Reactor-neutrino experiments to pin down θ_{13}

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Understanding of the Neutrino Sector

- Maki-Nakagawa-Sakata mixing matrix
(leptonic version of the CKM matrix)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν_e, ν_μ, ν_τ : flavor eigenstates.

ν_1, ν_2, ν_3 : mass eigenstates of $m = m_1, m_2, m_3$.

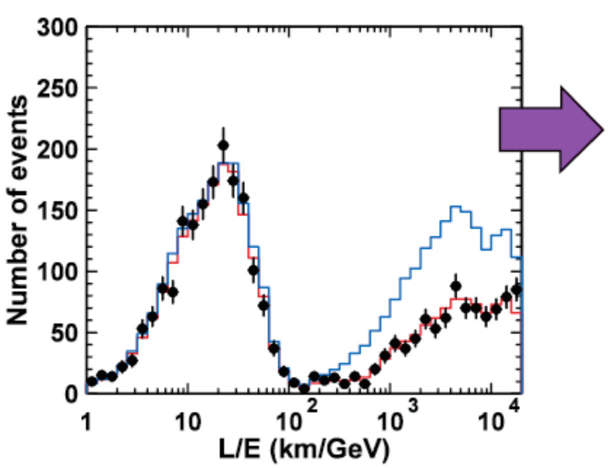
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{23}=\cos\theta_{23}$, etc.

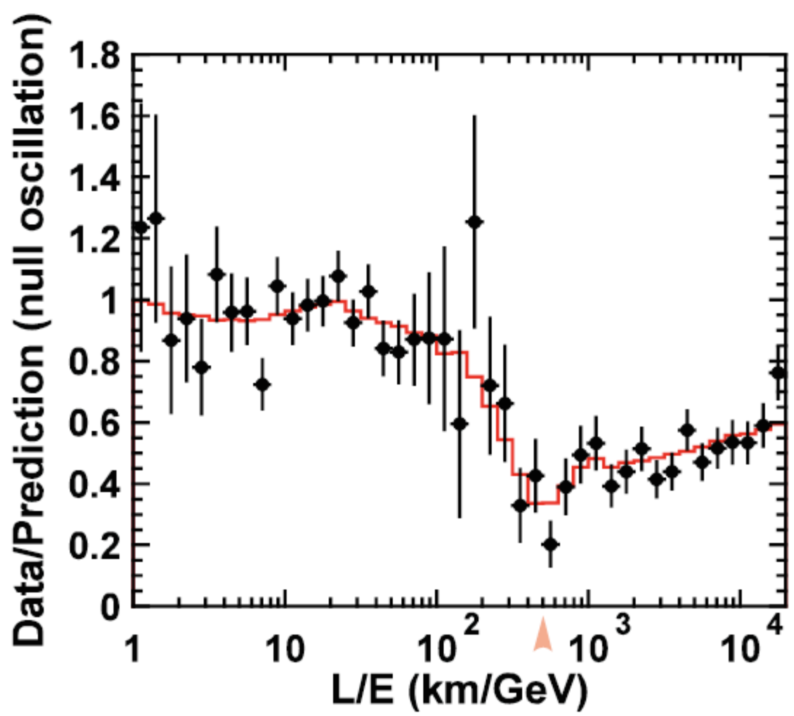
The (2-3) sector

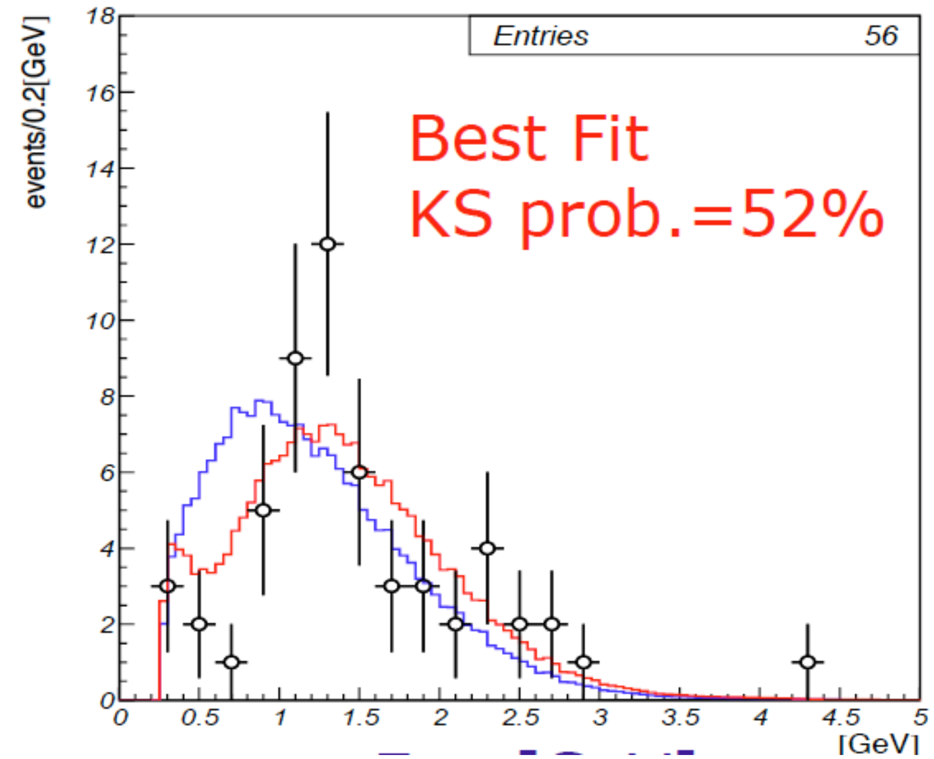
- Super-K atmospheric ν anomaly
- K2K/MINOS long-baseline experiments

Nakaya/ ν2004



Kearns/ ν2004



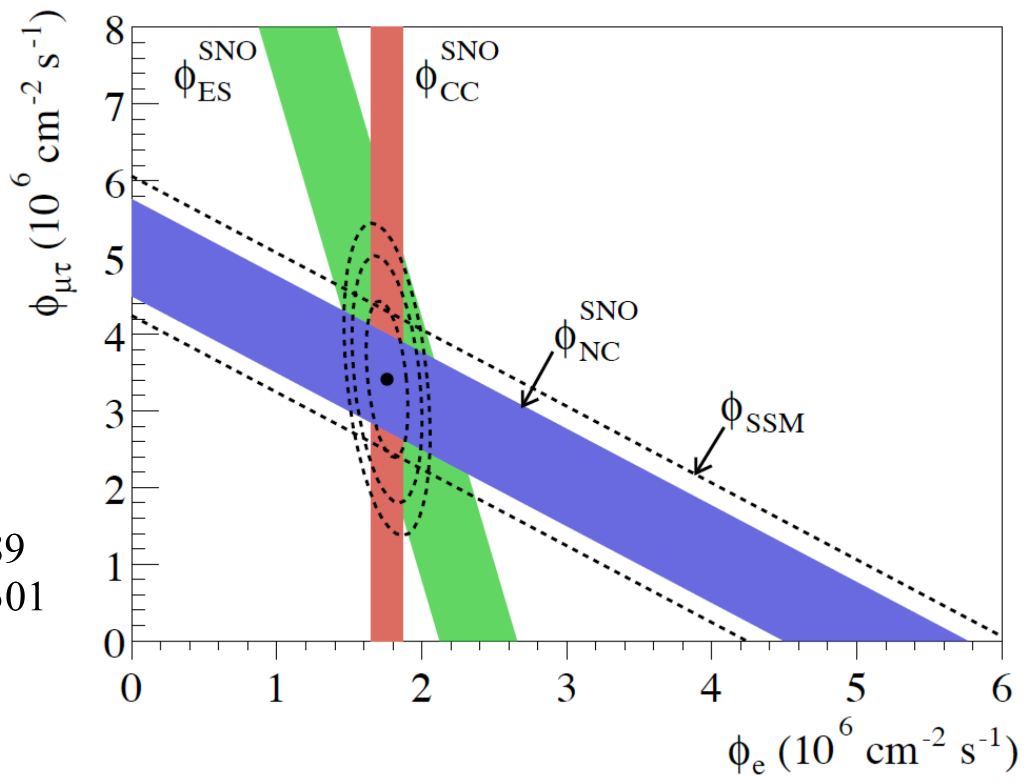


$\Delta m^2_{23} \sim 2.6\times10^{-3}\mathrm{eV}^2$, $\sin^2 2\theta_{23} \sim 1.0$ (nearly maximal mixing)

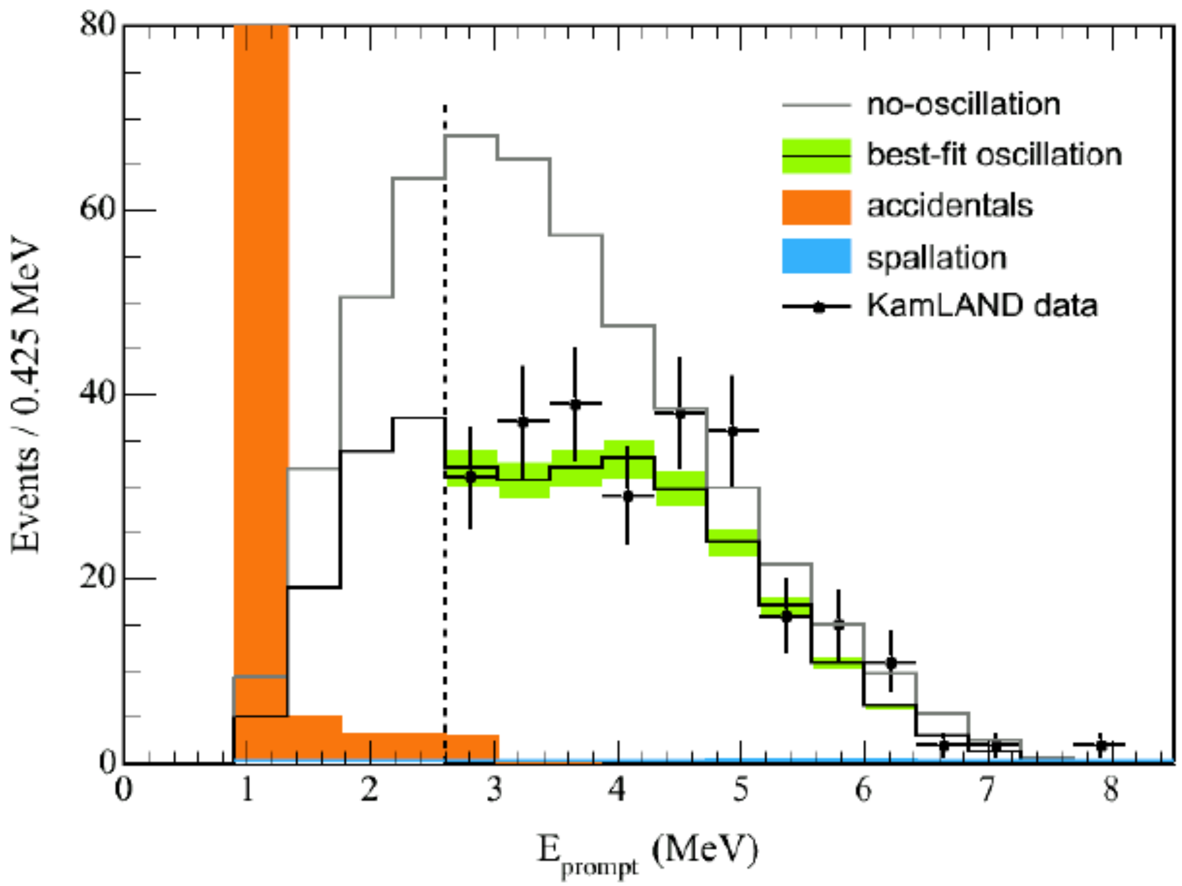
The (1-2) sector

- Solar neutrinos (SK+SNO+others)
- KamLAND reactor neutrinos

Gratta/ ν2004



SNO/PRL89 (2002)011301



Δm^2_{12}~8.0×10^{-5}eV^2, $\sin^2 2\theta_{12}$~0.85 (large mixing angle)

The unknown (1-3) sector

- Upper limit from CHOOZ reactor experiment:
  $\sin^2 2\theta_{13} < 0.15$ @ $\Delta m^2_{13} = 2.5\times10^{-3}\,\mathrm{eV}^2$

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

$\sin\theta_{13} e^{i\delta_l}$

$\sin\theta_{13} < 0.2$,

δ_l: totally unknown CPV phase

Next important step: measure θ_{13}

Note: $\Delta m^2_{13} = \Delta m^2_{12} + \Delta m^2_{23} \sim \Delta m^2_{23}$

θ_{13} also determines the detectability of CPV phase δ in future experiments.

Oscillation maximum:

$$1.27\Delta m^2(\text{eV}^2)L(\text{km})/E(\text{GeV})=(2n+1)\pi/2$$

- For $\Delta m^2_{23(13)} \sim 2.5\times10^{-3}$ eV^2 and E ~ 1 GeV,
  $\rightarrow$ L ~ O(400km): accelerator long-baseline exp't.

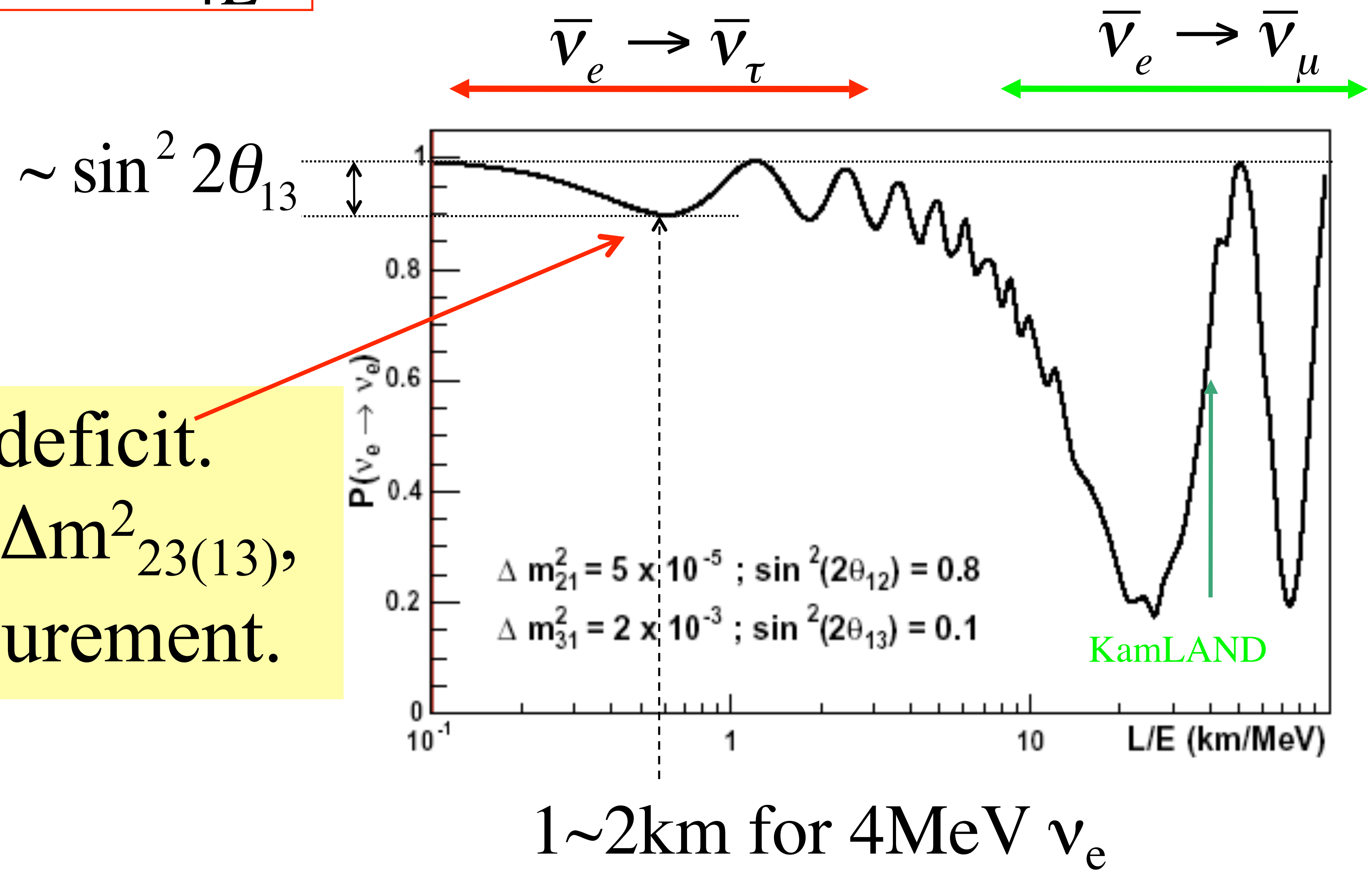
- For $\Delta m^2_{23(13)} \sim 2.5\times10^{-3}$ eV^2 and E ~ 4 MeV,
  $\rightarrow$ L ~ O(1.6km): reactor mid-baseline exp't.

- For $\Delta m^2_{12} \sim 0.8\times10^{-4}$ eV^2 and E ~ 4 MeV,
  $\rightarrow$ L ~ O(50km): reactor long-baseline exp't (KamLAND)

How to measure θ_{13} with reactor

- Disappearance of reactor anti-ν_e (E~4MeV, L=1~2km)

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E}$$ +O(10^{-3}) from Δm^2_{12} oscillation



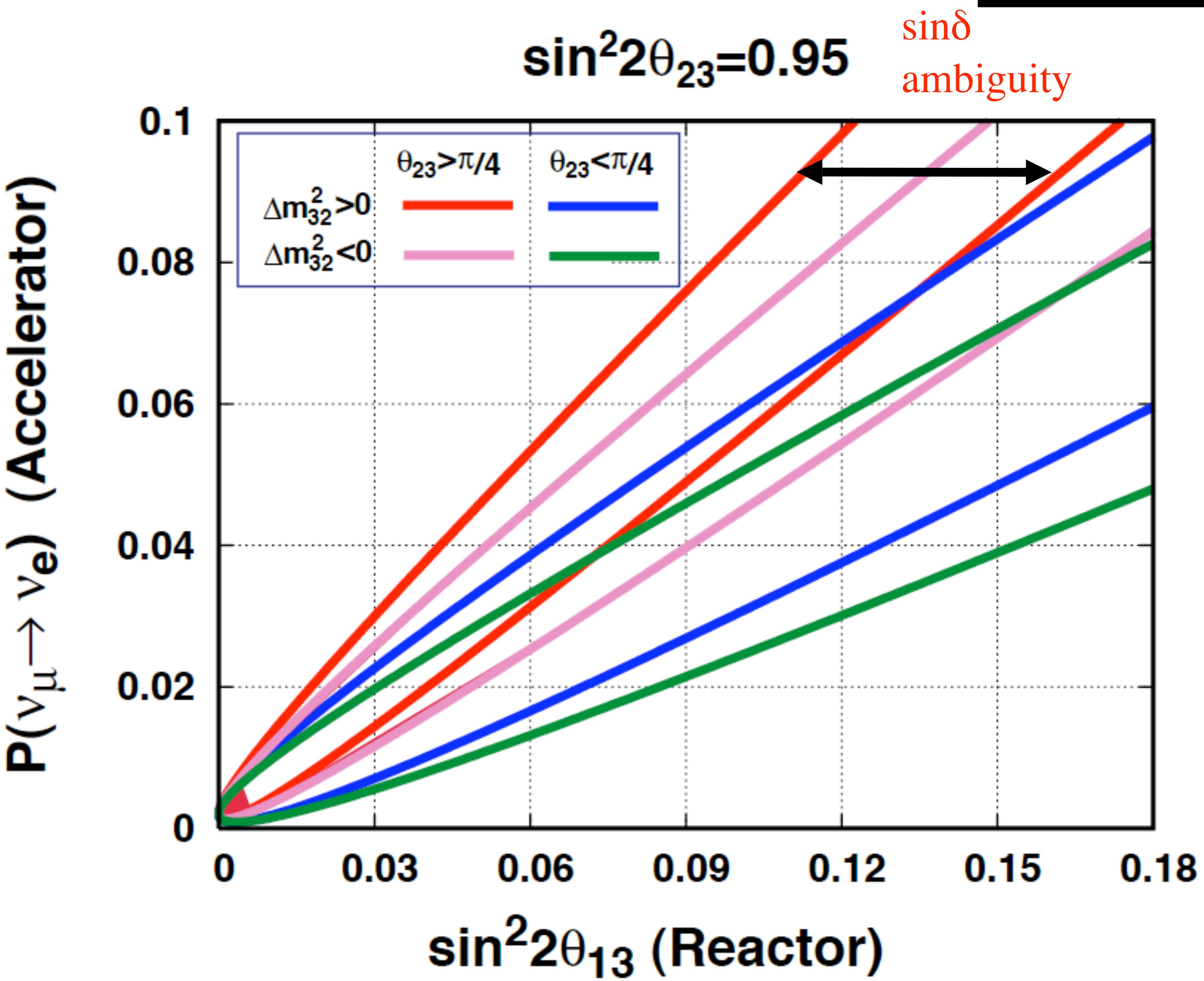
Measure this small deficit.
Thanks to $\Delta m^2_{12} << \Delta m^2_{23(13)}$,
it is a pure θ_{13} measurement.

Complementarity to accelerator-θ_{13} appearance exp't

$$
\begin{aligned}
P_{\rm app} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& \pm\ \alpha \sin 2\theta_{13}\, \xi \sin\delta_{\rm CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& +\ \alpha \sin 2\theta_{13}\, \xi \cos\delta_{\rm CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& +\ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2},
\end{aligned}
$$

$$\hat{A}\Delta = \frac{\sqrt{2}}{2} G_F n_e L$$

$$
\begin{aligned}
\alpha &= \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \simeq 0.03, \\
\Delta &\equiv \frac{\Delta m^2_{31} L}{4E}, \\
\xi &\equiv \sin 2\theta_{12} \sin 2\theta_{23}.
\end{aligned}
$$



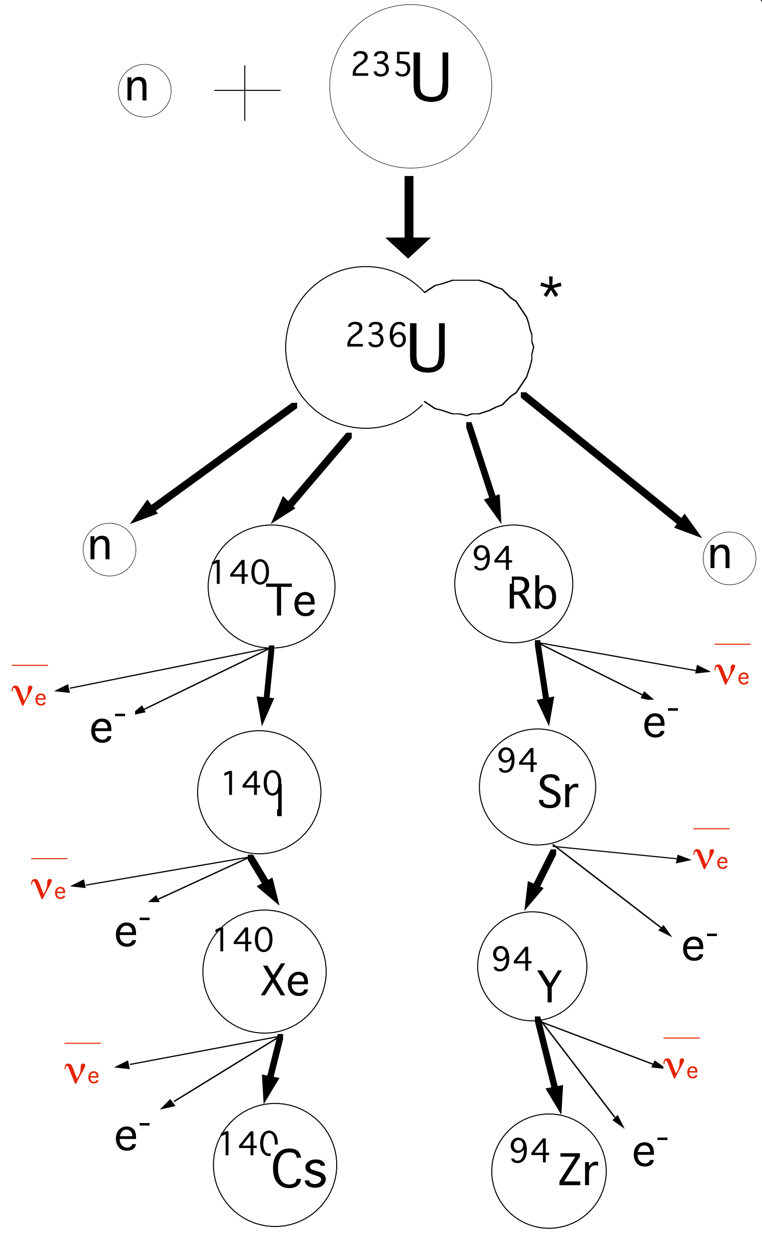
Measuring with both methods is important!

Short overview of reactor neutrinos

- ~6 ν's/fission, ~200MeV/fission

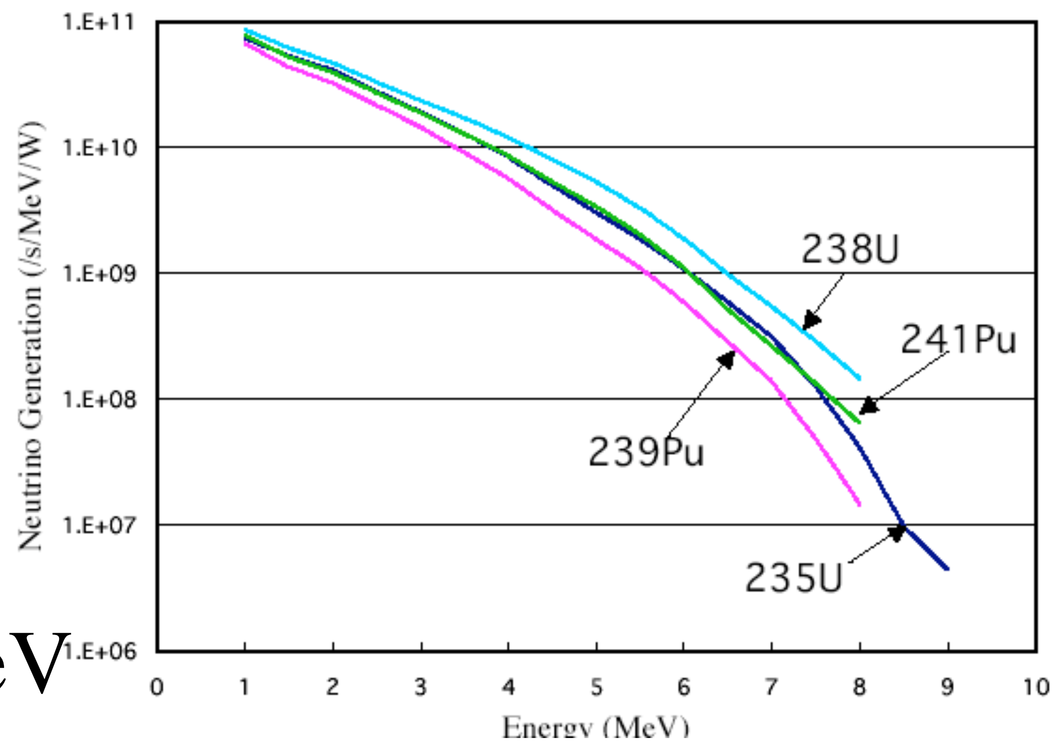
→ 6×10^{20} ν/sec for a typical reactor

(1GW power ~ 3GW thermal)



Reactors are powerful and "free" sources of low-energy neutrinos (though isotropic)

E_ν~ a few MeV



How to detect reactor anti-ν_e

- Inverse-beta decay (E_{thresh}=1.8MeV)

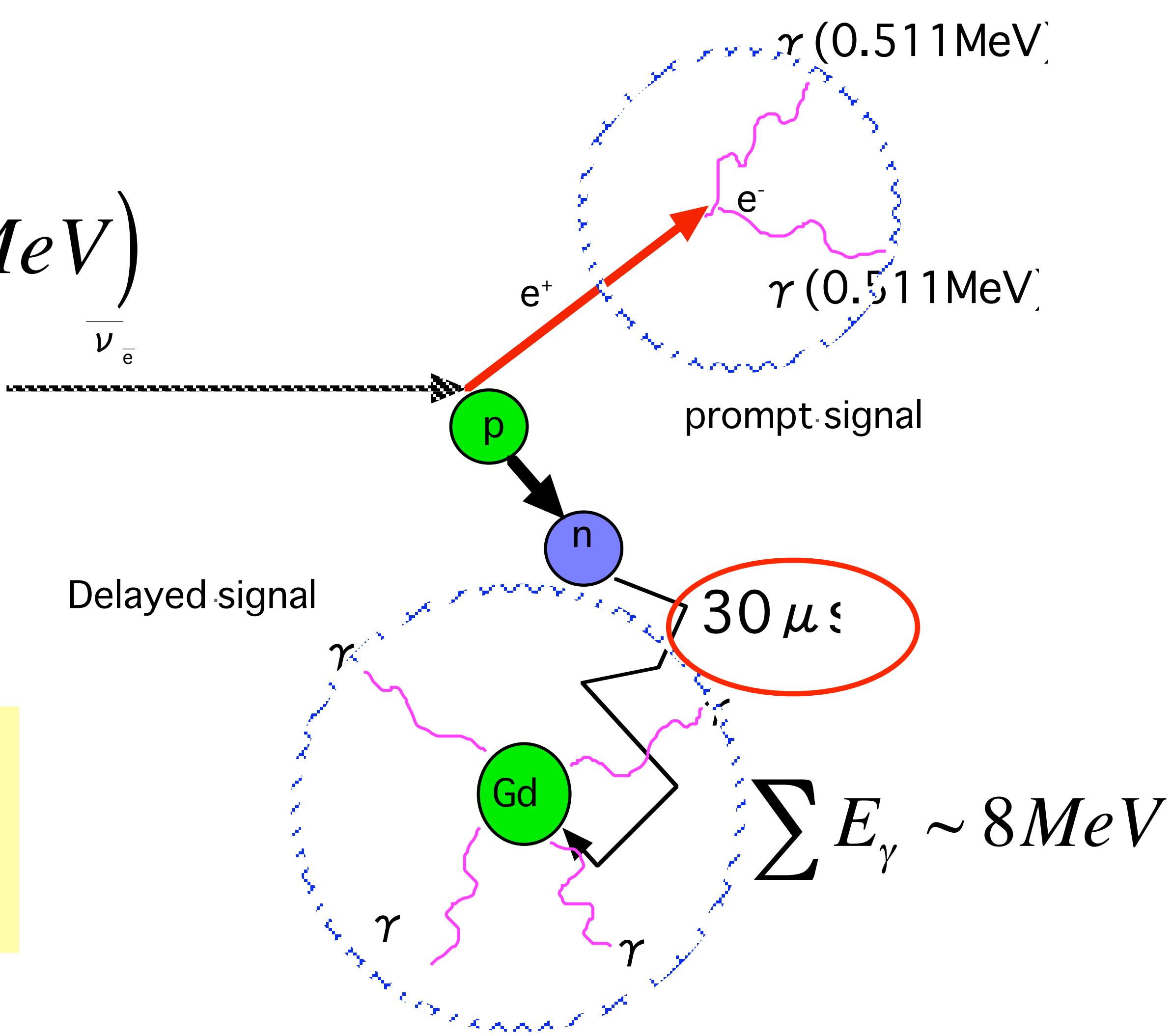
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$e^+ + e^- \rightarrow 2\gamma$$

$$(E_\nu - 0.8MeV)$$

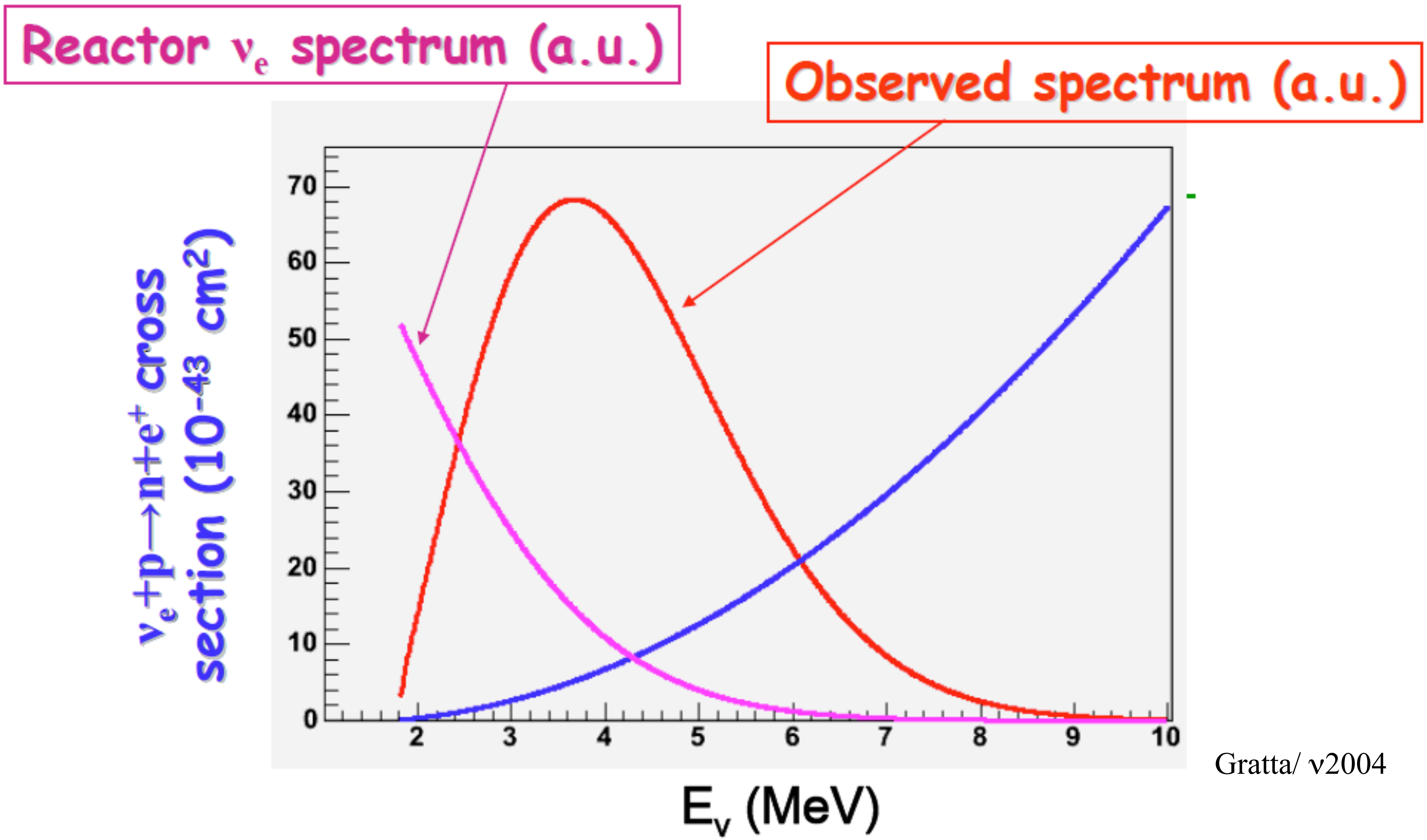
$$n + Gd \rightarrow Gd' + \gamma s\left(\sum E = 8MeV\right)$$

cf. KamLAND has no Gd
n+p→d+γ(2.2MeV)



"Delayed coincidence" drastically reduces the background.

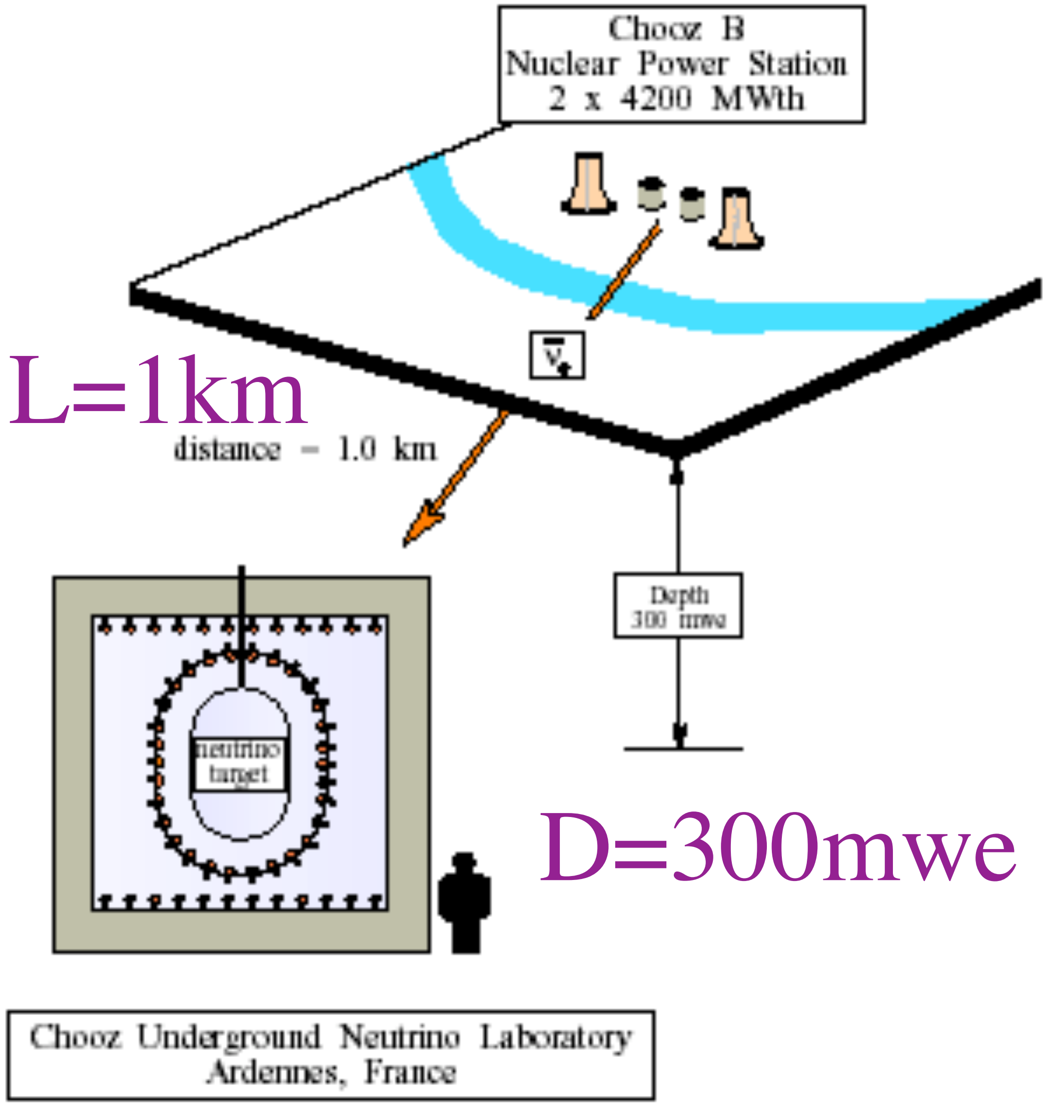
The energy spectrum peaks at 3.5~4 MeV



Gratta/ ν2004

Previous best-limit exp.: CHOOZ

$P=8.4GW_{th}$

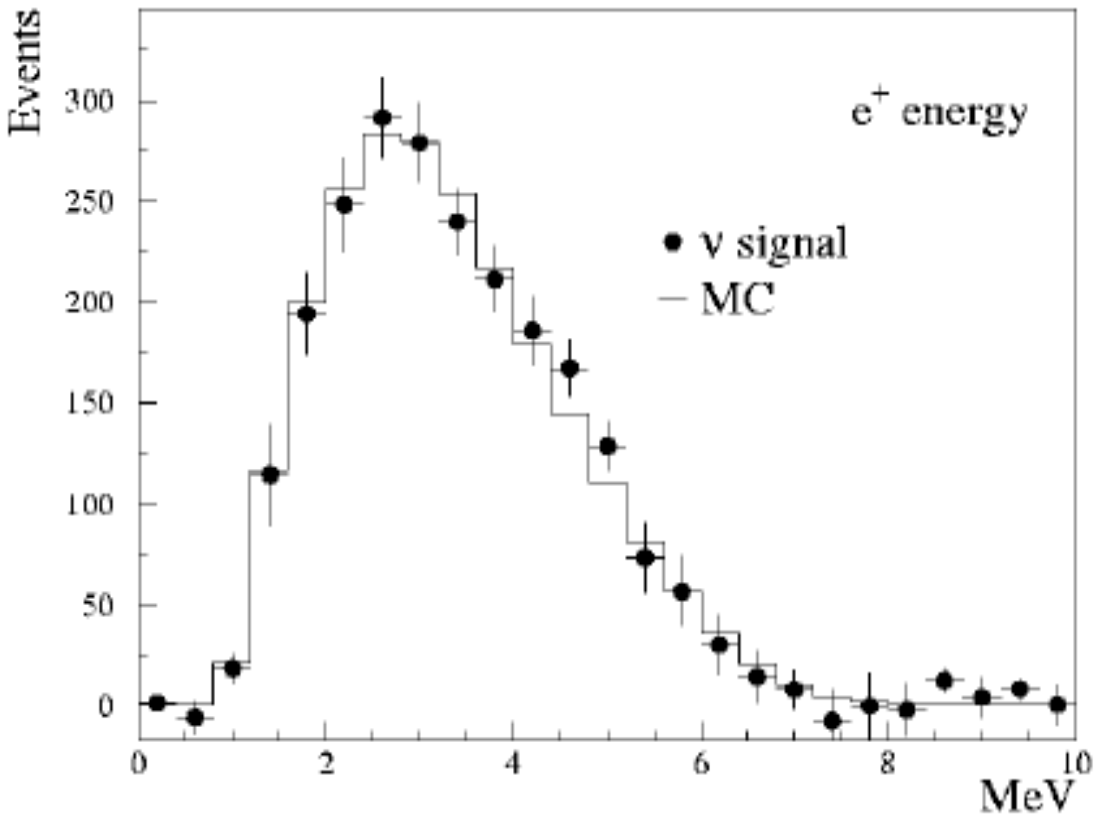


$L=1km$

$D=300mwe$

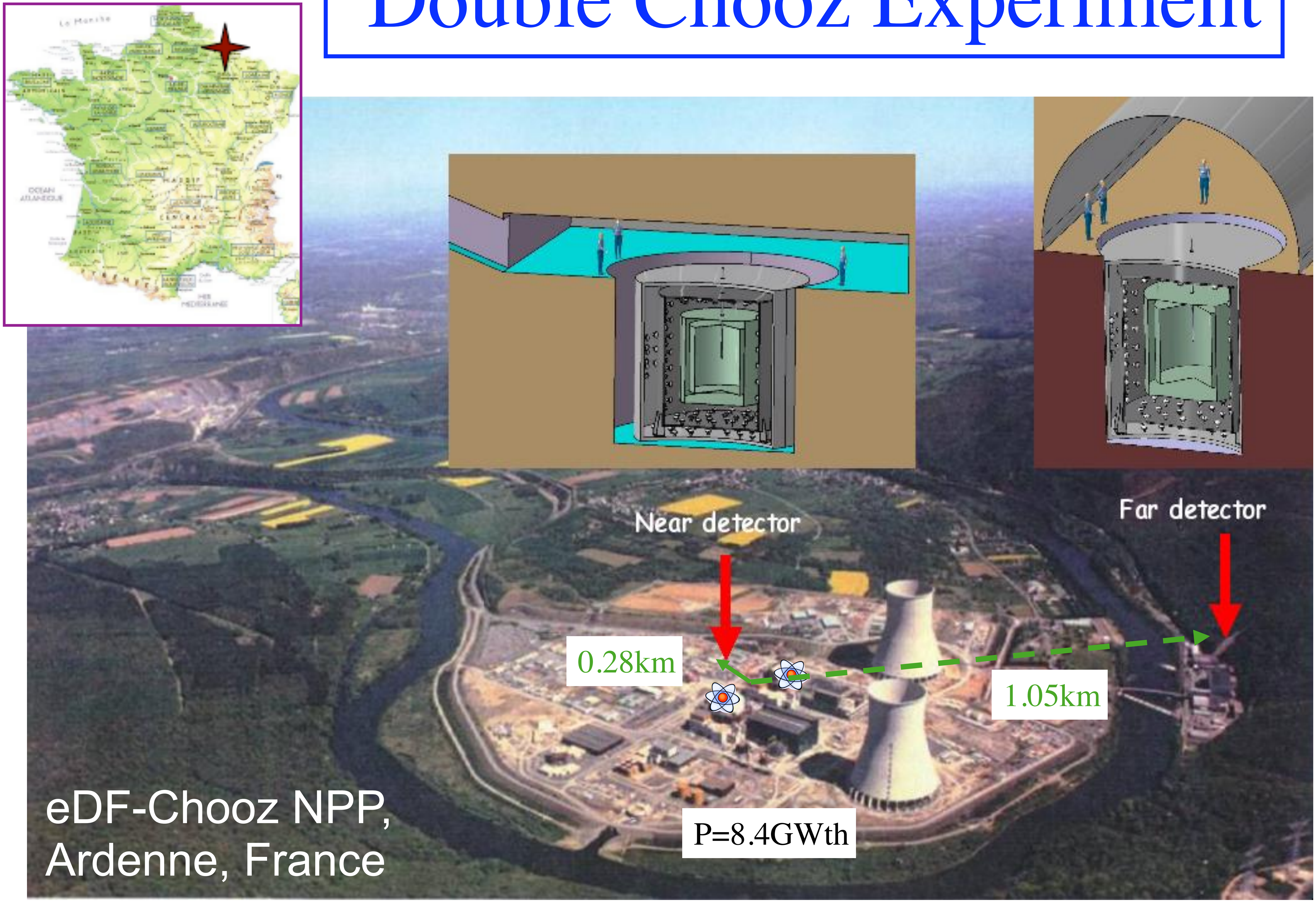
$M=5ton$

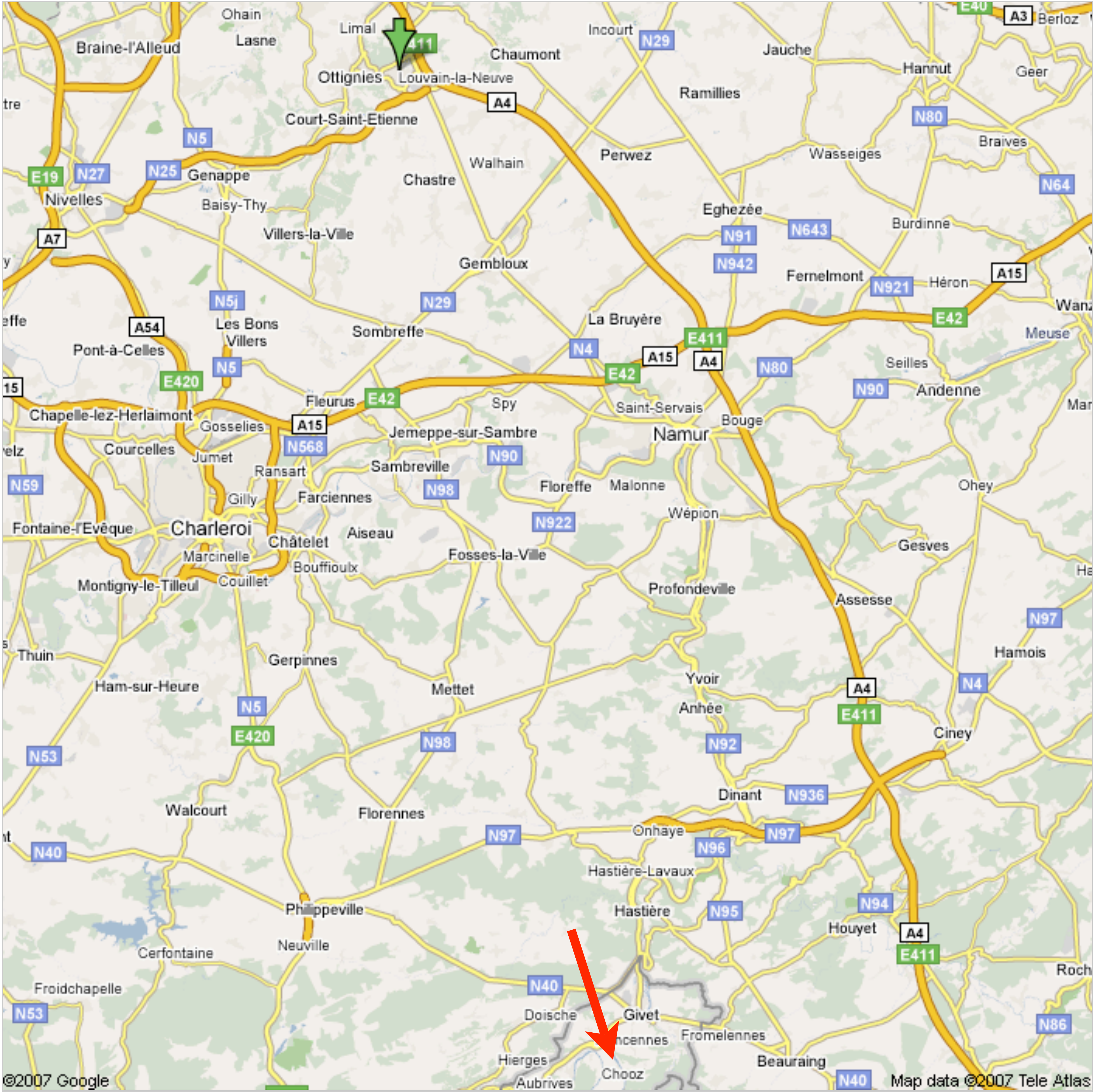
$\sigma_{sys.}=2.8\%, \sigma_{stat.}=2.7\%$



$\sin^2 2\theta_{13}<0.15$ @ $\Delta m^2=2.5\times10^{-3}$ eV^2

Double Chooz Experiment




Ohain
Limal
Incourt
N29
Jauche
A3
Berloz
Braine-l'Alleud
Lasne
Ottignies
Louvain-la-Neuve
Chaumont
Hannut
Geer
Ramillies
A4
Court-Saint-Etienne
N5
N80
Braives
Walhain
Perwez
Wasseiges
E19
N27
N25
Genappe
Chastre
N64
Nivelles
Baisy-Thy
Eghezée
Burdinne
N643
A7
Villers-la-Ville
N91
Gembloux
N942
Fernelmont
N921
Héron
A15
N5j
N29
La Bruyère
E42
A54
Les Bons Villers
Sombreffe
E411
Meuse
Pont-à-Celles
N4
A15
A4
N5
E42
N80
Seilles
E420
Fleurus
E42
N90
Andenne
Spy
Saint-Servais
Chapelle-lez-Herlaimont
Gosselies
A15
Bouge
Jemeppe-sur-Sambre
Namur
N568
Courcelles
Jumet
N90
Ransart
Sambreville
N59
N98
Floreffe
Malonne
Ohey
Gilly
Farciennes
Wépion
N922
Fontaine-l'Evêque
Charleroi
Aiseau
Châtelet
Marcinelle
Fosses-la-Ville
Gesves
Bouffioulx
Montigny-le-Tilleul
Couillet
Profondeville
Assesse
N97
Thuin
Hamois
Gerpinnes
Yvoir
Ham-sur-Heure
Mettet
A4
N4
N5
Anhée
E411
E420
Ciney
N98
N92
N53
Walcourt
Dinant
N936
Florennes
Onhaye
N97
N97
N40
N96
Hastière-Lavaux
Hastière
N95
N94
Philippeville
Houyet
A4
Neuville
Cerfontaine
E411
N40
Froidchapelle
Givet
Doische
N53
Fromelennes
N86
Hierges
Beauraing
Chooz
Aubrives
N40
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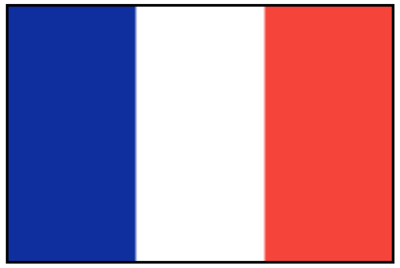
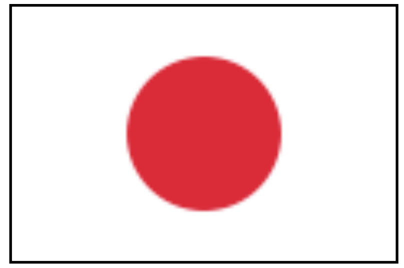
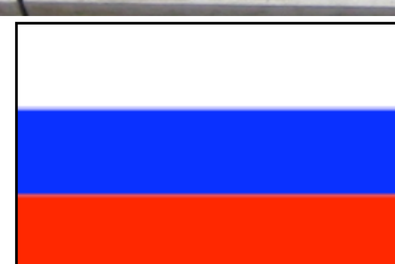
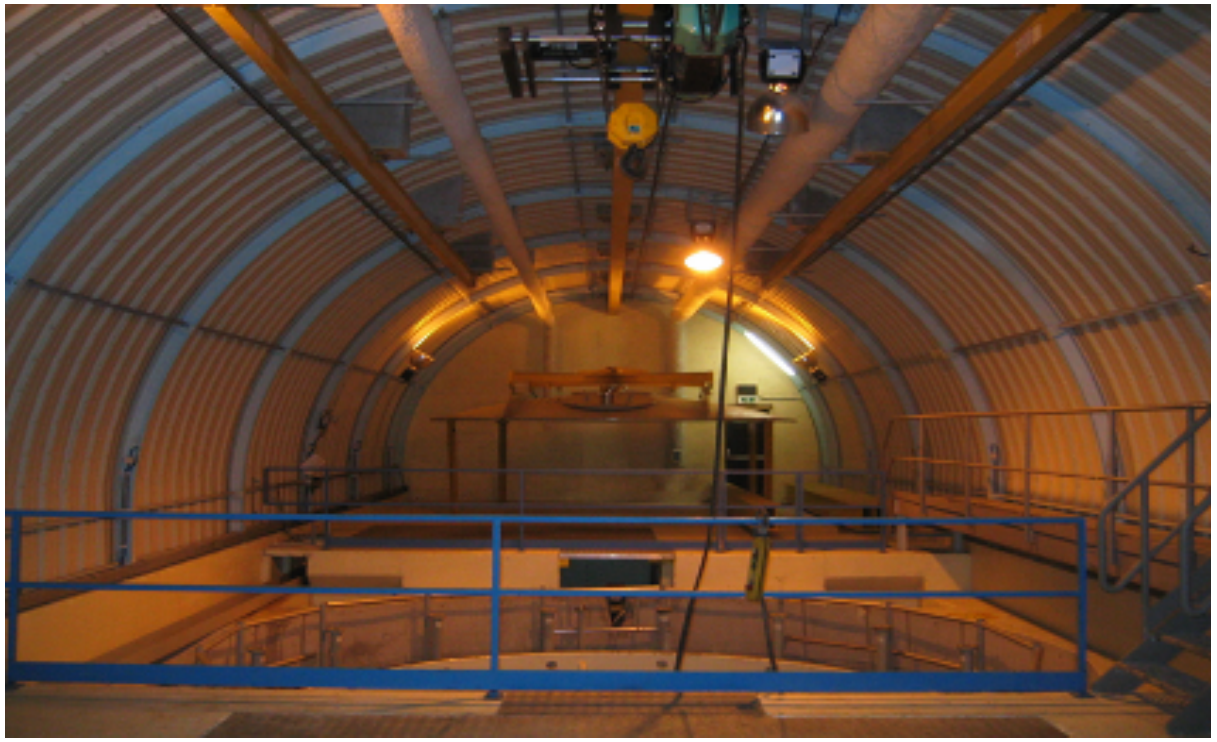
Double Chooz Collaboration

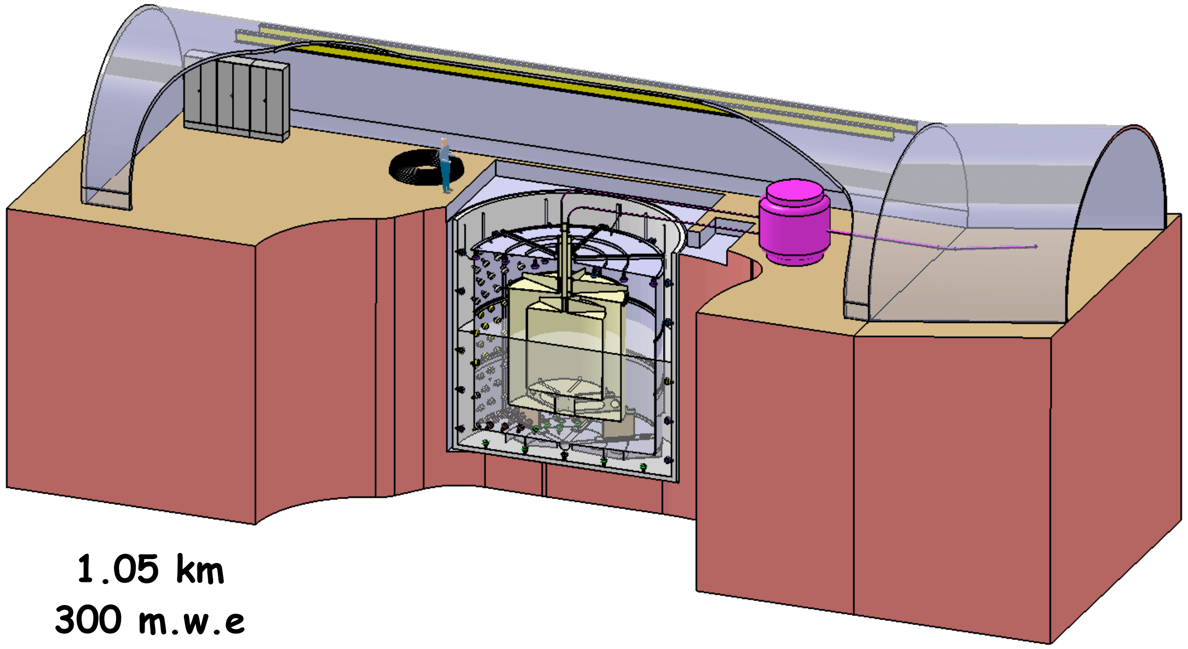



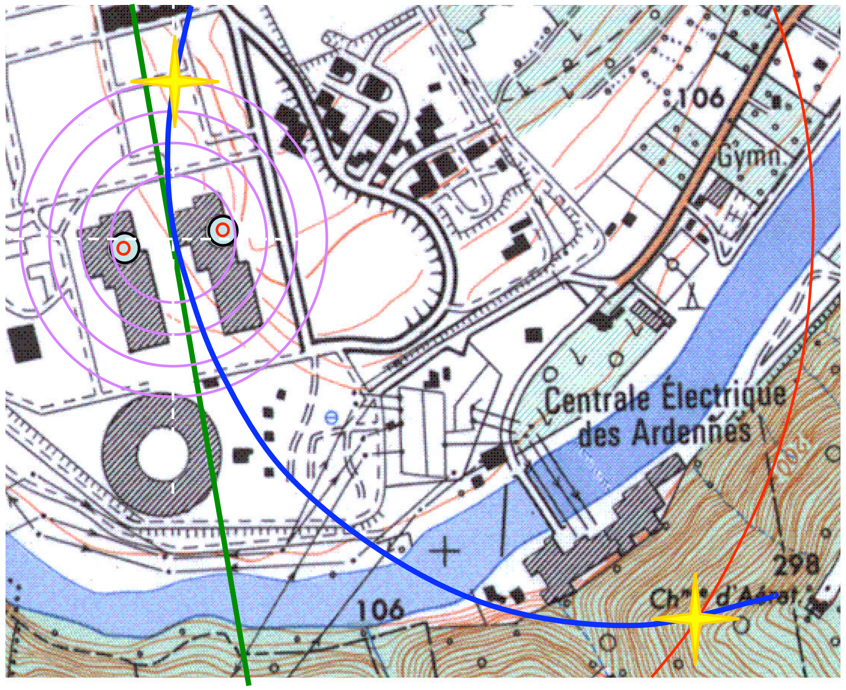
1 km site   280 m site



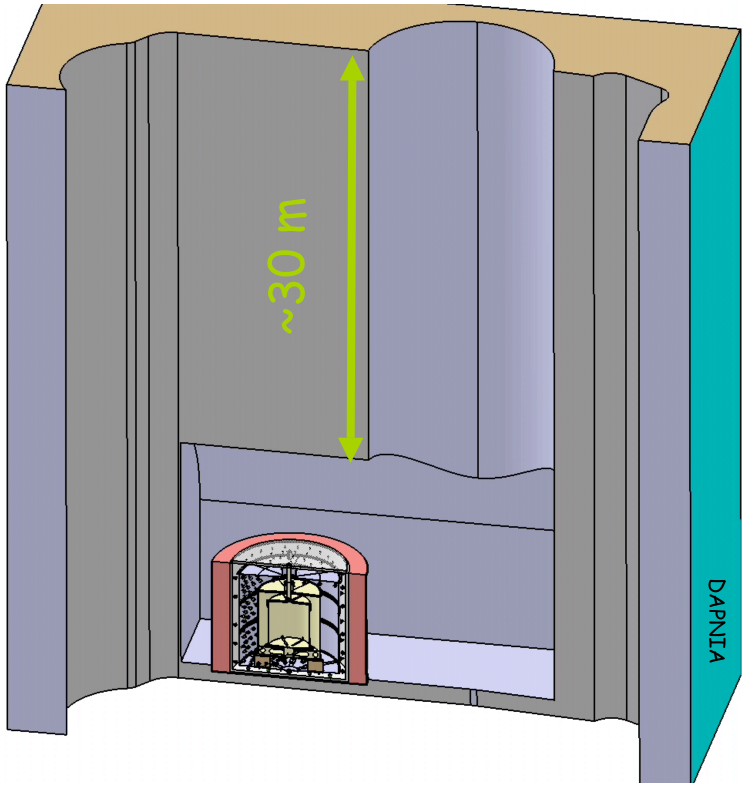
Integration to start mid-2007



1.05 km
300 m.w.e
15 000 events/y



280 m
80 m.w.e
150 000 events/y



Integration end of 2009

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

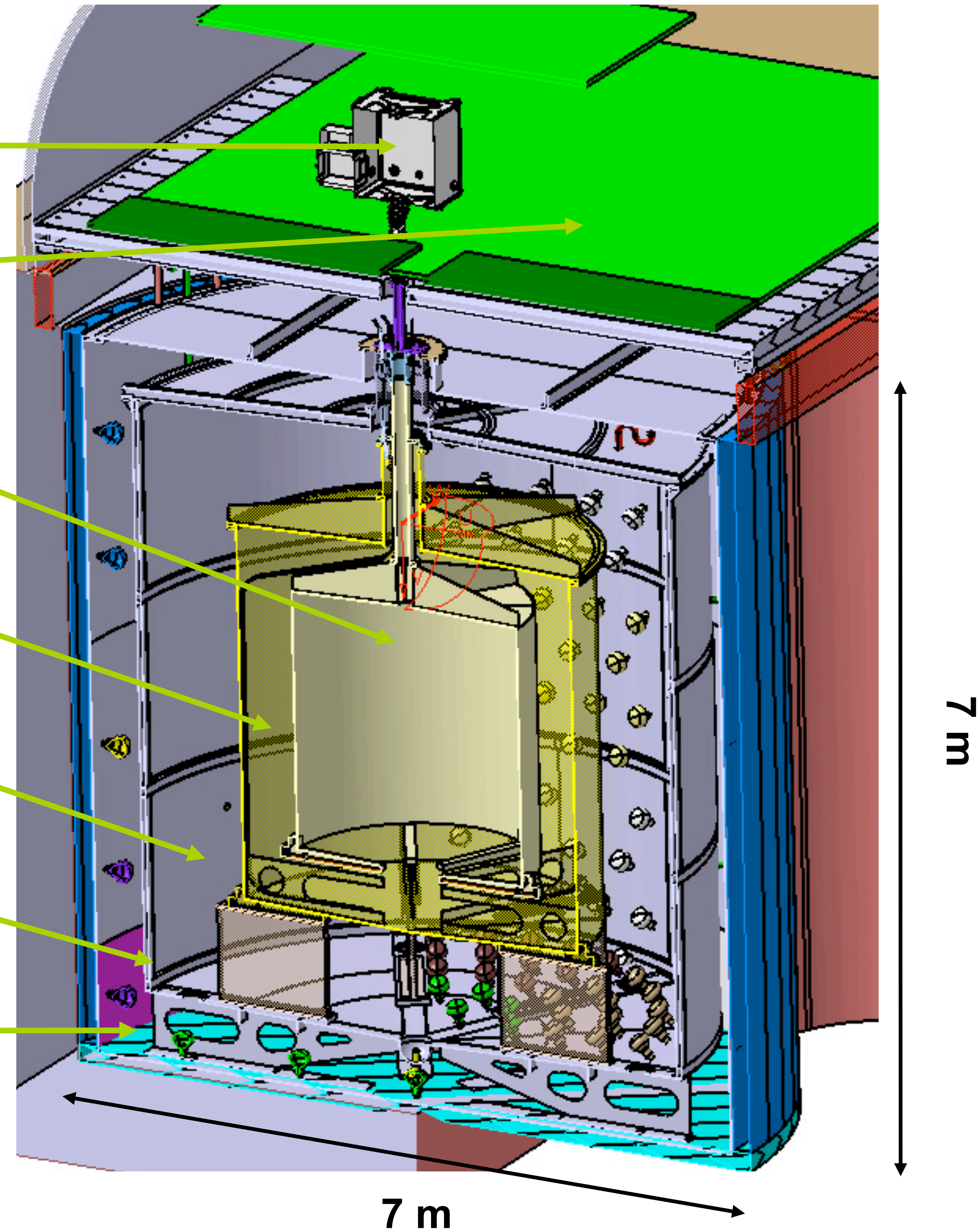
γ Catcher : 22,6 m^3
LS; 80% $C_{12}H_{26}$ + 20% PXE + PPO + Bis-MSB

Non scintillating Buffer : 114 m^3
mineral oil

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

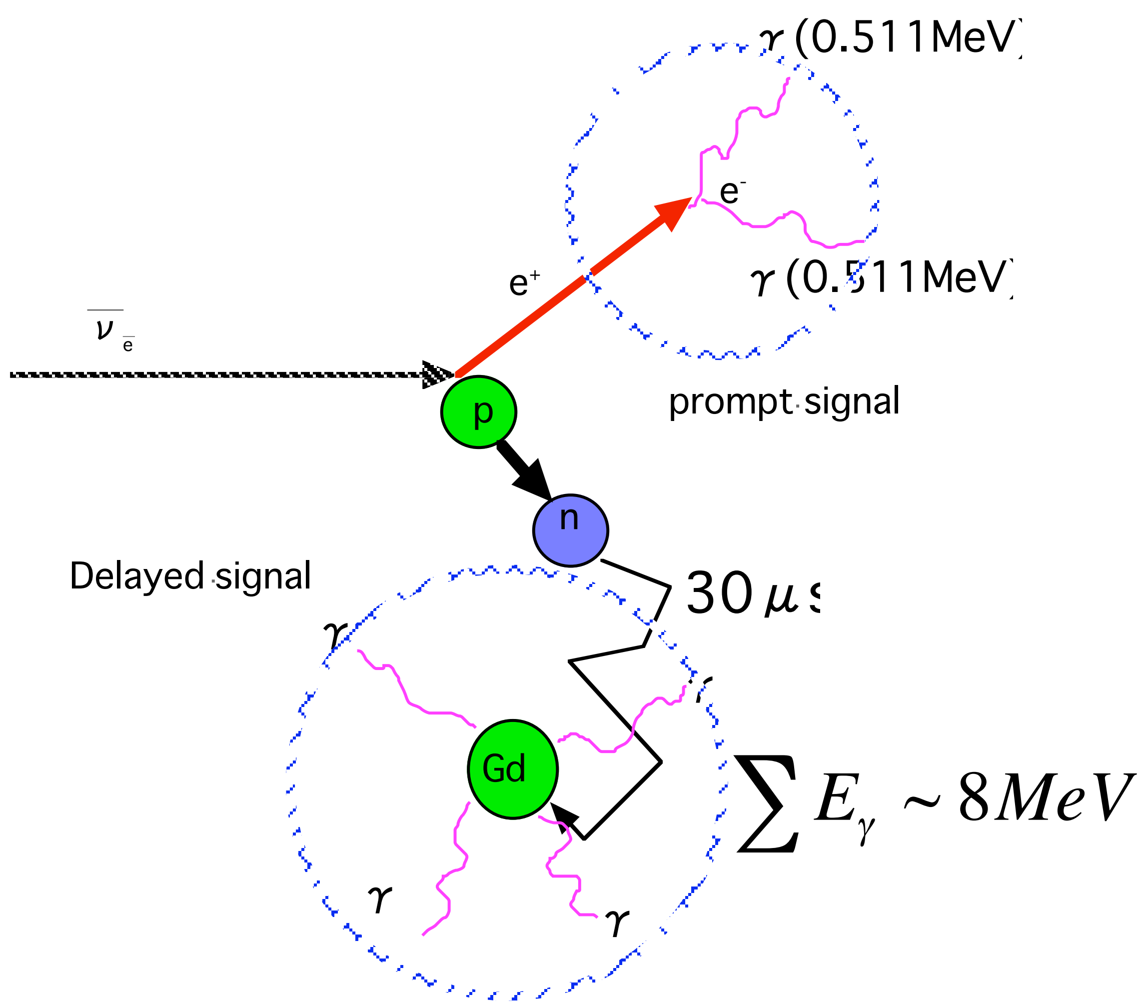
Inner Muon Veto : 90 m^3
mineral oil + 70 8" PMTs

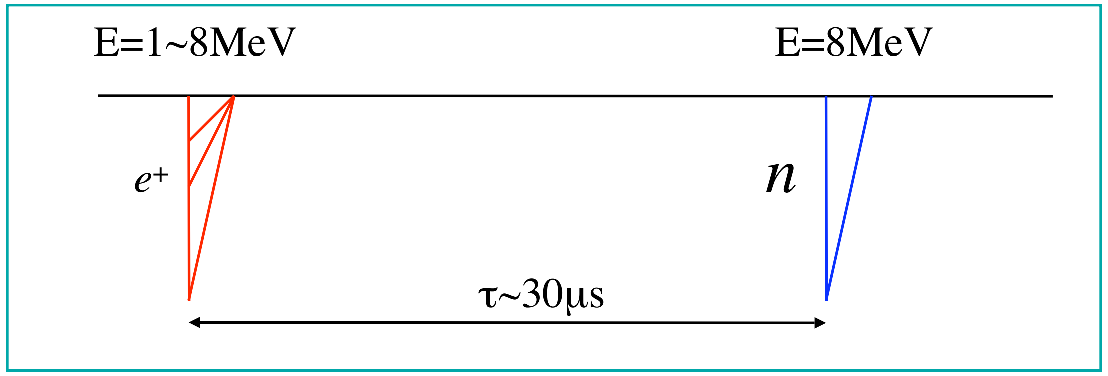
Steel Shielding :
17 cm steel, All around

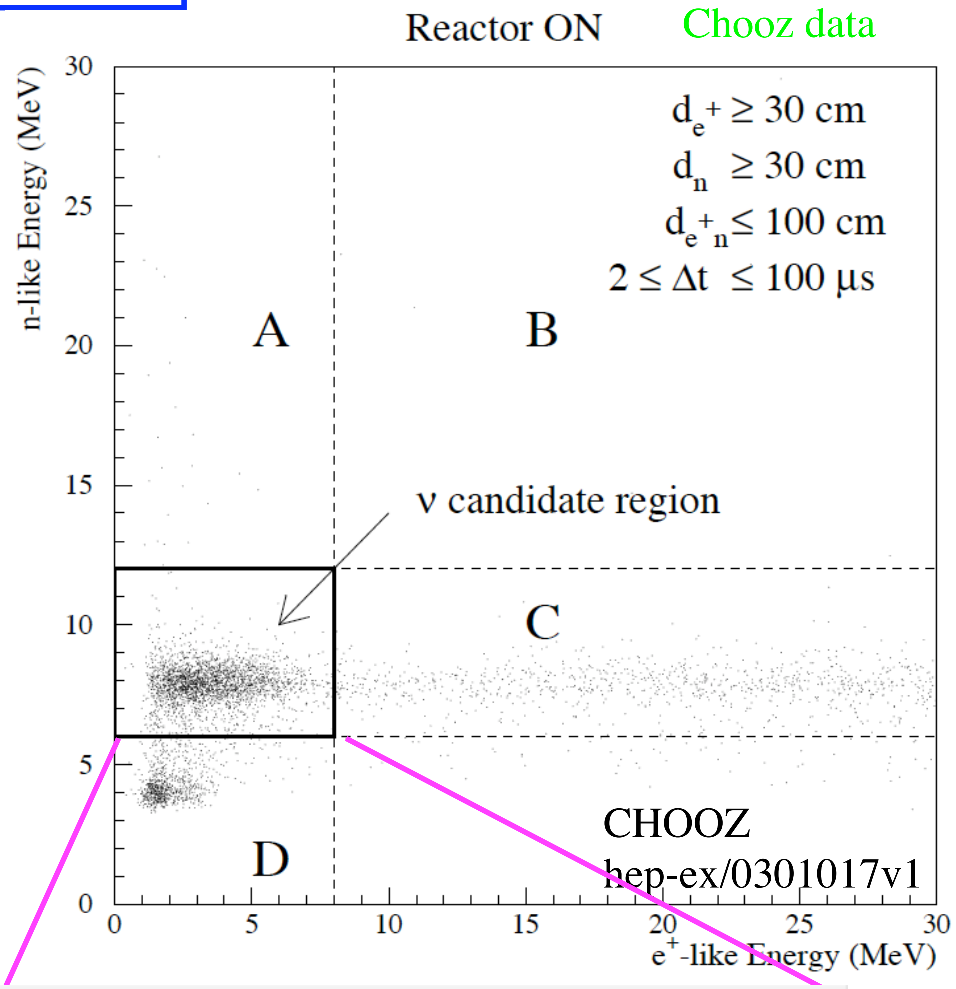


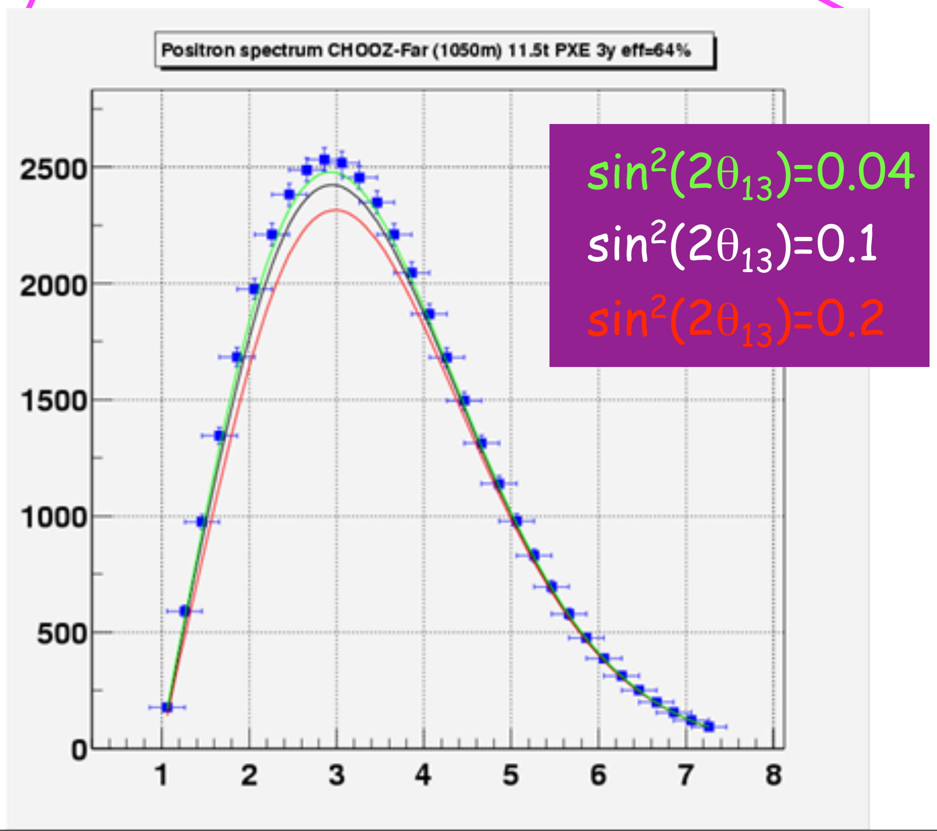
$\overline{\nu}_e$ Detection

Gd doped liquid scintillator



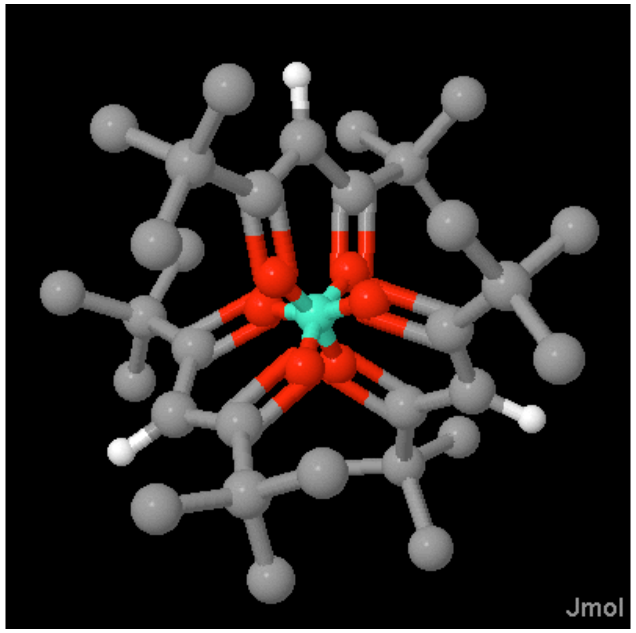






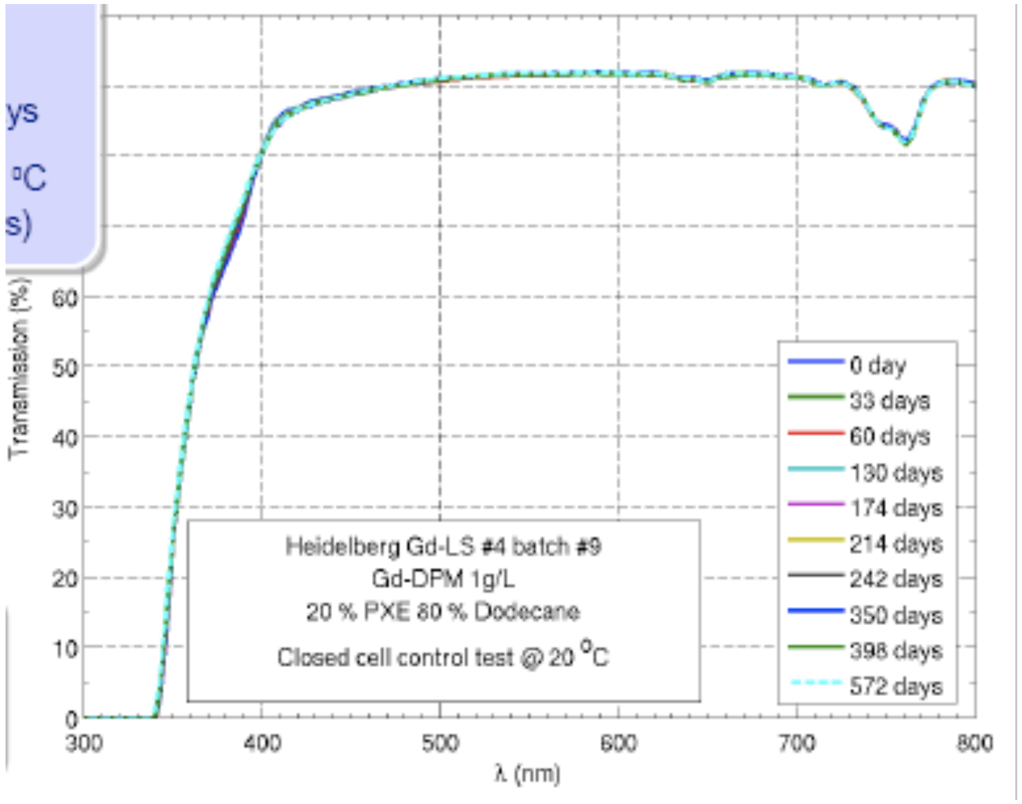
Gd doped scintillator

- **Solvent: 20% PXE – 80% Dodecane**
- **Gd loading: being developed @MPIK**
  - 0.1% Gd loading of Gd - Beta Dikitonate
  - Long term Stability promising
  - LY ~7000 ph/MeV: 6 g/l PPO + 50 mg/l Bis-MSB
  - Attenuation length: 5-10 m meters at 420 nm
  - Radiopurity → U: 10^{-12} g/g - Th: 10^{-12} g/g - K: 10^{-9} g/g



$Gd(dpm)_3$

MPIK new building for storage and purification of scintillators



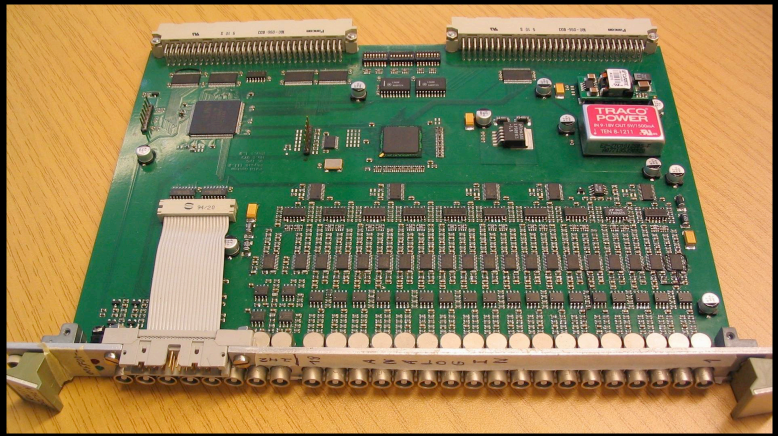
UV-VIS-IR scintillator transmission

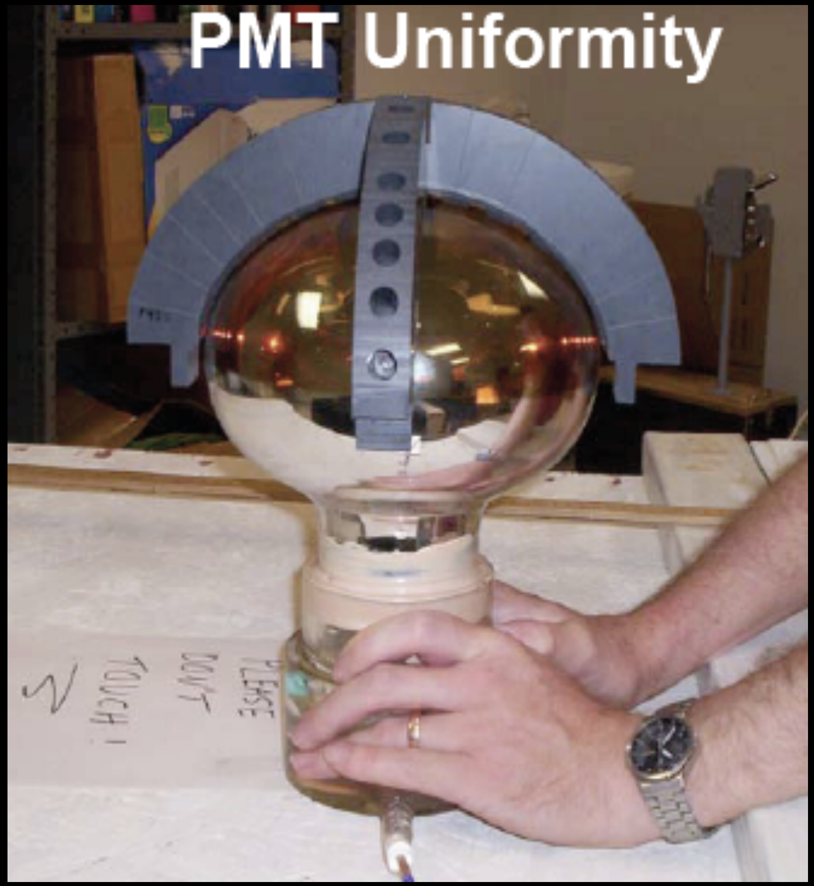
- Heidelberg MPIK →Transition to industrial production of 100 kg of Gd → summer 2007
- On-site storage building *available* at Chooz → Upgrade will be done in 2007

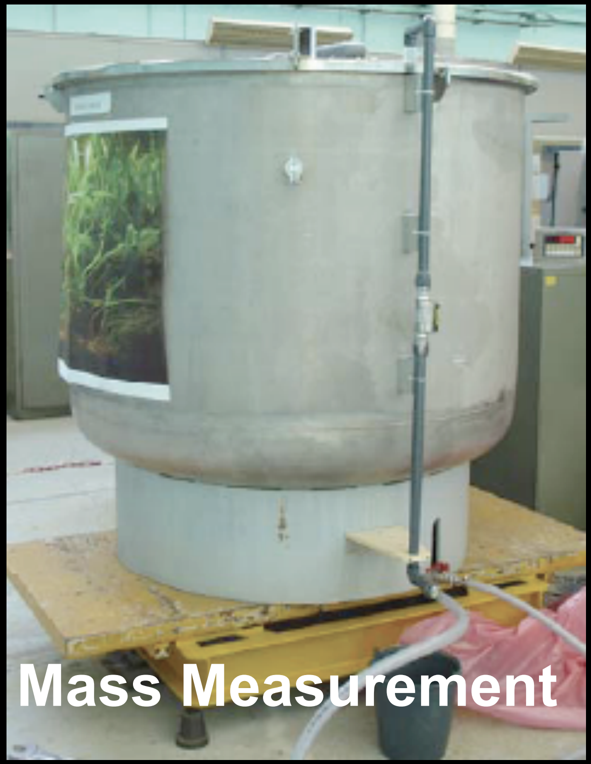
Testing & prototyping


Helmholtz-Coils

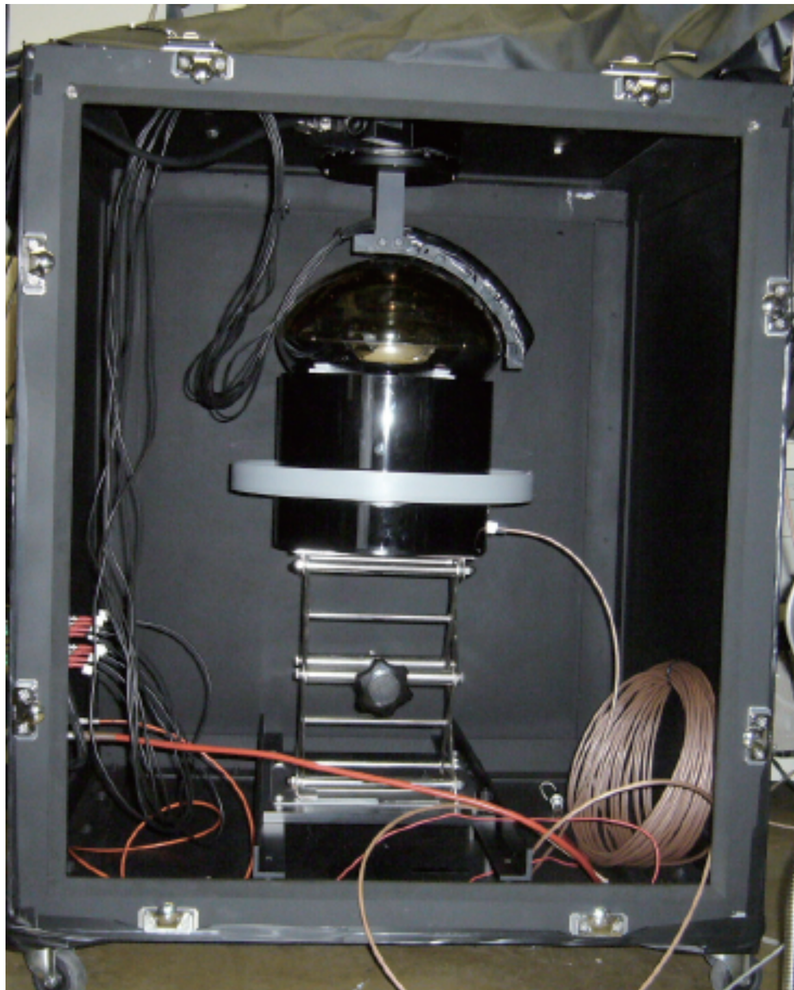
Demagnetization



L1 Trigger Board


PMT Uniformity

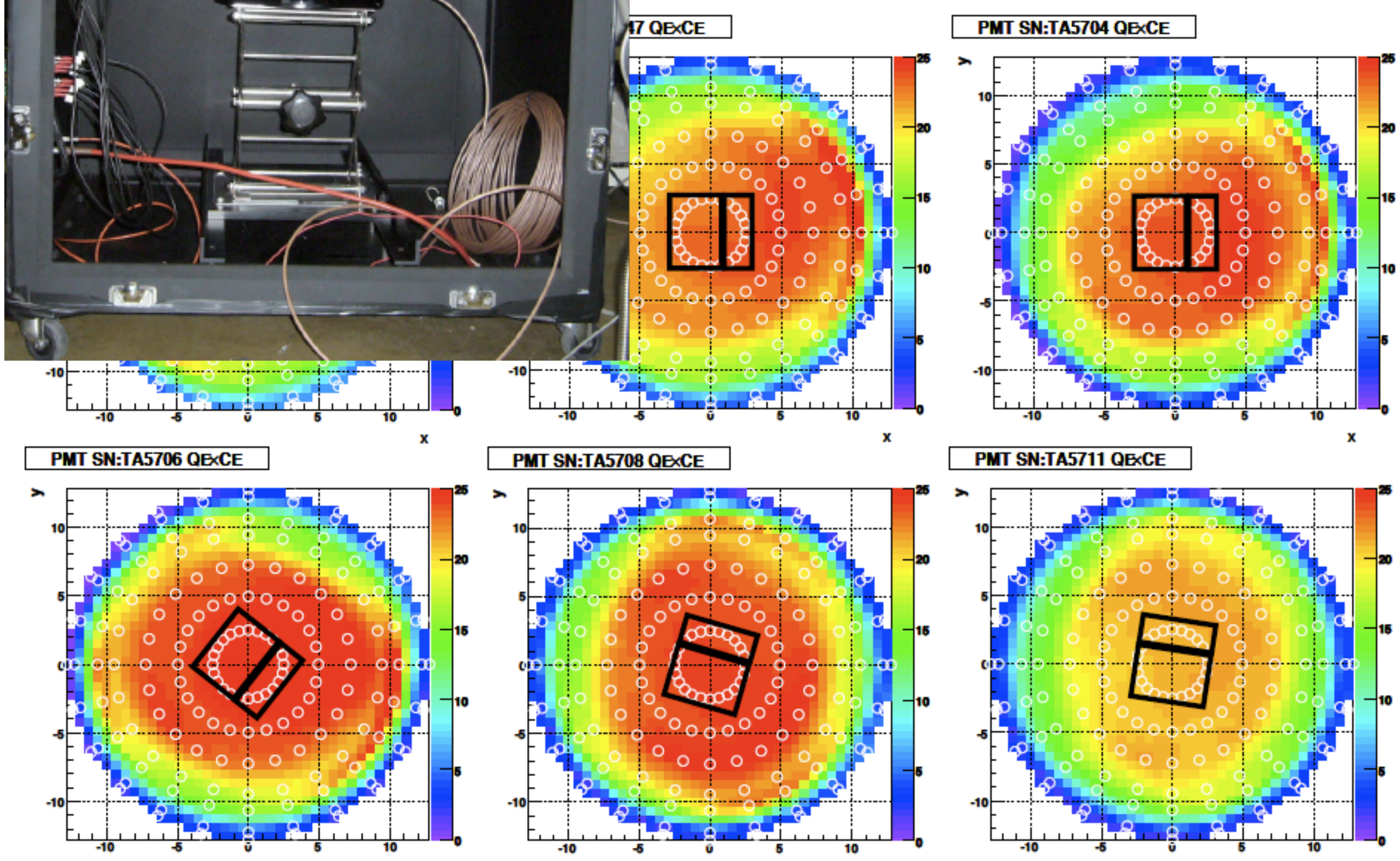

Mass Measurement

PMT system developments



Measurement box
in Tokyo:

QExCE mapping



HPK R7081
high performance
low background
10" PMT

Improving CHOOZ:

@CHOOZ: R = 1.01 ± 2.8%(stat)±2.7%(syst) → current θ_{13} limit

– Statistical error –

	CHOOZ	**Double-Chooz**
Target volume	5.6 m^3	10.3 m^3
Target composition	$6.8x10^{28}$ H/m^3	$6.8x10^{28}$ H/m^3
Data taking period	Few months	3-5 years
# of Events	2700	CHOOZ-far : 40 000/3 y CHOOZ-near: >$1x10^6$/3 y
Statistical error	2.7%	0.5%

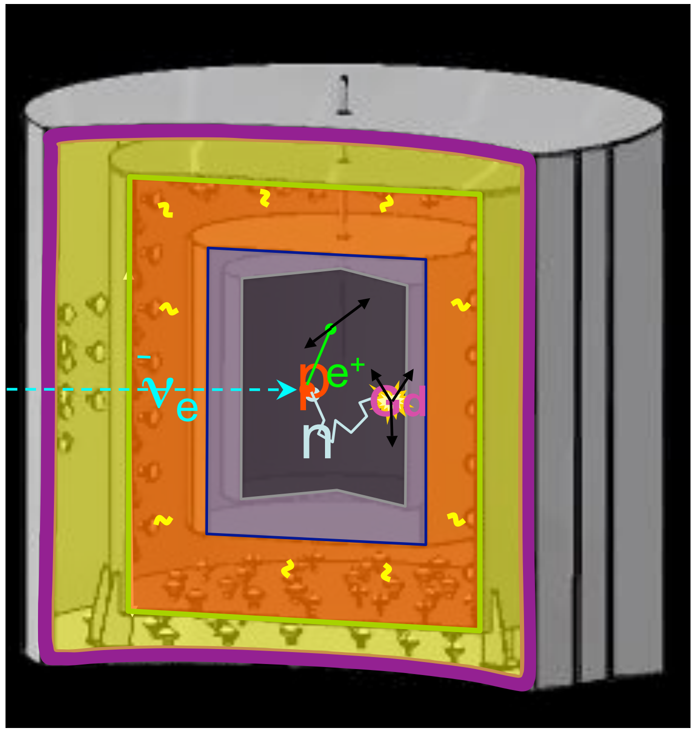
Luminosity increase L = Δt x P(GW) x Np

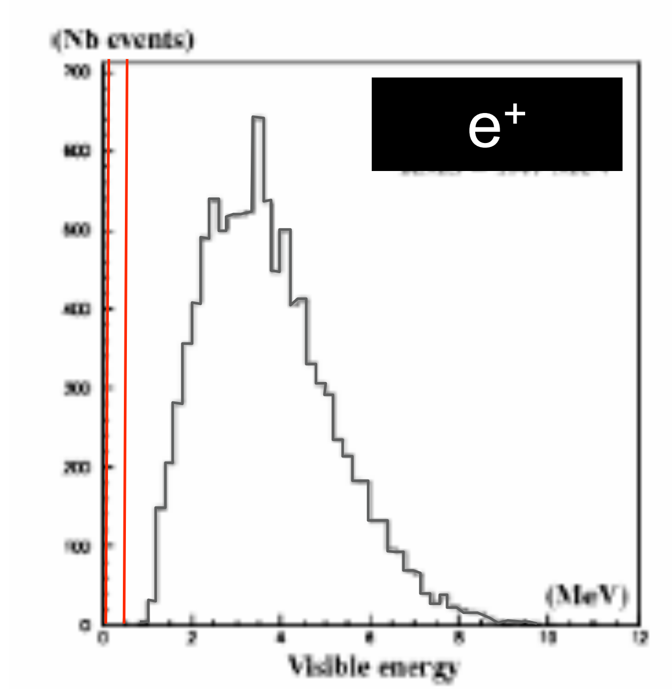
Systematics

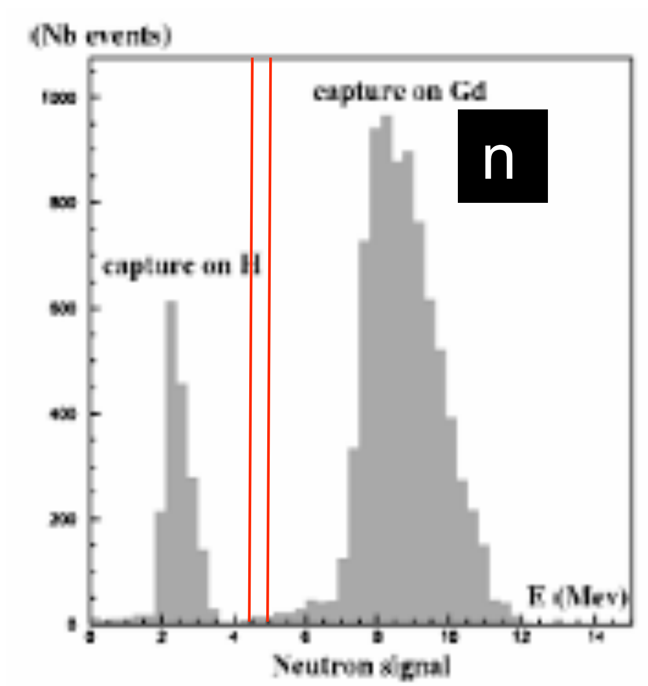
		Chooz	Double-Chooz	
Reactor-induced	ν flux and σ	1.9%	<0.1 %	Two ''identical'' detectors, Low bkg
	Reactor power	0.7%	<0.1 %	
	Energy per fission	0.6%	<0.1 %	
Detector - induced	Solid angle	0.3%	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Target Mass	0.3%	0.2%	Same weight sensor for both det.
	Density	0.3%	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2%	<0.2%	Same scintillator batch + Stability
	Spatial effects	1.0%	<0.1 %	''identical'' Target geometry & LS
	Live time	few %	0.25%	Measured with several methods
Analysis	From 7 to 3 cuts	1.5%	0.2 - 0.3 %	(see next slide)
	Total	**2.7%**	**< 0.6 %**	**(Total ~0.45% without contigency ….)**

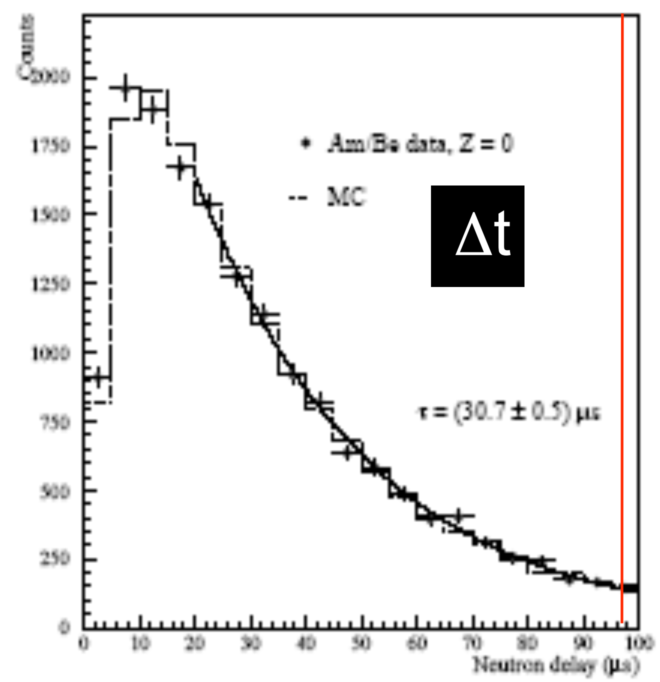
Relative Normalization: Analysis

- ✓ @Chooz: 1.5% syst. err.
  - 7 analysis cuts
  - Efficiency ~70%
- ✓ Goal Double-Chooz: ~0.3% syst. err.
  - 2 to 3 analysis cuts
- ✓ Selection cuts
  - neutron energy
  - (- distance e+ - n) [level of accidentals]
  - Δt (e+ - n)





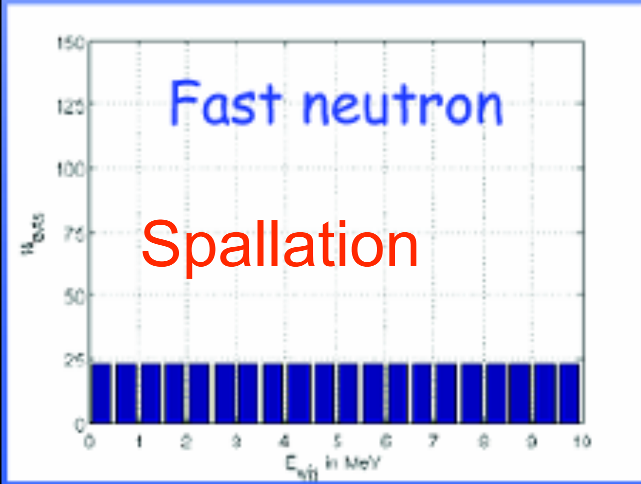


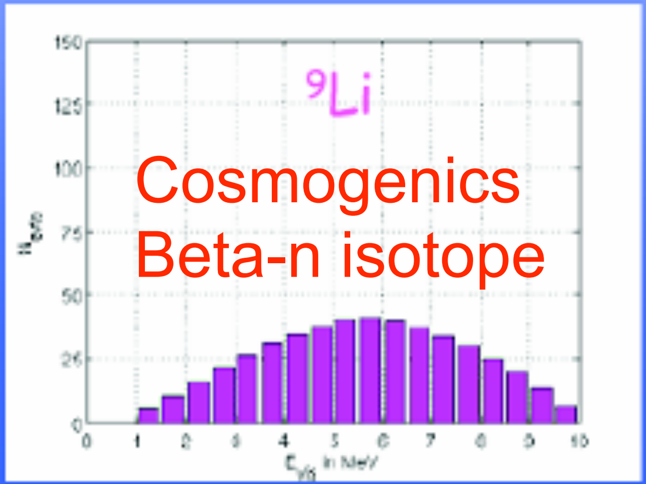


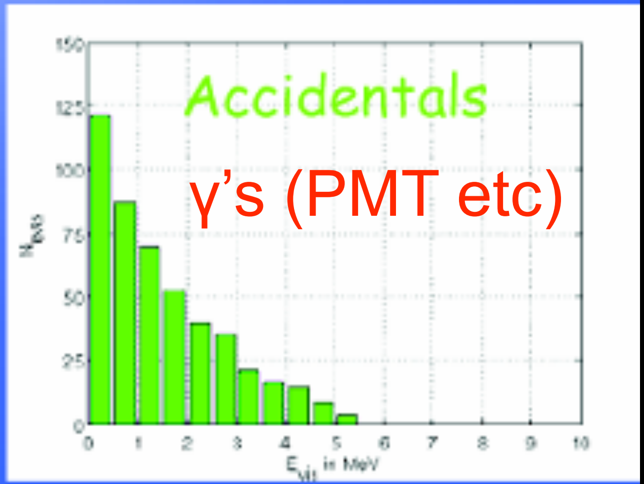
* Efficiency is insensitive to the energy scale error

* No fiducial cuts

Backgrounds







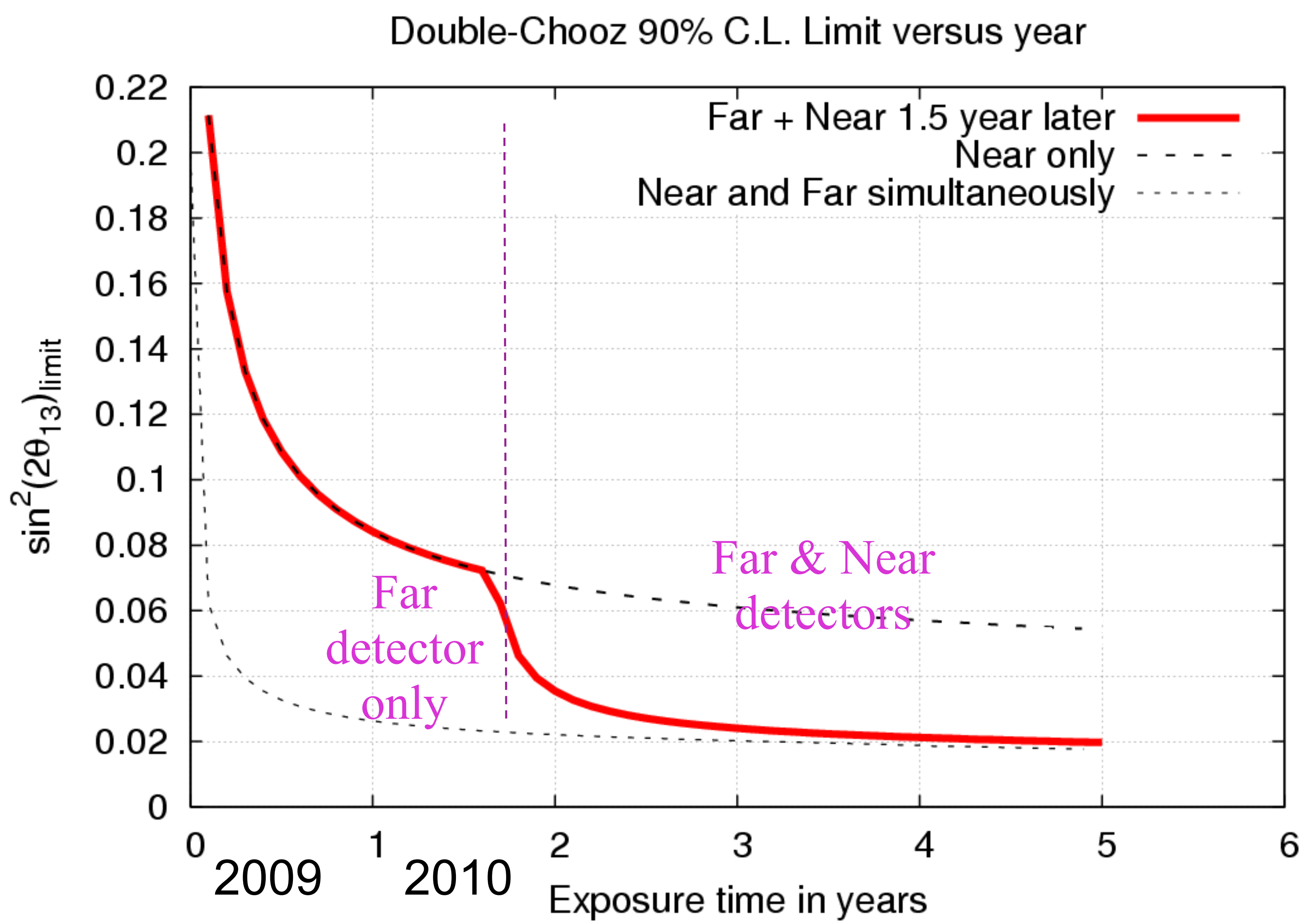
Detector	Site		Background				
			Accidental		Correlated		
			Materials	PMTs	Fast n	μ-Capture	^{9}Li
CHOOZ		Rate (d^{-1})	—	—	—	—	0.6 ± 0.4
(24 ν/d)		Rate (d^{-1})	0.42 ± 0.05		$1.01 \pm 0.04(stat) \pm 0.1(sys)$		
	Far	bkg/ν	1.6%		4%		
		Systematics	0.2%		0.4%		
Double Chooz		Rate (d^{-1})	0.5 ± 0.3	1.5 ± 0.8	0.2 ± 0.2	< 0.1	1.4 ± 0.5
(69 ν/d)	Far	bkg/ν	0.7%	2.2%	0.2%	<0.1%	1.4%
		Systematics	<0.1%	<0.1%	0.2%	<0.1%	0.7%
Double Chooz		Rate (d^{-1})	5 ± 3	17 ± 9	1.3 ± 1.3	0.4	9 ± 5
(1012 ν/d)	Near	bkg/ν	0.5%	1.7%	0.13%	<0.1%	1%
		Systematics	<0.1%	<0.1%	0.2%	<0.1%	0.2%

hep-ex/0606025

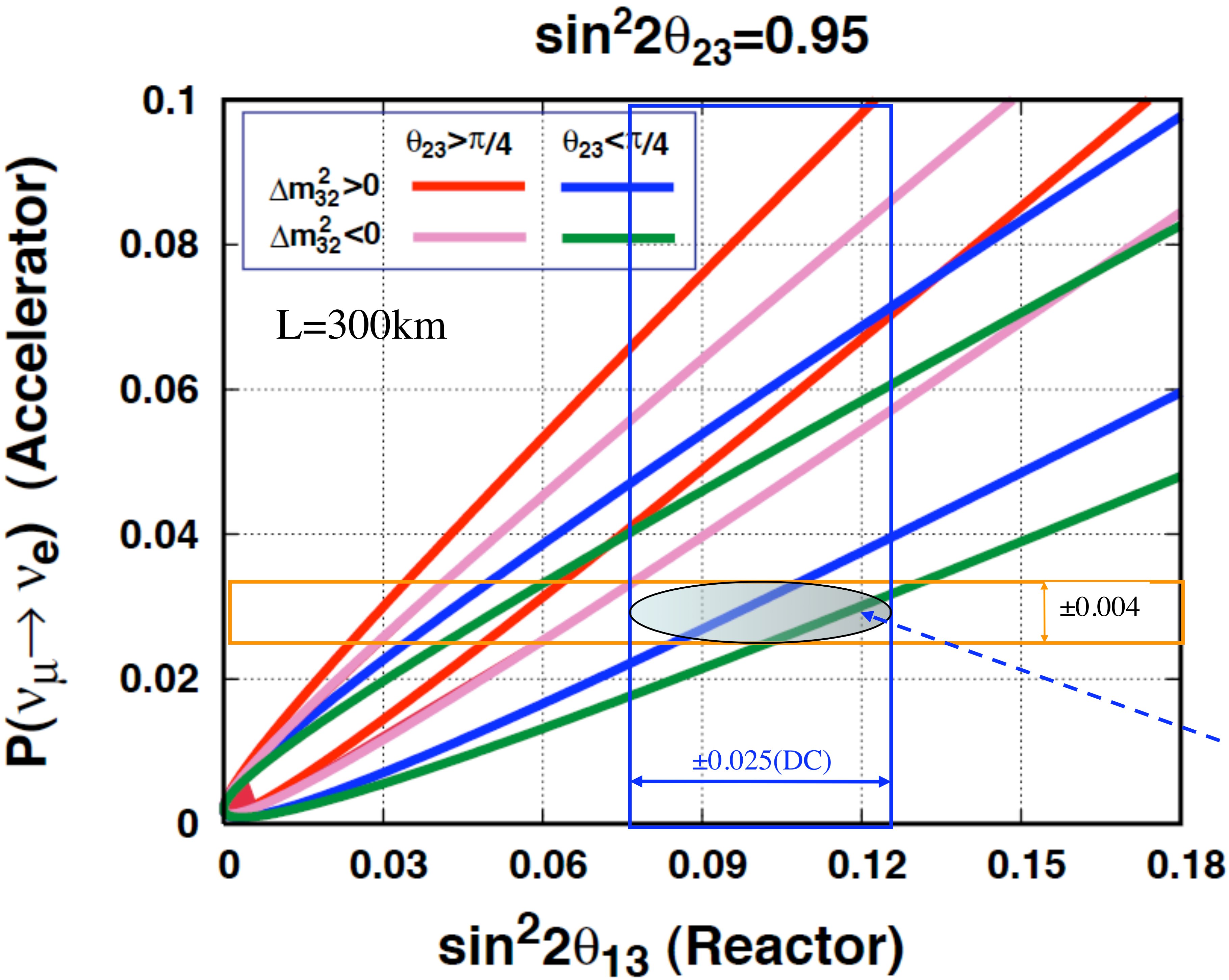
Sensitivity

Double-Chooz Far Detector starts early 2009
Double-Chooz Near detector follows 16 months later

90% C.L. contour if $\sin^2(2\theta)=0$
Δm^2_{atm} = 2.8x10^{-3} eV^2 is supposed to be known at 20% by MINOS



One possible case of Complementarity to Accelerator-θ_{13}



If ..

Degeneracy
Solved!

$\theta_{23}<\pi/4$

Daya Bay (hep-ex/0701029)

In Daya Bay, China

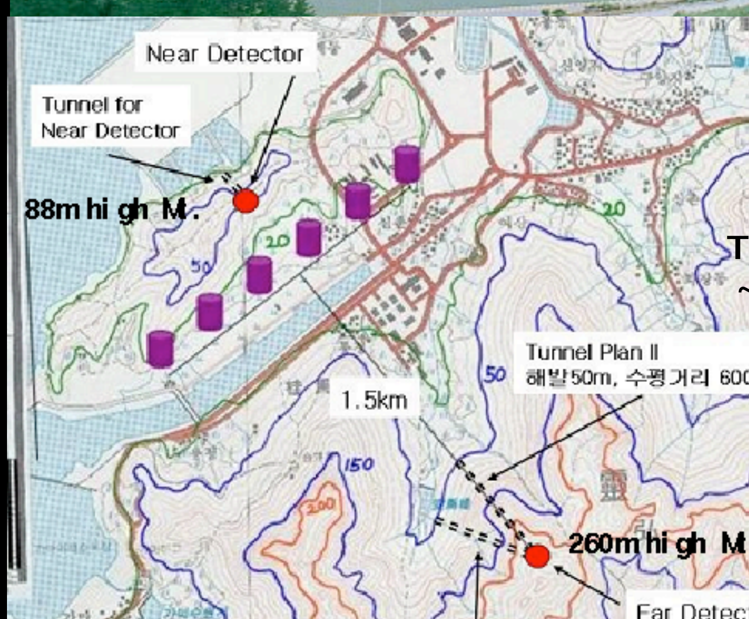
Average F. R.	DB	LA1	LA2
Dn1xyz (DB)	83.1%	11.4%	5.5%
Dn2xyz (LA)	6.5%	50.6%	42.8%
Dfxyz (Mid)	22.5%	47.1%	30.4%
Dfxyz (Far)	24.9%	37.4%	37.7%

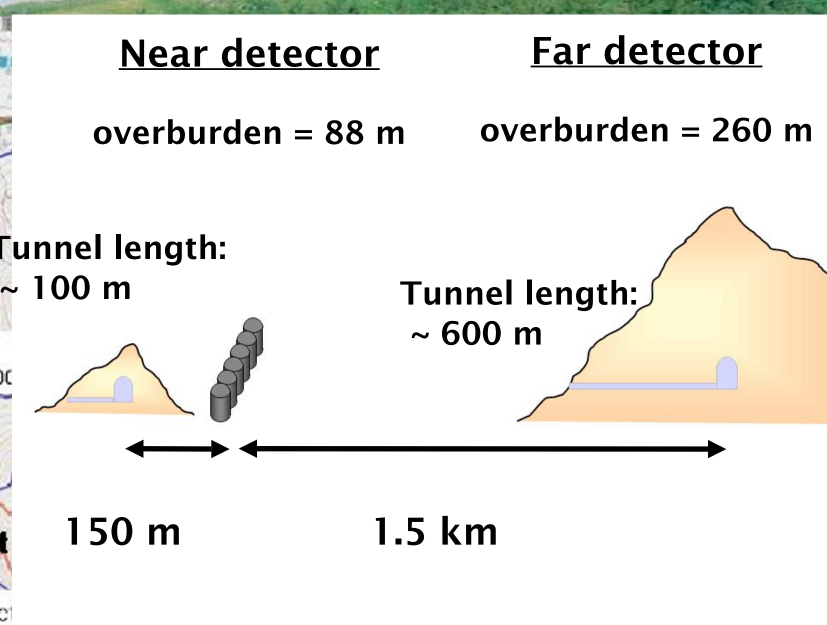
- **4 cores – 2 sites – 11.6 GWth**
  ⇨ 6 cores in 2011- with 17.4 GWth
- **2 near positions, (1 mid), 1 far**
  - far: 4 modules of 20 t
  - near: 2 modules of 20 t each
- **Civil Engineering**
  - ~ 3.4 km tunnels
  - 5 laboratories to be build
- **Statistics (including ε)**
  - far: 70 evt/day/mod
  - mid-site: 200 evts/day/mod
  - near: 600 evts/day/mod
- **Mobile modules** ⇨ swapping (Theo.)
- **Systematics**
  - reactors : ~ 0.1% - detectors : ~ 0.38%
- **Backgrounds**
  - B/S @ near sites: ~0.5% @ far site: ~0.2%
- **Sensitivity goal & Planning**
  1. Fast Measurement (Phase I)
     - DYB+Mid-site, 2008-2009
     - Sensitivity (1 year) ~ 0.035
  2. Complete measurement
     - DYB+LA+Far, from 2010
     - Sensitivity (3 years) < 0.008

RENO (http://neutrino.snu.ac.kr/RENO)

In South Corea Yongwang,

	R1	R2	R3	R4	R5	R6
Near	3%	8%	39%	39%	8%	3%
Far	15%	17%	18%	18%	17%	15%



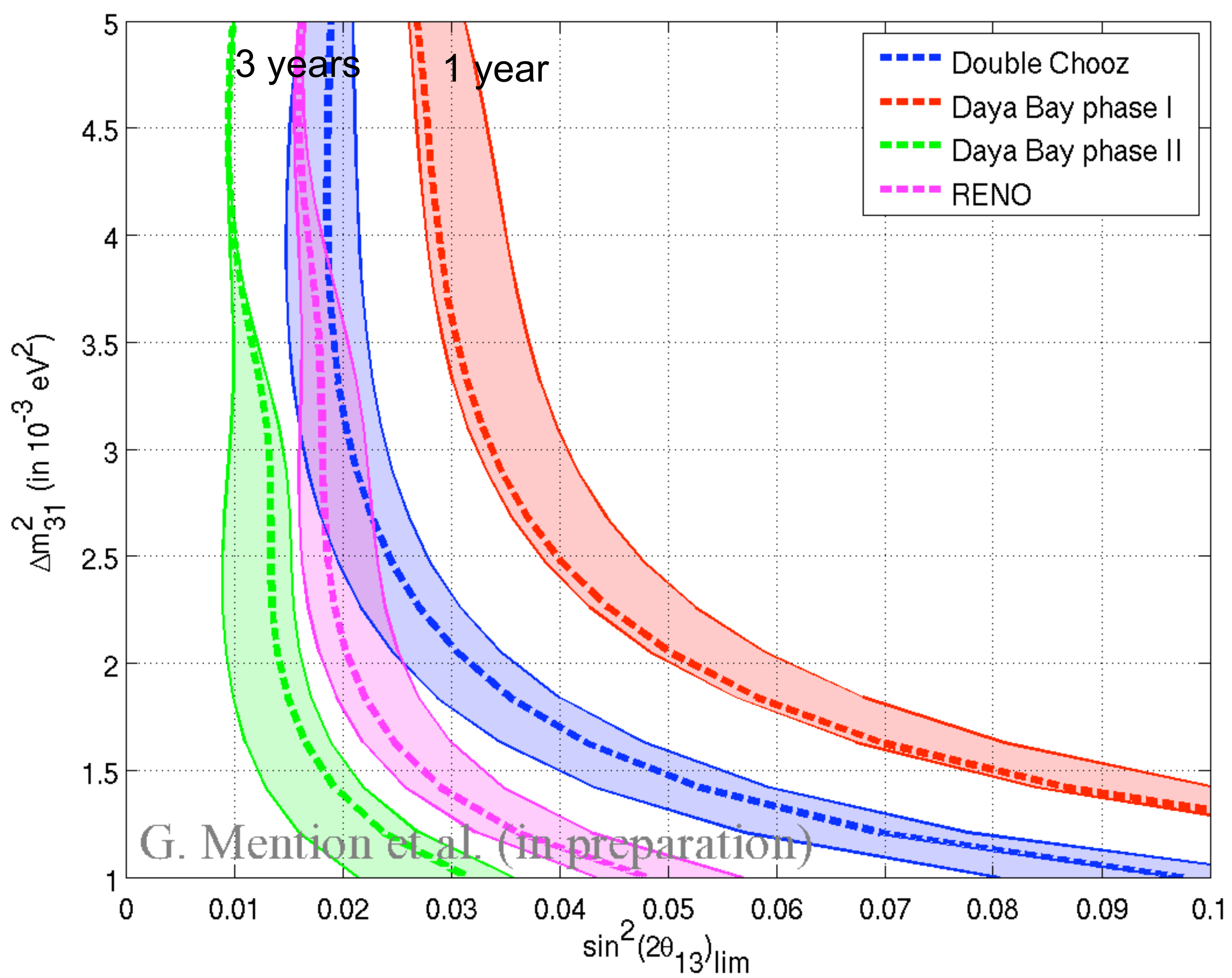


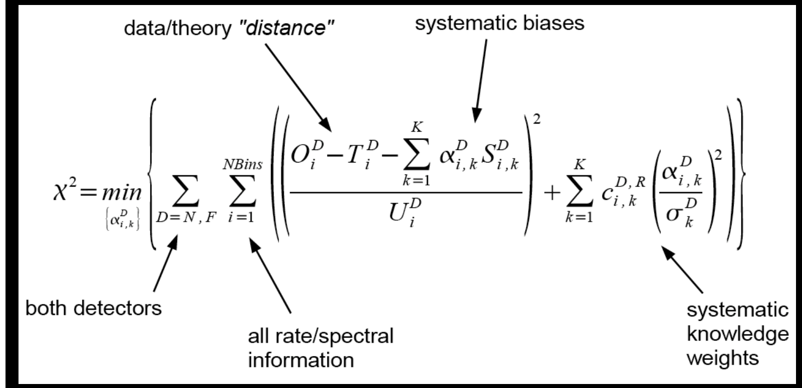
- **6 cores – 1 site – 16.4 GW_{th}**
- **1 near site, 1 far,**
- **3 *"very near"* sites**
  - target: 2 x 20 t
  - + target: 3 x ~ 200-300 kg
- **Civil Engineering**
  - ~ 700 m tunnels
  - 2 laboratories to be build
- **Statistics (including ε)**
  - Far: ~ 70 evts/day
  - Near: ~ 1,700 evts/day
- **Systematics**
  - total: ~ 0.5-1%
- **Overburden**
  - Far: ~ 700 mwe
  - Near: ~ 240 mwe
- **Sensitivity & Planning**
  - Start construction in 2007
  - Sensitivity: ~ 0.02

Unified Analysis of current projects

(G. Mention & T.L.)

T. Lasserre
KEKTC07





$$\chi^2 = \min_{\{\alpha^D_{i,k}\}} \left\{ \sum_{D=N,F} \sum_{i=1}^{NBins} \left(\frac{O_i^D - T_i^D - \sum_{k=1}^{K} \alpha^D_{i,k} S^D_{i,k}}{U_i^D} \right)^2 + \sum_{k=1}^{K} c^{D,R}_{i,k} \left(\frac{\alpha^D_{i,k}}{\sigma^D_k} \right)^2 \right\}$$

Worst limit
(prediction too optimistic)

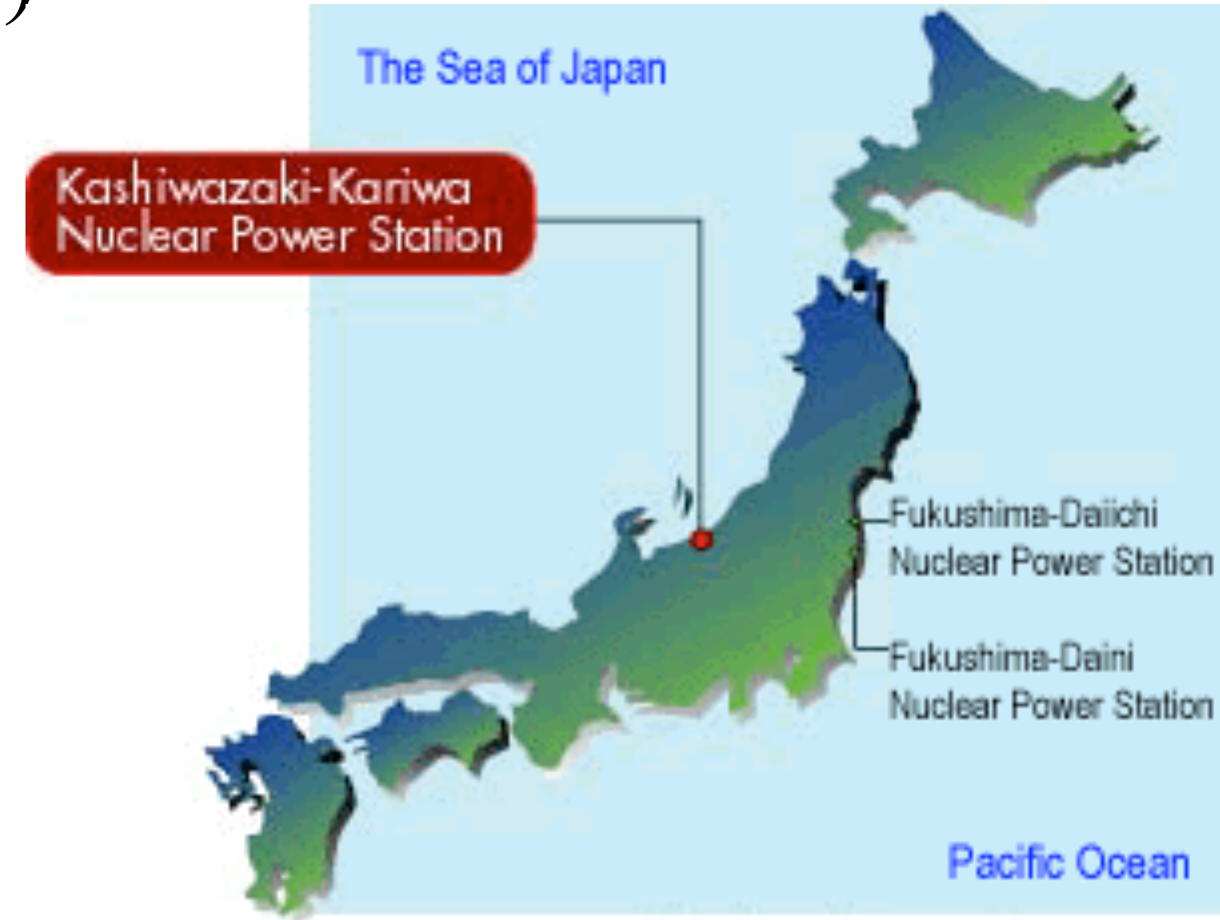
σ_{rel} = 0.18 %
σ_{pwr} = 2.0 %
σ_{abs} = 2.0 %

Best Limit
(prevision pessimistic)

σ_{rel} = 0.6 %
σ_{pwr} = 3.0 %
σ_{abs} = 3.0 %

KASKA project in Japan

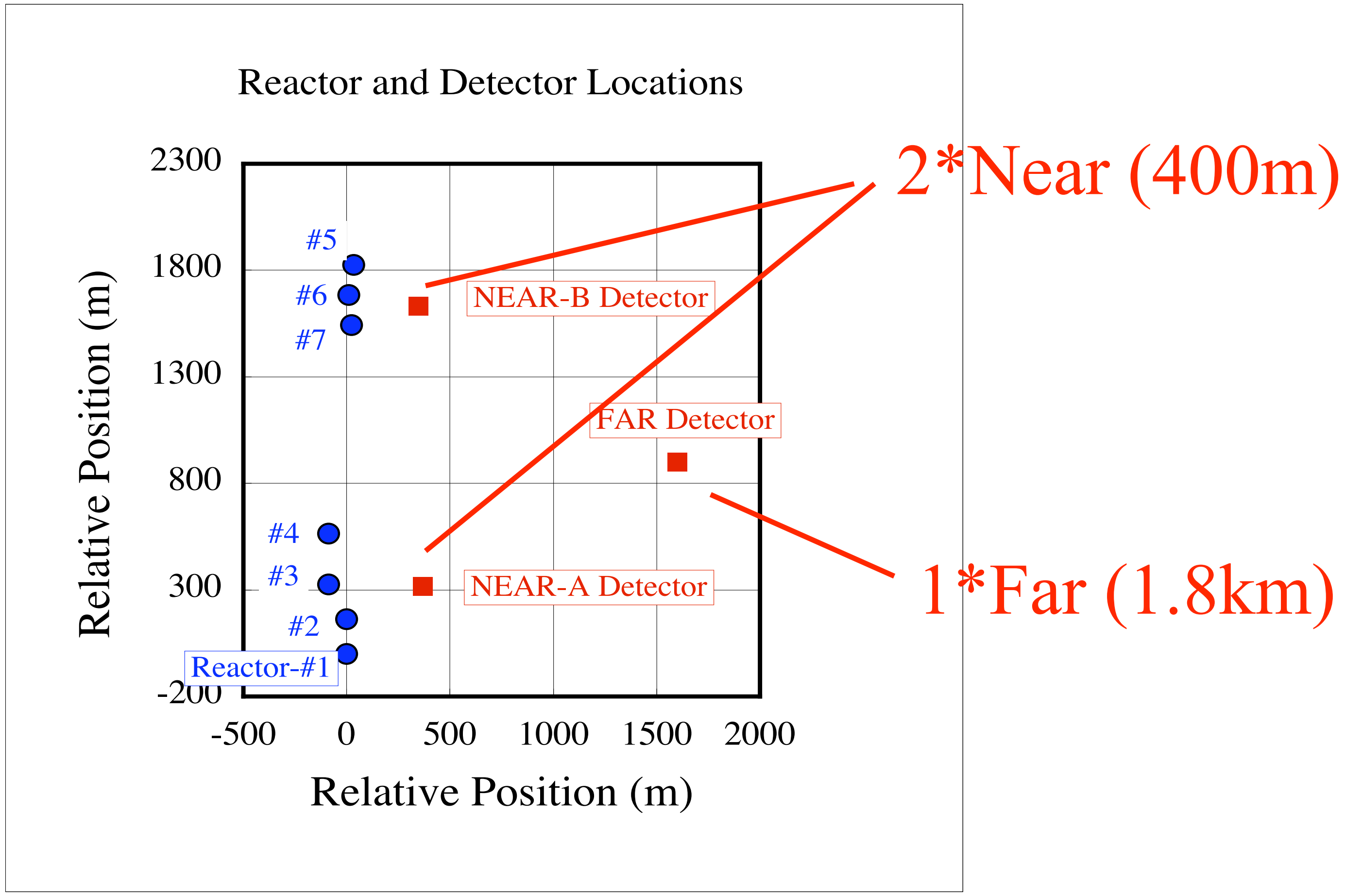
- Kashiwazaki-Kariwa Nuclear Power Station
  - World's largest reactor complex: 23.4GWth (8.2GWe)
  - Owned by Tokyo Electric Power Co. (K-K supplies 20% of total consumption of Tokyo area)
- 7 reactors in two clusters (3+4)

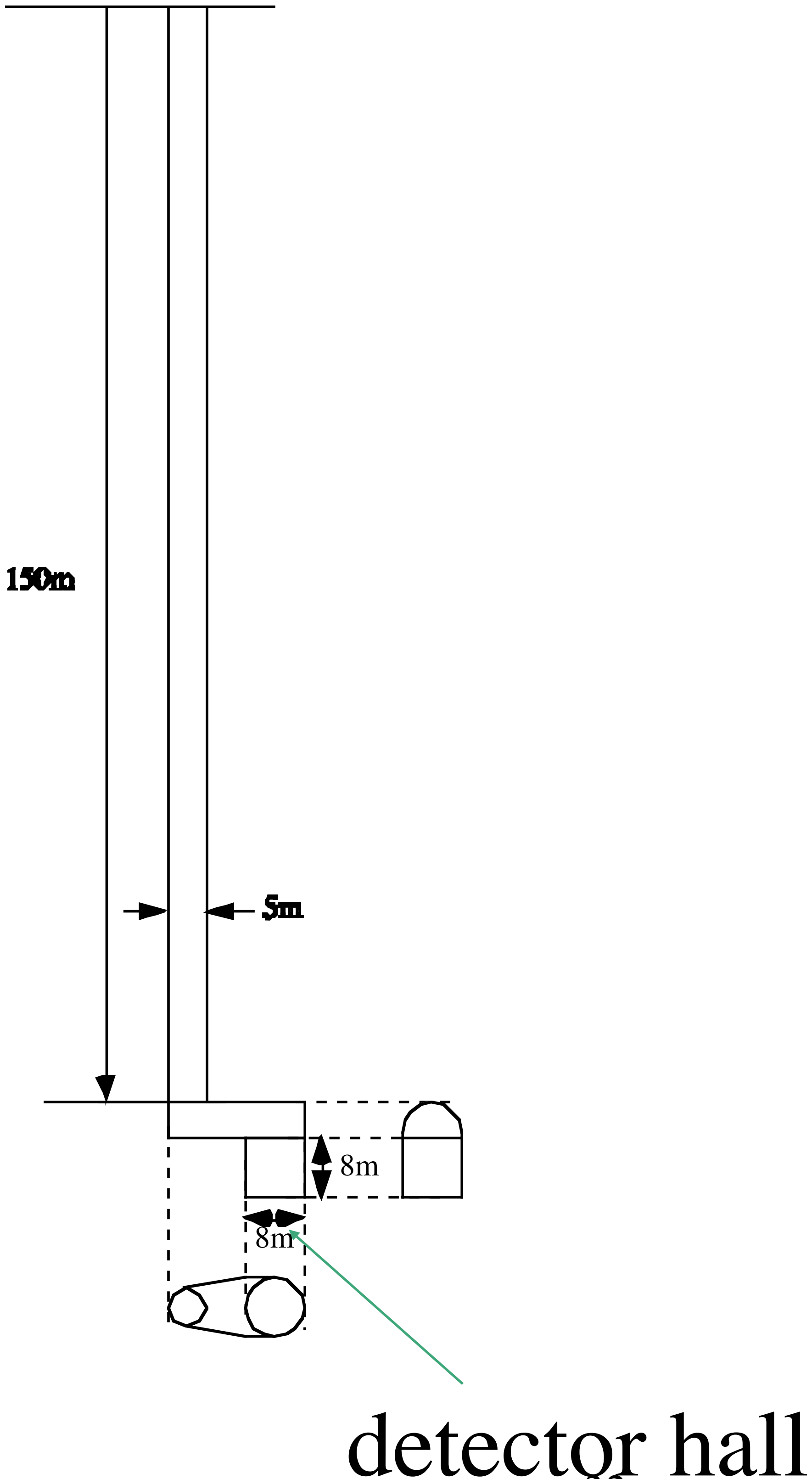


The Experiment

- Two near-detectors (50m depth = ~90mwe)
- One far-detector (150m depth = ~250mwe)

placed in vertical shafts (against cosmic rays)

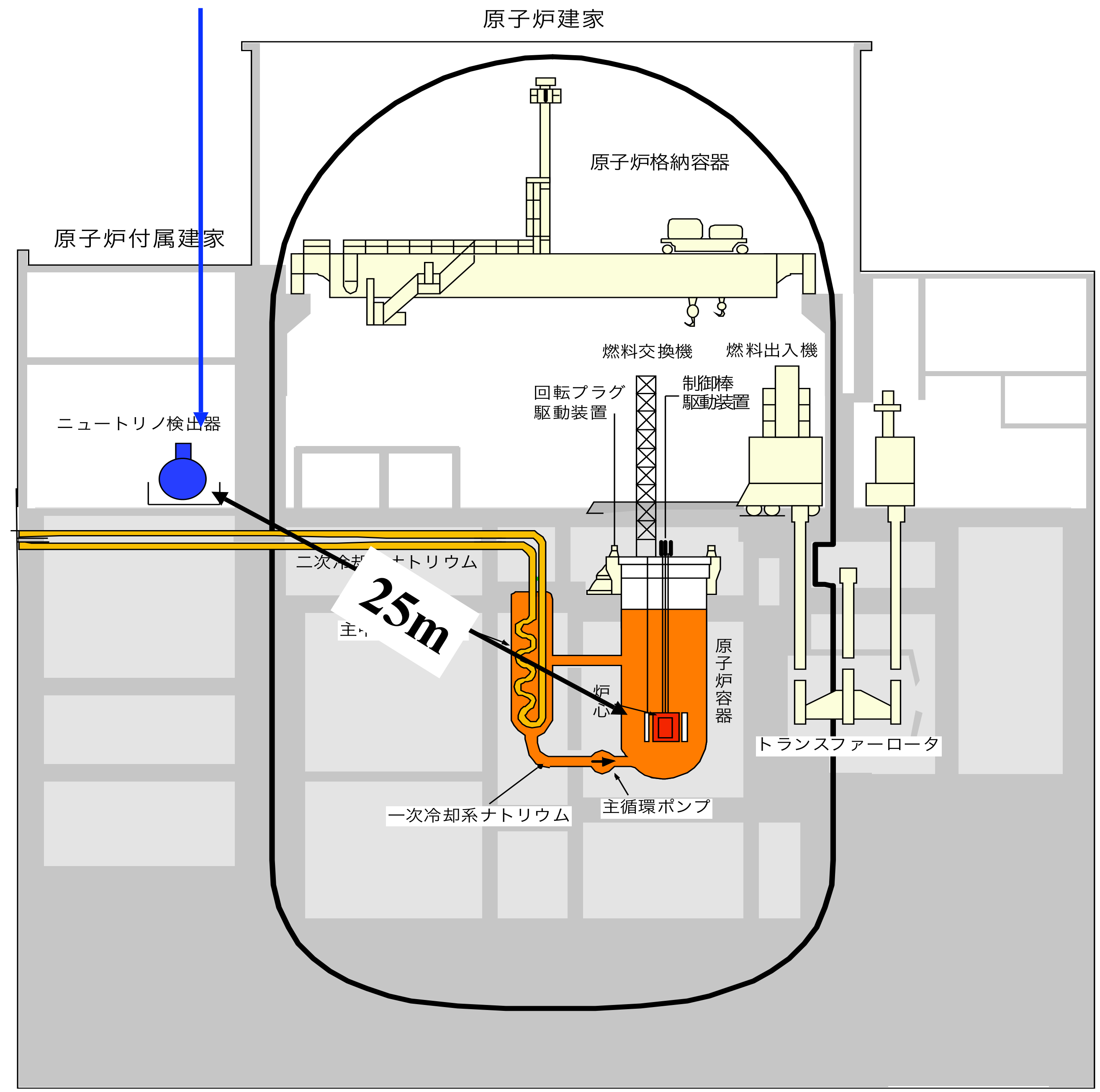




Prototype test at Research Fast Reactor

JOYO in Oarai, Ibaraki, Japan (http://www.jaea.go.jp/04/o-arai/joyo/indexs.htm)

KASKA prototype detector

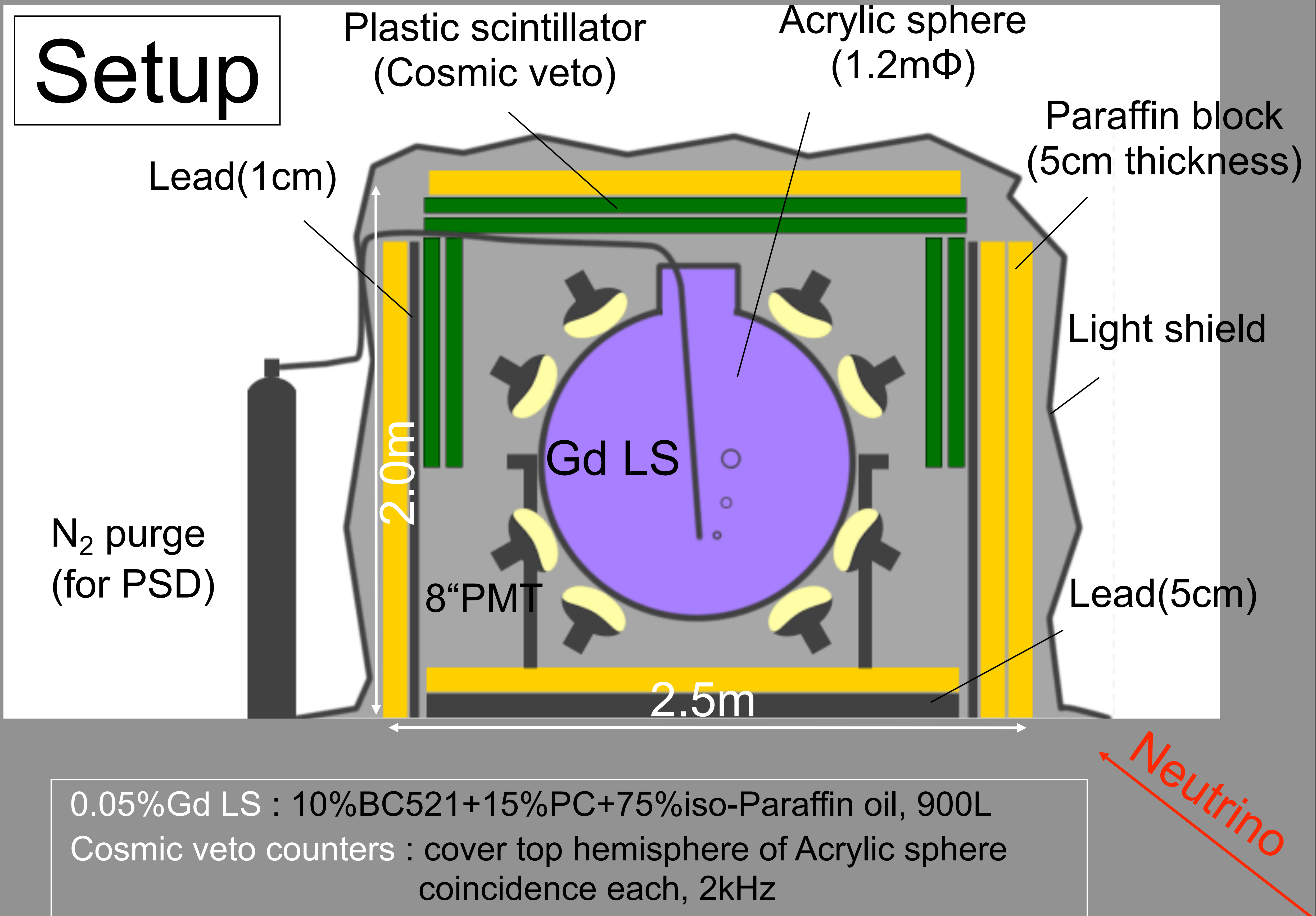


- P_{th}=140MWth(1/20 commercial reactor)
- Fuel : U(70wt %), Pu(30wt %)
- Operated by JAEA
- Operation days / Cycle : 60(rest 1cycle)
  → Easy on/off data taking
- L~25m
- Eν ~4MeV
- ~160 $\nu\, p \rightarrow e^+ n$ reactions/day

Data-taken until June 2007, total live time(on,off)=(60days,60days)

Concrete

Setup



0.05%Gd LS : 10%BC521+15%PC+75%iso-Paraffin oil, 900L

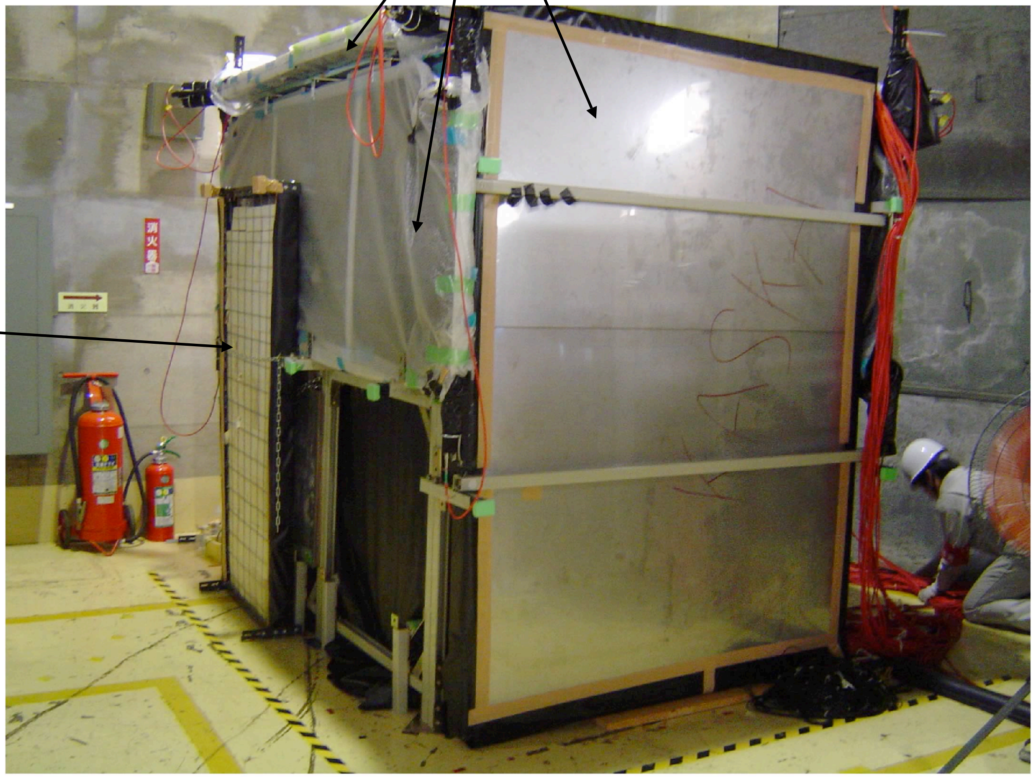
Cosmic veto counters : cover top hemisphere of Acrylic sphere coincidence each, 2kHz

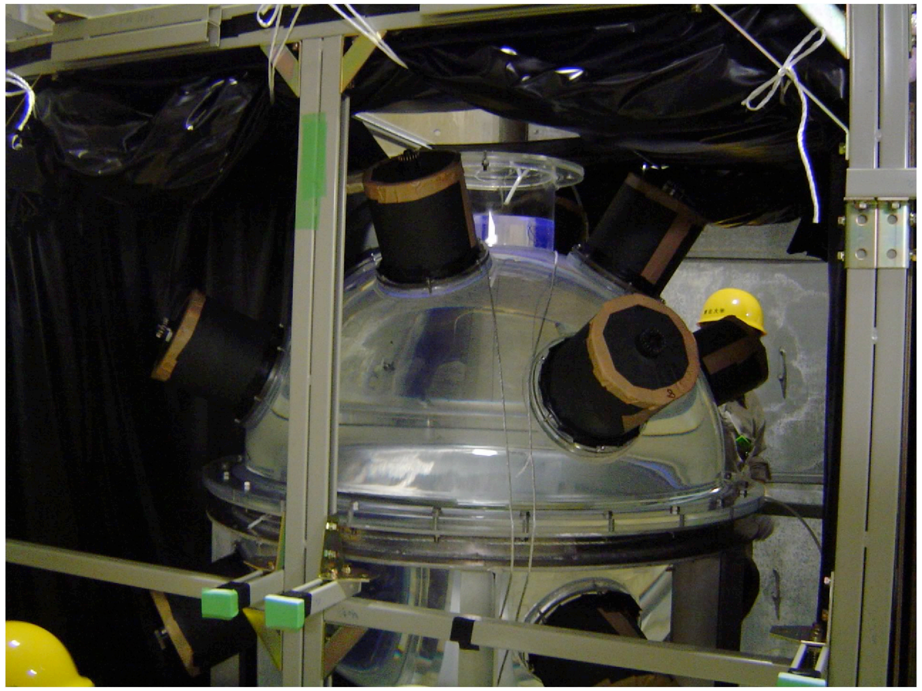
8"PMT's : R5912,16 PMT's(10%), covered each by μ-metal

Setup (picture)

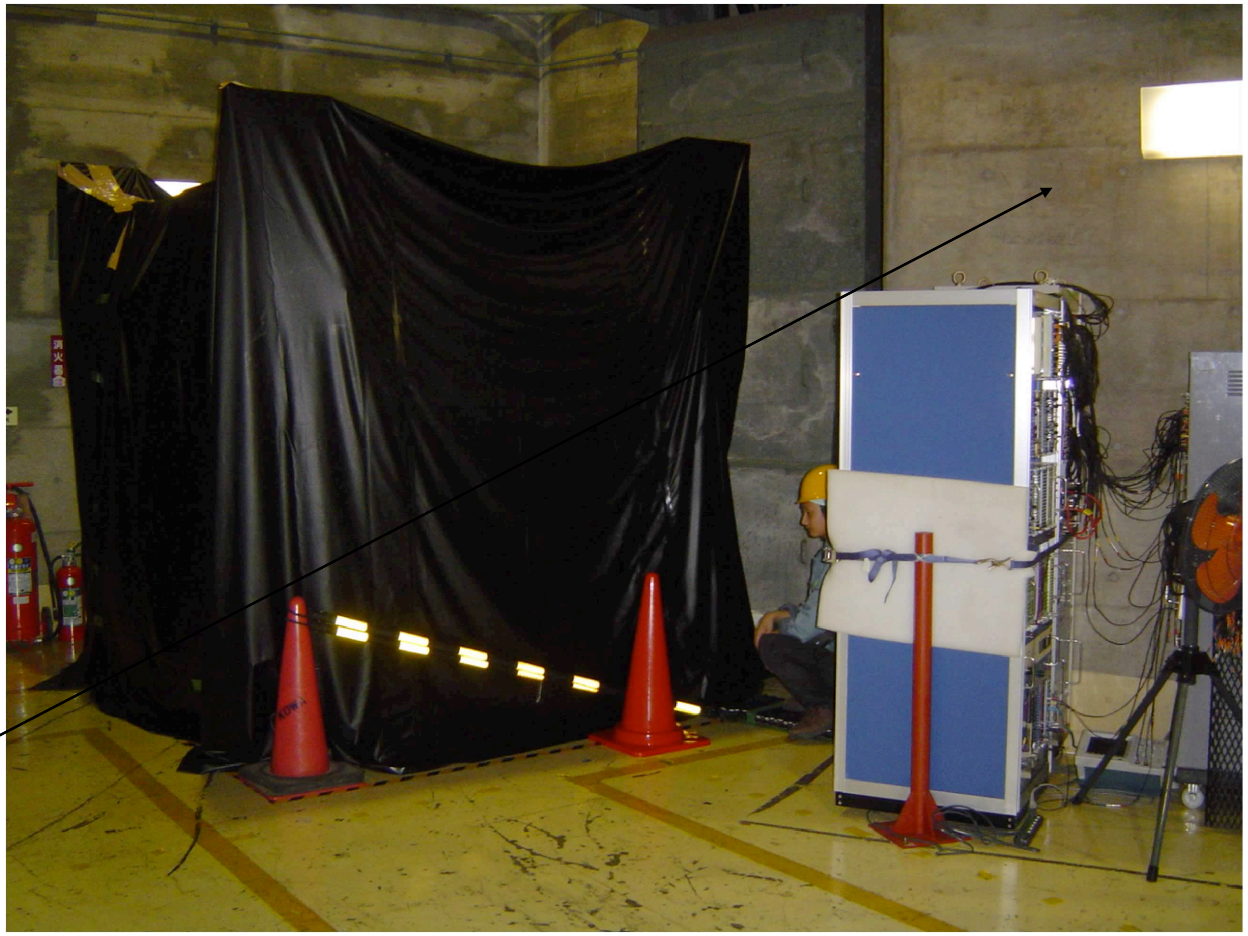
Cosmic veto counter

Paraffin blocks



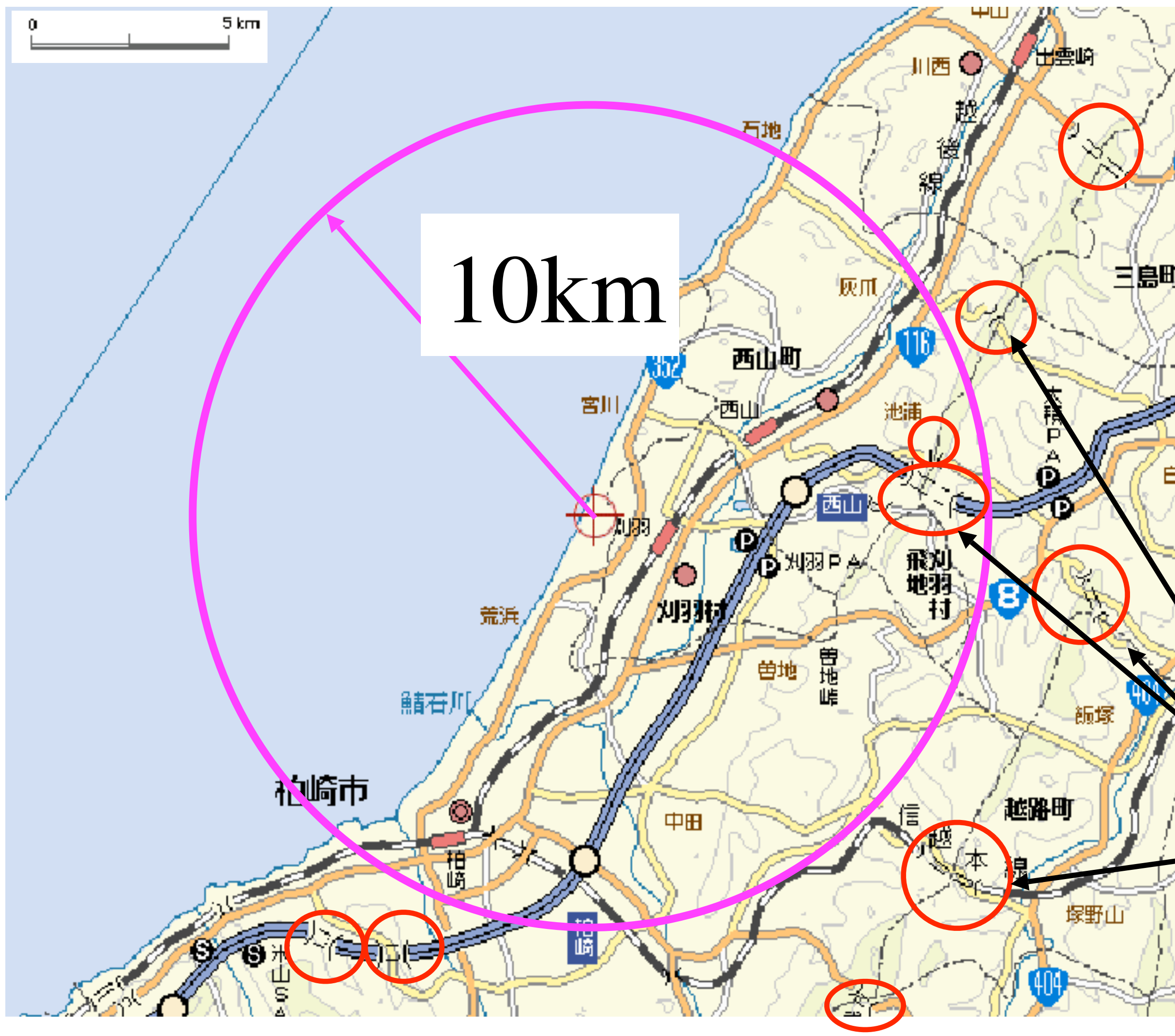


Acrylic sphere



Reactor is behind the wall.

KASKA–Δm^2_{13}

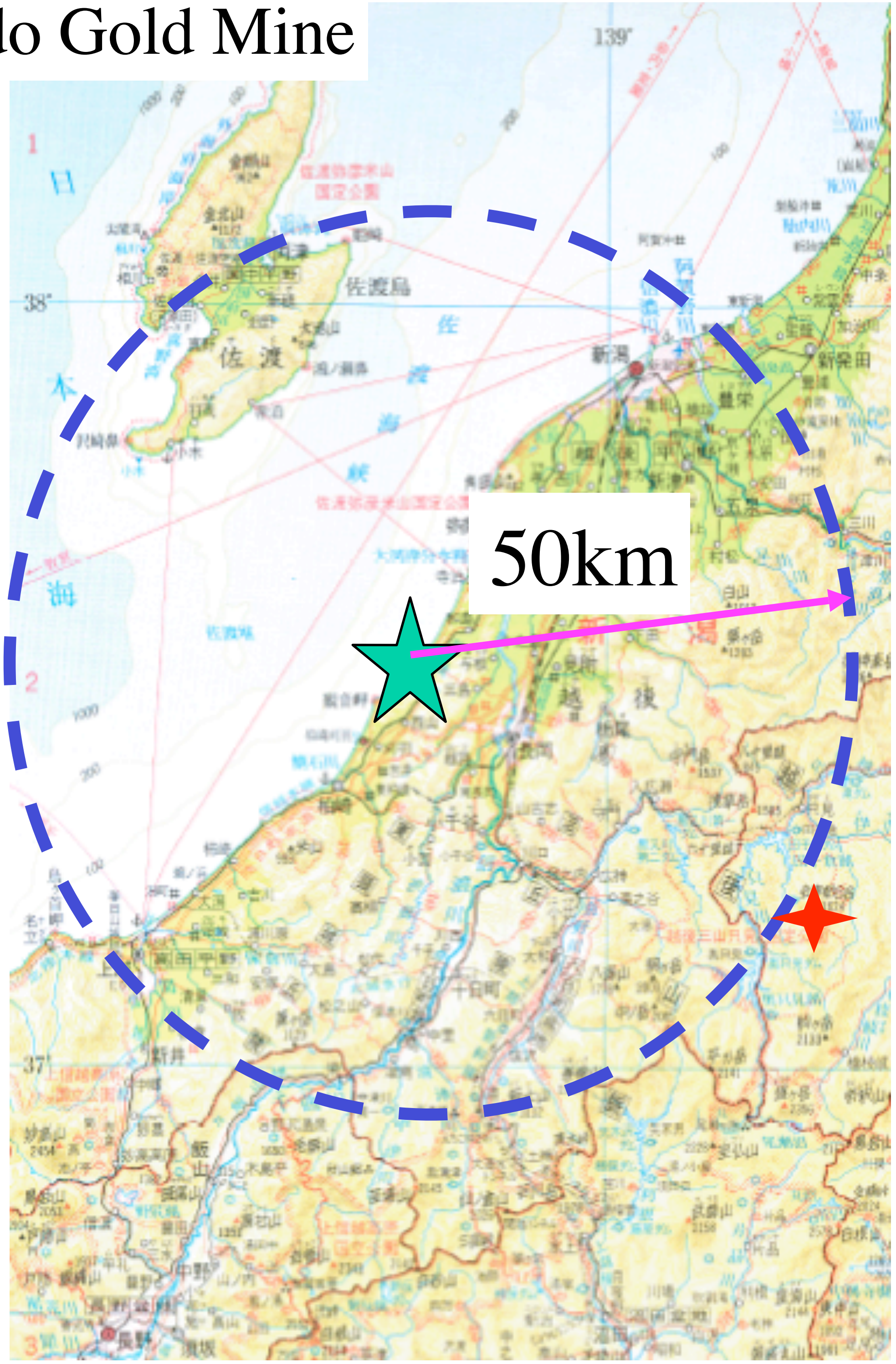


If $\sin^2 2\theta_{13}$ is measured to be relatively large, several oscillations will be observed in energy spectrum at L>5km
⇒precise Δm^2_{13} measurement

tunnels

KASKA-θ_{12}

Sado Gold Mine



θ_{12} Oscillation Max~50km

- KASKA-θ_{13} as front detectors
- Geo-neutrinos around this area will be understood by KamLAND.

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

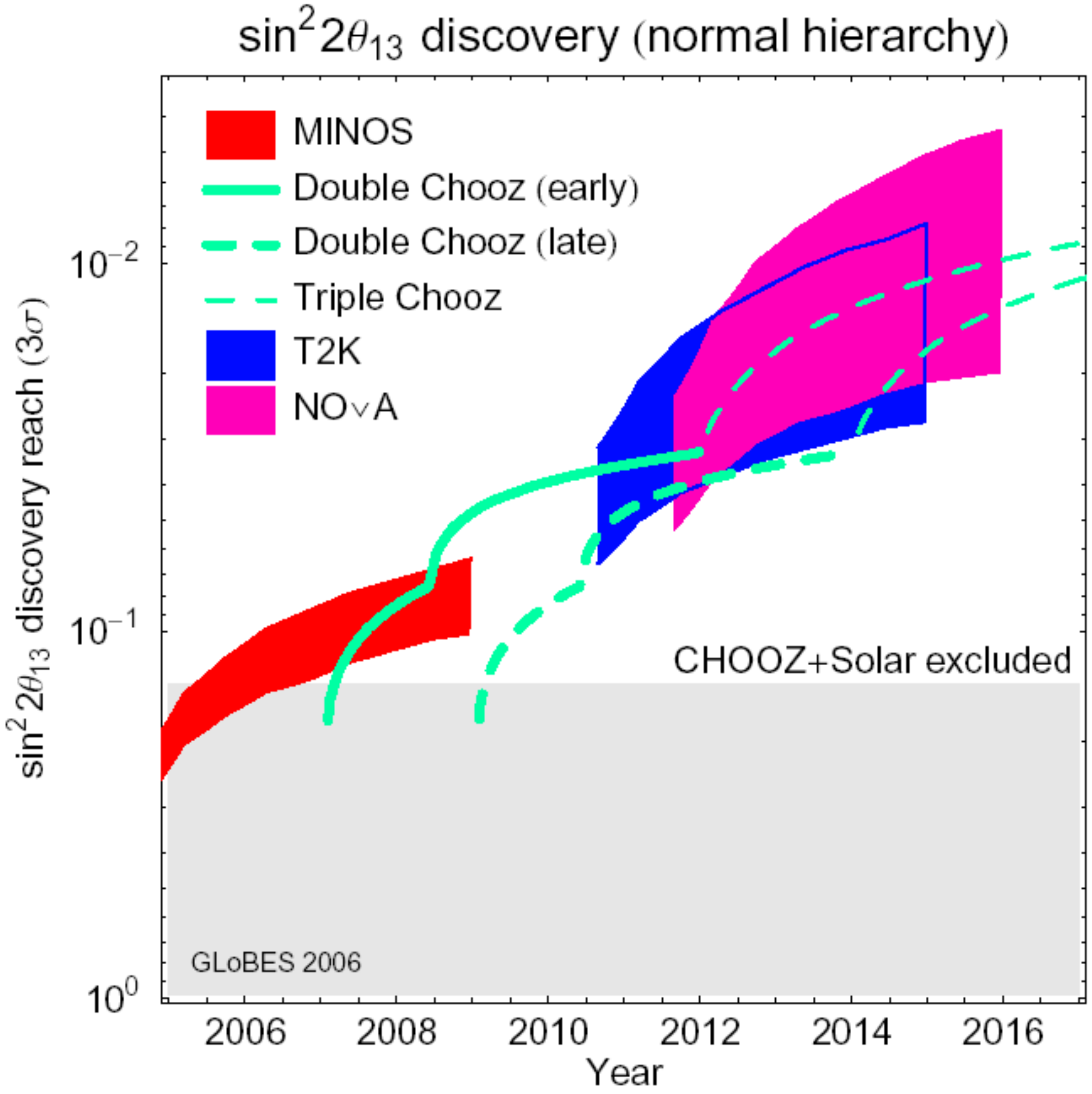
5-years running of KamLAND-scale detector with sys.=4%

This is much better than Solar +KamLAND+pp of 4%

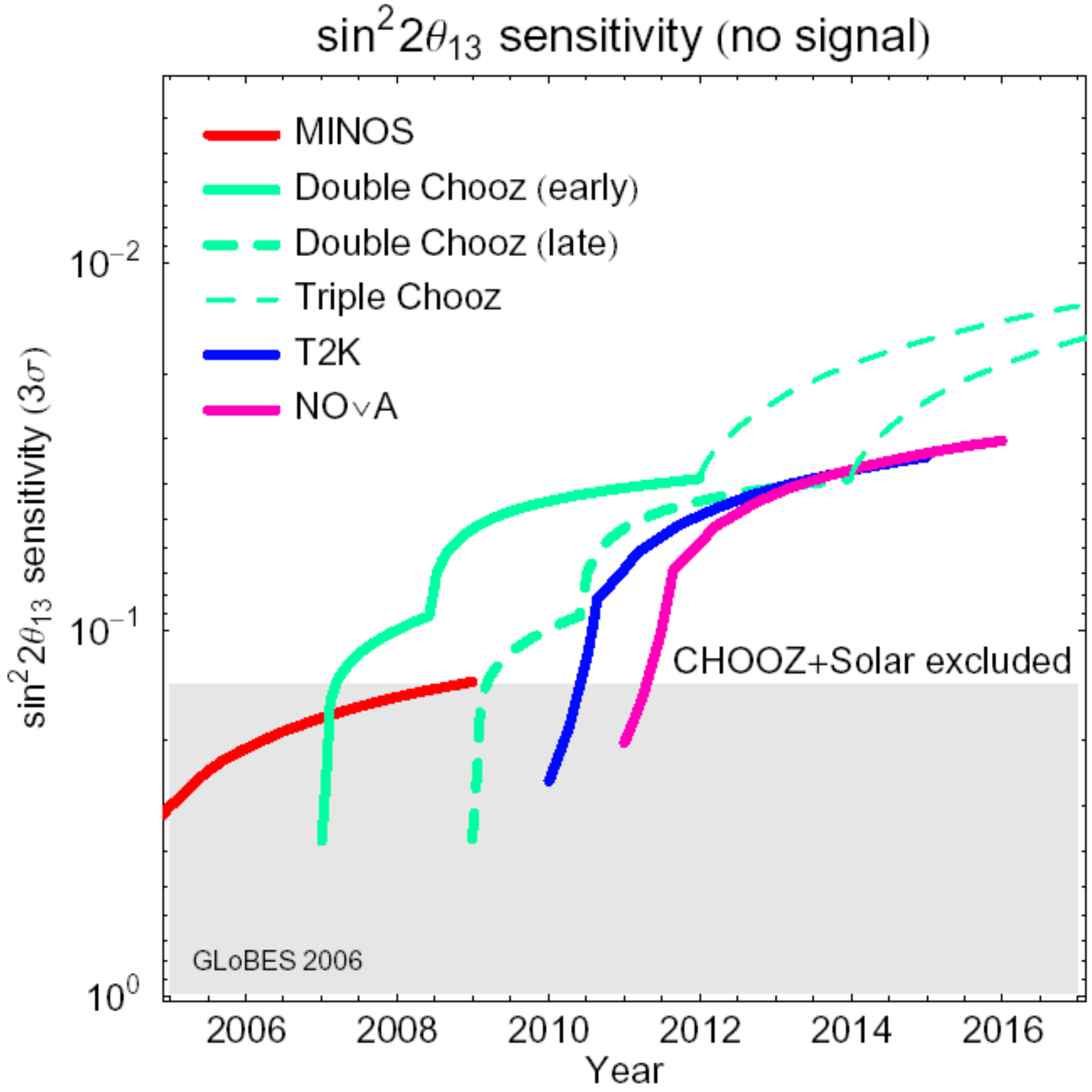
Minakata et al. hep-ph/0407326

Experimental context

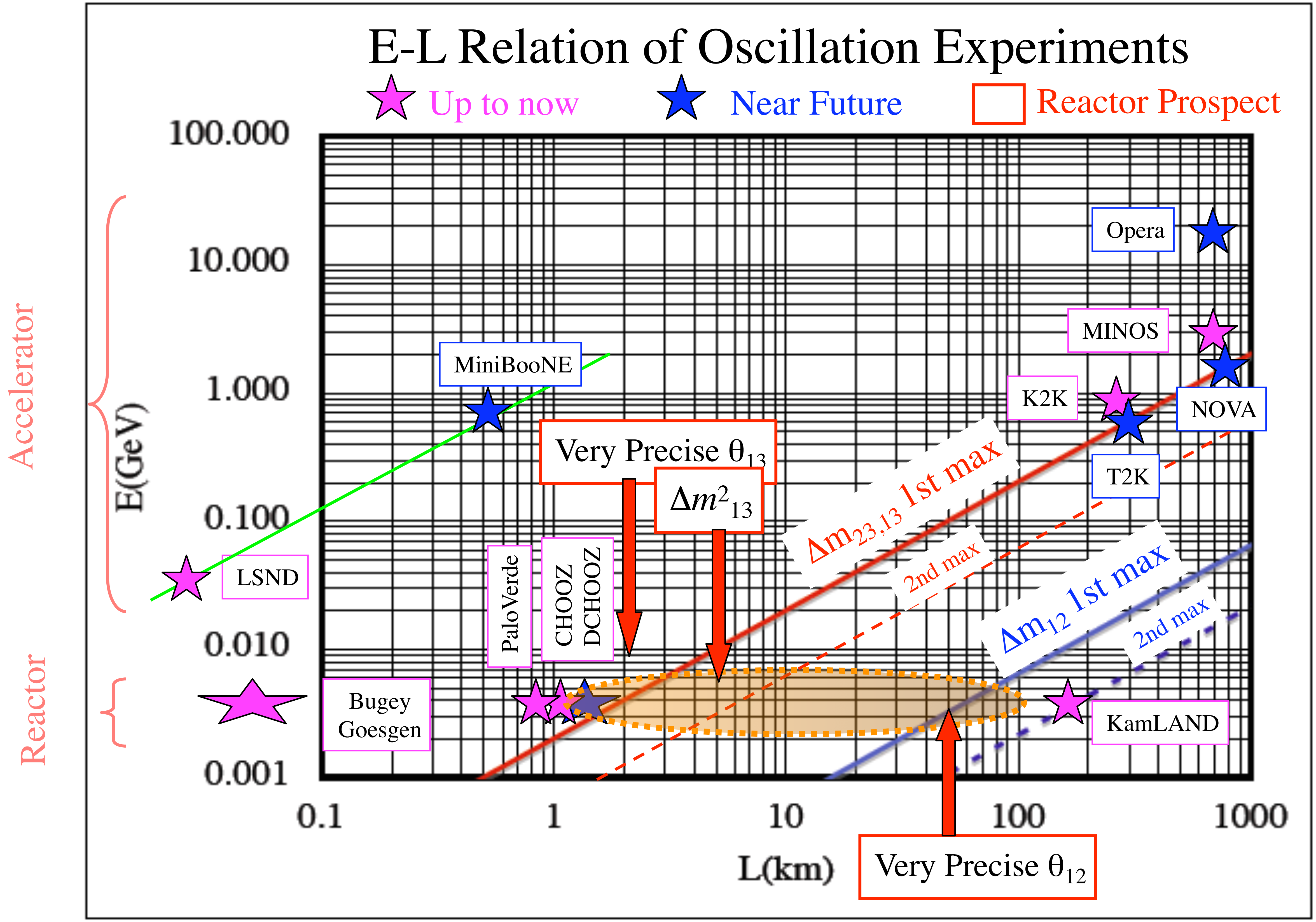
3σ discovery potential



3σ sensitivity (no signal)



Potential of Reactor ν experiments



Conclusion

- The quest for θ_{13} is *the* physics in ν experiments in next 5-10 years, paving a road to the possibility of measuring the *fundamental* CP-violation phase δ leptonic sector.
- Timely reactor medium-baseline experiments would be *complementary* to acc.-based experiments, leading to much richer physics outcome with their synergy.
- Double Chooz will take the lead, and Daya Bay/RENO. Precision in *systematics* is the experimental key. Second-generation projects are Angra(Brasil) and KASKA(Japan).
- Lots of variety and *fun* in future neutrino physics!