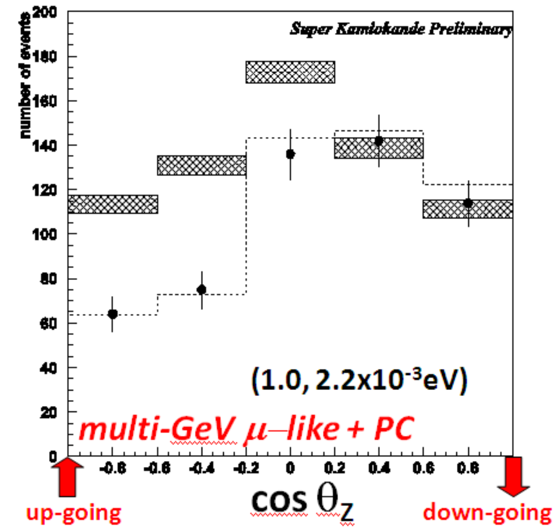
Solar and Atmospheric Neutrinos

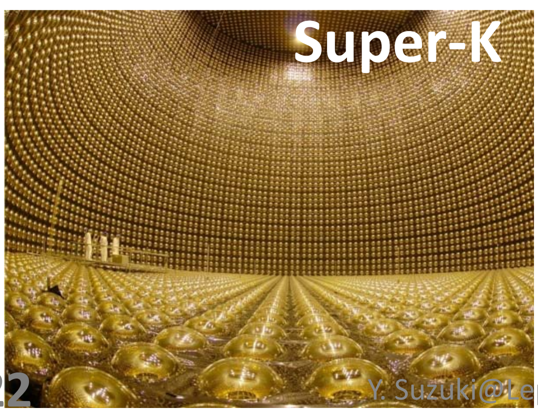
Yoichiro Suzuki

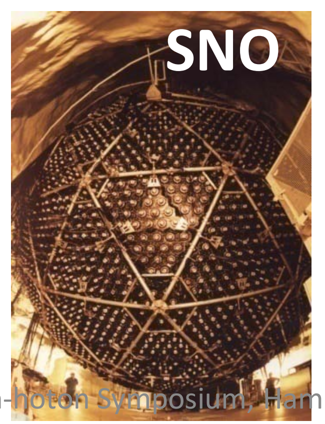
Kamioka Observatory, Institute for Cosmic Ray Research (ICRR),
The University of Tokyo, and
Kamioka Satellite, Institute for the Physics and Mathematics of the Universe (IPMU), The University of Tokyo

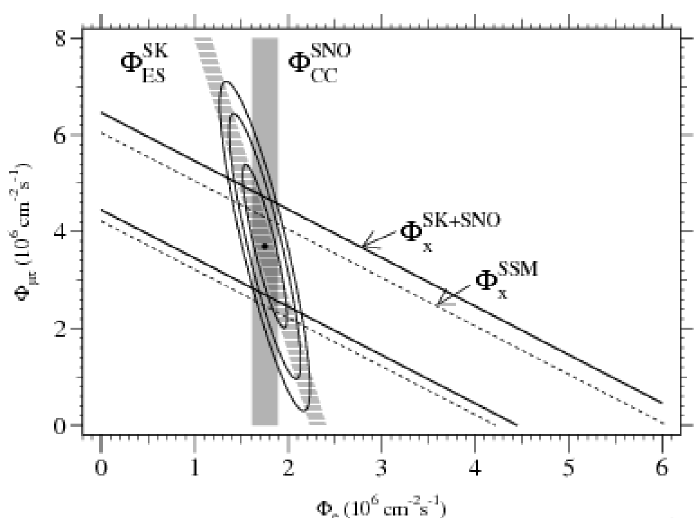
Discovery of Neutrino Oscillation

- **1998**: **Atmospheric Neutrino Oscillation** (***Super-Kamiokande***)
  - Asymmetry in zenith angle distribution
  - ν_μ deficits (up-going)
- **2001**: **Solar Neutrino Oscillation** (***SNO+Super-Kamiokande***)
  - SNO: charged current $\rightarrow \nu_e$
  - SK: Electron Scattering $\rightarrow \nu_e + 0.15(\nu_\mu + \nu_\tau)$









Oscillation Parameters
~10 years after the discovery

mixing: $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

flavor eigenstates — mass eigenstates

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

Atmospheric ν Long baseline (θ_{23}: maximal?)	Reactor, LongBL (θ_{13}: upper limit) Not determined yet	Solar ν Reactor LBL (θ_{12}: large)

Current
Best parameter value from a single experiment (except solar ν)

$\Delta m_{12}^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$	$(\sim 3\% @ \Delta\chi^2 = 1)$	[KamLAND : PRL100, 221803 (08)]
$\sin^2\theta_{12} = 0.31^{+0.02}_{-0.02}$	$(\sim 7\% @ \Delta\chi^2 = 1)$	[All solar experiments] done by SNOGr.
$\Delta m_{23}^2 = 2.43^{+0.13}_{-0.13} \times 10^{-3}\,\mathrm{eV}^2$	$(\sim 5\% @ \Delta\chi^2 = 1)$	[MINOS : PRL101, 131802 (2008)]
$= 2.19^{+0.14}_{-0.13} \times 10^{-3}\,\mathrm{eV}^2$	$(\sim 6\% @ \Delta\chi^2 = 1)$	[SuperK : Atmospheric ν L/E]
$\sin^2\theta_{23} = 0.51^{+0.05}_{-0.07}$	$(\sim 14\% @ \Delta\chi^2 = 1)$	[SuperK : Atmospheric ν 3f]
$\sin^2\theta_{13} < 0.04$	(@90%C.L.)	[CHOOZ]

- Solar – Atmospheric; better sensitivities for mixing angles
- Reactor; better sensitivities for solar mass difference
- Accelerator; will be better in atmospheric mass difference

Missing parameters: θ_{13} and CP phase

Oscillation Parameters

~10 years after the discovery

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

flavor eigenstates — mass eigenstates

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

Atmospheric ν Long baseline (θ_{23}: maximal?)	Reactor, LongBL (θ_{13}: upper limit) Not determined yet	Solar ν Reactor LBL (θ_{12}: large)

Current

Best parameter value from a single experiment (except solar ν)

$\Delta m_{12}^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$ (~ 3% @ $\Delta\chi^2 = 1$) [KamLAND : PRL100, 221803 (08)]

$\sin^2\theta_{12} = 0.31^{+0.02}_{-0.02}$

$\Delta m_{23}^2 = 2.43^{+0.13}_{-0.13} \times 10^{-3}\,\mathrm{eV}$

$= 2.19^{+0.14}_{-0.13} \times 10^{-3}\,\mathrm{eV}$

$\sin^2\theta_{23} = 0.51^{+0.05}_{-0.07}$ (~ 14% @ $\Delta\chi^2 = 1$) [SuperK : Atmospheric ν 3f]

$\sin^2\theta_{13} < 0.04$ (@90%C.L.) [CHOOZ]

SK Atm-ν:	**$\sin^2\theta_{13} < 0.06$**	
K2K:	**$\sin^2\theta_{13} < 0.075$**	**PRL93(04)**
MINOS:	**$\sin^2\theta_{13} < 0.073$**	**PRL101(08)**

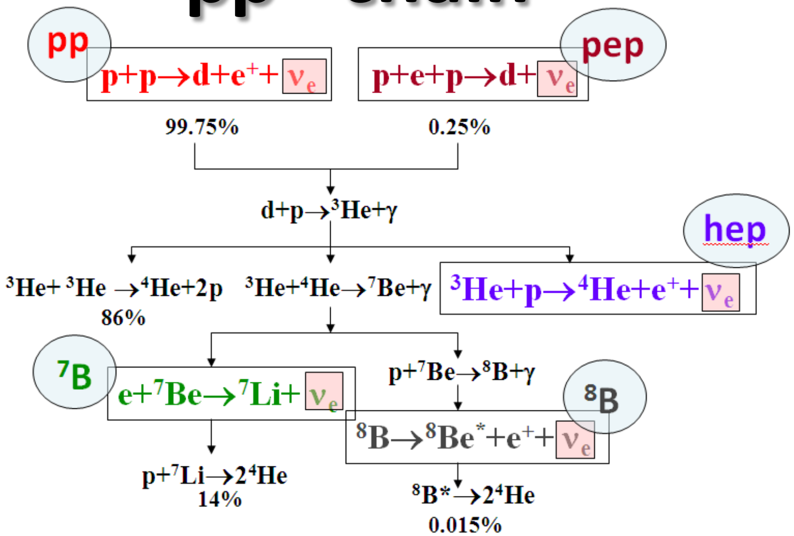
- **Solar – Atmospheric; better sensitivities for mixing angles**
- **Reactor; better sensitivities for solar mass difference**
- **Accelerator; will be better in atmospheric mass difference**

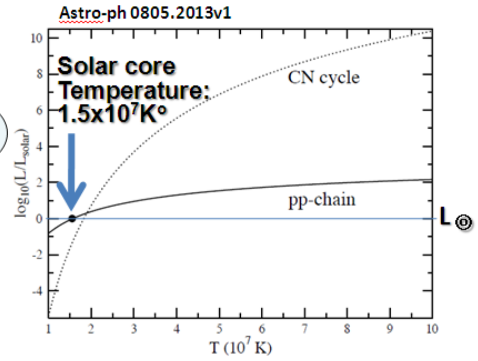
Missing parameters: θ_{13} and CP phase

Solar Neutrinos

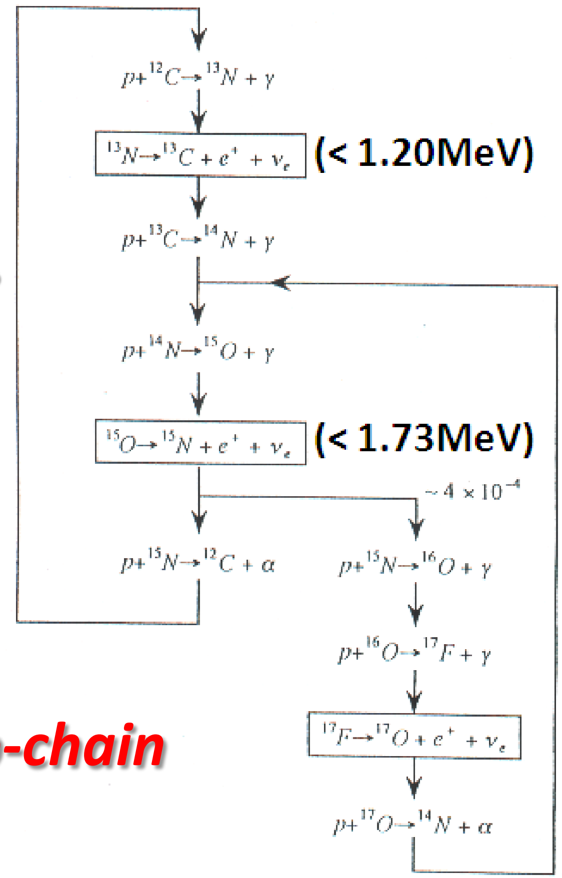
pp chain and CNO cycle

pp - chain





CNO cycle



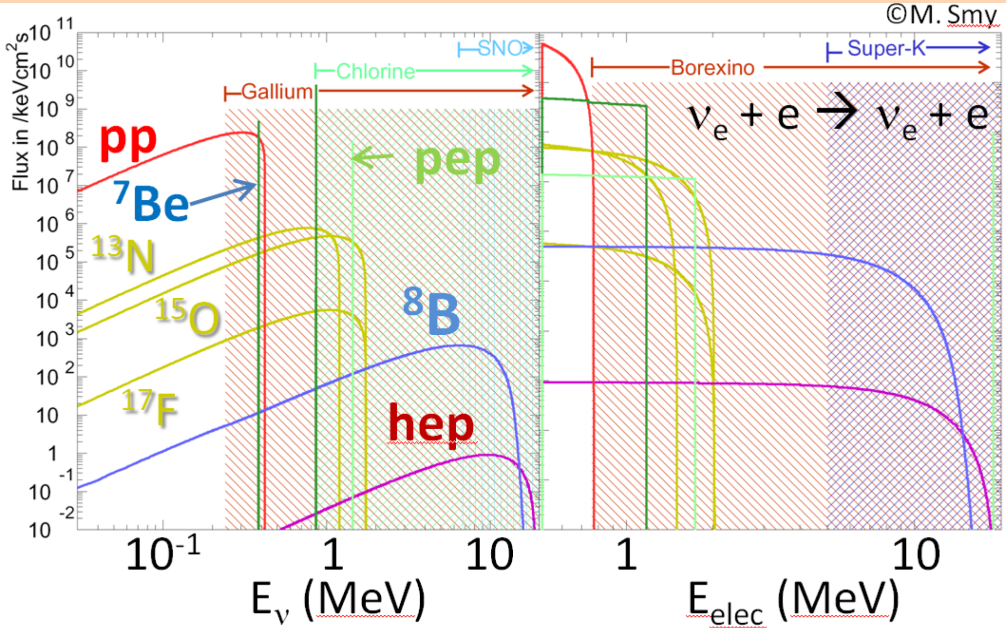
pp-chain

- *Dominant process in the sun*
- *5 processes produce neutrinos*
- *Detection of the ^{8}B neutrinos is a proof of pp-chain*

CNO cycle

- *Hydrogen is burned using a carbon as a catalyst*
- *< 1% of the solar energy production*
- *Relatively low energy neutrinos are produced*

Neutrino Spectrum and Solar Neutrino Experiments

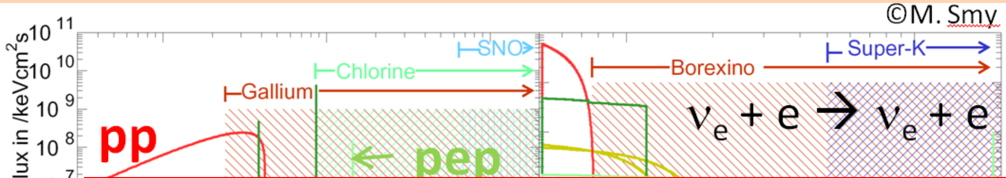


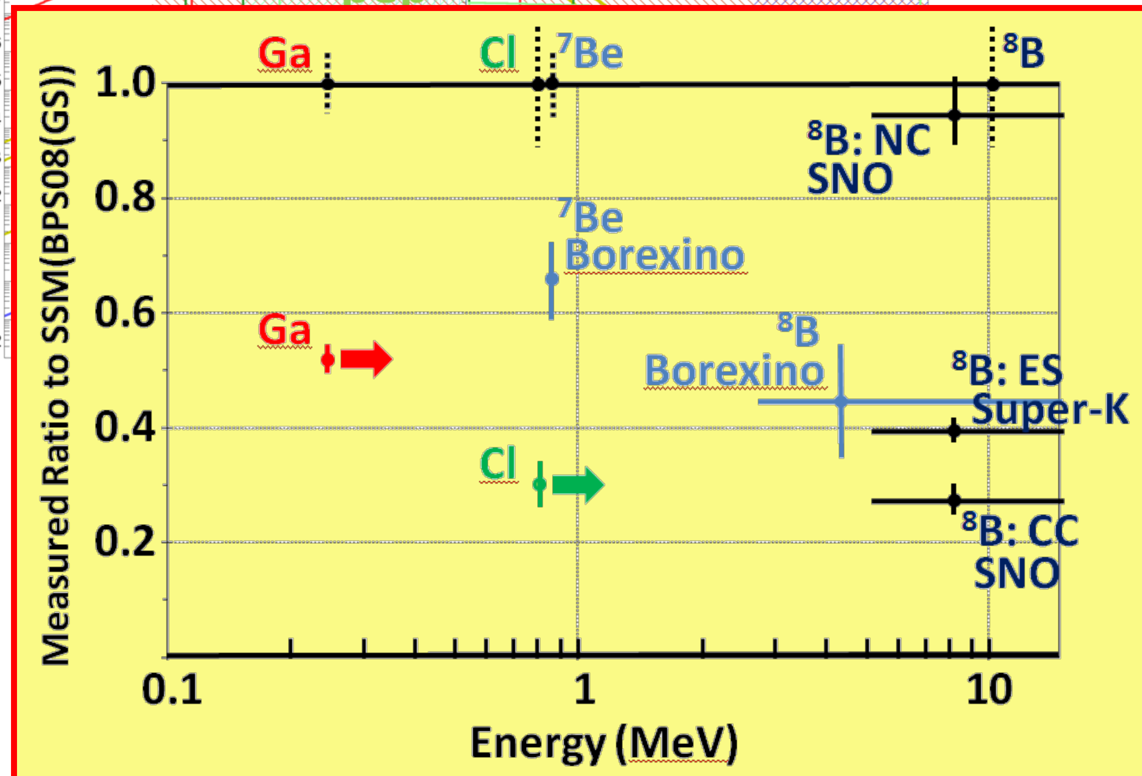
- **Radio-Chemical**
  - **Ga: SAGE, GALLEX/GNO (pp, ^{7}Be....)**
    - $\nu_e + ^{71}Ga \rightarrow e + ^{71}Ge$: E_ν >235keV
    - Meas: 66.1±3.1 SNU; R=0.52
    - Pred:$127.9^{+8.1}_{-8.0}$ SNU$_{BPS08(GS)}$
  - **Cl: Homestake (^{8}B, ^{7}Be,..)**
    - $\nu_e + ^{37}Cl \rightarrow e + ^{37}Cl$: E_ν > 816keV
    - Meas: 2.56±0.16±0.16 SNU
    - Pred:$8.46^{+0.87}_{-0.88}$ SNU$_{BPS08(GS)}$

- **Real time Counter**
  - **H_2O: Kamiokande(ES) (^{8}B)**
  - **H_2O: Super-Kamiokande(ES) (^{8}B)**
    - $\phi_{^8B}^{SK\text{-}I}$=2.35±0.02 ±0.08x10^{6}cm^2
    - Pred: 5.94(1±0.11)x10^{6}cm$^2_{BPS08(GS)}$
  - **D_2O: SNO(CC, NC, ES) (^{8}B)**
    - $\phi_{^8B}^{SNOIII(CC)}=1.67^{+0.05}_{-0.04}{}^{+0.07}_{-0.08}$x10^{6}cm^2
    - $\phi_{^8B}^{SNOIII(NC)}=5.54^{+0.33}_{-0.31}{}^{+0.36}_{-0.34}$x10^{6}cm^2
  - **Scinti: Borexino (ES) (^{7}Be, ^{8}B)**
    - ^{7}Be: Meas: 49±3$_{sta}$±4$_{sys}$ c/day/100ton
    - ^{7}Be: Pred: 74±4 c/day/100ton$_{BPS08(GS)}$:
    - ^{7}Be: Pee($\nu_e \rightarrow \nu_e$) = 0.56 ±0.10(1σ)
    - ^{8}B: $\phi_{^8B}^{Borexino}$=2.65±0.44 ±0.18x10^{6}cm^2

Neutrino Spectrum and Solar Neutrino Experiments

©M. Smy

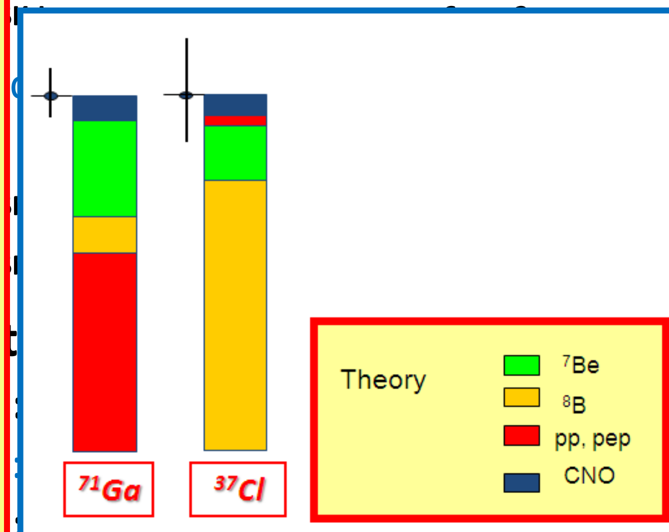




ime Counter

Kamiokande(ES)

Super-Kamiokande(ES)



– Cl: Homestake

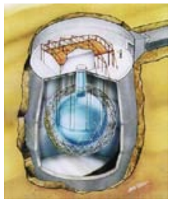
$\nu_e + {}^{37}Cl \rightarrow e + {}^{37}Cl$: E_ν > 816keV

Meas: 2.56±0.16±0.16 SNU

Pred:$8.46^{+0.87}_{-0.88}$ $SNU_{BPS08(GS)}$

^{8}B: $\phi_{^8B}^{Borexino}$=2.65±0.44 ±0.18x10^{6}cm^2

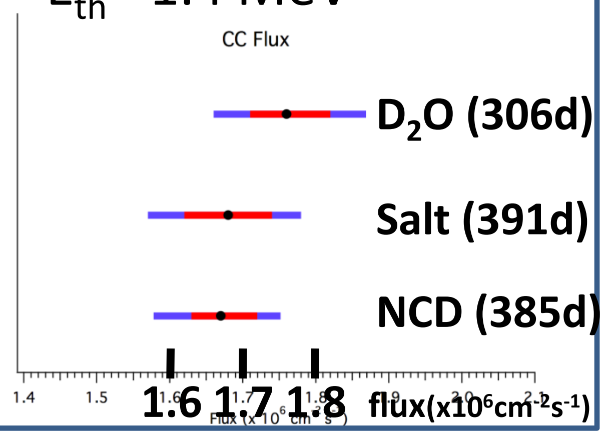
Neutral Current Measurements by SNO



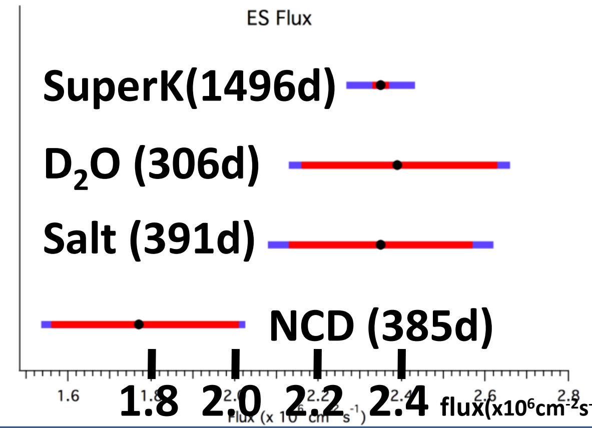
SNO: 1000tons D_2O
Started in Nov-99, and completed in Dec-06

NC: $\nu_e + d \rightarrow e^+ + p + n$

CC: $\nu_e + d \rightarrow e^+ + n + n$,
E_{th} =1.4 MeV



ES: $\nu_e + e \rightarrow \nu_e + e$



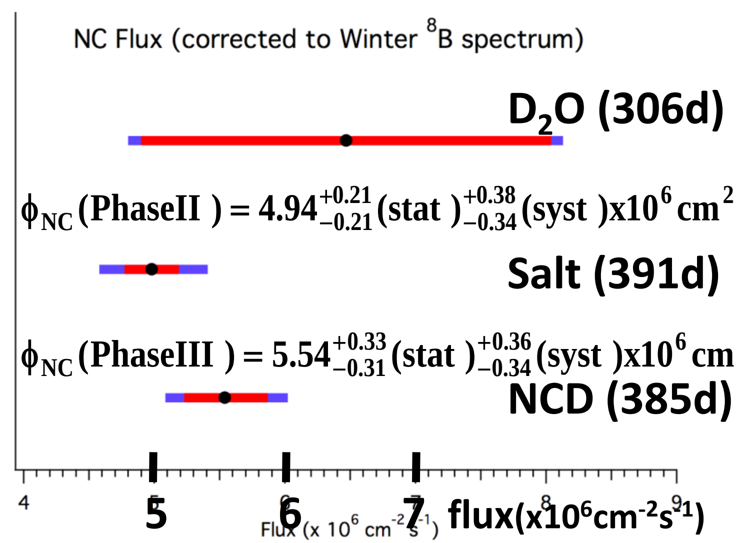
NC: 3 neutron detection methods:

Phase I: D_2O, $^2H(n,\gamma)^3H$, 6.25 MeV γ
Eff. ~14.4%

Phase II: Salt, $^{35}Cl(n,\gamma)^{36}Cl$, 8.6MeV γ
Eff. ~40%

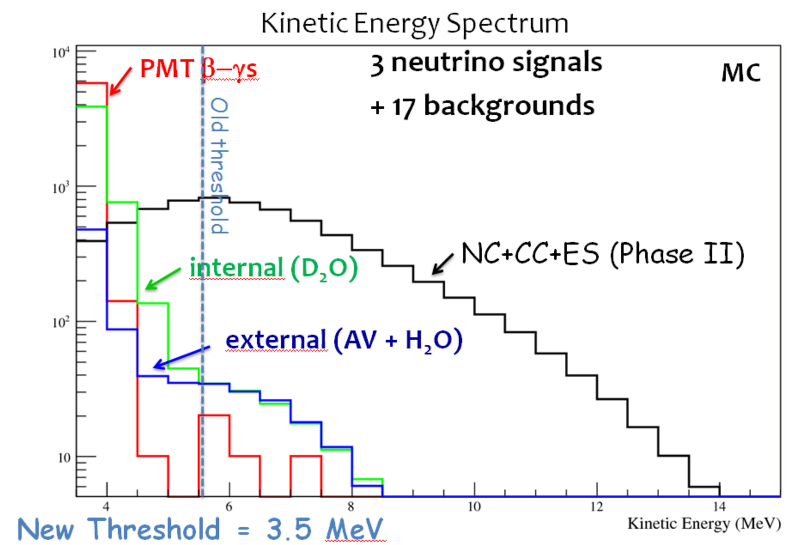
Phase III: ^3He neutron counters
$n + {}^3He \rightarrow p + {}^3H$
Eff. ~30%, but separated detection

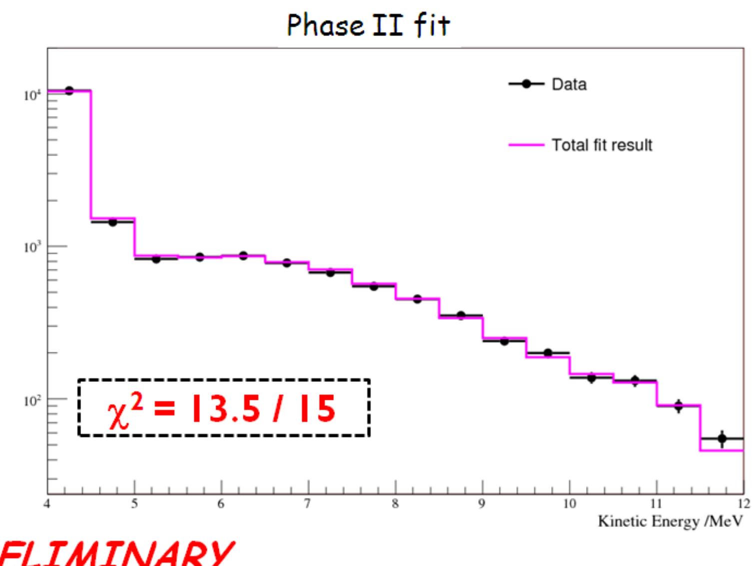
Comb. Error (NC): ~5.4% by hand (not from SNO)
⇔ ~11% SSM(^8B)



SNO LETA

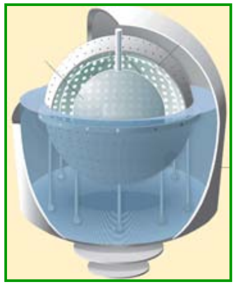
- **Phase I (>5MeV)+II(5.5MeV) will be jointly analyzed down to T_{eff} ~ 3.5 MeV**
  - CC interaction down to E_ν~6MeV
  - More than 50% increase of events for NC
  - But many backgrounds (background dominates)
    - Reduce BG
    - Reduce systematics
    - Make pdf for signals and backgrounds
- **Expect significant improvements of the SNO results soon**





Borexino ^{7}Be and CNO

- **270t liquid scintillator**

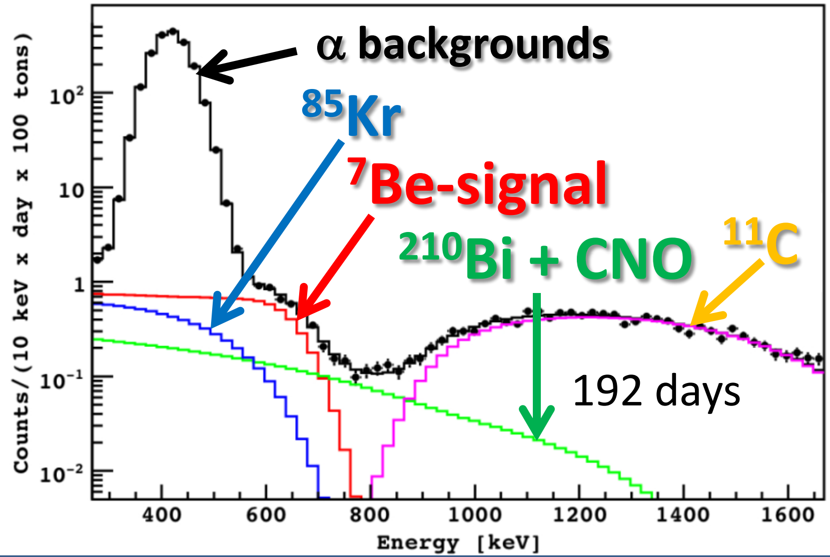


  - PC + PPO in a 150mm thick nylon vessel
  - Graded shielding
  - Two oil layers and water shields

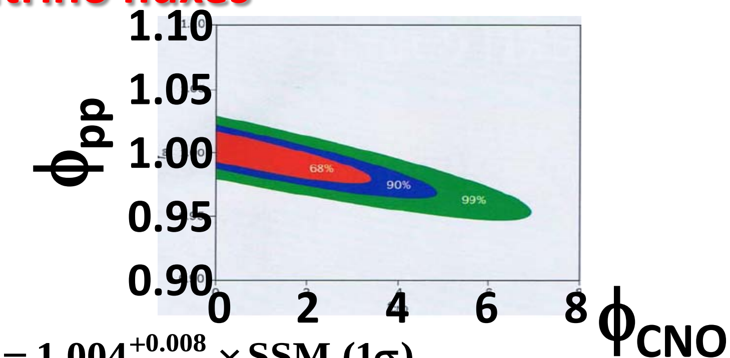
- **^{7}Be (192days):**
  - **Meas. $49\pm3_{sta}\pm4_{sys}$ c/day/100ton**
  - **Pred. 74 ± 4 c/day/100ton$_{BPS08(GS)}$**
    - BPS08(GS):$5.07(1 \pm 0.06)\times10^9/cm^2$
      - BPS07(GS) = 5.08 (Borexino paper)
  - P_{ee}: ν_e survival prob. <u>assuming SSM</u>

    $P_{ee} \sim (P_{meas} - \sigma(\nu_e)/\sigma(\nu_{\mu,\tau}))/(1 - \sigma(\nu_e)/\sigma(\nu_{\mu,\tau}))$

  ➔ **$P_{ee} = 0.56 \pm 0.10$ (1σ) @0.862MeV**



Solar Model(+luminosity constraint), LMA and Borexino data
➔ **improve constraints on other neutrino fluxes**

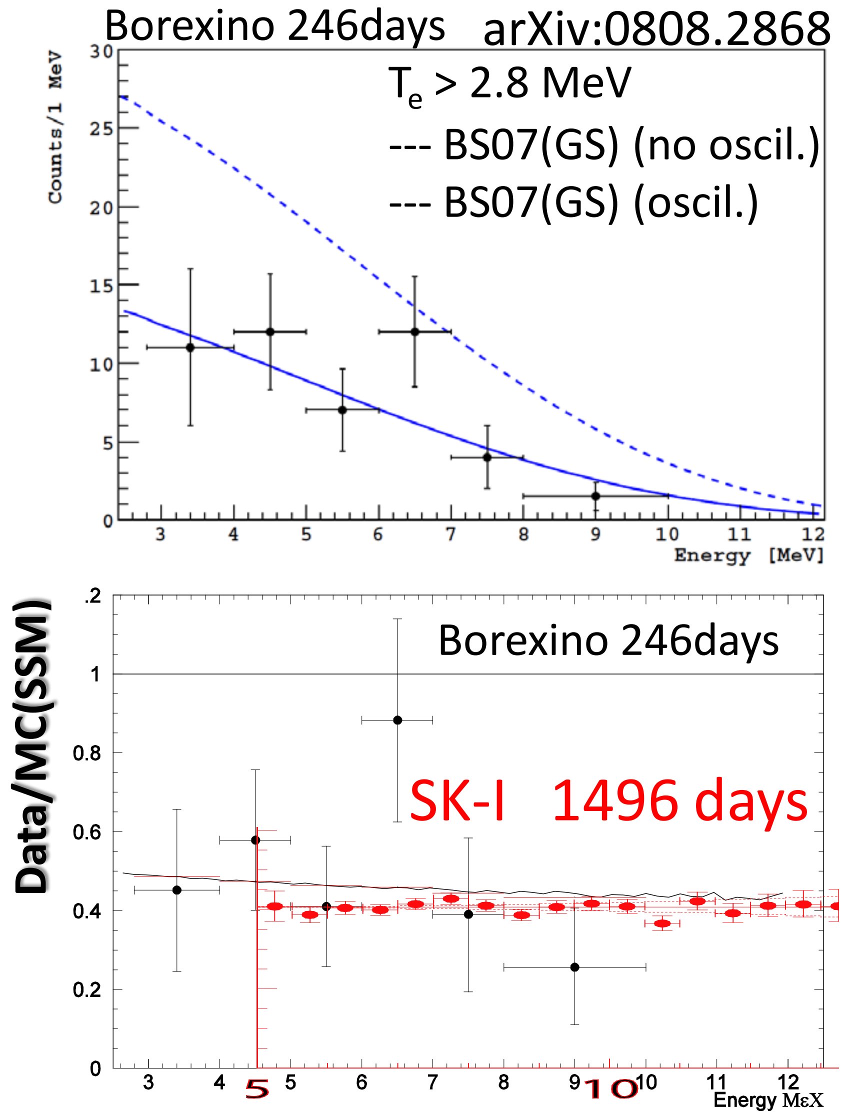


$\phi_{pp} = 1.004^{+0.008}_{-0.020} \times SSM\ (1\sigma)$

$\phi_{CNO} < 4.8 \times SSM\ (90\%C.L.)$

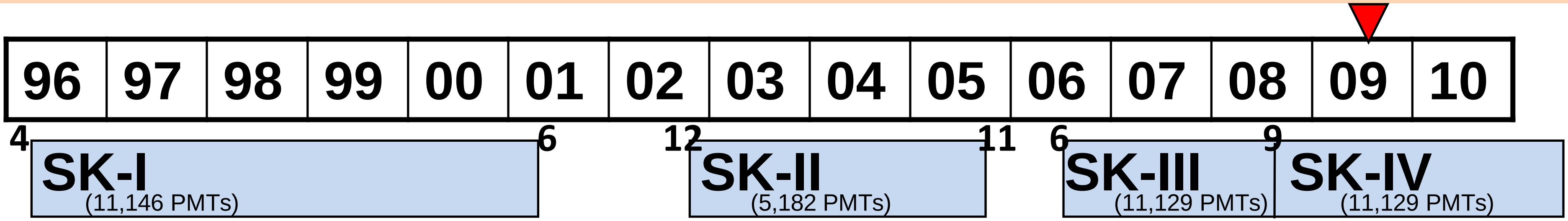
Borexino ^8B

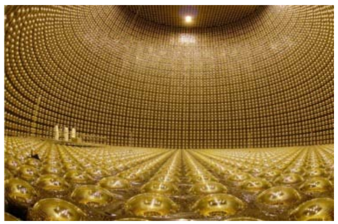
- ^8B: > 2.8 MeV
  - $\phi_{^8B}^{Borexino}$=2.65 ± 0.44 ±0.18x10^{6}cm^2
- ^8B: > 5 MeV (SK: >4.5 MeV)
  - $\phi_{^8B}^{Borexino}$=2.75±0.54 ±0.17x10^{6}cm^2
  - $\phi_{^8B}^{SK\text{-}I}$ =2.35±0.02 ±0.08x10^{6}cm^2
- P_{ee} = 0.35±0.10 at <T_e>=8.6 MeV
  (BPS07(GS) is used)



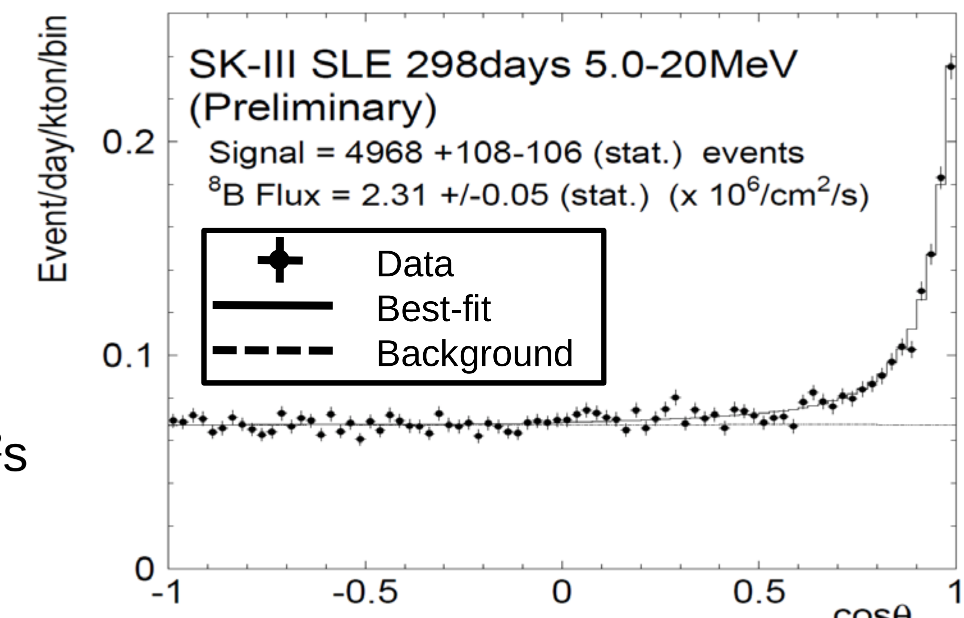
Note:
Super-K: Energy ← Total energy
Borexino: Energy ← Kinetic energy

SK Solar ν is back on

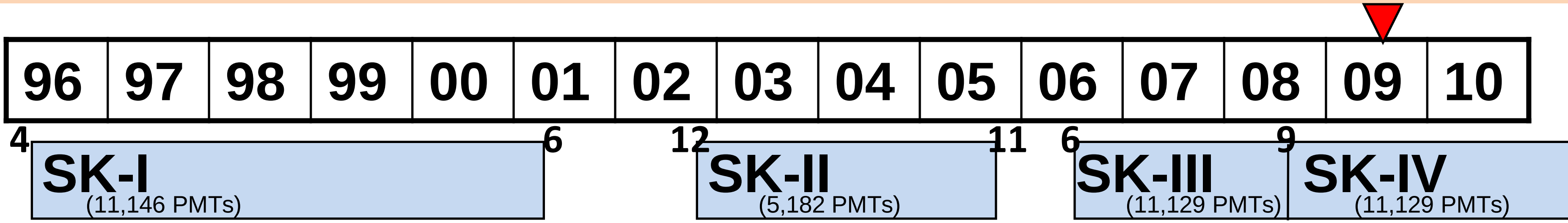




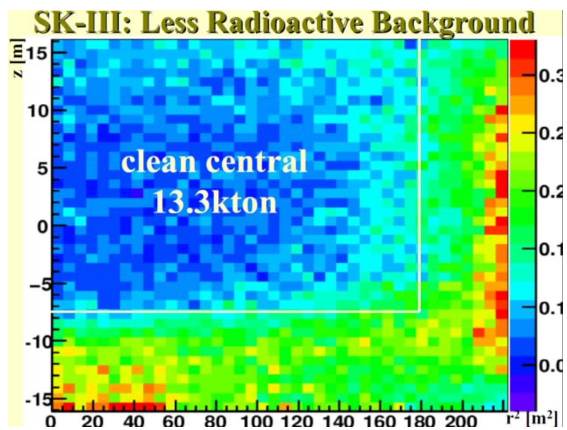
- **Full SK** was back on June-06
  ➔SK-III
  2.31±0.05(stat) x10^6/cm^{2}s
- SK-I ^{8}B flux:
  2.35±0.02(stat)±0.08(sys) x10^6/cm^{2}s
- consistent with SK-I flux within statistical uncertainty
- SK is now back in solar neutrino business

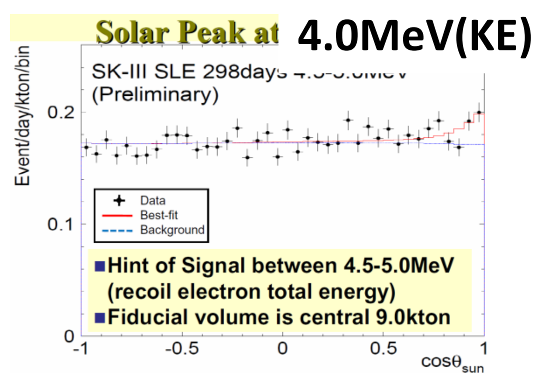


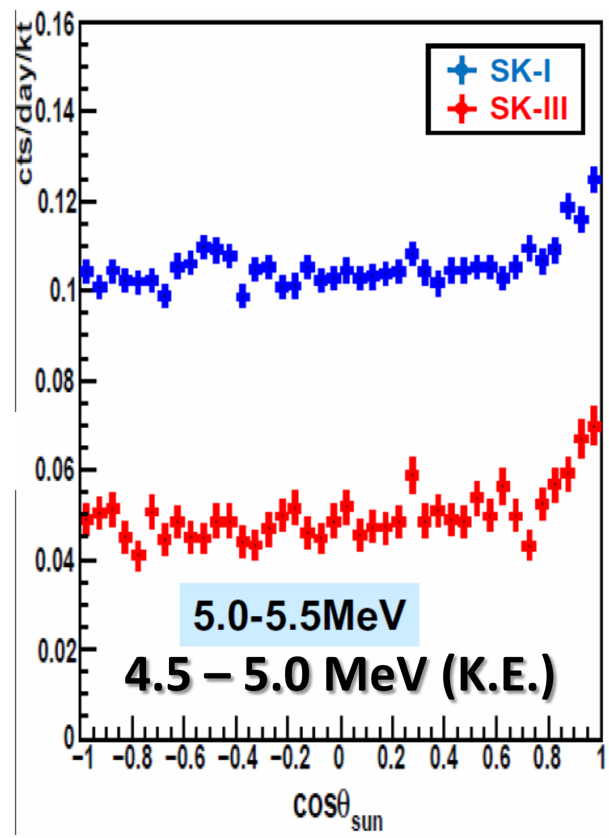
SK Solar ν is back on



- New electronics on September 09
  ➔ SK IV
- Lower background was achieved
- Threshold: 4 MeV (KE)
- Aim to measure transition region down to 4 MeV or may be 3.5 MeV



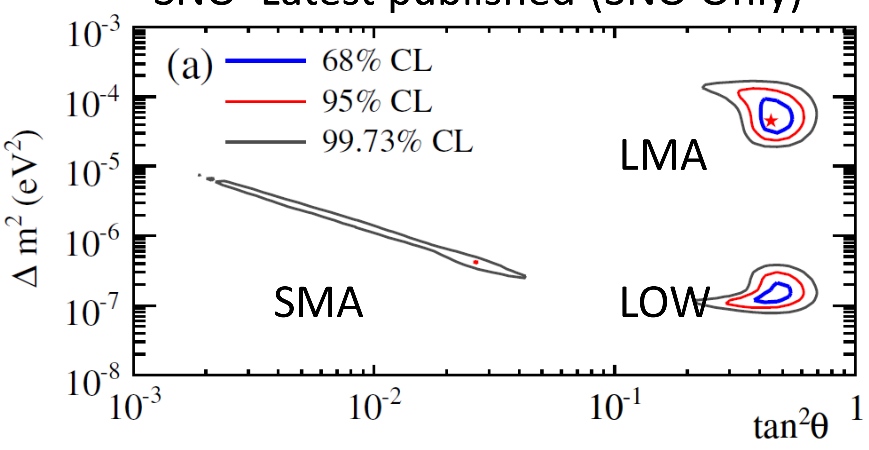




Solar Neutrino Oscillation (Global Analysis)

- **Need multiple solar neutrino experiments**
  ➔ to obtain LMA
- No single solar neutrino experiment can single out LMA.

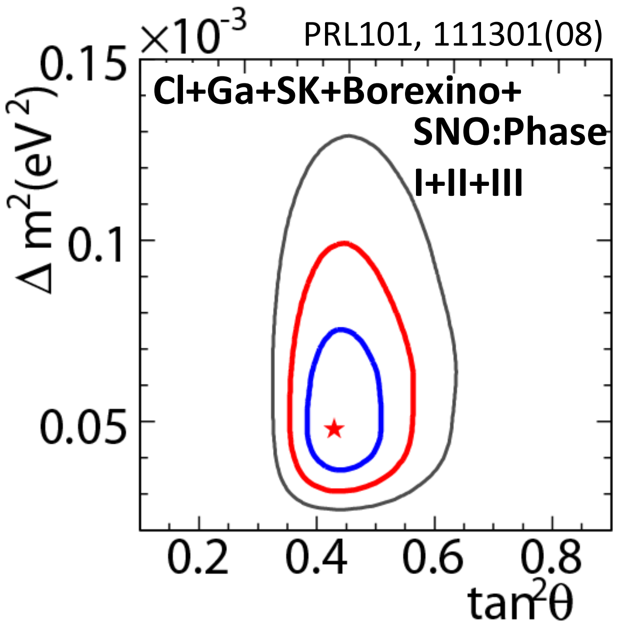
SNO Latest published (SNO Only)



- **A GLOBAL Analysis** Phase I+II+III
  (Ref: SNO Group Ph.I+II+III)
  [All solar neutrino experiments]

$$\Delta m^2 = 4.90^{+1.64}_{-0.93} \times 10^{-5}\,\mathrm{eV}^2$$
$$\tan^2\theta = 0.437^{+0.043}_{-0.040}$$

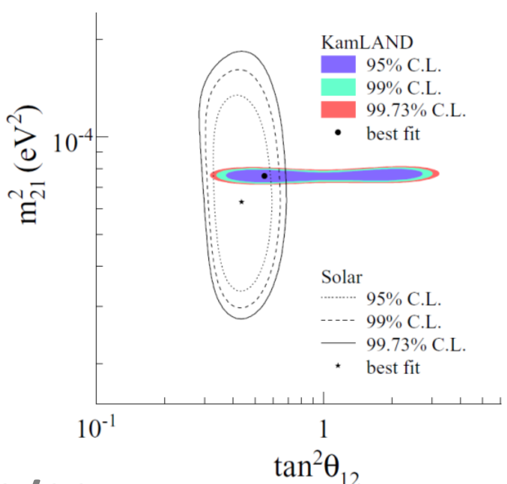
PRL101, 111301(08)



KamLAND and Global Analysis (sol+KL)

KamLAND (KL)

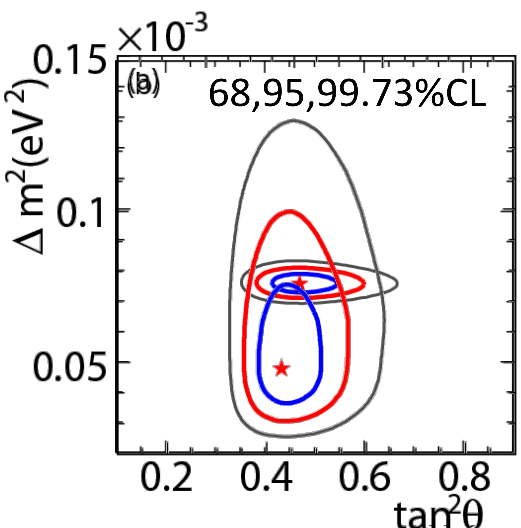
- Reactor neutrino experiment
  - L ~ 180 km
  - E ~ a few MeV
- Good Δm^2 determination:
  - better knowledge of L/E
- KL only
  - **Δm^2 = 7.58 x 10^{-5} eV^2 (2.7%)**
  - **$\tan^2\theta$ = 0.56 (~25%)**



- **Solar+KL**
  - Solar: Cl+Ga+SK+BorexinoSNO(PhaseI-II-III)) (SNO Analysis)
  - **Δm^2 = 7.59 x 10^{-5} eV^2 (~2.8%)**
  - **$\tan^2\theta$ = 0.468 (~10%)**

(Sol Only)

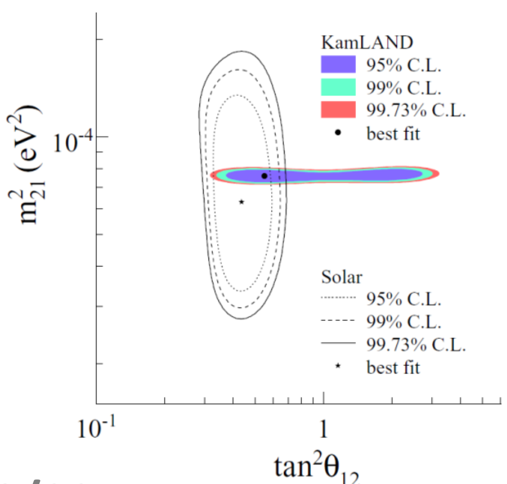
- **Δm^2 = 4.90 x 10^{-5} eV^2 (~34%)**
- **$\tan^2\theta$ = 0.437 (~10%)**



KamLAND and Global Analysis (sol+KL)

KamLAND (KL)

- Reactor neutrino experiment
  - L ~ 180 km
  - E ~ a few MeV
- Good Δm^2 determination:
  - better knowledge of L/E
- KL only
  - **Δm^2 = 7.58 x 10^{-5} eV^2 (2.7%)**
  - **$\tan^2\theta$ = 0.56 (~25%)**

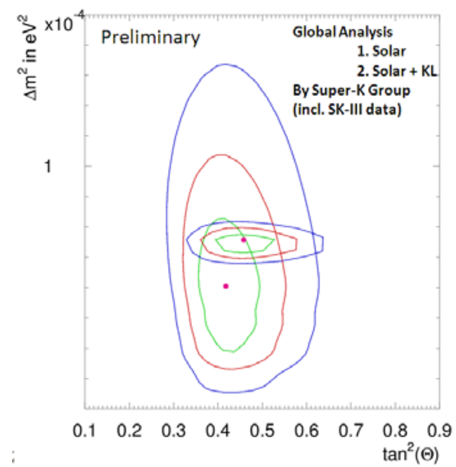


- **Solar+KL**

Global Analysis by SK-Group

1) All solar, 2) All solar + KL including SK-III

Δm^2 = 7.6 x 10^{-5} eV^2
$\tan^2\theta$ = 0.47

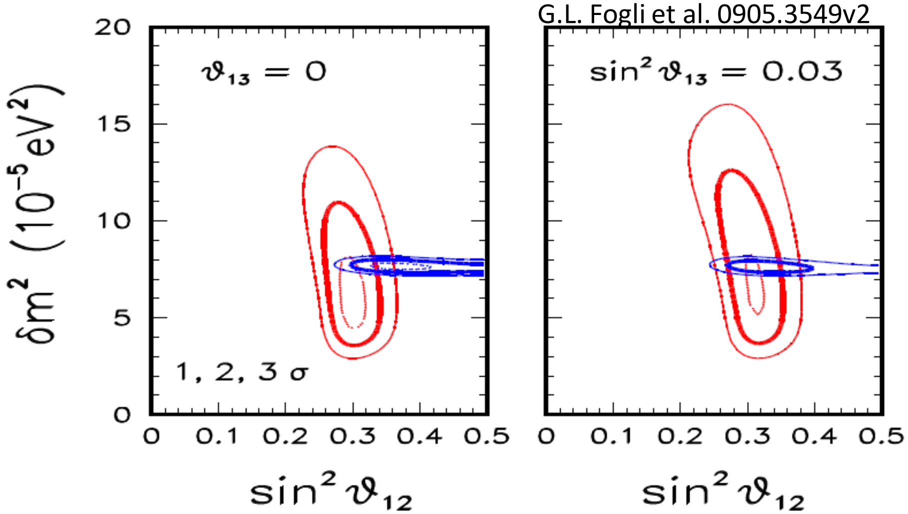


KamLAND vs Solar Neutrinos

- Solar
  - Good for $\sin^2\theta_{12}$
- KamLAND
  - Good for Δm^2
  - Getting better also on $\sin^2\theta_{12}$

➔ KamLAND vs Solar Neutrinos: slight tension
good place to study on the small effect like $\sin^2\theta_{13}$ in future

G.L. Fogli et al. 0905.3549v2

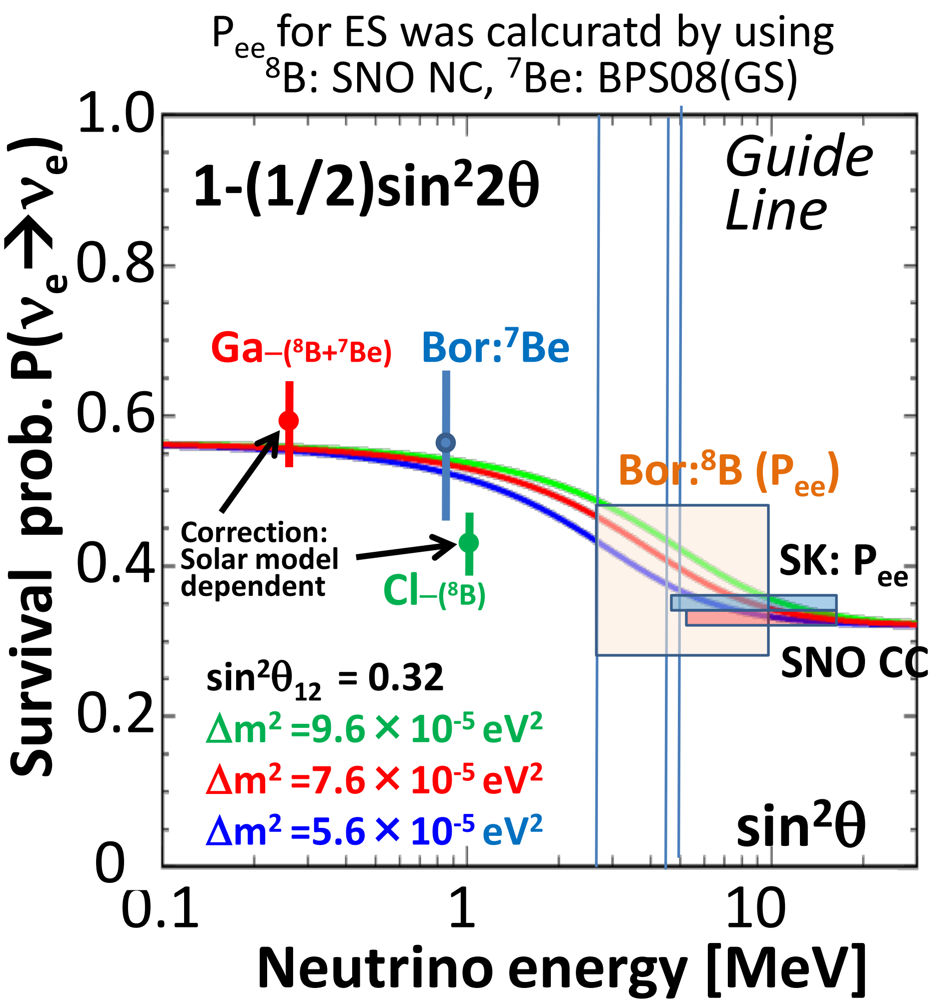


$$P_{ee}^{KL} \approx \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12} \sin^2\frac{\Delta m_{12}^2 L}{4E}\right)$$

$$P_{ee}^{Sol} \approx \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right) \quad \text{(LowEnergy)}$$

$$\approx \cos^4\theta_{13}\sin^2\theta_{12} \quad \text{(HighEnergy)}$$

Large Mixing Angle Solution



LMA

- **Vacuum in low energy:**
  - $P_{ee}=1-(1/2)\sin^2 2\theta$
- **Matter in high energy (>5 MeV):**
  - $P_{ee}=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$

    ➔ $P_{ee}=\sin^2\theta$ ($\theta_m \rightarrow \pi/2$)

$$\tan^2 2\theta_m = \frac{\tan^2 2\theta_V}{1-(2p\sqrt{2}G_F n_e)/(\Delta m^2 \cos 2\theta_V)}$$

= 0 **Resonance condition**

- **Δm^2 region 10^{-5} to 10^{-4} eV^2**

  $\Delta m^2 < 1.6\times10^{-4}$ eV^2 **resonance >10MeV**

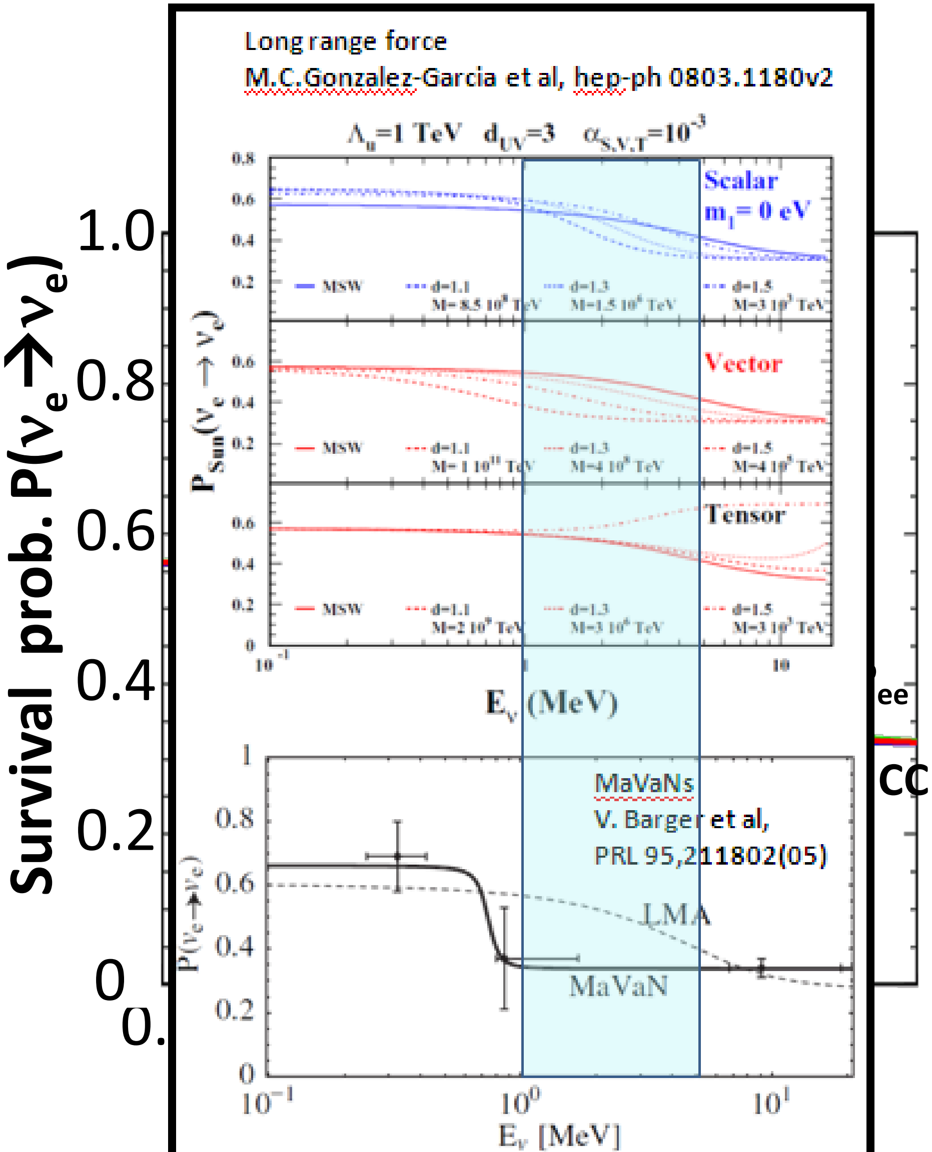
  $\Delta m^2 > 1.6\times10^{-5}$ eV^2 **no resonance <1MeV**

- **Transition Vac → Matter: 1~5 MeV**

  ➔ sensitivity on Δm^2 from the experiment

  ➔ good place to look for exotics

Large Mixing Angle Solution



LMA

- **Vacuum in low energy:**
  - $P_{ee}=1-(1/2)\sin^2 2\theta$
- **Matter in high energy (>5 MeV):**
  - $P_{ee}=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$

    ➔ $P_{ee}=\sin^2\theta\ (\theta_m \rightarrow \pi/2)$

$$\tan^2 2\theta_m = \frac{\tan^2 2\theta_v}{1-(2p\sqrt{2}G_F n_e)/(\Delta m^2 \cos 2\theta_v)}$$

= 0 **Resonance condition**

- **Δm^2 region 10^{-5} to 10^{-4} eV^2**

  $\Delta m^2 < 1.6\times10^{-4}\ eV^2$ **resonance >10MeV**

  $\Delta m^2 > 1.6\times10^{-5}\ eV^2$ **no resonance <1MeV**

- **Transition Vac ➔ Matter: 1~5 MeV**

  ➔ sensitivity on Δm^2 from the experiment

  ➔ good place to look for exotics

Remaining Problems/Tasks

- **Precise determination of oscillation parameters! and small effects ?**
  - Solar vs KamLAND
  - Transition region
    - Borexino
    - SNO low energy analysis
    - SK

Source	BPS08(GS)	BPS08(AGS)	Difference
pp	$5.97(1 \pm 0.006)$	$6.04(1 \pm 0.005)$	1.2%
pep	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.010)$	2.8%
hep	$7.90(1 \pm 0.15)$	$8.22(1 \pm 0.15)$	4.1%
^{7}Be	$5.07(1 \pm 0.06)$	$4.55(1 \pm 0.06)$	10%
^{8}B	$5.94((1 \pm 0.11)$	$4.72(1 \pm 0.11)$	21%
^{13}N	$2.88(1 \pm 0.15)$	$1.89(1\ ^{+0.14}_{-0.13})$	34%
^{15}O	$2.15(1\ ^{+0.17}_{-0.16})$	$1.34(1\ ^{+0.16}_{-0.15})$	31%
^{17}F	$5.82(1\ ^{+0.19}_{-0.17})$	$3.25(1\ ^{+0.16}_{-0.15})$	44%
Cl	$8.46^{+0.87}_{-0.88}$	$6.86^{+0.69}_{-0.70}$	
Ga	$127.9^{+8.1}_{-8.2}$	$120.5^{+6.9}_{-7.1}$	

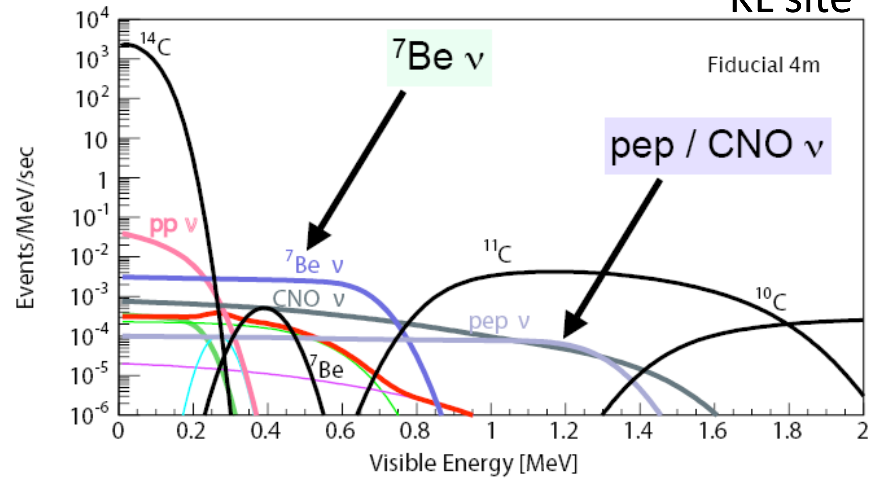
- **SSM problem**
  - Refined determination of the surface metallicity (AGS05)
  - Different total metallicity
    - Z/X=0.0165(AGS05): Low Z

  (BeforeAGS05:Z/X=0.0229 (GS98): High Z))
    - Especially, C,N,O, Ne, Mg are lower
    - ➔ Solar model conflicts with helioseismology
- **Does not change the global view of the solar ν oscillation, but affects on the search for small effects or precise study on the oscillation parameters.**
- **Can be tested by**
  - ^{8}B flux measurement
  - CNO measurements

Future Experiments

- SAGE(Ga), SK(ES), Borexino(ES)
  - will continue to be running
  - Low energy: below 5 MeV
- KamLAND(ES): liq. Scinti.
  - ^{7}Be, CNO
  - ^{7}Be? Purification test
  - → move to double β
- SNO+(ES): liq. Scinti.
  - pep, CNO
  - Lower background @ deeper site

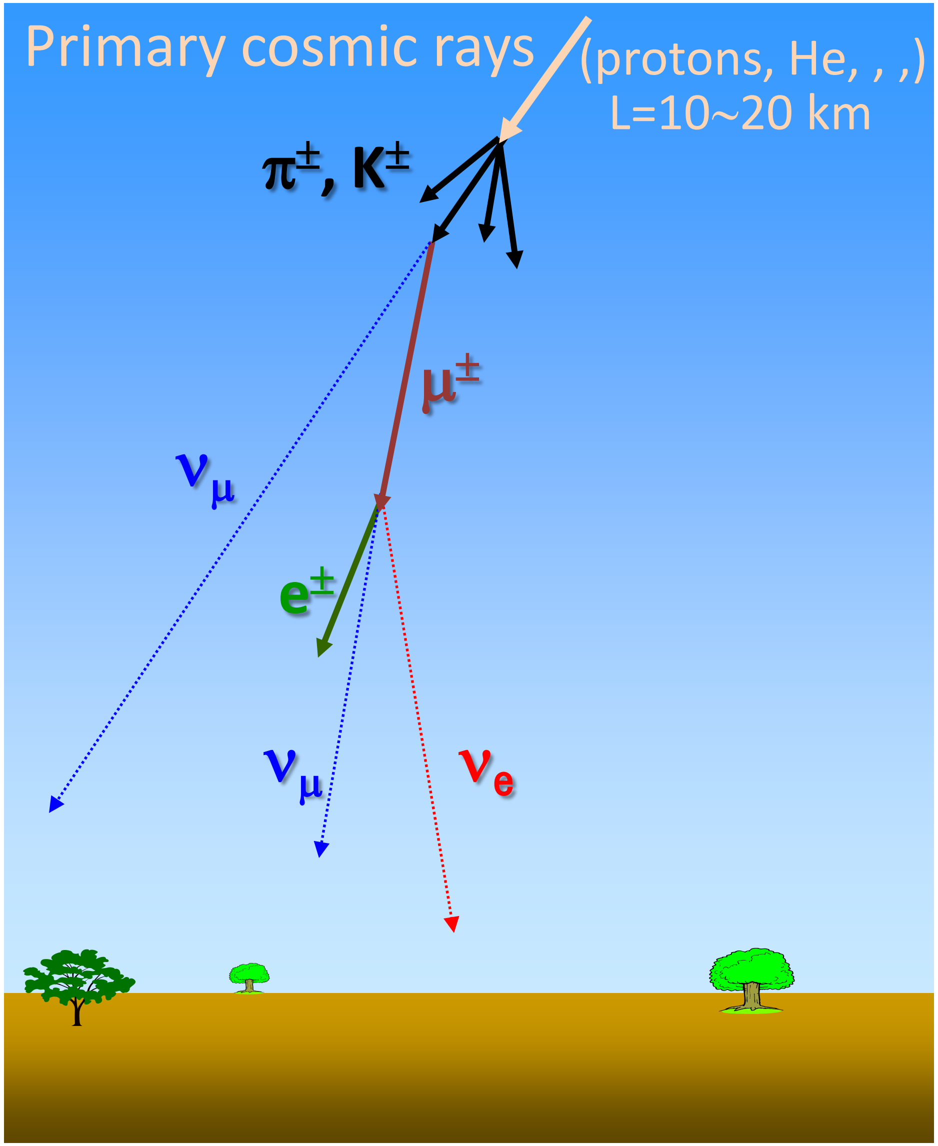
KL site



R&D/Proto-Type

Experiments	Aim	Technology	CC/ES
LENS	pp neutrino	In-loaded liq. Scinti.	CC
CLEAN	pp neutrino	Liq. Neon/Ar	ES
MOON	pp, ^{7}Be neutrino	Mo tracking calorimeter	CC
XMASS	pp neutrino	Liq. Xenon	ES

Atmospheric Neutrinos



$p/He + N \rightarrow \pi/K + X$

$\pi/K \rightarrow \mu + \nu_\mu$

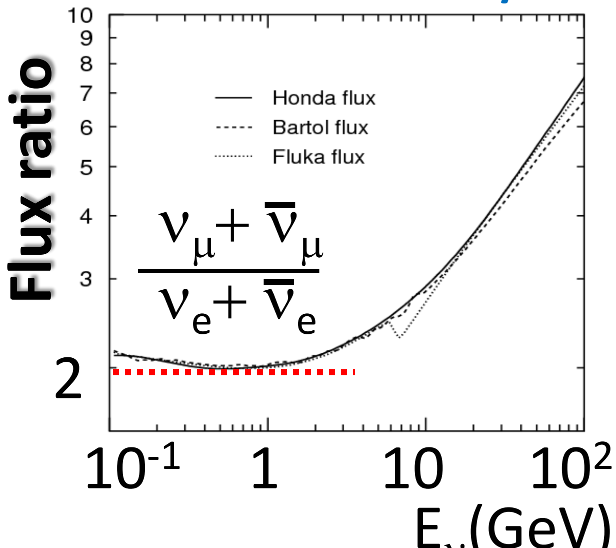
$\mu \rightarrow e + \nu_e + \nu_\mu$

For the low energy limit

- μ's decay before reaching the ground
- $\nu_\mu : \nu_e = 2 : 1$

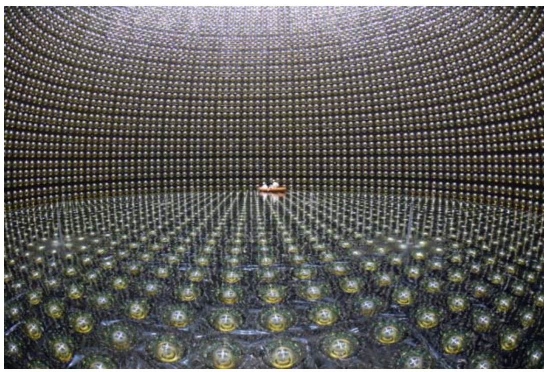
For higher energy:
$\pi/K \rightarrow \mu+\nu_\mu$

~~$e+\nu_\mu+\nu_e$~~



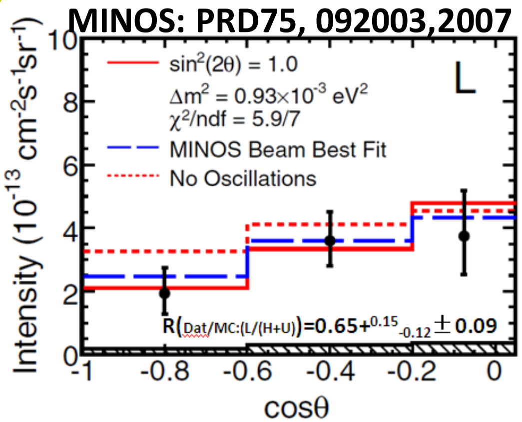
Experiments

- ***Historical Experiments***
  - **IMB** **(Water Ch. 3.3kt)**
  - **Frejeus** **(Calorimeter 0.7kt)**
  - **NUSEX** **(Calorimeter 0.1kt)**
  - **Kamiokande** **(Water Ch. 1.0kt)**
  - **Soudan II** **(Calorimaeter 1.0kt)**
  - **MACRO** **(Up-μ)**



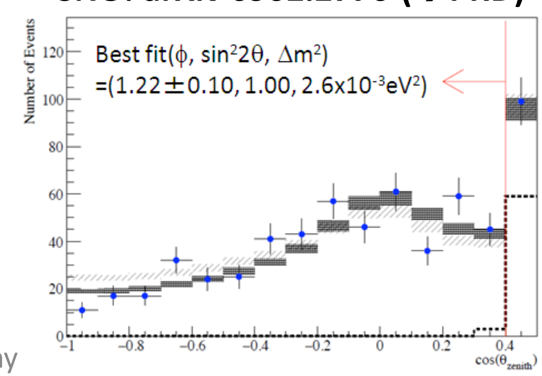
- **Super-Kamiokande (22.5kt)** provided the evidence and still provides largest statistics
  → today' report

MINOS: PRD75, 092003,2007

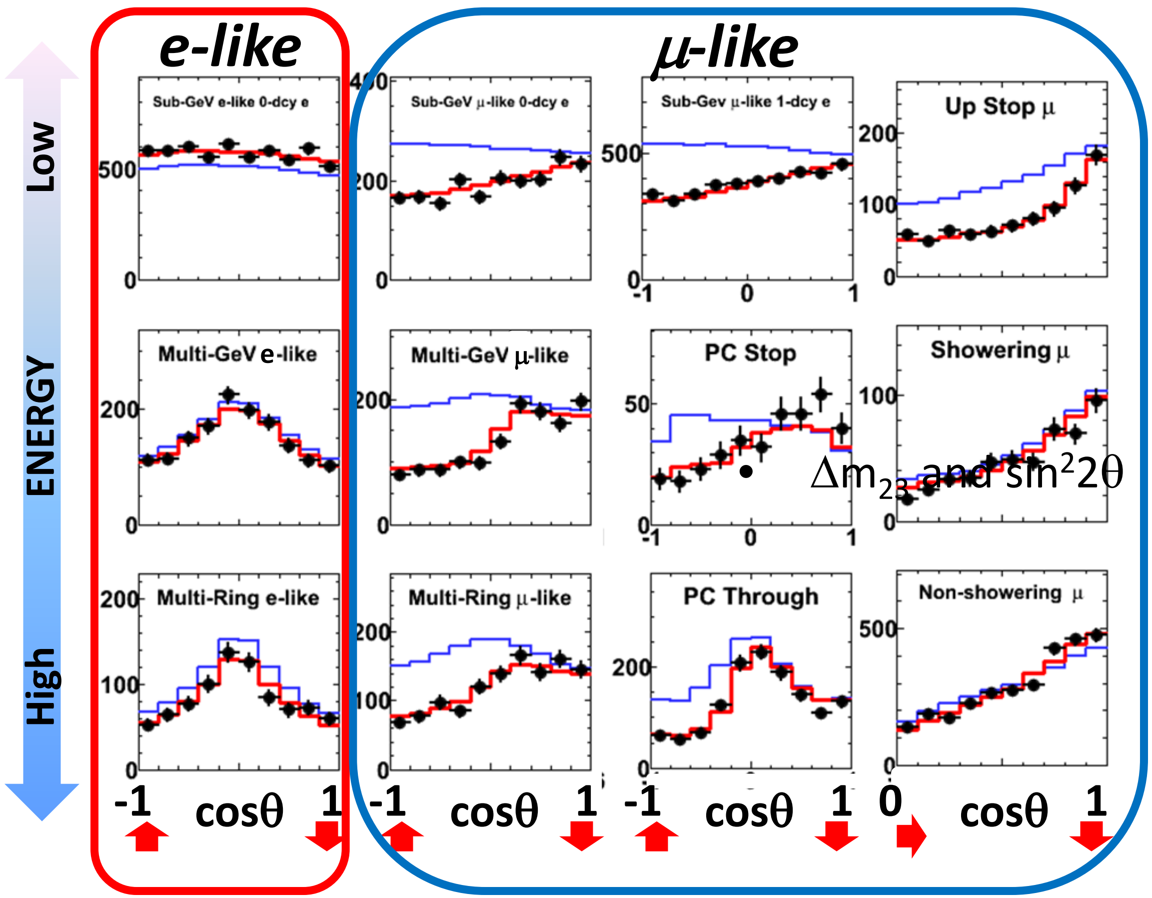


- ***New Measurements***
  - **MINOS (Calorimeter 5.4 kt)**
    - **- Up-μ**
  - **SNO (D$_2$O 1.0kt)**
    - **- Up-μ**

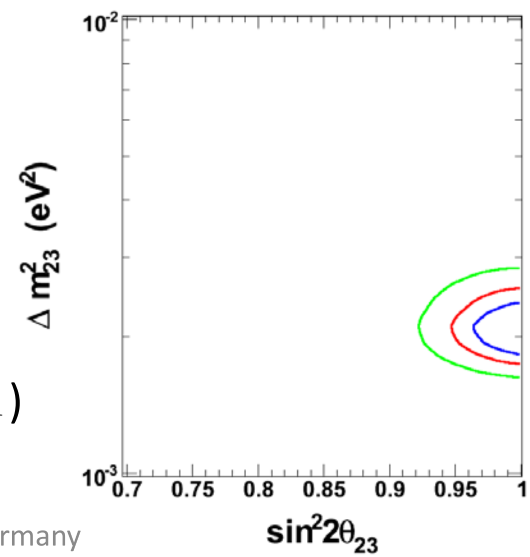
SNO: arXiv 0902.2776 (→PRD)



Experimental Results (Super-K)



- Latest SK results
  - SK-I,II,III combined
  - 2806days (173ktyr) for FC+PC
    - 24841 events
  - 3109days for up-μ
    - 4238 events

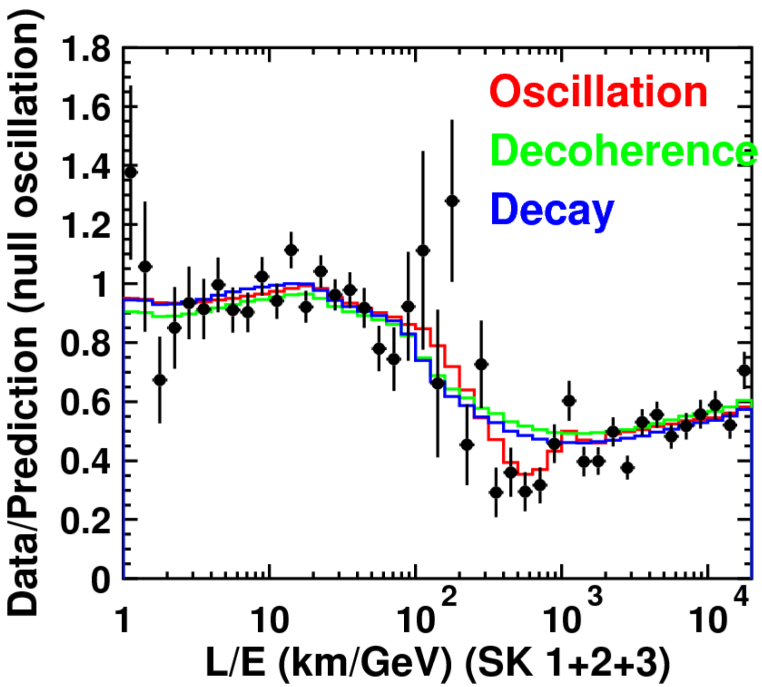


Physical Region

Δm_{23} = $2.11^{+0.11}_{-0.19}$ (1σ : $\Delta\chi^2=1$)

$\sin^2 2\theta$ = 1 (> 0.96 (90%C.L.))

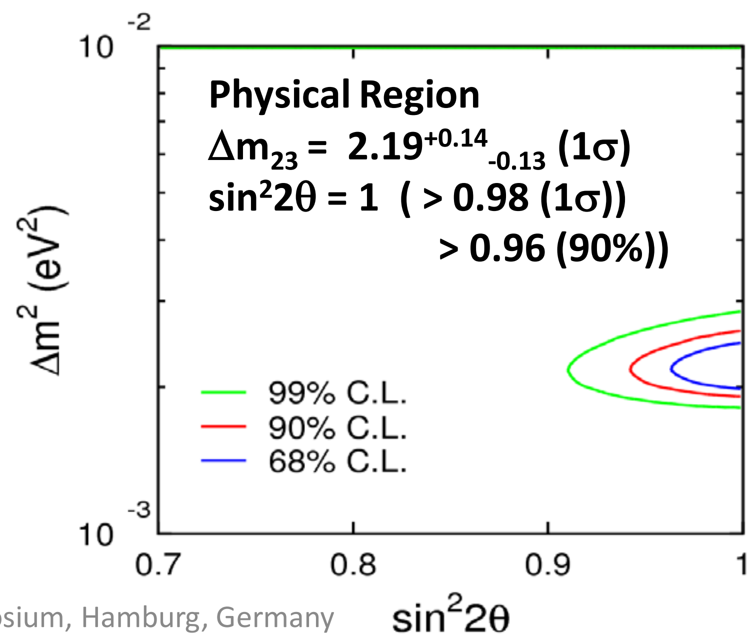
L/E plot



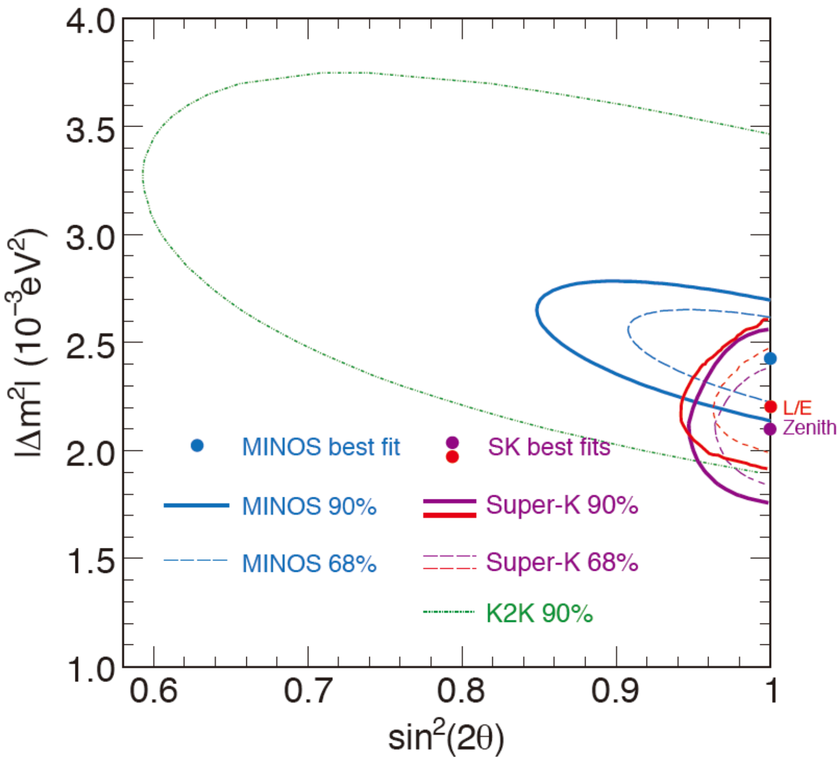
- Neutrino decay: 4.4σ
  - $\Delta\chi^2$= 19.8/126d.o.f.
- Decoherence: 5.4σ
  - $\Delta\chi^2$= 29.0/126d.o.f.

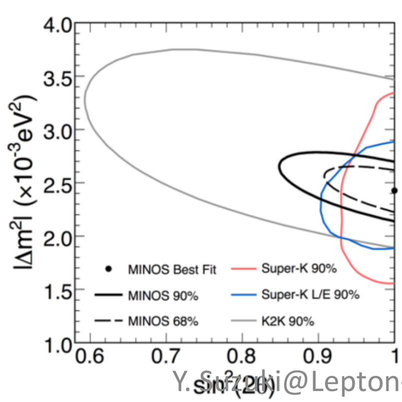
L/E analysis (SK I+II+III)

- Direct determination of Δm^2 ← E/λ
  - Position of the dip in L/E plot
- Select events with good L/E (Δ(L/E)<70%)
- Better sensitivity on Δm^2
- The first dip at ~500(km/GeV)



Oscillation Parameters





- $\Delta m_{23}^2 = 2.11^{+0.11}_{-0.19} \times 10^{-3}$ eV^2 (Atm-ν: Zenith)
- $\Delta m_{23}^2 = 2.19^{+0.14}_{-0.13} \times 10^{-3}$ eV^2 (Atm-ν: L/E)
- $\Delta m_{23}^2 = 2.43^{+0.13}_{-0.13} \times 10^{-3}$ eV^2 (MINOS)

- $\sin^2 2\theta > 0.96$ (90%) (Atm-ν)
- $\sin^2 2\theta > 0.90$ (90%) (MINOS)

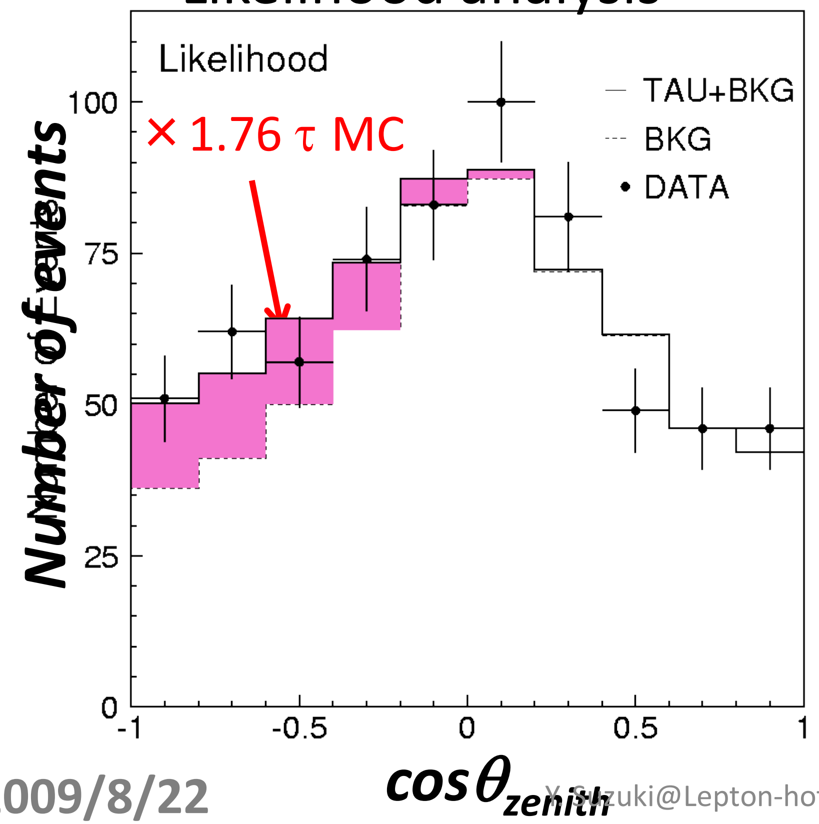
- Δm^2: comparable uncertainty
  - Probably better in future LBLE
- $\sin^2 2\theta$: better in atm-ν

Tau appearance

OLD Result

- Cannot: event-by-event analysis
  - ➔ need statistical analysis
- Not easy:
  - 🡐 E_{th}>3.5 GeV, low rate (S/BG~1/140)
- select enriched sample
  - 🡐 likelihood and neural network
- Make zenith angle distribution

Likelihood analysis



Fit in zenith angle distribution to evaluate τ contribution:

$$N_{total}(\cos\theta) = \alpha N_{tau} + \beta N_{bkg}$$

α = 1.76 and β = 0.9

Fitted # of τ events (corr. for 43% efficiency): 138 $\pm 48(\text{stat.})^{+14.8}_{-31.6}$

Expected # of τ events: 78.4±26(syst.)

Tau appearance : 2.4 σ

Neural Network Method provides similar result

Tau appearance

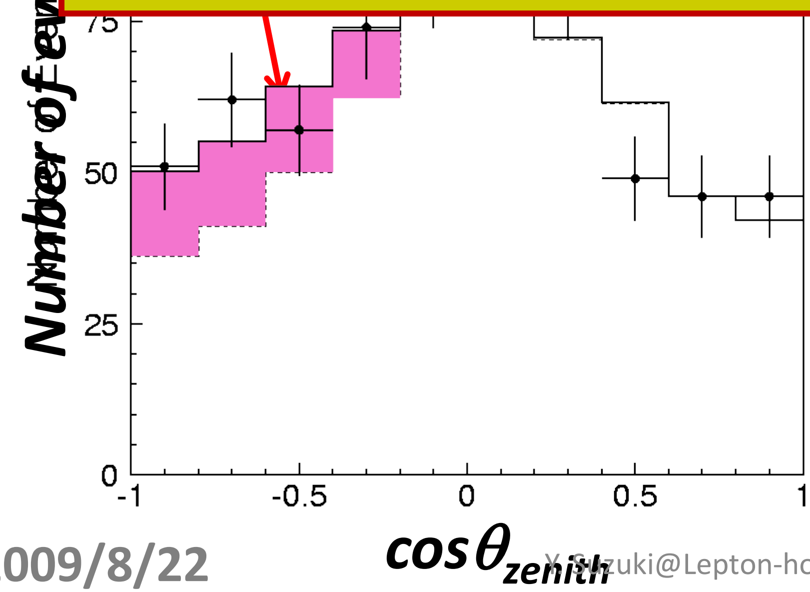
OLD Result

- Cannot: event-by-event analysis
  - ➔ need statistical analysis
- Not easy:
  - 🡐 E_{th}>3.5 GeV, low rate (S/BG~1/140)
- select enriched sample
  - 🡐 likelihood and neural network
- Make zenith angle distribution

Likelihood analysis

Fit in zenith angle distribution

Direct tau appearance experiment (OPERA) is taking data (1.25kt target; <E_ν>~17GeV, L=732km; <L/E>~43)
Expect ~10 events from 22.5x10^{19}POT exposure for 2.5x10^{-3} eV^2



Fitted # of τ events (corr. for 43% efficiency)	138 ±48(stat.)$^{+14.8}_{-31.6}$
Expected # of τ events	78.4±26(syst.)

Tau appearance : 2.4 σ

Neural Network Method provides similar result

Remaining Problems of Atmospheric ν

- **θ_{13} in atmospheric neutrinos**
- **Mass hierarchy**
- **Octant of θ_{23}**
- **CPV in atmospheric neutrinos**

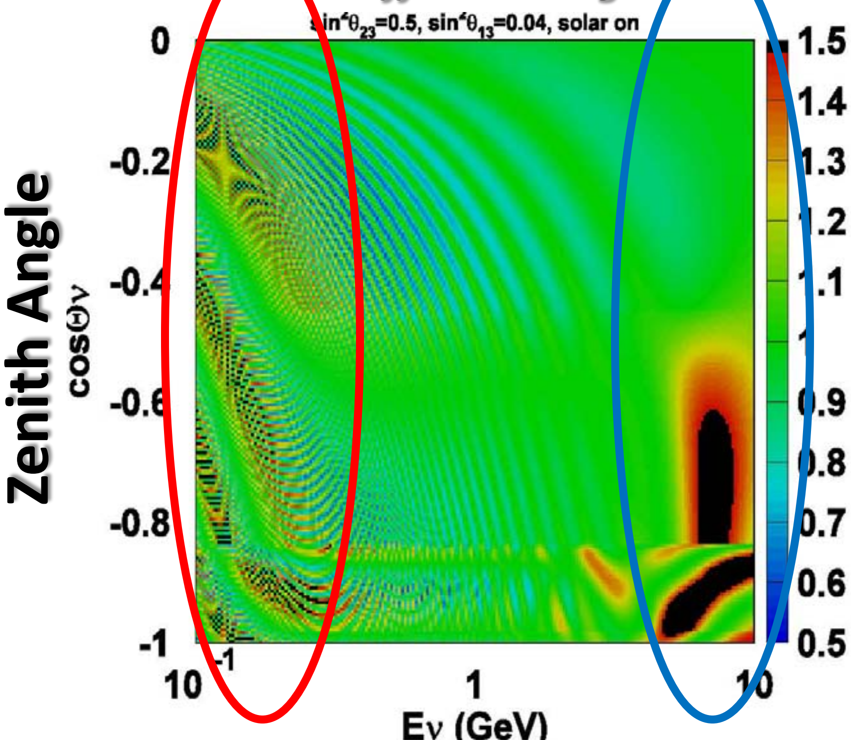
See subdominant effects in three flavour analysis

Three flavor analysis
ν_e appearance in atmospheric-ν

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong P_2(r \cdot c_{23}^2 - 1) - r \cdot \tilde{s}_{13} \cdot \tilde{c}_{13}^2 \cdot \sin 2\vartheta_{23} (\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2) + 2\tilde{s}_{13}^2 (r \cdot s_{23}^2 - 1)$$

- ~ : mixing angle in matter
- $P_2 = |A_{e\mu}|^2$: $\nu_e \rightarrow \nu_{\mu\tau}$ in matter
- $R_2 = \mathrm{Re}(A^*_{ee} A_{e\mu})$
- $I_2 = \mathrm{Im}(A^*_{ee} A_{e\mu})$

Matter effect through the earth



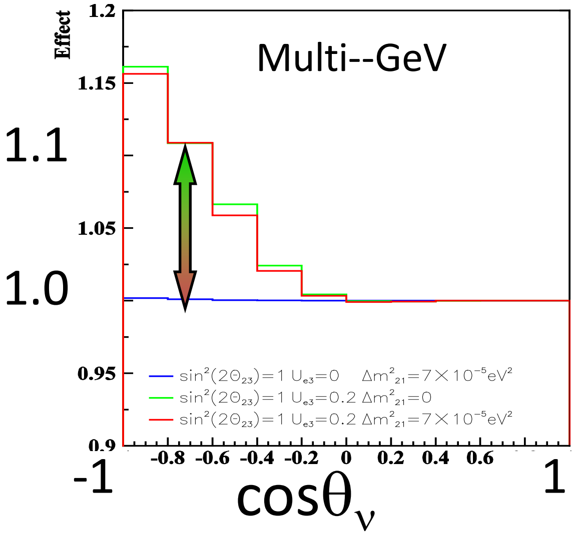
$s^2 2\theta_{12}$=0.825, $s^2\theta_{23}$=0.4, $s^2\theta_{13}$=0.04
δ_{cp}=45°, Δm^2_{12}=8.3x10^{-5}, Δm^2_{23}=2.5x10^{-3}

1st term: solar term (θ_{12}, Δm_{12})
mostly in low energy
cancellation effect (c^2_{23}=0.5, r=ν_μ/ν_e=2@LE)
1~2% effect

3rd term: θ_{13} term
> a few GeV (in multi-GeV data)
10~15% effect

2nd term: Interference
CP-Phase

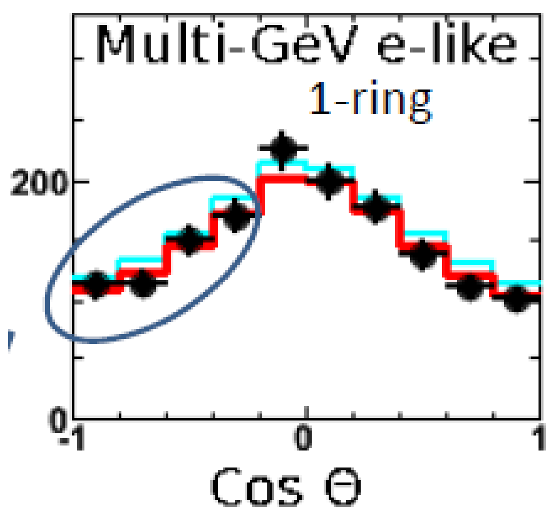
θ_{13}

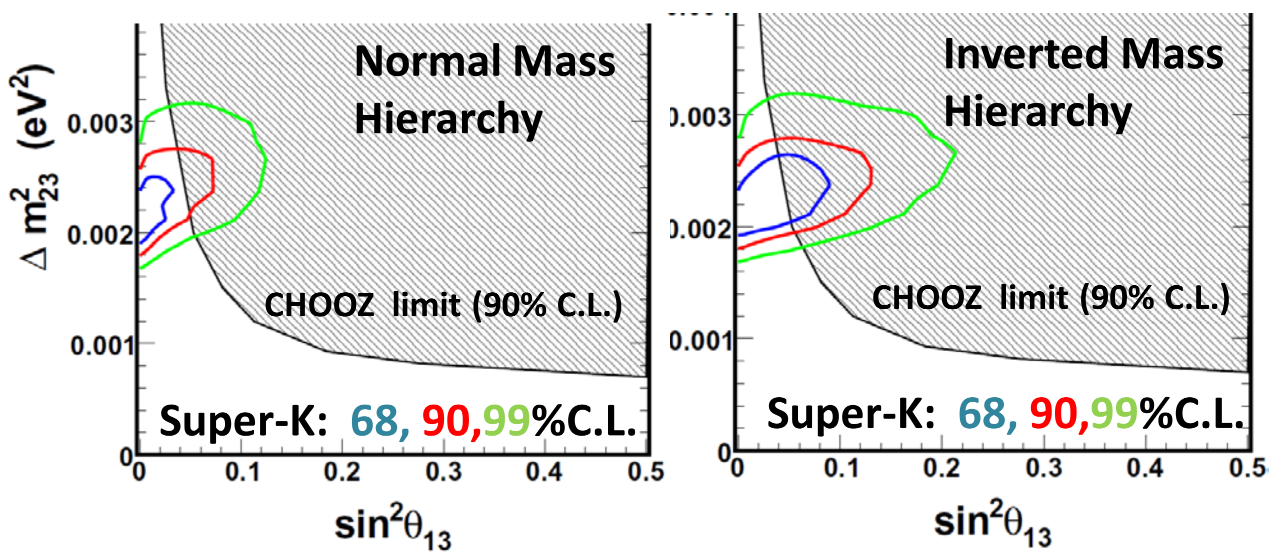


- Effect of θ_{13} can be seen in a few GeV electron data

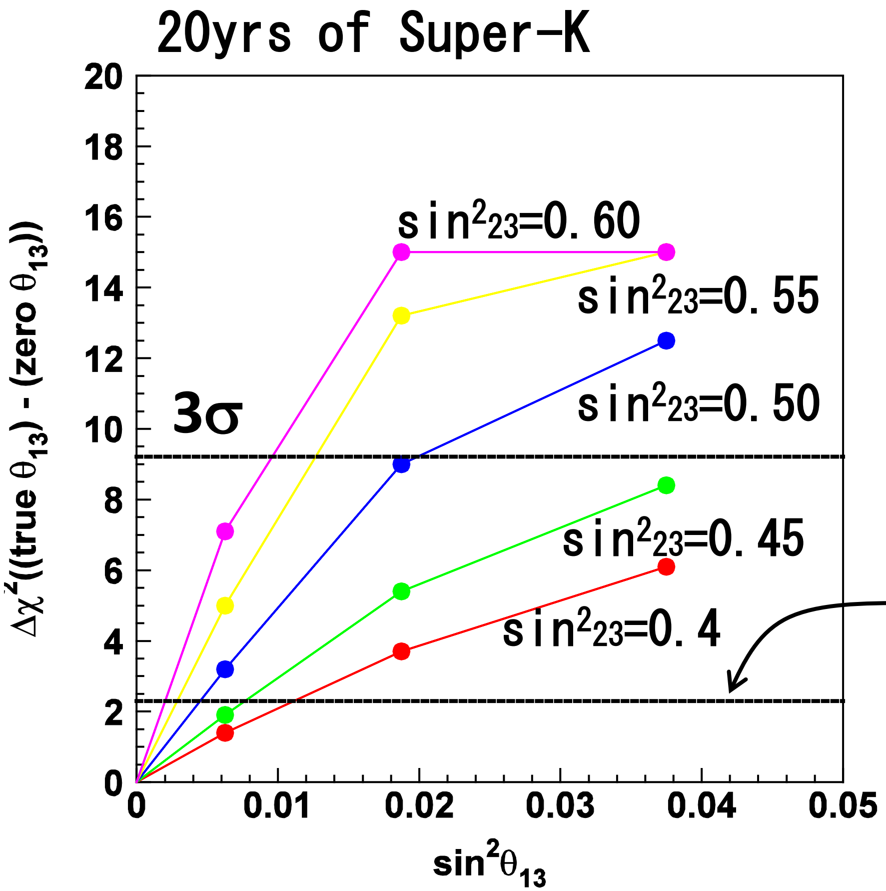
For SK-I, II, III combined data

- $\sin^2\theta_{13} < 0.07$ (90% C.L.)
  - Normal Hierarchy
- $\sin^2\theta_{13} < 0.13$ (90% C.L.)
  - Inverted Hierarchy





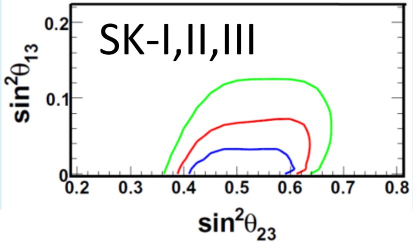
θ_{13} in future



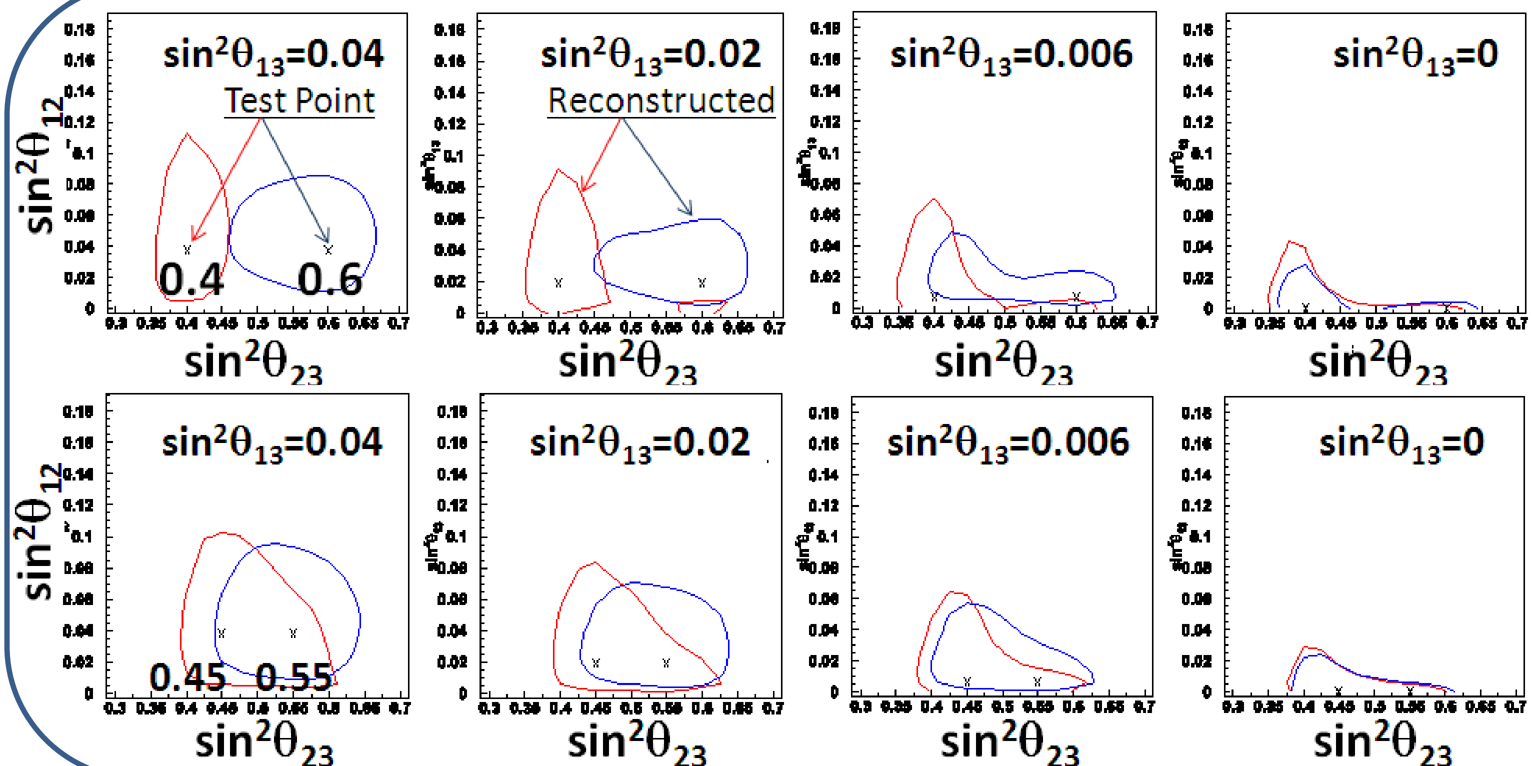
20yrs SK: Positive signal for nonzero θ_{13} can be seen if $\sin^2\theta_{13}$ is > 0.02 and $\sin^2\theta_{23}$ > 0.5

3σ for 80yrs SK
~4yrs HK

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00 \sim 0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3e-5$
$\Delta m^2_{23}=2.5e-3$



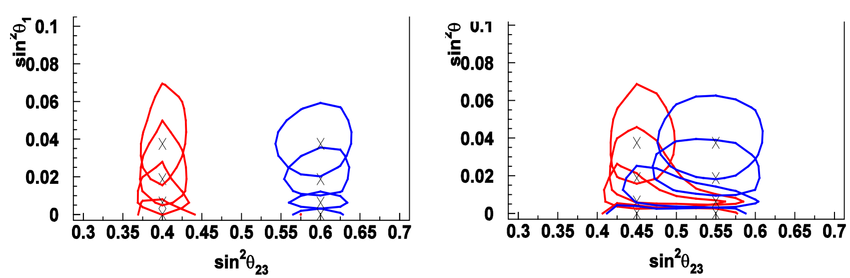
Octant (in future)



Monte Carlo
SK (22.5kt f.v.)
20 years

Can be seen: for $\sin^2\theta_{13}$>0.02 & $\sin^2\theta_{23}$<0.4 or $\sin^2\theta_{23}$>0.6

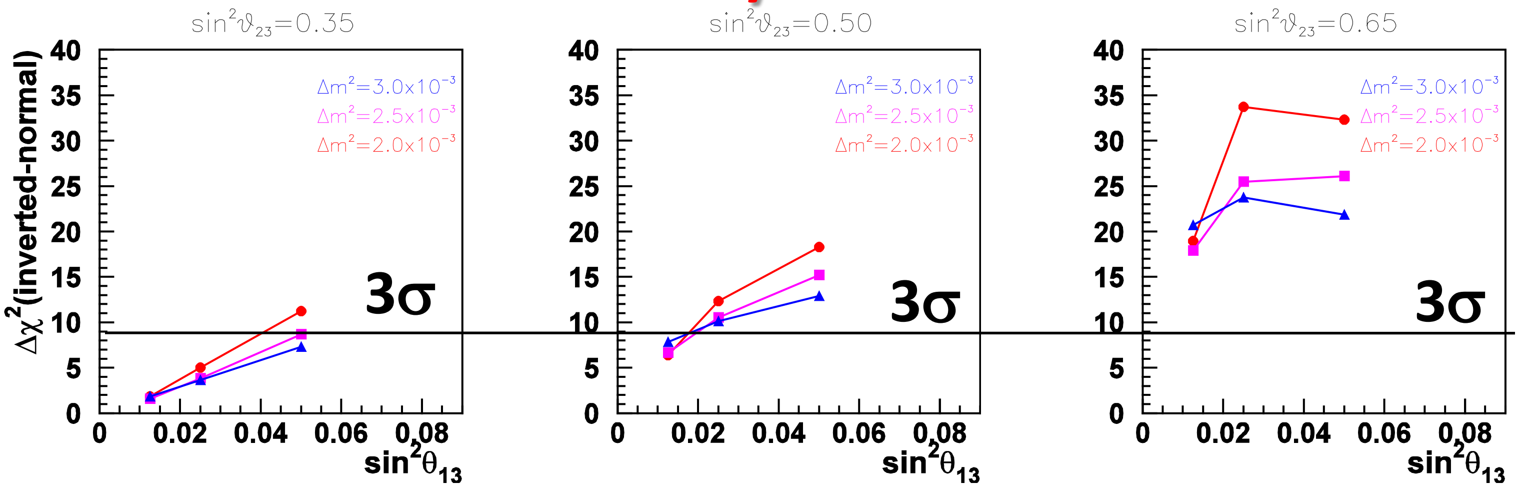
$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00 \sim 0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$



Monte Carlo
0.5Mt f.v. det.
3.6 years

Mass Hierarchy

True : normal mass hierarchy



1.8 Mton・yr

3.6yr HK

Can be seen

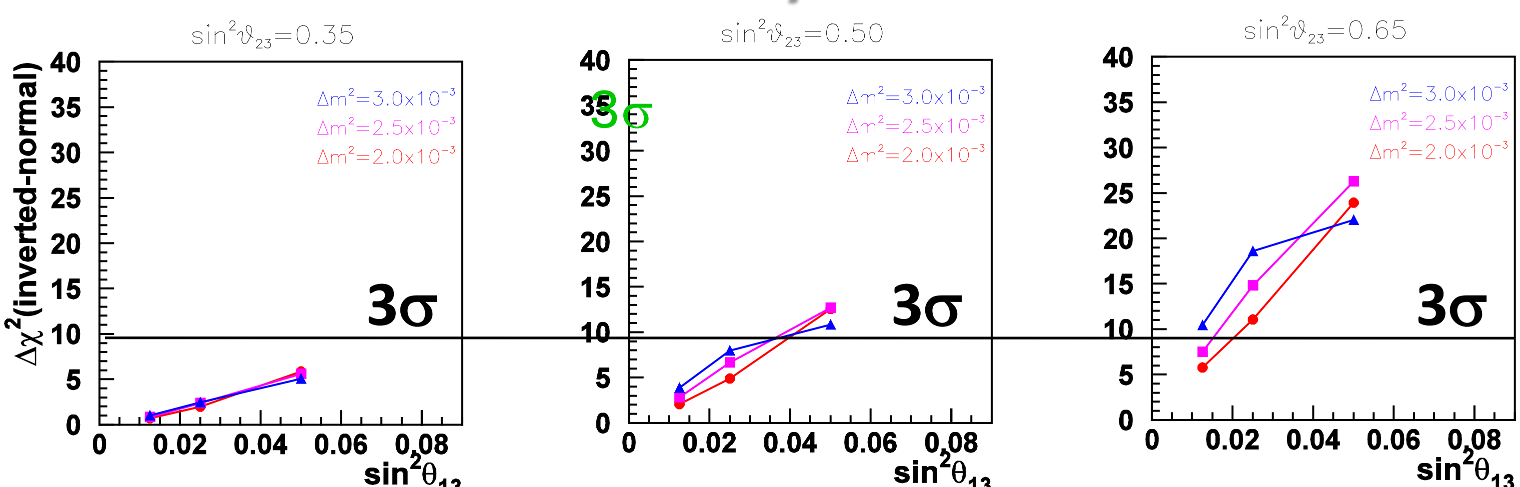
for

$\sin^2\theta_{13}$>0.02

$\sin^2\theta_{23}$>0.5

(normal)

True : inverted mass hierarchy



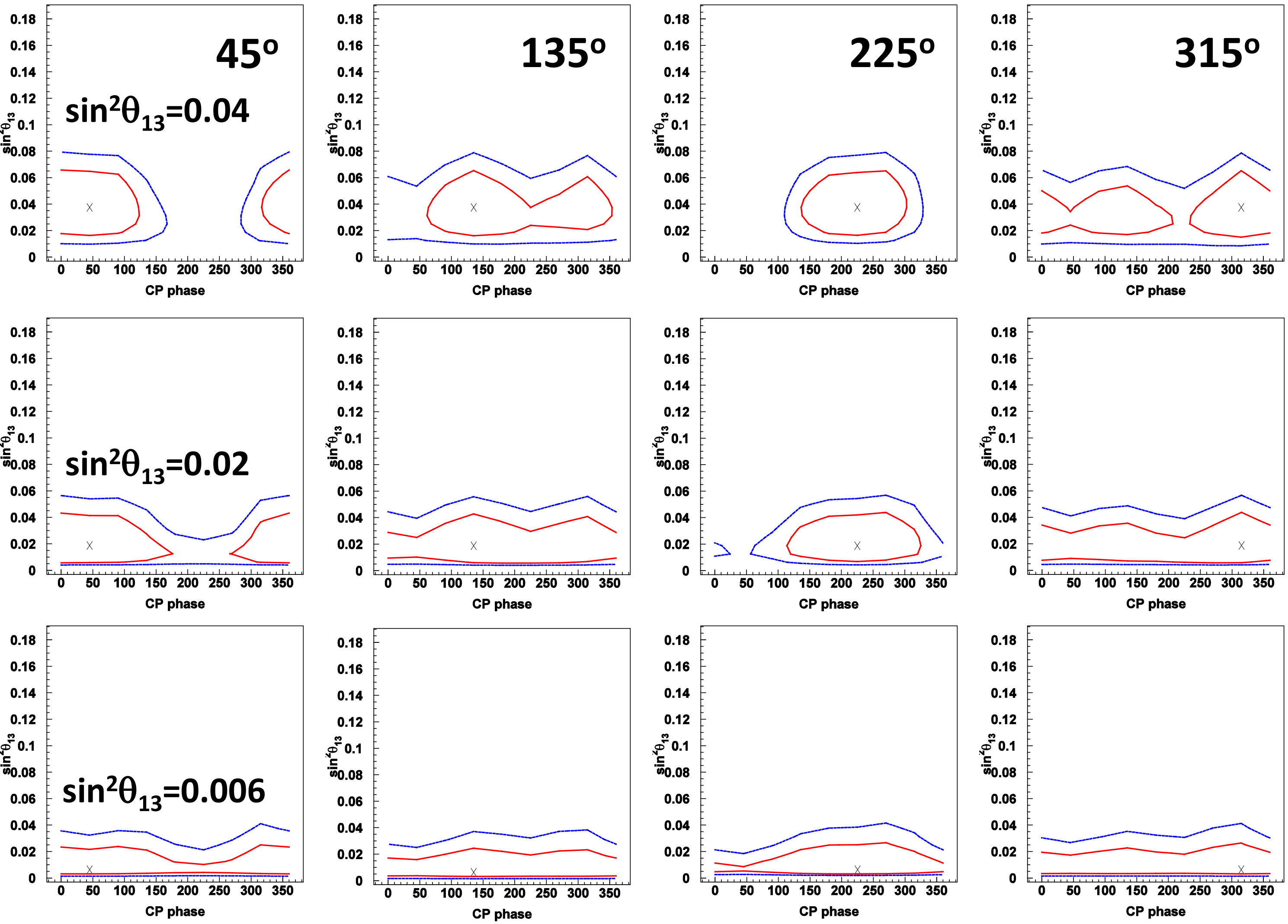
for

$\sin^2\theta_{13}$>0.02

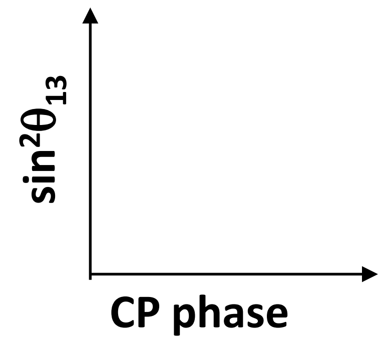
$\sin^2\theta_{23}$>0.65

(inverted)

Sensitivity for CPV (3.6 yrs HK)



$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.006\sim0.04$
$\delta cp=0^o\sim360^o$
$\Delta m^2_{12}=8.3\text{x}10^{-5}$
$\Delta m^2_{23}=2.5\text{x}10^{-3}$

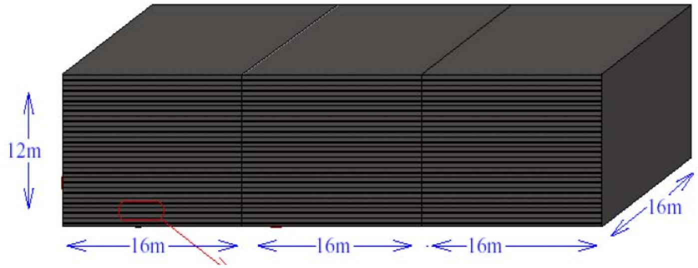


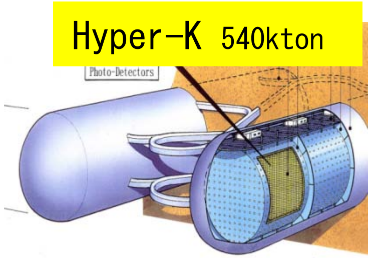
- For HK, CP phase may be seen if θ_{13} is close to the CHOOZ limit

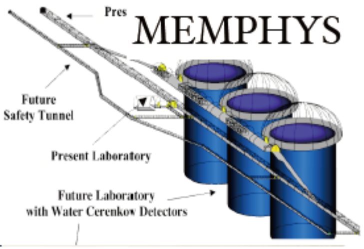
Future atmospheric neutrino experiments beyond Super-K

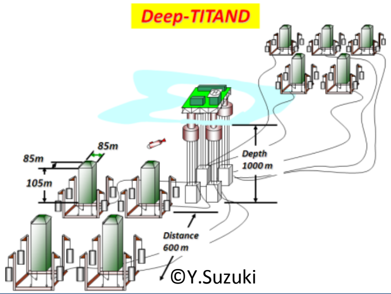
- INO
  - 50 kt magnetized (1.2 Tesla) iron
  - 3 modules
  - Each module = $16x16x12m^3$
  - Can measure charge
    ➔ Mass hierarchy

- Megaton (0.5Mt fid.) detectors (HK, DUSEL,....)
  - Water Cherenkov or Liquid Ar.
  - ➔ Octant
  - ➔ CP phase sensitivity
  - ➔ Mass hierarchy
  - Far detector of long baseline experiments









- **Multi-Megaton detectors (5-10Mt fid.) – Water Cherenkov**
  - Placed 1000m under water
  - Not only atmospheric
    - SN neutrino burst detection every year
    - Proton decay up to 10^{36} yrs

Summary

- $\sim$10 years after the discovery, oscillation parameters are now determined at a few % level
- Solar Neutrinos in future:
  - Transition region: low energy ^{8}B, CNO, pep, ^{7}Be
    - Sensitive to Δm^2
    - Deviation from LMA?
    - CNO is especially interest to resolving metallicity problem of the solar models.
- Atmospheric Neutrinos in future:
  - A complementary method to determine θ_{13} and other subdominant effects.
  - Future large detectors can be used for long baseline oscillation experiments, and can study proton decay as well as atmospheric neutrinos