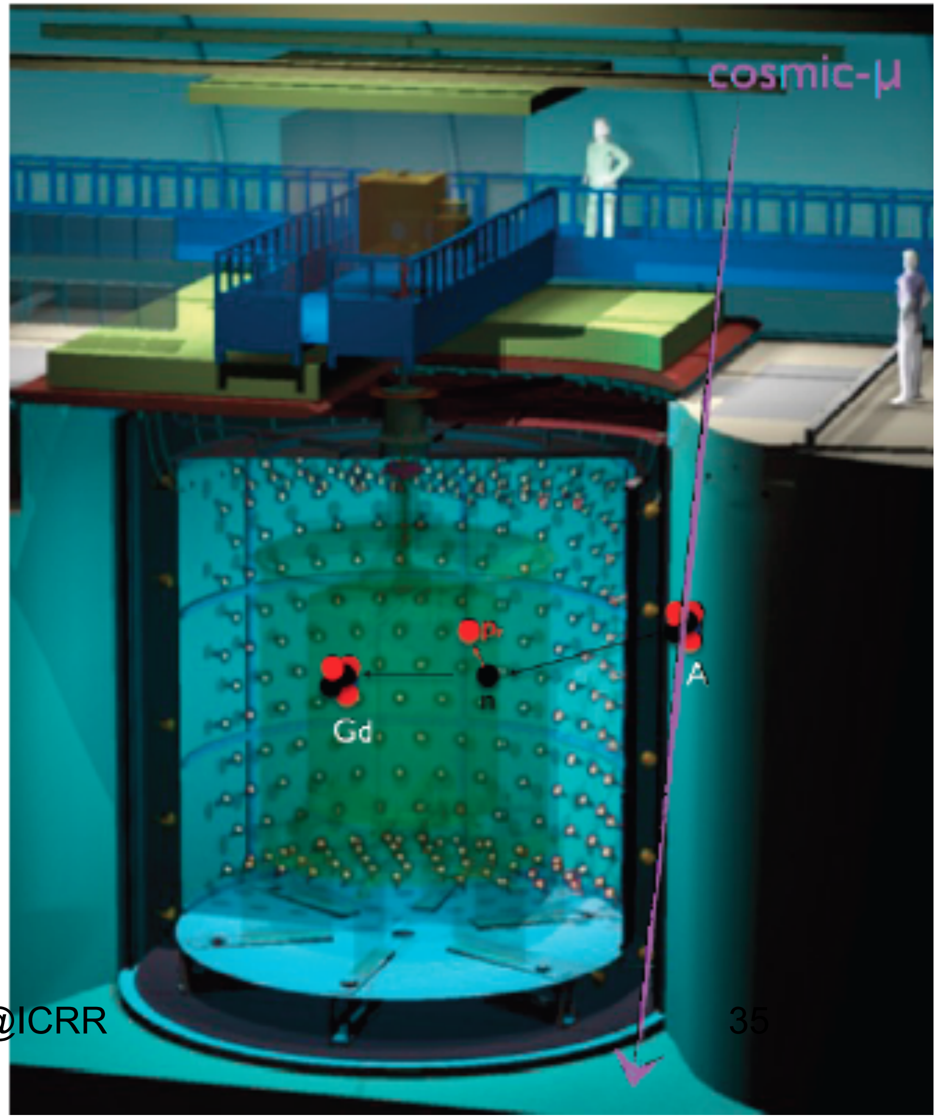
Prompt signal:

Recoil proton

Delayed signal

8MeV γ's from neutron capture on Gd





Number of BG events estimated from the spectrum at high energy

Rate: 0.8 ±0.4 events/day

Correlated BG: cosmogenic

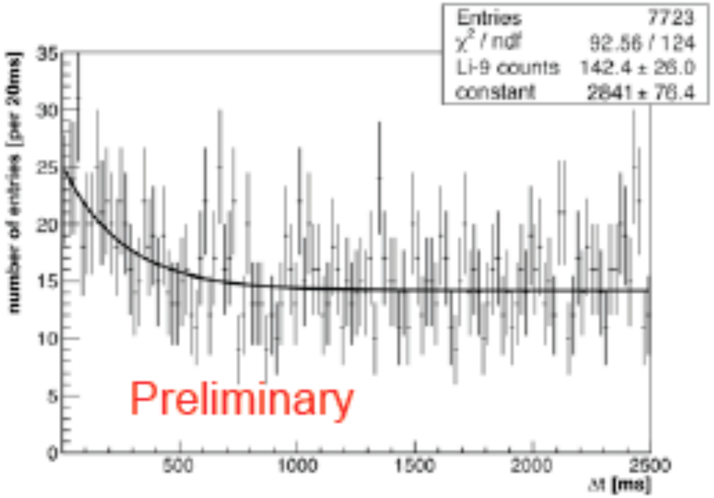
Cosmic-ray μ spallation products:

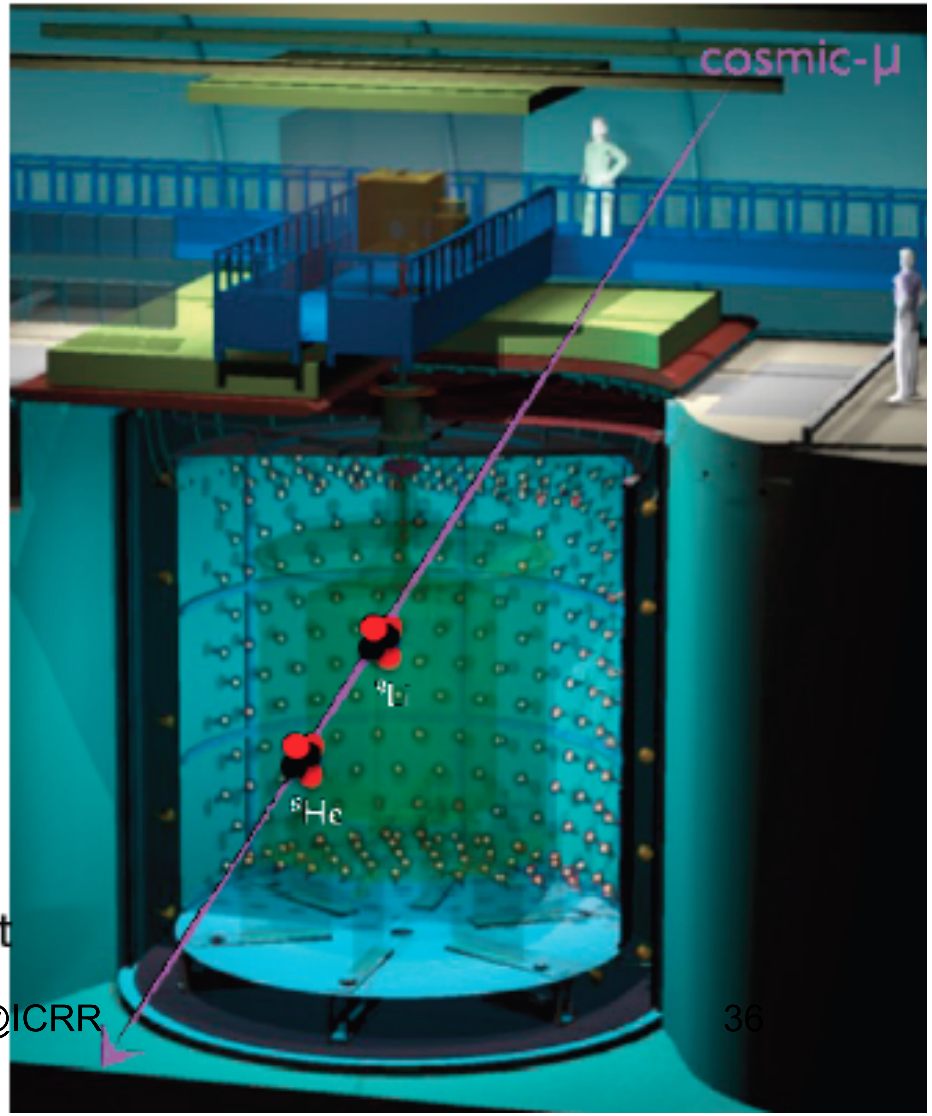
^{9}Li, ^{8}He

→ n+β decay with decay time of 200msec

completely mimic neutrino signal

$^{9}Li \rightarrow e^{-} + n + {}^{8}Be$ ($n + e^{-} < 11.9$MeV)



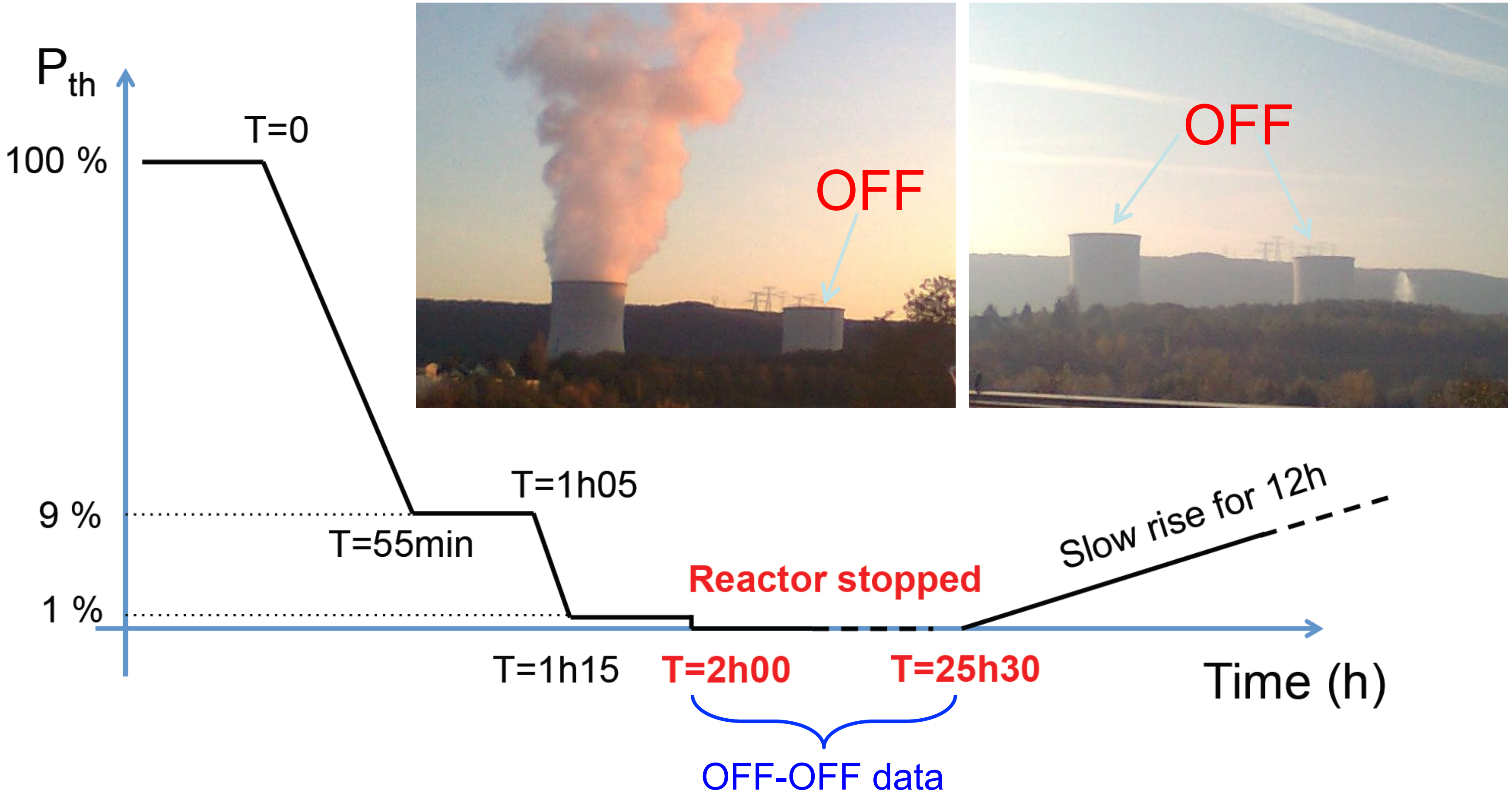


Number of BG events estimated from time correlation with showering μ

→Consistent with reactor OFF measurement

Rate: 2.3 ±1.2 events/day

Reactor Off-Off

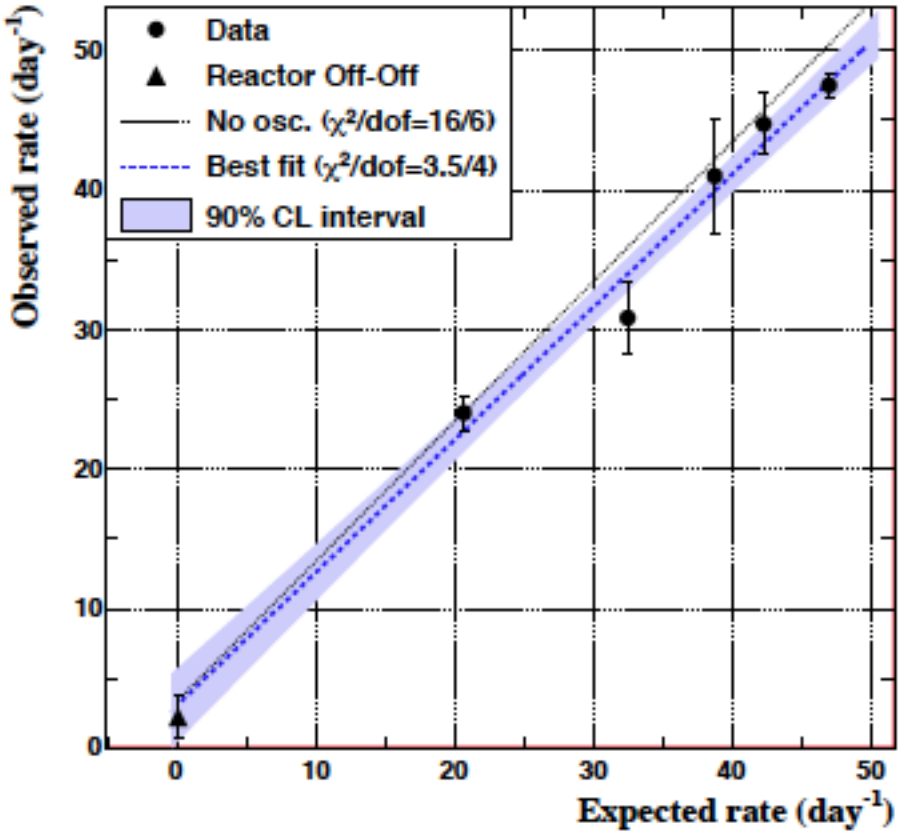


- Reactor 1 stopped for 2 months (refueling)
- Reactor 2 stopped for 1 day (maintenance)

→ In-situ background measurement (Unique capability of Double Chooz)

2 events within 0.7~12 MeV… (Agree with the estimation)

Observed vs. Expected



- Good linearity observed
- Number of expected background events is consistent with reactor OFF measurement (2 events in one-day)

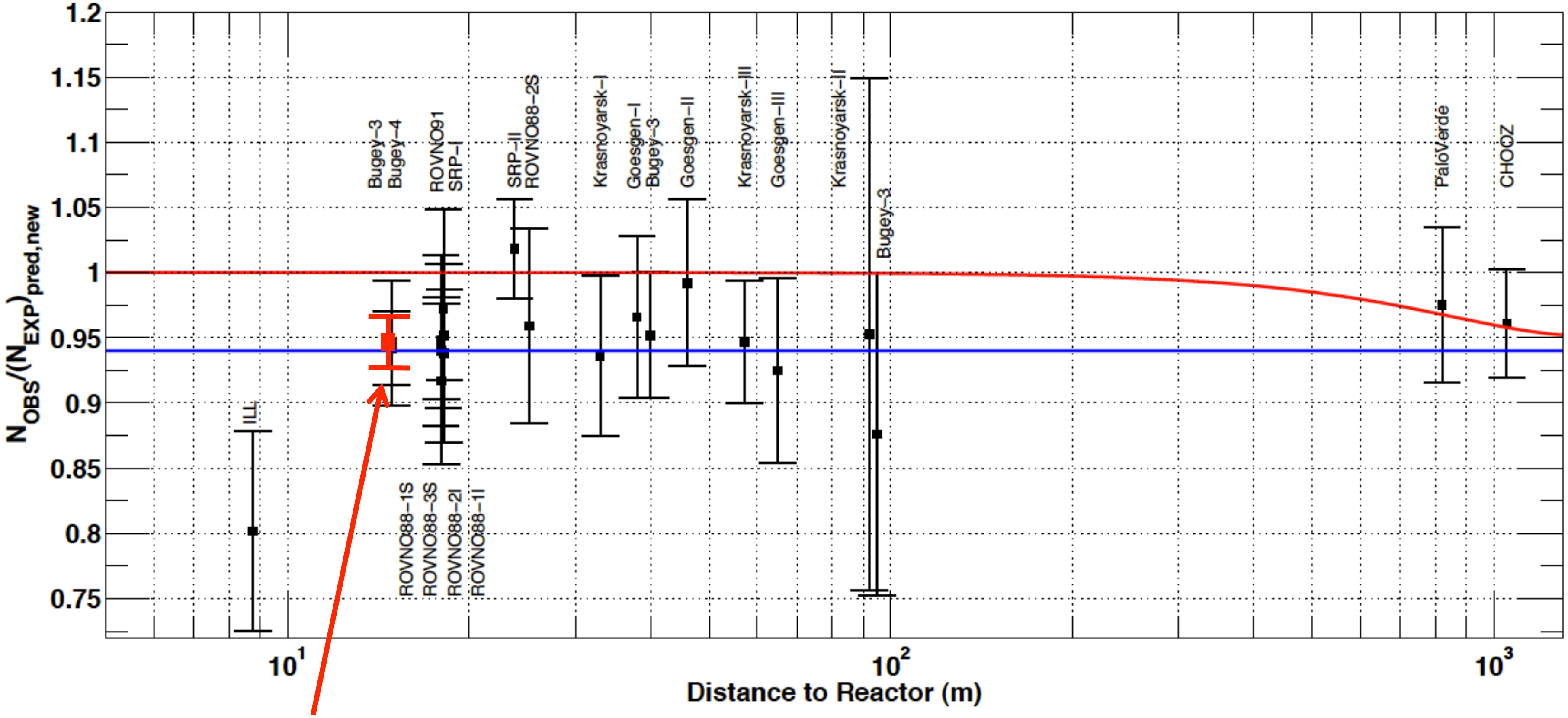
Background summary

Background	Rate/day	error(%)
Accidental	0.33	<0.1
Fast Neutron	0.83	0.9
^{9}Li	2.3	2.8
Total	3.46 (335events)	3.0

Observed Neutrino =4121-355=3766 events

Expected Neutrino Flux

Bugey4 (L~15m) is considered as "near detector".
(Water target & ^{3}He proportional counter. only neutron was tagged (=no prompt energy threshold))



Bugey4; Uncorrelated error with DC (1.7%)

Expected Neutrino Event rate Calculation

$$N_\nu^{\exp}(E,t) = \frac{N_p \varepsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

Average nergy release / fission

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

k=^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U

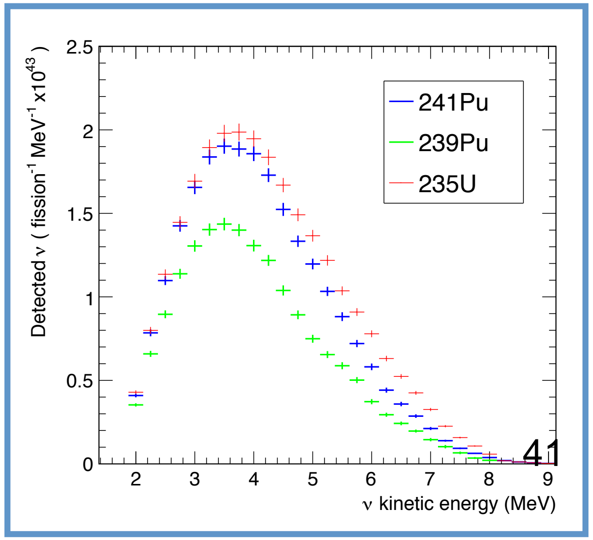
α_k: relative fission rate

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey}(t) \right) \langle \sigma_f \rangle_k$$

BGY4

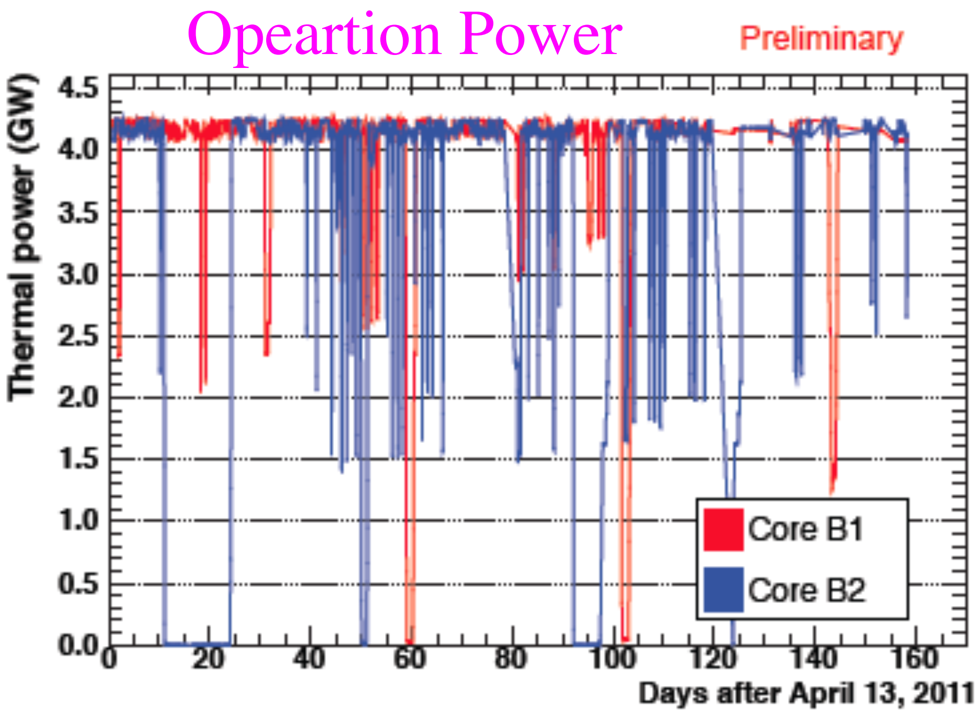
difference between BGY4 and DC

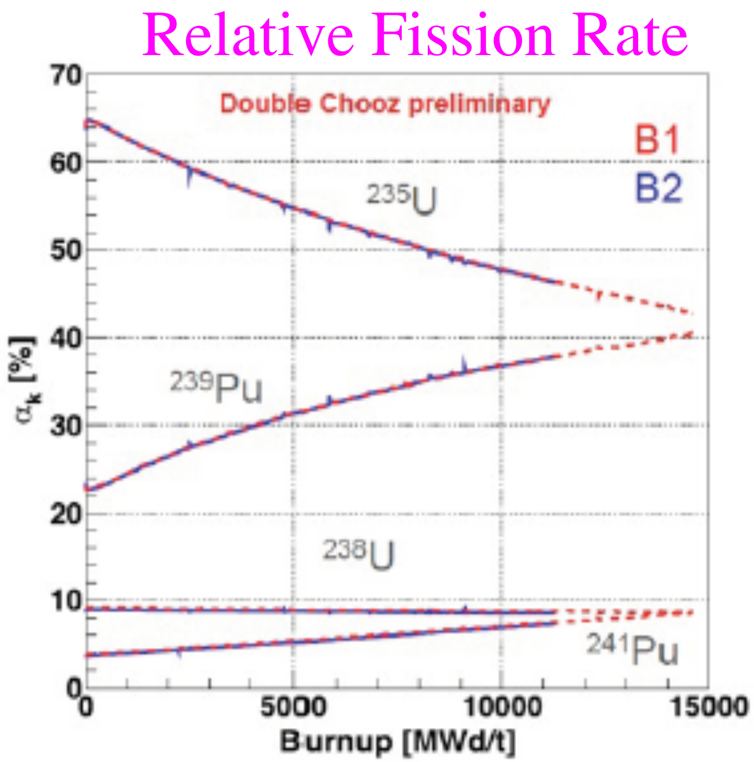
$$\langle \sigma_f \rangle_k = \int_0^\infty dE \cdot S_k(E) \cdot \sigma_{IBD}(E)$$



Reactor operation information

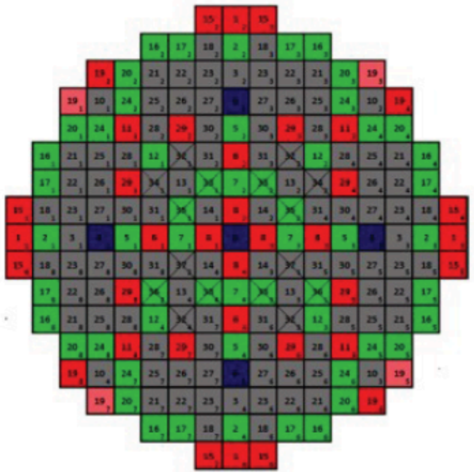
- Available from Electricité de France

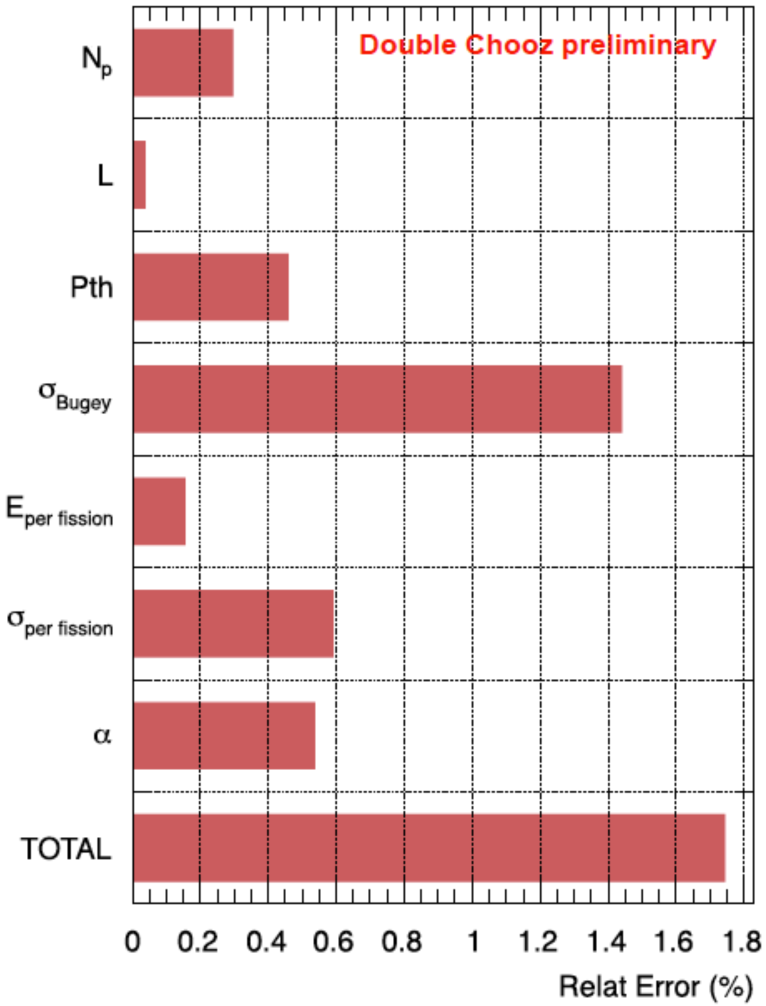




Expected Event Rate and Error

Very detailed simulation of all reactor cycle (MURE) and fuel evolution [reactor data input]





1.7% total error

Systematic error summary

Event Selection	Efficiency	error
Event selection	4121 events	1.0%
Background	355 events	3.0%
Spill in/out	+1.4%	0.4%
Expected Event rate	4344 events	1.7%
Energy response	-	1.7%
# of proton	-	0.3%
Total		4.0%

Observed 4121
Expected 4344

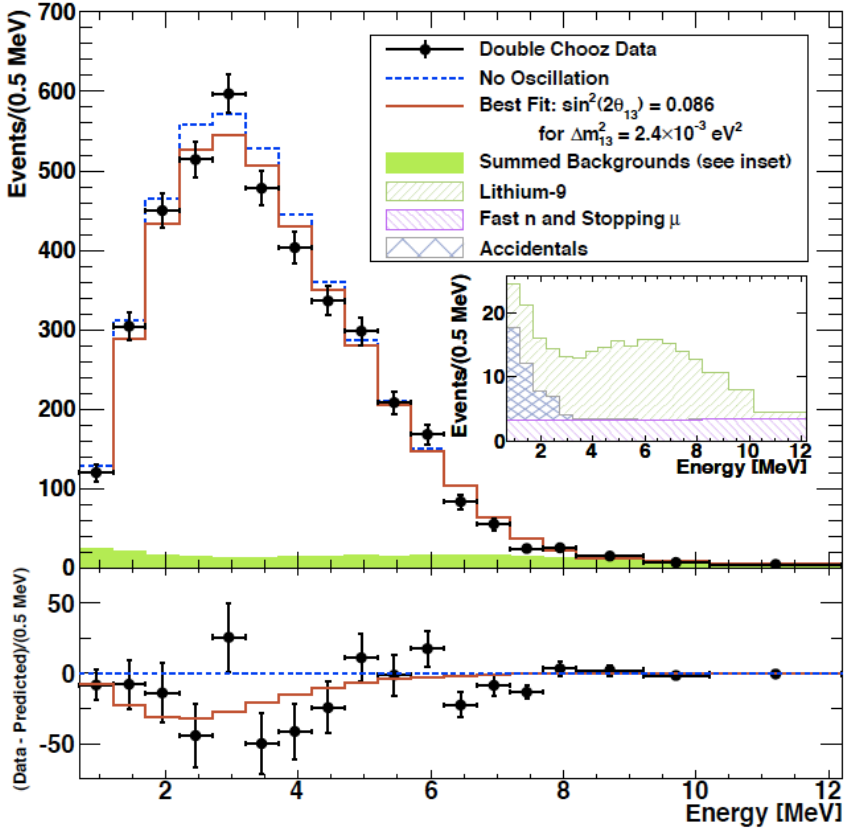
rate analysis

$$\frac{N_\nu^{obs}}{N_\nu^{\exp}} = \frac{N_{obs} - N_{BKG}}{N_{\exp} - N_{BKG}} = \frac{4121-335}{4344-335} \pm \frac{1}{\sqrt{4121}} \pm \sqrt{0.027^2 + 0.03^2}$$

$$= 0.944 \pm 0.016 \pm 0.040$$

$$\sin^2 2\theta_{13} = 0.104 \pm 0.030(stat.) \pm 0.076(syst.)$$

Spectrum analysis



Best fit: **$\sin^2 2\theta_{13}$ = 0.086±0.041(stat.)±0.030(syst.)**

χ^2/DOF = 23.7/17 (best fit); 26.6/18 ($\sin^2 2\theta_{13}$=0)

$\sin^2 2\theta_{13}$=0 excluded at 94.6%C.L.

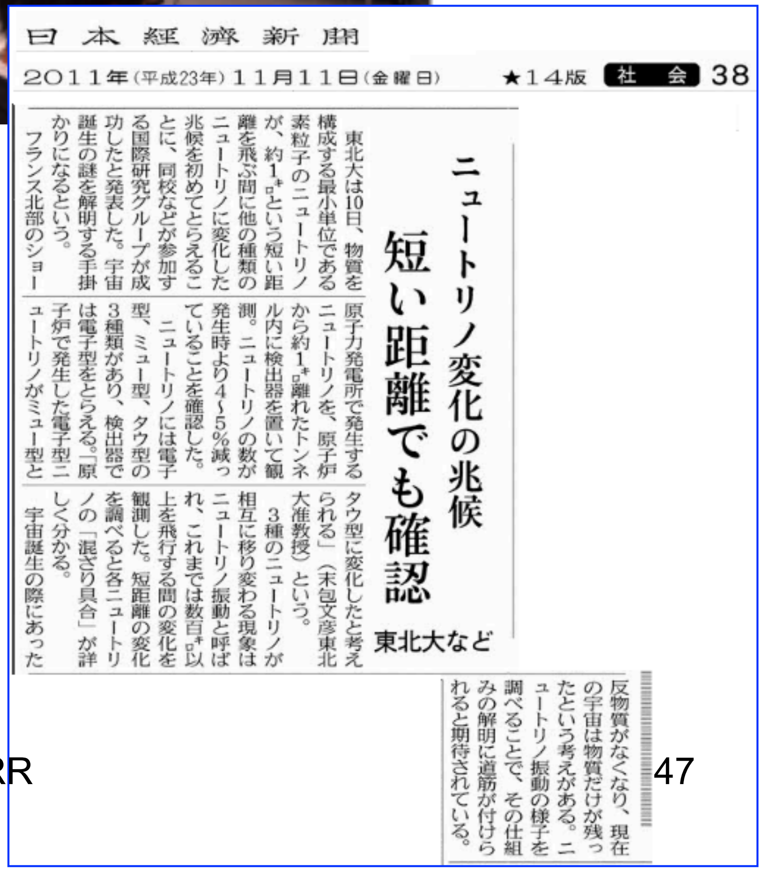
9/Nov./2011 1st result was shown @ LowNu conference Korea

Indication for the disappearance of reactor $\bar{\nu}_e$ in the Double Chooz experiment

Y. Abe,[28] C. Aberle,[21] T. Akiri,[4,15] J.C. dos Anjos,[5] F. Ardellier,[15] A.F. Barbosa,[5] A. Baxter,[26] M. Bergevin,[9] A. Bernstein,[16] T.J.C. Bezerra,[30] L. Bezrukhov,[14] E. Blucher,[6] M. Bongrand,[15,30] N.S. Bowden,[16] C. Buck,[21] J. Busenitz,[2] A. Cabrera,[4] E. Caden,[10] L. Camilleri,[8] R. Carr,[8] M. Cerrada,[7] P.-J. Chang,[17] P. Chimenti,[34] T. Classen,[9,16] A.P. Collin,[15] E. Conover,[6] J.M. Conrad,[20] S. Cormon,[25] J.I. Crespo-Anadón,[7] M. Cribier,[15,4] K. Crum,[6] A. Cucoanes,[25,15] M.V. D'Agostino,[3] E. Damon,[10] J.V. Dawson,[4,36] S. Dazeley,[16] M. Dierckxsens,[6] D. Dietrich,[33] Z. Djurcic,[3] M. Dracos,[24] V. Durand,[15,4] Y. Efremenko,[27] M. Elnimr,[25] Y. Endo,[29] A. Etenko,[19] E. Falk,[26] M. Fallot,[25] M. Fechner,[15] F. von Feilitzsch,[31] J. Felde,[9] S.M. Fernandes,[26] D. Franco,[4] A.J. Franke,[8] M. Franke,[31] H. Furuta,[30] R. Gama,[5] I. Gil-Botella,[7] L. Giot,[25] M. Göger-Neff,[31] L.F.G. Gonzalez,[35] M.C. Goodman,[3] J.TM. Goon,[2] D. Greiner,[33] B. Guillon,[25] N. Haag,[31] C. Hagner,[11] T. Hara,[18] F.X. Hartmann,[21] J. Hartnell,[26] T. Haruna,[29] J. Haser,[21] A. Hatzikoutelis,[27] T. Hayakawa,[22,15] M. Hofmann,[31] G.A. Horton-Smith,[17] M. Ishitsuka,[28] J. Jochum,[33] C. Jollet,[24] C.L. Jones,[20] F. Kaether,[21] L. Kalousis,[24] Y. Kamyshkov,[27] D.M. Kaplan,[13] T. Kawasaki,[22] G. Keefer,[16] E. Kemp,[35] H. de Kerret,[4,36] Y. Kibe,[28] T. Konno,[28] D. Kryn,[4] M. Kuze,[28] T. Lachenmaier,[33] C.E. Lane,[10] C. Langbrandtner,[21] T. Lasserre,[15,4] A. Letourneau,[15] D. Lhuillier,[15] H.P. Lima Jr,[5] M. Lindner,[21] Y. Liu,[2] J.M. López-Castanõ,[7] J.M. LoSecco,[23] B.K. Lubsandorzhiev,[14] S. Lucht,[1] D. McKee,[2,17] J. Maeda,[29] C.N. Maesano,[9] C. Mariani,[8] J. Maricic,[10] J. Martino,[25] T. Matsubara,[29] G. Mention,[15] A. Meregaglia,[24] T. Miletic,[10] R. Milincic,[10] A. Milzstajn,[15,*] H. Miyata,[22] D. Motta,[15,*] Th.A. Mueller,[15,30] Y. Nagasaka,[12] K. Nakajima,[22] P. Novella,[7] M. Obolensky,[4] L. Oberauer,[31] A. Onillon,[25] A. Osborn,[27] I. Ostrovskiy,[2] C. Palomares,[7] S.J.M. Peeters,[26] I.M. Pepe,[5] S. Perasso,[10] P. Perrin,[15] P. Pfahler,[31] A. Porta,[25] W. Potzel,[31] R. Queval,[15] J. Reichenbacher,[2] B. Reinhold,[21] A. Remoto,[25,4] D. Reyna,[3] M. Röhling,[33] S. Roth,[1] H.A. Rubin,[13] Y. Sakamoto,[32] R. Santorelli,[7] F. Sato,[29] S. Schönert,[31] S. Schoppmann,[1] U. Schwan,[21] T. Schwetz,[21] M.H. Shaevitz,[8] D. Shrestha,[17] J-L. Sida,[15] V. Sinev,[14,15] M. Skorokhvatov,[19] E. Smith,[10] J. Spitz,[20] A. Stahl,[1] I. Stancu,[2] M. Strait,[6] A. Stüken,[1] F. Suekane,[30] S. Sukhotin,[19] T. Sumiyoshi,[29] Y. Sun,[2] Z. Sun,[15] R. Svoboda,[9] H. Tabata,[30] N. Tamura,[22] K. Terao,[20] A. Tonazzo,[4] M. Toups,[8] H.H. Trinh Thi,[31] C. Veyssiere,[15] S. Wagner,[21] H. Watanabe,[21] B. White,[27] C. Wiebusch,[1] L. Winslow,[20] M. Worcester,[6] M. Wurm,[11] E. Yanovitch,[14] F. Yermia,[25] K. Zbiri,[25,10] and V. Zimmer[31]
(Double Chooz Collaboration)

Paper is accepted by PRL

Press conference and news on TVs and news papers



日本経済新聞

2011年（平成23年）11月11日（金曜日）　★14版　社会　38

ニュートリノ変化の兆候
短い距離でも確認
東北大など

東北大は10日、物質を構成する最小単位である素粒子のニュートリノが、約1キロという短い距離を飛ぶ間に他の種類のニュートリノに変化した兆候を初めてとらえることに、同校などが参加する国際研究グループが成功したと発表した。宇宙誕生の謎を解明する手掛かりになるという。

フランス北部のショー原子力発電所で発生するニュートリノを、原子炉から約1キロ離れたトンネル内に検出器を置いて観測。ニュートリノの数が発生時より4～5%減っていることを確認した。

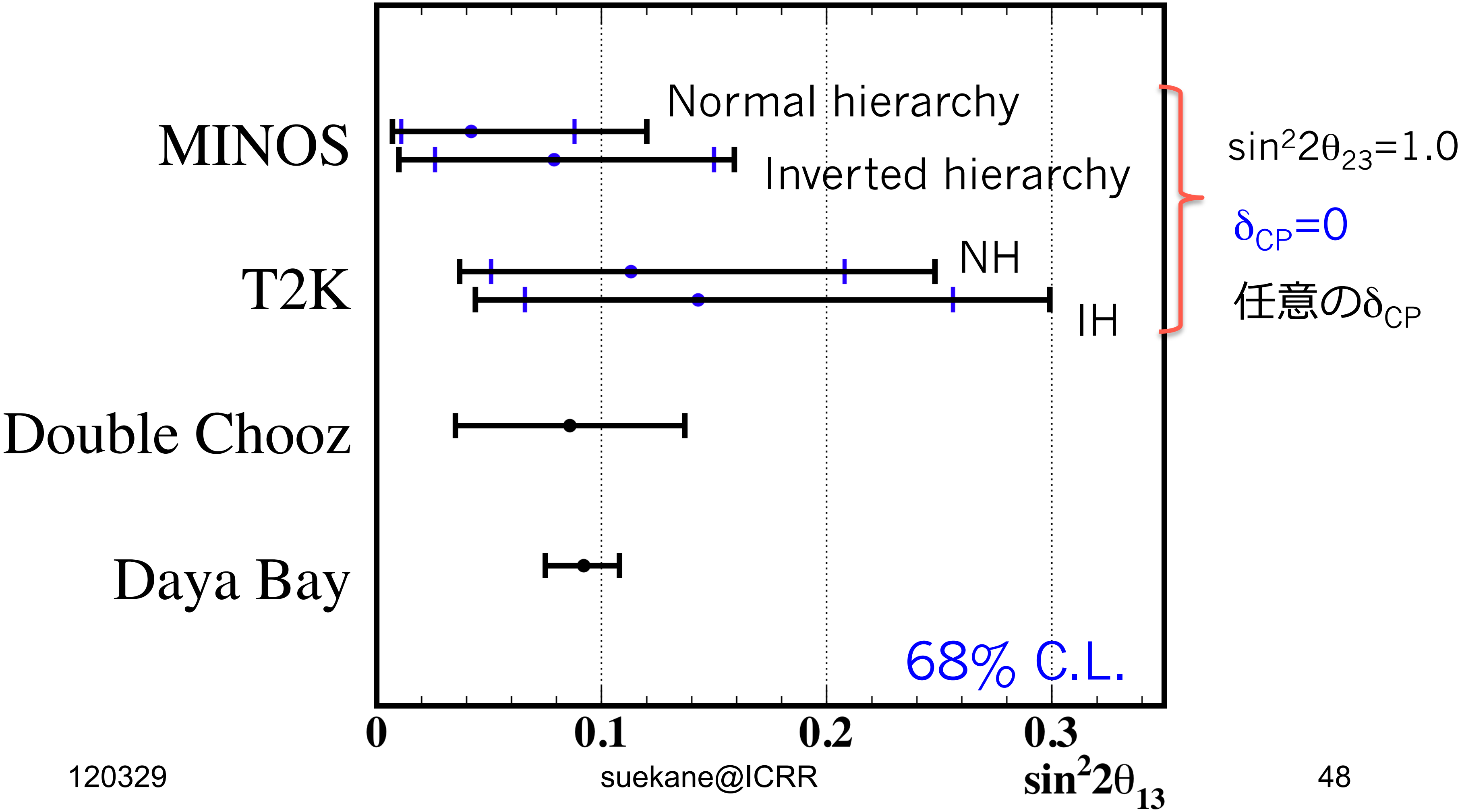
ニュートリノには電子型、ミュー型、タウ型の3種類があり、検出器では電子型をとらえる。「原子炉で発生した電子型ニュートリノがミュー型とタウ型に変化したと考えられる」（末包文彦東北大准教授）という。

3種のニュートリノが相互に移り変わる現象はニュートリノ振動と呼ばれ、これまでは数百キロ以上を飛行する間の変化を観測した。短距離の変化を調べると各ニュートリノの「混ざり具合」が詳しく分かる。

宇宙誕生の際にあった反物質がなくなり、現在の宇宙は物質だけが残ったという考えがある。ニュートリノ振動の様子を調べることで、その仕組みの解明に道筋が付けられると期待されている。

Comparison with other θ_{13} measurements

MINOS: PRL 107, 181802 (2011)
T2K: PRL 107, 041801 (2011)
Double Chooz: arXiv:1112.6353 [hep-ex]
DayaBay: rXiv:1203.1669 [hep-ex]



1st View of Reactor-Accelerator complementarity

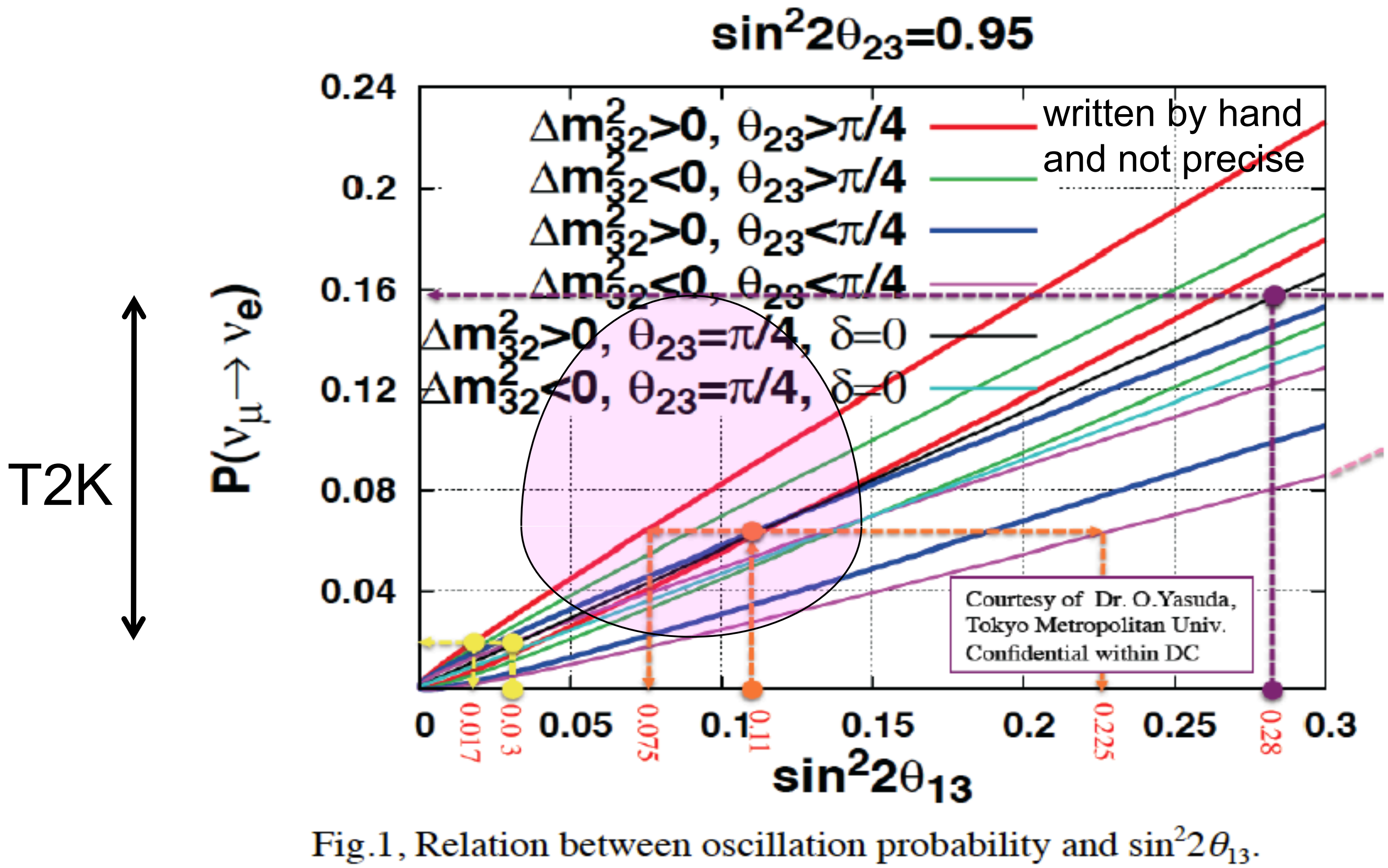
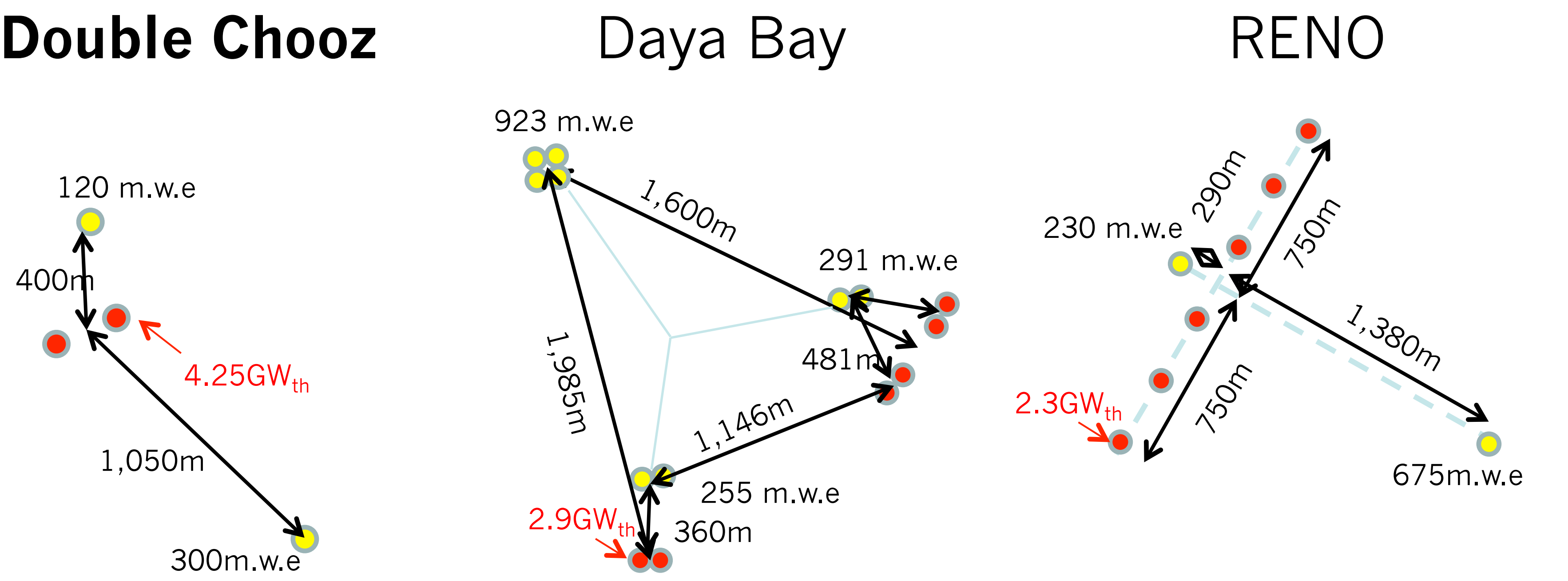


Fig.1, Relation between oscillation probability and $\sin^2 2\theta_{13}$.

↔ Double Chooz

(↔ Daya Bay)

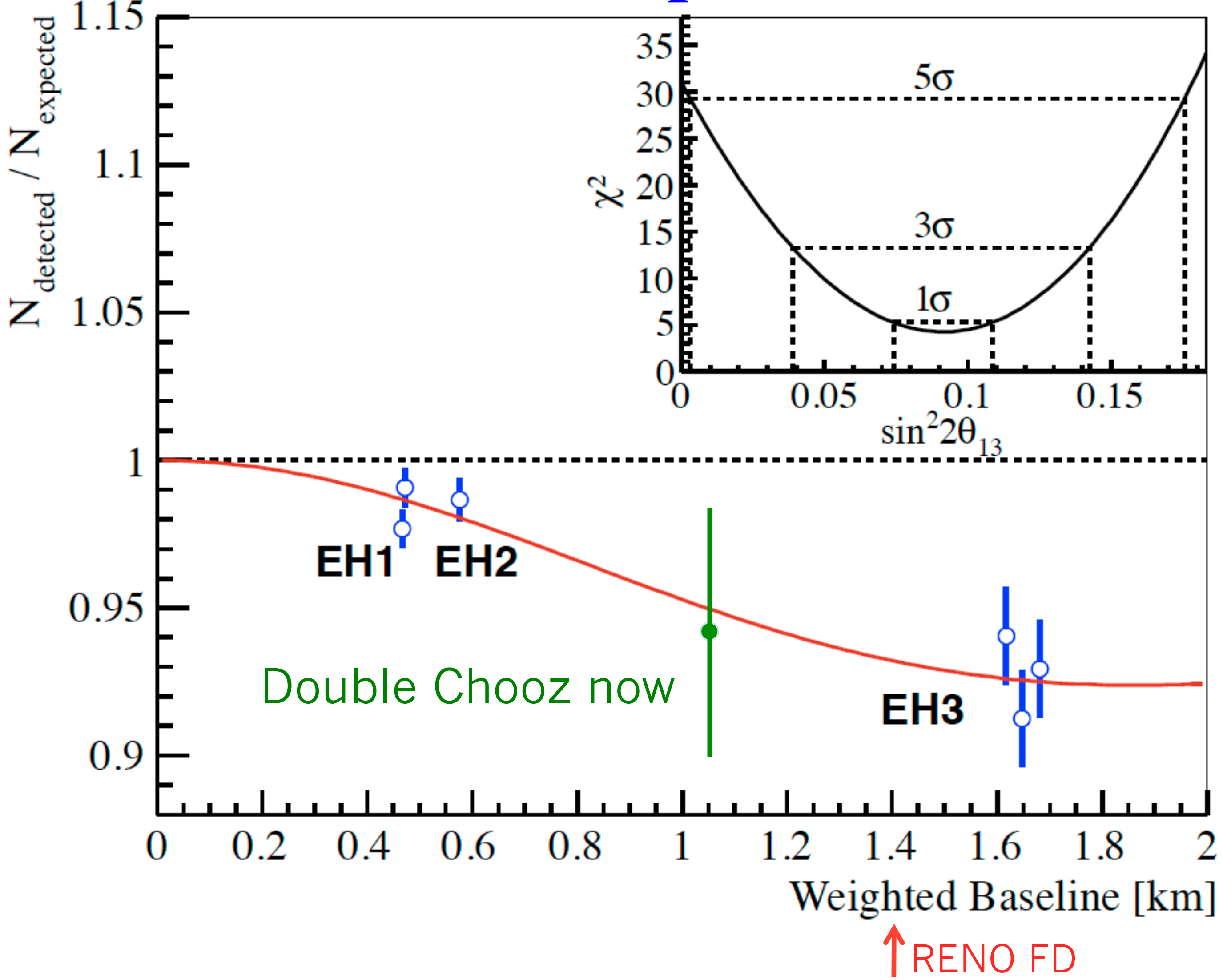
Unique features of Double Chooz



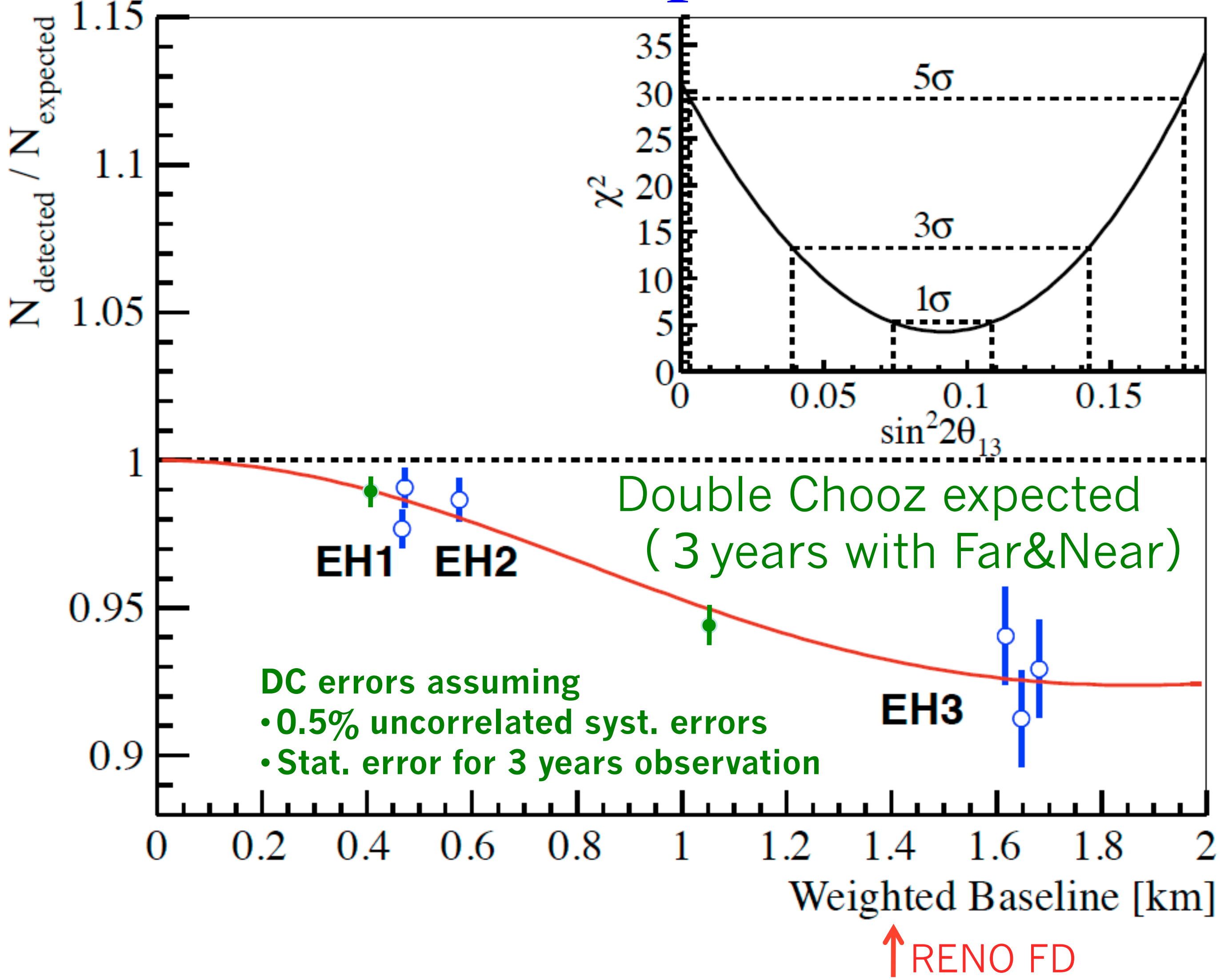
Double Chooz	Daya Bay	RENO
P=8.5GWth (2基)	P=17.4GWth (6基)	P=16.1GWth (6基)
L=1.05km	**L~1.8km**	**L~1.4km**
M=10ton	M=20ton x 4	M=20ton

* Baseline is shortest ➔ reactor complementarity
* # of reactor is only 2 ➔ direct background measurement

Measurement of L dependence of oscillation



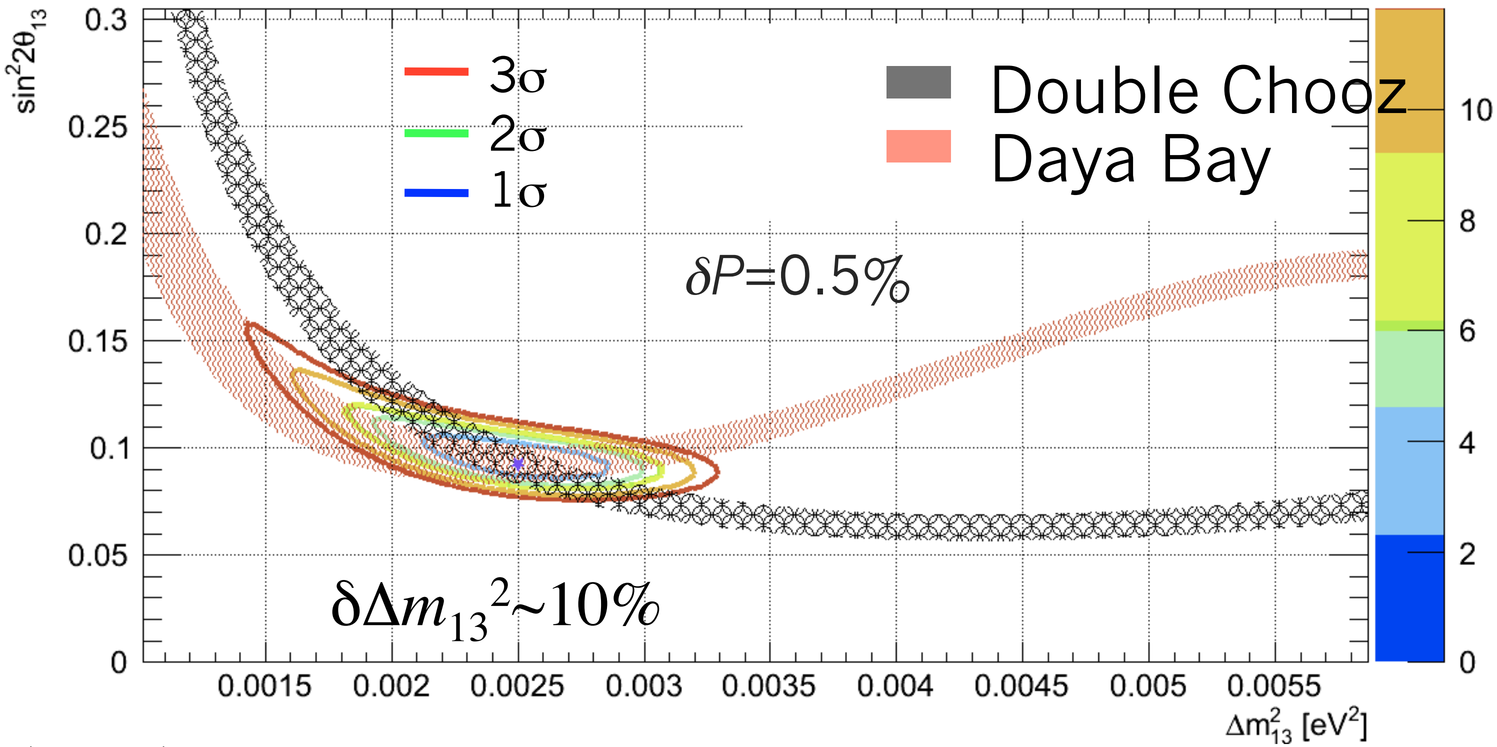
Measurement of L dependence of oscillation



(DB error will reduce also)

Measurement of $|\Delta m^2{}_{13}|$ by combination of reactor experiments

(DC & DB results use $|\Delta m_{23}{}^2|$)



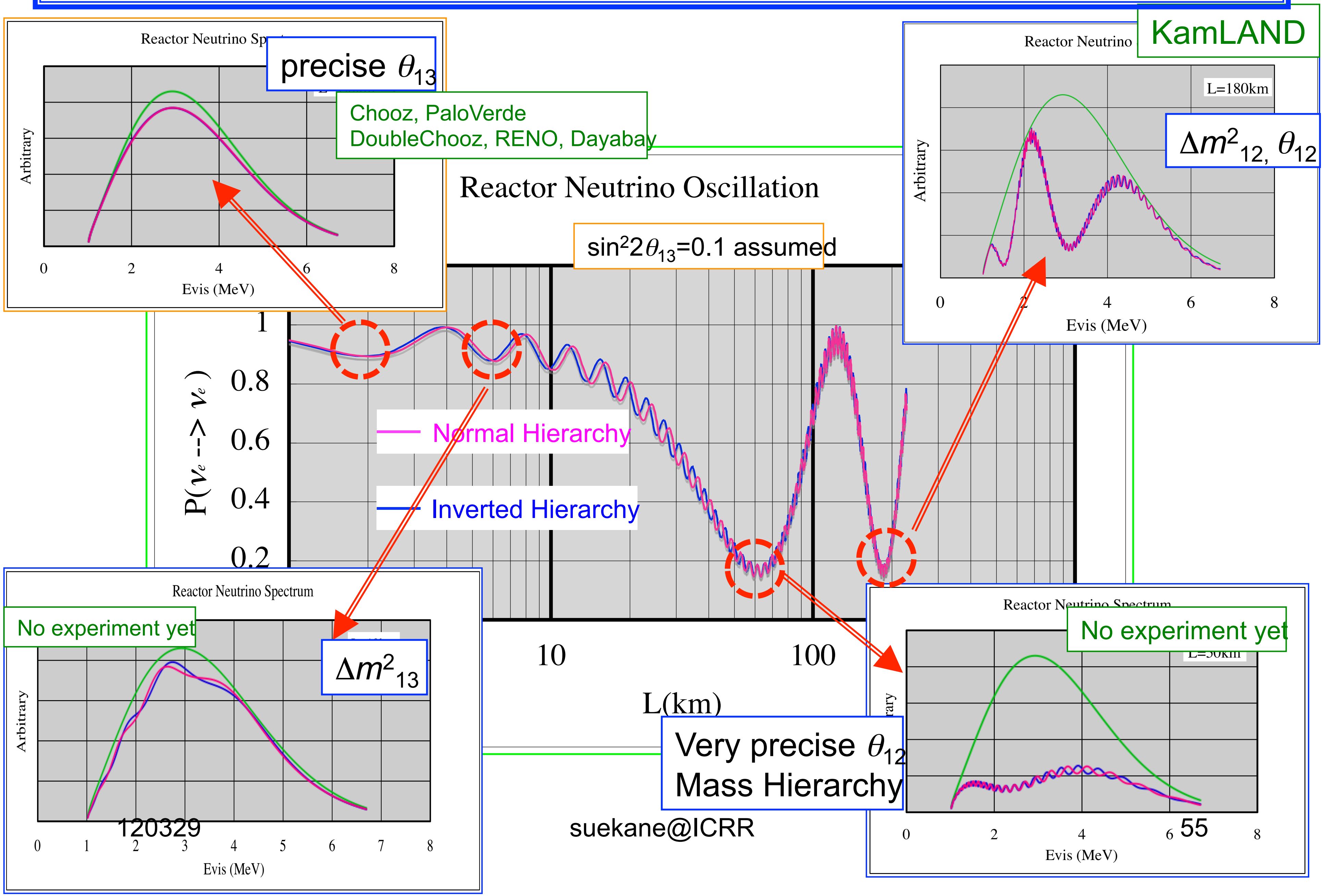
$$\frac{\left|\Delta m_{23}^2\right| - \left|\Delta m_{13}^2\right|}{\left|\Delta m_{23}^2\right|} \sim \cos 2\theta_{12} \frac{\Delta m_{12}^2}{\Delta m_{13}^2} \sim \pm 1\% << 10\%$$

Any significant Difference

=> new physics

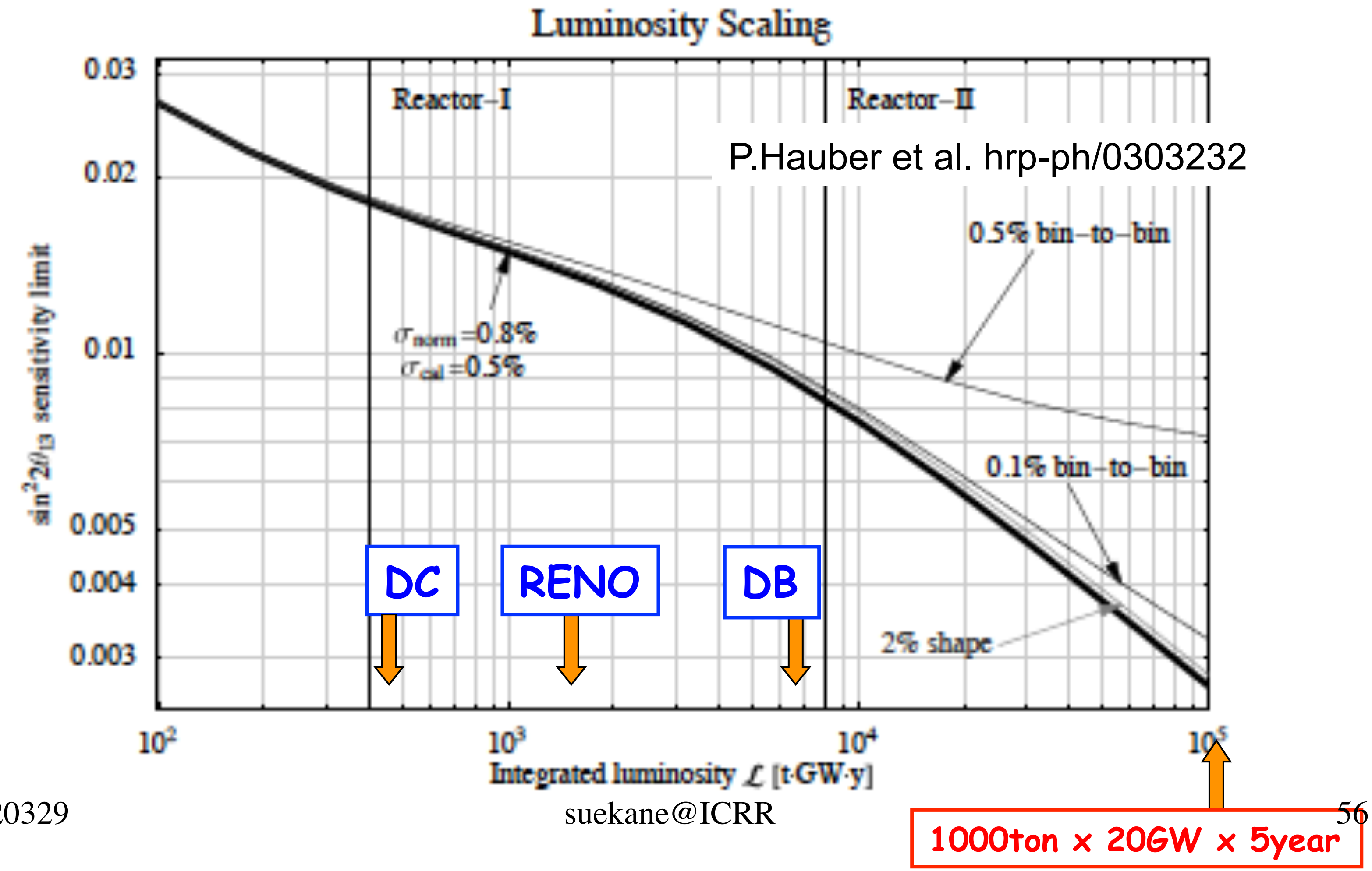
Double Chooz Near Lab.
2012 Near detector construction
2013 Data taking with Near + Far

What reactor neutrino could do in the future?



More Precise $\sin^2 2\theta_{13}$

Very high statistics ➔ $\sin^2 2\theta_{13}$ can be measured from distortion of spectrum precisely



Early "δ" detetion by Accelerator+ Reactor

ν mode operation of accelerator

$$P_{AC}(\nu_\mu \to \nu_e) \sim 0.5\sin^2 2\theta_{13} - 0.05\sin 2\theta_{13}\sin\delta$$

$$\equiv 0.5\sin^2 2\theta_{13}^{AC}$$

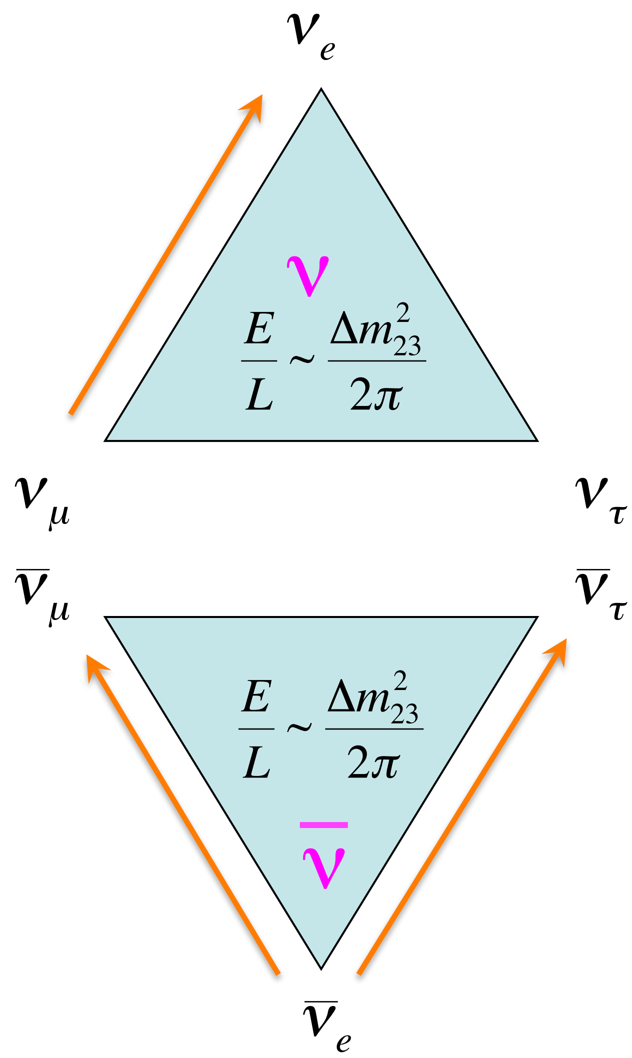
Reactor measurement

$$P_{RE}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \equiv 1 - \sin^2 2\theta_{13}^{RE}$$

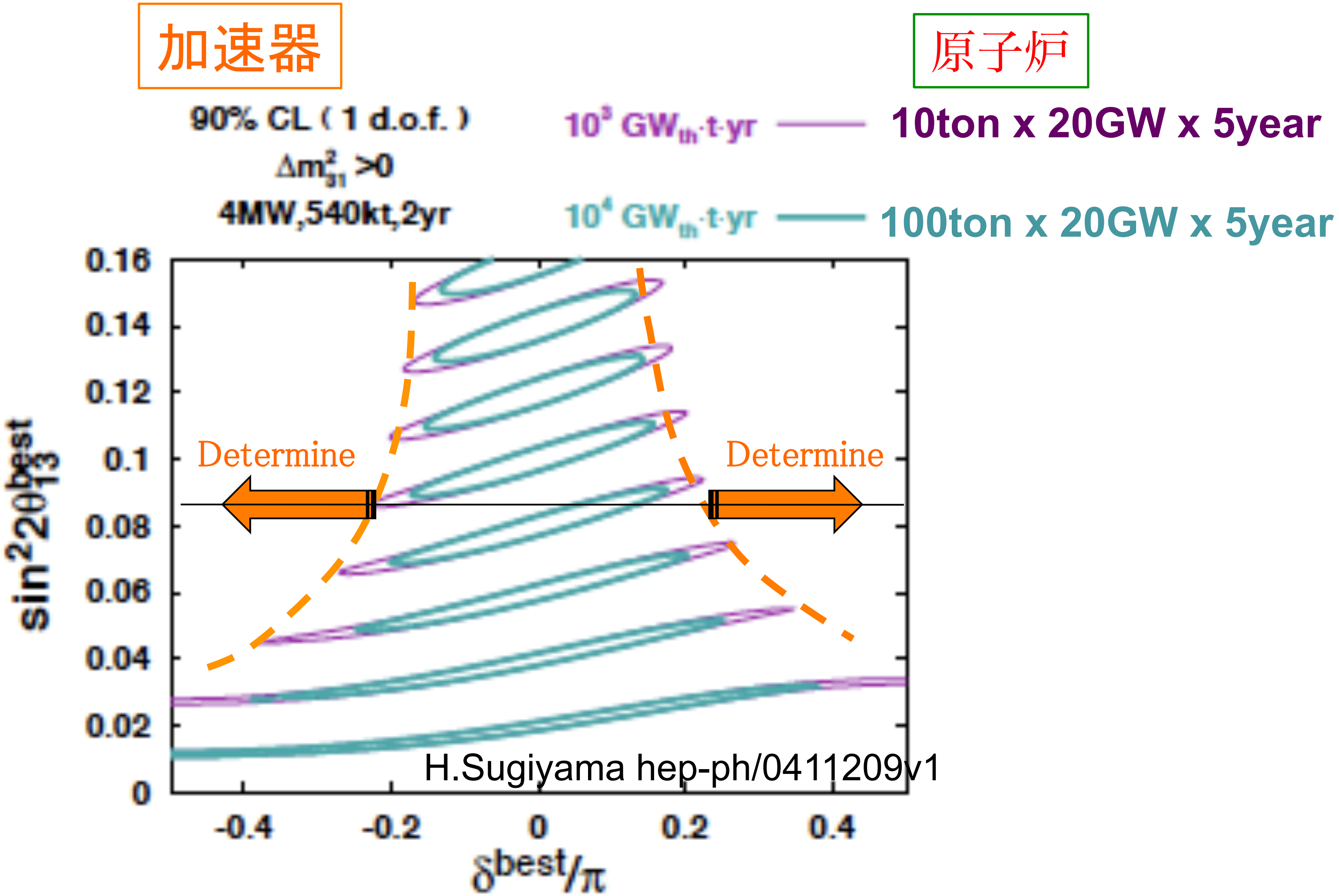
Difference between reactor θ_{13} & accelerator θ_{13} indicates $\sin\delta$

$$\sin\delta \sim 30 \times \left(\sin^2 2\theta_{13}^{RE} - \sin^2 2\theta_{13}^{AC}\right)$$

May be possible to identify finite δ before $\bar{\nu}$ mode operation which costs $$$



Parameter region to determine non-0 δ

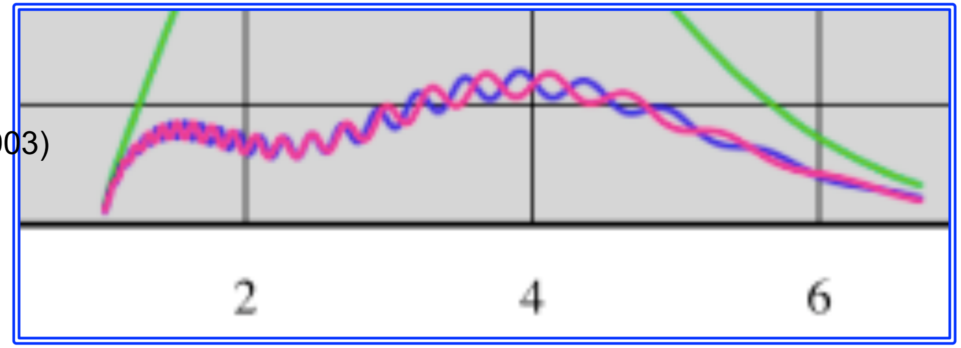


If $\sin^2 2\theta_{13} > 0.05$ there is a possibility to determine non-0 δ

Mass Hierarchy determination at 50km

Principle

Petcov et al., Phys. Lett. B 533, 94 (2002)
S.Choubey et al., Phys. Rev. D 68,113006 (2003)
J. Learned et al., hep-ex/062022
L.Zhan et al., hep-ex/0807.3203
M.Batygov et al., hep-ex/0810.2508
etc.



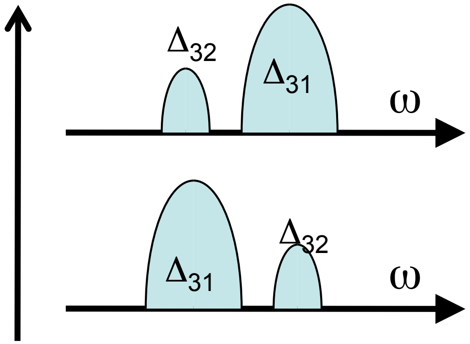
Ripple $\propto \sin^2 2\theta_{13}\left(\sin^2\Delta_{31} + \tan^2\theta_{12}\sin^2\Delta_{32}\right)$

It is essential that θ_{12} is not maximum ($\tan^2\theta_{12}$~0.4)

Foueier analysis will show peaks at $\omega = \left|\Delta m_{31}^2\right|, \quad \left|\Delta m_{32}^2\right|$

Smaller peak is $\left|\Delta m_{32}^2\right|$ larger peak is $\left|\Delta m_{31}^2\right|$,

Power



: Normal Hierarchy

: Inverted Hierarchy

Where is optimam L? Need more study.

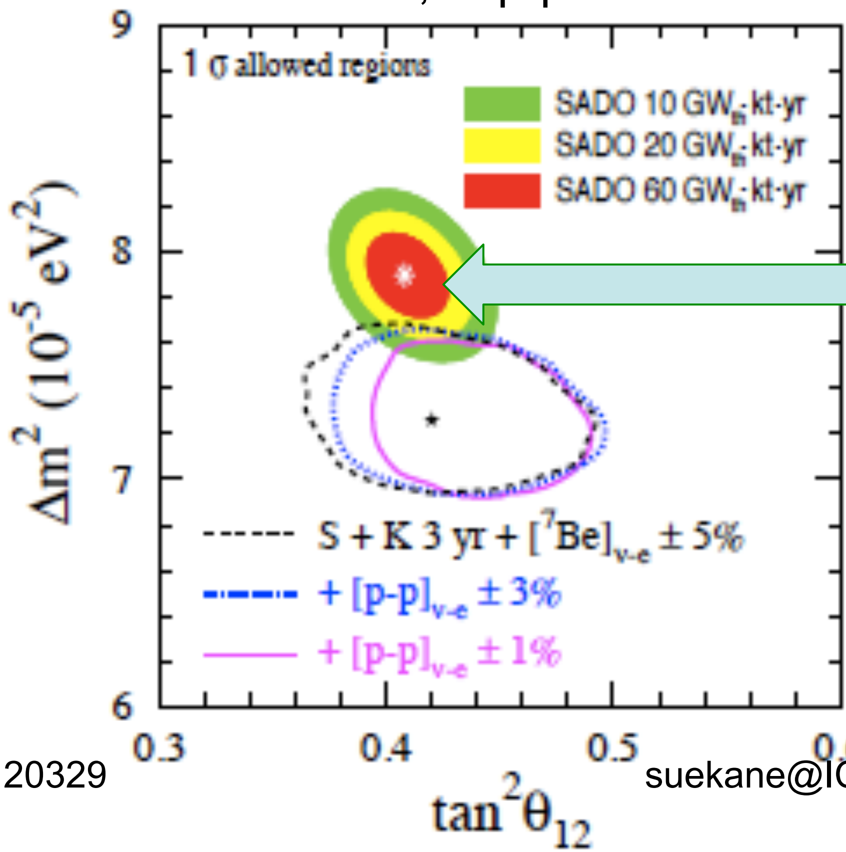
Precise θ_{12} @50km

$$P(\bar{\nu}_e \to \bar{\nu}_e) \sim \cos^4\theta_{13}\left(1-\underline{\sin^2 2\theta_{12}}\sin^2\Delta_{21}\right)$$

at 50km, ~80% of ν disappears due to N.O.

➔ A high sensitivity θ_{12} measurement is possible.

H.Minakata, hep-ph/07-1070



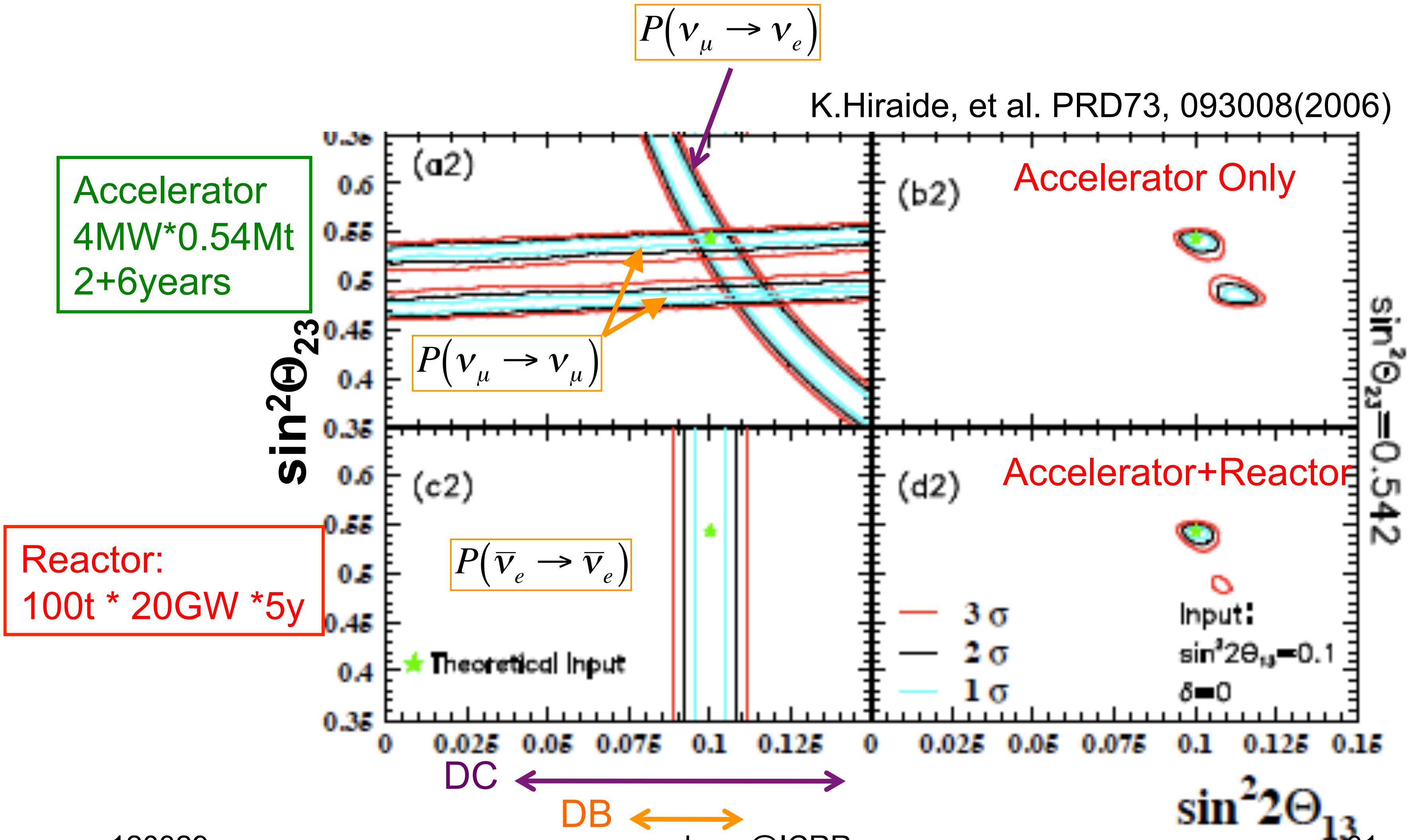
1kton x25GW x2.5y

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

Current Global fit

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

Settlement of θ_{23} Degeneracy



Conclusions

* 1st positive neutrino oscillation result from short baseline experiment.

  $\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat.}) \pm 0.030(\text{syst.})$ (rate+shape)

  $\theta_{13}=0$ is excluded with 94.6%CL

* Near Detector will be in operation in 2013.

  $\sin^2 2\theta_{13}$ error will be ± 0.02

* Relatively large θ_{13} opens up next round neutrino studies. Combinations of reactor and accelerator experiments will work effectively.