3rd CHIPP Swiss neutrino workshop

Where we stand in neutrino physics

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Max-Planck-Institute for Nuclear Physics, Heidelberg

10-yr anniversary of neutrino oscillations

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Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2] E. Kearns,[2] M.D. Messier,[2] K. Scholberg,[2] J.L. Stone,[2] L.R. Sulak,[2] C.W. Walter,[2] M. Goldhaber,[3] T. Barszczxak,[4] D. Casper,[4] W. Gajewski,[4] P.G. Halverson,[4,*] J. Hsu,[4] W.R. Kropp,[4] L.R. Price,[4] F. Reines,[4] M. Smy,[4] H.W. Sobel,[4] M.R. Vagins,[4] K.S. Ganezer,[5] W.E. Keig,[5] R.W. Ellsworth,[6] S. Tasaka,[7] J.W. Flanagan,[8,†] A. Kibayashi,[8] J.G. Learned,[8] S. Matsuno,[8] V.J. Stenger,[8] D. Takemori,[8] T. Ishii,[9] J. Kanzaki,[9] T. Kobayashi,[9] S. Mine,[9] K. Nakamura,[9] K. Nishikawa,[9] Y. Oyama,[9] A. Sakai,[9] M. Sakuda,[9] O. Sasaki,[9] S. Echigo,[10] M. Kohama,[10] A.T. Suzuki,[10] T.J. Haines,[11,4] E. Blaufuss,[12] B.K. Kim,[12] R. Sanford,[12] R. Svoboda,[12] M.L. Chen,[13] Z. Conner,[13,‡] J.A. Goodman,[13] G.W. Sullivan,[13] J. Hill,[14] C.K. Jung,[14] K. Martens,[14] C. Mauger,[14] C. McGrew,[14] E. Sharkey,[14] B. Viren,[14] C. Yanagisawa,[14] W. Doki,[15] K. Miyano,[15] H. Okazawa,[15] C. Saji,[15] M. Takahata,[15] Y. Nagashima,[16] M. Takita,[16] T. Yamaguchi,[16] M. Yoshida,[16] S.B. Kim,[17] M. Etoh,[18] K. Fujita,[18] A. Hasegawa,[18] T. Hasegawa,[18] S. Hatakeyama,[18] T. Iwamoto,[18] M. Koga,[18] T. Maruyama,[18] H. Ogawa,[18] J. Shirai,[18] A. Suzuki,[18] F. Tsushima,[18] M. Koshiba,[19] M. Nemoto,[20] K. Nishijima,[20] T. Futagami,[21] Y. Hayato,[21,§] Y. Kanaya,[21] K. Kaneyuki,[21] Y. Watanabe,[21] D. Kielczewska,[22,4] R.A. Doyle,[23] J.S. George,[23] A.L. Stachyra,[23] L.L. Wai,[23,‖] R.J. Wilkes,[23] and K.K. Young[23]
(Super-Kamiokande Collaboration)

3000+ citations

Outline

- Global fit to present oscillation data in the three-neutrino framework
  comment on possible “hints” for non-zero θ_{13}
- Brief outlook for upcoming oscillation experiments
- LSND puzzle in the light of MiniBooNE results
  the fate of sterile neutrino oscillation schemes

Slightly changing the title of my talk

Where we stand in neutrino physics

$\Rightarrow$ **Where we stand in neutrino oscillations**

Global data and three-neutrino oscillations

Maltoni, TS, Tortola, Valle, hep-ph/0309130, hep-ph/0405172

TS, Tortola, Valle, 0808.2016

Neutrino oscillation experiments

natural neutrino sources:

- solar neutrinos
  Homestake, SAGE+GNO, Super-K, SNO, Borexino
- atmospheric neutrinos
  Super-Kamiokande

artificial neutrino sources:

- reactor neutrinos
  Chooz (1 km), KamLAND (180 km)
- long-baseline accelerator experiments
  K2K (250 km), MINOS (735 km)

3-flavour oscillation parameters

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

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

atmospheric+LBL — Chooz — solar+KamLAND

3-flavour effects are suppressed because
$\Delta m^2_{21} \ll |\Delta m^2_{31}|$ and $\theta_{13} \ll 1$

$\Rightarrow$ dominant oscillations are well described by effective two-flavour oscillations

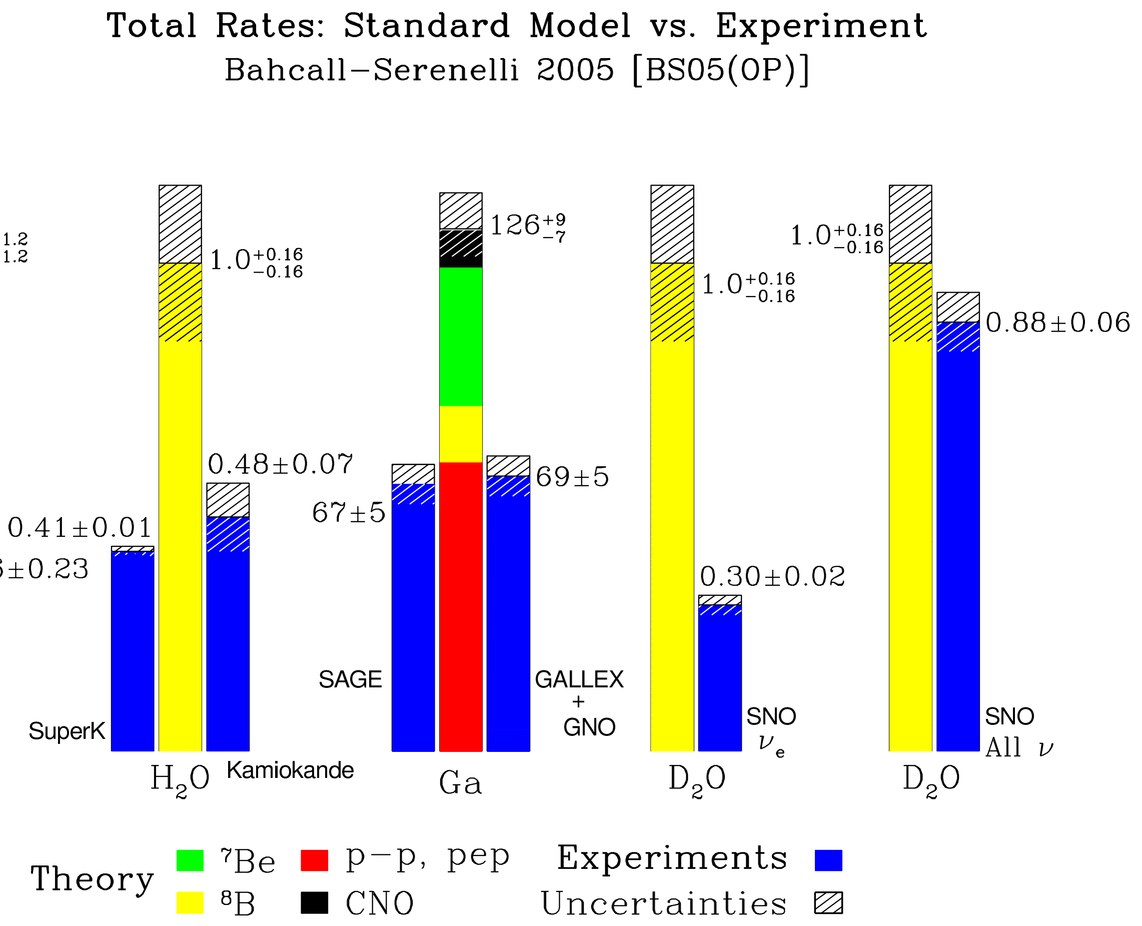
The “solar” parameters Δm^2_{21}, θ_{12}

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

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

atmospheric+LBL   Chooz   solar+KamLAND

Solar neutrino experiments

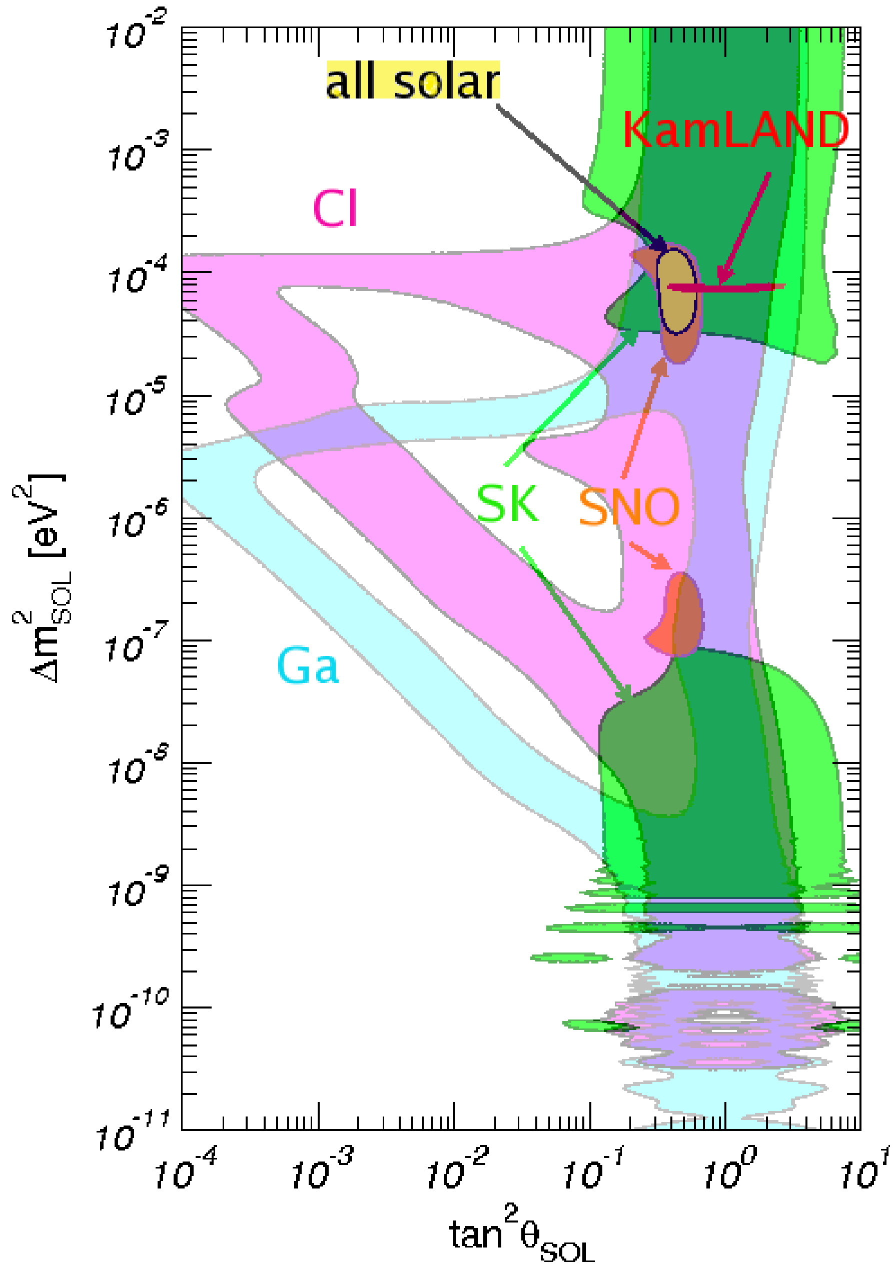


SNO: $$\nu_e + d \to p + p + e^-$$ $$\nu_x + d \to p + n + \nu_x$$

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

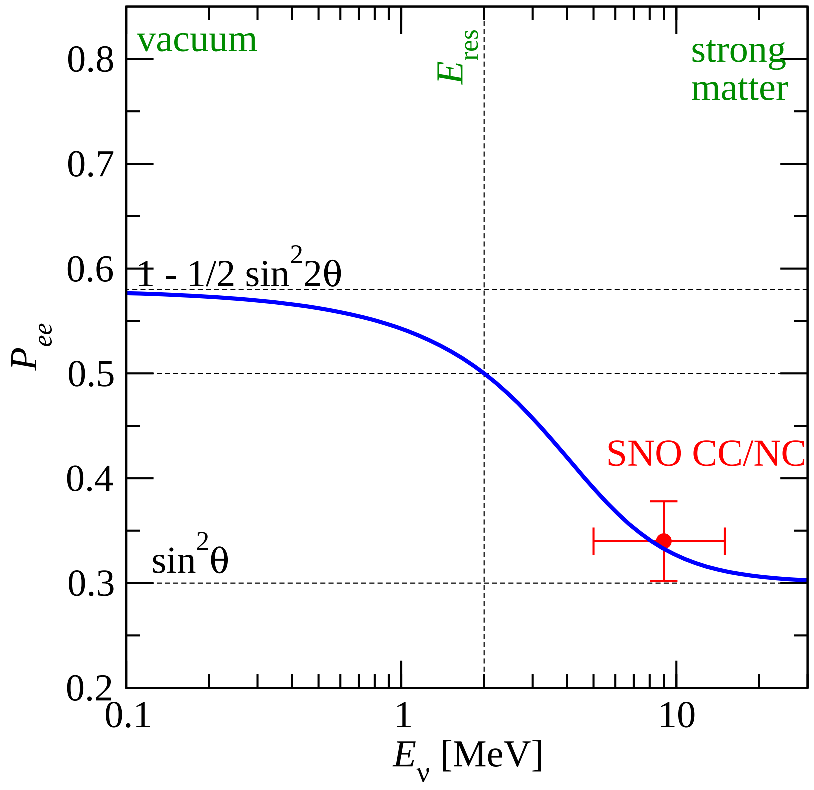
7σ evidence for a non-zero $\nu_{\mu,\tau}$ flux from the sun

’Solar’ parameters



The LMA-MSW solution

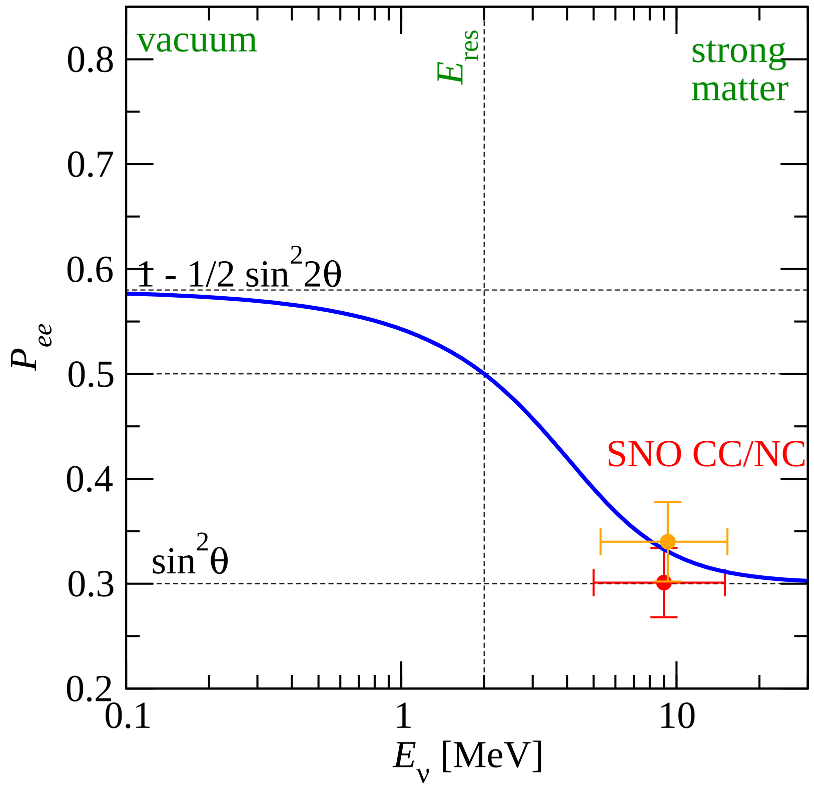
adiabatic evolution of the neutrino state from the center of the sun to the surface

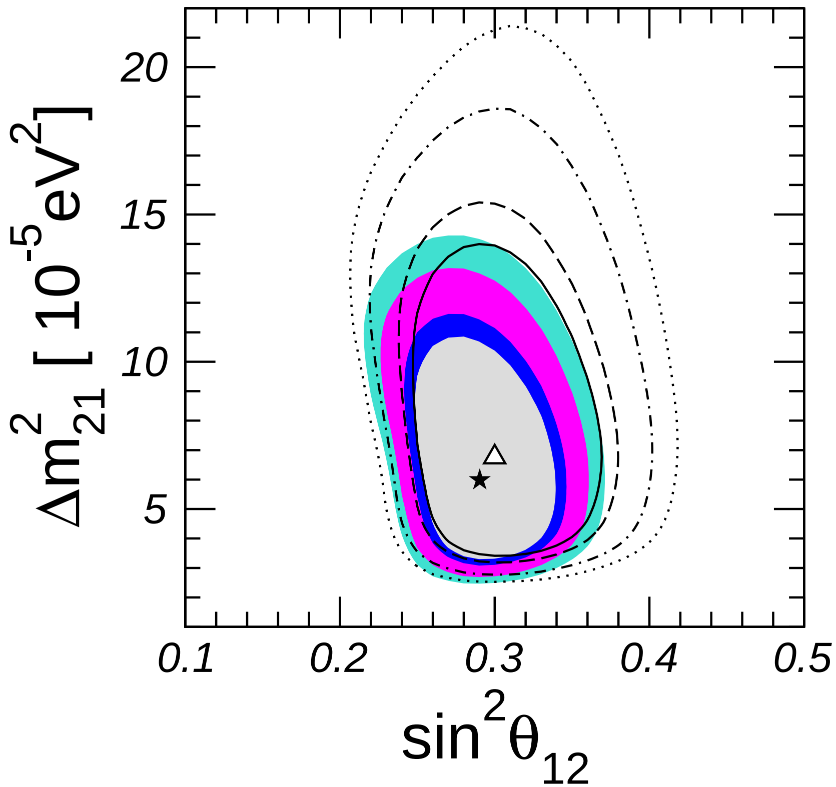


SNO CC/NC: constraint on $\sin^2\theta_{12}$, evidence for MSW effect

The LMA-MSW solution

adiabatic evolution of the neutrino state from the center of the sun to the surface

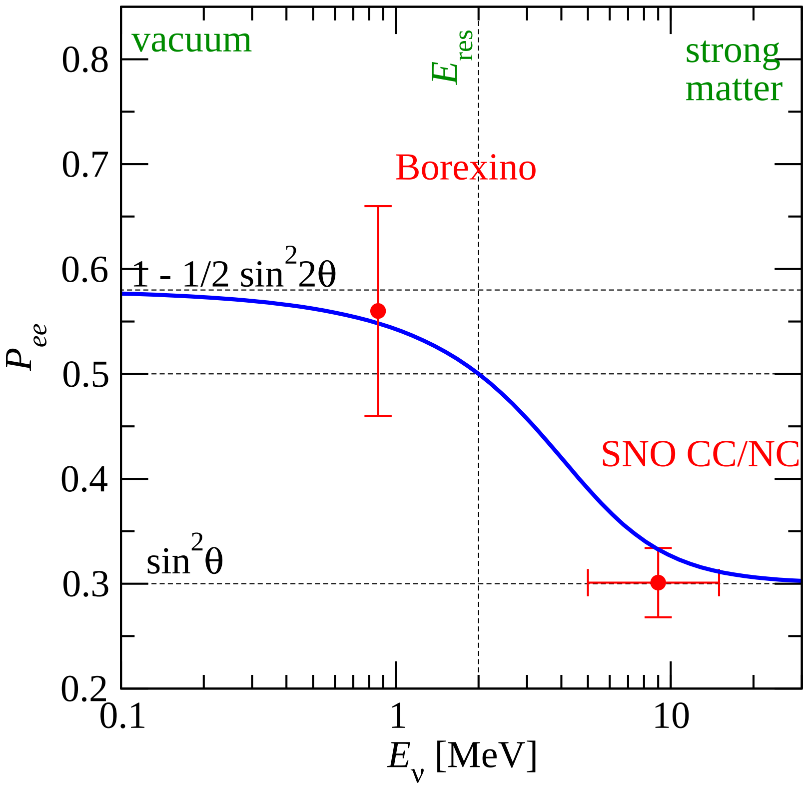


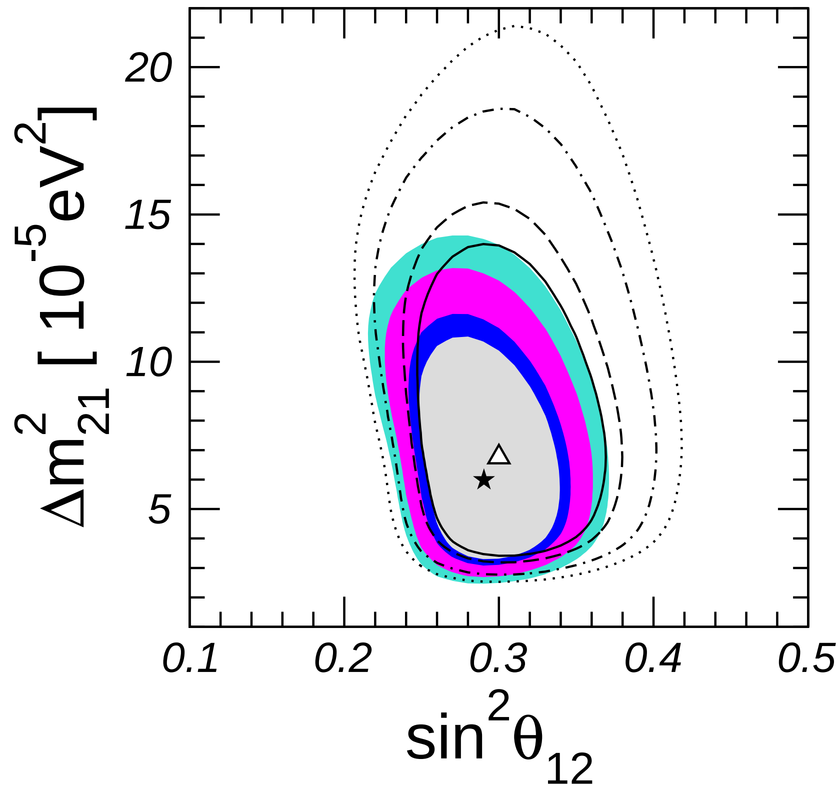


$$(\phi_{CC}/\phi_{NC})_{\rm salt} = 0.340 \pm 0.038 \to (\phi_{CC}/\phi_{NC})_{\rm NCD} = 0.301 \pm 0.033$$

The LMA-MSW solution

adiabatic evolution of the neutrino state from the center of the sun to the surface

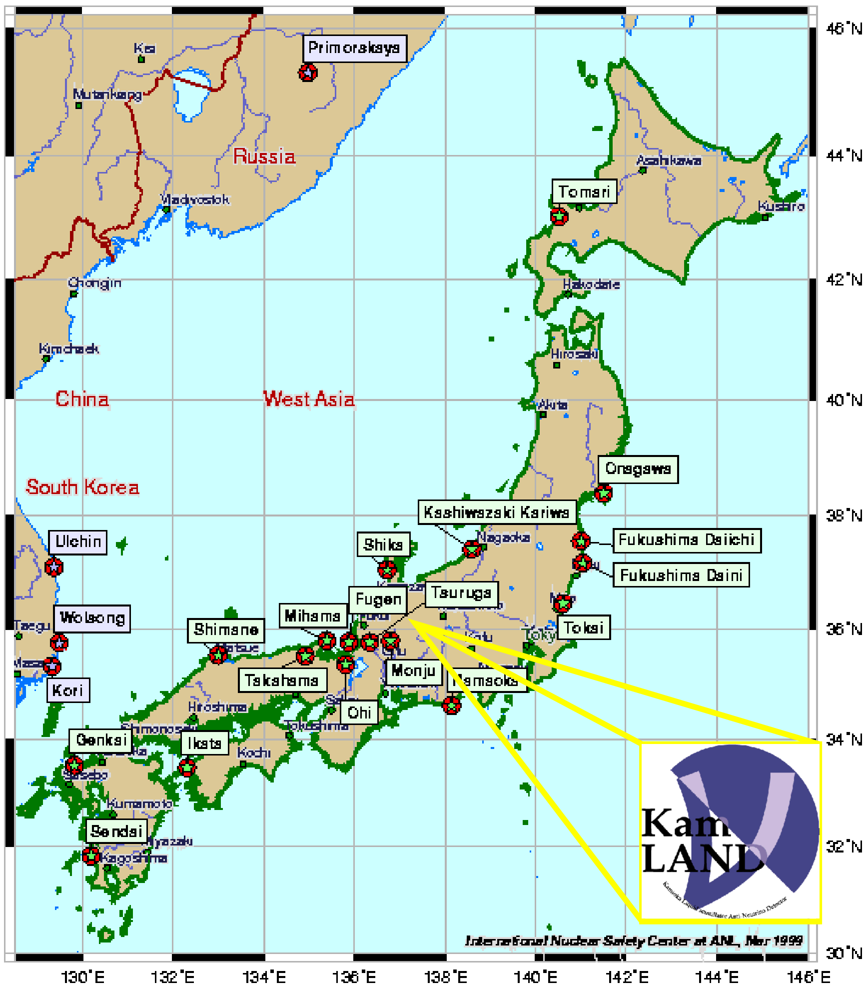




BOREXINO: measurment of the Be7 neutrino line at 0.862 MeV

The KamLAND reactor neutrino experiment

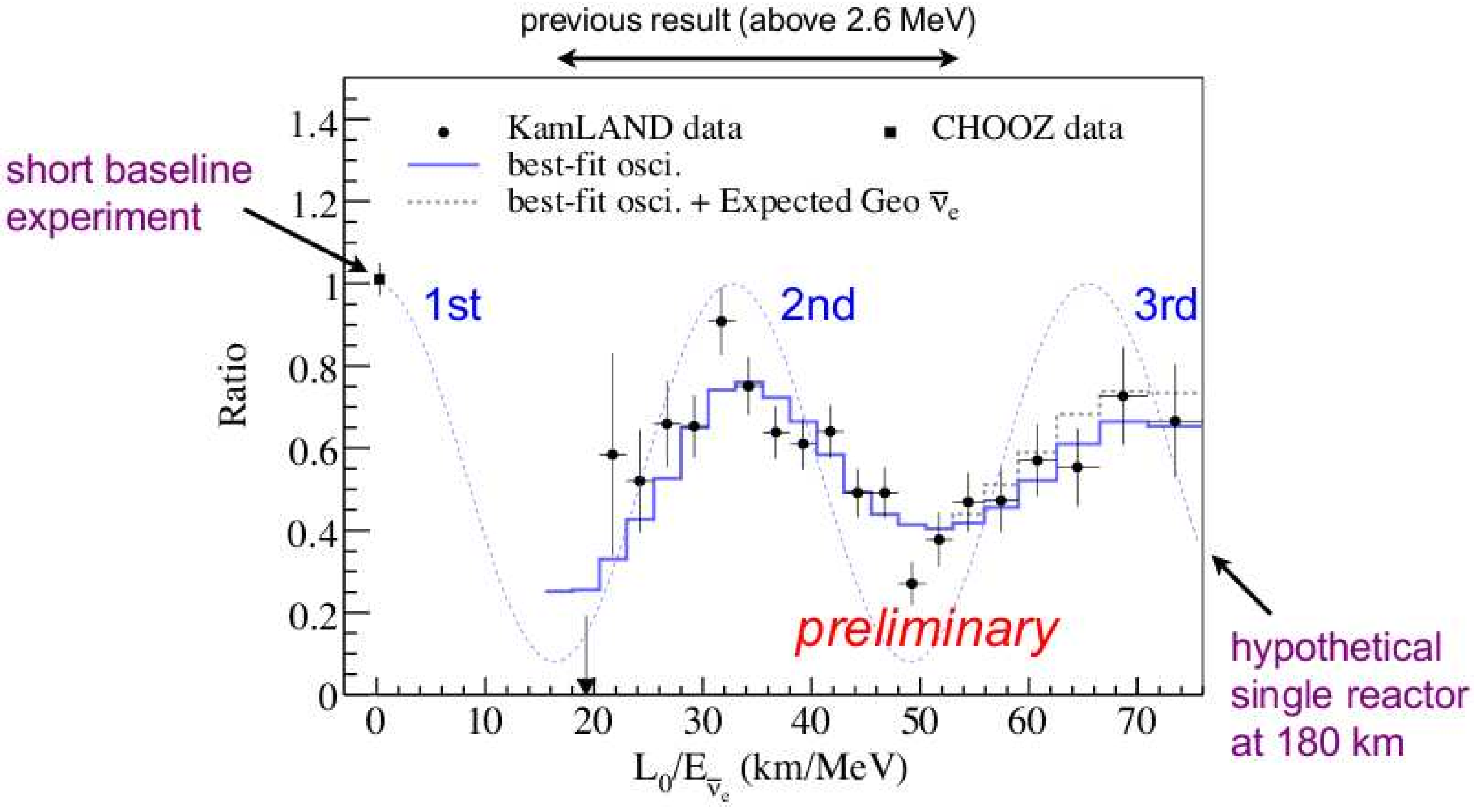
Kamioka Liquid scinitillator Anti-Neutrino Detector



detection of $\bar{\nu}_e$ produced in surrounding nuclear power plants

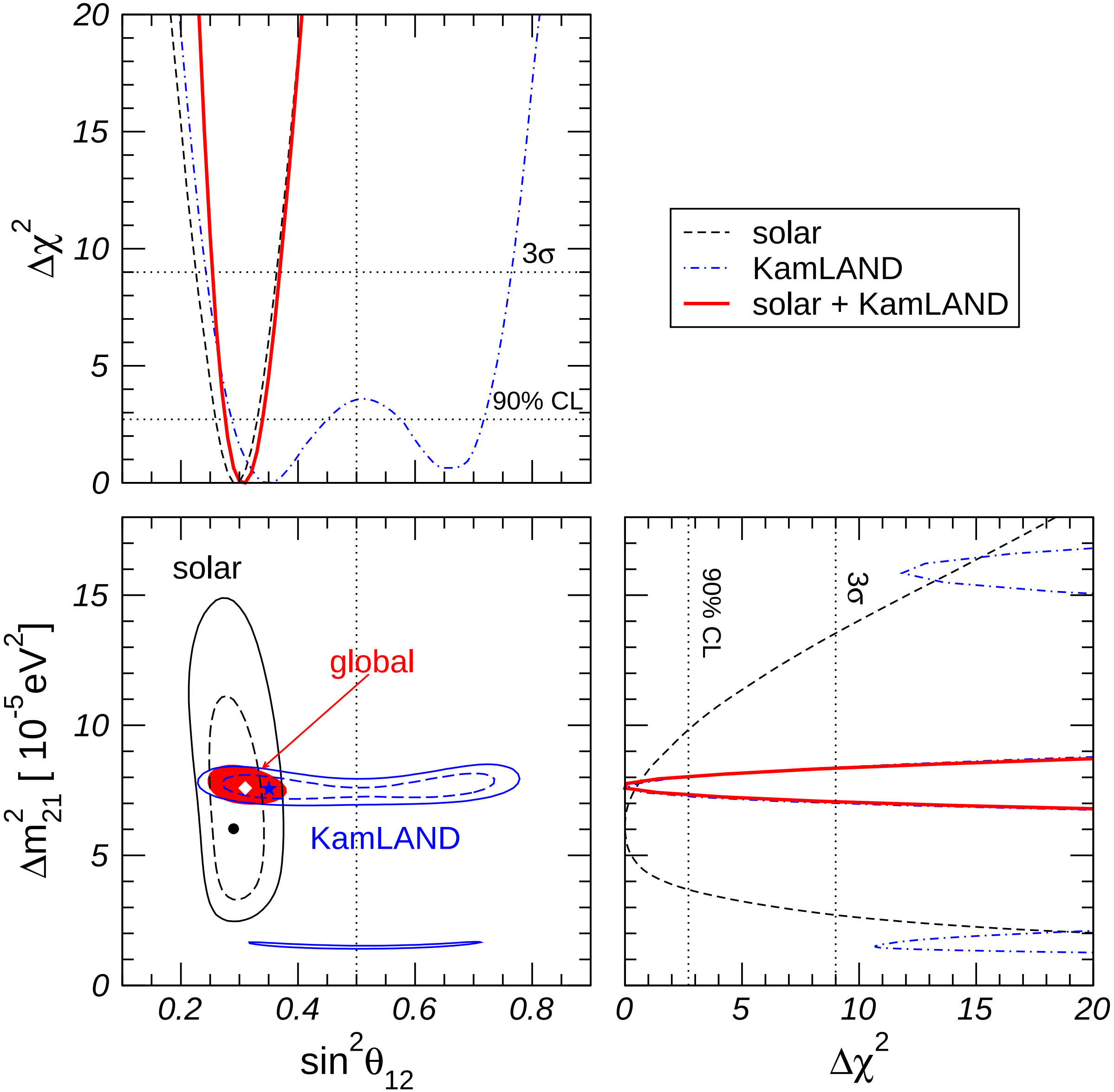
70 GW of nuclear power (7% of world total) is generated at a distance 175 ± 30 km from Kamioka

The KamLAND energy spectrum



evidence for oscillations in $1/E_\nu$

KamLAND vs solar data



$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}\,, \qquad \Delta m^2_{21} = 7.65^{+0.23}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$$

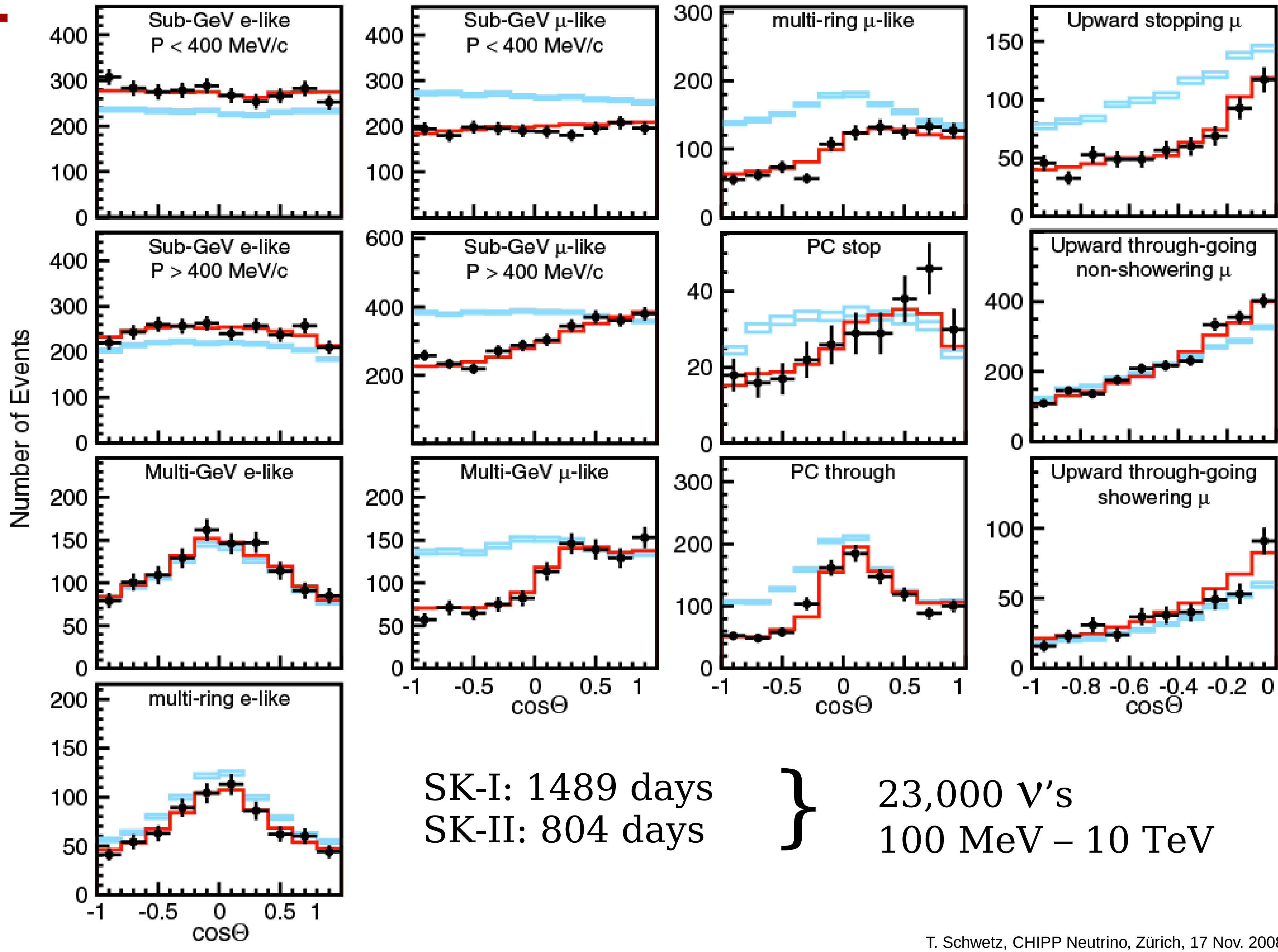
The “atmospheric” parameters Δm^2_{31}, θ_{23}

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

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

atmospheric+LBL   Chooz   solar+KamLAND

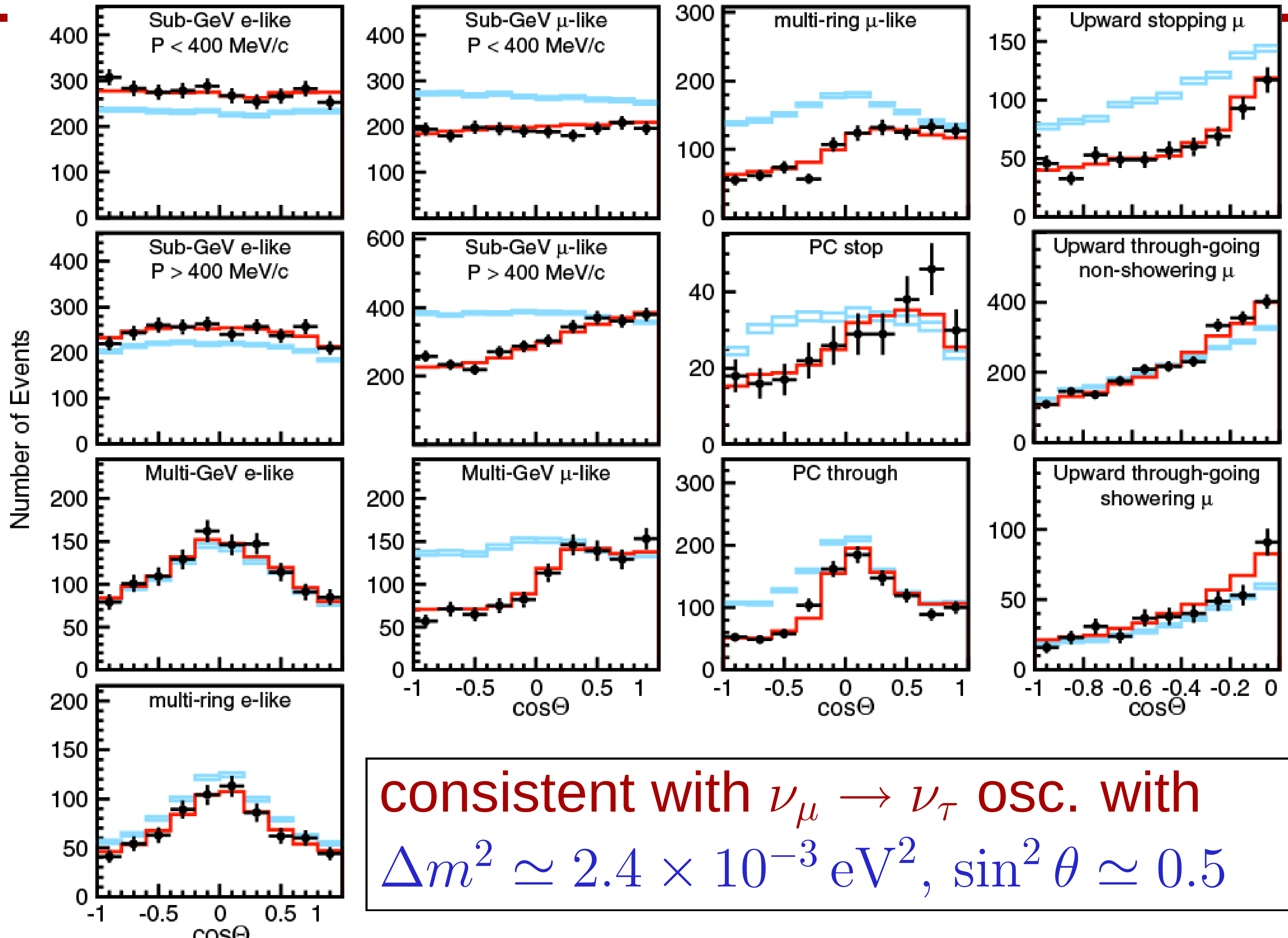
Super-K atmospheric neutrino data



SK-I: 1489 days
SK-II: 804 days

} 23,000 ν's
100 MeV – 10 TeV

Super-K atmospheric neutrino data



consistent with $\nu_\mu \to \nu_\tau$ osc. with
$\Delta m^2 \simeq 2.4 \times 10^{-3}\,\text{eV}^2$, $\sin^2\theta \simeq 0.5$

Long-baseline experiments

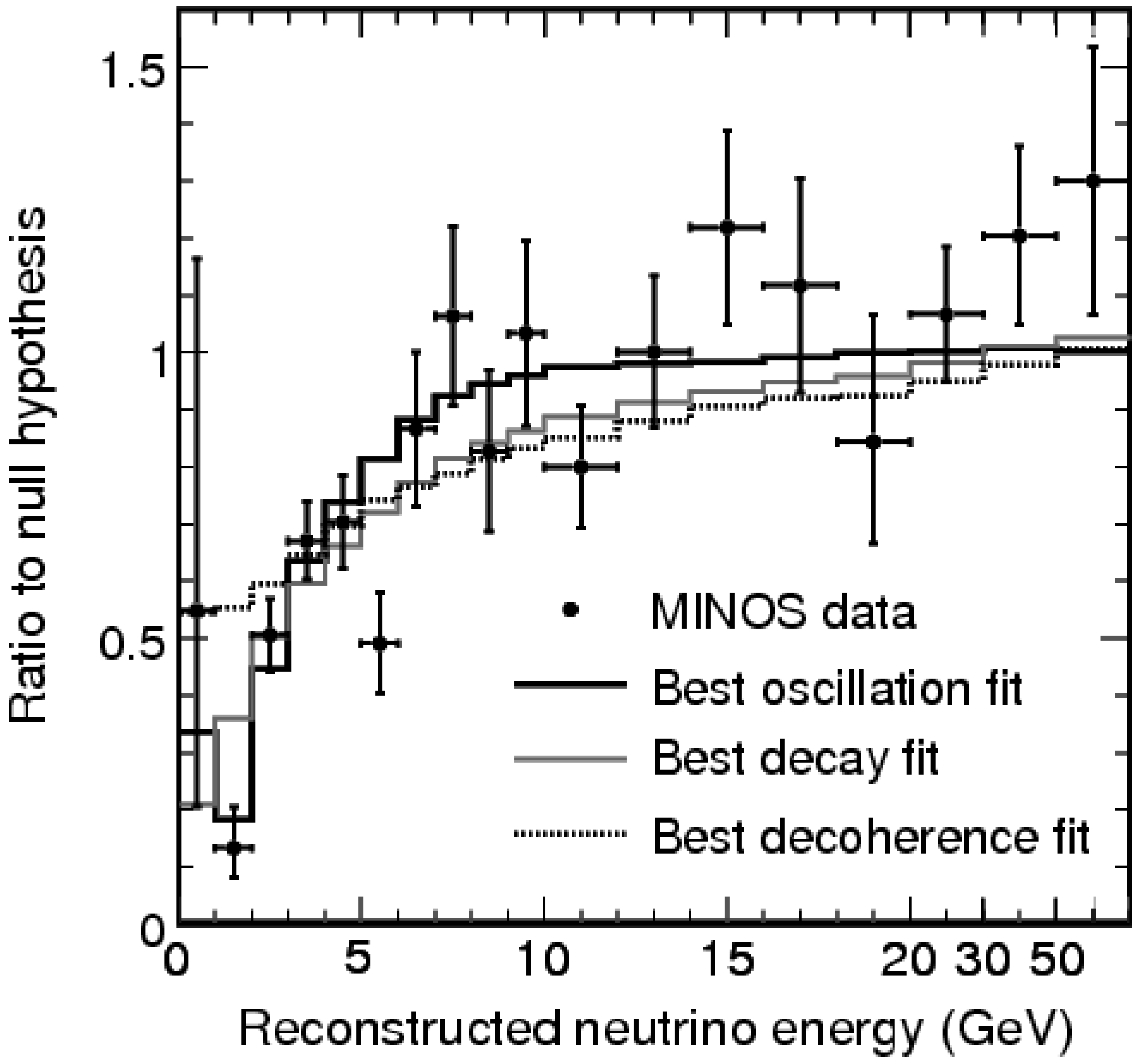
first generation of LBL experiments
($\nu_\mu \to \nu_\mu$ disappearance)

Long-baseline experiments

first generation of LBL experiments
($\nu_\mu \to \nu_\mu$ disappearance)

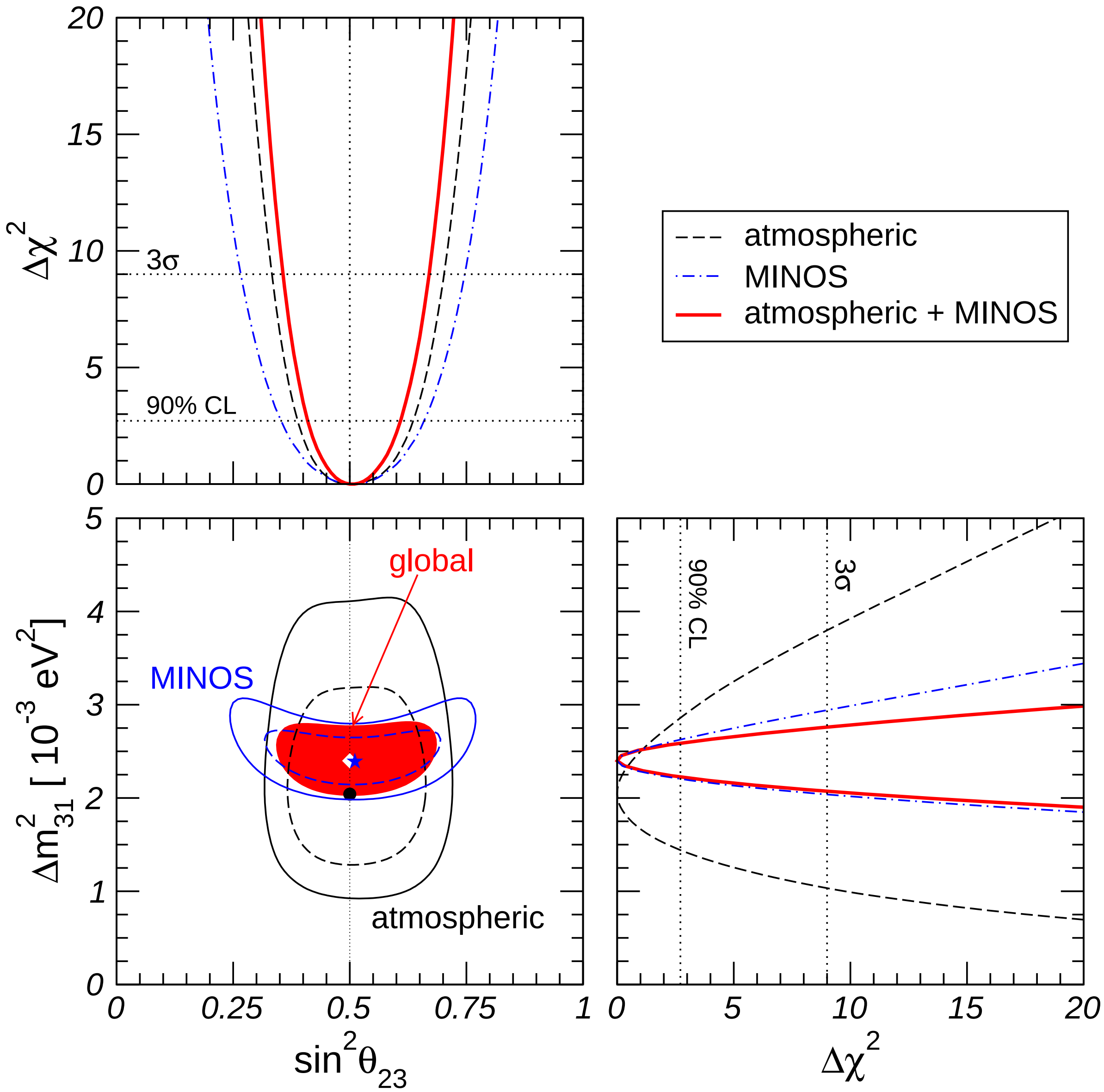
	K2K	MINOS
source	KEK	Fermilab
detector	Super-K	Soudan
baseline	250 km	735 km
neutrino energy	1.3 GeV	3 GeV
E_ν/L [eV^2]	5.2×10^{-3}	4.1×10^{-3}
obs. events	112	848
expect. w/o osc.	$158.1^{+9.2}_{-8.6}$	1065 ± 60

MINOS energy spectrum



arxiv:0806.2237, 3.4×10^{20} pot

Super-K + K2K + MINOS



$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}\,, \qquad |\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2$$

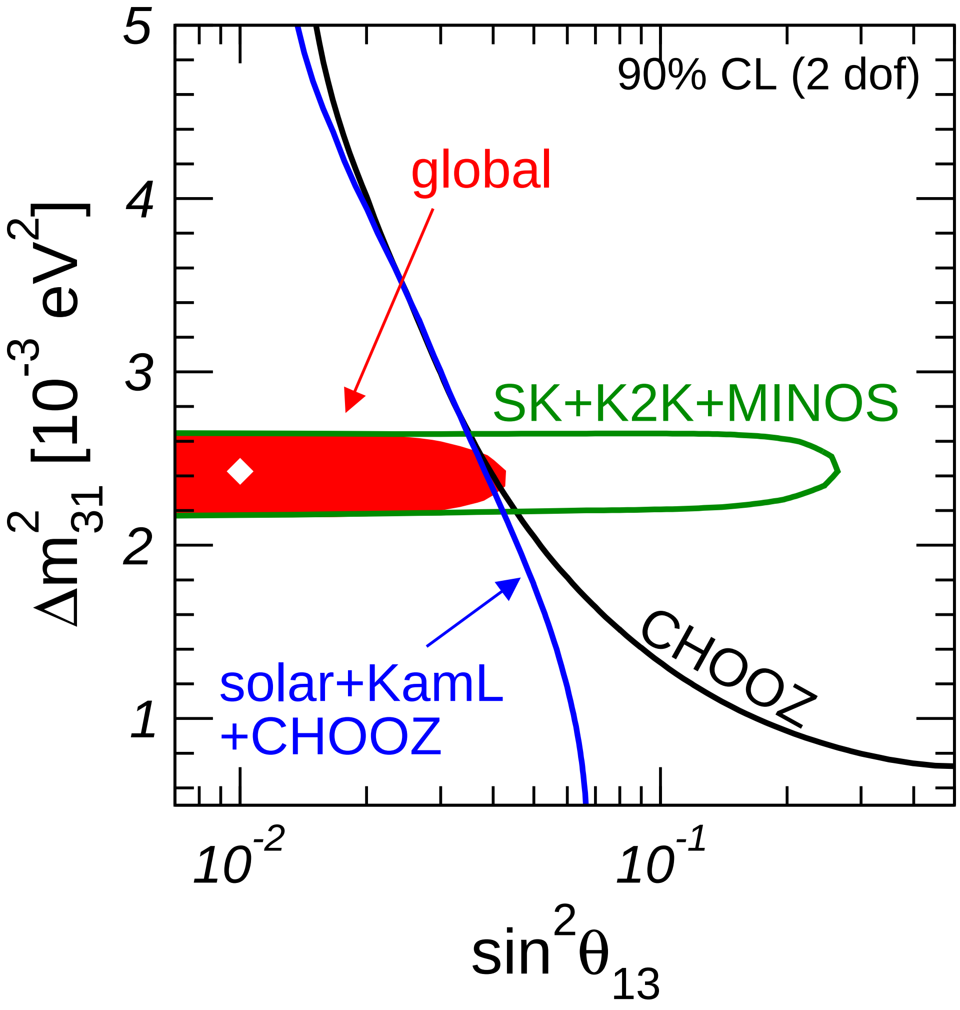
The status of θ_{13} and sub-leading 3-flavour effects

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\Delta m^2_{31}} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\Delta m^2_{21}}$$

atmospheric+LBL | Chooz | solar+KamLAND

The bound on θ_{13}

global data: $\sin^2\theta_{13} < 0.035\,(0.056)$ at 90% CL (3σ)



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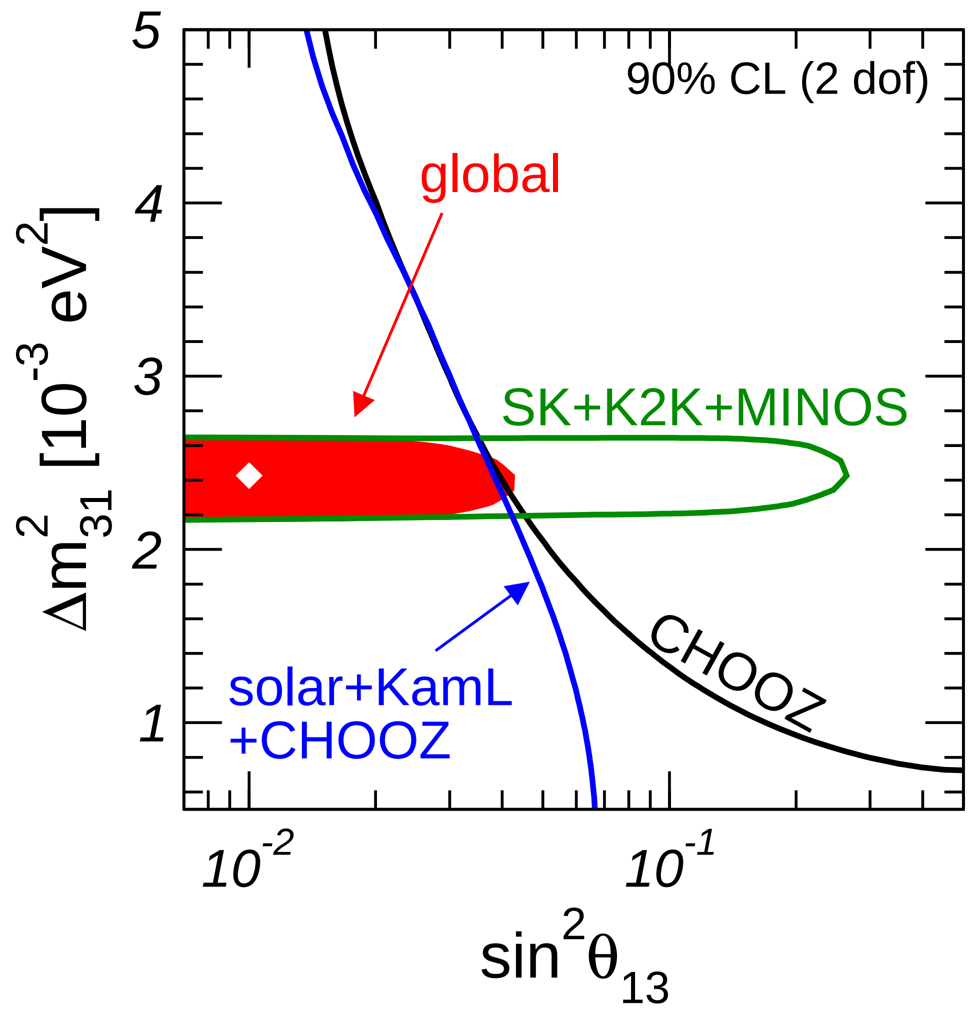
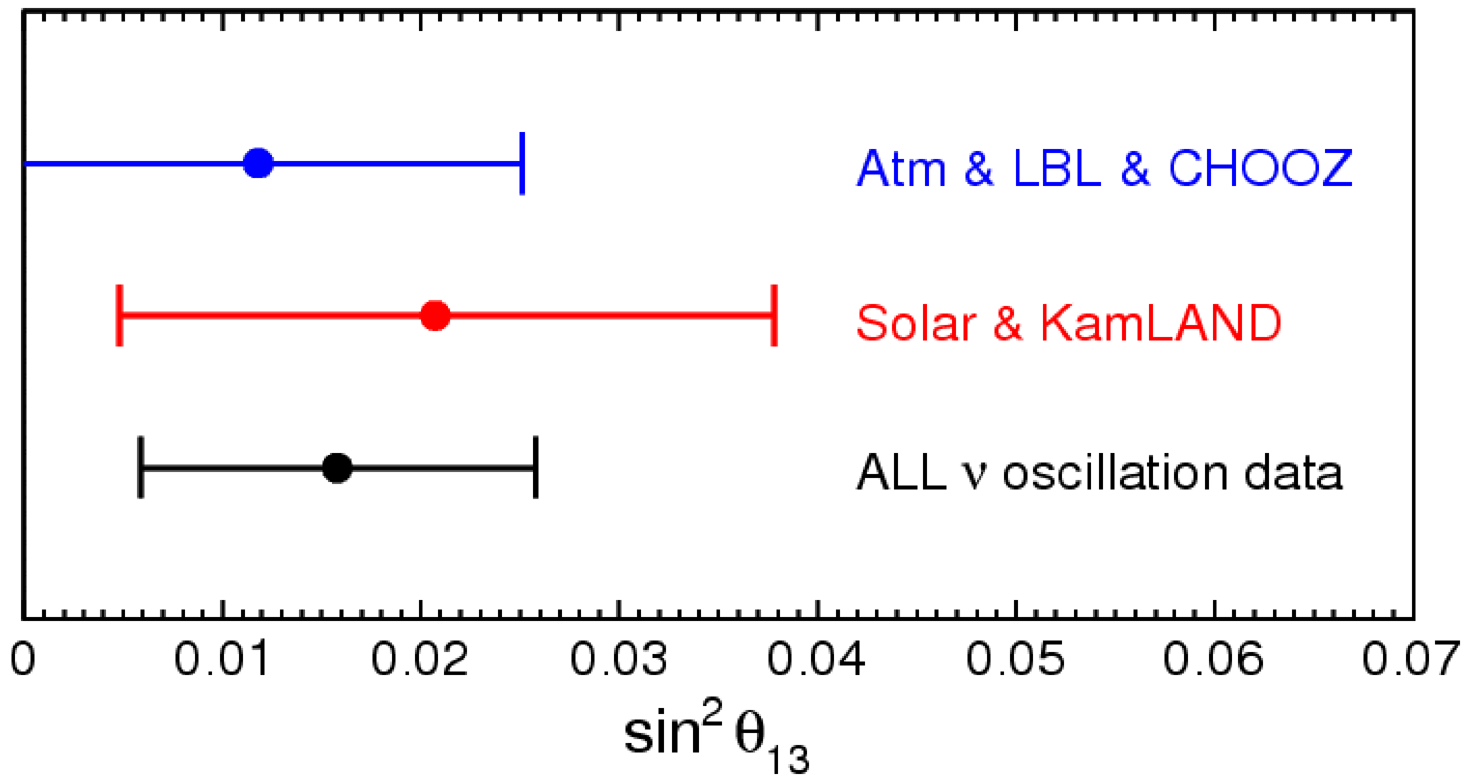


$$\sin\theta_{13} = |U_{e3}| < 0.237\,(3\sigma) \quad \leftrightarrow \quad |V_{us}| = 0.2257 \pm 0.0021$$

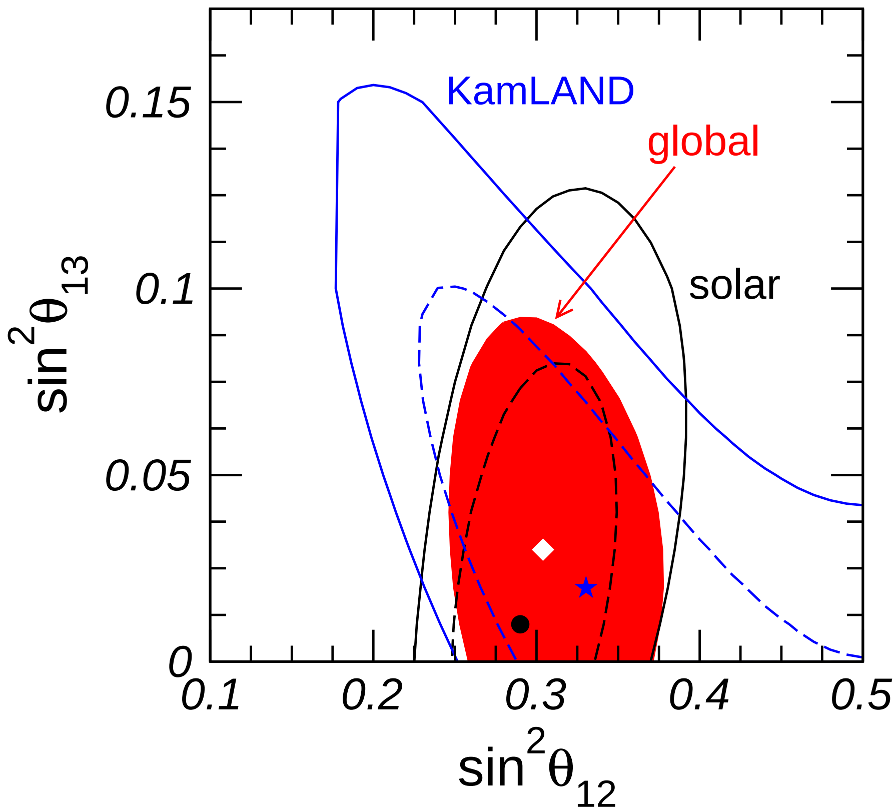
Hint for non-zero θ_{13}?



$$\sin^2\theta_{13} = 0.016 \pm 0.01 \quad (1\sigma)$$

Fogli, Lisi, Marrone, Palazzo, Rotunno, arxiv:0806.2649

θ_{13} *in Solar and KamLAND*



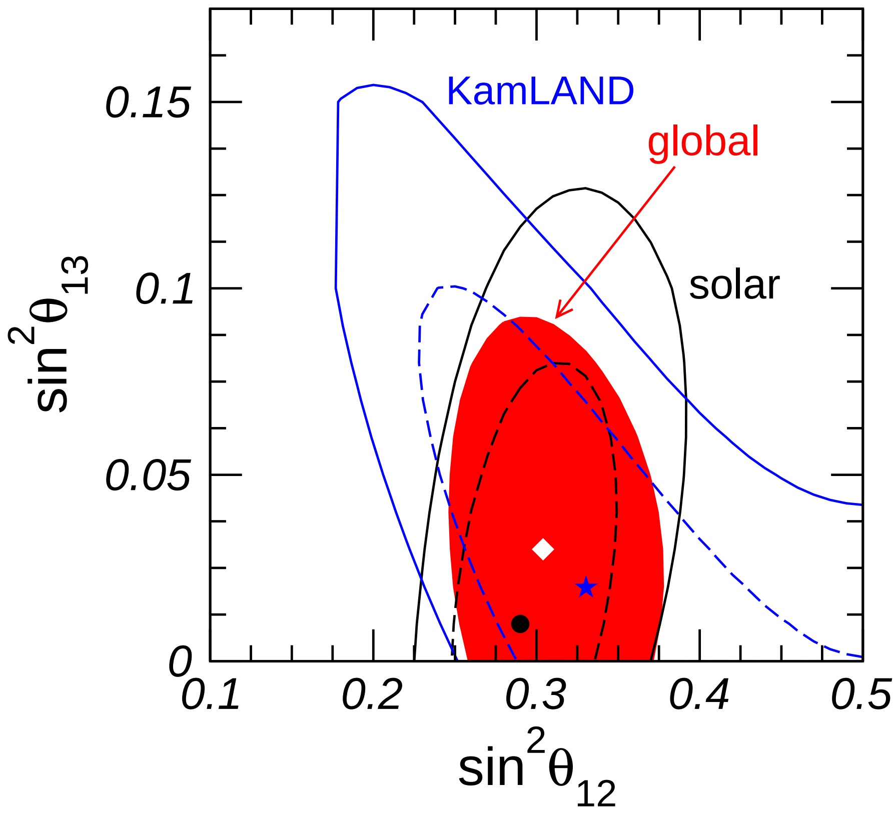
TS, Tortola, Valle, 0808.2016

see also Fogli et al., 0806.2649,
Balantekin, Yilmaz, 0804.3345,
Goswami,Smirnov,hep-ph/0411359,
Maltoni et al., hep-ph/0405172

$$P_{\rm KL} \approx (1 - 2\sin^2\theta_{13}) \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

$$P_{\rm Sol} \approx (1 - 2\sin^2\theta_{13}) \begin{cases} \sin^2\theta_{12} & \text{high } E_\nu \\ (1 - 0.5\sin^2 2\theta_{12}) & \text{low } E_\nu \end{cases}$$

θ_{13} in Solar and KamLAND



TS, Tortola, Valle, 0808.2016

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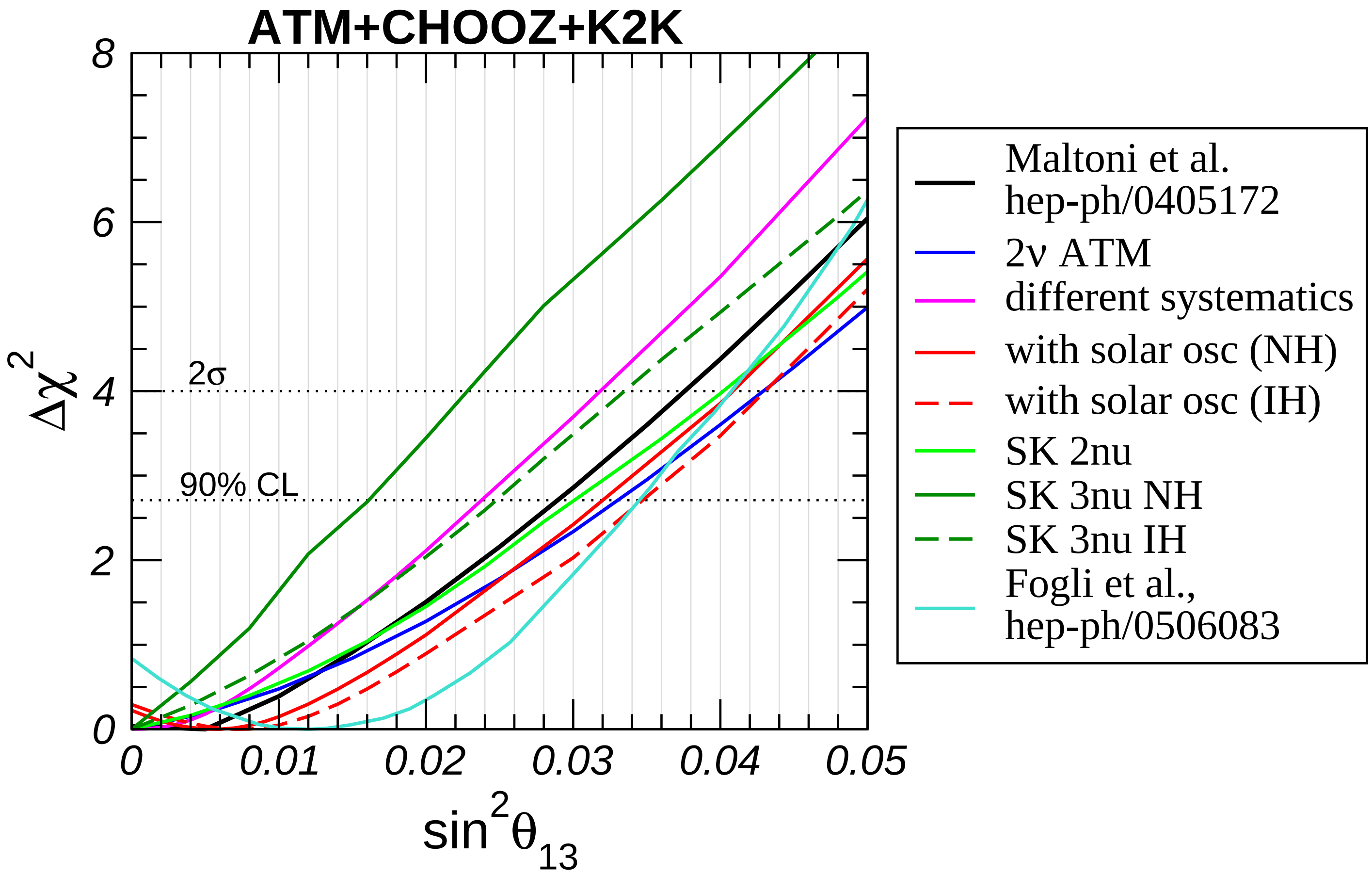
Goswami,Smirnov,hep-ph/0411359,
Maltoni et al., hep-ph/0405172

solar + KamLAND: $\sin^2\theta_{13} = 0.03 > 0$ at 1.5σ

Hint from atmospheric data??

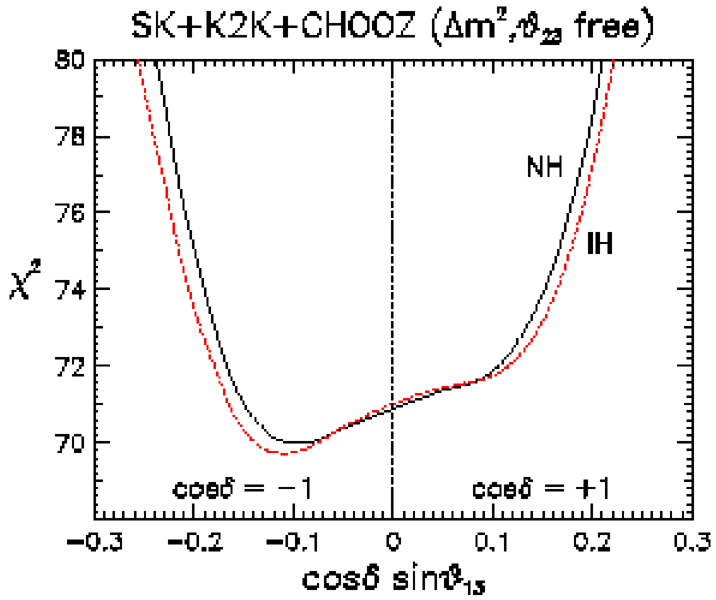


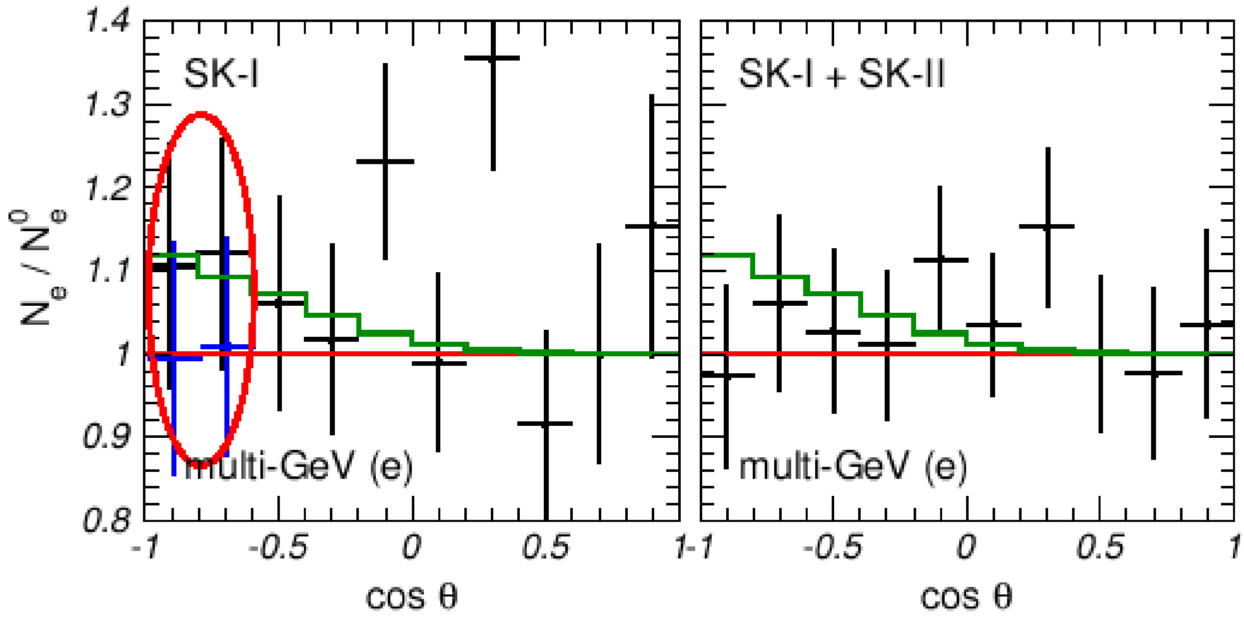
TS, hep-ph/0606060

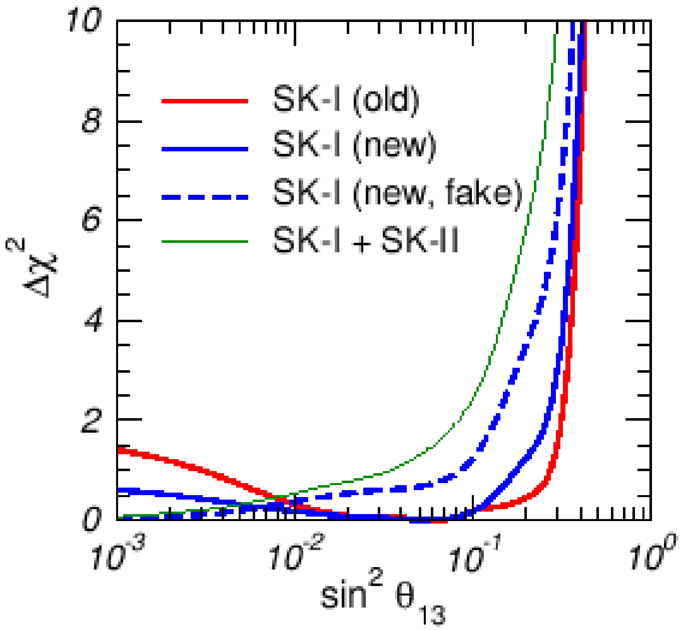
“hint” from atmospheric data depends on subtle effects (details of the analysis/treatment of systematics...)

Hint of non-zero θ_{13} in atmospheric data?

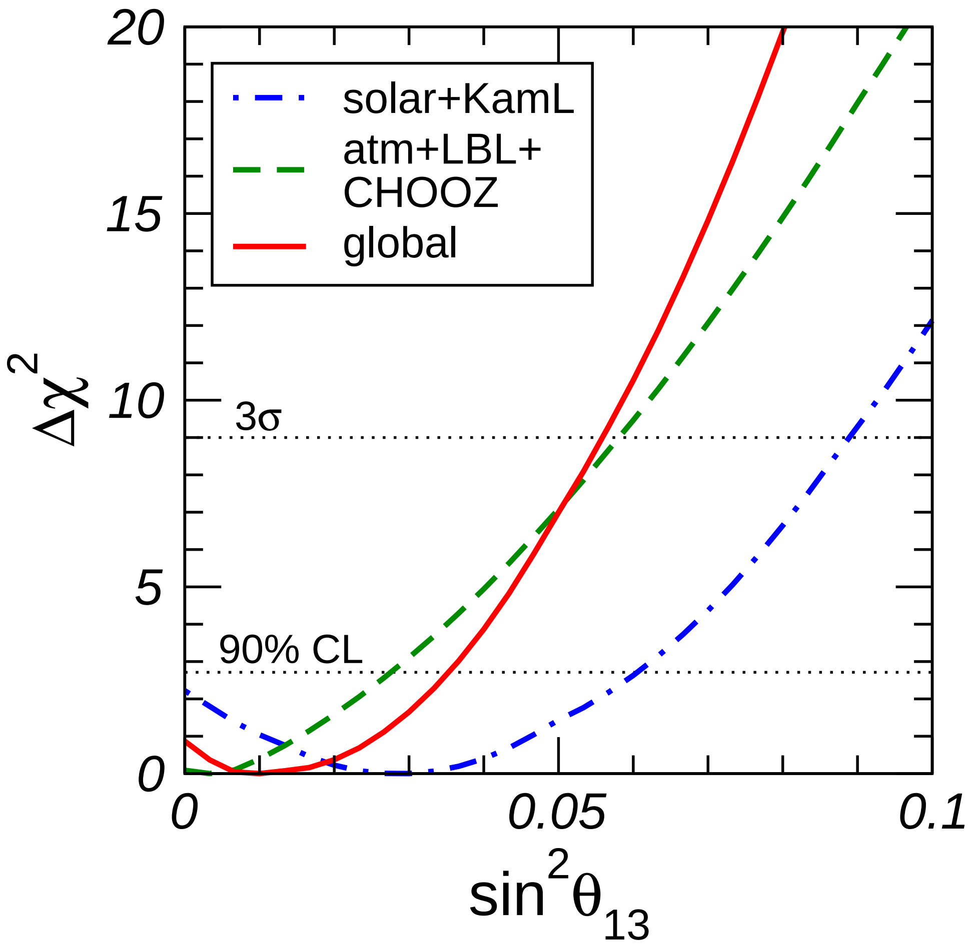
- Claim for an hint of non-zero θ_{13} in atm (+ LBL) data; [Fogli et al, hep-ph/0506083 & arXiv:0806.2649]
- its strength depends on the detail of the simulation;
- it is linked to a peculiar SK-I signature in multi-GeV e-like data, which **disappear** after SK-II data.







No hint from global data?

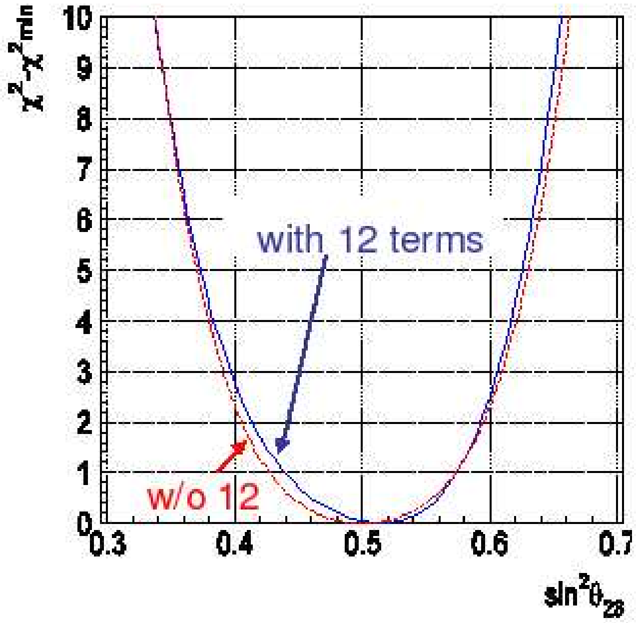


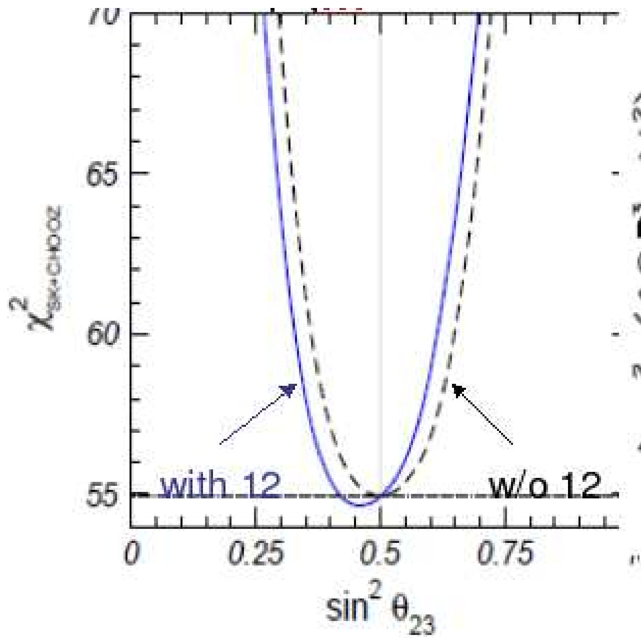
global: $\sin^2\theta_{13} = 0.01^{+0.016}_{-0.011} \qquad (0.9\sigma)$

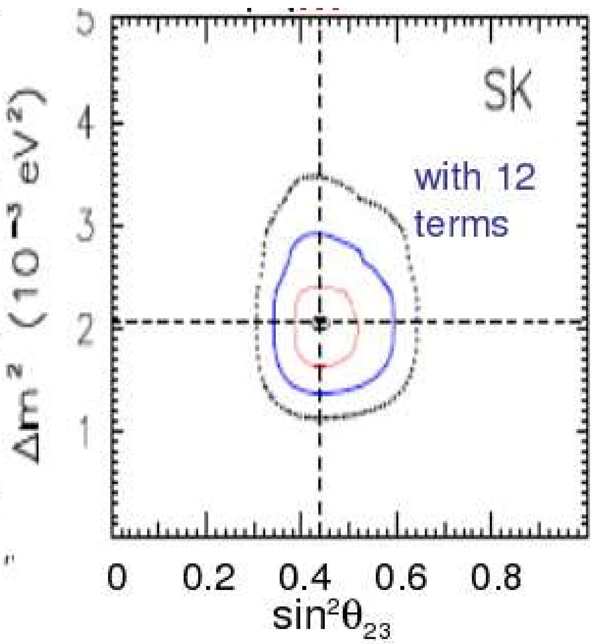
TS, Tortola, Valle, 08

Is there an indication for a non-max θ_{23}?

Super-K Coll. T. Kajita, NuFact05	Gonzalez-Garcia, Maltoni, Smirnov hep-ph/0408170	Fogli et al., hep-ph/0506083







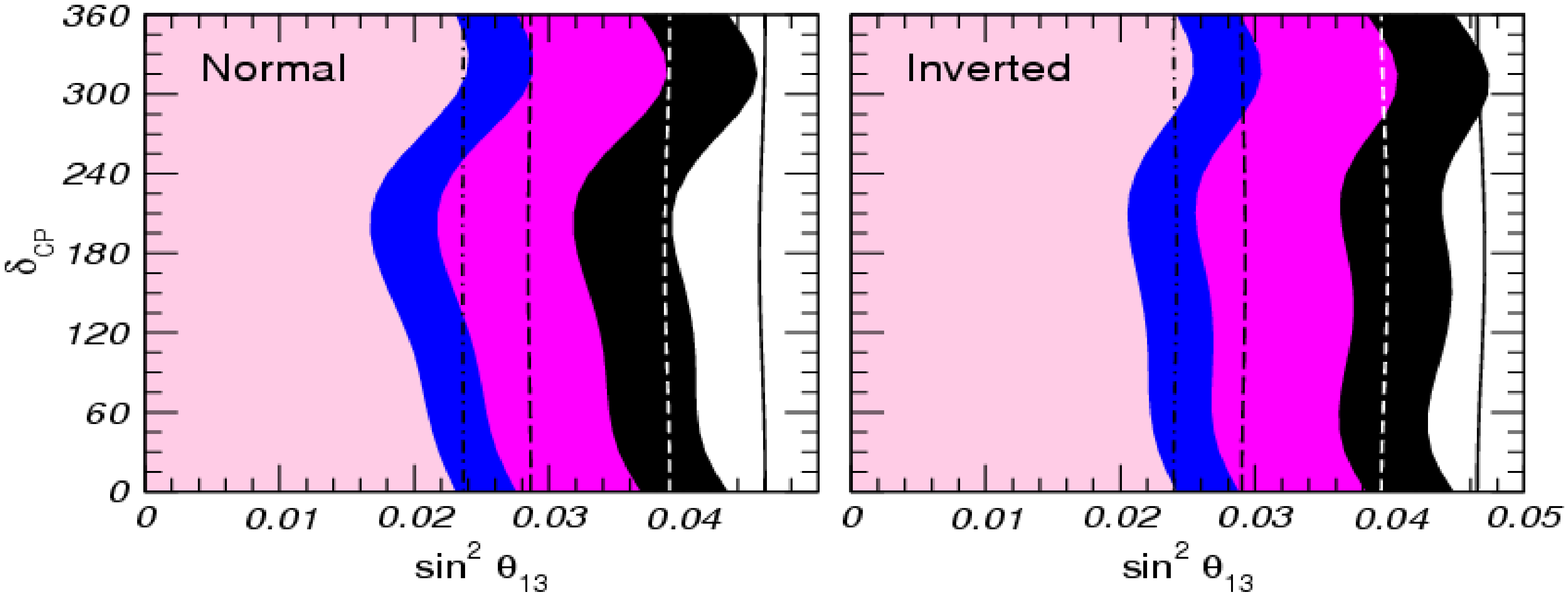
best fit: $\sin^2\theta_{23} = 0.51$ $\qquad$ $\sin^2\theta_{23} = 0.46$ $\qquad$ $\sin^2\theta_{23} = 0.44$

max θ_{23}: $\Delta\chi^2 \approx 0.1$ $\qquad$ $\Delta\chi^2 \approx 0.3$ $\qquad$ $\Delta\chi^2 \approx 0.8$

$\Rightarrow$ sub-GeV e-like event excess

$\delta_{\rm CP}$ *effects in present data*

bound on θ_{13} depends on $\delta_{\rm CP}$ and on hierarchy:
(atmospheric data)



Gonzalez-Garcia, Maltoni, 0704.1800

Personal comment:

Hints for

- non-zero θ_{13} and
- deviation from maximal θ_{23} mixing

are at the level of 1σ and should not be taken more seriously than that!

Summary 3-flavour oscillation parameters

3-flavour oscillation parameters

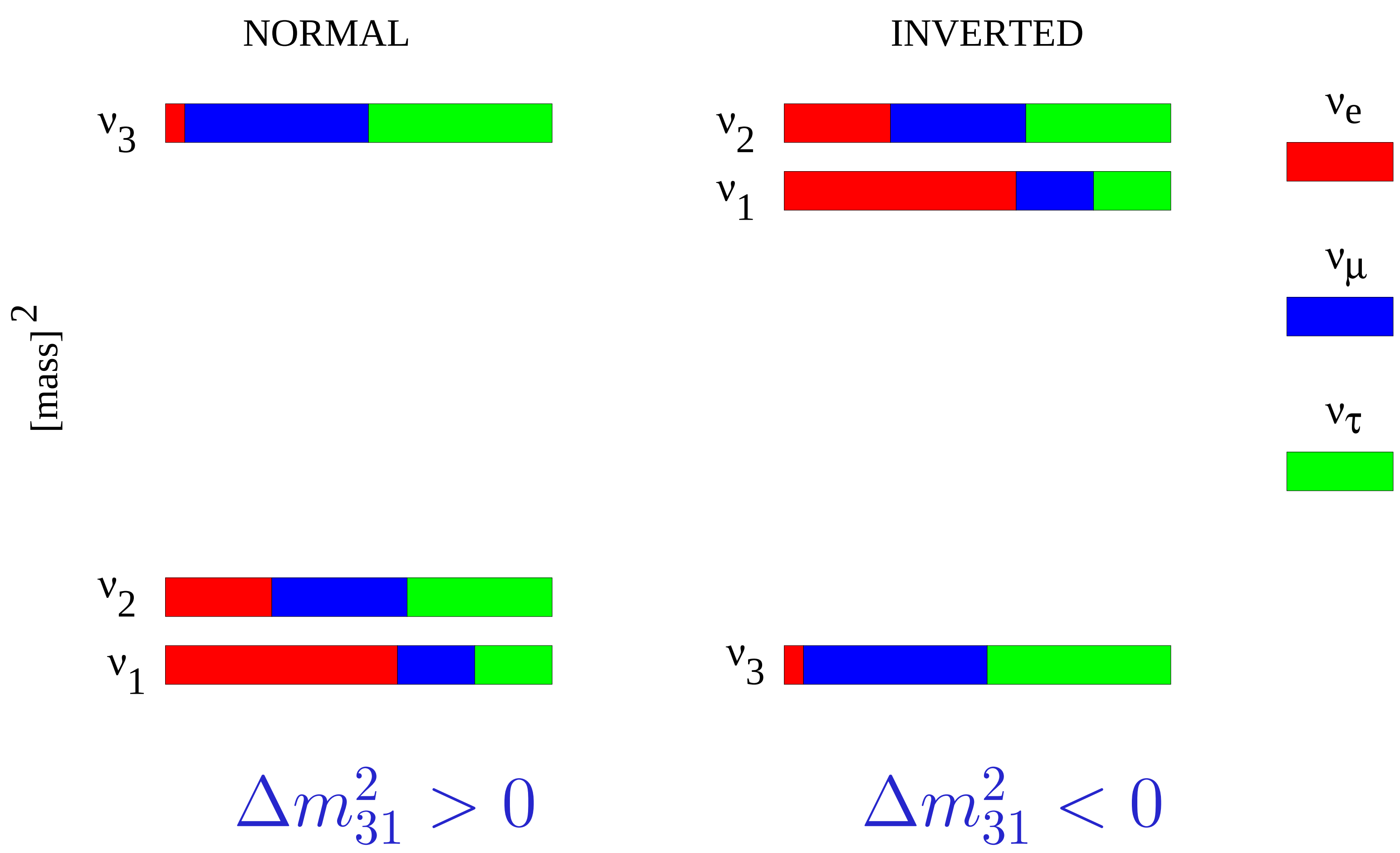
	bf $\pm 1\sigma$	acc. $@\, 3\sigma$	
Δm^2_{21}	$(7.65^{+0.23}_{-0.20})\, 10^{-5}\, \mathrm{eV}^2$	(8%)	KamLAND
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	(19%)	SNO
$\lvert\Delta m^2_{31}\rvert$	$(2.40^{+0.12}_{-0.11})\, 10^{-3}\, \mathrm{eV}^2$	(14%)	MINOS
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	(30%)	SK atm

$\sin^2\theta_{13} < 0.056\ @\, 3\sigma$ CHOOZ

TS, Tortola, Valle, 0808.2016

Three flavour osc. parameters summary

two possibilities for the neutrino mass spectrum



Is there a special pattern in lepton mixing?

example: Tri-bimaximal mixing

Harrison, Perkins, Scott, PLB 2002, hep-ph/0202074

$$\sin^2\theta_{12} = 1/3\,, \quad \sin^2\theta_{23} = 1/2\,, \quad \sin^2\theta_{13} = 0 \qquad \Rightarrow$$

$$U = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

3-flavour oscillations

Open questions:

- Is this basic picture correct?
  LSND hint?
  non-standard effects beyond oscillations?
- Increase the precision on solar and atmospheric parameters (e.g. Is θ_{23} exactly $45°$?)
- How small is θ_{13}?
- What is the value of the CP phase δ?
- Type of the neutrino mass ordering (sign of Δm^2_{31})

What is the value of θ_{13}?

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- naively one would expect $\theta_{12} \sim \theta_{23} \sim \theta_{13}$
  $\rightarrow \theta_{13}$ around the corner

- $\theta_{13} \ll 1$ hint for some symmetry

What is the value of θ_{13}?

- naively one would expect $\theta_{12} \sim \theta_{23} \sim \theta_{13}$
  $\rightarrow \theta_{13}$ around the corner
- $\theta_{13} \ll 1$ hint for some symmetry
- relatively large θ_{13} opens the possibilty to observe generic 3-flavour effects (CP-violation)

Measuring θ_{13}

- $\bar{\nu}_e \longrightarrow \bar{\nu}_e$ disappearance reactor experiments with near and far detectors: **D-Chooz, Daya Bay, RENO**

  “clean” measurement of θ_{13}:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}\left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2$$

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- LBL $\nu_\mu \to \nu_e$ appearance experiments

  (MINOS, CNGS) T2K, NOνA

  θ_{13} is correlated with other parameters, especially with the CP-phase δ.

Measuring θ_{13}

- $\bar{\nu}_e \to \bar{\nu}_e$ disappearance reactor experiments with near and far detectors: **D-Chooz, Daya Bay, RENO**
  "clean" measurement of θ_{13}:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}\left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2$$

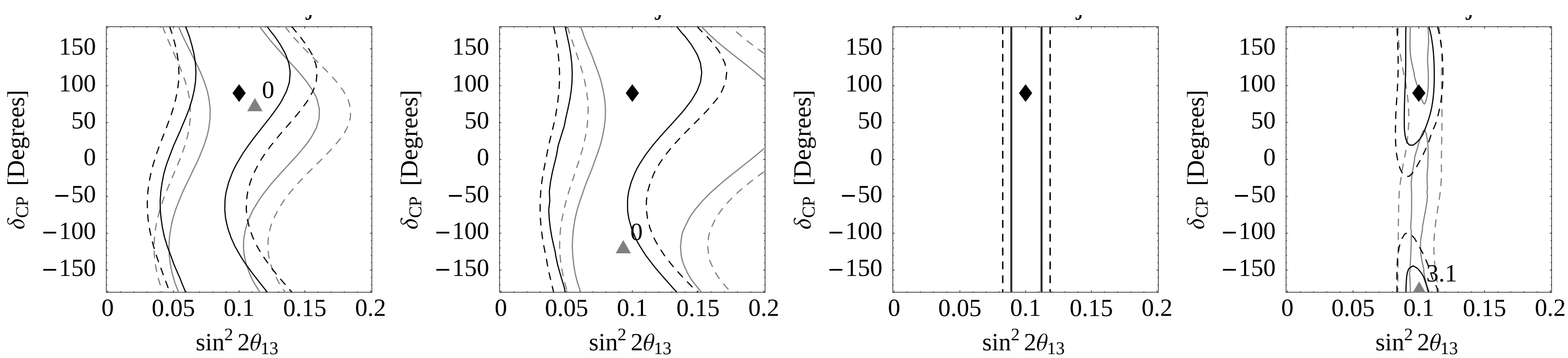
- LBL $\nu_\mu \to \nu_e$ appearance experiments
  (MINOS, CNGS) T2K, NOνA
  θ_{13} is correlated with other parameters, especially with the CP-phase δ.

$\Rightarrow$ Provide complementary information

Measuring $\sin^2 2\theta_{13}$ *at beams or reactors*

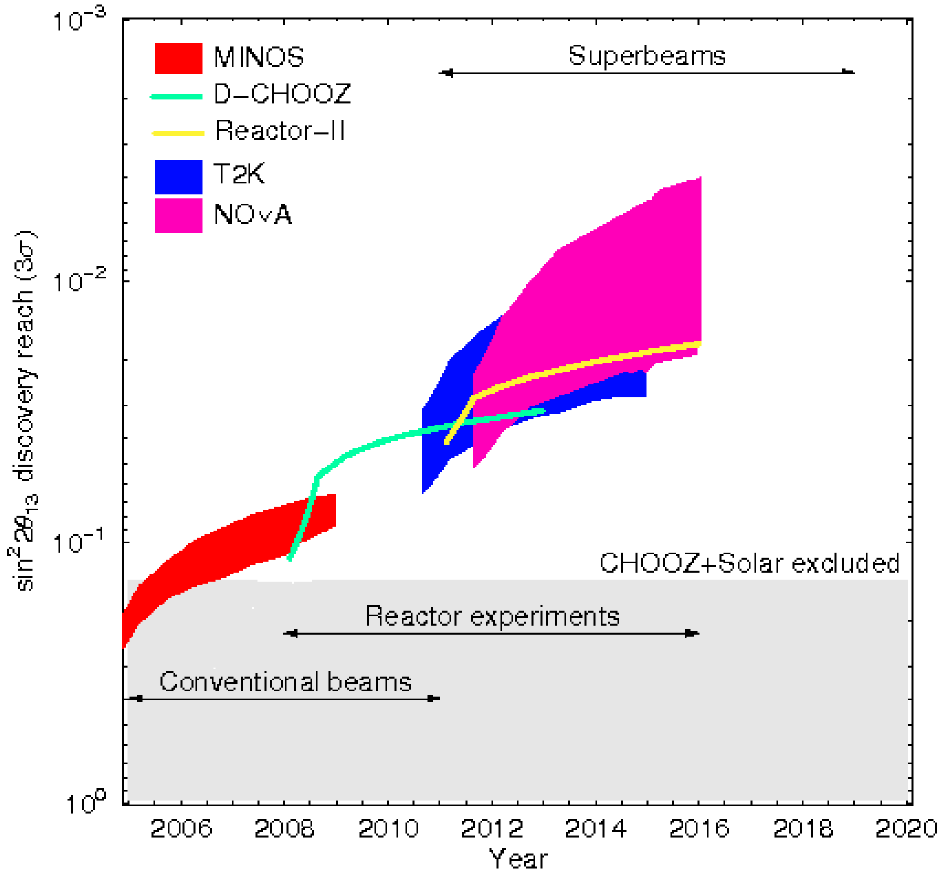
assume $\sin^2 2\theta_{13} = 0.1$

T2K **NOνA** **Reactor-II** combined



Huber, Lindner, Rolinec, Schwetz, Winter, hep-ph/0403068

The race for θ_{13}

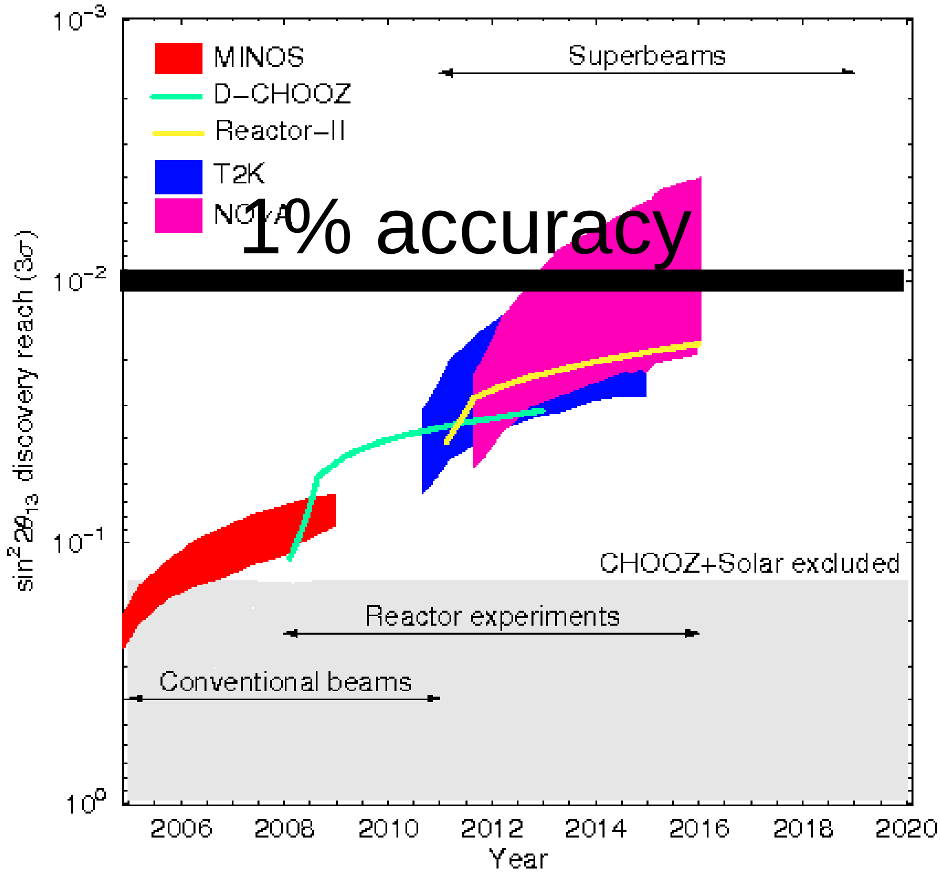


plot by W. Winter from Albrow et al., hep-ex/0509019

$\Delta m^2_{31} = +2.5 \times 10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1$

LBL exps.: neutrinos only

The race for θ_{13}



plot by W. Winter from
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LBL exps.: neutrinos only

Going beyond the next generation of experiments

The ultimate goals:

- measure the value of δ_{CP}
  establish CP violation
- determine the neutrino mass hierarchy
  $\rightarrow$ sgn(Δm^2_{31}), explore Earth matter effect

LBL experiments beyond ten years

- superbeam upgardes $(\nu_\mu \to \nu_e, \nu_\mu) + (\bar{\nu}_\mu \to \bar{\nu}_e, \bar{\nu}_\mu)$

  T2HK: beam 0.77 $\to$ 4 MW, SK (22.5 kt) $\to$ HK (500 kt)

  T2KK: second detector in Korea

  NOνA: proton driver, second detector

  WBB: wideband beam, $E_\nu \sim \mathrm{GeV}, L \gtrsim 1000\,\mathrm{km}$

  CNGS-upgrades (beam upgrade, liquid Ar detector)

  SPL: CERN to $\sim$Mt water Cerenkov at Frejus (130 km)

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- beta beams (**βB**) $(\nu_e \to \nu_\mu) + (\bar{\nu}_e \to \bar{\nu}_\mu)$
  low γ **βB** z.B. CERN-Frejus ($E_\nu \sim 0.4\,\mathrm{GeV}$) or
  high γ **βB** (longer BL), mono-energetic **βB**

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  $E_\nu \sim 20 - 50\,\mathrm{GeV},\ 1000\,\mathrm{km} \lesssim L \lesssim 7000\,\mathrm{km}$

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  see talks tomorrow

- beta beams ([illegible]) $(\nu_e \to \nu_\mu) + (\bar\nu_e \to \bar\nu_\mu)$

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The LSND puzzle and MiniBooNE results

Maltoni, TS, 0705.0107

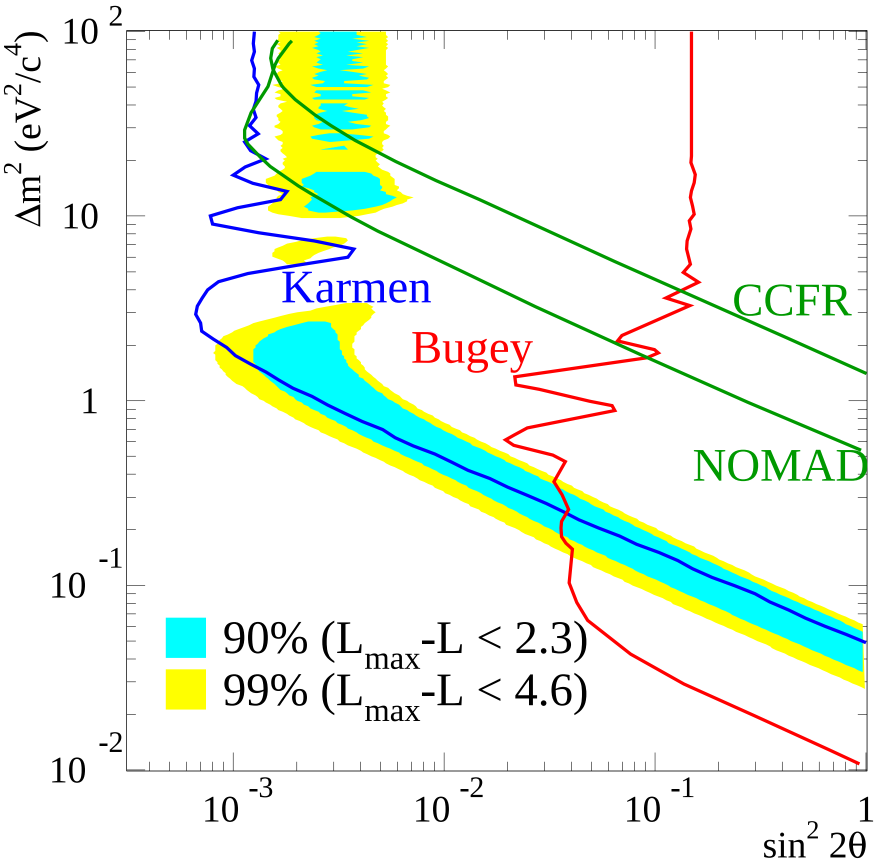
The LSND problem

evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, $(\sim 3.3\sigma)$

$87.9 \pm 22.4 \pm 6.0$ excess events, $P = (0.264 \pm 0.067 \pm 0.045)\%$,

the problem:

$\Delta m^2 \sim$ eV^2 not consistent with solar (8×10^{-5}) and atmospheric (3×10^{-3}) mass splittings for three neutrinos!



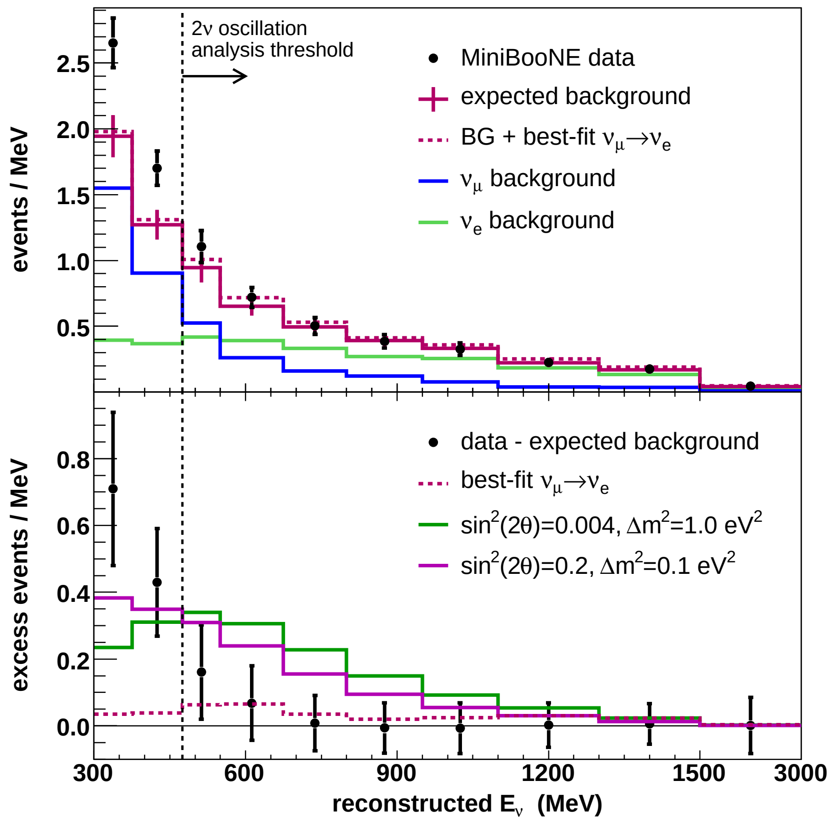
MiniBooNE results, April 2007

perform $\nu_\mu \to \nu_e$ search at same L/E as LSND

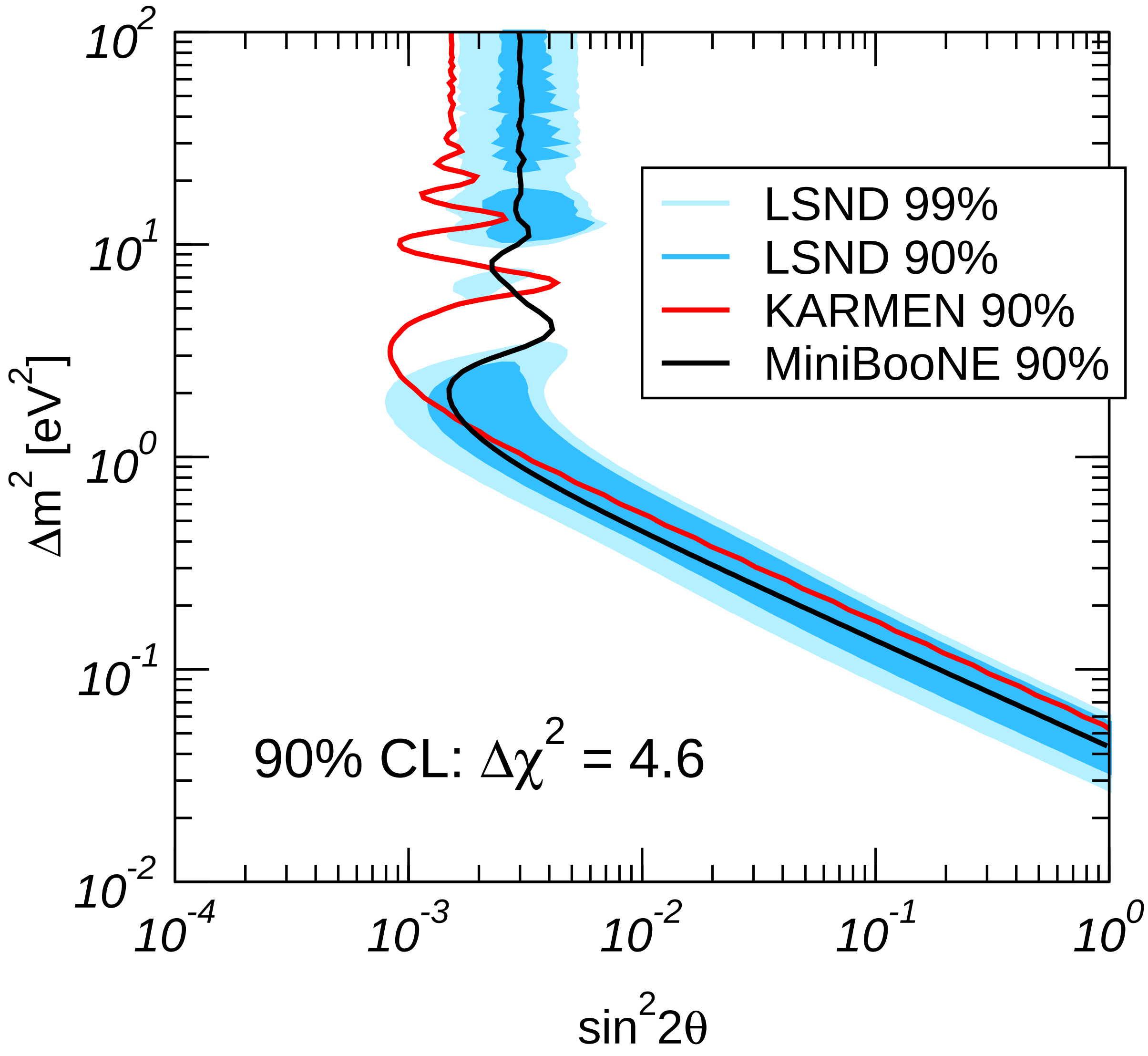
obs. events minus background:

$475 < E_\nu^{\rm QE} < 1250\,{\rm MeV}$:
$22 \pm 19 \pm 35$ events
(consistent with zero)

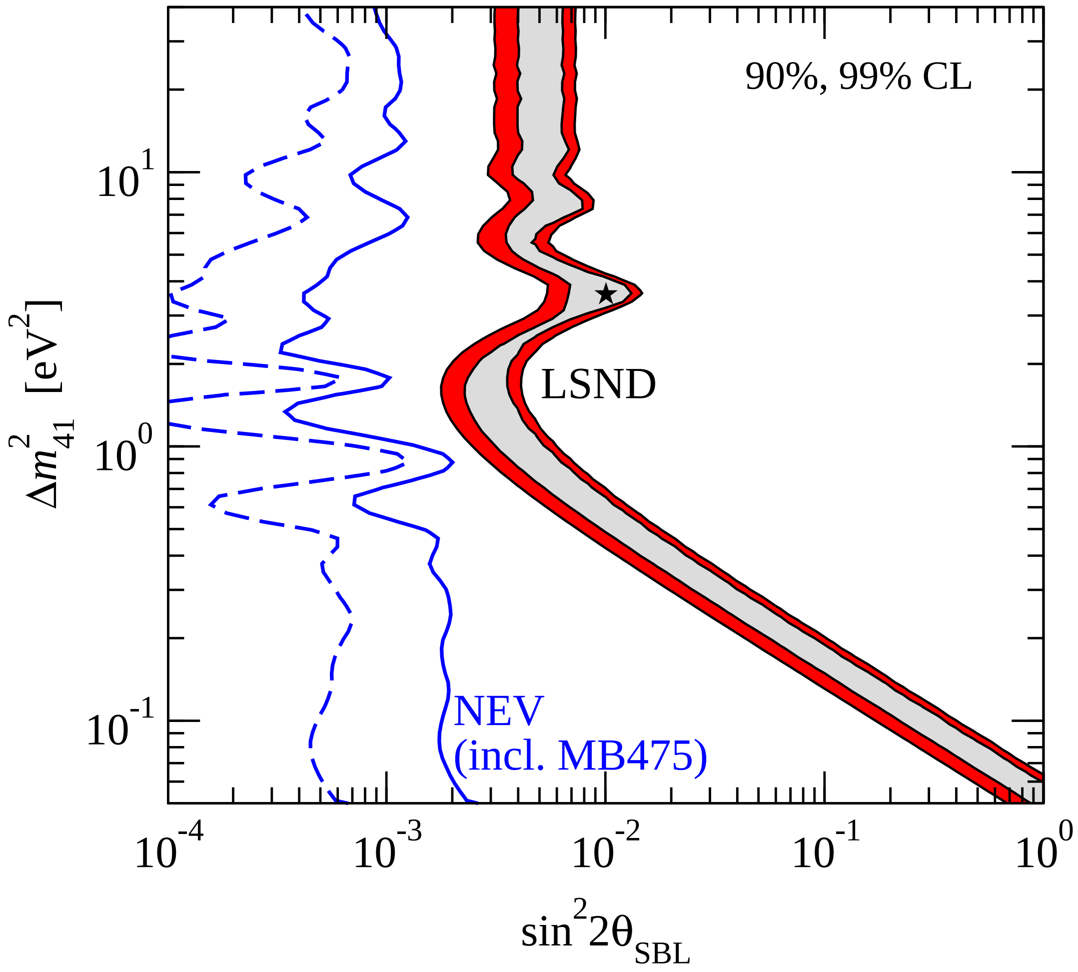
$300 < E_\nu^{\rm QE} < 475\,{\rm MeV}$:
$96 \pm 17 \pm 20$ events
(excess at 3.6σ)



The MiniBooNE 2-neutrino limit



(3+1) disfavoured by App. and Disapp. bounds



before MB:

$\chi^2_{\rm PG} = 20.9\,(2\,{\rm dof})$

MB incl.:

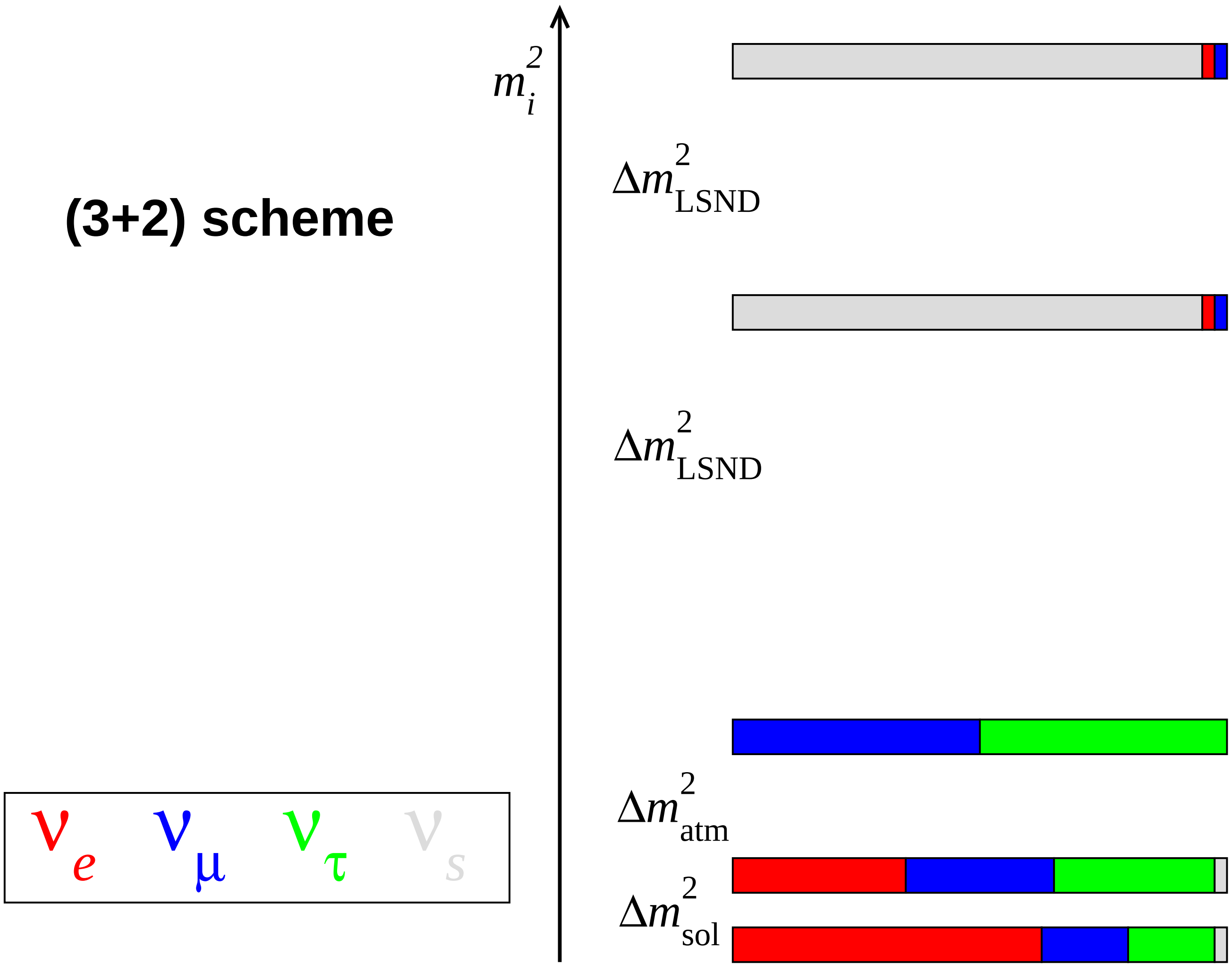
$\chi^2_{\rm PG} = 24.7\,(2\,{\rm dof})$

disagreement at about 4σ

Maltoni, TS, 0705.0107

5-neutrino oscillations?

(3+2) scheme



Sorel, Conrad, Shaevitz, hep-ph/0305255

(3+2) appearance probability

(3+2) osc. include the possibility of CP violation!

remember: MiniBooNE: neutrinos, LSND: anti-neutrinos

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} \\
&+ 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} \\
&+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta)
\end{aligned}
$$

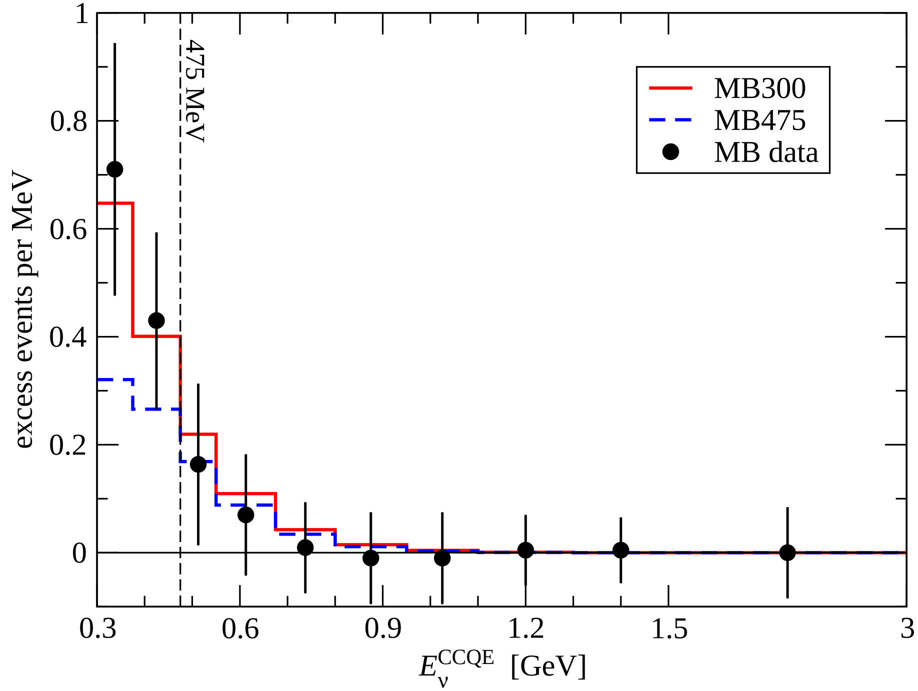
with the definitions

$$
\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}\,, \qquad \delta \equiv \arg\left(U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}\right)\,.
$$

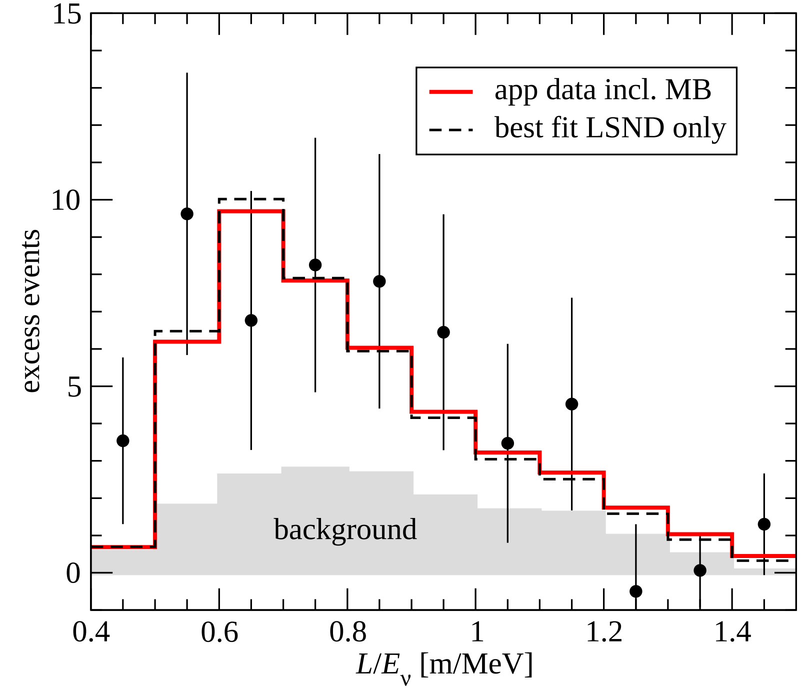
(3+2) appearance data

MB and LSND are perfectly consistent in (3+2)!

MiniBooNE



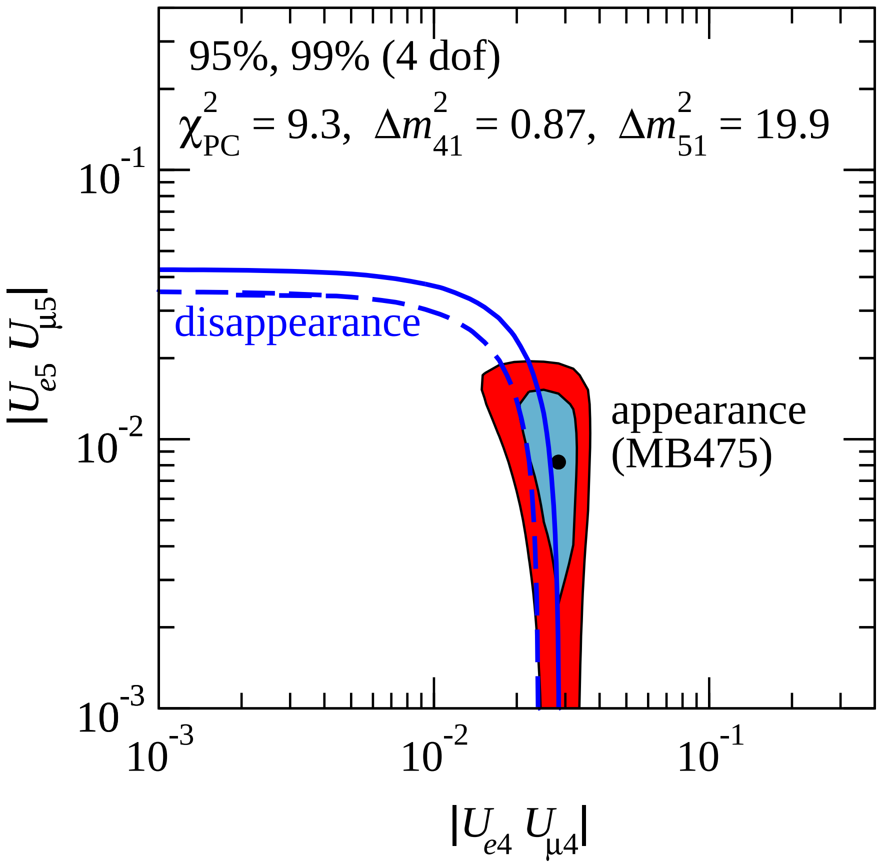
LSND



(MB with or without the low energy excess)

(3+2) appearance vs disappearance

However, there is sever tension between appearance and disappearance data, similar as in (3+1):



(3+2) global

testing consistency of disappearance and appearance (incl. MB475) data:

$$\chi^2_{\rm PG} = 17.2\,(4\,{\rm dof}) \qquad {\rm PG} = 0.18\%$$

parameters in common $|U_{e4}U_{\mu 4}|, |U_{e5}U_{\mu 5}|, \Delta m^2_{41}, \Delta m^2_{51}$

inconsistency at about 3.1σ

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without MB: $\chi^2_{\rm PG} = 17.5$

(3+2) is equally valid (or not-valid) now as before MB!

Maltoni, Schwetz, 0705.0109

Sterile neutrino oscillations - outlook

- CPV is being tested by MiniBooNE anti-neutrino data (problem of statistics?)
- the problem of (3+s) schemes heavily relies on SBL disappearance experiments
  Bugey ($\bar{\nu}_e$ reactor) and CDHS (ν_μ accelerator)
- could be worth to look for disappearance at the $\Delta m^2 \sim 1\,\mathrm{eV}^2$ scale at future reactor or LBL experiments (near detectors)
- sterile neutrinos with $\Delta m^2 \sim 1\,\mathrm{eV}^2$ might lead to large effects for high energy atmospheric neutrinos in IceCube S. Choubey, 0709.1937

More ’exotic’ proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, Schwetz 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation
  Kostelecky, Mews, 04; Gouvea, Grossman, 06; Katori, Kostelecky, Tayloe, 06
- mass varying neutrinos
  Kaplan, Nelson, Weiner 04; Zurek 04; Barger, Marfatia, Whisnant 05
- shortcuts of sterile neutrinos in extra dimensions
  Paes, Pakvasa, Weiler 05
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  Farzan, Schwetz, Smirnov, 08

KamLAND+atmospheric antineutrino data

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KARMEN, TWIST

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KamL spectrum, NuTeV

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KARMEN, TWIST

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energy dependence, MiniBooNE?

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The low-E excess in MB...

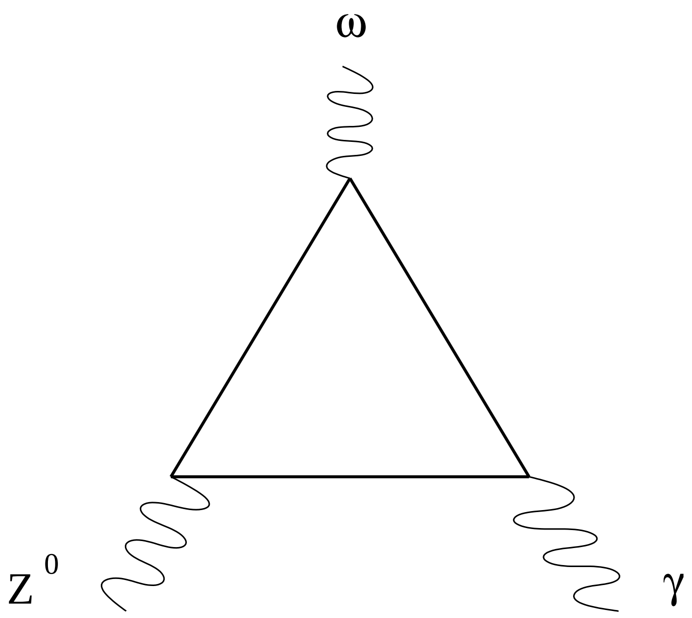
... is very hard to explain (should rise with $E^{-r}, r \gtrsim 4$)

The low-E excess in MB...

... is very hard to explain (should rise with $E^{-r}, r \gtrsim 4$)

... has stimulated interesting results, which might be relevant for future experiments: Harvey, Hill, Hill, 0708.1281

Anomaly mediated neutrino-photon interactions at finite baryon density



gives rise to

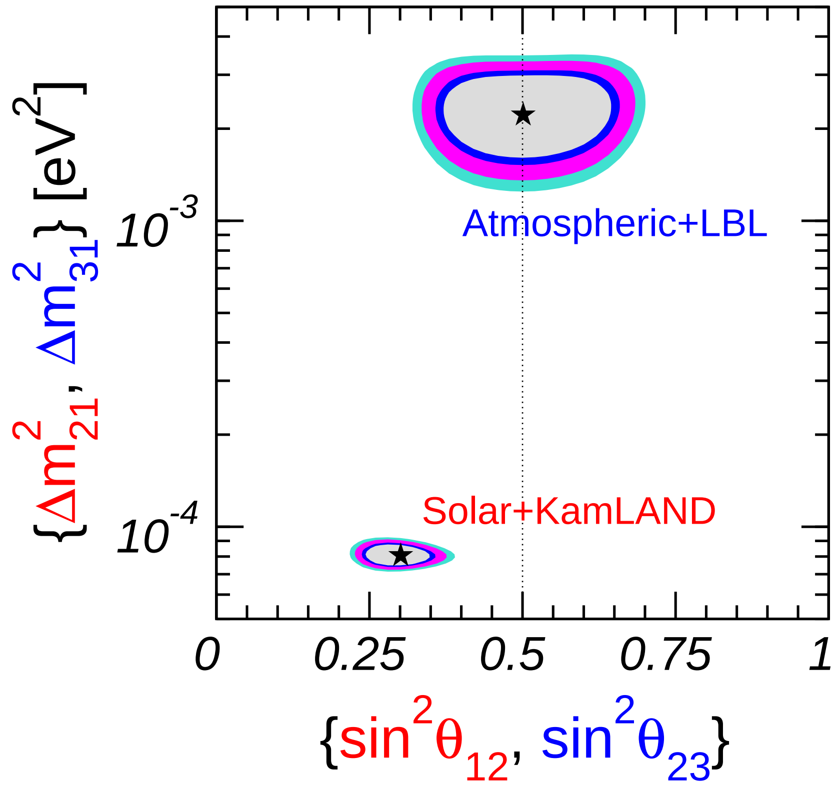
$$\nu + N \to \nu + \gamma + N'$$

with $\sigma \propto g_\omega^4 E_\nu^6$

To conclude. . .

To conclude. . .

prestent status



To conclude. . .

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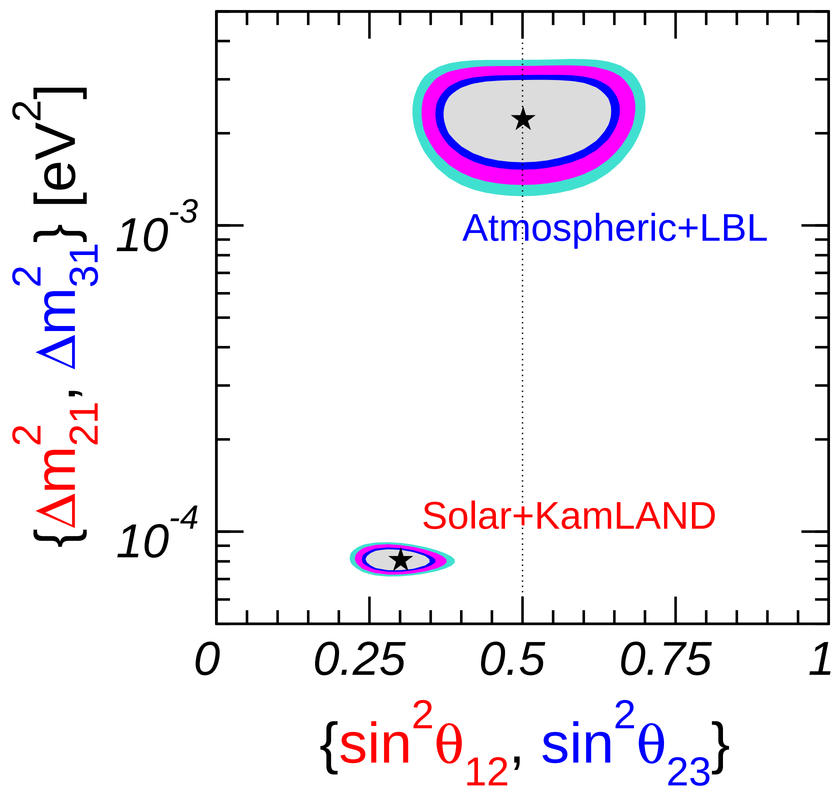
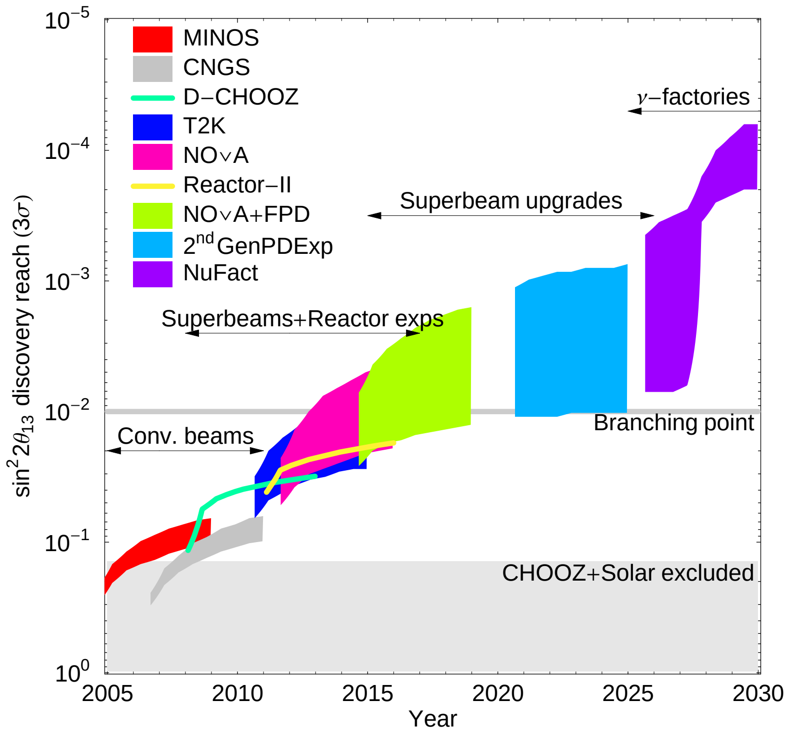
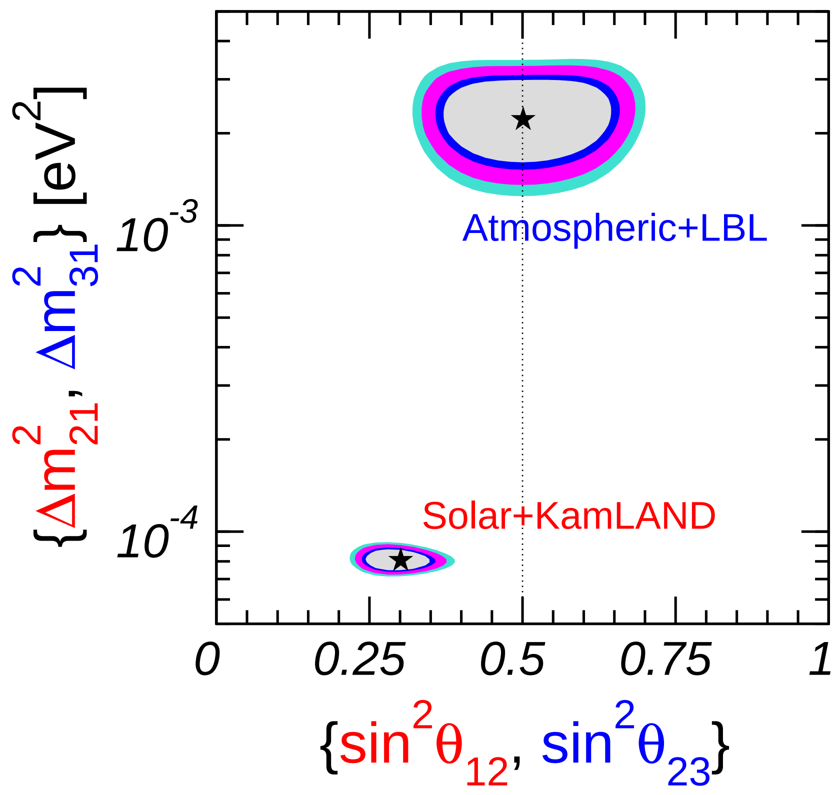


future



To conclude. . .

prestent status



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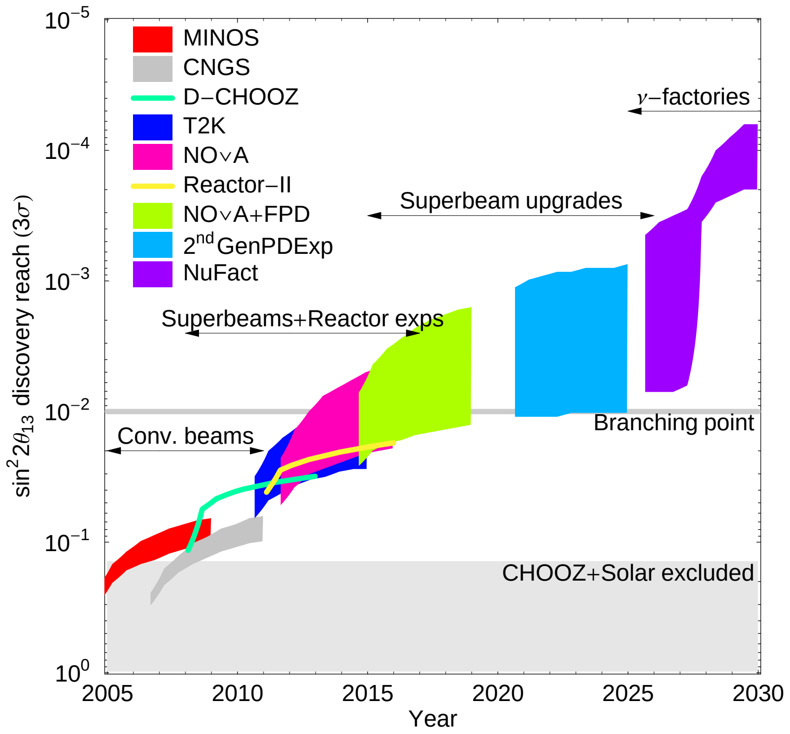

Thanks for your attention!