Aug. 9, 2004
@Hanoi

(Present long baseline neutrino experiments and)

Future Projects to measure θ_{13} and the CP violation phase

Takashi Kobayashi
IPNS, KEK

Contents

1. Introduction
2. Present LBL experiments
3. Future accelerator based projects
4. Reactor experiments
5. Summary

Introduction

- **Evidences of ν oscillation**
  - Atm ν (SK,1998) & solar ν (SK+SNO,2001)
  - Finite masses!! & Large mixings!!!!!
  - First evidence beyond SM
- **Definite confirmation w/ diff systematics**
  - Present (1st generation) long baseline (LBL) experiments (for atm ν)
  - Players: K2K (1999~), MINOS (2005~), ICARUS/OPERA(2006~)
- **Next steps**
  - Understand whole structure of ν mass/mixing
  - How similar/different from quark sector?
    - "Standard" mixing w/ 3x3 matrix?
    - Mass hierarchy?
    - CP violation?

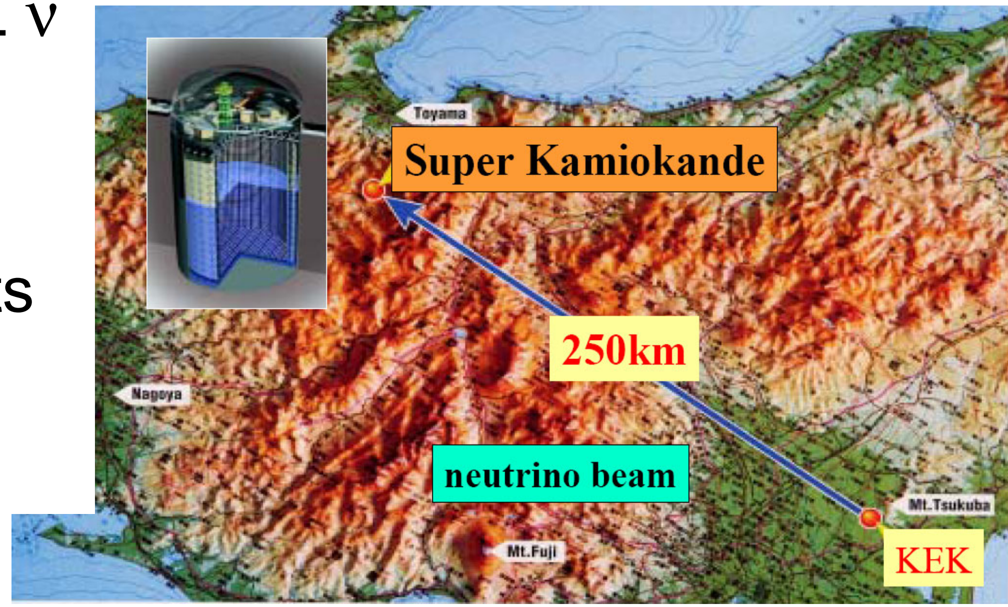
    Would lead physics beyond SM
  - Next generation LBL experiments and reactor exp.
    - w/ High statistics and small systematics
- **New era of precision "Neutrino Flavor Physics"**
  - Cf. Have been done last ~40yrs for quark sector

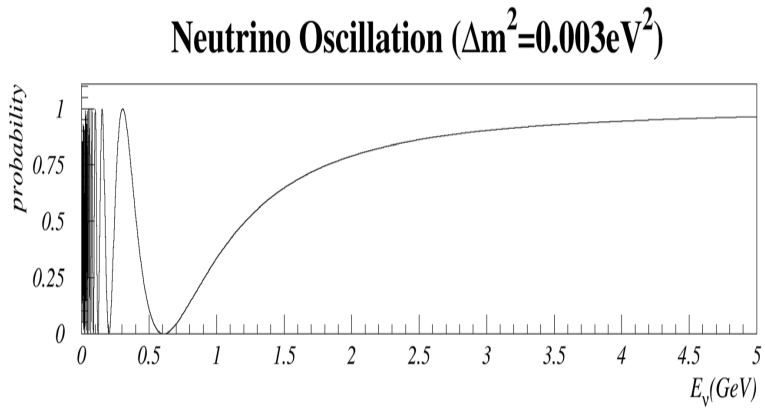
The K2K (KEK-to-Kamioka) Experiment

- The first & only running LBL ν osc. Experiment (1999~)

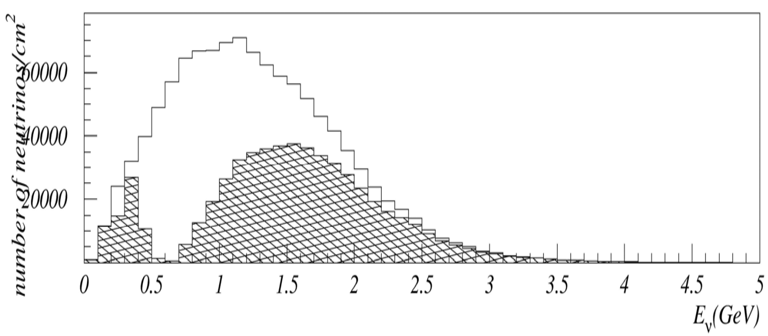
  ν_μ beam (99%) with <E> ~ 1.3GeV w/ KEK 12GeV-PS
- Confirmation of atm ν results

  ν_μ disappearance and ν_e appearance





$$prob. = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2\ L}{E_\nu}\right)$$



Signature (νμ→else)
•Reduction of # of events
•Spectrum distortion

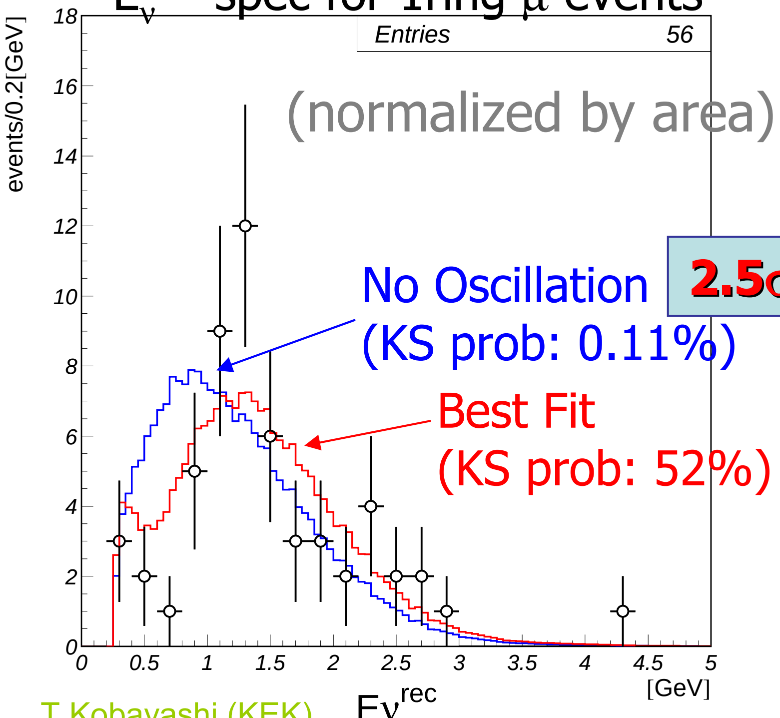
Latest Results on ν_μ disapp.(June 2004)

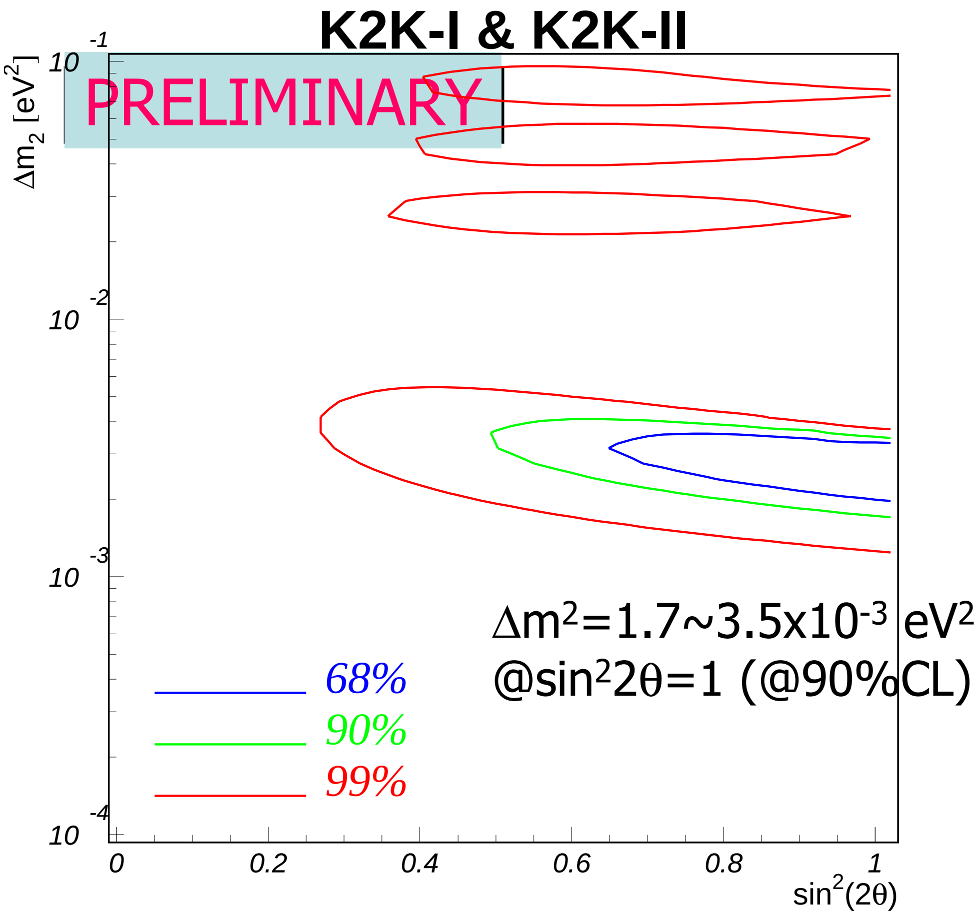
8.9×10^{19} POT (1999Jun~2004Feb)
(10^{20}POT proposed)

Number of events	
Observation:	108
Best Fit:	104.8
Null-oscillation	150.9 $^{-11.6}_{-10.0}$

2.9σ

E_ν^{rec} spec for 1ring μ events



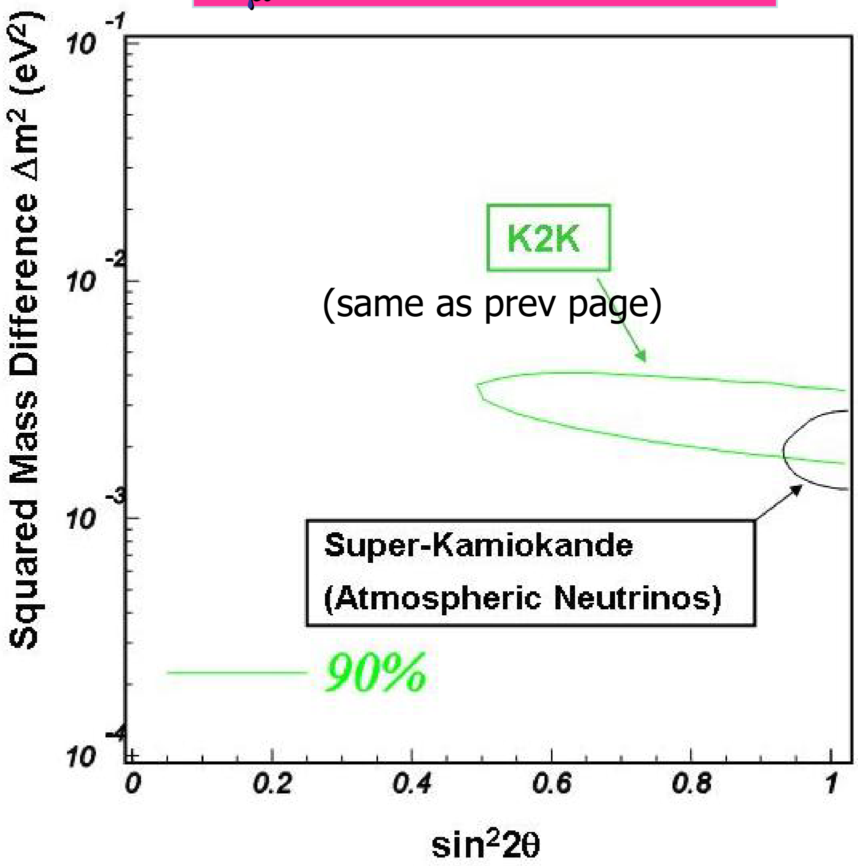


$\Delta m^2 = 1.7 \sim 3.5 \times 10^{-3}$ eV^2
@$\sin^2 2\theta = 1$ (@90%CL)

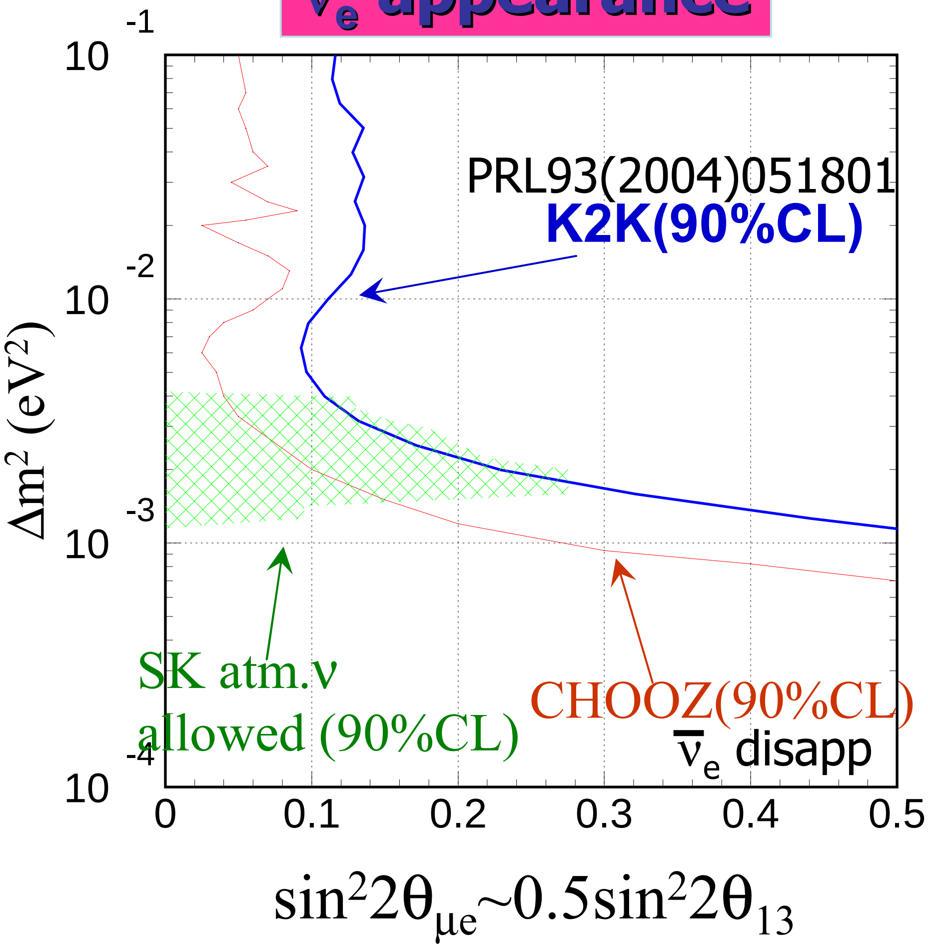
- Best fit in phys. (all) region
  - $\sin^2 2\theta$ = 1.00 (1.53)
    Δm^2 [eV^2] = 2.73×10^{-3} (2.12)
- Confirmed ν osc at **3.9σ** level

Comparison w/ other results

ν_μ disappearance



ν_e appearance

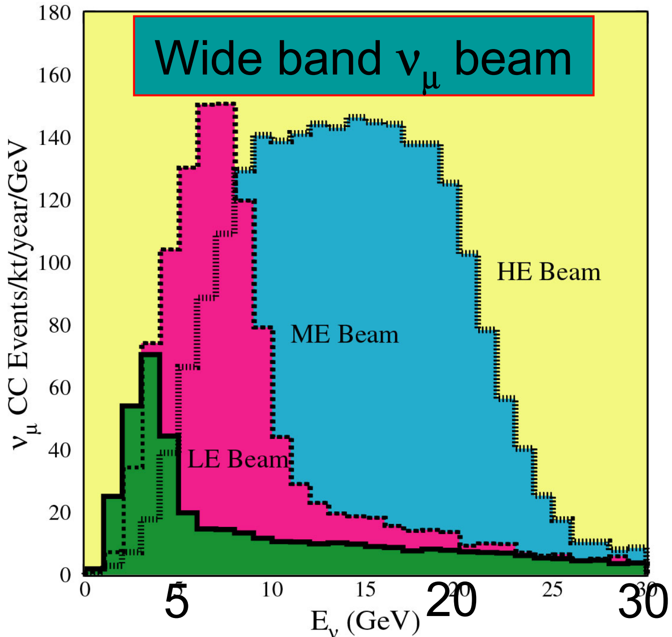


Consistent w/ SK atm ν result

MINOS

- wide band ν_μ beam w/ FNAL 120GeV Main Injector (0.4MW)
- (magnetized)Iron-scintillator sampling calorimeter
  - 5,400tons @ far, 980tons @ near

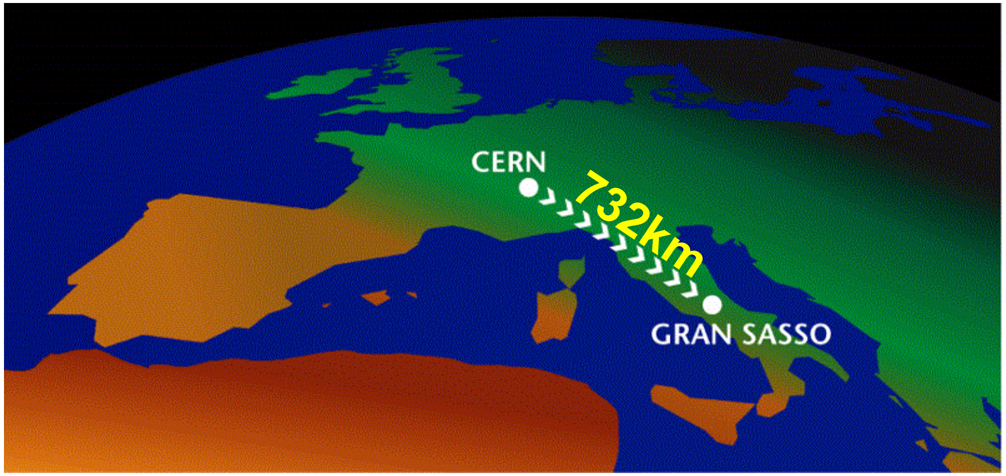
  ν_μ CC int./MINOS/yr ~ 2,500 (LE beam)
- **High precision ν_μ disappearance**
- Far detector fully operational since 2003
- Beam line almost completing
- **Start from 2005**

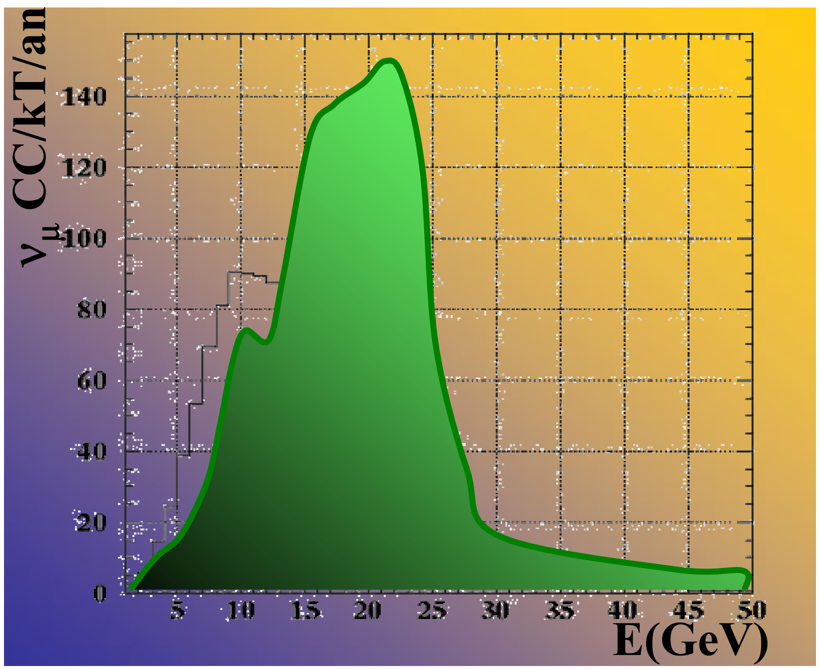


First Horn being Installed

Far detector

CERN Neutrino to Gran Sasso (CNGS)



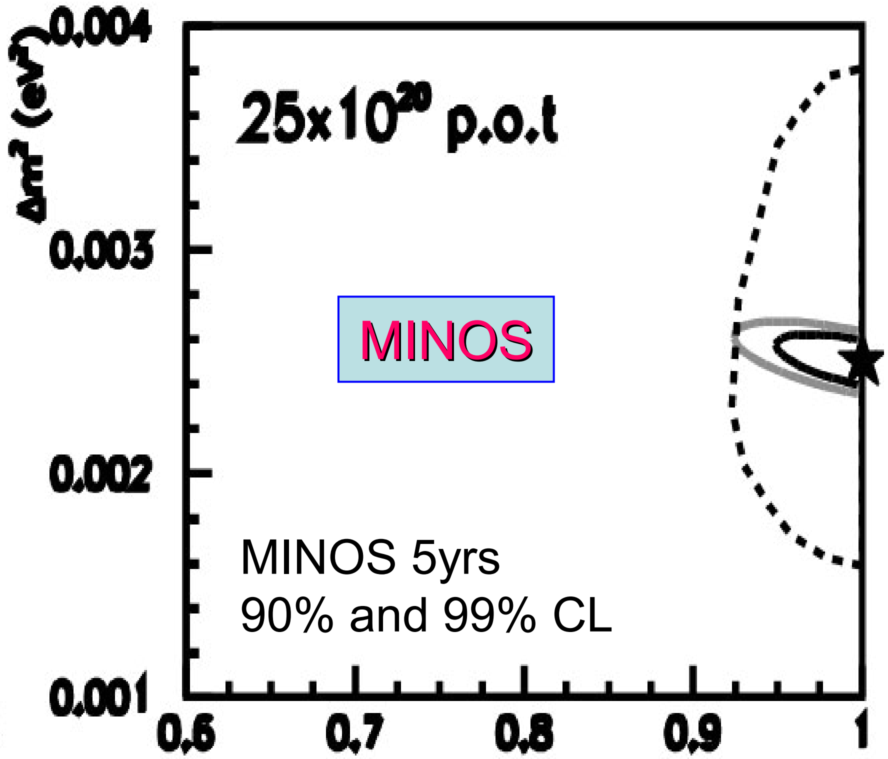


- Wide band ν_μ beam w/ CERN 400GeV SPS $\langle E_\nu \rangle \sim 17$GeV
- Two experiments
  - OPERA: 1.7kt Emulsion cloud chamber
  - ICARUS: 3kt Liq. Ar TPC
- ~5500ν_μ event/kt/yr

  ν_τ appearance
- Under construction
- **First beam to GS May 2006**

Expected sensitivities

ν_μ disappearance



For $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta = 1.0$

$\delta(\Delta m^2) \sim 2\times10^{-4}$eV^2

$\delta(\sin^2 2\theta) \sim 5\%$

read from above plot

ν_τ appearance

Expected signal

	Sig	BG
OPERA	17.2	1.1
ICARUS	11.9	0.7

$\Delta m^2 = 2.5\times10^{-3}$eV^2
Full mix.
5yrs of running
ICARUS: 1.5kt fid mass

3 flavor mixing

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

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

Weak   Mass eigenstates

m_i: 3 masses, Δm_{ij}: 2 differences

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

3 mixing angles and 1 CPV phase

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

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

Unknown 2 parameters

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

$\sin^2 2\theta_{23} \sim 1$
(Atm ν)

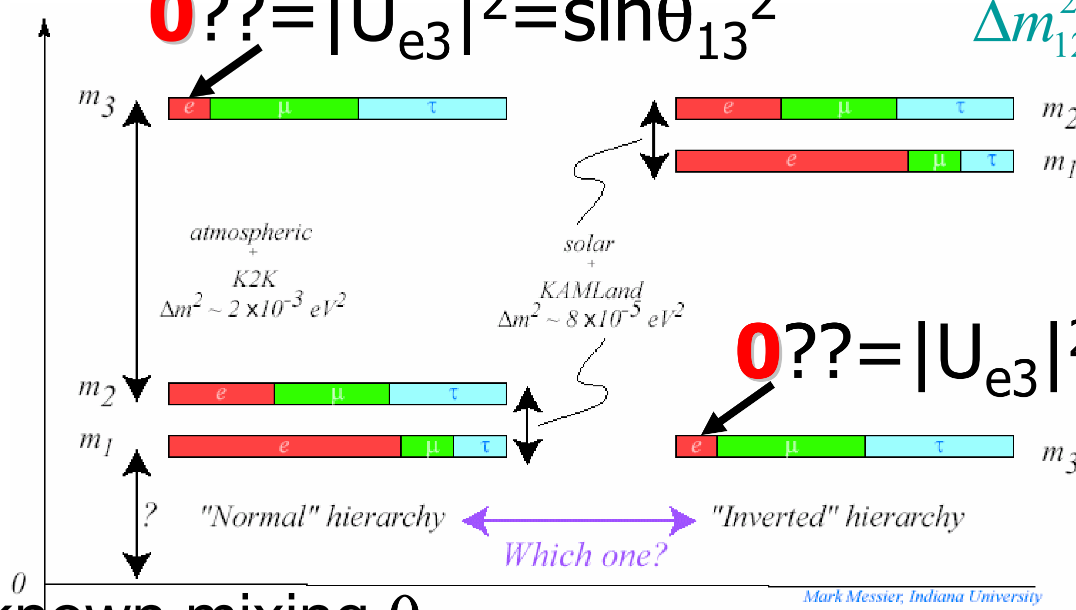
Reactor

LBL acc. experiments

What's next?

$0?? = |U_{e3}|^2 = \sin\theta_{13}^2$

$\Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2$



$0?? = |U_{e3}|^2 = \sin\theta_{13}^2$

- Only unknown mixing θ_{13}
  - Only upper bound from CHOOZ reactor exp
  - At the same Δm^2 as ν_μ disapp. → Support 3gen. mix. framework
  - Open possibility to search for CPV (θ_{any}=0 → No CPV)
- Mass hierarchy (sign of Δm^2)
- CPV
- Approaches
  - LBL experiment: Multi purpose (θ_{13}, sign(Δm^2),CPV, θ_{23},Δm_{23}^2)
  - Reactor-based $\bar{\nu}_e$ disappearance: single purpose (θ_{13}), complementary

$\nu_\mu \rightarrow \nu_e$ appearance in LBL exp

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} (1 - 2S_{13}^2)\right)$$ **Main**

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$ **CP-odd**

$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$ **Solar**

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} (1 - 2S_{13}^2)$$ **Matter**

$\delta \rightarrow -\delta$, $a \rightarrow -a$ for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

Matter eff.: $a = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$

$$A_{CP} \equiv \frac{P - \overline{P}}{P + \overline{P}} \approx \frac{\Delta m_{12}^2 L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin\delta$$

$N(\nu_e) \propto \sin^2 2\theta_{13}$; $A_{CP} \propto \frac{1}{\sin\theta_{13}}$

Size of θ_{13} critical !

T2K experiment (approved & start in 2009)

Long baseline neutrino oscillation experiment from Tokai to Kamioka.

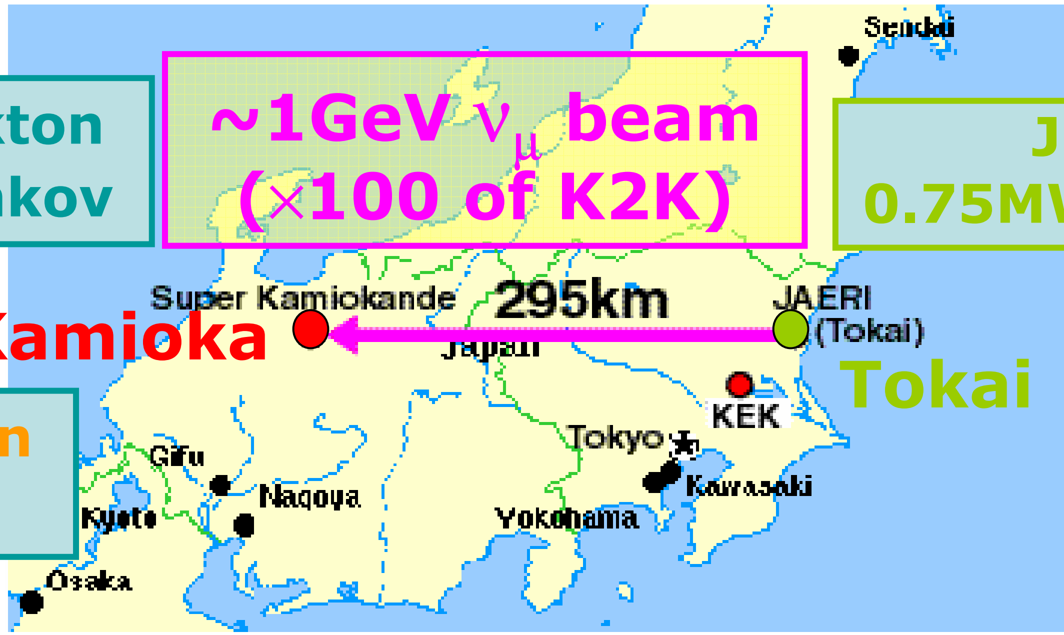
Super-K: 50 kton Water Cherenkov

Phase2: Mton Hyper-K?

~1GeV ν_μ beam ($\times$100 of K2K)

J-PARC 0.75MW 50GeV PS

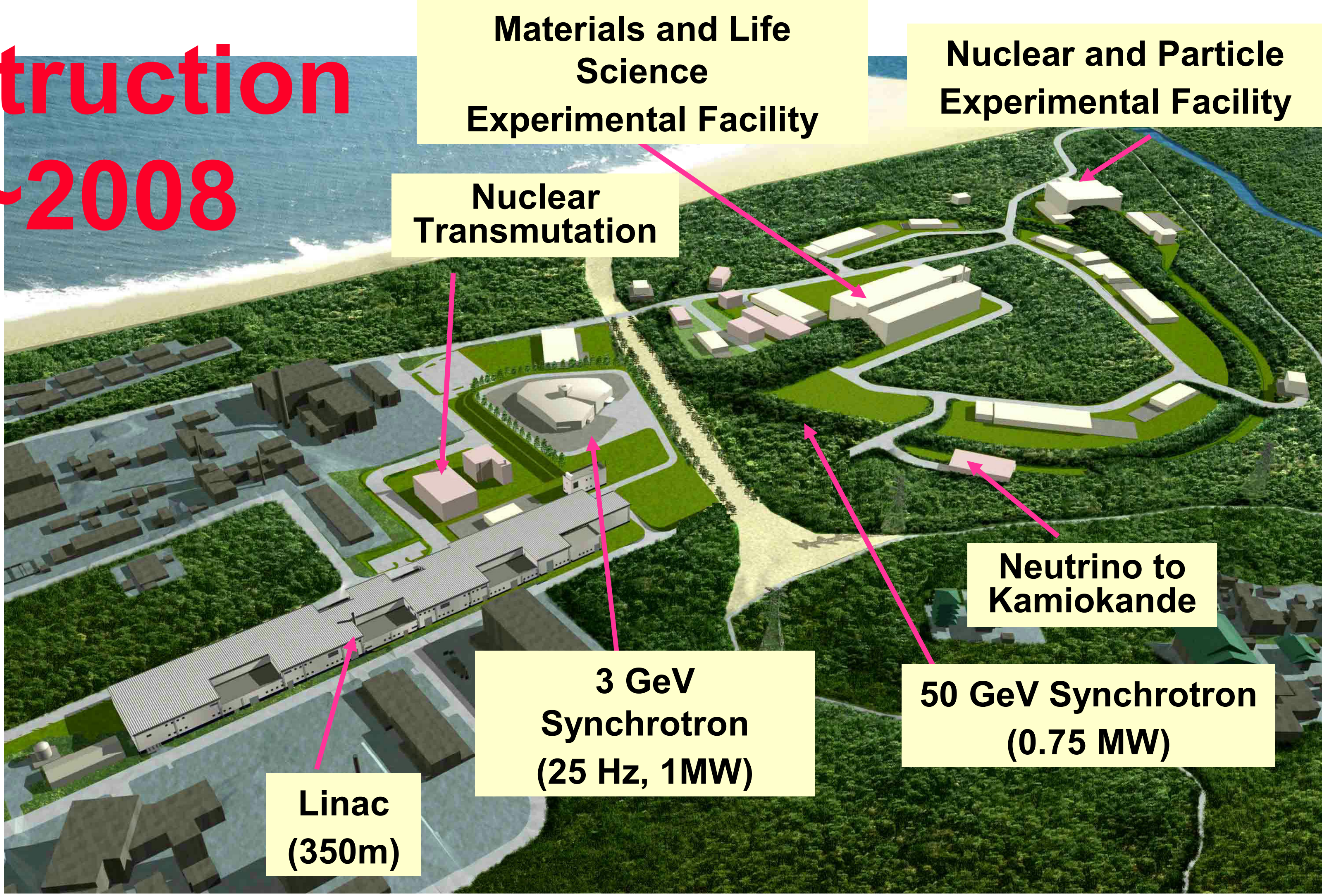
Phase2: 4 MW ?



Physics motivations

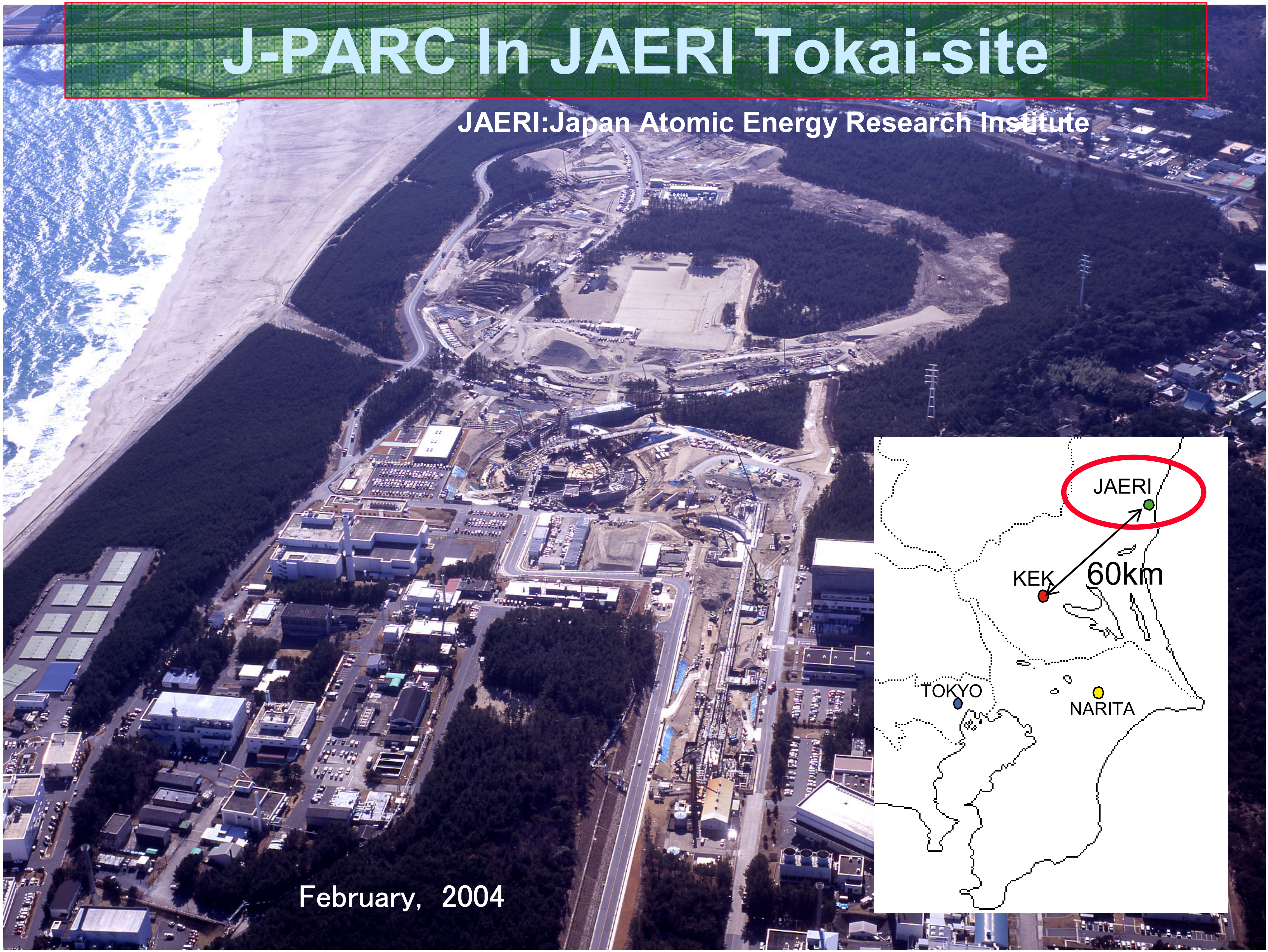
- Discovery of $\nu_\mu \rightarrow \nu_e$ appearance
- Precise meas. of disappearance $\nu_\mu \rightarrow \nu_x$
- Discovery of CP violation (Phase2)

Japan Proton Accelerator Research Complex (J-PARC)



J-PARC In JAERI Tokai-site

JAERI:Japan Atomic Energy Research Institute



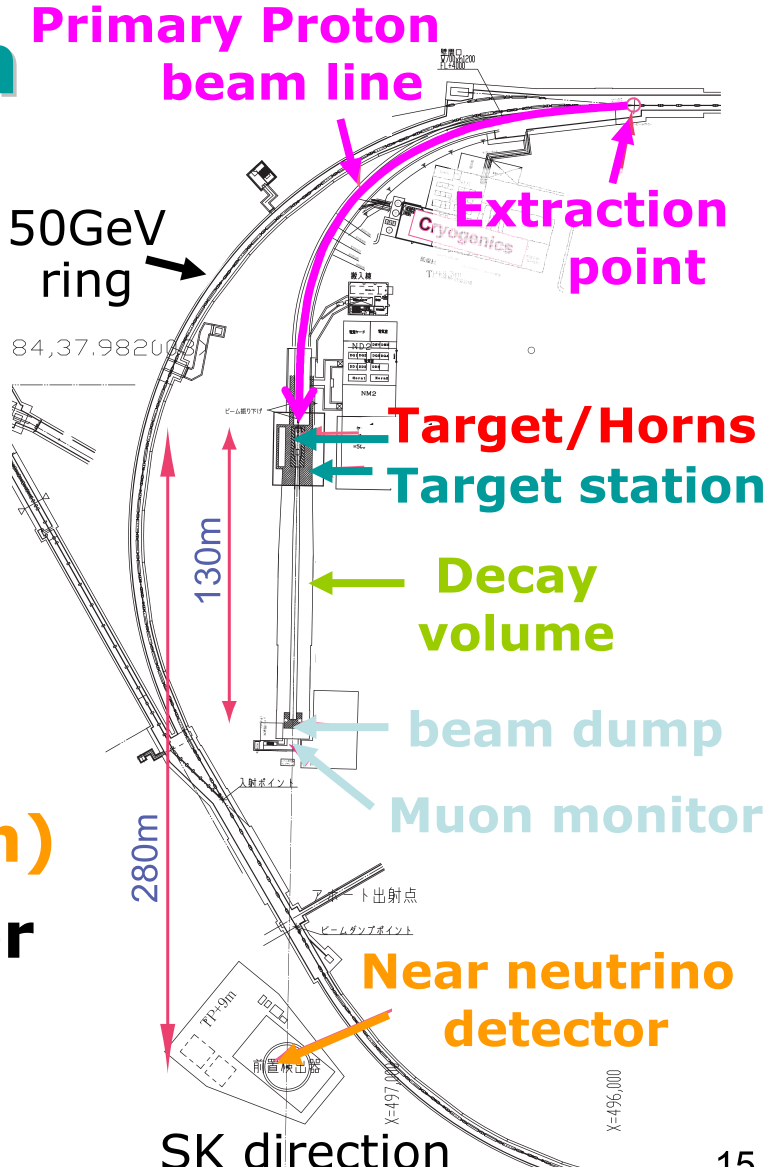
February, 2004

J-PARC Neutrino facility

Approved in Dec. 2003 for 5 years construction (2004~2008JFY)

Components

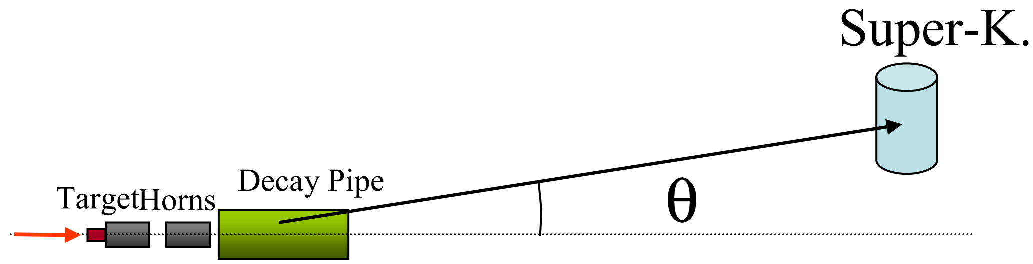
- Primary proton beam line
- Target/Horn system
- Decay volume (130m)
- Beam dump
- Muon monitor
- Near neutrino detector (280m)
- Second near neutrino detector (~2km): not approved yet



Ground breaking of ν facility @ J-PARC

- Decay volume part
- July, 2004

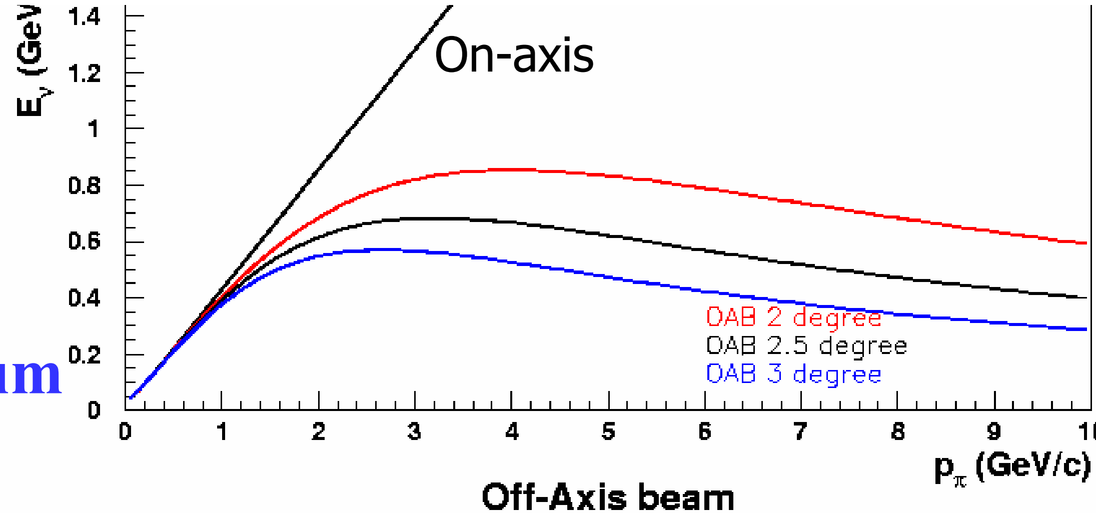
Off Axis Beam



(ref.: BNL-E889 Proposal)

- **Quasi Monochromatic Beam**
- **x 2~3 intense than NBB**
- **First real application**

Tuned at oscillation maximum



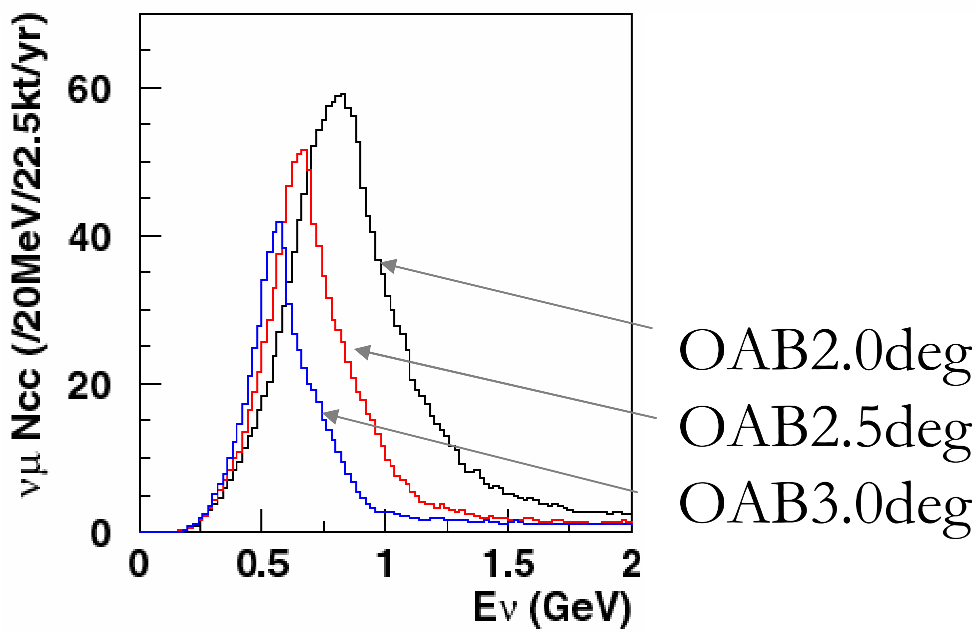
Statistics at SK

(OAB 2 deg,1 yr,22.5 kt)

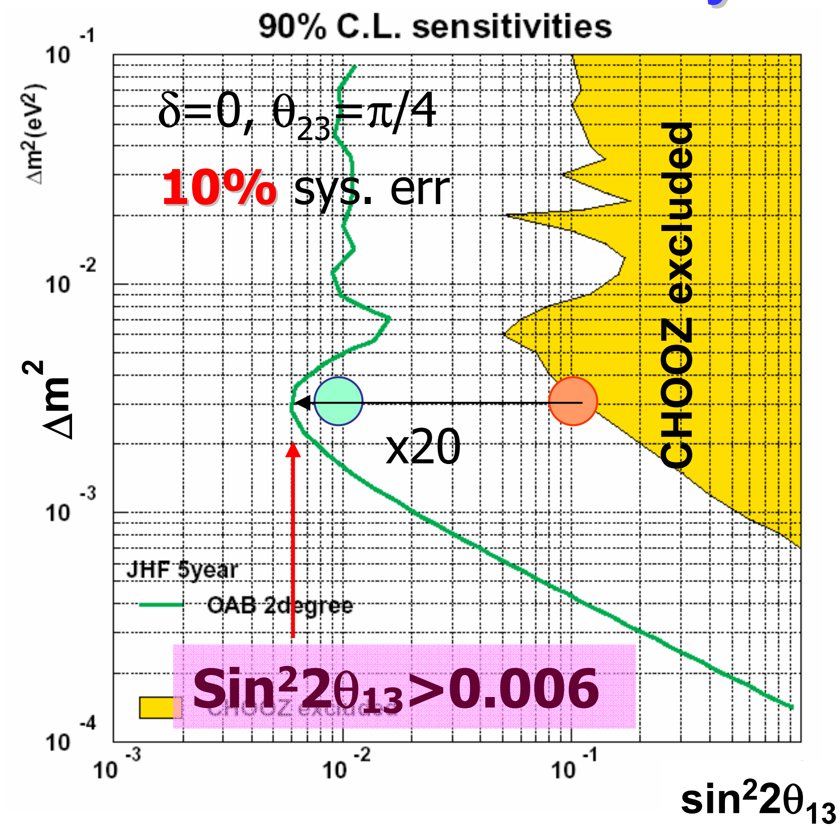
~ 4500 ν_μ tot

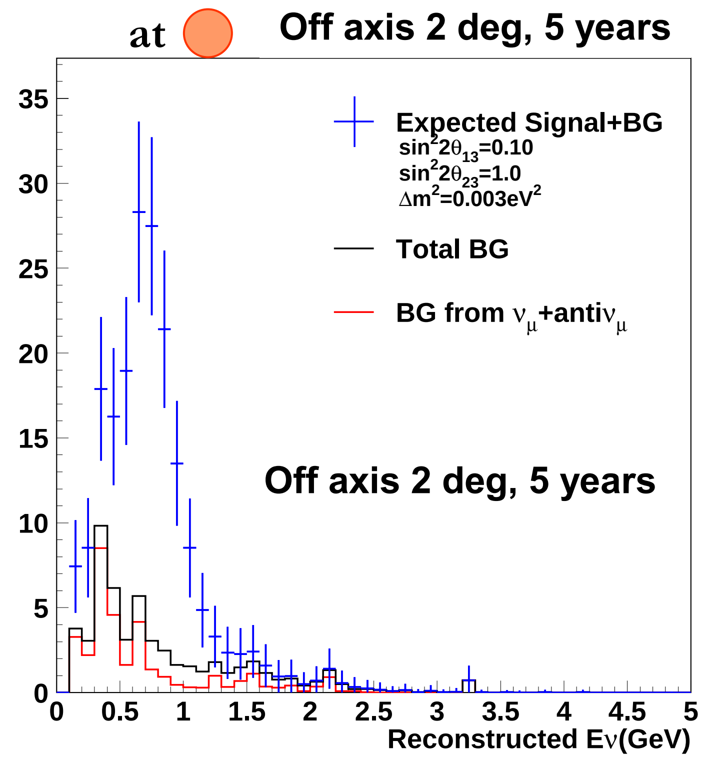
~ 3000 ν_μ CC

ν_e ~0.2% at ν_μ peak



T2K sensitivity on ν_e appearance





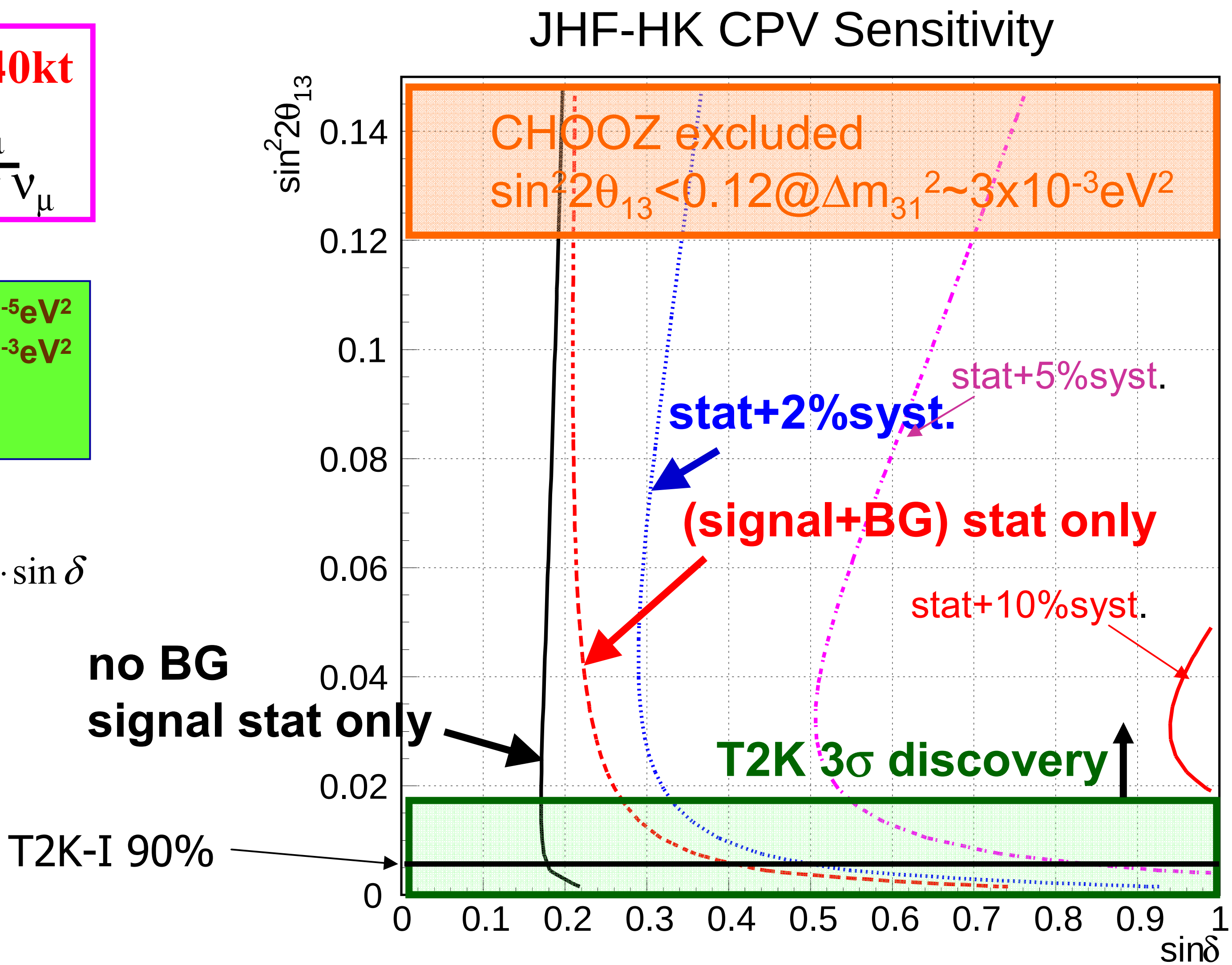
$\sin^2 2\theta_{13}$	Background in Super-K (as of Oct 25, 2001)					Signal	Signal + BG
	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	total		
0.1	12.0	10.7	1.7	0.5	24.9	114.6	139.5
0.01	12.0	10.7	1.7	0.5	24.9	11.5	36.4

Sensitivity for CPV in T2K-II

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

Δm_{21}^2=6.9x10^{-5}eV^2
Δm_{32}^2=2.8x10^{-3}eV^2
θ_{12}=0.594
θ_{23}=$\pi/4$

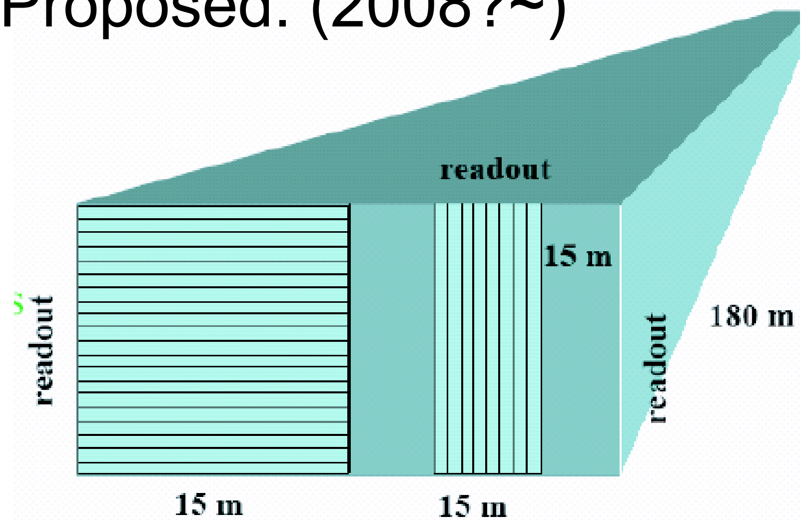
$$A_{CP} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

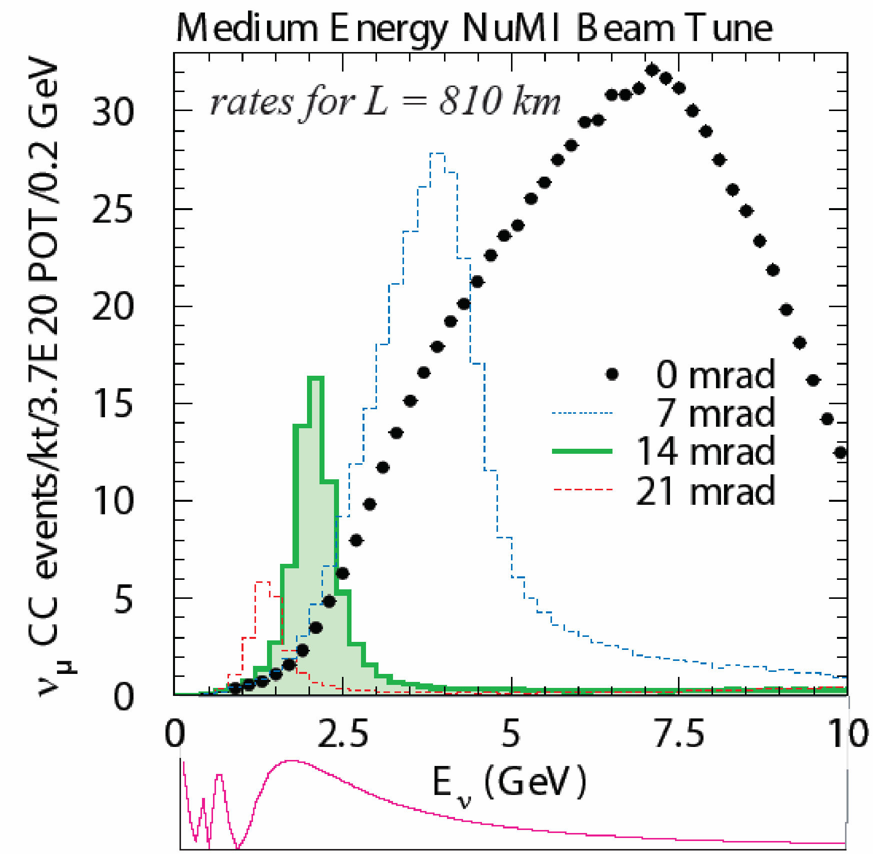


3σ CP sensitivity : |δ|>20° for $\sin^2 2\theta_{13}$>0.01 with 2% syst.

NOνA

- Use Existing NuMI beamline
- New 50kt fine grained detector @~800km and @ 12km off axis
- Liq scint. tracker & particle board absorber (1/3X_0)
  (Alternative:full active liq.sci.)
- Possible future upgrade of MI (0.4MW→2MW):Proton driver
- Proposed. (2008?~)



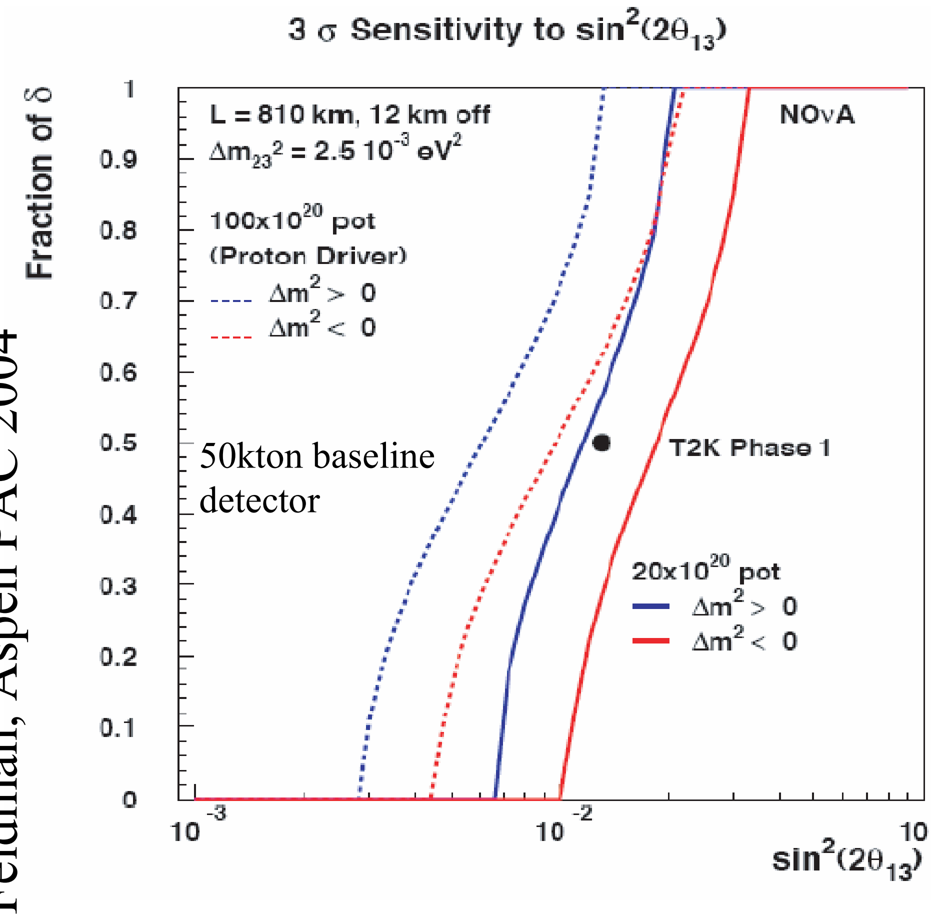


Assuming $\Delta m^2 = 2.5 \times 10^{-3} eV^2$

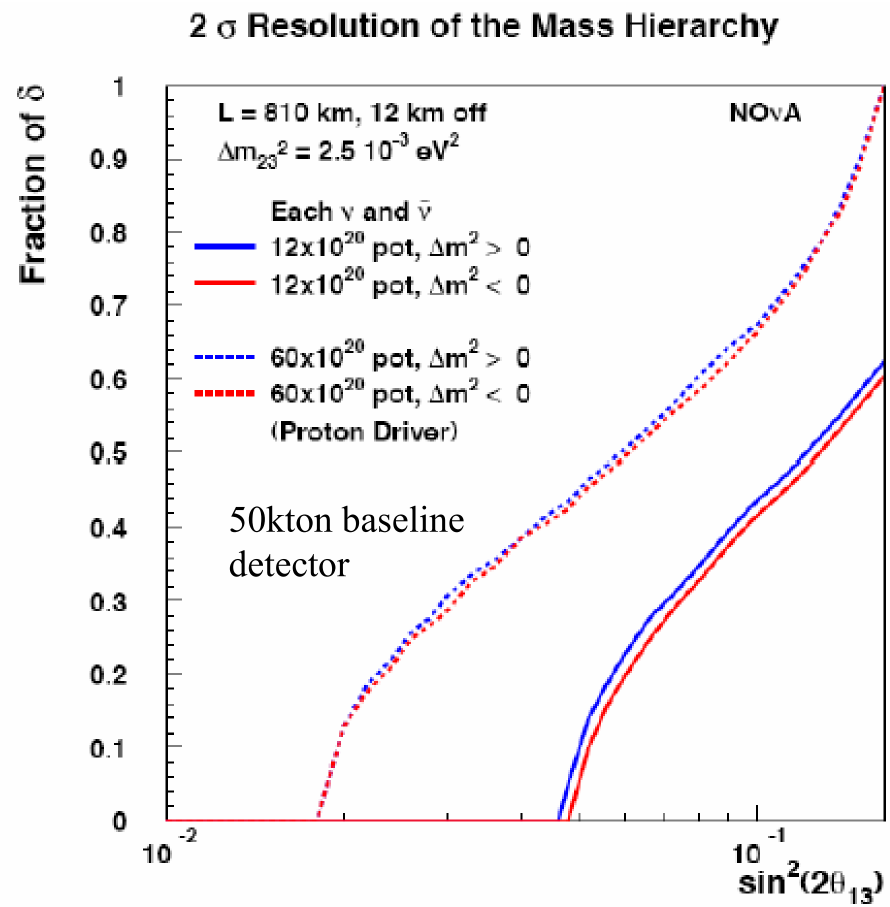
Messier, ν2004

NOνA Physics Reach

ν_e appearance



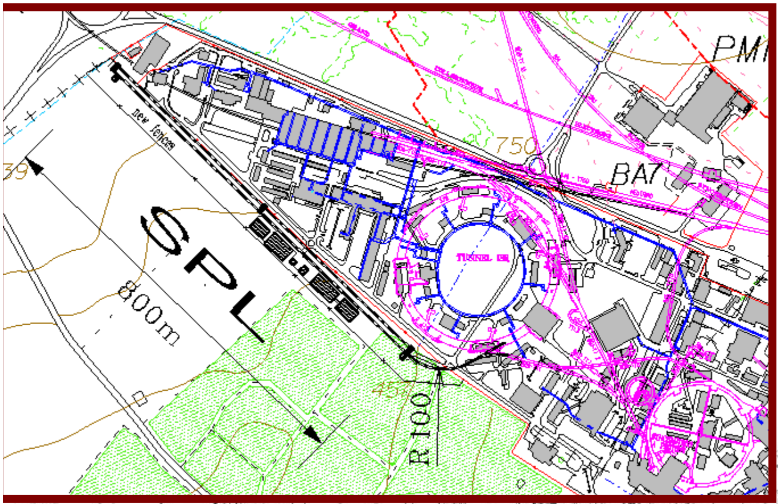
Mass hierarchy



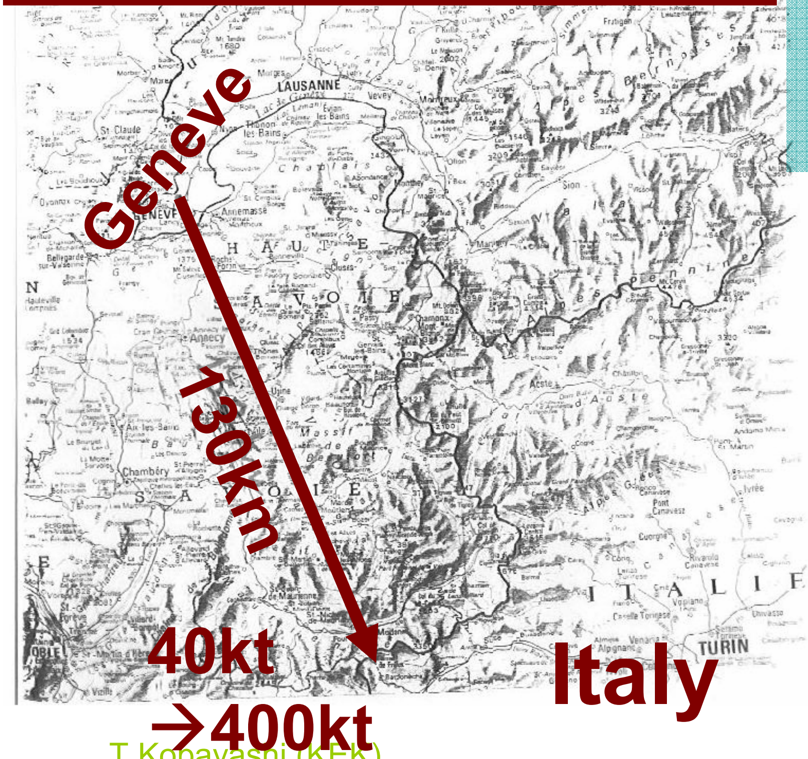
50kton baseline detector

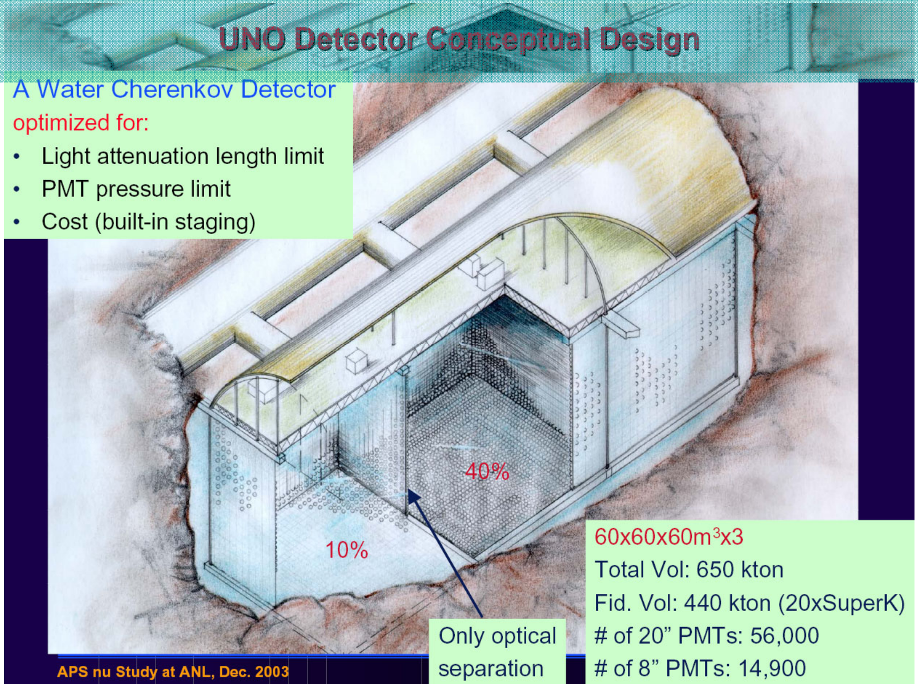
Feldman, Aspen PAC 2004

Europe: SPL→Frejus



- 4MW 2.2GeV Superconducting Proton Linac (SPL) @ CERN
- Low energy wide band (Eν~0.3GeV)
- L=130km
- Water Cherenkov 40→ 400kt (UNO)
- ~18,000 νμ CC/year/400kt
  θ_{13}, CPV
- Small matter effect
- SPL in R&D, UNO in conceptual design





T.Kobayashi (KEK)

(Ref: Diwan et al., PRD68, 012002, 2003)

BNL-Homestake

- 28GeV AGS upgrade to 1MW (2MW) cf current 0.1MW
- Wide band beam (0.5~6GeV)
- L=2,540km
- Mton detector
- ~13,000 ν_μ CC/year/500kt
- **Cover higher osc. maxima**

Goals

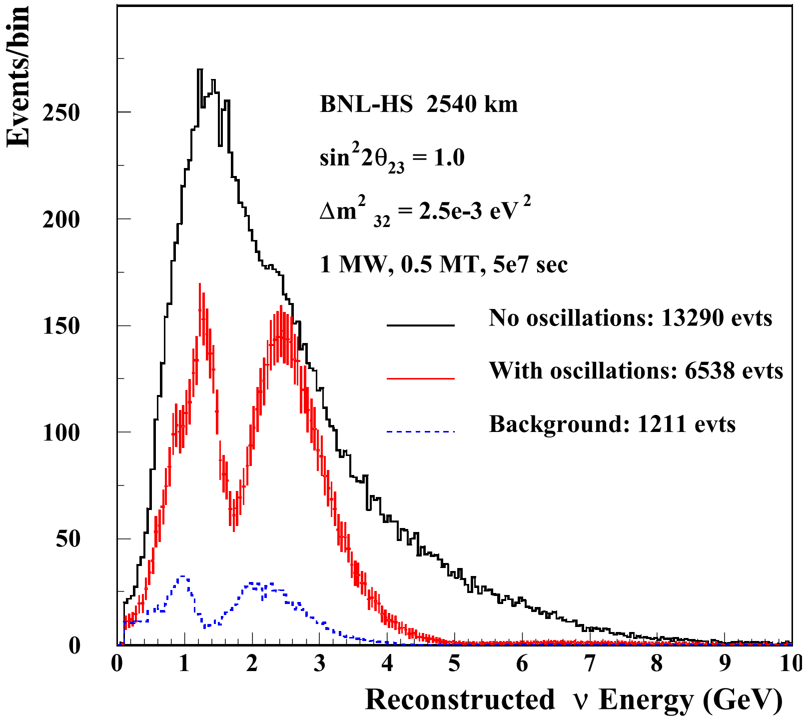
ν_e appearance

- Sign of Δm_{23}
- CPV

θ_{12}, Δm_{12}

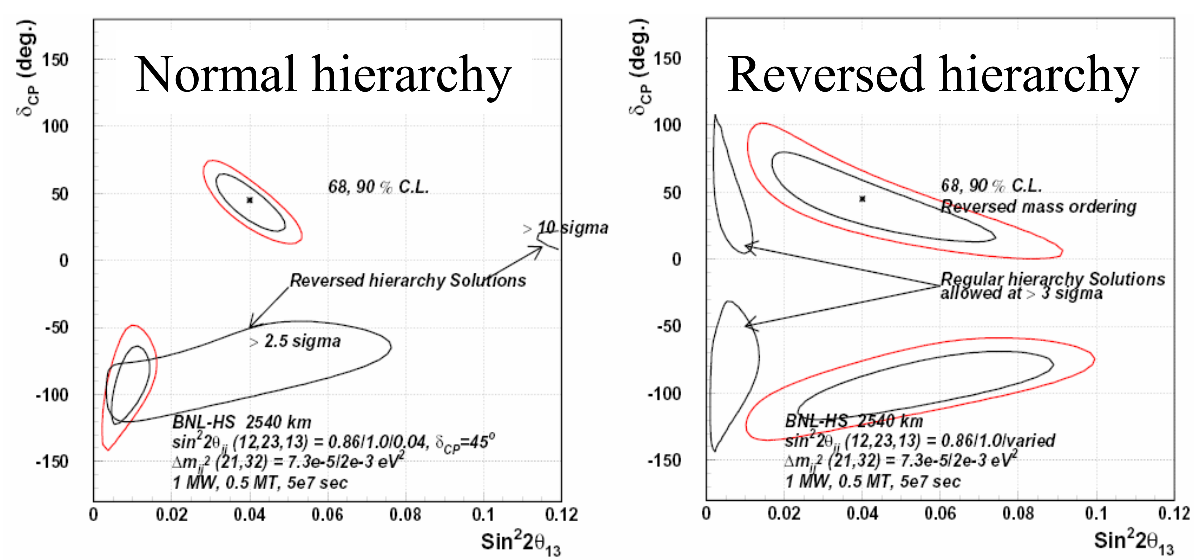
Possible w/ only ν run at certain parameter region

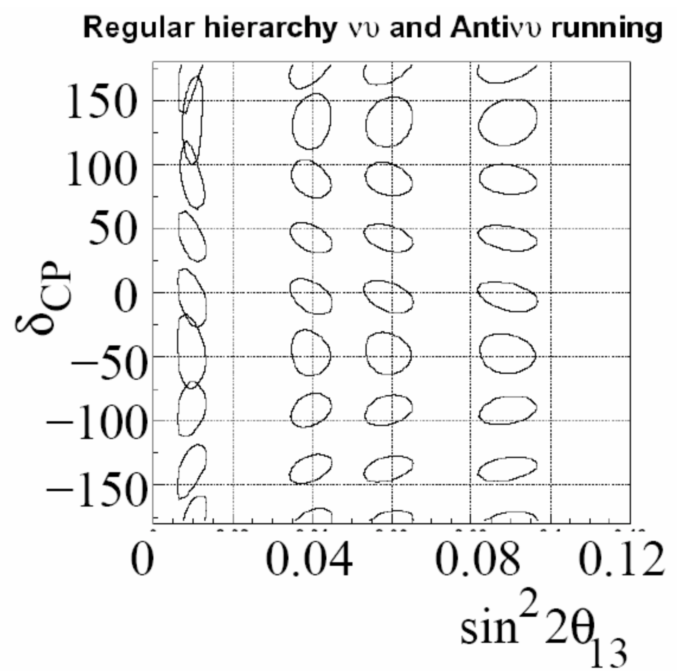
- LOI written.



Brookhaven to Homestake Physics Reach

Even with only ν data,
CP violation and mass hierarchy are visible
in some regions of parameter space.



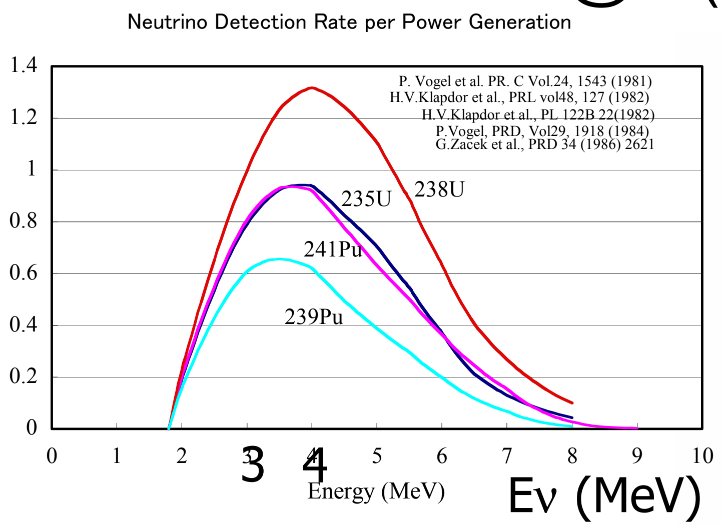


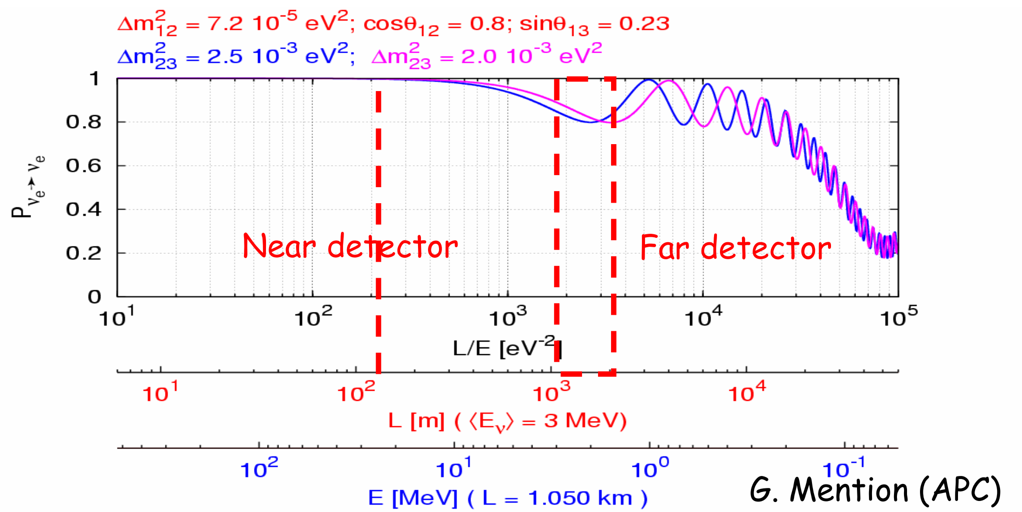
Diwan, 3/2004 APS study meeting

But with both ν and $\bar{\nu}$ running, CP precision much higher

Reactor $\bar{\nu}_e$ disappearance

- $\bar{\nu}_e$ from nuclear reactor <E>~3MeV
- $1-P(\nu_e \rightarrow \nu_e) = \sin^2(2\theta_{13})\sin^2(\Delta m^2_{31}L/4E) + O(\Delta m^2_{21}/\Delta m^2_{31})$: pure θ_{13}
- Small systematic error (<1%) required
- Identical near det @ O(100)m & far det @a few km





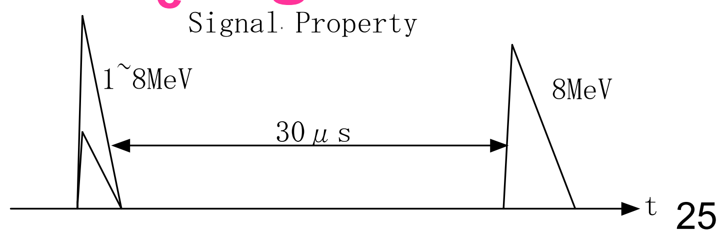
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$e^+ + e^- \rightarrow 2\gamma \quad (E_\nu - 0.8\,MeV)$$

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

T.Kobayashi (KEK)

$\bar{\nu}_e$ signature



Complementarity of Reactor-Accelerator Meas.

Reactor Measurement= Pure $\sin^2 2\theta_{13}$ measurement

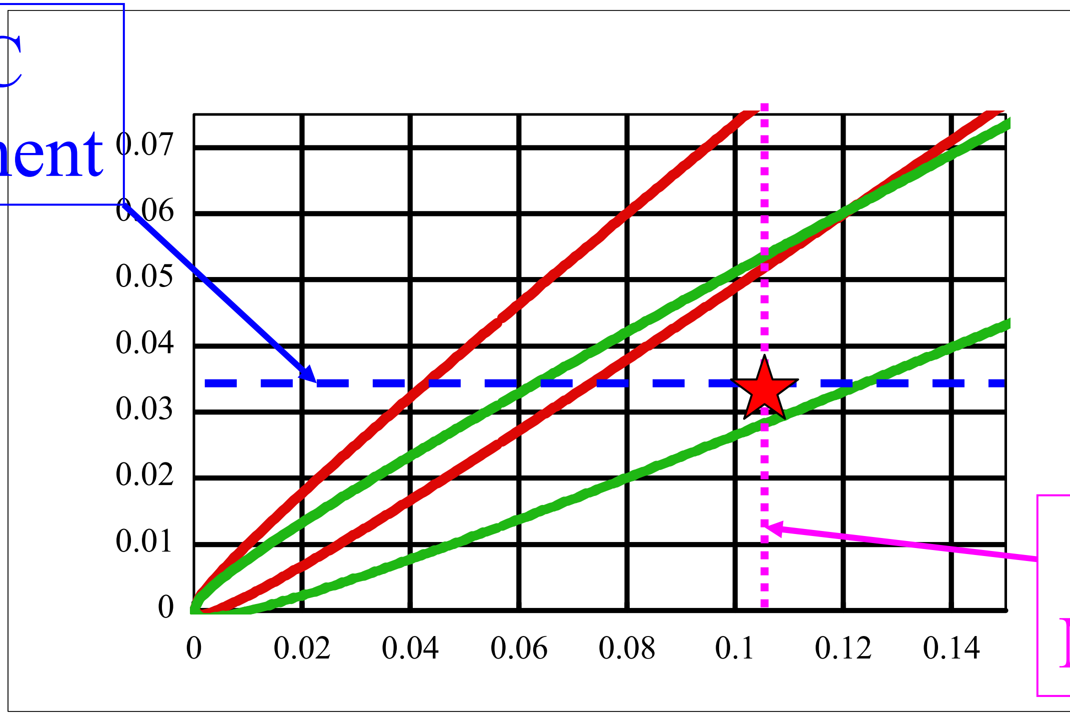
Reactor-Accelerator combination
=> a lot of physics potential

* Answer to θ_{23} degeneracy

$$\sin^2\theta_{23} = \begin{cases} \cancel{0.61} \\ 0.39 \end{cases}$$

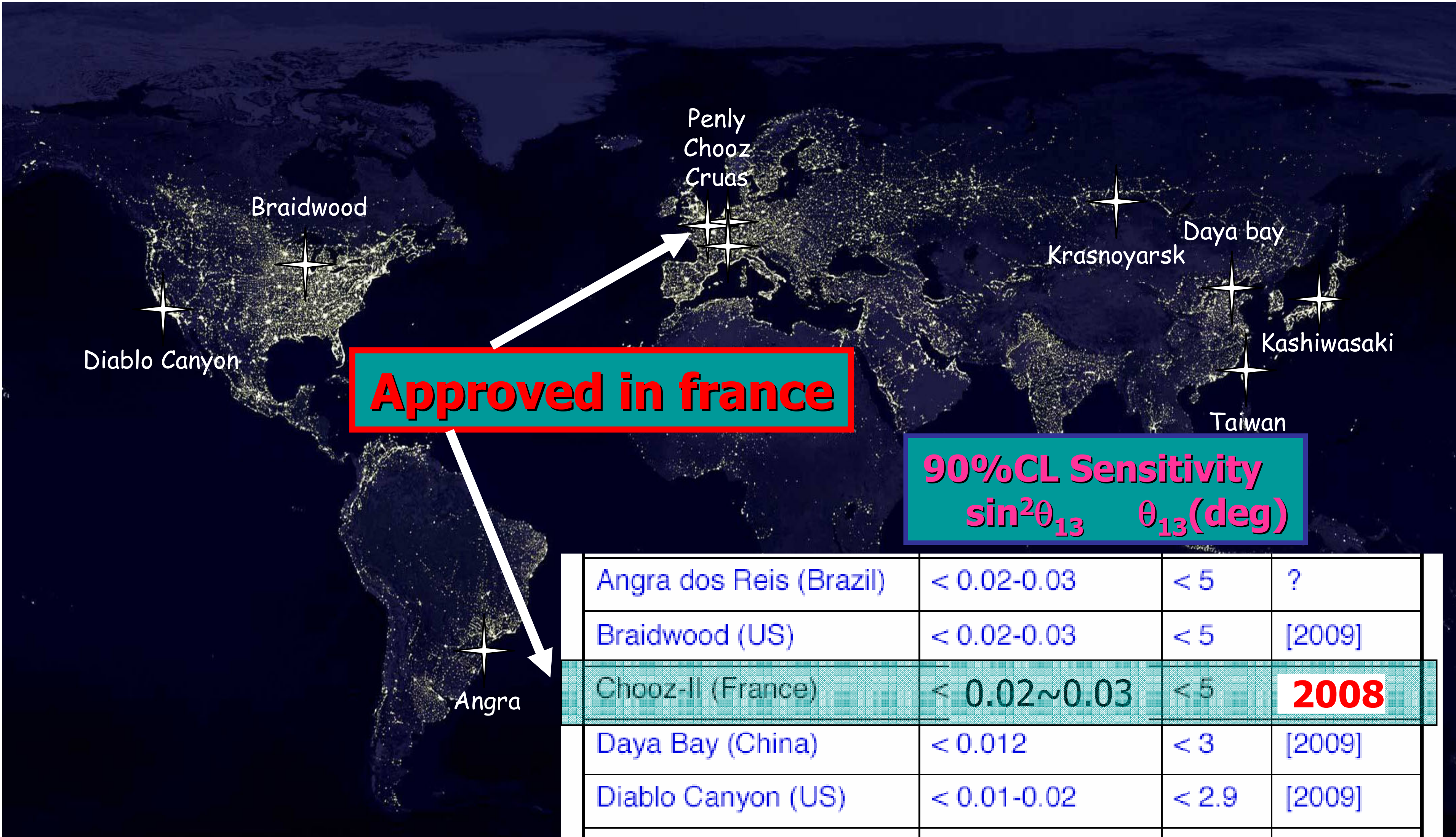
* If accuracy is good enough
=> $|\sin\delta_l|$

$P(\nu_\mu \to \nu_e)$



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

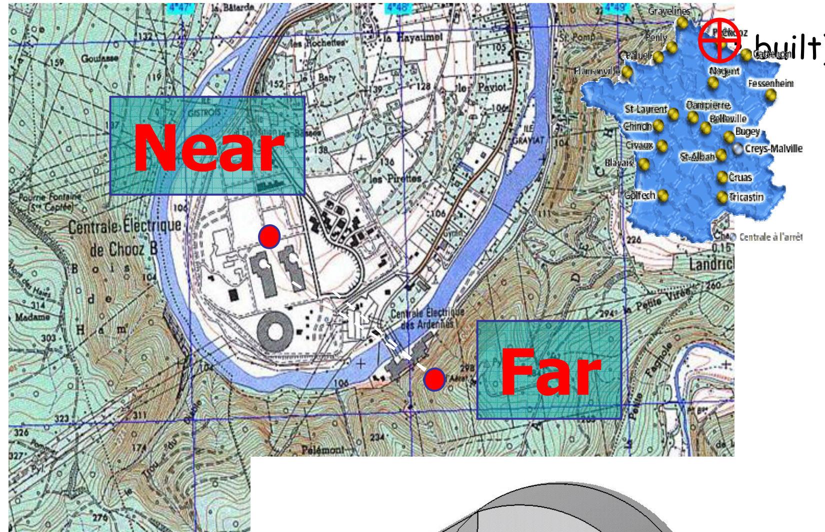
Reactor experiment proposals

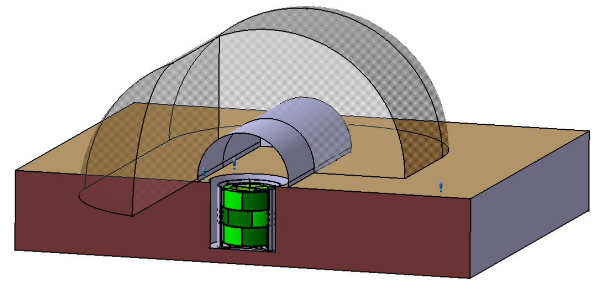


	90%CL Sensitivity $\sin^2\theta_{13}$	θ_{13}(deg)	
Angra dos Reis (Brazil)	< 0.02-0.03	< 5	?
Braidwood (US)	< 0.02-0.03	< 5	[2009]
Chooz-II (France)	< 0.02~0.03	< 5	**2008**
Daya Bay (China)	< 0.012	< 3	[2009]
Diablo Canyon (US)	< 0.01-0.02	< 2.9	[2009]
Krasnoyarsk (Russia)	< 0.016	< 3.6	?
Kashiwazaki (Japan)	< 0.026	< 4.6	[2008]

Double-CHOOZ

- Twin reactor cores
  - P=2x4.2 GWth
- Two 10 tons detectors
  - 80% dodecane + 20% PXE + 0.1% Gd
  - Near: 100-200 m – 60-80 mwe
  - Far: 1.05 km - 300 mwe
- 3 years Sensitivity
  - **0.6%** systematics
  - **No signal: $\sin^2(2\theta_{13}) < 0.02$-03 (90% C.L.)**
  - Signal: $\sin^2(2\theta_{13}) > 0.04$-05 ($3\sigma$)
- Prospect (**approved & funded in France**)
  - 2007: far detector running
  - **2008: near detector running**
  - Cost ~7Meuros + civil constr.





Summary

- First 1st generation experiment K2K
  - Confirmed ν oscillation observed in atm ν at SK @3.9σ
  - Waiting precise meas. from MINOS(2005~), ν_τ app. from CNGS(2006~)
- Next important issues
  - Discovery and measurement of only unknown mixing θ_{13}
  - Mass hierarchy
  - CP violation
- Next generation LBL experiments covers most
  - T2K using J-PARC and SK started construction. Start exp. In 2009
    - θ_{13} sensitivity ~0.006 (90%CL), ~0.018 (3σ)
    - $|\delta|$~20deg in phase 2
  - NOνA proposal w/ similar potential to T2K
- Pure θ_{13} measurements by reactor experiments
  - complementary to disentangle parameter relations
    θ_{13} sensitivity 0.01~0.03 (90%)
  - Systematic error (<1%) is key issue
  - Double-CHOOZ is partially approved
- Neutrino field will continue to be very exciting for coming decades