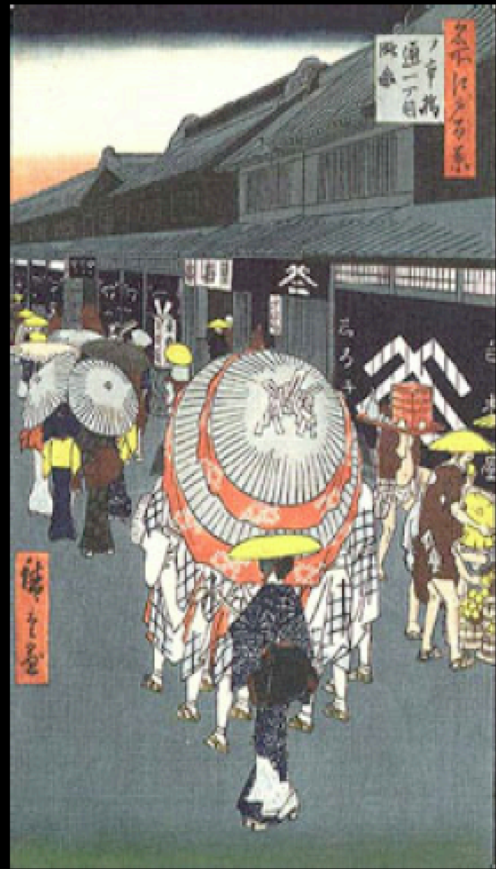
Neutrino Physics:
Theoretical Status

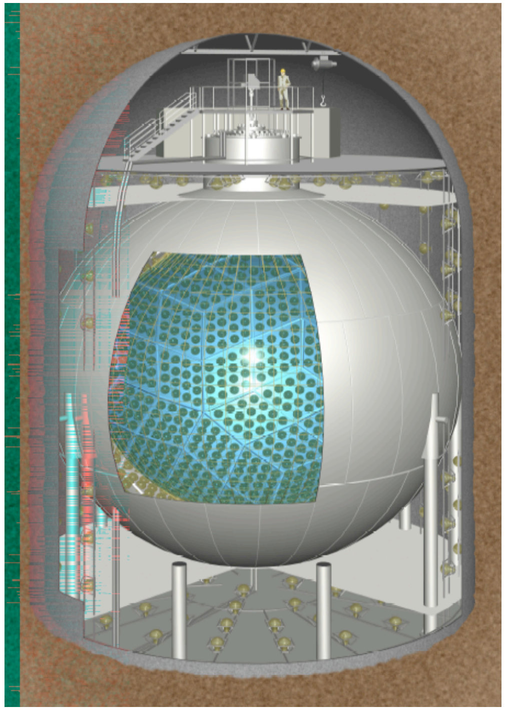
Hisakazu Minakata
(Tokyo Metropolitan University)

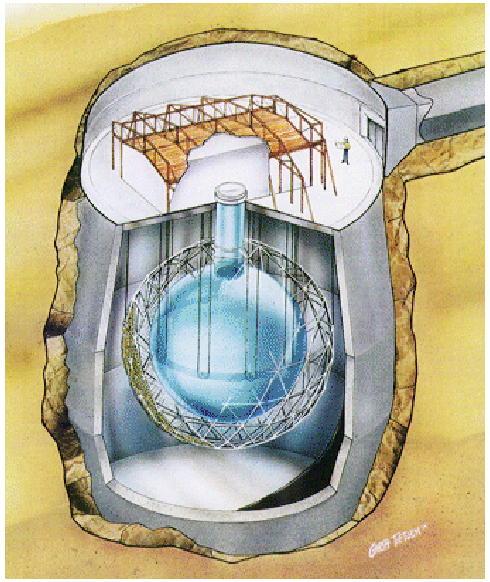
Past and Present

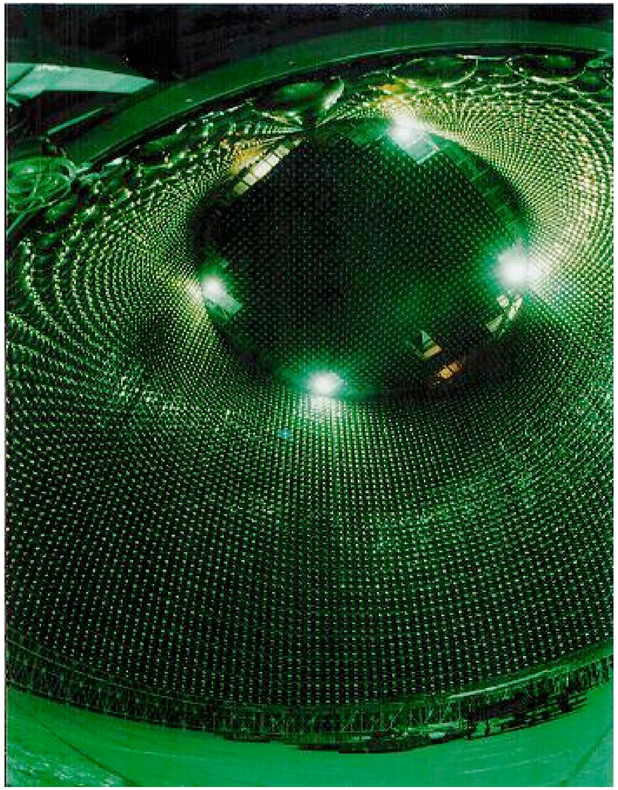


広重「名所江戸百景」より「日本橋通り一丁目略図」

In the last 5 years we have experienced the most exciting era in ν physics







If there is no LSND anomaly, I would have said

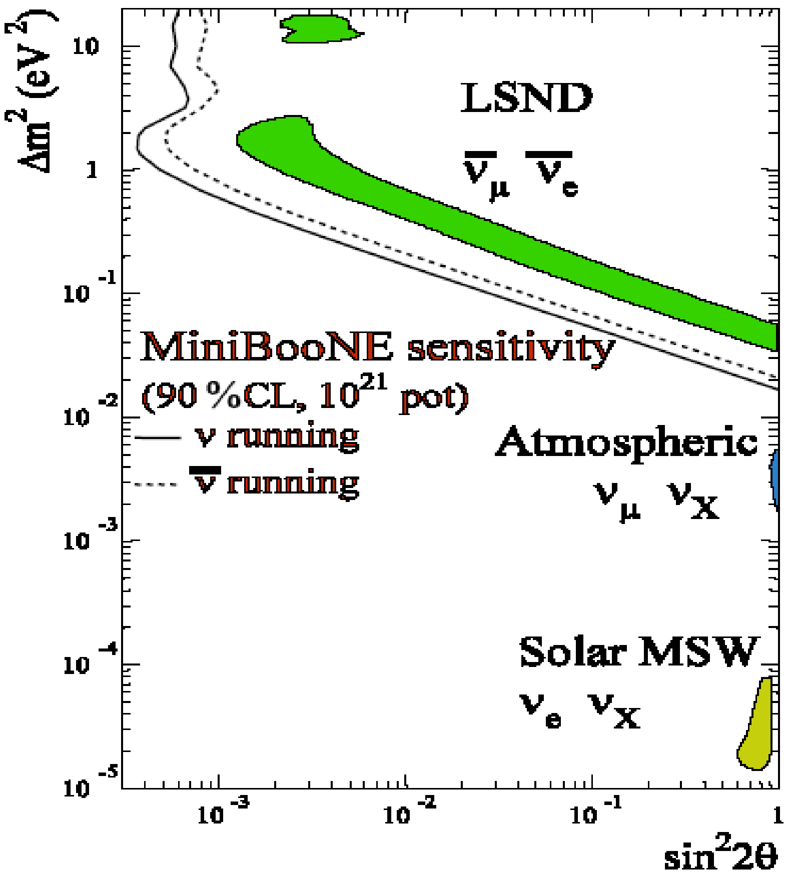
"An orthodox view of □ mass and mixing has emerged; the minimal extension of the standard model with □ mass with 3 generation of leptons and quarks"

LSND anomaly; "Bone in the throat", or the greatest remaining question in physics

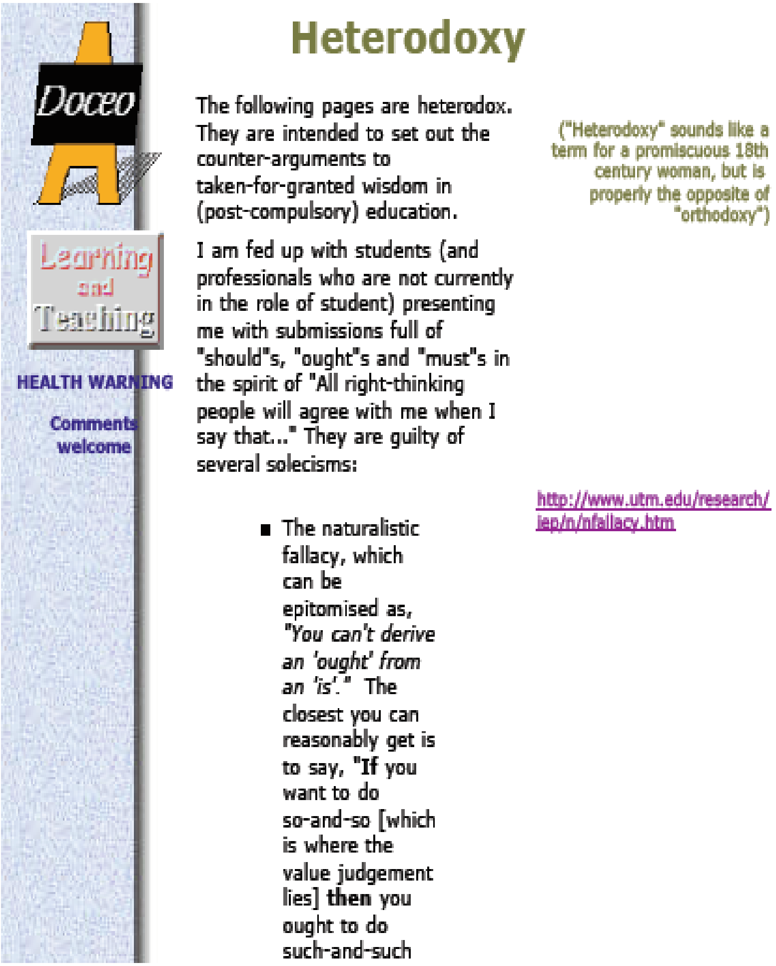
Whether Mini-BOONE confirms or refutes the LSND indication of another oscillation channel

If affirmative ==>

"revolution in particle physics"



Heterodoxy



Heterodoxy

Doceo

Learning and Teaching

HEALTH WARNING

Comments welcome

The following pages are heterodox. They are intended to set out the counter-arguments to taken-for-granted wisdom in (post-compulsory) education.

("Heterodoxy" sounds like a term for a promiscuous 18th century woman, but is properly the opposite of "orthodoxy")

I am fed up with students (and professionals who are not currently in the role of student) presenting me with submissions full of "should"s, "ought"s and "must"s in the spirit of "All right-thinking people will agree with me when I say that..." They are guilty of several solecisms:

- The naturalistic fallacy, which can be epitomised as, *"You can't derive an 'ought' from an 'is'."* The closest you can reasonably get is to say, "**If** you want to do so-and-so [which is where the value judgement lies] **then** you ought to do such-and-such

http://www.utm.edu/research/iep/n/nfallacy.htm

Various schemes are proposed motivated by the LSND data, which include:

- 2+2 sterile-active scheme
- 3+1
- 3+2
- CPT violation
- Sterile + CPT violation
- …..

(Are they really heterodox?)

“What did you, theorists, say when we have announced the atmospheric neutrino anomaly?”

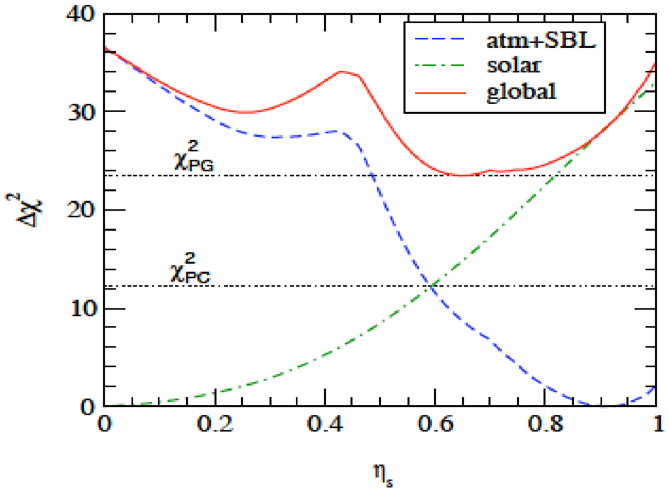
Yoji Totsuka
@JHF workshop
April 2001, KEK

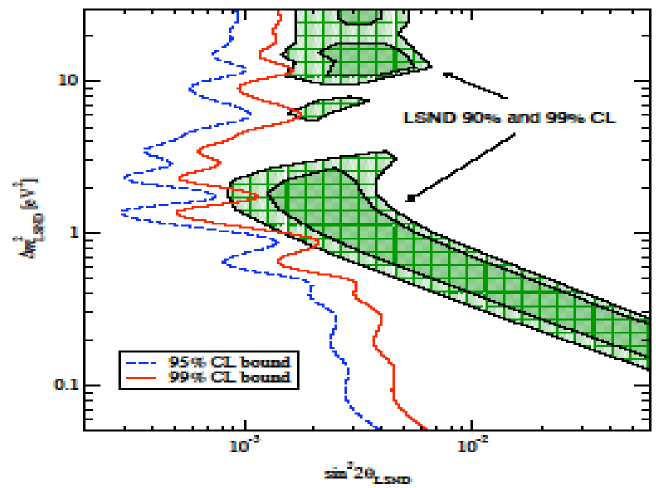
"What did you, everybody, say when we have announced the LSND anomaly?"

Bill Louis

@WIN2010

Four Neutrino Scenarios

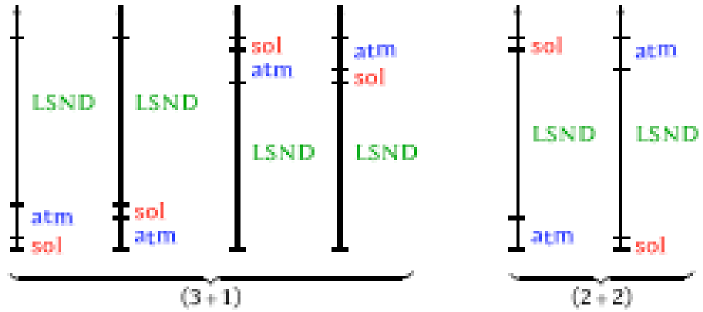




- 2+2 scheme: strongly disfavored by atmospheric and solar data (99.95% CL)
- 3+1 scheme: constrained by SBL experiments, allowed only marginally

(Maltoni, Schwetz Tortola, Valle

hep-ph/0209368)



3+2 Active-Sterile Scenario

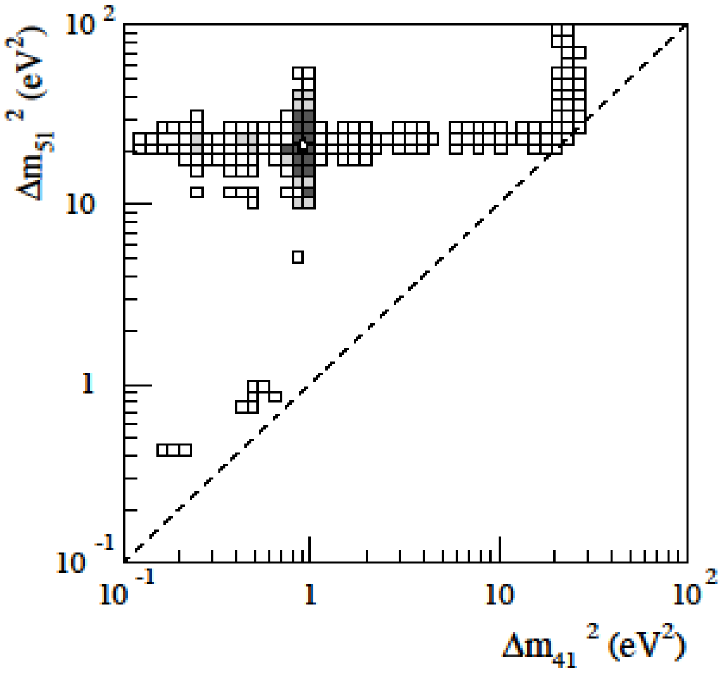
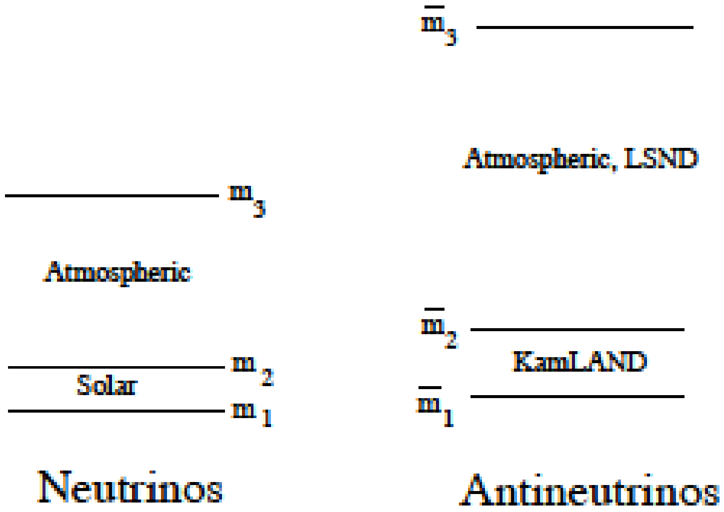


FIG. 6: Allowed ranges in $(\Delta m_{41}^2, \Delta m_{51}^2)$ space for (3+2) models, for the combined NSBL+LSND analysis, assuming statistical compatibility between the NSBL and LSND data sets. The star indicates the best-fit point, the grey-shaded regions indicate the 90, 95, 99% CL allowed regions. Only the $\Delta m_{51}^2 > \Delta m_{41}^2$ region is shown; the complementary region $\Delta m_{41}^2 > \Delta m_{51}^2$ can be obtained by interchanging Δm_{41}^2 with Δm_{51}^2.

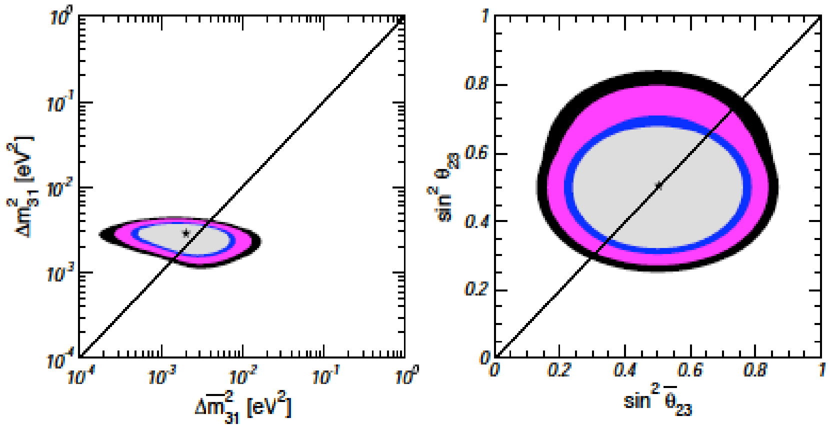
- Best-fit point utilizes a "dip" in sensitivity of SBL experiments
  (Sorel-Conrad-Shaevitz, hep-ph/0305255)
- Constrained by disappearance measurement in the Mini-BOONE (When?)

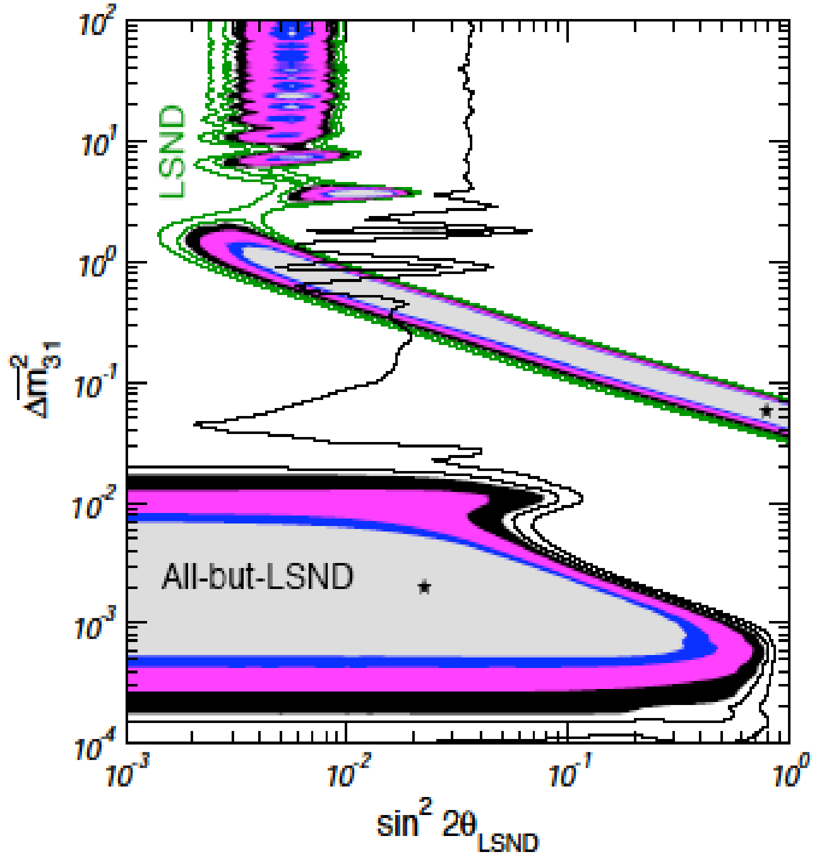
CPT Violation

- Mass pattern of ν and anti-ν as well as their mixing may be different
  (Murayama-Yanagida '01
  Barenboim et al. '02)



CPT Violation tightly constrained by atmospheric, solar & reactor data



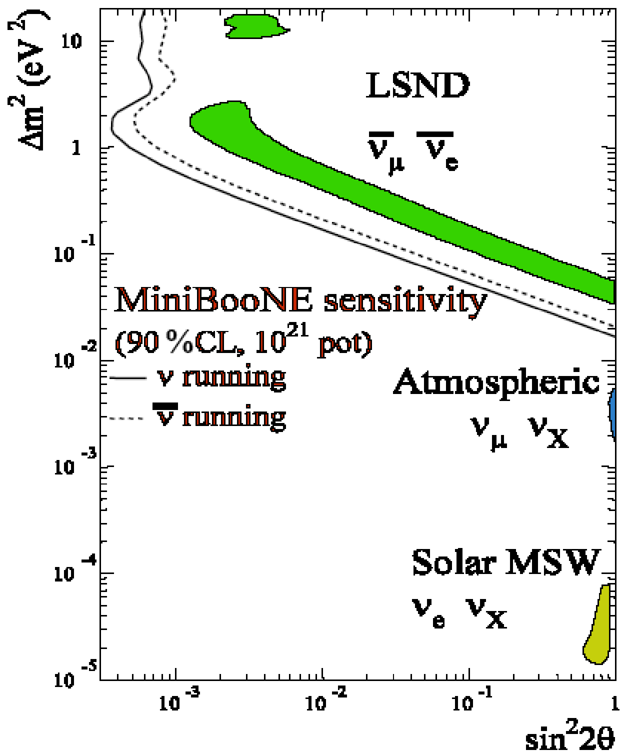


- Even if we allow ν and anti-ν independent, all data except for LSND prefer CPT conservation
- LSND parameter is more than 3σ away

(Gonzalez-Garcia-Maltoni-Schwetz 03)

Constraining LSND-like anomaly toward "unitarity triangle"

- Though LSND ν_e appearance signal might be killed by Mini-BOONE, there are potential possibility of other "high-Δm^2 anomaly".
- Disappearance measurement in SBL and/or reactor experiments can be important to constrain such potential "high-Δm^2 anomaly".
- Possible tie-up between reactor θ_{13} experiments and "sterile hunting"?



Organization of the talk:
with emphasis on future perspective

- Heterodoxy
- Orthodoxy

(1) atm+solar+reactor+accelerator

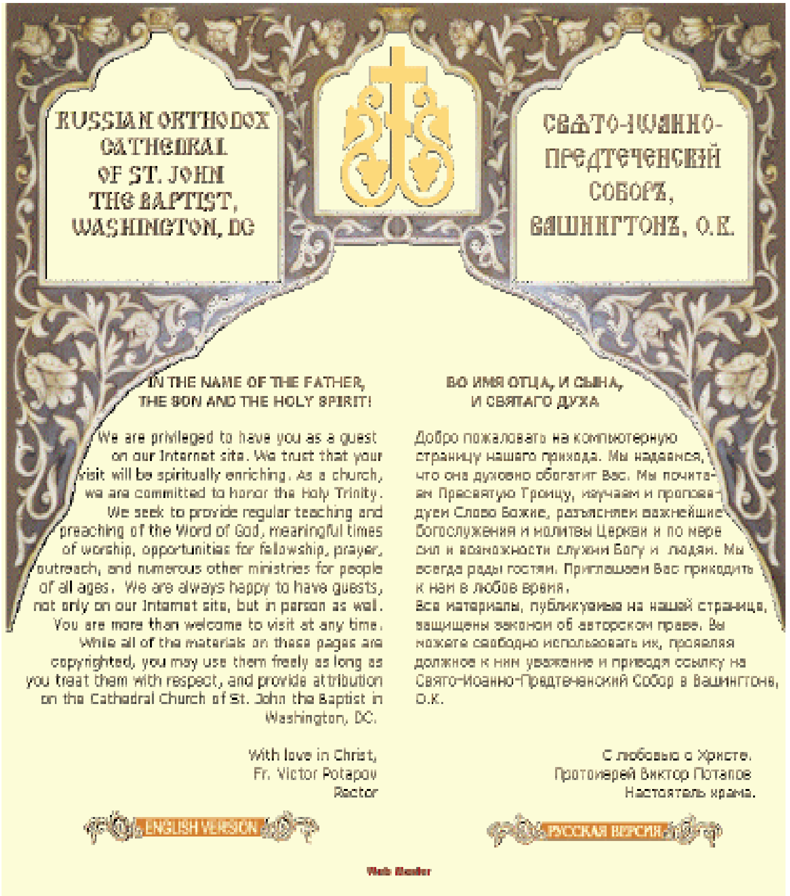
(2) θ_{13}: How to?

(3) Leptonic CP violation

(4) Absolute mass scale: Double beta

- Theoretical outlook
- “WINning” combination of disciplines?

Orthodoxy



Three-generation extension of neutrino (lepton) mixing scheme a la Maki-Nakagawa-Sakata:

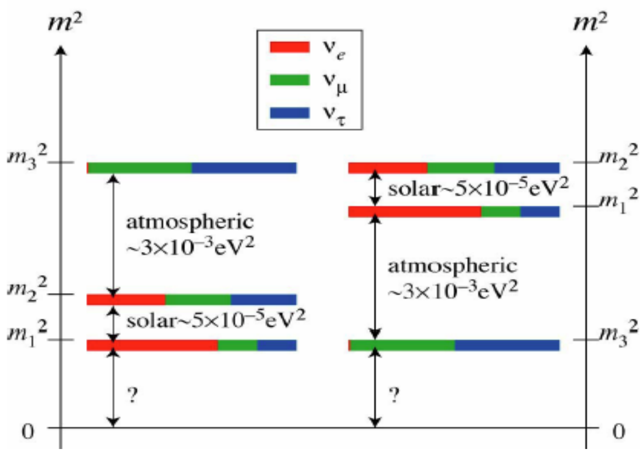
in complete harmony with 3 generation quark mixing scheme a la CKM

"lepton-quark correspondence" in the spirit of Nagoya model (Sakata et al., '60th)

MNS matrix and mass hierarchy; notation

$$U \equiv U_{\rm MNS} \cdot \Gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times {\rm diag}(1, e^{i\beta}, e^{i\gamma})$$

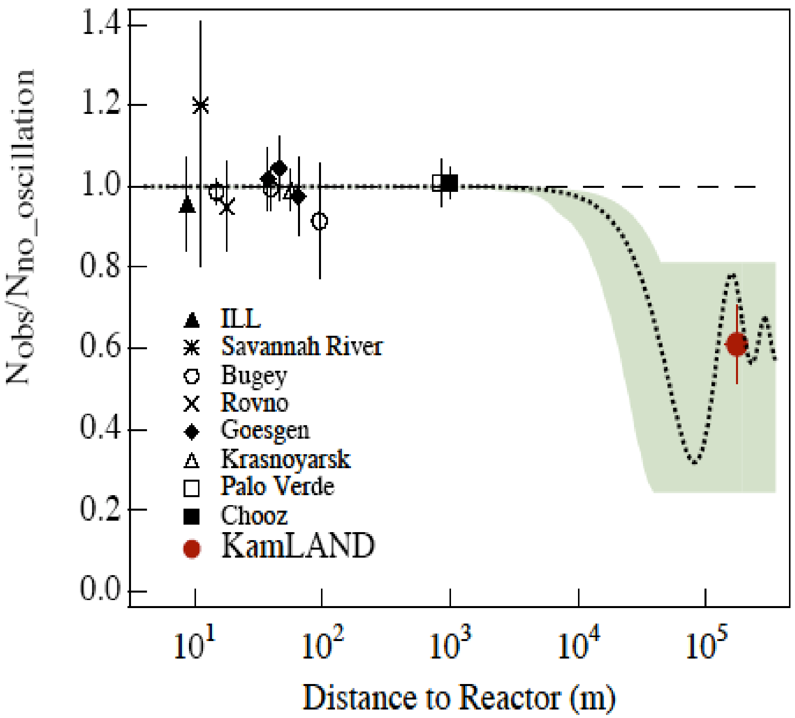
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \times {\rm diag}(1, e^{i\beta}, e^{i\gamma})$$

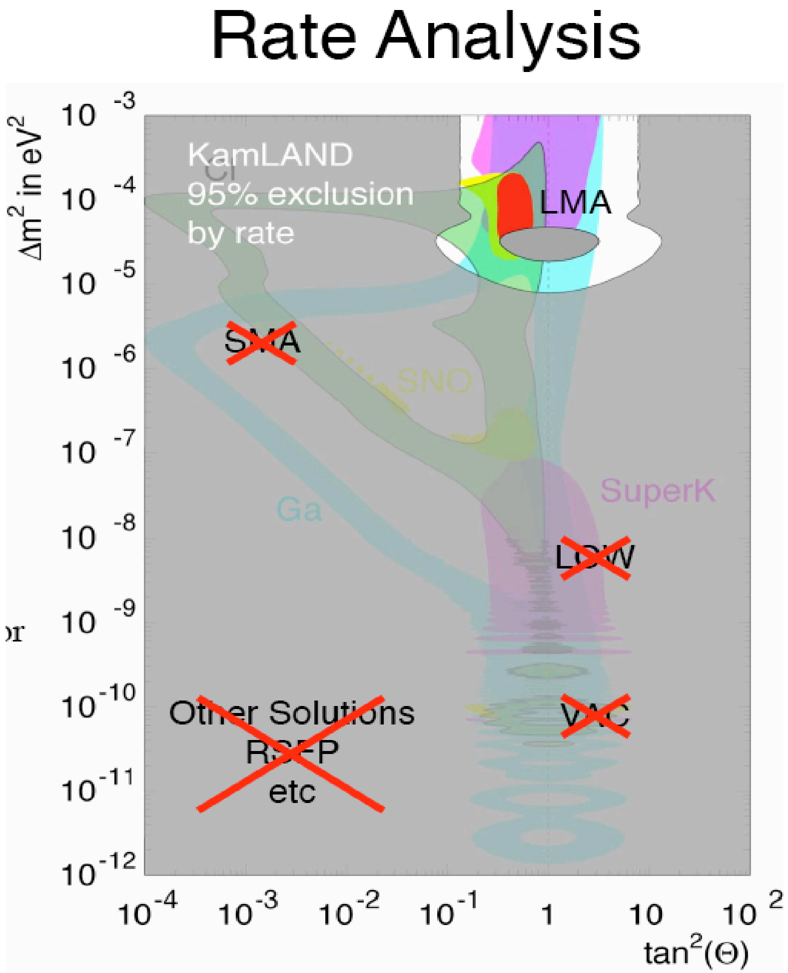


Neutrino mass hierarchies

- Left: “normal”
- Right: “inverted”

Way to the Orthodoxy #1.
KamLAND Massacre (December '02)





 magnetic moment, FCNC, etc. are excluded as dominant mechanism

Way to the Orthodoxy #2. Solar □: SNO salt data reassures □ sol. & LMA-I is the solution!

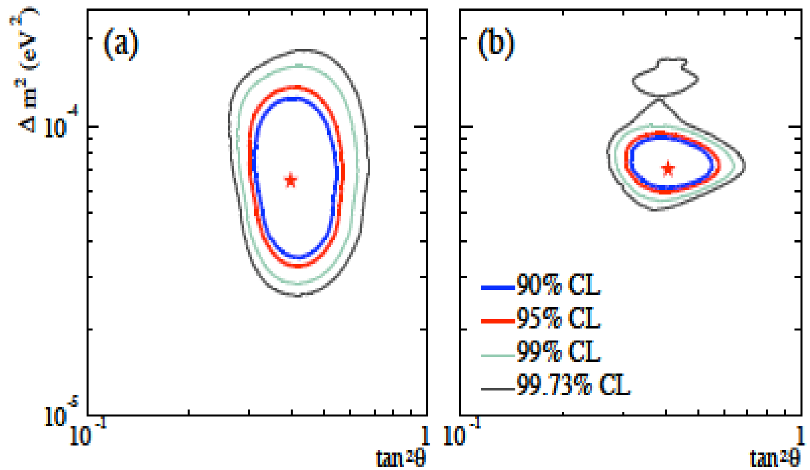


FIG. 5: Global neutrino oscillation contours. (a) Solar global: D_2O day and night spectra, salt CC, NC, ES fluxes, SK, Cl, Ga. The best-fit point is $\Delta m^2 = 6.5 \times 10^{-5}$, $\tan^2\theta = 0.40$, $f_B = 1.04$, with χ^2/d.o.f.=70.2/81. (b) Solar global + KamLAND. The best-fit point is $\Delta m^2 = 7.1 \times 10^{-5}$, $\tan^2\theta = 0.41$, $f_B = 1.02$. In both (a) and (b) the ^{8}B flux is free and the *hep* flux is fixed.

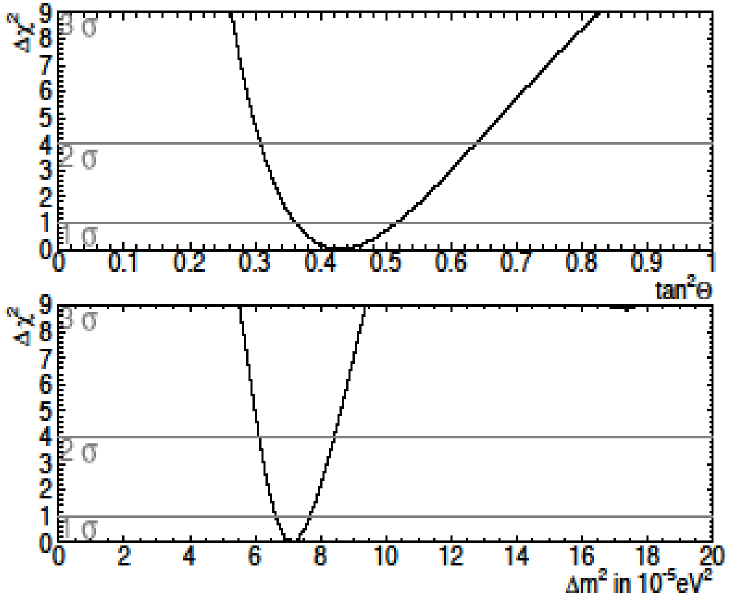


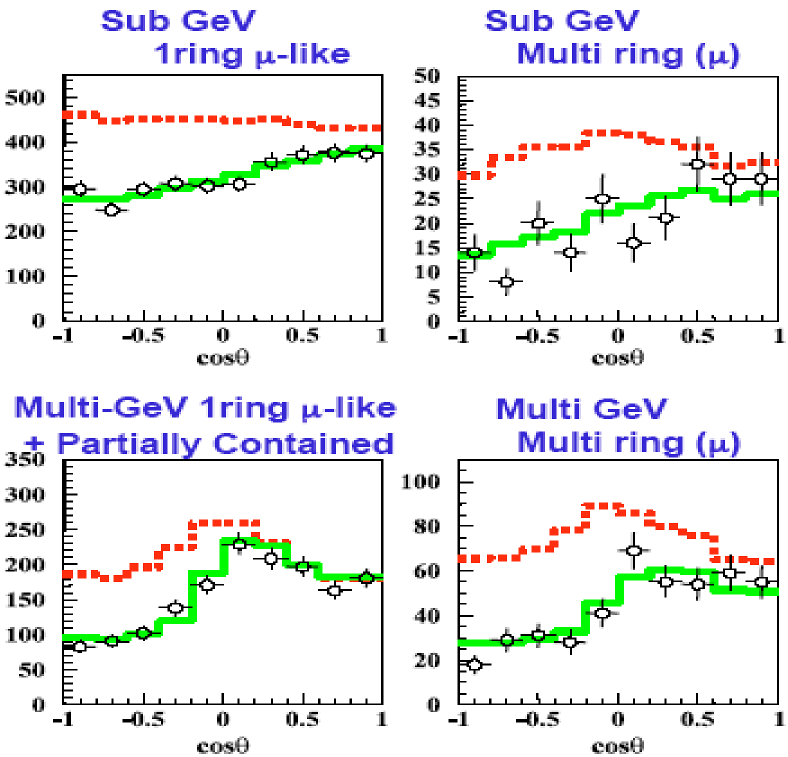
FIG. 7: $\Delta\chi^2$ Curves as a Function of Mixing (Top) and Δm^2 (Bottom) Using all Solar and KamLAND Data. Only LMA-I remains allowed at 3σ.

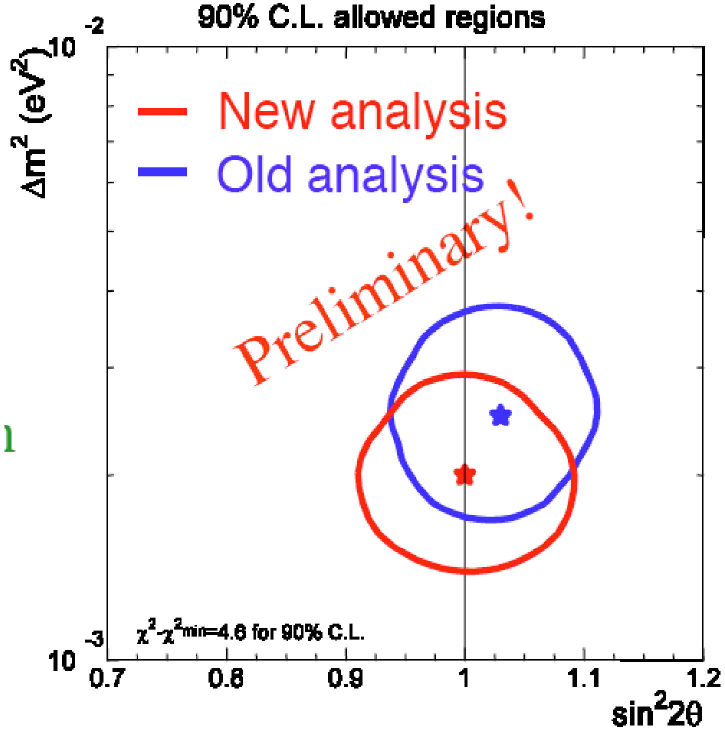
- SNO says LMA I at 99% CL (nucl-ex/0309004)
- SK says LMA I at 3 □ CL (hep-ex/0309011)

Way to the Orthodoxy #3.

Atmospheric □ robust, but □m^2 get lower

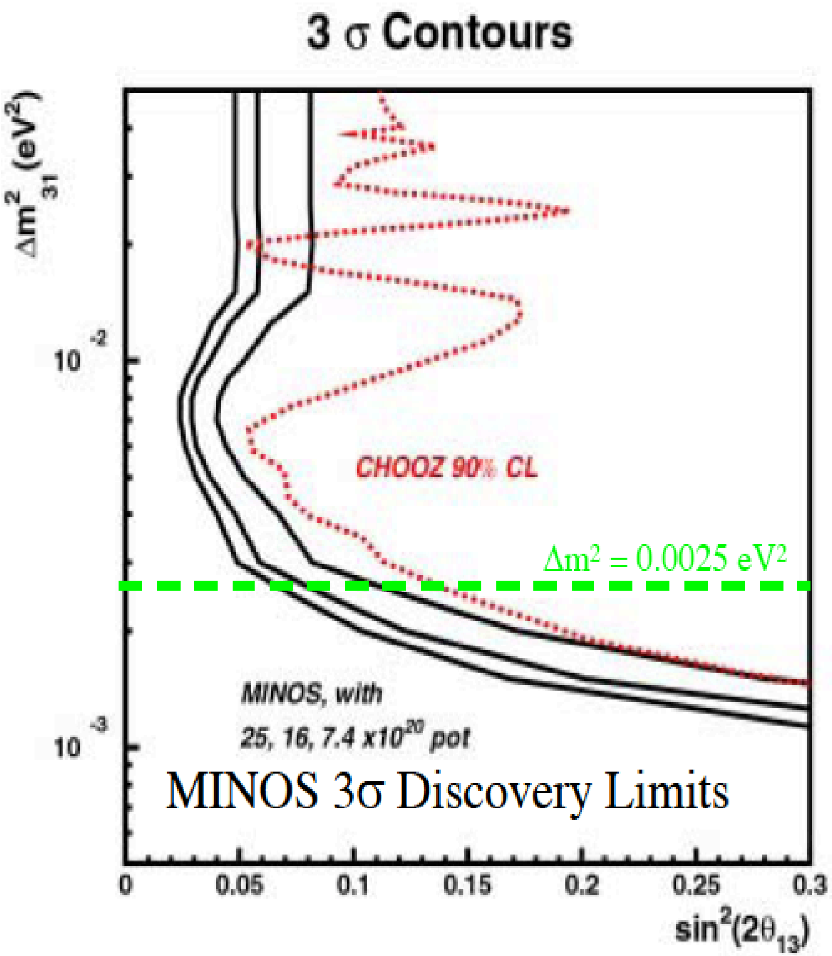
(Hayato, Europhys conference 03)





- Best fit: □m^2 = 2x10^{-3} eV^2 (□^{2}_min = 170.8/170d.o.f)
- 90% CL region: 1.3x10^{-3} < □m^2 < 3.0x10^{-3} eV^2

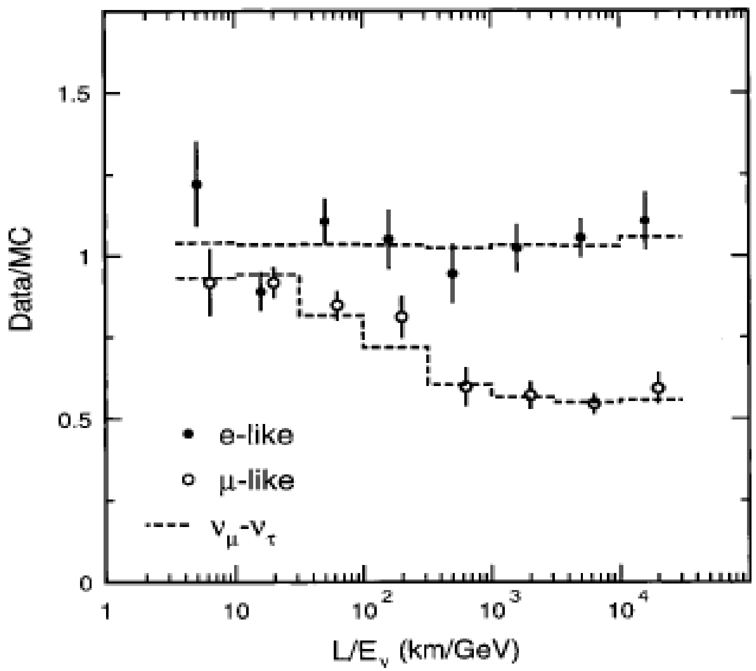
Lower atmospheric Δm^2: Good or bad?

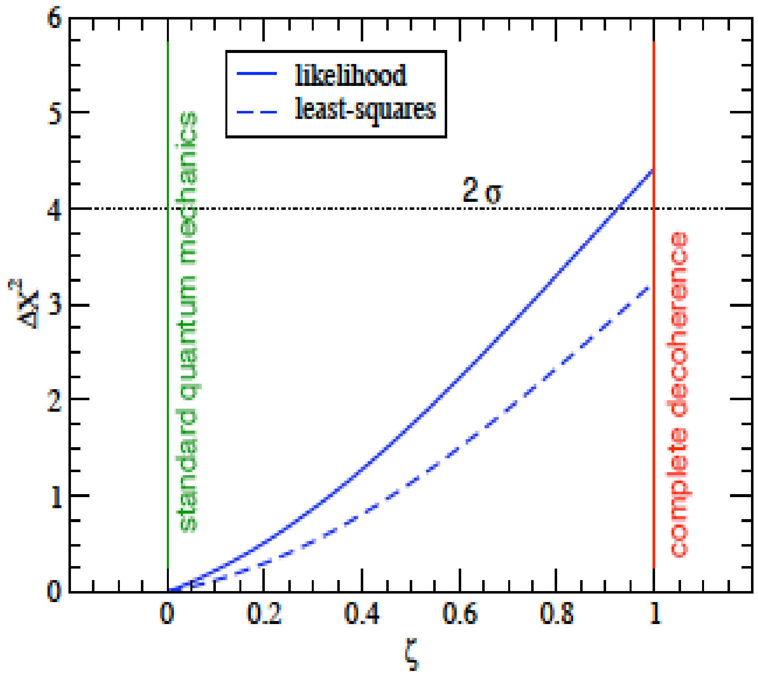


- Bad for LBL experiments; smaller event rate
- Good (?) for CP search; Larger $\Delta m^2_{solar}/ \Delta m^2_{atm}$ ratio
- Bonus; looser CHOOZ bound on θ_{13}

  (may be good news for reactor θ_{13} experiments)

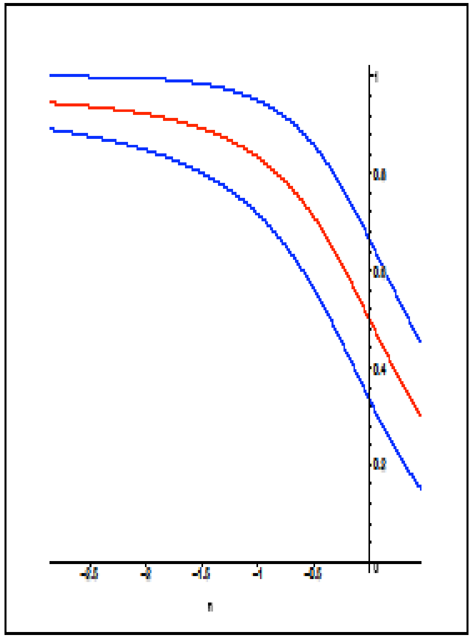
Did we see oscillation?



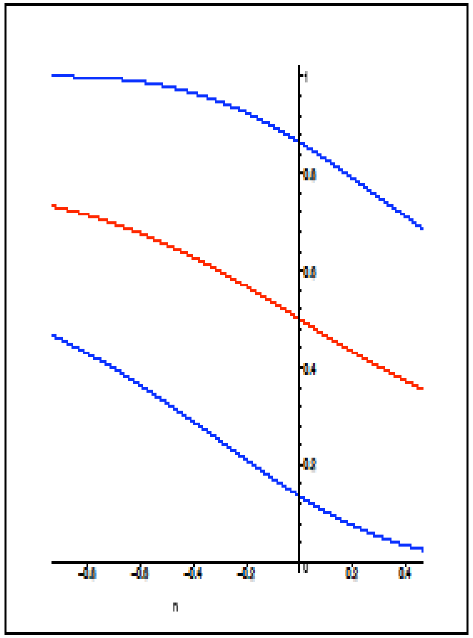


- Hard to see in atmospheric ν because L/E resolution is poor
- In Kam-LAND, the answer seems YES at 2 σ CL
  (Schwetz, hep-ph/0308003)

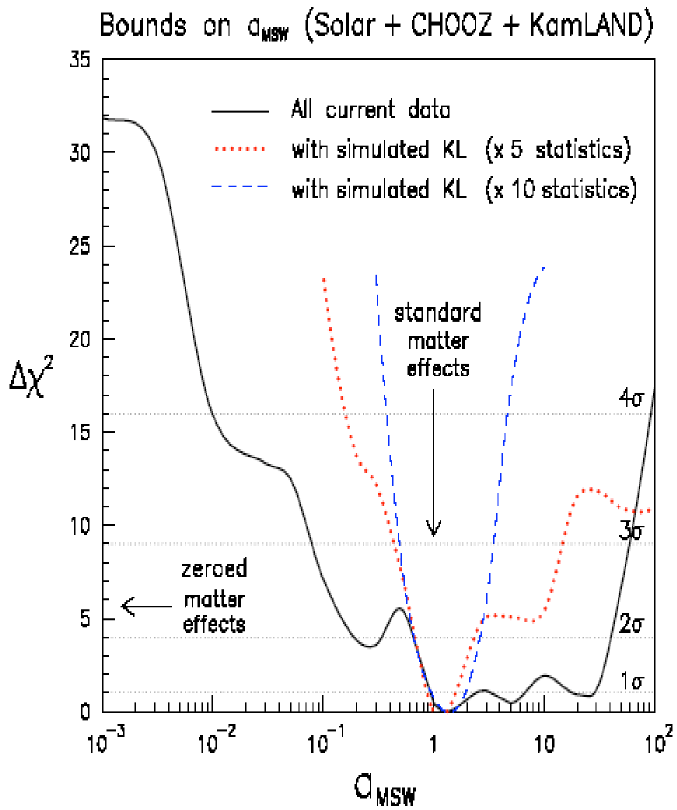
Did we see MS & W effects?



E=14 MeV



E=6 MeV



n = scaled density (n=0 at resonance)

matter effect 5.6 □

The answer is YES!

(left: Smirnov, hep-ph/0305106, right: Fogli et al., hep-ph/0309100)

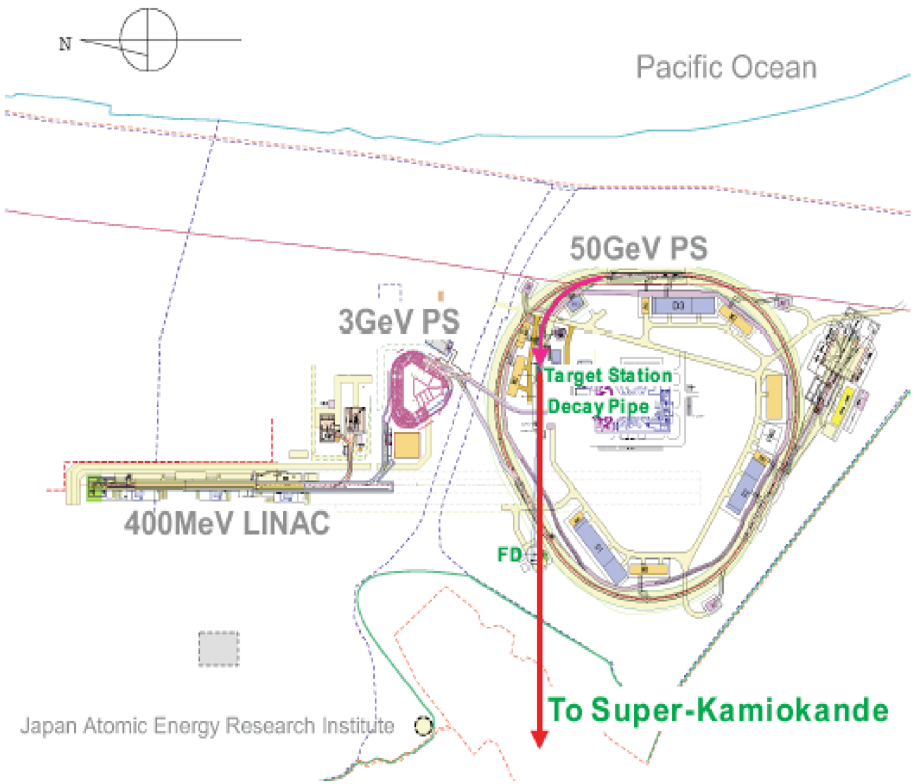
Future

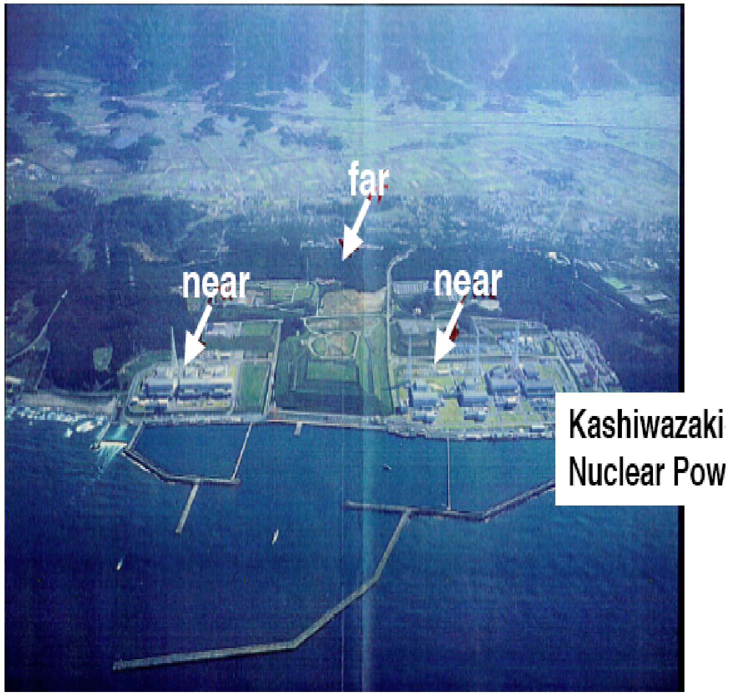
What is the next to come?

祝 JPARC-SK approved !

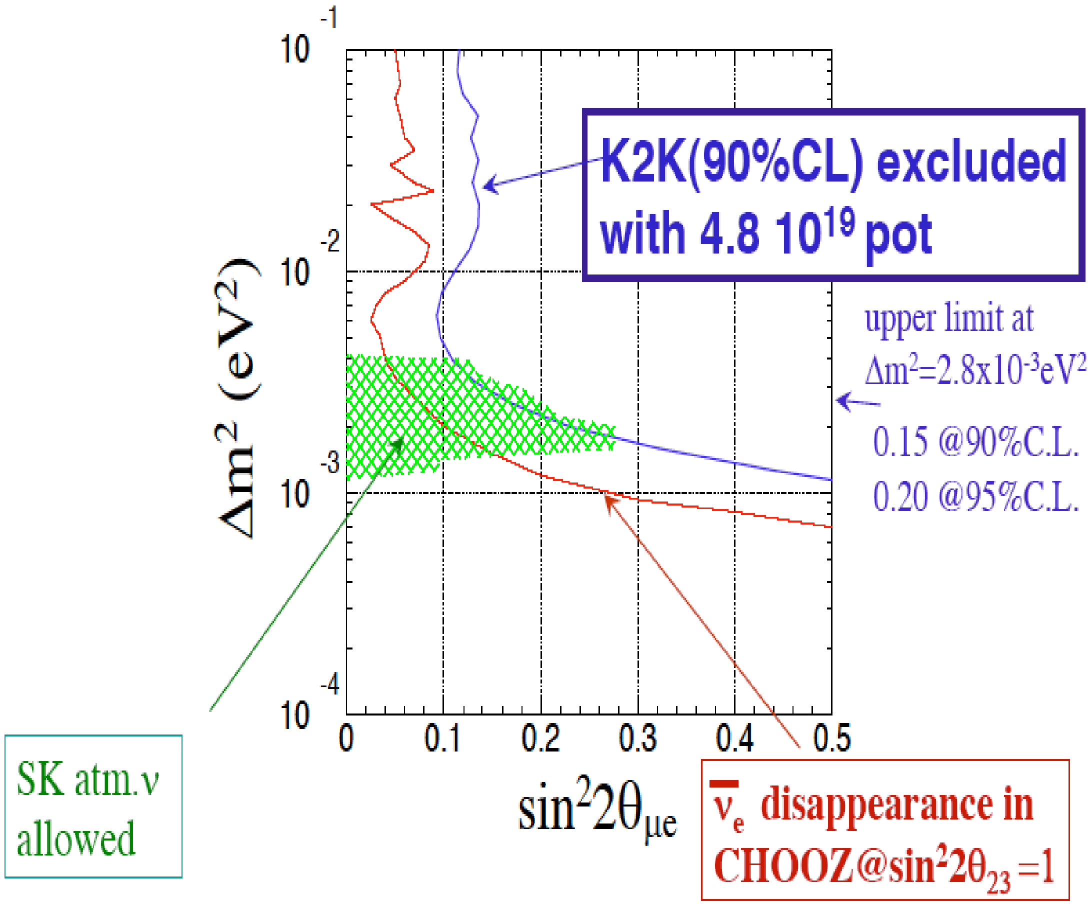
==> θ_{13} !

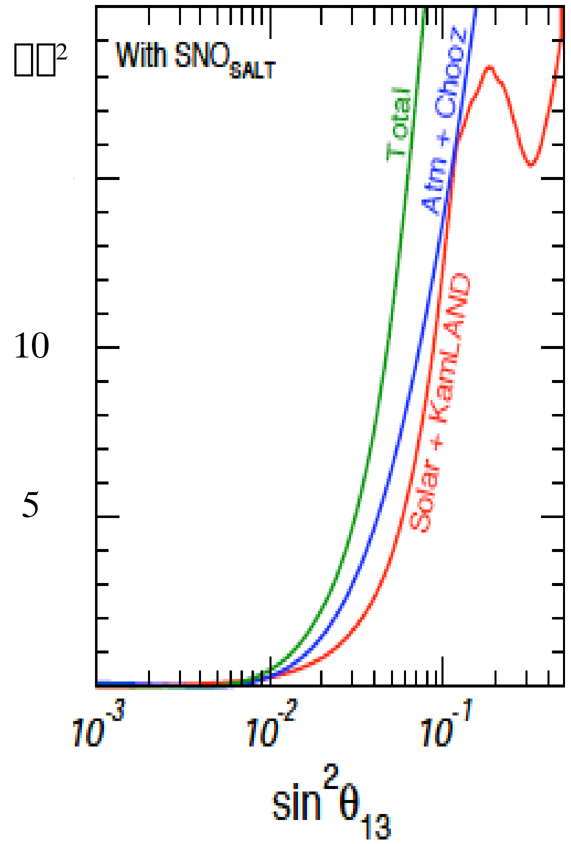
LBL superbeam vs. Reactor





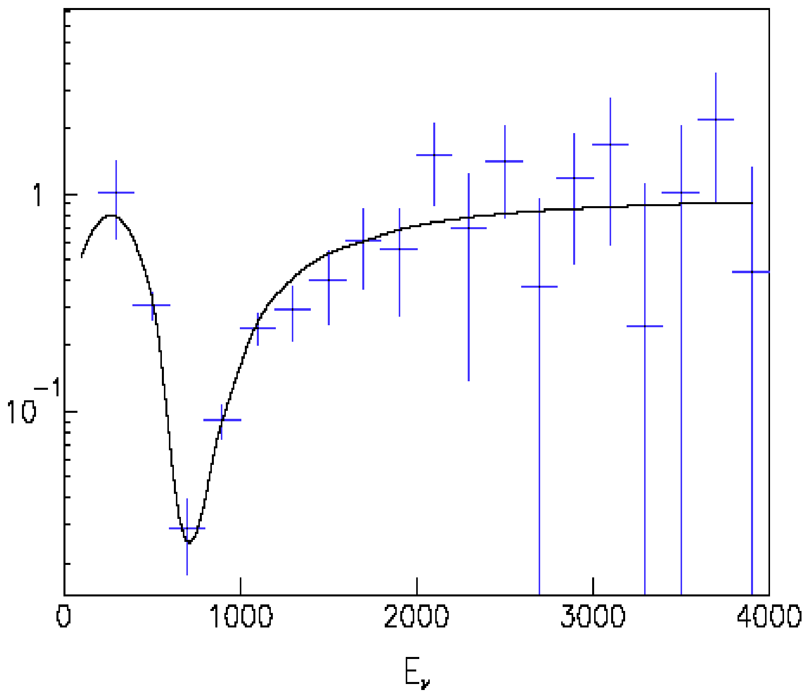
No indication yet of nonzero θ_{13} from atmospheric, solar and terrestrial ν



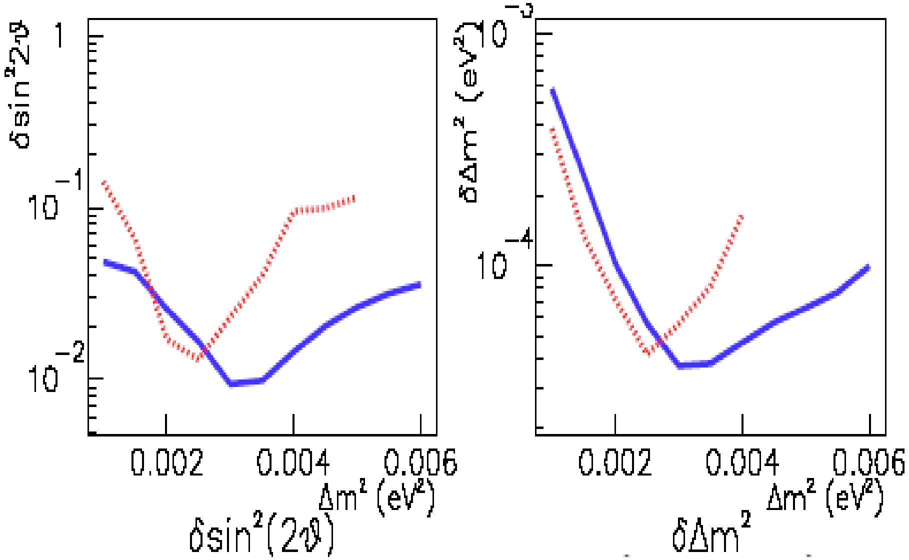


Maltoni et al.

LBL measurement of Δm^2_{23}, θ_{23}, θ_{13}



$$1 - P(\nu_\mu \to \nu_\mu) = \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



- position of dip --> Δm^2_{23} (~10% accuracy, JPARC-SK, LOI)
- depth of the dip --> $\sin^2 2\theta_{23}$ (~1 % accuracy)
- number of ν_e appearance events --> $\sin^2 2\theta_{13}$

LBL measurement of θ_{13}

$$P(\nu_\mu \to \nu_e) = \left|\sqrt{P_{atm}} + e^{i\left(\delta \pm \frac{\Delta_{31}}{2}\right)}\sqrt{P_{solar}}\right|^2$$

Very simple form !

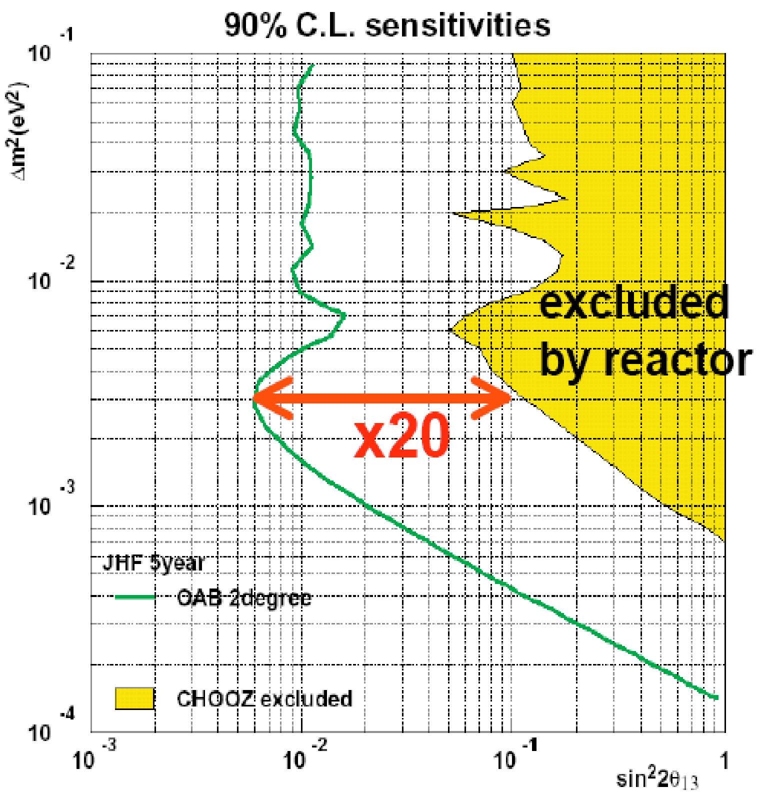
$$P_{atm} = \left(s_{13} s_{23} \Delta_{31} \frac{\sin\left(\frac{\Delta_{31} \mp aL}{2}\right)}{\left(\frac{\Delta_{31} \mp aL}{2}\right)} \right)^2$$

$$P_{solar} = \left(c_{12} s_{12} c_{23} \Delta_{21} \frac{\sin\left(\frac{aL}{2}\right)}{\left(\frac{aL}{2}\right)} \right)^2$$

$$\Delta_{31} \equiv \frac{|\Delta m^2_{31}| L}{2E}, \quad a = \sqrt{2} G_F N_e(x),$$

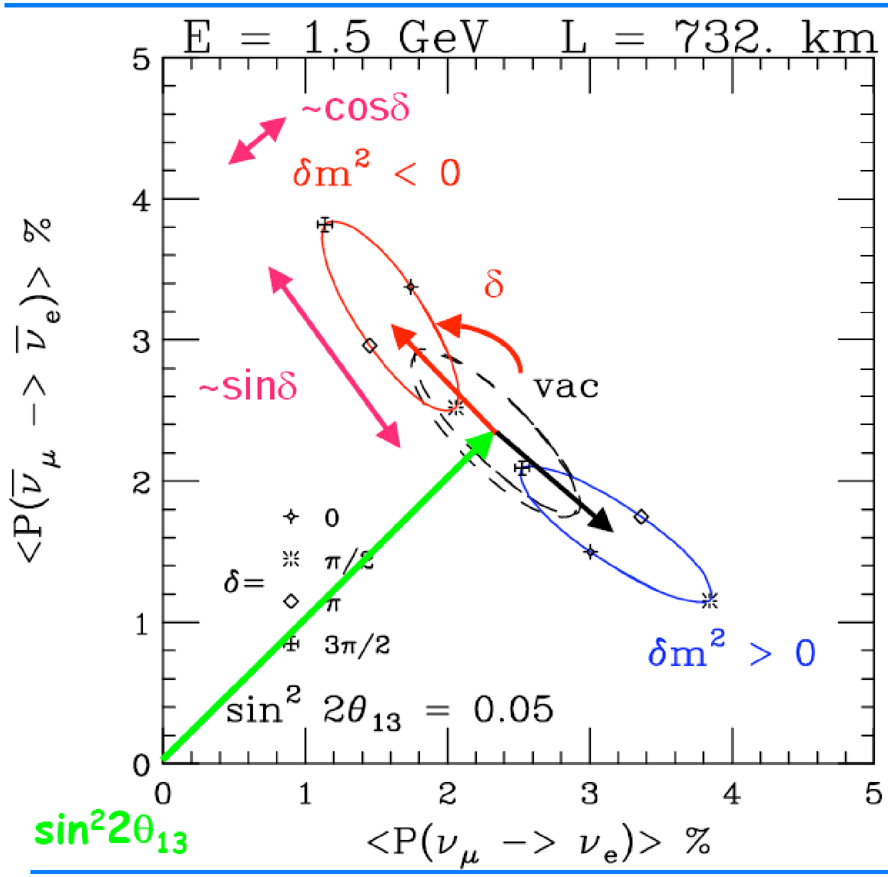
$$\pm = \text{sign of } \Delta m^2_{31}$$

Search for ν_e appearance



JPARC-SK θ_{13} sensitivity; OA2°, 5 years

Anatomy of Bi-probability ellipses



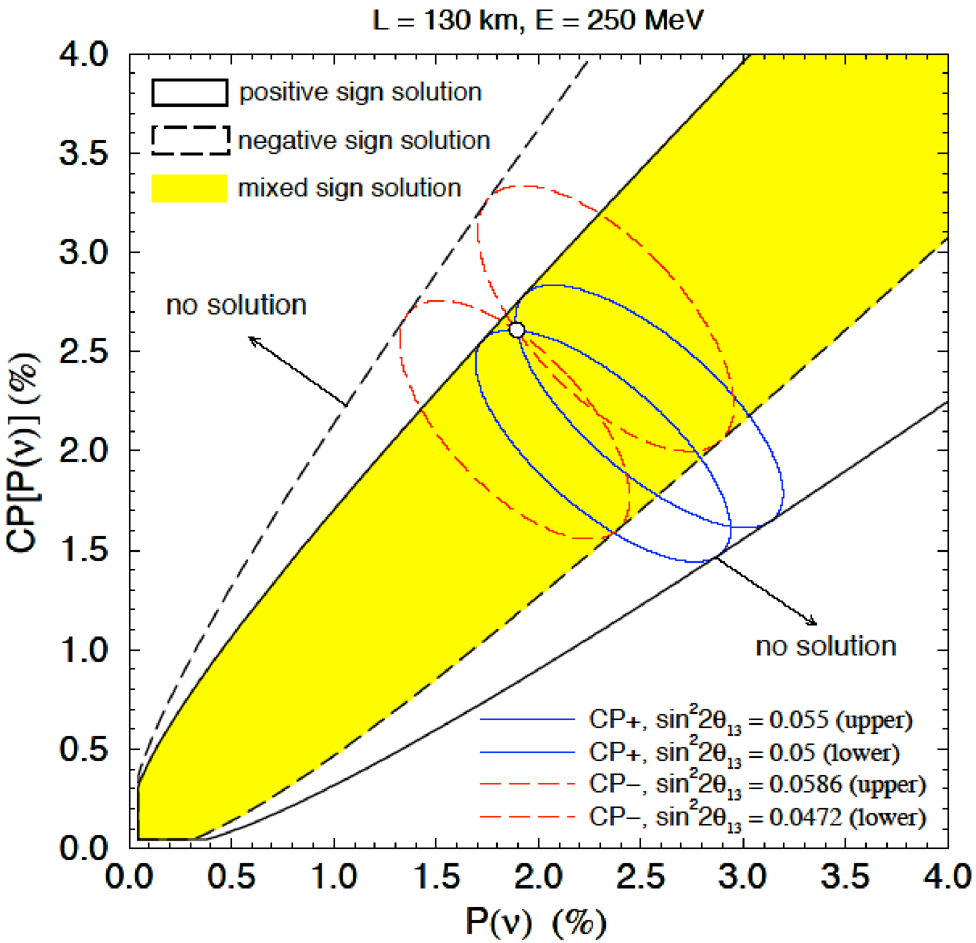
Minakata and Nunokawa, hep-ph/0108085

Observables are:

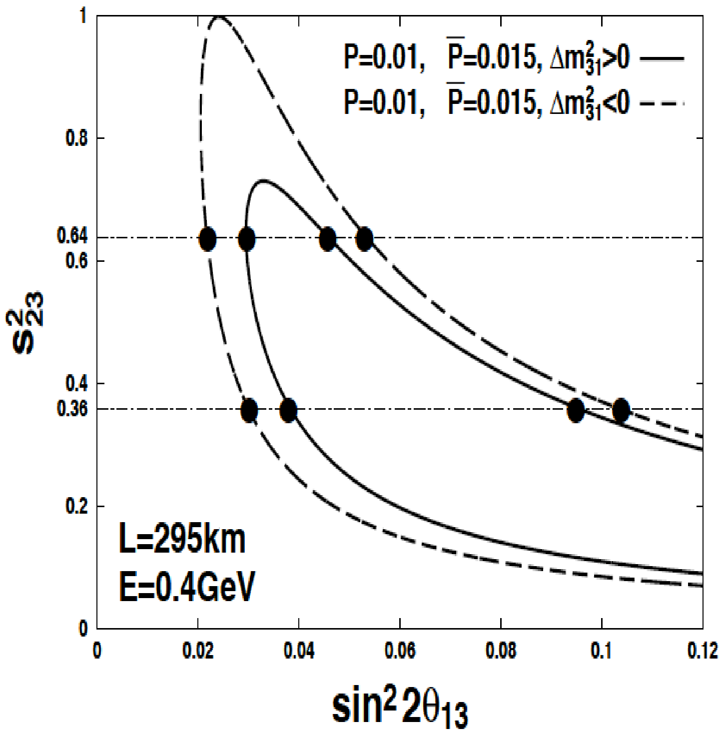
- P
- $\bar{P}$

Interpretation in terms of $\sin^2 2\theta_{13}$, δ and sign of Δm^2_{23} depends on the value of these parameters and on the conditions of the experiment: L and E

Parameter degeneracy

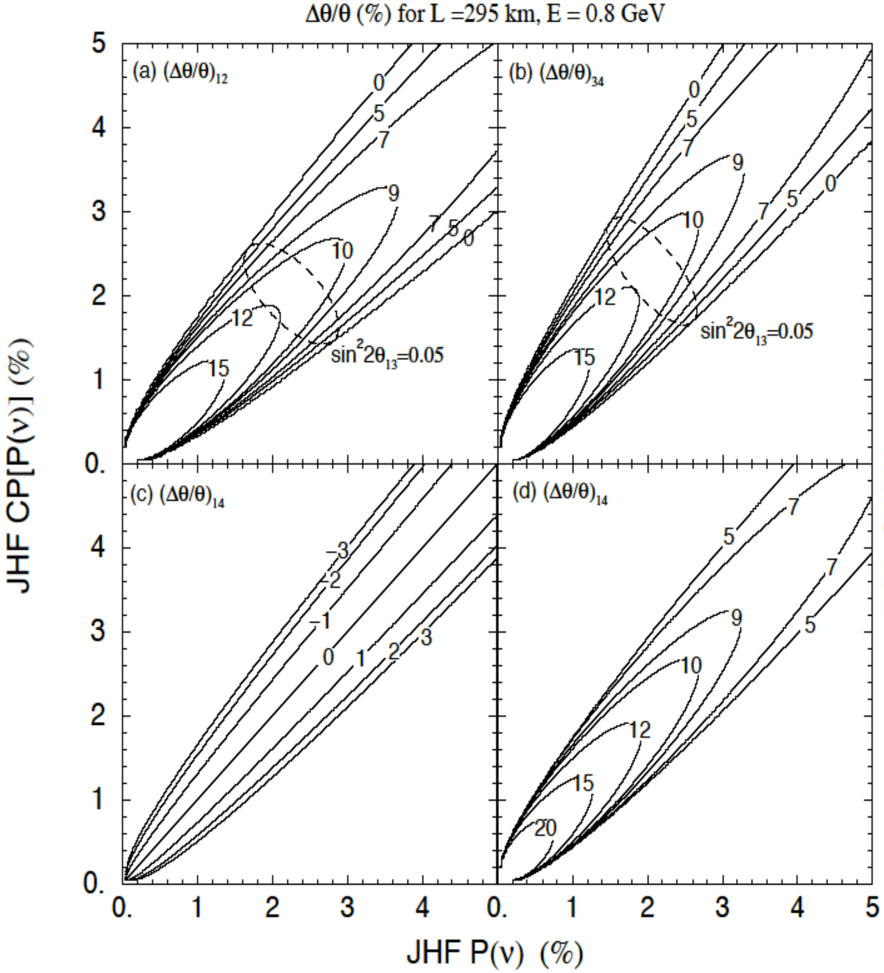


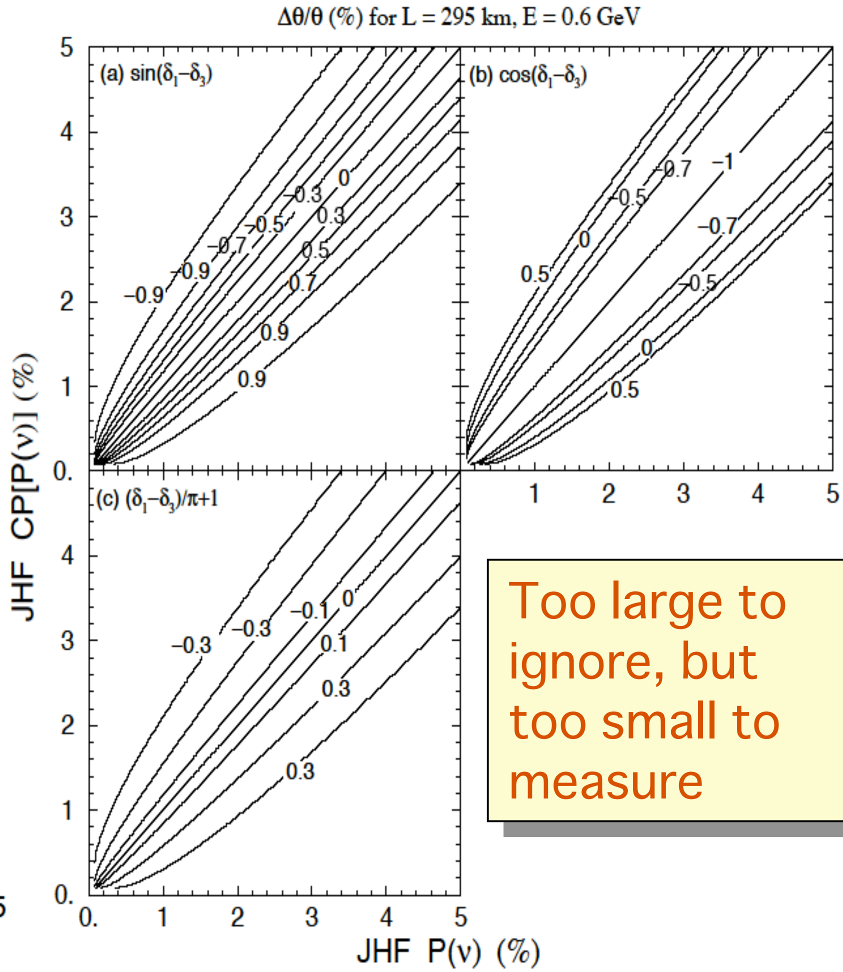
If $\theta_{23} \neq \pi/4$



Refs. MNP2; hep-ph/0208163,
MSYIS; hep-ph/0211111

How ambiguous are the parameters?





Too large to ignore, but too small to measure

(MNP2 updated with LMA-I)

□ mass hierarchy; sign of □m^2_{13}

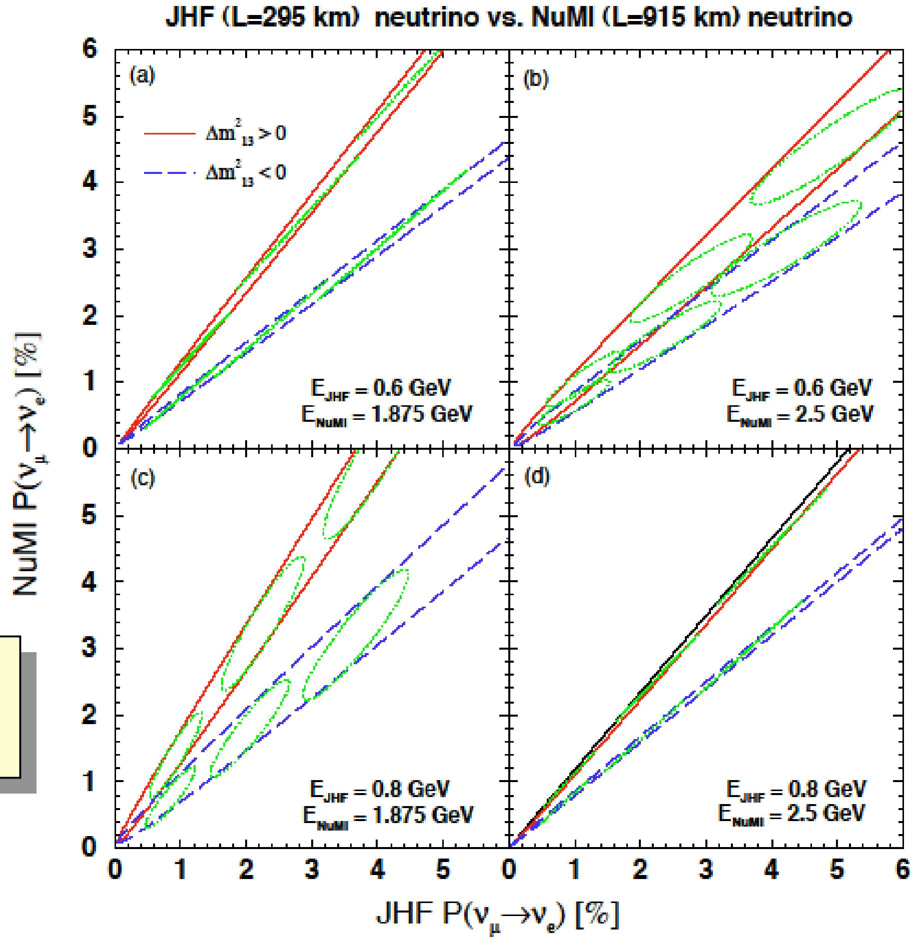
- Any long-baseline experiments (L > 1000 km) with □ and anti-□ can see it
- But a large detector required => not easy
- May need international/inter-continental collaboration;

JPARC-SK-NuMI Off-Axis

(E/L)NuMI < (E/L)JPARC preferred MNP3 =>

JPARC-SK-Beijin (Seoul) etc.

Longer Baseline for NuMI



Reactor measurement of θ_{13}

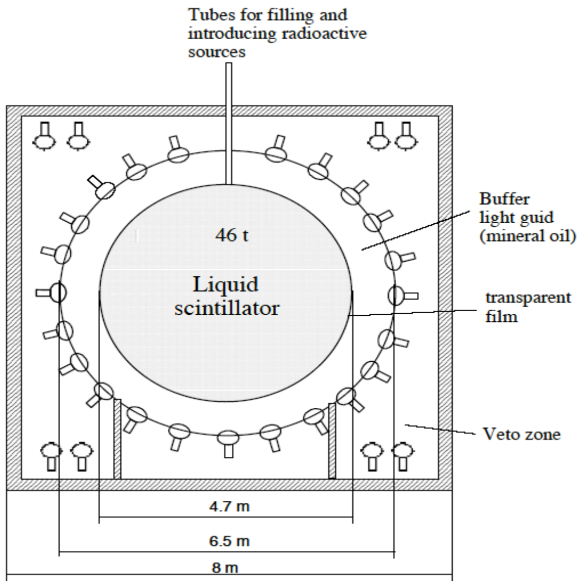
ν_e disappearance probability

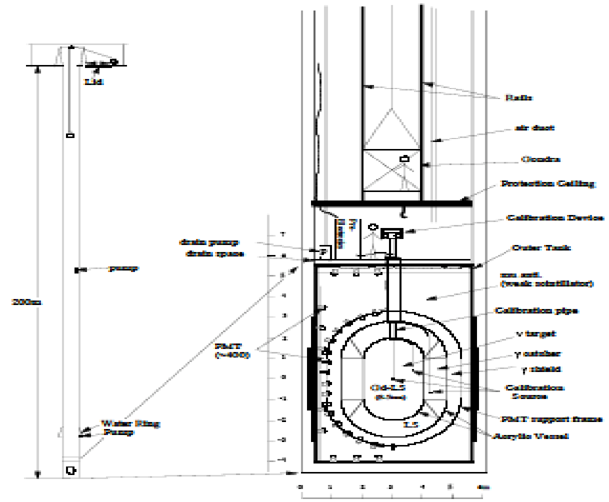
$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(\epsilon s^2_{13}) + O(\epsilon^2)$$

$$\epsilon \equiv \Delta m^2_{21} / \Delta m^2_{31} \simeq 0.03$$

- Independent of δ, matter effect, θ_{23}, θ_{12}, solar Δm^2

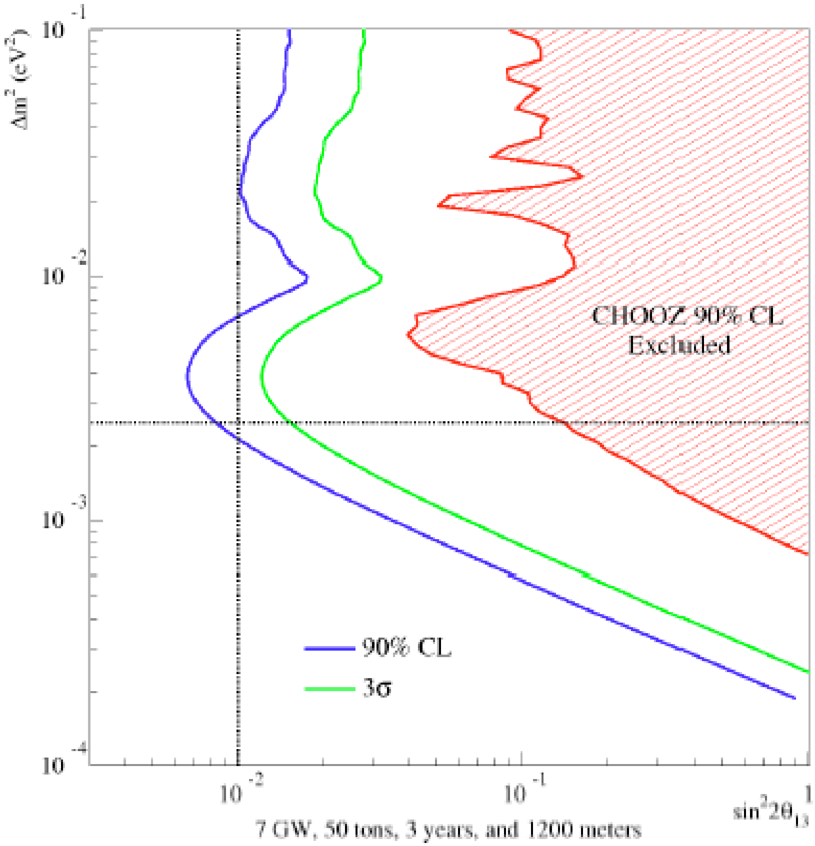
=> Pure measurement of θ_{13}





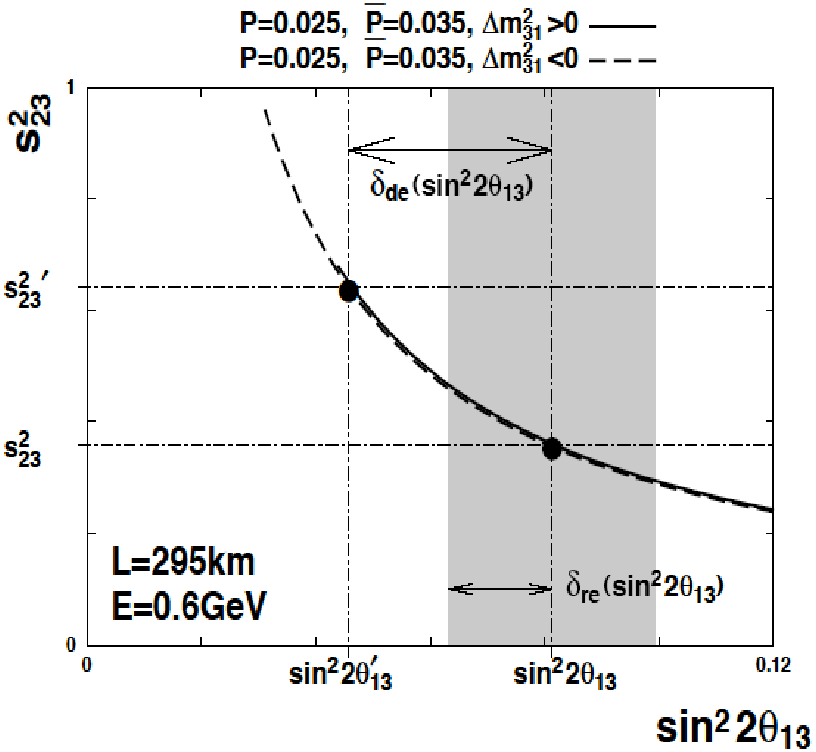
The most optimistic case

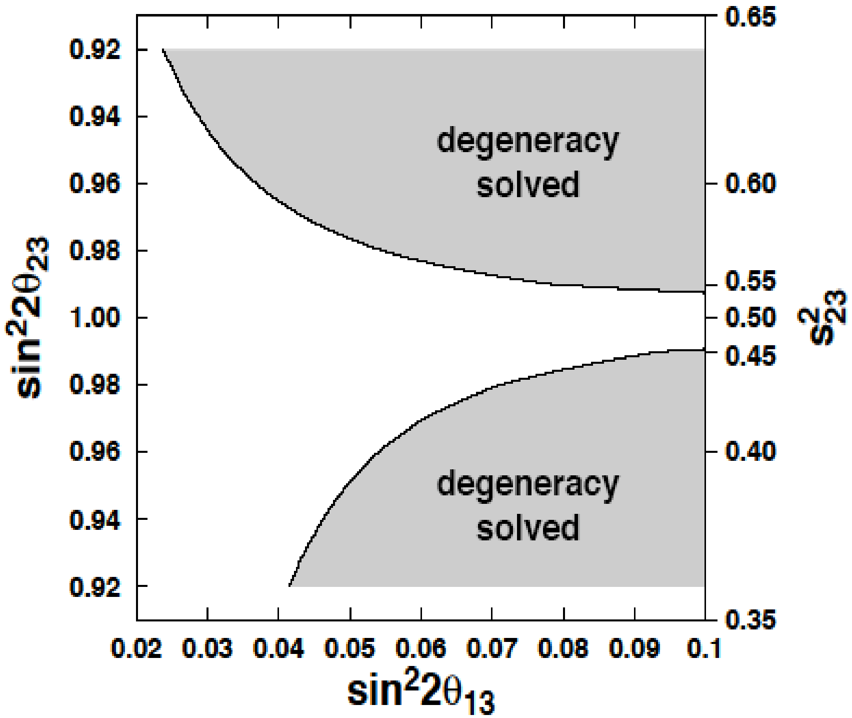
<-- As Americans are (were?) always!



- Movable detector on "railway" (Shaevitz-Link, hep-ph/0306031)
- The (smallest!) systematic relative error of 0.16 % claimed

Reactor-LBL complementarity I





- Pure measurement of θ_{13} by reactors help resolve (θ_{23} <–> $\pi/2 - \theta_{23}$) degeneracy
- If lucky, one may see CP & mass hierarchy

(H.M. Sugiyama, Yasuda, Inoue, Suekane, hep-ph/0211111)

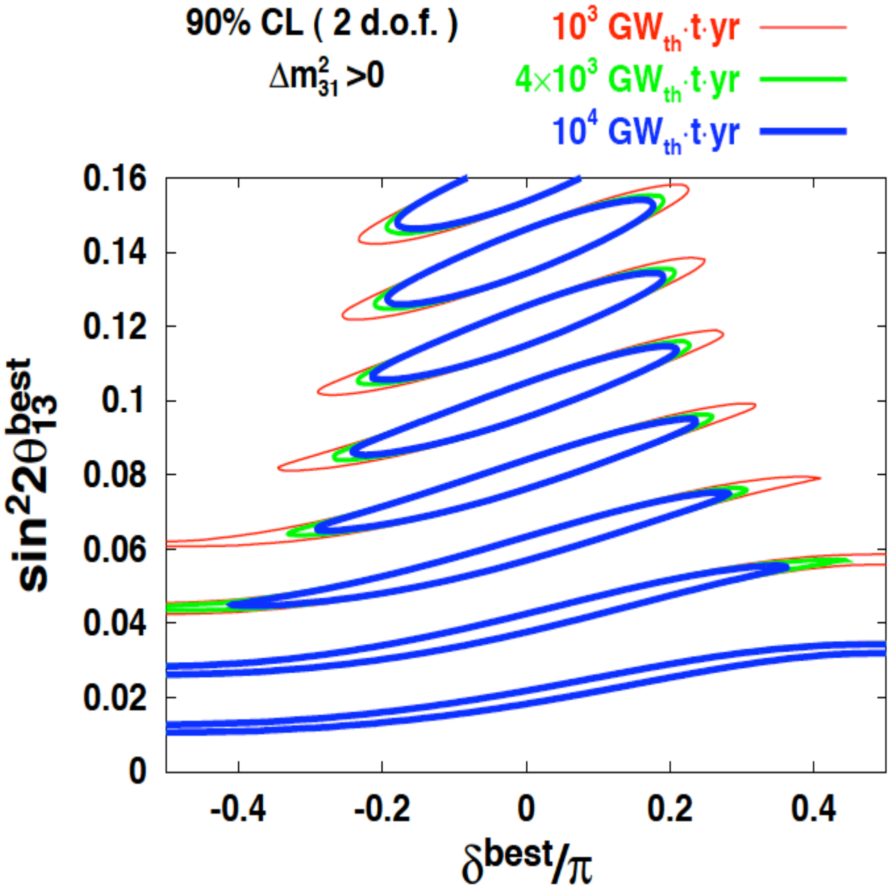
Reactor-LBL complementarity II

CP violation sensitivity assuming

- JPARC-HK neutrino mode, 2 years
  (4 MW & 540 kton)
- 100 ton detectors @Kashiwazaki-Kariwa reactors, 1/2-5 years
- CP violation can be detected by reactor-LBL combination !
- Sign(□m²)-independent

(H.M. H.Sugiyama, hep-ph/0309323)

$$\sin\delta = \frac{P(\nu_\mu \to \nu_e) - P_{solar} - X_\pm s_{13}^2}{\mp Y_\pm s_{13}}$$



Reactor vs. superbeam

- Clean measurement of $\square_{13}$

Theorist's comment !

--> free from $\square$, $\square_{23}$, etc.

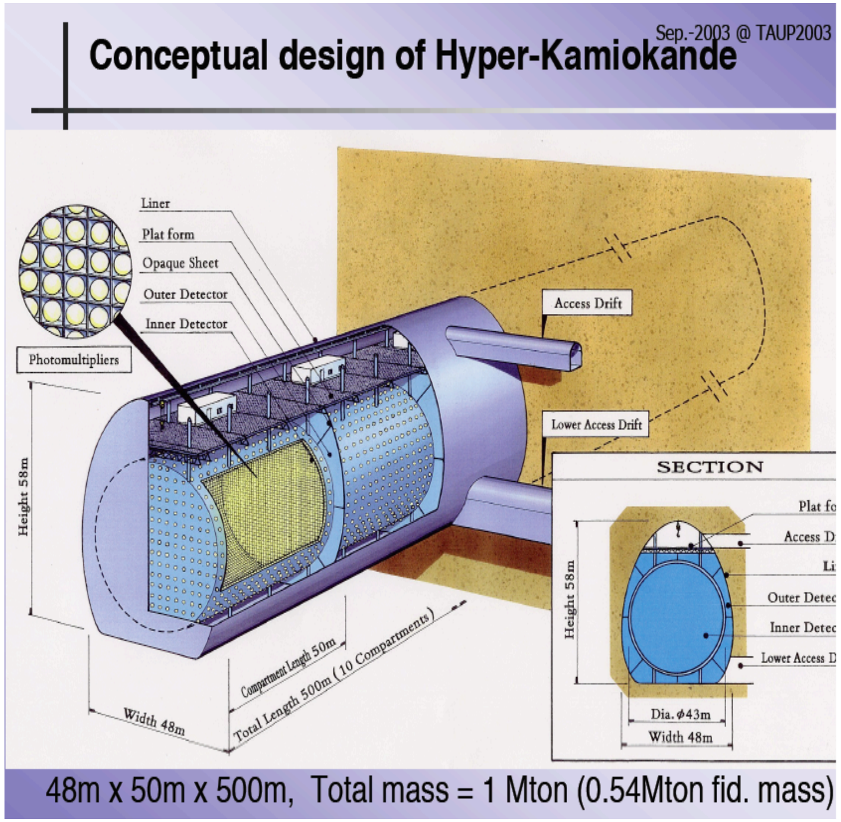
- Single purpose
- Faster & cheaper (~ $20 M)
- Long-range view: important for solving parameter degeneracy (and possibly CP)
  --> phase II

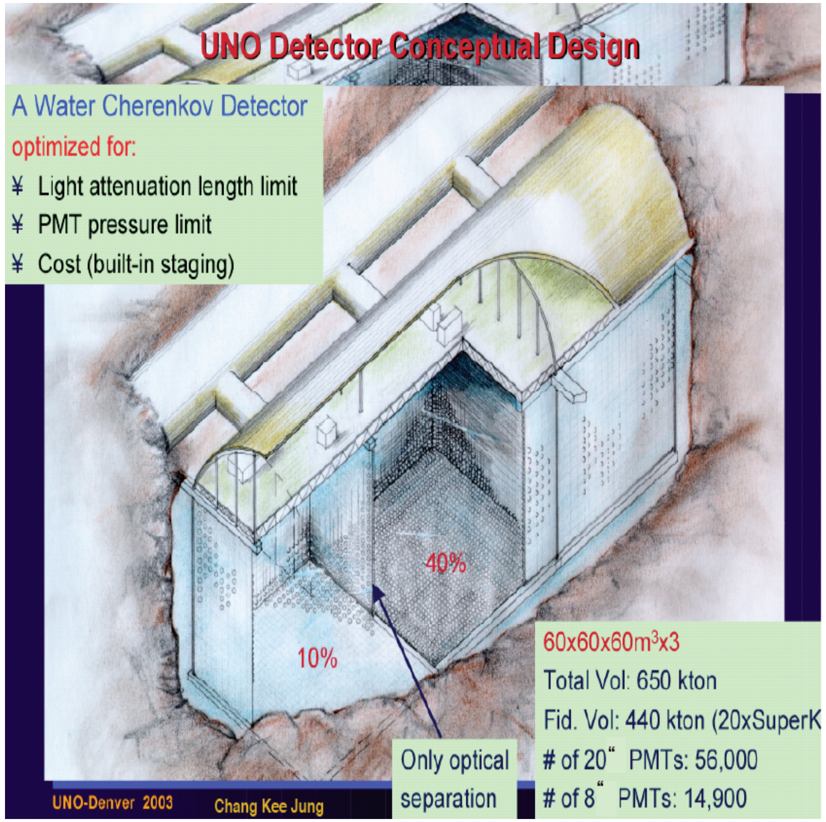
- Cleaner signature (electron appearance)
- Multi-purpose --> extendable to CPV
- Expensive (though not so much as nufact)

No problem once approved !

- Different L, E possible; International complementary tuning?

CP Violation (and proton decay)





- Can explore ultimate fundamental scale of matter

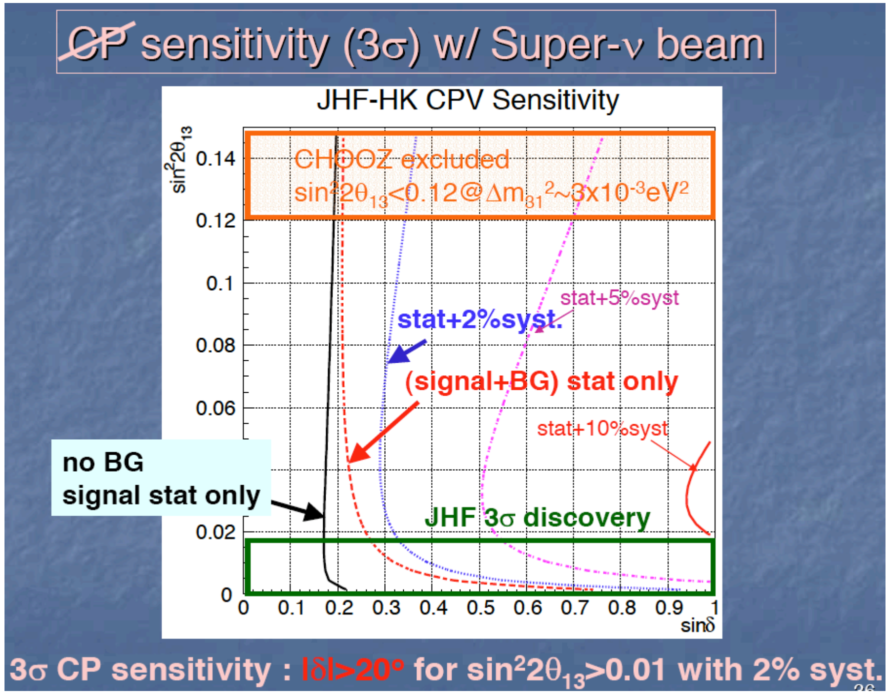
<=background ?

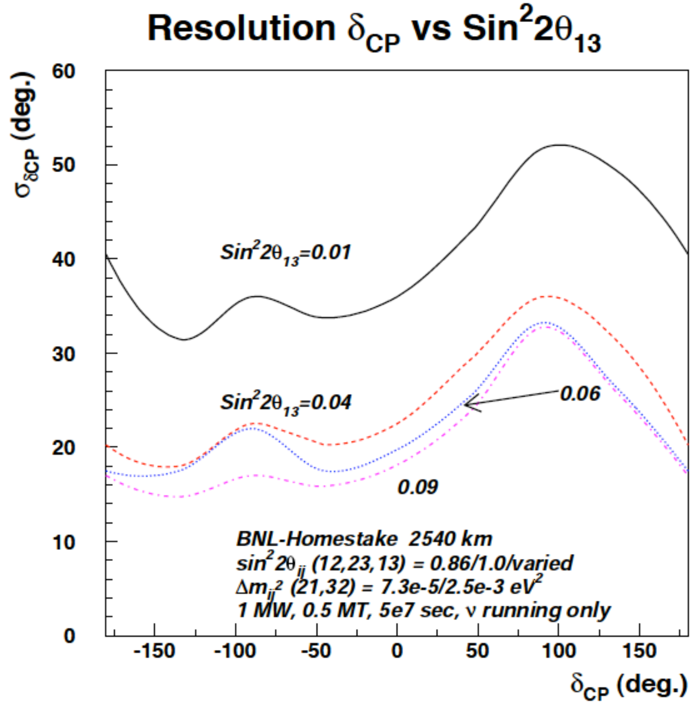
JPARC-HK vs. BNL proposal

- L=295 km/E=0.7 GeV vs. L=2540 km/E=0.5-5GeV

==> 1st oscillation maximum vs. 1st-3rd oscillation max.

- Clean environment for CPV vs. exploring oscillation pattern, sign of □m^2_{13}, can prove solar □m^2, can run with only □





Neutrino factory; a long-range project

- Various channels are available in principle

□$^+$ -> e$^+$ + □$_□$-bar + □$_e$

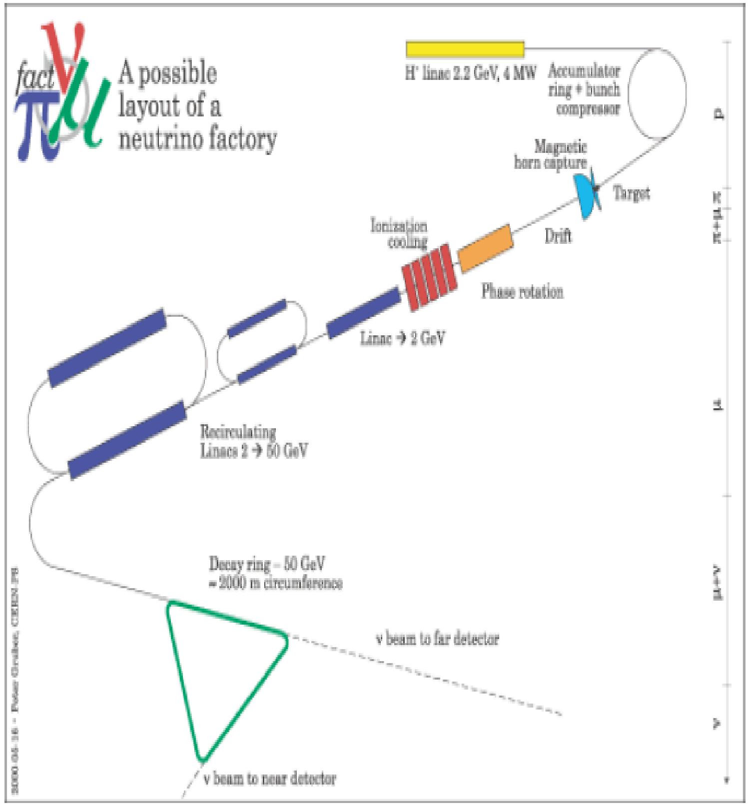
□$_e$ --> □$_□$ ==> □$^□$

□$_□$-bar =========> □$^+$

□$_{e-}$-bar--> □$_□$-bar

□$_e$ --> □$_□$

- Intense muon flux allows to use far distant detectors
- Background very small --> greater sensitivity to small □$_{13}$
- Can do T-violation by combining with nearby superbeam



Optimization of L and E

- Full correlation of errors (including matter density) must be taken into account ==>

  E ~ 50 GeV,

  L~ 3000 km

  (Pinney-Yasuda, hep-ph/093008)

- How accurately do we know matter density in earth ?

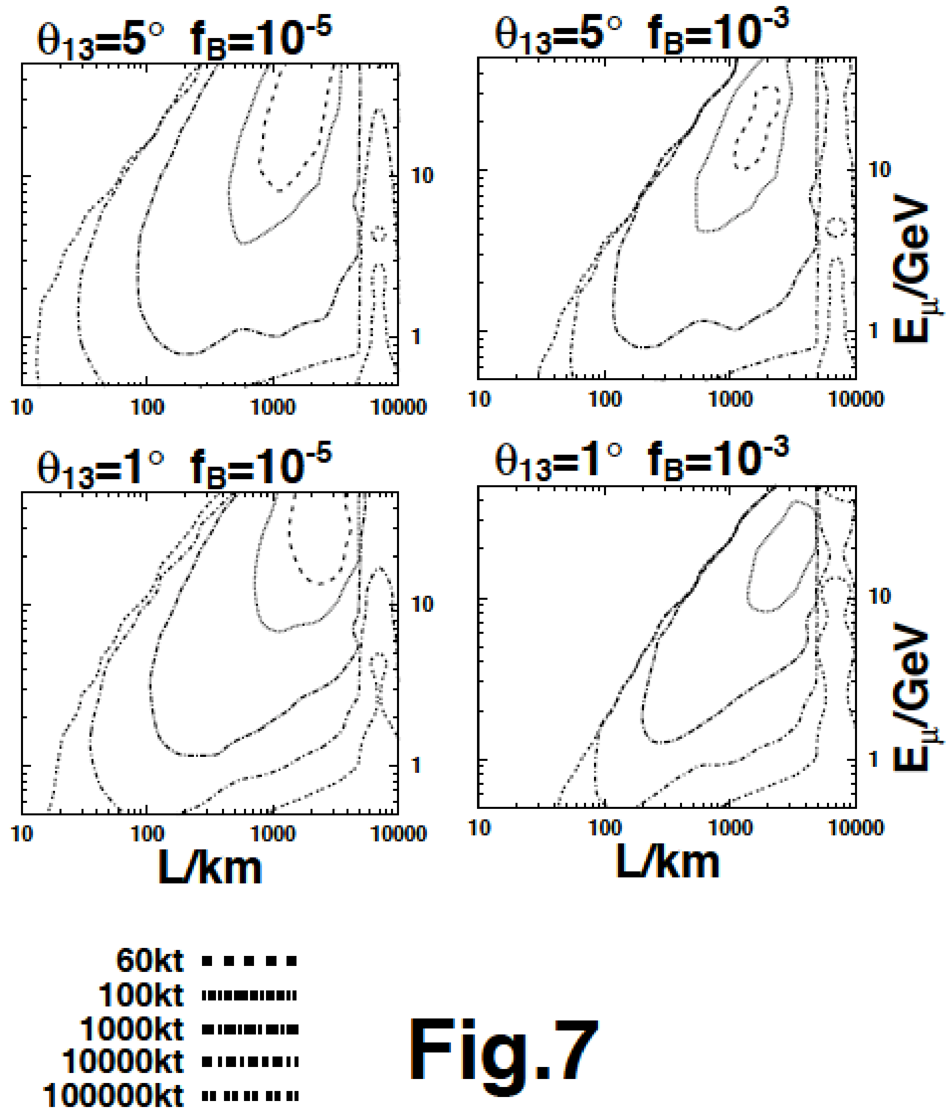
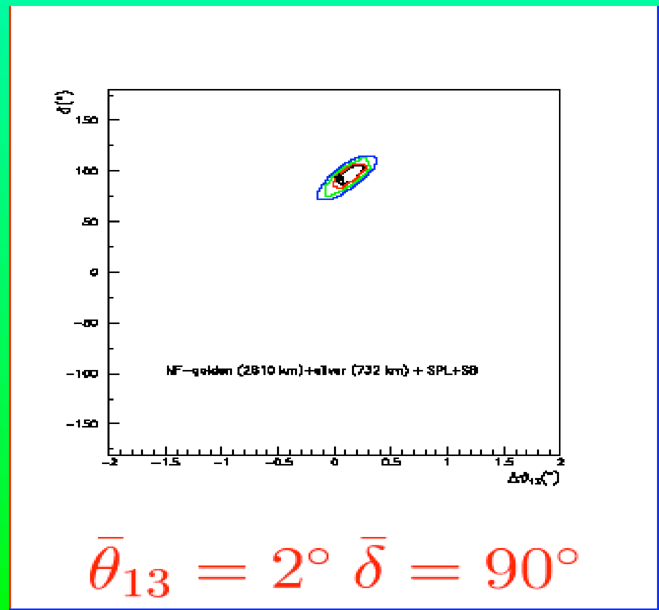


Fig.7

Neutrino factory as ultimate degeneracy solver

- 40 Kton MID
- 4 Kton ECC
- 400 Kton WC



- By combining at 3 detectors at 130, 730, and 2810 km, it was claimed that neutrino factory can resolve all the 8-fold degeneracy if $\theta_{13} > 1^\circ$ (Donini, NuFACT03)

Which strategy to be chosen?

superbeam vs. reactor vs. neutrino factory

Very optimistic view !

- Dectated by the size of θ_{13}:

Very roughly speaking,

- $0.01 (0.005) < \sin^2 2\theta_{13} < 0.2$

==> reactor + superbeam

(well-defined and complementary schemes exist!)

- $\sin^2 2\theta_{13} < 0.01\text{-}0.0001$

==> neutrino factory

- “natural time-ordering”

  (no more serious discussion on which is better, unless $\sin^2 2\theta_{13} = 0.005\text{-}0.01$)

Two phase program

Phase I (~ $100-200 M, running 2007 – 2014)

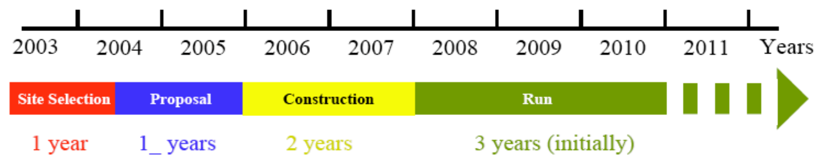
- 50 kton (fiducial) detector with ε~35-40%
- 4×10^{20} protons per year
- 1.5 years neutrino (6000 ν_μ CC, 70-80% 'oscillated')
- 5 years antineutrino (6500 ν_μ CC, 70-80% 'oscillated')

Phase II (running 2014-2020)

- 200 kton (fiducial) detector with ε~35-40%
- 20×10^{20} protons per year (new proton source?)
- 1.5 years neutrino (120000 ν_μ CC, 70-80% 'oscillated')
- 5 years antineutrino (130000 ν_μ CC, 70-80% 'oscillated')

June 11, 2003 1st Yamada Symposium, NDM 2003
Adam Para, Fermilab

Aggressive Experiment Timeline



Site Selection: Currently underway.

The proto-collaboration is currently working on a white paper. This effort could transition into proposal writing.

Run Phase: Initially planned as a three year run. Results or events may motivate a longer run.

An exotic way; supernova ν may probe mass hierarchy and θ_{13} (the problem is when?)

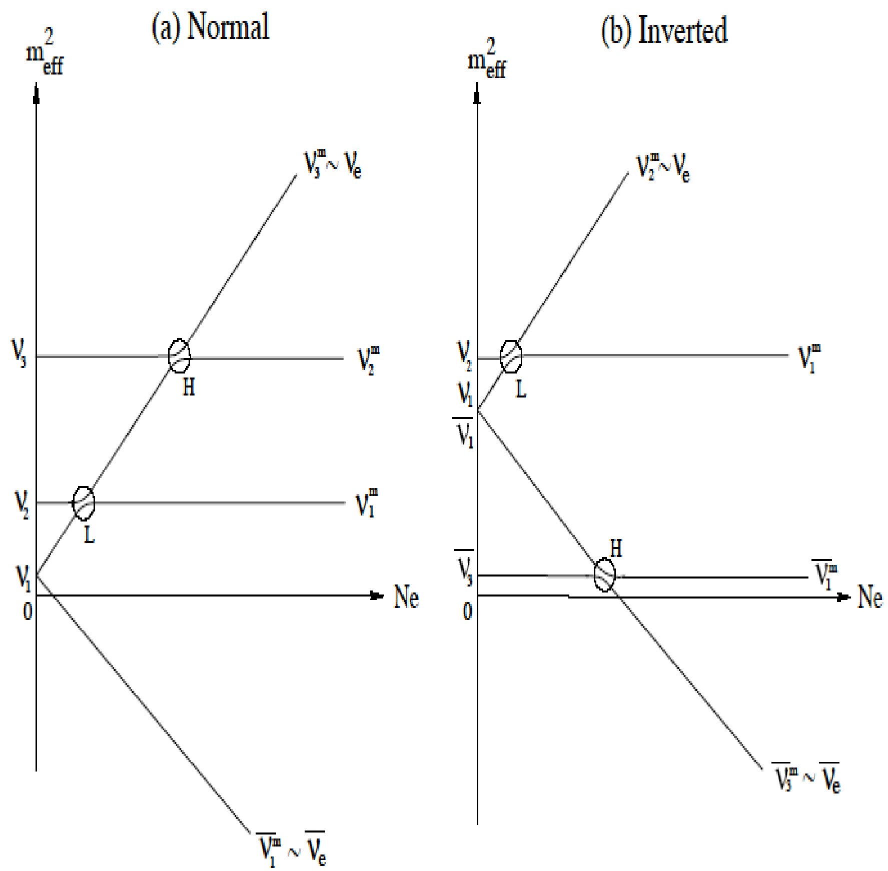
- Every SN ν experiences two (H & L) level crossings
- Resonance in ν (anti-ν) channel in normal (inverted) hierarchy
- Event structure depend on:

(1) if H-resonance is adiabatic or not

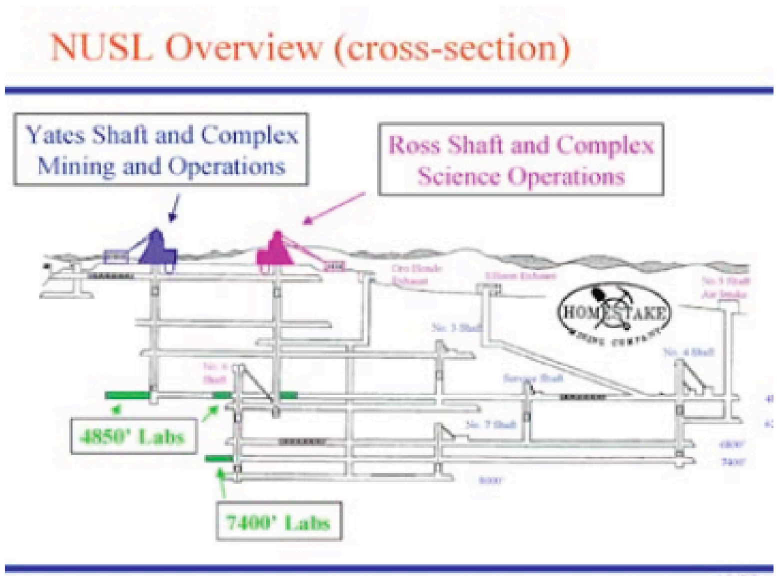
(2) if ν_μ/ν_τ temperature is higher than ν_e/ anti-ν_e

- Can probe $s_{13}^2 \sim 10^{-4}$

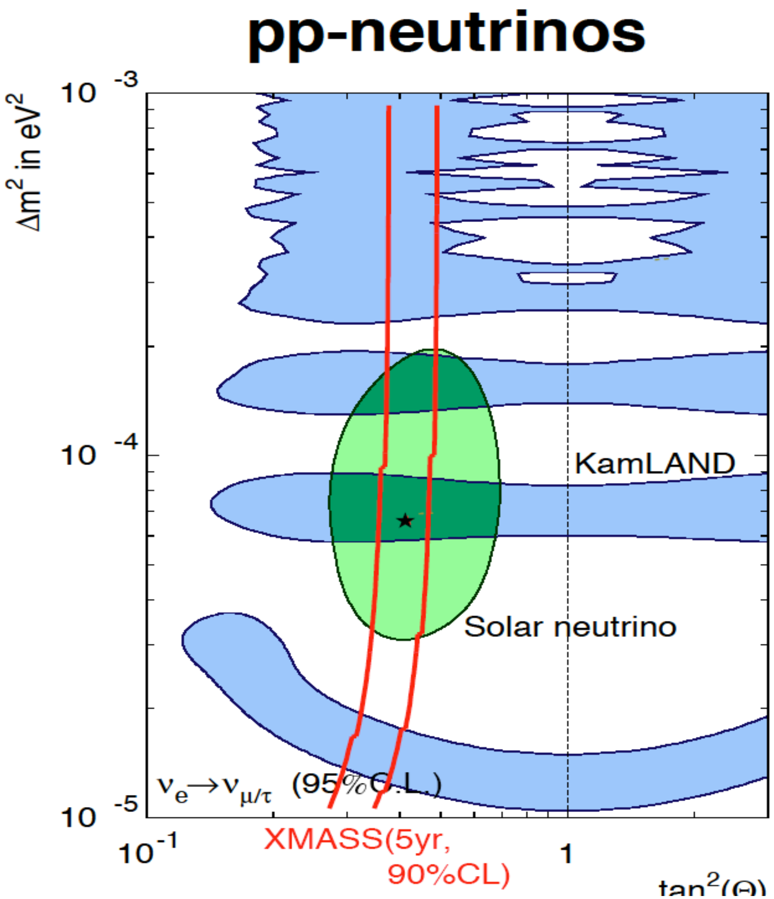
(H.M.-H.Nunokawa, PRD41(1990) ===>
hep-ph/0010240
Dighe-Smirnov, hep-ph/9907423)



Toward the frontier: non-accelerator underground physics



Best θ_{12} sensitivity by pp solar neutrino observation



We shouldn't forget solar ν experiment !

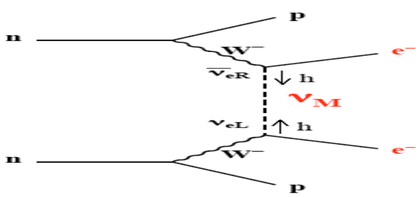
- **Statistical error and SSM prediction error(1%)**
  (XMASS 5 yr, 90 % CL)

- **Accuracy of mixing angle:**
  $\sin^2 2\theta = 0.77 \pm 0.03$(stat.+SSM)

(courtesy: Yoichiro Suzuki)

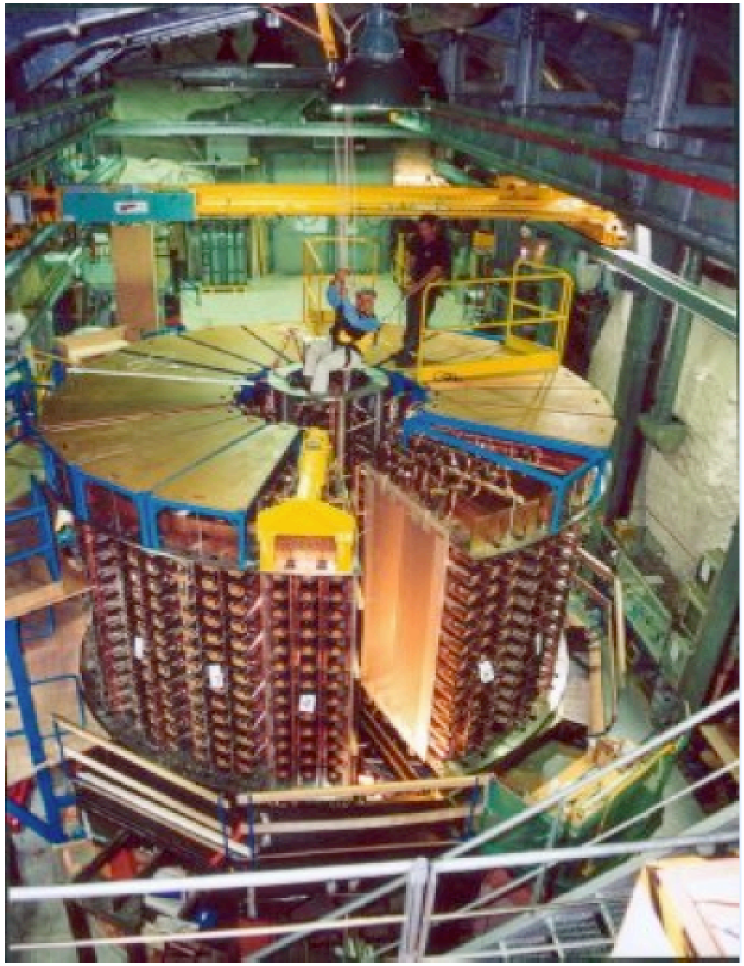
Neutrinoless double beta decay

- Most sensitive (terrestrial) probe of the absolute neutrino mass
- Unique way of proving Majorana nature of □
- If Majorana □ is the only mechanism, ===>



$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

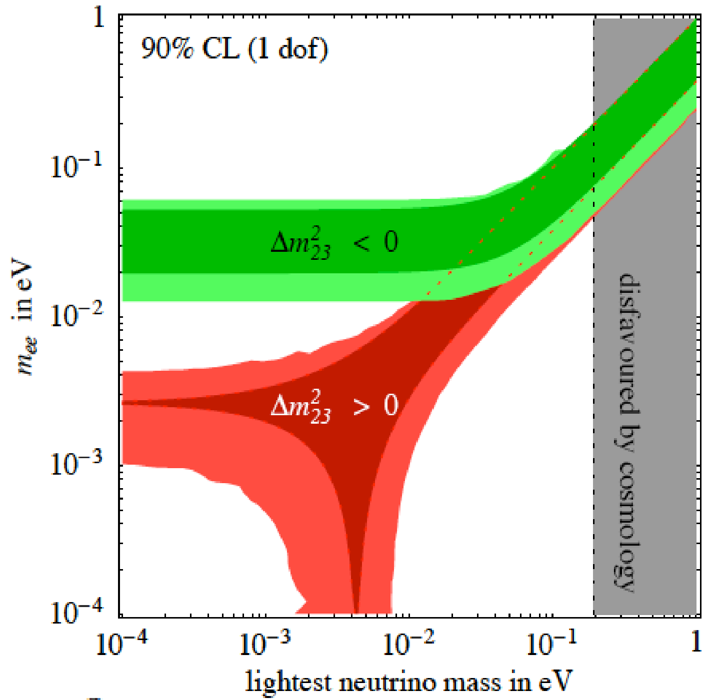
$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$



What LMA implies for neutrinoless double beta decay?

- If inverted mass hierarchy, there must be signal when one go down at $\langle m \rangle_{\beta\beta} = \sqrt{\Delta m^2_{atm}}$ = a few tens of meV

Strumia, ν telescope ->



$$< m >_{\beta\beta} \ \geq \ c_{13}^2 \left| m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\beta} \right| - m_3 s_{13}^2$$

$$\geq \ c_{CH}^2 \left| m_1 c_{12}^2 - m_2 s_{12}^2 \right| - m_3 s_{CH}^2$$

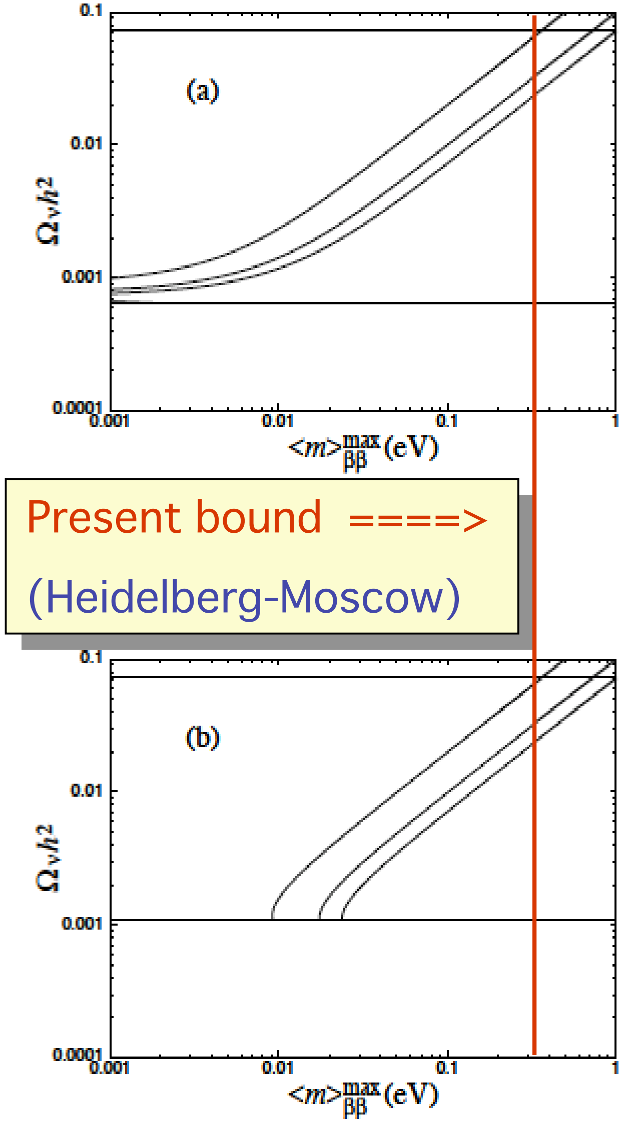
Further implication of neutrinoless double beta decay

- Upper bound on $\Omega_\nu h^2$ can be obtained; $\Omega_\nu h^2 < 0.03$ (assuming LMA best fit θ_{12})
- but severer bound obtained by WMAP; $\Omega_\nu h^2 < 0.0076$
- Is Majorana phase observable?

(No-Go? Barger et al. 02)

$$< m >_{\beta\beta} \geq c_{13}^2 \left| m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\beta} \right| - m_3 s_{13}^2$$

$$\geq c_{CH}^2 \left| m_1 c_{12}^2 - m_2 s_{12}^2 \right| - m_3 s_{CH}^2$$



Background reexamined by Klapdor-Kleingrothaus et al.

(hep-ph/0308275)

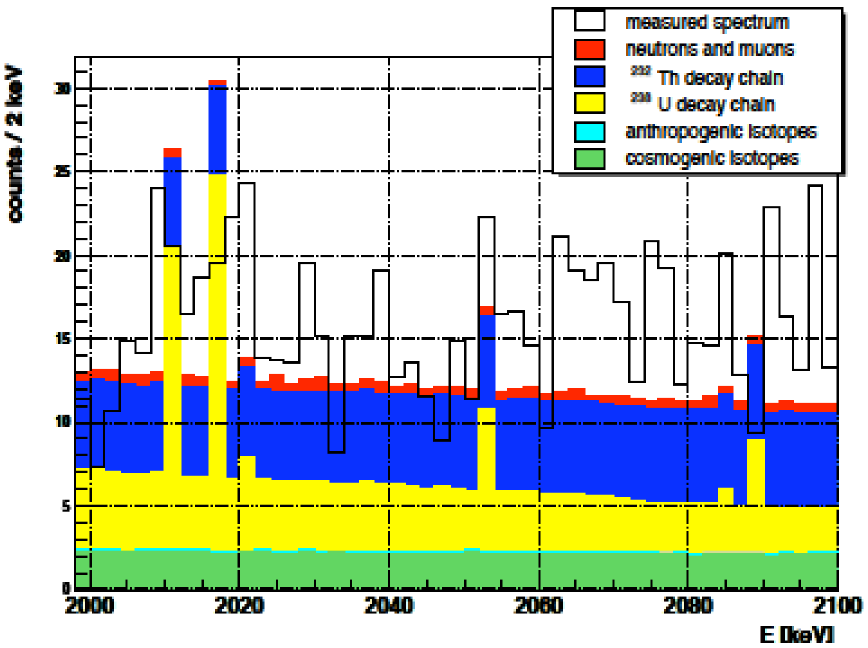


Figure 12: Simulated background of the HEIDELBERG-MOSCOW experiment in the energt range from 2000 to 2100 keV with all known background components. The black trough-drawn line corresponds to the measured data from 20.11.1995 to 16.4.2002 (55.57 kg y).

Ample future projects

(from Gratta, Lepton-Photon 03)

A (probably incomplete) list of the different ideas discussed by various groups

Experiment	Nucleus	Detector	$T^{0\nu}$ (y)	< m_ν > eV
CUORE	^{130}Te	.77 t of TeO_2 bolometers (nat)	7×10^{26}	.014-.091
EXO	^{136}Xe	10 t Xe TPC + Ba tagging	1×10^{28}	.013-.037
GENIUS	^{76}Ge	1 t Ge diodes in LN	1×10^{28}	.013-.050
Majorana	^{76}Ge	1 t Ge diodes	4×10^{27}	.021-.070
MOON	^{100}Mo	34 t nat.Mo sheets/plastic sc.	1×10^{27}	.014-.057
DCBA	^{150}Nd	20 kg Nd-tracking	2×10^{25}	.035-.055
CAMEO	^{116}Cd	1 t $CdWO_4$ in liquid scintillator	$> 10^{26}$	.053-.24
COBRA	^{116}Cd, ^{130}Te	10 kg of CdTe semiconductors	1×10^{24}	.5-2.
Candles	^{48}Ca	Tons of CaF_2 in liq. scint.	1×10^{26}	.15-.26
GSO	^{116}Cd	2 t Gd_2SiO_5:Ce scint in liq scint	2×10^{26}	.038-.172
Xmass	^{136}Xe	1 t of liquid Xe	3×10^{26}	.086-.252

Note that the sensitivity numbers are somewhat arbitrary, as they depend on the author's guesstimate of the background levels they will achieve

How to proceed toward the goal?

- Necessary to control nuclear matrix elements

==> does systematics help with various nuclei (=decay channels)?

==> photon/lepton probe of the nuclear matrix elements?

- Conspiracy with single beta decay experiment?

KATRIN ==>
m_{ν} ~ 0.3 eV

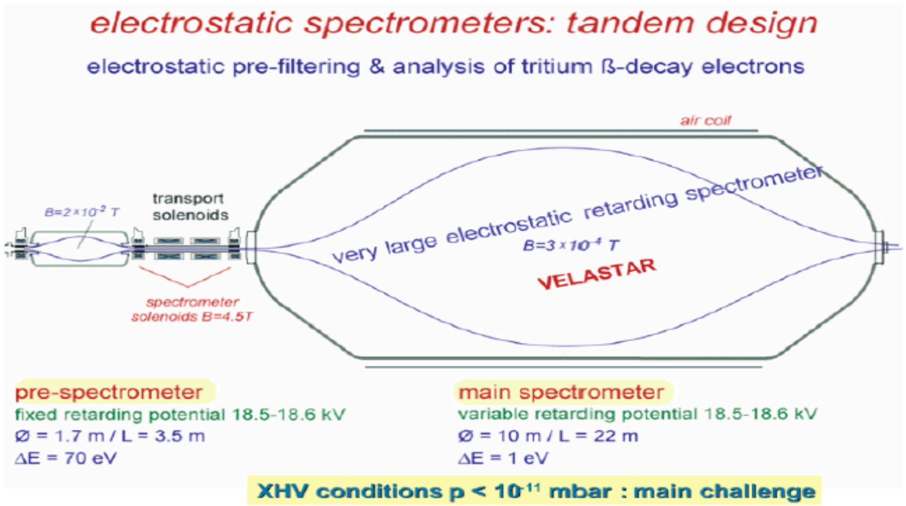


Figure: Pre-Spectrometer and Main Spectrometer

Leptogenesis

(Fukugita-Yanagida '86)

- Lepton # asymmetry generated by Majorana converted to baryon # asym. by "spharelon"
- Offers interesting connection between neutrino mass and cosmological baryon number asymmetry
- Can give rise to bound on neutrino mass, $\sqrt{m^2} < 0.3$ eV
- Degenerate mass disfavored

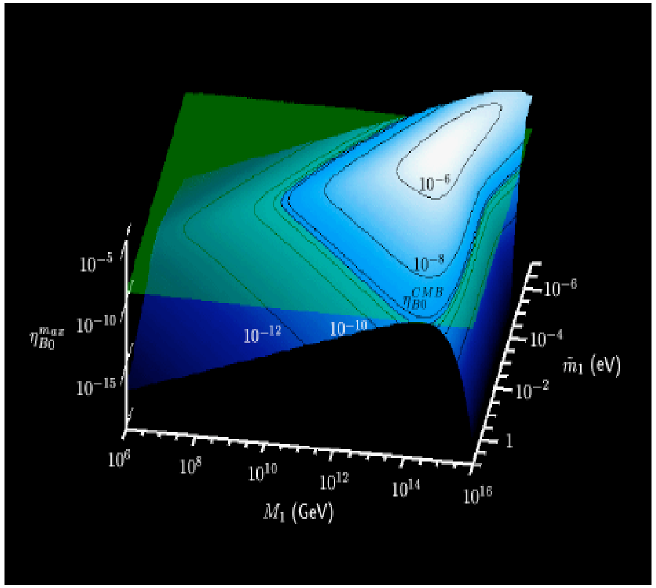
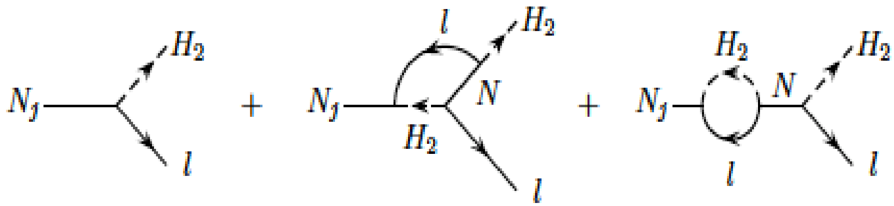


Figure 2: *Maximal baryon asymmetry* η_{B0}^{max} *(blue) as function of* $\widetilde{m}_1$ *and* M_1 *for* $\overline{m} =$ 0.05 *eV. The black lines are curves of constant baryon asymmetry with the value indicated. The lines around the intersection with the green plane correspond to the measured value and the upper/lower limits at* 3σ.

(Buchmuller et al.)

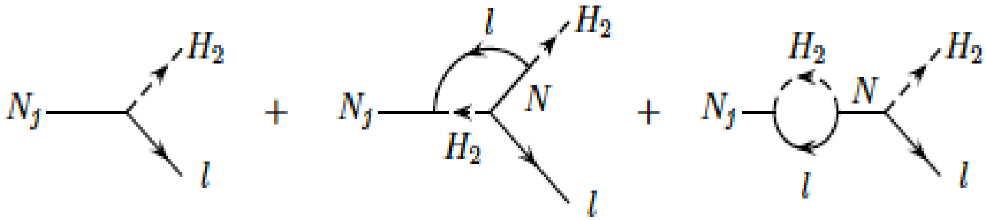


Seesaw mechanism as a paradigm of neutrino mass

- $W = N^c Y_{□} LH - E^c Y_{□} LH +$ (1/2) $N^c M N$

(N=R-handed Majorana, L=left doublet, E=charged lepton, H=higgs)

- $m_{□} = Y_{□}{}^{□} (□_{diag})^{-1} Y_{□}$
- $Y_{□}$ has 6 phases
- Leptogenesis is sensitive to $Y_{□} Y_{□}{}^{+}$ (3 left phases, independent of low energy CPV phase)
- CP violating LFV appears from $Y_{□}{}^{+} Y_{□}$ (1 right phase)



Yanagida, Gell-Mann-Ramond-Slansky, ...

Neutrino mass from the standard model ?

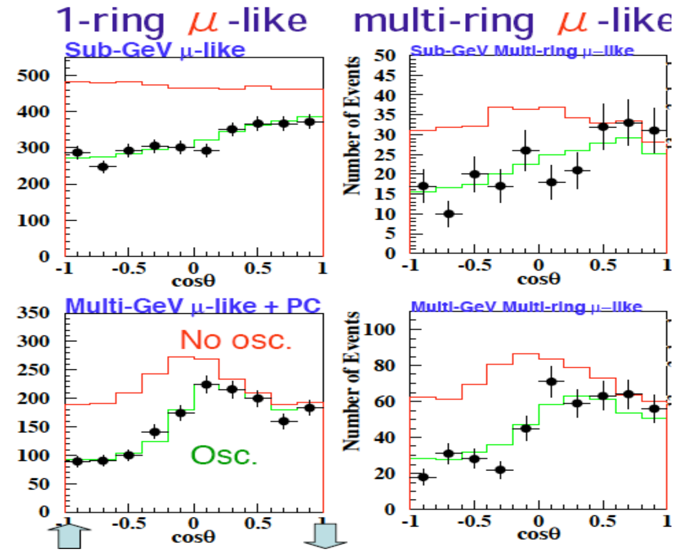
- YES if lepton # violating new physics at big scale M_G ==>

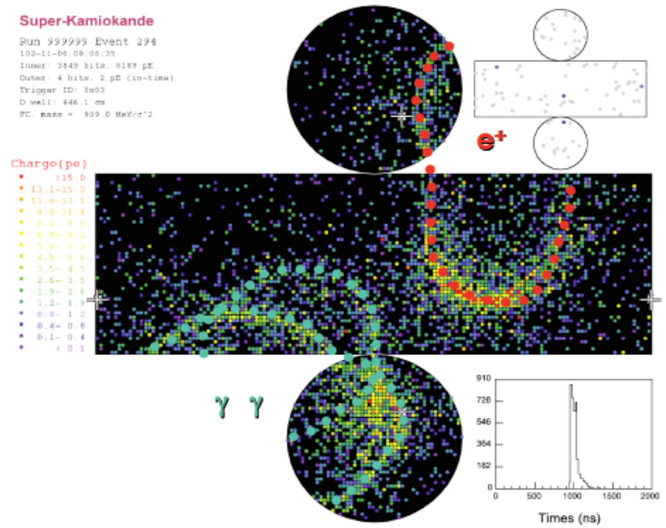
$L_{mass}=(1/\ M_G)<\square>^2\square\square$

- the “same origin” as baryon # violating operators which let proton decay:

$L_{BV}=(1/\ M_G)^2$ uude

- M_G origin of $m_\square$ will be confirmed by proton decay ==> Hyper-K/UNO





Bi-large mixing; from where ???

- Lopsided structure of mass matrix (see below)

  (Sato-Yanagida '97/98, Ramond et al. '98, Albright et al. '98)

- Mass matrix texture zeros

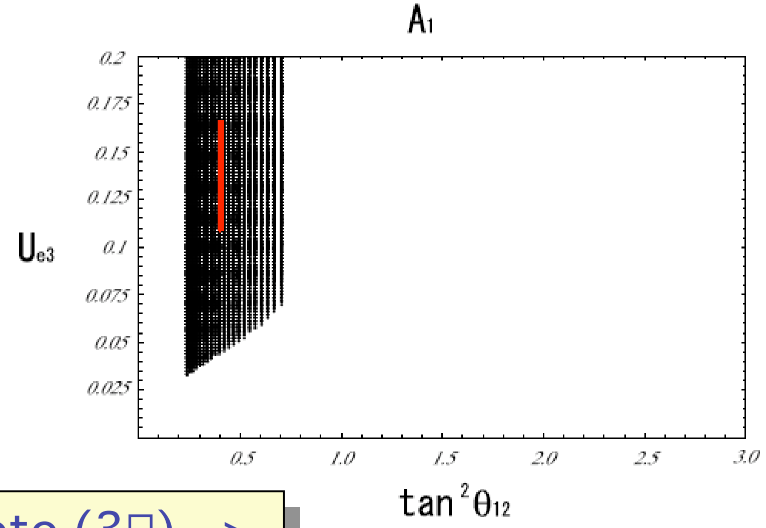
(Frampton et al. 02, Xing 02, Barbieri et al. '03, Ibarra-Ross 03, Tanimoto et al. 02/03, Bando et al. 03)

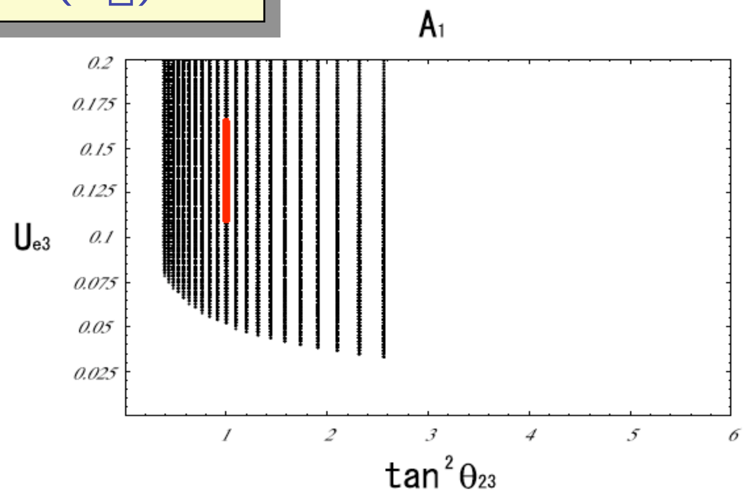
- Grand unified theories;

  SO(10) etc. ==> Talks by Mohapatra & Albright tomorrow

$$A_1 \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}, \quad A_2 \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

Tanimoto (3□) =>





Lopsided lepton mass matrix (explanatory sheet)

- Consider SU(5) GUT

  $5^* = [d^c, (\nu, e)_L]$

  $10 = [u^c, (u, d)_L, e^c]$

- Quark mass

  $m_{LR}^{down} = 10 \cdot 5^* \langle H_1 \rangle$

- Charged lepton mass

  $m_{LR}^{lepton} = 5^* \cdot 10 \langle H_2 \rangle$

==> $m^{lepton} = (m^{down})^T$

==> lopsided structure; left-handed mixing of m^{lepton} = right-handed mixing of m^{down}

- $m^{d,l}\, m^{d,l+} = S\, m_i^2\, S^+$
- $U_{MNS} = S^{(\nu)+} S^{(lepton)}$

$$m^{down} = c \begin{bmatrix} \lambda^4 & \lambda^3 & \lambda^4 \\ x & \lambda^2 & \lambda^2 \\ y & z & 1 \end{bmatrix}, \quad m^{down}(m^{down})^\dagger = c^2 \begin{bmatrix} \lambda^6 & \lambda^5 & \lambda^4 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^4 & \lambda^2 & 1 \end{bmatrix}$$

$$m^{lepton}(m^{lepton})^\dagger = c'^2 \begin{bmatrix} x^2+y^2 & yz+\lambda^2 x & y+\lambda^2 x \\ yz+\lambda^2 x & z^2 & z \\ y+\lambda^2 x & z & 1 \end{bmatrix}$$

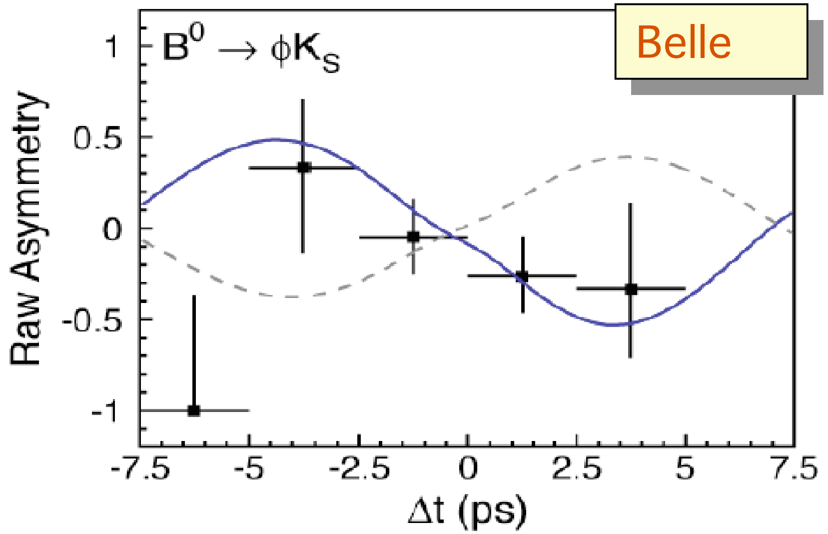
λ=0.2, x, y, z = O(1)==> Large lepton mixing arises from quark mass

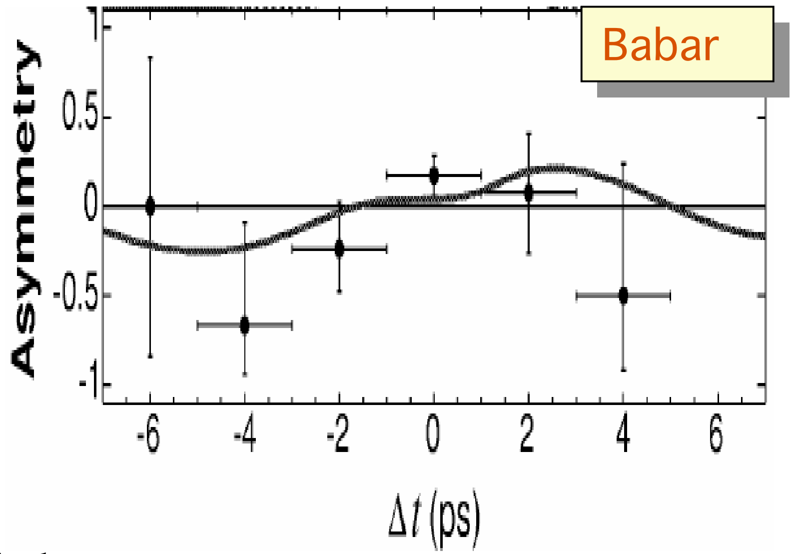
WINning combination of □ and B physics?

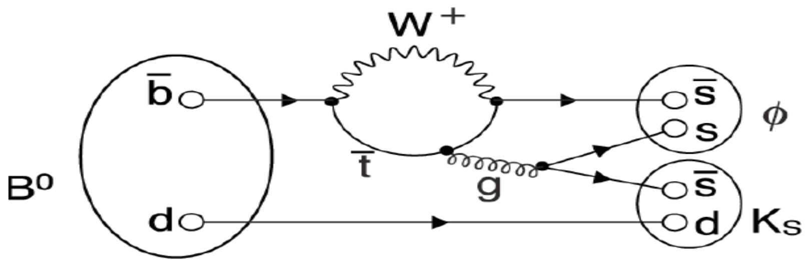
- "Lopsided" interpretation of large mixing angle suggest large right-handed b-s mixing ==>

  Anomaly in B->□K_s

Moroi '00, Goto-Okada-Shimizu-Shindou-Tanaka '02, Hisano-Shimizu '03, Harnik-Larson-Murayama '03







Anomalous B->□K_s examined in SYSY models

- In susy models (incl. SU(5) + □$_R$ model) which satisfy all the constraints, B->□K_s asymmetry cannot go down to -1 but to ~zero (welcome Babar-Belle average)

(Goto-Okada-Shimizu-Shindou-Tanaka, hep-ph/0306093)

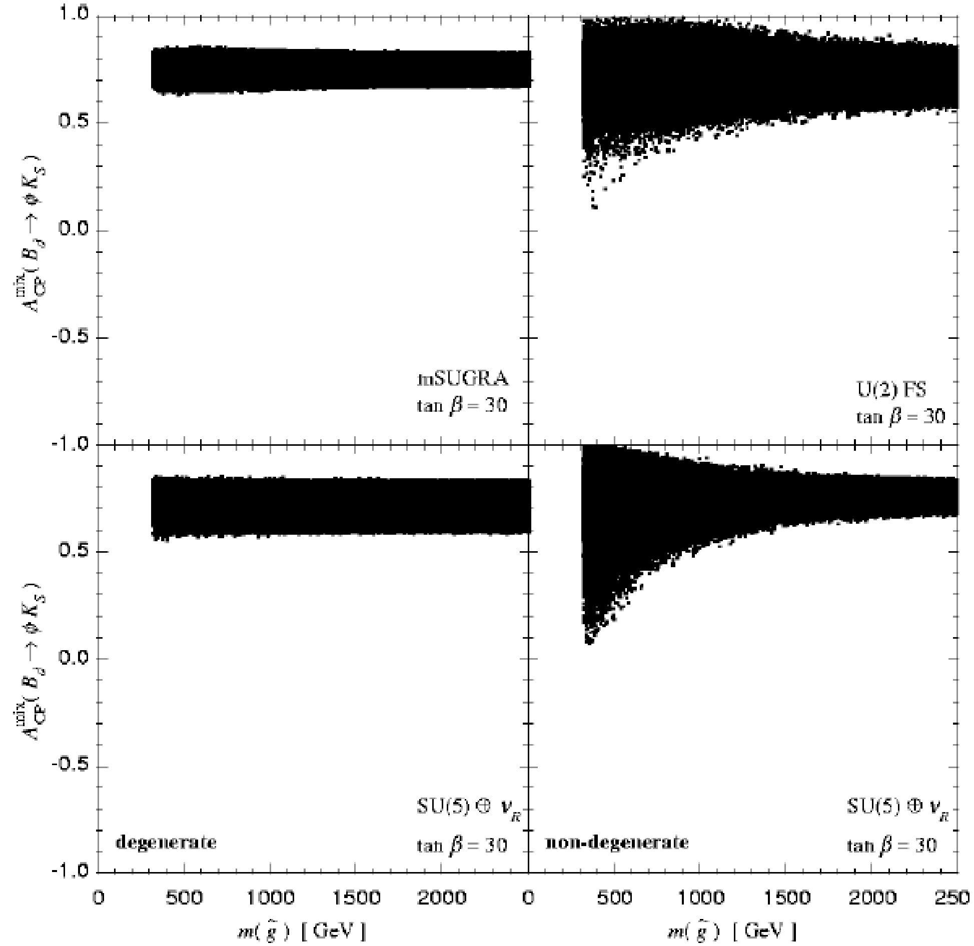


FIG. 8: The mixing-induced CP asymmetry in $B_d \to \phi K_S$ as a function of the gluino mass.

Conclusion

- After the most exciting 5 years, we will have busy 5-10 years to complete our understanding of lepton flavor mixing
- Strategies for exploring MNS structure are well developed assuming $\square_{13}$ is not too small
- Absolute □ mass and demonstrating Majorana properties require longer path (and hard work!)
- Tiny □ mass probably due to high mass scale but what does large & small mixing imply?
- Exploration of high-mass scale physics requires input from interdisciplinary areas, WINning area, cosmology …

Explore the beautiful world !

RELAXING IN LIBRARY PARK

FALL AT THE LAKE FRONT

LAKE FRONT WALK

SPRING IN LAKE GENEVA

Bi-large mixing; from where ???

- Lopsided structure of mass matrix (see below)

  (Sato-Yanagida '97/98, Ramond et al. '98, Albright et al. '98)

- Mass matrix texture zeros

(Frampton et al. 02, Guo-Xing 02, Barbieri et al. '03, Ibarra-Ross 03, Tanimoto et al. 02/03, Bando et al. 03)

(1,1) ==> (1-2)

- Grand unified theories;

  SO(10) etc. ==> Talks by Mohapatra & Albright tomorrow