중성미자 진동의 정밀 측정을 위해

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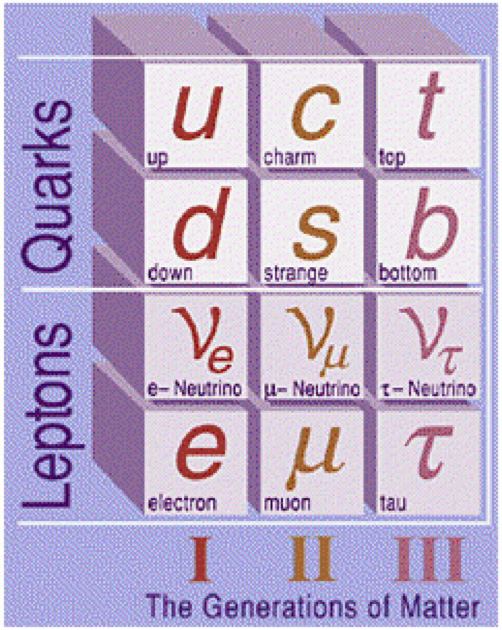
Neutrinos in Particle Physics and Cosmology

- ❑ **Probing GUT scale physics**
  (Neutrino masses and oscillations)
- ❑ **Related to expansion of Universe**
  (Dark matter)
- ❑ **Mixing in the leptonic sector**
  (MNS matrix)
- ❑ **Neutrino astronomy**
  (UHE neutrinos, Supernova neutrinos, …)



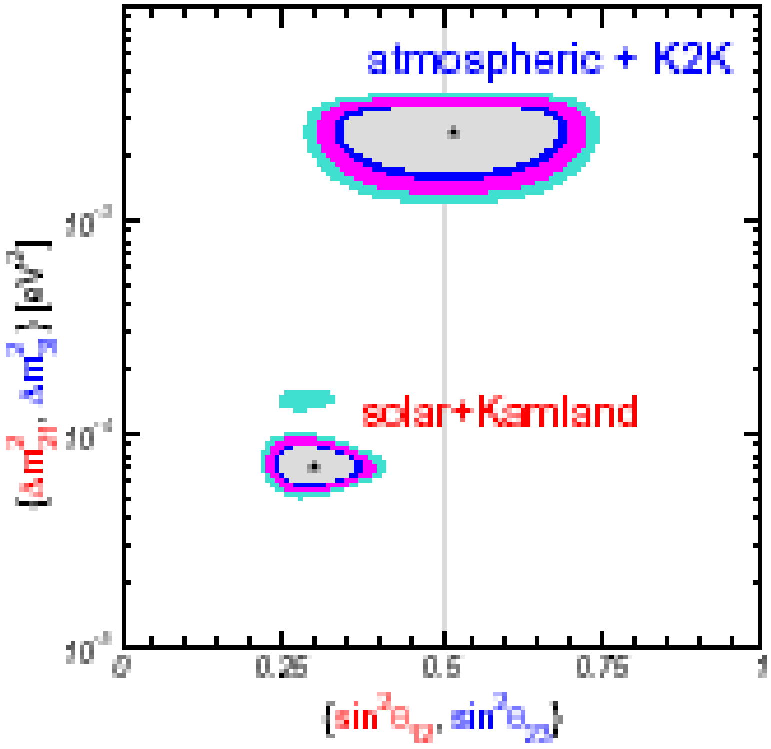
Summary of neutrino oscillation data

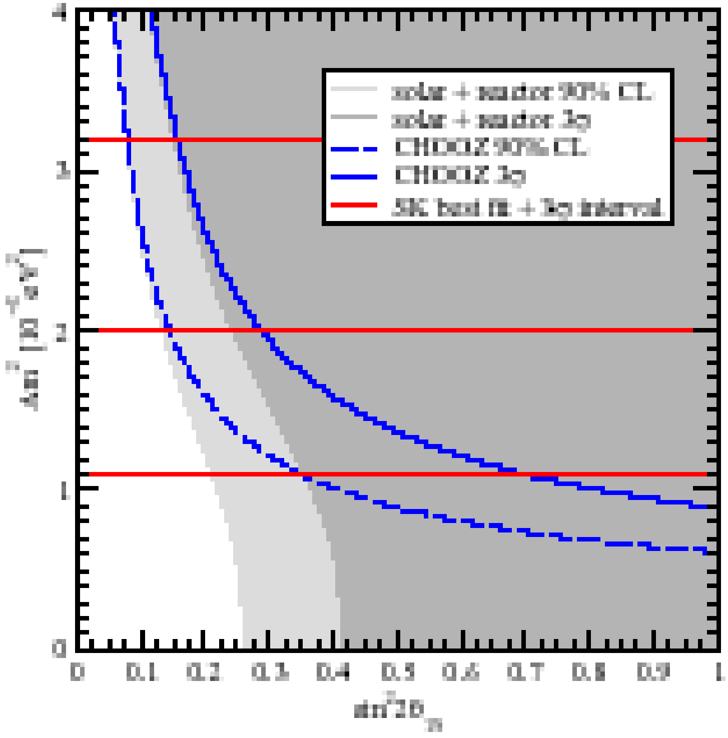
- Atmospheric neutrino (SK)/ K2K data ($\nu_\mu \leftrightarrow \nu_\tau$):
  - $\Delta m_{23}^2 = (2^{+1.2}_{-0.9})\times 10^{-3}\mathrm{eV}^2$ $\quad \sin^2 2\theta_{23} \approx 1.0 \quad (\theta_{23} \approx 45°)$

- Solar neutrino (SK, SNO)/ KamLAND data ($\nu_e \rightarrow \nu_\mu / \nu_\tau$):
  - $\Delta m_{12}^2 = (6.9^{+2.6}_{-1.5})\times 10^{-5}\mathrm{eV}^2$ $\quad \sin^2\theta_{12} = 0.3^{+0.09}_{-0.07}$

- Reactor neutrino (CHOOZ)
  - $\sin^2(2\theta_{13}) < 0.14 \sim 0.20 \quad (\theta_{13} < 10°)$ at $\Delta m_{23}^2 = 2\times 10^{-3}\mathrm{eV}$

Summary of neutrino oscillation data





3 Flavor Mixing

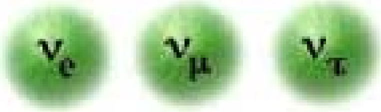
- If neutrinos are massive particles, then it is possible that the **mass eigenstates** and the **weak eigenstates** are not the same:

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

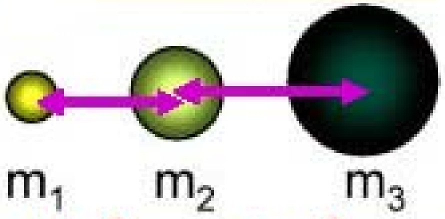
Weak eigenstates
„flavor eigenstates"

3 independent parameters
+ 1 complex phase

Mass eigenstates



$\theta_{12}, \theta_{23}, \theta_{13}$
$+ \delta$



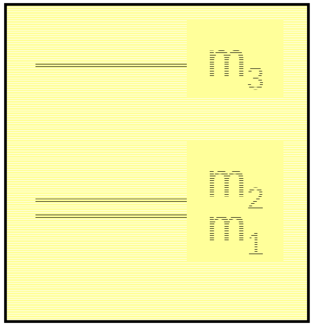
$\Delta m^2_{12}, \Delta m^2_{23}$

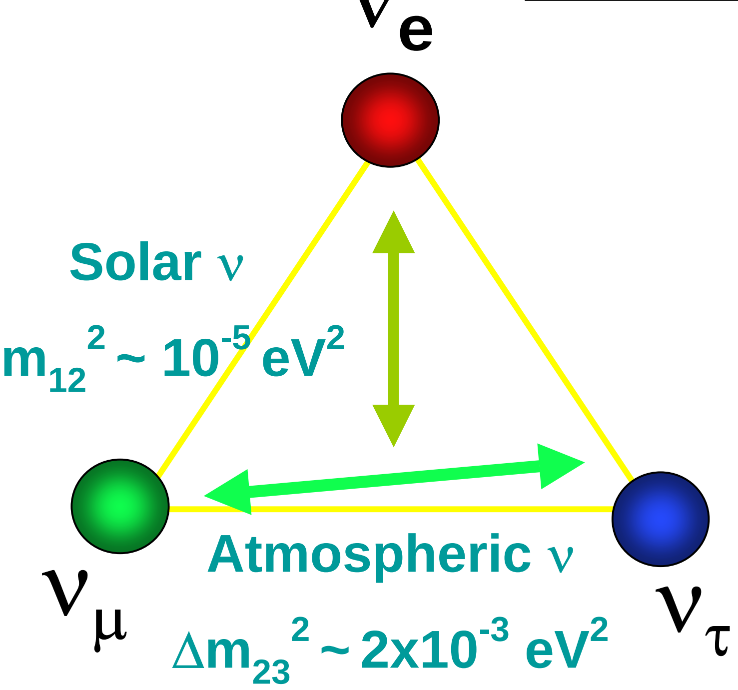
MNS (Maki-Nakagawa-Sakata) matrix

Allowed region for 3-flavor oscillations

$(\Delta m^2 = \Delta m_{23}^2 \sim \Delta m_{13}^2)$

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



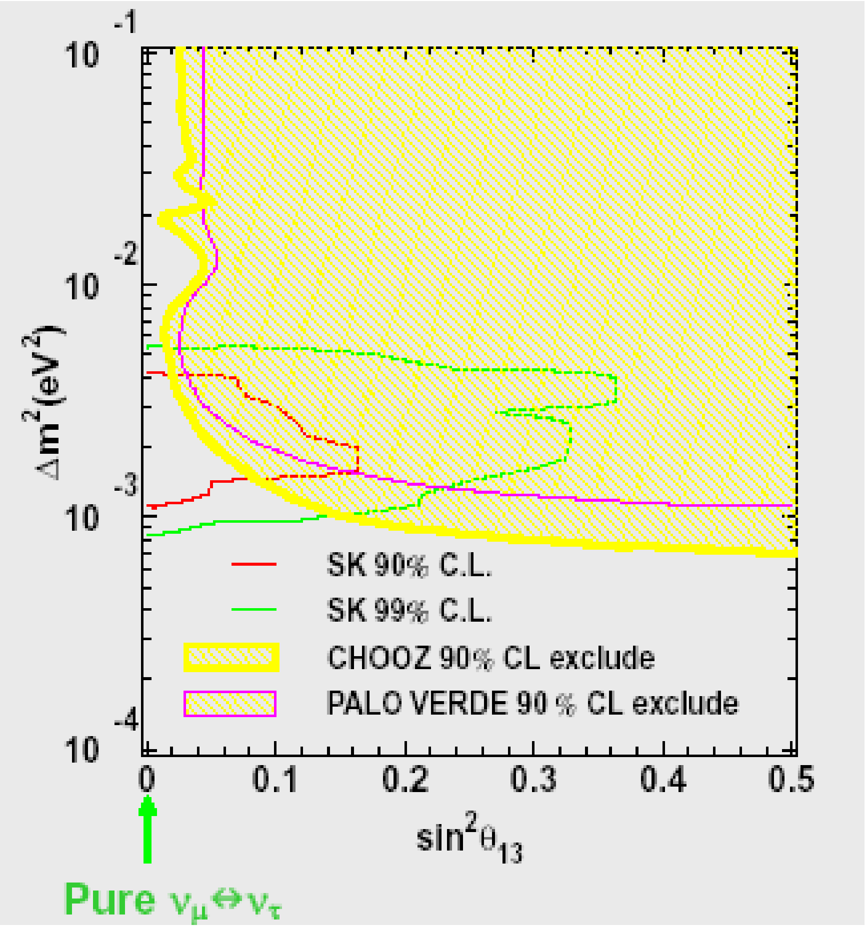


Solar ν

$\Delta m_{12}^2 \sim 10^{-5}$ eV^2

Atmospheric ν

$\Delta m_{23}^2 \sim 2\text{x}10^{-3}$ eV^2



getting close to CHOOZ's limit on θ_{13}

Flavor Mixing in the Leptonic Sector

(A new field of particle phyiscs has begun!)

- MNS(Maki-Nakagawa-Sakata) Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \\ U_{\alpha i} \\ \\ \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad (\Delta \mathrm{m}_{12}^2 + \Delta \mathrm{m}_{23}^2 + \Delta \mathrm{m}_{31}^2 = 0)$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{aligned} \mathrm{P}(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} &- 4\sum_{i>j} \mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \Phi_{ij} \\ &\pm 2\sum_{i>j} \mathrm{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \Phi_{ij} \end{aligned}$$

$$\Phi_{ij} \equiv \Delta \mathrm{m}_{ij}^2 L / 4E_\nu = 1.27 \Delta \mathrm{m}_{ij}^2 [\mathrm{eV}^2] L[\mathrm{km}] / E_\nu [\mathrm{GeV}]$$

CP Violation in Neutrino Oscillations

- $P(\nu_\mu \to \nu_e) = 4C_{12}^2 C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}$ (the largest term)

$$+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

(CP conserving term: even in δ → –δ)

$$\boxed{- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}}$$

(CP violating term: odd in δ → –δ)

$$+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21}$$

(suppressed by $\sin^2(\Delta m_{21}^2 L/ 4E_\nu)$)

$$- 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \cos\Phi_{32} \sin\Phi_{31} \frac{aL}{4E_\nu}$$ (matter effect)

- $A_{CP} = \dfrac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})} \cong \boxed{\dfrac{\Delta m_{12}^2 L}{4E_\nu} \cdot \dfrac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta}$

J-PARC 중성미자 실험

1GeV 뮤온 중성미자 빔

물 5만톤의 지하 검출기

50 GeV 양성자가속기

J-PARC (Japan Proton Accelerator Research Complex):

핵폐기물 처리 연구, 핵동위원소 생산, 물성 구조 및 재료물리학, 의료 및 생명과학 연구, 핵물리학, 입자물리학

J-PARC Neutrino Experiment Collaboration

- ☐ Submitted to Japanese government in Jan. 2003
  Approved in Jan. 2004
- ☐ International Collaboration:
  Canada, China, France, Italy, Japan, Korea,
  Poland, Russia, Spain, Switzerland, UK, USA

연구개발비

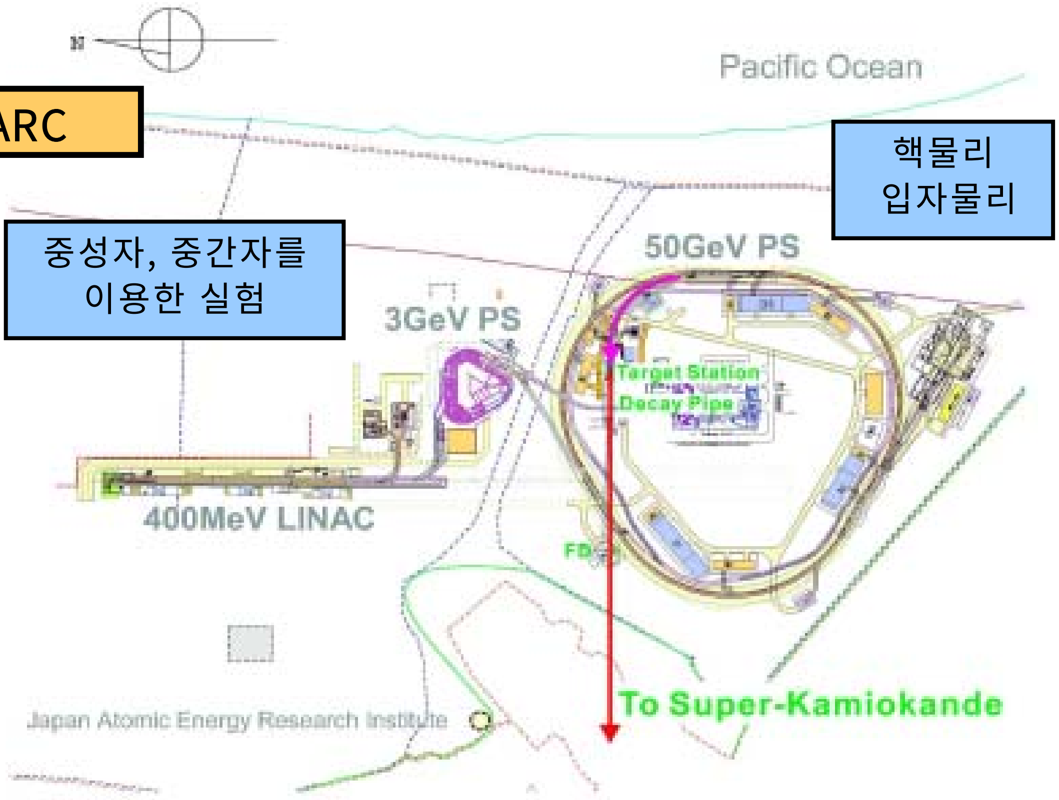
- □ J-PARC의 가속기 건설 (2001-2006)
  - 일본: 약 14억 달러 (1.7조원)
- □ 중성미자 빔과 검출기 건설
  - 일본 (2002-2007): 약 2,000억원
  - 한국 (2003-2008): 약 10억원 (중간위치 검출기)
  - 미국, 캐나다, 유럽 등: 약 200억원

J-PARC Neutrino Beam

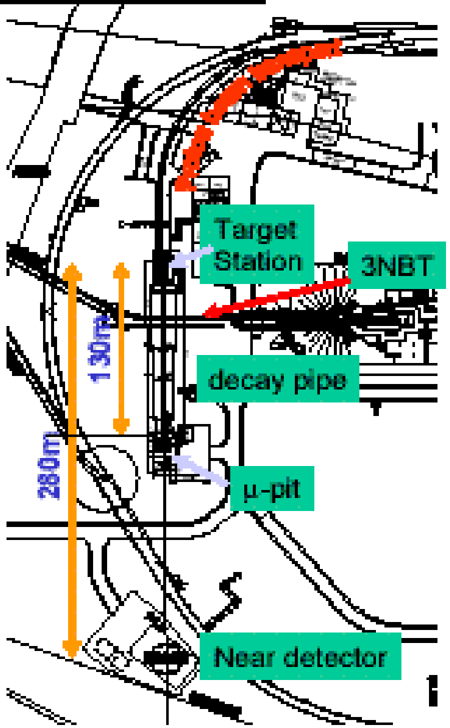
J-PARC

중성자, 중간자를
이용한 실험

핵물리
입자물리



중성미자 빔 시설



Physics Goals of the J-PARC ν Experiment

(1st Phase)

중성미자 진동 ($\nu_\mu \rightarrow \nu_\tau$)의 정밀 측정

- 맛깔 섞임의 세기 각도: $\delta(\sin^2 2\theta_{23}) = 0.01$ (1%) (×8 개선)
- 질량 차이: $\delta(\Delta m_{23}^2) = 10^{-4}\ \mathrm{eV}^2$ (10%) (×10 개선)

θ_{13} 측정 ($\nu_\mu \rightarrow \nu_e$)

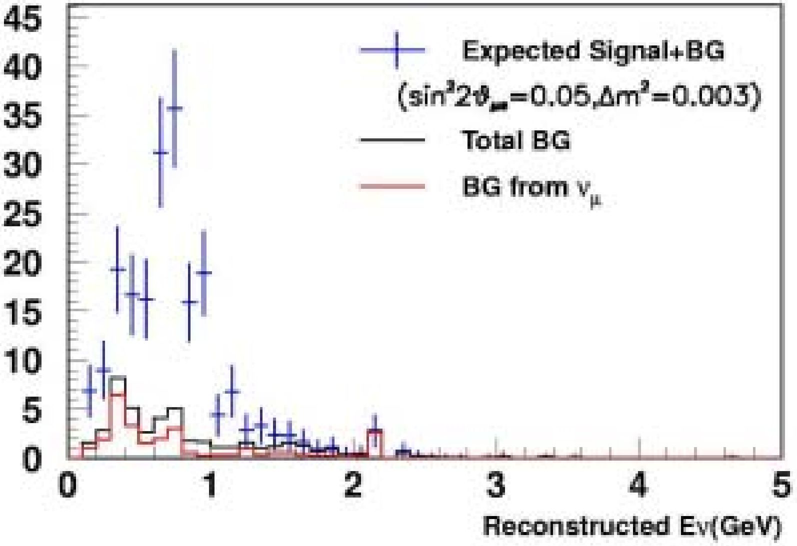
- $\sin^2 2\theta_{13} \cong 2\sin^2 2\theta_{\mu e} > 0.006$ 까지 측정 (×20 개선)

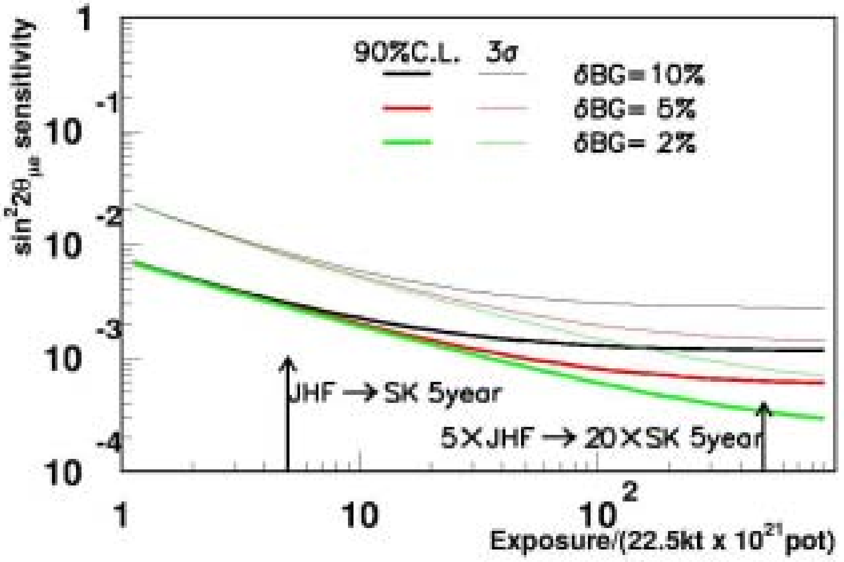
$\nu_\mu \rightarrow \nu_s$ 진동탐색

$\nu_\mu \to \nu_e$의 탐색과 θ_{13} 측정

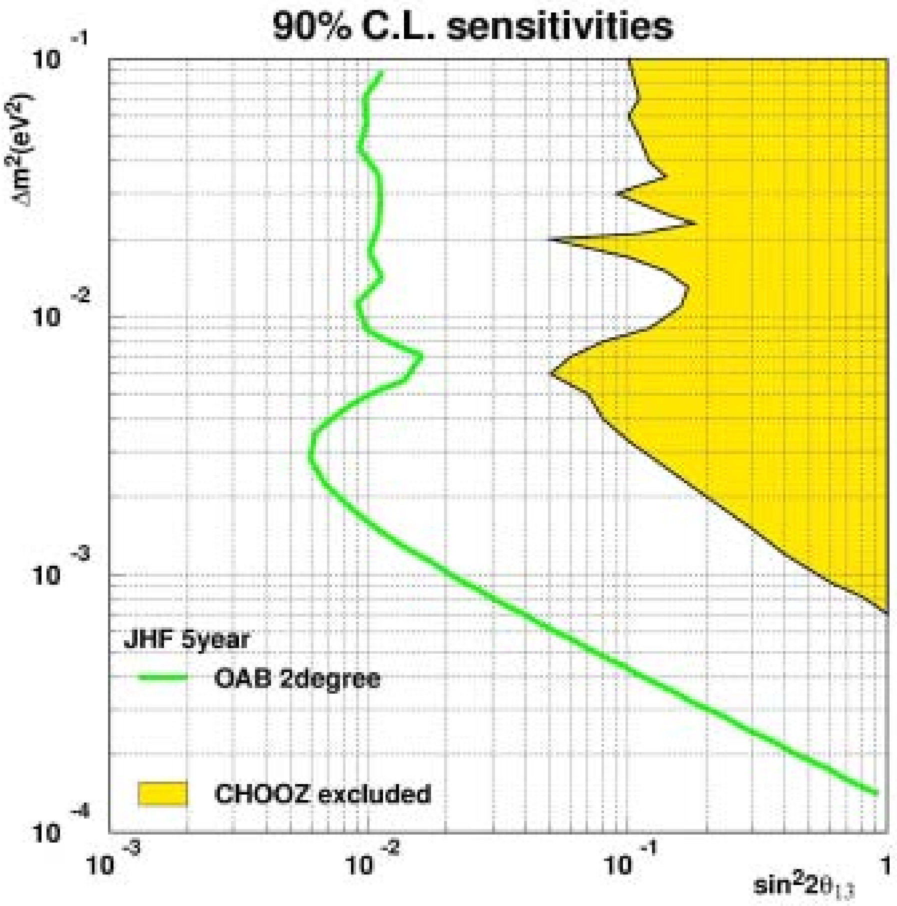
- Small ν_e contaminatin (0.2% at the peak energy)
- Enhanced ν_e appearance signal by tuning the neutrino beam energy at its expected oscillation maximum (**$\Delta m^2 \sim 3\text{x}10^{-3}$ eV^2**)

$\sin^2 2\theta_{13} \cong 2\sin^2 2\theta_{\mu e} > 0.006$





Sensitivity for $\nu_\mu \rightarrow \nu_e$ Oscillations



$$\sin^2 2\theta_{13} \cong 2\sin^2 2\theta_{\mu e} > 0.006$$

$\nu_\mu \to \nu_\tau$ 의 진동에서 θ_{23}와 Δm_{23} 의 정밀 측정

Measured/Expected with no oscillation

QE scattering events (after subtracting non-QE backgrounds)

(MeV)

$\delta(\sin^2 2\theta_{23}) = 0.01$

$\delta(\Delta m_{23}^2) = 10^{-4}\ \mathrm{eV}^2$

off-axis 3°

off-axis 2°

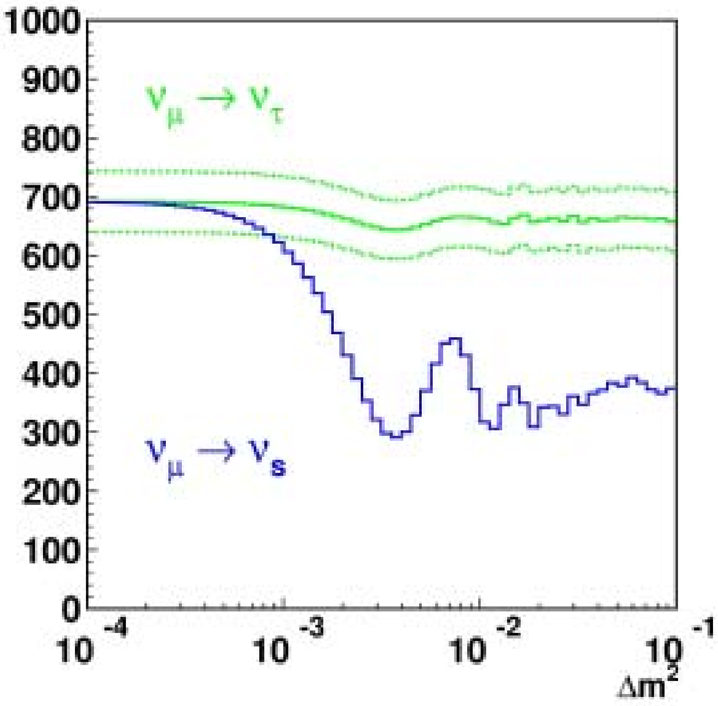
Maximal mixing($\sin^2 2\theta_{23} \cong 1.0$) → constraint on quark-lepton unification

Search for Sterile Neutrinos(ν_s) in ν_μ Disappearance

- NC neutrino events ($\nu + N \rightarrow \nu + N' + \pi^0$) :

  Measurement of $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ oscillations

  $\Rightarrow$ $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ oscillations



Expected number of events for 5 years of off-axis beam

$\Rightarrow$ Clear separation for **$\Delta m^2 > 10^{-3}$ eV^2**

Physics Goals of the J-PARC ν Experiment
(2nd Phase)

* Upgrades in accelerator (×5) and detector (×25):

(4MW PS)　　　(1Mton Hyper-Kamiokande)

☐ Measurement of CP phase δ:

$\delta >$ 10-20 degrees

☐ Precise measurement of θ_{13} :

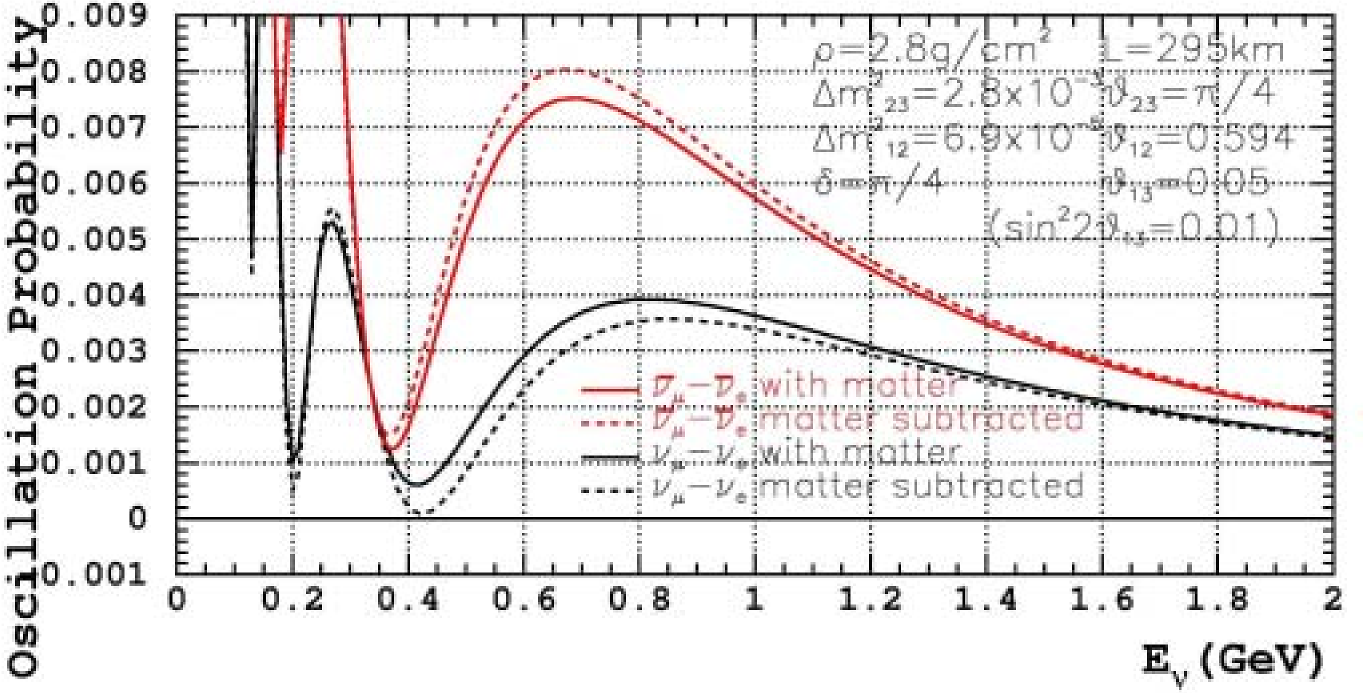
$\mathbf{sin^2 2\theta_{13}}$ sensitivity below 0.001

☐ Test the unitarity triangle in the leptonic sector

☐ Search for proton decays ($p \rightarrow e^+\pi^0, \bar{\nu}K^+$):

10^{35} yrs,　3×10^{34} yrs

경입자의 CP 대칭성 깨짐 탐색



2년의 ν_μ 빔과 6년의 $\bar{\nu}_\mu$ 빔

→ 생성된 ν_e 와 $\bar{\nu}_e$의 비교

CP phase δ:

$\delta >$ **10-20도** 까지 탐색

Physics Implications

❑ Precise measurement of $\Delta \mathbf{m}^2$

+ Proton decay lifetime

⇒ Probing GUT scale physics

❑ Precise measurement of mixing parameters

(MNS matrix elements)

⇒ Possible clue to “the generation problem”

❑ CP violations in lepton/quark sectors

+ Proton decay lifetime

⇒ Matter-Antimatter asymmetry in the Universe

국내에서의 중성미자 진동 실험 추진

□ J-PARC 중성미자 on-axis 빔의 한국에서 검출 가능성 추진
(1,000km 이상의 장거리 진동 연구)
⇒ 국내 중성미자 망원경 건설

□ 국내 고에너지 양성자가속기 건설
⇒ 중성미자 빔
⇒ 국내의 중성미자 진동 연구 (200 ~ 400 km)
⇒ 수퍼카미오칸데/하이퍼카미오칸데 검출기로 투사
(1,000km 이상의 장거리 진동 연구)

θ_{13} 측정의 세계적 상황과 한국에서의 실험 가능성

Motivation of reactor neutrino experiment

❑ Discovery of neutrino oscillations:

- a direct indication of physics beyond the Standard Model
- a unique new window to explore physics at high mass scale including unification, flavor dynamics, and extra dimensions

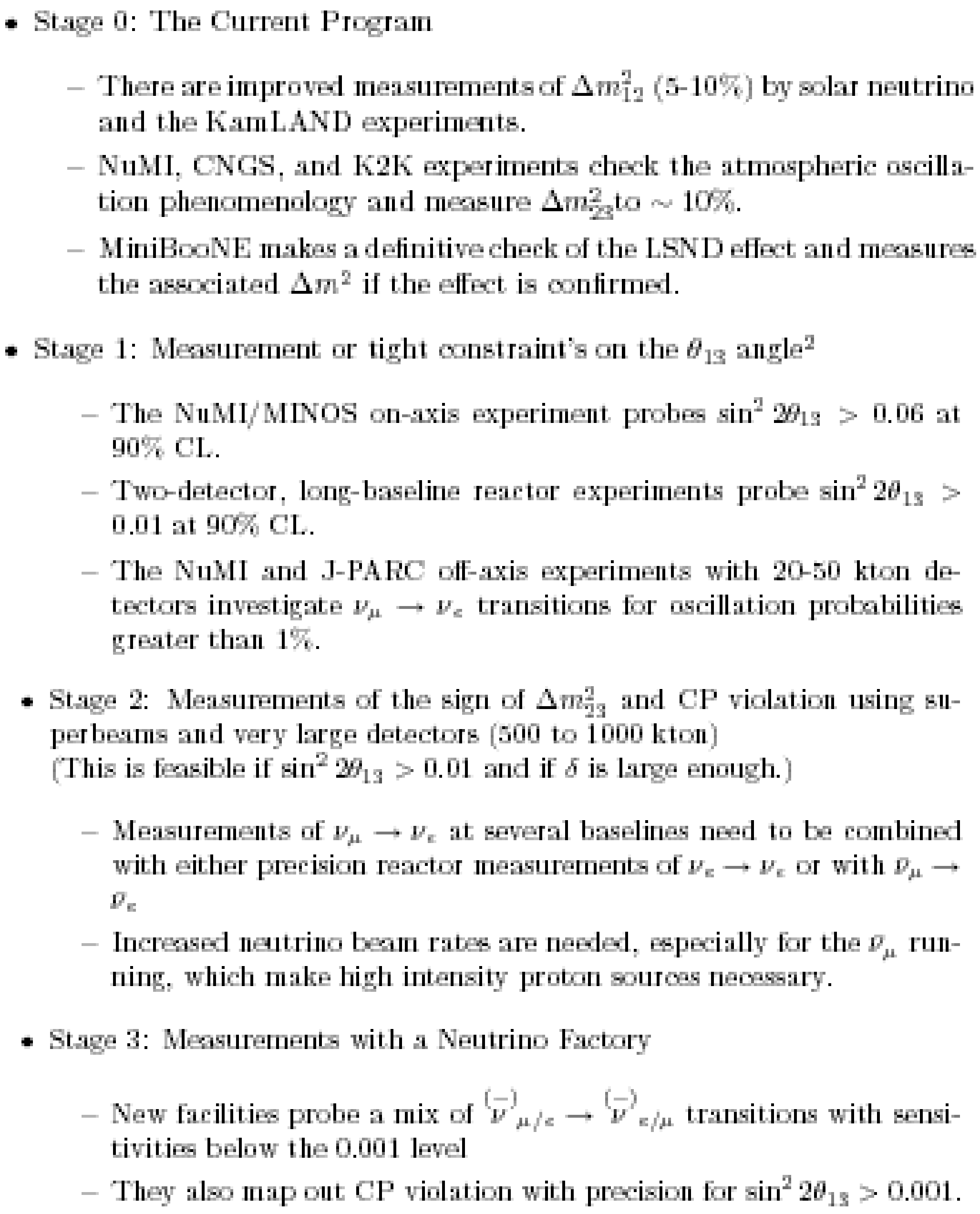
❑ Precise measurement of oscillation parameters

- mixing angles (MNS matrix)
- neutrino mass difference

❑ Measure θ_{13}

- CP violation only if $\sin^2(2\theta_{13}) > O(0.01)$

Road map for future neutrino oscillation measurements



- Stage 0: The Current Program
  - There are improved measurements of Δm^2_{12} (5-10%) by solar neutrino and the KamLAND experiments.
  - NuMI, CNGS, and K2K experiments check the atmospheric oscillation phenomenology and measure $\Delta m^2_{23}$to $\sim$ 10%.
  - MiniBooNE makes a definitive check of the LSND effect and measures the associated Δm^2 if the effect is confirmed.
- Stage 1: Measurement or tight constraint's on the θ_{13} angle[2]
  - The NuMI/MINOS on-axis experiment probes $\sin^2 2\theta_{13} > 0.06$ at 90% CL.
  - Two-detector, long-baseline reactor experiments probe $\sin^2 2\theta_{13} > 0.01$ at 90% CL.
  - The NuMI and J-PARC off-axis experiments with 20-50 kton detectors investigate $\nu_\mu \to \nu_e$ transitions for oscillation probabilities greater than 1%.
- Stage 2: Measurements of the sign of Δm^2_{23} and CP violation using superbeams and very large detectors (500 to 1000 kton)
  (This is feasible if $\sin^2 2\theta_{13} > 0.01$ and if δ is large enough.)
  - Measurements of $\nu_\mu \to \nu_e$ at several baselines need to be combined with either precision reactor measurements of $\nu_e \to \nu_e$ or with $\bar{\nu}_\mu \to \bar{\nu}_e$
  - Increased neutrino beam rates are needed, especially for the $\bar{\nu}_\mu$ running, which make high intensity proton sources necessary.
- Stage 3: Measurements with a Neutrino Factory
  - New facilities probe a mix of $\overset{(-)}{\nu}_{\mu/e} \to \overset{(-)}{\nu}_{e/\mu}$ transitions with sensitivities below the 0.001 level
  - They also map out CP violation with precision for $\sin^2 2\theta_{13} > 0.001$.

Reactor neutrino θ_{13} experiment

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

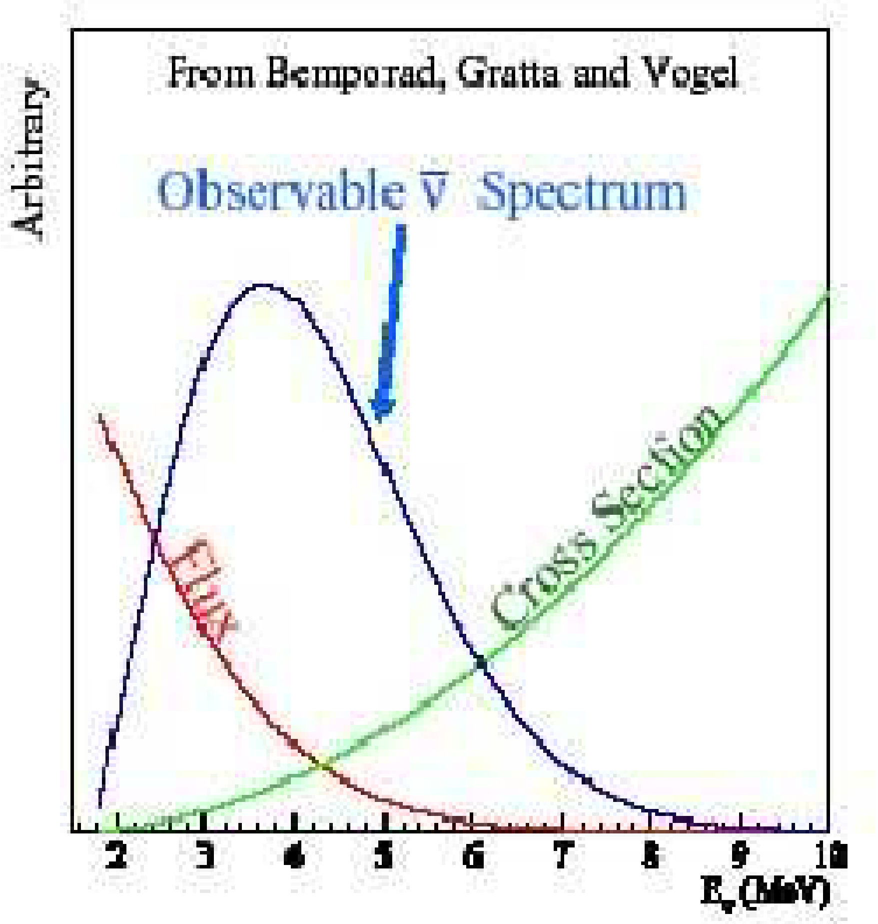
❑ Search for energy dependent $\bar{\nu}_e$ disappearance using two (or more) detectors

❑ Need to be located underground in order to reduce backgrounds from cosmic rays and cosmic ray induced spallation

❑ The detectors need to be designed identically in order to reduce systematic errors to 1% or less

❑ Need control of the relative detector efficiency, fiducial volume, and good energy calibration

Reactor neutrino flux, cross section, and observable neutrino spectrum



Reactor neutrino detector

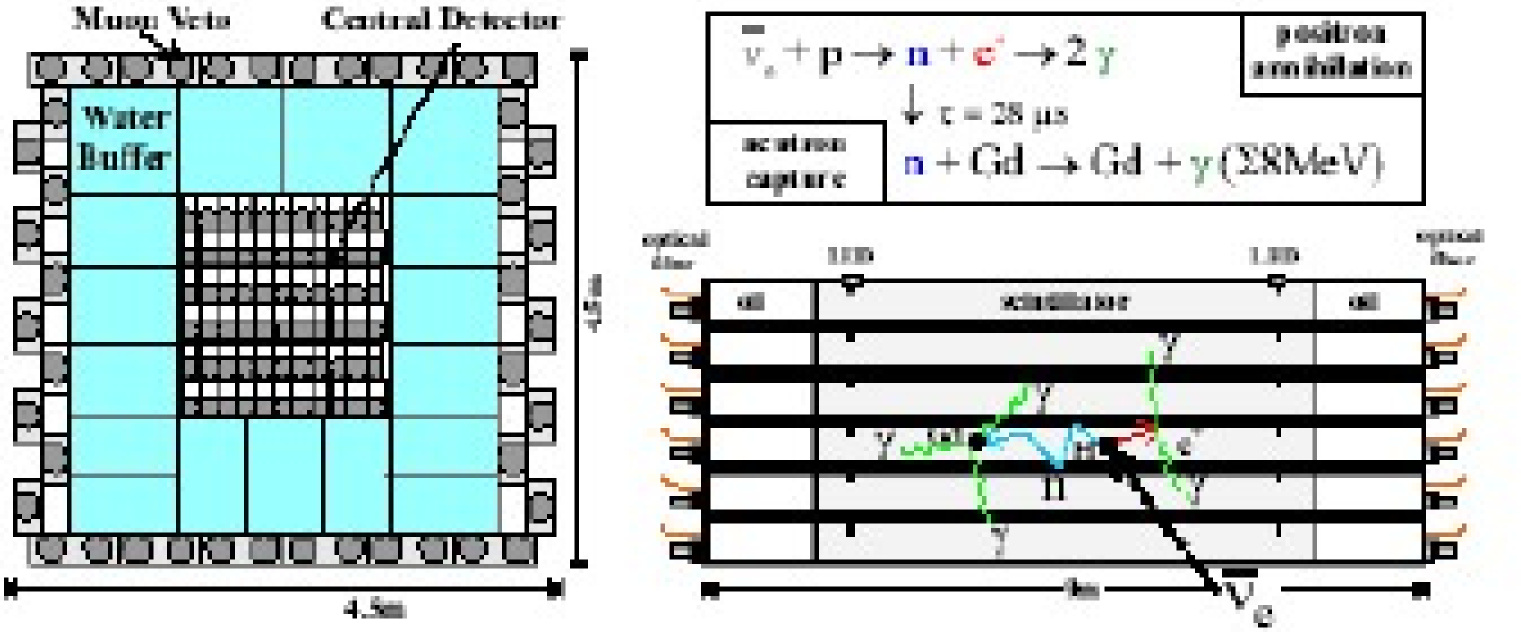


Figure 15: Schematic view of the detector and the inverse β-decay reaction producing a *triple* coincidence pattern inside the detector.

(Paolo Verde detector as an example)

Experimental motivation for non-zero θ_{13}

❑ The most remarkable property of of leptonic mixing:
  - two large mixing angles ($\sin^2 2\theta_{23} \approx 1.0$ and **$\tan^2\theta_{12} \approx 0.44$)**
  (← many theorists expected lepton mixing to be similar to quark mixing)
  - no particular reason to expect θ_{13} to be extremely small or even zero

❑ 3-flavor oscillation result from SK atmospheric neutrino data:
  - consistent allowed-region with CHOOZ

❑ The possibility of measuring CP violation can be fulfilled only if $\sin^2 2\theta_{13}$ > O(0.01).

Theoretical motivation for non-zero θ_{13}

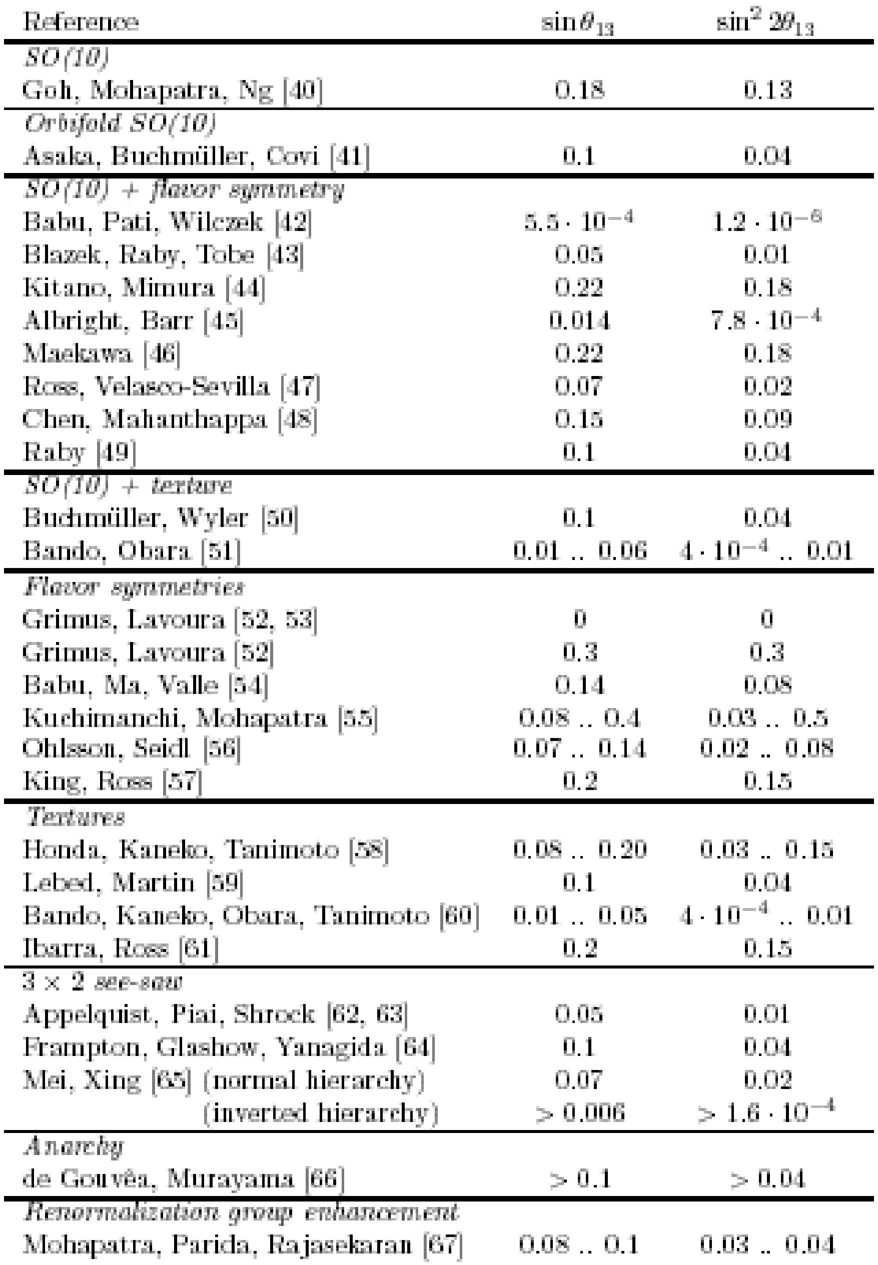
❑ A reason for expecting a particular value of θ_{13} does clearly not exist as long as one extends the SM only minimally to accommodate neutrino masses

❑ A sizable value of θ_{13} can be predicted for models in the framework of GUT and for models using flavor symmetries

❑ For MSSM one finds a shift $\Delta \sin^2(2\theta_{13}) > 0.01$ for a considerable parameter range

❑ Neutrino masses and mixing parameters are subject to quantum corrections between low scales (measurements) and high scales (predictions) → θ_{13} may run to a finite value or an increased value

Theoretical prediction of non-zero θ_{13}



Reference	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	0.13
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	0.18
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	0.18
Ross, Velasco-Sevilla [47]	0.07	0.02
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	0.3
Babu, Ma, Valle [54]	0.14	0.08
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
King, Ross [57]	0.2	0.15
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
Lebed, Martin [59]	0.1	0.04
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	0.15
3×2 *see-saw*		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	0.04
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

Neutrino oscillation probability of reactor experiment

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

(MNS matrix)

$$\begin{aligned} 1 - P(\bar{\nu}_e \to \bar{\nu}_e) &= \sin^2 2\theta_{13} \sin^2 \Delta_{31} \\ &+ 1/2\, c_{12}^2 \sin^2 2\theta_{13} \sin 2\Delta_{31} \sin 2\Delta_{21} \\ &+ c_{13}^4 \sin^2 2\theta_{12} \sin^2 \Delta_{21} \\ &+ c_{12}^2 \sin^2 2\theta_{13} \cos 2\Delta_{31} \sin^2 \Delta_{21}, \end{aligned}$$

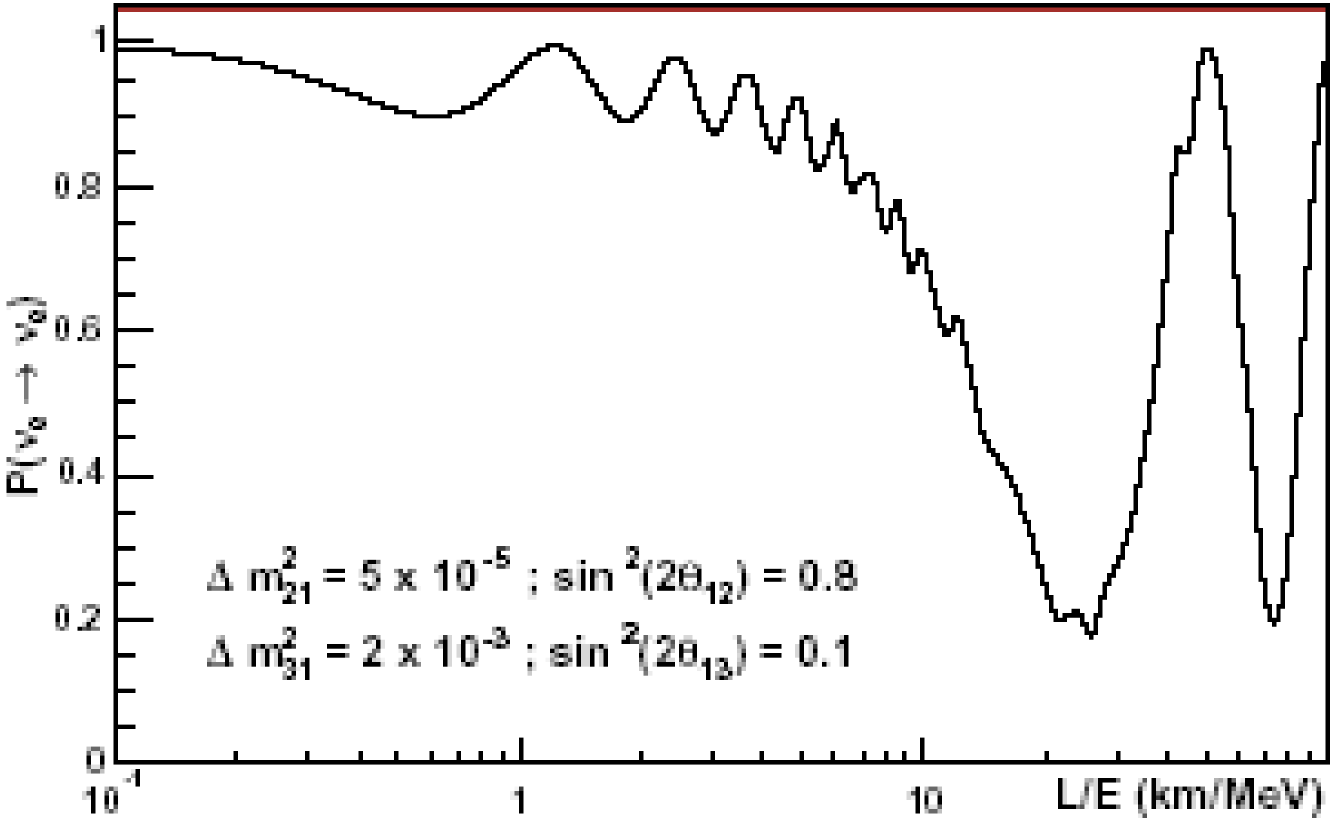
where $\Delta_{ij} \equiv \Delta m_{ij}^2 L/(4E)$

for $\Delta_{21} \ll 1$ (for the baselines considered) $\qquad \alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2,$

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{31} + \alpha^2 \Delta_{31}^2\, c_{13}^4 \sin^2 2\theta_{12}.$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{atm}^2 L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

Neutrino oscillation of reactor experiment



Sensitivity of reactor θ_{13} experiment

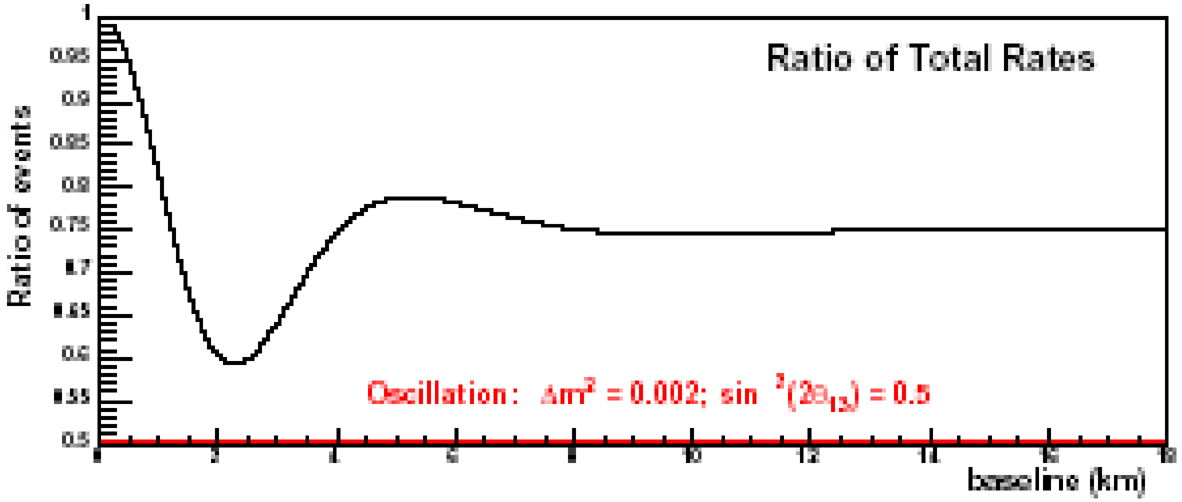


Figure 9: The ratio of the expected number of neutrino events with and without oscillations as a function of distance from the reactor core. This calculation was made for a luminosity of 600 t GW y and includes the true neutrino energy spectrum. The oscillation is assumed to have $\Delta m^2 = 0.002$ and an amplitude of $\sin^2(2\theta_{13}) = 0.5$ which is 2.5 times the current allowed limit.

- ❑ $\sin^2 2\theta_{13} > 0.01$ with 12 t•GW•yr ~ 400 t•GW•yr (400 t•GW•yr: a 10(40) ton far detector and a 14(3.5) GW reactor in 3 years)

Sensitivity of reactor θ_{13} experiment

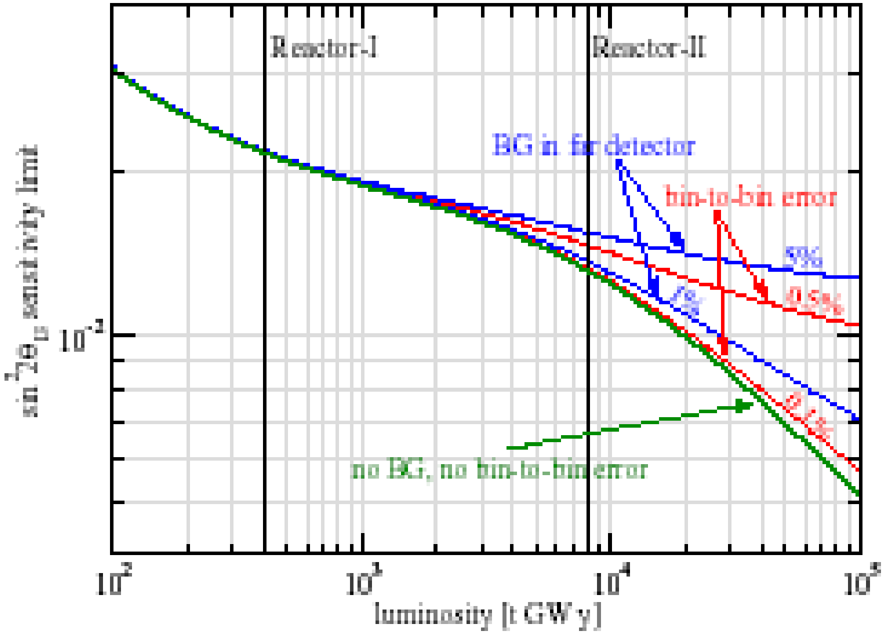
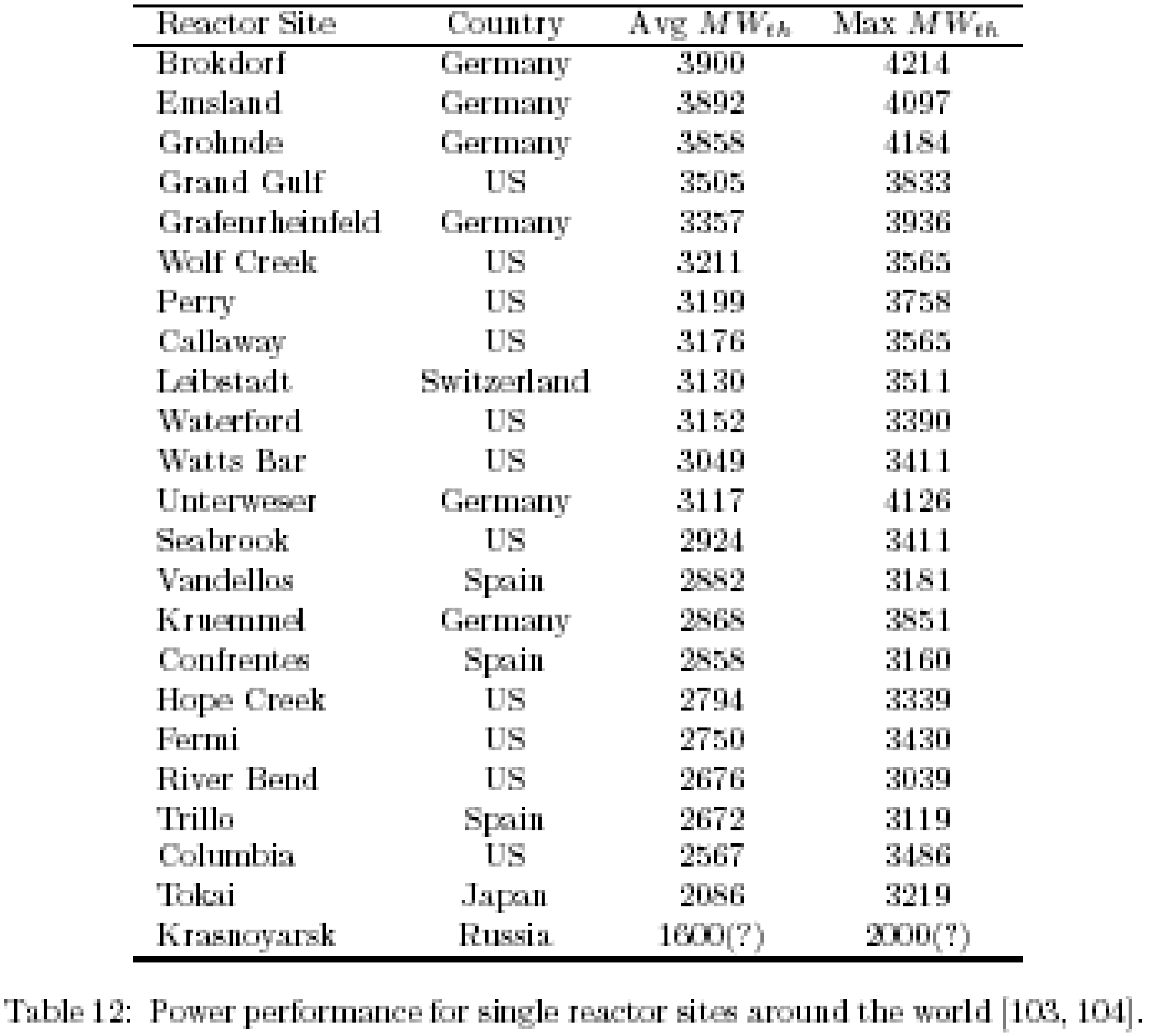


Figure 13: Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL as a function of the luminosity for an uncorrelated experimental systematic error ("bin-to-bin error") $\sigma_{\rm exp} = 0.1\%$ and 0.5%, and background levels in the far detector relative to the total number of events for no oscillations of 1% and 5%. Here $L_{ND} = 0.2$ km, $L_{FD} = 1.7$ km, $\Delta m^2_{31} = 2 \times 10^{-3}$ eV^2, and $\sigma_{\rm shape} = 2\%$. Identical detector masses are assumed for near and far detectors.

Possible reactor sites

(single reactor sites)

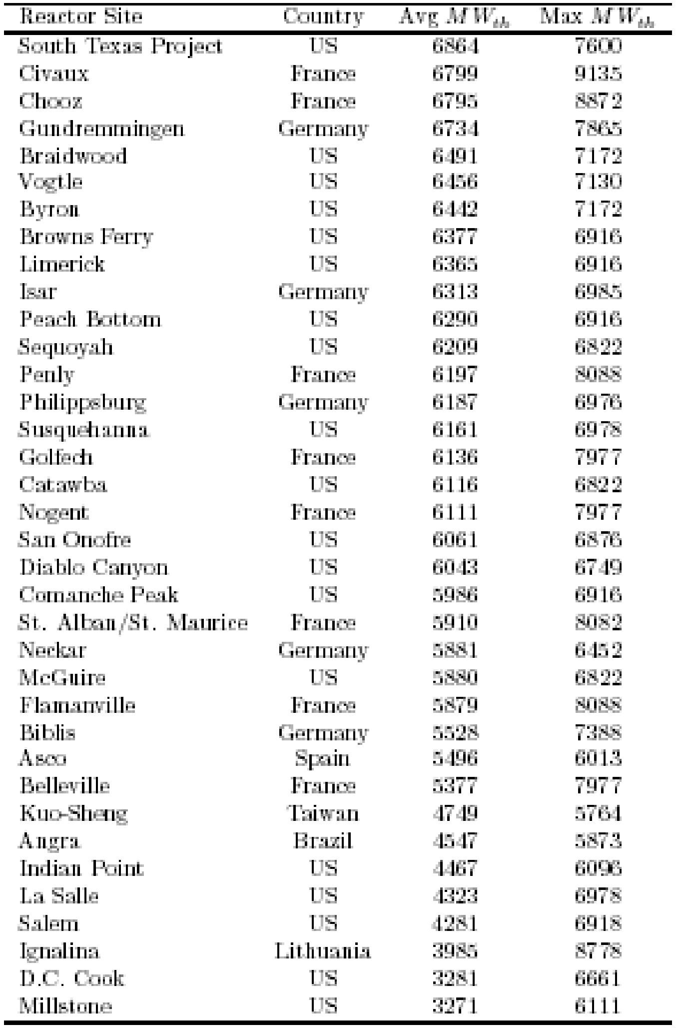


Reactor Site	Country	Avg MW_{th}	Max MW_{th}
Brokdorf	Germany	3900	4214
Emsland	Germany	3892	4097
Grohnde	Germany	3858	4184
Grand Gulf	US	3505	3833
Grafenrheinfeld	Germany	3357	3936
Wolf Creek	US	3211	3565
Perry	US	3199	3758
Callaway	US	3176	3565
Leibstadt	Switzerland	3130	3511
Waterford	US	3152	3390
Watts Bar	US	3049	3411
Unterweser	Germany	3117	4126
Seabrook	US	2924	3411
Vandellos	Spain	2882	3181
Kruemmel	Germany	2868	3851
Confrentes	Spain	2858	3160
Hope Creek	US	2794	3339
Fermi	US	2750	3430
River Bend	US	2676	3039
Trillo	Spain	2672	3119
Columbia	US	2567	3486
Tokai	Japan	2086	3219
Krasnoyarsk	Russia	1600(?)	2000(?)

Table 12: Power performance for single reactor sites around the world [103, 104].

Possible reactor sites

(double reactor sites)

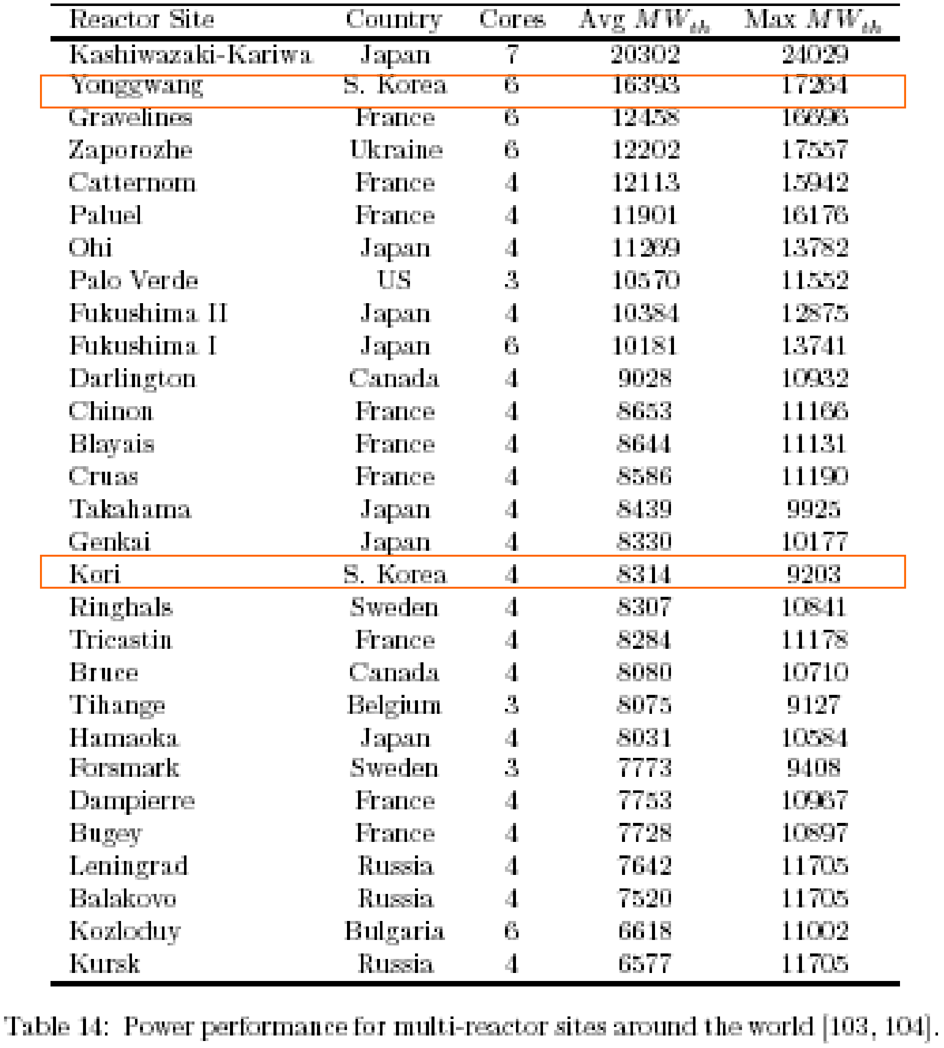


Reactor Site	Country	Avg MW_{th}	Max MW_{th}
South Texas Project	US	6864	7600
Civaux	France	6799	9135
Chooz	France	6795	8872
Gundremmingen	Germany	6734	7865
Braidwood	US	6491	7172
Vogtle	US	6456	7130
Byron	US	6442	7172
Browns Ferry	US	6377	6916
Limerick	US	6365	6916
Isar	Germany	6313	6985
Peach Bottom	US	6290	6916
Sequoyah	US	6209	6822
Penly	France	6197	8088
Philippsburg	Germany	6187	6976
Susquehanna	US	6161	6978
Golfech	France	6136	7977
Catawba	US	6116	6822
Nogent	France	6111	7977
San Onofre	US	6061	6876
Diablo Canyon	US	6043	6749
Comanche Peak	US	5986	6916
St. Alban/St. Maurice	France	5910	8082
Neckar	Germany	5881	6452
McGuire	US	5880	6822
Flamanville	France	5879	8088
Biblis	Germany	5528	7388
Asco	Spain	5496	6013
Belleville	France	5377	7977
Kuo-Sheng	Taiwan	4749	5764
Angra	Brazil	4547	5873
Indian Point	US	4467	6096
La Salle	US	4323	6978
Salem	US	4281	6918
Ignalina	Lithuania	3985	8778
D.C. Cook	US	3281	6661
Millstone	US	3271	6111

Table 13: Power performance for double reactor sites around the world [103, 104].

Possible reactor sites

(multi-reactor sites)



Reactor Site	Country	Cores	Avg MW_{th}	Max MW_{th}
Kashiwazaki-Kariwa	Japan	7	20302	24029
Yonggwang	S. Korea	6	16393	17264
Gravelines	France	6	12458	16696
Zaporozhe	Ukraine	6	12202	17557
Catternom	France	4	12113	15942
Paluel	France	4	11901	16176
Ohi	Japan	4	11269	13782
Palo Verde	US	3	10570	11552
Fukushima II	Japan	4	10384	12875
Fukushima I	Japan	6	10181	13741
Darlington	Canada	4	9028	10932
Chinon	France	4	8653	11166
Blayais	France	4	8644	11131
Cruas	France	4	8586	11190
Takahama	Japan	4	8439	9925
Genkai	Japan	4	8330	10177
Kori	S. Korea	4	8314	9203
Ringhals	Sweden	4	8307	10841
Tricastin	France	4	8284	11178
Bruce	Canada	4	8080	10710
Tihange	Belgium	3	8075	9127
Hamaoka	Japan	4	8031	10584
Forsmark	Sweden	3	7773	9408
Dampierre	France	4	7753	10967
Bugey	France	4	7728	10897
Leningrad	Russia	4	7642	11705
Balakovo	Russia	4	7520	11705
Kozloduy	Bulgaria	6	6618	11002
Kursk	Russia	4	6577	11705

Table 14: Power performance for multi-reactor sites around the world [103, 104].

~ Uljin

Experimental prospects

❑ Recent efforts:

- three workshops by the International Working Group
  (April 30~May 1, 2003 at the U. of Alabama
  October 9~11, 2003 at Technical U. of Munich
  March 20~22, 2004 at Niigata U.)
- White Paper Report (Feb. 2004)

❑ Possible experiment under discussion:

- Double-CHOOZ (approved, ~$10M)
- Diablo Canyon in California
- Kashiwazaki in Japan
- Krasnoyarsk reactor underground at Zhelezhnogorsk in Russia
- Angra reactor in Brazil
- Daya Bay in China