June 9, 2004
@Fermilab

Neutrino Initiatives in Japan

Takashi Kobayashi
KEK

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    1. Super-Kamiokande (atmospheric neutrino)
    2. T2K experiment
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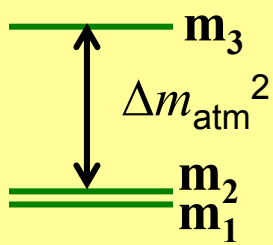
Next goals in neutrino physics

- Establish 3 flavor framework (or deny)
  - Discovery of ν_e appearance (θ_{13}>0?).
    Only remaining unknown mixing
    Critical step to go further
  - Precision measurements of ocs. params.
    Test exotic models, 3x3 mixing structure
- Sign of Δm^2
- Search for CPV in lepton sector
  - Give hint on Matter/Anti-matter asymmetry in the universe

What can be measured in LBL exp.

Oscillation probabilities

$$\Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2 = \Delta m_{\text{atm}}{}^2$$
$$\Delta m_{ij}^2 = m_j^2 - m_i^2$$



➢ ν_μ disappearance: θ_{23}

$$P_{\nu\mu \to \nu\mu} \approx 1 - \underbrace{\cos^4\theta_{13}}_{\sim 1} \cdot \sin^2 2\theta_{23} \cdot \sin^2\left(1.27\,\Delta m_{\text{atm}}{}^2 L / E_\nu\right)$$

Same

➢ ν_e appearance: θ_{13}

$$P_{\nu\mu \to \nu e} \approx \underbrace{\sin^2\theta_{23} \cdot \sin^2 2\theta_{13}}_{\sim 0.5} \cdot \sin^2\left(1.27\,\Delta m_{\text{atm}}{}^2 L / E_\nu\right)$$

$\sin^2 2\theta_{\mu e}$

➢ δ: ~~CP~~ in ν_e appearance

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

Neutrino osc. experiments in Japan

Running experiments

- **Super-Kamiokande(1996~)**
  - 50kt water cherenkov
  - Atm ν and solar ν
  - Discovery of neutrino oscillation in atm ν (1998)
- **K2K(1999~2005?)**
  - (First) acc.-based long baseline experiment
  - ~1GeV ν_μ beam, 250km, Super-Kamiokande
  - Confirming SK atm ν results. Null osc. prob. < 1% (2002)
- **KamLAND(2002~)**
  - 1,000ton Liq. Scint.
  - Reactor anti-ν, (geoneutrino and solar ν in future)
  - Concluded the solar neutrino problem. Evidence of oscillation (2003)

Approved experiment

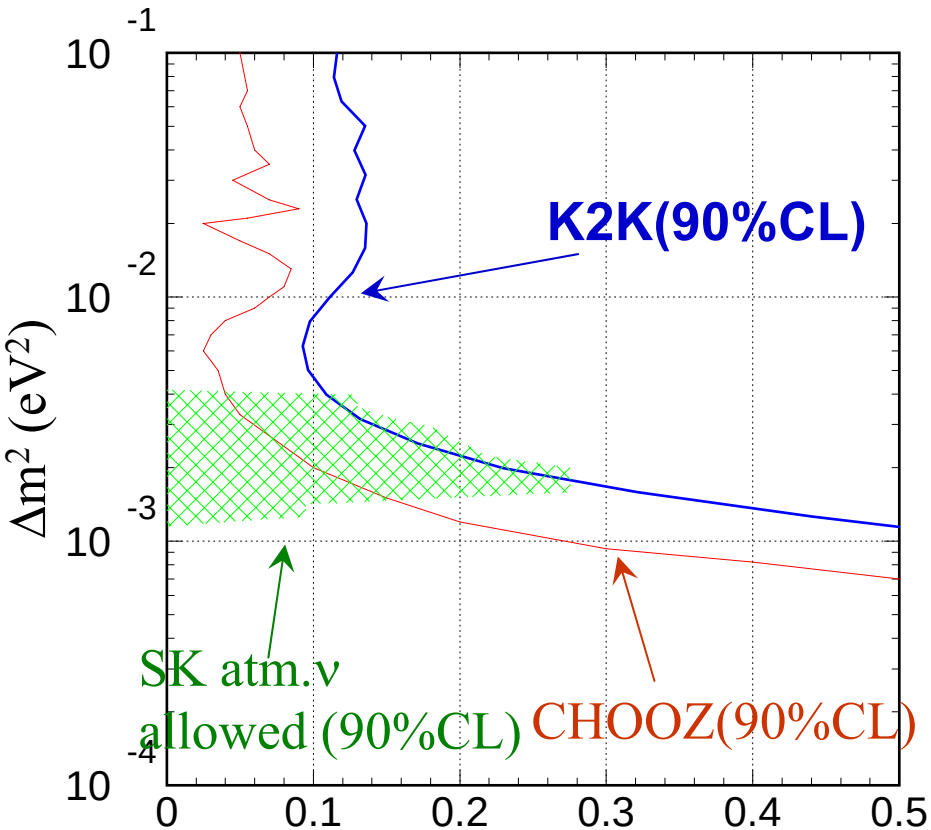
- **T2K (2009~)** :
  - 2nd gen. LBL exp. ~10^2 times more stat than K2K
  - Discovery of ν_e appearance, precision measurements

Proposed experiment

- **KASKA (2009??~)**
  - 2-detector reactor neutrino experiment
  - Discovery of non-0 $\nu_e \rightarrow \nu_x$ in atm ν region

Current knowledge of Δm_{23}^2, θ_{23} and θ_{13}

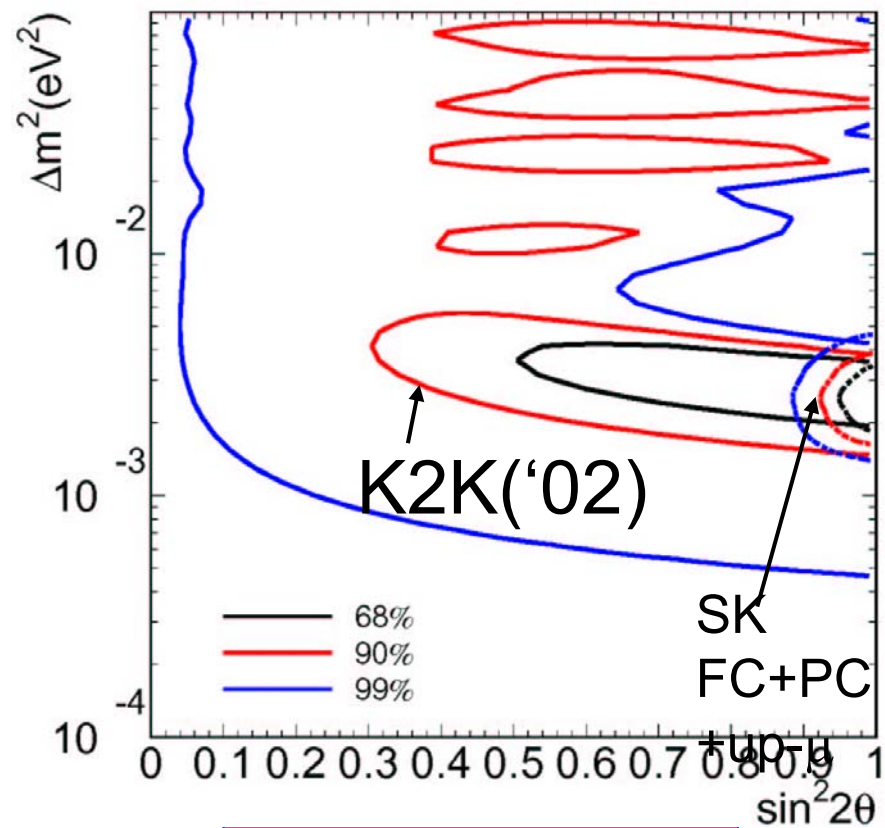
θ_{13}



$\sin^2 2\theta_{\mu e} \sim 0.5 \sin^2 2\theta_{13}$

Small!! Only upper limit

θ_{23}



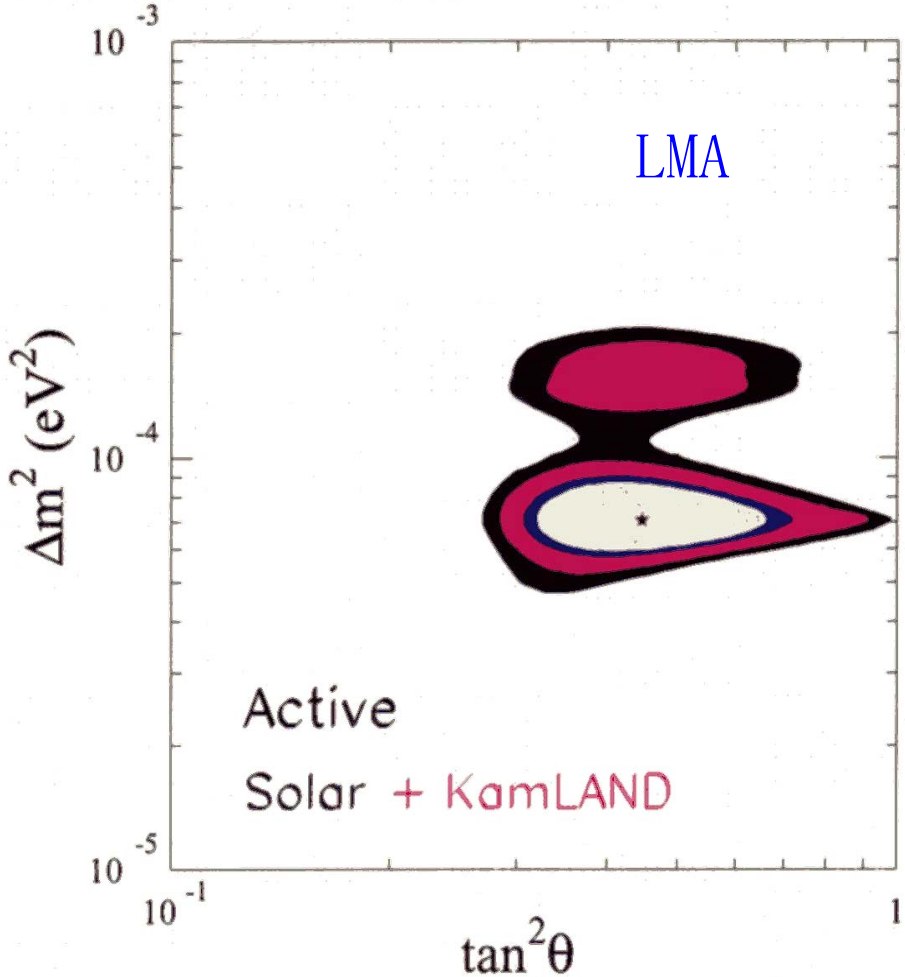
Nearly maxmal!

New results from K2K coming soon

ν_e(bar) disappearance (θ_{12}, Δm_{12}^2)

- Combined results of
  - Solar neutrino observations (SK, SNO, …)
  - Reactor anti-ν observation (KamLAND)
- "Solar neutrino problem" concluded
- Large mixing!

New results from KamLAND very soon



J.N. Bahcall et al., J. High Energy Phys. (2003)

K2K status

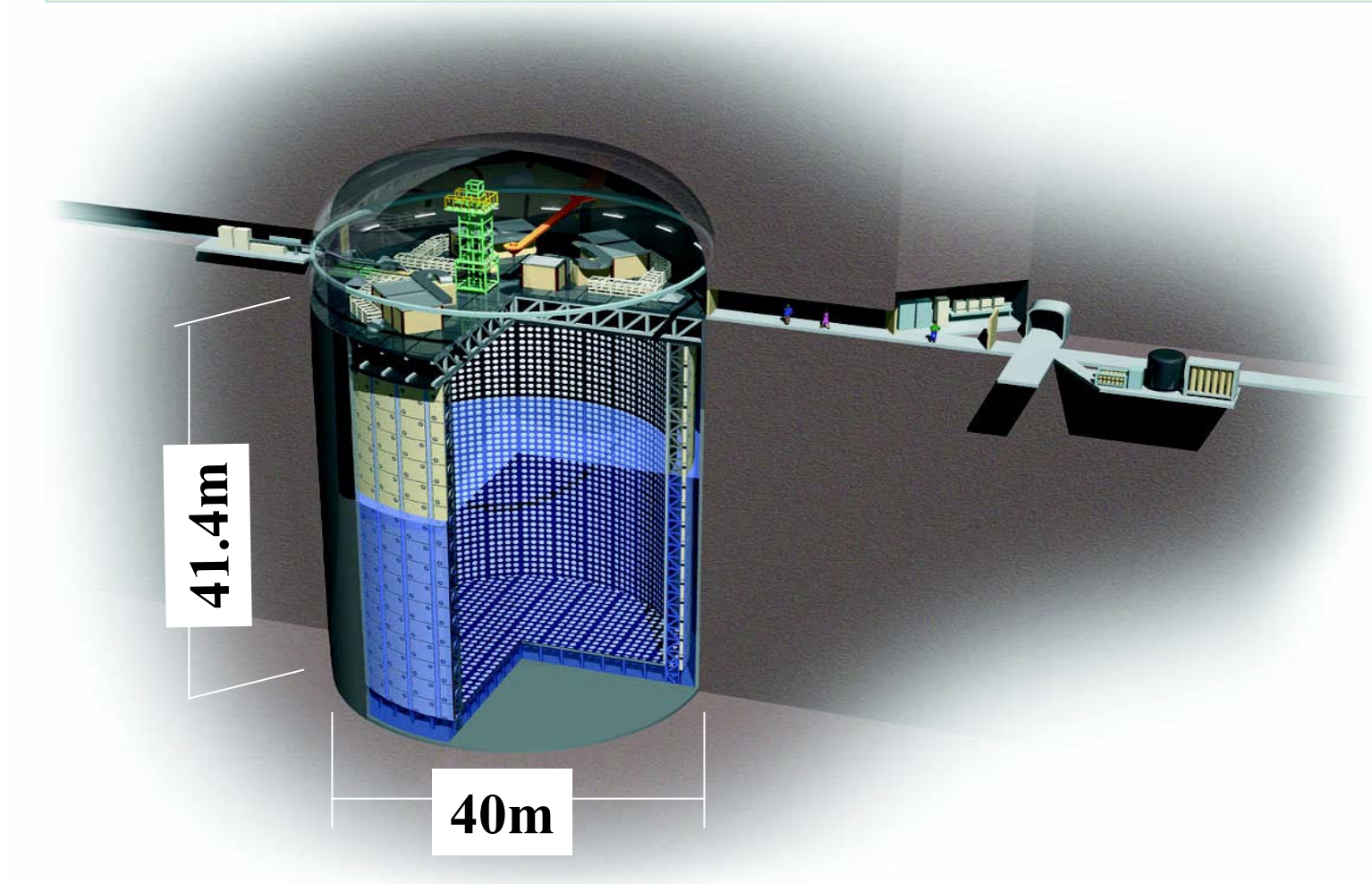
- K2K is presenting new results based on 8.9×10^{19}POT(taken by Feb.2004) in ν2004
- Accumulate at least 10^{20}pot
- Probably reaches around end of 2004
- Hope run by the end of JFY2004 (mar. 2005)
  - Double scibar data → neutrino int
    - ➔ use multi-ring sample in SK
  - Some engineering run in numubar mode
    - Based on Cho, flux ~1/2. xsec~1/3 to 1/2 ➔ ~1/5 # of int.
  - Just requested. To be discussed

（April 1996 commissioned）

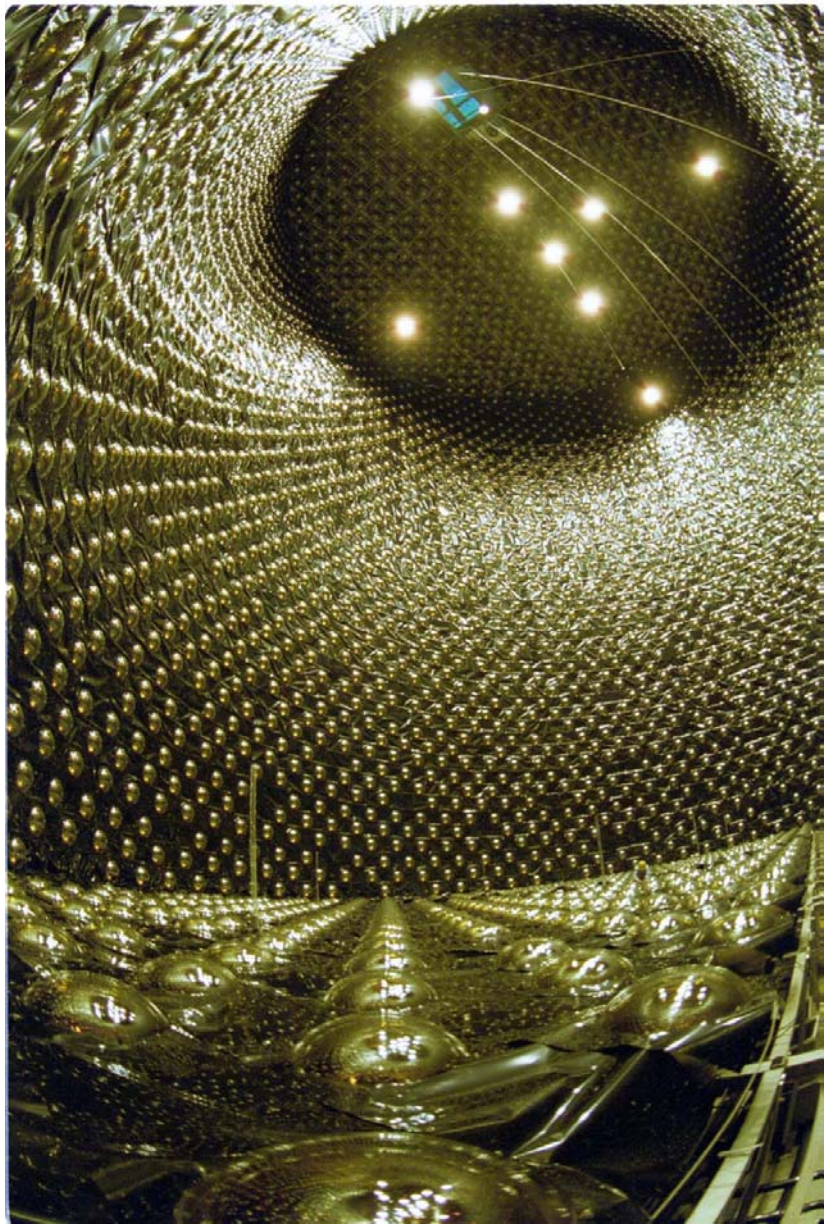
Super-Kamiokande

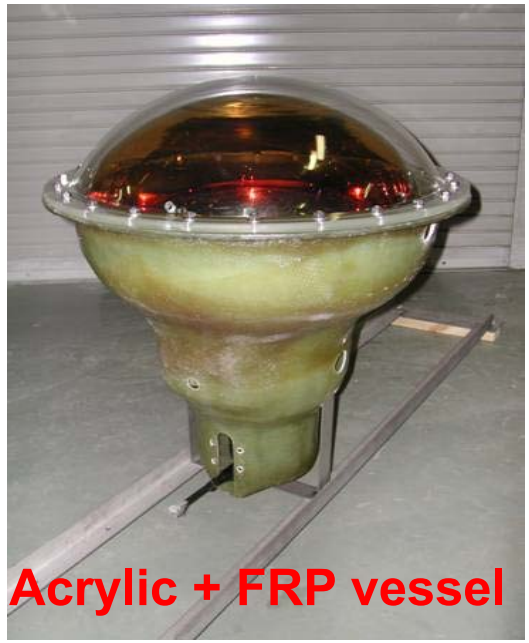
50,000 ton water Cherenkov detector (22.5 kton fiducial volume)

Optically separated INNER and OUTER detector



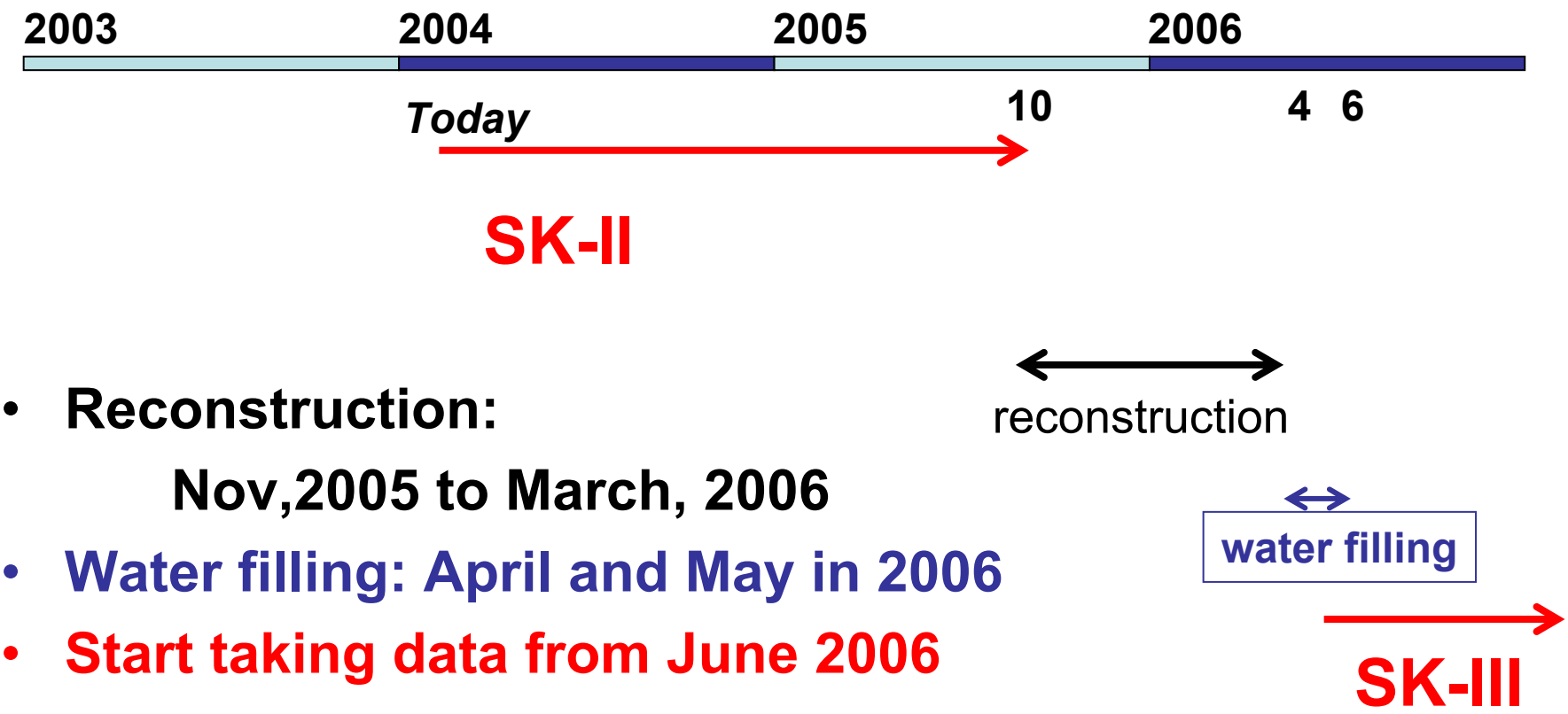
Reconstruction of Super-K II





- **Reconstructed in October 2002**
  - 47% of the PMTs (~5200)
  - Full OD 8 inch PMTs (1885)
  - PMTs in plastic shells to prevent future chain implosions

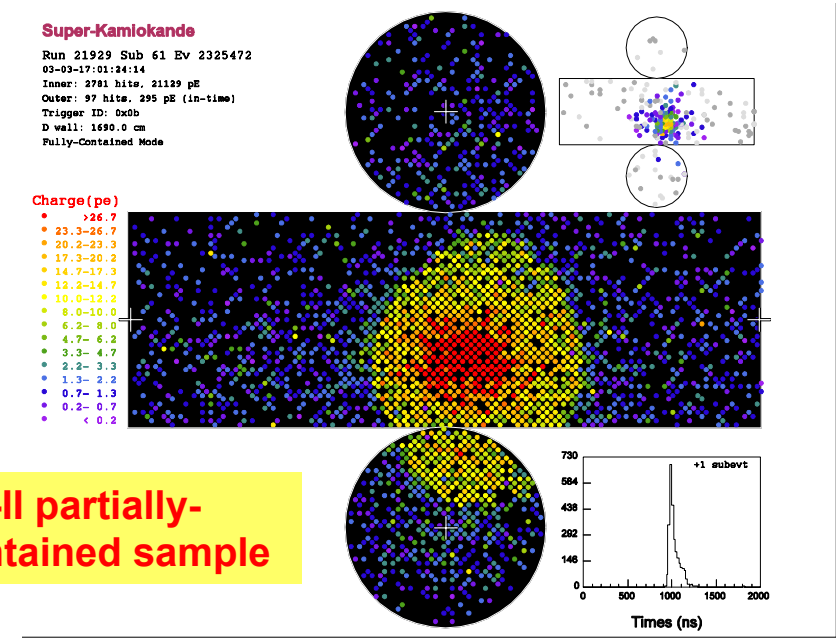
Full reconstruction schedule (approved)



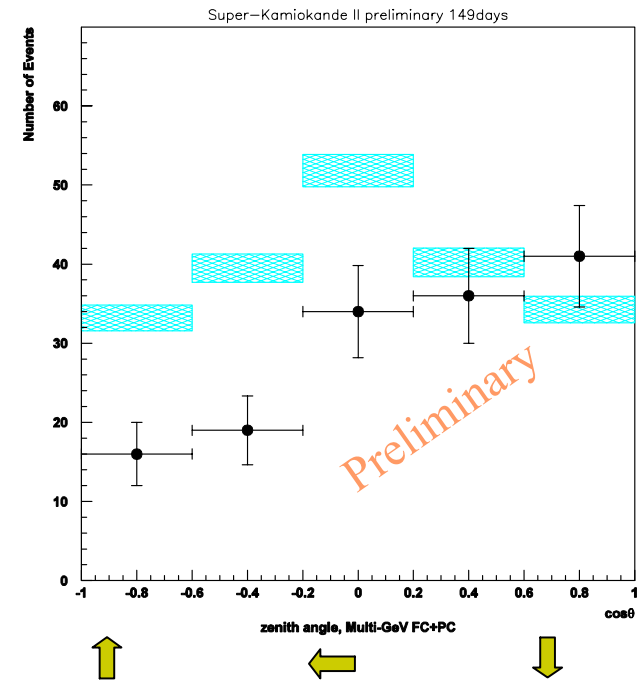
- **Reconstruction:**

  Nov,2005 to March, 2006
- **Water filling: April and May in 2006**
- **Start taking data from June 2006**

SK-II is taking data, started in December, 2002



SK-II partially-contained sample



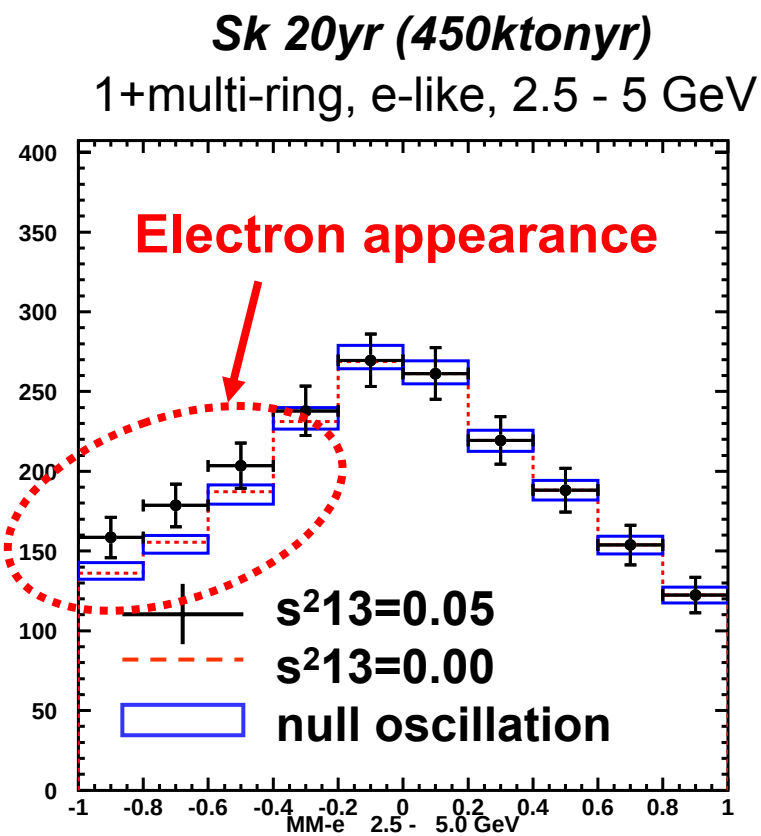
Multi-GeV FC μ-like +PC

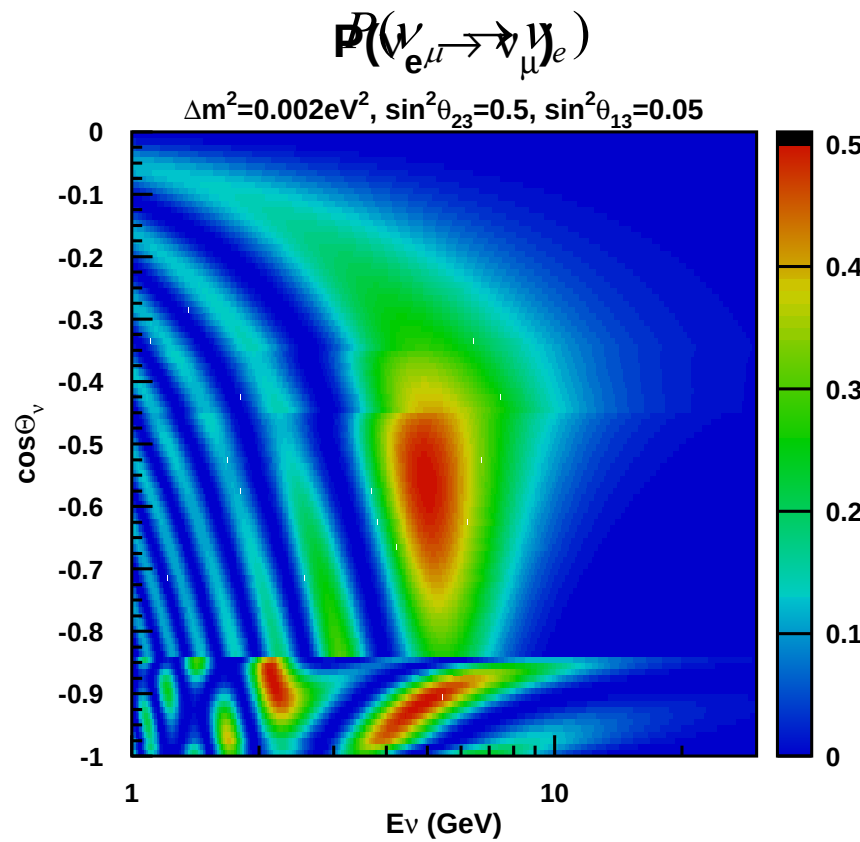
Number of events & Event rate

(Preliminary)

	SK-II 149.3 days	SK-I 1489 days
Fully-contained	1245 (8.33±0.24)	12180 (8.18±0.07)
Partially-contained	80 (0.54±0.06)	911 (0.62±0.02)

θ_{13} measurements in atmospheric neutrinos in Future

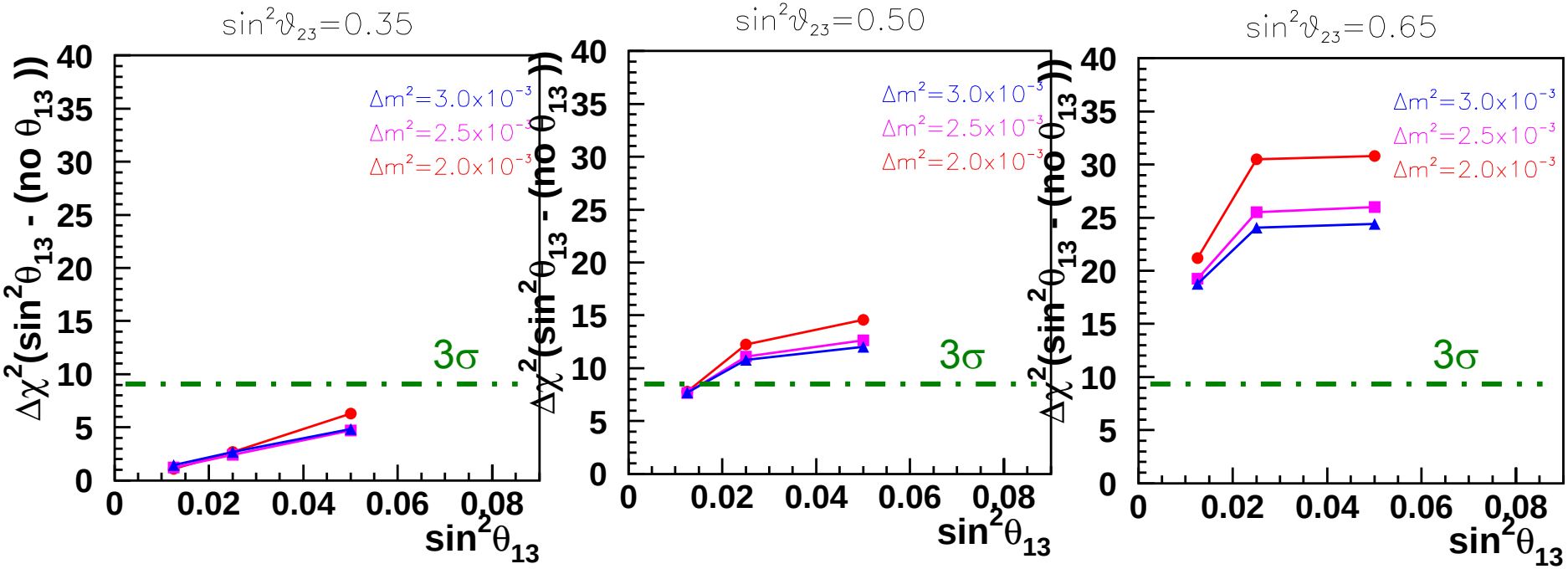




Matter Effect

Sensitivity for non-zero θ_{13}

SK 20 years (450 ktonyr)



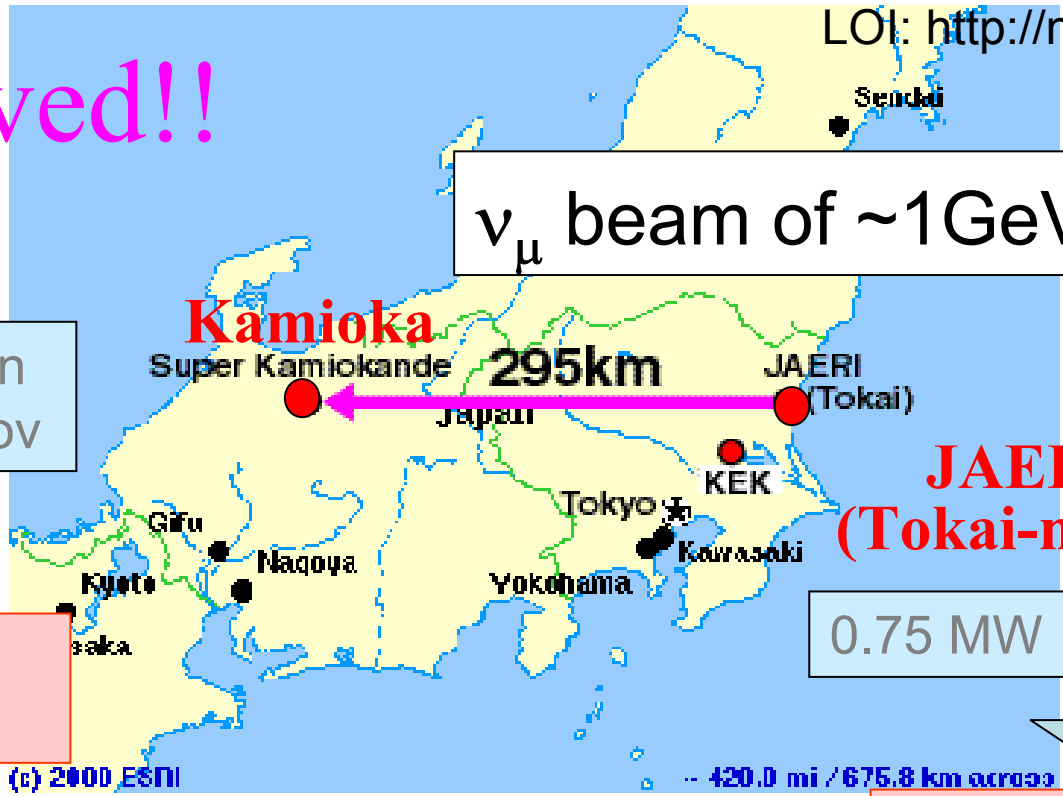
3σ discovery when $\sin^2\theta_{13}$>0.015 ($\sin^2 2\theta_{13}$>0.06) @ $\theta_{23}=\pi/4$

"T2K" (Tokai-to-Kamioka) neutrino experiment

LOI: http://neutrino.kek.jp/jhfnu

Approved!!

ν_μ beam of ~1GeV



Super-K: 50 kton Water Cherenkov

~Mt "Hyper Kamiokande"

JAERI (Tokai-mura)

0.75 MW 50 GeV PS

4MW 50GeV PS

Approved exp (x10^2 of K2K)

- $\nu_\mu \rightarrow \nu_x$ disappearance
- $\nu_\mu \rightarrow \nu_e$ appearance
- NC measurement

Future Extension

- CP violation
- proton decay

Strategy

- High statistics by high intensity ν beam
- Tune $E\nu$ at oscillation maximum
- Narrow band beam to reduce BG
- Sub-GeV ν beam for Water Cherenkov

0.75MW JHF 50GeV-PS

Off-Axis ν beam ***Super-Kamiokande***

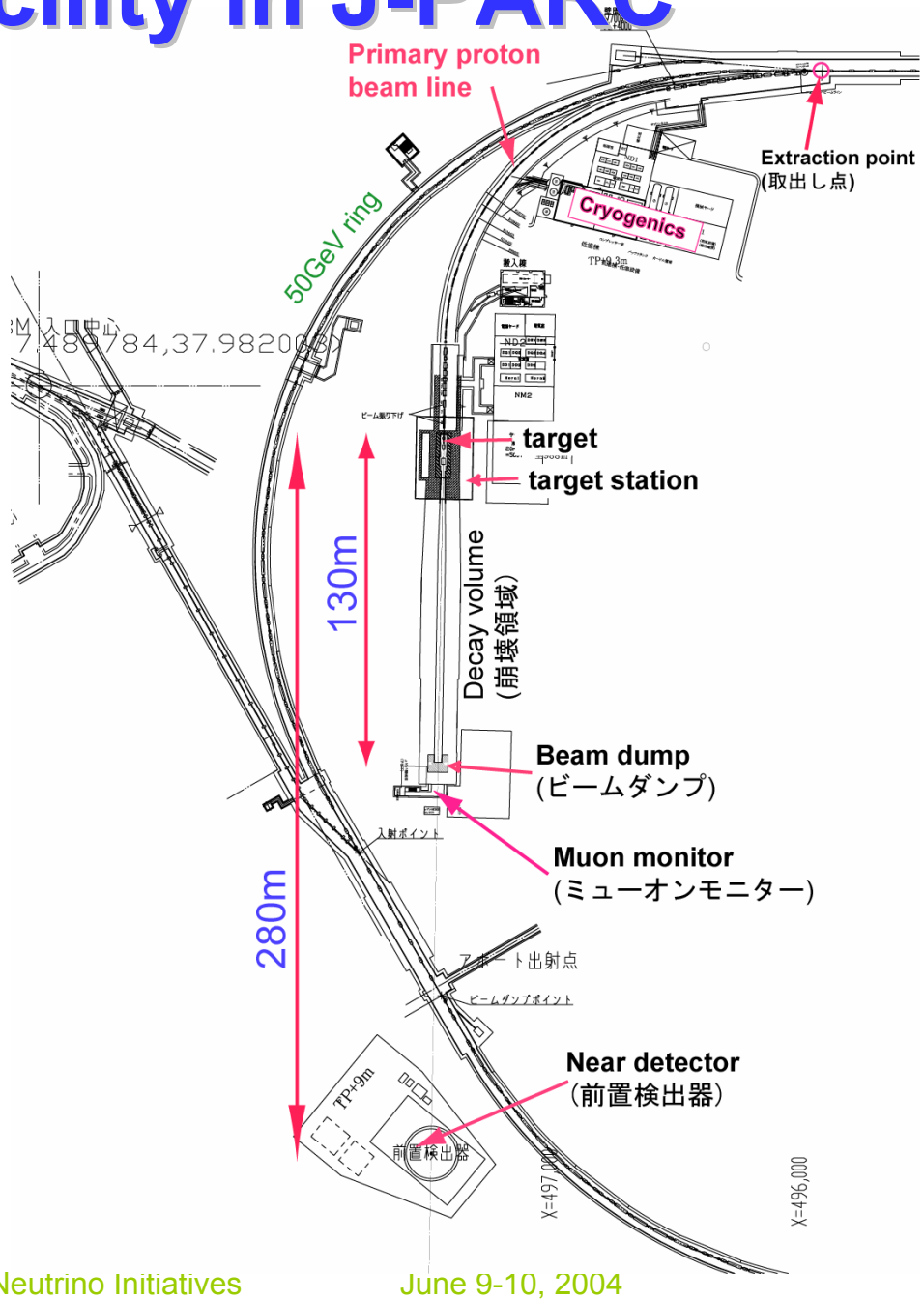
Neutrino facility in J-PARC

Special Features

- Superconducting combined function magnets
- Off-axis beam

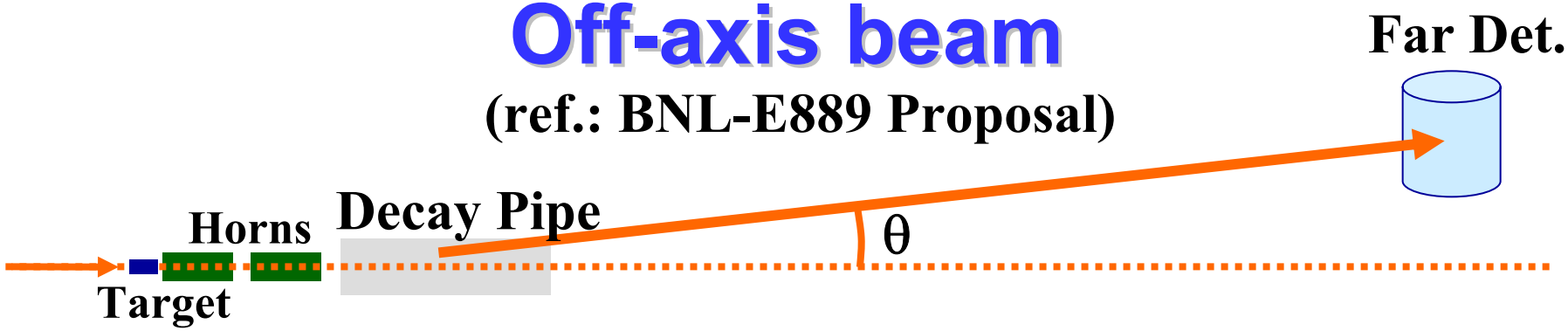
Approved in Dec.2003

- 5 year construction Apr.2004~Mar.2009
- 16.0B yen (~160M$)



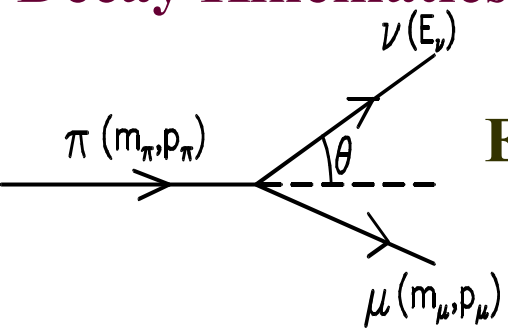
Off-axis beam

(ref.: BNL-E889 Proposal)

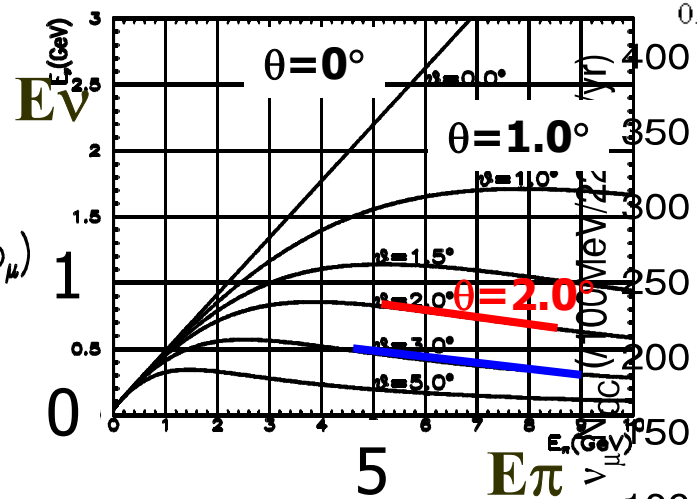


WBB w/ intentionally misaligned beam line from det. axis

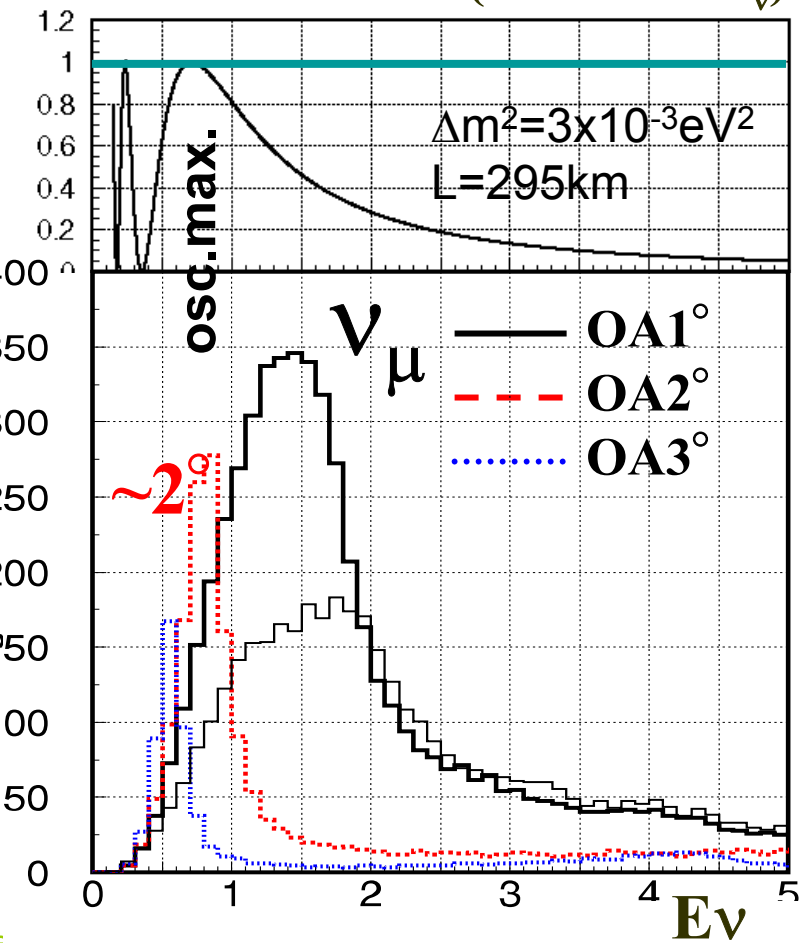
Decay Kinematics



$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$



Osc. Prob.=$\sin^2(1.27\Delta m^2 L/E_\nu)$



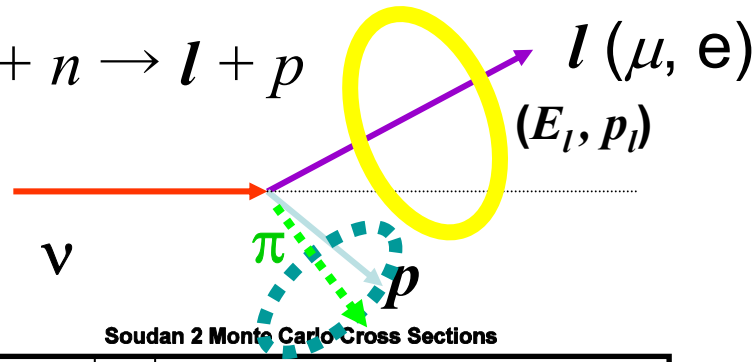
~3000 CC int./22.5kt/yr

ν_e: 1.0% (0.2% @ peak);

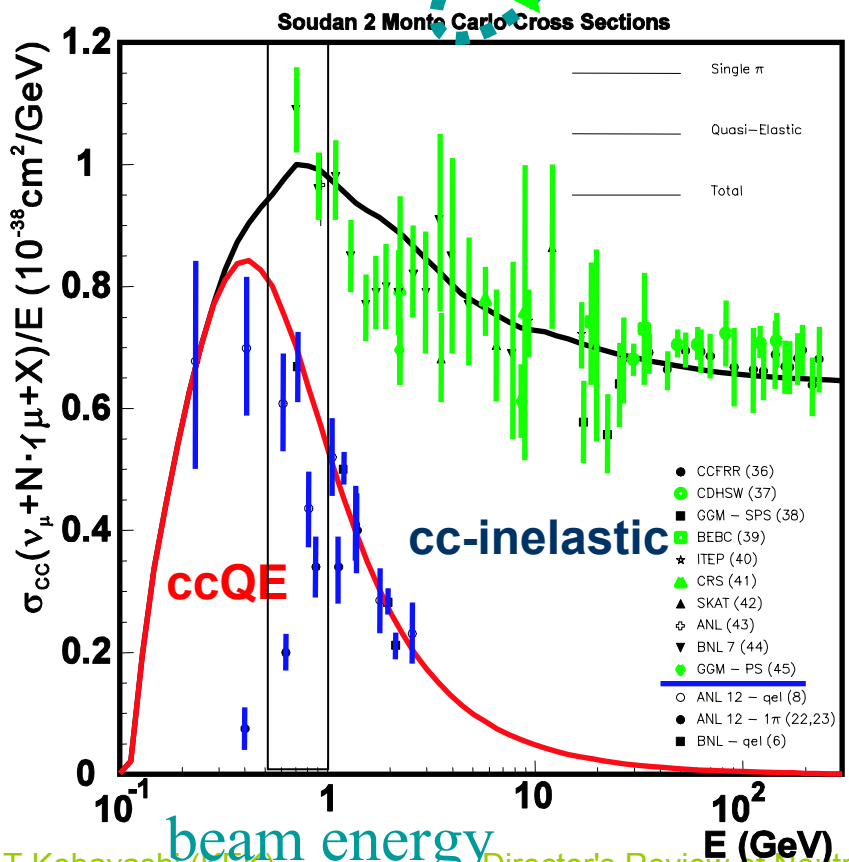
Eν reconstruction in water Cherenkov

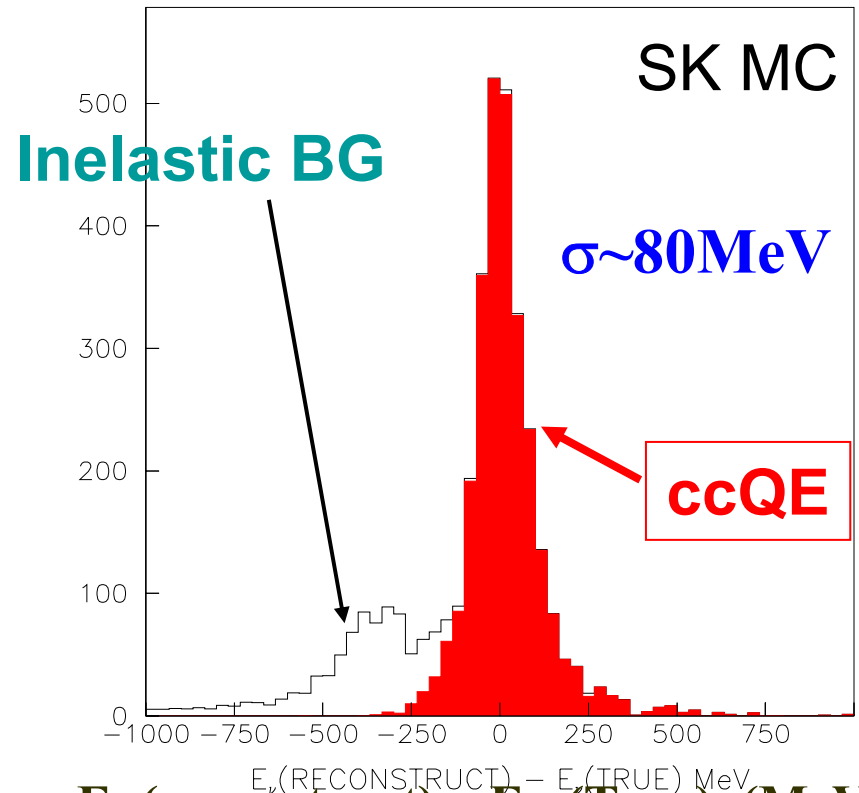
Assume CC Quasi Elastic (QE) reaction

$$\nu_\mu + n \rightarrow l + p$$

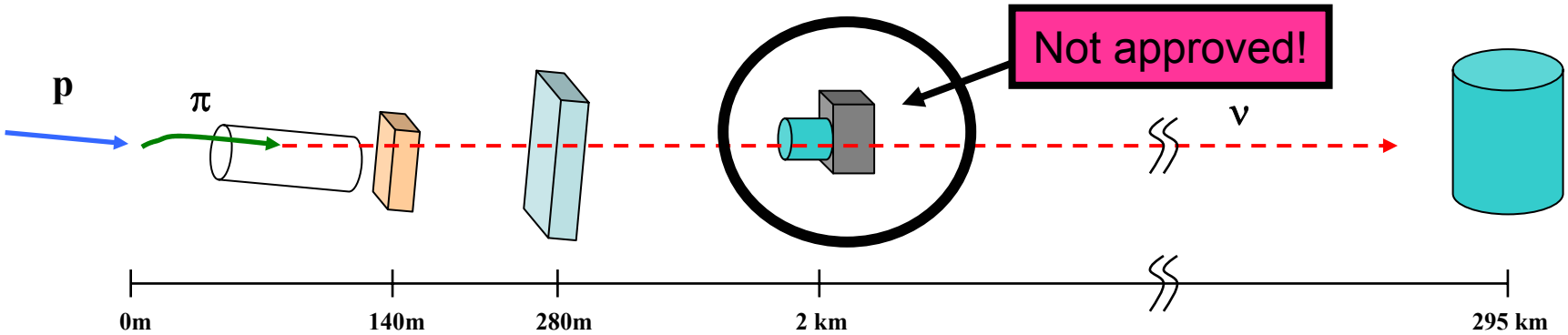


$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$



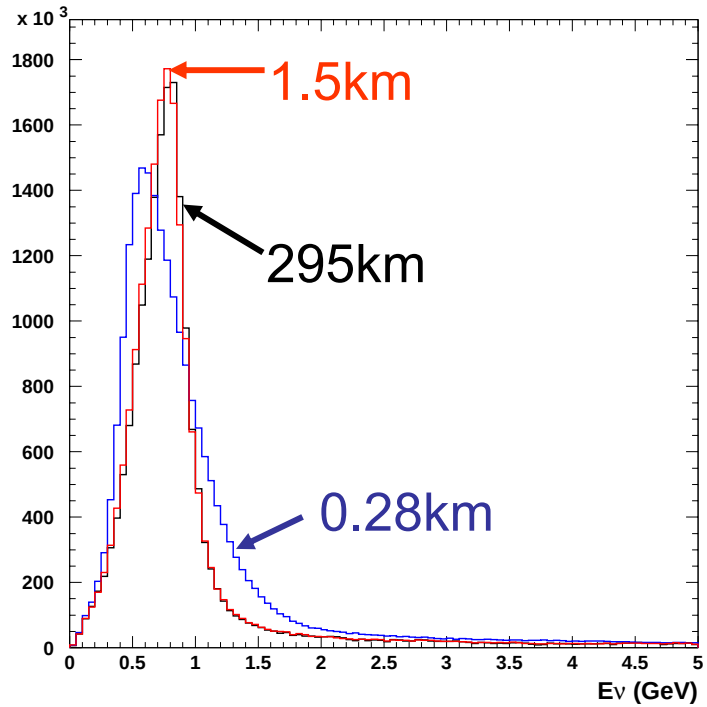


Detector complex

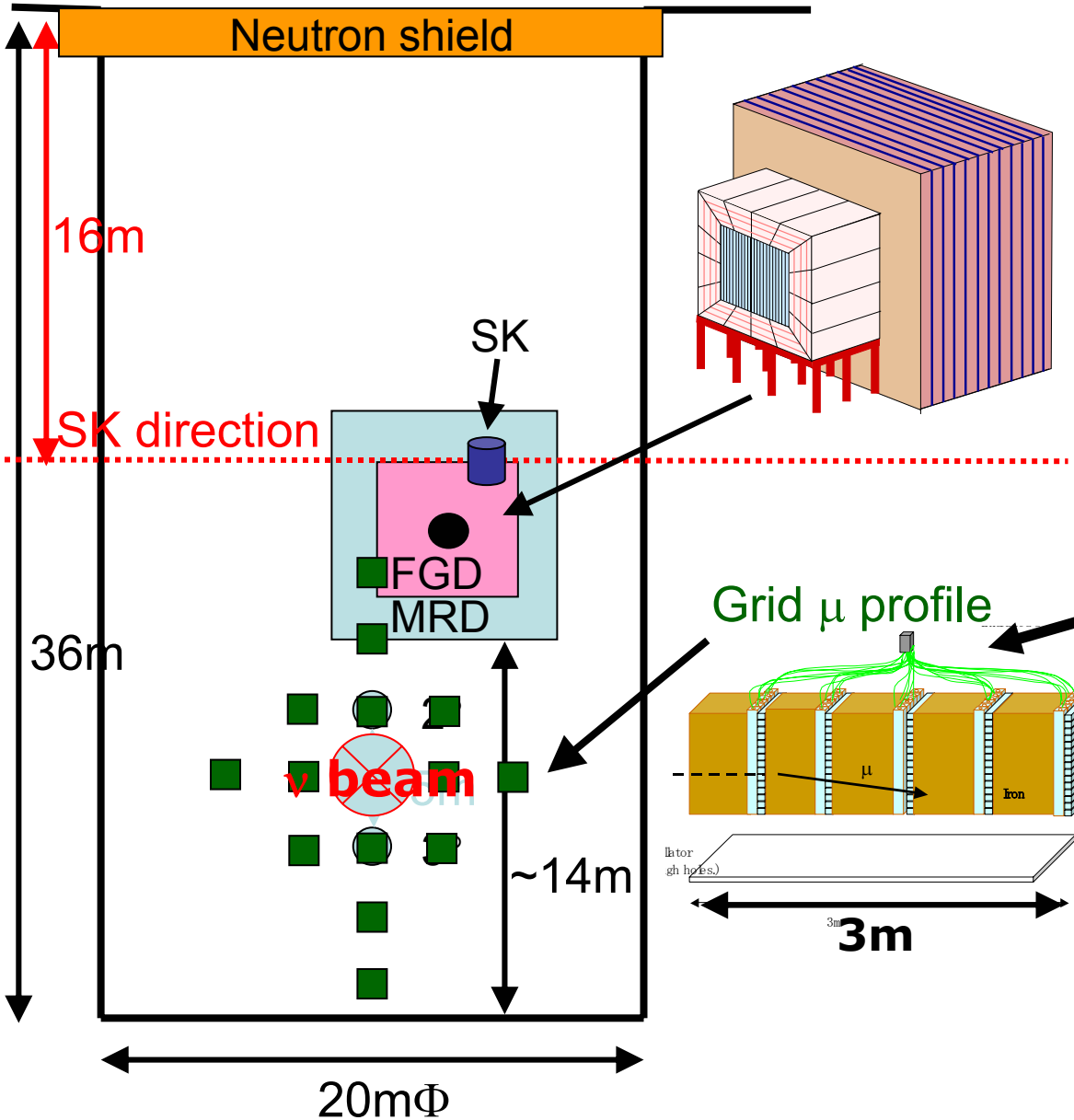


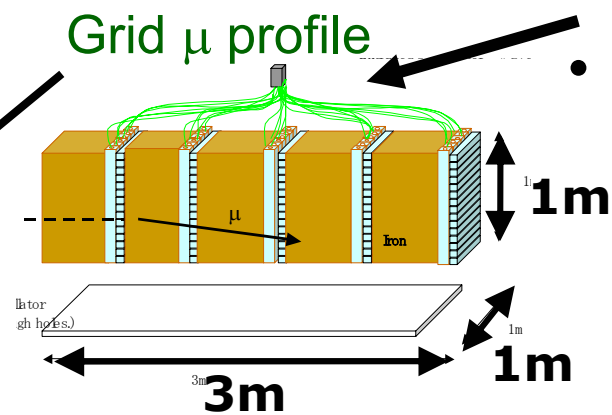
- **Muon monitors @ ~140m**
  - Fast (spill-by-spill) monitoring of beam direction/intensity
- **First Front detector @280m**
  - Intensity, Direction, Spectrum, ν interaction
- **Second Front Detector @ ~2km (not approved)**
- **Far detector @ 295km**
  - **Super-Kamiokande (50kt)**

Neutrino spectra at diff. dist



Concept of Near Neutrino Detector



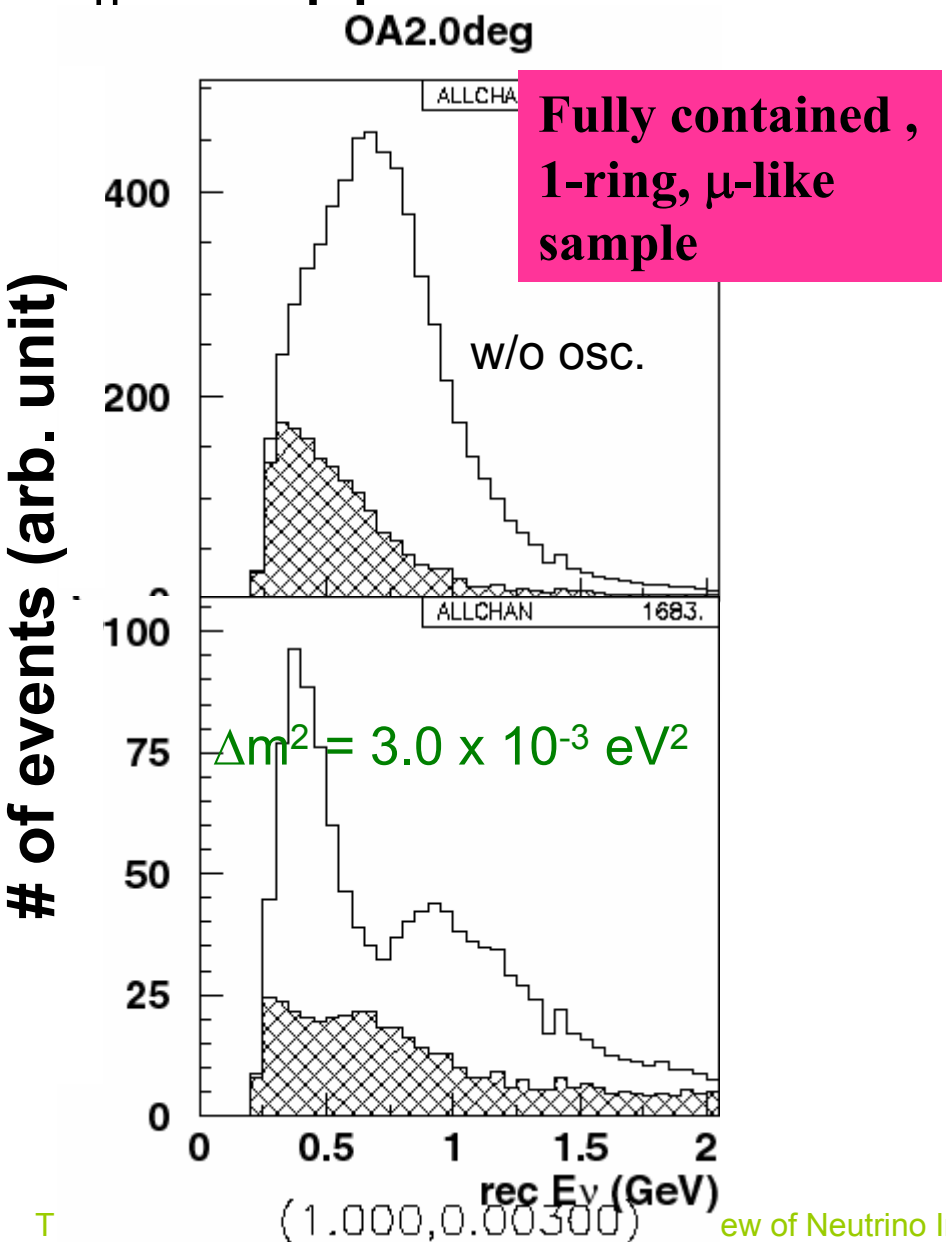


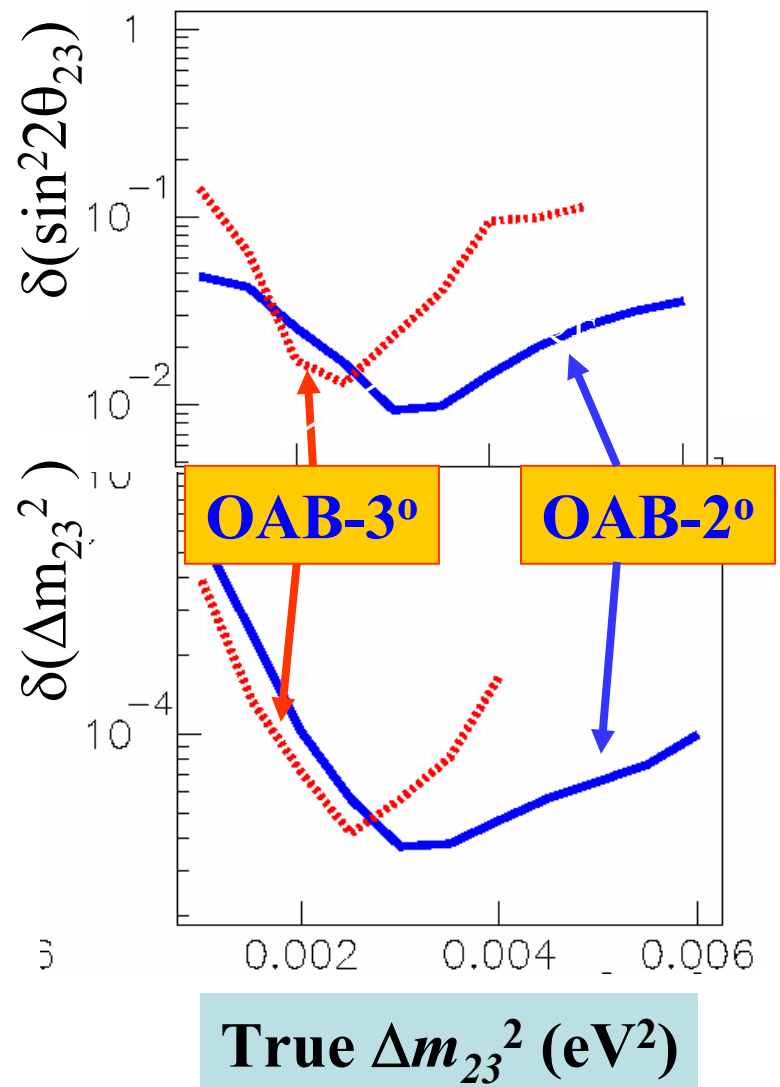
- **Off-axis (~2°)**
  - ν_μ and ν_e neutrino fluxes and the spectra.
  - ν interaction study (CC-QE, non-QE, π^0,)
  - Kaon Contributions
- **On-axis (0°)**
  - Beam direction
  - Beam stability
  - (Spectrum)?

The detector design is just started

Measurement of $\sin^2 2\theta_{23}$, Δm^2_{23}

ν_μ disappearance





$\delta(\sin^2 2\theta) \sim 0.01$

$\delta(\Delta m^2) \sim < 1 \times 10^{-4}$

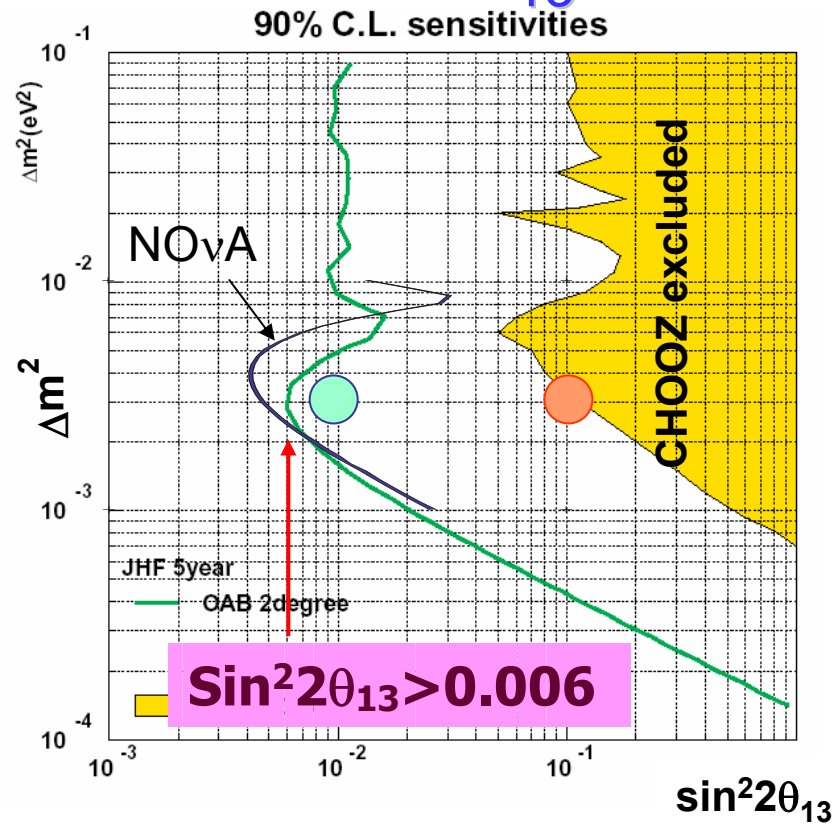
Systematic error effects (ν_μ disappearance)

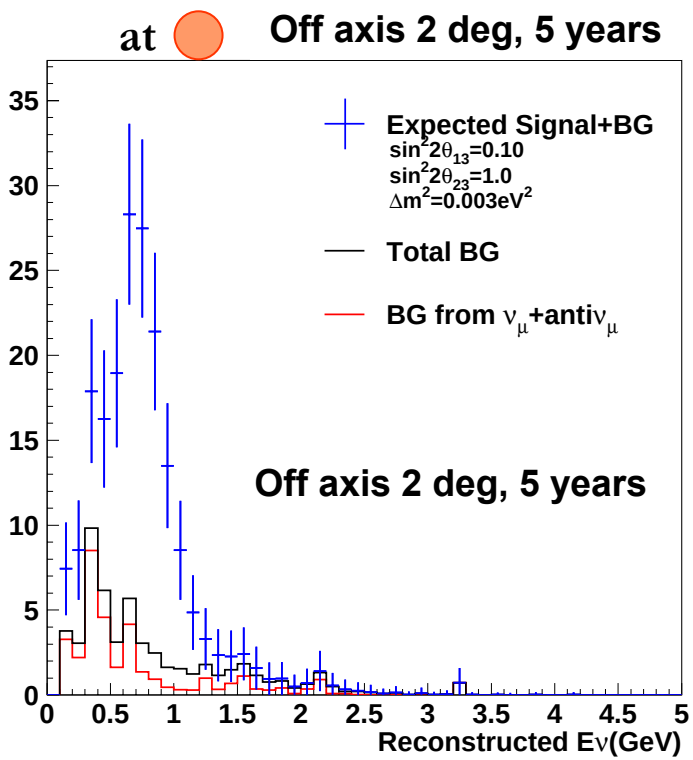
For (1.00, 3E-3eV^2) (OAB2deg)	assumed errors	effect	Size of effect
Flux normalization	10%	$\sin^2 2\theta$	~1 %
NonQE Fraction	20%	Δm^2	~1%
Energy scale	4%	Δm^2	~1%

Achieved in K2K

- Even current level of systematic errors in K2K is acceptable
- More study is needed for other items (neutrino interaction, etc..)
- These uncertainty should be reduced by near detector measurement

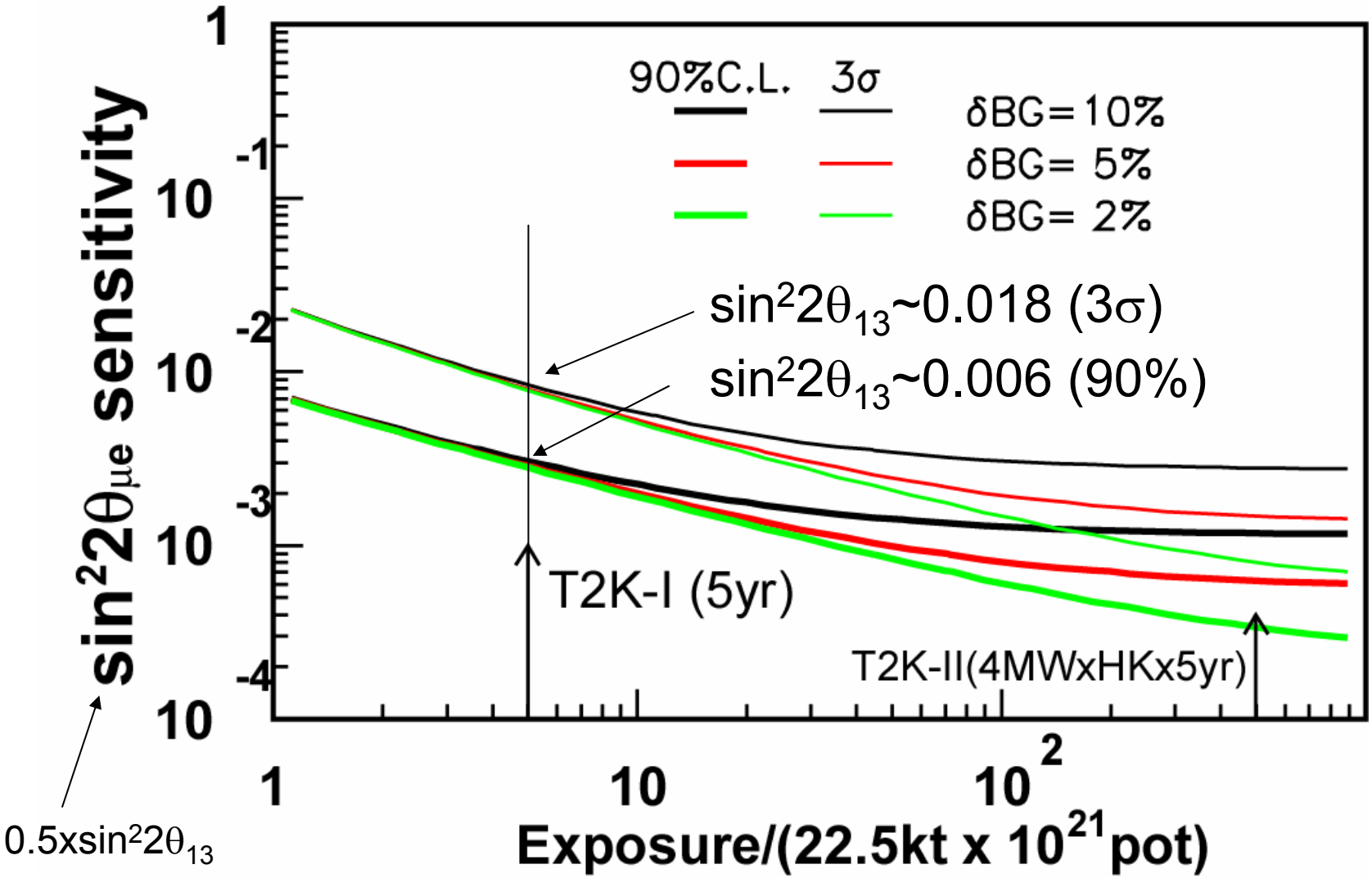
$\sin^2 2\theta_{13}$ from ν_e appearance





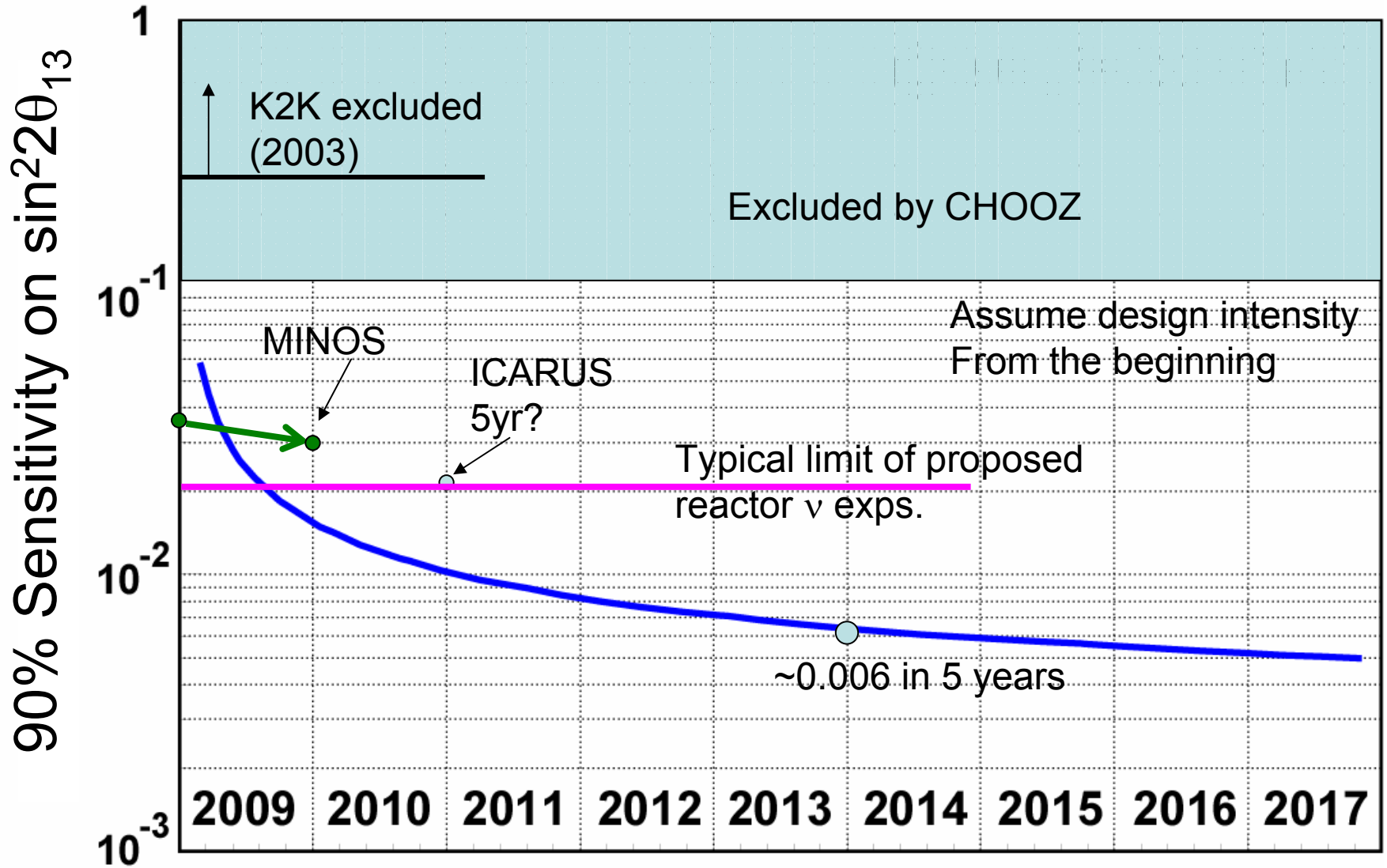
$\sin^2 2\theta_{13}$	Background in Super-K (as of Oct 25, 2001)					Signal	Signal + BG
	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	total		
0.1	12.0	10.7	1.7	0.5	24.9	114.6	139.5
0.01	12.0	10.7	1.7	0.5	24.9	11.5	36.4

Sensitivity for Mixing Angle

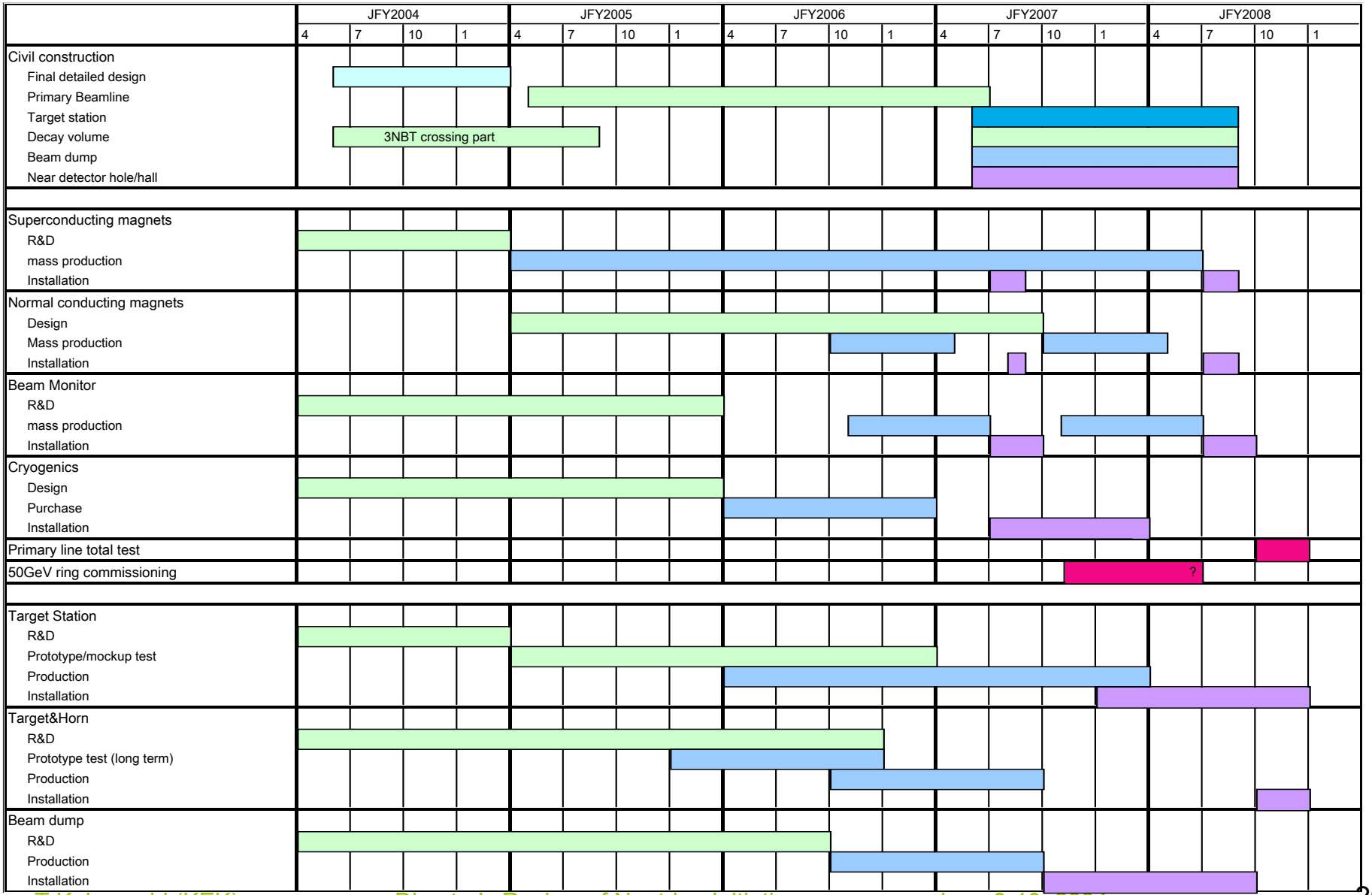


Background systematic error required to be ~ less than 10%

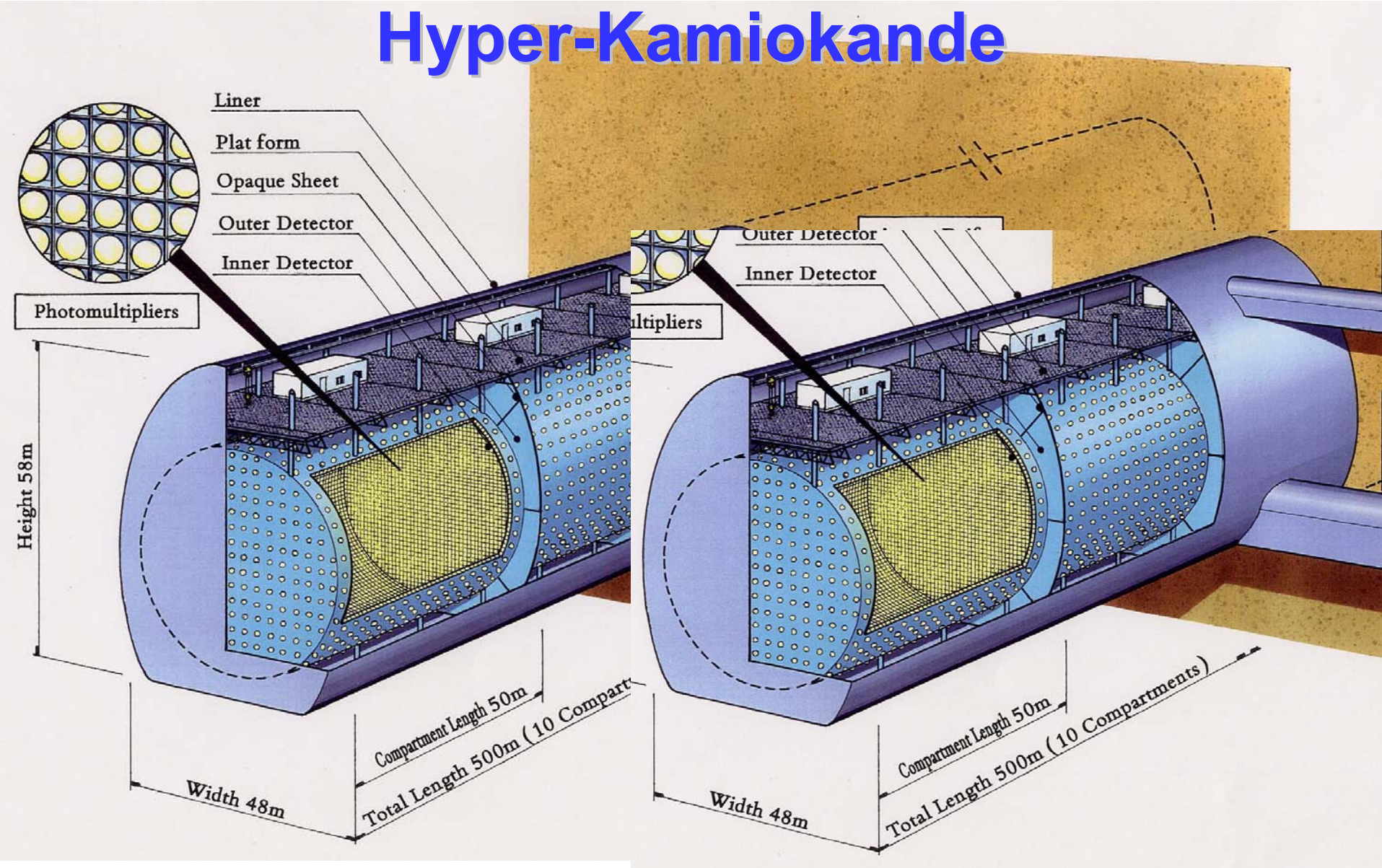
Sensitivity on ν_e appearance



Neutrino facility time schedule

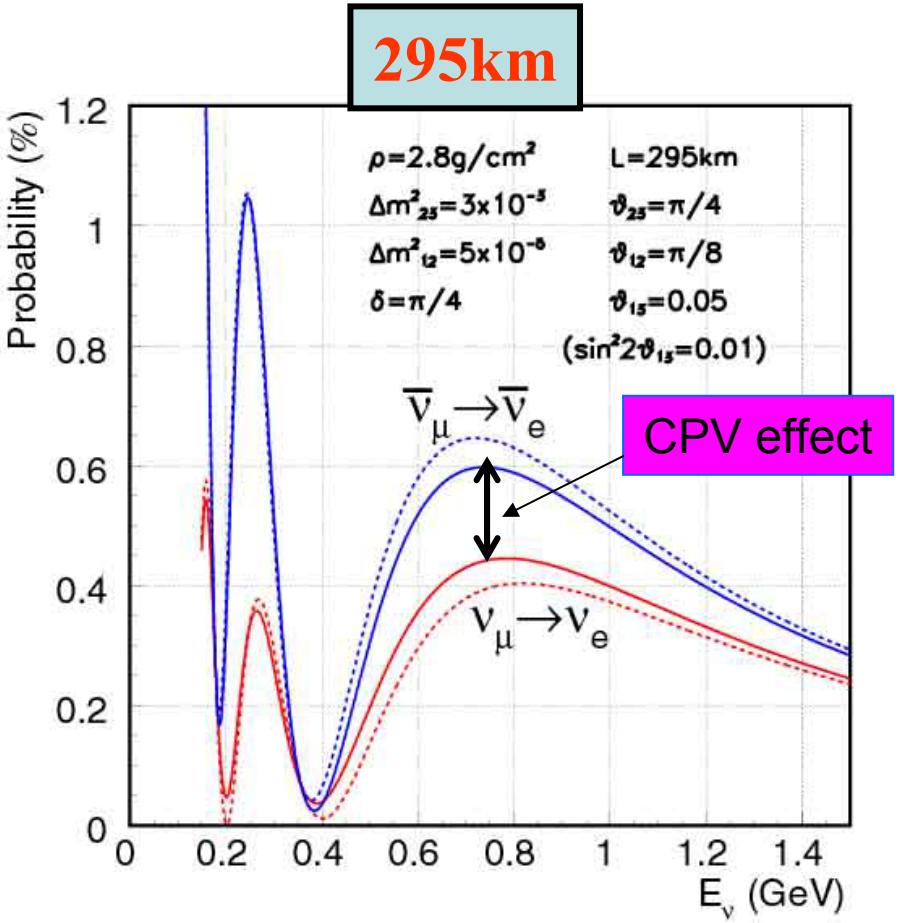


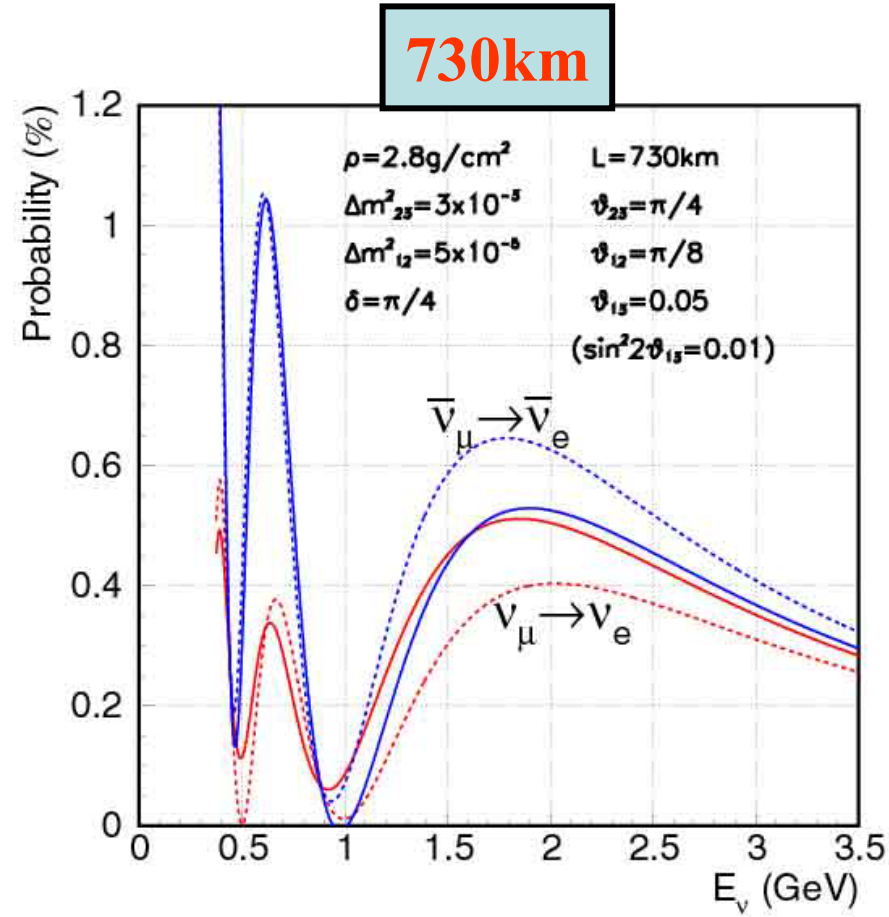
Possible future extension: Hyper-Kamiokande



2 detectors × 48m × 50m × 250m, Total mass = 1 Mton

$\nu_\mu \rightarrow \nu_e$ oscillation probability





Solid line: w/ matter
Dashed line: w/o matter

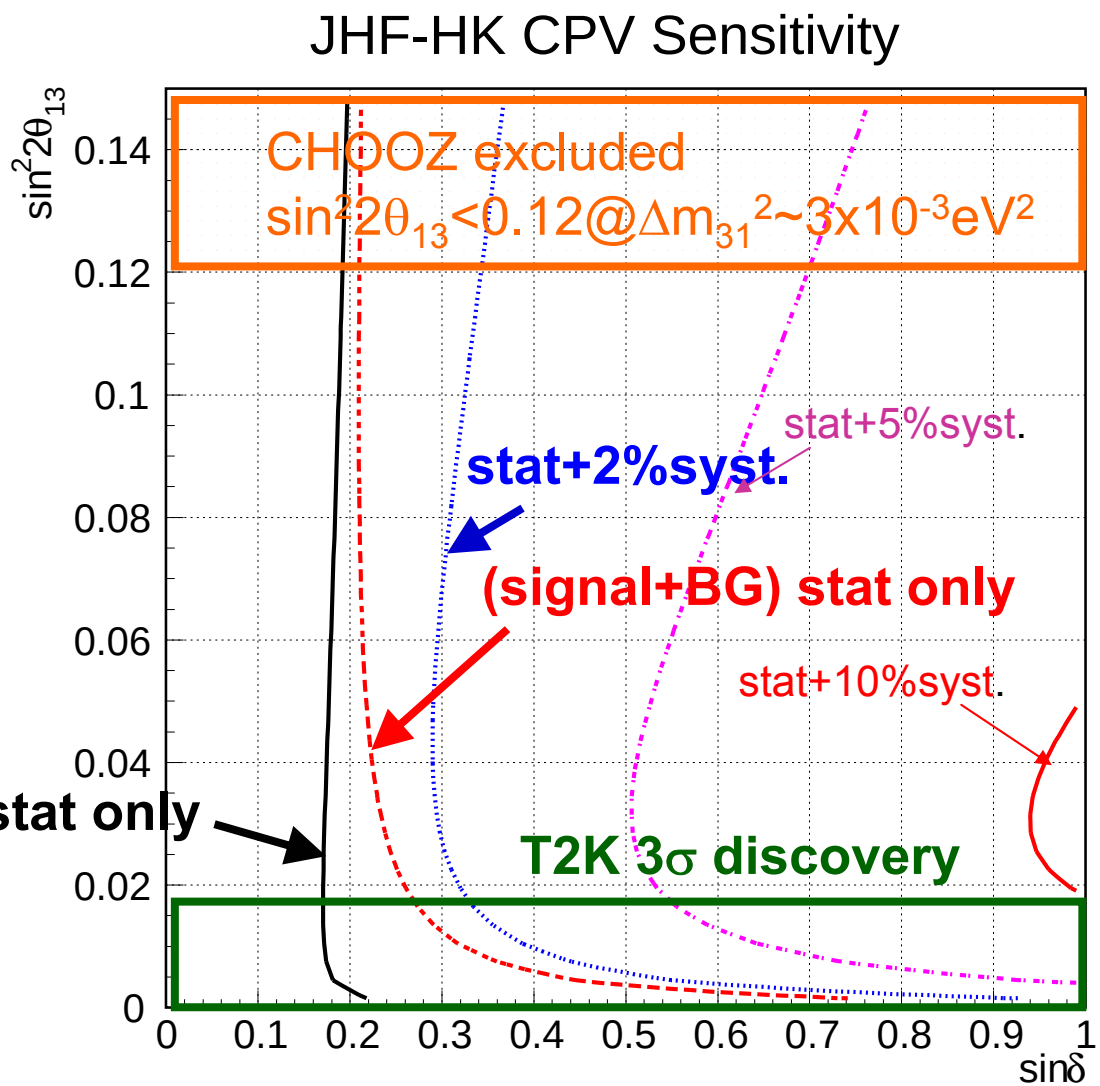
Small Matter Effect at 295km.

Future Extension: Search for CPV

4MW, 540kt
2yr for ν_μ
6~7yr for $\bar{\nu}_\mu$

#sig $\propto$ $\sin^2 2\theta_{13}$

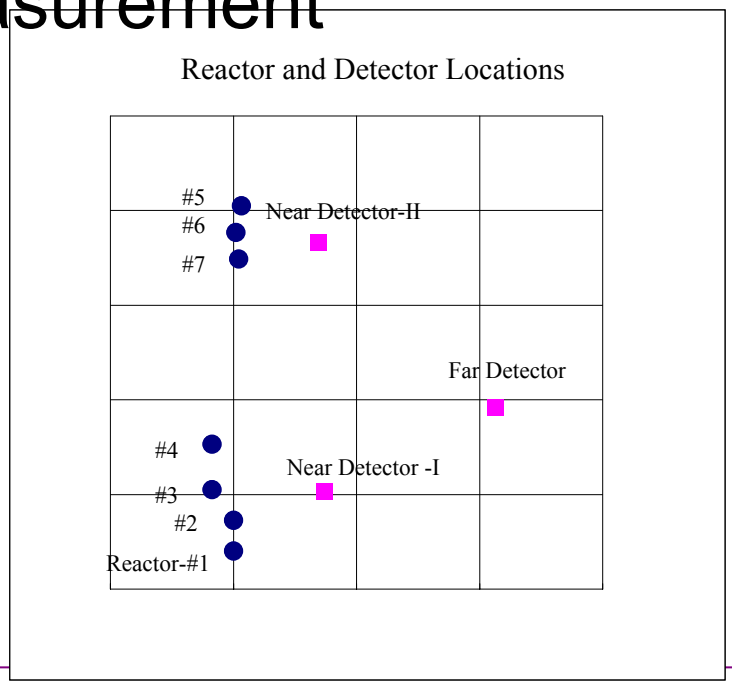
$$A_{CP} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$



3σ CP sensitivity : |δ|>20° for $\sin^2 2\theta_{13}$>0.01 with 2% syst.

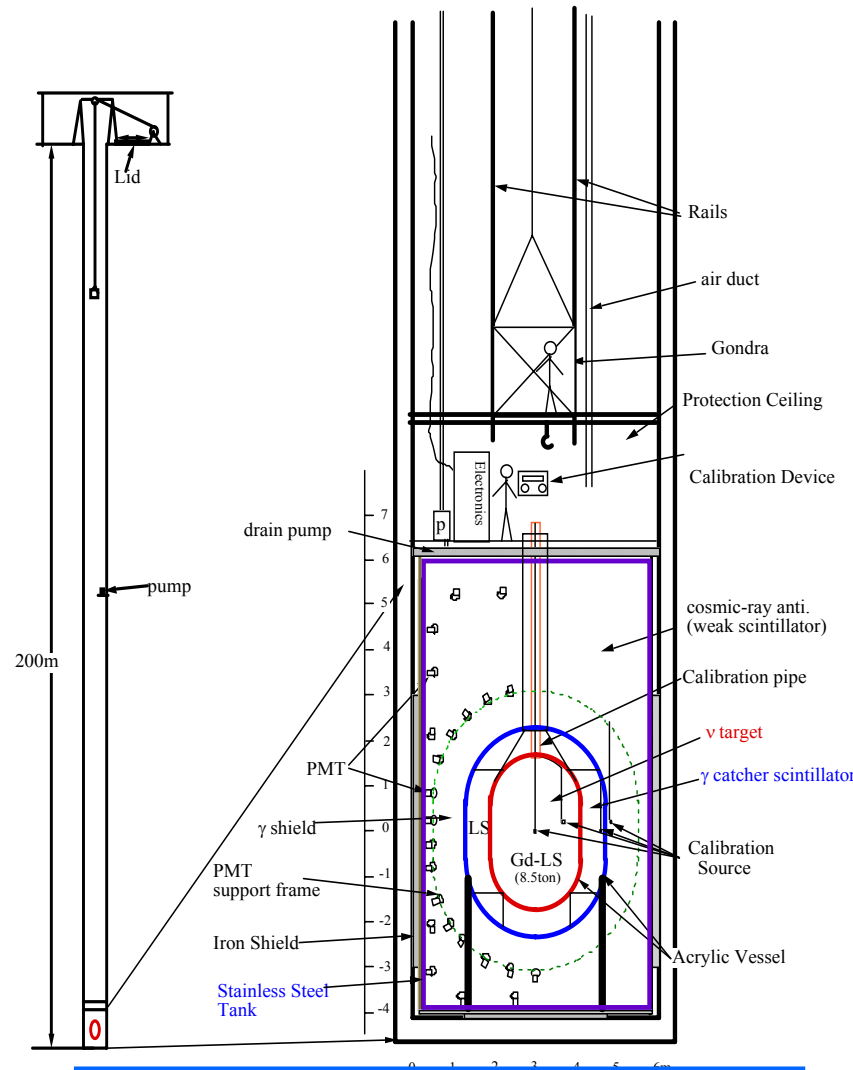
The KASKA experiment

- **Kas**hiwazaki-**Ka**riwa reactor neutrino experiment
  - World most powerful reactor
- ν_e disappearance for θ_{13} measurement



Identical near/far detectors
=> systematics cancellation

Suekane et.al.



Gd-loaded liq. scint. 8.5ton

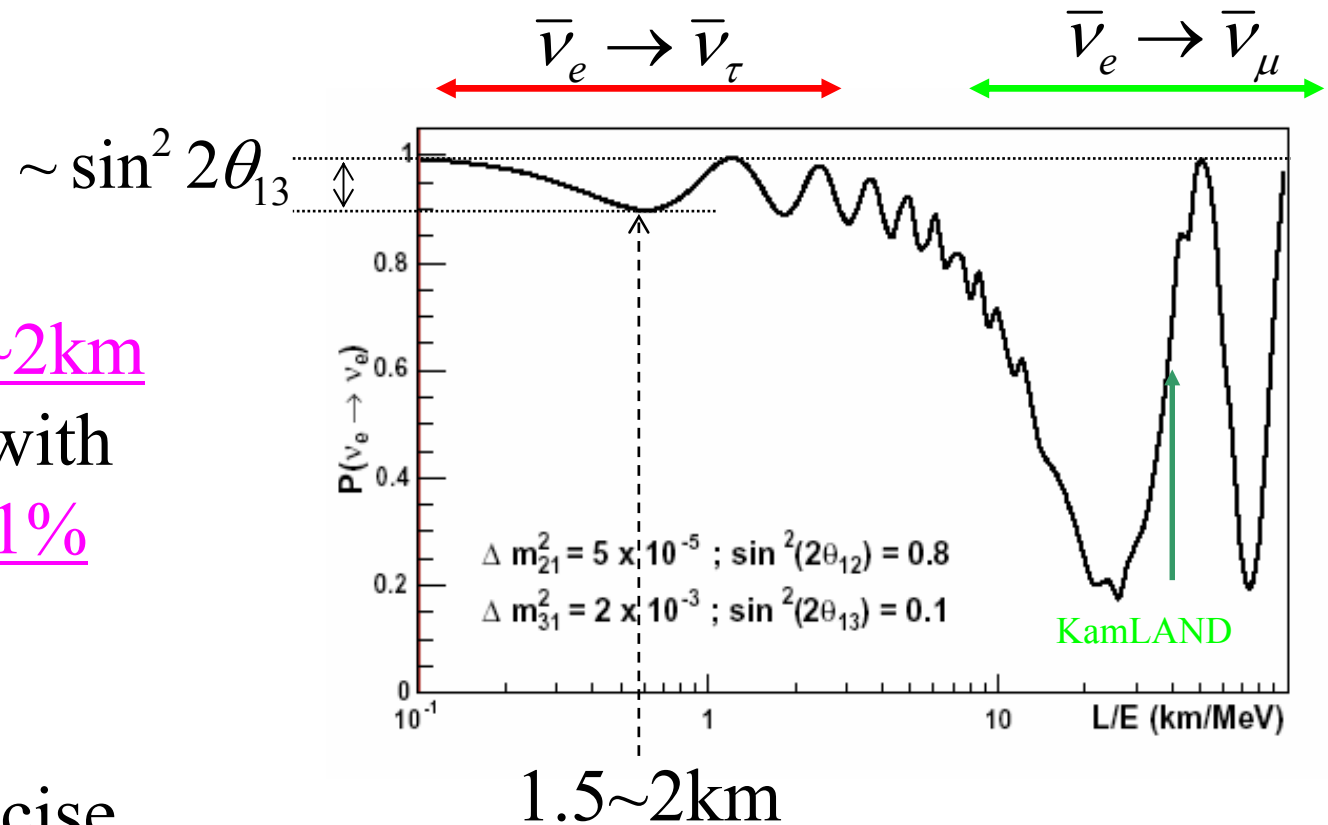
How to measure θ_{13} by reactor neutrinos

Baseline 1~2km

ν_e deficit with accuray~1%

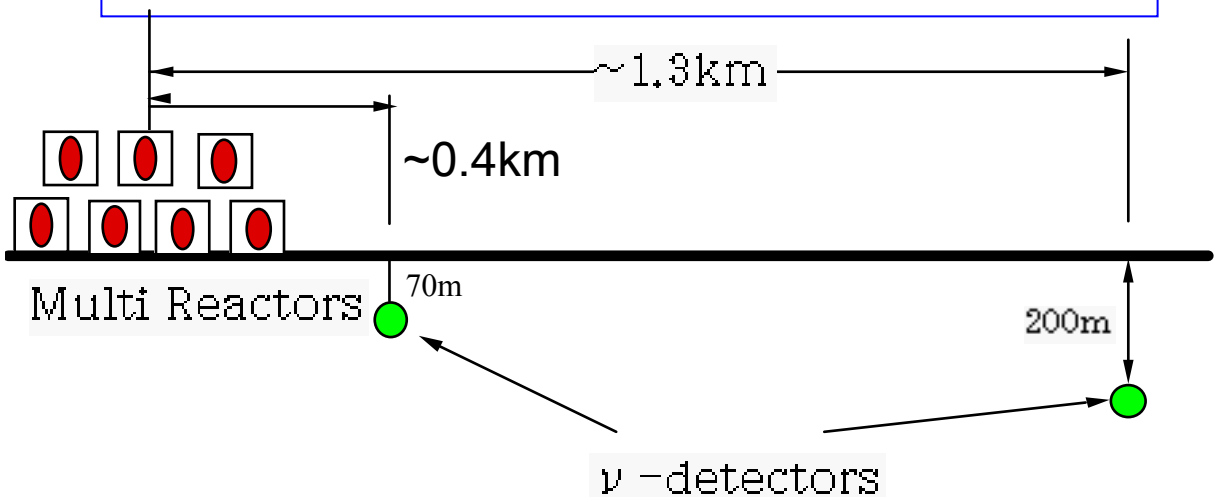
↓

Pure & Precise $\sin^2 2\theta_{13}$ Measurement



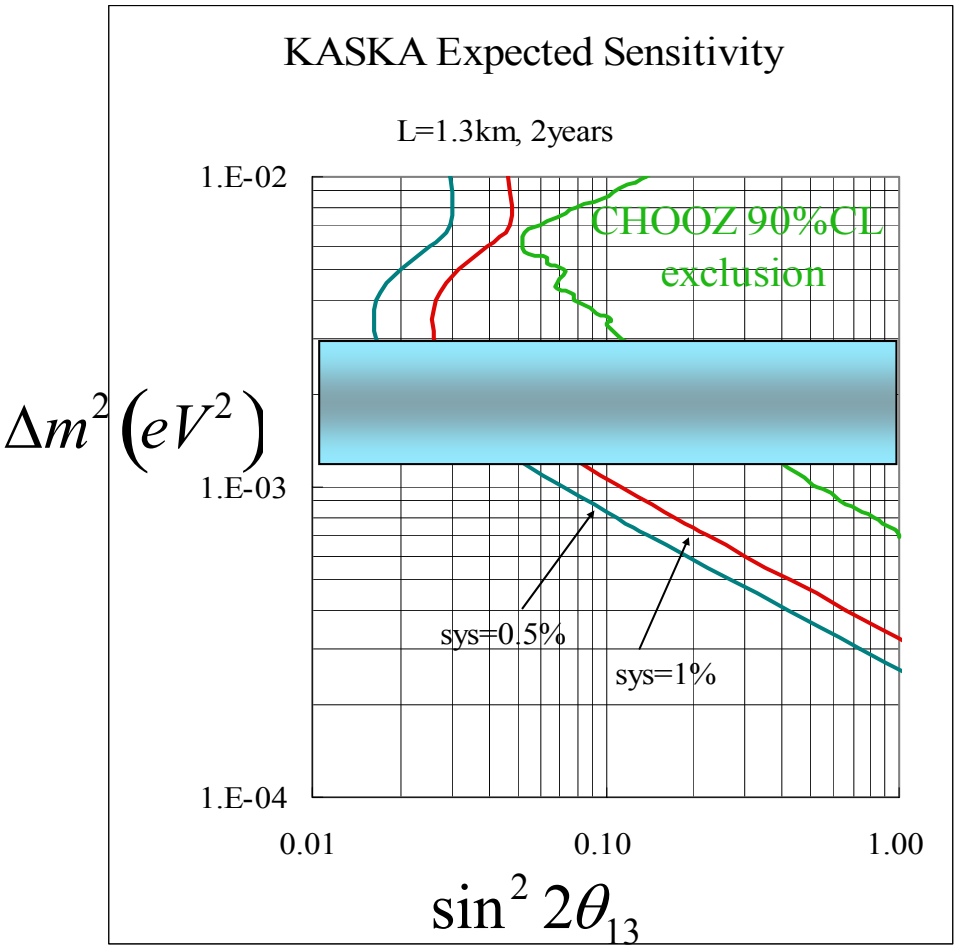
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E}$$

KASKA vs CHOOZ



	KASKA (far)	CHOOZ
Reactor Power	24.3GW	8.4GW
Baseline	1.3km	1km
Target mass	8ton	5ton
depth	350mwe	300mwe
Error	$<1\%_{sys}+0.5\%_{stat}$	$2.8\%_{sys}+2.7\%_{stat}$
$\sin^2 2\theta_{13}$ sensitivity @$\Delta m^2=0.002eV^2$	0.03	0.2

Expected sensitivity



σ_{sys} <1% (CHOOZ 2.7%)

σ_{stat}~0.5% (CHOOZ 2.8%)

5~7 times better sensitivity than CHOOZ

& Comparable to Accelerator θ_{13} sensitivity.

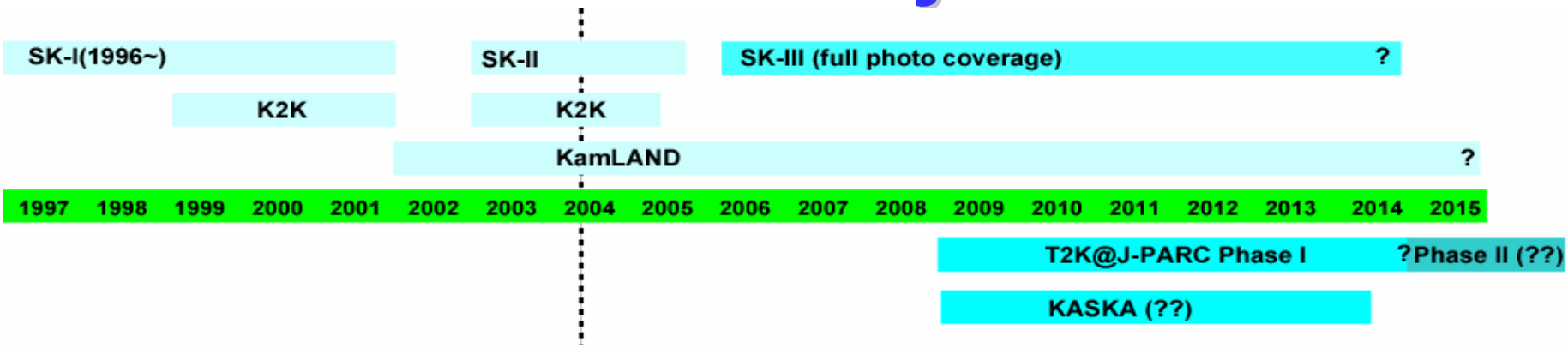
$\sin^2 2\theta_{13}$ ~ 0.02 @ Δm^2~3×10^{-3}eV (90%CL)

KASKA: Possible schedule

2003: Conceptual Design
Investigation of Site Availability
2004: R&D
2005: R&D
2006: Start Construction
2007: Construction Continues
2008: Start Data Taking
2009: Initial Result

Grant for R&D is approved in this year

Summary



- Japanese experiments have been playing major role in understanding neutrino physics
- For the next critical step: $\sin^2 2\theta_{13}$ sensitivity
  - KASKA(?) : ~0.02(90%) ~2011??
  - T2K(approved):0.018(3σ)/0.006(90%) ~2014
  - SK(running) :0.06 (3σ) ~2017
- Even more future prospect
  - 1Mton Hyper-Kamiokande + 4MW J-PARC (T2K-II)
  - Search for CPV in lepton sector (down to δ~20deg)

Introduction: Neutrino experiments in Japan

- History of neutrino experiment in Japan was opened by the pioneering work of Prof. Koshiba on **Kamiokande** (1983~)
  - Real time solar neutrino detection
  - Supernova neutrino detection (1987)
  - ➔ Nobel prize to Prof. Koshiba in 2002
- The seed bear several fruits in ’90s, ’00s
  - **Super-Kamiokande** (1996~)
  - **K2K**(1999~) : First long baseline experiment
  - **KamLAND** (2002~) : 1kt liq. Scint
- Now, some grandchildren(?) are growing….
  - **T2K** (2009~) : 2nd gen. LBL exp. (APPROVED!!)
  - **KASKA** (2009??~) : 2-detector reactor exp.

Neutrino mixing

If neutrino have finite mass, weak and mass eigenstates can differ

$$\left|\nu_l\right\rangle = \Sigma U_{li}\left|\nu_i\right\rangle$$

Weak — Mass eigenstates

m_i: 3 masses, Δm_{ij}: 2 differences

Maki-**N**akagawa-**S**akata **Matrix** $s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

3 mixing angles and 1 CPV phase

Unknown 2 parameters

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

$\sin^2 2\theta_{12}\sim 0.8$ (Solar)

$\sin^2 2\theta_{23}\sim 1$ (Atm ν)

Reactor

Long baseline experiments

Mile stones in the past

- 1999.4 : JHFν working group formed (ICRR/KEK/Kyoto/Kobe/Tohoku/TRIUMF)
- 2001.4: Neutrino Facility Const. G. formed officially in KEK
- 2002.12 : LOI submitted to J-PARC office
- 2003.5 :International collaboration formed (Spokesperson: K.Nishikawa)
- **2003.12: J-PARC NEUTRINO FACILITY APPROVED.**
  - **5 years budget(Apr.2004 ~ Mar.2009)**
  - **Total of 16.0Byen (~160M$)**
- **2004.4: Neutrino beam construction started!!**

(*) Formerly J-PARC was called JHF

WW International Collaboration

Country/Institute		#of collaborators
1.Japan	(9 inst's)	45
1	ICRR, U. Tokyo	13
2	KEK	12
3	Tohoku U.	6
4	Hiroshima U.	3
5	Kyoto U.	3
6	Kobe U.	3
7	Osaka City U.	2
8	U. Tokyo	2
9	Miyagi U. of Education	1
2.US	(14 inst's)	38
1	UCI	5
2	SUNY-SB	5
3	U. Rochester	5
4	U. Pennsylvania	4
5	Boston U.	4
6	CSU, Dominguez Hills	3
7	BNL	3
8	UCB/LBL	2
9	U. Hawaii	2
10	ANL	1
11	MIT	1
12	LSU	1
13	LANL	1
14	U. Washington	1
3.Korea	(8 inst's)	10
1	Seoul National U.	2
2	Chonnam National U.	2
3	Dongshin U.	1
4	Kangwon U.	1
5	Kyungpook National U.	1
6	KyungSang National U.	1
7	SungKyunKwan U.	1
8	Yonsei U.	1
4.Poland	(1 inst's)	1
1	Warsaw U.	1
5.Spain	(2 inst's)	5
1	U. Barcelona	2
2	U. Valencia	3
6.Switzerland	(1 inst's)	2
1	U. Geneva	2
7.Russia	(1 inst's)	4
1	INR	4
8.Italy	(4 inst's)	7
1	U. Roma	3
2	U. Bari	2
3	U. Napoli	1
4	U. Padova	1
9.France	(1 inst's)	5
1	CEA Saclay	5
10.Canada	(6 inst's)	20
1	TRIUMF	12
2	U. Alberta	3
3	York U.	2
4	U. Toronto	1
5	U. Victoria	1
6	U. Regina	1
11.China	(1 inst's)	4
1	IHEP (Inst. Of High Energy Phys.)	4
12.UK	(4 inst's)	7
1	RAL	1
2	Imperial College London	2
3	Queen Mary Westfield College London	1
4	U. Liverpool	3

- Formed in May 2003
- 12 countries, 52 institutions
- 148 collaborators (not incl. students)
- Spokesperson: K.Nishikawa (Kyoto U.)

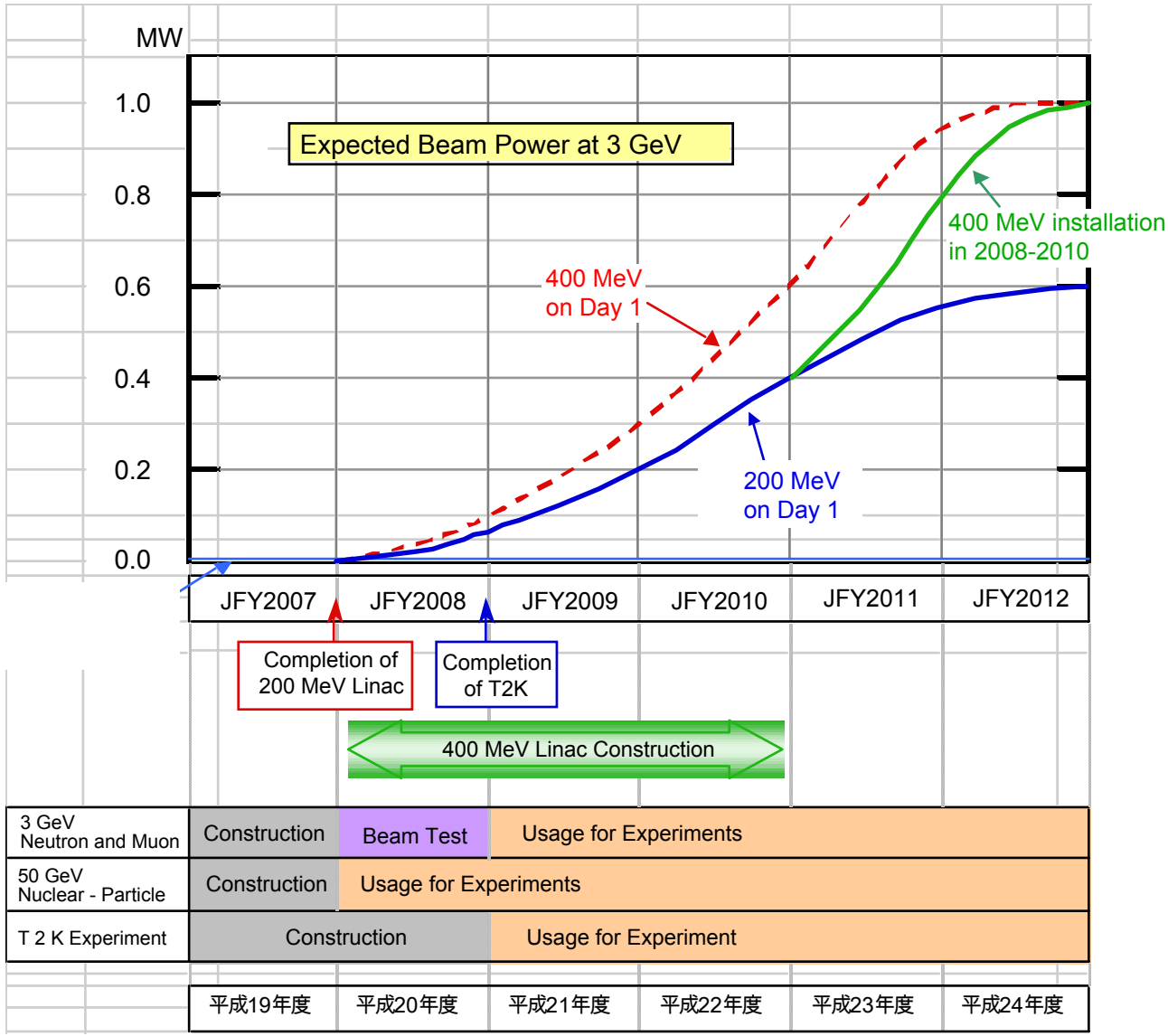
Fast-extraction beam

E (GeV)	Harm.#	Bunch	Period (s)	I(μA)	P (kW)	E_{lin}(MeV)
40*	9	8	3.53	9	360	181
40*	18	15	3.38	17.4	700	181
<for comparison>						
40	9	8	3.53	15	600	400
50	9	8	3.53	15	750	400

* The ratio of per bunch intensity between 181 MeV and 400 MeV of 0.6 is assumed.

- Beam energy is limited to 40 GeV due to the lack of a flywheel.

Expected Beam Power



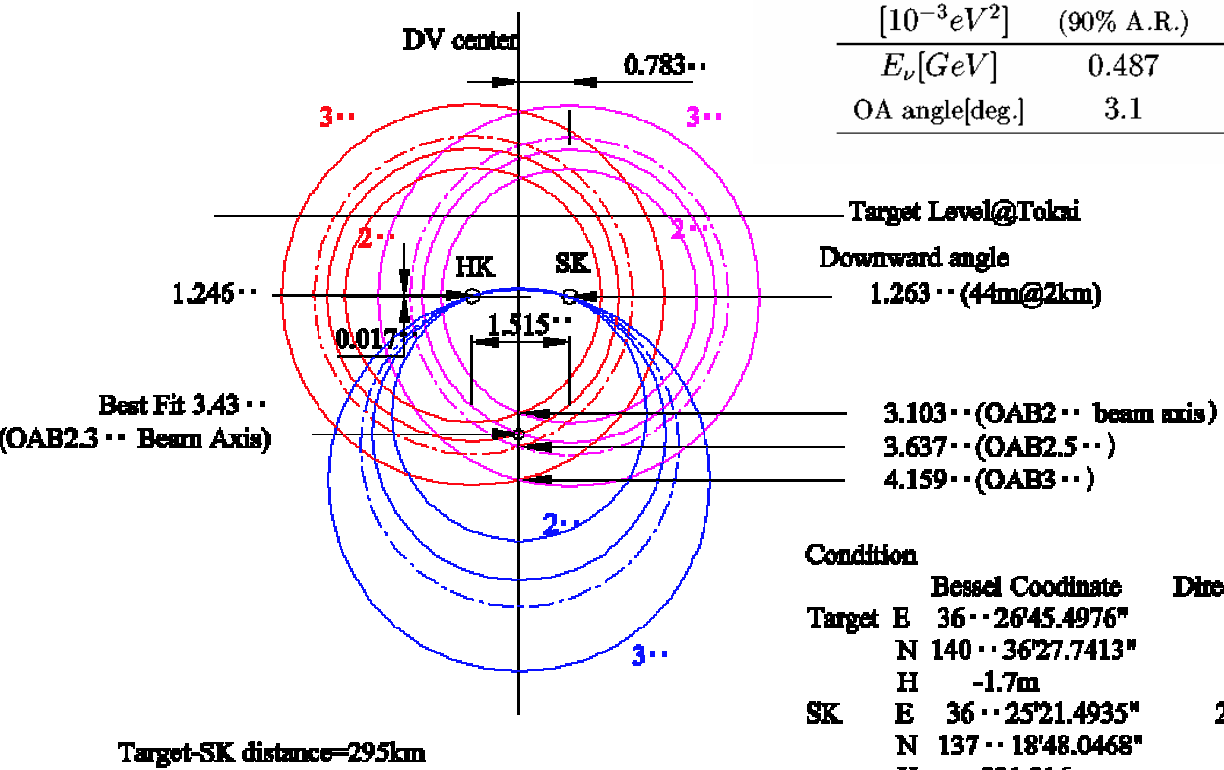
Optimization of Decay Volume

Peak Eν is determined by off-axis angle.

表 3.1: E_ν at the oscillation maximum for the baseline length of 295km and corresponding off-axis angle.

Δm^2	2.04	2.18	2.75	3.17	3.28
$[10^{-3}eV^2]$	(90% A.R.)	(80% A.R.)	(best fit)	(80% A.R)	(90 % A.R)
$E_\nu[GeV]$	0.487	0.520	0.656	0.756	0.782
OA angle[deg.]	3.1	3.0	2.4	2.1	2.0

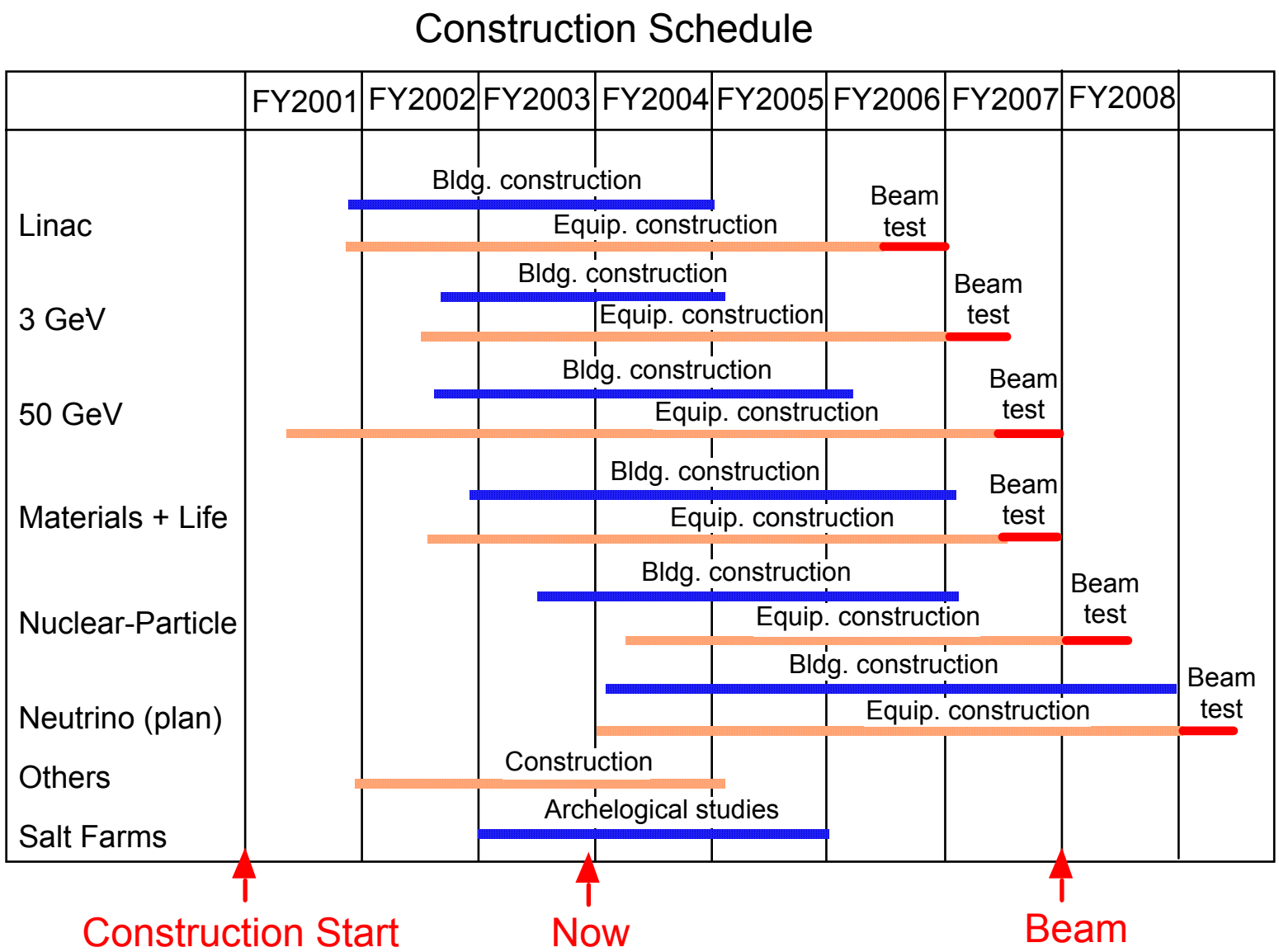
Cover this region



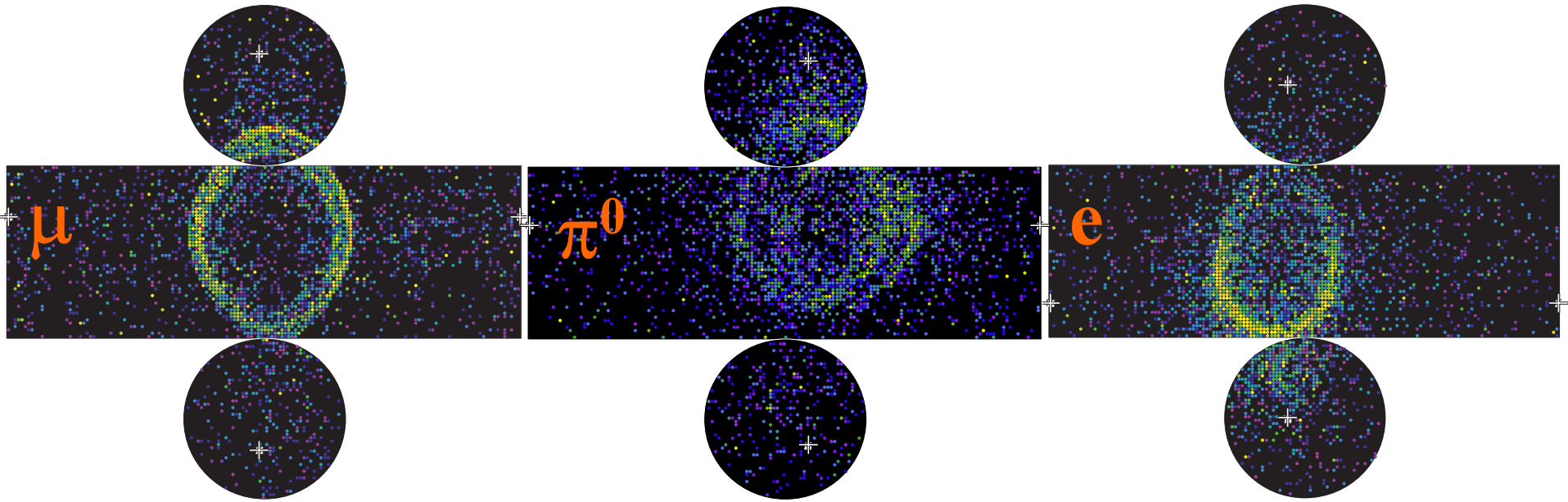
Condition

		Bessel Coodinate	Direction Angle
Target	E	36··26'45.4976"	
	N	140··36'27.7413"	
	H	-1.7m	
SK	E	36··25'21.4935"	270.4764
	N	137··18'48.0468"	1.2626
	H	321.216m	
HK	E	36··21'08"	268.9618
	N	137··18'49"	1.2463
	H	412.175m	

Construction Schedule



ν_e appearance in "T2K"



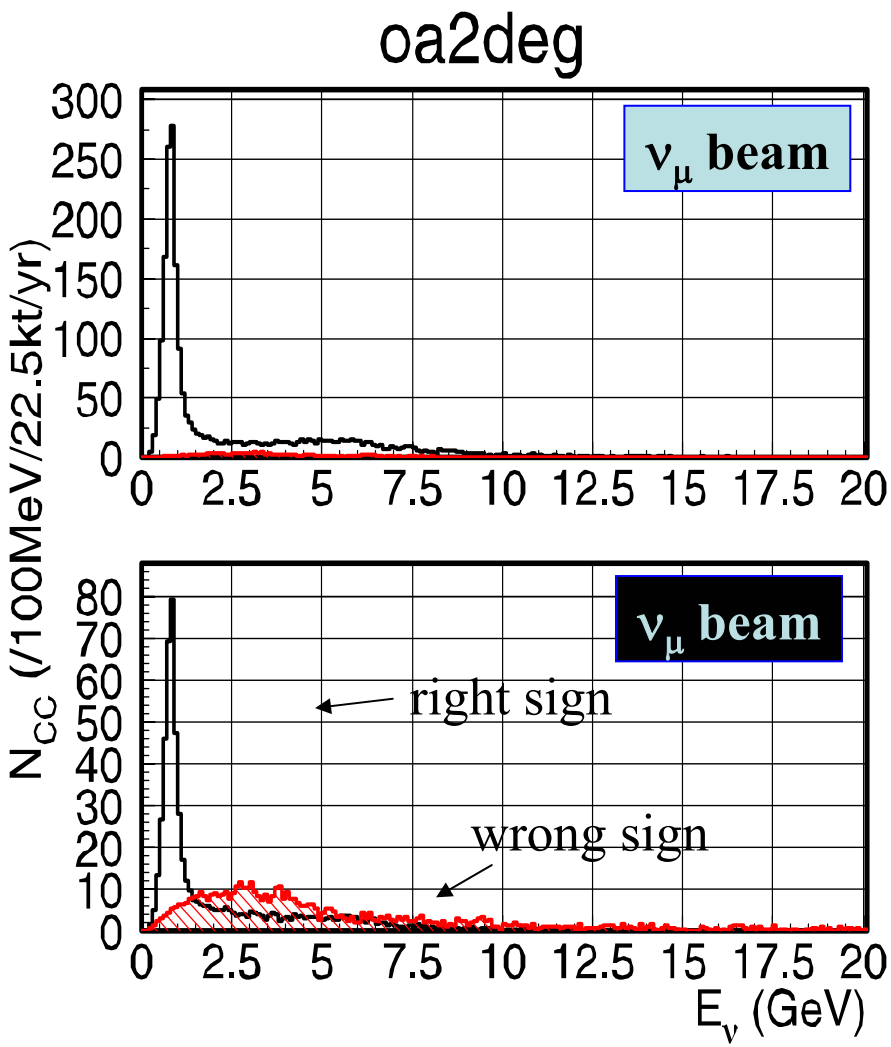
Back ground for ν_e appearance search

- Intrinsic ν_e component in initial beam
- Merged π^0 ring from ν_μ interactions

Requirement ⇨ 10% uncertainty for BG estimation

The K2K 1kt π^0 data will be studied for exercise

$\nu_\mu / \bar{\nu}_\mu$ # of CC int.



10^{21}pot/yr (1st phase)

- # of int. for $\bar{\nu}_\mu$ is factor ~3 smaller than ν_μ due to cross section.
- Wrong sign contamination is worse for OAB.

Error Summary

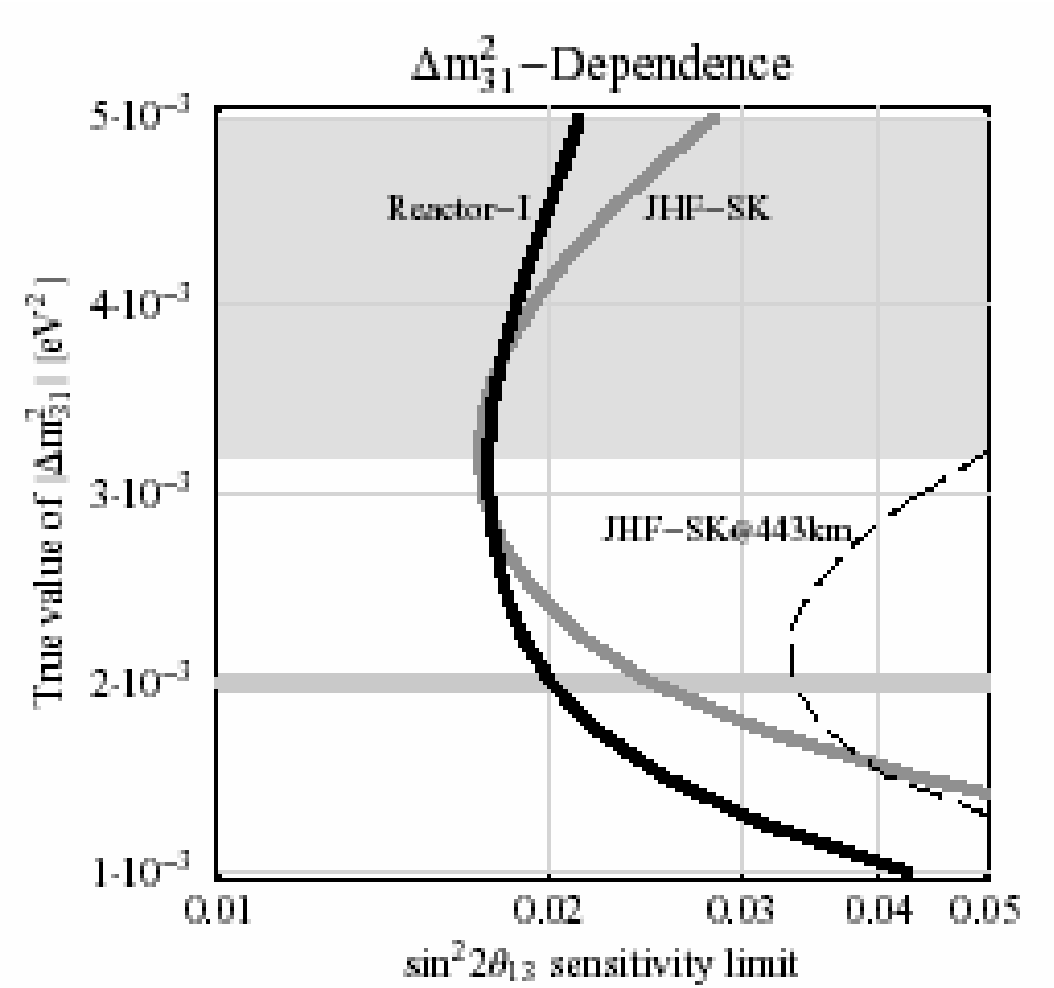
Statistic Error: 40,000/2years => 0.5%

Systematic Error:	e^+ cut	<0.5%
	n cut	<0.5%
	timing cut	0.3%
	LS volume	<0.5%
	n flux	0.2%
	BKG	0.3%
	Total	<1%

One advantage of KASKA
=> systematic estimation can be checked by 2 front detectors

$\sin^2 2\theta_{13}$ Limit by Accelerator

hep-ex/0402041



Reactor: 400tGWy
(=2KASKA years)

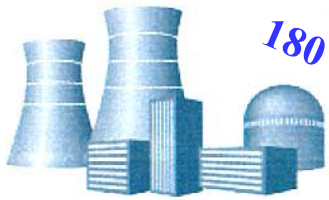
KamLAND future

1. KamLAND Experiment

1,000 ton liquid scintillator neutrino detector

1st phase experiment
(E_{th} = 1.8 MeV)
$\bar{\nu}_e + p \rightarrow e^+ + n$

○ Neutrino Oscillation Search by Reactor Anti-neutrinos

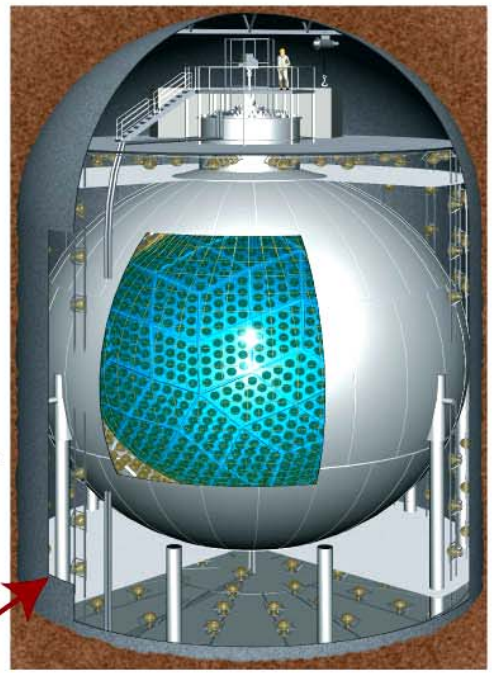


180 km

$\bar{\nu}_e$

○ Terrestrial Anti-neutrino Detection

$\bar{\nu}_e$



2nd phase experiment
(E_{th} =300 keV)
$\nu_e + e^- \rightarrow \nu_e + e^-$

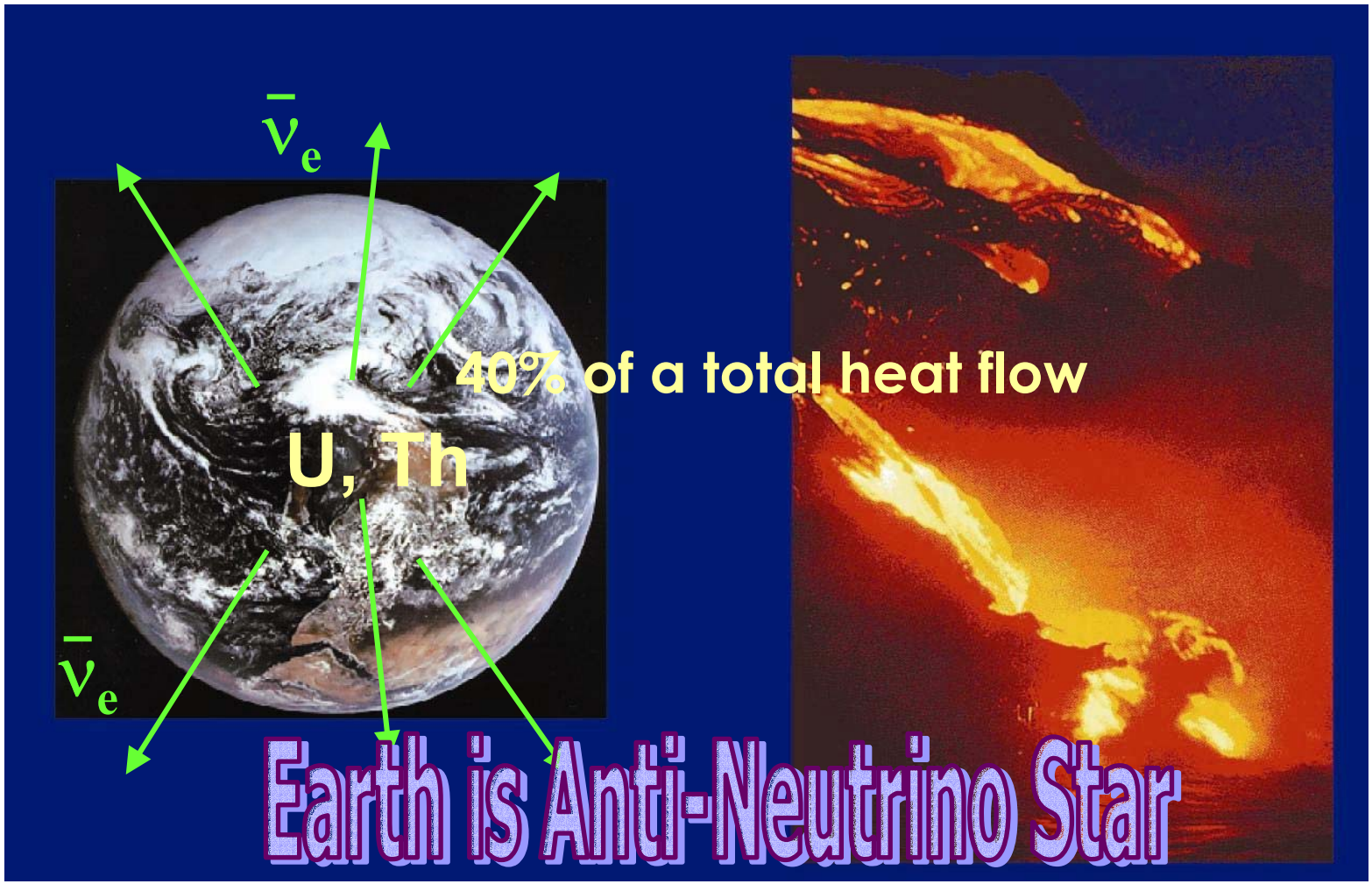
○ Solar neutrino Detection

^{7}Be Neutrino

ν_e

supernova-burst ν, relic supernova ν,
atmospheric ν, Proton Decays, · · ·

4. Geoneutrino Detection



Geoneutrino Generation

- Heat Generation inside the Earth
  - -- total heat flow ~ 40 TW ?
  - -- U/Th contribution ~ 16 TW ???

$$^{238}U \rightarrow {}^{206}Pb + 8\,{}^{4}He + 6\,e^{-} + 6\,\bar{\nu}_e + 51.7\ MeV$$
$$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^{4}He + 4\,e^{-} + 4\,\bar{\nu}_e + 42.7\ MeV$$

- Geochemical Earth Model
  - -- no reliable values of U/Th concentration in Crust, Mantle and Core

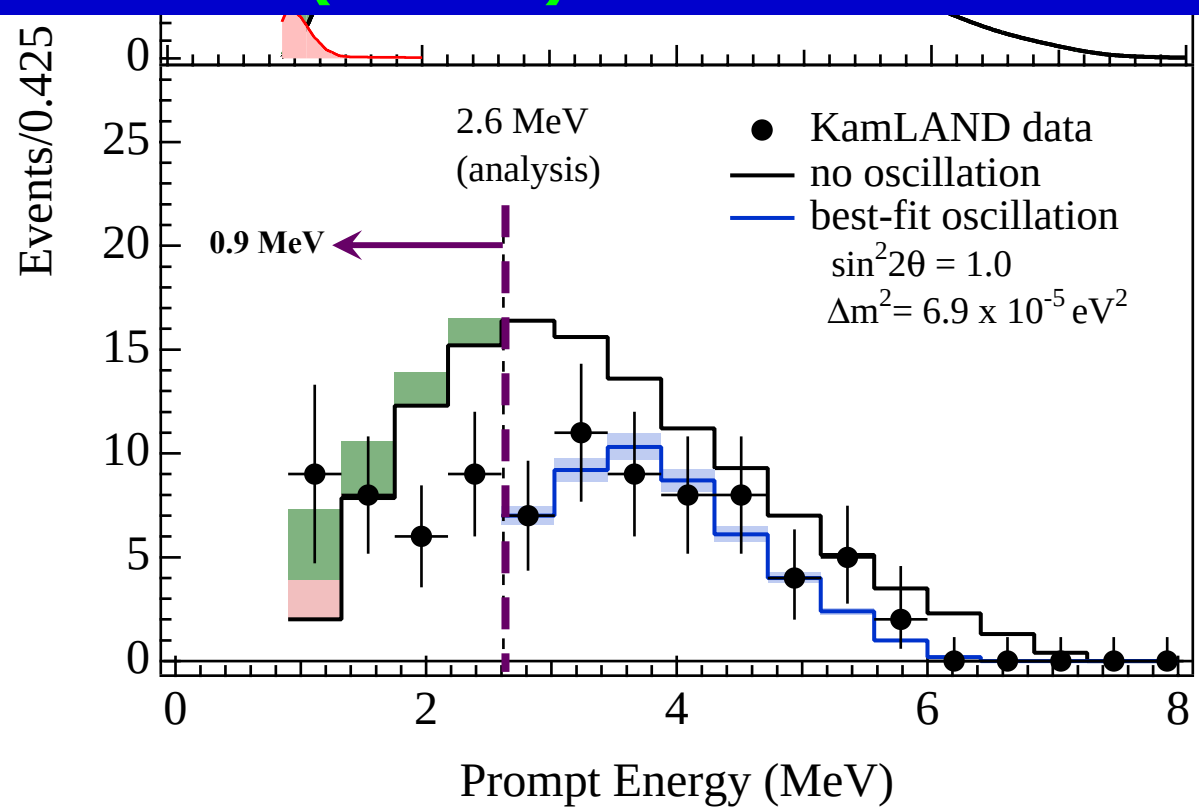
$\bar{\nu}_e$ detection is essential

Geoneutrino Flux ?

~ $4\bar{\nu}_e$: ^{238}U ~ $5\bar{\nu}_e$: ^{232}Th

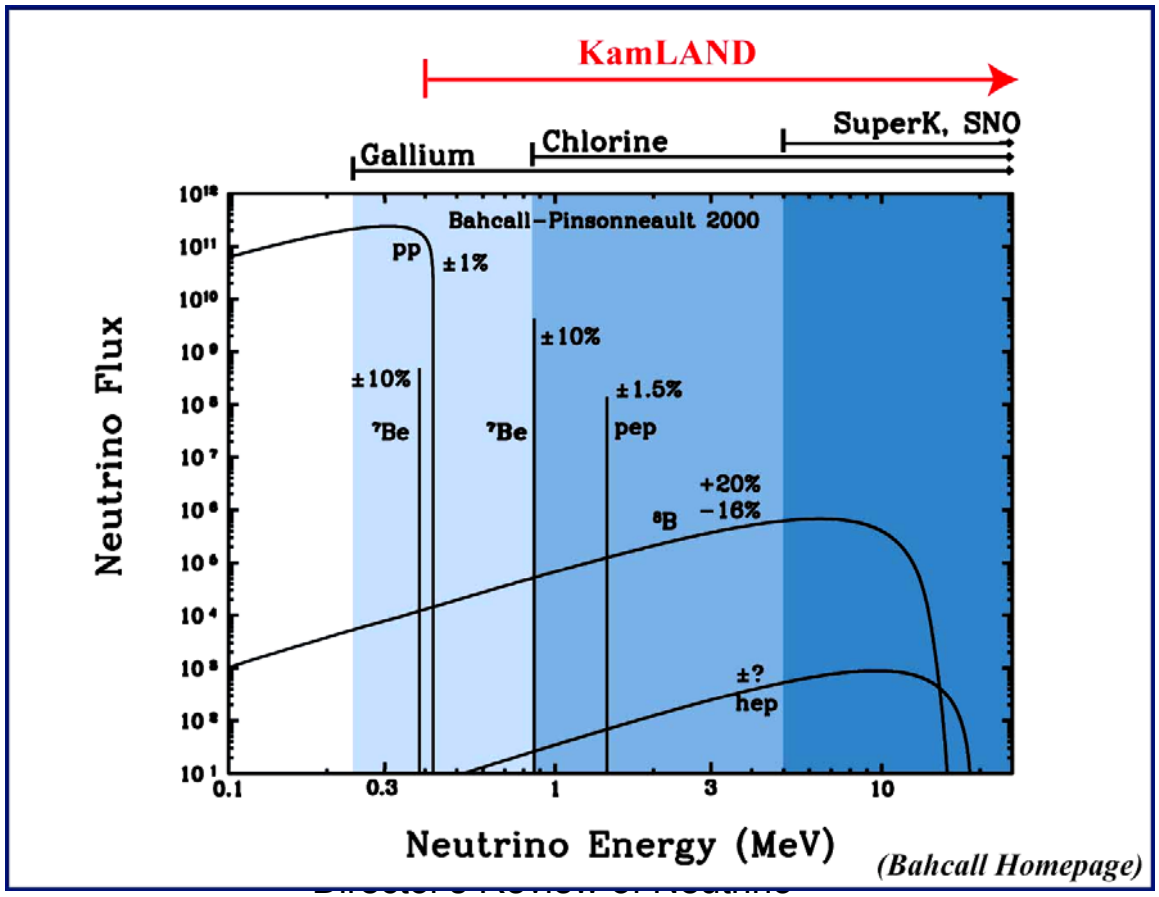
Radiogenic heat : ~40TW (model-dependent)

(0 – 110) TW at 95 % C.L.



5. Plan : ^{7}Be Solar Neutrino Detection

$\nu_e + e^- \rightarrow \nu_e + e^-$ $\sim$200 ν/kton•day

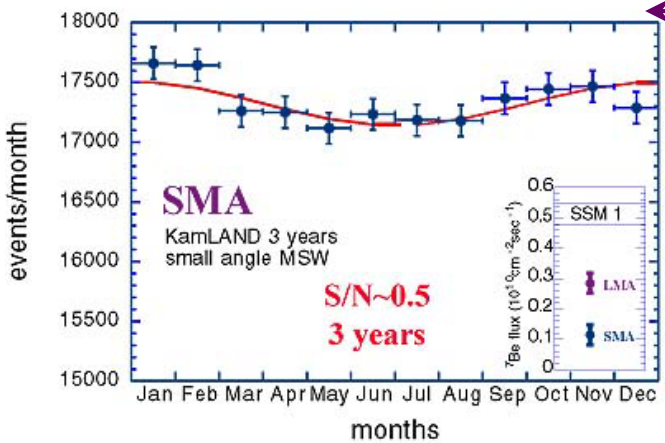


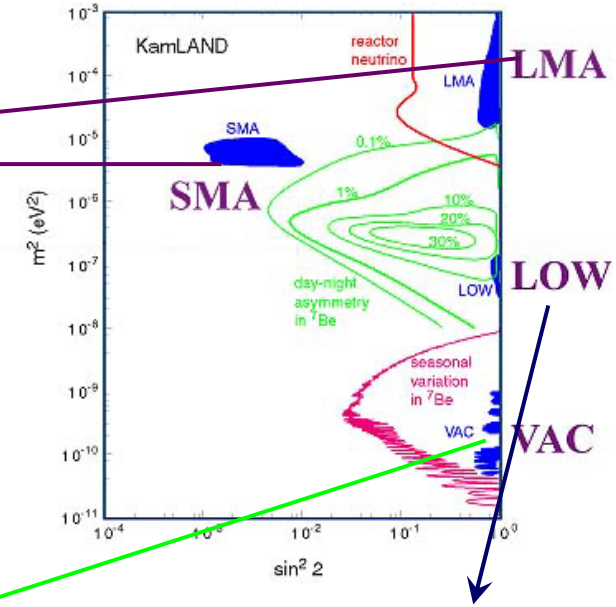
Requirements & Achievements of Radioactive Impurities in Liquid Scintillator

impurities	present	goal	reduction
^{238}U	$(3.5 \pm 0.5) \times 10^{-18}$ g/g	10^{-16} g/g	☺
^{232}Th	$(5.2 \pm 0.8) \times 10^{-17}$ g/g	10^{-16} g/g	☺
^{40}K	$< 2.7 \times 10^{-16}$ g/g	10^{-18} g/g	$\sim 10^{-2}$
^{85}Kr	~ 1 Bq/m^3	~ 1 μBq/m^3	10^{-6}
^{210}Pb	~ 100 Bq/m^3	~ 1 μBq/m^3	10^{-6}

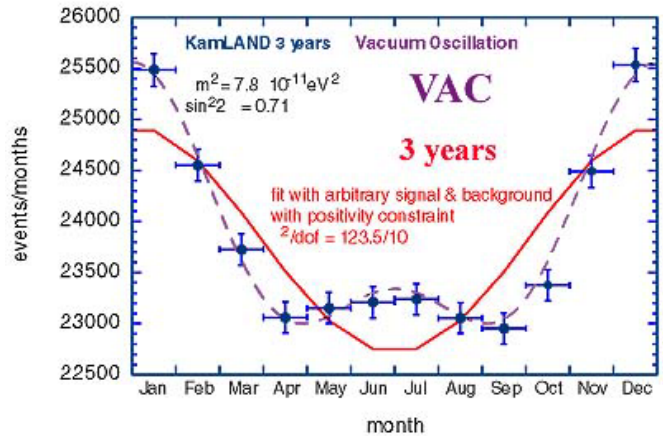
Physics 1 : Reconfirmation of Oscillation Solution

Seasonal Variation

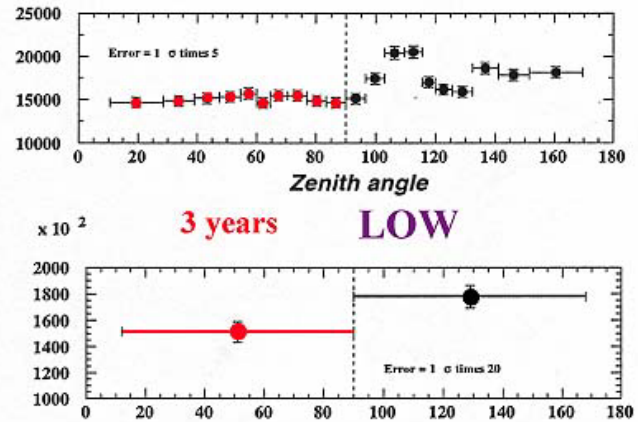




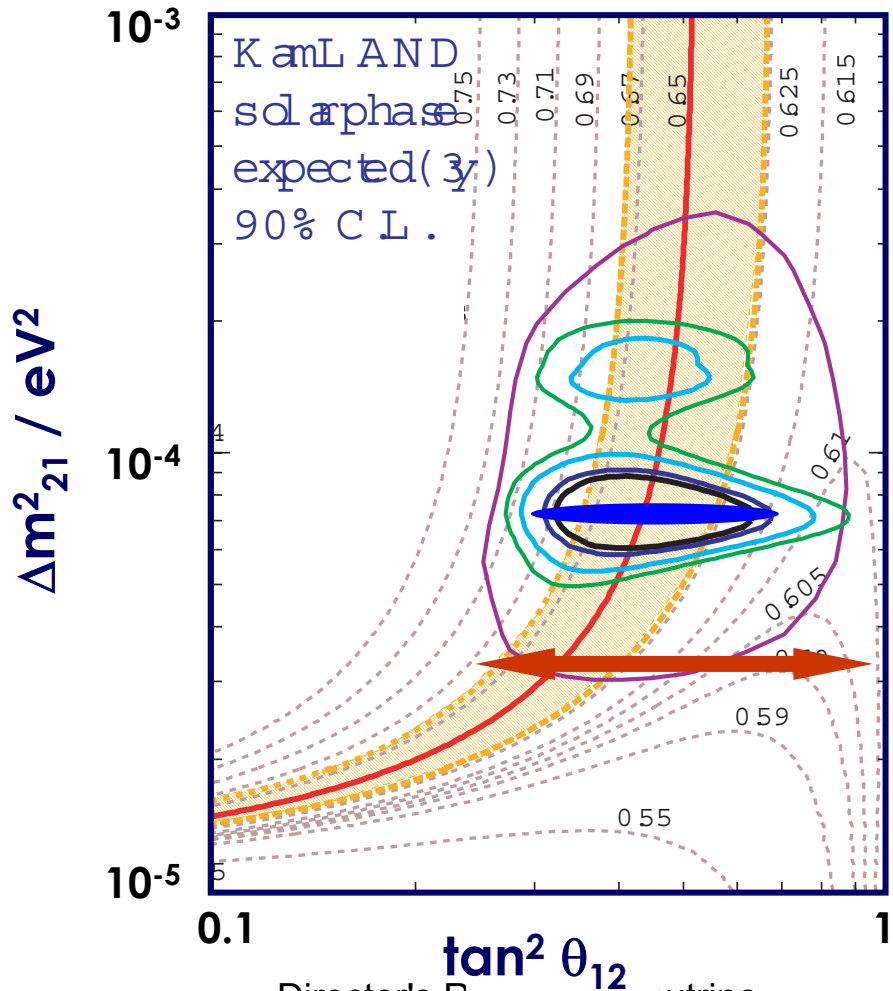
Just So Resonance



Day / Night Variation



Physics 2 : Determination of Θ_{12} ?

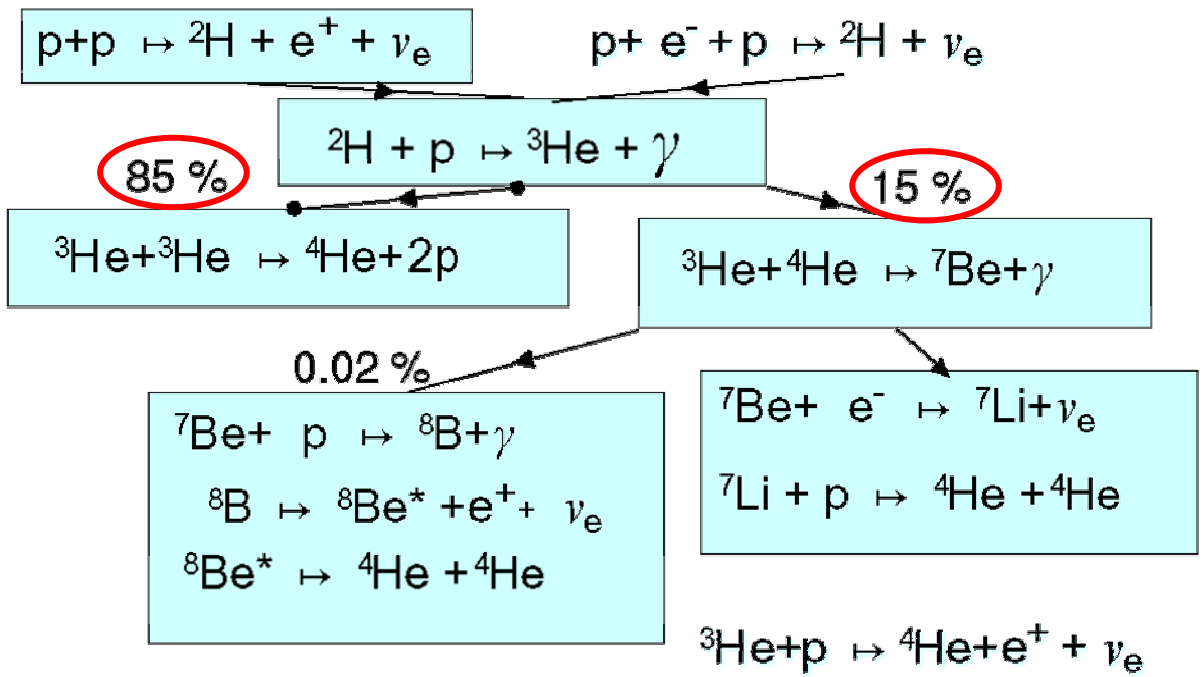


A.Bandyopadhyay et al., hep-ph/0302243 (2003)

KamLAND reactor

flux uncertainties ± 10 %

Physics 3 : Test of Standard Solar Model

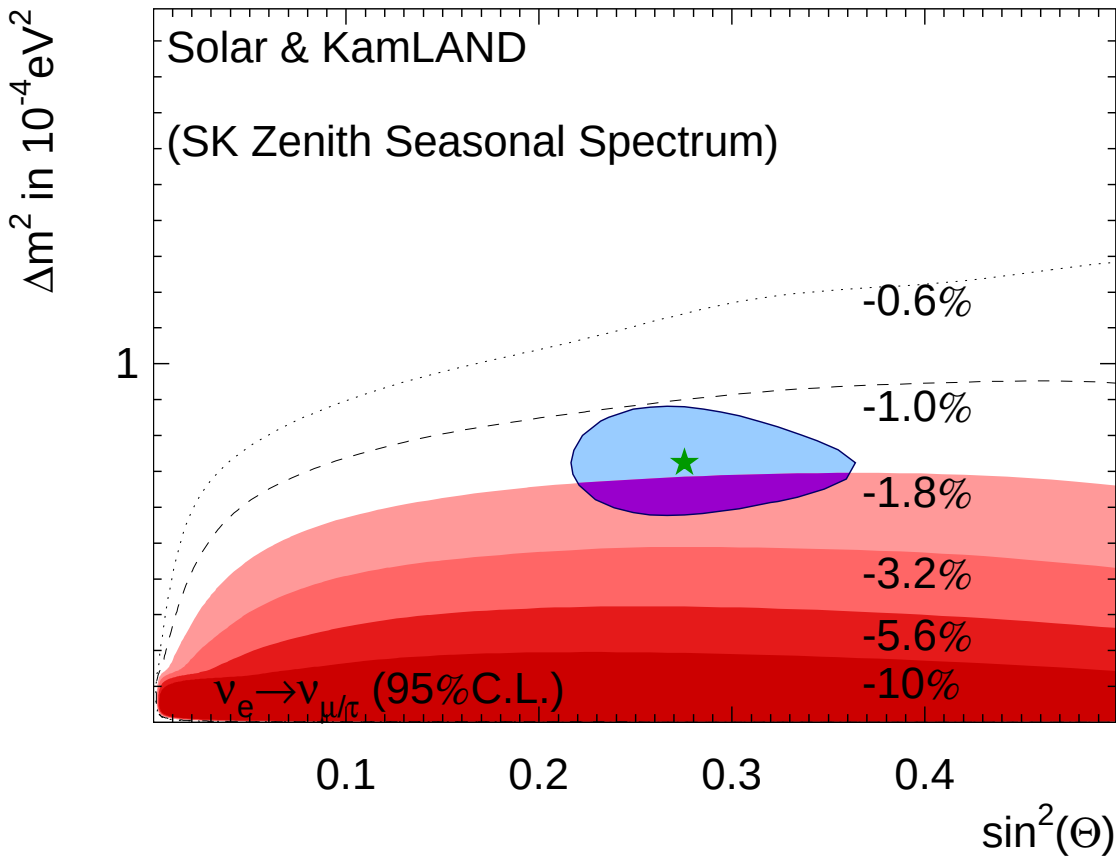


$$\frac{<{}^3He + {}^4He>}{<{}^3He + {}^3He>} = \frac{2\phi({}^7Be)}{\phi(pp) - \phi({}^7Be)}$$

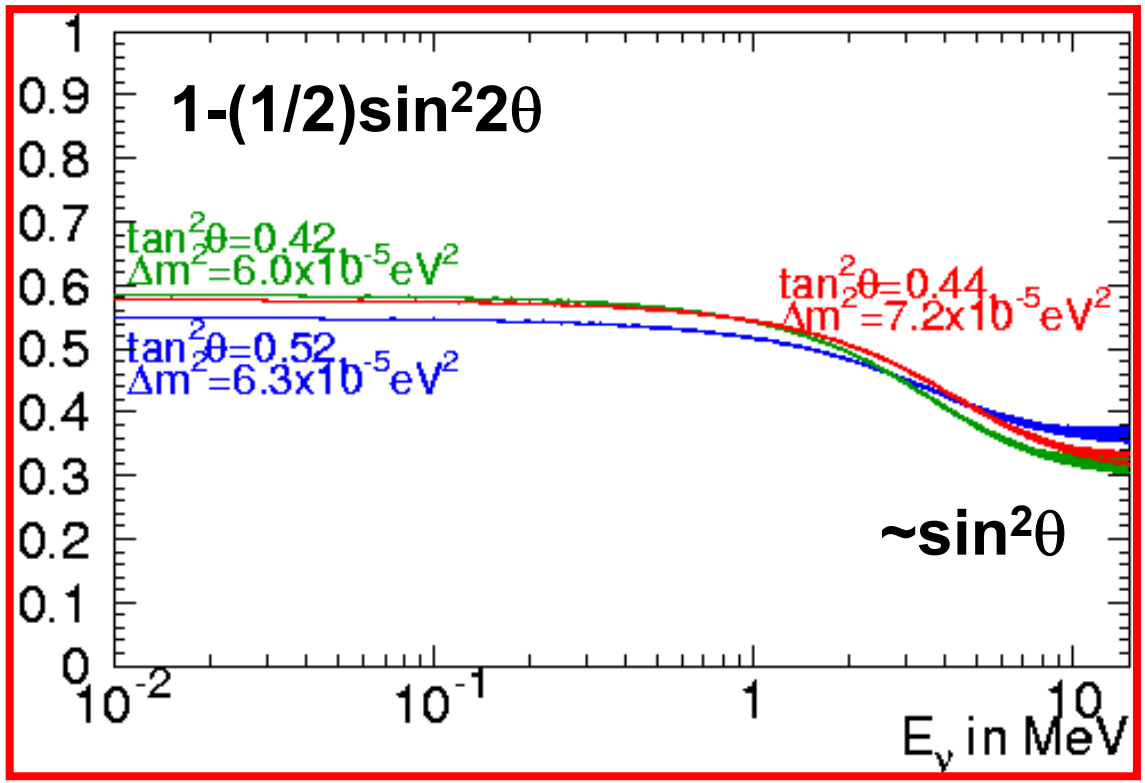
Super-K Solar neutrino

Future solar neutrino observation in Super-K

Day / Night flux differences

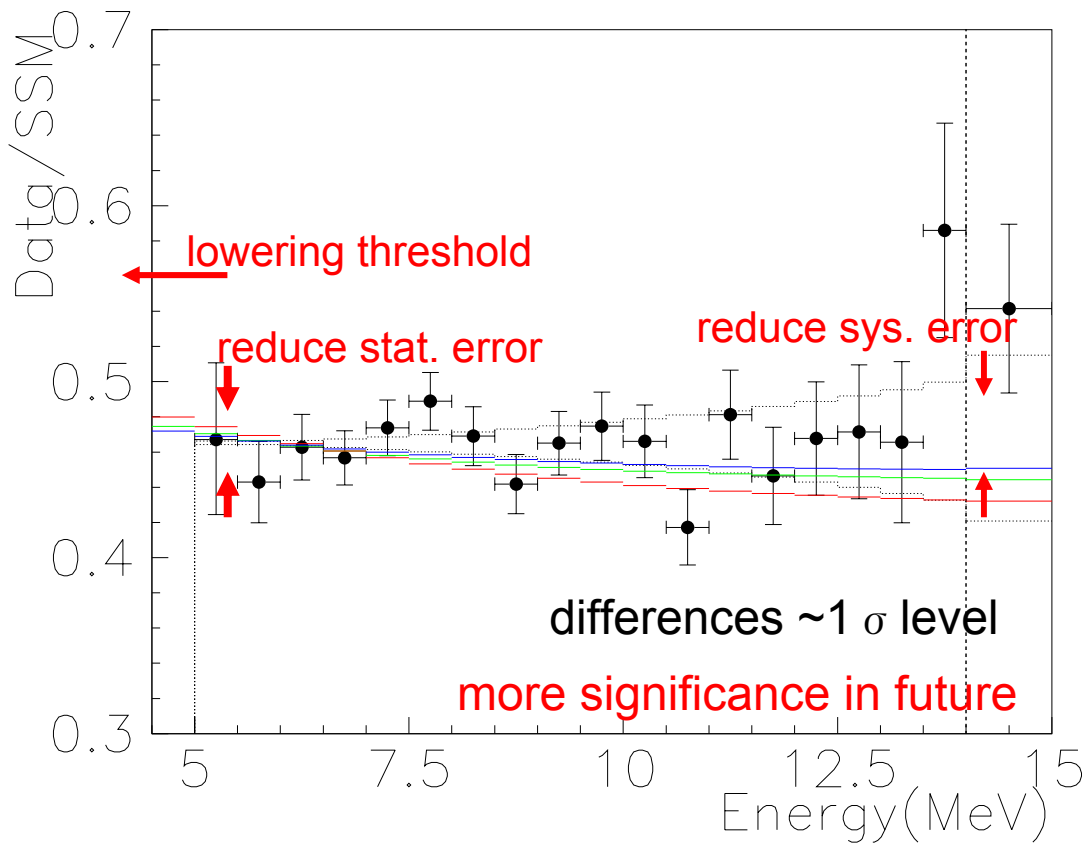


Future solar neutrino observation in Super-K

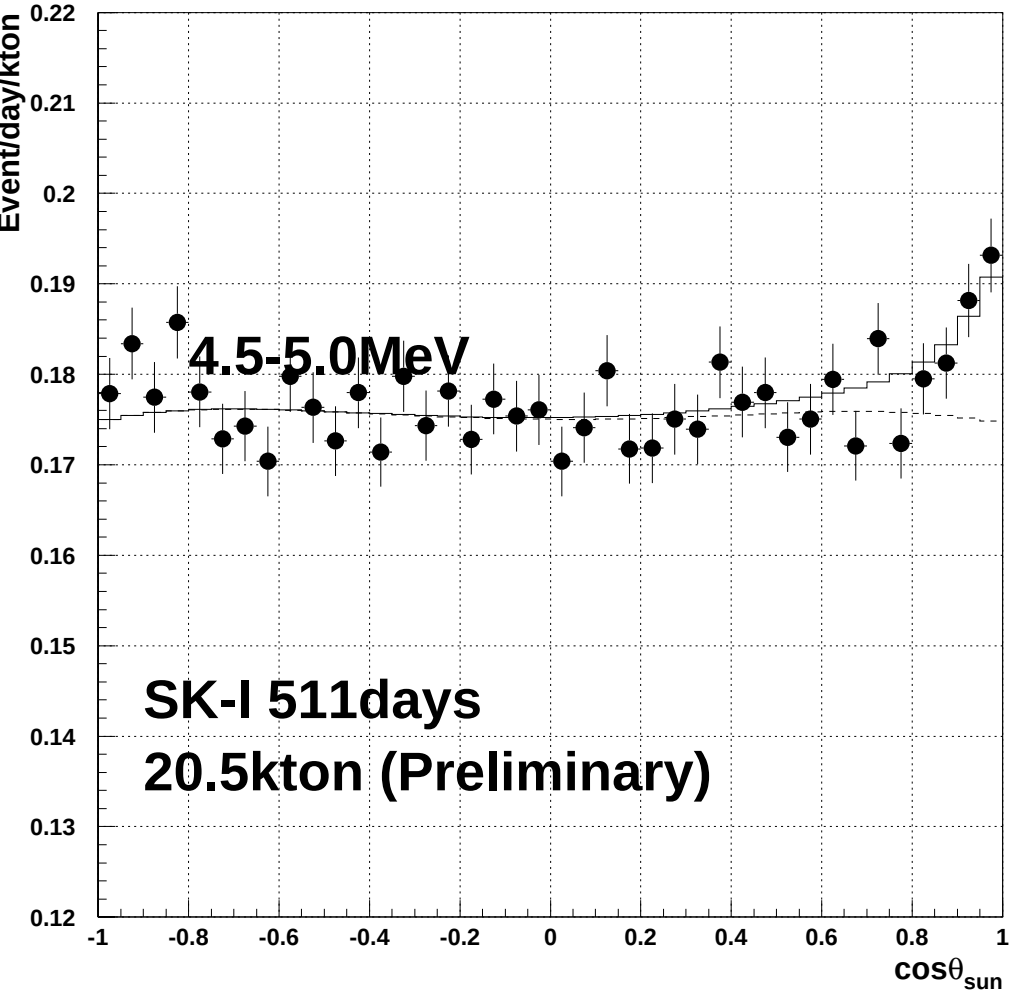


Upturn in low energy is expected for LMA

Future solar neutrino observation in Super-K



Lowering threshold



In SK-I, after install the 2nd level trigger system, the efficiency above 4.5MeV became ~100% (Sep. 2000~)

Remaining B.G. for lower energy
→gamma from the rock
→radio isotope (e.g. Rn)

Acrylic cover againt Rn From PMT (for SK-III)

Possibility to lower the threshould Below 4.0 MeV