Neutrino oscillations:

Present status and outlook

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CERN

Outline

- Introduction
- Global fit to present oscillation data
  impact of 2007 new data
- LSND puzzle in the light of MiniBooNE results
- Future oscillation experiments
  prospects for measuring θ_{13}
  CP violation, determination of the mass hierarchy

I will not speak about...

Measurements of absolute neutrino masses

- Tritium beta-decay
- neutrinoless double beta-decay
- neutrino mass determination from cosmology

... but focus on neutrino oscillations

Neutrino mixing

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} W^\rho \sum_{\alpha=e,\mu,\tau} \bar\nu_{\alpha L} \gamma_\rho \ell_{\alpha L} + \text{h.c.}$$

$$\mathcal{L}_{\rm M} = -\frac{1}{2} \sum_i \nu_{iL}^T C^{-1} \nu_{iL} m_i + \text{h.c.}$$

with $$\nu_{\alpha L} = \sum_i U_{\alpha i}\, \nu_{iL}\,, \qquad (\alpha = e, \mu, \tau)$$

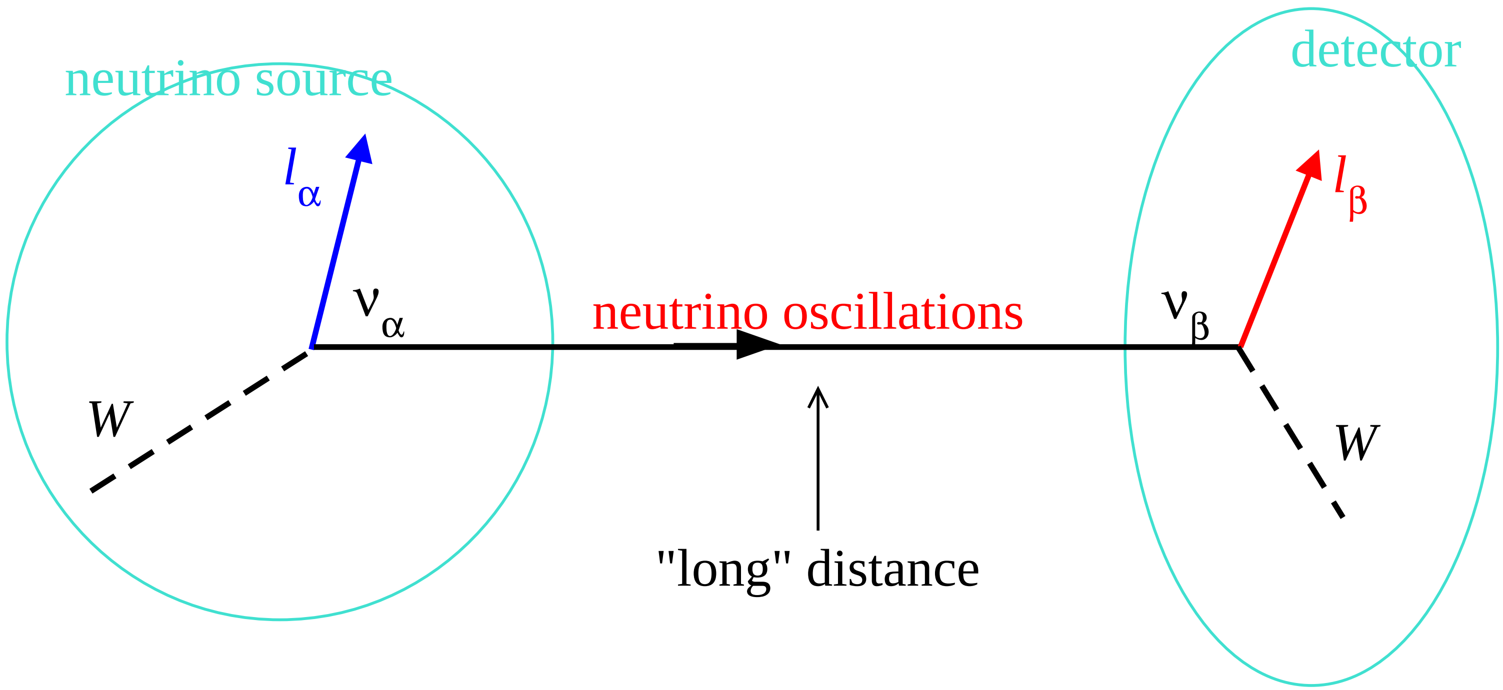
$\nu_{\alpha L}$: neutrinos with CC interaction (“flavour neutrinos”)

ν_{iL} : neutrinos with mass m_i

$U_{\alpha i}$: PMNS lepton mixing matrix

in a basis where the charged lepton mass matrix is diagonal

Neutrino oscillations



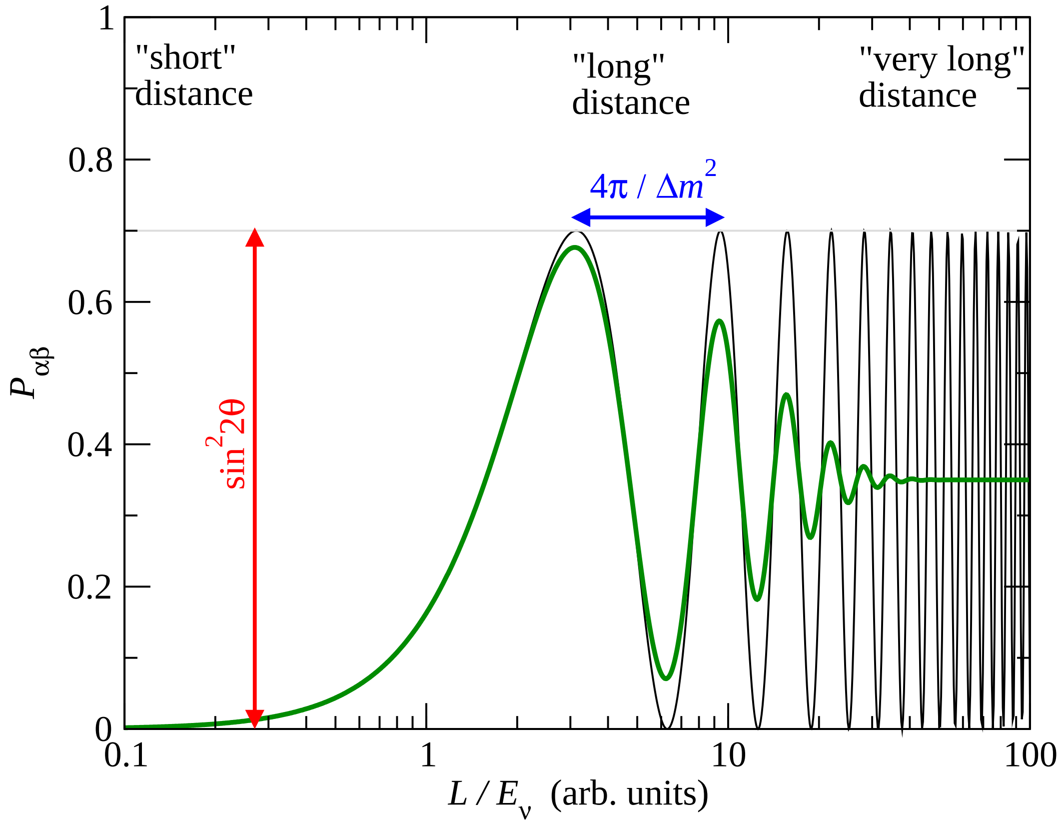
$$|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle \qquad e^{-i(Et-p_i x)} \qquad |\nu_\beta\rangle = U^*_{\beta i}|\nu_i\rangle$$

osc.prob. (vac): $P_{\nu_\alpha \to \nu_\beta}(L) = \sum_{jk} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \exp\left[-i\frac{\Delta m^2_{kj} L}{2\,E_\nu}\right]$

2-neutrino oscillations

Two-flavour limit:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad P = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$



Neutrino oscillations in matter

MSW effect (3 flavours):

$$H_{\rm mat} = \underbrace{U \textsf{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger}_{H_{\rm vac}} \pm \underbrace{\textsf{diag}(\sqrt{2} G_F N_e, 0, 0)}_{V^{\rm eff}}$$

$N_e(x)$: electron density along the neutrino path

$$i\frac{d}{dt}\begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix} = H_{\rm mat}(t) \begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix}$$

Global data and three-neutrino oscillations

Maltoni, TS, Tortola, Valle, hep-ph/0405172 v6; TS, 0710.5027

Neutrino oscillation experiments

- solar neutrinos

  Homestake, SAGE+GNO, Super-Kamiokande, SNO, Borexino

- atmospheric neutrinos

  Super-Kamiokande

- reactor neutrinos

  Chooz (1 km), KamLAND (180 km)

- long-baseline accelerator experiments

  K2K (250 km), MINOS (735 km)

3-flavour oscillation parameters

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

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

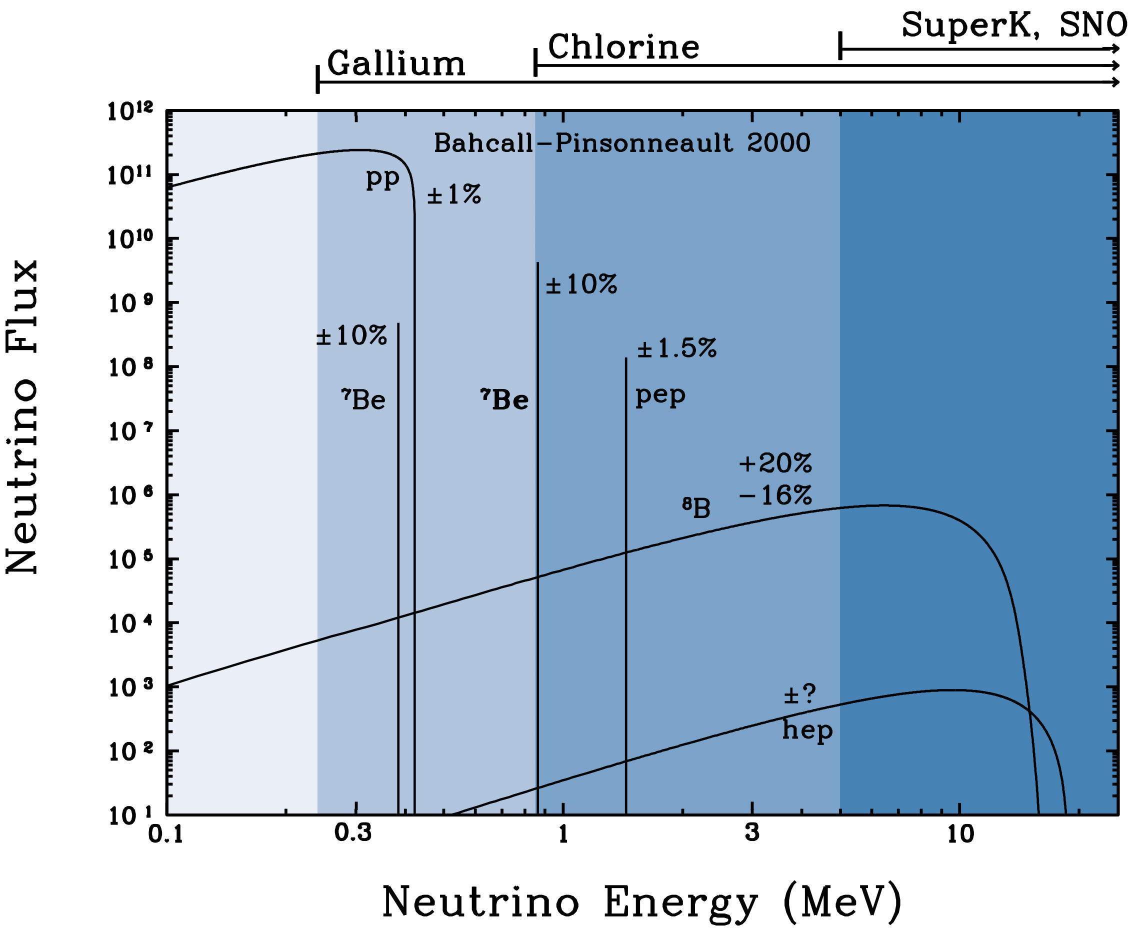
atmospheric+LBL — Chooz — solar+KamLAND

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

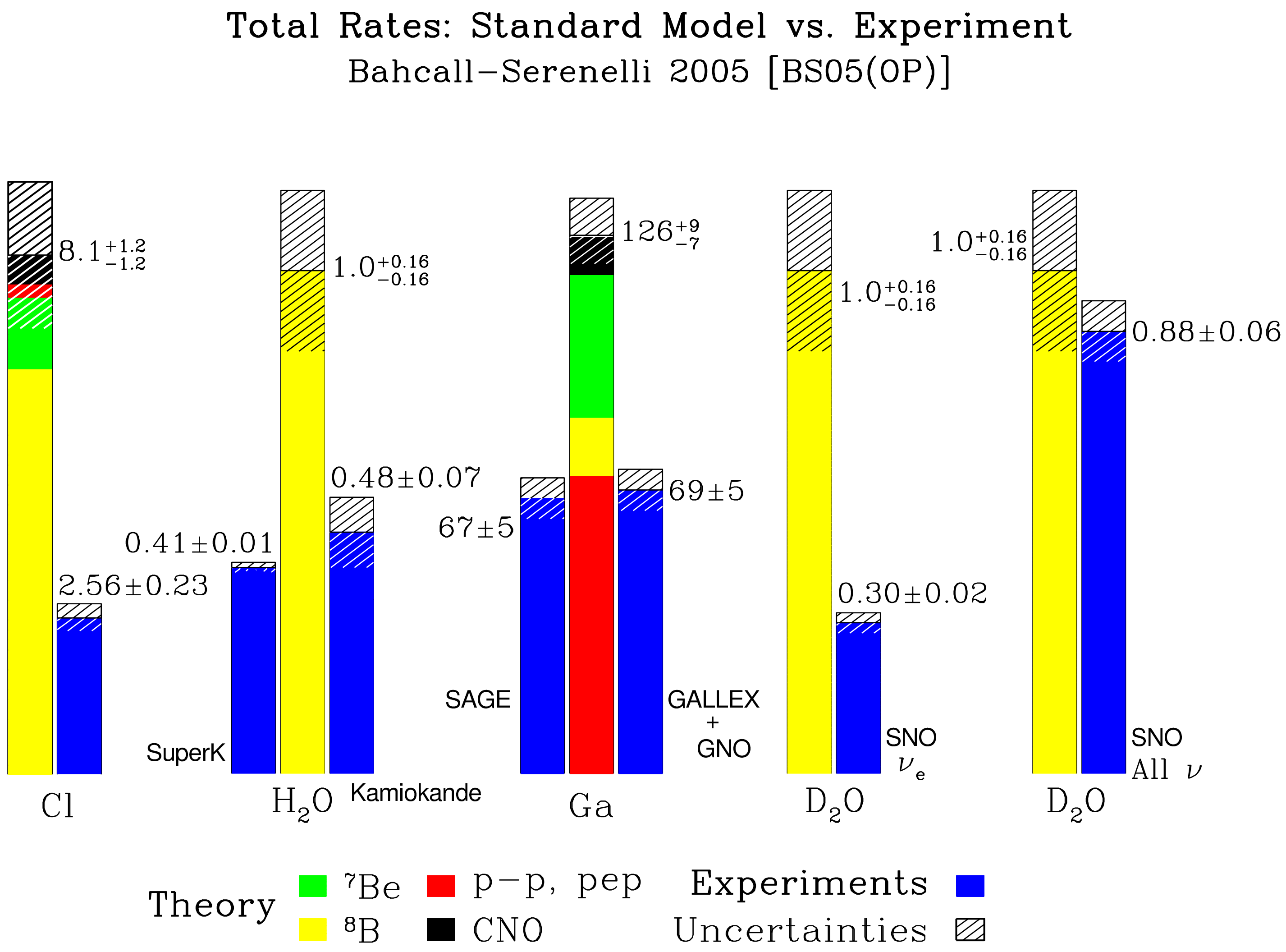
$\Rightarrow$ dominant oscillations are well described by effective two-flavour oscillations

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

The solar neutrino flux



Solar neutrino experiments



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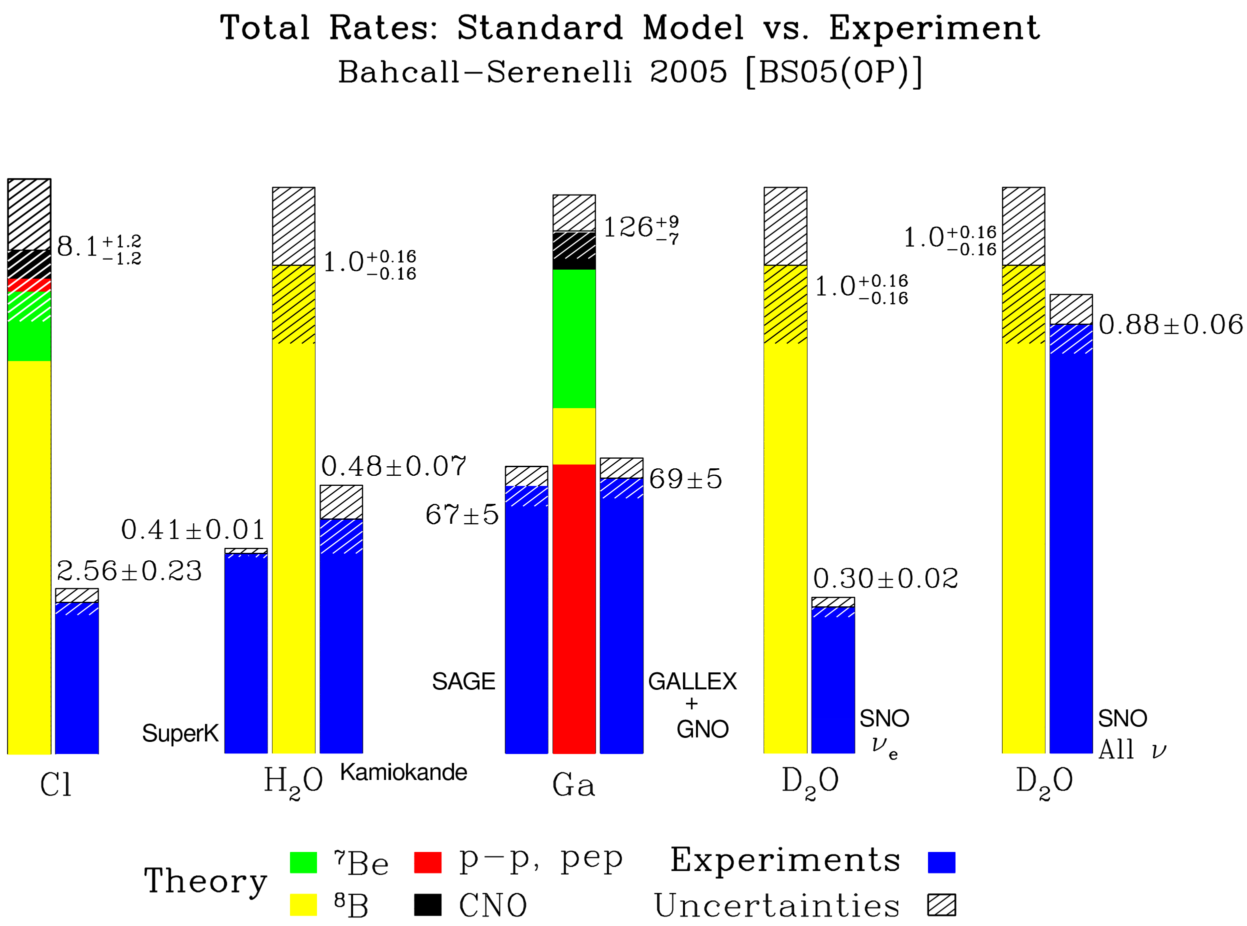
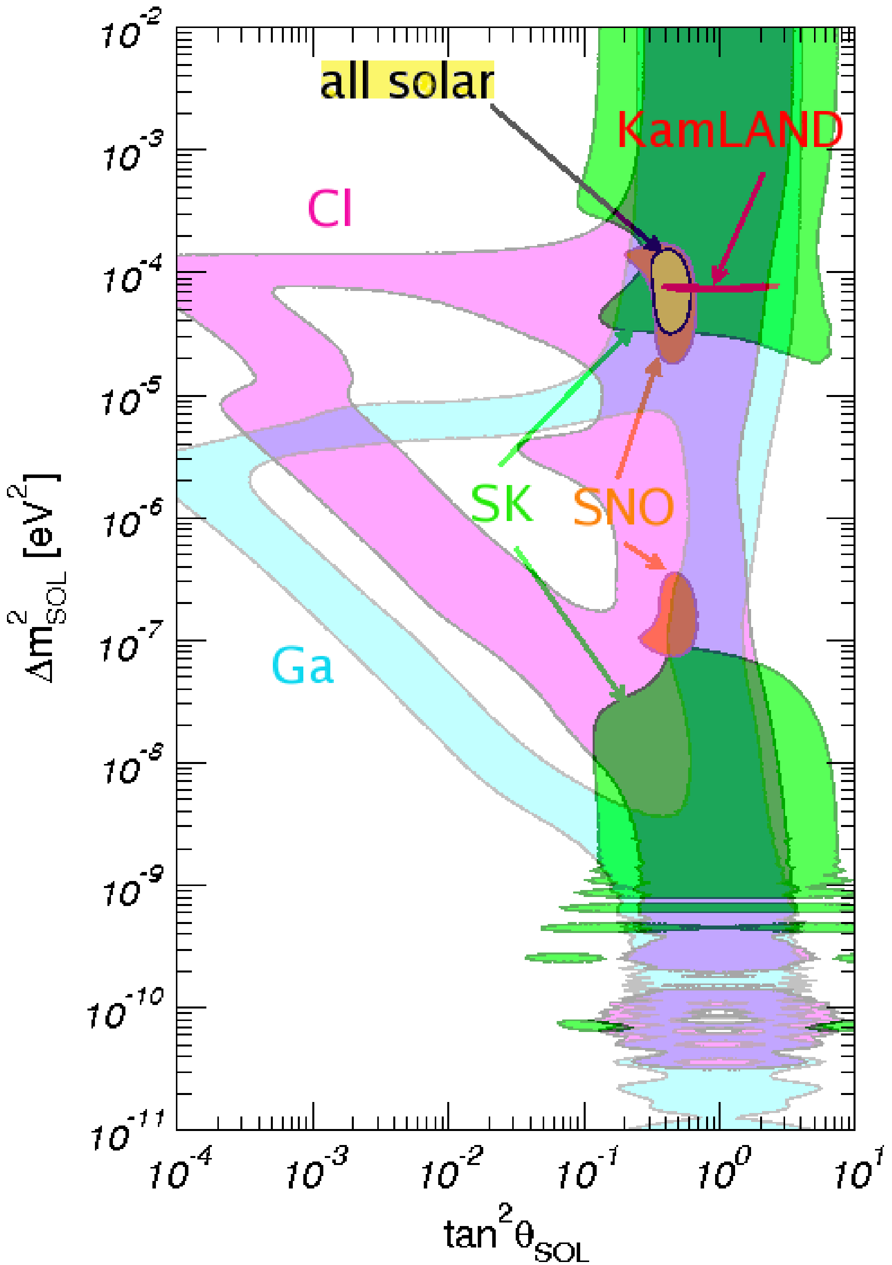


SNO: $$\nu_e + d \to p + p + e^-$$ $$\nu_x + d \to p + n + \nu_x$$

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023 \pm 0.030$$

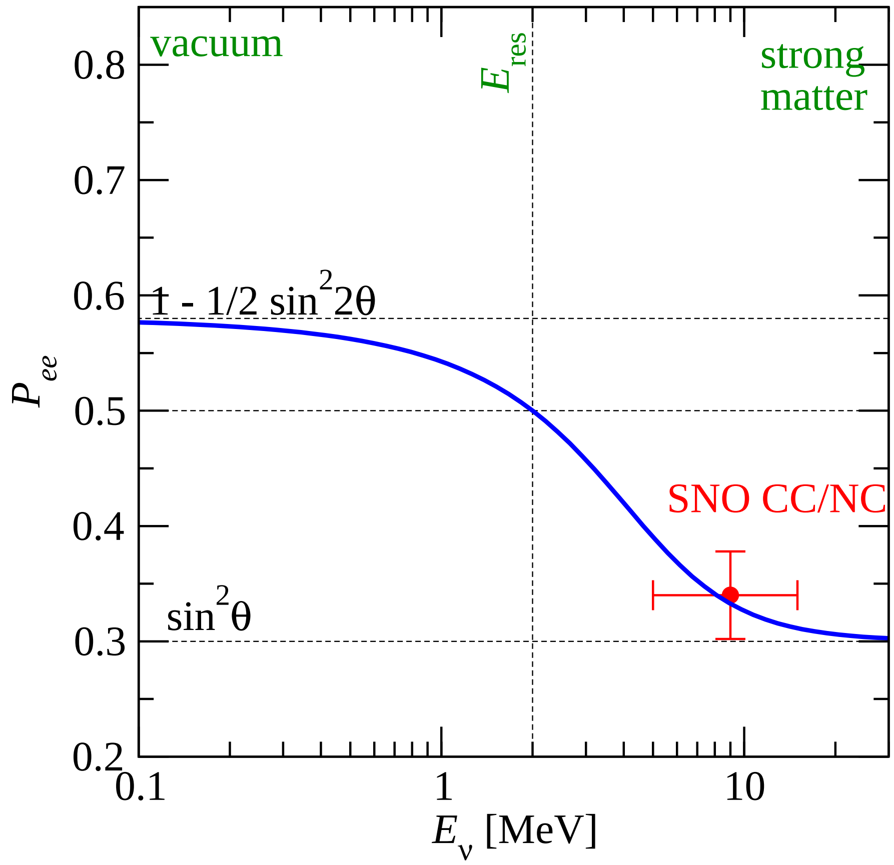
7σ evidence for a non-zero $\nu_{\mu,\tau}$ flux from the sun

’Solar’ parameters



The LMA-MSW solution

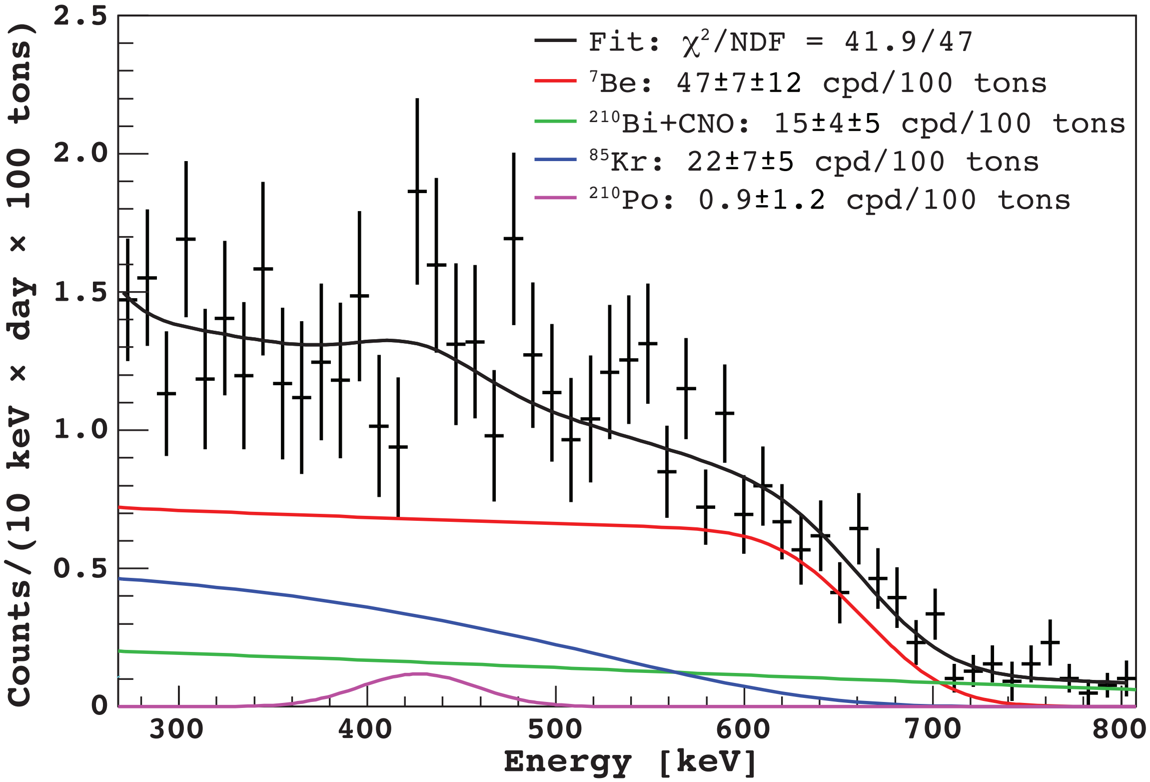
adiabatic evolution of the neutrino state from the center of the sun to the surface



First data from Borexino

0708.2251 [astro-ph] measurment of the Be7 neutrino line at 0.862 MeV by $e\nu \to e\nu$ scattering $(\Rightarrow)$

47 ± 7(stat) $\pm\, 12$(sys) ev/(day x 100t), without osc.: 75 ± 4



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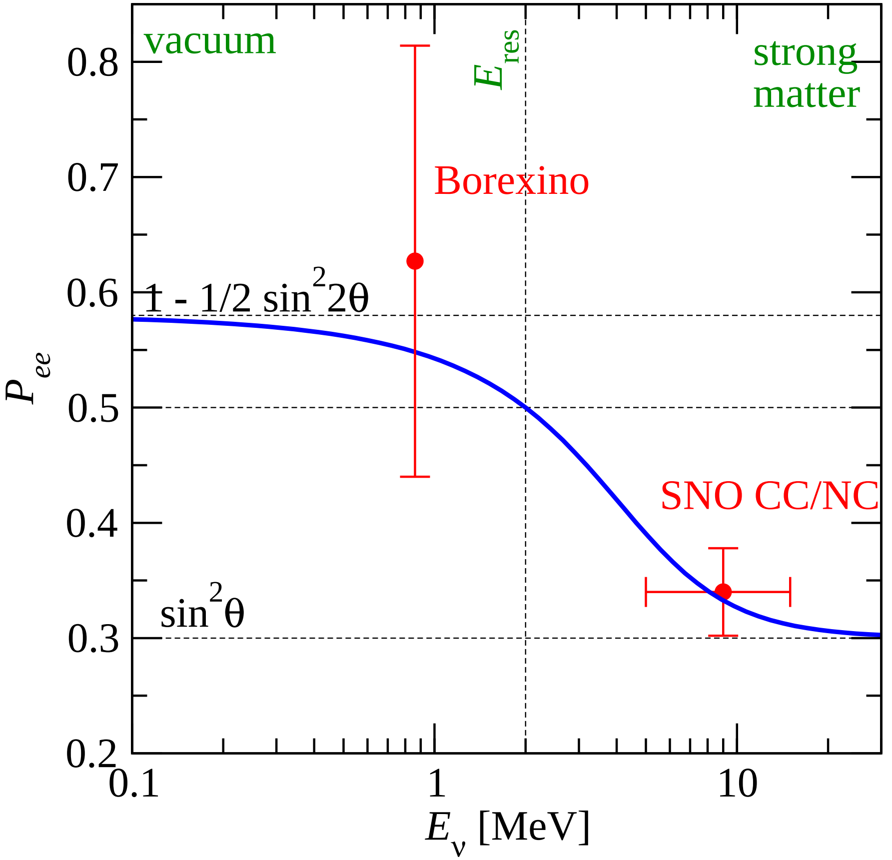
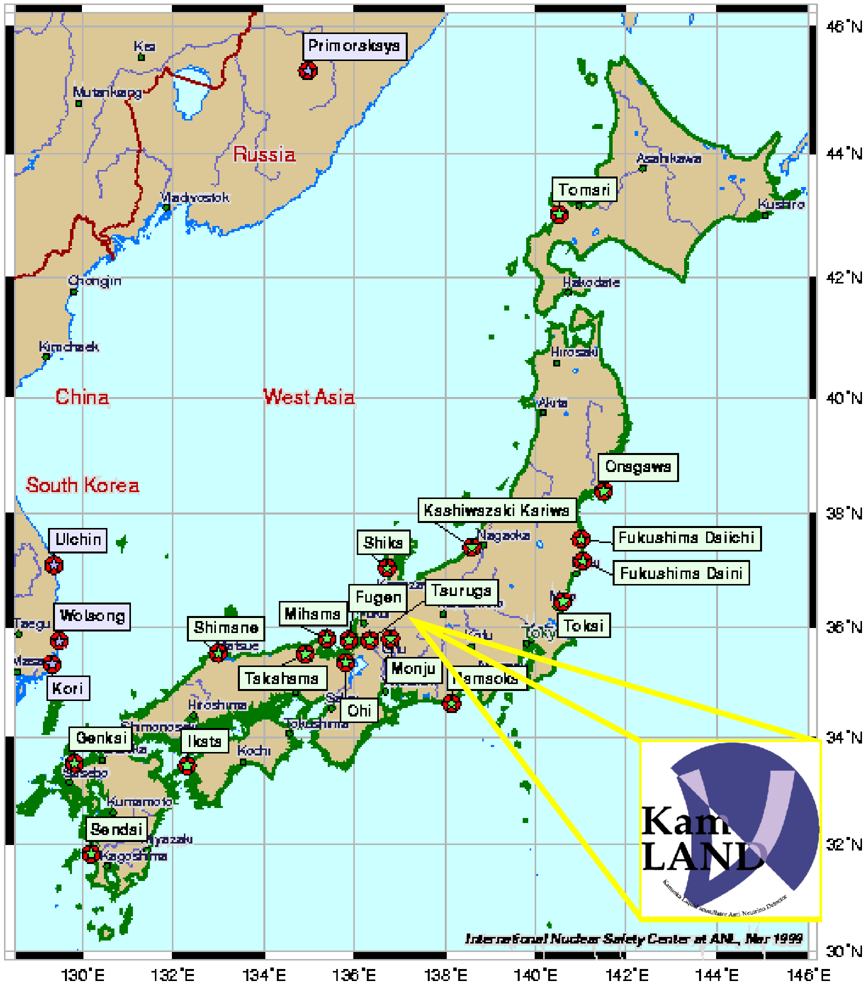


The KamLAND reactor neutrino experiment

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

KamLAND update

New data released this summer:

- 2881 ton yr data

  4 times more than previous 2004 data

- reduced syst. error due to full volume calibration from 4.7% to 1.8%

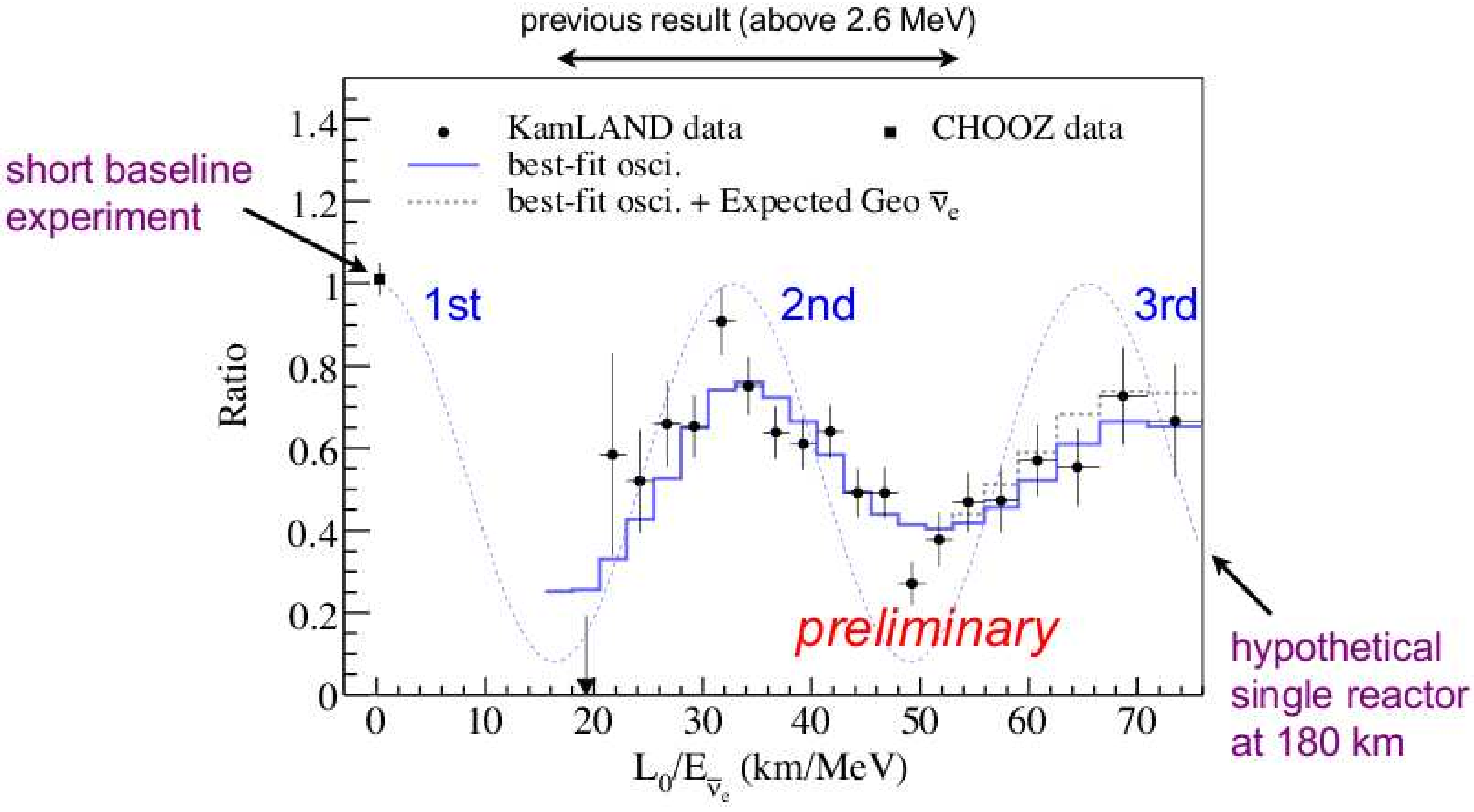
  dominating error for Δm^2 determination is now the uncertainty on the energy scale of 1.5%

observed number of events: 985

expectation without oscillations:

1550 reactor neutrino events + 63 background

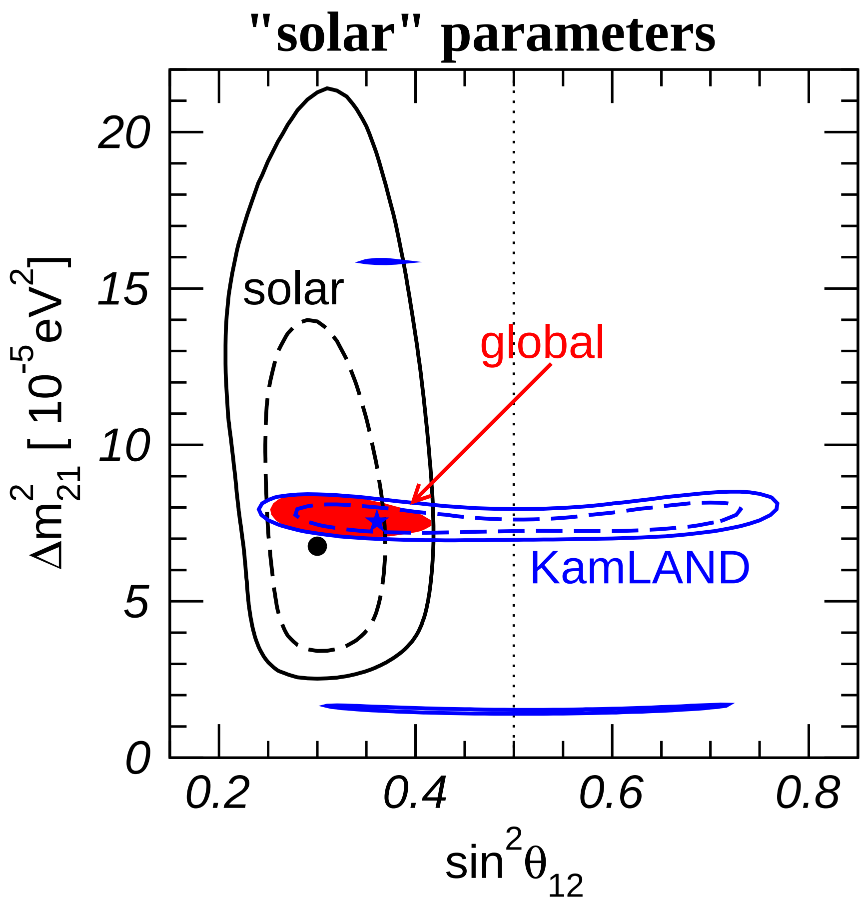
The KamLAND energy spectrum



evidence for oscillations in $1/E_\nu$

KamLAND vs solar data

90% and 99.73% CL contours



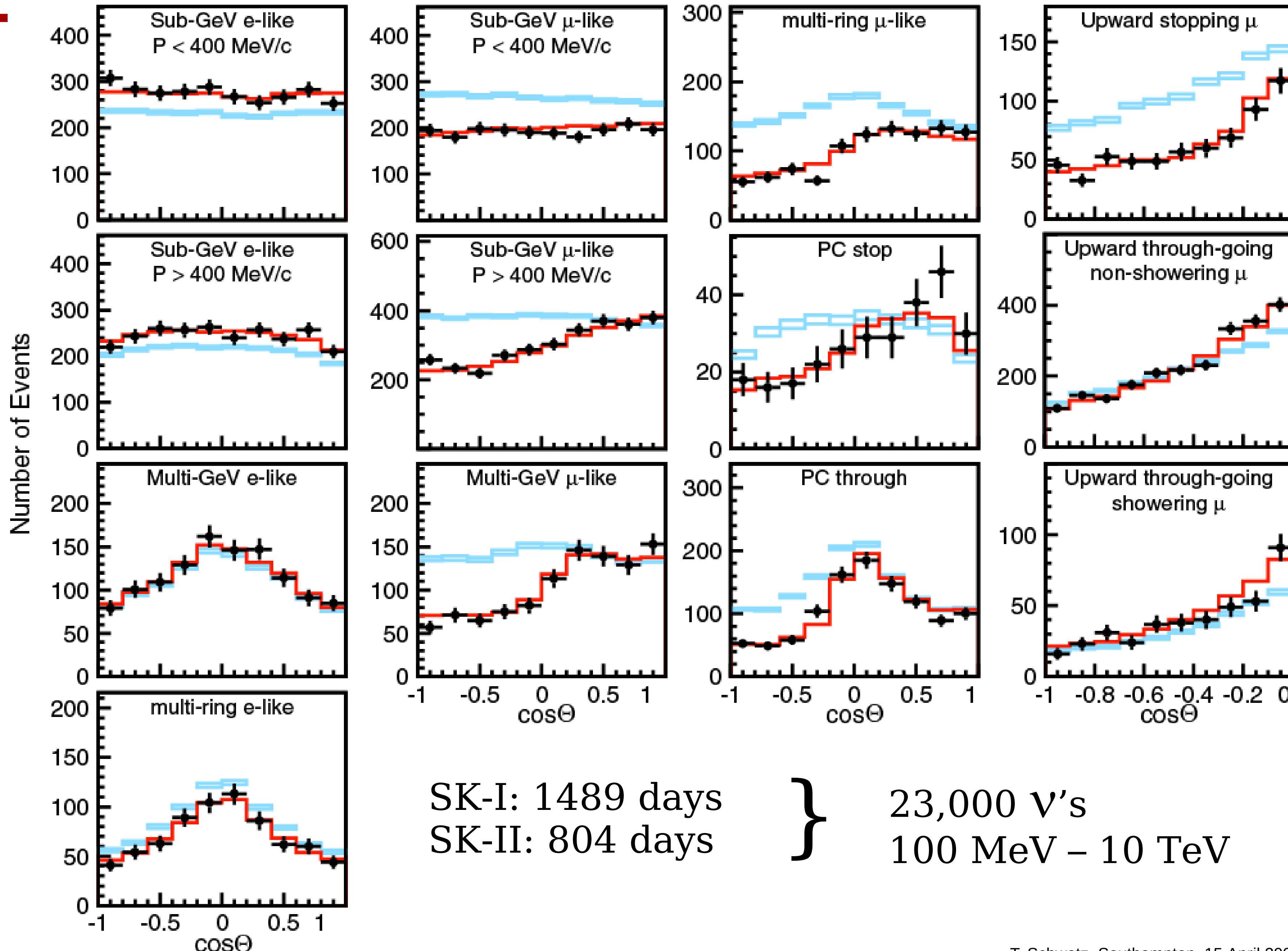
Δm^2_{21}:
measured by KamLAND

$\sin^2\theta_{12}$:
measured by SNO

$$\Delta m^2_{21} = 7.6 \pm 0.20 \times 10^{-5}\,\mathrm{eV}^2,\ \sin^2\theta_{12} = 0.32 \pm 0.023$$

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

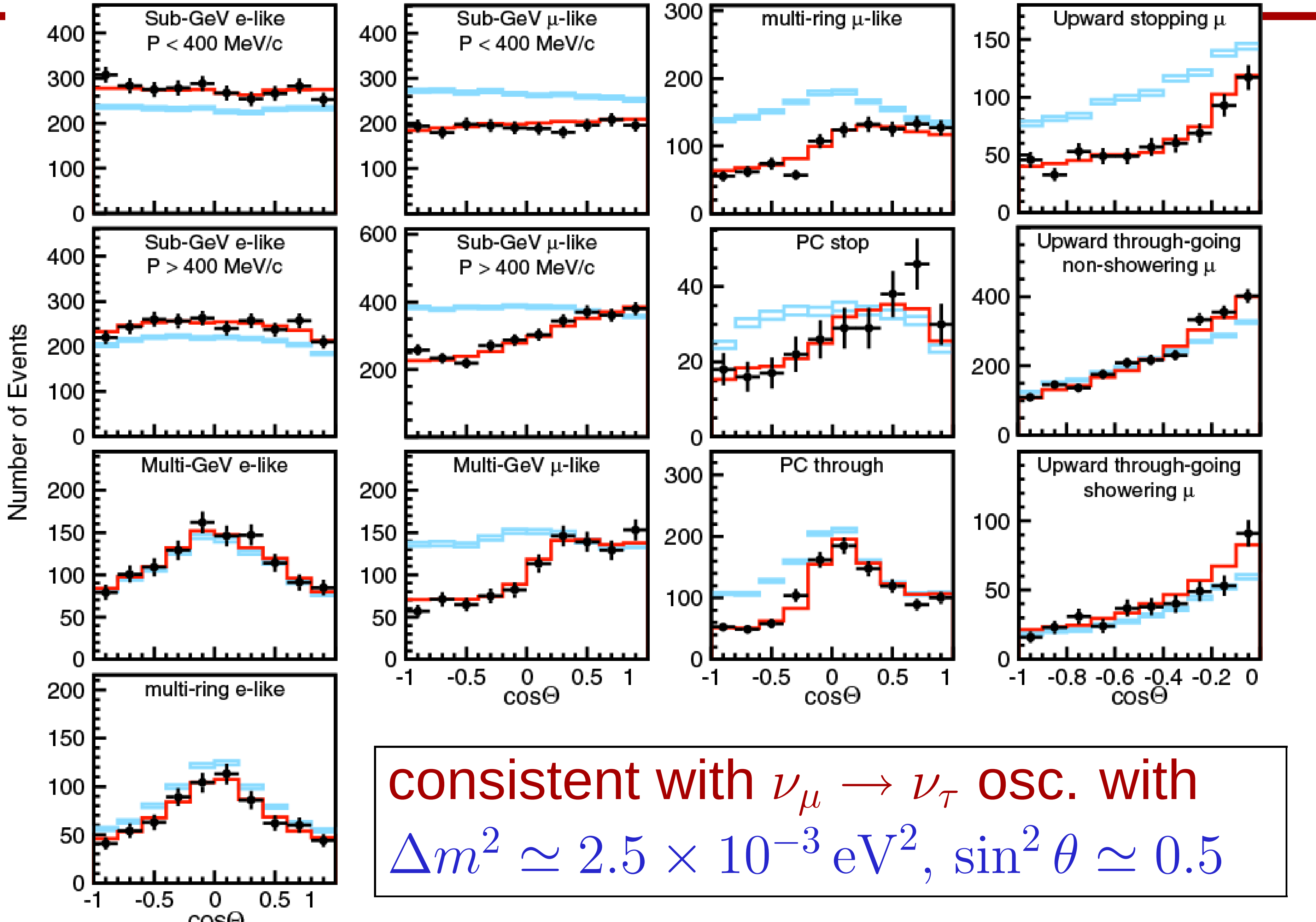
Super-K atmospheric neutrino data



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

$\Delta m^2 \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2,\ \sin^2\theta \simeq 0.5$

Long-baseline experiments

first generation of LBL experiments
(ν_μ-disappearance)

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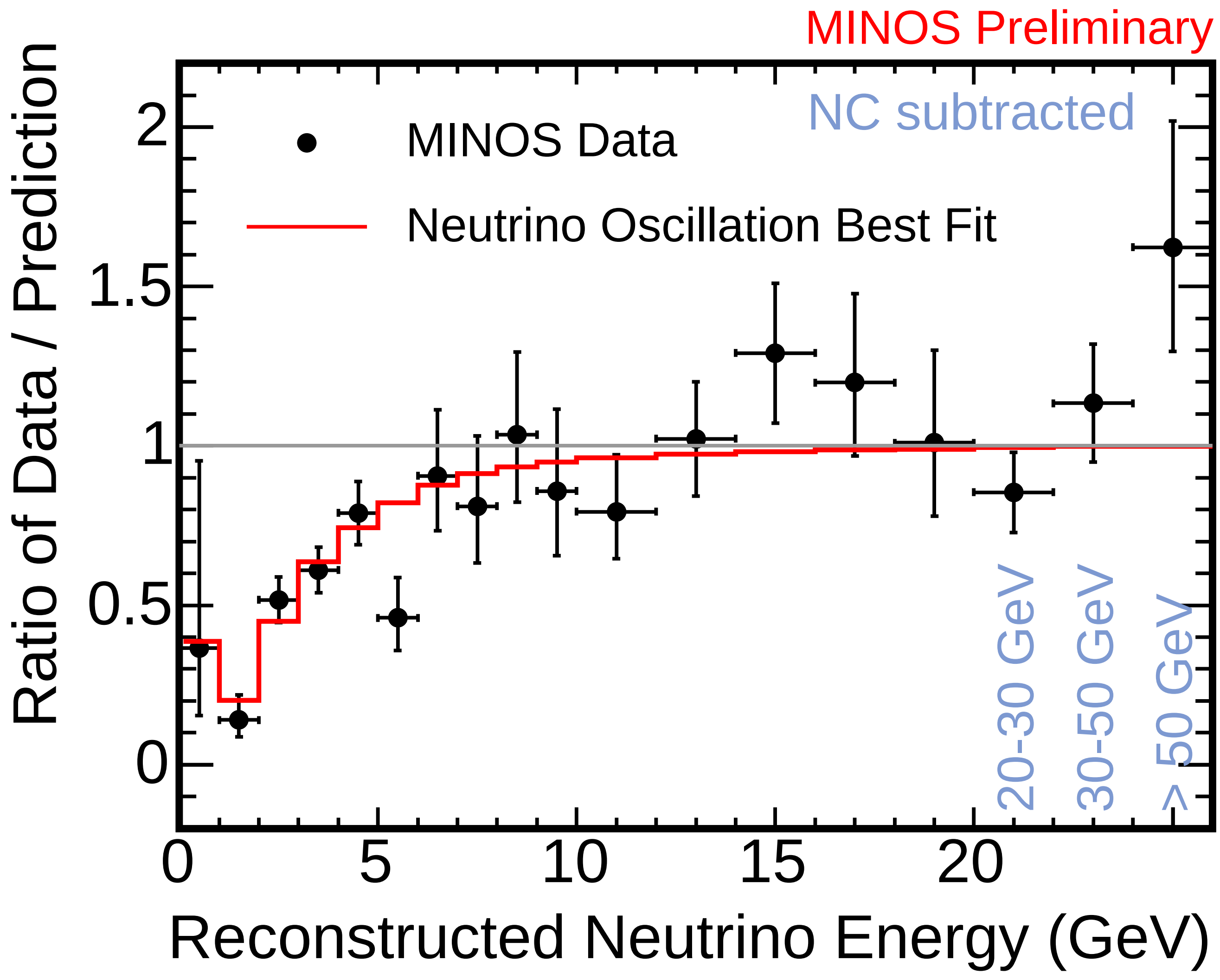
	K2K	MINOS
source	KEK	Fermilab
detector	Super-K	Soudan
baseline	250 km	735 km
neutrino energy	1.3 GeV	3 GeV
E_ν/L [eV^2]	5.2×10^{-3}	4.1×10^{-3}
obs. events	112	563
expect. w/o osc.	$158.1^{+9.2}_{-8.6}$	738 ± 30

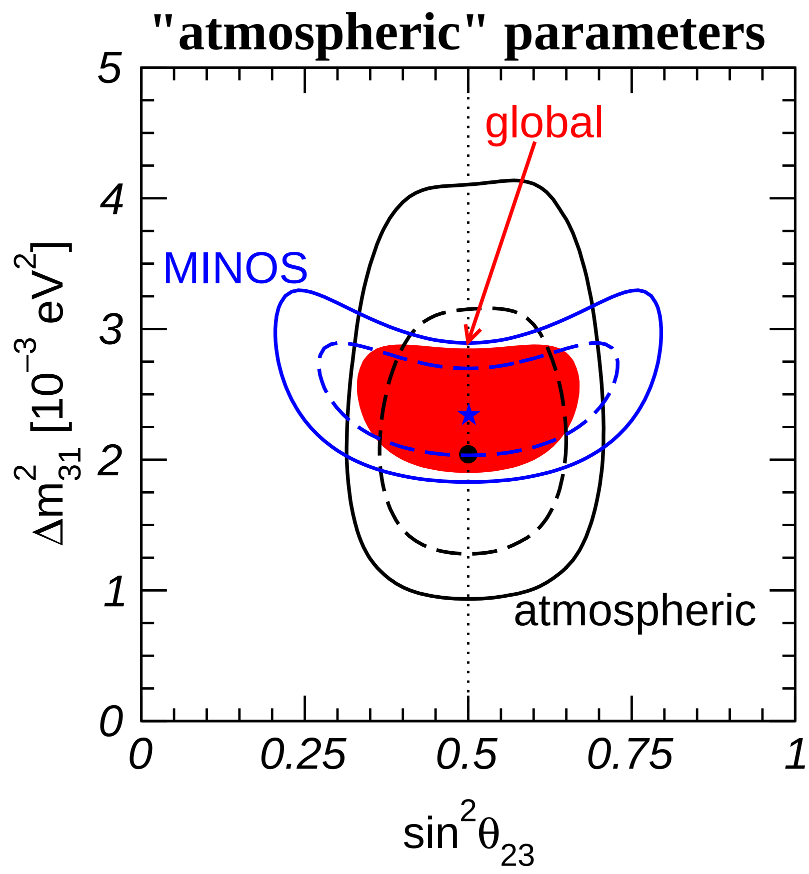
MINOS energy spectrum



arxiv:0708.1495, 2.5×10^{20} pot

Super-K + K2K + MINOS

90%, 99.73% CL regions



$$\Delta m^2_{31} = 2.4 \pm 0.15 \times 10^{-3}\,\mathrm{eV}^2,\ \sin^2\theta_{23} = 0.50 \pm 0.063$$

The bound on θ_{13}

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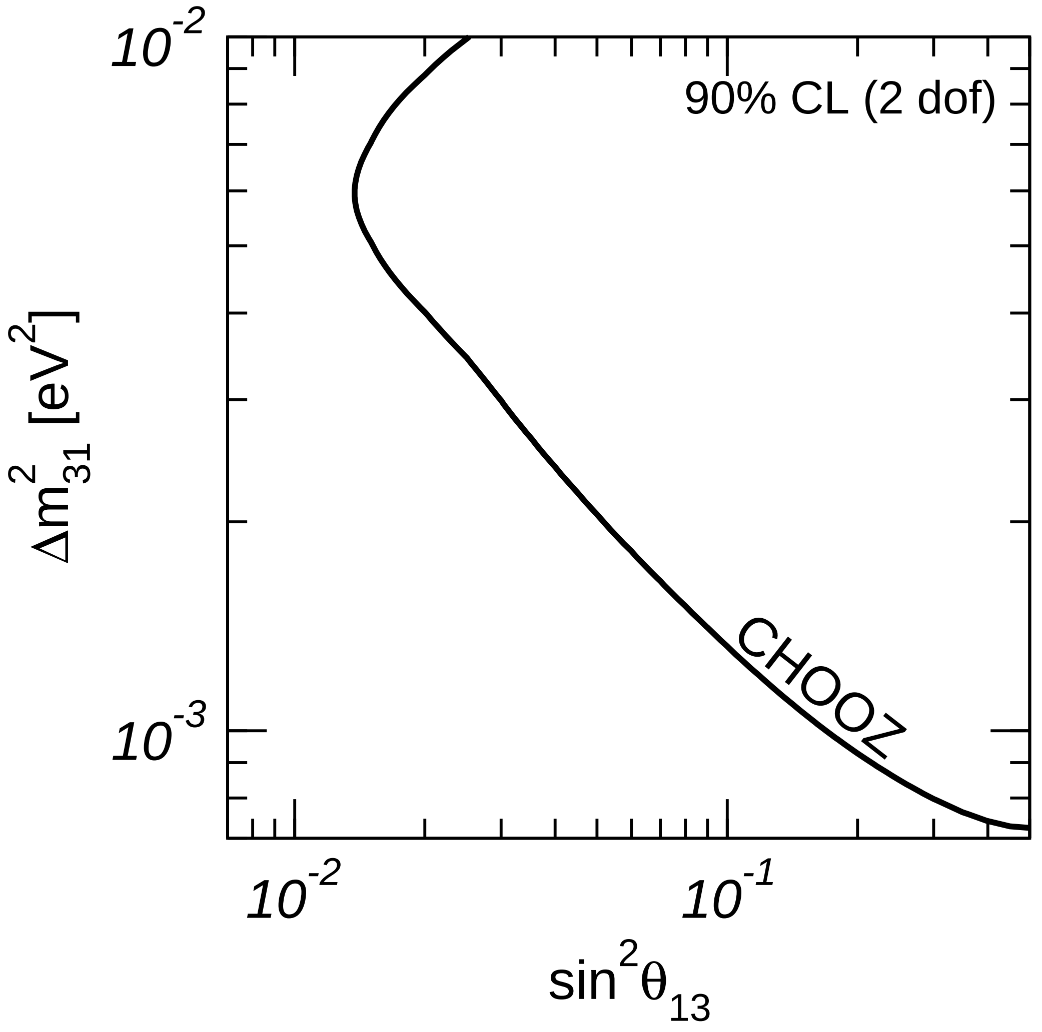
The bound on θ_{13} emerges from an interplay of the global data



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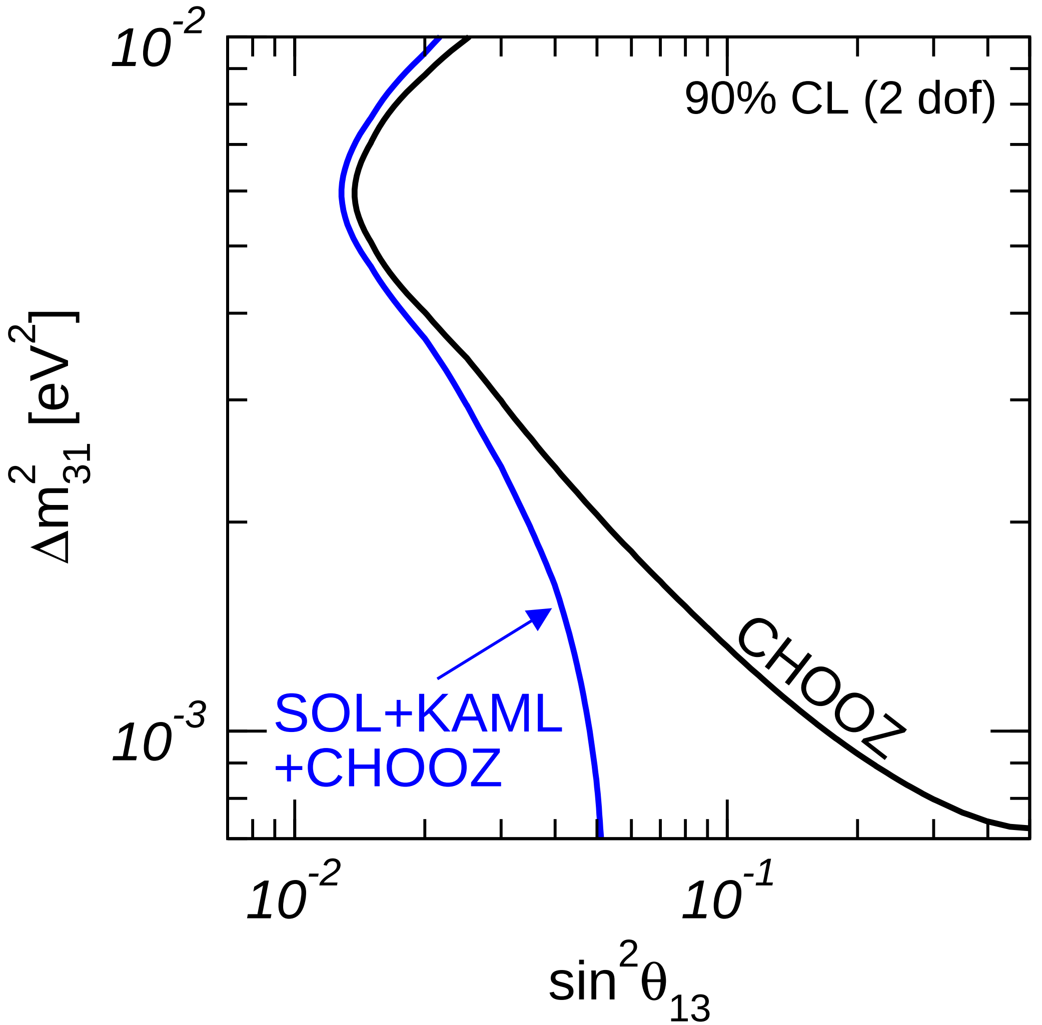

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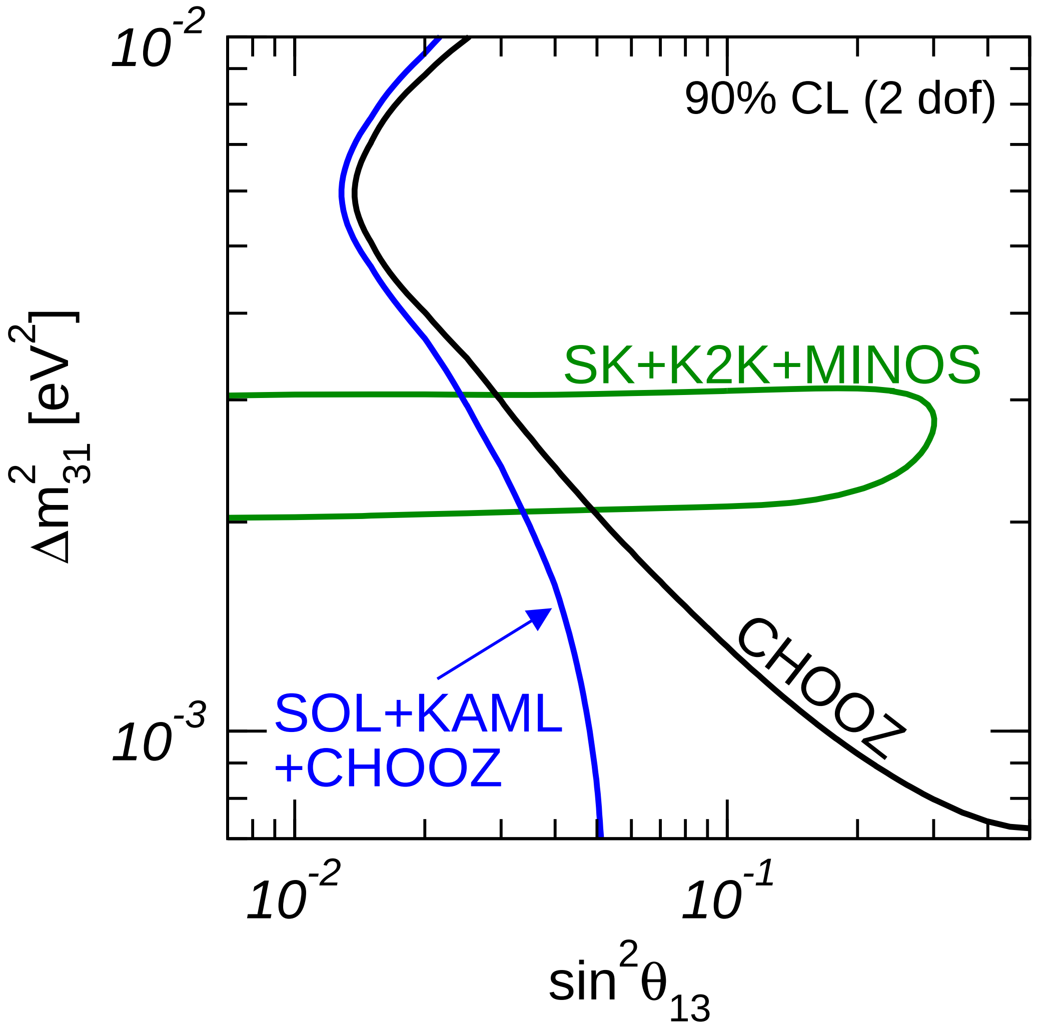
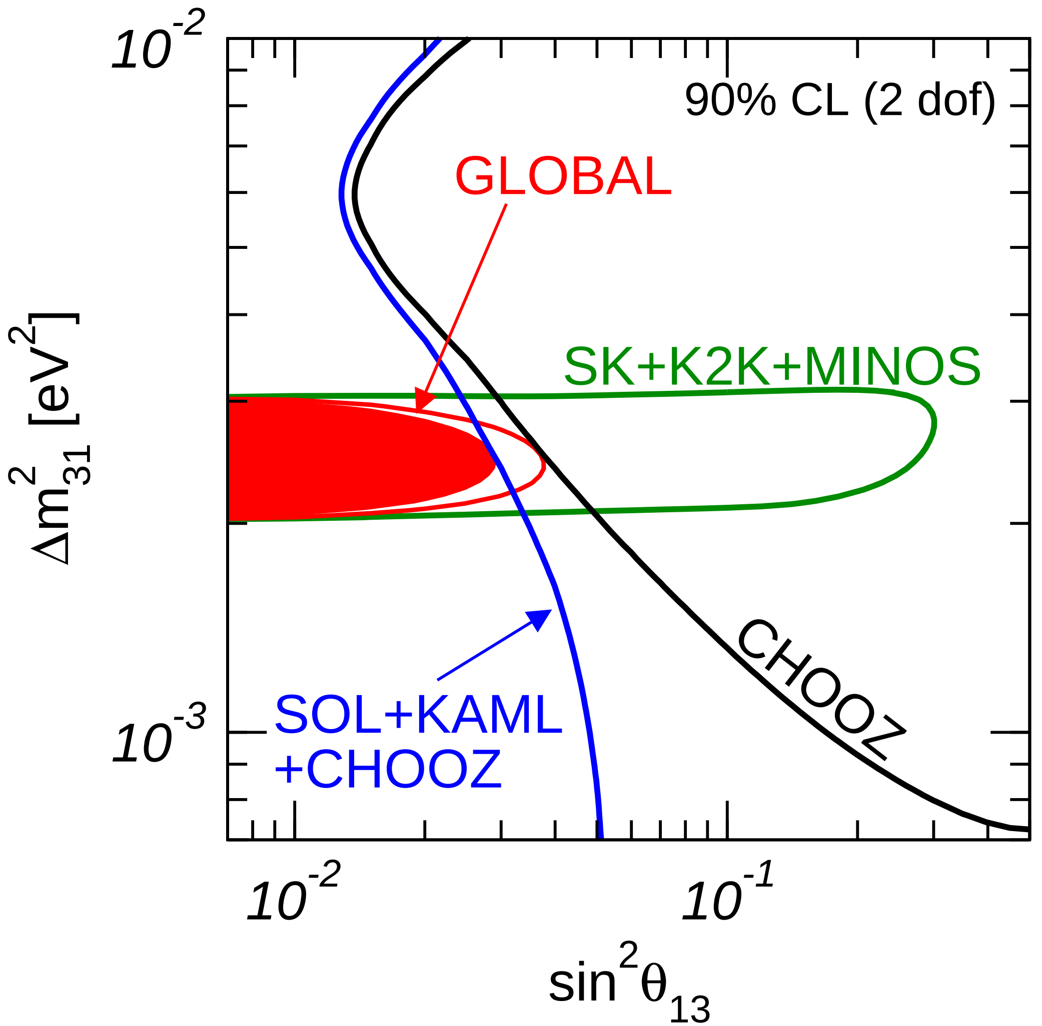


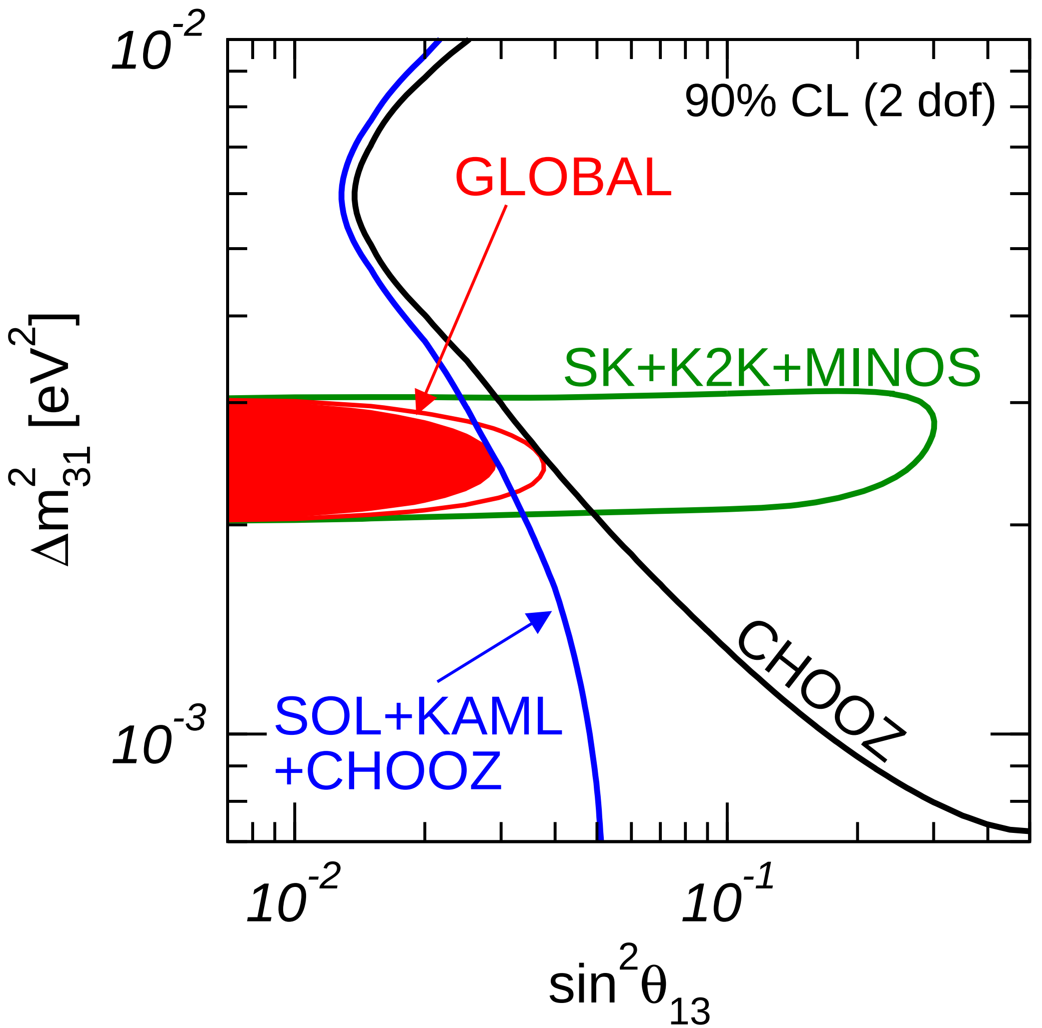
The bound on θ_{13}

global data: $\sin^2\theta_{13} < 0.05$ at 3σ



The bound on θ_{13}

$$\sin\theta_{13} = |U_{e3}| < 0.224\,(3\sigma) \quad \leftrightarrow \quad |V_{us}| = 0.2257 \pm 0.0021$$



Summary 3-flavour oscillation parameters

3-flavour oscillation parameters

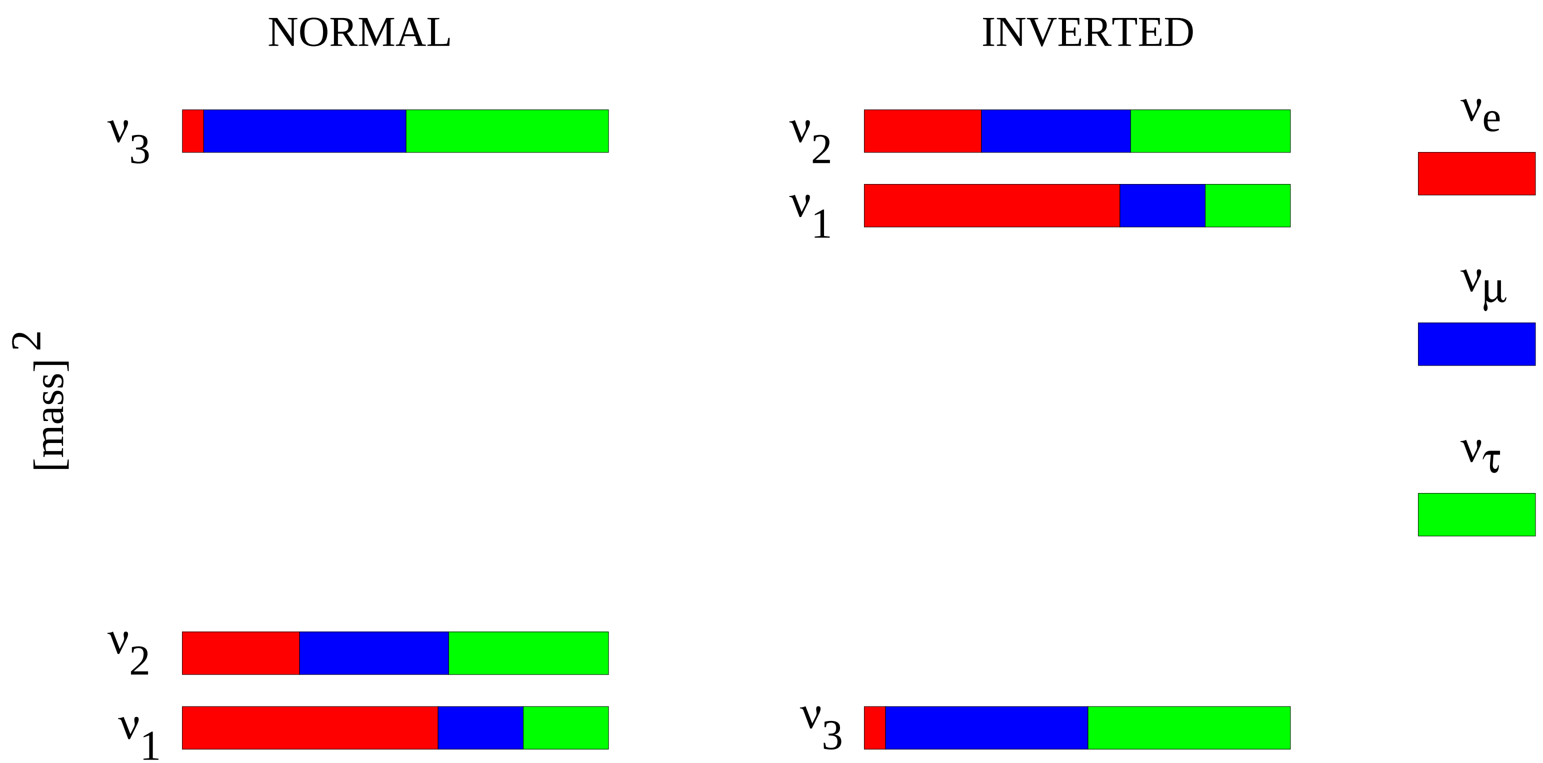
	bf $\pm 1\sigma$	acc. $@\,3\sigma$	
Δm^2_{21}	$(7.6 \pm 0.2)\,10^{-5}\,\mathrm{eV}^2$	(8%)	KamLAND
$\sin^2\theta_{12}$	0.32 ± 0.023	(22%)	SNO
$\lvert\Delta m^2_{31}\rvert$	$(2.4 \pm 0.15)\,10^{-3}\,\mathrm{eV}^2$	(17%)	MINOS
$\sin^2\theta_{23}$	0.50 ± 0.063	(33%)	SK atm

$\sin^2\theta_{13} < 0.05\ @\,3\sigma$ CHOOZ

Maltoni, TS, Tortola, Valle, hep-ph/0405172 v6; TS, 0710.5027

Three flavour osc. parameters summary

two possibilities for the neutrino mass spectrum



$\Delta m^2_{31} > 0$ $\Delta m^2_{31} < 0$

What do we learn from these numbers?

Do they indicate some structure?

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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:

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  LSND hint?
  non-standard effects beyond oscillations?

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  (e.g. Is θ_{23} exactly 45°? Tri-bimaximal mixing?)

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3-flavour oscillations

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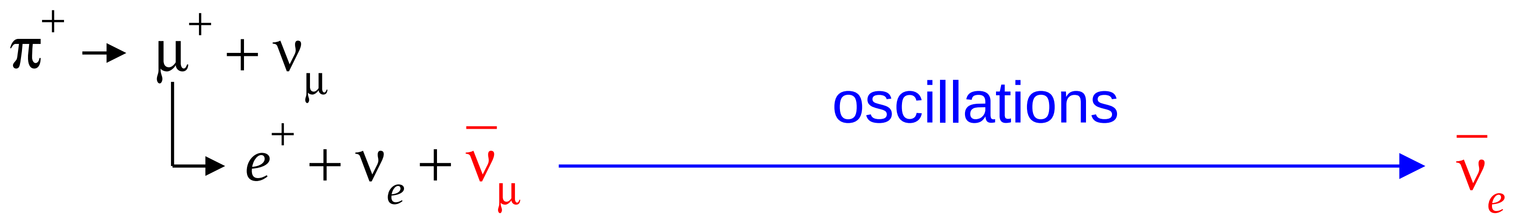
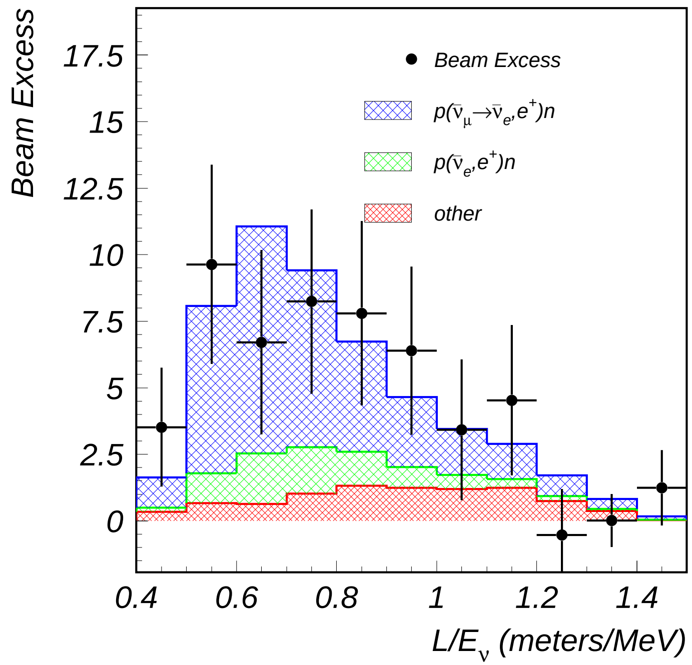
- How small is θ_{13}?
- What is the value of the CP phase δ?
- Type of the neutrino mass ordering (sign of Δm^2_{31})

The LSND puzzle and MiniBooNE results

Maltoni, TS, 0705.0107

The LSND signal





$L \simeq$ 35 m

evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

A. Aguilar *et al.*, PRD 64 (2001) 112007

$87.9 \pm 22.4 \pm 6.0$ excess events

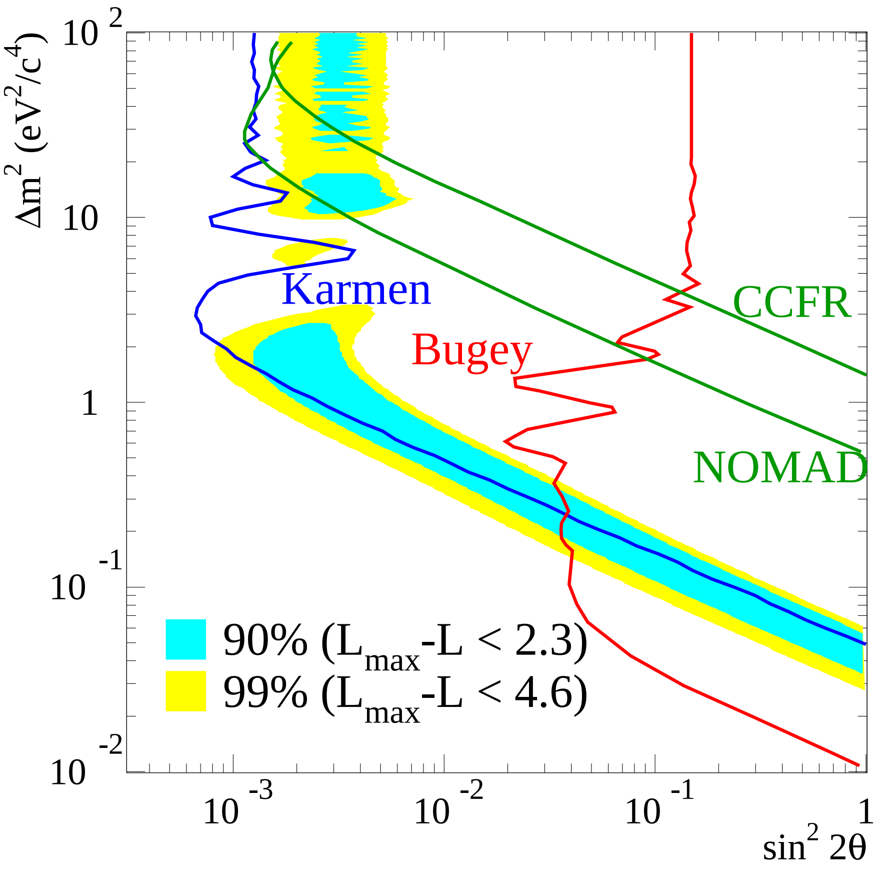
$P = (0.264 \pm 0.067 \pm 0.045)\%$

$\sim 3.3\sigma$ away from zero

Oscillation interpretation of LSND

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!



Check LSND with MiniBooNE

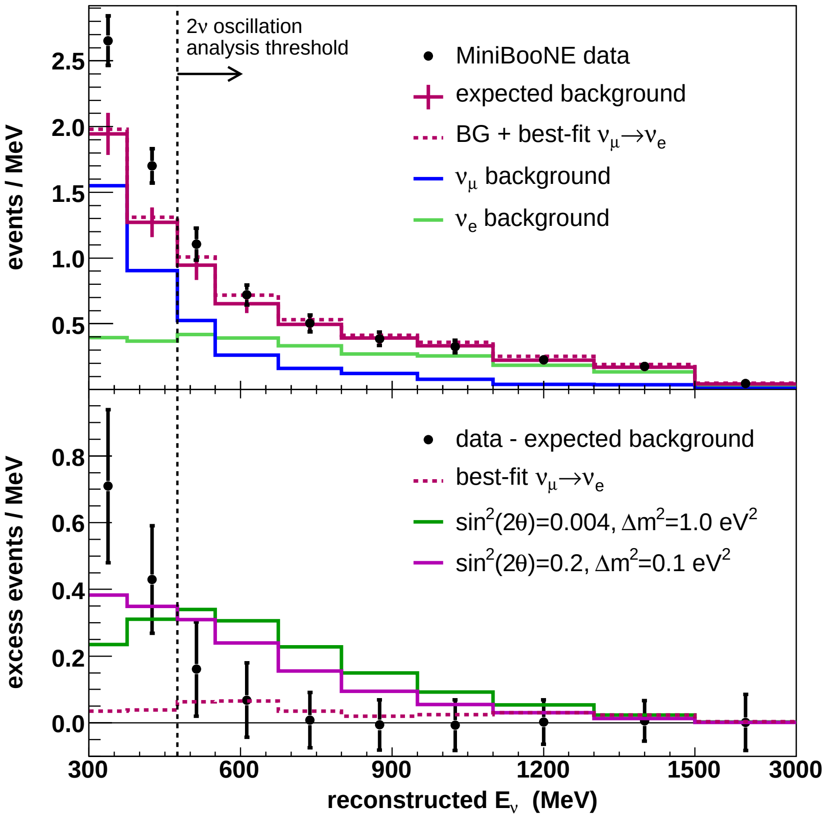
	LSND	MiniBooNE
energy	30 MeV	500 MeV
baseline	30 m	500 m
	same L/E_ν value	
channel	$\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$	$\nu_\mu \longrightarrow \nu_e$

MiniBooNE results, April 2007

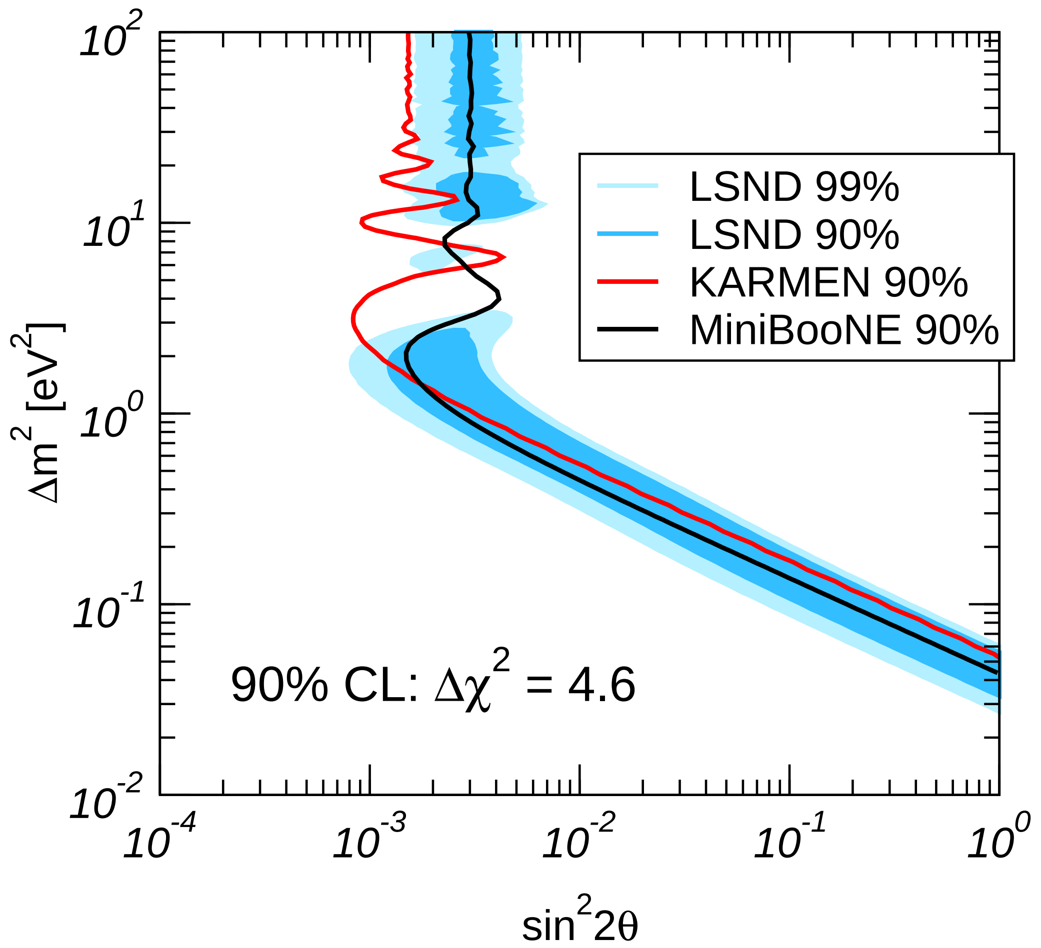
obs. events minus background:

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

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



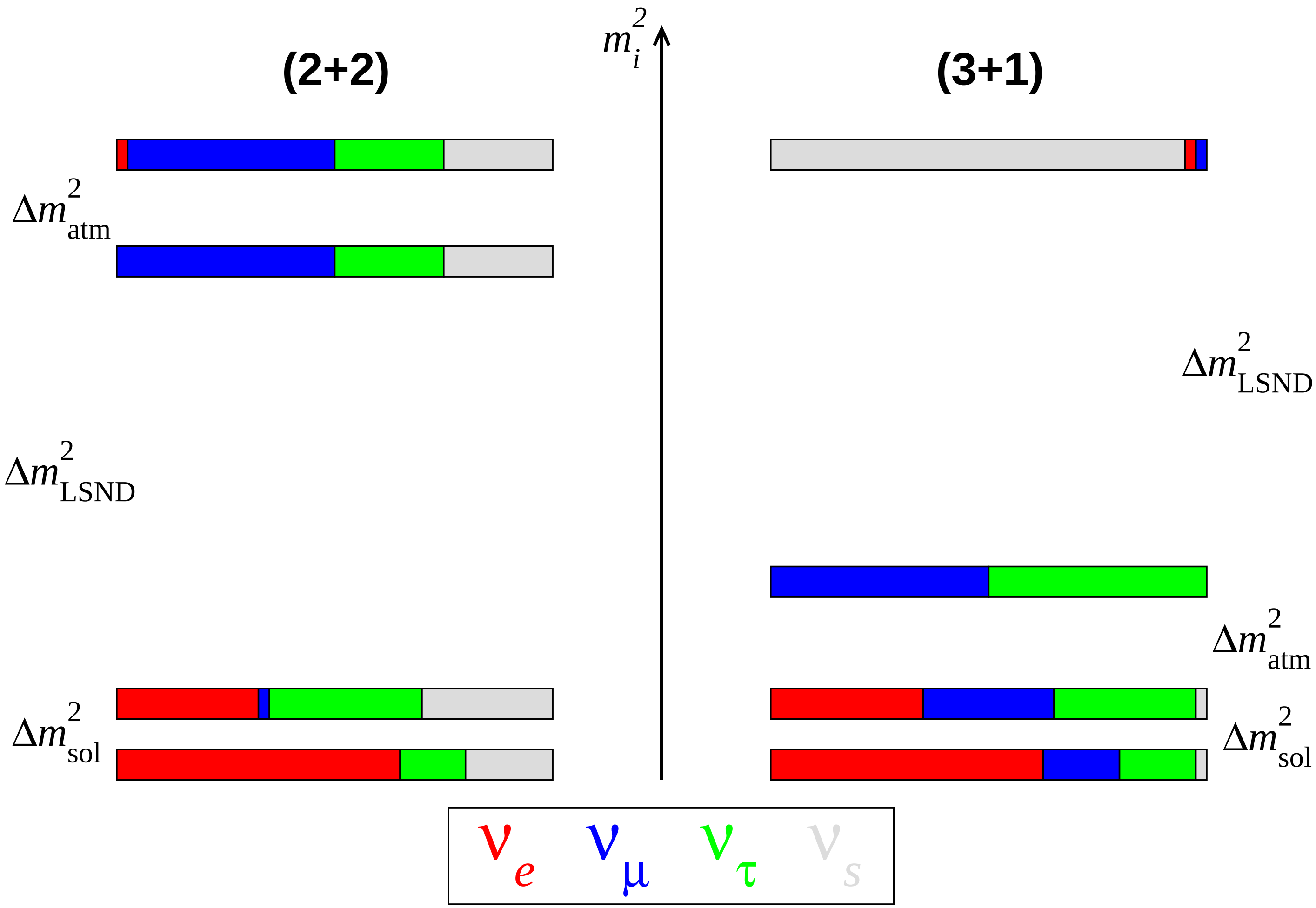
The MiniBooNE 2-neutrino limit



In the 2-neutrino framework MiniBooNE and LSND are incompatible at the 98% CL Aguilar-Arevalo et al., PRL08

Adding a sterile neutrino

4-neutrino mass schemes:



Adding a sterile neutrino

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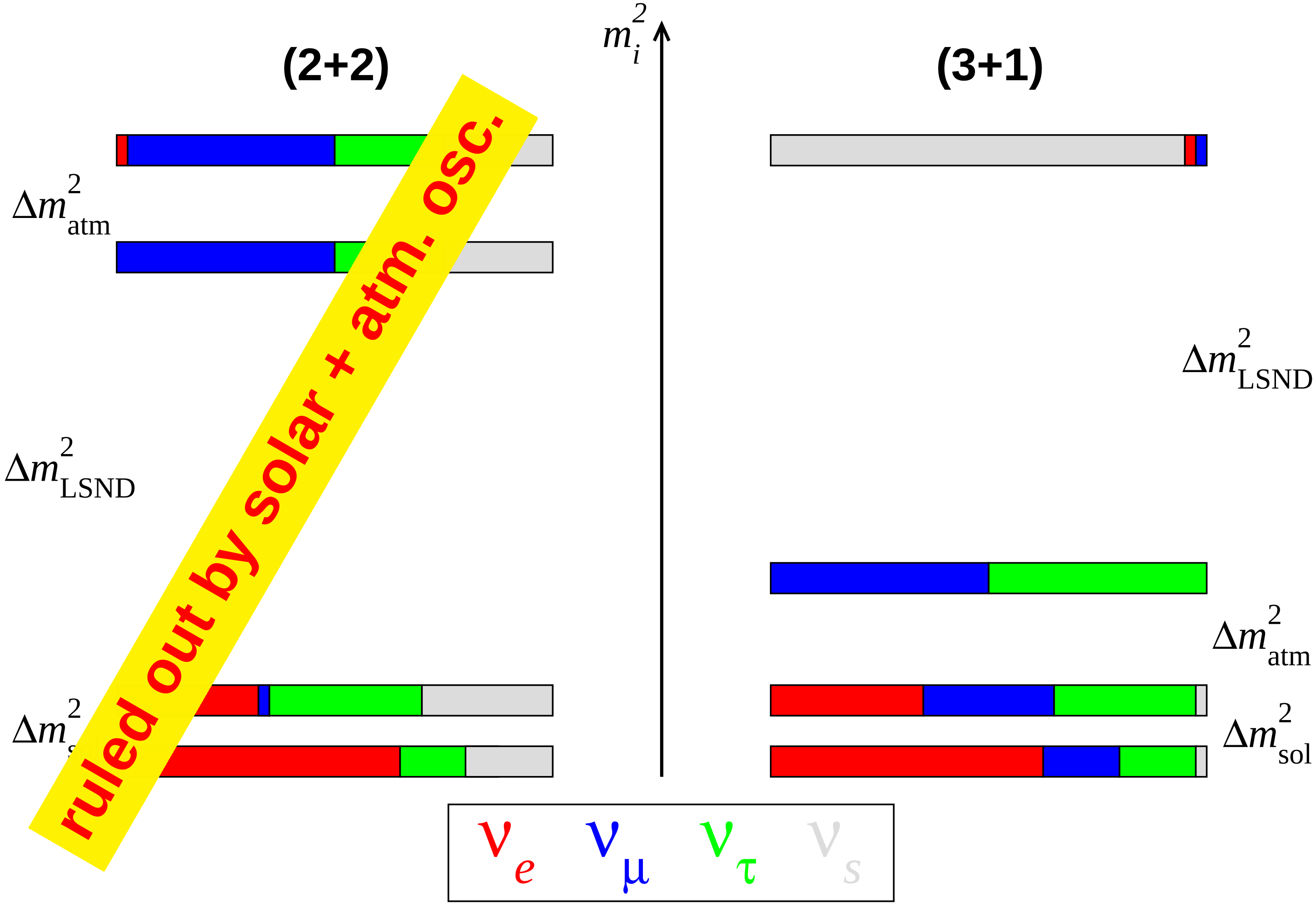


MB vs LSND in (3+1)

In (3+1) schemes the SBL appearance probability is effectively 2-ν oscillations:

$$P_{\mu e} = \sin^2 2\theta_{\rm SBL} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

with

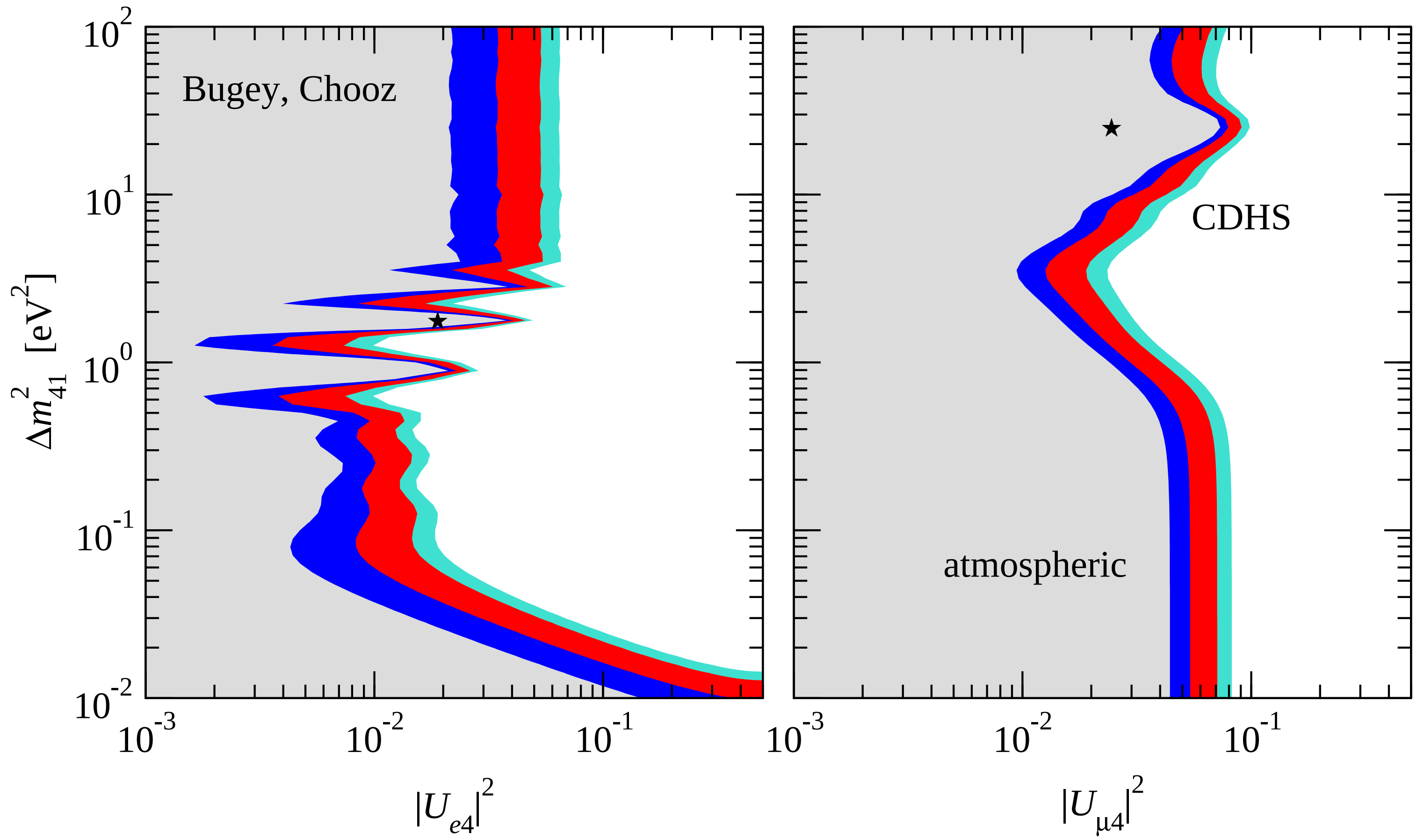
$$\sin^2 2\theta_{\rm SBL} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

LSND / MiniBooNE inconsistency is the same as in the 2-flavour analysis presented by the MiniBooNE collaboration (98% CL)

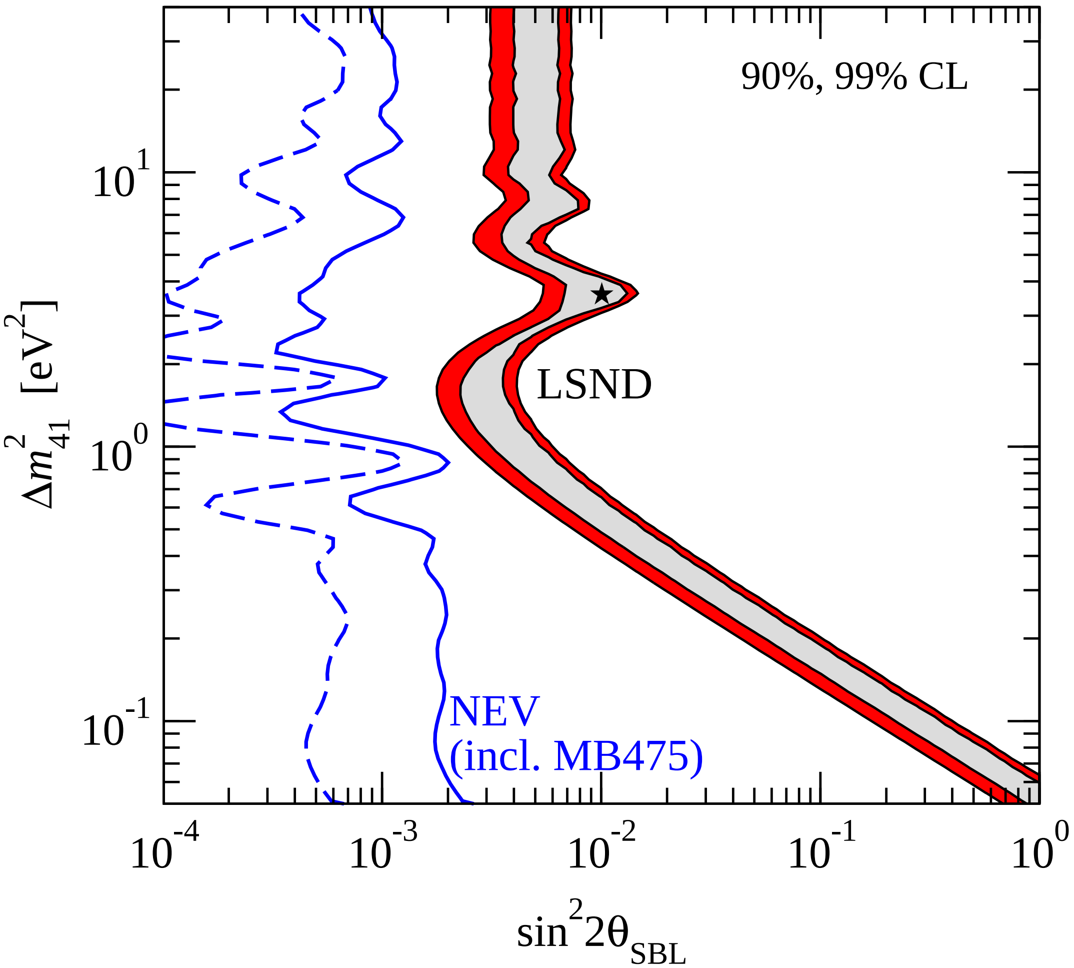
Appearance vs disappearance in (3+1)

appearance amplitude $\sin^2 2\theta_{\mathrm{SBL}} = 4|U_{e4}|^2|U_{\mu 4}|^2$

disappearance experiments bound $|U_{e4}|^2$ and $|U_{\mu 4}|^2$



(3+1) global



before MB:
$\chi^2_{\mathrm{PG}} = 20.9\,(2\,\mathrm{dof})$

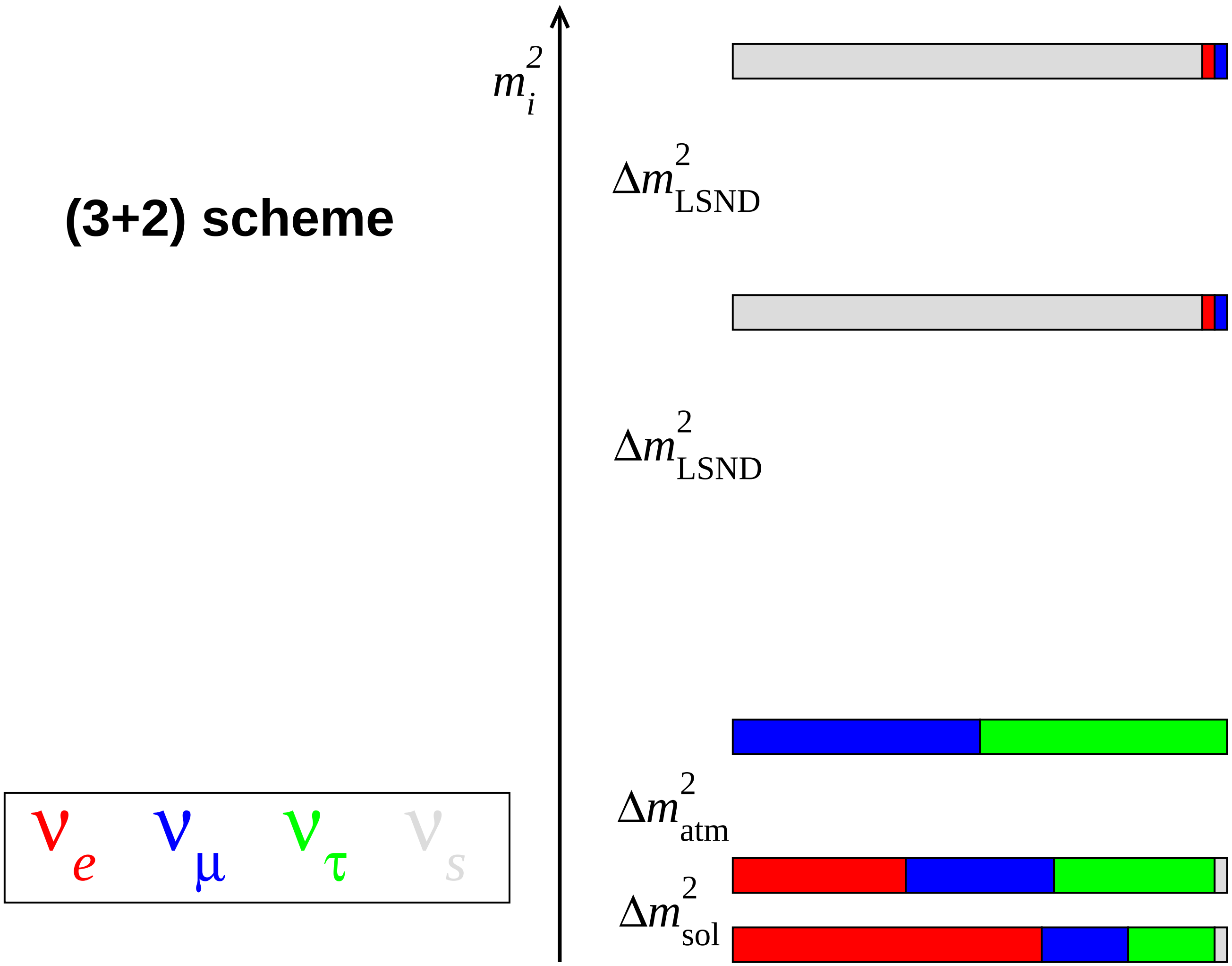
MB incl.:
$\chi^2_{\mathrm{PG}} = 24.7\,(2\,\mathrm{dof})$

disagreement at about 4σ

More sterile neutrinos?

5-neutrino oscillations

(3+2) scheme



Sorel, Conrad, Shaevitz, hep-ph/0305255

(3+2) appearance probability

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

with the definitions

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

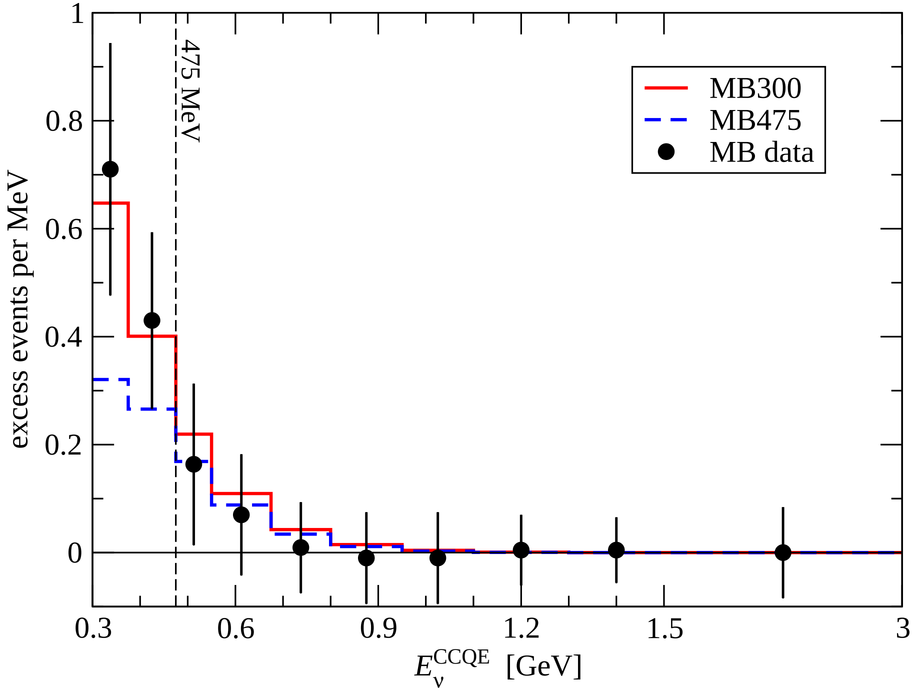
(3+2) osc. include the possibility of CP violation!

remember: MiniBooNE: neutrinos, LSND: anti-neutrinos

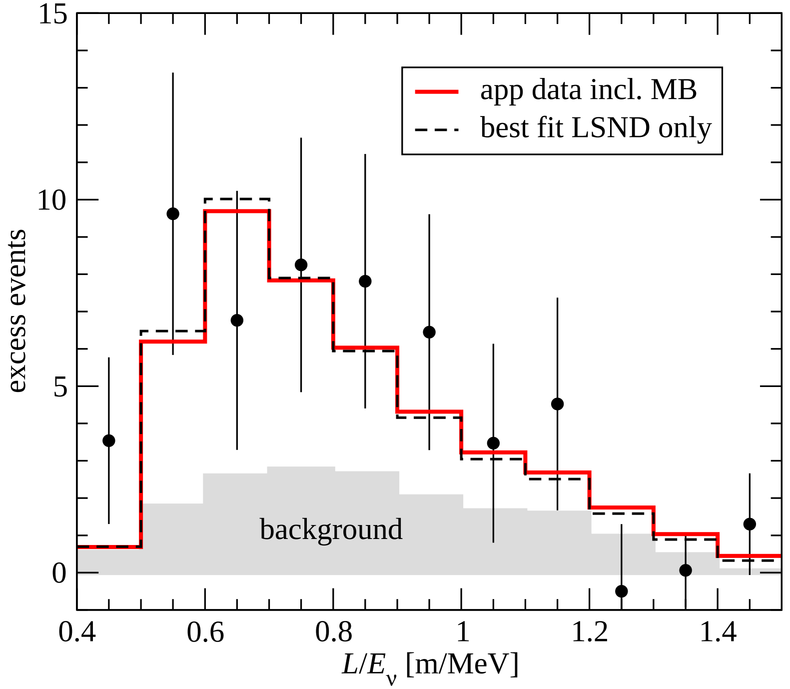
(3+2) appearance data

best fit point spectra:

MiniBooNE



LSND



Perfect fit to appearance data:

w/o MB low energy excess: $\chi^2_{\rm min} = 16.9/(29-5)$

with MB low energy excess: $\chi^2_{\rm min} = 18.5/(31-5)$

(3+2) disappearance data

what about the disappearance data?

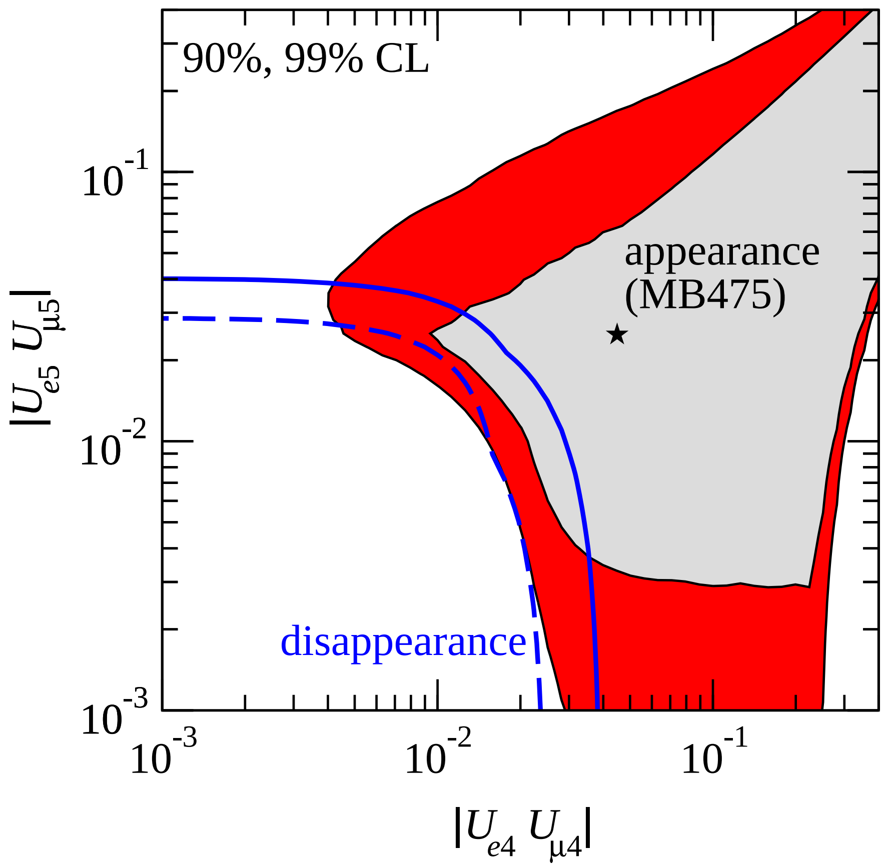
$$\begin{aligned} P_{\nu_\alpha \to \nu_\alpha} &= 1 - 4 \left(1 - \sum_{i=4,5} |U_{\alpha i}|^2 \right) \sum_{i=4,5} |U_{\alpha i}|^2 \sin^2 \phi_{i1} \\ &- 4\, |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54} \end{aligned}$$

$\Rightarrow$ bound $|U_{ei}|$ and $|U_{\mu i}|$ ($i = 4, 5$), similar as in (3+1)

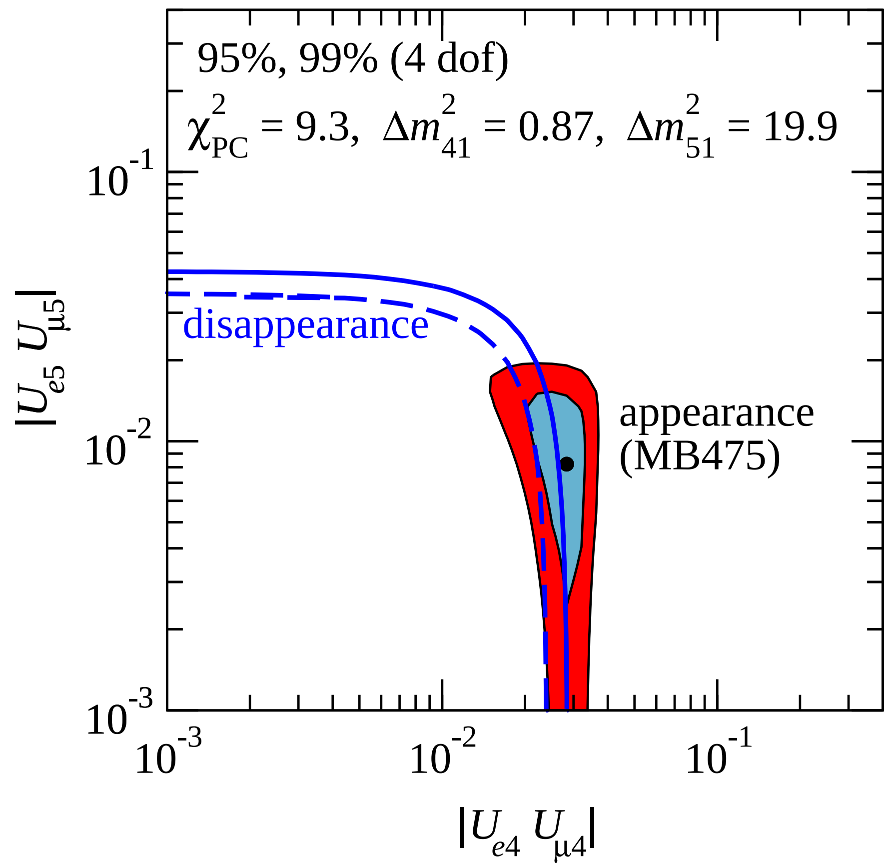
to be reconciled with appearance amplitudes $|U_{ei} U_{\mu i}|$

(3+2) app vs disap

projection



section



(3+2) global

testing consistency of disappearance and appearance data:

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

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

inconsistency at about 3.1σ

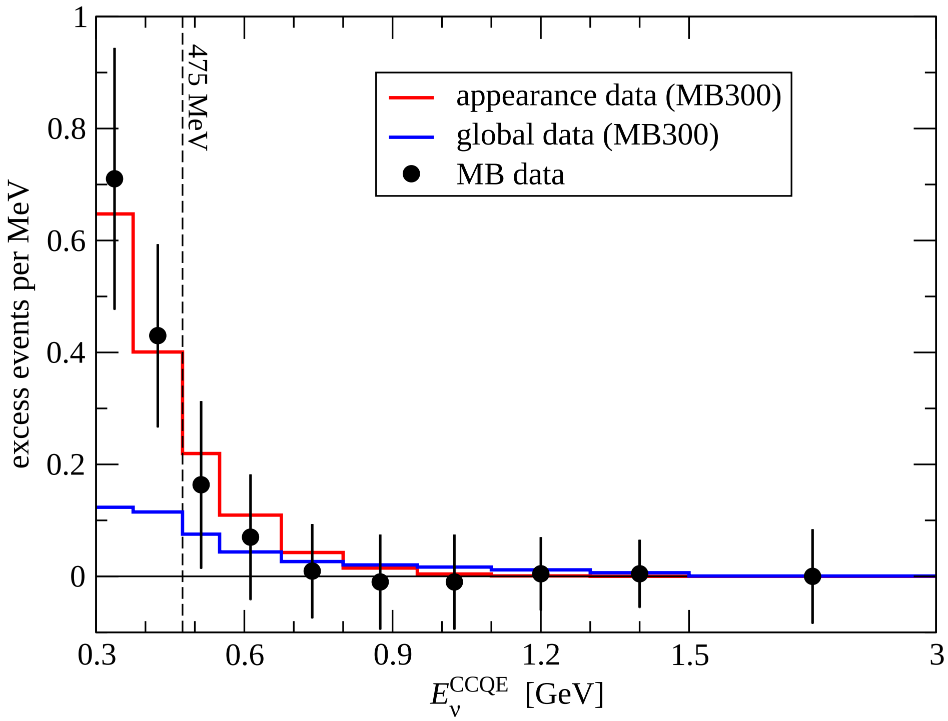
parameters in common $|U_{e4}U_{\mu 4}|, |U_{e5}U_{\mu 5}|, \Delta m^2_{41}, \Delta m^2_{51}$

best fit: $\Delta m^2_{41} = 0.9$ eV^2, $\Delta m^2_{51} = 6.5$ eV^2, $\chi^2_{\rm min} = 94.5/(107-7)$

$\chi^2_{\text{min, global (3+1)}} - \chi^2_{\text{min, global (3+2)}} = 6.1/4$ dof (81% CL)

the low energy MB excess in the (3+2) fit

the MB low energy excess is not reproduced at the global best fit point:



$$\chi^2_{\rm MB300} = 104.4/(109-7)$$

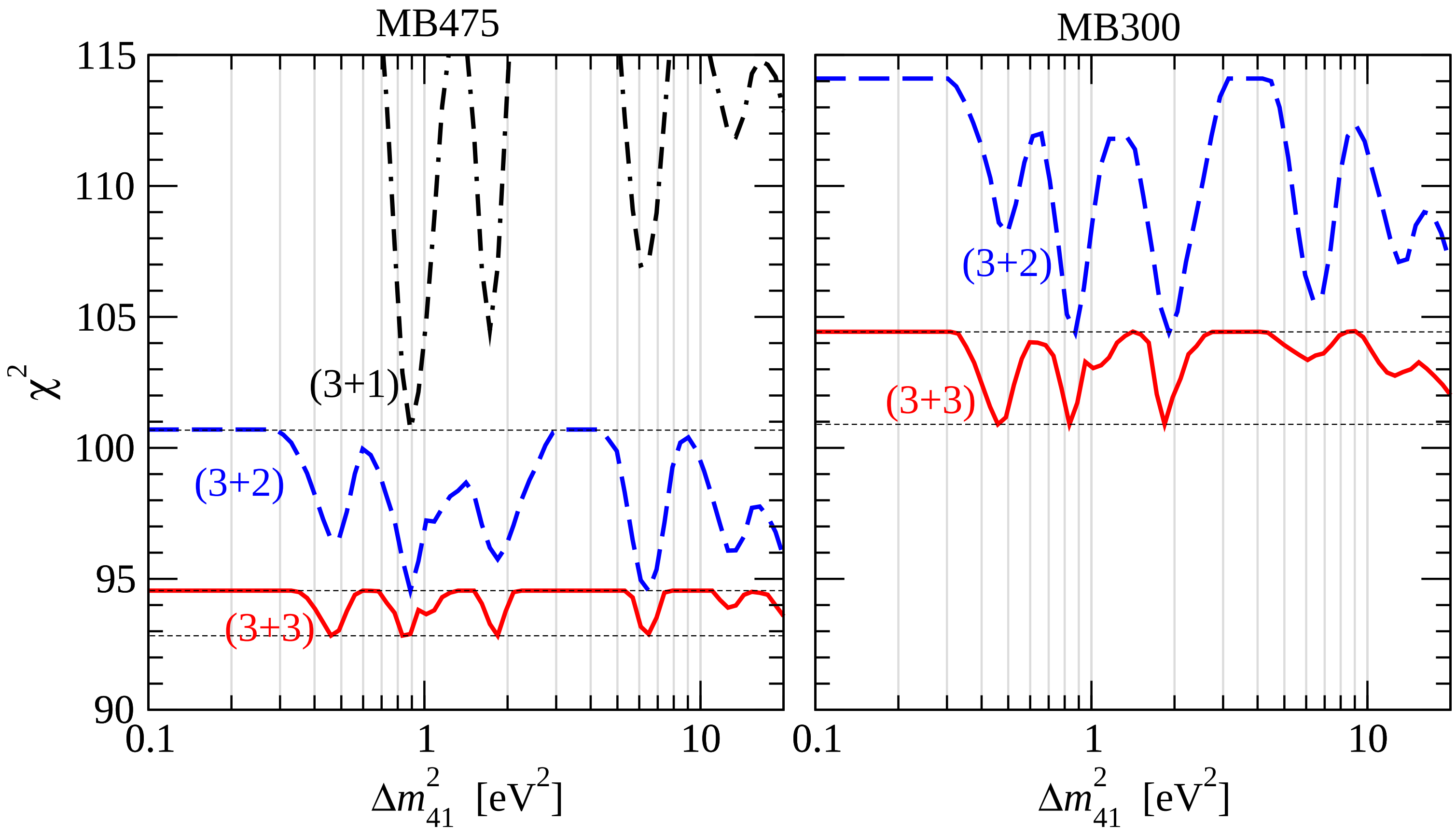
$$\chi^2_{\rm MB475} = 94.5/(107-7)$$

$$\chi^2_{\rm PG} = 25.1/4$$

$$\mathrm{PG} = 4.8 \times 10^{-5}\ (4\sigma)$$

adding another sterile: (3+3)

(3+3) global fit



	Δm^2_{41}	Δm^2_{51}	Δm^2_{61}	$\chi^2_{\rm min}$	$\chi^2_{(3+2)} - \chi^2_{(3+3)}$	CL
MB475	0.46	0.83	1.84	92.8	$1.7/4$	20%
MB300	0.46	0.83	1.84	100.9	$3.5/4$	52%

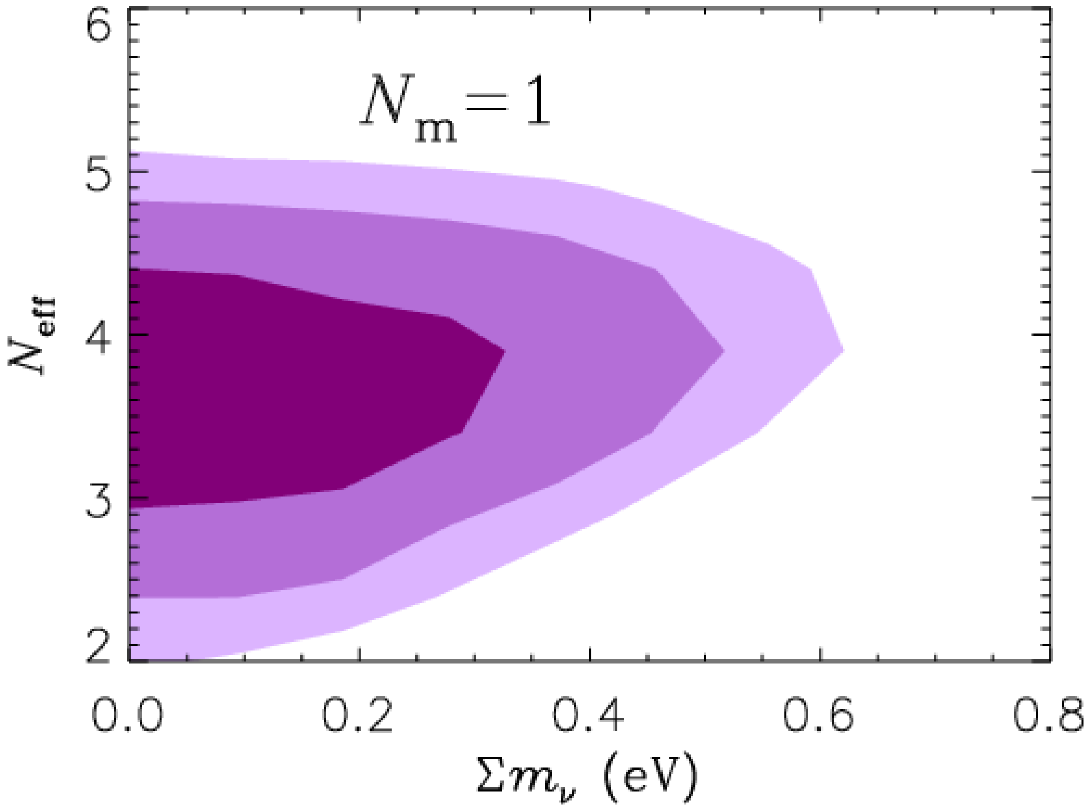
All these sterile neutrino schemes

have problems with cosmology

- sterile states contribute to the relativistic degrees of freedom (CMB, BBN)
- conflict with bound on the sum of neutrino masses from various cosmological data sets (LSS)

Cosmology

SN Ia, LSS (2dF, SDSS), BAO, CMB (WMAP, BOOMERANG)



68%, 95%, 99% CL

Hannestad, Raffelt, astro-ph/0607101

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
- 1 decaying sterile neutrino Palomares-Riuz, Pascoli, Schwetz 05
- 2 decaying sterile neutrinos with CPV
- sterile neutrinos and new gauge boson Nelson, Walsh 07

KamLAND+atmospheric antineutrino data

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KARMEN, TWIST

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- 1 decaying sterile … Palomares-Riuz, Pascoli, Schwetz 05 **MiniBooNE**
- 2 decaying sterile neutrinos with CPV
- sterile neutrin… ge boson Nelson, Walsh 07 **MINOS+atmospheric?**

An exotic sterile neutrino with energy dependent mass or mixing

TS, 0710.2985

Energy dependent sterile neutrino

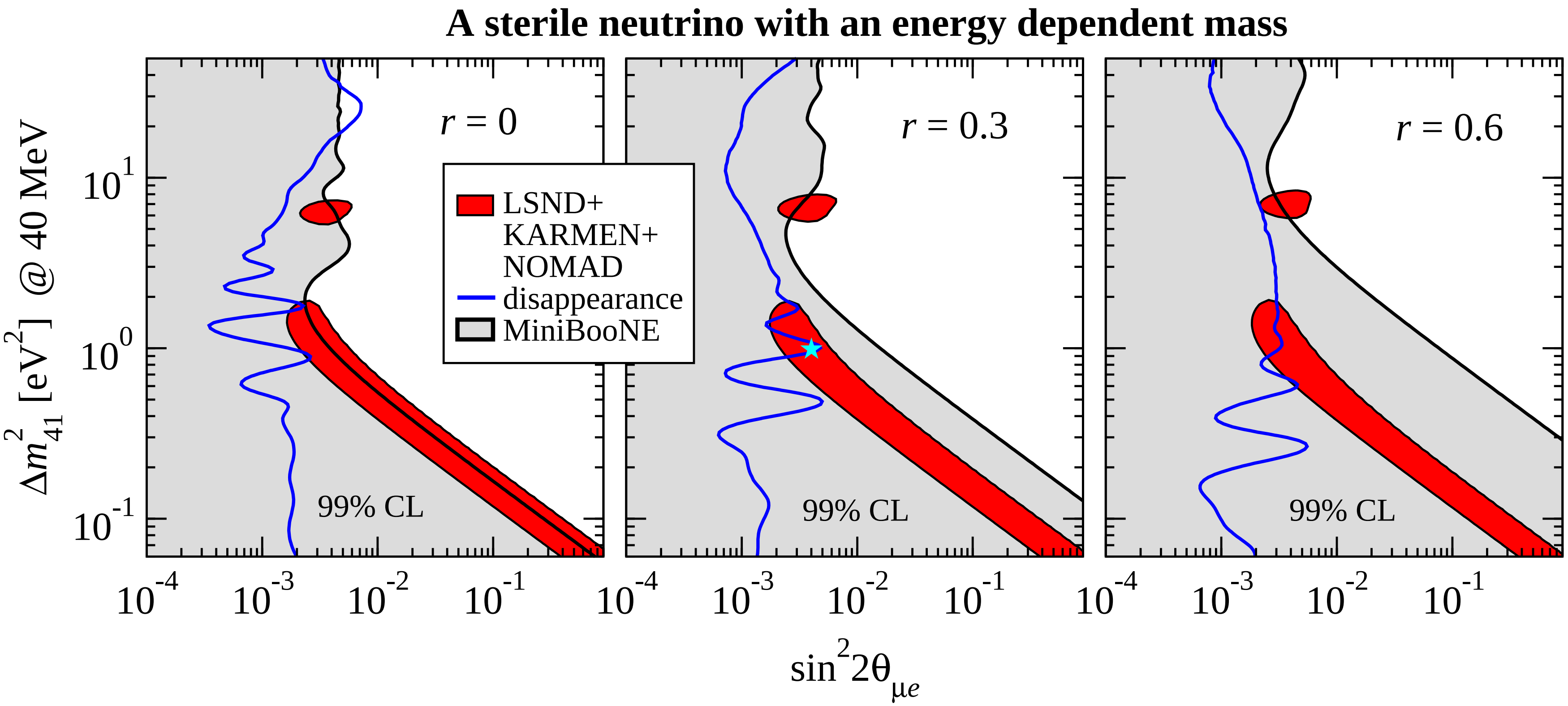
Experiment	Channel	$\langle E_\nu \rangle$
Bugey	$\bar\nu_e \to \bar\nu_e$	4 MeV
Chooz	$\bar\nu_e \to \bar\nu_e$	4 MeV
Palo Verde	$\bar\nu_e \to \bar\nu_e$	4 MeV
LSND	$\bar\nu_\mu \to \bar\nu_e$	40 MeV
KARMEN	$\bar\nu_\mu \to \bar\nu_e$	40 MeV
MiniBooNE	$\nu_\mu \to \nu_e$	700 MeV
CDHS	$\nu_\mu \to \nu_\mu$	1 GeV
NOMAD	$\nu_\mu \to \nu_e$	50 GeV

e.g., assume a 4th neutrino with an energy dependent mass:

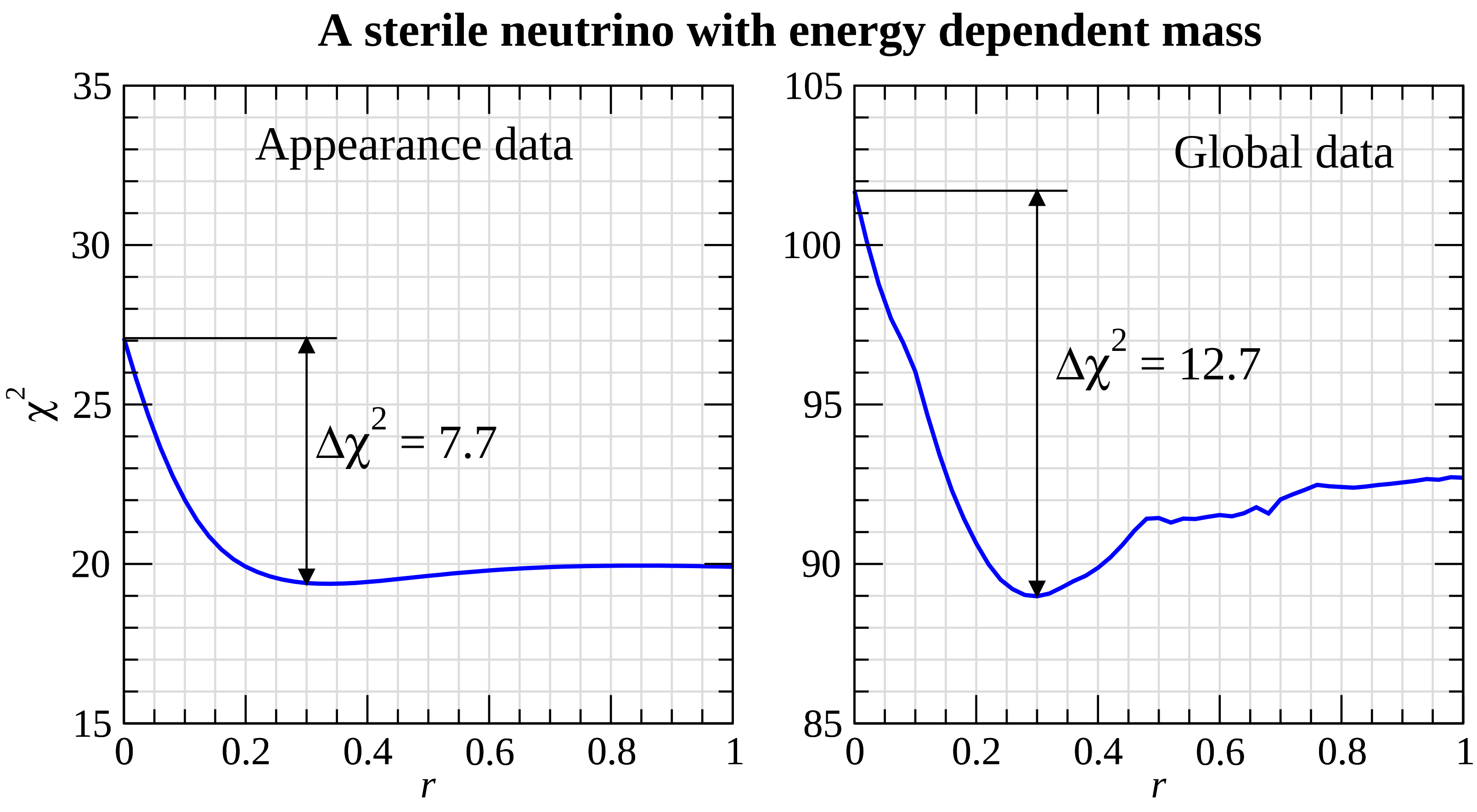
$$m_4^2 = m_*^2 \left(\frac{E_*}{E_\nu} \right)^r$$

$(r \geq 0)$

Energy dependent sterile neutrino



Energy dependent sterile neutrino



Summary LSND

- **(3+1)**: strongly disfavoured
- **(3+2)**: LSND and MiniBooNE are consistent
  but: severe tension in the global fit
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- **(3+1)**: strongly disfavoured
- **(3+2)**: LSND and MiniBooNE are consistent
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For the rest of this talk I will assume a non-oscillation explanation for the LSND signal and the low-energy MiniBooNE excess, and stick to the three-neutrino oscillation framework.

Future oscillation experiments

Upcoming experiments

Conventional beam experiments: **Reactor experiments with near and far detectors:**   **Off-axis superbeams:**

Upcoming experiments

Label	L	$\langle E_\nu \rangle$	mass	channel
Conventional beam experiments:				
MINOS	$735\,\mathrm{km}$	$3\,\mathrm{GeV}$	$5.4\,\mathrm{kt}$	$\nu_\mu \to \nu_\mu, \nu_e$
Reactor experiments with near and far detectors:				
Off-axis superbeams:				

MINOS:
Fermilab to Soudan mine, 5.4 kt magnetized iron calorimeter

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MINOS	$735\,\mathrm{km}$	$3\,\mathrm{GeV}$	$5.4\,\mathrm{kt}$	$\nu_\mu \to \nu_\mu, \nu_e$
OPERA	$732\,\mathrm{km}$	$17\,\mathrm{GeV}$	$1.65\,\mathrm{kt}$	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$
Reactor experiments with near and far detectors:				
Off-axis superbeams:				

CNGS: CERN to Gran Sasso, ν_τ appearance

OPERA: 1.65 kt emulsion cloud chamber

Upcoming experiments

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D-Chooz	$1.05\,\mathrm{km}$	$\sim 4\,\mathrm{MeV}$	$\sim 10\,\mathrm{t}$	$\bar\nu_e \to \bar\nu_e$
Daya Bay	$2./1.6\,\mathrm{km}$	$\sim 4\,\mathrm{MeV}$	$\sim 80\,\mathrm{t}$	$\bar\nu_e \to \bar\nu_e$
Off-axis superbeams:				

D-Chooz: new experiment at Chooz site (50 000 events)

Daya Bay: “big” reactor experiment in China (500 000 ev)

Upcoming experiments

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Off-axis superbeams:				
T2K	$295\,\mathrm{km}$	$0.76\,\mathrm{GeV}$	$22.5\,\mathrm{kt}$	$\nu_\mu \to \nu_e, \nu_\mu$
NOνA	$812\,\mathrm{km}$	$2.22\,\mathrm{GeV}$	$20\,\mathrm{kt}$	$\nu_\mu \to \nu_e, \nu_\mu$

T2K: Tokai (JPARC) to Kamioka (SK) 22.5 kt water Cherenkov

NOνA: TASD detector, off-axis angle of 0.72°

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 ~Mt water Cerenkov at Frejus (130 km)

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  low γ *β***B** z.B. CERN-Frejus ($E_\nu \sim 0.4\,\mathrm{GeV}$) or
  high γ *β***B** (longer BL), mono-energetic *β***B**

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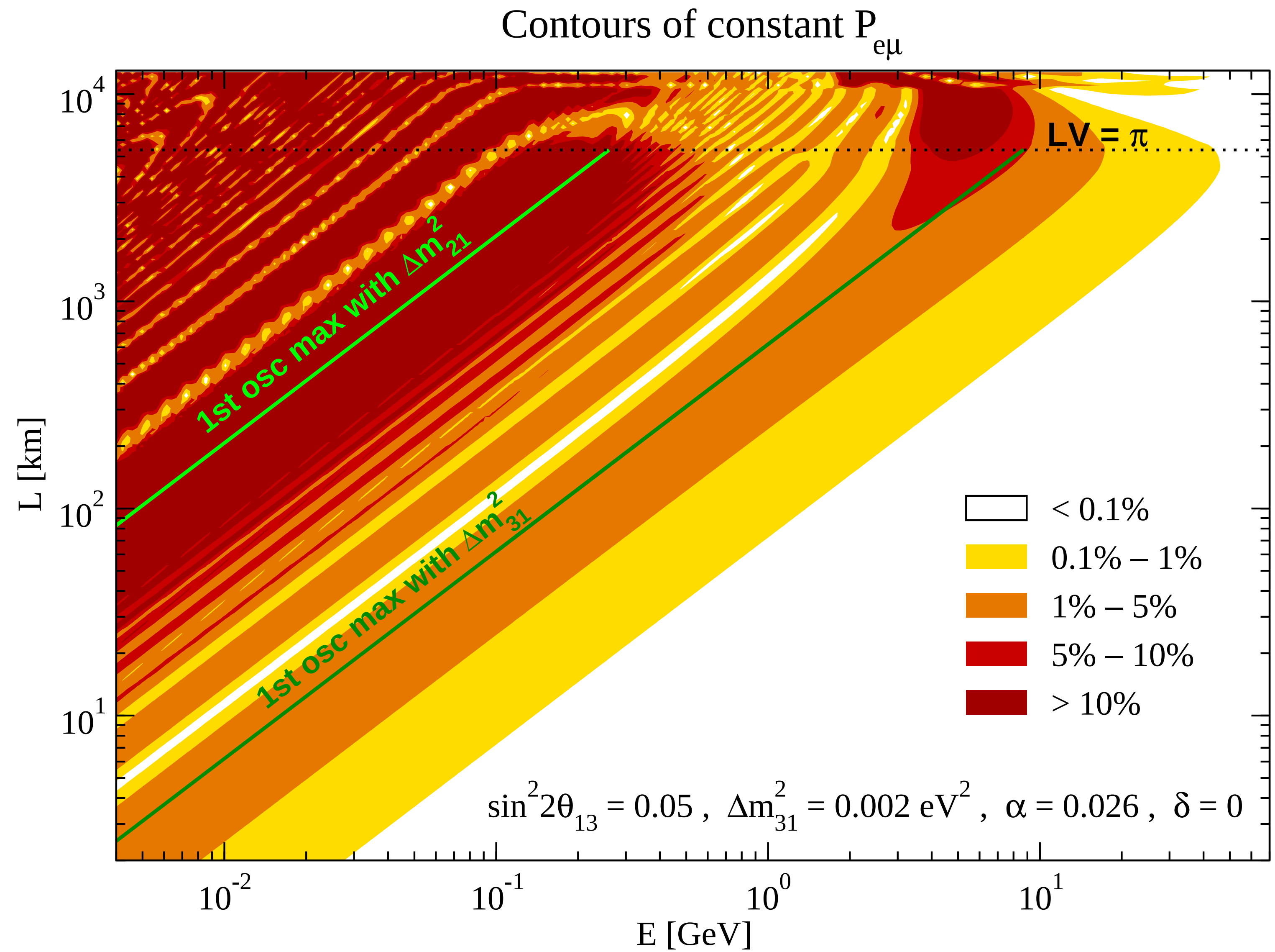
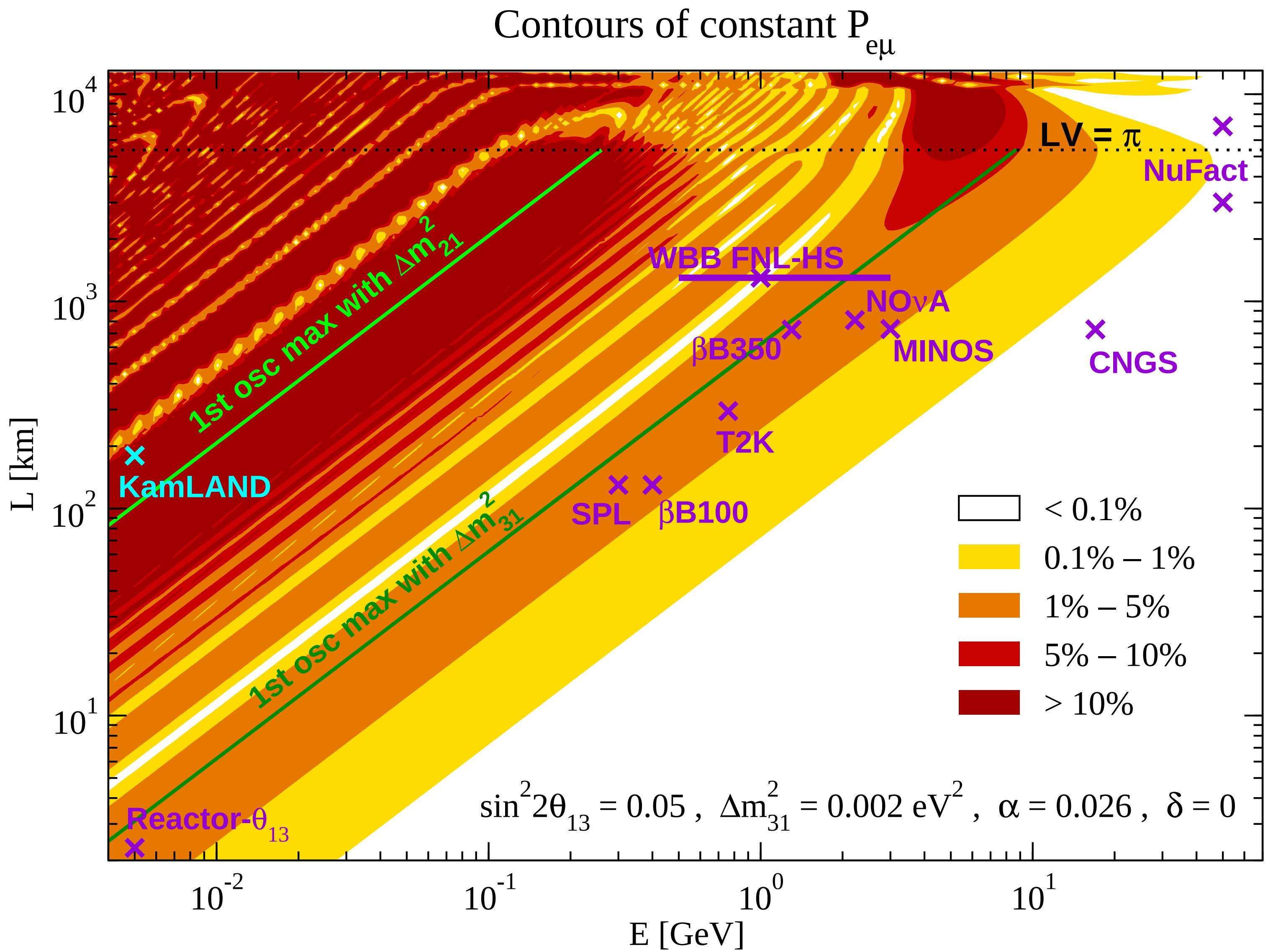
  high γ **βB** (longer BL), mono-energetic **βB**
- neutrino factory (**NuFact**) $(\nu_e, \nu_\mu \to \nu_\mu) + (\bar{\nu}_e, \bar{\nu}_\mu \to \bar{\nu}_\mu)$
  $E_\nu \sim 20 - 50\,\mathrm{GeV},\ 1000\,\mathrm{km} \lesssim L \lesssim 7000\,\mathrm{km}$

LBL oscillation probability



LBL oscillation probability



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

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- naively one would expect $\theta_{12} \sim \theta_{23} \sim \theta_{13}$
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- $\theta_{13} \ll 1$ 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**
- LBL $\nu_\mu \longrightarrow \nu_e$ appearance experiments **(MINOS, CNGS) T2K, NOνA**

Measuring θ_{13} by $\nu_\mu \to \nu_e$ at beams

The measurement of θ_{13} with the $\nu_\mu \to \nu_e$ appearance channel suffers from correlations and degeneracies:

G.L. Fogli, E. Lisi, Phys. Rev. D54 (1996) 3667
J. Burguet-Castell et al., Nucl. Phys. B608 (2001) 301
H. Minakata, H. Nunokawa, JHEP 10 (2001) 001
V.Barger, D.Marfatia, K.Whisnant, Phys. Rev. D65 (2002) 073023; D66 (2002) 053007
P.Huber, M.Lindner, W.Winter, Nucl. Phys. B645 (2002) 3; Nucl. Phys. B654 (2003) 3
and many more

Not $\sin^2 2\theta_{13}$, but only a specific parameter combination is measured very accurately

The LBL appearance oscillation probability

$$
\begin{aligned}
P_{\mu e} \;&\simeq\; \sin^2 2\theta_{13}\, \sin^2\theta_{23}\, \frac{\sin^2(1-A)\Delta}{(1-A)^2} \\
&+\; \sin 2\theta_{13}\, \hat{\alpha}\, \sin 2\theta_{23}\, \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\Delta + \delta_{\rm CP}) \\
&+\; \hat{\alpha}^2\, \cos^2\theta_{23}\, \frac{\sin^2 A\Delta}{A^2}
\end{aligned}
$$

with

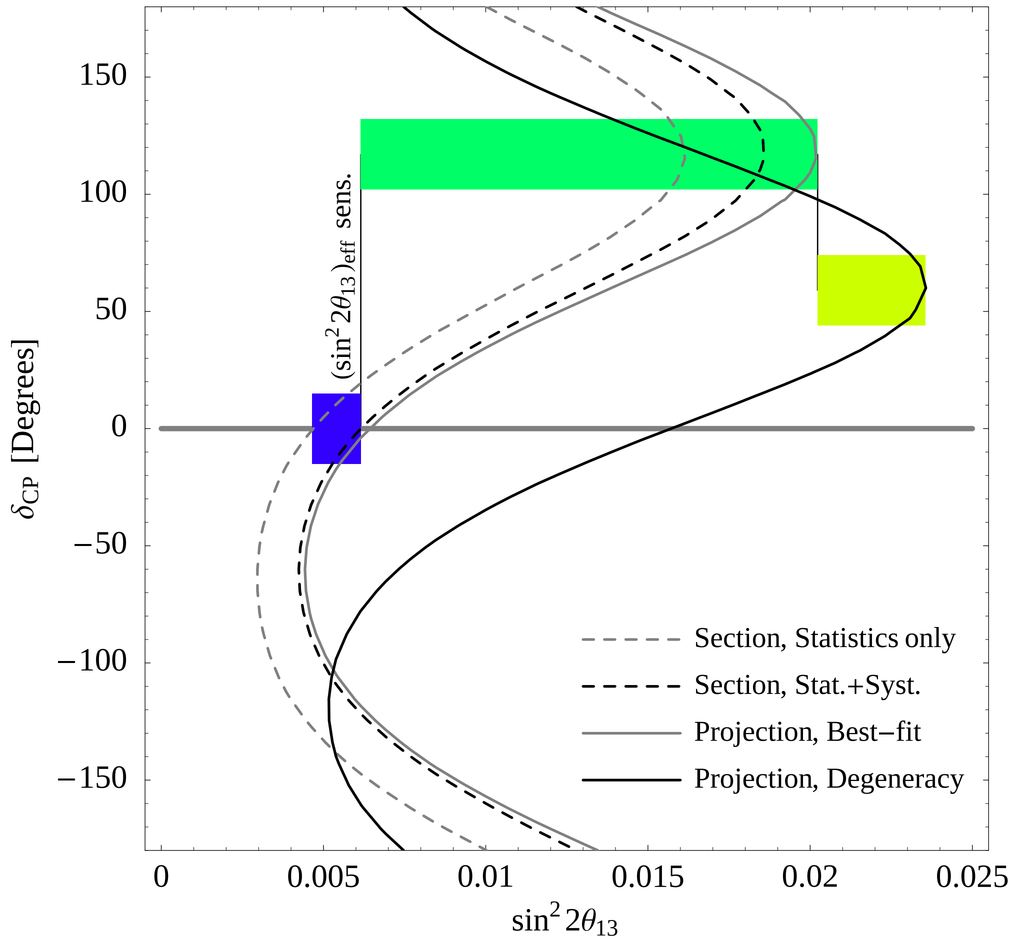
$$
\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}\,, \quad \hat{\alpha} \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sin 2\theta_{12}\,, \quad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}
$$

anti-ν: $\delta_{\rm CP} \to -\delta_{\rm CP}$, $A \to -A$, $\quad P_{e\mu}$: $\delta_{\rm CP} \to -\delta_{\rm CP}$

other hierarchy: $\Delta \to -\Delta$, $A \to -A$, $\hat{\alpha} \to -\hat{\alpha}$

Measuring θ_{13} *by* $\nu_\mu \to \nu_e$ *at beams*

T2K: $\delta - \theta_{13}$ correlation:



Huber, Lindner, Rolinec, TS, Winter, 2004

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

"Clean" measurement of $\sin^2 2\theta_{13}$:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13}\, \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$

last term negligible for $\frac{\Delta m^2_{31} L}{4E_\nu} \sim \pi/2$ and $\sin^2 2\theta_{13} \gtrsim 10^{-3}$

determination of θ_{13} is free of correlations and degeneracies

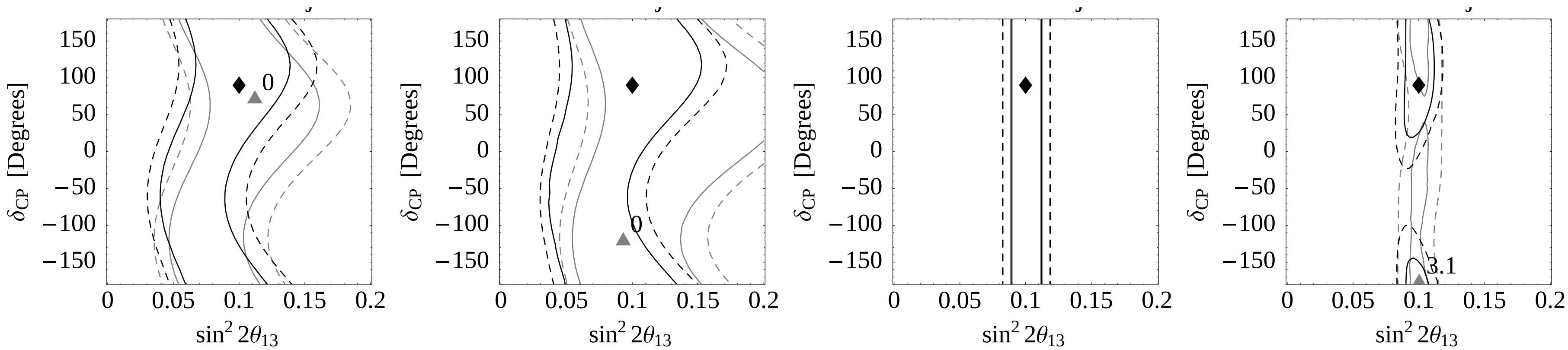
Minakata, Sugiyama, Yasuda, Inoue, Suekane, hep-ph/0211111

Huber, Lindner, TS, Winter, hep-ph/0303232

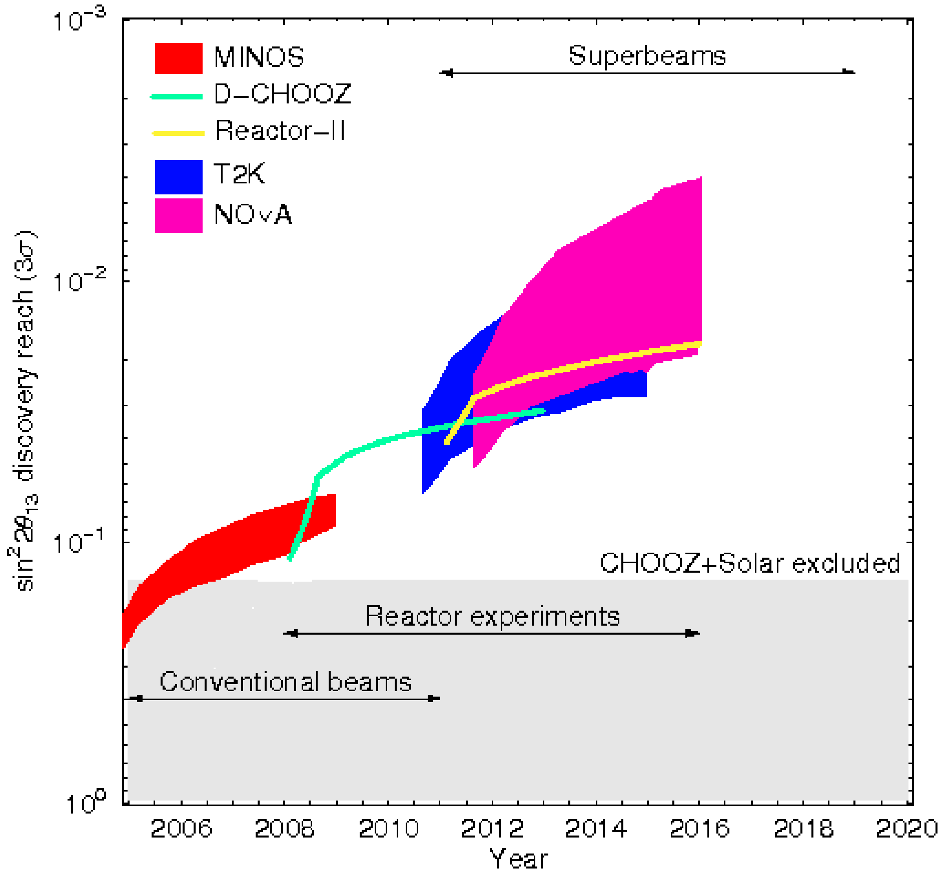
Measuring $\sin^2 2\theta_{13}$ *at beams or reactors*

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

T2K **NOνA** **Daya Bay** combined



$\sin^2 2\theta_{13}$ *discovery reach evolution*



plot by W. Winter from

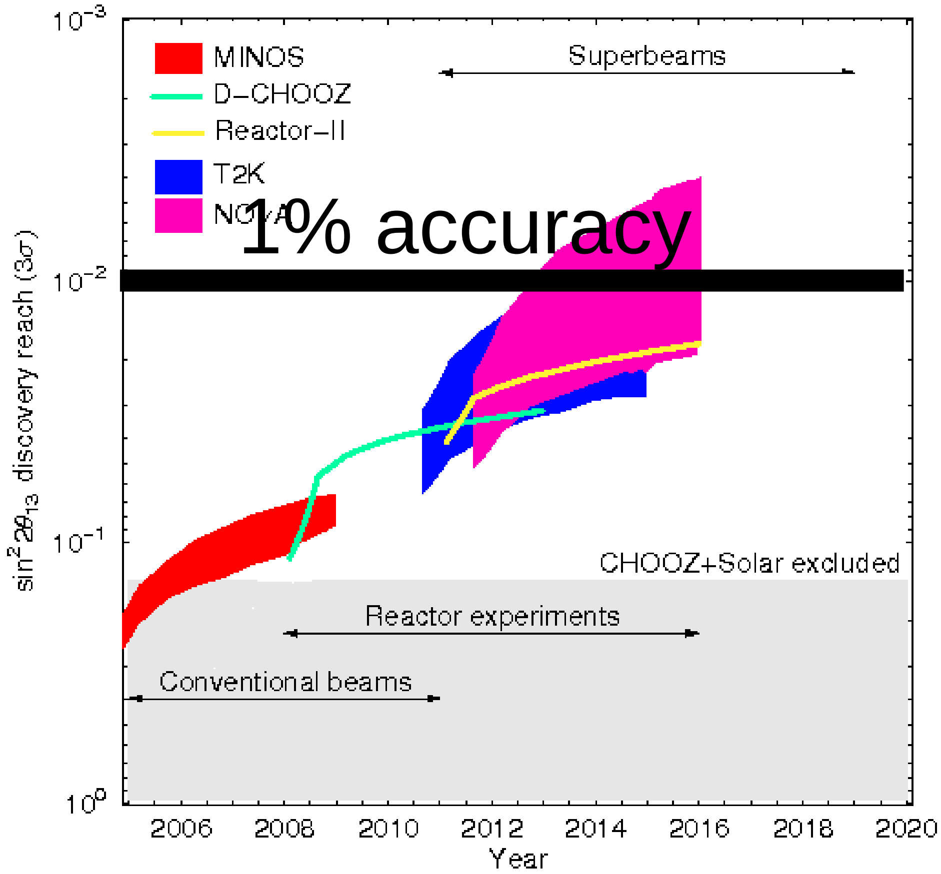
Albrow et al., hep-ex/0509019

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

$\sin^2 2\theta_{23} = 1$

LBL exps.: neutrinos only

$\sin^2 2\theta_{13}$ *discovery reach evolution*



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$\sin^2 2\theta_{23} = 1$

LBL exps.: neutrinos only

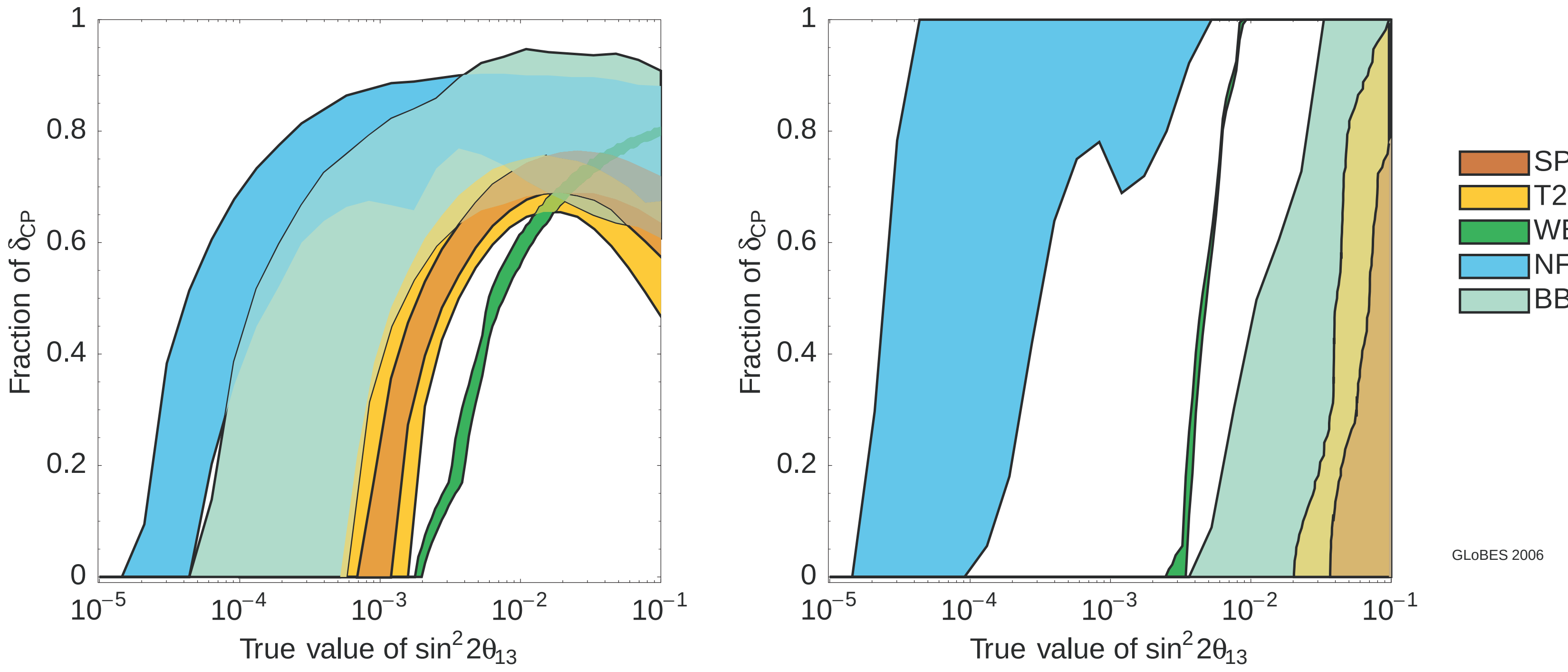
Going beyond the next generation of experiments

The ultimate goals:

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

CPV, mass hierarchy sensitivities

The ISS Physics Working Group report arxiv:0710.4947



CP violation

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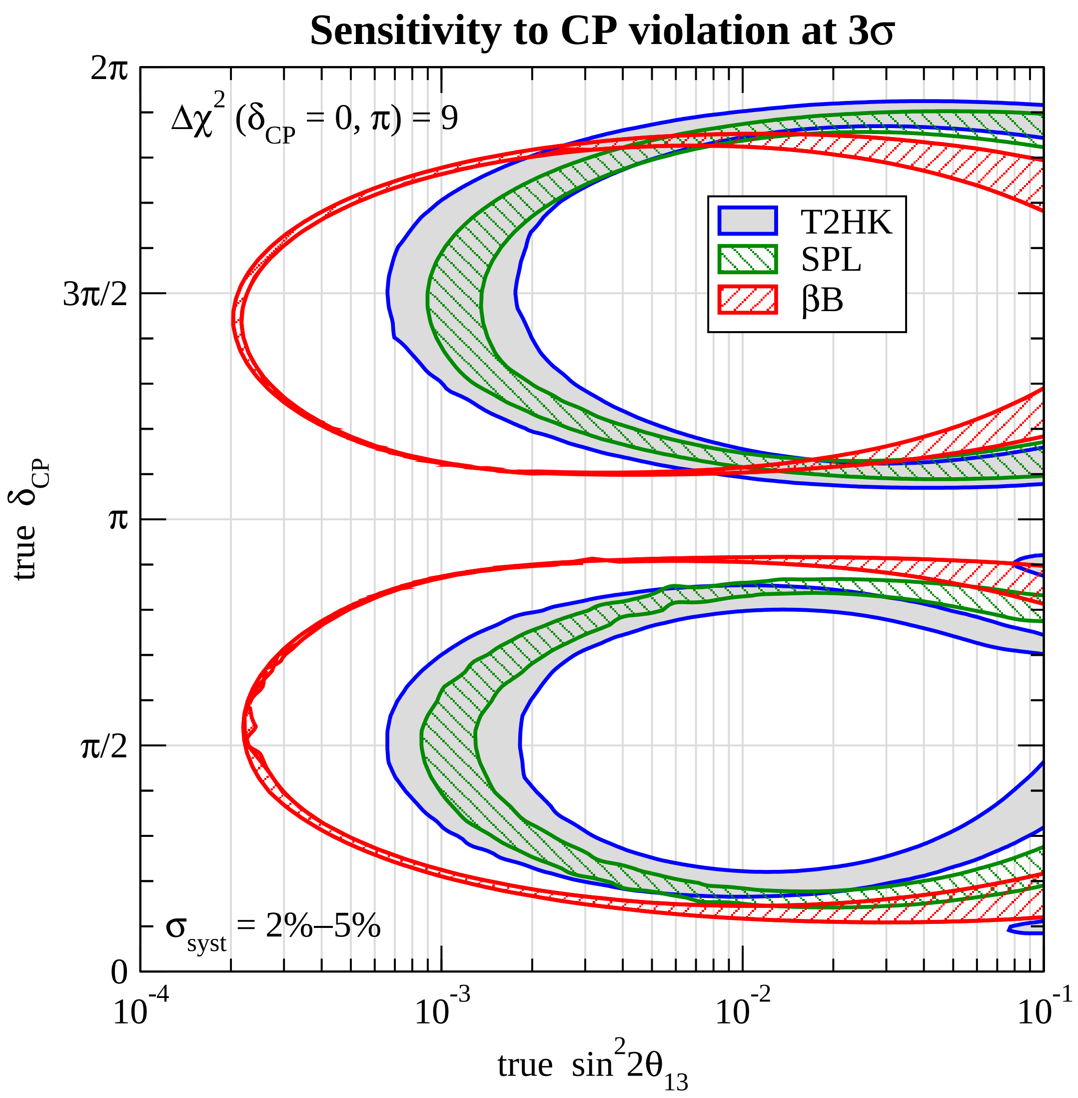
Assume standard 3-flavour oscillations
perform a parametric fit to δ

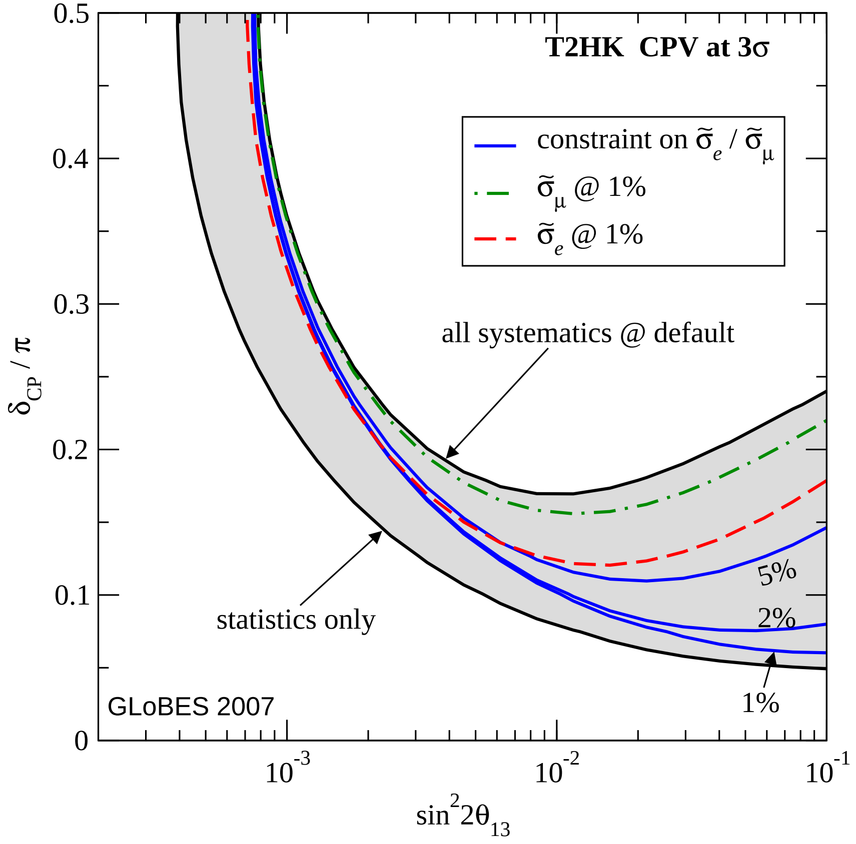
CP violation



Campagne, Maltoni, Mezzetto, Schwetz, hep-ph/0603172

Systematics in superbeam experiments

Uncertainties on fluxes and cross sections have a big impact on the sensitivity to CP violation:



Huber, Mezzetto, Schwetz, arXiv:0711.2950

Determination of the mass hierarchy

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the vacuum oscillation probability is invariant under

$$\Delta m^2_{31} \to -\Delta m^2_{31} \qquad \delta_{\rm CP} \to \pi - \delta_{\rm CP}$$

$\to$ the key to resolve the hierarchy degeneracy is the matter effect

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$\longrightarrow$ the key to resolve the hierarchy degeneracy is the matter effect

resonance condition for $\nu_\mu \to \nu_e$ oscillations:

$$\pm \frac{2EV}{\Delta m^2_{31}} = \cos 2\theta_{13} \approx 1$$

can be fulfilled for

neutrinos if $\Delta m^2_{31} > 0$ (normal hierarchy)

anti-neutrinos if $\Delta m^2_{31} < 0$ (inverted hierarchy)

Determination of the mass hierarchy

- LBL experiments need very long BL: $\gtrsim 1000$ km
  wideband beam seems to be a very appealing option:
  sensitivities somewhat below $\sin^2 2\theta_{13} = 10^{-2}$
  (**WBB** FNL to DUSEL, 1290 km, or T2KK, 1050 km)

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    Huber, Maltoni, Schwetz, 05, Campagne, Maltoni, Mezzetto, Schwetz, 06

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  - Combination of superbeam and beta beam works even at relatively short baselines (130 km) Schwetz, hep-ph/0703279
- if $\sin^2 2\theta_{13} \ll 10^{-2}$ probably only a **NuFact** can determine the hierarchy ($L >$ several 1000 km, e.g., 3000 & 7000)

Determination of θ_{13}, $\delta_{\rm CP}$, sgn(Δm^2_{31})

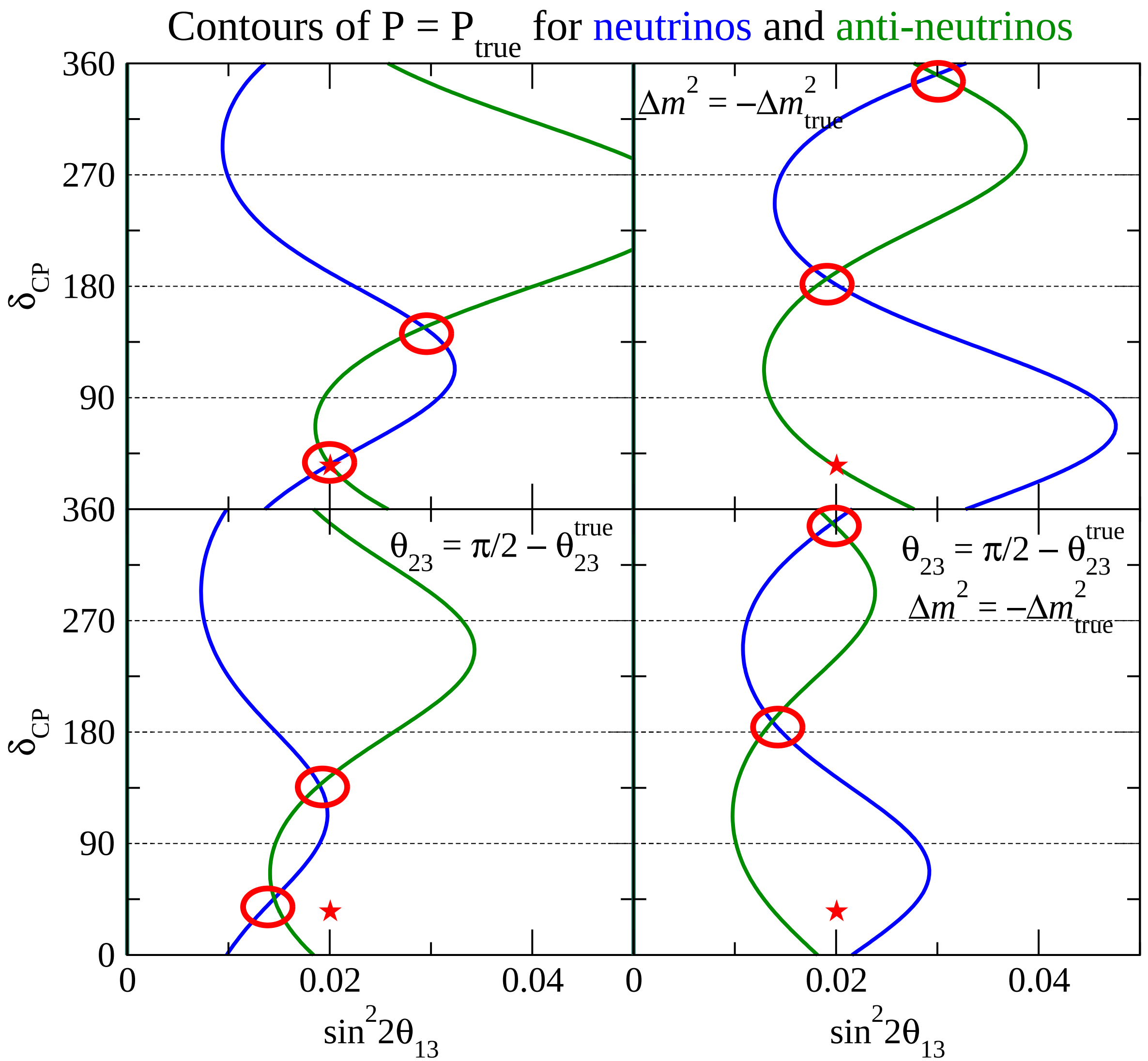
or the problem of

Degeneracies

G.L. Fogli, E. Lisi, Phys. Rev. D54 (1996) 3667; J. Burguet-Castell et al., Nucl. Phys. B608 (2001) 301; H. Minakata, H. Nunokawa, JHEP 10 (2001) 001; V.Barger, D.Marfatia, K.Whisnant, Phys. Rev. D65 (2002) 073023; D66 (2002) 053007; P.Huber, M.Lindner, W.Winter, Nucl. Phys. B645 (2002) 3; Nucl. Phys. B654 (2003) 3; J. Burguet-Castell et al., Nucl.Phys. B646 (2002) 301; O. Yasuda, New J. Phys. 6 (2004) 83; A.Donini, D.Meloni, S.Rigolin, JHEP **0406** (2004) 011

and many more

The eight-fold degeneracy



$\Delta\hat{m}^2_{21} = 7.9 \times 10^{-5}\text{eV}^2$

$\Delta\hat{m}^2_{31} = 2.5 \times 10^{-3}\text{eV}^2$

$\sin^2\hat{\theta}_{12} = 0.3$

$\sin^2\hat{\theta}_{23} = 0.4$

$\sin^2 2\hat{\theta}_{13} = 0.02$

$\hat{\delta}_{CP} = 36^\circ$

$E_\nu = 2.2$ GeV

$L = 812$ km

(**NOνA**)

Barger, Marfatia, Whisnant, Phys. Rev. D65 (2002) 073023

Resolving the degeneracies

several possibilities to resolve the degeneracies are known:

- combining information from detectors at different baselines
- "Magic baseline" ~ 7000 km (NuFact)
- using additional oscillation channels ($\nu_e \longrightarrow \nu_\tau$)
- spectral information (wide band beam)
- adding information on θ_{13} from a reactor experiment
- adding information from (Mt scale) atmospheric neutrino experiments
- ...

To conclude...

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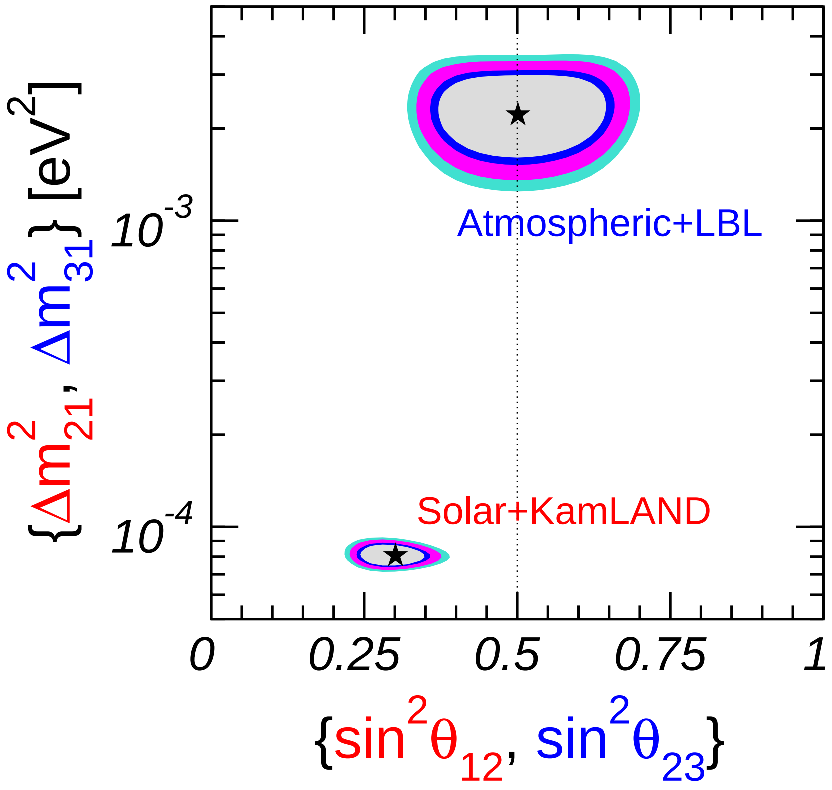
prestent status



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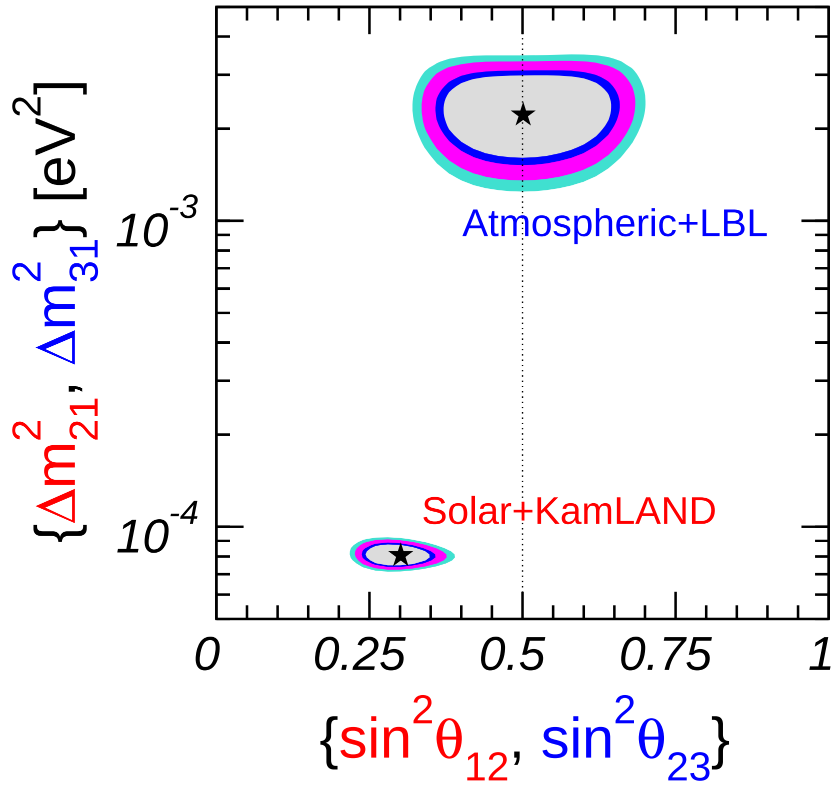
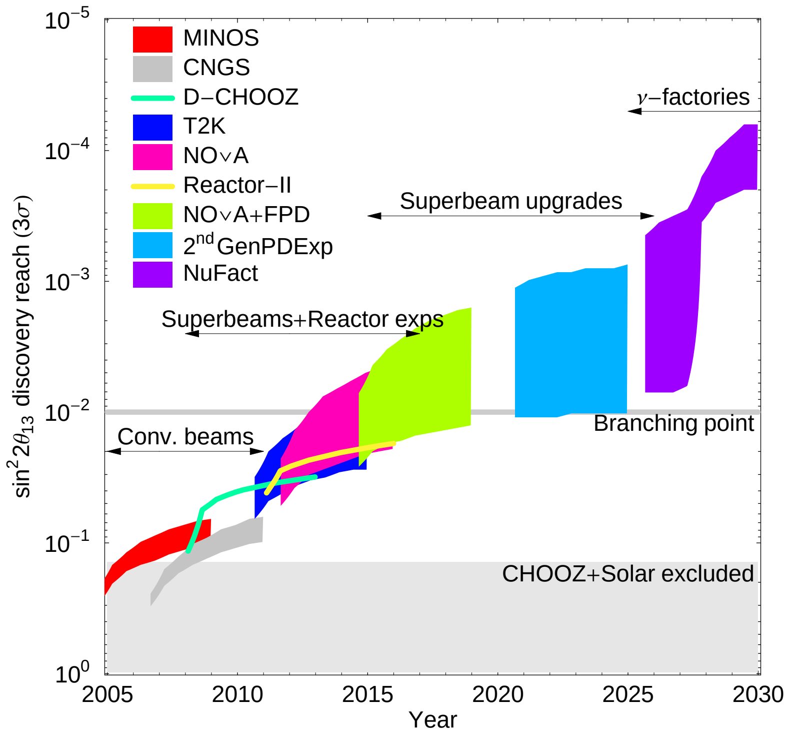
prestent status



future



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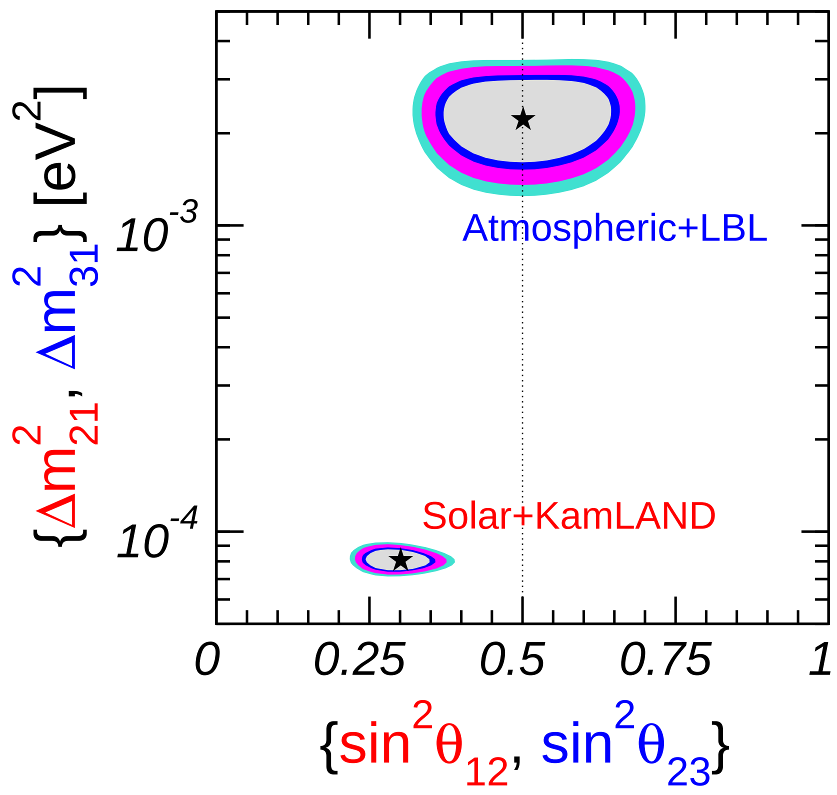

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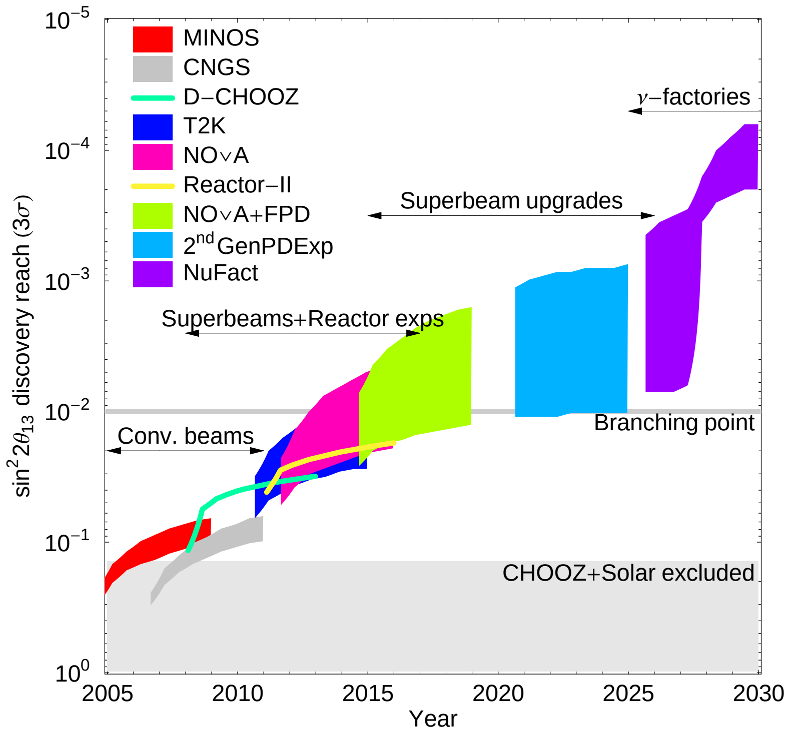

Thanks for your attention!