Status of global fits to neutrino oscillation data

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Outline

* Introduction
* The solar neutrino sector: (Δm^2_{21} , θ_{12})
* The atmospheric neutrino sector: (Δm^2_{32} , θ_{23})
* The reactor mixing angle θ_{13}
* New data released in Neutrino 2012.
* Open questions in neutrino physics.
* Summary

If neutrinos are massive …

In general, the flavor eigenstates are an admixture of the mass eigenstates:

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\, \nu_{iL}$$

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

θ_{23}
θ_{13}
θ_{12}
δ

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

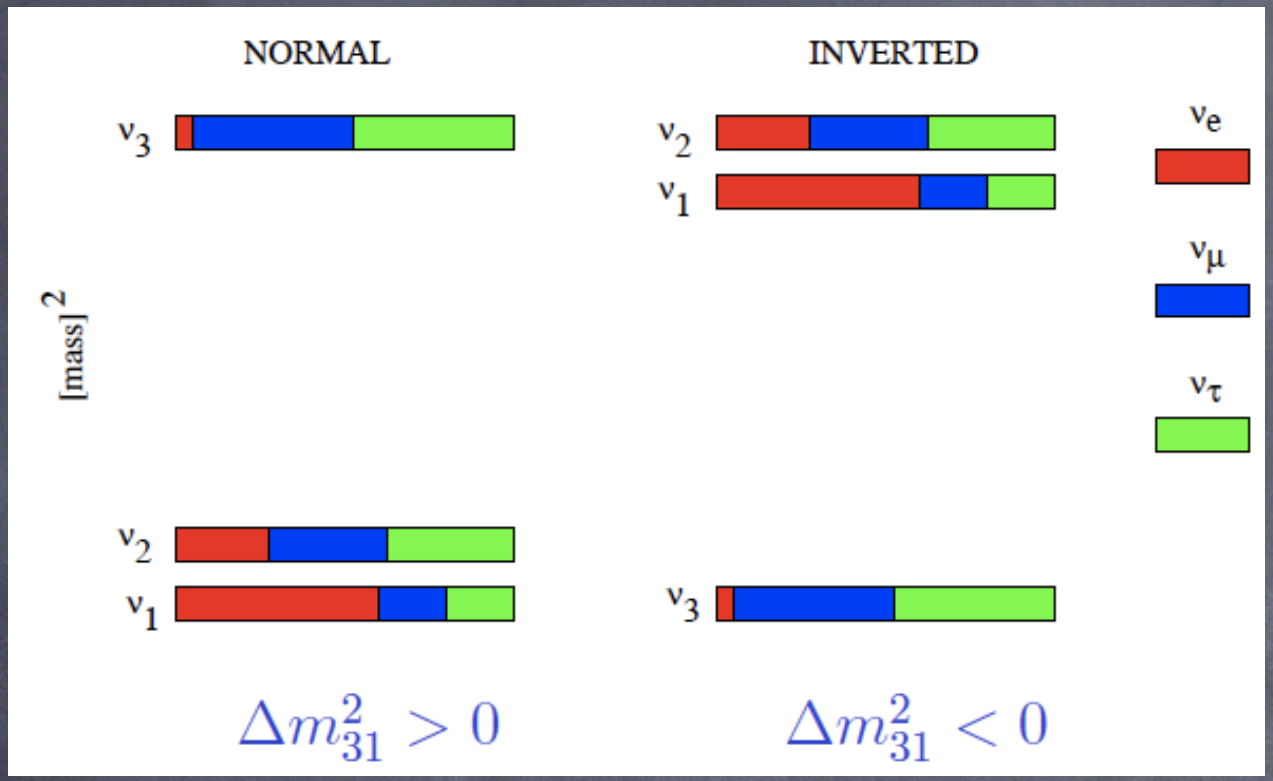
From Atmospheric and Long Baseline Disappearance Measurements

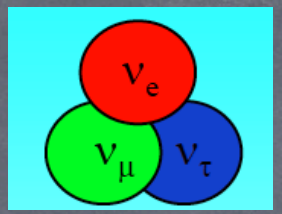
From Reactor Disappearance Measurements

From Appearance Measurements

From Solar Neutrino Measurements

There are two possible mass orderings:





- Neutrino oscillations are sensitive only to Δm^2_{ij}
  - Δm^2_{31} : atmospheric + long-baseline
  - Δm^2_{21} : solar + KamLAND
- absolute scale m_ν: laboratory measurements + cosmology

Absolute scale of neutrino mass

* Tritium β-decay experiments:

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

→ m_β < 2.3 (2.1) eV at 95%CL Mainz (Troitsk) Kraus et al, EPJ C40 (2005) 447

Troitsk Collaboration PRD 84 (2011) 112003

→ KATRIN sensitivity m_β~0.2 eV

* Neutrinoless double β-decay:

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

→ 90%CL upper limit from Heidelberg-Moscow < 0.35 eV

Klapdor-Kleingrothaus et al, EPJ A12 (2001) 147.

* Cosmology: $\Sigma\, m_i = m_1 + m_2 + m_3$

Model	Observables	Σm_ν (eV) 95% Bound
$\alpha\omega\mathrm{CDM} + \Delta N_{\mathrm{rel}} + m_\nu$	CMB+HO+SN+BAO	≤ 1.5
$\alpha\omega\mathrm{CDM} + \Delta N_{\mathrm{rel}} + m_\nu$	CMB+HO+SN+LSSPS	≤ 0.76
$\Lambda\mathrm{CDM} + m_\nu$	CMB+H0+SN+BAO	≤ 0.61
$\Lambda\mathrm{CDM} + m_\nu$	CMB+H0+SN+LSSPS	≤ 0.36
$\Lambda\mathrm{CDM} + m_\nu$	CMB (+SN)	≤ 1.2
$\Lambda\mathrm{CDM} + m_\nu$	CMB+BAO	≤ 0.75
$\Lambda\mathrm{CDM} + m_\nu$	CMB+LSSPS	≤ 0.55
$\Lambda\mathrm{CDM} + m_\nu$	CMB+H0	≤ 0.45

González-García et al, JHEP 1008 (2010) 117.

WMAP-7yr + SDSSIII + HST:

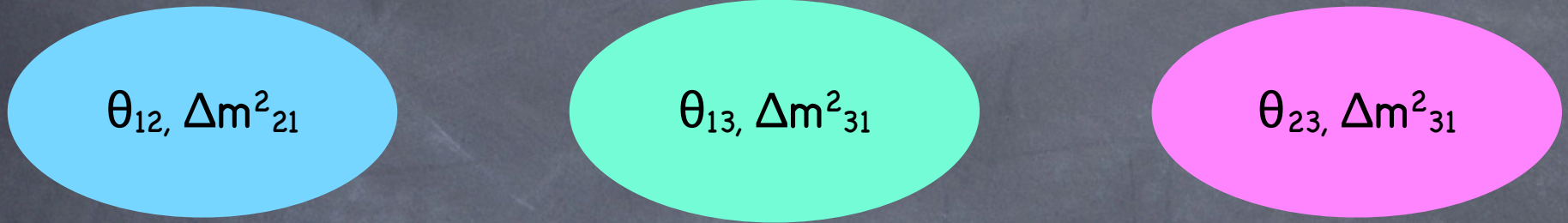
Σ m_i < 0.26-0.36 (95% CL)

de Putter et al, arXiv: 1201.1909

Determination of oscillation parameters from global ν data

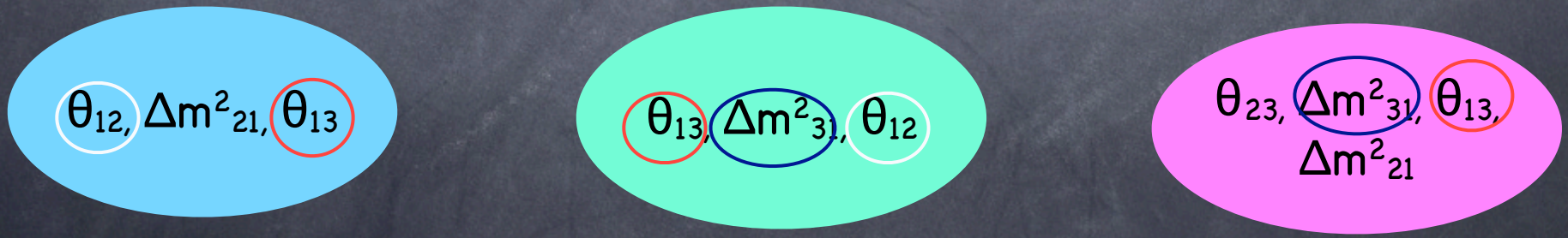
two-neutrino approximation:

$\Delta m^2_{21} \ll \Delta m^2_{31}$



solar + KamLAND | Reactor | atmospheric + LBL

three-neutrino analysis:



all data samples are connected → a global 3ν analysis is required.

The solar neutrino sector: (Δm^2_{21}, $\sin^2\theta_{12}$)

Solar neutrinos

* produced in nuclear reactions in the core of the Sun:

$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + \gamma$

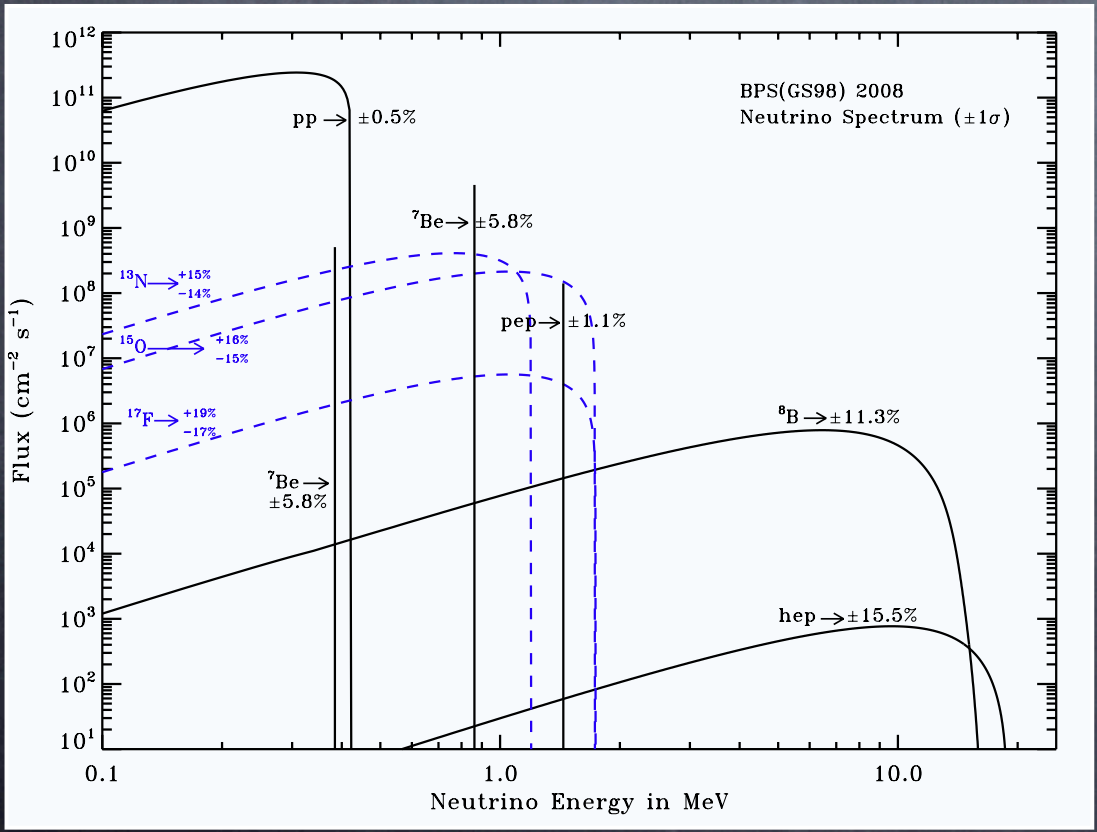
pp cycle

CNO

Reaction	source	Flux ($cm^{-2}s^{-1}$)
$p\ p \rightarrow d\ e^+\ \nu$	pp	$5.97(1 \pm 0.006)\times10^{10}$
$p\ e^-\ p \rightarrow d\ \nu$	pep	$1.41(1 \pm 0.011)\times10^{8}$
$^3He\ p \rightarrow {}^4He\ e^+\ \nu$	hep	$7.90(1\pm 0.15)\times10^{3}$
$^7Be\ e^- \rightarrow {}^7Li\ \nu\ \gamma$	^{7}Be	$5.07(1 \pm 0.06)\times10^{9}$
$^8B \rightarrow {}^8Be^*\ e^+\ \nu$	^{8}B	$5.94(1 \pm 0.11)\times10^{6}$
$^{13}N \rightarrow {}^{13}C\ e^+\ \nu$	^{13}N	$2.88(1 \pm 0.15)\times10^{8}$
$^{15}O \rightarrow {}^{15}N\ e^+\ \nu$	^{15}O	$2.15(1 \pm {}^{0.17}_{0.16})\times 10^{8}$
$^{17}F \rightarrow {}^{17}O\ e^+\ \nu$	^{17}F	$5.82(1 \pm {}^{0.19}_{0.17})\times10^{6}$

ν fluxes

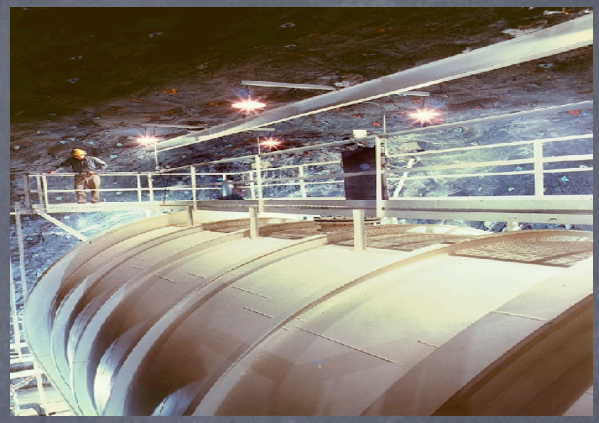
SSM predictions



ν energy spectra

Peña-Garay & Serenelli,arXiv:0811.2424

Solar neutrino detectors

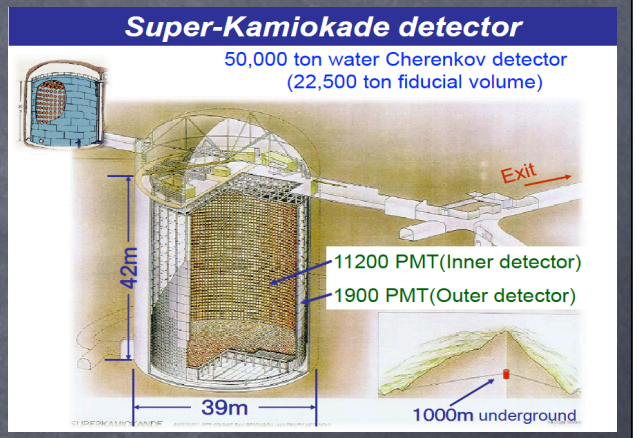


Radiochemical experiments

- Homestake (Cl)
- Gallium experiments (GALLEX/GNO, SAGE)

-> total # ν_e , no energy or time information

-> 33-50% of SSM prediction detected



Real-time detectors

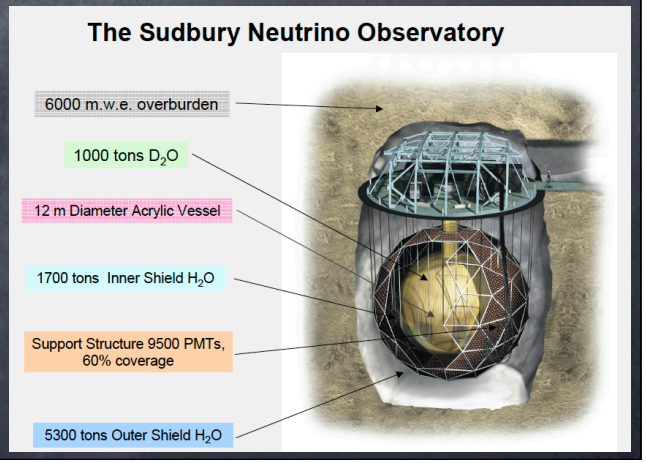
- Super-Kamiokande (water Cherenkov): ES
- SNO (heavy water): CC, NC, ES
- Borexino (liquid scintillator): ES

-> provide information about neutrino spectrum and time of interaction

-> sensitive to all ν flavours:

[CC]~30%, [ES]~40%, [NC]~100%

⇒ all produced solar neutrinos are detected.



Solar ν oscillation parameters

Homestake ($E_\nu > 0.814$ MeV)

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

SAGE/GALLEX-GNO ($E_\nu > 0.233$ MeV)

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

Super-Kamiokande ($E_e \gtrsim 5$ MeV)

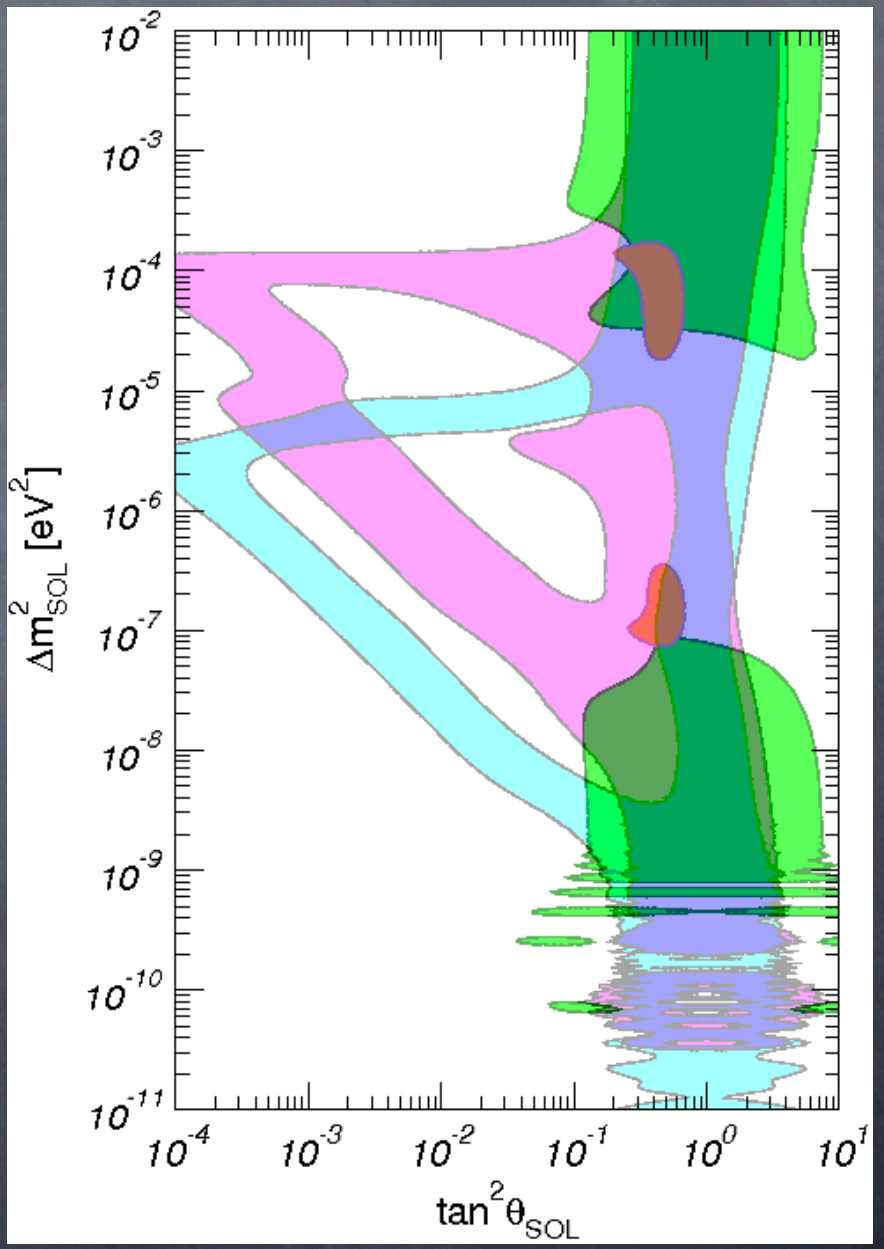
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

SNO ($E_e \gtrsim 5$ MeV)

[CC] $\nu_e + d \rightarrow p + p + e^-$

[NC] $\nu_x + d \rightarrow \nu_x + n + p$

[ES] $\nu_x + e^- \rightarrow \nu_x + e^-$



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SNO ($E_e \gtrsim 5$ MeV)

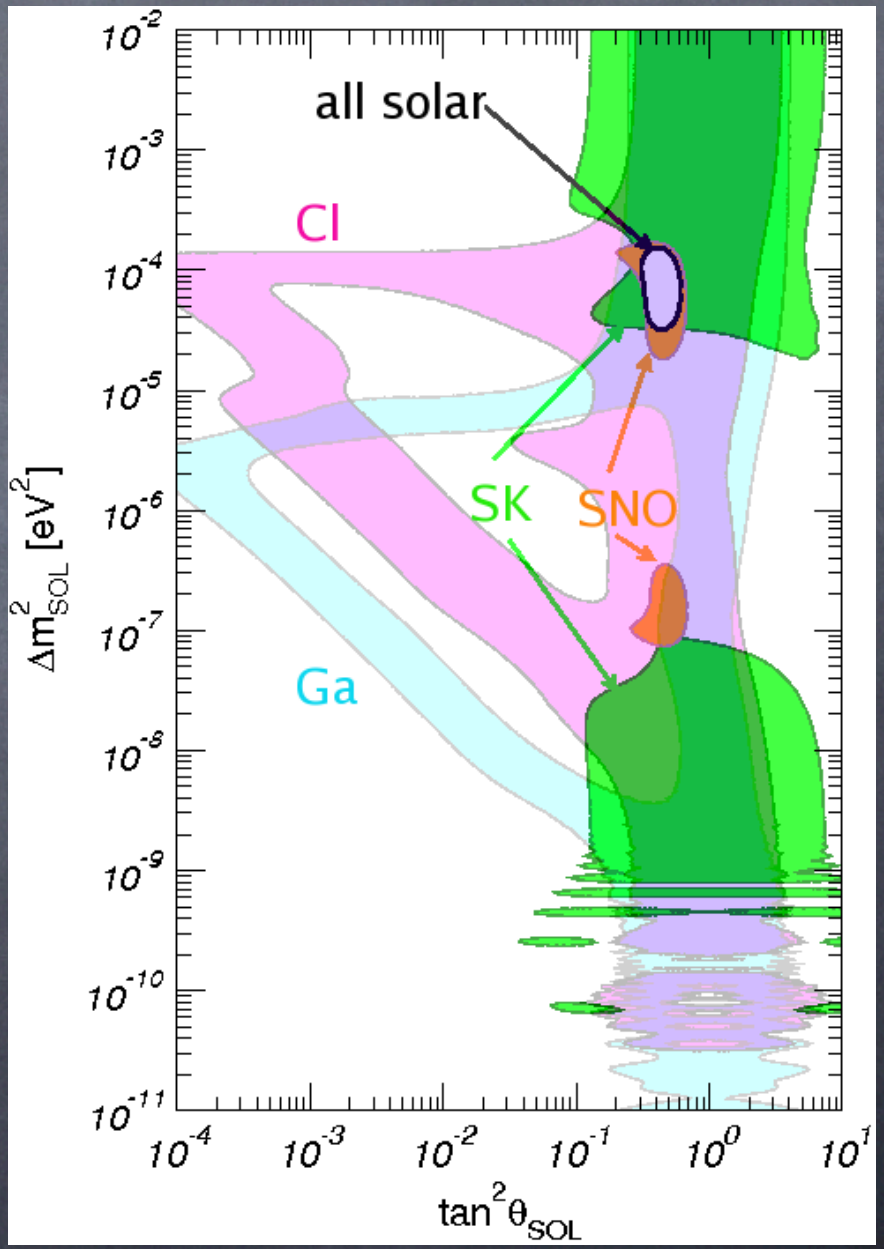
[CC] $\nu_e + d \rightarrow p + p + e^-$

[NC] $\nu_x + d \rightarrow \nu_x + n + p$

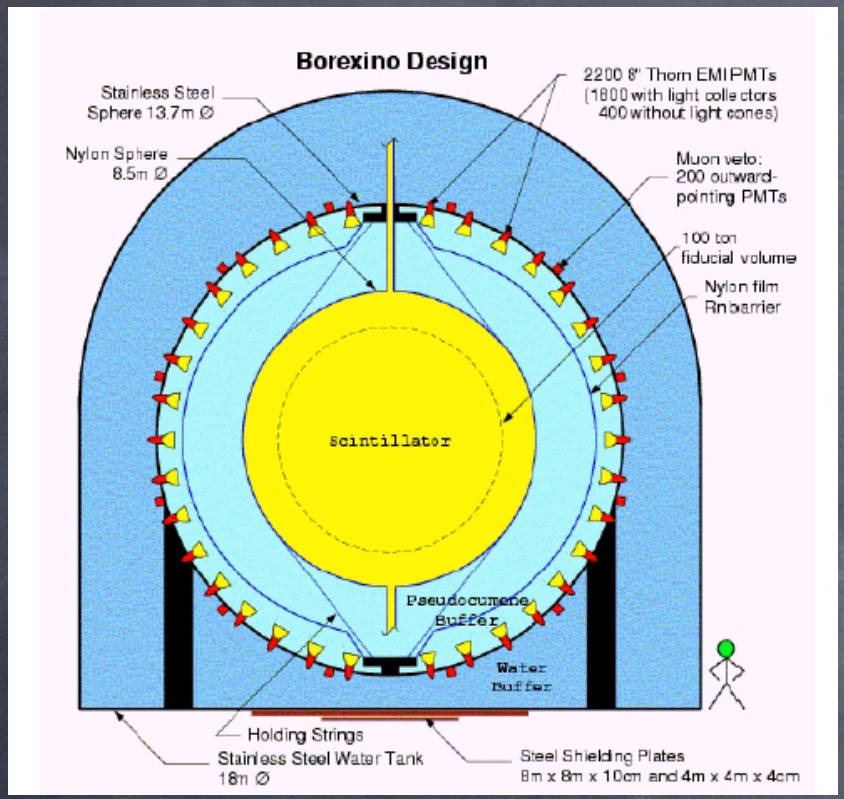
[ES] $\nu_x + e^- \rightarrow \nu_x + e^-$

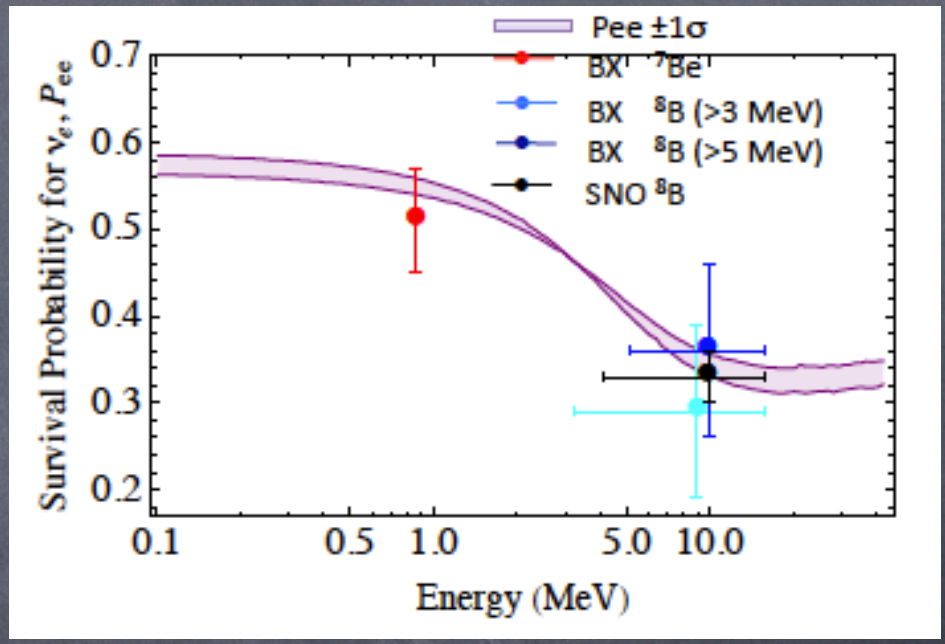
→ only LMA allowed at 3σ

→ max. mixing excluded at 5σ



Borexino: detection of low energy solar neutrinos





- 300 ton. liquid scintillator
- first real-time measurement of 7Be neutrinos (< 5% error)
- first real-time measurement of 8B flux below 4 MeV

→ consistent with LMA parameters

The KamLAND reactor experiment

* reactor experiment: $\bar{\nu}_e + p \rightarrow e^+ + n$
* CPT invariance: (Δm^2_{21} , θ_{12})
* average distance ~ 180 km

→ sensitive to $\Delta m^2_{21} \sim 10^{-5}$ eV^2 (Δm^2_{LMA})

2002: First evidence $\bar{\nu}_e$ disappearance

→ confirmation of solar LMA ν oscillations

KamLAND Coll, PRL 90 (2003) 021802

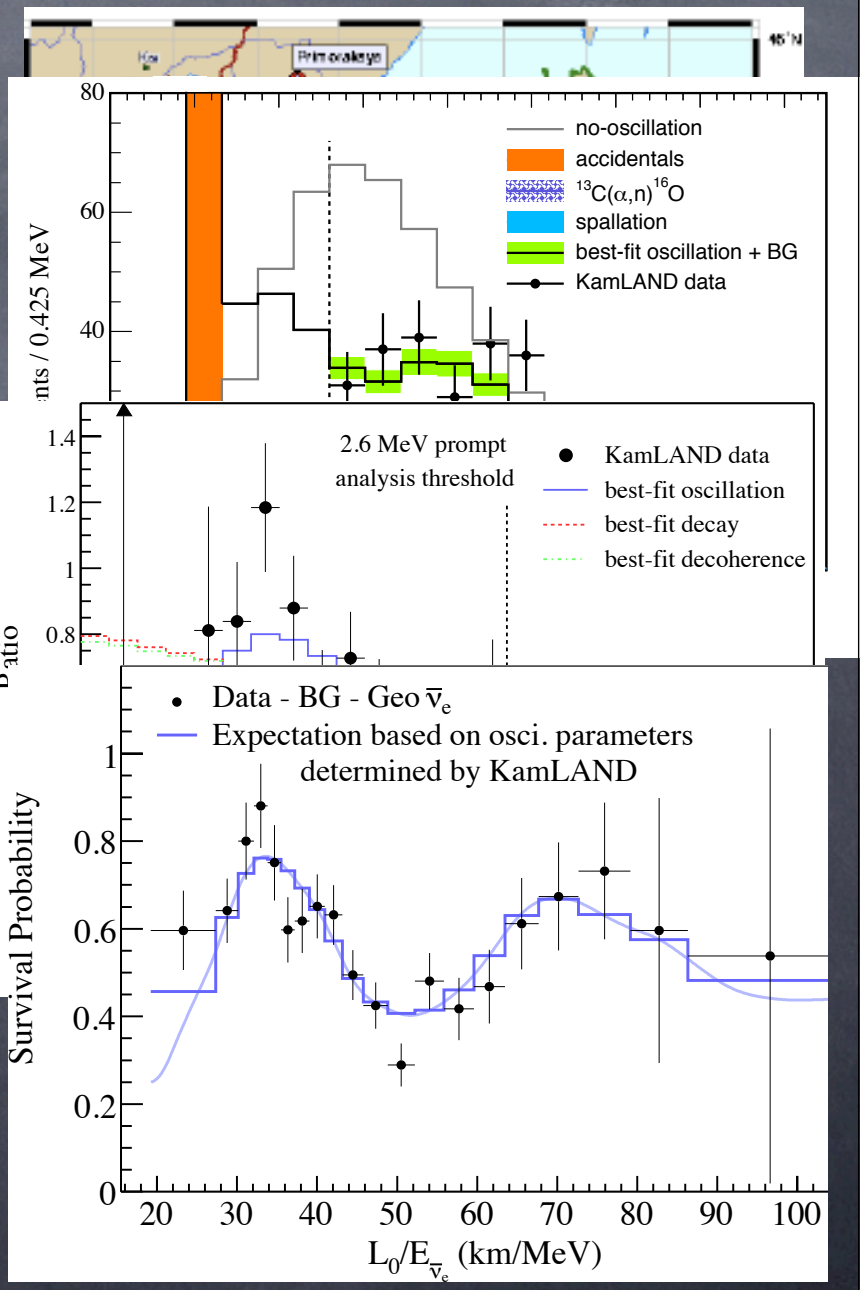
2004: spectral distortions (L/E)

KamLAND Coll, PRL 94 (2005) 081801

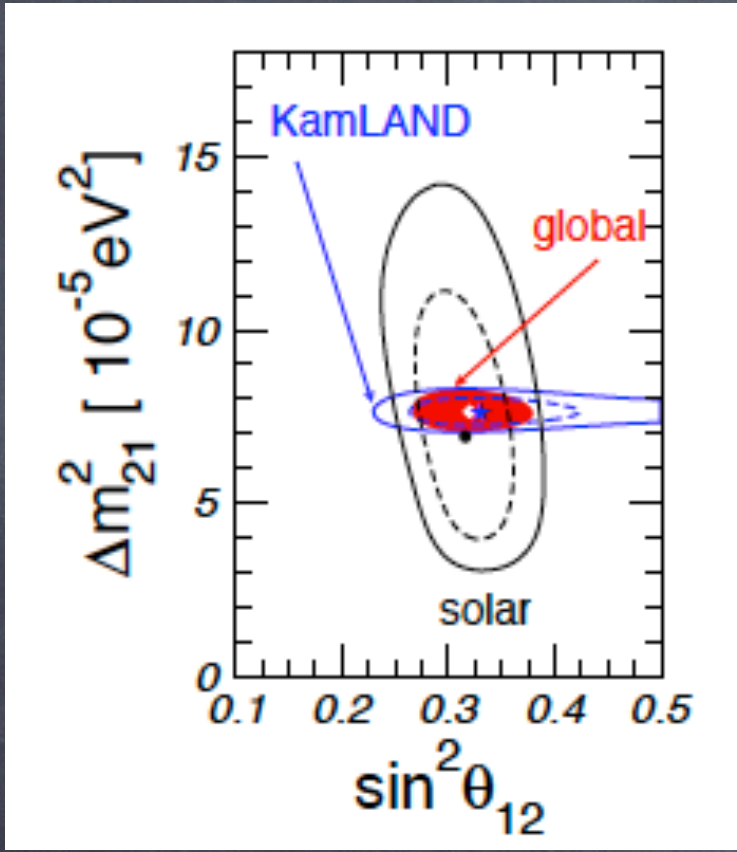
2008: 1-period oscillations observed

→ high precision determination Δm^2_{21}

KamLAND Coll, PRL 100 (2008) 221803



Combined analysis solar + KamLAND data



- KamLAND confirms LMA
- Best fit point:
  $\sin^2\theta_{12} = 0.320\ ^{+0.015}_{-0.017}$
  $\Delta m^2_{21} = 7.62 \pm 0.19 \times 10^{-5}$ eV^2
- max. mixing excluded at more than 7σ

Forero, M.T., Valle, arXiv:1205.4018 [hep-ph]

➡ Bound on θ_{12} dominated by solar data.

➡ Bound on Δm^2_{21} dominated by KamLAND.

The atmospheric neutrino sector: (Δm^2_{31}, $\sin^2\theta_{23}$)

Atmospheric neutrinos

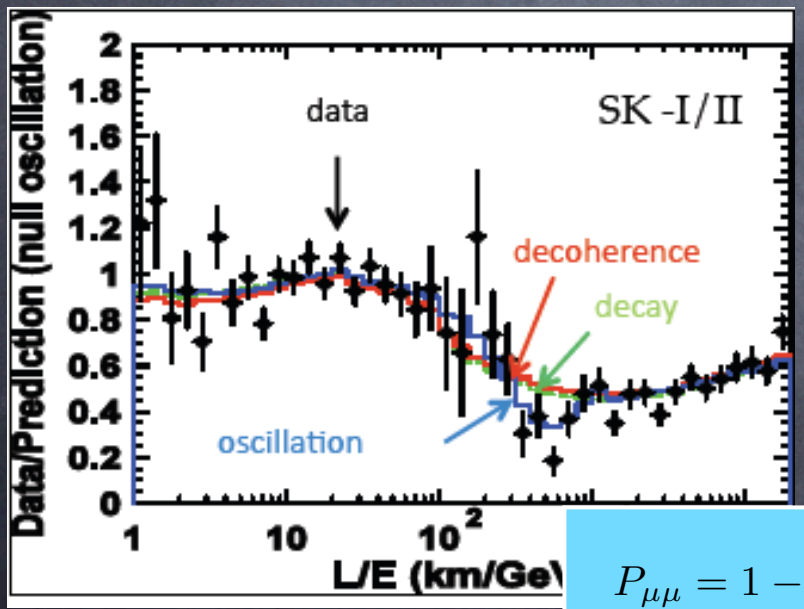
Cosmic rays interacting with the Earth atmosphere producing pions and kaons, that decay generating neutrinos:

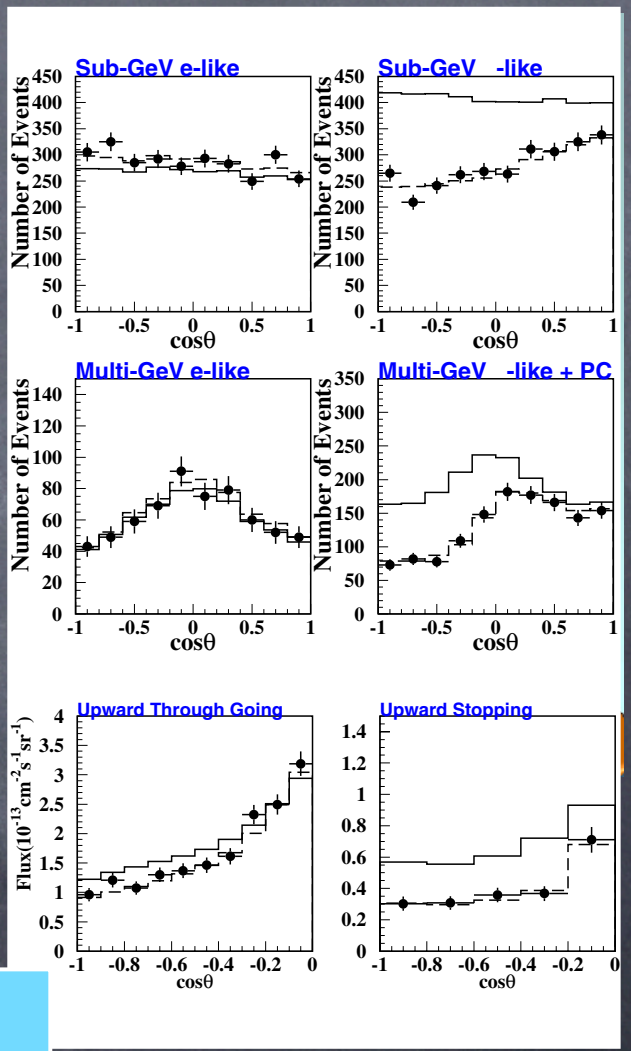
$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

1998: Evidence ν_μ oscillations at Super-K: $\nu_\mu \to \nu_\tau$

2004: oscillatory L/E pattern





$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4}\frac{L}{E_\nu}\right)$$

Super-K Coll, PRL93, 101801 (2004)

Super-K Coll., PRL 8 (1998) 1562.

Long-baseline accelerator experiments

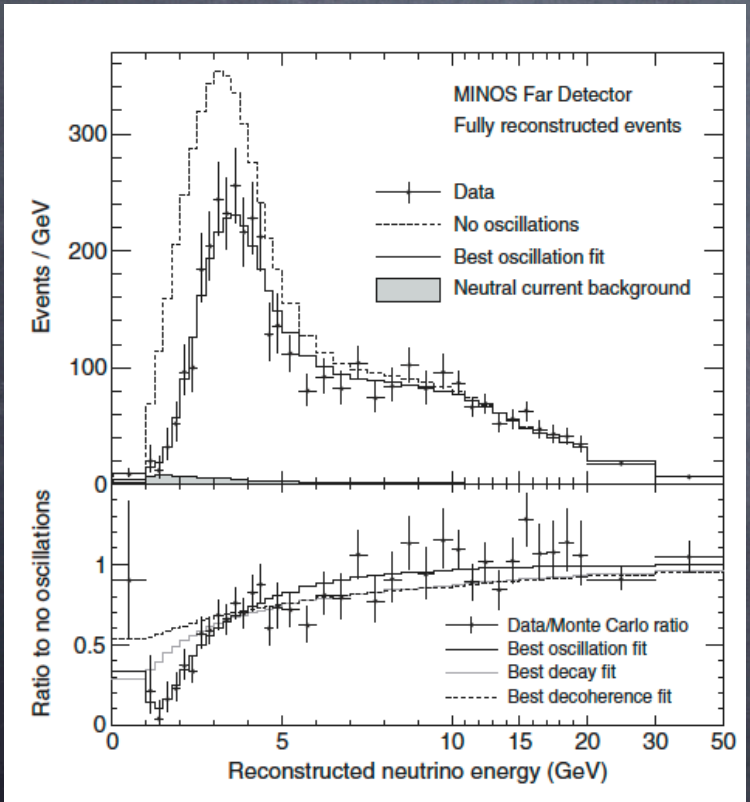
Neutrino beam production:

$$p + X \rightarrow \pi^{\pm} + Y$$

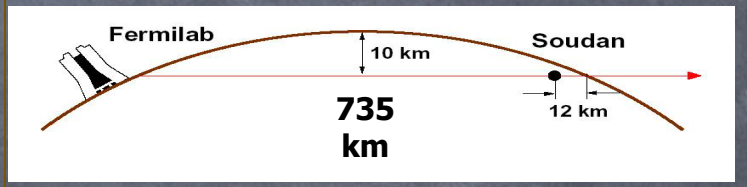
$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

Goal: test atmospheric oscillations and improve parameter determination.
-> the experimental setup must be adjusted to be sensitive to $\Delta m^2 \sim 10^{-3}$ eV^2.



MINOS: Fermilab → Soudan



- ν_μ disappearance
- spectral distortions

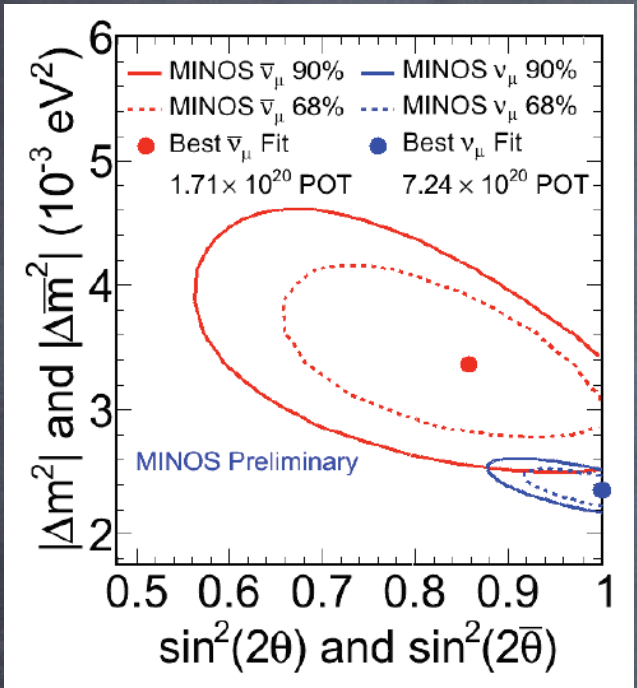
→ consistent with atmospheric data

→ atm oscillations confirmed by lab. exps.

[MINOS Collaboration], PRL106, 181801 (2011)

MINOS neutrino and neutrino results

[MINOS Collaboration], PRL107, 021801 (2011)

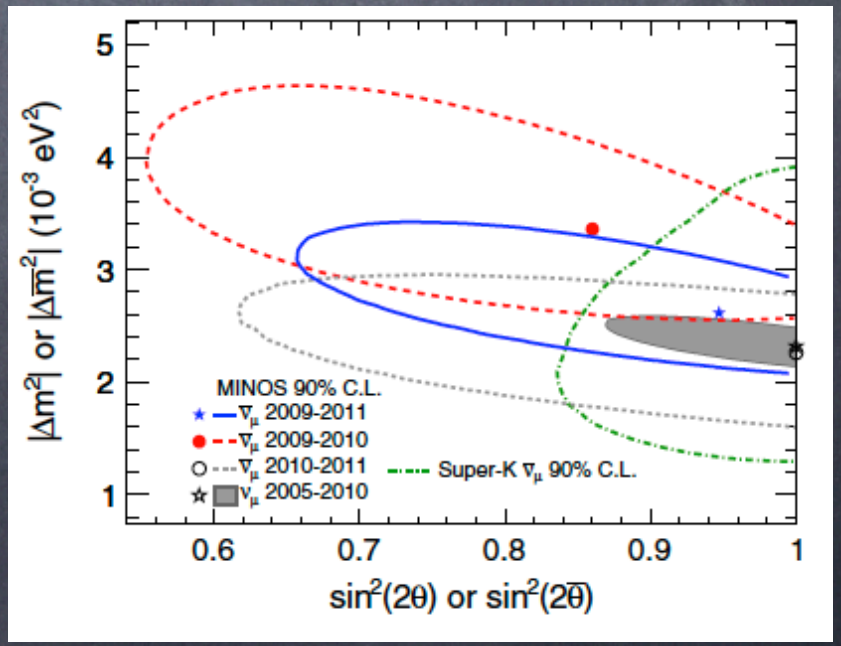


$$|\Delta m^2| = 2.35^{+0.11}_{-0.08}\times10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(2\theta) > 0.91\,(90\%\,\mathrm{C.L.})$$

$$|\overline{\Delta m^2}| = 3.36^{+0.45}_{-0.40}\times10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}) = 0.86\pm0.11$$

2σ inconsistency

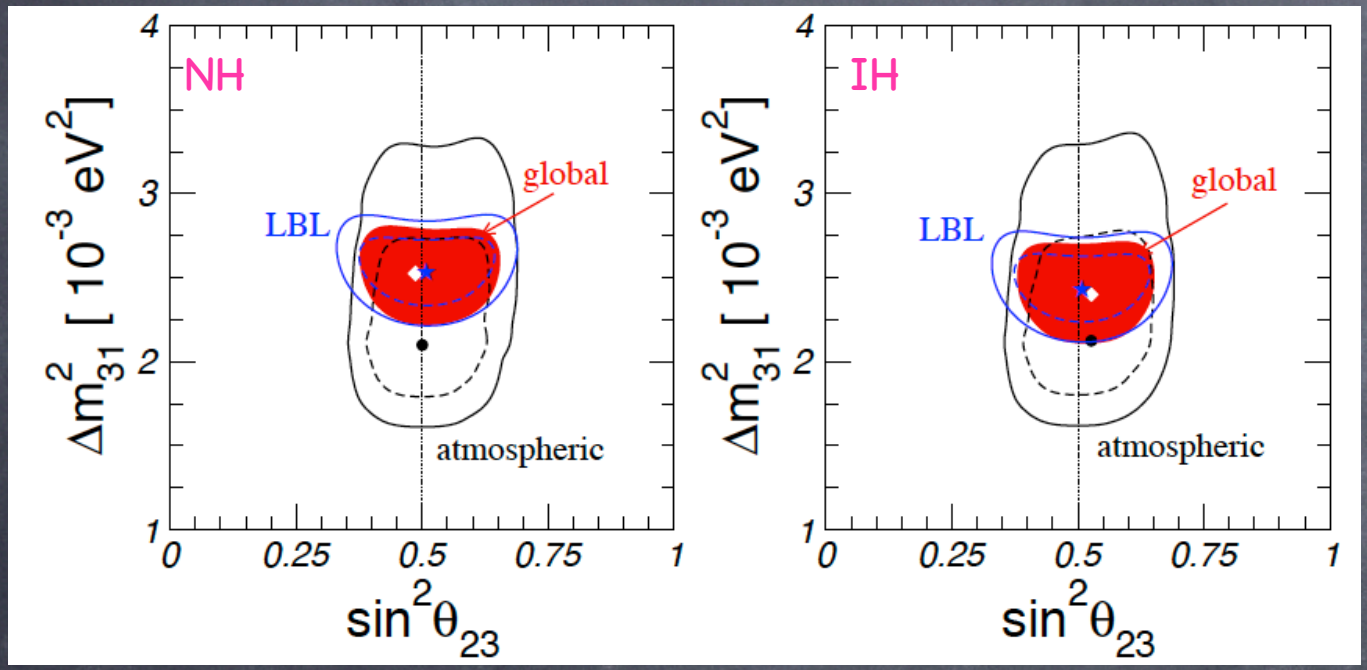
[MINOS Collaboration], PRL108, 191801 (2012)



$$\Delta\bar{m}^2 = [2.62^{+0.31}_{-0.28}(\mathrm{stat})\pm0.09(\mathrm{syst})]\times10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}) = 0.95^{+0.10}_{-0.11}(\mathrm{stat})\pm0.01(\mathrm{syst}),$$
$$\sin^2(2\bar{\theta}) > 0.75(90\%\mathrm{C.L.}),$$

Combined analysis atmospheric + LBL data

- Super-Kamiokande (I + II + III) + K2K and MINOS long-baseline data



- Determination of θ_{23} and Δm^2_{31} is now dominated by LBL data

Forero, M.T., Valle, arXiv:1205.4018 [hep-ph]

* Best fit point:

$\sin^2\theta_{23} = 0.49^{+0.08}_{-0.05}$

$\Delta m^2_{31} = 2.53^{+0.08}_{-0.10} \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.53^{+0.05}_{-0.07}$

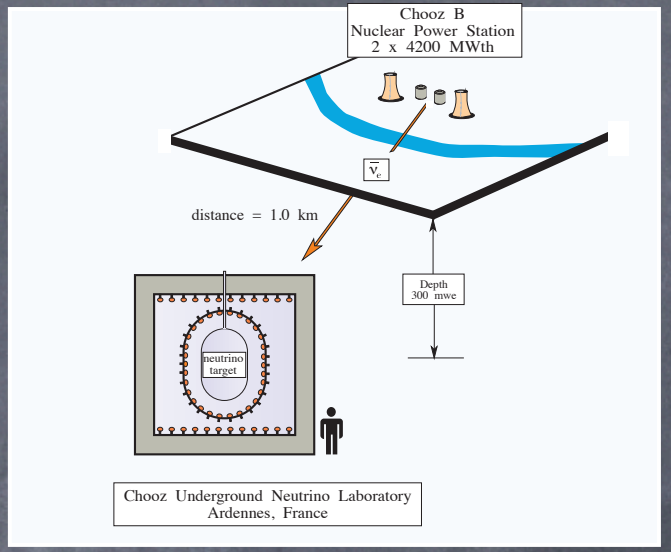
$\Delta m^2_{31} = -(2.40^{+0.10}_{-0.07} \times 10^{-3})$ eV^2

The reactor mixing angle θ_{13}

The CHOOZ reactor experiment

- disappearance reactor ν_e
- L = 1 km, E~MeV
- 2ν approx: Δm^2_{31} , θ_{13}

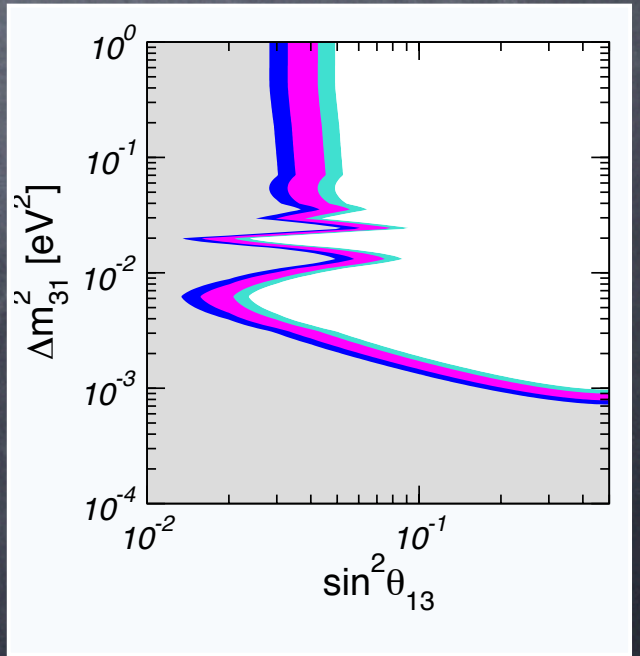
$$P_{ee} = 1 - 2\sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



- non-observation of ν_e disappearance:

R = 1.01 ± 2.8%(stat) ± 2.7%(syst)

→ Exclusion plot (Δm^2_{31} , θ_{13}) plane



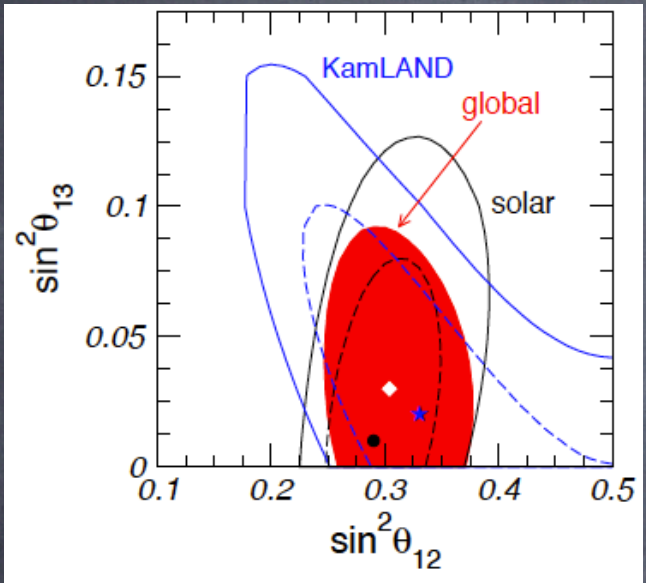
For Δm^2_{31} = 2.5·10^{-3} eV^2

-> $\sin^2\theta_{13}$ < 0.039 (90%CL)

CHOOZ Collaboration, EPJ C27 (2003) 331.

Hints on $\theta_{13} \neq 0$ from combined analysis

solar + KamLAND



Schwetz, MT, Valle, NJP 10 (2008) 113011

→ the interplay between solar and KamLAND data leads to a non-trivial constraint on θ_{13}:

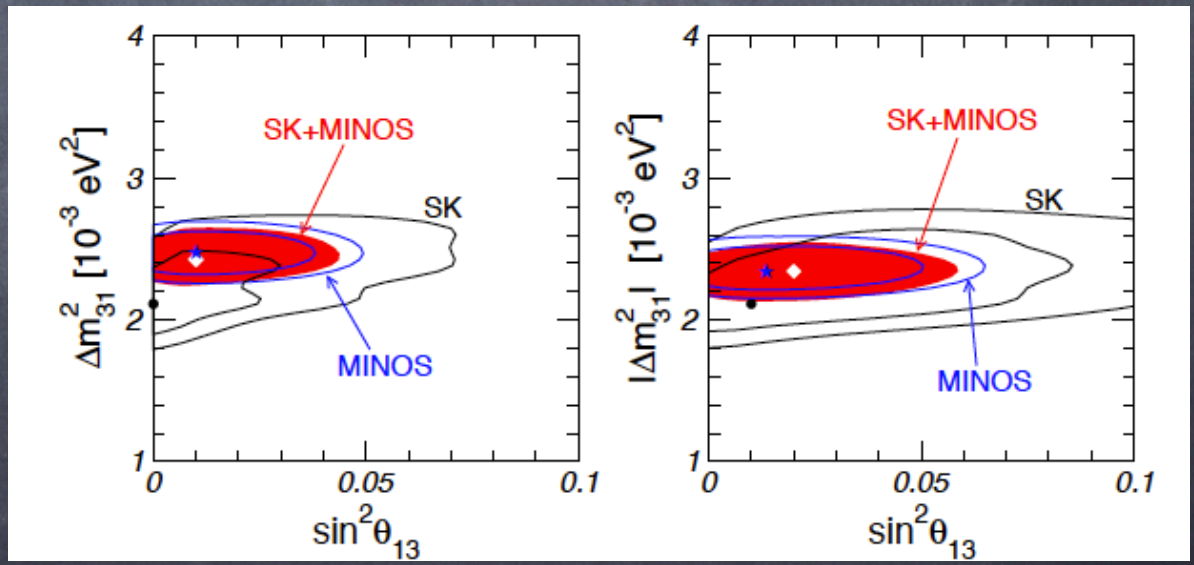
$$\sin^2\theta_{13} = 0.035 \pm {}^{0.016}_{0.015}$$

(2012-updated values)

with $\theta_{13}=0$ disfavoured at 2.3σ

atmospheric + LBL

→ a mismatch between BFP for Δm^2 from atm and LBL data results in a prefered non-zero value for θ_{13}



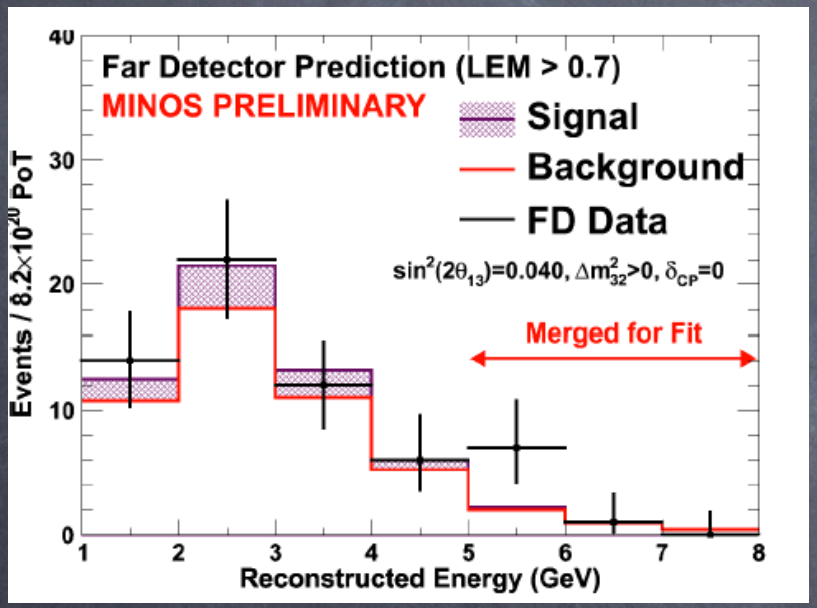
For IH, $\sin^2\theta_{13} = 0.023 \pm {}^{0.015}_{0.012}$

Schwetz, MT, Valle, NJP 13 (2011) 063004

Searches for ν_e appearance

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E) + \ldots$$

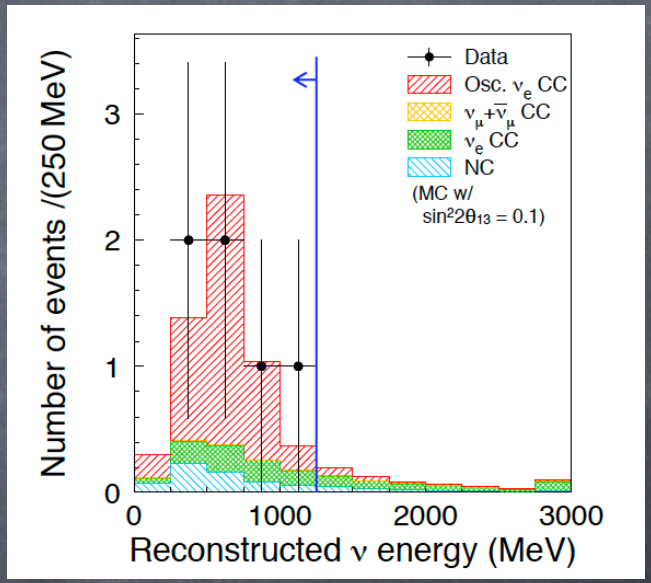
MINOS (8.2x10^{20} p.o.t.)



- 62 electron events observed
- 49.5 ± 7.0 (stat) ± 2.8 (syst) expected
  - ➡ 1.7σ excess

[MINOS Collaboration], PRL107, 181802 (2011)

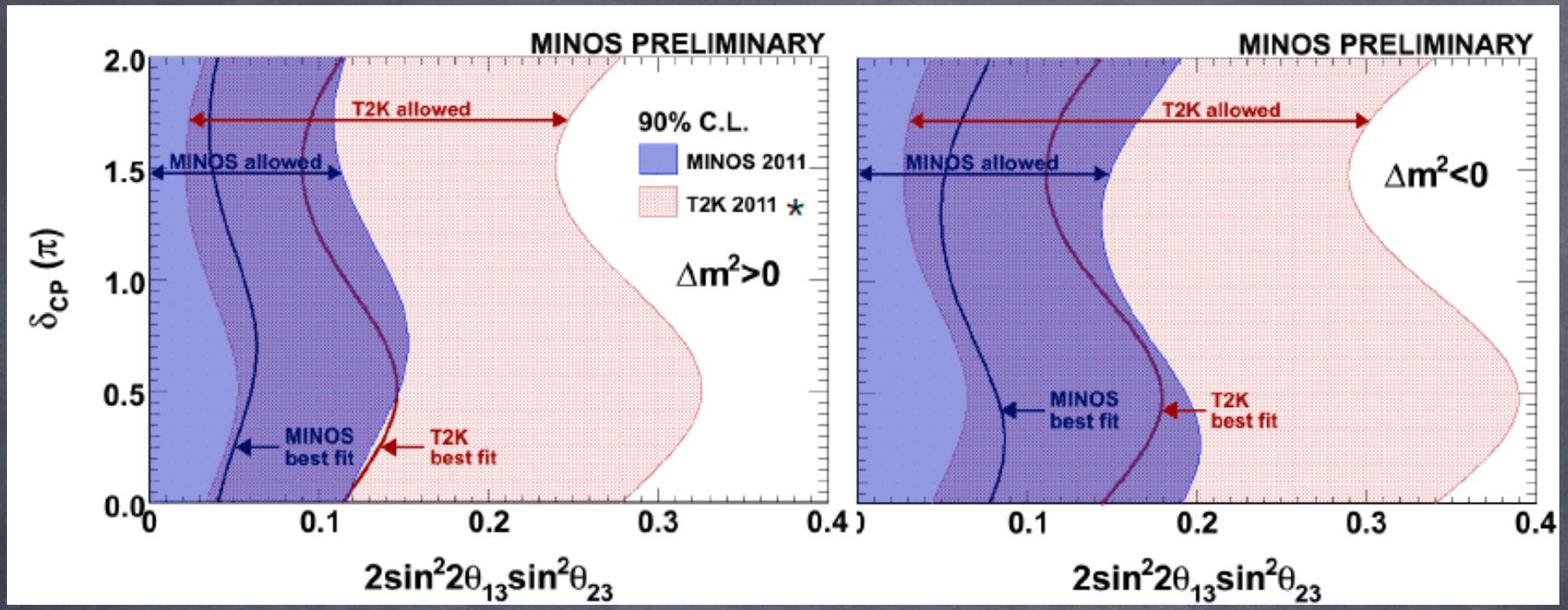
T2K (1.43x10^{20} p.o.t.)



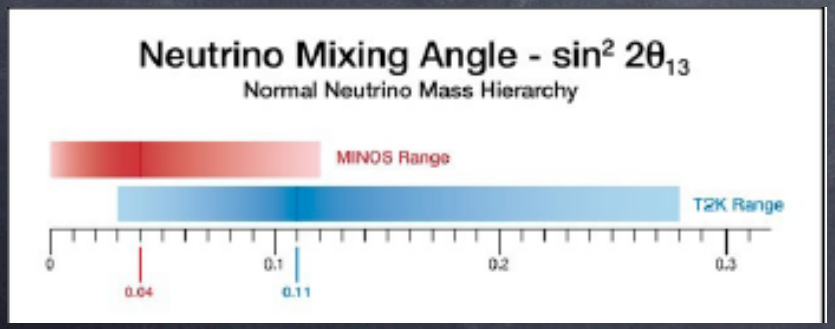
- 1.5 events expected
- 6 candidate events
  - ➡ 2.5σ significance

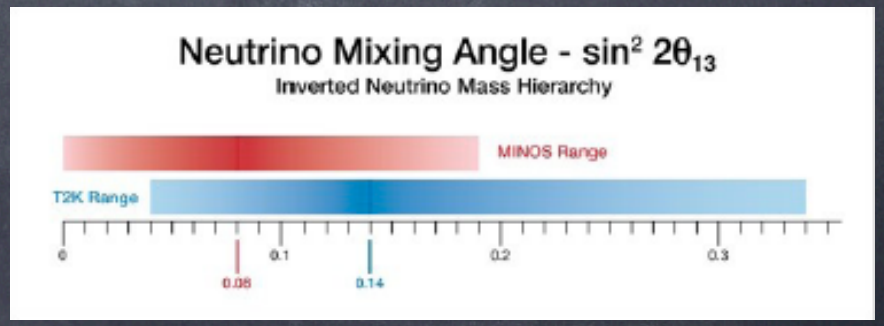
[T2K Collaboration], PRL107, 041801 (2011).

Comparison of MINOS and T2K results

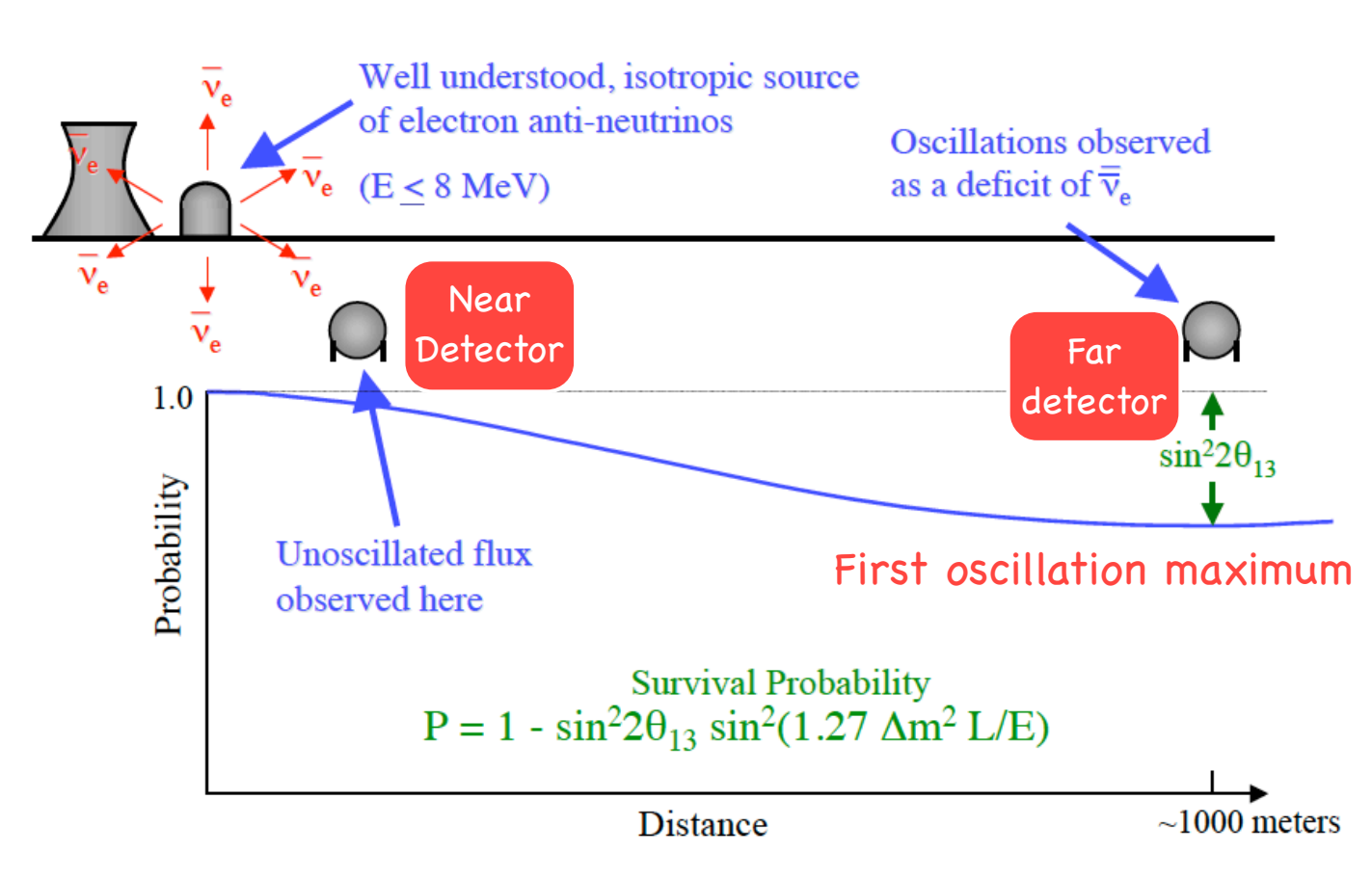


Overlay of the two 90% CL allowed regions ($\delta=0$, $\theta_{23}=\pi/4$)





New generation reactor experiments



- more powerful reactors (multi-core)
- larger detector volume
- 2-3 detectors at 100 m - 1 km.
- sensitivity after 3 years (90% C.L.): $\sin^2\theta_{13} \sim 0.0025 - 0.008$

The race for θ_{13}

29/12/2011

2 reactor cores + 1 FD (ND 2013)

livetime: 101 days

$\sin^2(2\theta_{13}) = 0.086 \pm 0.041\ (stat) \pm 0.030\ (syst)$

Double Chooz Coll, PRL 108 (2012) 131801

→ θ_{13}=0 excluded at 2σ

08/03/2012

6 reactor cores + 6 neutrino detectors (3ND,3FD)

livetime: 55 days

$\mathbf{Sin^2 2\theta_{13} = 0.092 \pm 0.016(stat) \pm 0.005(syst)}$

Daya Bay Coll., PRL 108 (2012) 171803

→ θ_{13}=0 excluded at 5.2σ

03/04/2012

6 reactor cores + 2 neutrino detectors (ND,FD)

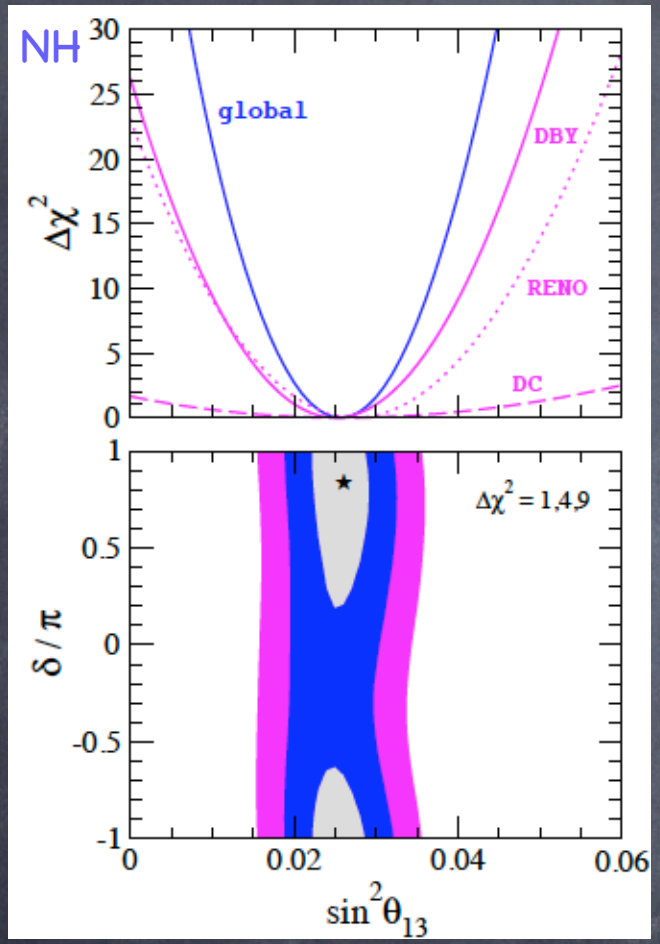
livetime: 229 days

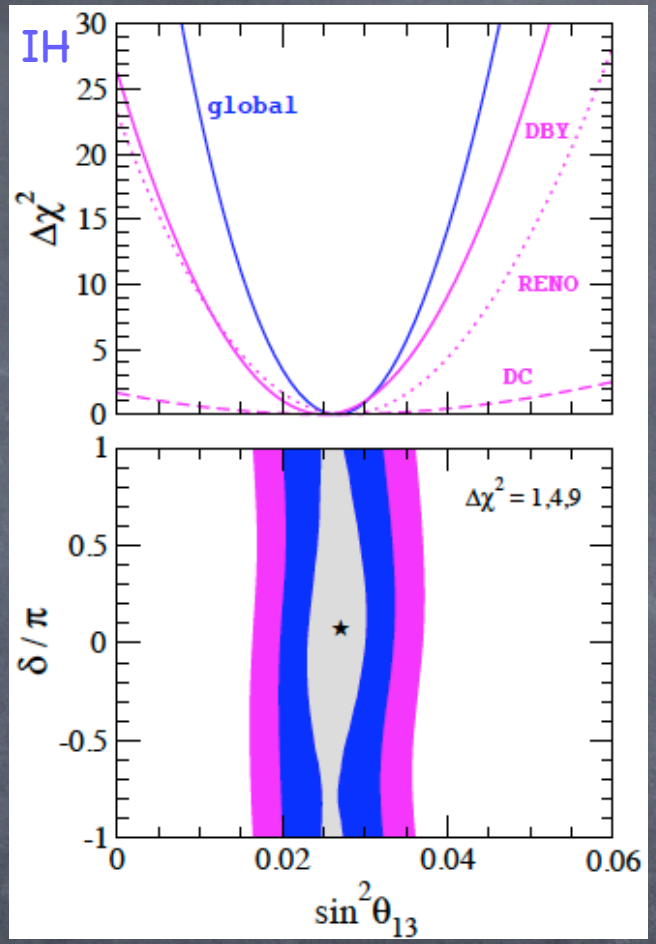
$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$

RENO Coll., PRL 108 (2012) 191802

→ θ_{13}=0 excluded at 4.9σ

θ_{13} determination from global analysis





NH

$$\sin^2\theta_{13} = 0.026^{+0.003}_{-0.004}$$

IH

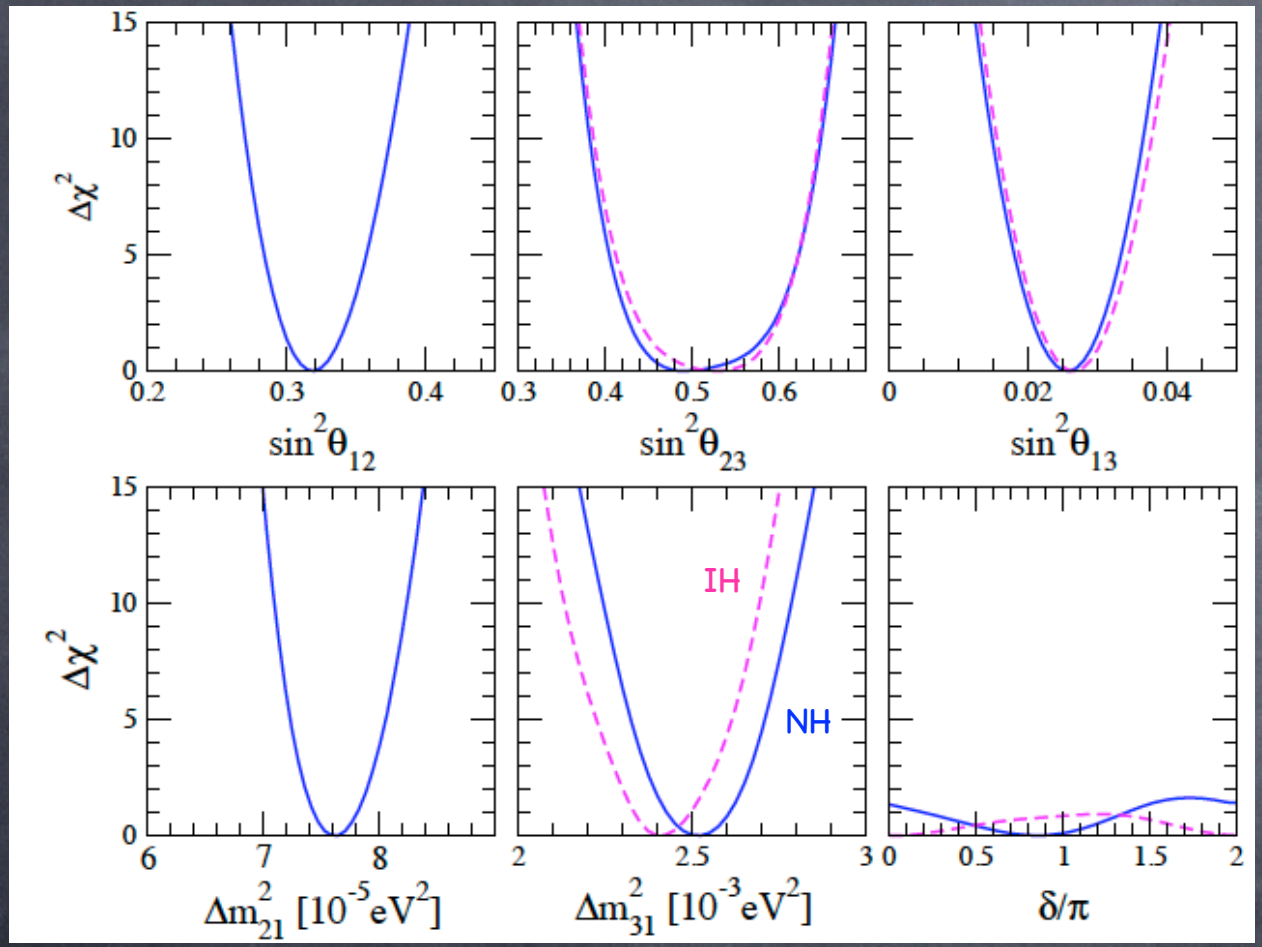
$$\sin^2\theta_{13} = 0.027^{+0.003}_{-0.004}$$

$\theta_{13} = 0$ excluded at 8σ for both hierarchies

Forero, M.T., Valle, arXiv:1205.4018 [hep-ph]

- Bound on θ_{13} dominated by Daya Bay and RENO
- weak sensitivity to CP phase δ

3-flavour oscillation parameters



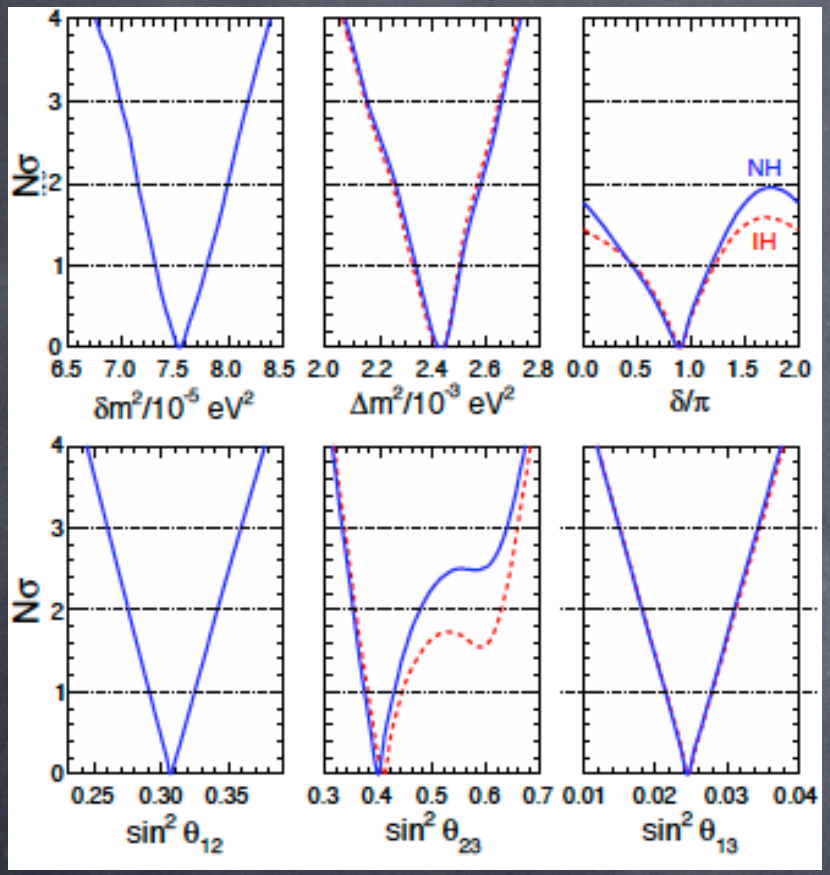
parameter	best fit $\pm 1\sigma$	
Δm^2_{21} [10^{-5}eV^2]	7.62 ± 0.19	3%
Δm^2_{31} [10^{-3}eV^2]	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	4%
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	5%
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	10%
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	15%
δ	$(0.83^{+0.54}_{-0.64})\,\pi$ 0.07π [a]	

- No significant deviations from 2-3 maximal mixing
- Poor sensitivity to δ_{CP}
- No indication for correct mass ordering

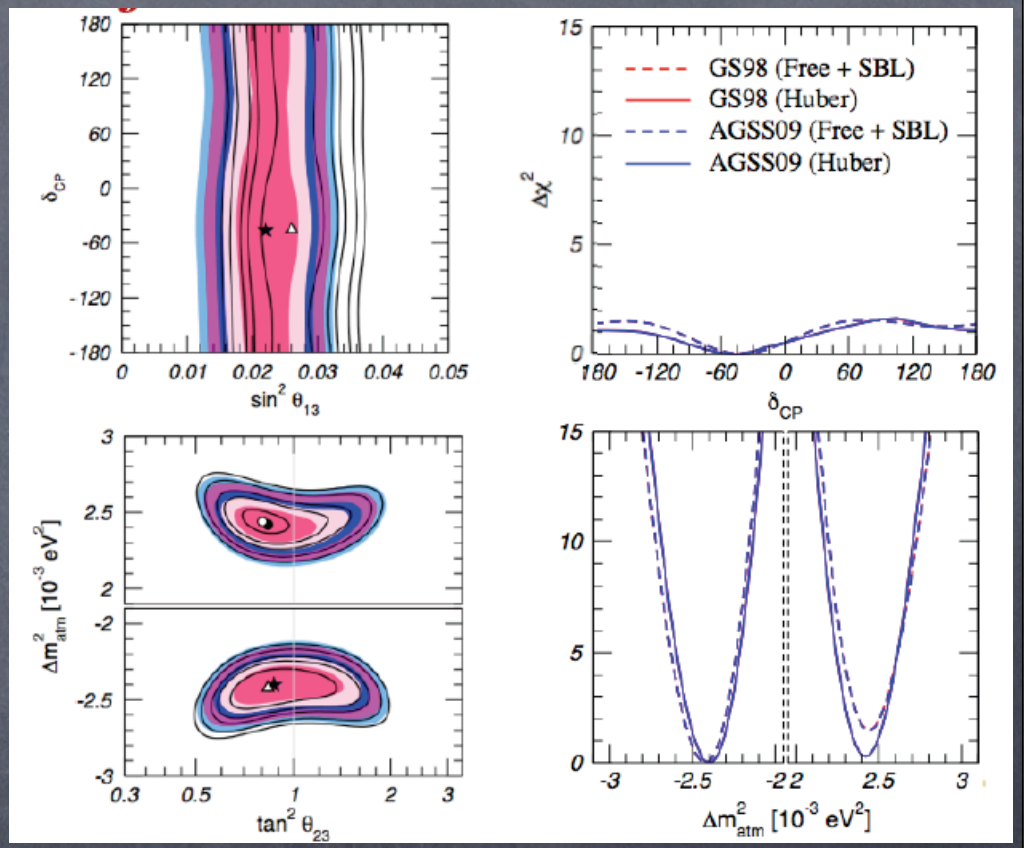
Forero, M.T., Valle, arXiv:1205.4018 [hep-ph]

Alternative global pre-ν2012 analysis

Fogli et al, arXiv:1205.5254 [hep-ph]



González-García et al., T. Schwetz @ NuTURN



* main difference: θ_{23} determination

⇒ Fogli et al. find $\theta_{23} < 45°$, with maximal mixing at ~2σ.

⇒ González-García et al. find weak preference for $\theta_{23} < 45°$ ($\theta_{23}=45°$ allowed at 1σ)

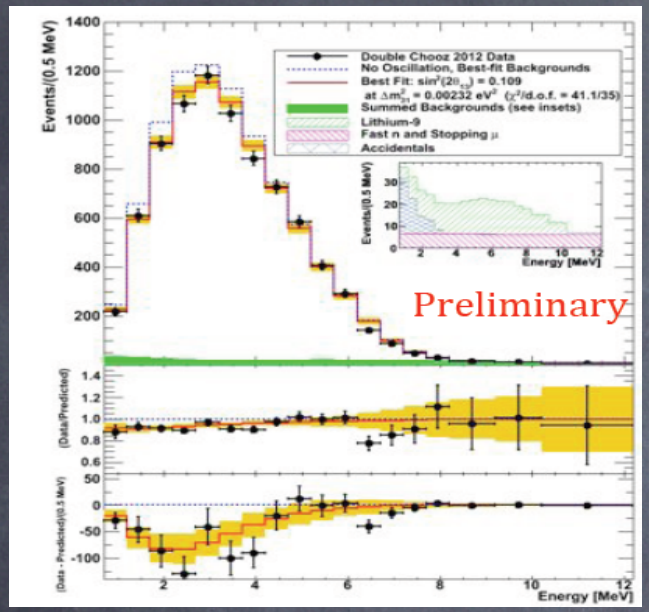
⇒ differences in the analysis of atmospheric and LBL neutrino data

New data released in Neutrino 2012

New reactor data

Double Chooz

M. Ishitsuka @ Neutrino 2012



96.8 -> 227.9 days livetime

rate only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035\ (\text{stat}) \pm 0.040\ (\text{syst})$

rate + shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030\ (\text{stat}) \pm 0.025\ (\text{syst})$

→ $\sin^2 2\theta_{13} = 0$ excluded at 3.1σ

Daya Bay

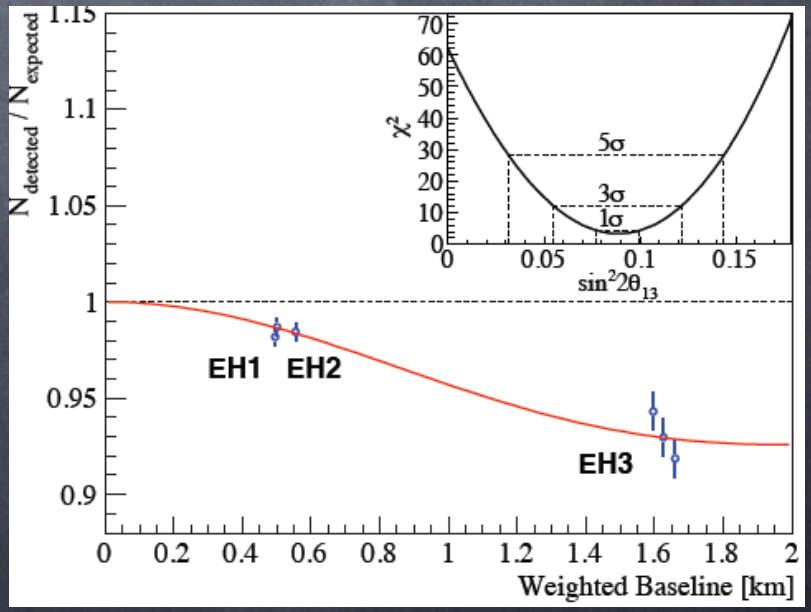
D. Dwyer @ Neutrino 2012

2.5 times more data

$R = 0.944 \pm 0.007\ (\text{stat}) \pm 0.003\ (\text{syst})$

$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\text{stat}) \pm 0.005\ (\text{syst})$

→ $\sin^2 2\theta_{13} = 0$ excluded at ~ 8σ

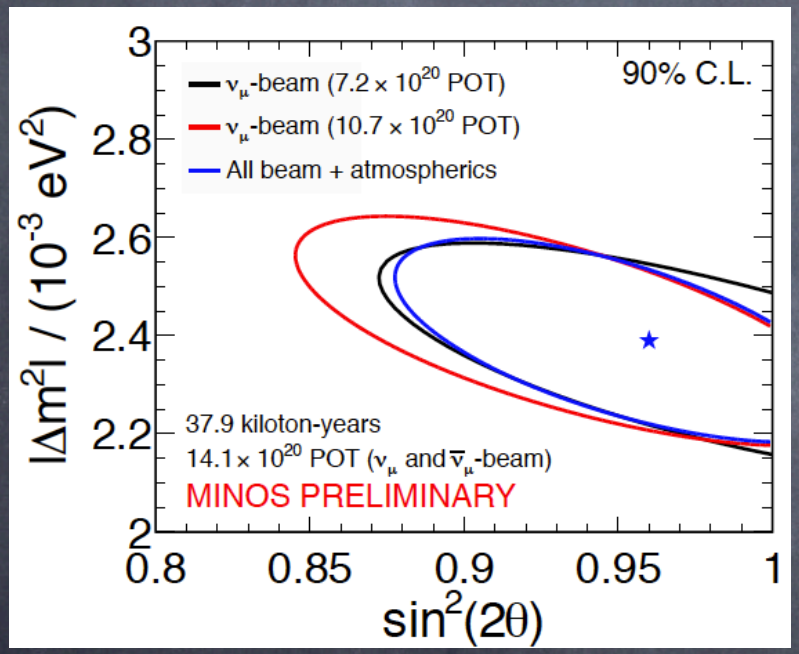


Final MINOS data on ν_μ disappearance

- atmospheric data: 37.9 kton-years, 2072 events observed
- ν_μ beam data: 10.71×10^{20} pot, 2894 events observed vs 3564 expected
- $\bar{\nu}_\mu$ beam data: 3.36×10^{20} pot, 357 events observed vs 464 expected

R. Nichol @ Neutrino 2012

neutrino parameters

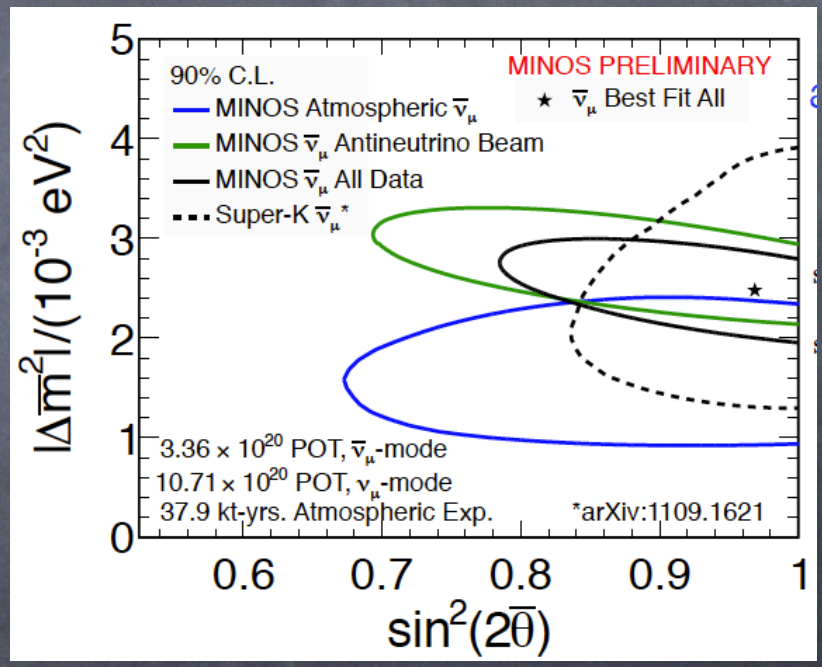


$|\Delta m^2| = 2.39\ ^{+0.09}_{-0.10} \times 10^{-3}\ eV^2$

$\sin^2(2\theta) = 0.96 \pm 0.04$

$\sin^2(2\theta) > 0.90$ at 90%CL

antineutrino parameters



$|\Delta \bar{m}^2| = 2.48\ ^{+0.22}_{-0.27} \times 10^{-3}\ eV^2$

$\sin^2(2\bar{\theta}) = 0.97\ ^{+0.03}_{-0.08}$

$\sin^2(2\bar{\theta}) > 0.83$ at 90%CL

New results on ν_e appearance at LBL

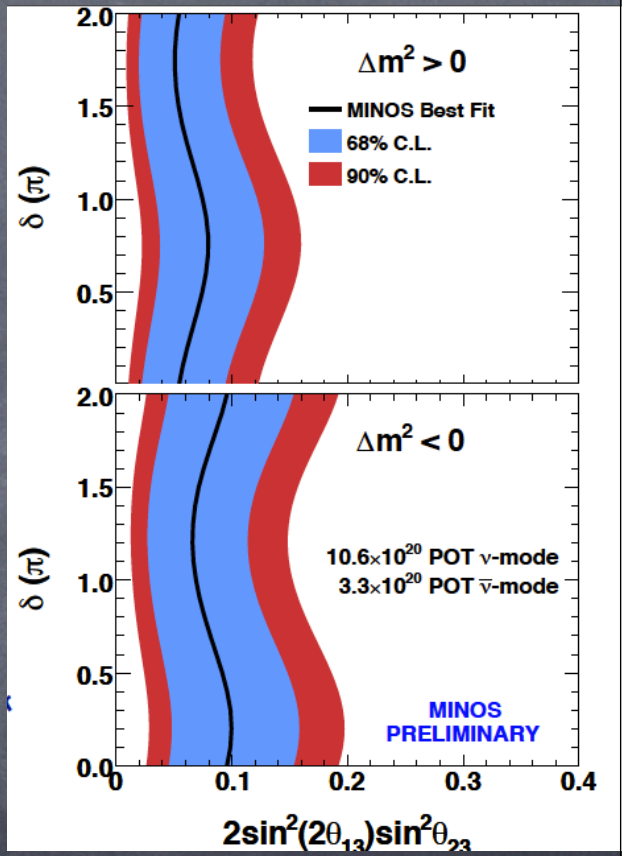
MINOS

R. Nichol @ Neutrino 2012

ν beam: 152 events observed vs 128.6±32.5

$\bar{\nu}$ beam: 20 events observed vs 17.5±33.7

→ $\theta_{13} = 0$ disfavoured at 96% CL (NH, $\delta_{CP} = 0$)

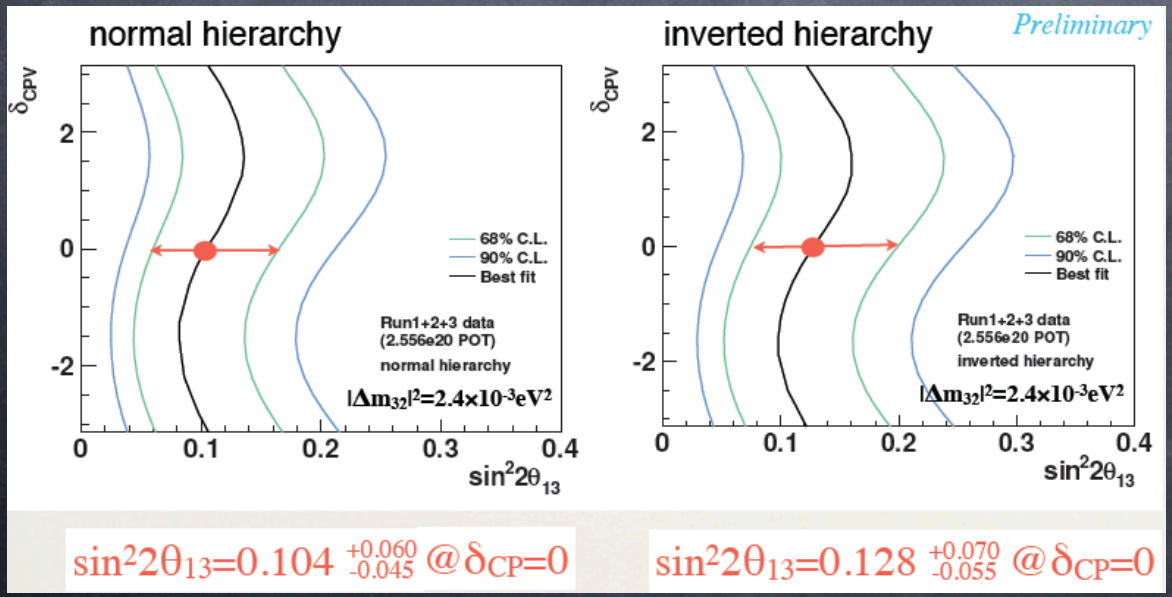


T2K

T. Nakaya @ Neutrino 2012

10 ν_e events observed over a bg of 2.73±0.37

→ ν_e appearance confirmed at 3.2σ



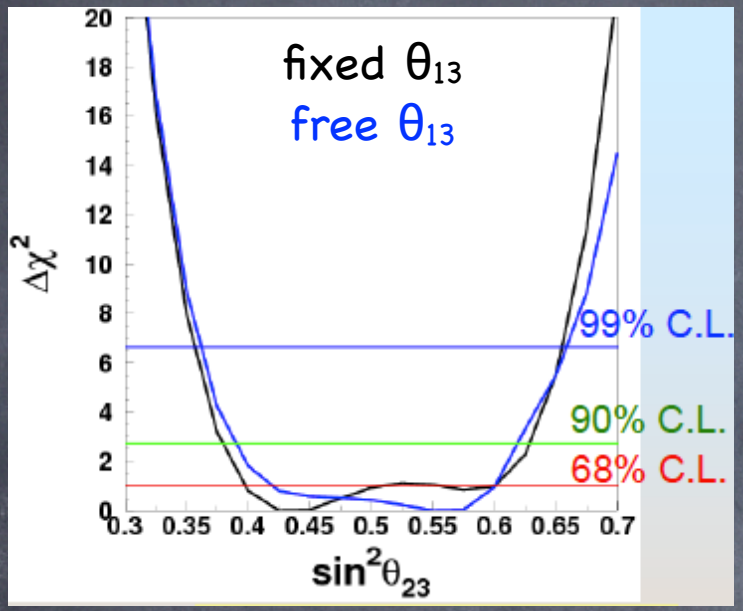
In agreement with previous LBL app and reactor data

Updated SK atmospheric ν analysis

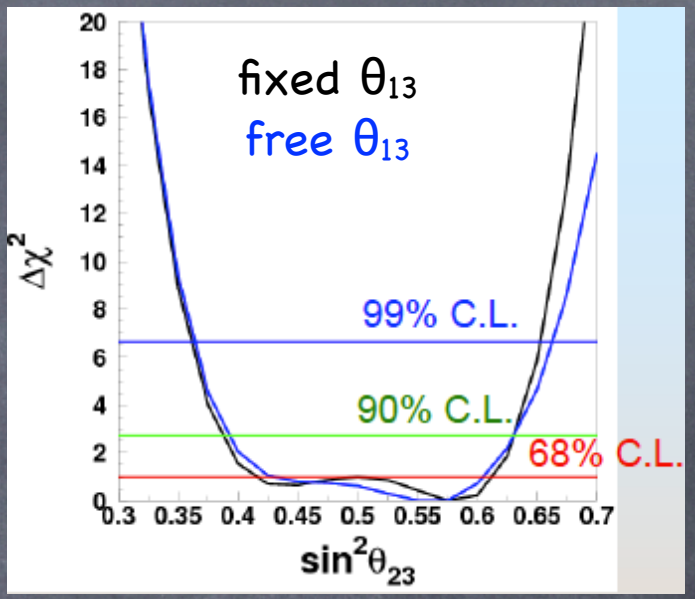
SKI-IV (total 3903 days)

Y. Itow @ Neutrino 2012

NH



IH



$\sin^2\theta_{23}$ = 0.425
[0.391-0.619] at 90% C.L.

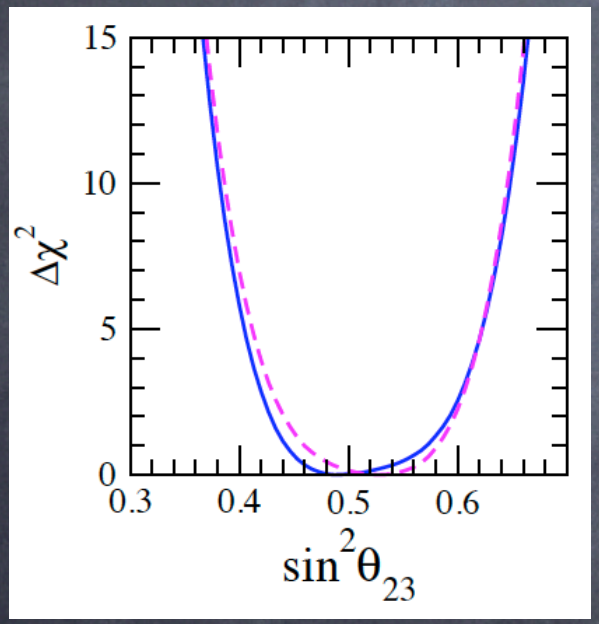
$\sin^2\theta_{23}$ = 0.575
[0.393-0.630] at 90% C.L.

* correlation between octant preference and mass hierarchy.
* no significative hint for mass hierarchy: $\chi^2_{\min}(NH) - \chi^2_{\min}(IH) = 1.2$

Open questions in neutrino physics

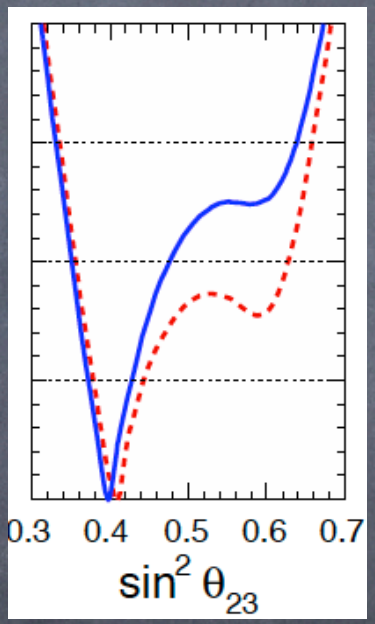
Open questions in ν physics

- θ_{23} octant: is ν_μ-ν_T mixing maximal?



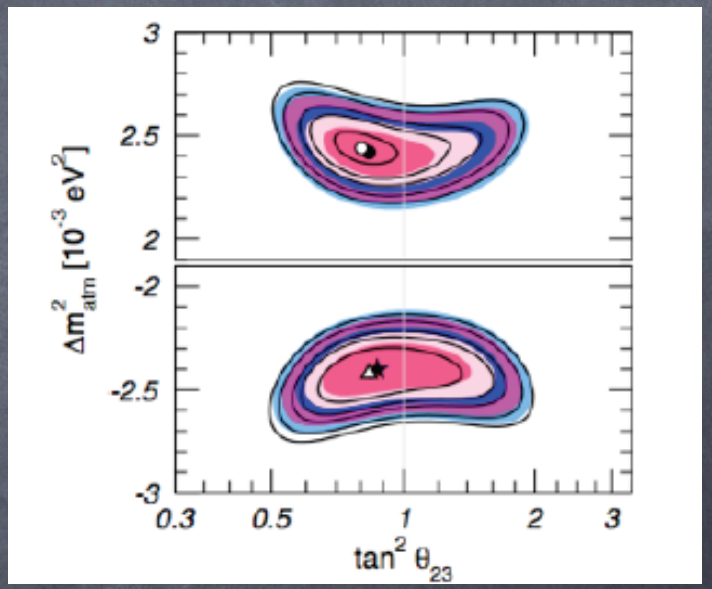
Forero, MT, Valle, 2012

nearly maximal:
$\sin^2\theta_{23}$ = 0.49(0.53)
no siginificative preference



Fogli et al, 2012

first octant
$\sin^2\theta_{23} \approx 0.40$
max. mixing at 2σ (NH)

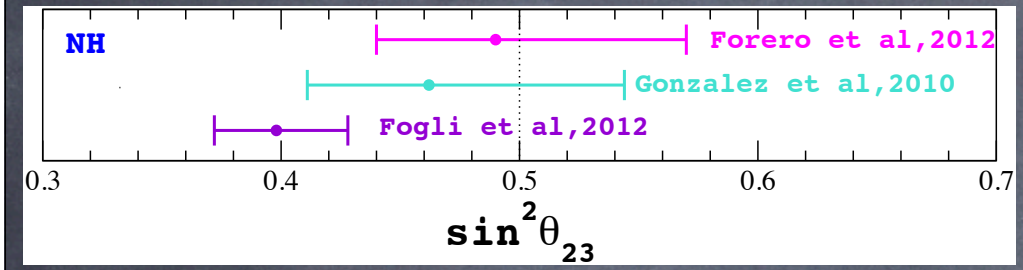


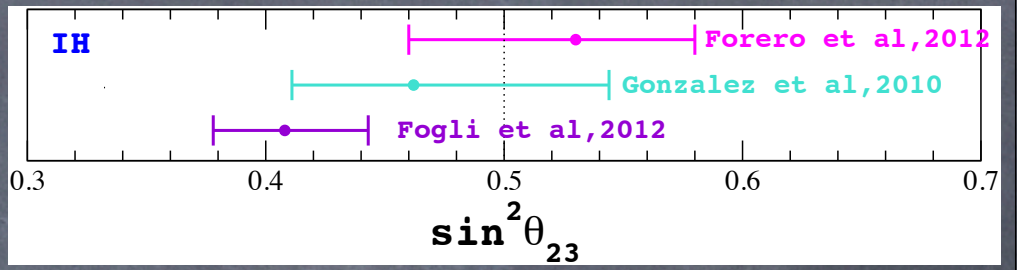
González-García et al, 2012

first octant
$\sin^2\theta_{23} \approx 0.46$
max mixing allowed at 1σ

Open questions in ν physics

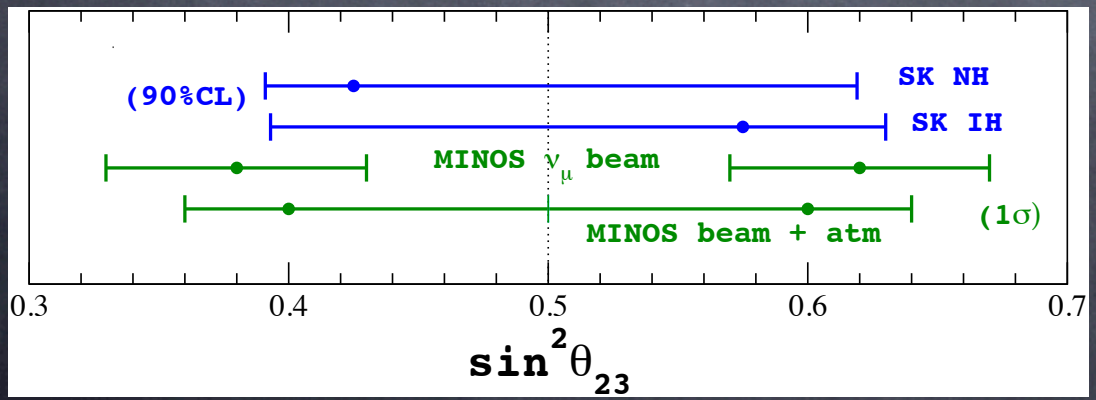
- θ_{23} octant: is ν_μ-ν_T mixing maximal?





1σ range

After Neutrino 2012: still no clear picture...



Updated analysis with new MINOS data will show larger departures from maximality

Open questions in ν physics

- θ_{23} octant: is ν_μ-ν_τ mixing maximal?

  ⇒ combination LBL accelerator + SBL reactor

appearance at LBL:

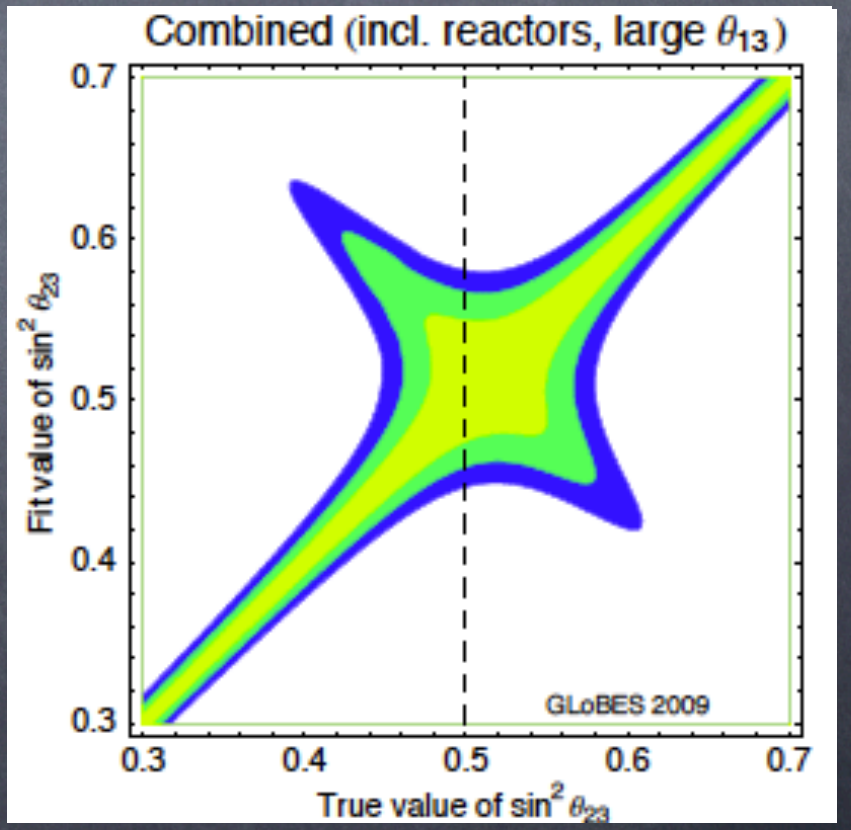
$$P_{\mu e} = \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \text{correc}$$

⇒ anticorrelation θ_{23}-θ_{13}

disappearance at SBL reactor:

$$P_{ee} = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \text{correc}$$

⇒ indep. measurement of θ_{13}

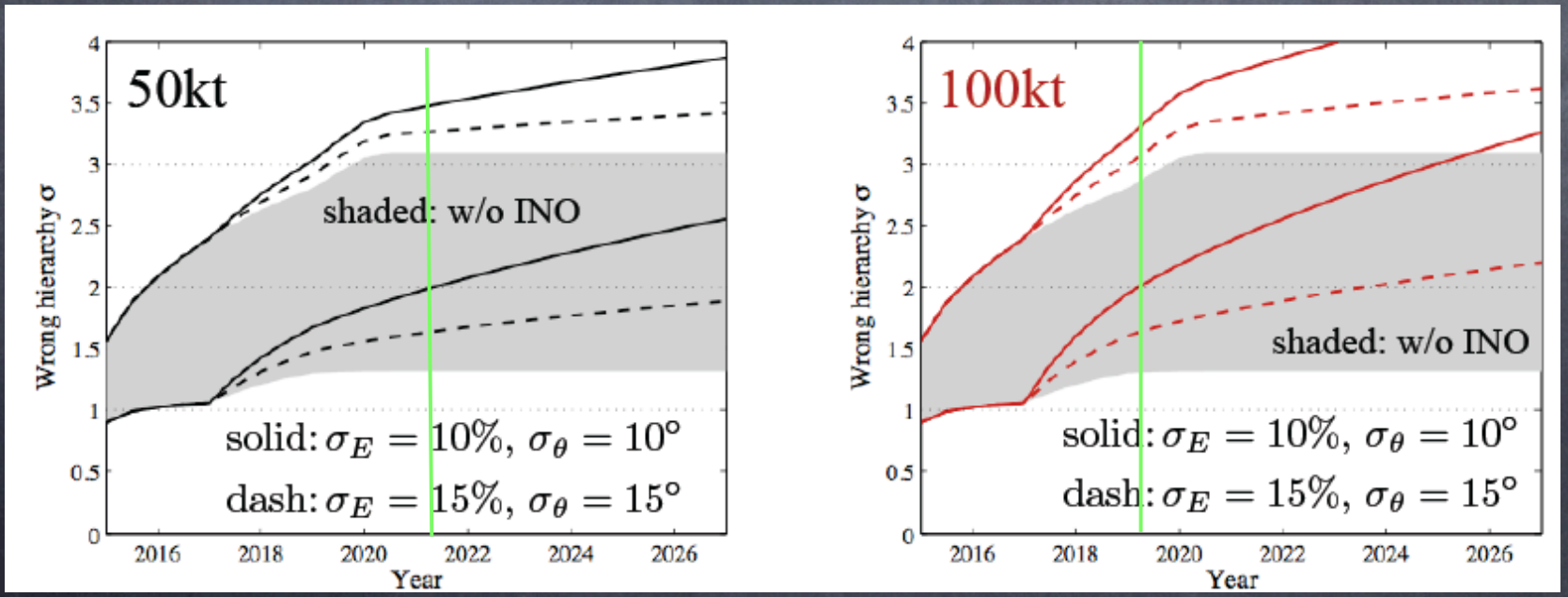


Huber et al, JHEP 0911 (2009) 044.

Open questions in ν physics

- θ_{23} octant: is ν_μ-ν_τ mixing maximal?
- neutrino mass hierarchy: NH or IH

  ⇒ combined analysis of NOvA and atmospheric neutrinos in INO



Blennow and Schwetz, arXiv:1203.3388[hep-ph]

2σ rejection ~ 2020

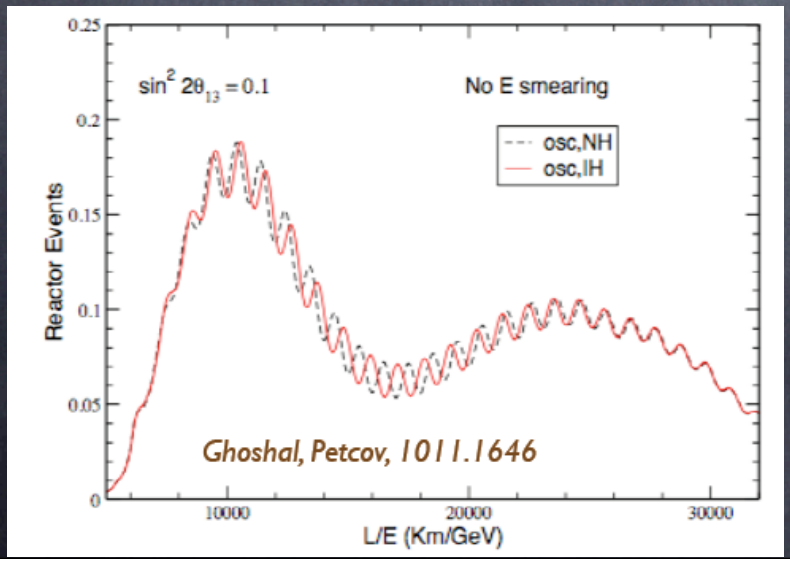
Open questions in ν physics

- θ_{23} octant: is ν_μ-ν_T mixing maximal?
- neutrino mass hierarchy: NH or IH

⇒ reactor experiment with intermediate baseline (~60 km)

$$P^{NH(IH)}(\bar{\nu}_e \to \bar{\nu}_e)\Big|_{\frac{\Delta m^2_\odot L}{2\pi E_\nu}=1} = 1 - 2\sin^2\theta\cos^2\theta - \cos^4\theta\sin^2 2\theta_\odot \overset{(+)}{-} \cos 2\theta_\odot 2\sin^2\theta\cos^2\theta\cos\pi\frac{\Delta m^2_{31}}{\Delta m^2_\odot}$$

maximum of Δm^2_{12} osc



Petcov and Piai, PLB 533 (2002) 94 (2002)

10 kton detector with very good energy resolution -> MH at 90%CL in 5 years.

Zhan et al, PRD 79 (2009) 073007.

Open questions in ν physics

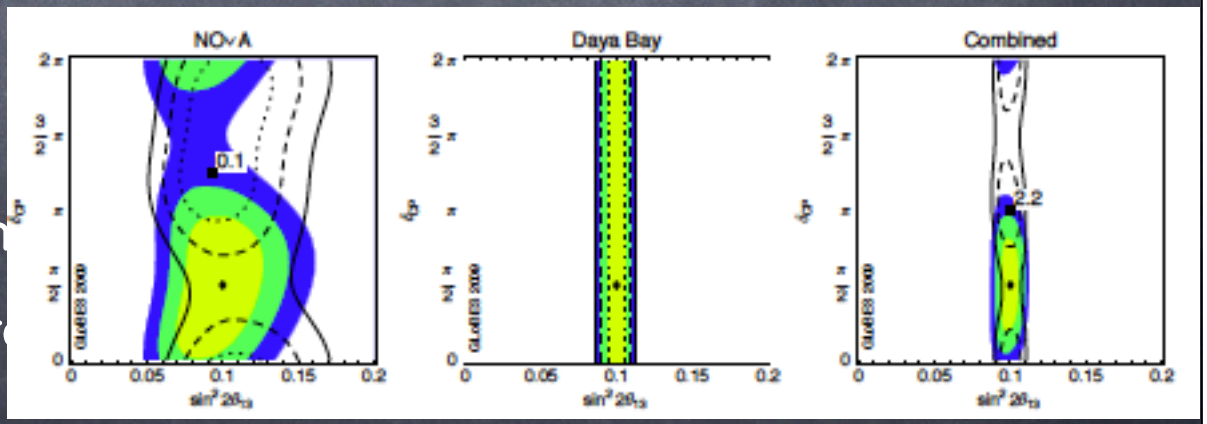
- θ_{23} octant: is ν_μ-ν_T mixing maximal?
- neutrino mass hierarchy: NH or IH
- CP violation in the neutrino sector

T2K and NOvA have poor discovery potential for δ_{CP}

⇒ combination with reactors

⇒ new generation of experim

will perform a more solid det



Huber et al, JHEP 0911 (2009) 044.

Open questions in ν physics

- θ_{23} octant: is ν_μ-ν_τ mixing maximal?
- neutrino mass hierarchy: NH or IH
- CP violation in the neutrino sector
- absolute neutrino mass

⇒ slight improvement on Σm_ν expected from Planck.

(weak lensing of galaxies + Planck ~ 0.05 eV)

Hannestad et al, JCAP 0606 (2006) 025

⇒ direct mass searches: β, 2β decay.

Open questions in ν physics

- θ_{23} octant: is ν_μ-ν_τ mixing maximal?
- neutrino mass hierarchy: NH or IH
- CP violation in the neutrino sector
- absolute neutrino mass
- Dirac or Majorana?

⇒ positive signal in $2\beta0\nu$ decay experiment

Open questions in ν physics

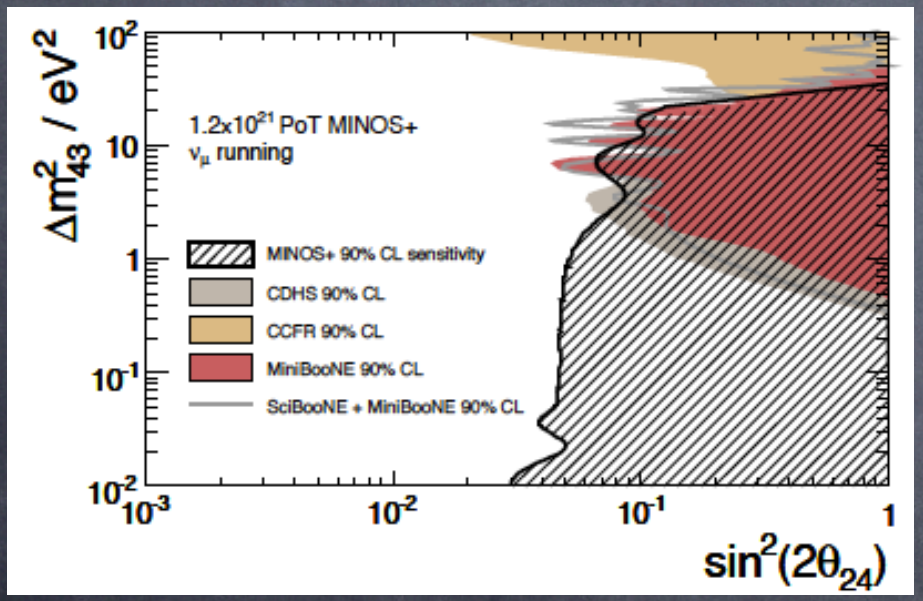
- θ_{23} octant: is ν_μ-ν_τ mixing maximal?
- neutrino mass hierarchy: NH or IH
- CP violation in the neutrino sector
- absolute neutrino mass
- Dirac or Majorana?
- are there sterile neutrinos, NSI?

  ⇒ new SBL experiments, cosmological data, MINOS+

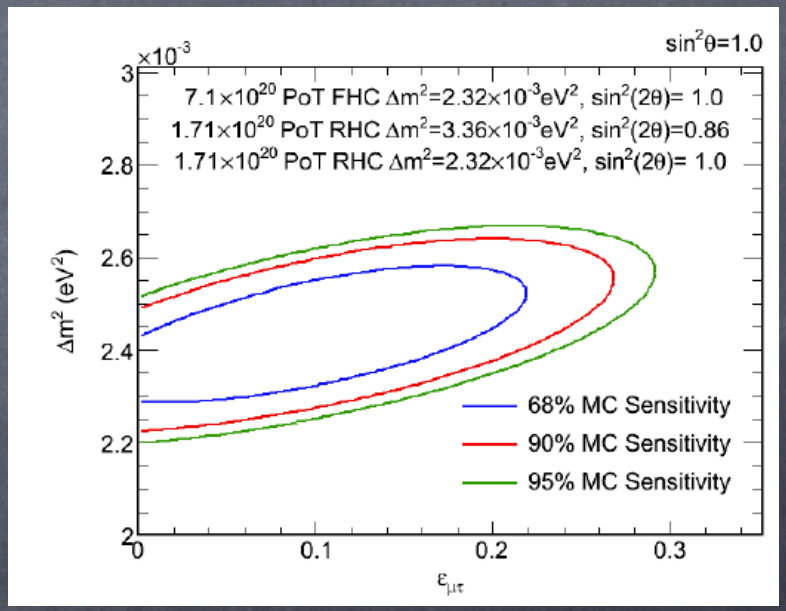
MINOS+ searches for new physics

MINOS+: running of MINOS during NovA era

⇒ high statistics neutrino data collected in MINOS FD will test the existence of NSI and sterile neutrinos



MINOS+ sensitivity to θ_{24}



MINOS+ sensitivity to NSI coupling $\varepsilon_{\mu\tau}$

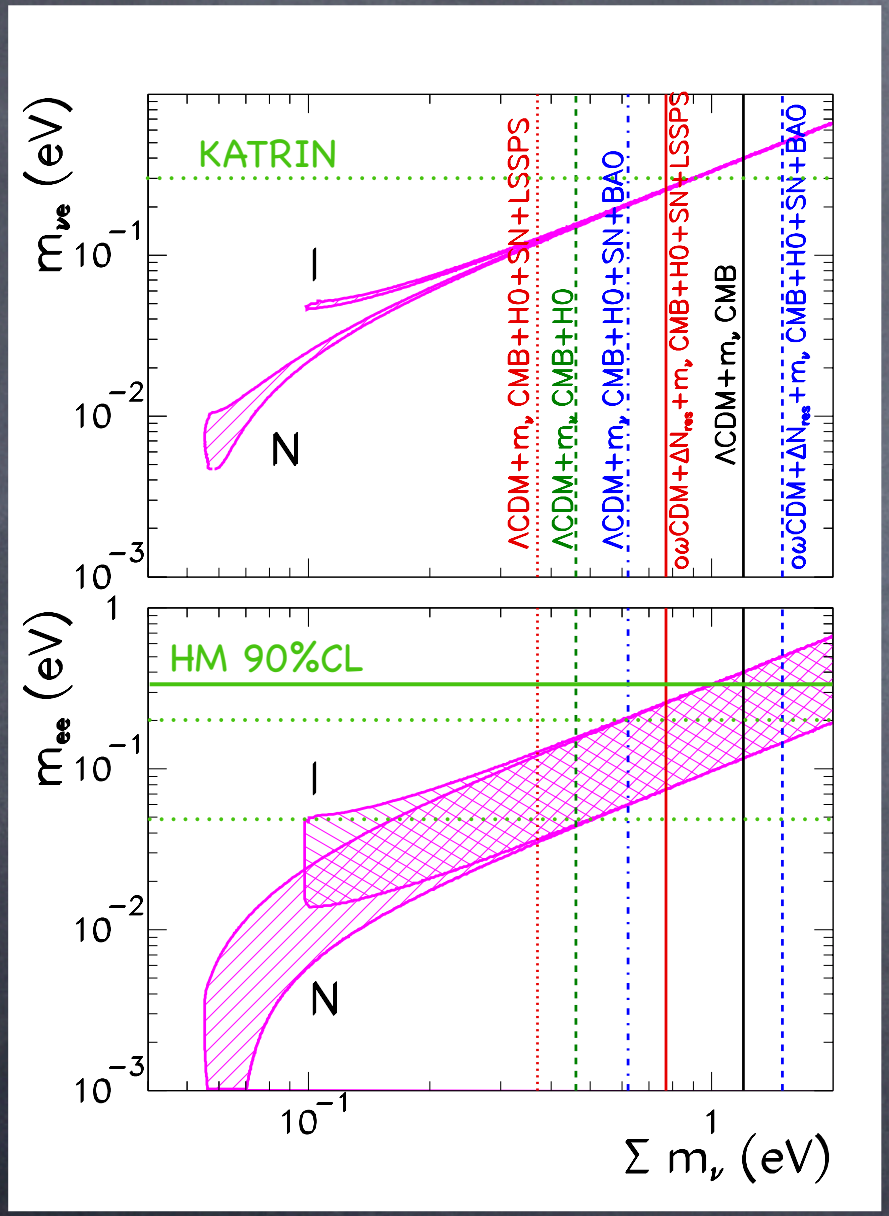
MINOS+ proposal, Tzanankos et al, FERMILAB-PROPOSAL-1016.

Summary

* Neutrino oscillations are well stablished with observations in several experiments, with natural and artificial sources.
* Oscillation parameters are measured accurately ($\lesssim 10\%$) by the combination of different experiments.
* The mixing angle θ_{13} has been measured at 3 reactor experiments with good level of statistical significance.
* The relatively large value of θ_{13} makes easier the determination of the mass hierarchy and opens the possibility of measure CP violation.
* Questions to be answered by the next generation of neutrino experiments: δ_{CP}, mass hierarchy, new physics...

Backup slides

Constraints on m_ν from neutrino oscillations



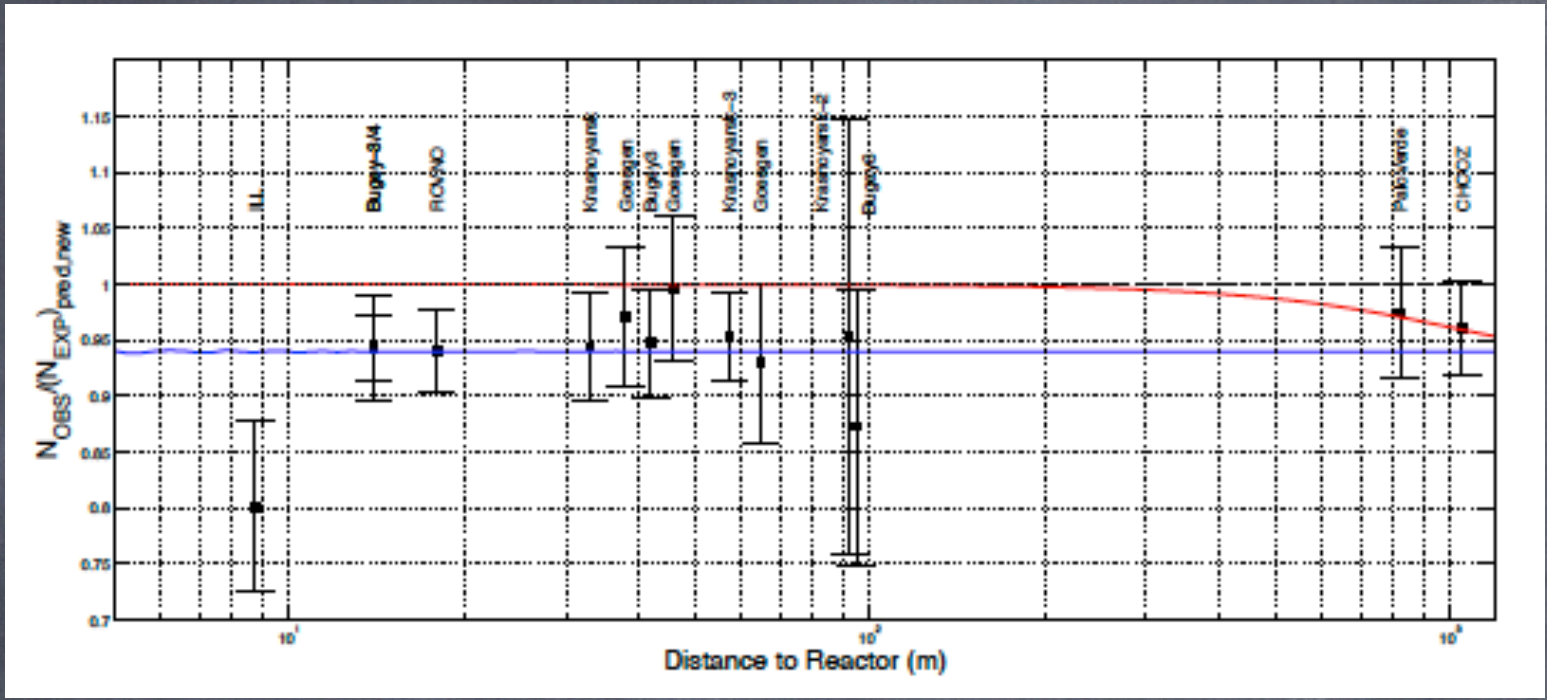
95% CL regions

⇒ most of the bounds out of reach for KATRIN

⇒ next generation of $2\beta0\nu$ exp. will test allowed ranges

González-García et al, JHEP 1008 (2010) 117.

The reactor antineutrino anomaly



Mention et al, arXiv:1101.2755

* increase of 3.5% in the reactor antineutrino fluxes
  ⇒ SBL reactor experiments show a deficit in the number of detected over expected neutrinos: R = 0.937 ± 0.027
* possible explanations: sterile neutrino(s) with $\Delta m^2 \sim 1\ eV^2$
* SBL exps. should be included in a 3ν fit, to account for normalization of reactor exps. (CHOOZ, KamLAND) at short distances.

Reevaluation of the CHOOZ bound after new flux predictions (2011)

Old flux predictions:

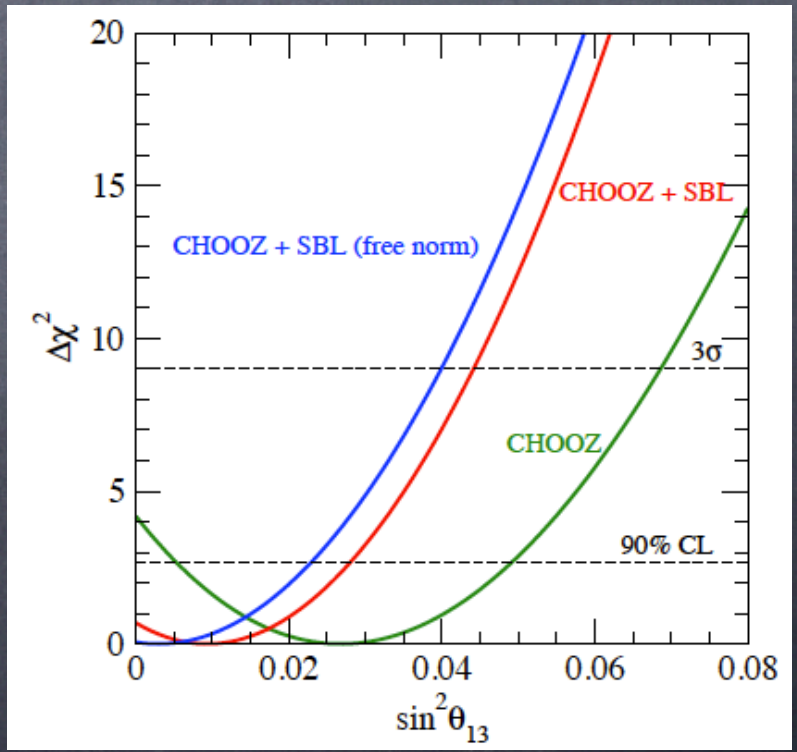
For $\Delta m^2_{31} = 2.5 \cdot 10^{-3}$ eV^2

-> $\sin^2\theta_{13} < 0.039$ (90%CL) ($\sin^2 2\theta_{13} < 0.15$)

New flux predictions:

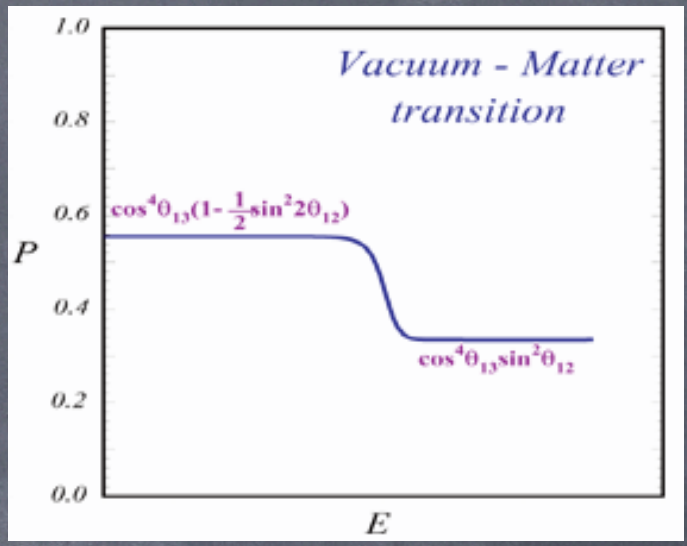
For $\Delta m^2_{31} = 2.5 \cdot 10^{-3}$ eV^2 :

- without SBL: $\sin^2\theta_{13} < 0.049$ (90%CL)
  ($\sin^2 2\theta_{13} < 0.19$)
- with SBL: $\sin^2\theta_{13} < 0.028$ (90%CL)
  ($\sin^2 2\theta_{13} < 0.11$)
- SBL + free norm: $\sin^2\theta_{13} < 0.023$(90%CL)
  ($\sin^2 2\theta_{13} < 0.09$)



Low energy solar experiments

* real time measurements pp, pep, ^{7}Be fluxes
  [ES] KamLAND, CLEAN, SNO+
  [CC] LENS, MOON, XMASS

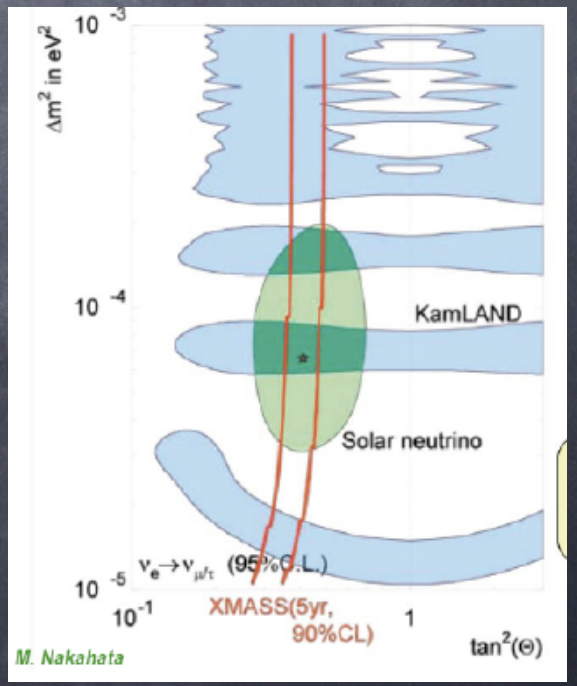


⇒ constrain SSM

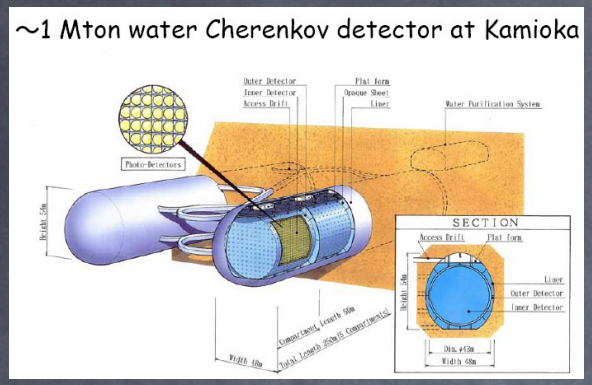
⇒ transition low to high energies

⇒ θ_{12} precision measurements

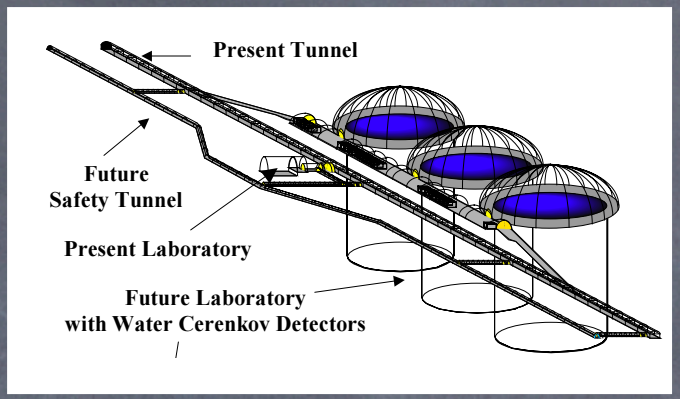
⇒ signatures of new physics



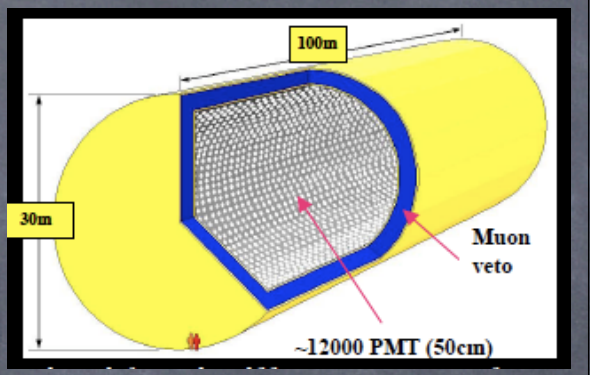
Large underground detectors



Hyper-Kamiokande



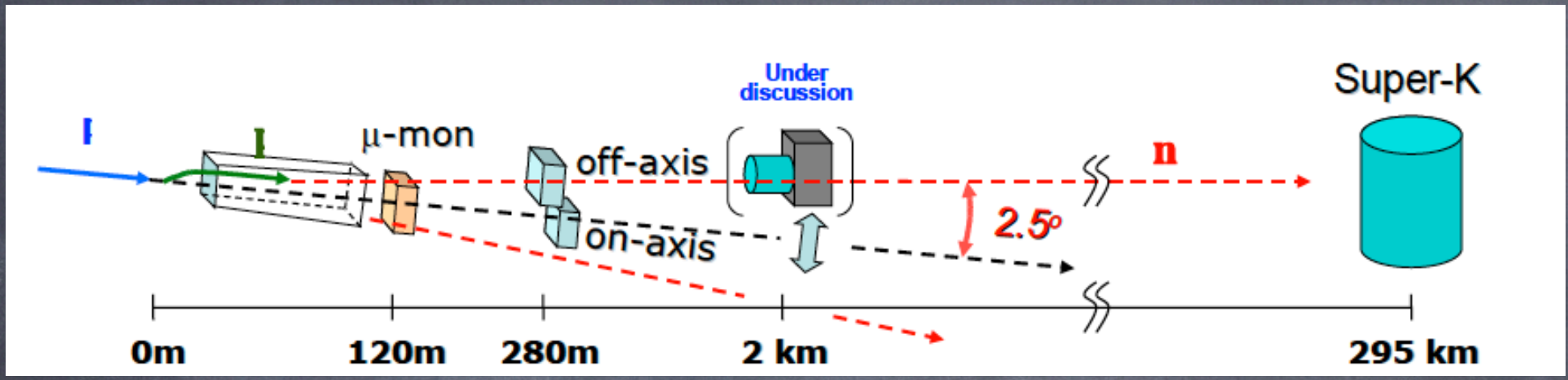
MEMPHYS



LENA

* proposals in USA (DUSEL), Europe (LAGUNA) and Japan (Hyper-K).
* detector technology:
  * Mton water Cerenkov: Hyper-Kamiokande, MEMPHYS, UNO
  * liquid scintillator: LENA
  * liquid Argon: GLACIER
* multi-purpose: p decay, supernova, LBL, solar, atmospheric, ...

LBL off-axis experiments: T2K, NovA



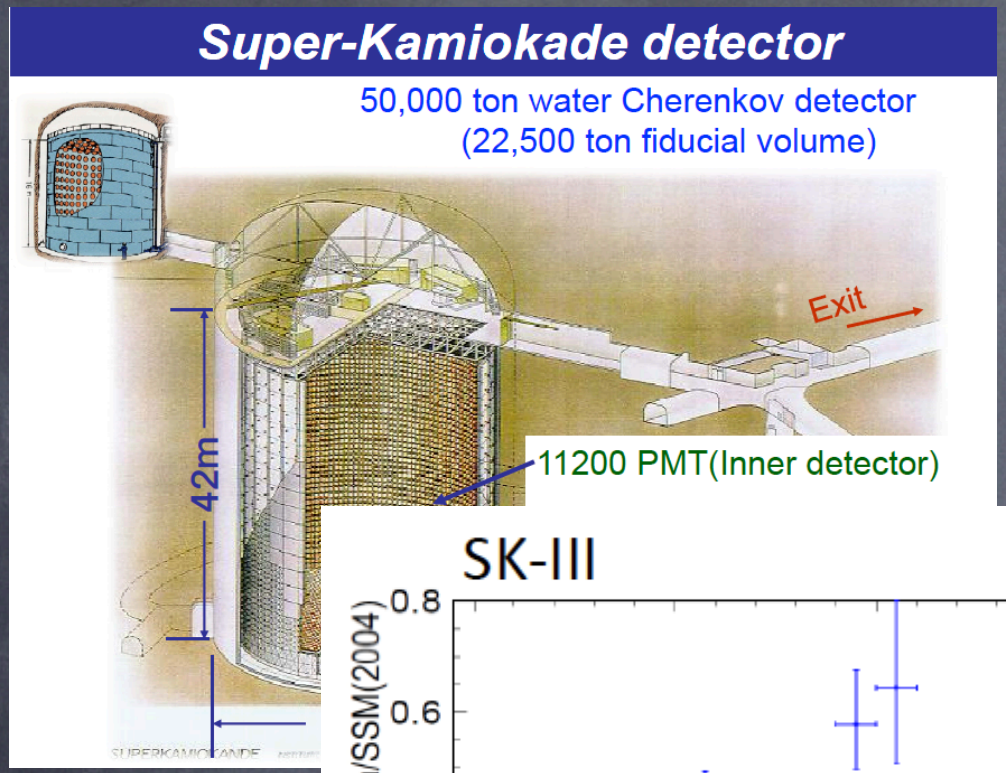
- long-baseline experiments (300 - 800 km)
- "off-axis" technology-> monoenergetic neutrino beam.
- precision measurements of atmospheric oscillation parameters (1%).
- optimized to search for ν_e appearance in a ν_μ beam.
- potentially sensitive to CP violation.

Further in the future...

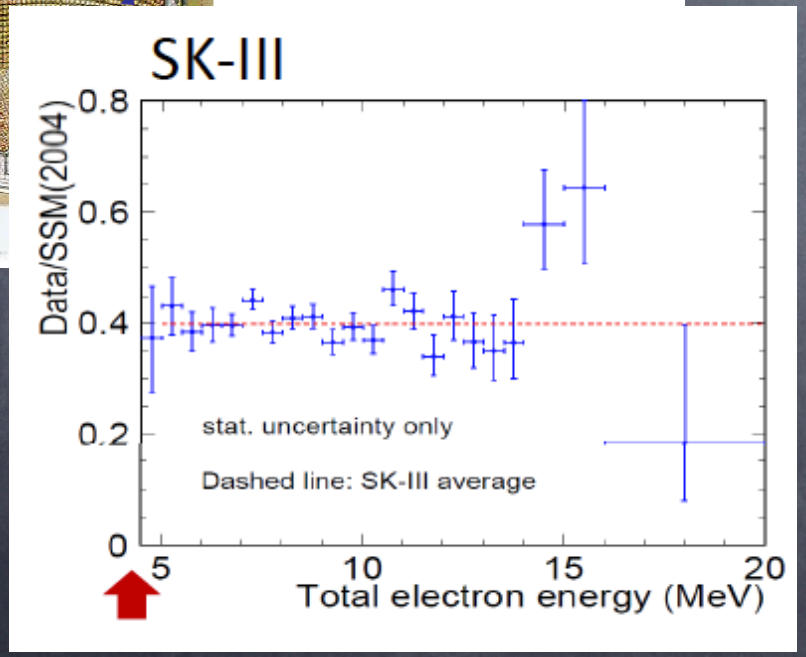
β-beams (2015-2020??):
* improved sensitivity: $\sin^2 2\theta_{13} \lesssim 10^{-3}$
* discovery potential for δ_{CP} and hierarchy if $\theta_{13} \gtrsim 1º$

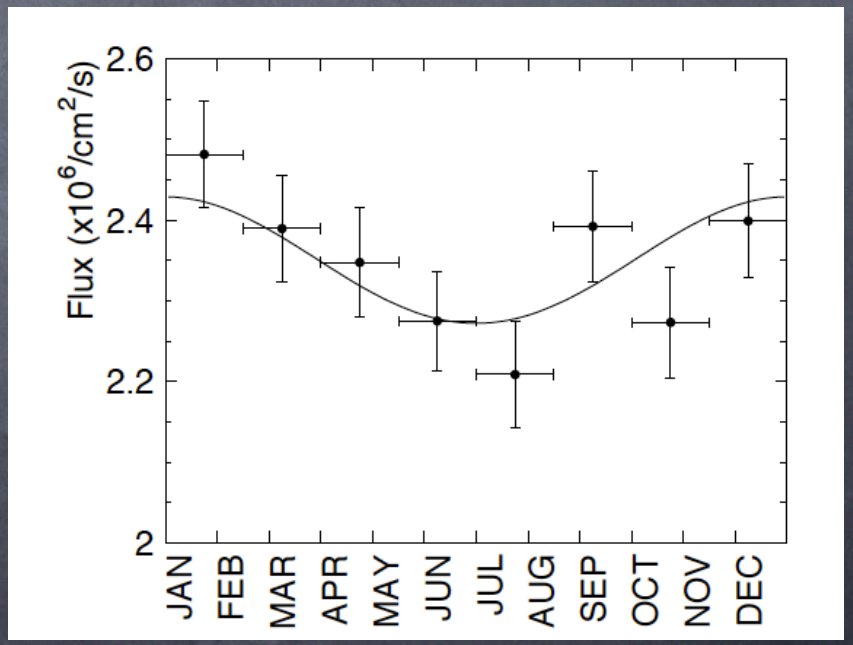
Neutrino Factory (> 2020):
* sensitivity on θ_{13}, δ_{CP}, mass hierarchy.

Solar neutrinos in Super-Kamiokande



- water cherenkov detector
- sensitive to all neutrino flavors:
  $\nu_x\ e^- \rightarrow \nu_x\ e^-$
- threshold energy ~ 4-5 MeV
- real-time detector: (E, t)

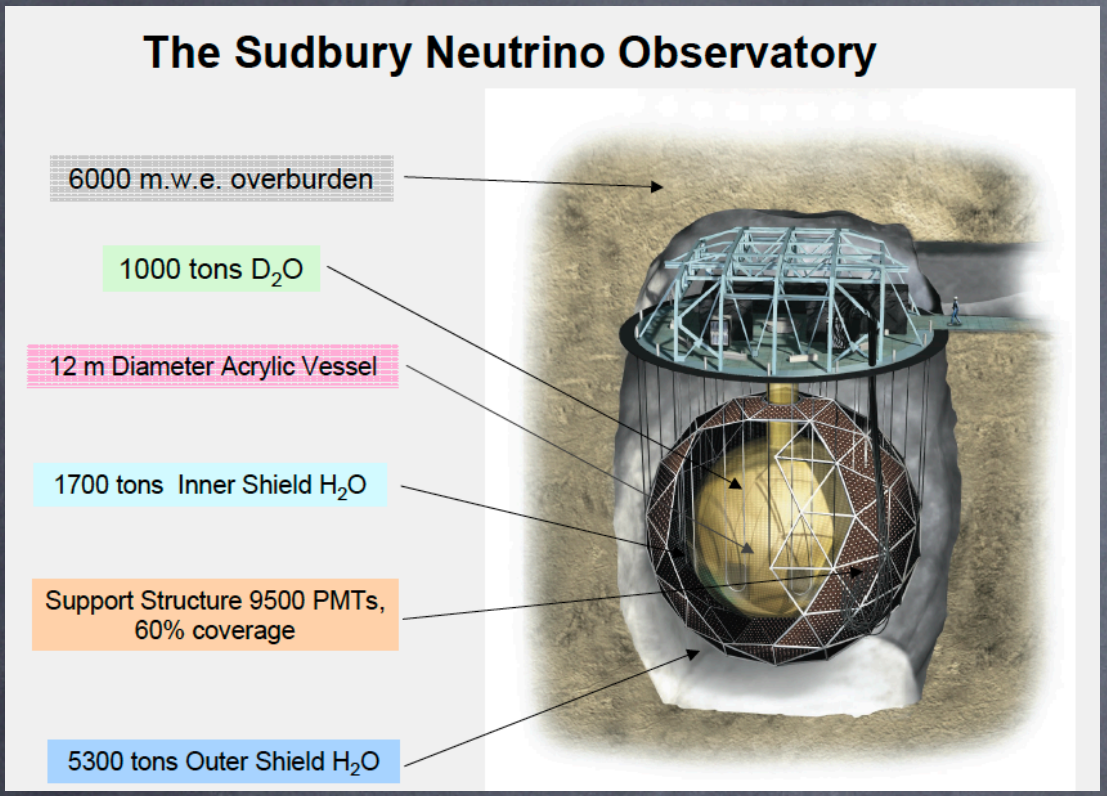




➡ Super-Kamiokande detects less neutrinos than expected according to the SSM (40%)

The Sudbury Neutrino Observatory, SNO

The Sudbury Neutrino Observatory

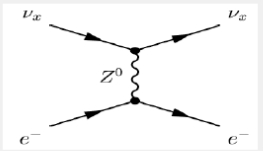


SNO is sensitive to all ν flavors:

SNO interactions

Elastic-scattering (ES):

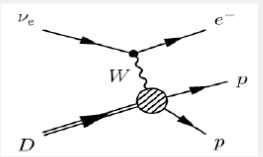
$$\nu_x + e^- \rightarrow \nu_x + e^-$$



ν_e mainly strong directional sensitivity

Charged-currents (CC):

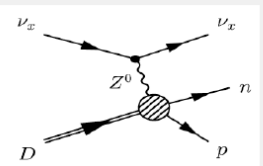
$$\nu_e + d \rightarrow p + p + e^-$$



ν_e only
E_e well correlated with E_ν

Neutral-currents (NC):

$$\nu_x + d \rightarrow p + n + \nu_x$$



All flavors equally
Total neutrino flux

3 phases:

D_2O phase:

$n + d \rightarrow t + \gamma + 6.25$ MeV

Salt phase (D_2O + 2 tons of NaCl):

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$'s + 8.6 MeV

NCD phase (^{3}He proportional counters):

$n + {}^3He \rightarrow p + t + 0.76$ MeV

ν_e flux (CC):

$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033$$

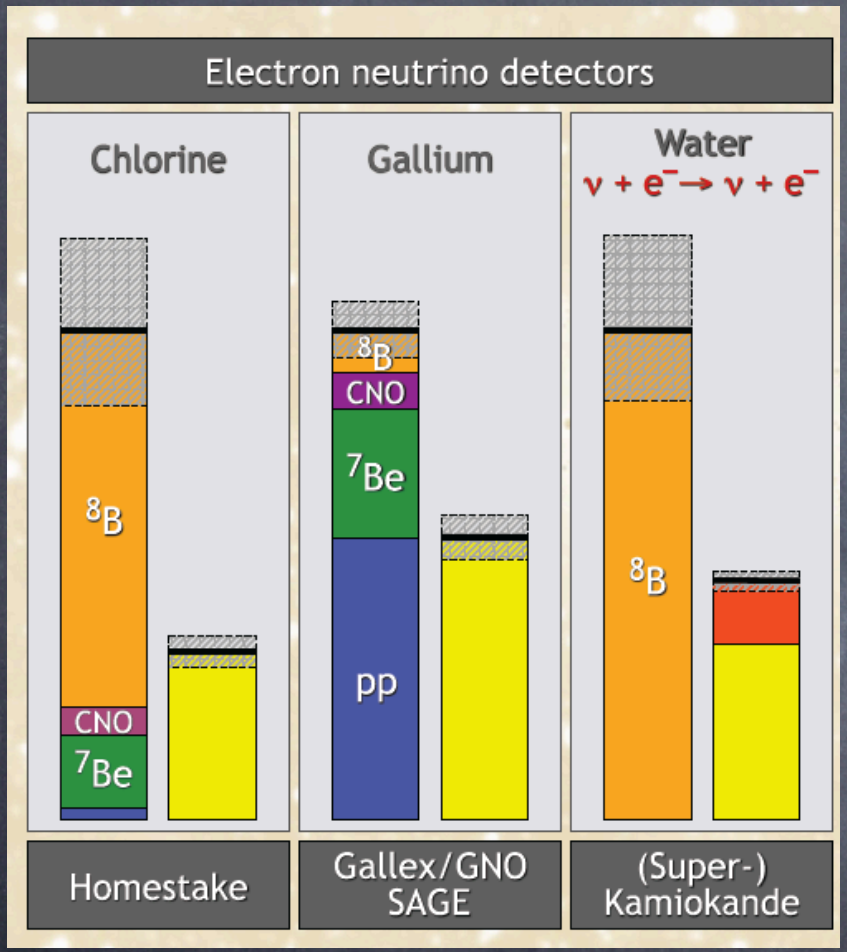
30%

total ν flux (NC):

$$\phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}(stat)^{+0.36}_{-0.34}(syst)$$

100% !!

The solar neutrino problem



~30% ~50% ~40%

➡ All the experiments detect less neutrinos than expected (30-50%)

What is happening?

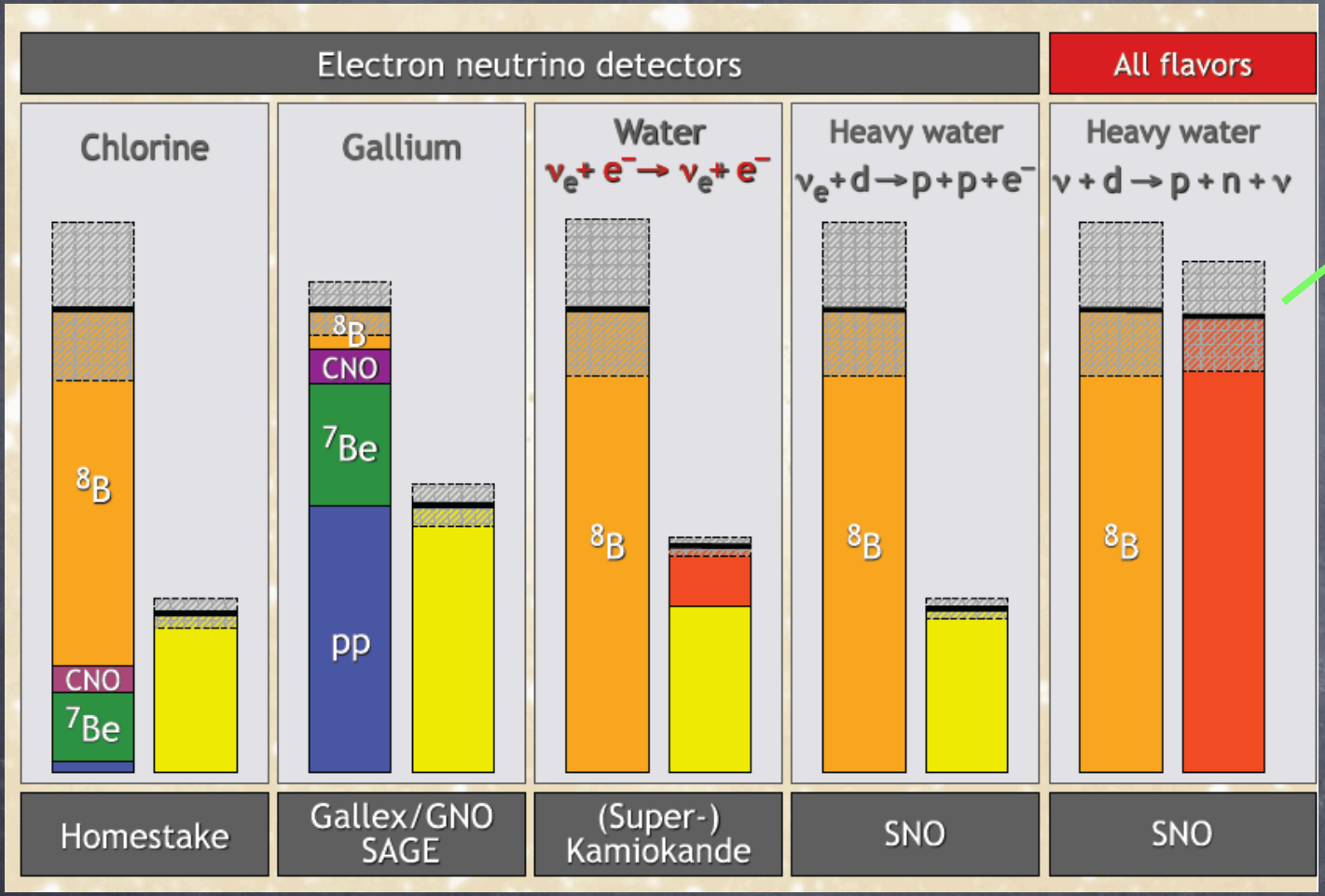
- experimental errors ?
  -> different kinds of experiments.

- errors in the Standard Solar Model?

- something is happening with neutrinos in their way from the Sun to the Earth?

- new particle physics needed ??

The solar neutrino problem



All neutrinos are there!!

The Sun produces ν_e that arrive to the Earth as 1/3 ν_e + 1/3 ν_μ + 1/3 ν_τ

➡ flavor conversion: $\nu_e \rightarrow \nu_x$

Conversion mechanism ?
Neutrino oscillations ??